FEARS STRUCTURAL ENGINEERING LABORATORY

PURLIN STUDIES
Progress Report
STANDING SEAM ROOF SYSTEMS

by

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and
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Sponsored by

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CHAPTER I

INTRODUCTION

A research program to study the behavior of metal building roof systems has been undertaken at the Fears Structural Engineering Laboratory, University of Oklahoma, under the sponsorship of Star Manufacturing Company. The purpose of the portion of the research reported here was to experimentally verify the current design procedures used by Star Manufacturing Company for the design of standing seam roof systems. The design procedure is based on the following:

a) The stress distribution on a cross-section can be approximated assuming constrained bending, e.g. $f = My/I$

b) The failure criteria (allowable stresses) in the current AISI specifications are adequate.

A primary objective of the research was to measure lateral restraint forces in the intermediate bracing system. In the context used here, lateral restraint refers to the force and stiffness required to prevent lateral movement of Z-purlins to a degree that conditions (a) and (b) are valid.

Sub-objectives for determining necessary restraint for the roof system were as follows:

1) Determine if the current bracing system is adequate,

2) Determine what level of brace force exists in an intermediate bracing system,

3) Determine if the brace force accumulates from eave to ridge, and

4) Determine what level of brace force is transferred to the eave strut through the roof diaphragm.

To accomplish these objectives, a series of single and multi-span tests of the complete roof system, panel, clips, purlins and intermediate braces, was conducted. A specially constructed, fully instrumented vacuum chamber was used for the testing. Parameters varied in the test series included number of bays, span length, and intermediate bracing locations. The complete test matrix is shown in Table 1 with configurations and purposes as follows:

Test Series I

Configuration:

25 ft. 0 in. simple span, spacing 5 ft. 0 in.; one Z-test purlin; two adjacent Z-purlins; stiff ridge member; 1/3rd point intermediate bracing; indeterminate bracing system; ribs cut on panel; nominal 12 psf live load; Tests 1A and 1B.

Purposes:

To determine the load carrying capacity of the system. To determine the magnitude of the brace forces. To determine the distribution of brace forces between the eave and the ridge.

Test Series II

Configuration:

Two bays @ 25 ft. 0 in.; spacing 5 ft. 0 in.; continuous spans; one Z-test purlin line; two adjacent purlin lines; stiff ridge; 1/3rd point intermediate bracing system; ribs cut on panel; nominal 12 psf live load; Tests 2A and 2B.

Purposes:

Same as Test Series I except for a two span condition.

Test Series III

Configuration:

Two bays @ 25 ft. 0 in.; spacing 5 ft. 0 in.; continuous spans; one Z-test purlin line; two adjacent Z-purlin lines; stiff ridge; 1/3rd point intermediate bracing system; ribs cut on panel; nominal 20 psf live load; Tests 3A and 3B.

Purposes:

Same as Test Series II.

Test Series IV

Configuration:

25 ft. 0 in. simple span; various spacing; one Z-test purlin; two adjacent Z-purlins (except 4B); stiff eave member; various bracing schemes; determinate bracing; nominal 30 psf live load; Test 4A, 4B, 4C, 4D and 4E.

Purposes:

To investigate the effect of various bracing schemes on purlin strength; to measure brace force accumulation from eave to ridge.

Test 4A

Configuration: Intermediate braces at 1/3rd points; spacing 4 ft. 10 in.; three purlin setup; strain gaged cross-section.

Purpose: Base test.

Test 4B

Configuration: No intermediate braces; spacing 7 ft. 3 in.; two purlin setup; panel-to-purlin clips not installed.

Purpose: To determine the effect of panel "hugging" on lateral restraint.

Test 4C

Configuration: Same as Test 4A except no strain gages.

Purpose: Same as Test 4A.

Test 4D

Configuration: Intermediate braces at midspan; spacing 4 ft. 10 in.; three purlin test setup.

Purpose: To determine effects of a single line of intermediate braces at midspan.

Test 4E

Configuration: No intermediate braces; spacing 4 ft. 10 in.; three purlin test setup; panel to purlin clips installed.

Purpose: To determine purlin strength without intermediate braces.

Test Series V

Configuration:

Three bays @ 20 ft. 0 in.; spacing 4 ft. 9 in.; continuous spans; one Z-test purlin line; stiff eave; 1/3rd point intermediate bracing for Test 5A; midspan bracing for Test 5B; nominal 20 psf live load; Tests 5A and 5B.

Purposes:

Same as Test Series I except for a three span system.

Test Series VI

Configuration:

Three bays @ 20 ft. 0 in.; spacing 4 ft. 9 in.; continuous spans; one Z-test purlin line; two adjacent purlins; stiff eave; midspan intermediate bracing; nominal 40 psf live load; Test 6A and 6B.

Purposes:

Same as Test Series V.

For all tests the purlins were supported by short sections of typical building rafters and simulated live load was applied using vacuum as described in Chapter II. Figure 1 shows purlin and intermediate brace locations for the six test series. The purlins were oriented with the top flanges facing in the same direction as shown in Figures 2 and 3. Intermediate braces were either right angles or sections of steel tubing with threaded stud inserts. The braces were attached to the purlin as shown in Figure 4 and anchored to a relatively stiff structural member at either the eave, or the ridge location. For Test Series I through III, the restraining member was located at the simulated ridge and was made of two channels bolted together as shown in Figure 2(c). For Test Series IV through VI, the restraining member was located at the simulated eave and was made of two channels and one purlin as shown in Figure 3(b). The following is a complete description of the testing procedure and test results. Comparison with analytical predictions from the Star Manufacturing Company design program are also made.

Table 1
Test Matrix

Parameters / Tests	Thickness (in.)	Purlin Spacing (ft)	Span & Bay Size	Standard Brace (1/3 Pts)	℄ Brace	No Brace	Clips Installed	Remarks
1-A	.084"	5'	1@25'	X			X	The deck rib was cut at all purlin locations.
1-B	.084"	5'	1@25'	X			X	
2-A	.064"	5'	2@25'	X			X	Same as Series I.
2-B	.064"	5'	2@25'	X			X	
3-A	.096"	5'	2@25'	X			X	Same as Series I.
3-B	.096"	5'	2@25'	X			X	
4-A	.096"	4'9"	1@20'	X			X	
4-B	.096"	4'10"	1@20'			X		
4-C	.096"	4'10"	1@20'	X			X	
4-D	.096"	4'10"	1@20'		X		X	
4-E	.096"	4'10"	1@20'			X	X	
5-A	.056,.064	4'9"	3@20'	X			X	
5-B	.056,.064	4'9"	3@20'		X		X	
6-A	.064,.084	4'9"	3@20'		X		X	
6-B	.064,.084	4'9"	3@20'		X		X	

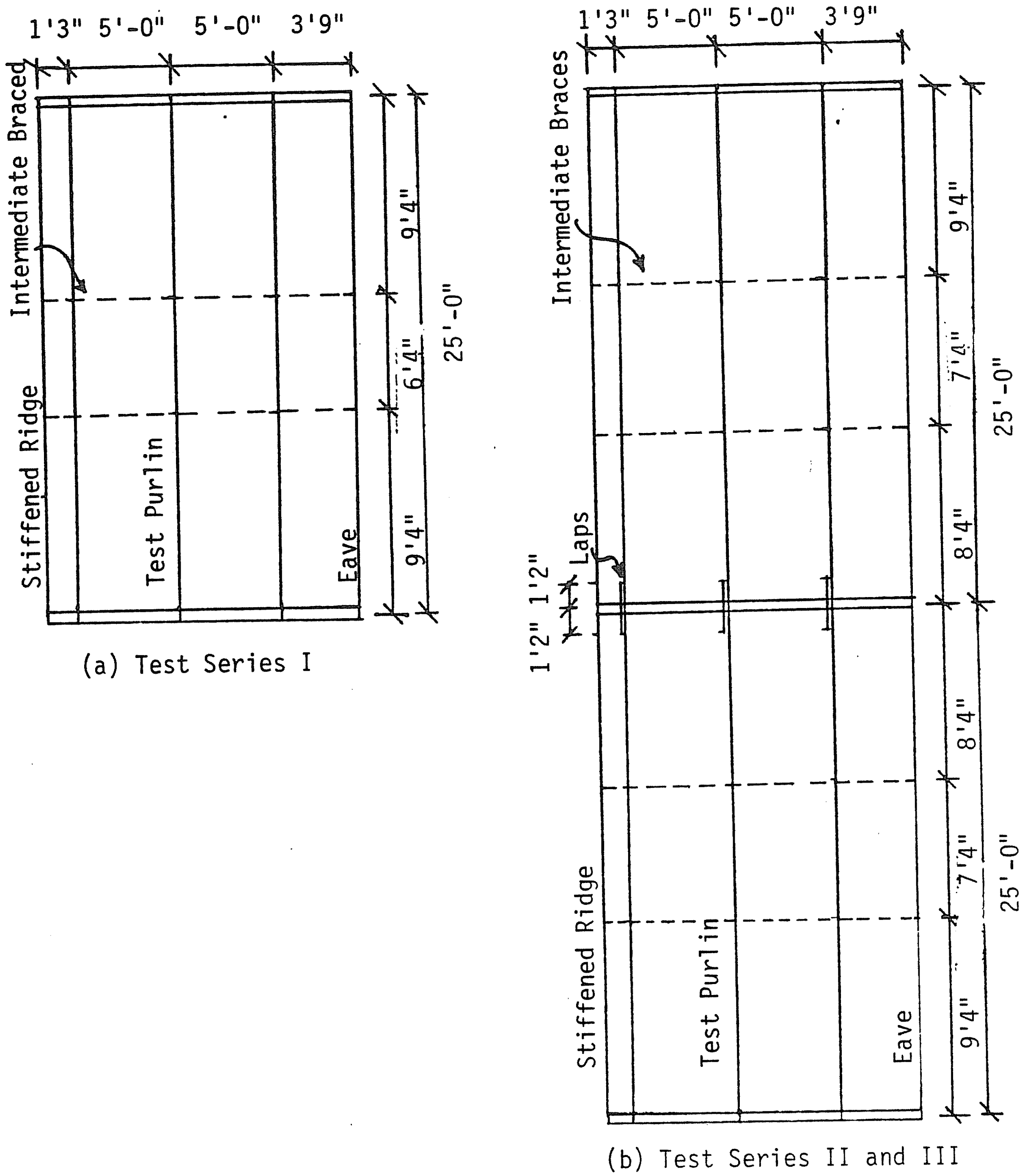
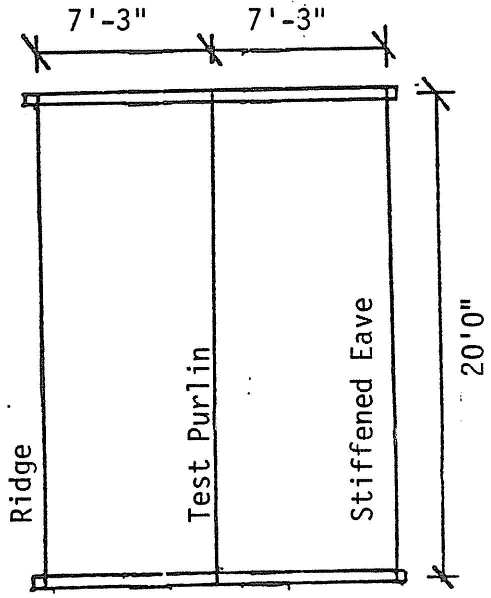
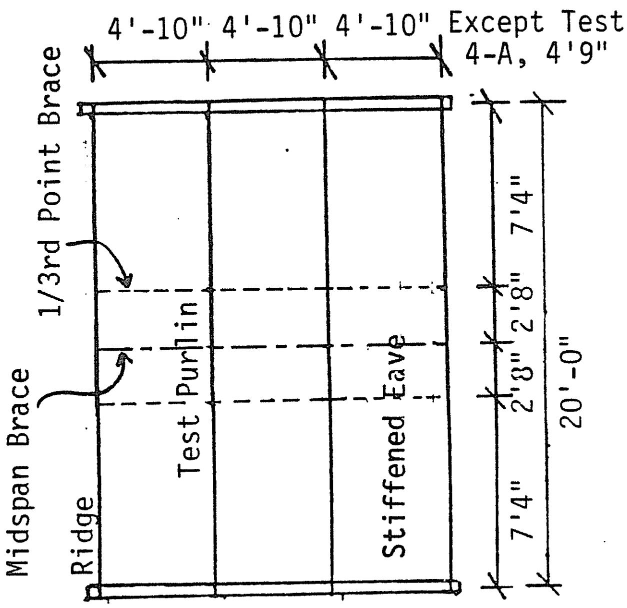


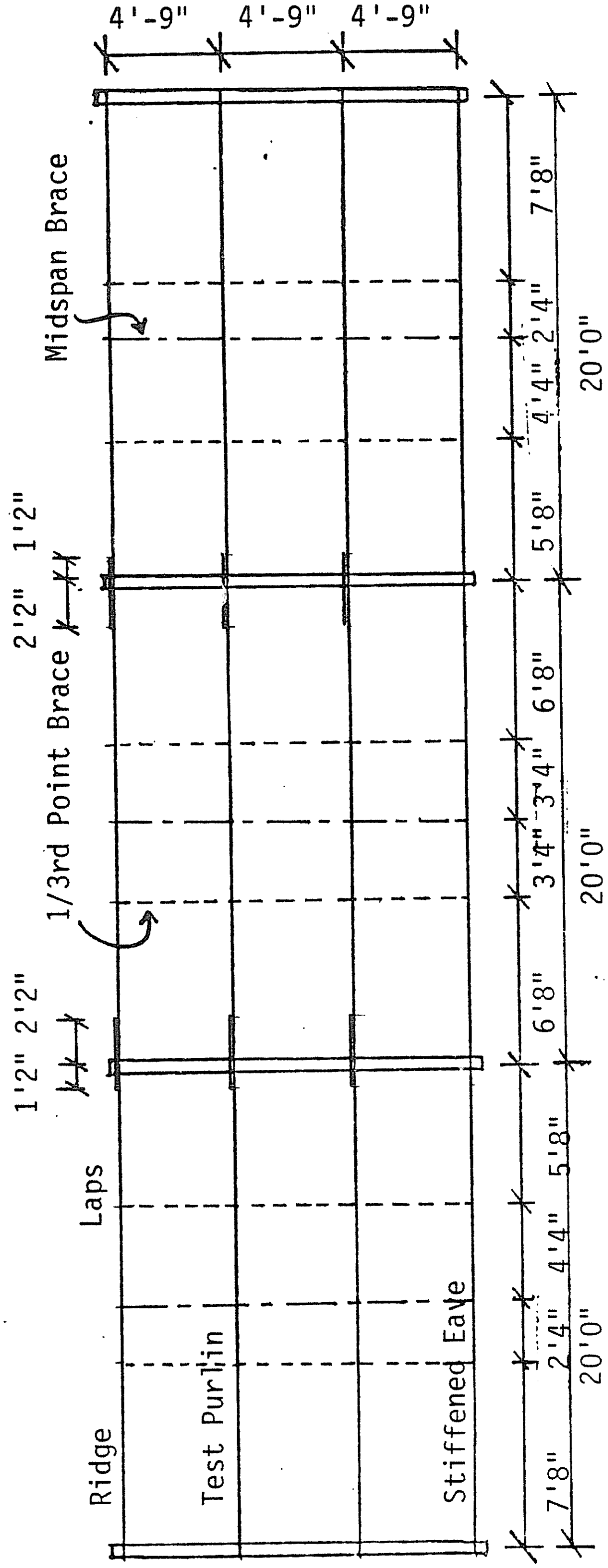
Figure 1. Plan View of Test Set-Ups



(c) Test 4-B

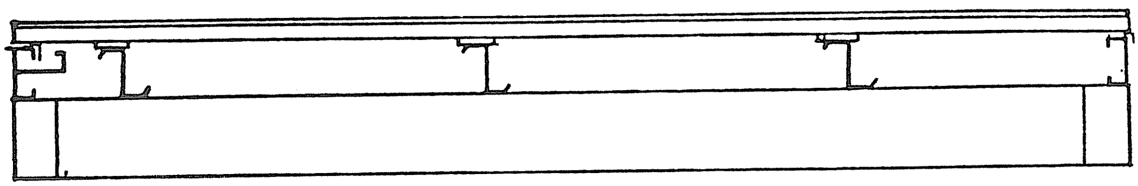


(d) Test Series IV
Except 4-B

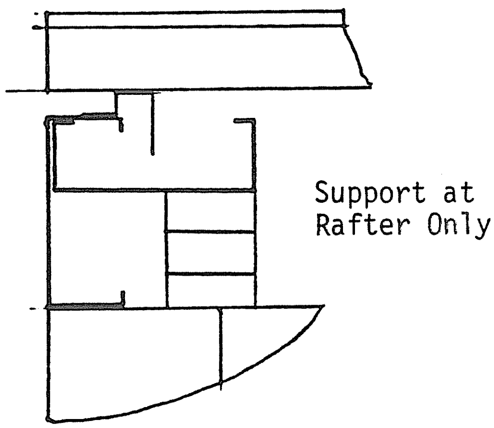


(e) Test Series V and VI

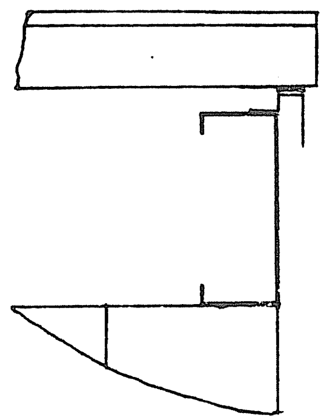
Figure 1. Plan View of Test Set-Ups, Continued



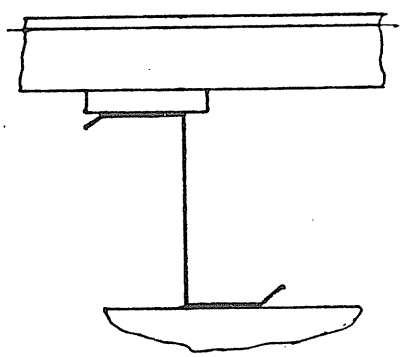
(a) Elevation of Test Set-Up



(c) Stiffened Ridge

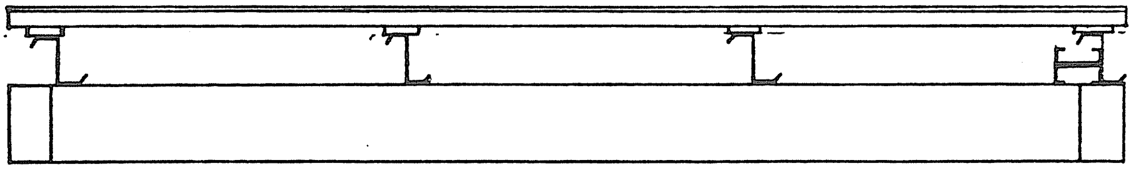


(b) Eave

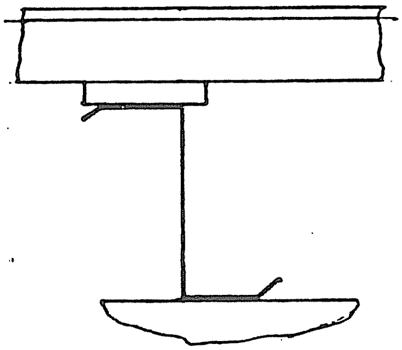


(d) Typical Purlin

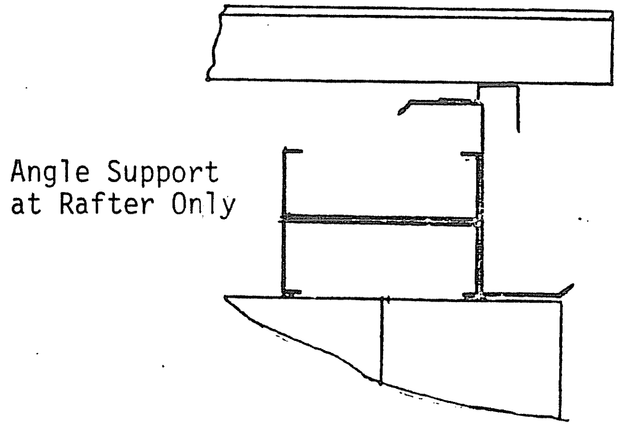
Figure 2. Support Details for Test Series I, II, and III



(a) Elevation of Test Set-Up

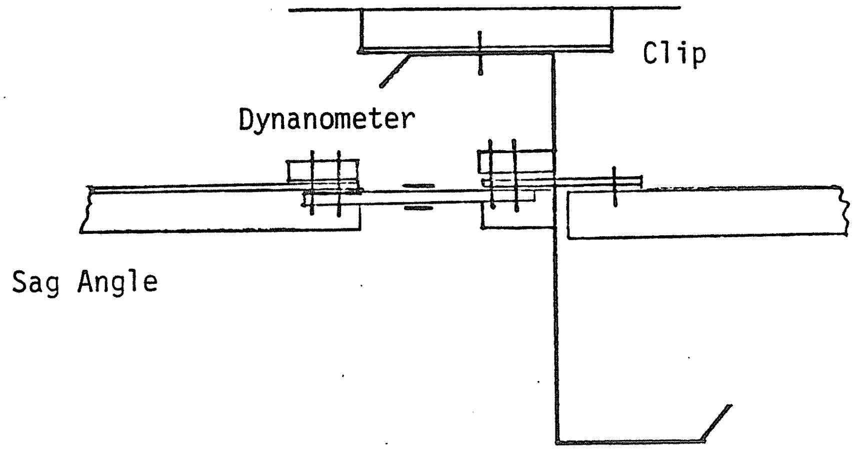


(c) Typical Purlin

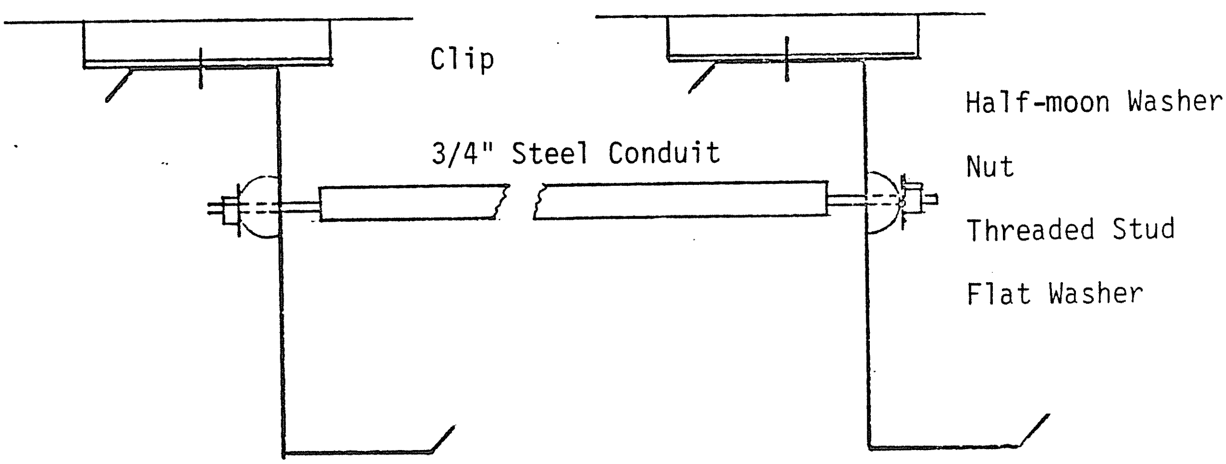


(b) Stiffened Eave

Figure 3. Support Details for Test Series IV, V, and VI



(a) Sag Angle Brace for Test Series I, II, & III



(b) Tension Brace for Test Series IV, V, and VI

Figure 4. Intermediate Brace Details

CHAPTER II

TEST DETAILS

2.1 Test Components

Z-Purlins. The Z-purlins used for this test were supplied by Star Manufacturing Company. All Z-purlins were carefully measured and the dimensions are shown in Table 2. Cross-sectional properties and load and deflection data for a uniformly loaded member were calculated using AISI criteria and a stiffness analysis program. This data is shown in Table 3 for an assumed yield stress of 56 ksi.

Panels, Clips, and Fasteners. The panels were standing seam panels with profile as shown in Figure 5(a). Each sheet was a 24 in. wide pan section with the edges formed into a 2 in. high box rib plus a 7/8 in. high seam, forming a 2 7/8 in. overall panel height. The panel flat was embossed with 3/32 in. deep cross ribs at 6 in. on-center. The material used to form the panel was nominally 24 gage. The panel clips (Figure 5(b)) were of a sliding design to allow for expansion and contraction movement of the roof panel. The clip supports the panel 1 in. above the secondary framing to prevent crushing of insulation installed between the panel and the structural members. The clips were fastened to the purlin with 1/4" by 1" bolts through predrilled holes in the purlins. This procedure differs from standard Star Manufacturing Company practice and was used only to permit reuse of the panel material.

2.2 Test Set-Ups

The test set-up was constructed in a specially designed vacuum chamber. The outside walls of the chamber are metal panels bolted together and attached to the laboratory floor. Lateral support for the walls is provided at the top by angle braces. Once the roof system was completely in place, the entire assembly was covered with 6 mil polyethelene and sealed using vinyl tape. Suction was applied using a vacuum pump and two auxiliary 55 gallon drum type industrial vacuum cleaners.

Three basic test configurations were used in this investigation. The configurations are referred to as one purlin, two purlin and three purlin test set-ups depending on the number of Z-purlins expected to fail in a test.

The one purlin configurations shown in Figures 1(a) and (b) were used for Test Series I, II and III. In these configurations all purlins were of identical cross-section and because of the variable spacing only the purlin adjacent to the ridge was expected to fail. From preliminary testing it was found that, because of the flexural stiffness of the panel and the stiffened ridge, the panel tended to distribute load to the outside member resulting in less than desired load on the test purlins. To counter this effect, the panel ribs were cut in a vertical line at each purlin location. The result was a determinate panel system with known load on the test purlin. The intermediate braces used in this set-up were "sag angles" $1\frac{5}{8} \times 1\frac{5}{8} \times .056$ in. as provided by Star Manufacturing Company. The brace-to-purlin connection is shown in Figure 4(a). The main support for these braces was the stiffened ridge made up of two channels bolted together as shown in Figure 2(c).

The two purlin test configuration, Figure 1(c), was used for Test 4-B only. The lateral support for the system was provided by a stiffened eave. Two channels were bolted back-to-back and then bolted to a Z-purlin as shown in Figure 3(b). The ridge purlin was sized to deflect with the test purlin eliminating the need to cut the panel ribs. Both the test purlin and ridge purlin were expected to fail in this test. No intermediate braces were used in this test.

The three purlin test set-up was used for the remaining tests in Series IV and for Series V and VI, Figure 1(d) and (e). Lateral restraint to the panel was the same as used for the two purlin test set-up. The stiffened eave was also used to anchor the intermediate braces which were fabricated from 3/4 in. diameter steel electrical conduit. Nuts were welded into each end of the conduit and a 9 in. length of ½ in. diameter threaded stud was inserted. Connection to the purlin was made using half moon and flat washers together with standard nut as shown in Figure 4(b). Connection between the stiffened eave and the intermediate brace was made in a similar manner.

In all test set-ups, the purlins were bolted to rafter sections which in turn were supported on short column sections resting on the laboratory floor. To provide for rotation of the supports, ½ in. diameter rollers were inserted between the rafter and column sections except at the north end where knife edge supports were used.

2.3 Instrumentation

Instrumentation consisted of calibrated dynanometers, strain gages, dial gages, U shape monometers, a pressure transducer, and linear displacement transducers.

The dynanometers used to measure lateral brace force for Series I to III were strain gaged coupons bolted in line with the sag angles used for intermediate braces. The strain induced in the gaged dynanometer was measured and then converted into load. The dynamometers used for Series IV to VI were 3/4 in. diameter steel electrical conduit with a full strain gage bridge installed at approximately the brace mid length. The braces were then calibrated using a universal testing machine. Calibrated dynanometer locations are shown in Figure 6.

Strains were measured at one location along each test purlin line except Tests 4-B through 4-E where no gages were installed. For Series I through III nine gages at each cross-section were used, positioned as shown in Figure 7(a). Ten gages were used for Test 4-A and Series V and VI, Figure 7(b). The gaged cross-section was typically located where the highest stress was expected. Locations are shown in Figure 6.

Five linear displacement transducers were used to measure vertical and lateral displacements. In all the tests three transducers were placed at the centerline of the north span, two were used to measure the lateral movement at the top and bottom purlin flanges and the third was used to measure the vertical displacement. Measurements were made at the same cross-section and the displacement transducers were positioned as shown in Figure 8. The remaining two transducers were placed at locations where the displacement was considered to be critical to either test purlin behavior or the test set-up performance. Dial gages were placed directly beneath the test purlin support points on the rafter. Data from these gages permitted a correction for rafter deflection.

The applied vacuum load was measured by either U-tube monometers, an electronic monometer or both. The U-tube monometers were calibrated in 0.5 in. of water and have an estimated accuracy ±0.1 in. of water. The electronic monometer was calibrated in psf with an estimated accuracy of ±0.1 psf.

2.4 Testing Procedure

At the beginning of each test a vacuum of 2 in. of water (10.4 lbs per square foot) was applied and then removed and no data was recorded. Following this initial loading, zero readings were recorded for all dynanometers, strain gages, displacement transducers and the dial gages. The system was then loaded by slowly increasing the vacuum in 1 in. of water increments. After each increment, readings of all instrumentation were recorded. When the purlins were near failure as determined from plotted load-deflection curves, the loading rate was decreased to 0.25 or 0.5 in. of water per increment. Notes were taken concerning deformation of the roof system and the failure mode.

2.5 Supplementary Tests

Standard tensile coupon tests were made from samples cut from the test purlins and typical panel material. Results from these tests are given in Table 5.

Table 2
Measured Z-Purlin Dimensions

Test No.		Total Depth (in)	Thickness (in)	Top W_1 (in)	Top T_1 (in)	Top R_1 (in)	Top R_2 (in)	Top θ_1 (deg.)	Bottom W_2 (in)	Bottom T_2 (in)	Bottom R_3 (in)	Bottom R_4 (in)	Bottom θ_2 (deg.)
1-A		8.1	.083	2.98	.72	.5	.406	50	3.08	.64	.5	.406	45
1-B		7.92	.083	3.02	.74	.406	.50	48	3.04	.64	.5	.375	48
2-A	N	7.94	.066	3.12	.54	.313	.375	42	2.92	.56	.688	.344	42
2-A	S	8.04	.064	3.2	.52	.563	.594	42	2.98	.58	.563	.344	42
2-B	N	7.92	.065	3.06	.54	.375	.438	42	2.94	.54	.438	.438	42
2-B	S	7.98	.065	3.04	.54	.406	.406	42	2.94	.56	.438	.375	42
3-A	N	8.14	.099	2.94	.77	.375	.563	43	3.02	.52	.438	.625	40
3-A	S	8.02	.097	3.02	.72	.438	.406	42	3.10	.54	.438	.375	43
3-B	N	8.12	.099	2.90	.76	.375	.563	42	3.02	.55	.438	.625	42
3-B	S	8.10	.097	3.00	.77	.375	.563	42	3.10	.68	.438	.375	42
4-A		8.00	.094	2.88	.88	.469	.406	50	2.80	.76	.469	.406	47
4-B		7.98	.093	3.02	.88	.5	.406	58	2.64	.68	.375	.406	40
4-C		8.10	.096	3.00	.90	.375	.375	52	3.02	.50	.5	.375	68
4-D		8.02	.099	2.92	.82	.469	.375	56	2.96	.88	.313	.313	46
4-E		8.02	.099	2.82	1.02	.5	.375	64	2.54	.785	.406	.375	50
5-A	N	7.85	.066	2.92	.810	.344	.375	48	2.87	.527	.344	.344	51
5-A	C	7.98	.055	2.90	.588	.344	.25	48	2.88	.60	.313	.313	52
5-B	N	8.04	.065	2.98	.52	.406	.406	44	2.82	.48	.406	.406	44
5-B	C	7.96	.059	2.76	.52	.344	.281	42	2.76	.68	.375	.313	39
6-A	N	8.03	.080	3.01	.57	.438	.438	41	2.94	.66	.375	.375	42
6-A	C	7.93	.066	2.94	.78	.406	.344	51	2.94	.76	.438	.375	51
6-B	N	7.90	.084	2.96	.66	.406	.406	50	2.80	.80	.406	.5	48
6-B	C	8.11	.064	2.95	.78	.406	.406	52	2.64		.406	.5	55

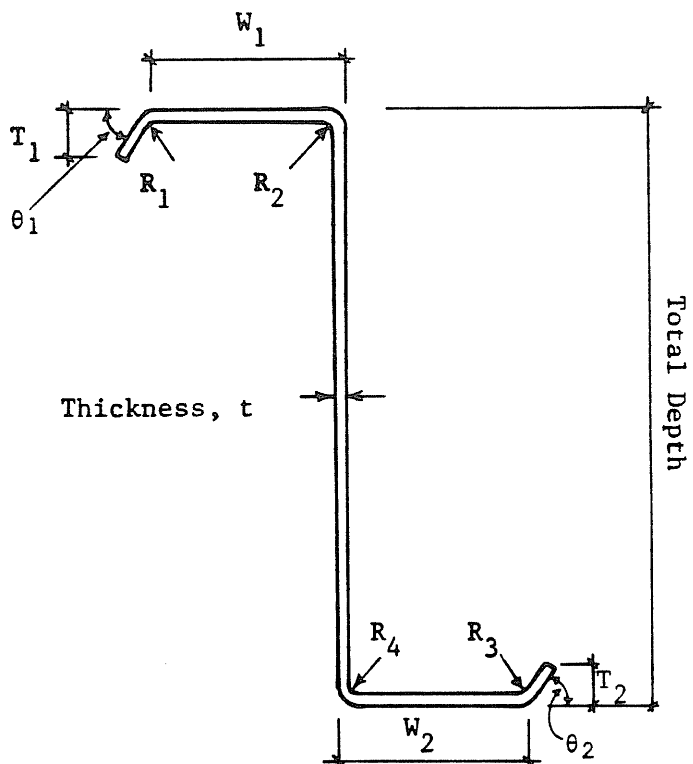


Table 3
Z-Purlin Properties As Computed Using AISI Criteria

Test No.		Gross I (in^4)	Gross S_t (in^3)	Gross S_b (in^3)	Strength I (in^4)	Strength S_t (in^3)	Strength S_b (in^3)	b_e (in)	Deflection I (in^4)	Deflection Δ/100 plf (in)	Span (Ft)
1-A		13.590	3.377	3.403	13.590	3.377	3.403	2.491	13.590	2.192	25
1-B		12.93	3.322	3.278	12.93	3.322	3.278	2.531	12.930	2.304	25
2-A	N	10.254	2.615	2.595	9.845	2.447	2.557	2.286	10.240	1.07	25
2-A	S	10.315	2.628	2.546	9.927	2.467	2.511	2.158	10.291	-	25
2-B	N	9.846	2.523	2.491	9.519	2.388	2.461	2.234	9.846	1.12	25
2-B	S	10.007	2.554	2.503	9.620	2.395	2.468	2.191	9.992	-	25
3-A	N	15.808	3.970	3.895	15.808	3.97	3.895	2.279	15.808	0.70	25
3-A	S	15.779	4.028	3.941	15.779	4.028	3.941	2.515	15.779	-	25
3-B	N	15.665	3.934	3.878	15.665	3.934	3.878	2.239	15.665	0.70	25
3-B	S	15.758	3.997	3.881	15.758	3.997	3.881	2.341	15.758	-	25
4-A		14.484	3.732	3.599	14.484	3.732	3.599	2.380	14.484	0.843	20
4-B		14.518	3.762	3.605	14.518	3.762	3.605	2.520	14.518	0.845	20
4-C		15.695	3.962	3.883	15.695	3.962	3.883	2.529	15.695	0.778	20
4-D		15.225	3.925	3.767	15.225	3.925	3.767	2.446	15.225	0.802	20
4-E		15.082	3.890	3.730	15.082	3.890	3.730	2.346	15.082	0.809	20
5-A	N	9.938	2.573	2.535	9.694	2.470	2.512	2.235	9.938	0.63	20
5-A	C	8.310	2.112	2.083	7.697	1.867	2.025	1.907	8.035	-	20
5-B	N	10.02	2.523	2.503	9.694	2.391	2.473	2.179	10.02	0.63	20
5-B	C	8.658	2.191	2.193	8.259	2.031	2.155	1.999	8.589	-	20
6-A	N	12.534	3.225	3.19	12.534	3.225	3.190	2.439	12.534	0.48	20
6-A	C	10.177	2.577	2.483	9.827	2.434	2.451	2.2	10.177	-	20
6-B	N	12.595	3.149	3.188	12.524	3.12	3.182	2.468	12.595	0.48	20
6-B	C	9.829	2.553	2.449	9.559	2.438	2.224	2.197	9.829	-	20

t = top
b = bottom

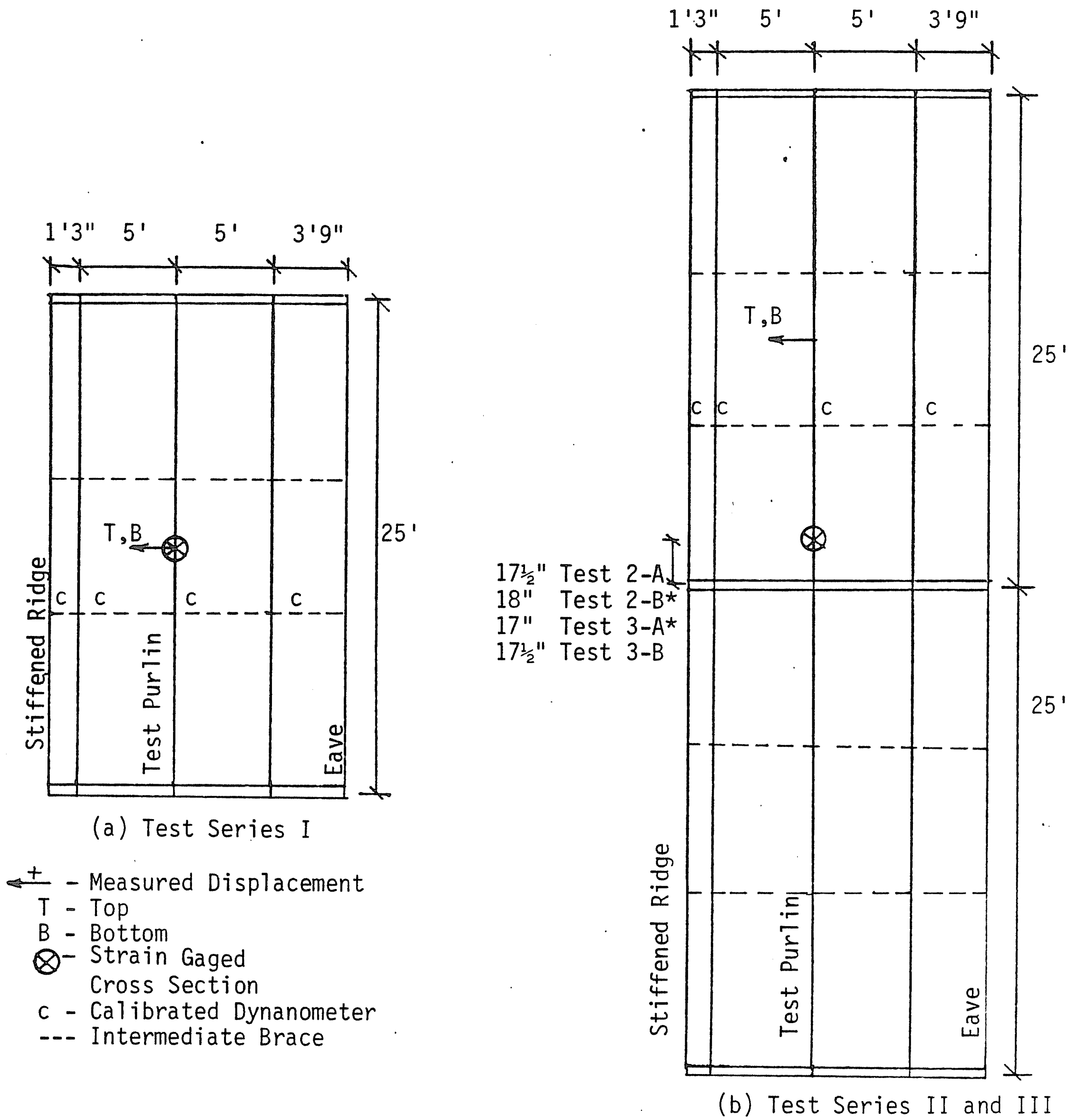
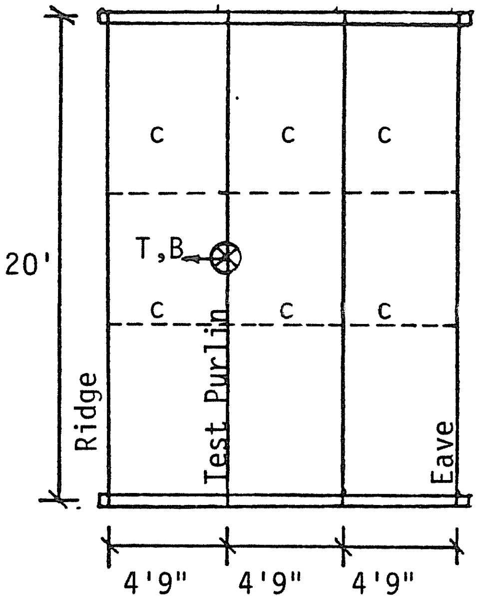
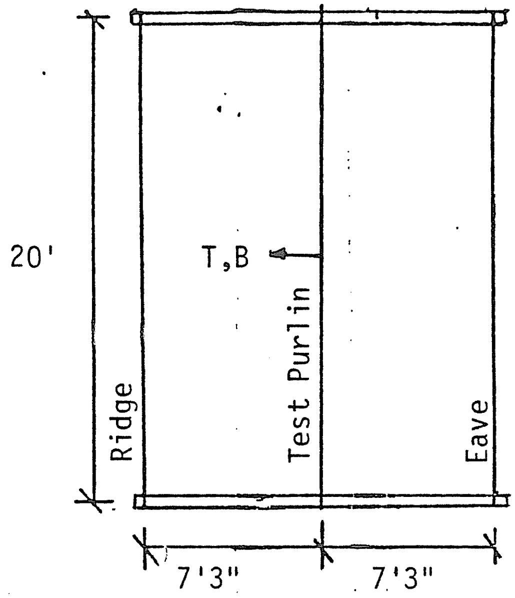


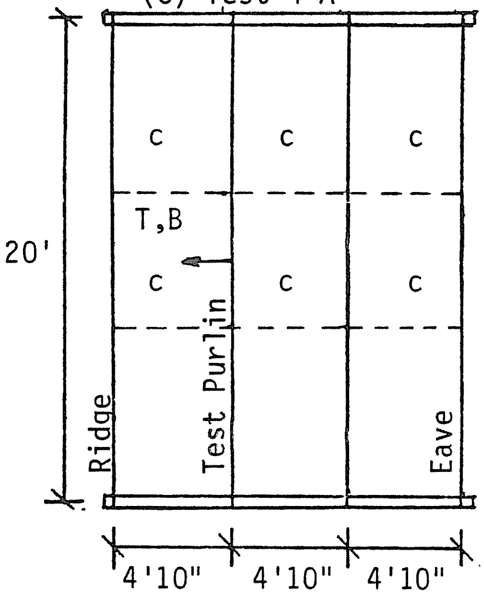
Figure 6. Instrumentation Locations



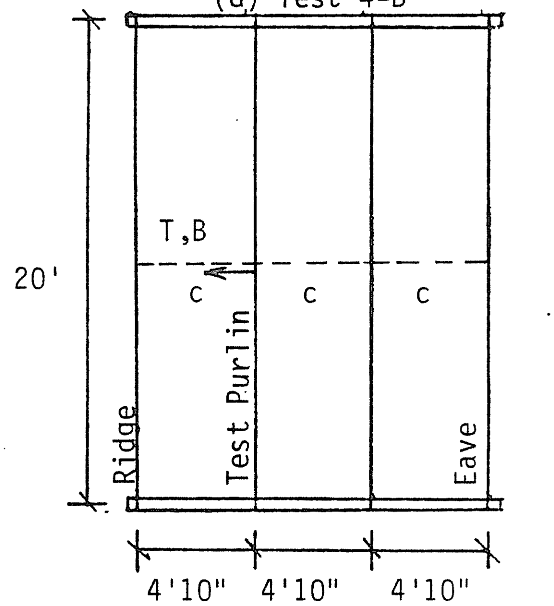
(c) Test 4-A



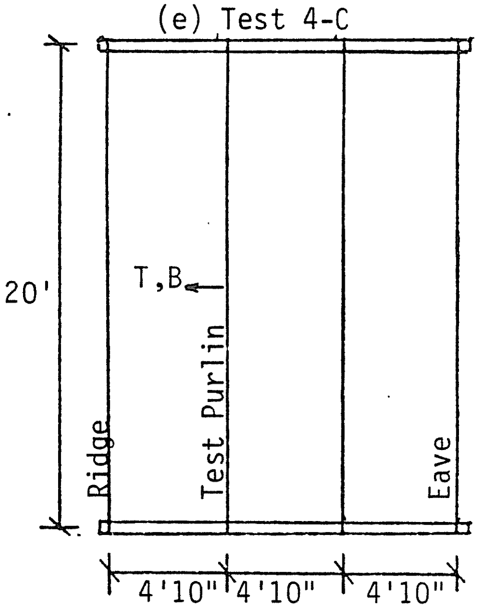
(d) Test 4-B



(e) Test 4-C



(f) Test 4-D



(g) Test 4-E

← - Measured Displacement
T - Top
B - Bottom
⊗ - Strain Gaged Cross-Section
c - Calibrated Dynanometer
--- Intermediate Brace

Figure 6. Instrumentation Locations, Continued

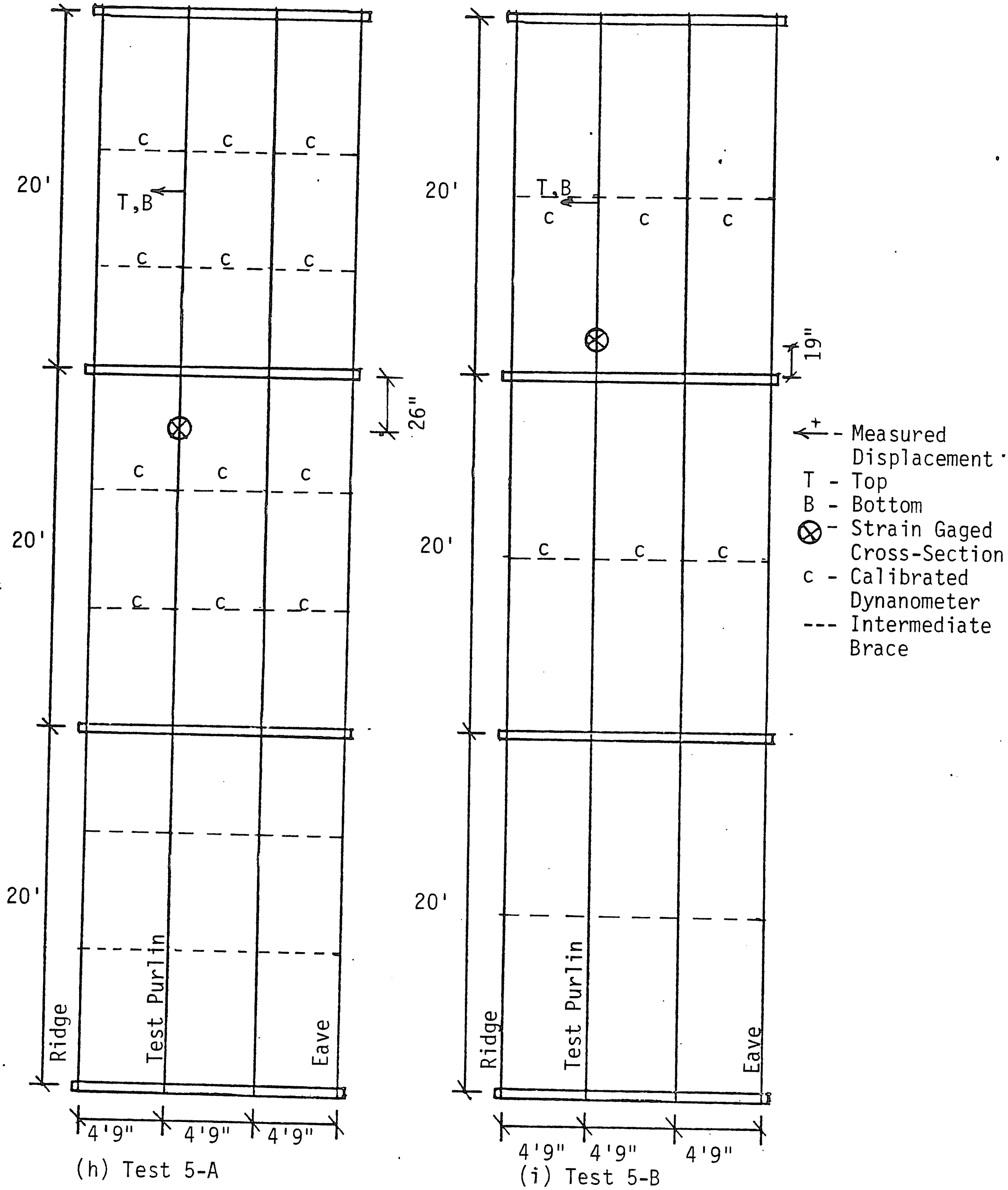
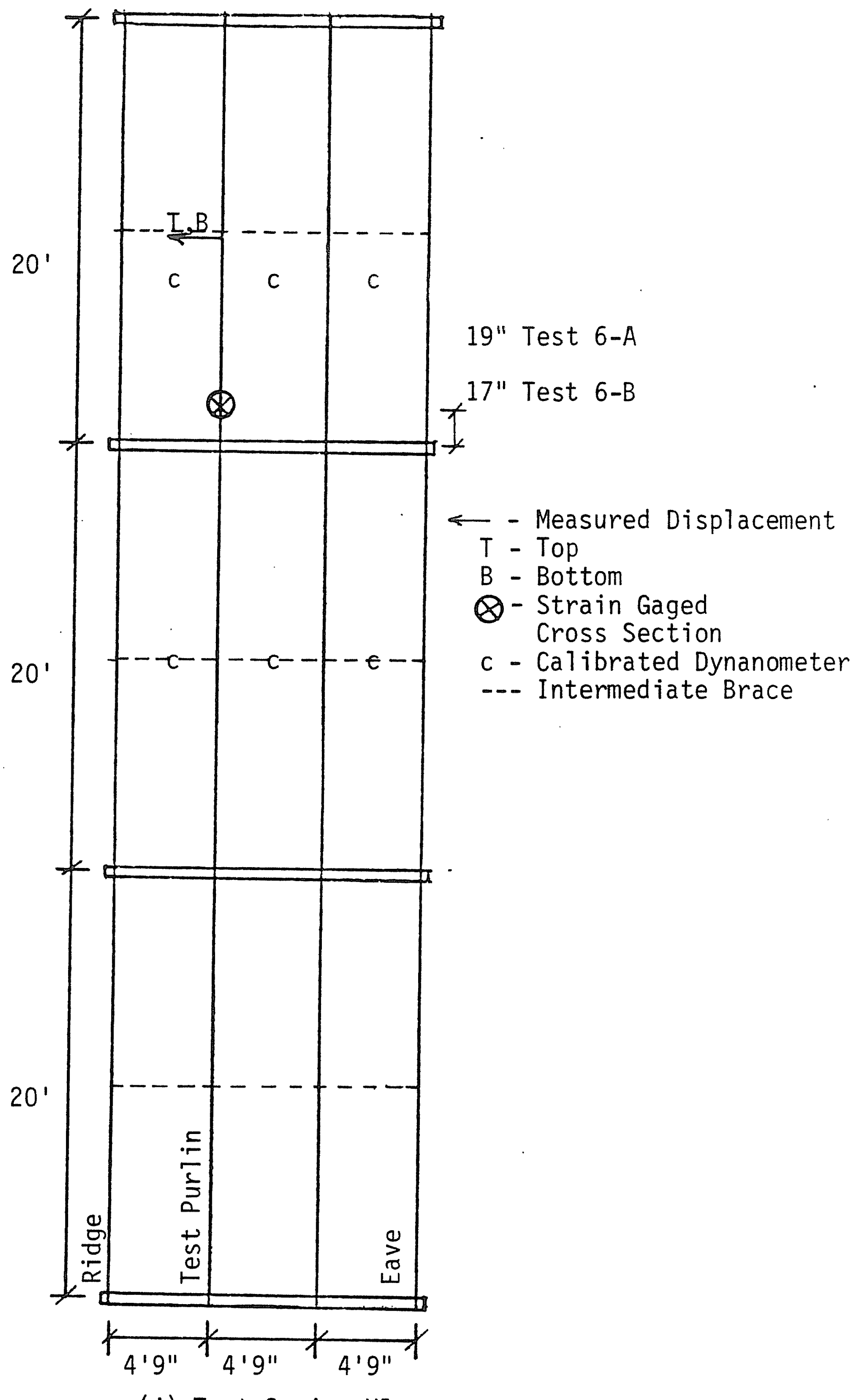
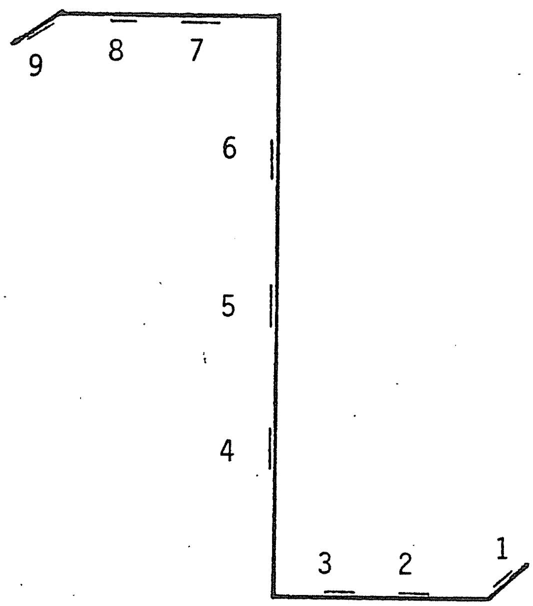


Figure 6. Instrumentation Location, Continued

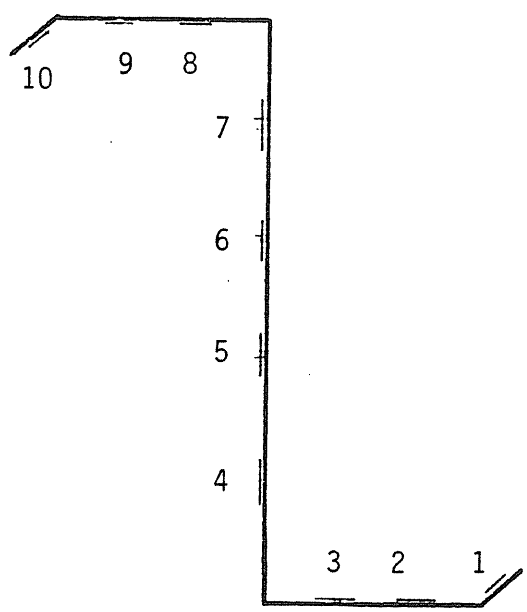


(j) Test Series VI

Figure 6. Instrumentation Locations, Continued



(a) Test Series I, II, and III



(b) Test Series IV, V, and VI

Figure 7. Strain Gaged Cross-Sections

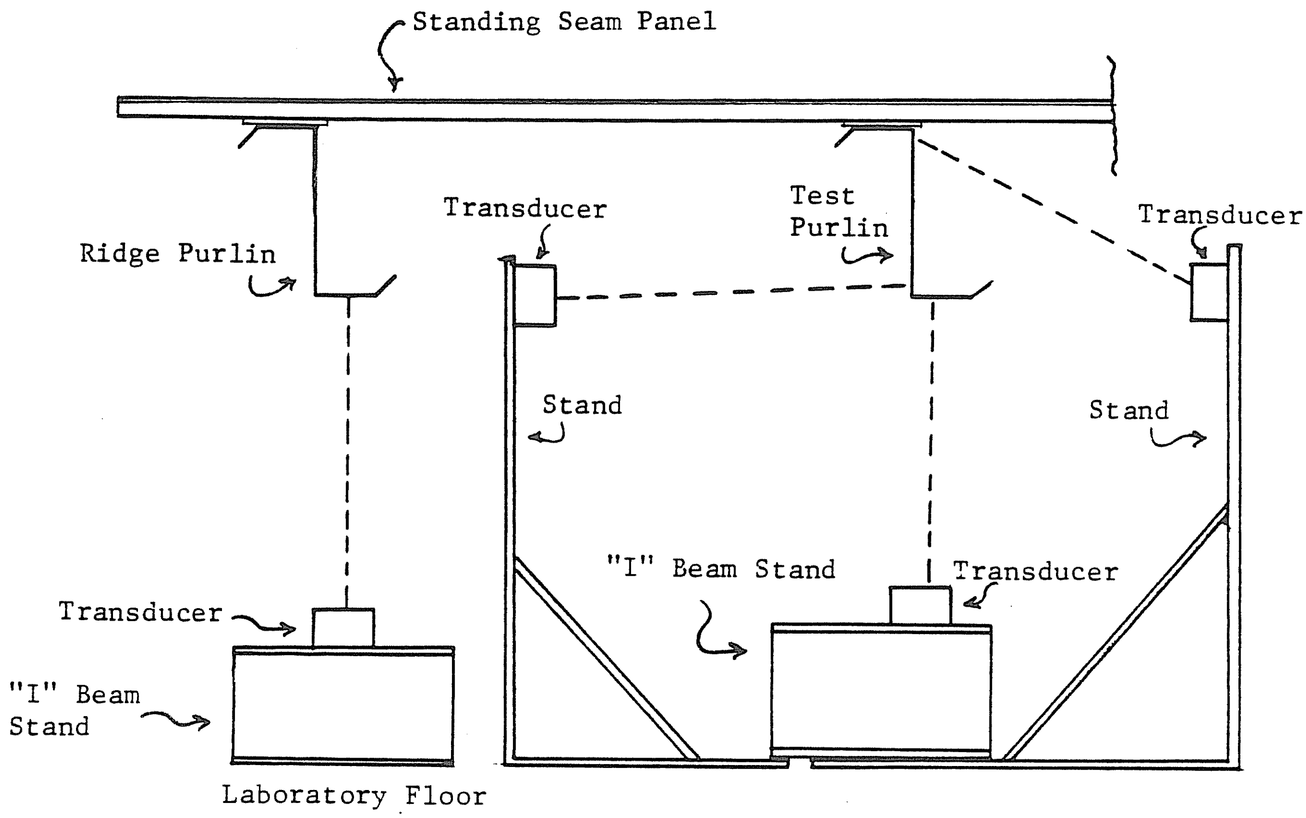


Figure 8. Displacement Transducer Placement

CHAPTER III

TEST RESULTS

3.1 General

Test results consist of load versus deflection data, load versus dynamometer data, photographic record and description of failure load. Load vs. deflection data includes plots of simulated live load vs. vertical deflection at the centerline of each purlin, and simulated live load vs. lateral displacements of the top and bottom flanges of the test purlin. Also included are simulated live load vs. intermediate brace forces for at least one half of one span.

The vertical deflection plots include theoretical deflection as computed assuming constrained bending. For the simple span tests the midspan deflection was calculated using

$$\Delta = \frac{5wL^4}{384EI}$$

where I = the moment of inertia of the purlin with respect to the horizontal axis, w = uniform load, L = span, and E = modulus of elasticity. For multi-span tests, standard plane frame analyses were conducted. The lapped portion of the purlin line was modeled assuming a moment of inertia equal to the sum of the moments of inertia of the purlins forming the lap. Moments of inertia were calculated using the provisions of the AISI Specification[1].

Strain measurements made at a cross-section were converted to stress using Hooke's law with an assumed modulus of elasticity of 29,000 ksi. Results are presented as stress distributions on a cross-section. Linear curve fitting techniques were used to define distributions over each element, e.g. lip, flange and web. An assumed yield stress of 56.0 ksi was used to develop the plots. Plots were made for at least two load levels for each test. (Although not technically correct, henceforth, these plots will be referred to as measured "stress distributions".)

Predicted failure loads were calculated using Star Manufacturing Company's purlin design computer program. A unity check of 1.67 was used to define a failure load. The predictions were based on certain assumptions concerning lateral bracing spacing (See Section 4.2 for details).

Results for Test Series I to VI are found in Appendices A through F, respectively. Table 4 is a summary of results and Tables 6 and 7 are comparisons of results at working and higher loads.

3.2 <u>Test Series I</u>

The purpose of this test series was to develop base data for a lightly loaded (12 psf), simple span (25 ft. 0 in.) system. Two tests were conducted, both with intermediate braces at the 1/3rd points (nominally).

At the onset of the Test 1-A the measured load vs. deflection curve was in very poor agreement with the predicted curve. After several tests to working load and an analysis of the test set-up as a grid, it was concluded that due to the flexural stiffness of the panel, the panel was transferring load to adjacent members. These members were either identical Z-purlins, the eave channel, or the stiffened ridge purlin. Since the tributary area for the outside members was only one-half of that for the test purlin, reserve capacity existed in these members. In an attempt to obtain better load distribution, the ribs of the panel were cut above the interior purlins to form a determinate panel/purlin system. After this modification, the load vs.

deflection curve showed good agreement with the predicted constrained bending deflection.

For Test 1-A failure occurred at 143.0 plf by local buckling of the compression flange and lip at the centerline of the span. Using Star Manufacturing Company's purlin design program with a unity check of 1.67, the predicted failure load was 146 plf or 2% greater than the test load.

For Test 1-B the failure mode was the same as test 1-A but with a failure load of 117 plf. The predicted failure load was 146 plf or 24% higher than the actual failure load. A possible explanation for the discrepancy is that adjacent members were damaged in Test 1-A causing premature failure in this test. Additional evidence for this explanation is given in subsequent test descriptions.

In both tests, measured vertical deflections were in good agreement with predicted deflections as shown in Figures A.4 and A.13.

Brace forces were measured at the north 1/3rd point and were found to vary from tension at the ridge to compression at the eave for both tests as shown in Figures A.5 and A.14. Maximum brace force for Test 1-A was 434 lbs. compression and for Test 1-B, 518 lbs. compression. Because each line of intermediate braces is indeterminate, brace force accumulation is difficult to evaluate.

Measured stress distributions are shown in Figures A.6 to A.8 and A.15 and A.16. Results for Test 1-A confirm the constrained bending assumption; results for Test 1-B are not in as good agreement with the assumption. Yielding did not occur in either test before failure.

Lateral displacements were at midspan for both tests. Maximum displacement was less than 0.5 in. as shown in Figures A.9 and A.17. The plots indicate that lateral buckling did not occur before failure.

3.3 Test Series II

The purpose of this series was to extend the data obtained in Series I to the two span condition. The nominal live load for the system was 12 psf with spans of 25 ft. 0 in. each. The test configuration was the same as for the Series I tests with expansion to two bays. The panel ribs above each purlin were cut as described in Section 3.2.

Test summary sheets found in Appendix B detail the results for this series. The failure mode for both tests was local buckling of the compression flange and lip immediately outside the lapped portion of the test purlin line at values of 130 plf and 117 plf for Tests 2-A and 2-B, respectively. Using the Star Manufacturing Company's purlin design program the predicted failure loads were 149 plf and 146 plf or 14.6% and 25% higher than the test values.

The load versus vertical deflection curves for tests 2-A and 2-B, Figure B.5 and B.15, show fair agreement with predicted deflections from a plane frame stiffness analysis assuming constrained bending.

Intermediate brace forces were measured at the 1/3rd point nearer the lap of the south span. As in Series I, the brace nearest the ridge showed tension and the one nearest the eave compression. The maximum brace forces were 624 lbs and 375 lbs compression for Test 2-A (Figure B.6) and 2-B (Figure B.16), respectively. Again, accumulation effects are difficult to evaluate for this bracing scheme.

The strain gaged cross-section for both tests was immediately outside the lapped portion of the test purlin line. Stress distributions at three load levels are shown in Figures B.7 to B.9 for Test 2-A. The measured pattern does not confirm the constrained bending assumption. Yielding of the lower (compression) flange/lip occurred at loads near failure and the lip apparently buckled, Figure B.9. Stress distributions for Test 2-B are shown in Figure B.17 and B.18. Results are similar to Test 2-A.

Lateral displacements were measured at the midspan of the south bay of the test purlin line. Results are shown in Figures B.10 and B.19. Figure B.10 indicates lateral buckling may have occurred prior to failure.

3.4 Test Series III

The purpose of this series was to provide data for the standing seam roof system with a medium live load and a two span condition; 20 psf live load, two bays at 25 ft. 0 in. The test configuration was the same as used for Test Series II.

Test summary sheets in Appendix C detail the results. The failure mode for Tests 3-A and 3-B was local buckling of the compression flange and lip immediately outside the lapped portion of the test purlin line. Failure loads were 255 and 247 plf, respectively. The predicted failure loads were 244 and 243 psf, respectively.

Measured and predicted vertical deflections at midspan of the south bay were in fair agreement as shown in Figures C.5 and C.20. For both tests the measured deflections were greater than predicted values.

Vertical load versus measured intermediate brace force plots are shown in Figures C.6 and C.18. The distribution was similar to that found in Series I and II, e.g. tension at the ridge and compression at the eave. Maximum brace force was 1089 lb for Test 3-A and 714 lbs for Test 3-B. Comparing with Series II tests, the brace forces increased approximately in proportion to increased vertical load.

Stress distribution plots for Test 3-A are given in Figures C.7 to C.10 and for Test 3-B in Figures C.19 to C.22. The distributions do not confirm the constrained bending assumption. Local buckling of the lower lip is indicated and yielding was not detected.

Significant lateral displacements were measured in Test 3-A with maximum displacement exceeding 1 in. Maximum lateral displacement for Test 3-B was less than 0.5 in.

An additional test was conducted prior to the final loading of setup 3-A. The purpose was to compare the behavior of the system with and without intermediate bracing. Results are shown in Figure C.12 to C.15. Load versus vertical deflection for both cases is shown in Figure C.13. The unbraced case showed slightly more deflection than the braced case, both are in fair agreement with predicted deflections. Stress distributions at 104 plf for the braced and unbraced cases are shown in Figures C.13 and C.14, respectively. The shape and magnitudes are essentially the same for both cases, although the stresses for the braced case are slightly higher. Lateral displacements at midspan of the south bay for both cases are shown in Figure C.15. Lateral movement was greater in the unbraced case indicating full restraint is not provided by the panel-to-purlin clip.

3.5 Test Series IV

The purpose of this series was to investigate the effect of intermediate brace bracing spacing and panel-to-purlin connection clips on purlin strength. Four tests using identical purlins with 1/3rd point, centerline or no bracing were conducted. In addition, one test was conducted without intermediate bracing and without the connection clips installed. Test summaries for the five tests are found in Appendix D.

To eliminate the need to cut the panel rib at purlin locations as was done in Series I to III, the test set-up was modified as shown in Figures 1(c) and (d) and Figure 3. The stiffened ridge was eliminated and replaced by a Z-purlin. A stiffened eave was constructed as shown in Figure 3(b). The ridge purlin was selected to have approximately 60% of the flexural stiffness (moment of inertia) and strength of the test purlin. Since the tributary area for the ridge purlin is approximately 50% of the tributary area of the test failure of the ridge purlin was anticipated. This set-up also resulted in a determinate intermediate brace system. Strain gages were installed only for Test 4-A.

Test 4-B was conducted without intermediate bracing or panel-to-purlin clips installed to determine the effect of panel "drape" or "hugging" on lateral restraint. The test set-up was as shown in Figure 1(c); purlin spacing was 7 ft. 3 in. Failure occurred by lateral buckling at a load of 128.2 plf. The predicted failure load assuming an unbraced length equal to the span was 35 plf. The large difference indicates some "drape" effect. Poor agreement was obtained between measured and predicted vertical deflections. Lateral displacements at midspan were found to be excessive, greater than 2.5 in. at failure.

The remaining tests in the series were conducted with the connection clips installed. Test 4-A and 4-C were conducted with 1/3rd point intermediate bracing, Test 4-D with midspan bracing and Test 4-E with no bracing. Actual and predicted failure loads are as follows: Test 4-A, 226 and 327 plf; Test 4-C, 234 and 327 plf; Test 4-D, 249 and 217 plf and Test

4-E, 246 and 50 plf. Test failure loads as a percentage of predicted failure loads were 69%, 72%, 115% and 492% for the four tests, respectively. The failure mode for all four tests was local buckling of the compression flange and lip near midspan. It is believed that the low failure loads for Tests 4-A and 4-C were caused by premature failure of the ridge purlin. In addition, it is evident from Figures D.21 and D.22 that the ridge purlin of Test 4-C came into contact with the chamber wall before failure. Failure load results for Tests 4-A and 4-C are not considered valid.

For all tests reasonably good agreement was found between predicted and measured vertical deflections, although in all cases measured deflections were greater than predicted deflections (Figures D.4, D.20, D.26 and D.32).

In the set-up used in this series, all brace forces are tension and accumulation effects can be evaluated. For Test 4-A (1/3rd point braces), brace forces increased approximately linearily, Figure D.5. (The initial portion of the curve for Brace #1 is due to instrument malfunction. At 31.2 psf, the ratio of brace forces in the direction of eave to ridge was 3.90: 2.19:1.0 to a ratio of tributary areas of 5:3:1. These brace forces as a percent of stabilized vertical load are 5.3%, 5.0% and 6.9%.

The configuration for Test 4-C was identical to Test 4-A. At 20.7 psf, the ratio of brace forces was 2.90:2.33:1.0 and as a percent of stabilized vertical load 6.9%, 9.2% and 11.9%, in the direction of eave to ridge. As previously noted, the ridge purlin came into contact with the vacuum chamber before failure.

Measured brace forces for Test 4-D (midspan brace only) are erratic above 150 plf per purlin (31.6 psf), Figure D.27. At 10.9 psf ratios were 3.37:1.90:1.0 and at 31.6 psf 6.00:3.07:1.00. The ratio of the tributary areas was 5:3:1. Brace forces as a percent of stabilized vertical load at 10.9 psf were 6.2%, 5.8% and 9.2% and at 31.6 psf 5.3%, 4.5% and 4.4%, eave to ridge.

Measured stress distributions at midspan of Test 4-A are shown in Figures D.7 to D.9. The distributions tend to confirm the constrained bending assumption. Yielding did not occur in any test.

Lateral displacement versus vertical load relationships are shown in Figures D.11, D.16, D.22, D.28 and D.33 for the five tests of this series. The direction of movement of both the top and bottom flanges for all tests was toward the ridge or "uphill". For tests with braces (4-A, 4-C, 4-D) the bottom flange movement was more than the top flange movement. For Test 4-B the reverse was true and for Test 4-E the movements were approximately equal.

3.6 Test Series V

The purpose of this series was to study the behavior of a three span system with intermediate bracing at the 1/3rd points or at the midspan of each bay. The nominal span length was 20 ft. and the design load for the system was 20 psf. The test set-up was the same as for Series IV but extended to three bays. Both the test purlins and the ridge purlins were lapped at the interior rafter location. The lap length for the test purlin line was 3 ft. 6 in., 1 ft. 2 in. into the exterior bay and 2 ft. 4 in. into the center bay. The lap length for the ridge purlin was adjusted depending on the size of purlin used so that the deflection of the ridge and test purlins were approximately equal.

For Test 5-A intermediate braces were located at Star Manufacturing Company's standard bracing location, approximately the 1/3rd points of each span. For Test 5-B intermediate braces were installed only at the midspan of each bay. Results for both tests are found in Appendix E.

The failure mode for Test 5-A was local buckling of the compression flange and lip immediately outside the lap of the north exterior bay. For Test 5-B the failure mode was web crippling at the north reaction of the test purlin line. Failure loads for Tests 5-A and 5-B were 251 plf and 191 plf, respectively. The predicted load for Test 5-A, from Star Manufacturing Company's purlin design program, was 273 plf or 8.8% higher than the test value. For Test 5-B the predicted failure load was 203 plf or 6.3% higher than the test value.

Both tests were in good agreement with predicted vertical deflection. Plots of load versus vertical deflection at the midspan of the north exterior bay are shown in Figures E.5 and E.18 for Test 5-A and 5-B, respectively.

In Test 5-A, intermediate brace forces were measured at all brace locations in the north and center bays, e.g. twelve locations. Results are shown in Figures E.7 to E.9. At all locations the forces increased linearily with increasing vertical load until failure. The largest forces were recorded at the exterior 1/3rd point of the north exterior bay and the smallest at the interior 1/3rd point of this bay. Forces at the two lines in the center bay were consistent. The ratio of the tributary areas for all brace lines was 5:3:1, eave to ridge. Brace force ratios, eave to ridge and north exterior to south center, are 3.59:2.08:1.0, 1.96:1.24:1.0, 4.22:2.77:1.00, and 4.07:2.53:1.0. At 52.8 psf or approximately the failure load, the ratios were 5.94:2.70:1.0, 2.57:1.67:1.0, 5.32:3.15:1.0 and 5.07:2.77:1.0 or approximately in proportion to the tributary areas. The brace forces as a percentage of the stabilized vertical load for the north external and center bay at 20.7 psf were 14%, 14%, and 26% and 12%, 13%, and 15%, respectively. At 52.8 psf, they were 16%, 13%, and 18% and 15%, 14%, and 14%, respectively, measured from the eave to ridge.

In Test 5-B, brace forces were measured at the midspan of the north exterior bay and the center bay. Results are shown in Figure E.19 and E.20. At 19.8 psf, or approximately working load, the brace force ratios were 2.30:2.10:1.00 and 2.75:2.10:1.0 and at 40.1 psf or approximately failure load, 1.84:1.48:1.0 and 4.06:2.83:1.0, eave to ridge, north exterior and center bays, respectively.

For Test 5-B the brace force as a percentage of stabilized vertical load for the external and internal bays at 19.8 psf were 8%, 12% and 16%, and 5%, 7%, and 9%, respectively; at 40.1 psf they were 8%, 11%, and 22%, and 6%, 7%, and 7%, respectively, measured from eave to ridge.

Strains were measured in Test 5-A immediately outside the lap at the north interior support of the center bay. For Test 5-B strain measurements were made at the north interior support of the north bay immediately outside the lap. Stress plots for Test 5-A are shown in Figures E.10 to E.12 and for Test 5-B in Figures E.21 to E.23. For Test 5-A, Figure E.12 shows buckling of the bottom flange and lip near failure. FigureE.23 shows buckling of the bottom lip in Test 5-B, again near failure. The stress distributions shown do not confirm the constrained bending assumption.

Plots of vertical load versus lateral displacements for Tests 5-A and 5-B are shown in Figure E.13 and E.24, respectively. Measurements were made at the centerline of the north exterior bay. In Test 5-A the top and bottom flanges of the test purlin moved toward the ridge approximately the same amount. In Test 5-B the top and bottom flanges also moved toward the ridge, but the bottom flange moved more.

3.7 Test Series VI

The purpose of this series was to study the behavior of a three span system with midspan intermediate bracing in each bay. The nominal spans were 20 ft. and the design load was 50 psf. The test set-up was identical to that used in Series V, including test purlin line lap lengths. The lap lengths for the ridge line were determined in the same manner. Two tests were conducted in this series, however, an error in the erection of Test 6-A resulted in premature failure and the results are not considered valid. Test data for that test is found in Appendix F, for reference, but results will not be discussed here. Test 6-B was a retest of 6-A.

The failure mode for Test 6-B was local buckling of the compression flange and lip immediately outside the lap in the north exterior bay at a load of 285 plf. The predicted failure load was 298 plf or 4.6% higher than the test value.

Measured vertical deflections at the midspan of the north exterior bay were greater than predicted as shown in Figure F.18. The measured load deflection curve was linear until near failure.

Measured brace forces versus vertical load for the center and north spans are shown in Figures F.19 and F.20. The forces vary linearily to near failure. At a load of 37.0 psf, or approximately working load, the brace force ratios for the external and internal spans were 3.24:1.92:1.0 and 2.81:1.84:1.0, respectively, and at 60 psf, or approximately failure load, the ratios were 3.24:1.92:1.0 and 3.34:1.73:1.0, respectively, both eave to ridge. Brace forces as a percentage of the stabilized vertical load for the external and internal bays at 37 psf were 9.2%, 9.1%, and 14.2% and 5.1%, 5.6%, and 9.1%, respectively, and at 60 psf the percentages were 7.7%, 8.3%, and 14.3% and 4.3%, 5.9%, and 11.7%, respectively.

Strain measurements were made immediately outside the lap in the north exterior bay. Stress plots are found in Figures F.21 to F.24 and show stress reversal in both the top and bottom lips. Yielding did not occur and the constrained bending assumption was not confirmed.

Lateral displacements at the midspan of the north exterior bay are shown in Figure F.25. The top and bottom flanges moved toward the ridge with the bottom flange moving more.

3.8 Results of Supplementary Tests

Coupon test results from samples of test purlins are given in Table 5. The average yield stress for the 23 samples was 54.6 ksi, the highest was from the Test 5-A center purlin with a value of 63.9 ksi, and the lowest was 46.7 ksi for the Test 3-B south purlin.

Table 4
Summary of Test Results

Test No.	No. of Spans	Failure Loads: S.M.C.[1] (plf)	Actual (plf)	$\frac{Act}{Pre}$x100	Failure Mode	Remarks
1A	1	146	143	97.9	Local buckling of compression flange & lip	Panel was cut Intermediate bracing @ 1/3 pts.
1B	1	145	117	80.7	Local buckling of compression flange & lip	Panel was cut Intermediate bracing @ 1/3 pts.
2A	2	149	130	87.2	"	"
2B	2	146	117	80.7	"	"
3A	2	244	235	104.5	"	"
3B	2	243	247	101.6	"	"
4A	1	327	226	69.1	"	Intermediate bracing @ 1/3 pts.
4B	1	50	128	256.0	"	No intermediate bracing or clips.
4C	1	327	234	71.6	"	Intermediate bracing @ 1/3 pts.
4D	1	217	249	114.7	"	Intermediate brace @ ℄.
4E	1	50	246	492.0	"	No intermediate bracing.
5A	3	273	251	91.9	"	Intermediate bracing @ 1/3 pts.
5B	3	203	191	94.1	Web crippling	Intermediate bracing @ ℄.
6A	3	289	259	89.6	Local buckling of compression flange & lip	Failure of intermediate brace. Results invalid.
6B	3	298	285	95.6	Local buckling of compression flange & lip	Intermediate bracing @ ℄.

[1]Star Manufacturing Company analysis including effects of unbraced length.

Table 5
Coupon Test Results

Test		Thickness (in)	Yield Stress (ksi)	Ultimate Stress (ksi)	Elongation 2 in. %
1-A		.086	51.8	62.4	34
1-B		.0868	51.4	62.4	33
2-A	N	.0683	52.4	61.9	26
2-A	S	.067	53.3	62.3	29
2-B	N	.066	51.5	62.9	27.5
2-B	S	.0648	55.1	64.7	29
3-A	N	.0978	50.4	74.9	29
3-A	S	.100	51.9	74.5	28.5
3-B	N	.0976	48.9	73.8	26.5
3-B	S	.0996	46.7	72.9	28
4-A		.0975	55.7	80.7	19
4-B		.0936	56.0	80.6	26.5
4-C		.0965	57.4	80.5	29
4-D		.099	58.3	78.0	30
4-E		.098	57.9	80.9	29.5
5-A	N	.0655	61.0	70.4	26
5-A	C	.0592	63.9	79.1	27.5
5-B	N	.0688	51.4	63.2	29
5-B	C	.0598	58.7	77.3	28
6-A	N	.085	51.6	64.1	31.5
6-A	C	.066	57.0	73.3	29.5
6-B	N	.082	53.4	72.8	27.5
6-B	C	.0653	59.3	70.6	29.5

Table 6
Comparison of Results at Working Loads

Test	Spans	Bracing Spacing (Points)	Load (psf)	Midspan Vertical Deflection (in)	$\frac{\Delta_m}{\Delta_p}$	Measured Brace Force as a Percent of Stabilized Load (%)*						Lateral Displacement (in.)		Measured Stress (ksi)	
						1	2	3	4	5	6	Top	Bot.	Ten.	Comp.
1-A	1	1/3	10.4	1.203	1.06							0.183	-.233	14.4	-12.2
1-A	1	1/3	10.4	1.269	1.06							0.050	-.067	14.4	-11.3
2-A	2	1/3	10.4	0.775	1.39							-.270	-.210	15.6	-13.7
2-B	2	1/3	10.4	0.740	1.27							-.30	-.18	12.5	-10.8
3-A-1	2	1/3	20.8	1.055	1.45							-.472	-.366	24.5	-25.3
3-A-2	2	None	20.8	1.066	1.46							-.574	-.524	26.3	-28.2
3-A	2	1/3	20.8	1.037	1.42							-.492	-.373	21.8	-23.1
3-B	2	1/3	20.8	0.963	1.32							0.253	NA	26.9	-26.6
4-A	1	1/3	31.4	1.436	1.14	6.9	5.0	5.3				0.467	0.870	27.2	-28.1
4-B	1	None	15.5	1.033	1.63							1.783	0.445		
4-C	1	1/3	31.1	1.460	1.25	17.3	8.6	9.7				0.170	0.425		
4-D	1	1/2	31.5	1.453	1.19	4.4	4.5	5.3				0.340	0.404		
4-E	1	None	30.2	1.445	1.22							0.361	0.259		
5-A	3	1/3	20.7	0.572	0.92	26.1	14.3	14.3	15.0	13.1	12.4	0.188	0.209	14.2	-10.8
5-B	3	1/2	19.8	0.774	1.31	16.5	11.5	7.6	9.4	6.6	5.1	0.183	0.489	13.6	-12.9
6-A	3	1/2	42.4	1.534	1.59	3.4	11.1	12.2	11.7	5.9	6.1	0.594	0.756	27.6	-27.2
6-B	3	1/2	41.8	1.294	1.36	10.2	5.5	4.9	13.2	8.3	9.1	0.207	0.940	24.3	-26.1

Notes: *For 1/3rd point bracing 1, 2, 3 and 4, 5, 6 are at outside and inside locations respectively, in the north exterior span, ridge to eave.
For midspan bracing, 1, 2, 3 and 4, 5, 6 are at midspan of north exterior and center bays, ridge to eave.
m = measured
p = predicted

Table 7
Comparison of Results at Higher Loads

Test	Spans	Bracing Spacing (Points)	Load (psf)	Load Factor Actual/Working	Midspan Vertical Deflection (in)	Δ_m / Δ_p	Measured Brace Force as a Percent of Stabilized Load (%)*						Lateral Displacement (in.)		Measured Stress (ksi)	
							1	2	3	4	5	6	Top	Bot.	Ten.	Comp.
1-A	1	1/3	20.8	1.73	2.454	1.08							.333	-.150	29.9	-24.4
1-B	1	1/3	20.8	1.73	2.689	1.12							.2	0.0	29.9	-28.8
2-A	2	1/3	20.8	1.73	1.565	1.41							.45	.39	30.6	-23.9
2-B	2	1/3	20.8	1.73	1.59	1.37							.36	.36	21.2	-56
3-A	2	1/3	40.0	2.0	2.309	1.65							-.86*	-.695	42.4	-43.4
3-B	2	1/3	40.0	2.0	2.537	1.81									48.0	-47.6
4-A	1	1/3	46.5	1.5	2.140	1.15	5.9	5.6	5.6				.955	1.450	42.3	-47.8
4-B	1	None	16.1	-	1.285	1.29		8.2					2.42	-2.92		
4-C	1	1/3	47.2	1.5	2.244	1.27	5.7	3.8	6.4				.276	.518		
4-D	1	1/2	47.0	1.5	2.220	1.22	*		5.2				.722	.487		
4-E	1	None	44.9	1.5	2.543	1.45		13.0					.976	.197		
5-A	3	1/3	41.7	2.1	1.156	0.92	21.9	11.6	14.2	13.7	12.8	13.0	.397	.334	27.5	-20.4
5-B	3	1/2	40.1	2.0	2.759	2.30	21.7	9.3	8.0	7.3	6.8	5.9	1.161	.856	32.2	-27.9
6-A	3	1/2	49.3	1.23	2.014	1.80	*	5.4	11.6	13.0	6.8	7.0	.828	.890	39.1	-38.6
6-B	3	1/2	50.11	1.25	1.618	1.42	10.2		4.7	11.2	8.4	9.2	.021	1.209	29.2	-31.7

Notes: *For 1/3rd point bracing 1, 2, 3 and 4, 5, 6 are at outside and inside locations respectively, in the north exterior span, ridge to eave.
For midspan bracing, 1, 2, 3 and 4, 5, 6 are at midspan of north exterior and center bays, ridge to eave.
m = measured
p = predicted

CHAPTER IV

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

4.1 Summary

Six series of tests of a standing seam roof system are reported here. One, two and three span configurations of systems designed for light, medium and heavy live loads were tested. A total of fifteen tests were conducted. Each set-up was fully instrumented and loading was to failure of the system. Emphasis was placed on determining intermediate brace forces and brace force accumulation effects.

The complete test matrix is given in Table 1, a summary of results is found in Table 5 and comparisons of results at nominal design loads (working loads) and at a factored working load are found in Tables 6 and 7, respectively. General conclusions and recommendations follow.

4.2 Conclusions and Recommendations

Failure Load Predictions. Except for Tests 4-A and 4-C, actual failure loads were either greater than or within 20% of predicted loads. In Tests 4-A and 4-C, premature failure was caused by failure of the ridge purlin which, for testing purposes as explained in Section 3.5, was nonstandard in size. Of the remaining tests, the actual failure loads were either greater than or within 13% of predicted loads except for Tests 1-B and 2-B. Both of the tests were conducted using the same set-up as the previous test in the series with only damaged material replaced. It is believed this procedure caused the lower failure loads in the second tests. For the two tests without intermediate bracing, Test 4-B and 4-E, the actual loads were over 200% greater than the predicted loads. The predicted loads were based on an unbraced length equal to the span length. Obviously, some lateral restraint is provided by panel "drop" and friction in the clip.

Predicted failure loads were all obtained using Star Manufacturing Company's purlin design program. For analyses of single spans, the unbraced length of the purlin compression flange is assumed to be equal to the distance from the rafter to an intermediate brace or to the distance between intermediate braces. When the top flange is in compression in a multi-span analysis, brace points are assumed to be at the inflection points and at the intermediate brace locations. When the bottom flange is in compression, only the rafter locations and the inflection points are considered to be brace points. The failure load was defined as the applied load which produced a unity check value of 1.67. From the results of this testing program, it is concluded that Star Manufacturing Company's program is adequate for the design of standing seam roof systems of one, two or three continuous spans and with 1/3rd point, midspan or no intermediate bracing, constructed as described herein.

Failure Modes. Except for Test 5-B, the failure mode for all tests was local buckling of the compression flange and lip. The failure mode for Test 5-B was web crippling at an exterior support. In Test 4-B, local buckling was influenced by excessive lateral displacements. The location of local buckling was approximately 12 in. either side of midspan for single span tests and immediately outside the lap in an exterior bay for multi-span tests.

Vertical Deflections. Vertical deflections were estimated using the constrained bending assumption and standard stiffness analysis for multi-span tests. For all tests except 5-A, measured vertical deflections were greater than predicted deflections ($\Delta_m/\Delta_p > 1.0$ in Table 7). For Test 5-A, vertical deflections were slightly less than predicted.

At working loads, the ratio of measured to predicted deflections varied from 0.92 to 1.63 (Table 6) and at loads above working loads from 0.92 to 2.30 (Table 7). Possibly a better estimate of vertical deflections can be obtained using the procedure suggested in References 2 and 4.

Intermediate Brace Forces. Unfortunately the test set-up used for Series I, II and III resulted in an indeterminate intermediate brace system. Evaluation of the results for these series is beyond the scope of this report, but will be addressed in a future report.

The bracing system used for Series IV, V and VI was determinate and preliminary evaluation can be made. Tables 6 and 7 show brace forces as a percent of stabilized load for working loads and higher loads, respectively. For 1/3rd point bracing schemes, brace numbers 1, 2, 3 and 4, 5, 6 are outside and inside locations, respectively, of the north exterior rafter for multi-span tests and the two brace lines for single span tests. For midspan bracing, 1, 2, 3 are at the midspan location of single spans or of the north exterior span and 4, 5, 6 are at the midspan location of the center span. Numbering is from ridge (1) to eave (3). If the percent of stabilized load is the same for all three braces at a location, full accumulation is indicated.

For the single span tests, Series IV, brace forces as a function of stabilized load varied from 3.8 to 9.7 except for one case (Brace 1 of Test 4-C, Table 6) and values were relatively consistent at a brace line. The magnitudes are considerably lower than found for similar tests using conventional panel[4].

For Test 5-A, three spans with intermediate braces at the 1/3rd points of all spans, higher forces were measured in the exterior span, with the highest forces at the exterior 1/3rd point. Full accumulation is indicated except at the eave location at the exterior 1/3rd point of the north exterior span where very large forces were measured. Values at this location were 21.9% and 26.1% and varied at the other five locations for both loads from 12.8% to 15.0%.

For the three span tests with midspan bracing, Test 5-B and Series VI, measured forces were erratic. In general full accumulation was not realized and the forces were higher in the exterior span than in the center span.

A more detailed evaluation of the brace force distribution will be provided in a future report.

Stress Distribution. Stress distributions determined from strain gage measurements generally confirmed the constrained bending assumption at midspan locations, but considerable difference was found at locations immediately outside the lap. Generally, yielding was not detected before failure. It is believed the techniques suggested in References 2 and 4 will provide a better estimate of the stress distribution at the lap location.

Lateral Displacements. Lateral displacement of the test purlins was erratic as shown in Tables 6 and 7. It is believed initial "plumbness" of the purlin webs and initial sweep along the span significantly effect lateral displacements. No further analysis of the phenomenon is planned.

REFERENCES

1. "Specification for the Design of Cold-Formed Steel Structural Members", American Iron and Steel Institute, Washington, D.C., September 1980.

2. Wallace, B.J. and Murray, T.M., "Web Buckling of Continuous Lapped Z-Sections", with Benjamin Wallace, Research Report submitted to Star Manufacturing Company, January, 1979, 80 pages.

3. Wallace, B.J. and Murray, T.M., "Experimental and Analytical Studies of Continuous Lapped Z-Purlins under Gravity Loading", Research Report submitted to Star Manufacturing Company, July, 1980, 59 pages.

4. Ghazanfari, Ahmad and Murray, Thomas M., "Simple Span Z-Purlin Tests with Various Restraint System", Research Report submitted to the Metal Building Manufacturers Association, Fears Structural Engineering Laboratory, University of Oklahoma, Report No. FSEL/MBMA 82-01, Norman, Oklahoma, February 1982.

APPENDIX A

TEST SERIES I RESULTS

TEST SUMMARY

Project: Star Manufacturing Company

Test No.: 1A

Test Date: 5/28/81

Purpose: Base Test

Span(s): 25'-0" Single Span

Thickness: 0.083 Moment of Inertia: 13.589 in^4

Parameters: Intermediate Bracing @ 1/3 pt.

Clips in place.

No insulation

Spacing @ 5'-0"

Failure Load: 143.0 plf

Failure Mode: Local buckling of the compression flange & lip

Predicted Failure Loads:

Method	Star (u.c. = 1.669)	Load	146 plf
Method	(AISI Constrained) x 1.67	Load	201.5 plf
Method		Load	

Discussion:

-At the onset of this test very poor load vs. deflection results were observed. After several tests to working load and an analysis of the test set-up as a grid, it was concluded that due to the stiffness of the deck and the strength of the clip the deck was transferring load to the outside purlin. All purlins in the set-up were identical and, since the tributary area for this purlin was only one-half of the interior purlins, reserve capacity existed.

-Ribs of the deck were cut close to the interior purlins to allow the test purlin to deflect independently of adjacent purlins.

-After this modification, the load vs. deflection curve showed good agreement with the deflection predicted through constrained bending analysis.

-Failure occurred because of local buckling of the compression flange and lip at the center line of the span.

-The test failure load was 38.0% less than that predicted using constrained bending theory and AISI criteria.

-The Star Manufacturing Company failure load prediction was 2% greater than the test load. This prediction was based on a laterally unbraced span equal to the intermediate bracing spacing.

-The stress distribution over the cross-section at working load is close to constrained bending.

-The maximum stress at failure load was 39.6 ksi at the bottom flange to web junction.

- An attempt was made to instrument standard Star intermediate bracing to produce dynamometers. Success was limited and brace force results should be used with caution.

- Brace dynamometer #3 was not working at the time of the tests.

- Dynamometer #1, which was between the last purlin and the simulated eave (a relatively stiff member in the lateral direction), was in compression throughout the test. Dynamometer #2, on the next downhill purlin, was near zero and Dynamometer #4, which was attached to the eave, was in tension.

- Lateral movement of the top and bottom flange was in opposite directions. The top flange of the purlin displaced more than the bottom flange.

- From the plot it appears as if the bottom flange displacement transducer may have slipped at the first reading.

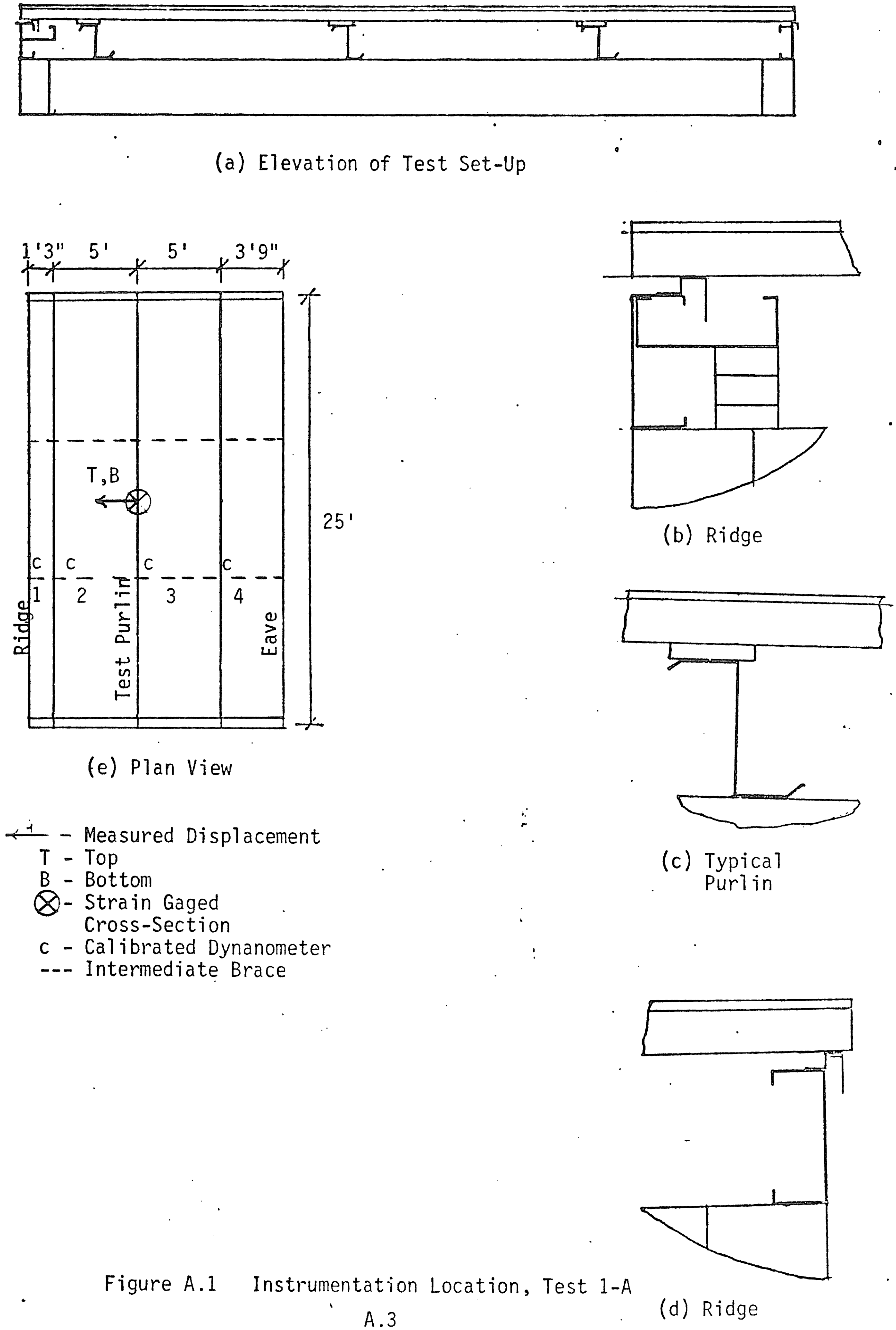


Figure A.1 Instrumentation Location, Test 1-A

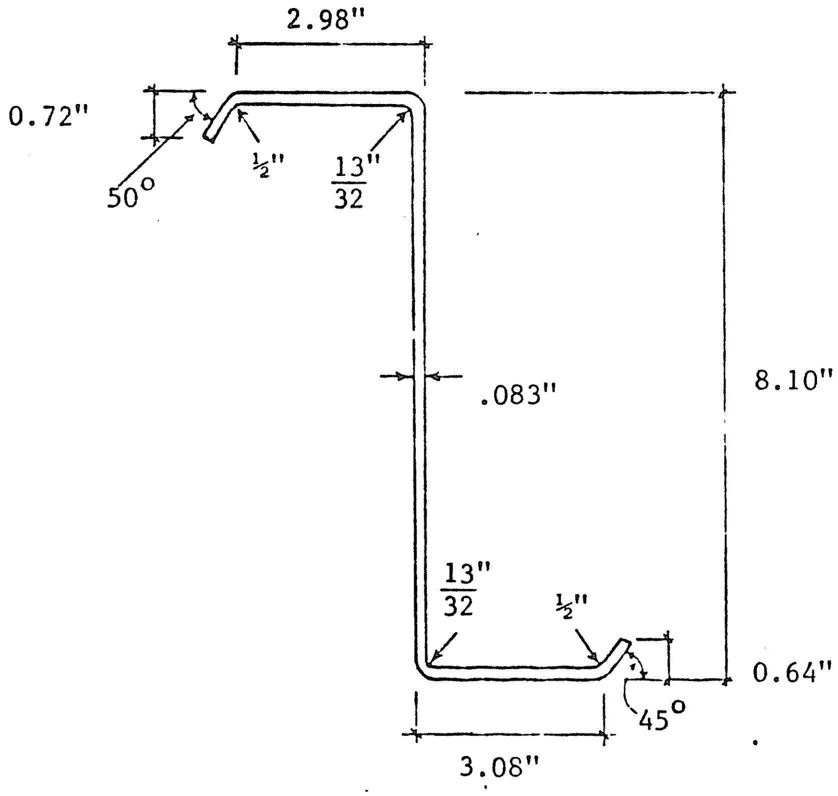


Figure A.2 Measured Purlin Dimensions, Test 1-A

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A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: STAR PURLIN TEST 1-A
```

	TOP	BOTTOM
FLANGE(in)	2.980	3.080
LIP(in)	0.720	0.640
LIP ANGLE(deg)	50.000	45.000
RADIUS L/F(in)	0.500	0.500
RADIUS F/W(in)	0.406	0.406

TOTAL DEPTH(in)	8.1
THICKNESS(in)	0.083
YIELD STRENGTH(ksi)	51.8

	MOMENTS OF INERTIA(in^4)	SECTION MODULII(in^3) TOP	SECTION MODULII(in^3) BOTTOM
GROSS=	13.590	3.377	3.403
STRENGTH=	13.590	3.377	3.403
DEFLECTION=	13.590		

BE=	2.491	in
FC=	31.080	ksi
FT=	31.080	ksi
FBW=	30.337	ksi

Figure A.3 AISI Cross-Section Analysis, Test 1-A

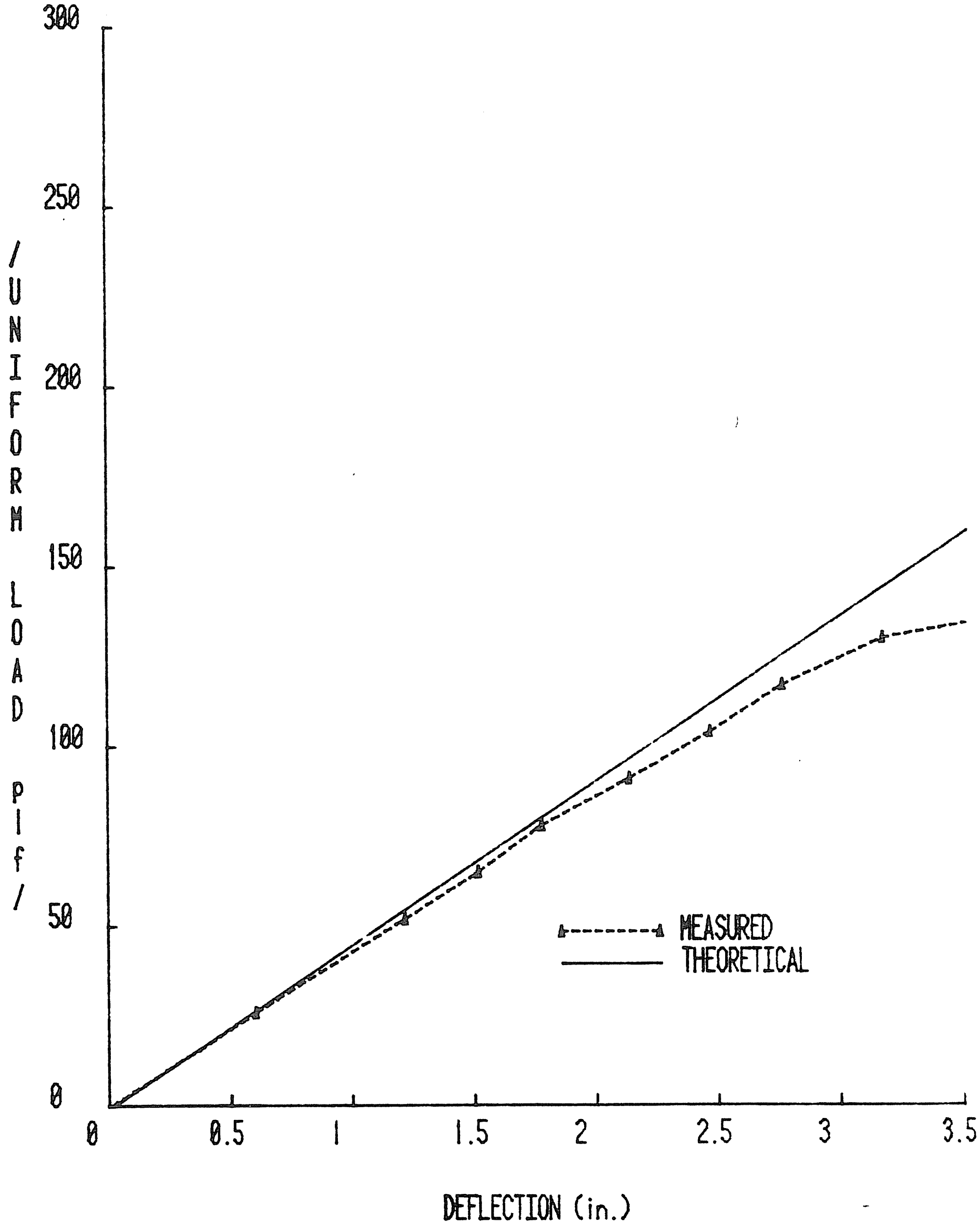


Figure A.4 Load vs. Vertical Deflection, Test 1-A

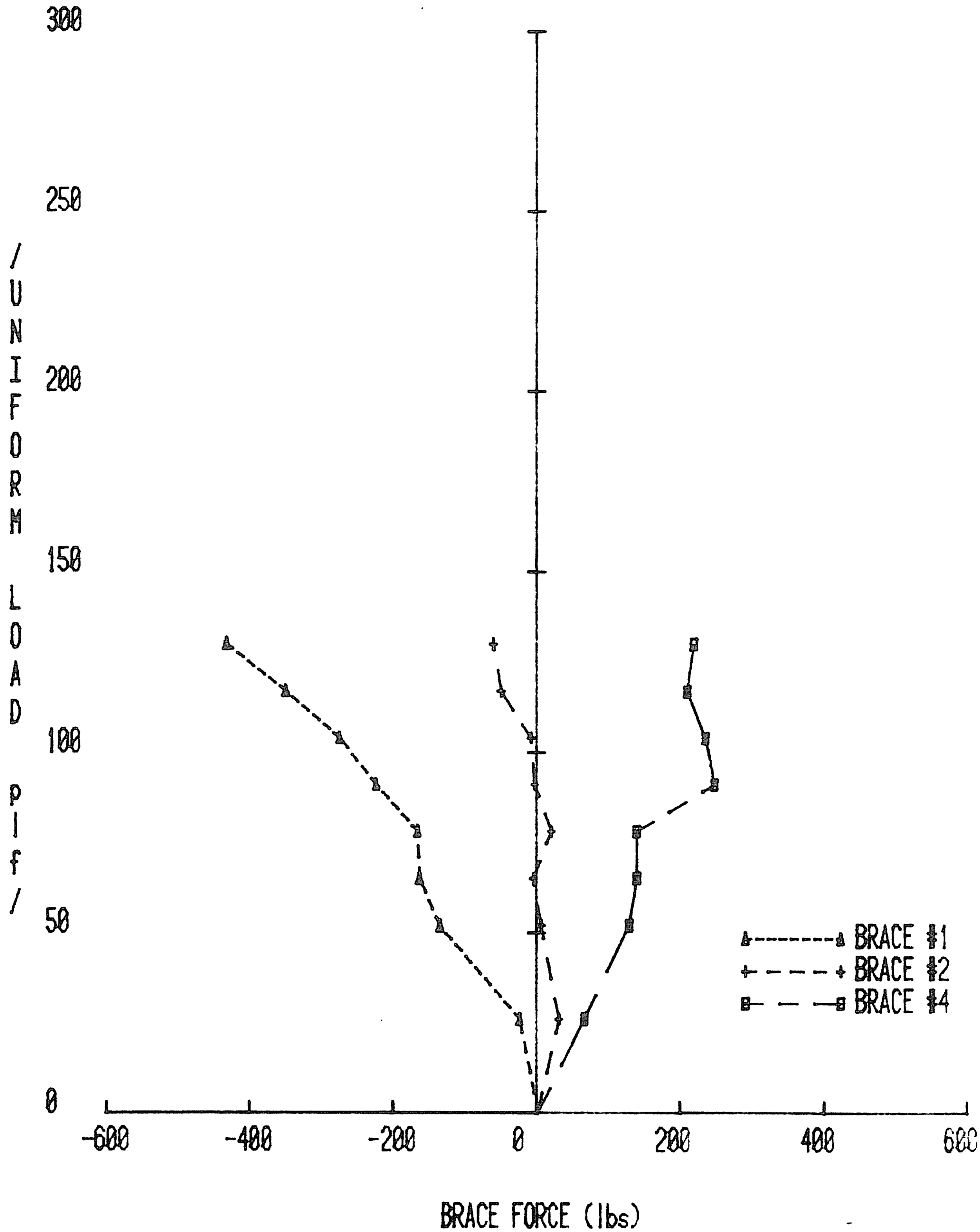


Figure A.5 Vertical Load vs. Brace Force at 1/3 Point of Span, Test 1-A

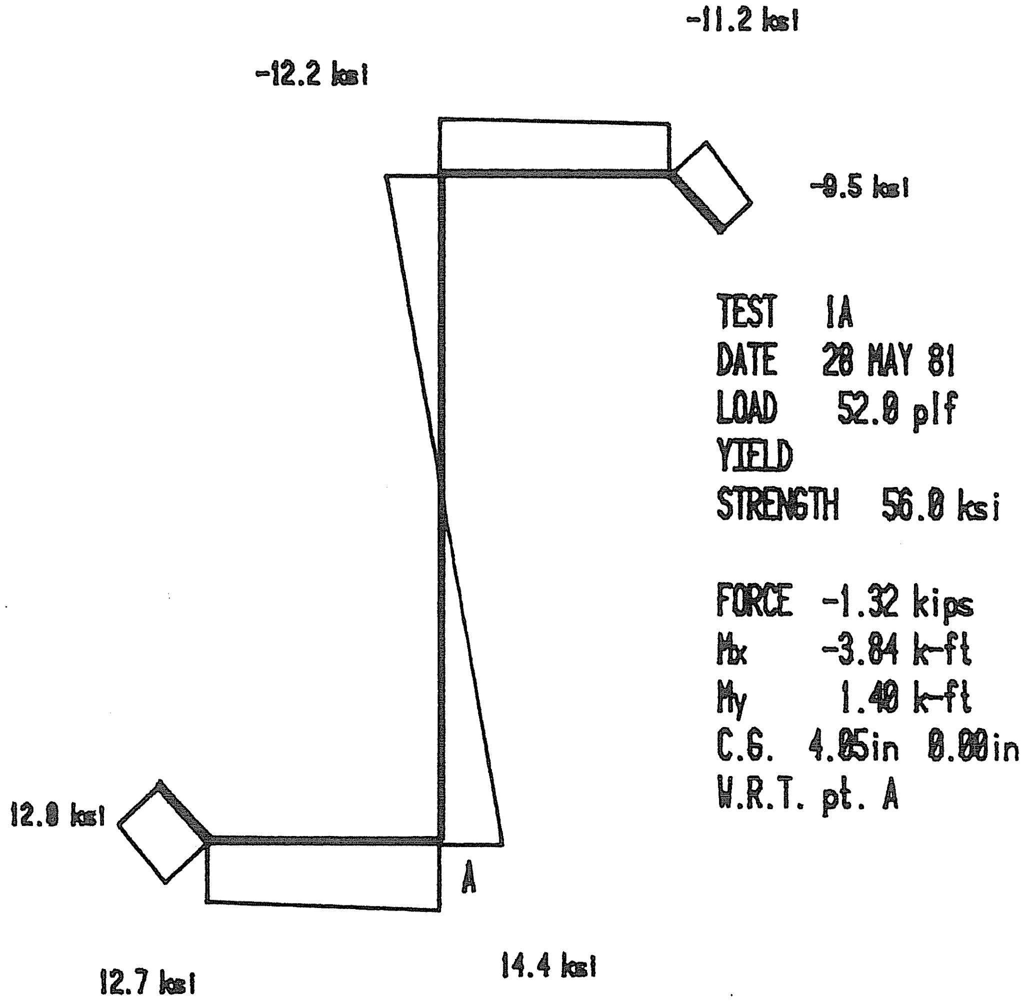


Figure A.6 Stress Distribution at 52 plf, Test 1-A

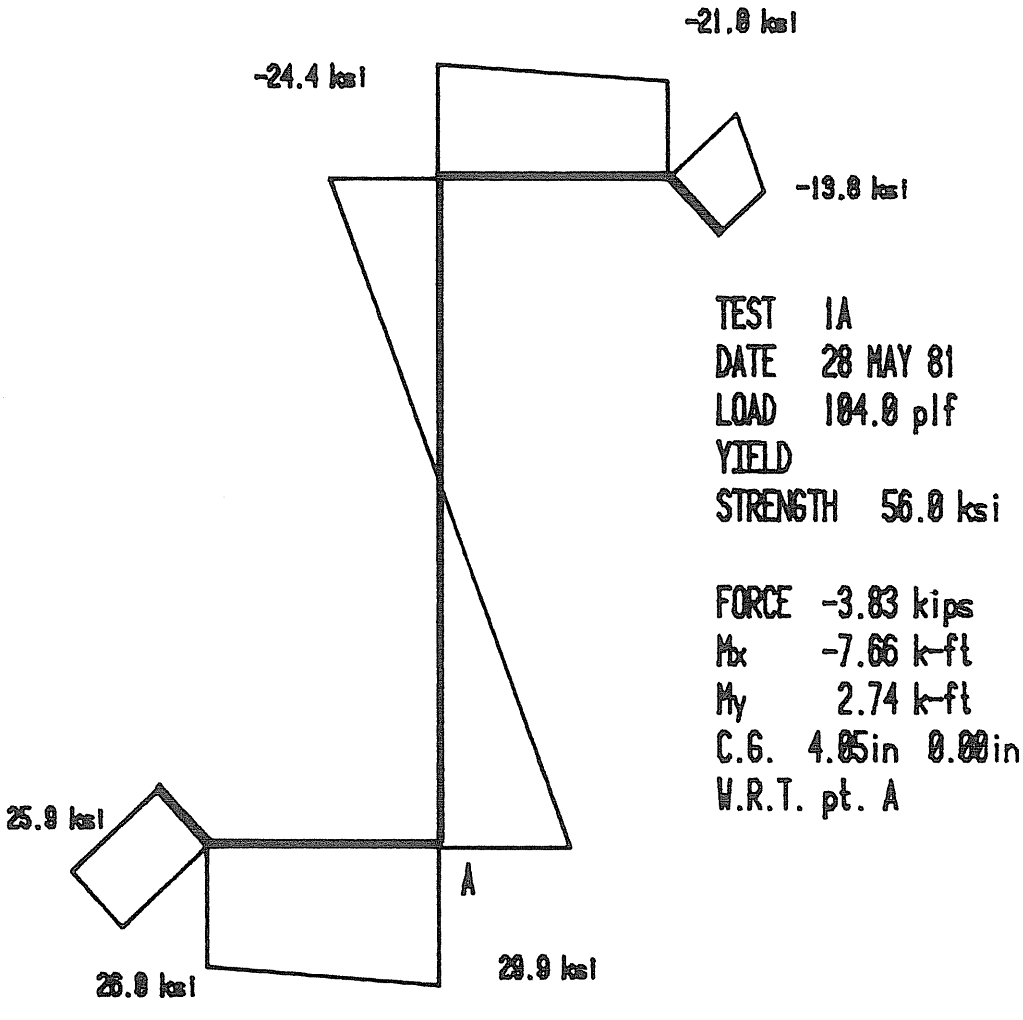


Figure A.7 Stress Distribution at 104 plf, Test 1-A

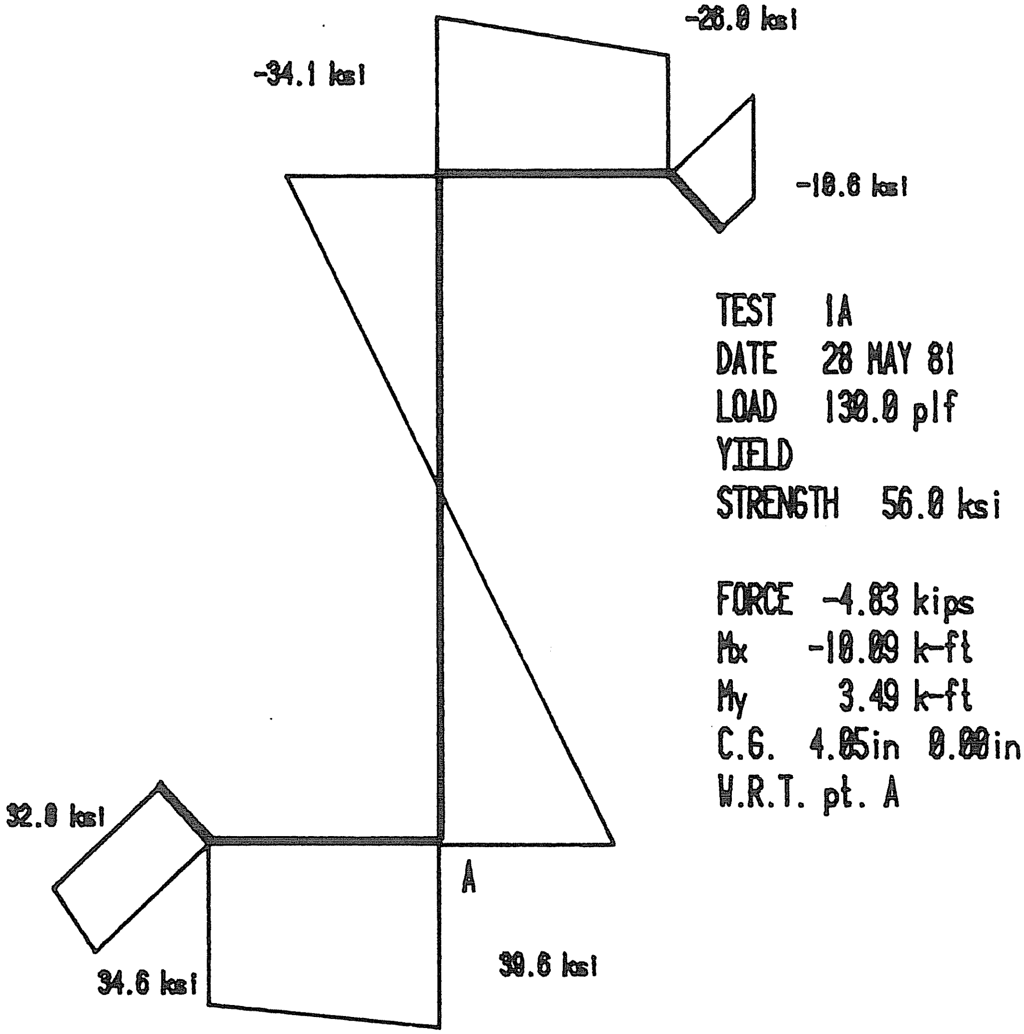


Figure A.8 Stress Distribution at 130 plf, Test 1-A

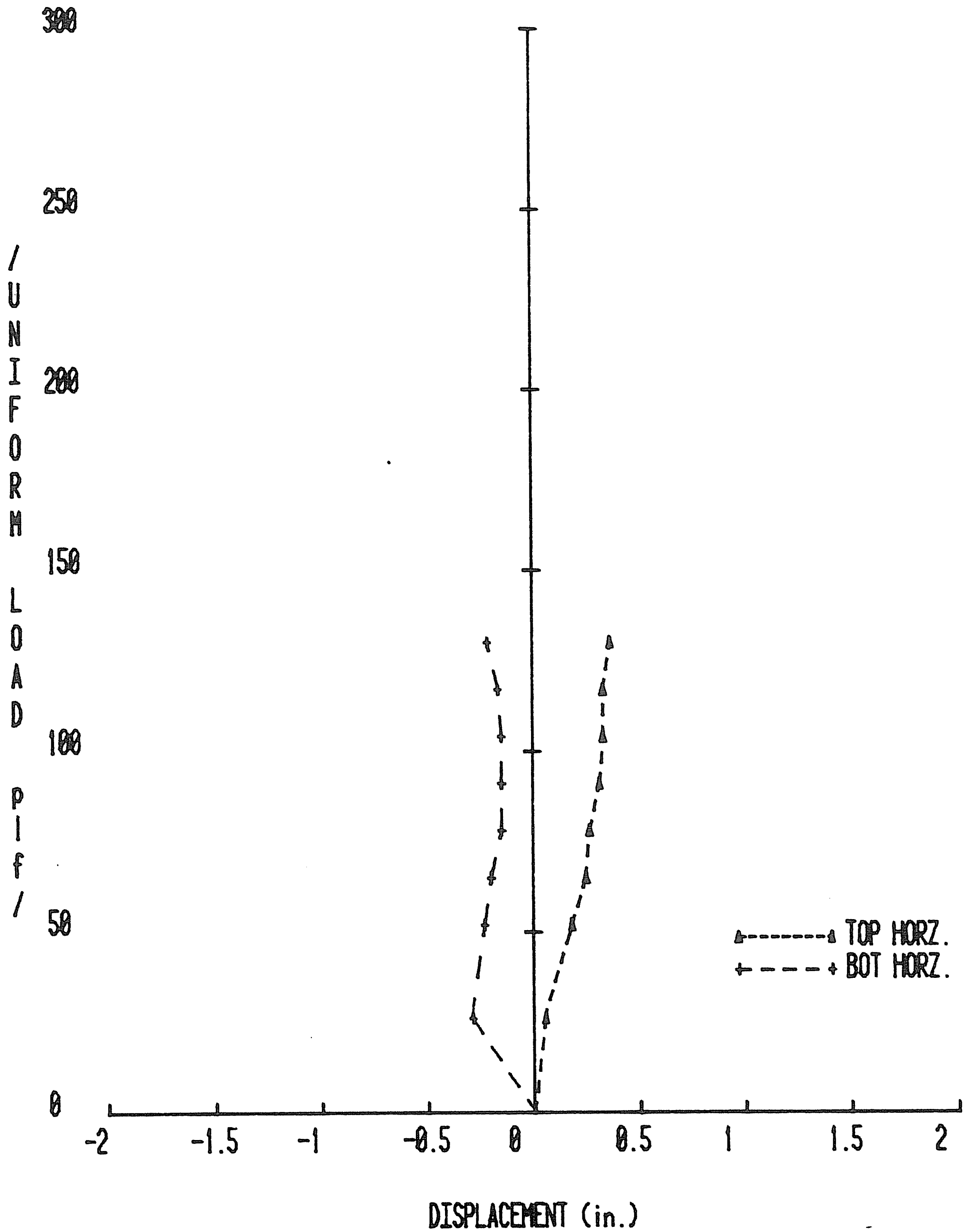


Figure A.9 Vertical Load vs. Lateral Displacements, Test 1-A

TEST SUMMARY

Project: Star Manufacturing Company

Test No.: 1B

Test Date: 6/3/81

Purpose: Base Test

Span(s): 25'-0" Single Span

Thickness: 0.083 Moment of Inertia: 12.929 in^4

Parameters: Intermediate Bracing @ 1/3 pt. $I_{x_{star}}$ = 12.334 in^4

Clips in place.

No insulation.

Spacing @ 5'-0"

Failure Load: 117 plf

Failure Mode: Local buckling of the compression flange & lip @ ℄

Predicted Failure Loads:

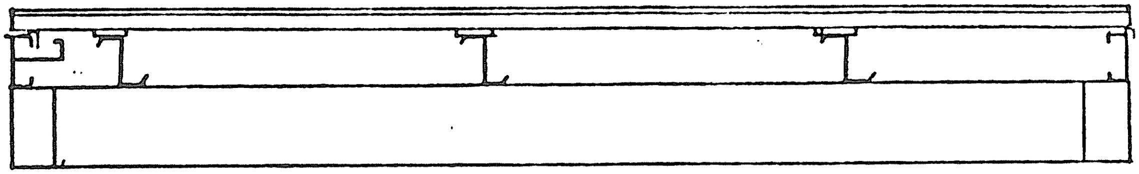
Method Star (u.c. 1.669) Load 145 plf

Method (AISI Constrained) x 1.65 Load 195.1 plf

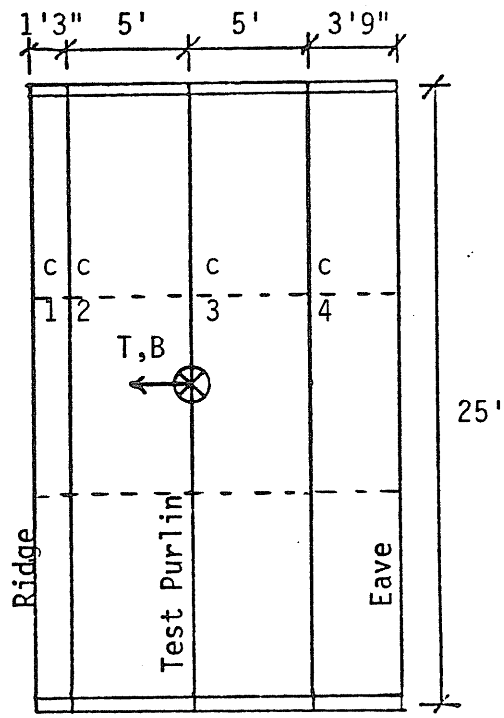
Method Load

Discussion:

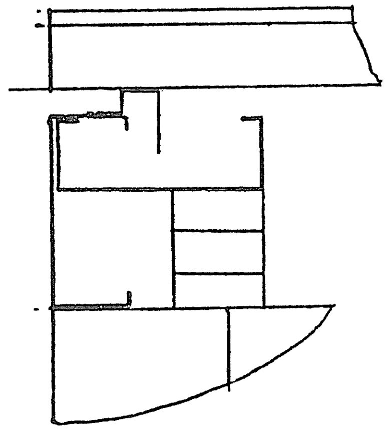
- -This test is identical to Test 1A; only the test purlin was replaced.
- -Deflection of the purlin adjacent to the test purlin was observed to be greater than that of the test purlin. Premature failure of this purlin may have influenced the test.
- -Failure occurred because of local buckling of the compression flange and lip at the centerline of the span.
- -The measured load vs. deflection curve for the tet purlin was in good agreement with the constrained bending prediction.
- -The predicted constrained bending AISI failure load was 66.7% higher than the test failure load.
- -The Star predicted failure load was 23.9% higher than the test failure load. This prediction was based on lateral buckling.
- -The maximum stress on the purlin was at the top flange to web junction and was 42.6 ksi comp.
- -Intermediate brace forces were relatively consistent. Braces near the ridge were in compression and those near the eave in tension. Only the brace near the ridge showed significant load.
- -The top flange lateral displacement was higher than the bottom flange up to 80 plf at which point bottom flange changed direction and moved the same magnitude as the top flange.



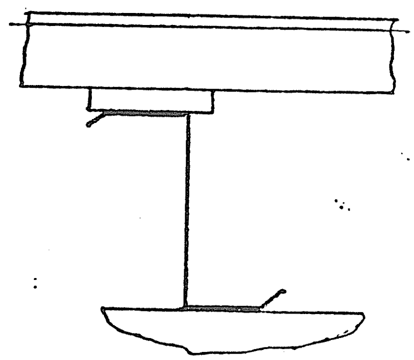
(a) Elevation of Test Set-Up



(e) Plan View

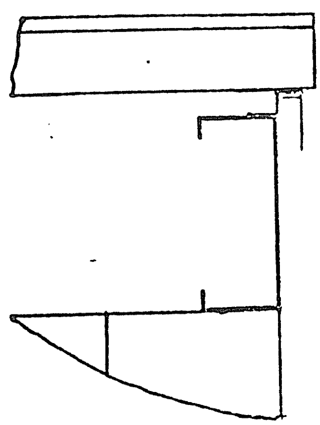


(b) Ridge



(c) Typical Purlin

- Measured Displacement
T - Top
B - Bottom
⊗ - Strain Gaged Cross-Section
c - Calibrated Dynanometer
--- Intermediate Brace



(d) Ridge

Figure A.10 Instrumentation Location, Test 1-B

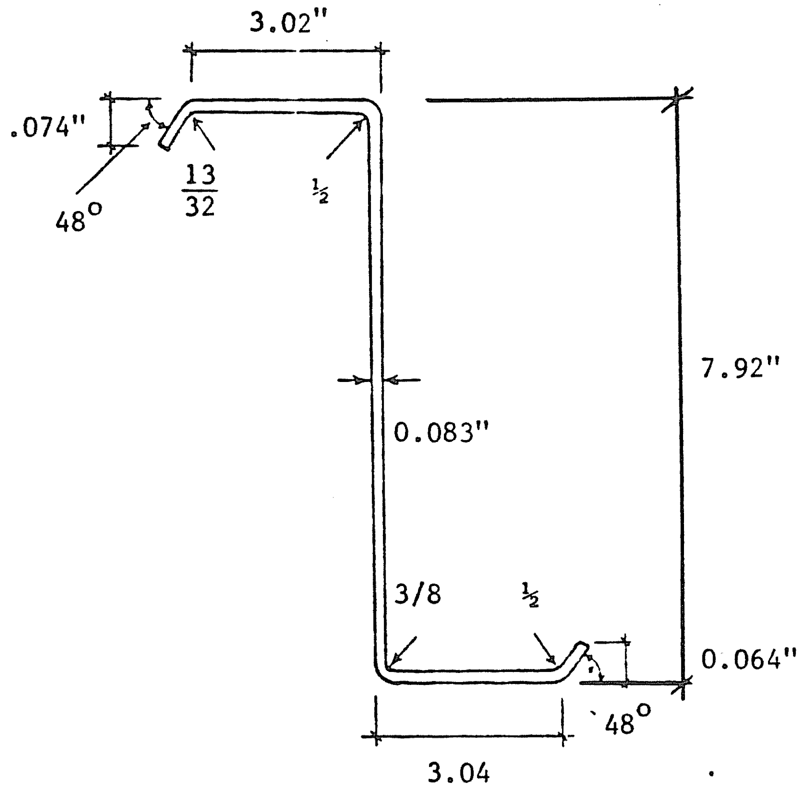


Figure A.11 Purlin Dimensions, Test 1-B

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A I S I  P U R L I N  A N A L Y S I S
IDENTIFICATION: STAR PURLIN TEST 1-B
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	TOP	BOTTOM
FLANGE(in)	3.020	3.040
LIP(in)	0.740	0.640
LIP ANGLE(deg)	48.000	48.000
RADIUS L/F(in)	0.500	0.500
RADIUS F/W(in)	0.406	0.375

TOTAL DEPTH(in)	7.92
THICKNESS(in)	0.083
YIELD STRENGTH(ksi)	51.4

MOMENTS OF INERTIA(in^4)		SECTION MODULII(in^3) TOP	SECTION MODULII(in^3) BOTTOM
GROSS=	12.930	3.322	3.278
STRENGTH=	12.930	3.322	3.278
DEFLECTION=	12.930		

```
BE=   2.531   in
FC=   30.795  ksi
FT=   30.840  ksi
FBW=  30.293  ksi
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Figure A.12 AISI Cross-Section Analysis, Test 1-B

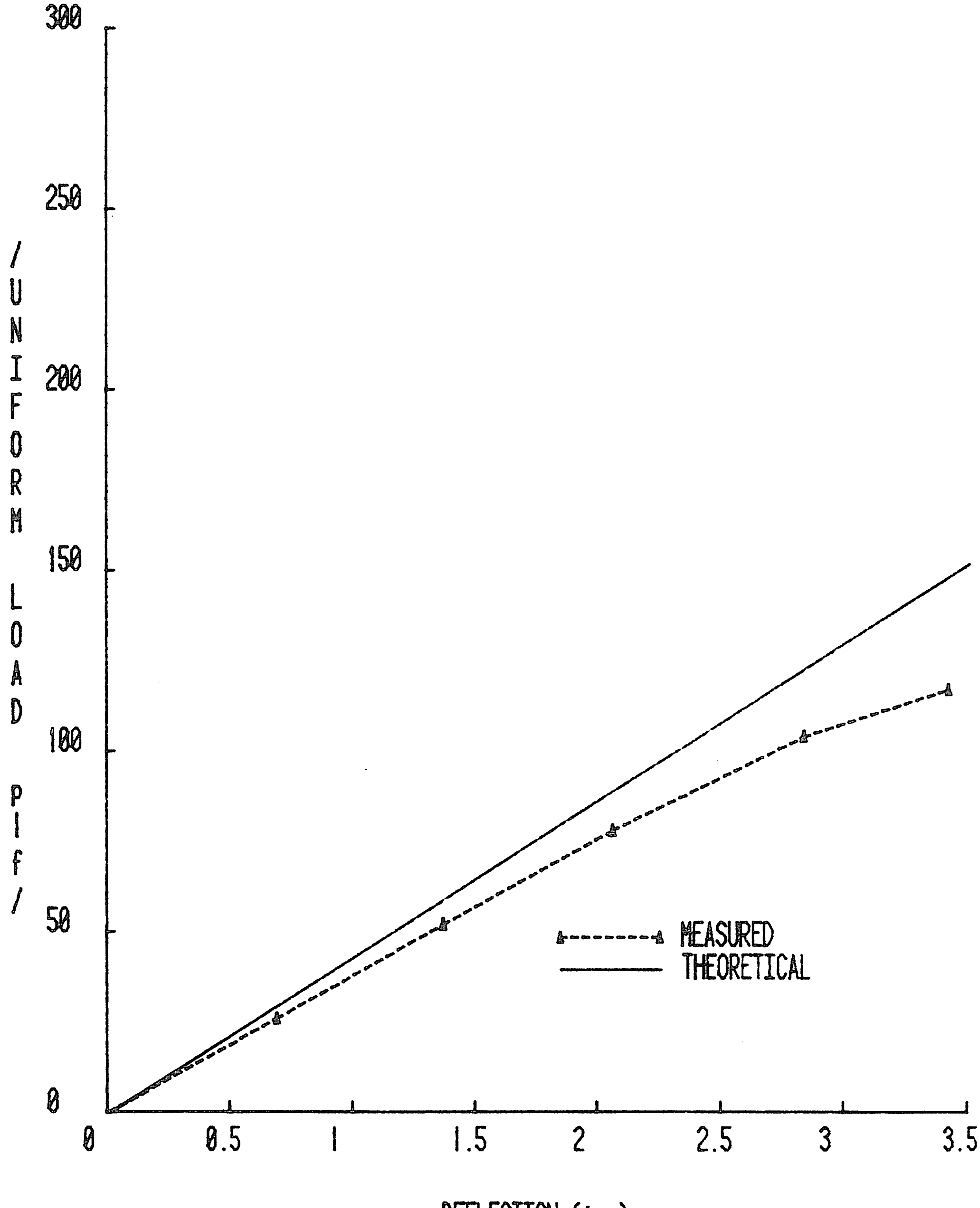


Figure A.13 Load vs. Vertical Deflection, Test 1-B

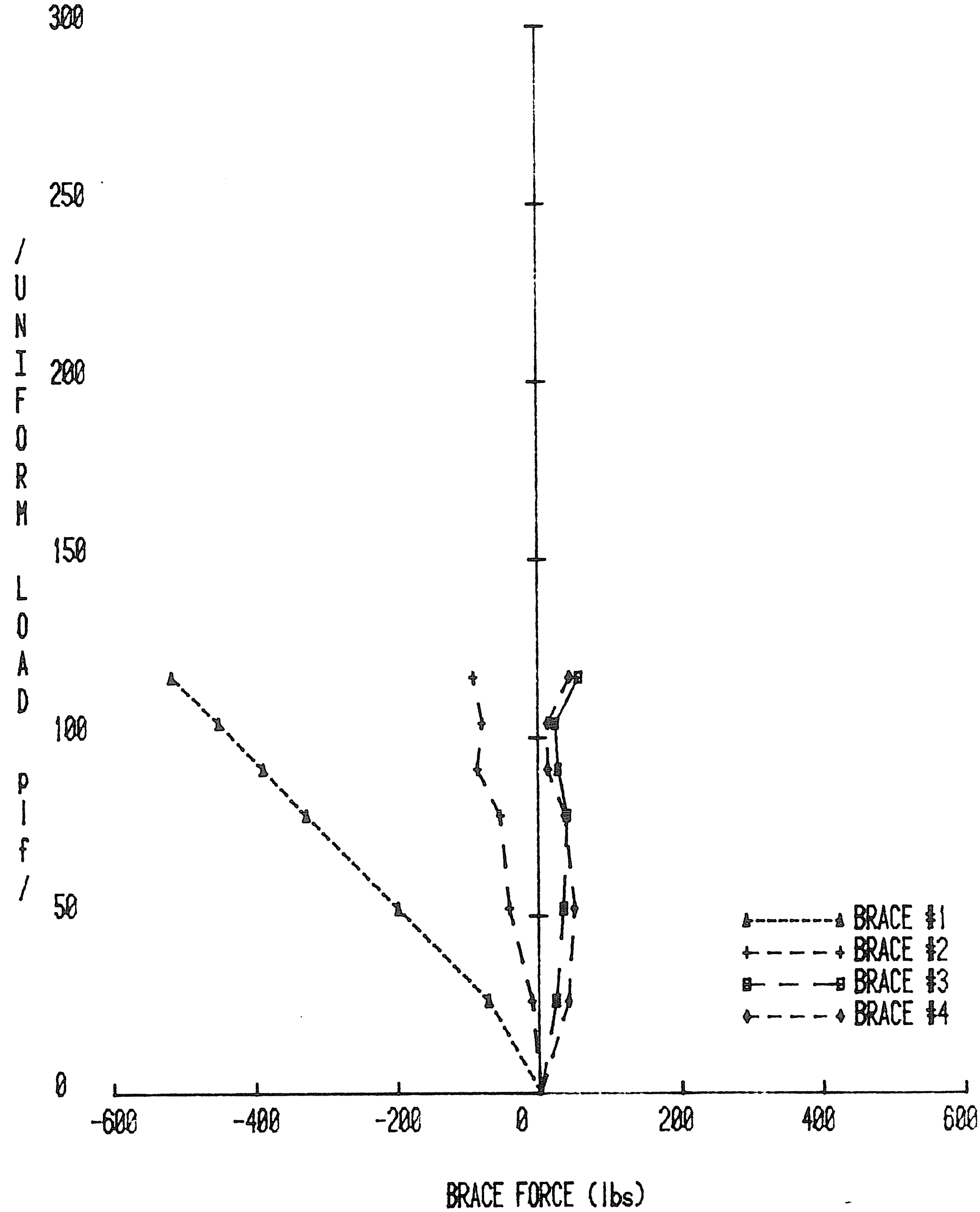


Figure A.14 Vertical Load vs. Brace Force at 1/3 Point of Span, Test 1-B

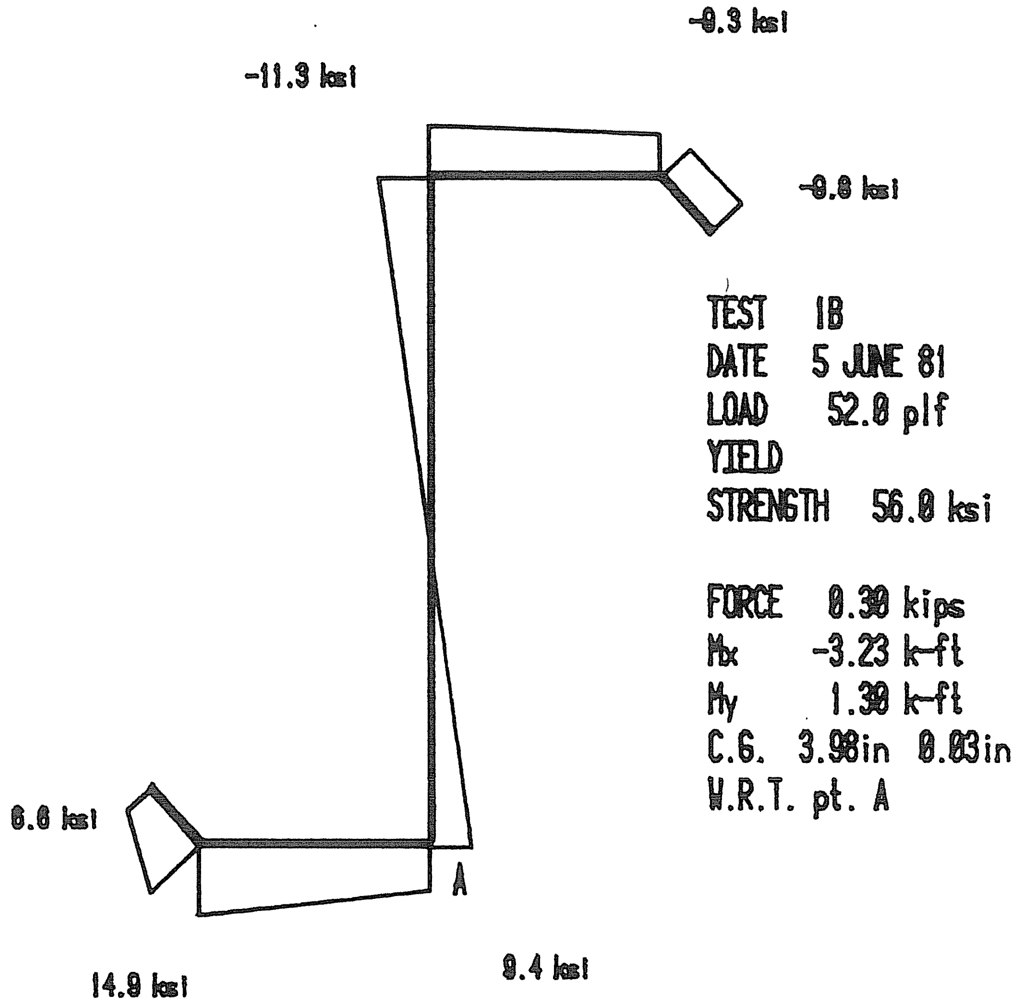


Figure A.15 Stress Distribution at 52 plf, Test 1-B

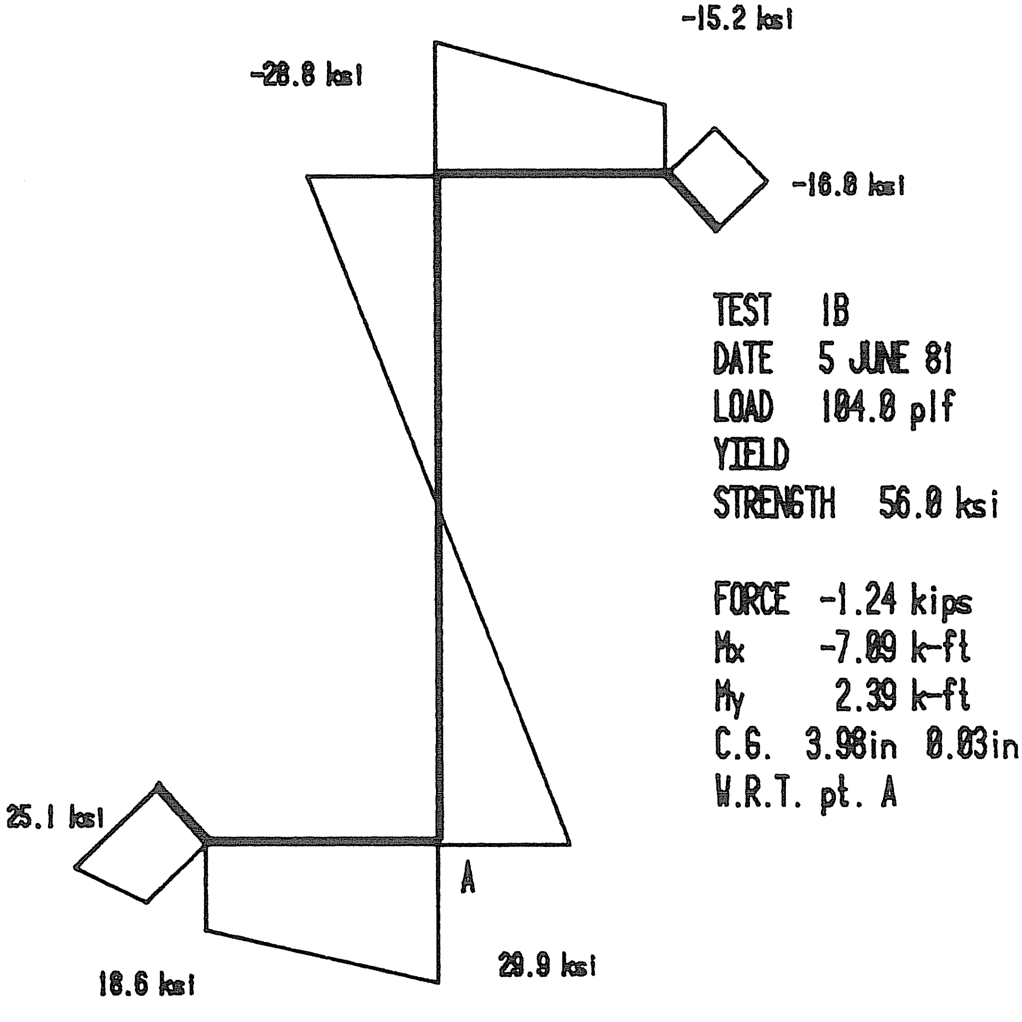


Figure A.16 Stress Distribution at 104 plf, Test 1-B

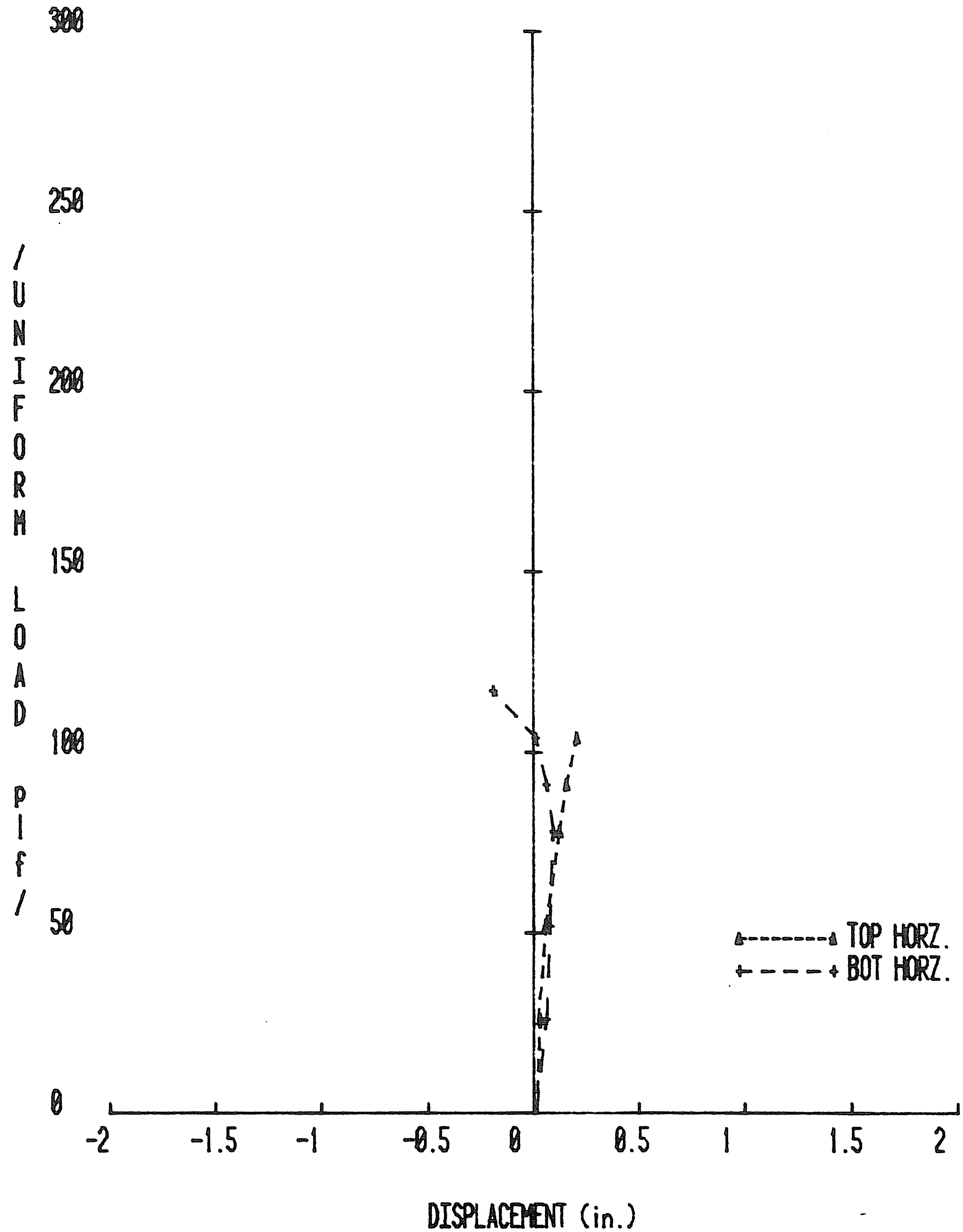


Figure A.17 Vertical Load vs. Lateral Displacements, Test 1-B

APPENDIX B

TEST SERIES II RESULTS

TEST SUMMARY

Project: Star Manufacturing Company

Test No.: 2-A

Test Date: 7/17/81

Purpose: Base Test

Span(s): 2 @ 25'-0"

Thickness: N=0.66", s=0.64" Moment of Inertia: N=10.34 in^4, S=10.315 in^4

Parameters: Intermediate Braces @ 1/3 pt. Star (N=0.814 in^4, S=9.825 in^4)

Clips in place.

No insulation

Spacing @ 5'-0"

Failure Load: 130 plf

Failure Mode: Local buckling

Predicted Failure Loads:

Method Star (U.C. 1.660) Load 149 plf

Method AISI Constrained x 1.67 Load 174 plf

Method Load

Discussion:

-The failure mode was local buckling of the compression flange immediately outside the lap.

-The rib of the deck was cut as was done in Tests 1A and 1B.

-The predicted load vs. deflection (assuming constrained bending) curve was in good agreement with test data.

-The Star predicted failure load was 14.6% higher than the test value.

-The AISI predicted, constrained bending failure load was higher than tested.

-A purlin cross-section immediately outside of the lap was strain gaged.

-The stress distribution over the cross section at working load shows max. stress on the tension side at the web to top flange junction.

-The stress distribution over the cross section near the failure load shows maximum stress at the outside of the lip and at the flange to lip junction both on the compression side.

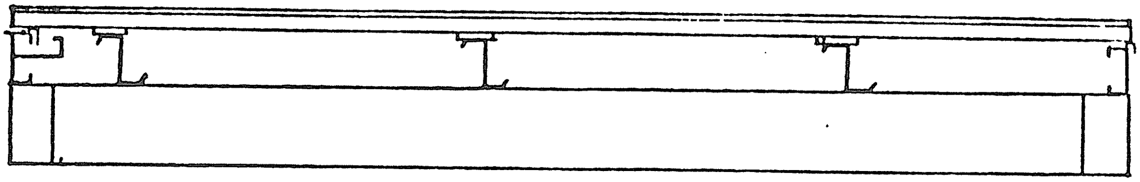
-Only the exterior line of intermediate braces in one span was instrumented.

-Brace forces were found to be as high as 650 lb. compressions at the ridge.

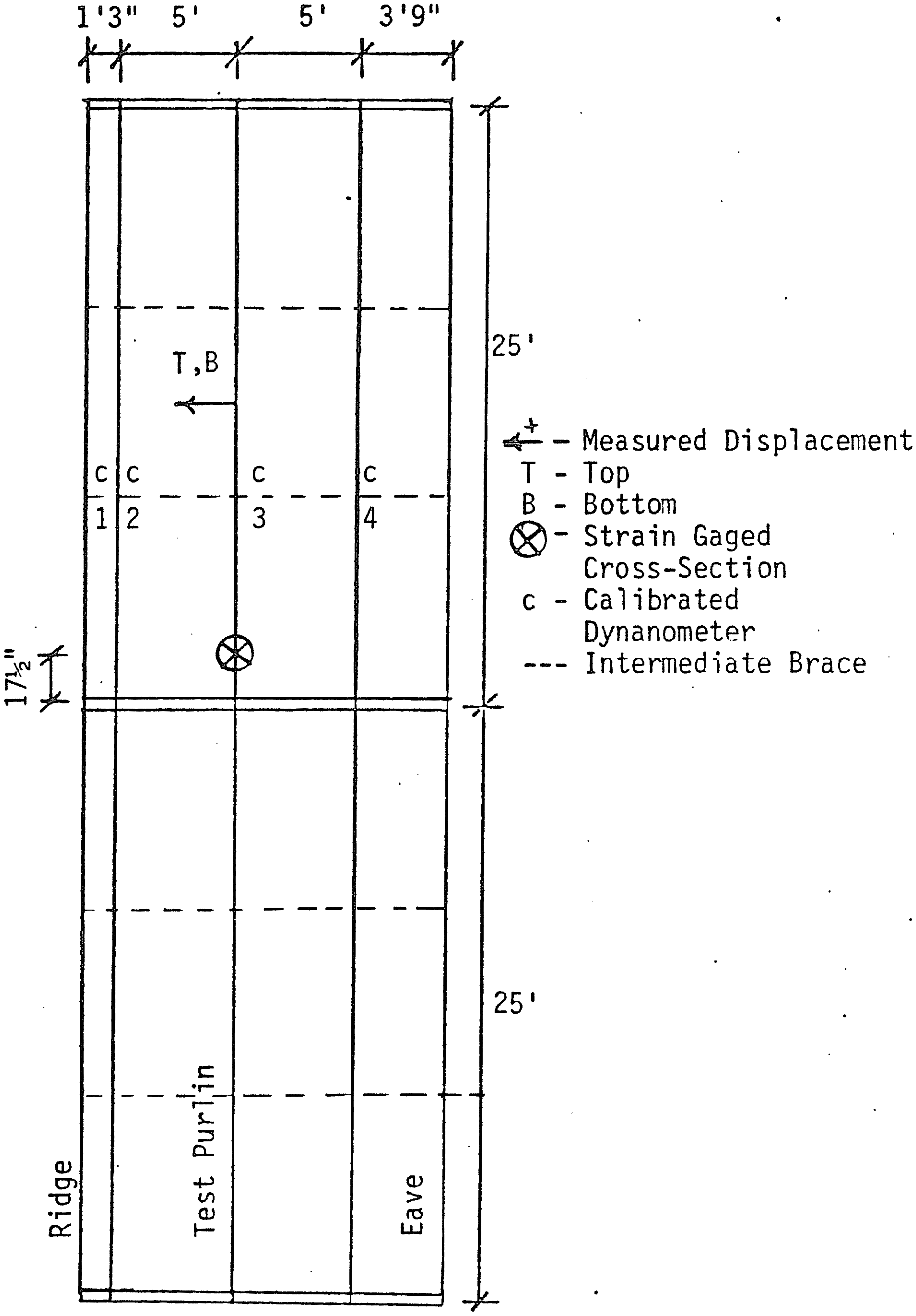
-Brace forces decreased in the direction of the eave and were in tension adjacent to the eave.

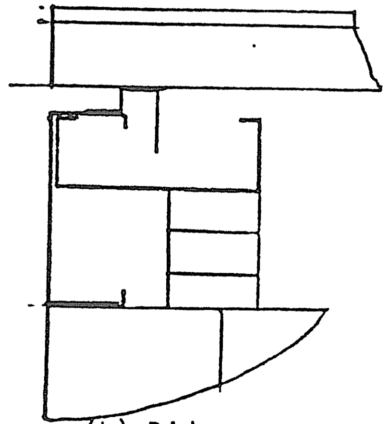
-The top and bottom flange lateral displacements were in the same direction and had about the same magnitude until 105 plf at which point the bottom flange began to move more than the top flange and the top flange changed in direction.

-The maximum lateral displacement was 1.05 in. @ the bottom flange.

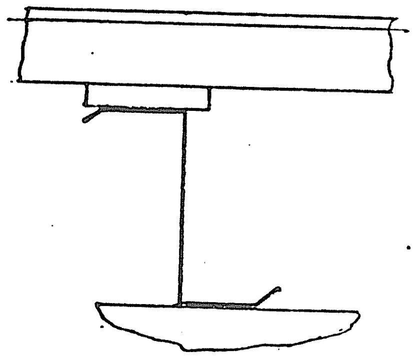


(a) Elevation of Test Set-Up





(b) Ridge



(c) Typical Purlin

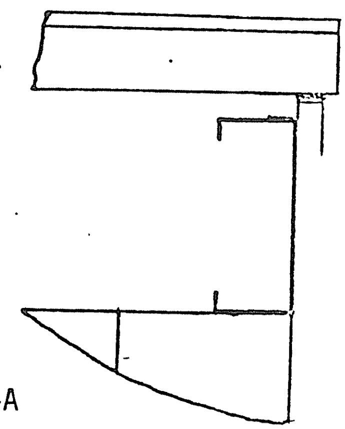
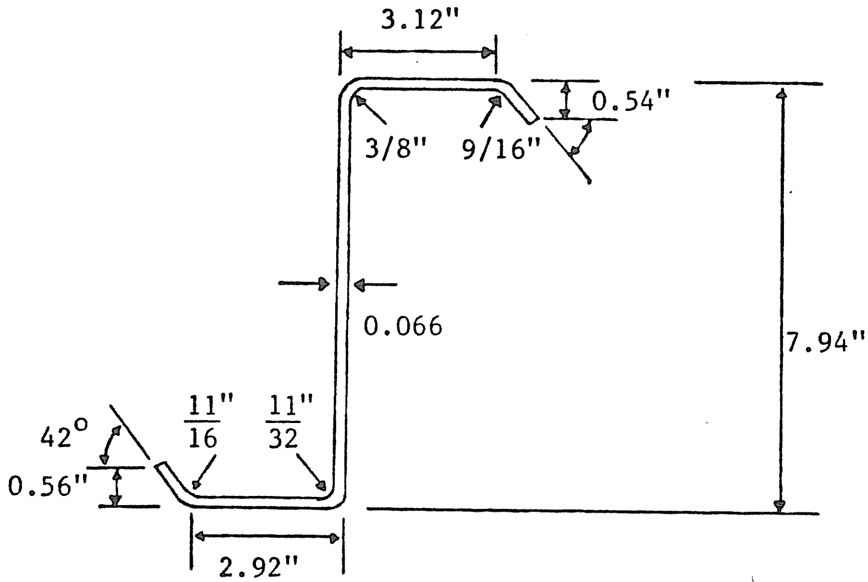
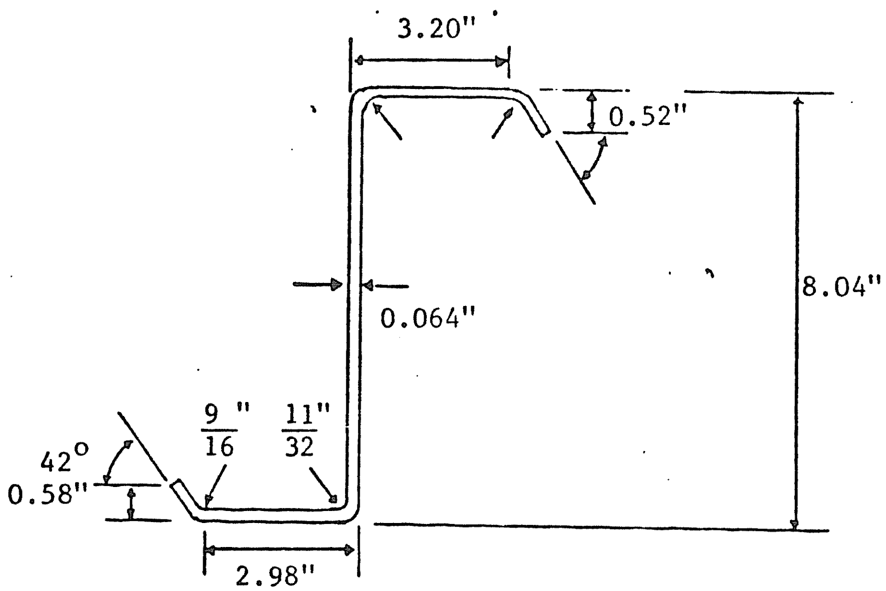


Figure B.1 Instrumentation Location, Test 2-A

(d) Eave



North Span



South Span

Figure B.2 Measured Purlin Dimensions, Test 2-A

A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: STAR PURLIN TEST 2-A NORTH

	TOP	BOTTOM
FLANGE(in)	3.120	2.920
LIP(in)	0.540	0.560
LIP ANGLE(deg)	42.000	42.000
RADIUS L/F(in)	0.313	0.688
RADIUS F/W(in)	0.375	0.344

TOTAL DEPTH(in)	7.94
THICKNESS(in)	0.066
YIELD STRENGTH(ksi)	52.4

	MOMENTS OF INERTIA(in^4)	SECTION MODULII(in^3) TOP	SECTION MODULII(in^3) BOTTOM
GROSS=	10.254	2.615	2.595
STRENGTH=	9.845	2.447	2.557
DEFLECTION=	10.240		

BE=	2.286	in
FC=	30.151	ksi
FT=	31.440	ksi
FBW=	28.888	ksi

Figure B.3 AISI Cross-Section Analysis Test 2-A, North Span

```
------------------------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: STAR PURLIN TEST 2-A SOUTH
------------------------------------------------------------------------
                        TOP                BOTTOM
FLANGE(in)             3.200                2.980
LIP(in)                0.520                0.580
LIP ANGLE(deg)        42.000               42.000
RADIUS L/F(in)         0.563                0.563
RADIUS F/W(in)         0.594                0.344

TOTAL DEPTH(in)                8.04
THICKNESS(in)                  0.064
YIELD STRENGTH(ksi)            53.3
                                          SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)              TOP                BOTTOM
GROSS=          10.315                    2.628               2.546
STRENGTH=        9.927                    2.467               2.511
DEFLECTION=     10.291
BE=     2.158   in
FC=    31.980   ksi
FT=    31.980   ksi
FBW=   28.882   ksi
```

Figure B.4 AISI Cross-Section Analysis, Test 2-A, South Span

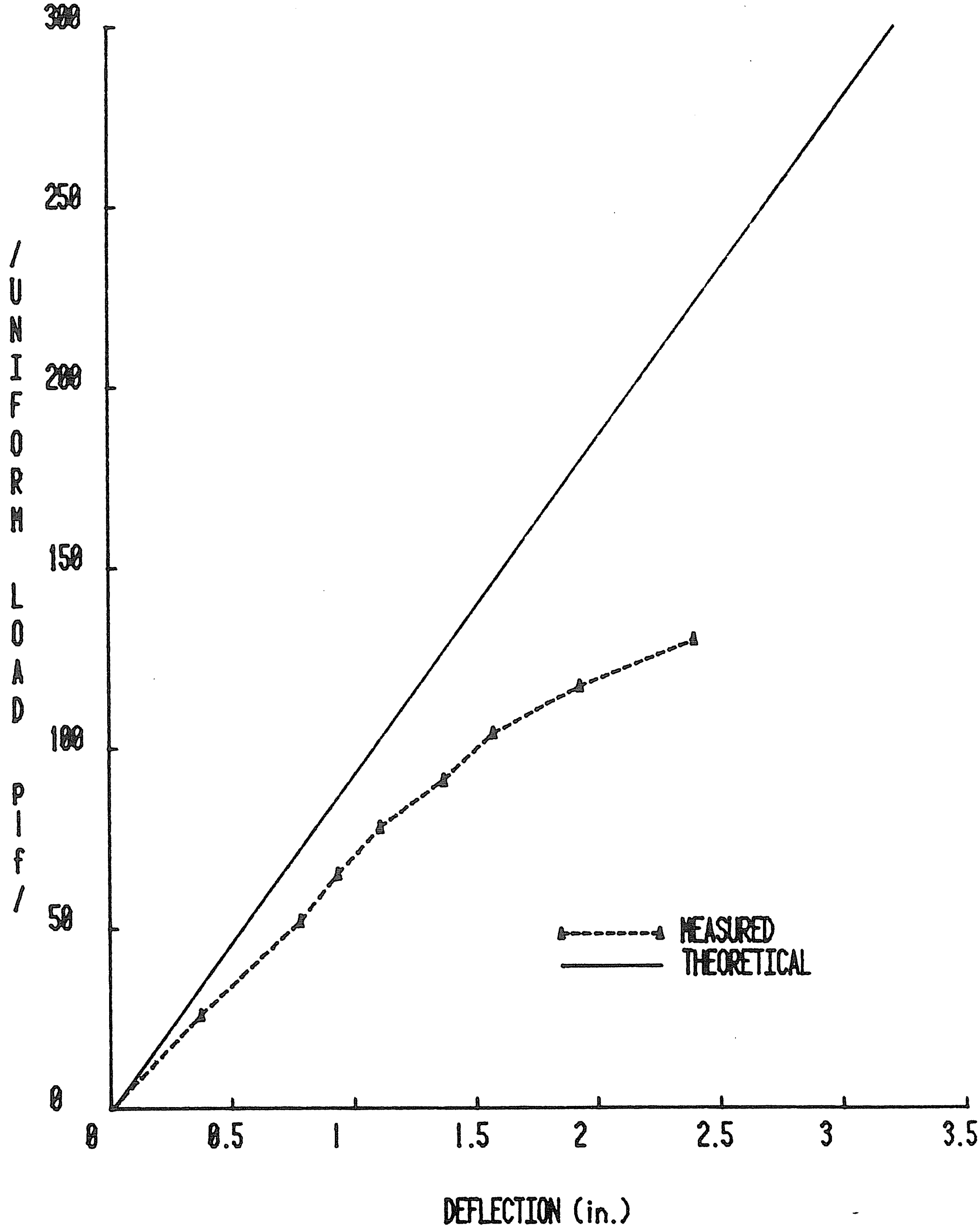


Figure B.5 Load vs. Vertical Deflection, Test 2-A

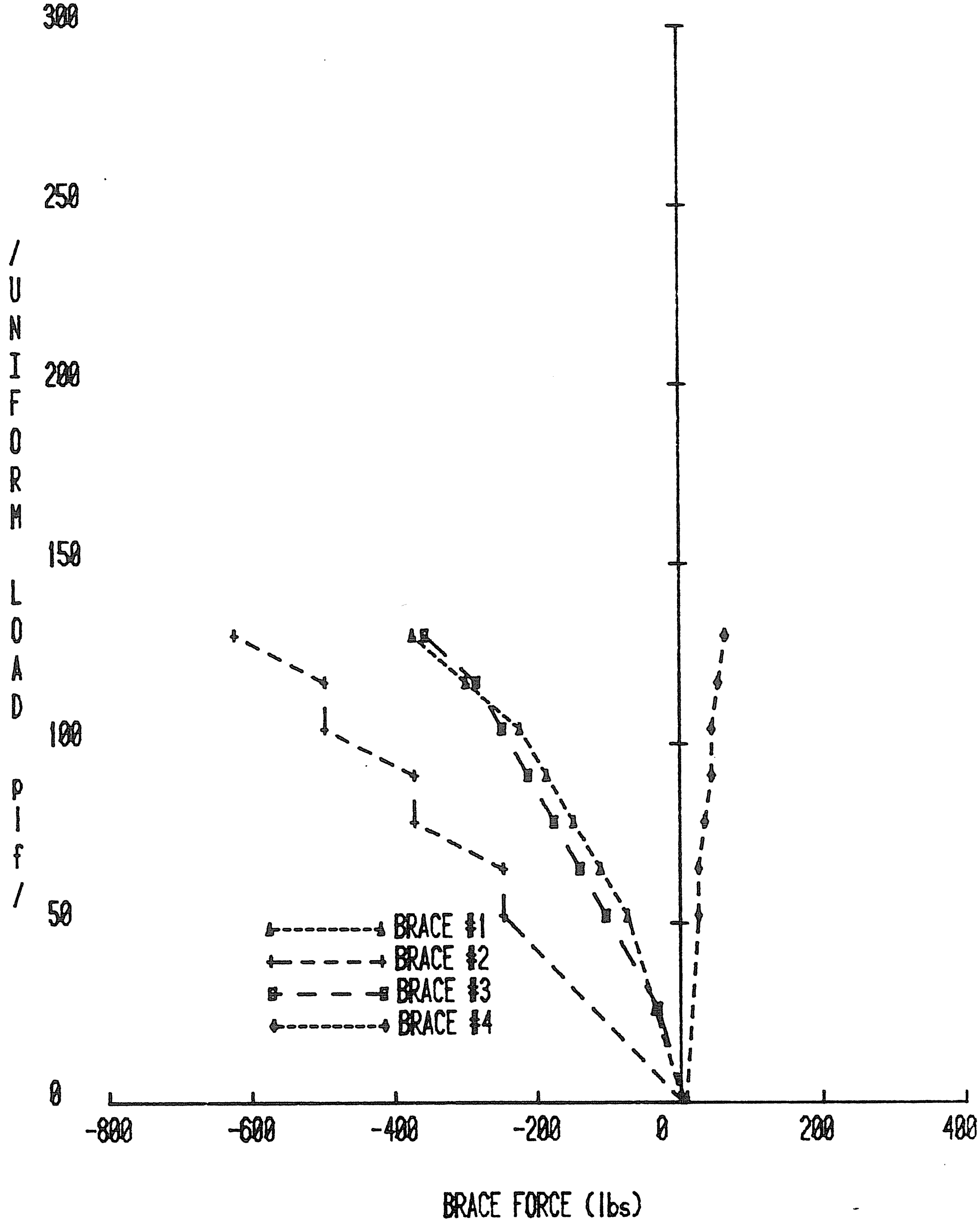


Figure B.6 Vertical Load vs. Brace Force at 1/3 Point of Span, Test 2-A North Bay

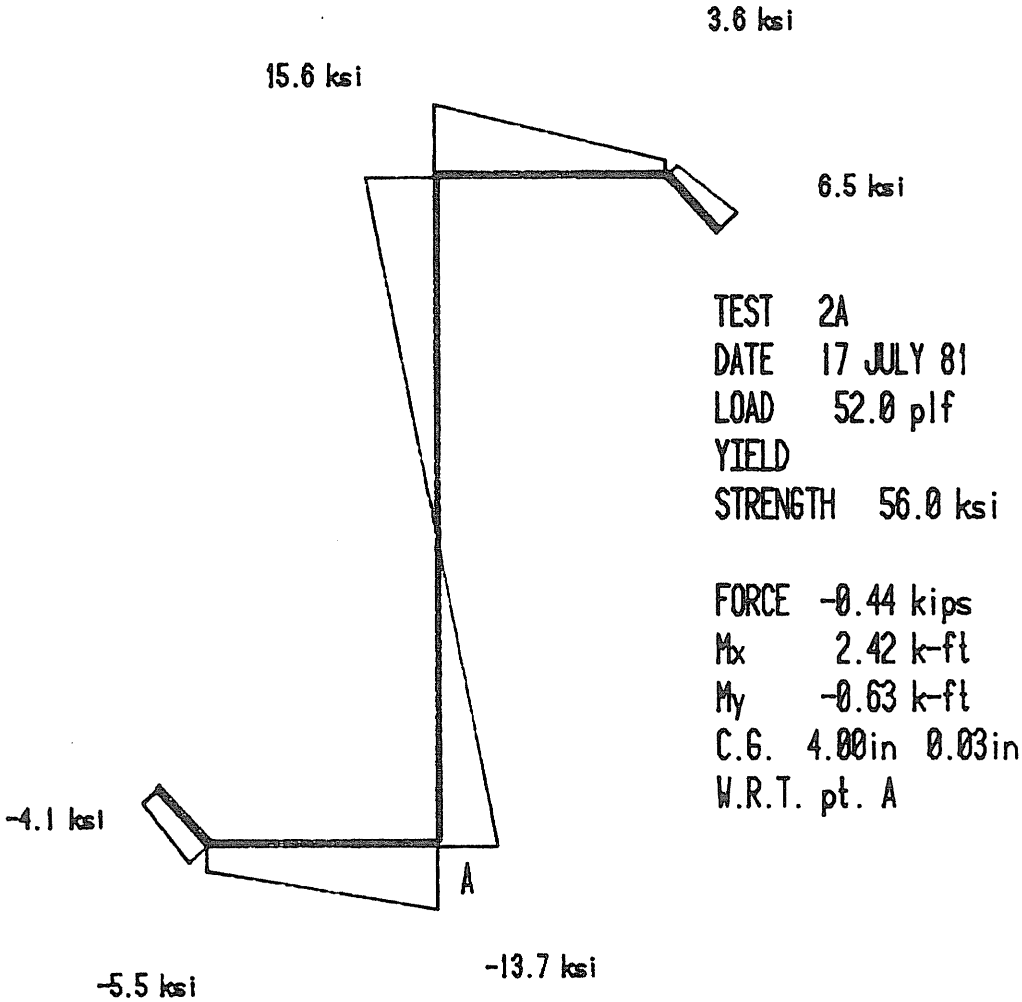


Figure B.7 Stress Distribution at 52 plf, Test 2-A

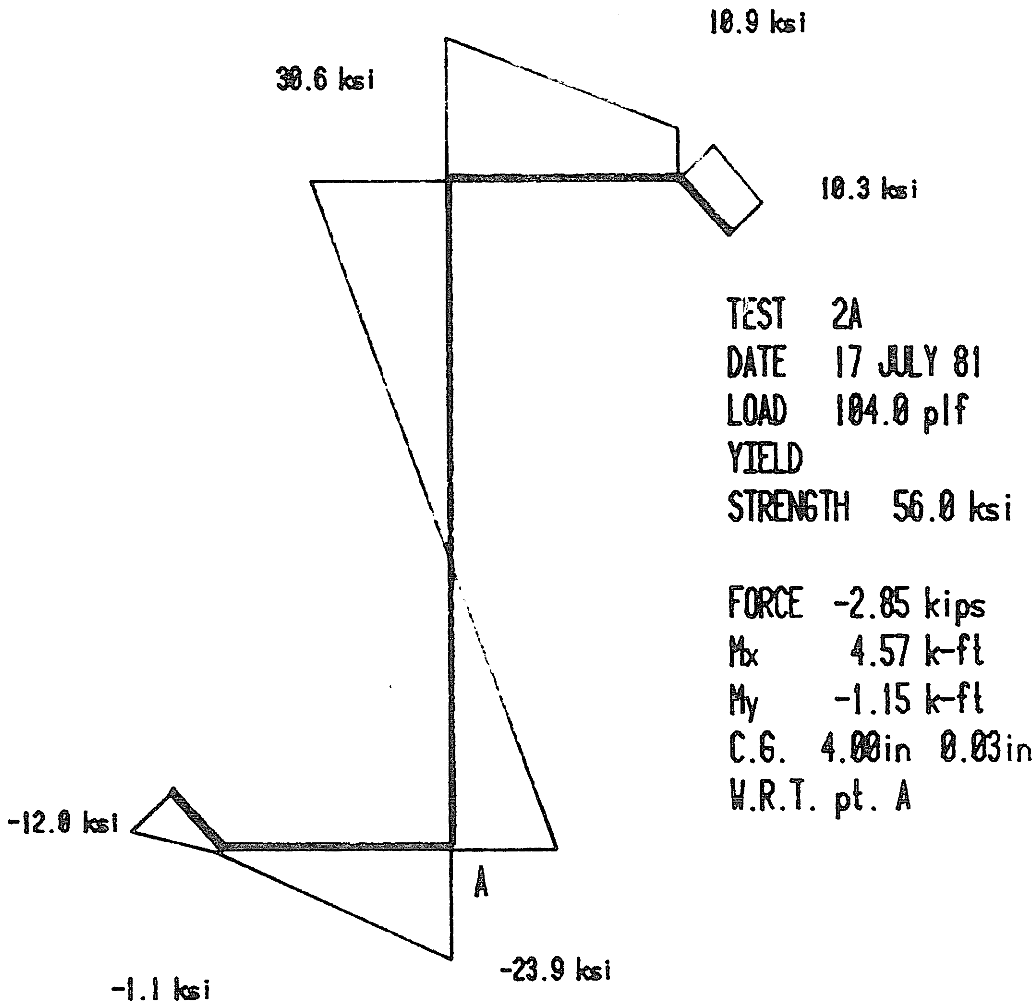


Figure B.8 Stress Distribution at 104 plf, Test 2-A

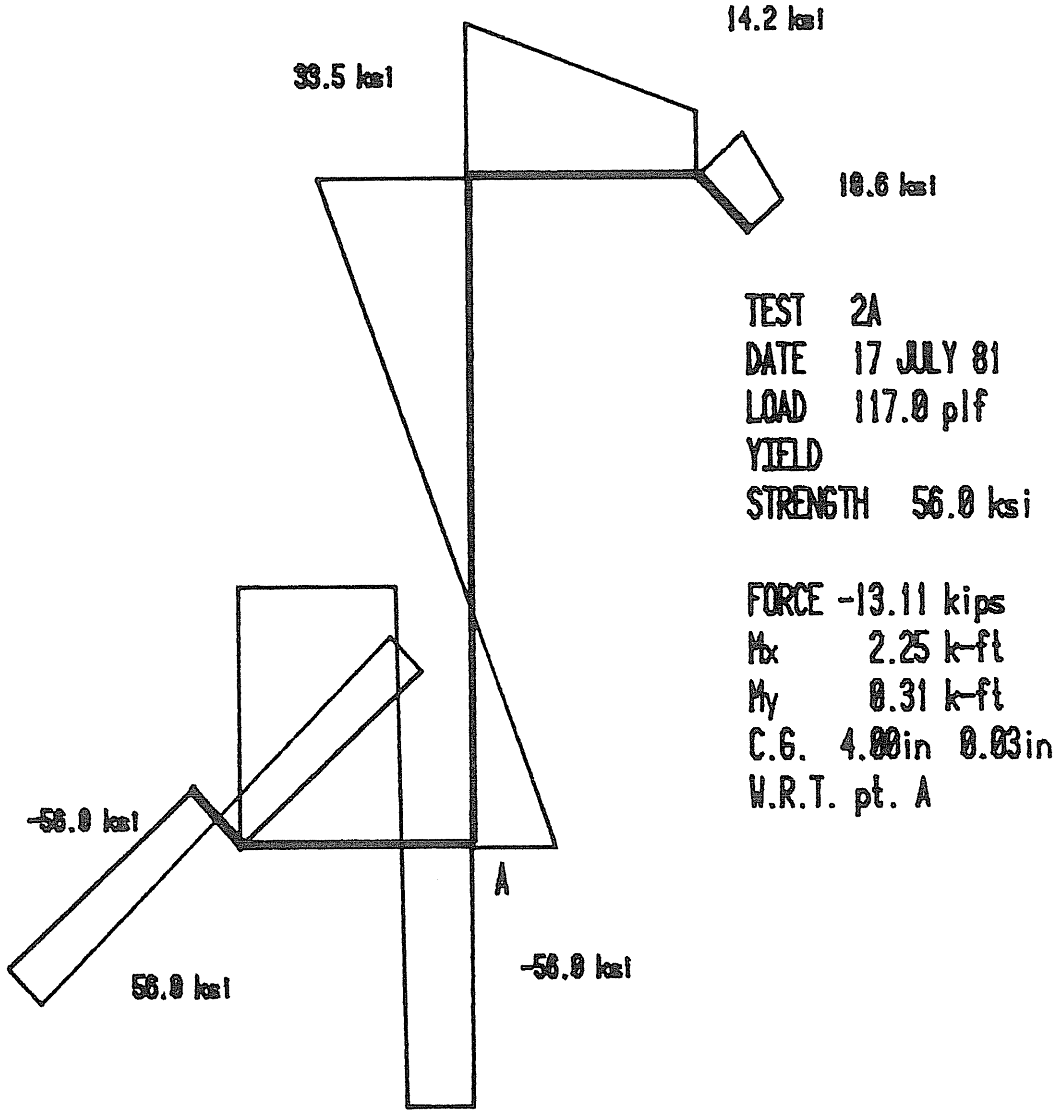


Figure B.9 Stress Distribution at 117 plf, Test 2-A

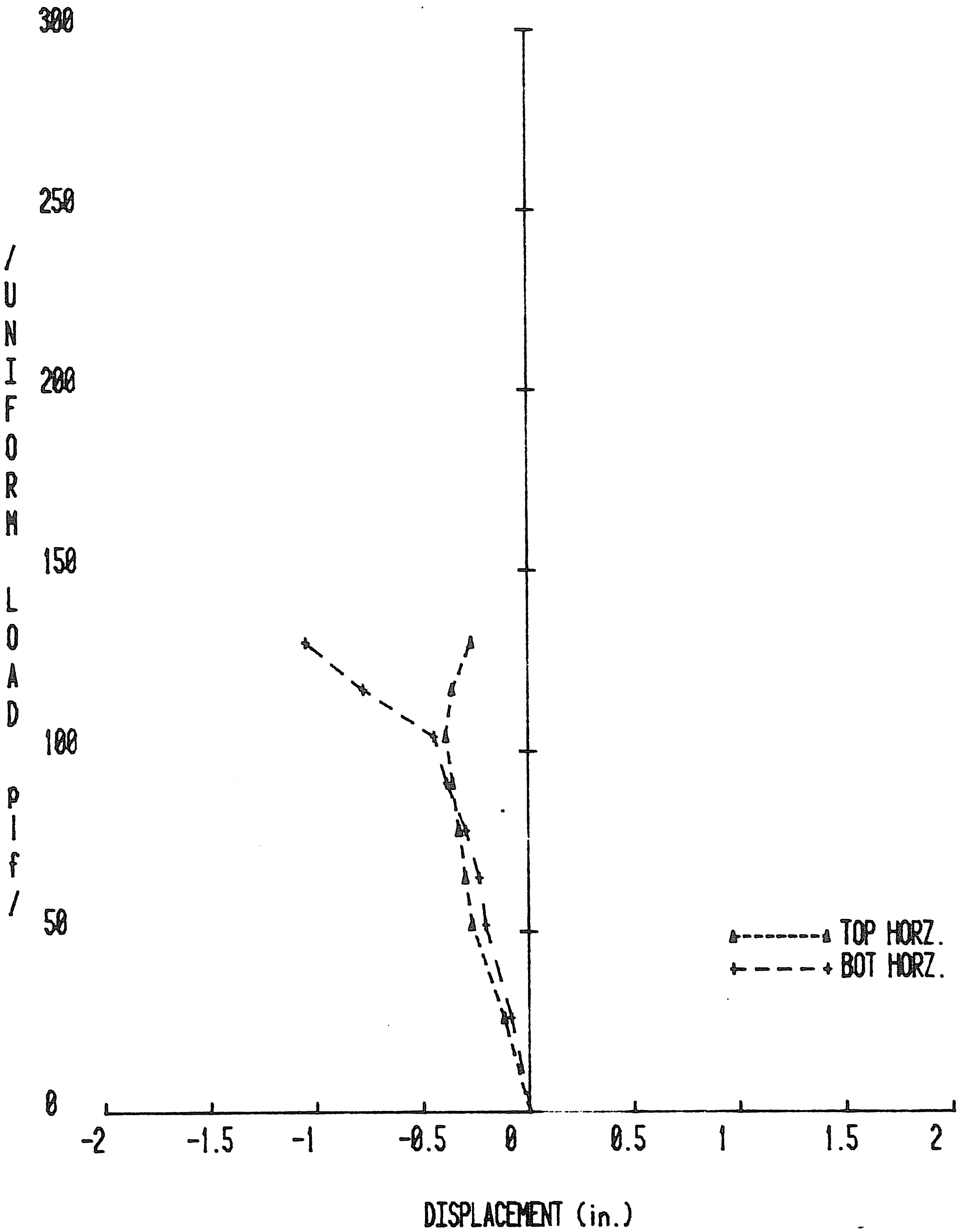


Figure B.10 Vertical Load vs. Lateral Displacements, Test 2-A

TEST SUMMARY

Project: Star Manufacturing Company

Test No.: 2B

Test Date: 7/24/81

Purpose: Base Test

Span(s): 2 @ 25'-0"

Thickness: N=0.065", S=0.065" Moment of Inertia: N=0.85 in^4, S=10.08 in^4

Parameters: Intermediate bracing @ 1/3 pt.

Clips in place

No insulation

Spacing @ 5'-0"

Failure Load: 117 plf

Failure Mode: Local buckling

Predicted Failure Loads:

Method Star (u.c. 1.668) Load 146 plf

Method AISI Constr. x 1.65 Load 162 plf

Method Load

Discussion:

-The failure mode of the test purlin was local buckling of the compression lip and flange immediately outside of the lap.

-This test was similar to 2A. The deck ribs were cut near each purlin.

-Test data was in good agreement with the predicted (constrained bending) load vs. deflection relationship.

-The down hill purlin showed more deflection than the test purlin and it is possible that this purlin failed first.

-The Star predicted failure load was 24.8% higher than the experimental load.

-The AISI predicted failure load was higher than the experimental load.

-A section immediately outside of the lap was strain gaged.

-The maximum stress on the gaged cross section at working load was 31.4 ksi tension at the web to flange junction.

-The maximum stress on the gaged cross-section at failure load was 46.6 ksi tension at the web to flange junction.

-The distribution of brace forces was similar to Test 2A. The magnitudes were considerably less than in Test 2A.

-The top and bottom flange lateral displacements were in the same direction and were of approximately the same magnitude until 90 plf at which point the displacement of the top flange changed in direction.

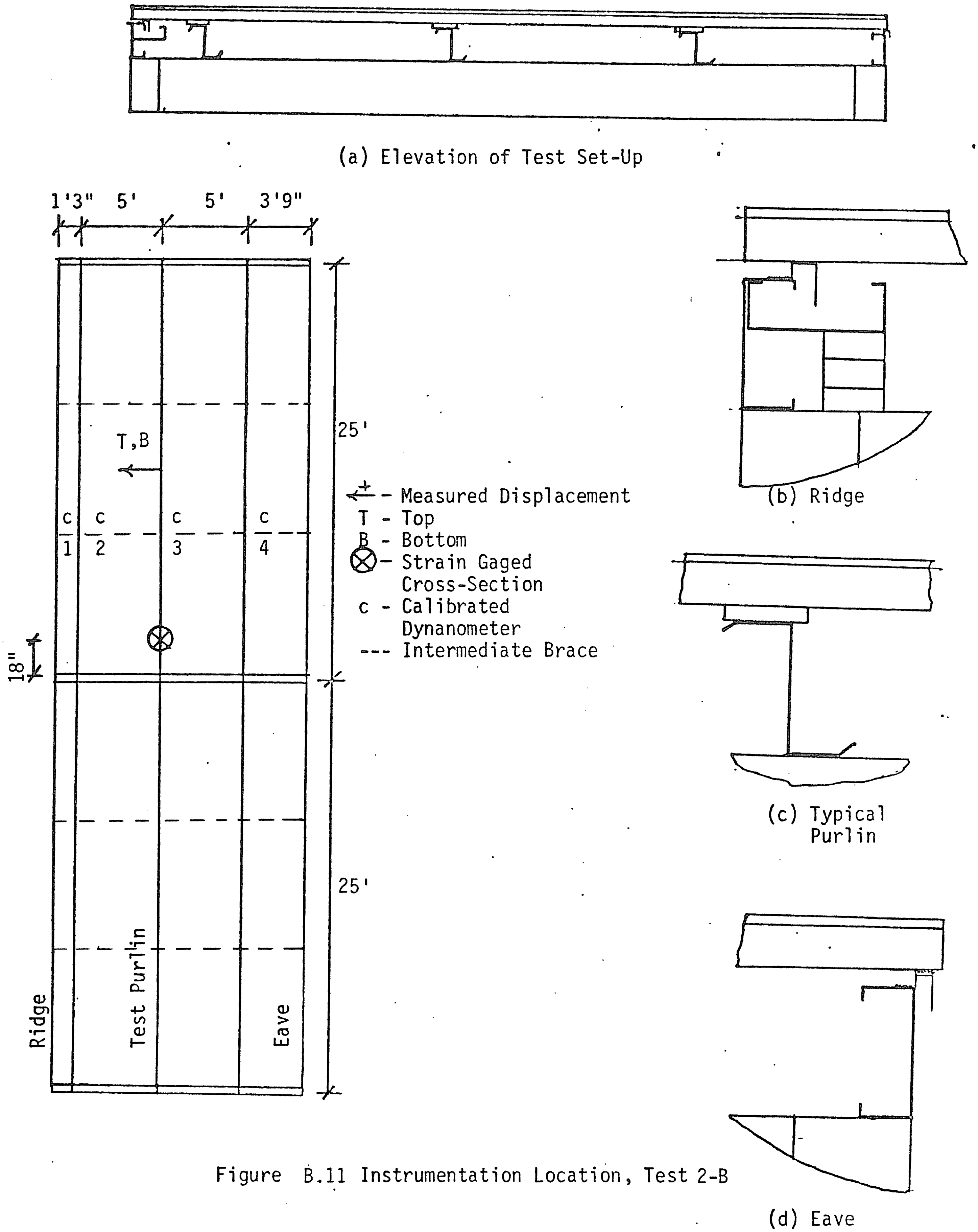
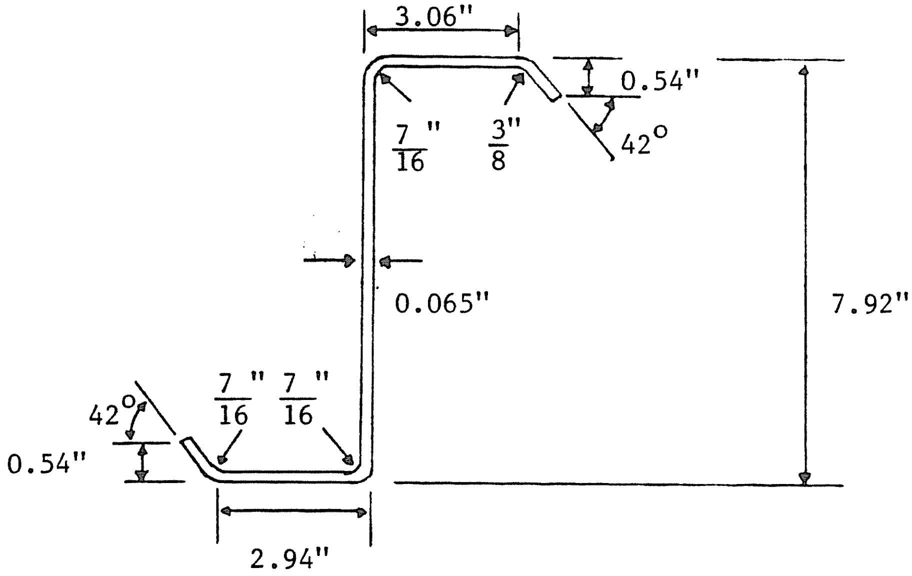
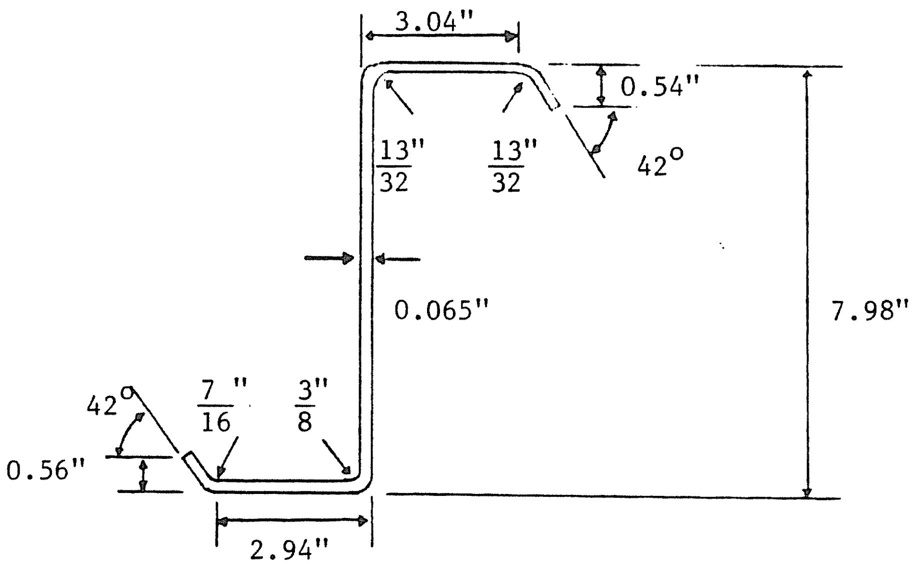


Figure B.11 Instrumentation Location, Test 2-B



North Span



South Span

Figure B.12 Measured Purlin Dimensions, Test 2-B

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----------------------------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: STAR PURLIN TEST 2-B NORTH
----------------------------------------------------------------------------
                       TOP              BOTTOM
FLANGE(in)            3.060              2.940
LIP(in)               0.540              0.540
LIP ANGLE(deg)       42.000             42.000
RADIUS L/F(in)        0.375              0.438
RADIUS F/W(in)        0.438              0.438

TOTAL DEPTH(in)               7.92
THICKNESS(in)                 0.065
YIELD STRENGTH(ksi)           51.5
                                          SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)           TOP                BOTTOM
GROSS=          9.846                  2.523               2.491
STRENGTH=       9.519                  2.388               2.461
DEFLECTION=     9.846
BE=    2.234   in
FC=    29.922  ksi
FT=    30.900  ksi
FBW=   28.353  ksi
```

Figure B.13 AISI Purlin Analysis, Test 2-B, North Span

A I S I   P U R L I N   A N A L Y S I S

IDENTIFICATION: STAR PURLIN TEST 2-B SOUTH

	TOP	BOTTOM
FLANGE(in)	3.040	2.940
LIP(in)	0.540	0.500
LIP ANGLE(deg)	42.000	42.000
RADIUS L/F(in)	0.406	0.438
RADIUS F/W(in)	0.406	0.375

TOTAL DEPTH(in)	7.98
THICKNESS(in)	0.065
YIELD STRENGTH(ksi)	55.1

	MOMENTS OF INERTIA(in^4)	SECTION MODULII(in^3) TOP	BOTTOM
GROSS=	10.007	2.554	2.503
STRENGTH=	9.620	2.395	2.468
DEFLECTION=	9.992		

BE= 2.191 in

FC= 31.861 ksi

FT= 33.060 ksi

FBW= 29.926 ksi

Figure B.14 AISI Purlin Analysis, Test 2-B, South Span

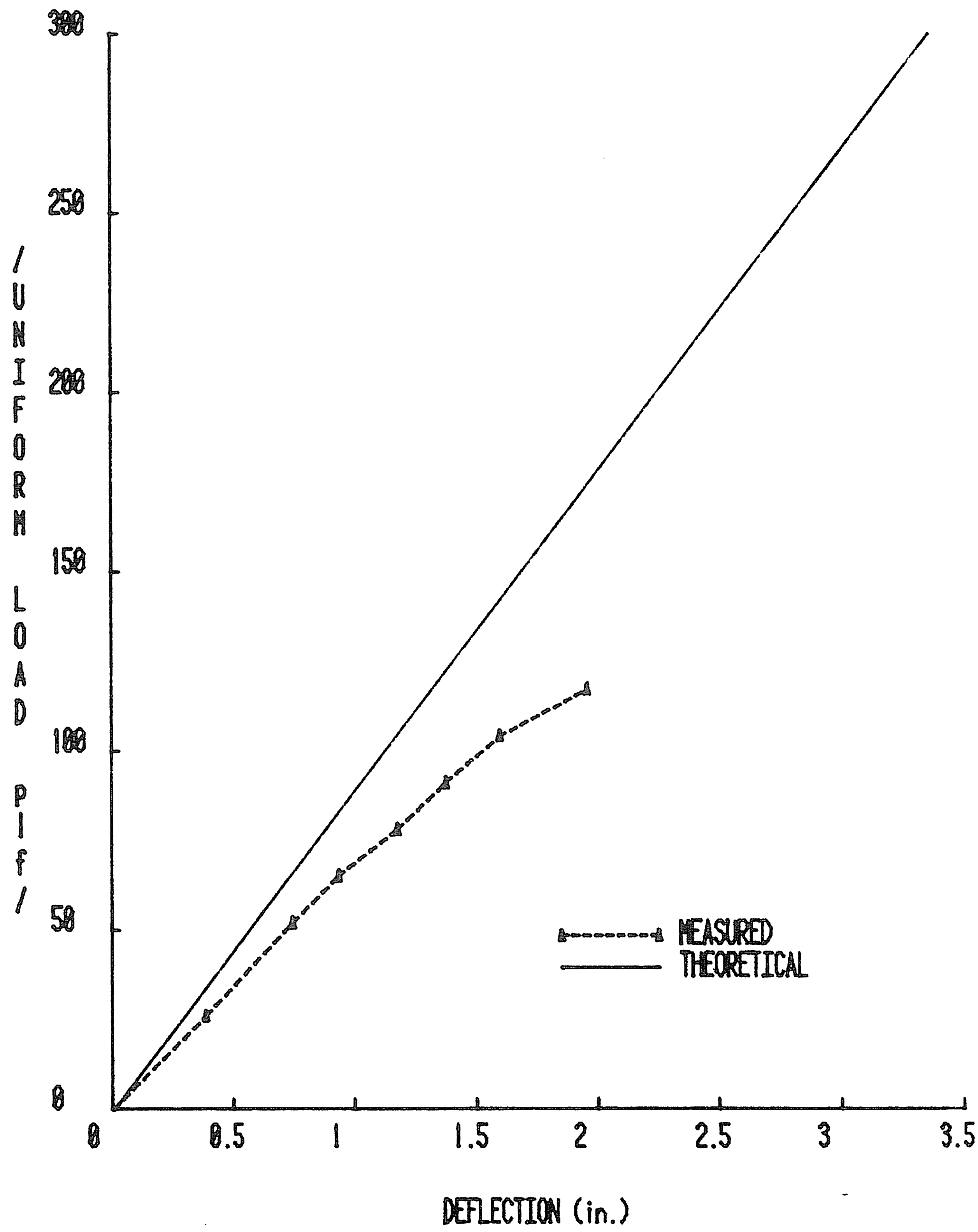


Figure B.15 Load vs. Vertical Deflection, Test 2-B

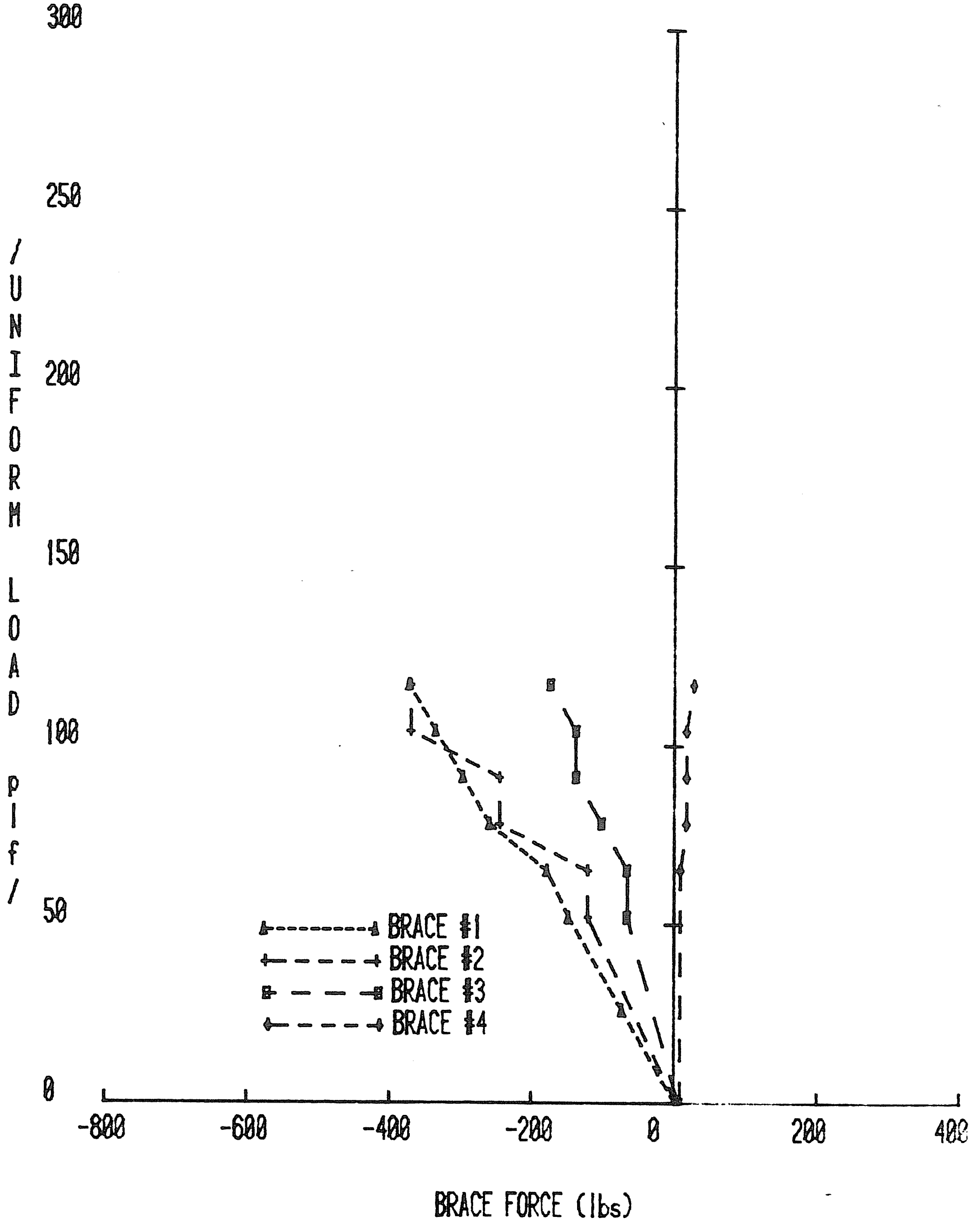


Figure B.16 Vertical Load vs. Brace Force at 1/3 Point of Span, Test 2-B North Bay

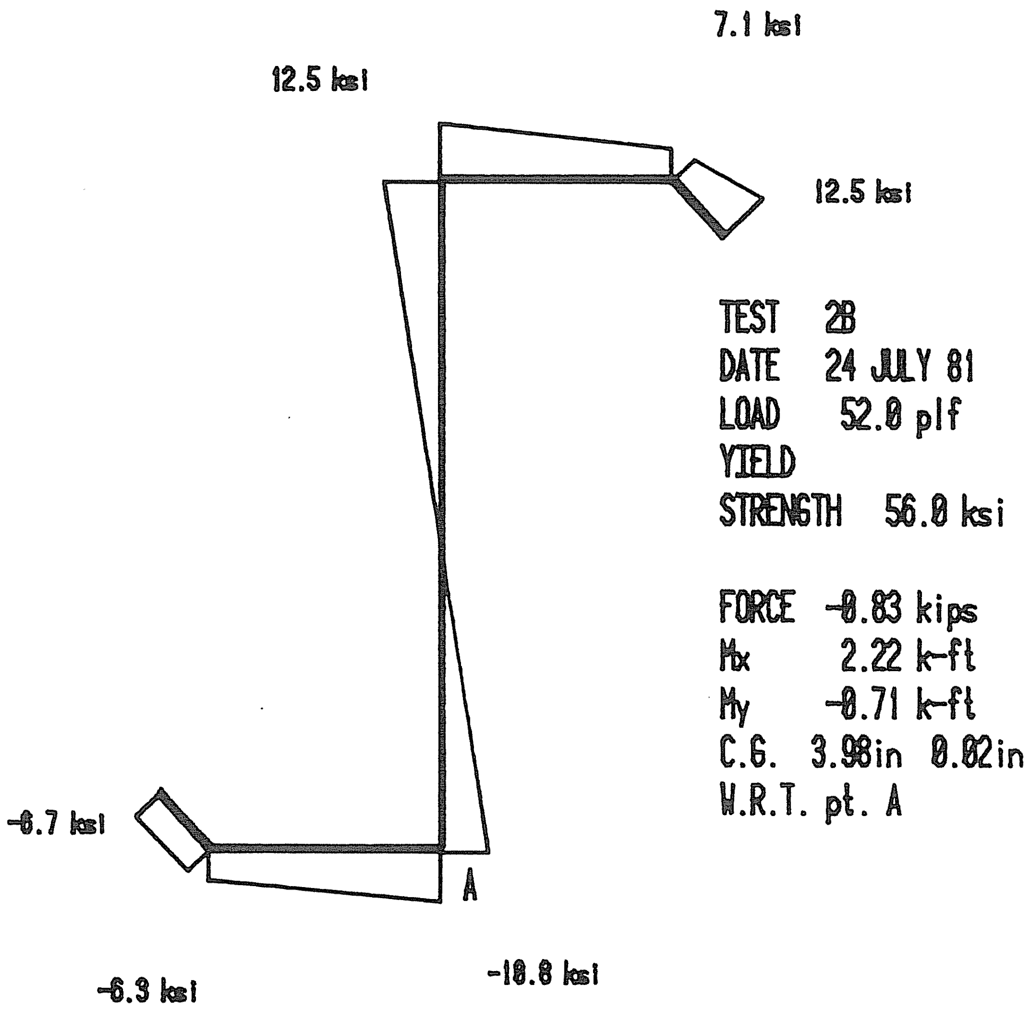


Figure B.17 Stress Distribution at 52 plf, Test 2-B

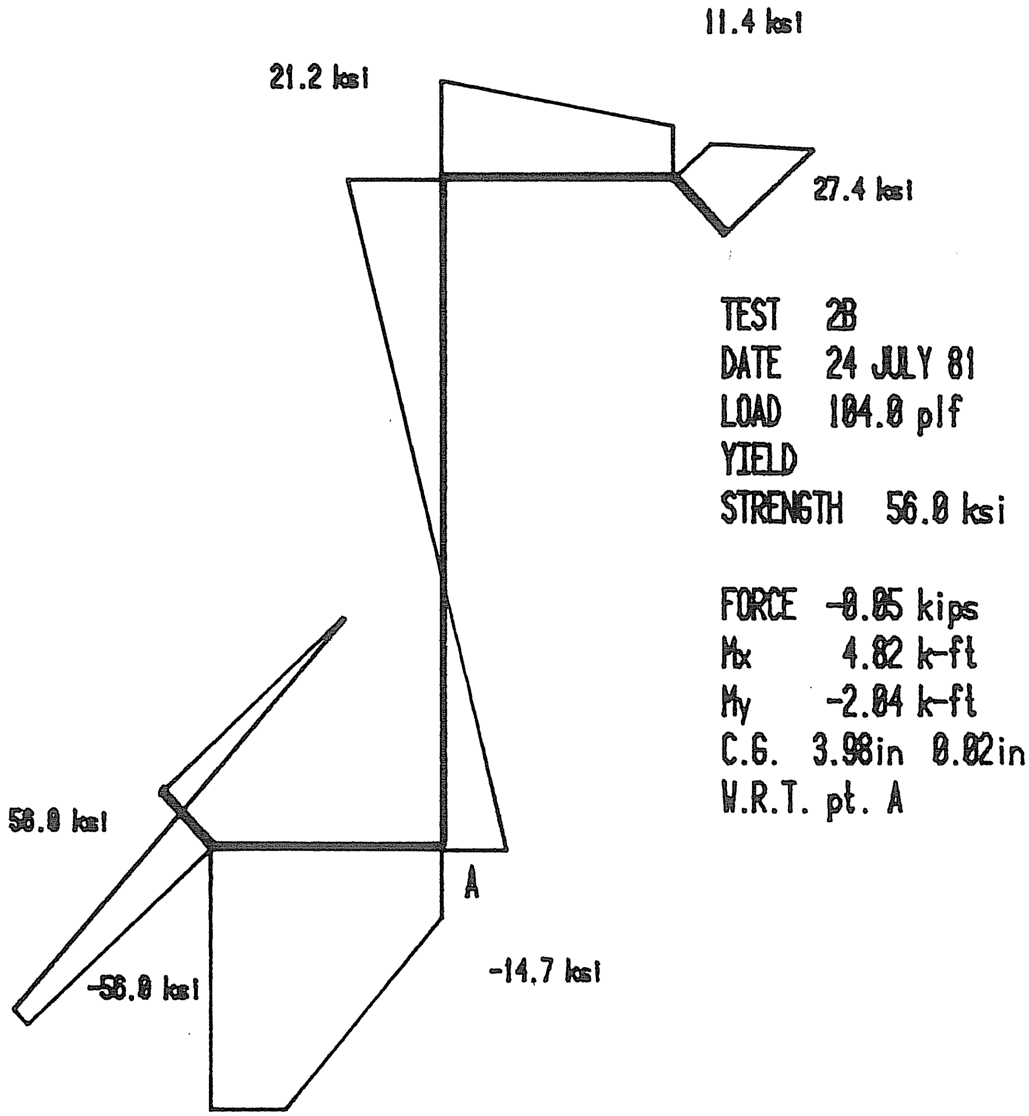


Figure B.18 Stress Distribution at 104 plf, Test 2-B

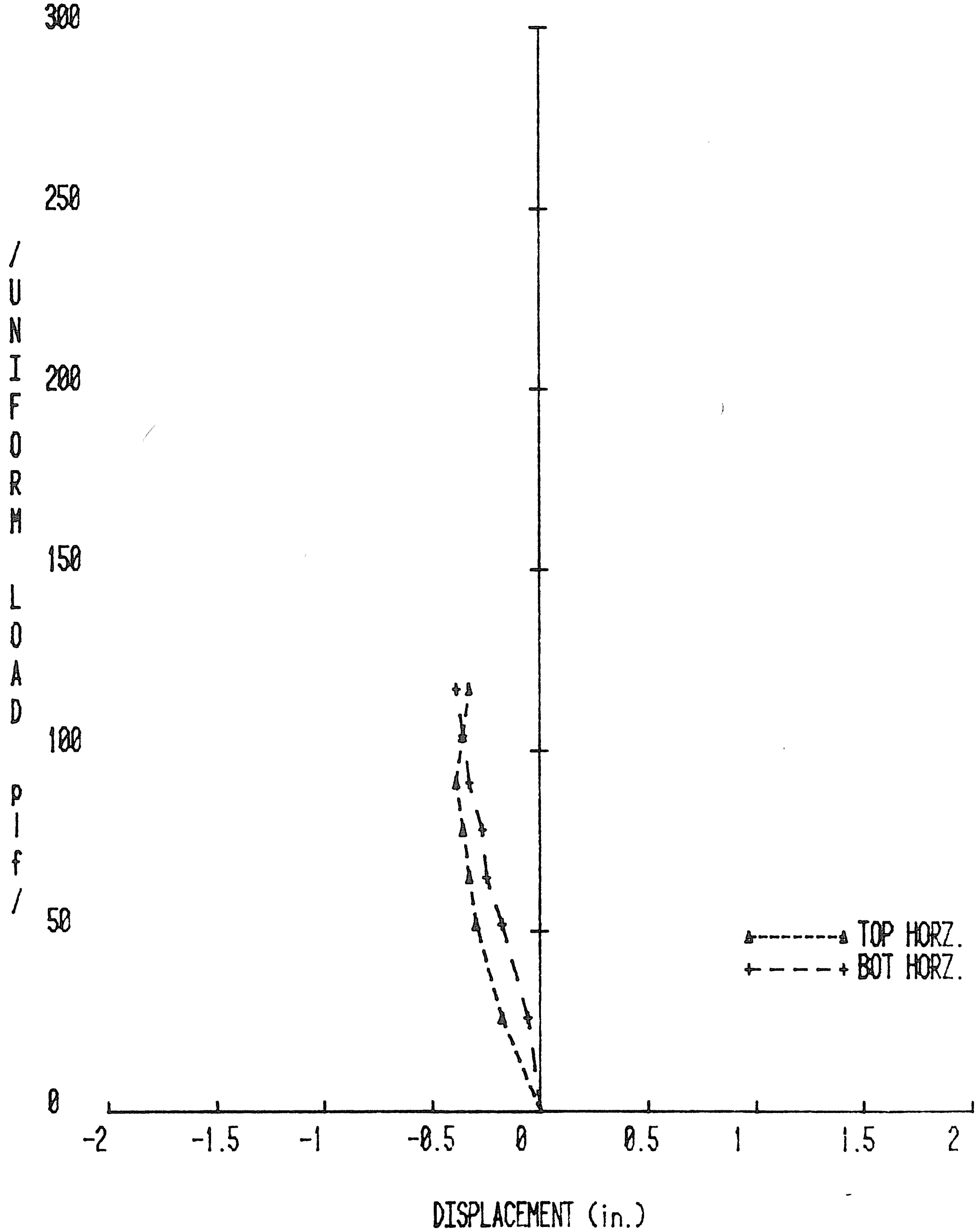


Figure B.19 Vertical Load vs. Lateral Displacement, Test 2-B

APPENDIX C

TEST SERIES III RESULTS

TEST SUMMARY

Project: Star Manufacturing Company

Test No.: 3A

Test Date: 7/30/81

Purpose: Base Test

Span(s): 2 @ 25'-0"

Thickness: N=.099", S=.097" Moment of Inertia: N=15.81 in^4, S=15.47 in^4

Parameters: Intermediate Bracing @ 1/3 pt.

Clips in place

No insulation

Spacing @ 5'-0"

Failure Load: 265.2 plf

Failure Mode: Local buckling

Predicted Failure Loads:

Method Star (u.c. 1.666) Load 244 plf

Method AISI Constrained x 1.67 Load 273.8 plf

Method Load

Discussion:

-Failure mode was local buckling of the lip and flange just outside of the lip.

-Load vs. deflection plot showed good agreement between constrained bending and test data.

-The Star predicted failure load was 8.0% lower than the experimental failure load.

-The AISI predicted failure load was 13.5% lower than the experimental failure load.

-The stress at working load showed a max. stress of 38.5 ksi comp. at the flange to web junction.

-The stress at failure load showed yield stress at both the top and bottom web to flange junctions.

-The magnitude of the compressive force in brace #1 & #2 were approximately the same. Brace forces #3 and #4 were approximately the same until approximately 120 plf at which point brace #3's compressive force increased while #4's went from compression to tension.

-The maximum brace force for all the braces is as follows: #1, 1089 lbs compression; #2, 1000 lbs compression; #3, 398 lbs compression; #4, 346 lbs tension.

-The lateral movement of the top and bottom flanges was in the same direction. The top flange of the purlin displaced more than the bottom flange.

-The maximum lateral displacement of the top and bottom flanges was 1.169 in. and 0.945 in., respectively.

-In this test two extra tests were performed to compare braced and unbraced cases. Comparisons between these two cases are discussed below.

-The load vs. deflection curves for the braced and unbraced cases were very close. The unbraced case had more vertical deflection. Both the braced and unbraced cases had more deflection than theoretical predictions.

-The stress plots were made at 104 plf. The overall shapes of the plots were very similar. The stresses were higher for the unbraced case.

-For the unbraced case, the lateral displacements measured at the centerline of the span were higher than for the braced case. The displacements of the top and bottom flanges were 17.8% and 30% higher, respectively.

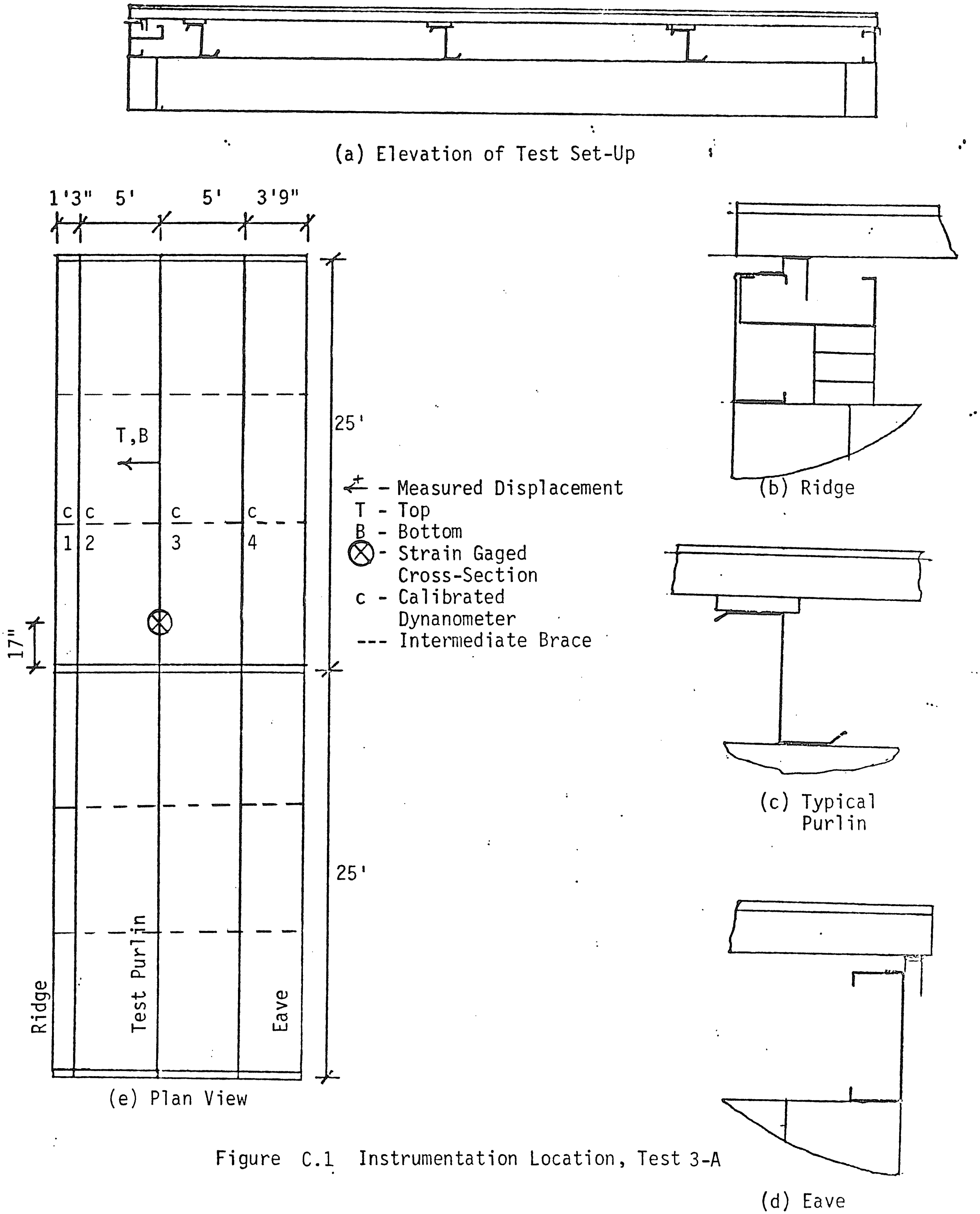
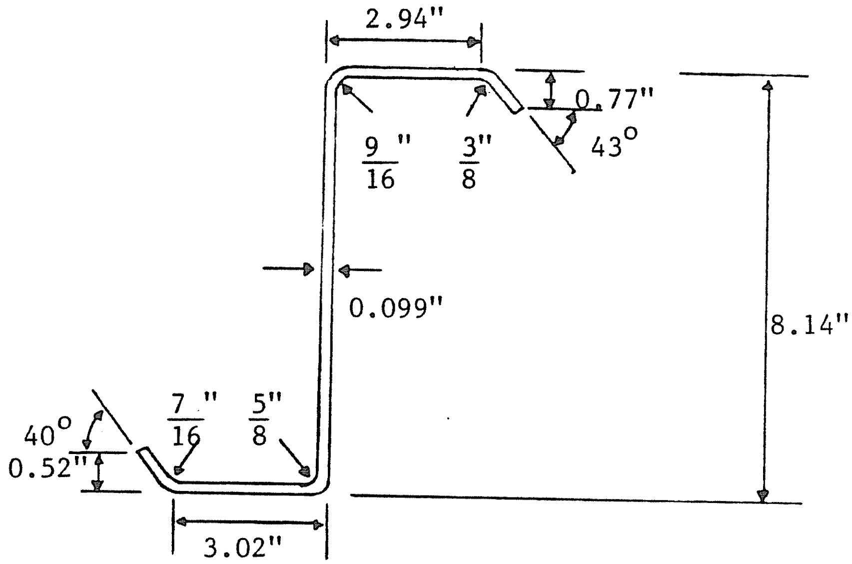
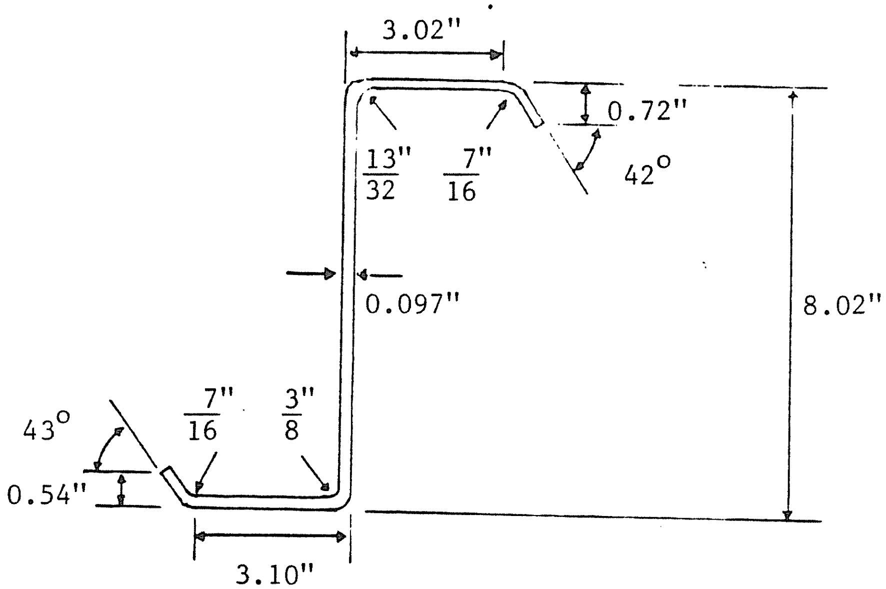


Figure C.1 Instrumentation Location, Test 3-A



North Span



South Span

Figure C.2 Measured Purlin Dimensions, Test 3-A

```
-------------------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: STAR PURLIN TEST 3-A NORTH
-------------------------------------------------------------------
                          TOP            BOTTOM
FLANGE(in)               2.940            3.020
LIP(in)                  0.770            0.520
LIP ANGLE(deg)          43.000           40.000
RADIUS L/F(in)           0.375            0.438
RADIUS F/W(in)           0.563            0.625

TOTAL DEPTH(in)                 8.14
THICKNESS(in)                   0.099
YIELD STRENGTH(ksi)             50.4
                                          SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)            TOP              BOTTOM
GROSS=          15.808                  3.970            3.895
STRENGTH=       15.808                  3.970            3.895
DEFLECTION=     15.808
BE=     2.279   in
FC=     29.666   ksi
FT=     30.240   ksi
FBW=    30.240   ksi
```

Figure C.3 AISI Purlin Analysis, Test 3-A, North Span

```
---------------------------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: STAR PURLIN TEST 3-A SOUTH
---------------------------------------------------------------------------
                          TOP              BOTTOM
FLANGE(in)              3.020               3.100
LIP(in)                 0.720               0.540
LIP ANGLE(deg)         42.000              43.000
RADIUS L/F(in)          0.438               0.438
RADIUS F/W(in)          0.406               0.375

TOTAL DEPTH(in)                   8.02
THICKNESS(in)                     0.099
YIELD STRENGTH(ksi)               51.9
                                            SECTION MODULII(in^3)
       MOMENTS OF INERTIA(in^4)             TOP              BOTTOM
GROSS=            15.779                   4.028              3.941
STRENGTH=         15.779                   4.028              3.941
DEFLECTION=       15.779
BE=     2.515   in
FC=     31.132   ksi
FT=     31.140   ksi
FBW=    31.140   ksi
```

Figure C.4 AISI Purlin Analysis, Test 3-A, South Span

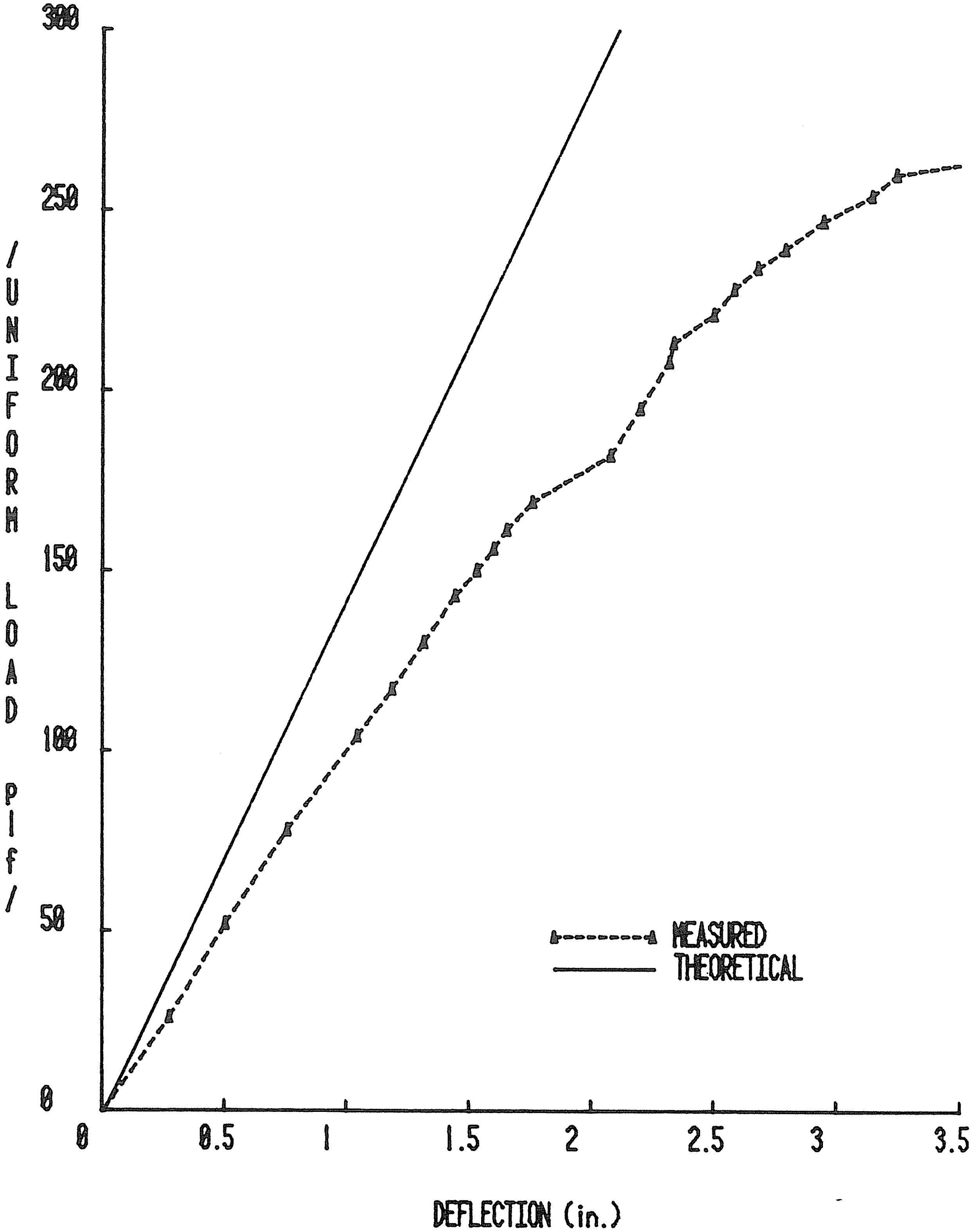


Figure C.5 Load vs. Vertical Deflection, Test 3-A

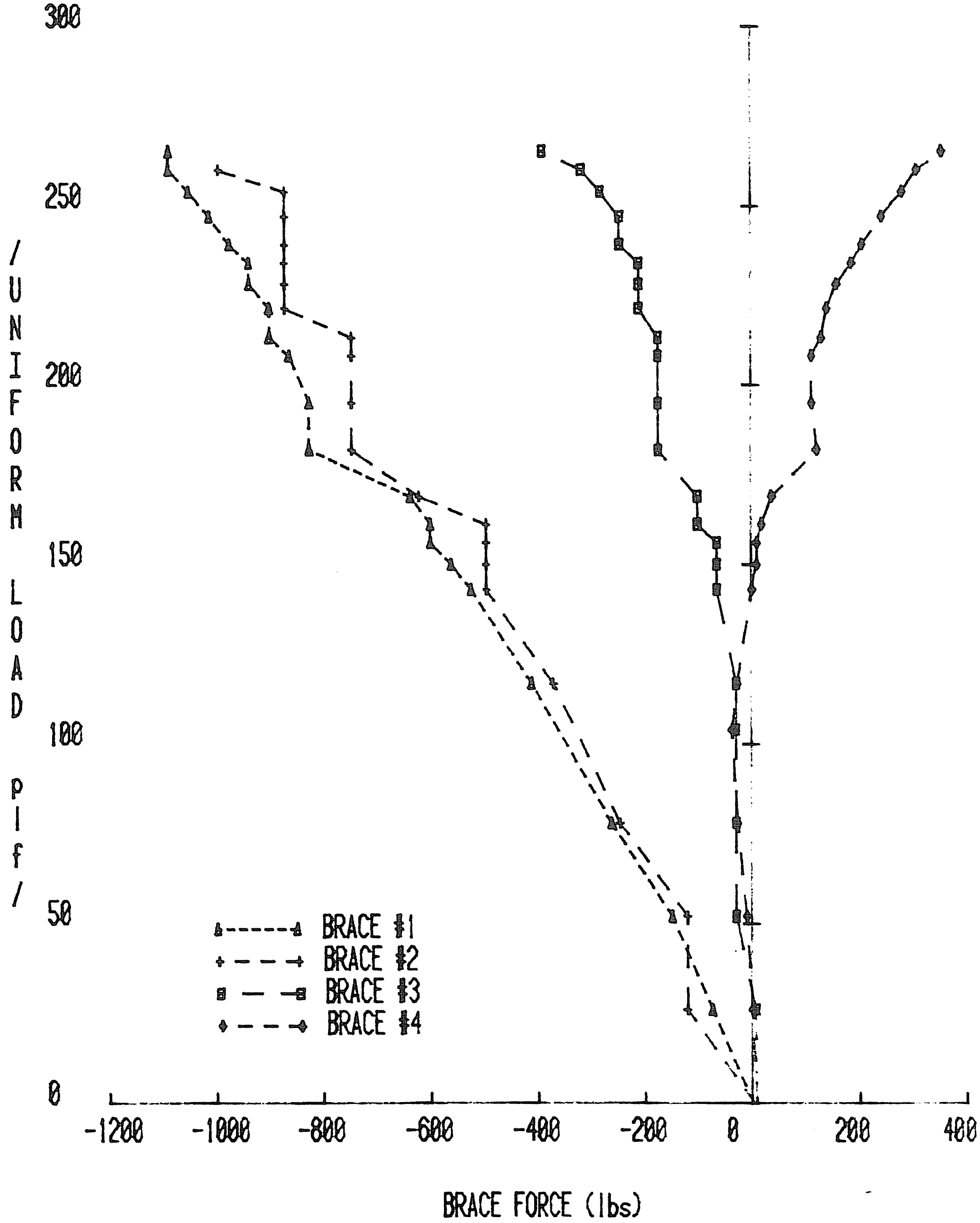


Figure C.6 Vertical Load vs. Brace Force at 1/3 Point of Span, Test 3-A North Span

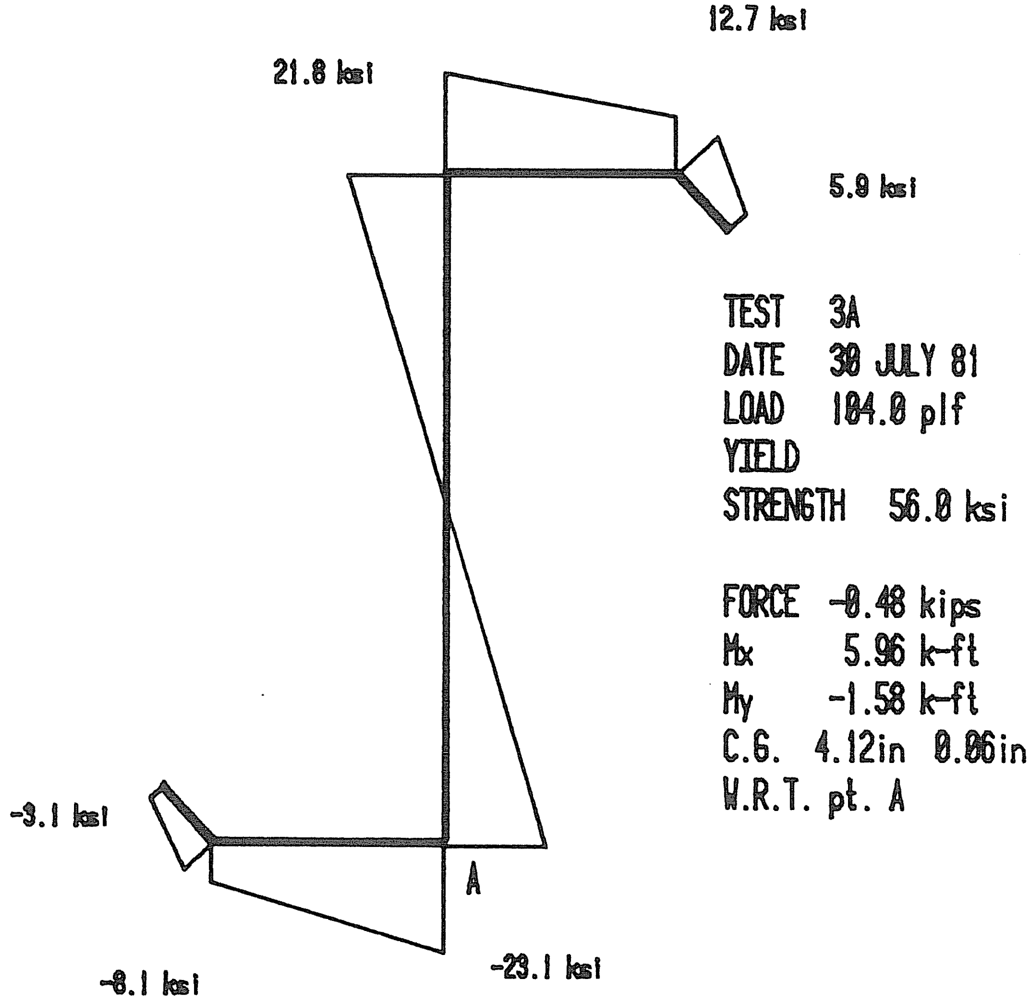


Figure C.7 Stress Distribution at 104 plf, Test 3-A

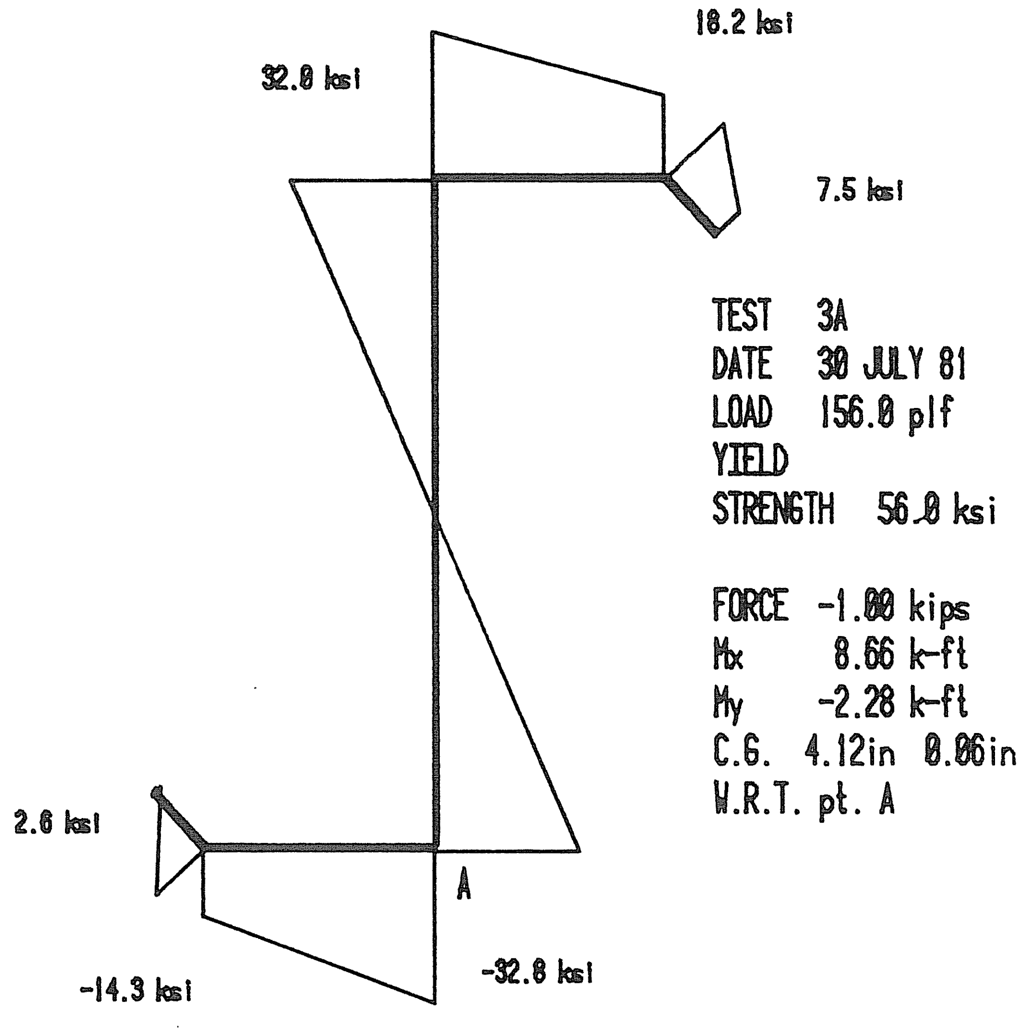


Figure C.8 Stress Distribution at 156 plf, Test 3-A

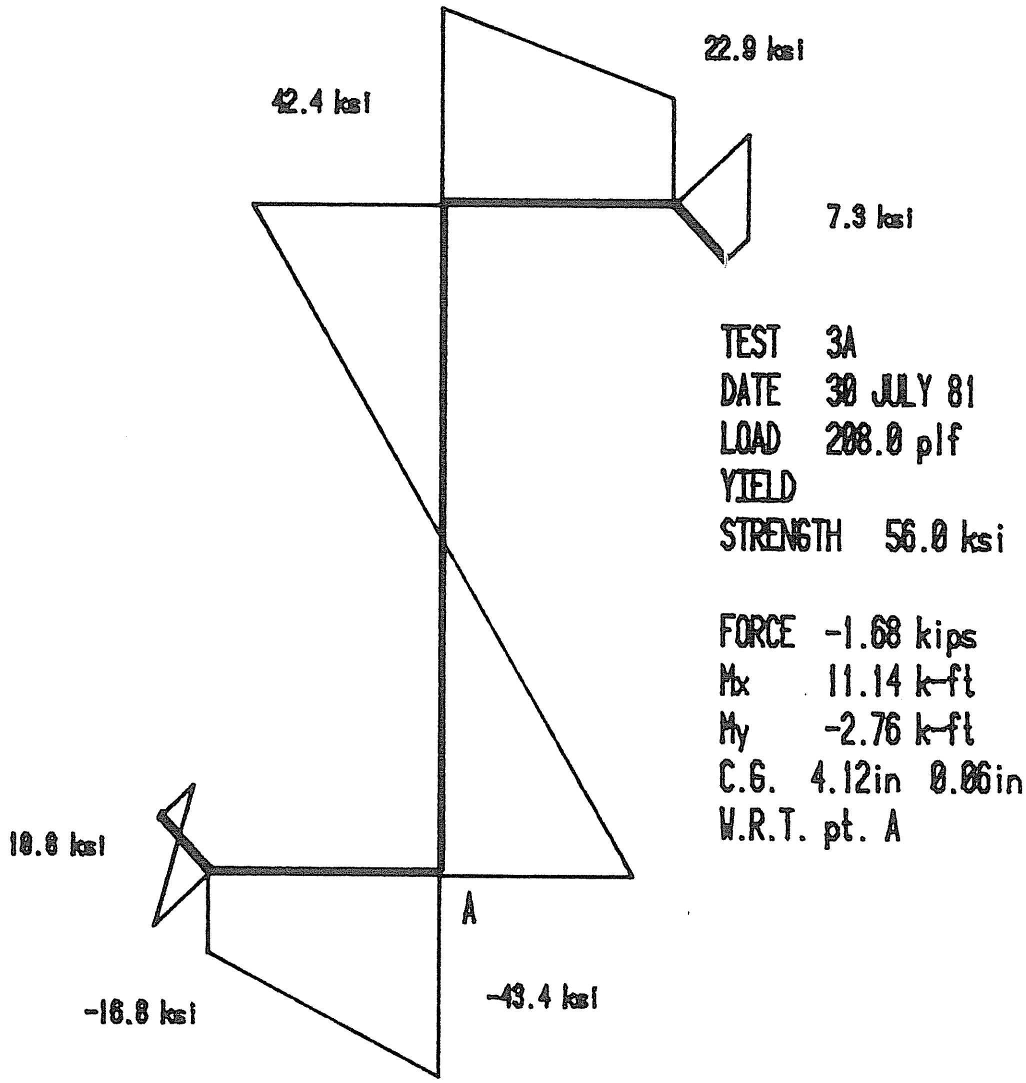


Figure C.9 Stress Distribution at 208 plf, Test 3-A

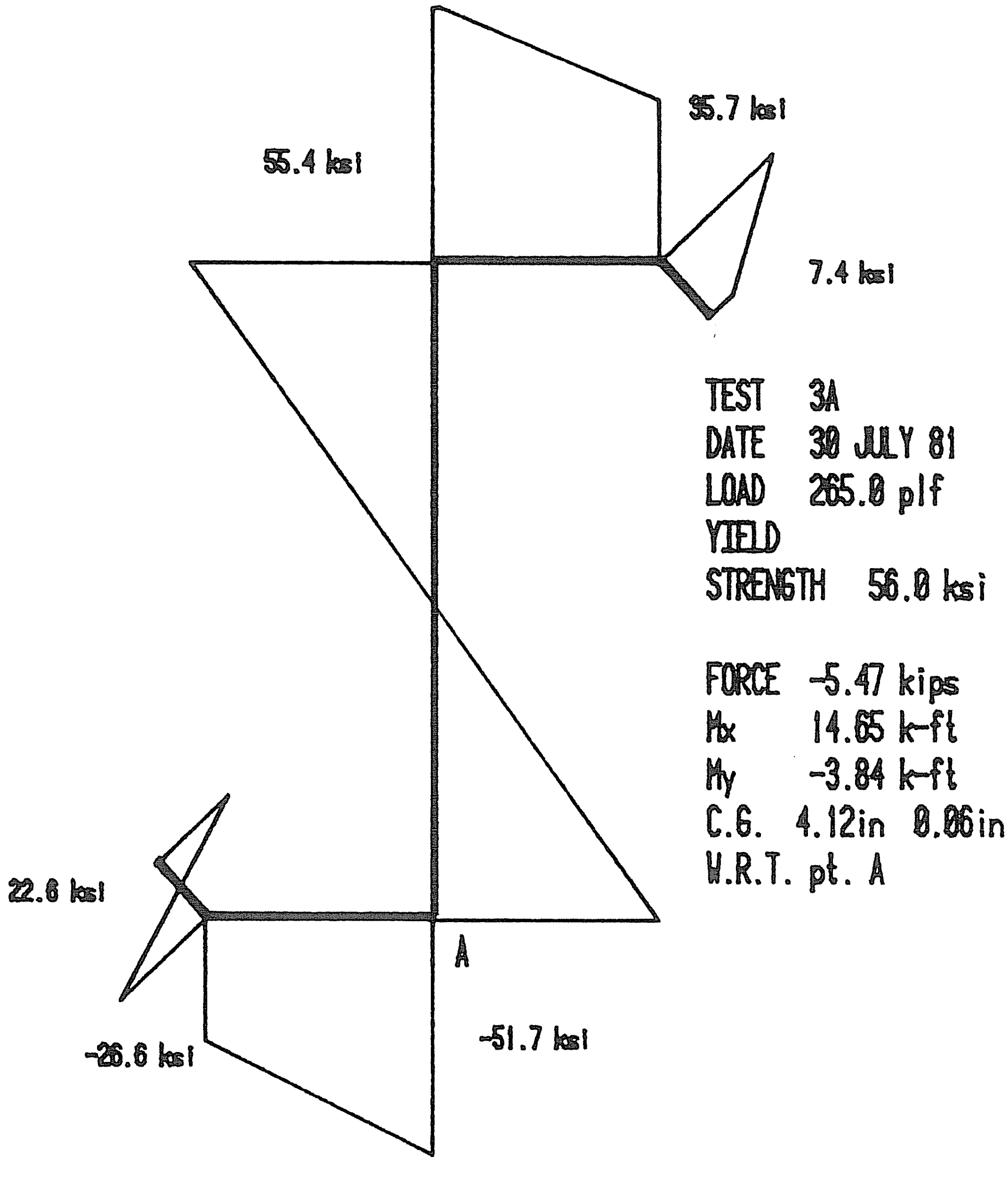


Figure C.10 Stress Distribution at 265 plf, Test 3-A

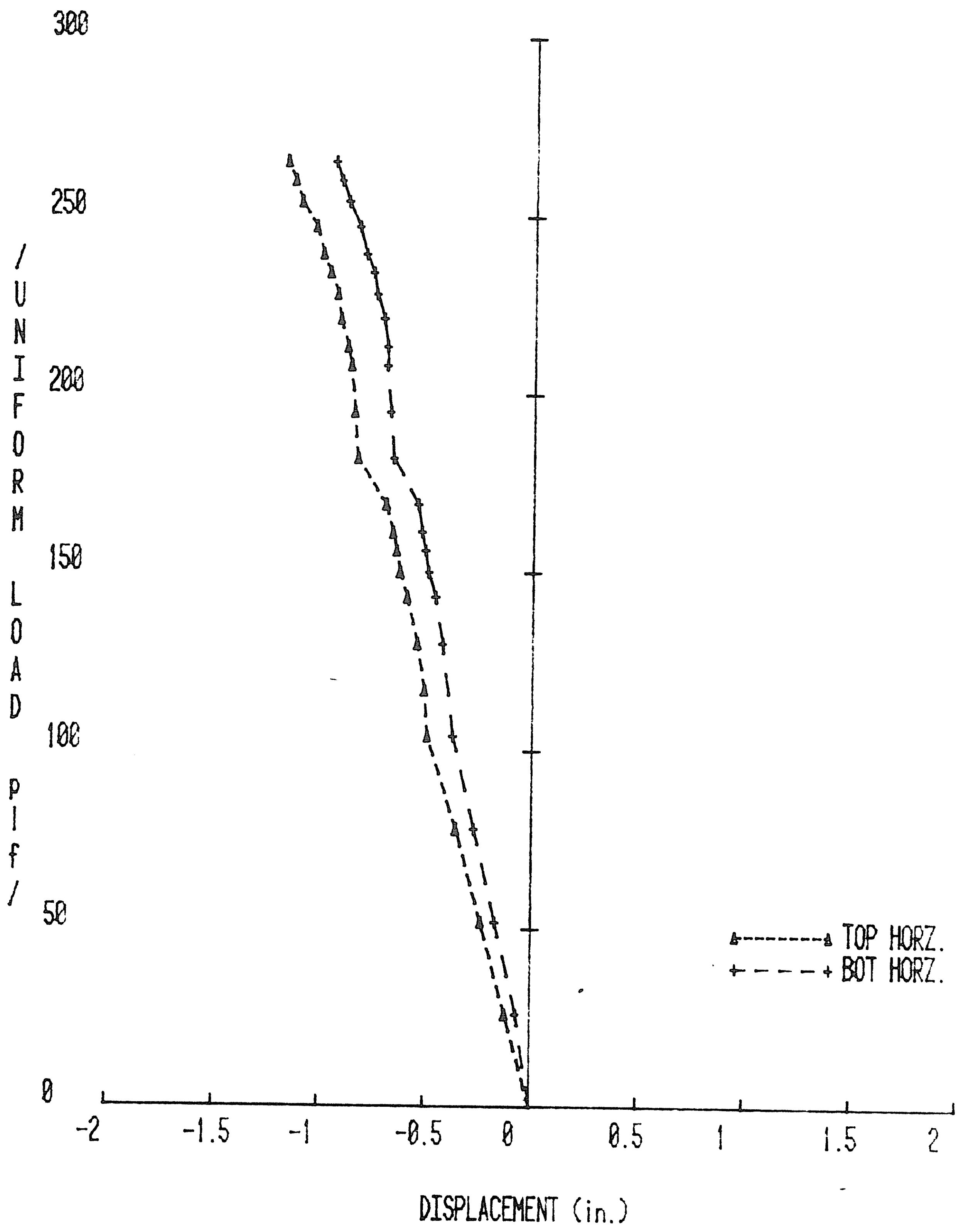


Figure C.11 Vertical Load vs. Lateral Displacement, Test 3-A

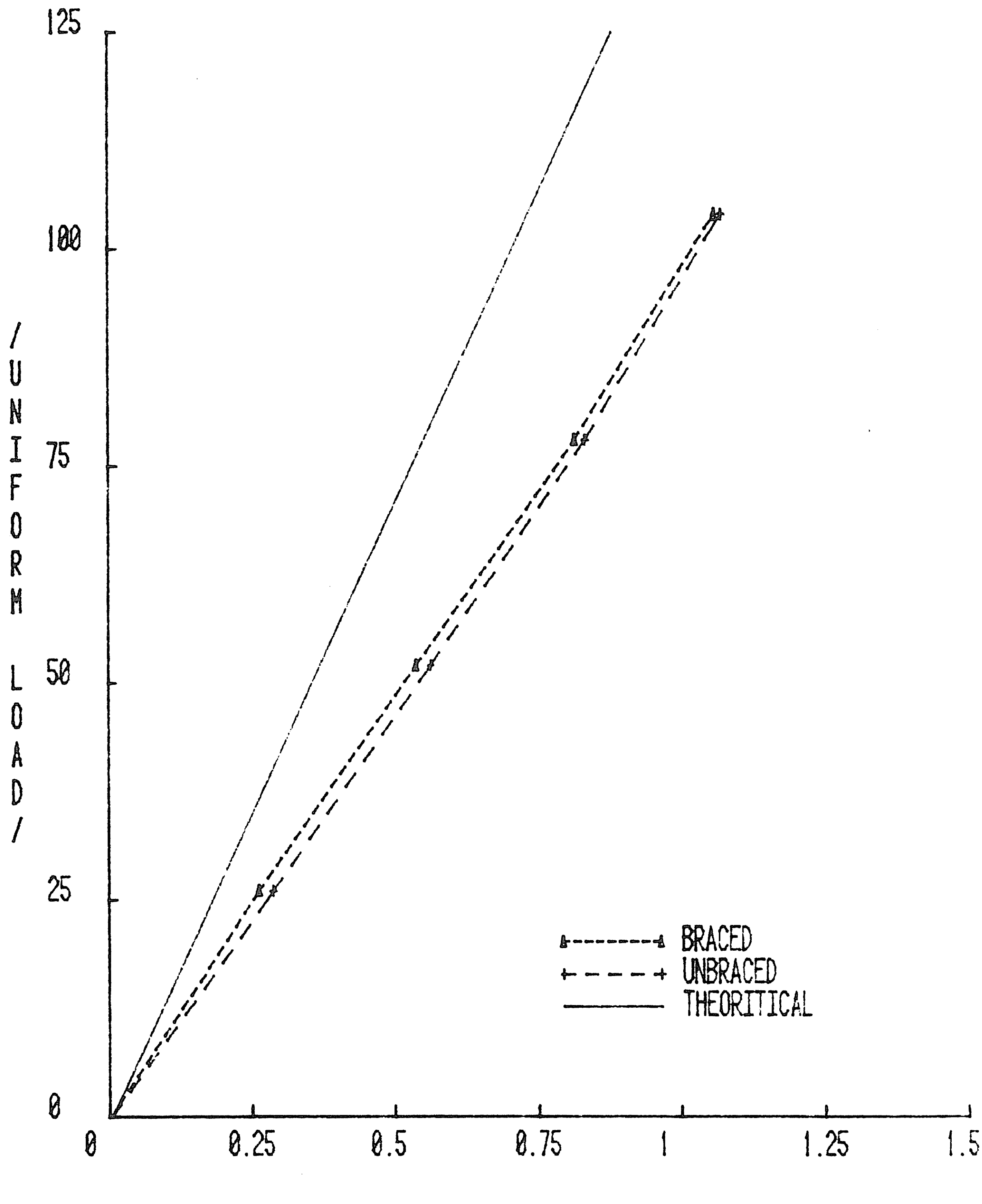


Figure C.12 Load vs. Vertical Displacement for Braced and Unbraced Purlins, Test 3-A

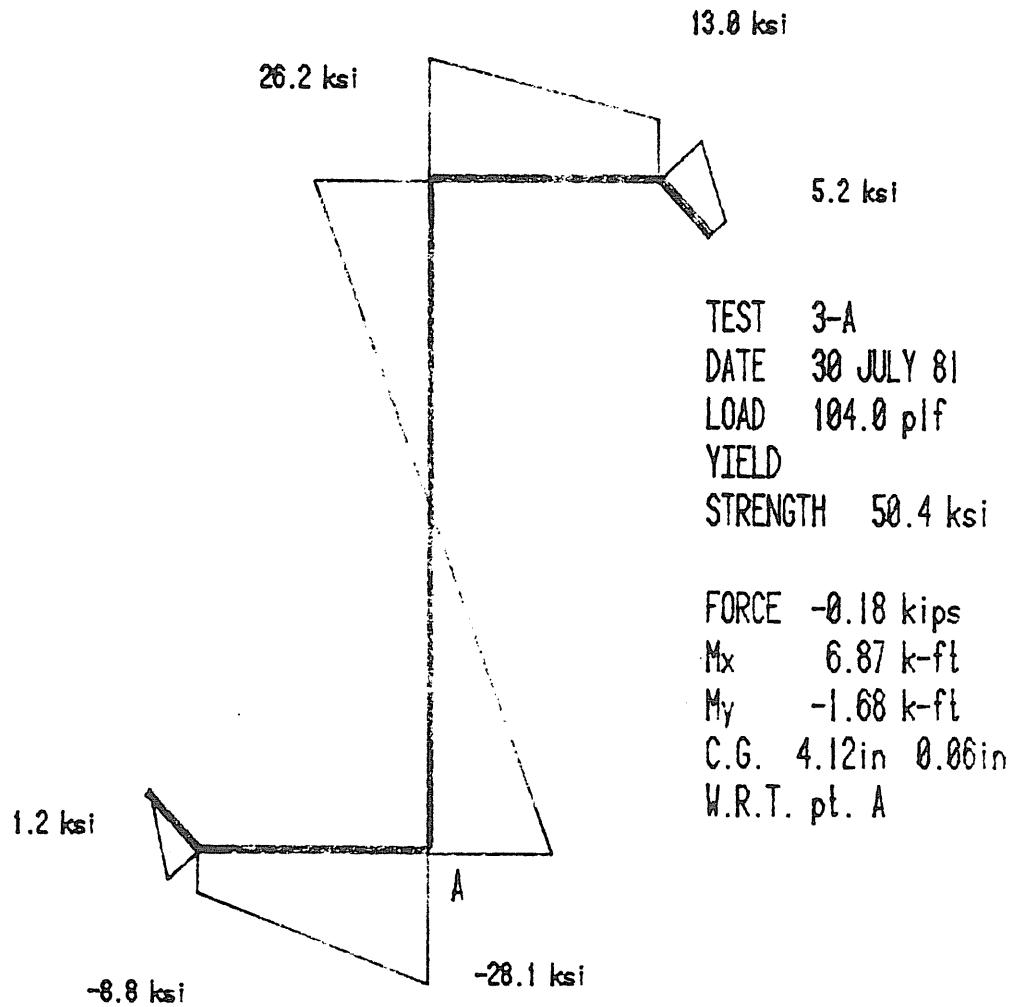


Figure C.14 Stress Distribution on Unbraced Purlin, Test 3-A

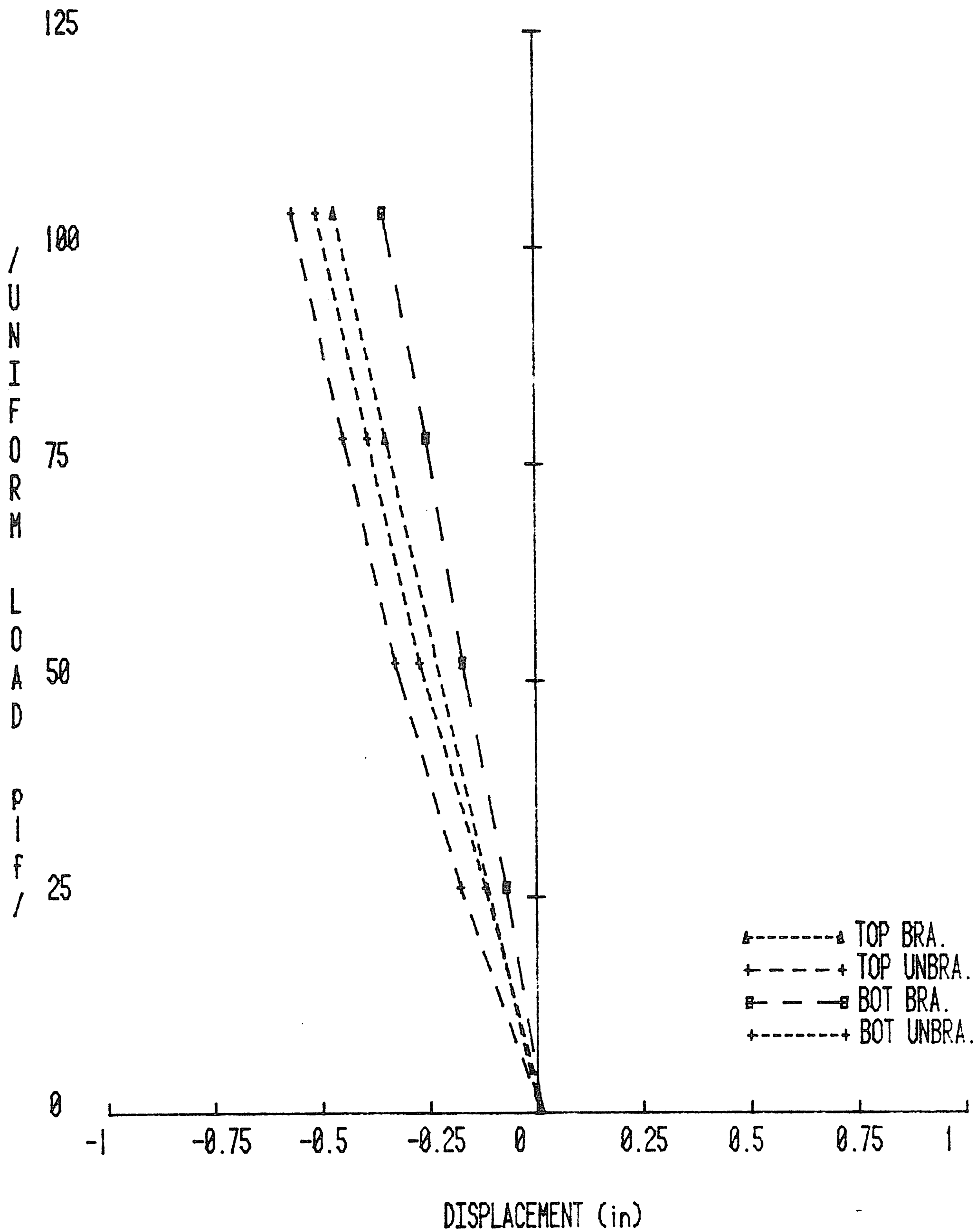


Figure C.15 Vertical Load vs. Lateral Displacement for Braced and Unbraced Purlins, Test 3-A

<u>TEST SUMMARY</u>

Project: Star Manufacturing Company

Test No.: 3B

Test Date: 8/3/81

Purpose: Base Test

Span(s): 2 @ 25'-0"

Thickness: N=.099", S=.097" Moment of Inertia: N= 15.665 in^4, S=15.758 in^4

Parameters: Intermediate Bracing @ 1/3 pt. Star N=15.144; S=15.278

Clips in place

No insulation

Spacing @ 5'-0"

Failure Load: 247 plf

Failure Mode: Local buckling

Predicted Failure Loads:

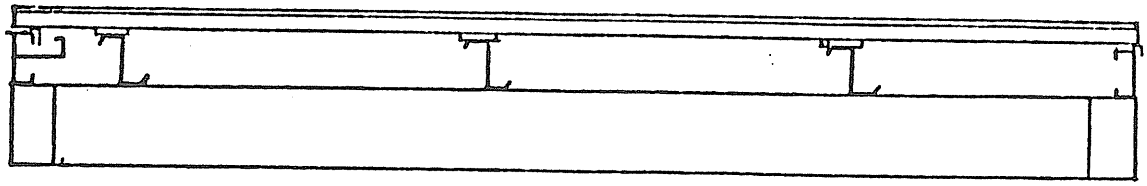
Method Star u.c. 1.666 Load 243 plf

Method AISI Constrained x 1.67 Load 270.3 plf

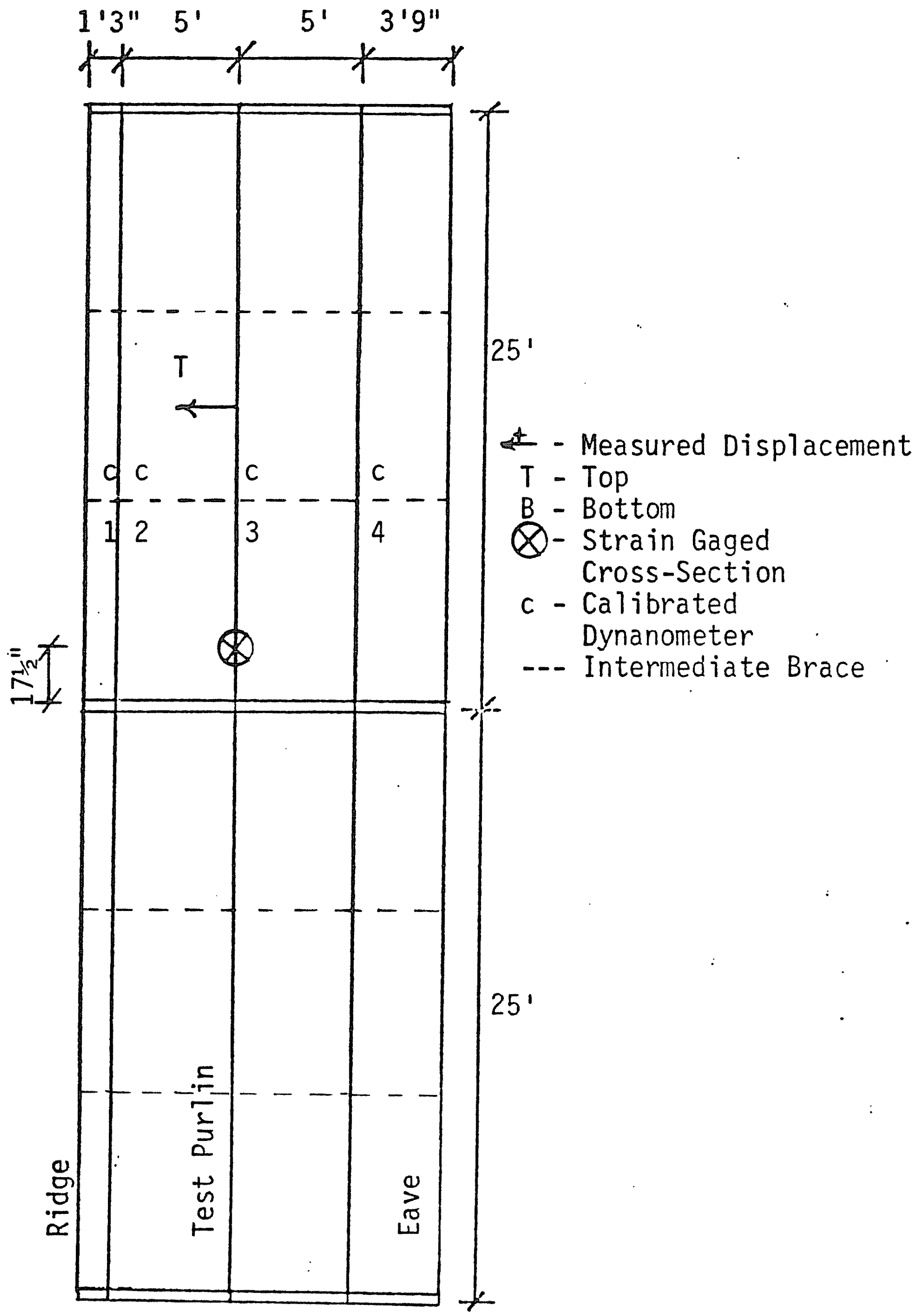
Method ____ Load ____

Discussion:

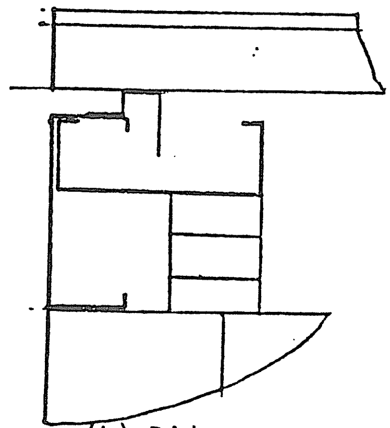
- Failure mode was local buckling of lip and flange.
- Load vs. deflection curve showed good agreement up to about 180 plf then the experimental curve began to deviate from theoretical predictions.
- It was observed that the displacement of the downhill purlin was more in this test than in test 3A. This could explain the failure load being lower than that of test 3A.
- The Star predicted failure load was 1.6% lower than the experimental failure load.
- The AISI predicted failure load was 8.3% higher than the experimental failure load.
- The stress on the cross section at working load shows a maximum stress of 42.6 ksi tension at the top flange to web junction.
- The stress on the cross section at failure load shows yield stress at both top and bottom flange to web junctions.
- The brace forces in braces #1 and @2 were similar to test 3A. Brace #4 was in tension from the onset of the test and showed very little load throughout the test.
- The maximum brace forces are as follows: #1, 714 lbs compression; #2, 500 lbs compression; #3, 108 lbs compression; #4, 247 lbs tension.
- Top horizontal displacement transducer was not working at the time of testing.



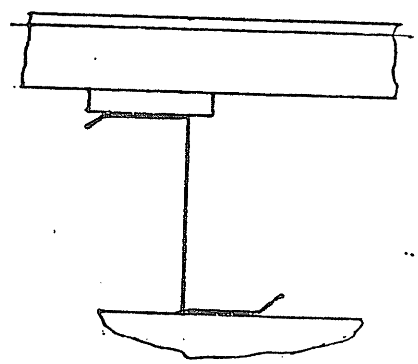
(a) Elevation of Test Set-Up



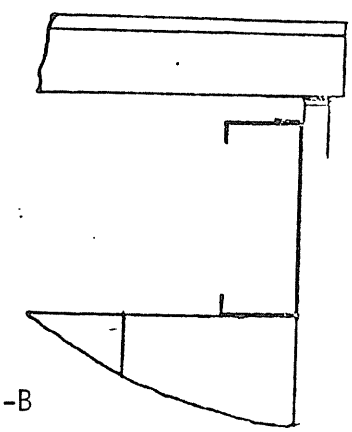
(e) Plan View



(b) Ridge

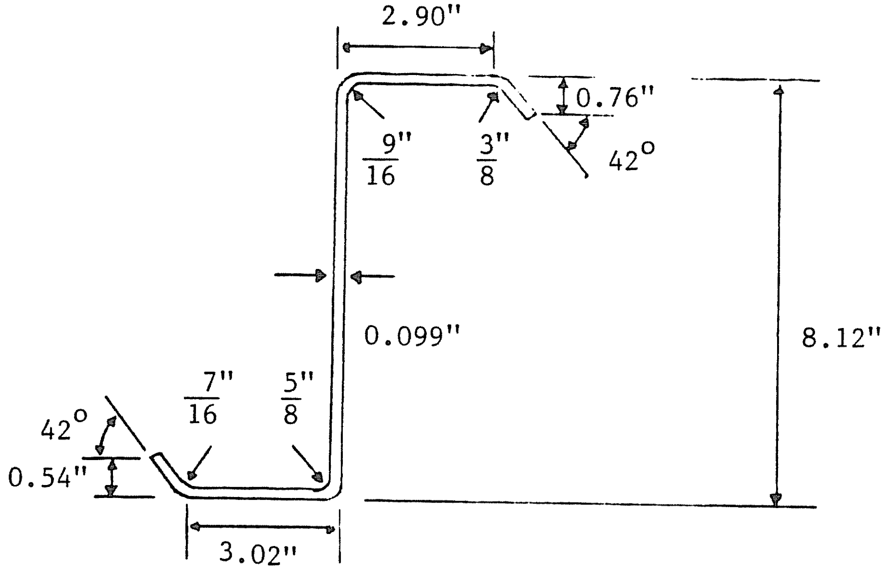


(c) Typical Purlin

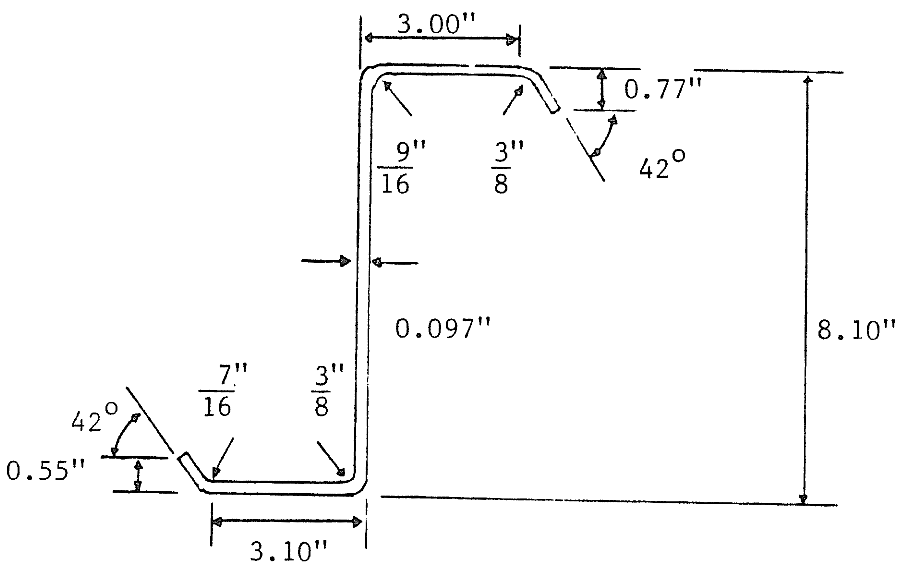


(d) Eave

Figure C.16 Instrumentation Location, Test 3-B



North Span



South Span

Figure C.17 Measured Purlin Dimensions, Test 3-B

A I S I P U R L I N A N A L Y S I S
IDENTIFICATION: STAR PURLIN TEST 3-B NORTH

	TOP	BOTTOM
FLANGE(in)	2.900	3.020
LIP(in)	0.760	0.540
LIP ANGLE(deg)	42.000	42.000
RADIUS L/F(in)	0.375	0.438
RADIUS F/W(in)	0.563	0.625

TOTAL DEPTH(in)	8.12
THICKNESS(in)	0.099
YIELD STRENGTH(ksi)	48.9

MOMENTS OF INERTIA(in^4)		SECTION MODULII(in^3) TOP	BOTTOM
GROSS=	15.665	3.934	3.878
STRENGTH=	15.665	3.934	3.878
DEFLECTION=	15.665		

BE= 2.239 in
FC= 28.808 ksi
FT= 29.340 ksi
FBW= 29.340 ksi

Figure C.18 AISI Purlin Analysis, Test 3-B, North Span

```
---------------------------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: STAR PURLIN TEST 3-B SOUTH
---------------------------------------------------------------------------
                          TOP             BOTTOM
FLANGE(in)              3.000              3.100
LIP(in)                 0.770              0.550
LIP ANGLE(deg)         42.000             42.000
RADIUS L/F(in)          0.375              0.438
RADIUS F/W(in)          0.563              0.375

TOTAL DEPTH(in)              8.1
THICKNESS(in)                0.097
YIELD STRENGTH(ksi)          46.7
                                       SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)        TOP                 BOTTOM
GROSS=         15.758               3.997                3.881
STRENGTH=      15.758               3.997                3.881
DEFLECTION=    15.758
BE=     2.341   in
FC=     27.398  ksi
FT=     28.020  ksi
FBW=    28.020  ksi
```

Figure C.19 AISI Purlin Analysis Test 3-B, South Span

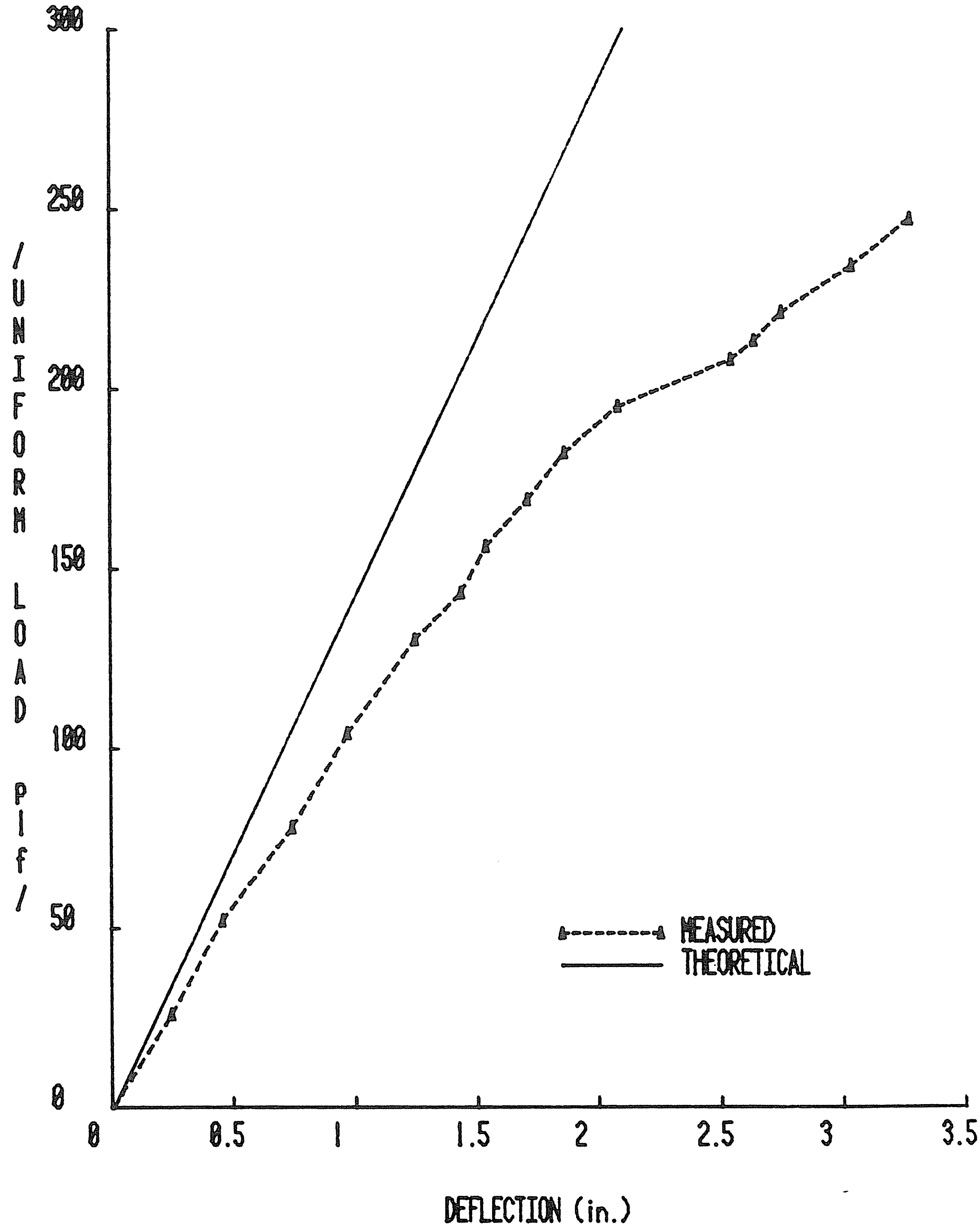


Figure C.20 Load vs. Vertical Deflection, Test 3-B

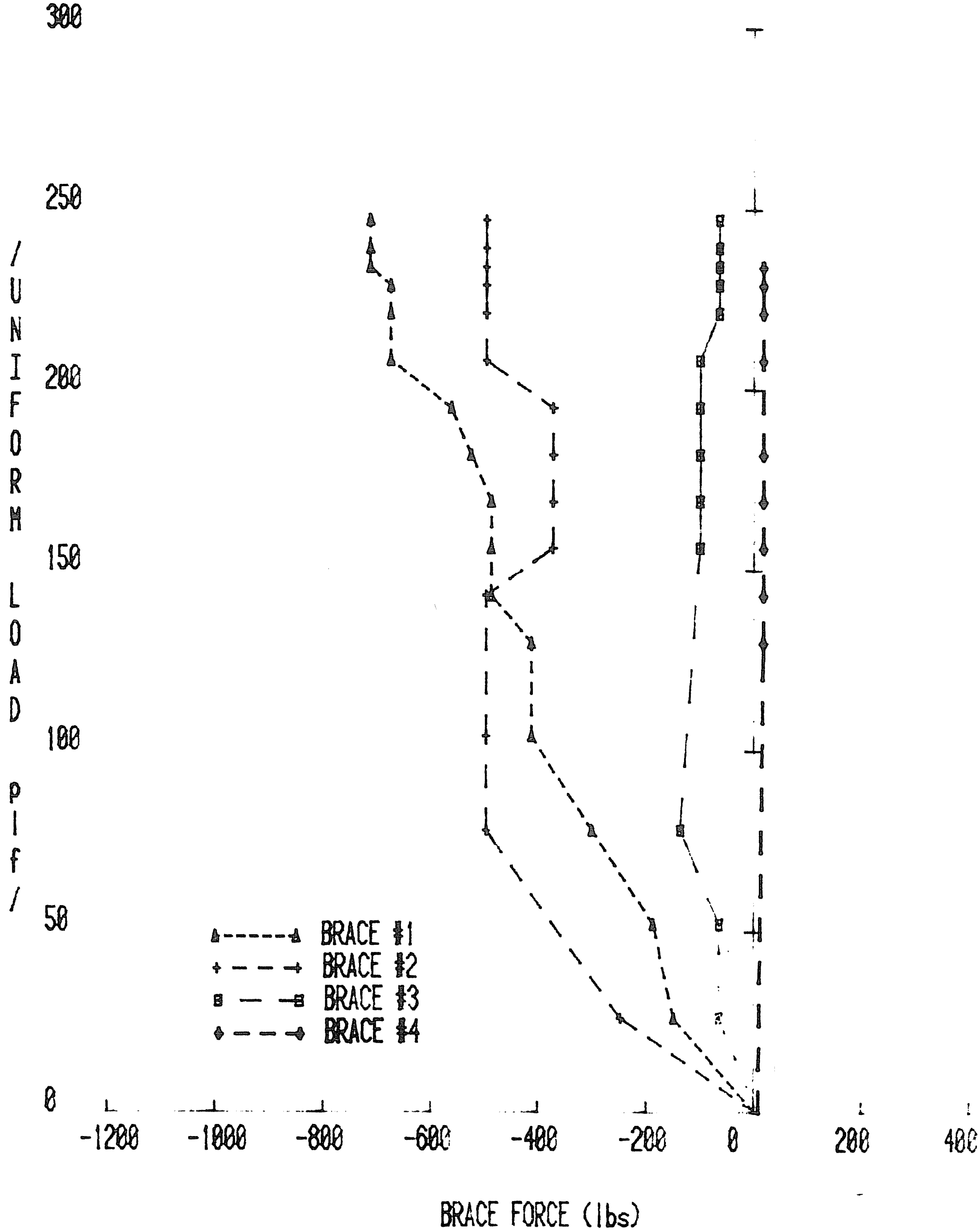


Figure C.21 Vertical Load vs. Brace Force at 1/3 Point of Span, Test 3-B North Span

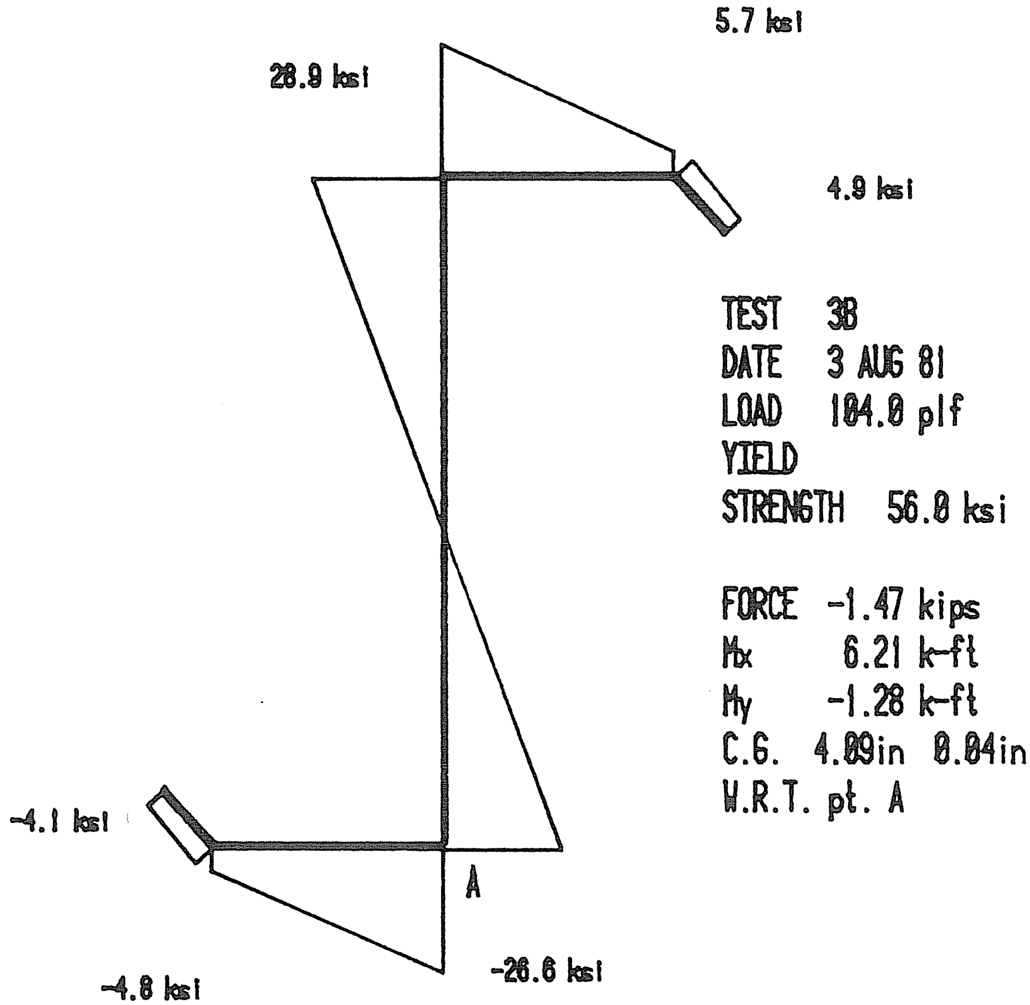


Figure C.22 Stress Distribution at 104 plf, Test 3-B

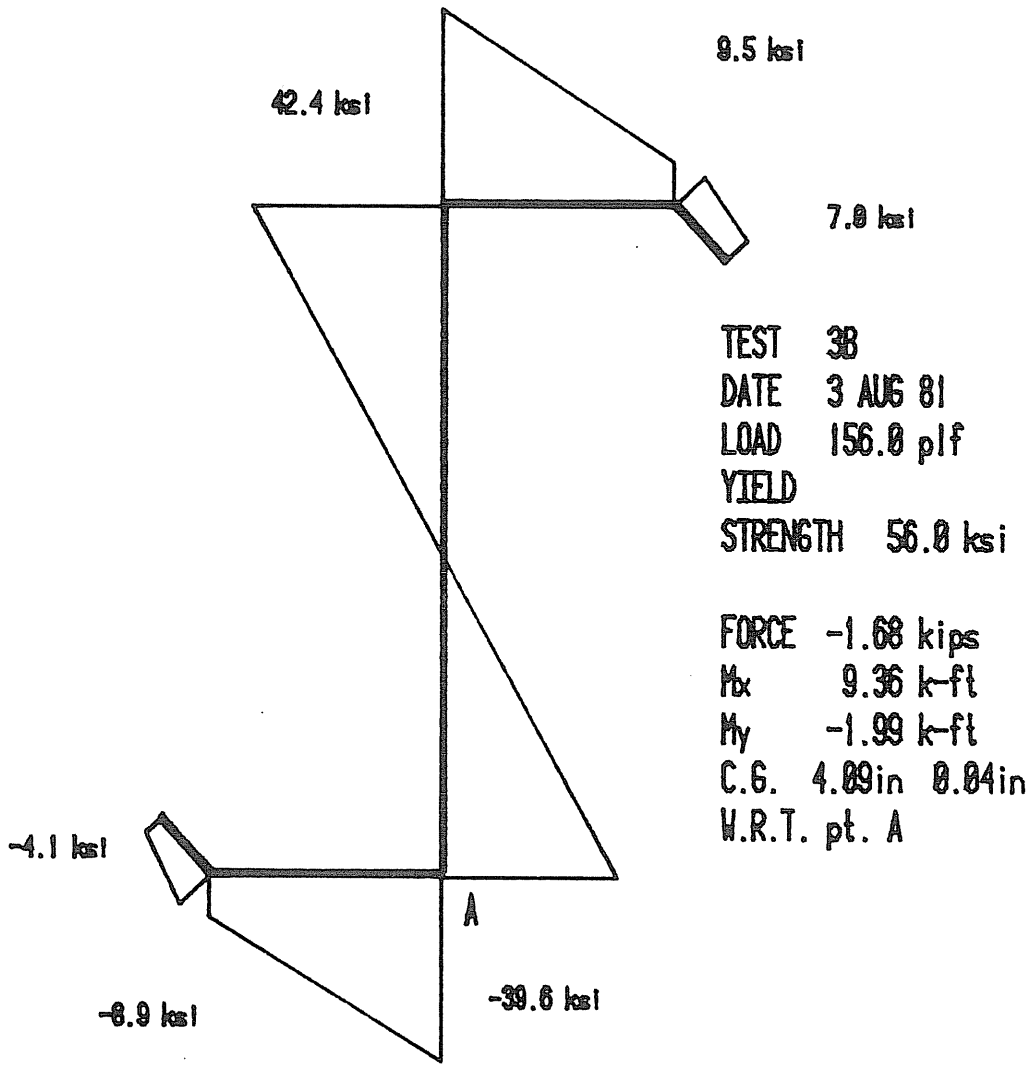


Figure C.23 Stress Distribution at 156 plf, Test 3-B

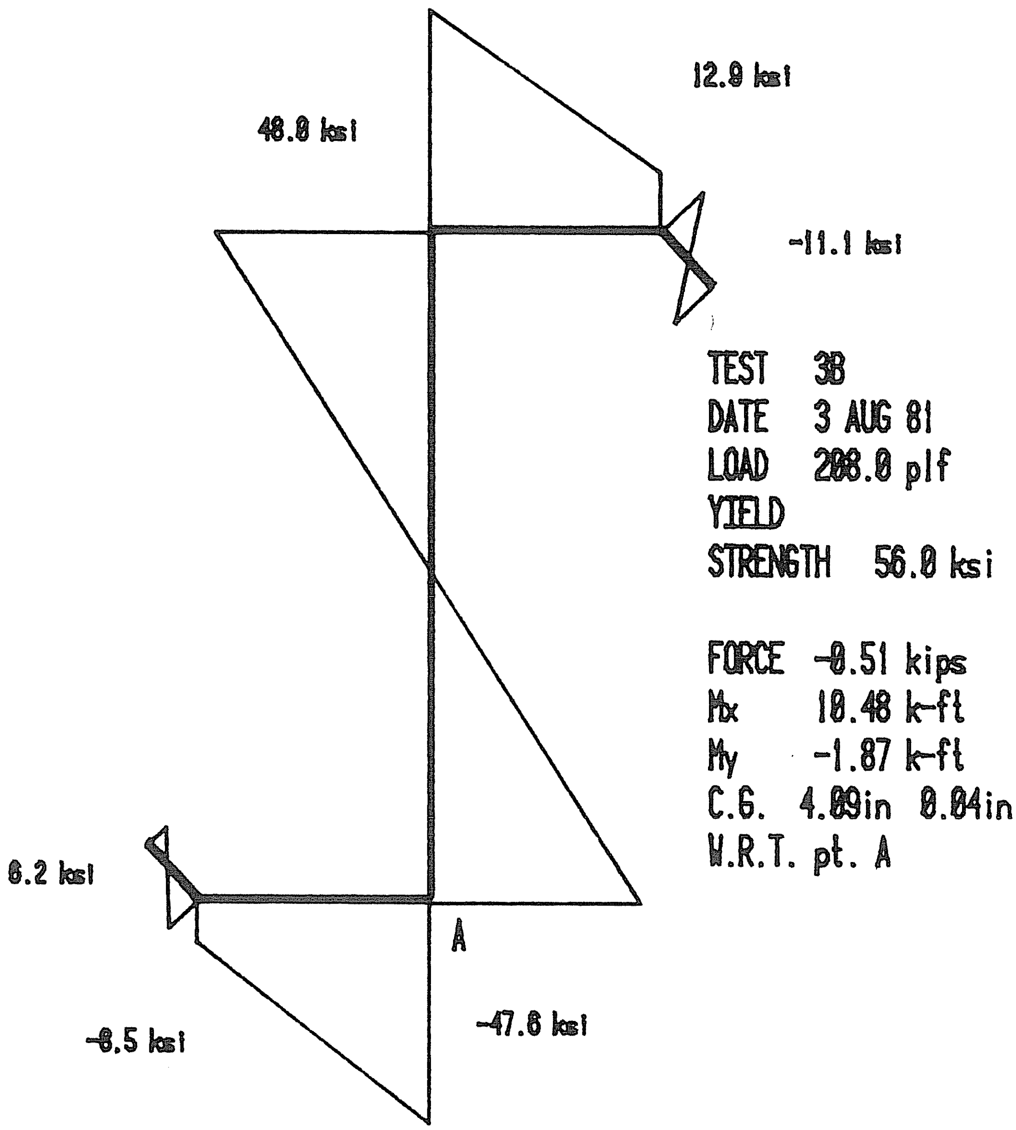


Figure C.24 Stress Distribution at 208 plf, Test 3-B

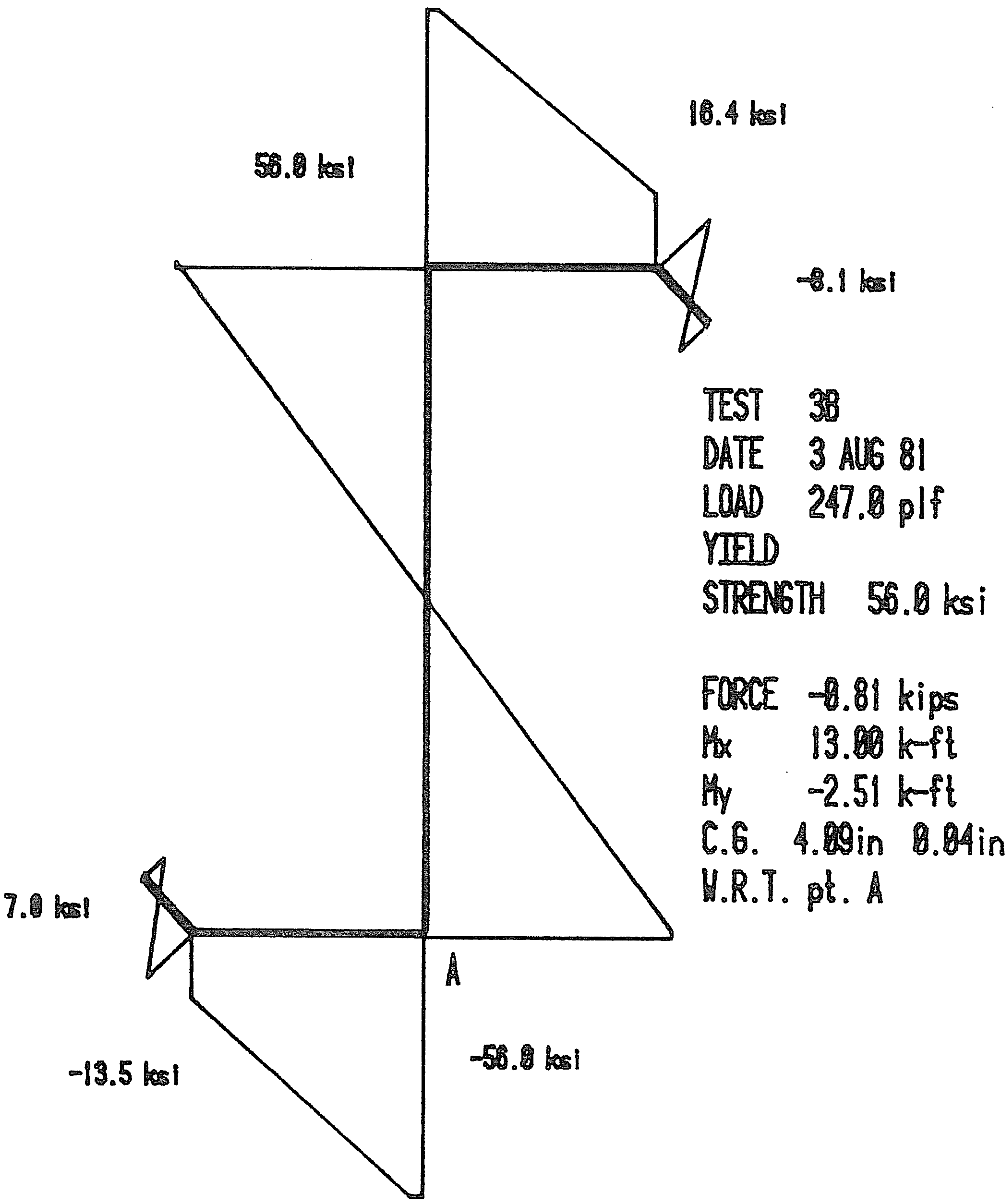


Figure C.25 Stress Distribution at 247 plf, Test 3-B

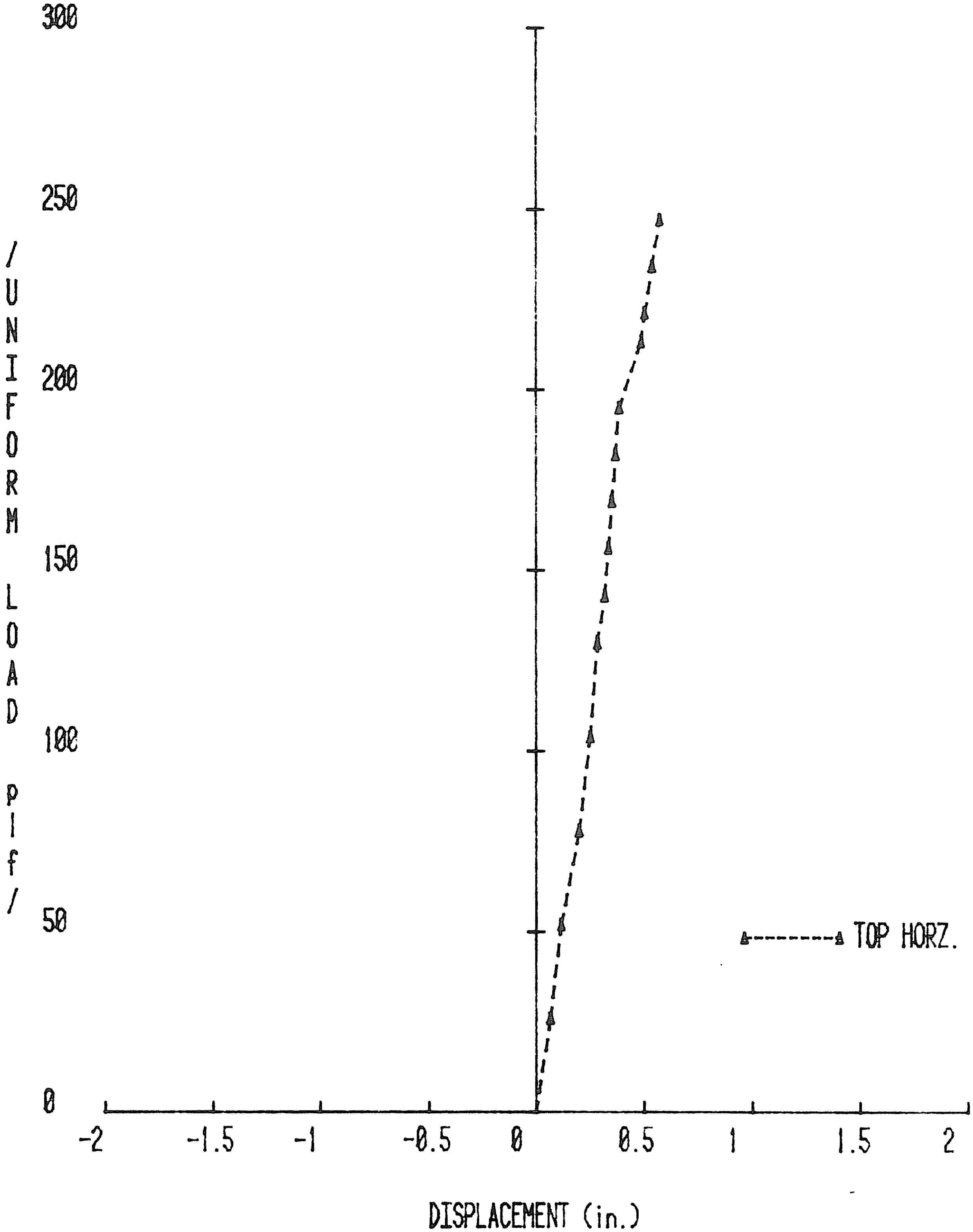


Figure C.26 Vertical Load vs. Lateral Displacement, Test 3-B

APPENDIX D

TEST SERIES IV RESULTS

TEST SUMMARY

Project: Star Manufacturing Company

Test No.: 4-A

Test Date: 1/18/82

Purpose: Test 4A w/o Insulation

Span(s): 1 @ 25'-0"

Thickness: 0.094" Moment of Inertia: 14.484 in^4

Parameters: Intermediate Braces @ 1/3 pt.

Clips in place

No insulation

Spacing 4'-9"*

Strain gages @ ℄ of purlin

Failure Load: 225.6 plf

Failure Mode: Compression buckling of flange @ flange & web node.

Predicted Failure Loads:

Method	Load
AISI x 1.65	336.554 plf

Discussion:

- -The purlins were spaced @ 4'9" to provide more room on the outside of the test set-up so that the ridge purlin would not hit the chamber wall.
- -The failure mode was local buckling of the compression flange and web at the center of the span.
- -There was good agreement between the predicted and experimental load vs. deflection curves.
- -From the load deflection curve, deflection of the test purlin seems to be linear up to the point of failure. It would appear that the ridge purlin again failed before the test purlin.
- -The AISI predicted failure load was 47.2% higher than the experimental failure load.
- -From the stress plot @ failure load the max. stress was 47.8 ksi compression at the flange to web junction.
- -With the adjustment in the test set-up the brace forces did not reduce in magnitude at higher loads.
- -Brace forces increased approximately linearily.
- -At 31.2 psf the ratio of brace forces was 1:1.79:3.09 (in the direction of ridge to eave). The ratio of tributary areas was 1:3:5.
- -At 31.2 psf the brace forces as a percentage of stabilized vertical load was 19.8%, 18.9% and 17.2% in the direction of ridge to eave.
- -The top and bottom flanges moved laterally in the same direction. The top flange moved more than the bottom flange.

-There was more lateral displacement of both the top and bottom flanges as compared to the 4C test, ie. @ 200.9 plf, 4A Top, 0.70 in; 4C Top, .255 in; 4A Bottom, 1.201 in; 4C Bottom, .507 in.

-The maximum lateral displacement of the eave was 0.815 in. @ the centerline.

-The maximum lateral displacement of the first purlin was 0.439 in.

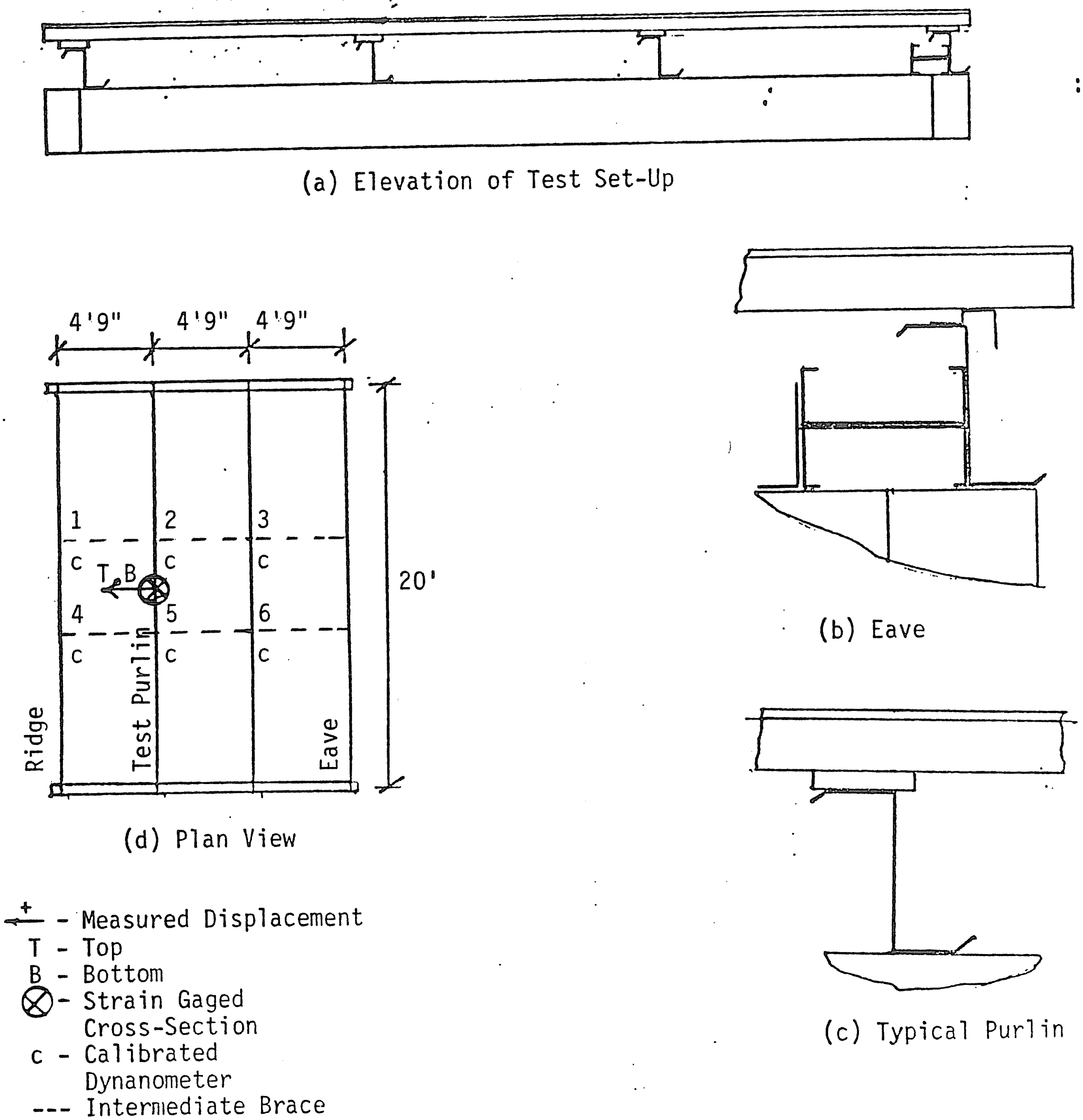


Figure D.1 Instrumentation Location, Test 4-A

```
------------------------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: STAR PURLIN TEST 4-A
------------------------------------------------------------------------
                          TOP              BOTTOM
FLANGE(in)               2.880              2.800
LIP(in)                  0.880              0.680
LIP ANGLE(deg)          50.000             49.000
RADIUS L/F(in)           0.469              0.469
RADIUS F/W(in)           0.406              0.406

TOTAL DEPTH(in)                8
THICKNESS(in)                  0.094
YIELD STRENGTH(ksi)            55.7
                                            SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)          TOP                  BOTTOM
GROSS=          14.484                3.732                3.599
STRENGTH=       14.484                3.732                3.599
DEFLECTION=     14.484
BE=     2.380   in
FC=     32.374  ksi
FT=     33.420  ksi
FBW=    33.391  ksi
```

Figure D.3 AISI Cross-Section Analysis, Test 4-A

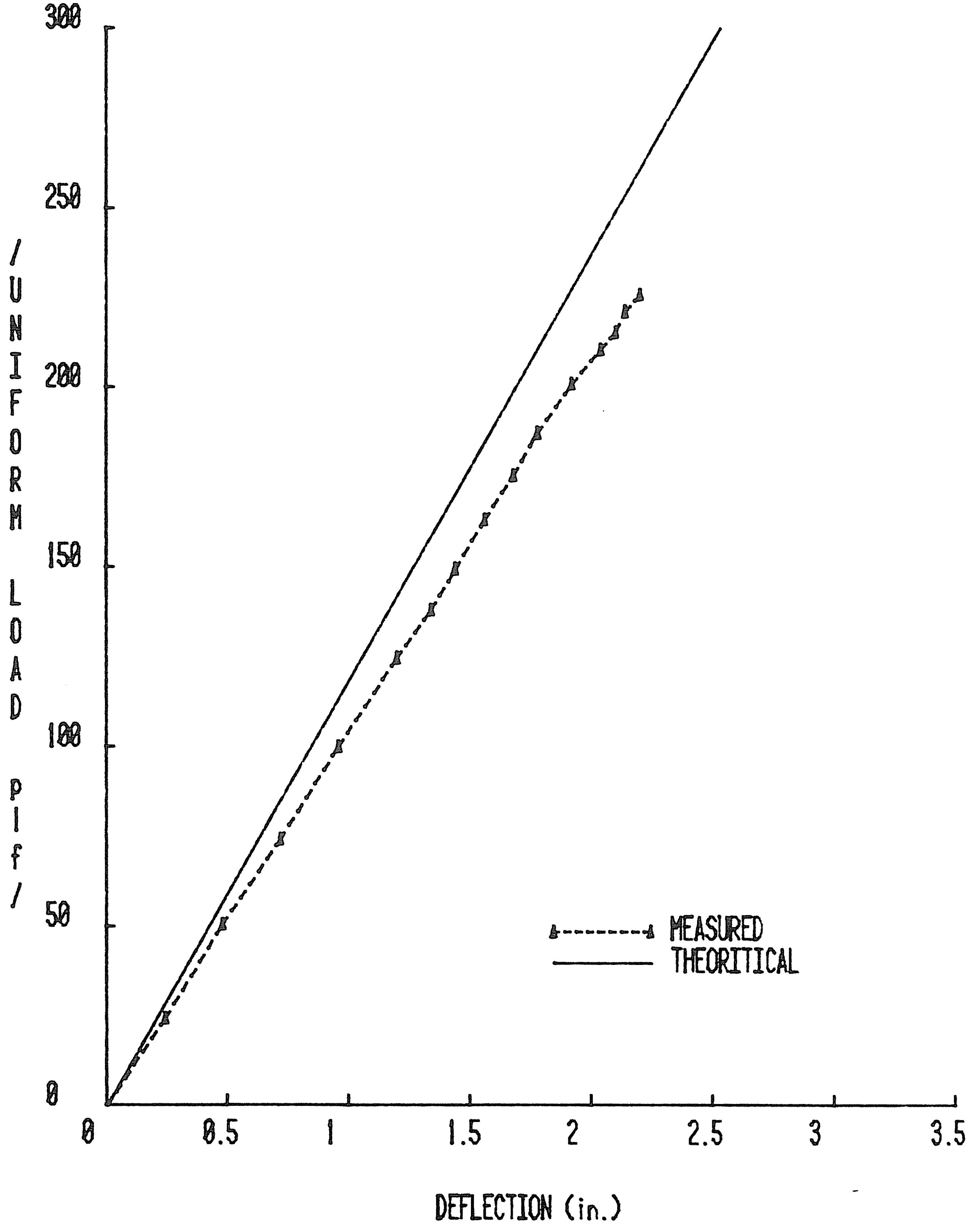


Figure D.4 Load vs. Vertical Deflection, Test 4-A

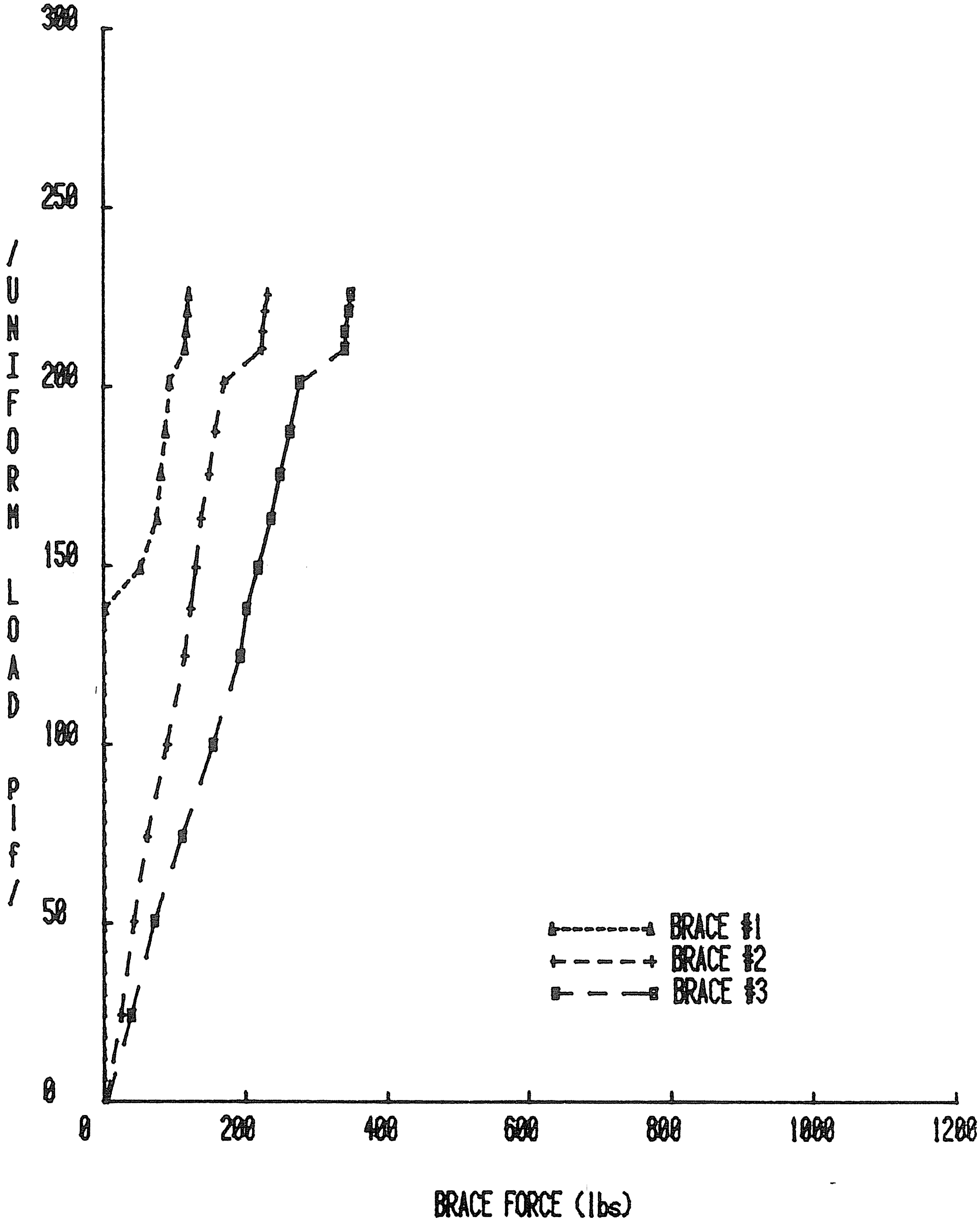


Figure D.5 Vertical Load vs. Brace Force at 1/3 Point of Span, Test 4-A

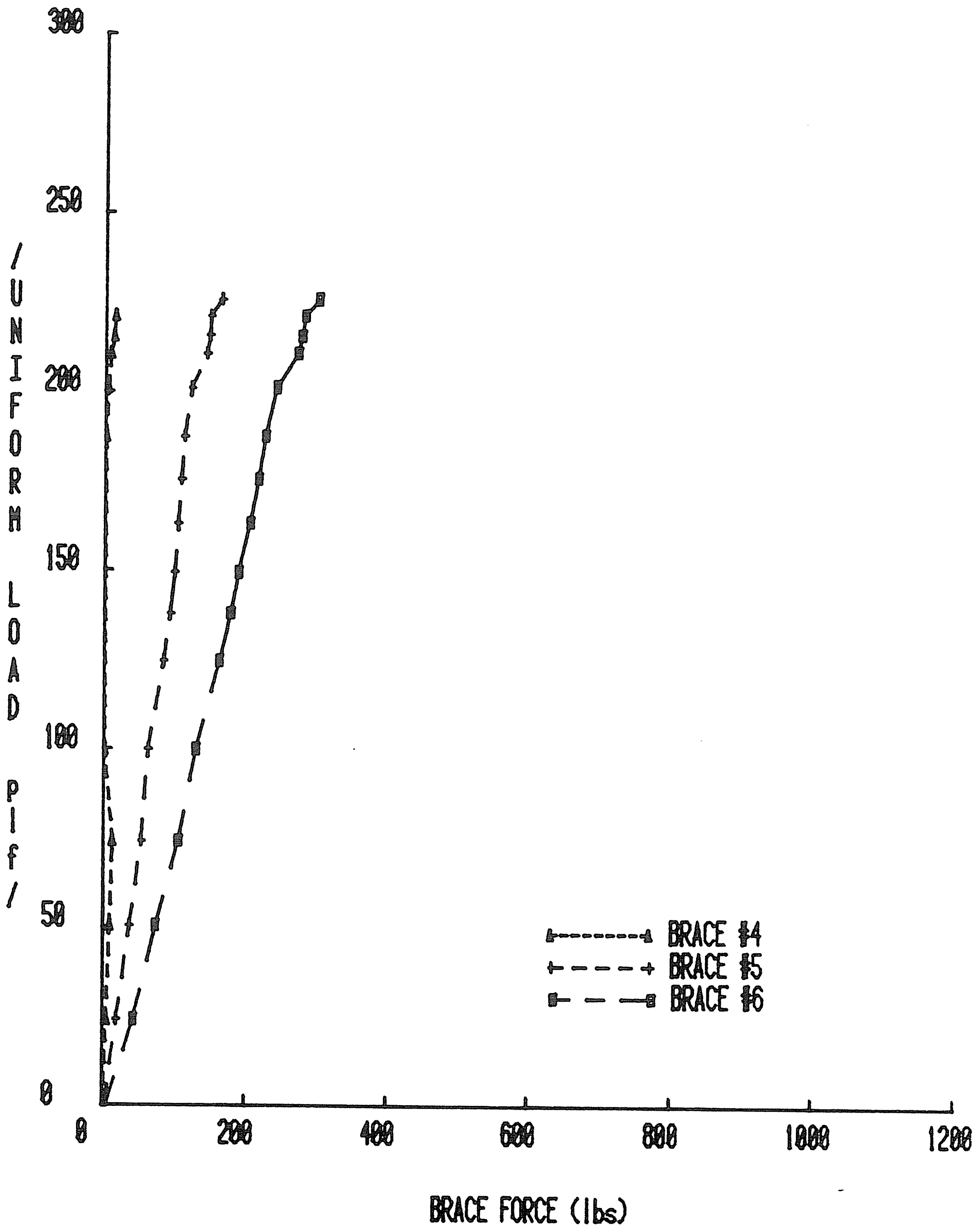


Figure D.6 Vertical Load vs. Brace Force at 1/3 Point of Span, Test 4-A

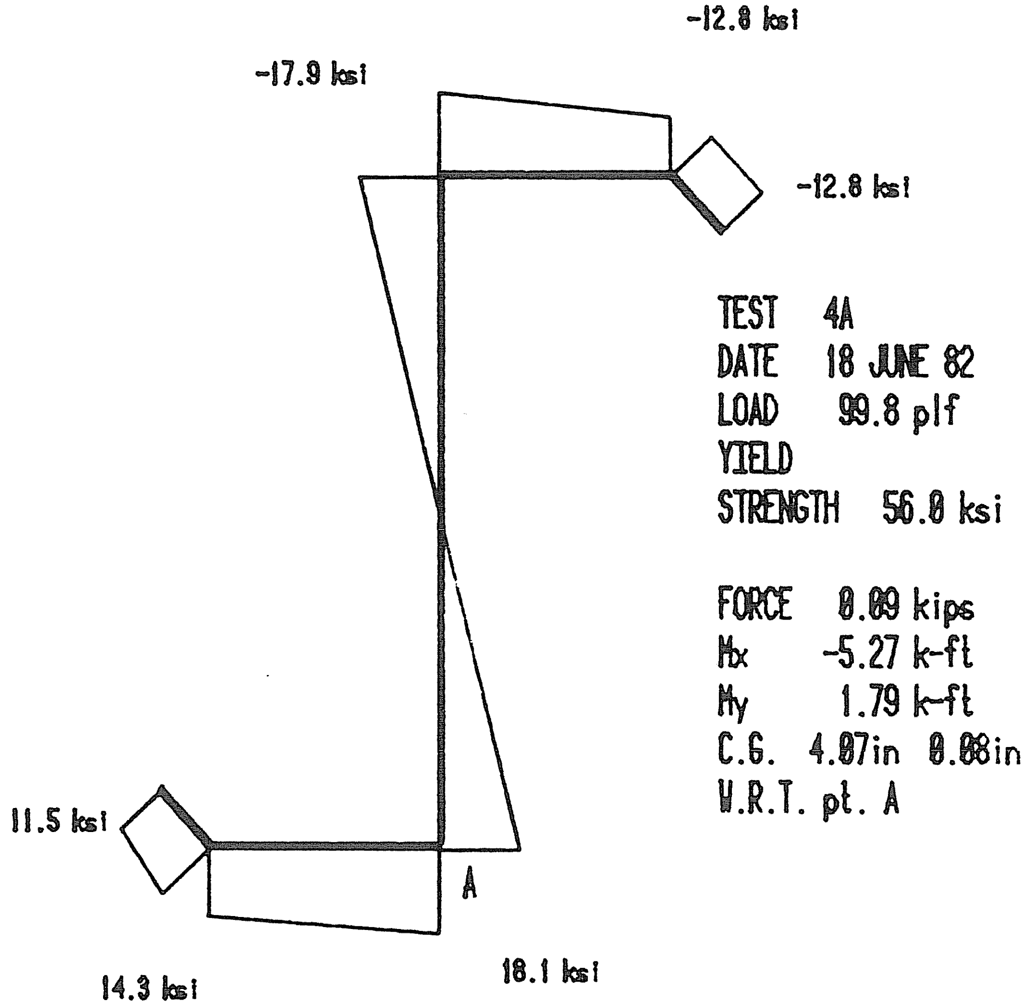


Figure D.7 Stress Distribution at 99.8 plf, Test 4-A

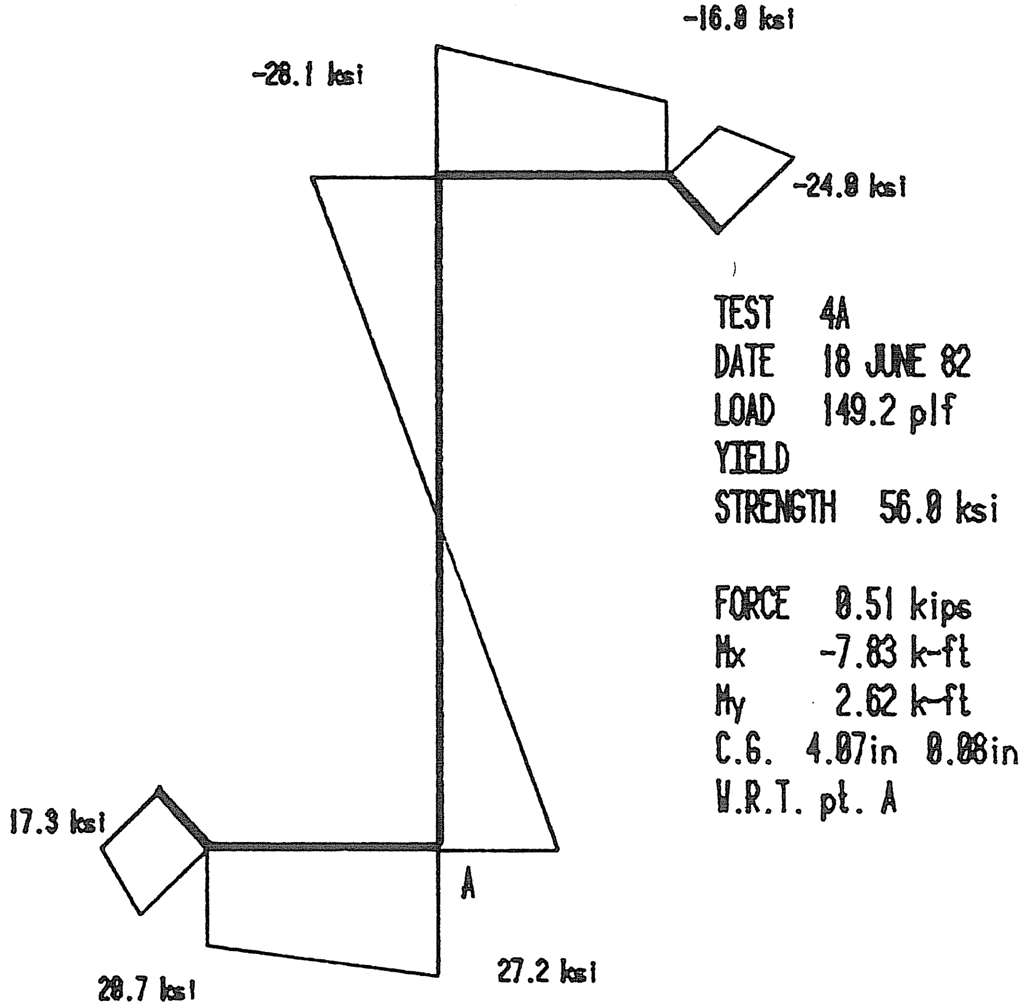


Figure D.8 Stress Distribution at 149.2 plf, Test 4-A

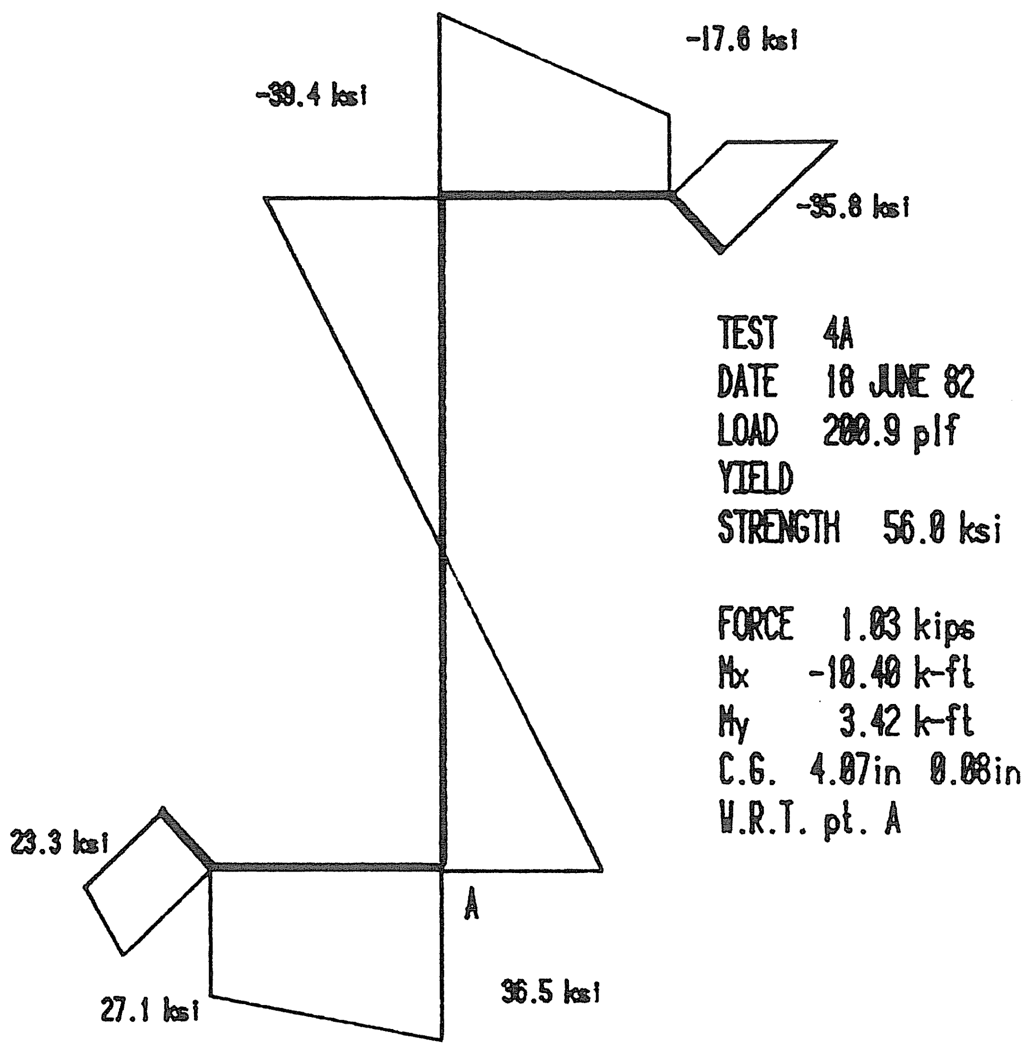


Figure D.9 Stress Distribution at 200.9 plf, Test 4-A

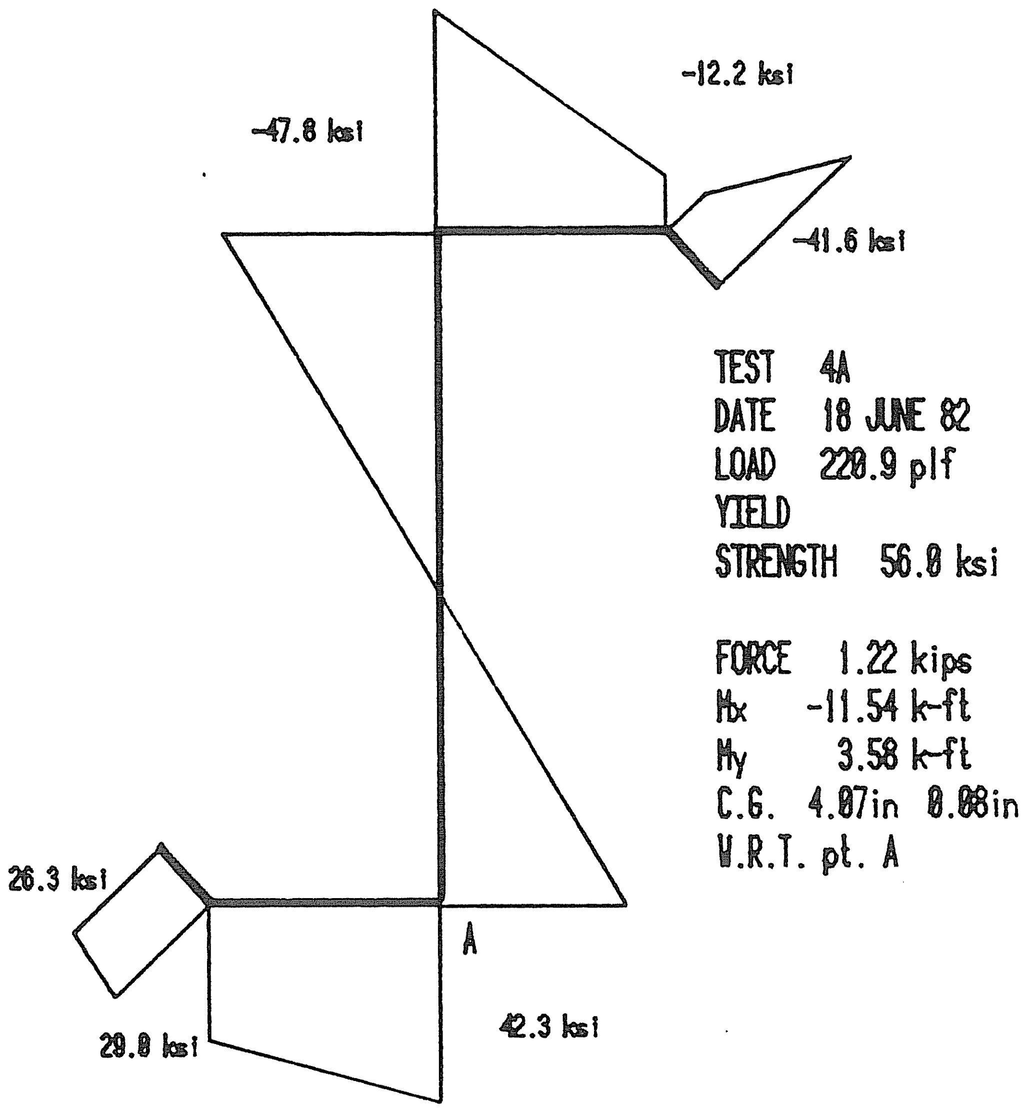


Figure D.10 Stress Distribution at 220.9 plf, Test 4-A

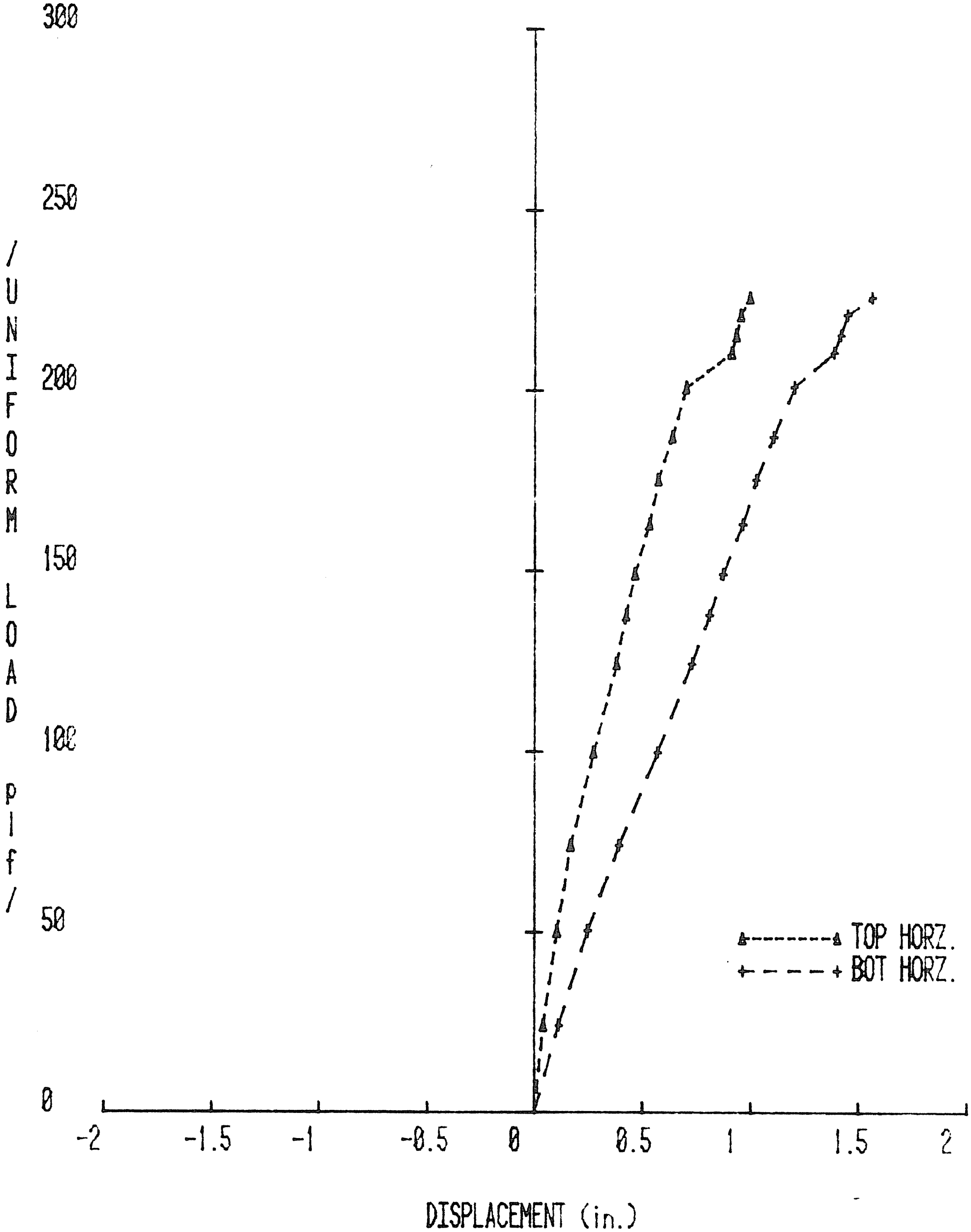


Figure D.11 Vertical Load vs. Lateral Displacements, Test 4-A

TEST SUMMARY

Project: Star Manufacturing Company

Test No.: 4B

Test Date: December 3, 1981

Purpose: Effect of panel "hugging" on lateral restraint.

Span(s): Single span 20'-0"

Thickness: 0.094 in. Moment of Inertia: 14.44 in^4

Parameters: No intermediate bracing — Star I_x = 13.769 in^4

No clips

No insulation

Spacing 7'-3"

Failure Load: 128.2 plf

Failure Mode: Extreme lateral displacement

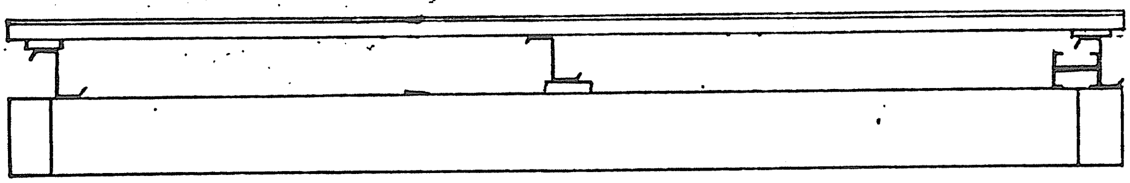
Predicted Failure Loads:

Method	Load
Star (u.c. x 1.672)	35 plf unbraced
AISI Constrained Bending	335.4 plf w/FS=1.67

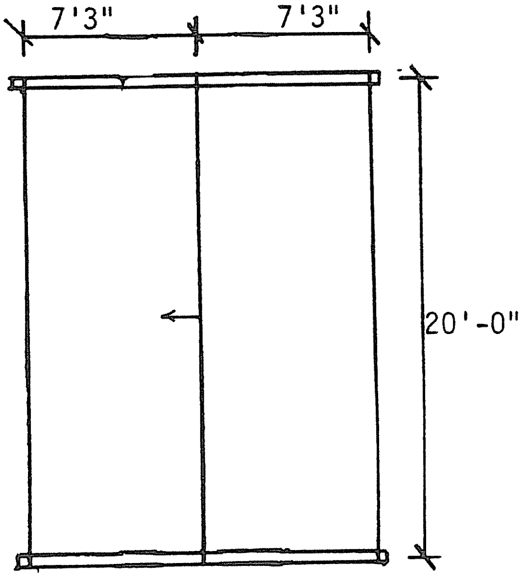
Discussion:

-Top flange lateral displacements were very large.

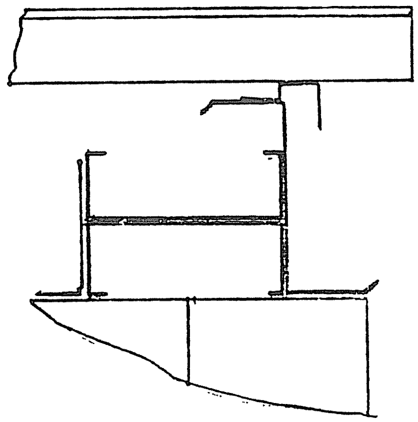
-Test was stopped when it was determined that the outside purlins were taking the load. (See load vs. displacement curve.)



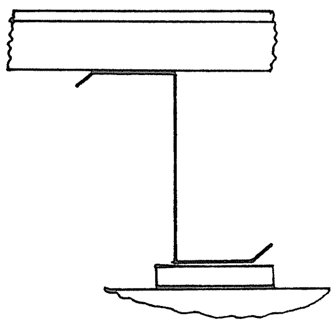
(a) Elevation of Test Set-Up



(d) Plan View



(b) Eave



(c) Typical Purlin

← - Measured Displacement
T - Top
B - Bottom
⊗ - Strain Gaged Cross-Section
c - Calibrated Dynanometer
--- Intermediate Brace

Figure D.12 Instrumentation Location, Test 4-B

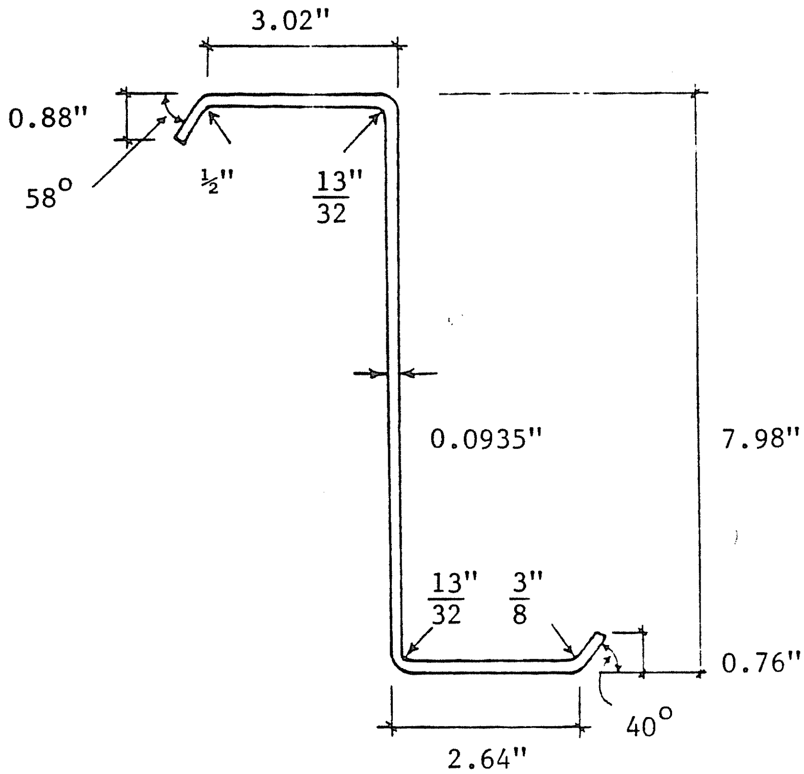


Figure D.13 Measured Purlin Dimensions, Test 4-B

```
------------------------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: STAR PURLIN TEST 4-B
------------------------------------------------------------------------
                          TOP              BOTTOM
FLANGE(in)              3.020              2.640
LIP(in)                 0.880              0.760
LIP ANGLE(deg)         58.000             40.000
RADIUS L/F(in)          0.500              0.375
RADIUS F/W(in)          0.406              0.406

TOTAL DEPTH(in)                7.98
THICKNESS(in)                  0.094
YIELD STRENGTH(ksi)            56
                                            SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)             TOP              BOTTOM
GROSS=          14.518                   3.762             3.605
STRENGTH=       14.518                   3.762             3.605
DEFLECTION=     14.518
BE=     2.520   in
FC=     33.600   ksi
FT=     33.600   ksi
FBW=    33.569   ksi
```

Figure D.14 AISI Cross-Section Analysis, Test 4-B

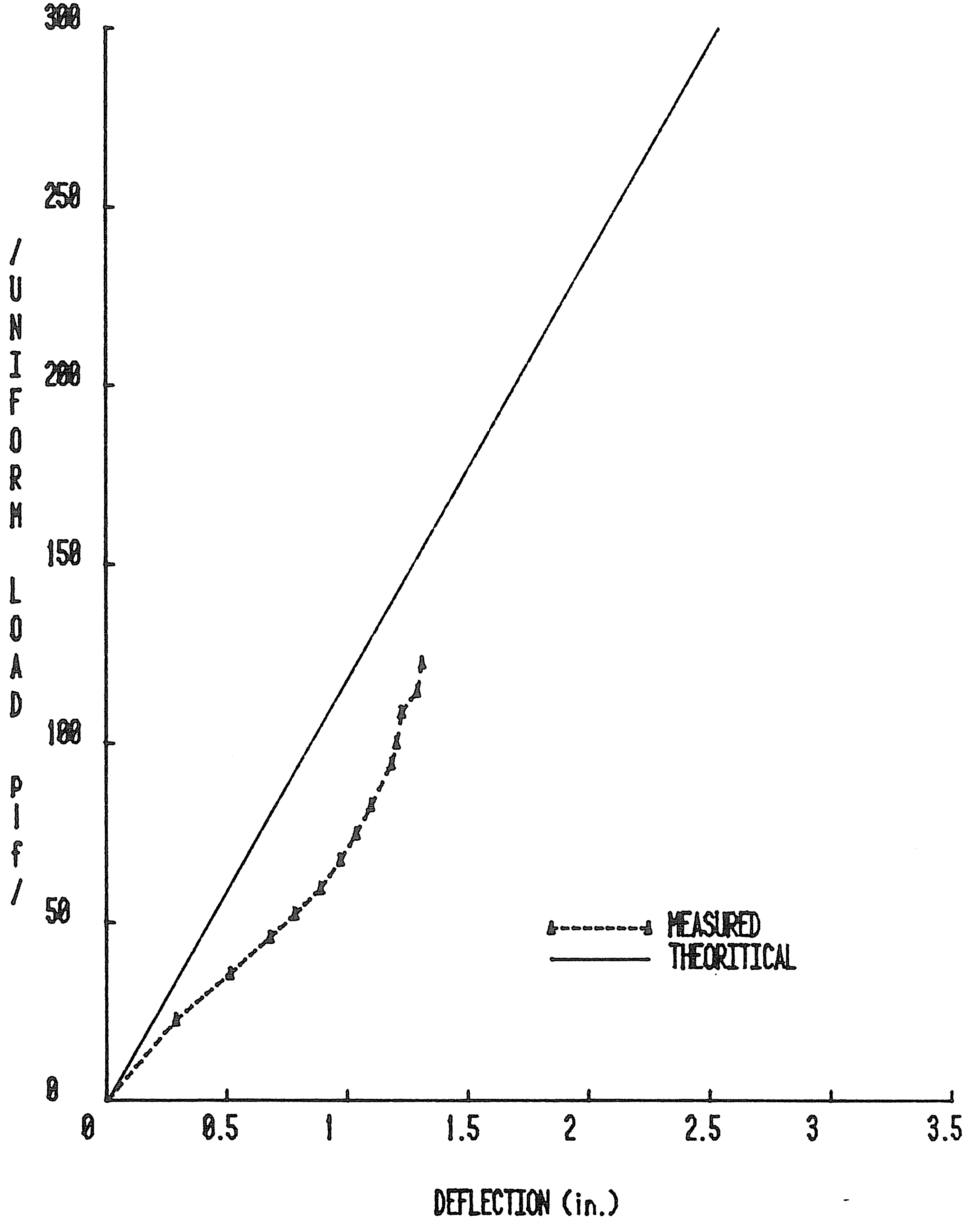


Figure D.15 Load vs. Vertical Deflection, Test 4-B

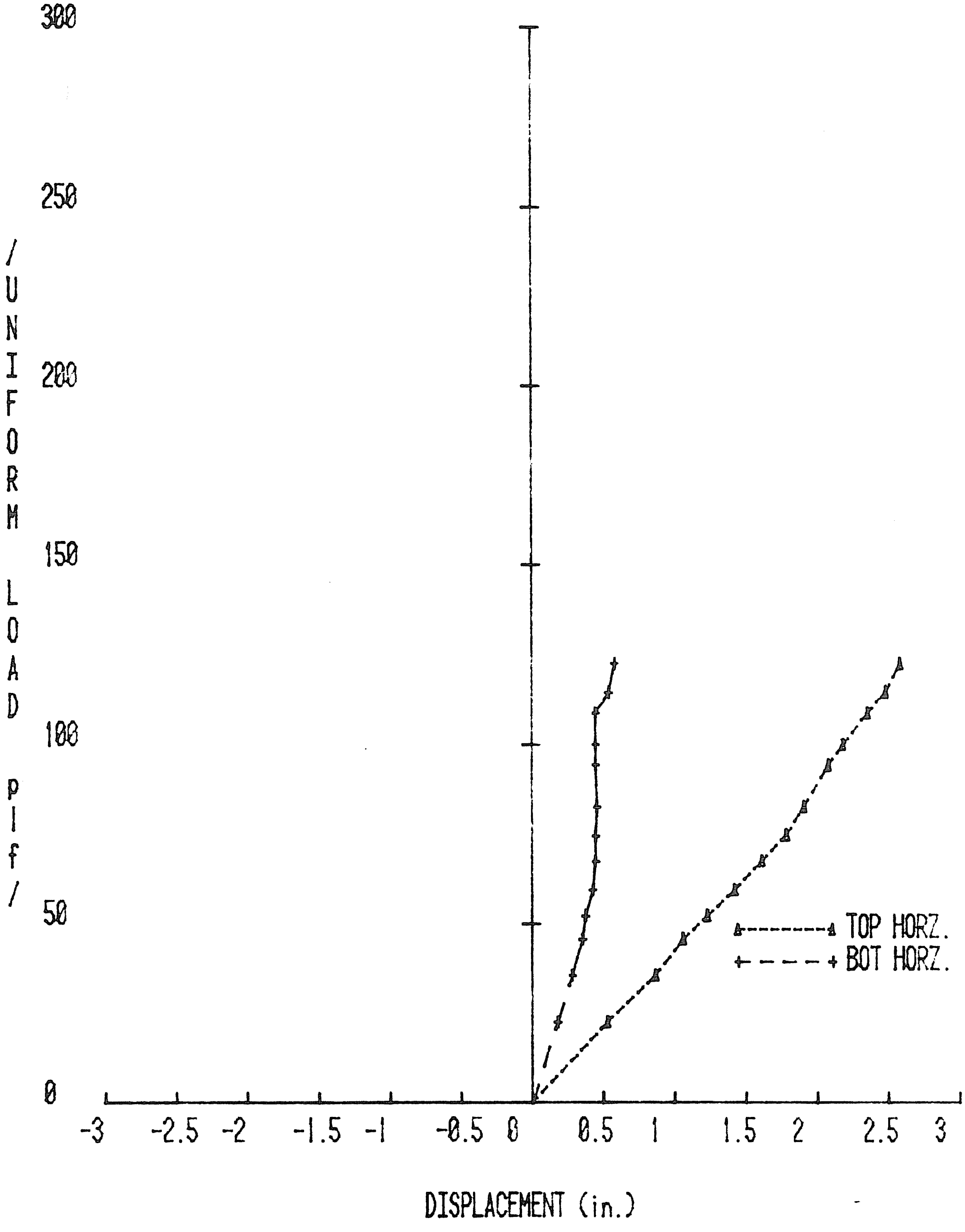


Figure D.16 Vertical Load vs. Lateral Displacements, Test 4-B

TEST SUMMARY

Project: Star Manufacturing Company

Test No.: 4C

Test Date: November 3, 1981

Purpose: Base Test

Span(s): Single Span 20'-0"

Thickness: 0.096" Moment of Inertia: 15.695 in^4 (Gross)

Parameters: Intermediate Bracing at 1/3 pts. Star I_x = 15.024 in^4

Clips installed

No insulation

Spacing 4'-10"

Failure Load: 233.7 plf

Failure Mode: Local buckling

Predicted Failure Loads:

Method		Load	
Method	Star u.c. x 1.668	Load	327 plf
Method	AISI Constrained Bending	Load	357.7 plf w/FS = 1.67
Method		Load	

Discussion:

- Failure occurred because of local buckling of the compression flange near the centerline at 237.7 plf.
- Vertical deflections were approximately 25% greater than constrained bending predictions.
- Measured vertical deflections were approximately linear.
- From lateral displacement and intermediate brace vs. load plots, it appears that the system deflected into the west side of the vacuum chamber and was then restrained by the chamber wall.
- No strain measurements were made.
- Brace forces were reasonably consistent until contact with the chamber wall.
- Brace forces increased approximately linearily.
- At 31.2 psf (6 in. of H_2O) the ratio of brace forces was 1:2.32:2.82 (in the direction of ridge to eave). At 10.4 the ratio was 1:2.03:2.55. The ratio of tributary areas was 1:3:5.
- When tributary areas are considered it is evident that the brace forces did not accumulate in proportion to tributary area.
- At 31.2 psf, the brace forces as a percentage of stabilized vertical load were 17.3%, 13.4% and 9.7% in the direction of ridge to eave and at 10.4 psf, 24.0%, 16.2% and 12.2%.
- Maximum centerline horizontal displacement of the top flange of the test purlin was approximately 0.5 in.
- The top and bottom flanges of the test purlin moved in the same direction.

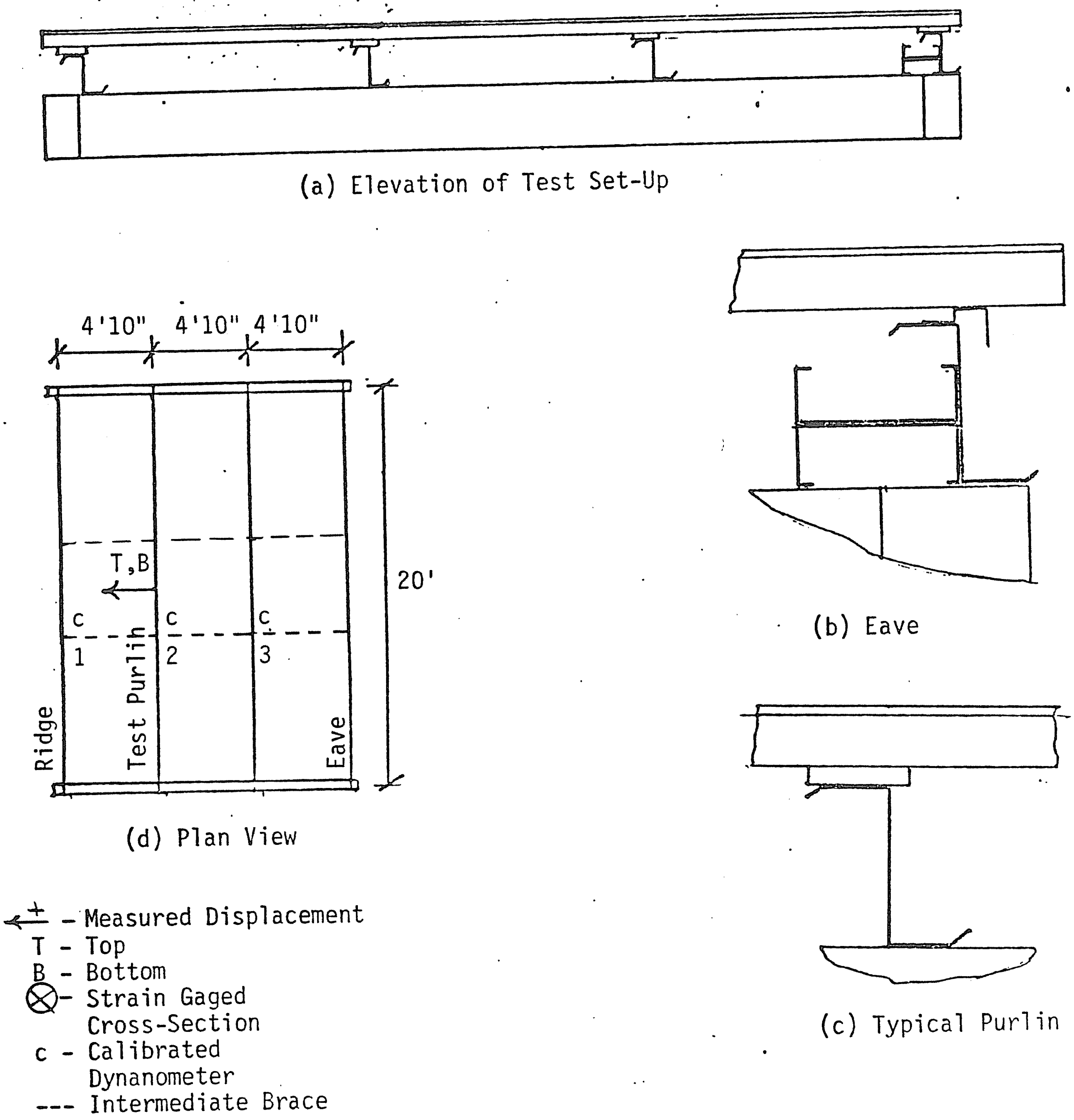


Figure D.17 Instrumentation Location, Test 4-C

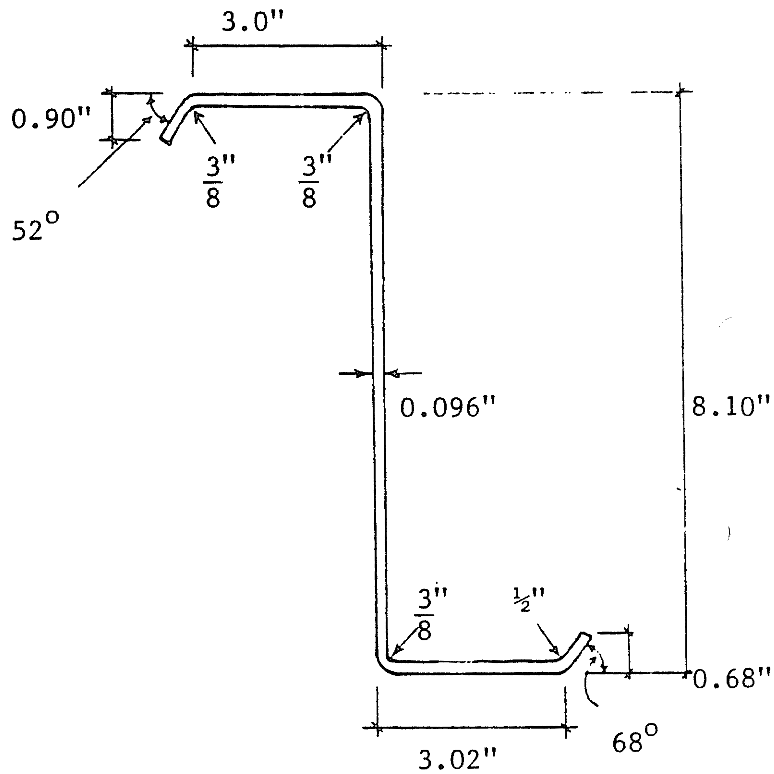


Figure D.18 Measured Purlin Dimensions, Test 4-C

A I S I   P U R L I N   A N A L Y S I S

IDENTIFICATION: STAR PURLIN TEST 4-C

	TOP	BOTTOM
FLANGE(in)	3.000	3.020
LIP(in)	0.900	0.680
LIP ANGLE(deg)	52.000	53.000
RADIUS L/F(in)	0.375	0.500
RADIUS F/W(in)	0.375	0.375

TOTAL DEPTH(in)	8.1
THICKNESS(in)	0.096
YIELD STRENGTH(ksi)	57.4

	MOMENTS OF INERTIA(in^4)	SECTION MODULII(in^3) TOP	SECTION MODULII(in^3) BOTTOM
GROSS=	15.695	3.962	3.883
STRENGTH=	15.695	3.962	3.883
DEFLECTION=	15.695		

BE= 2.529 in

FC= 33.114 ksi

FT= 34.440 ksi

FBW= 34.364 ksi

Figure D.19 AISI Cross-Section Analysis, Test 4-C

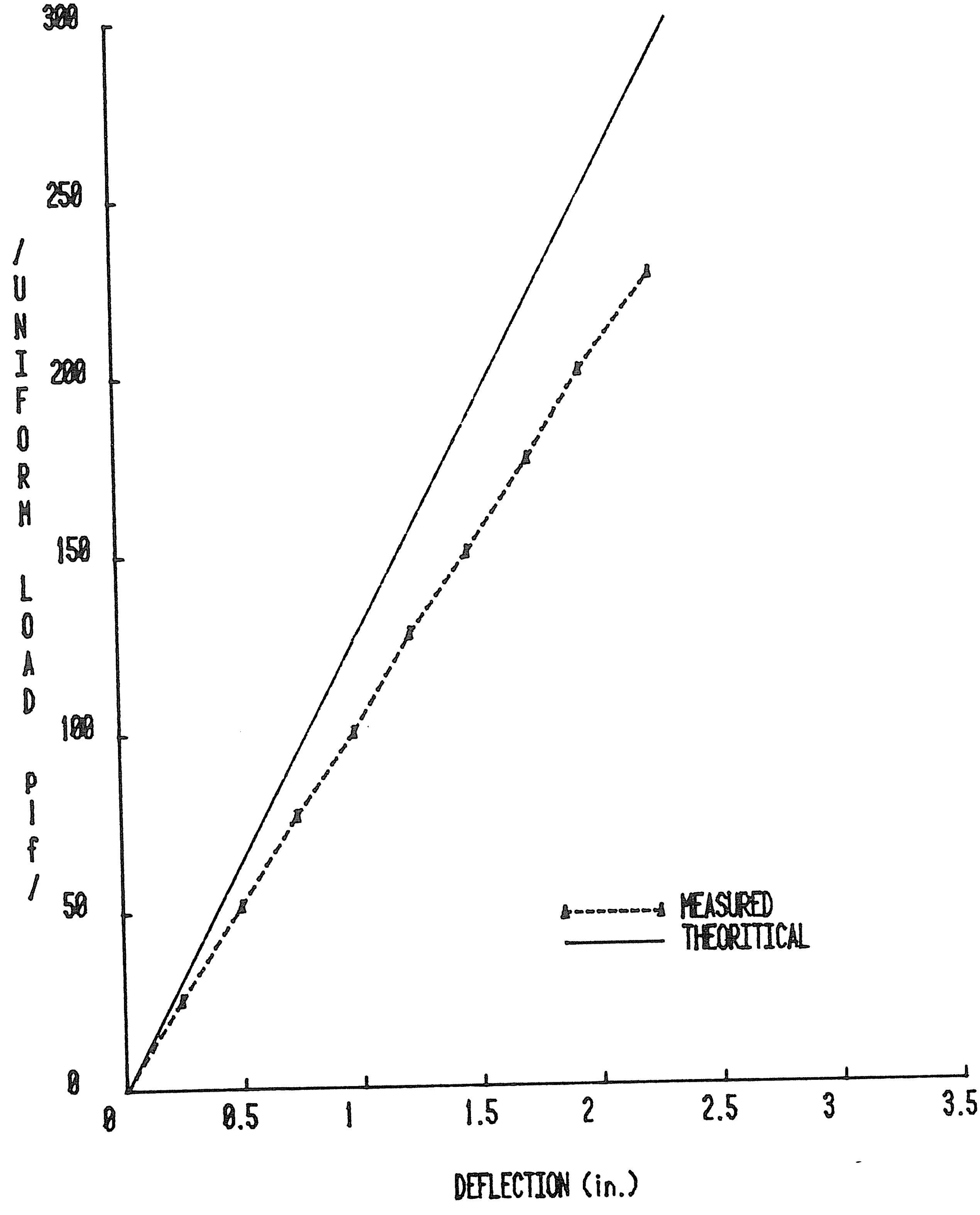


Figure D.20l Load vs. Vertical Deflection, Test 4-C

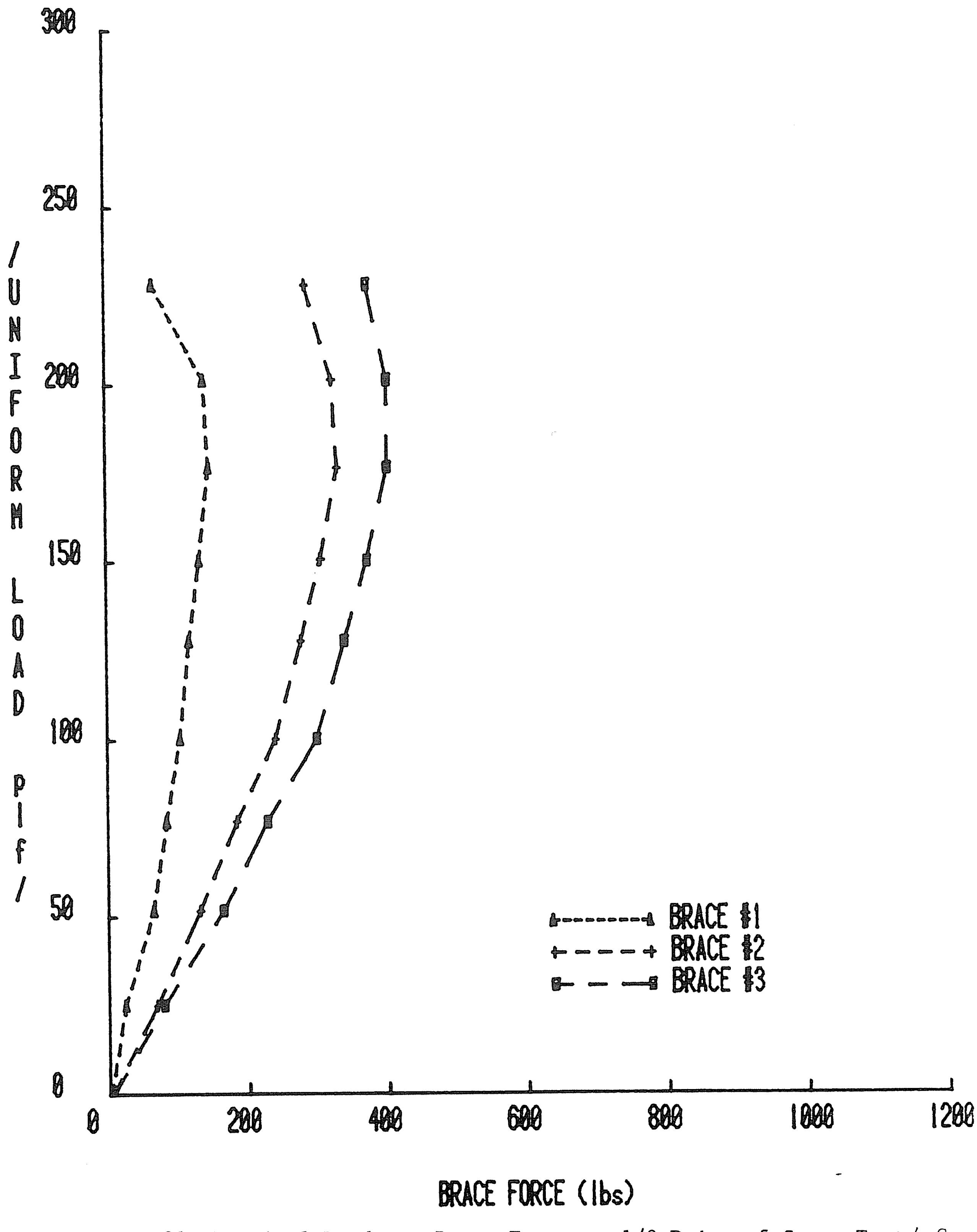


Figure D.21 Vertical Load vs. Brace Force at 1/3 Point of Span, Test 4-C

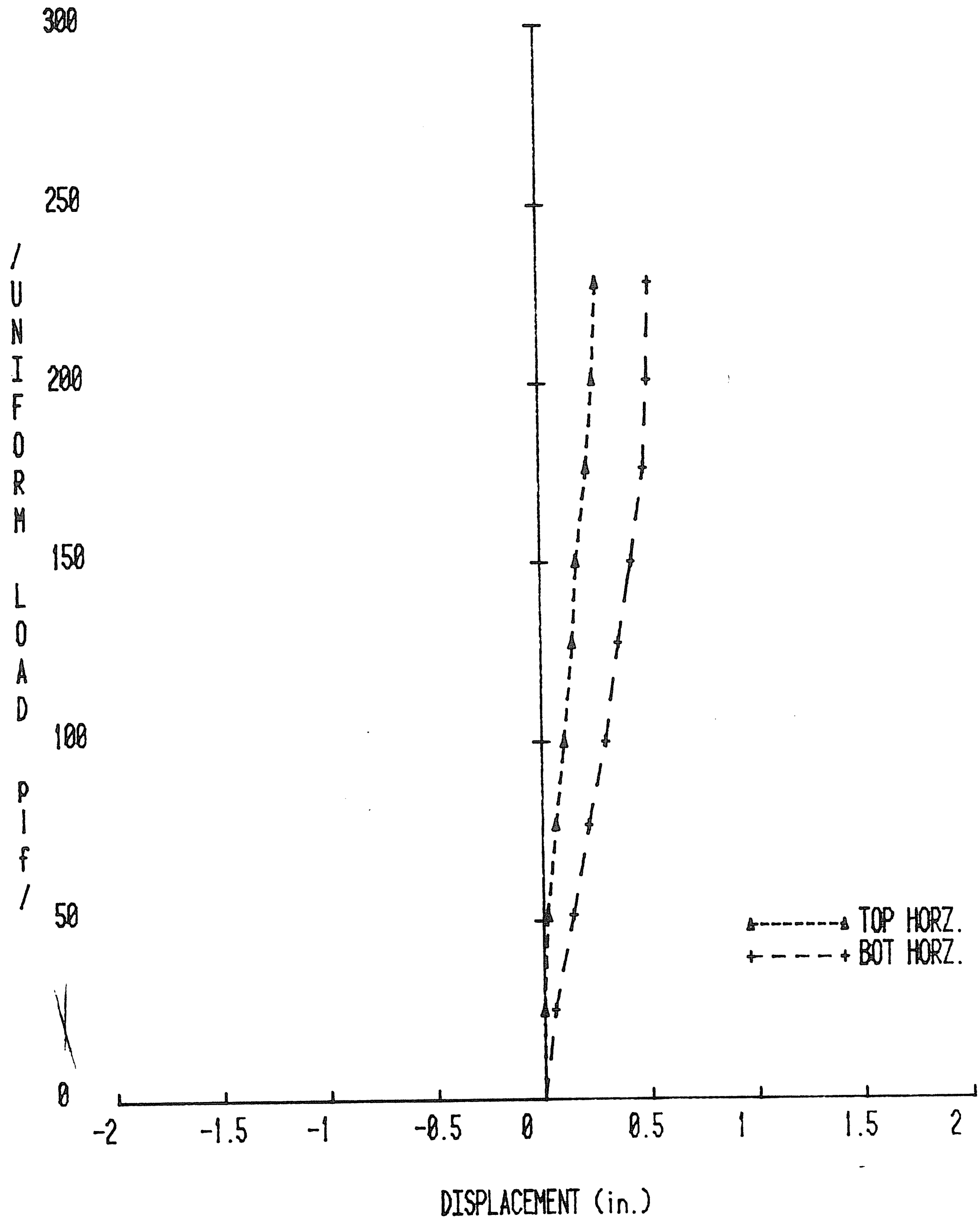


Figure D.22 Vertical Load vs. Lateral Displacements, Test 4-C

TEST SUMMARY

Project: Star Manufacturing Company

Test No.: 4D

Test Date: November 19, 1981

Purpose: Adequacy of single brace at midspan

Span(s): Single span 20'-0"

Thickness: 0.099 in. Moment of Inertia: 15.23 in^4

Star $I_x = 14.680\ in^4$

Parameters: Intermediate bracing at centerline

Clips installed

No insulation

Spacing 4'-10"

Failure Load: 248.8 plf

Failure Mode: Local buckling

Predicted Failure Loads:

Method Star u.c. x 1.674 Load 217. plf

Method AISI Constrained Bending Load 352.33 plf w/FS=1.67

Method Load

Discussion:

-Failure occurred due to local buckling of the compression flange at 248.8 plf.

-Vertical deflections were 15-20% greater than predicted by constrained bending.

-No strain measurements were made.

-From the plot of intermediate brace force vs. load it appears that the system deflected into the west chamber wall and was then restrained.

-Brace forces increased approximately linearily until contact was made with the chamber wall.

-At 26.3 psf (5 in. of water) the ratio of brace forces was 1:3.0:5.39 (in the direction of ridge to eave). At 10.9 psf (2 in. of water) the ratio was 1:1.5:3.36. The ratio of tributary areas was 1:3:5.

-Brace forces appear to accumulate in proportion to the tributary area at higher loads.

-At 26.3 psf, the brace forces as a percentage of stabilized vertical load were 5.7%, 4.7% and 5.5% in the direction of ridge to eave and at 10.9 psf 7.8%, 4.9% and 5.2%.

-Maximum horizontal displacement of the top flange of the test purlin was approximately 1 in.

-The top and bottom flanges of the test purlin moved in the same direction.

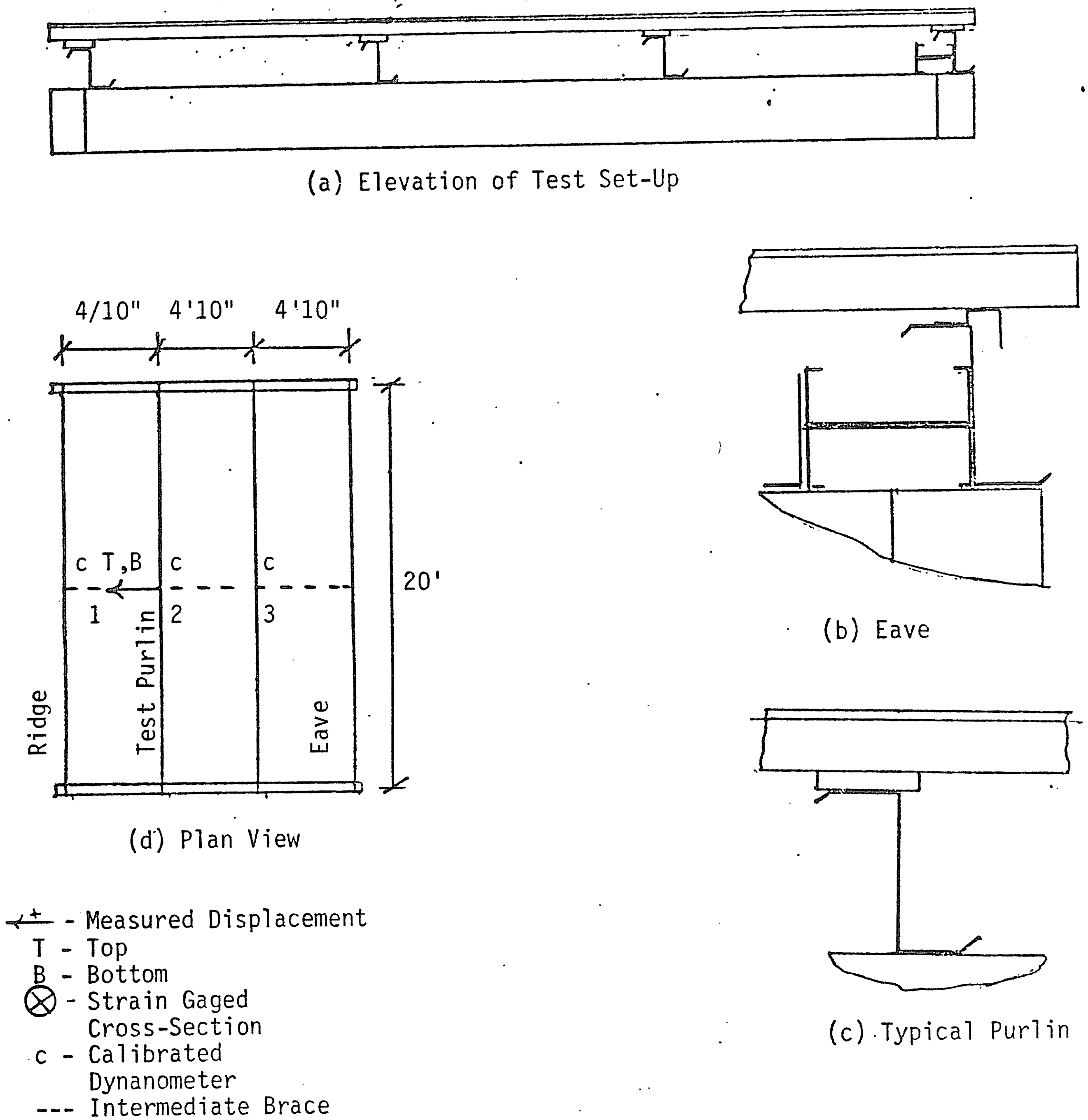


Figure D.23 Instrumentation Location, Test 4-D

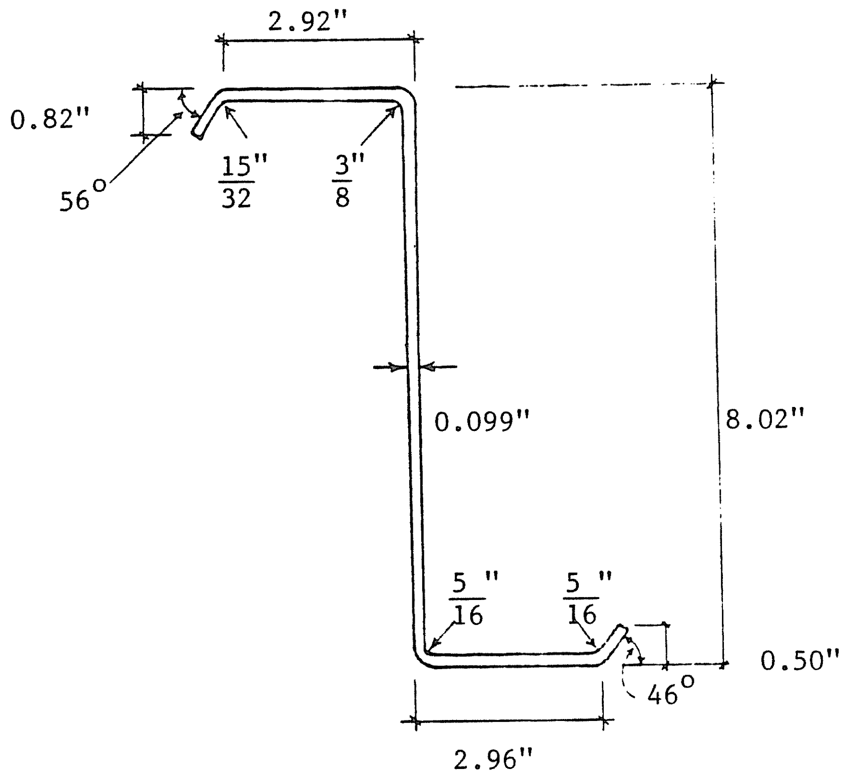


Figure D.24 Measured Purlin Dimensions, Test 4-D

```
------------------------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: STAR PURLIN TEST 4-D
------------------------------------------------------------------------
                         TOP             BOTTOM
FLANGE(in)             2.920             2.960
LIP(in)                0.820             0.500
LIP ANGLE(deg)        56.000            46.000
RADIUS L/F(in)         0.469             0.313
RADIUS F/W(in)         0.375             0.313

TOTAL DEPTH(in)              8.02
THICKNESS(in)                0.099
YIELD STRENGTH(ksi)          58.3
                                        SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)          TOP                BOTTOM
GROSS=          15.225                 3.925              3.767
STRENGTH=       15.225                 3.925              3.767
DEFLECTION=     15.225
BE=    2.446    in
FC=    34.980   ksi
FT=    34.980   ksi
FBW=   34.980   ksi
```

Figure D.25 AISI Cross-Section Analysis, Test 4-D

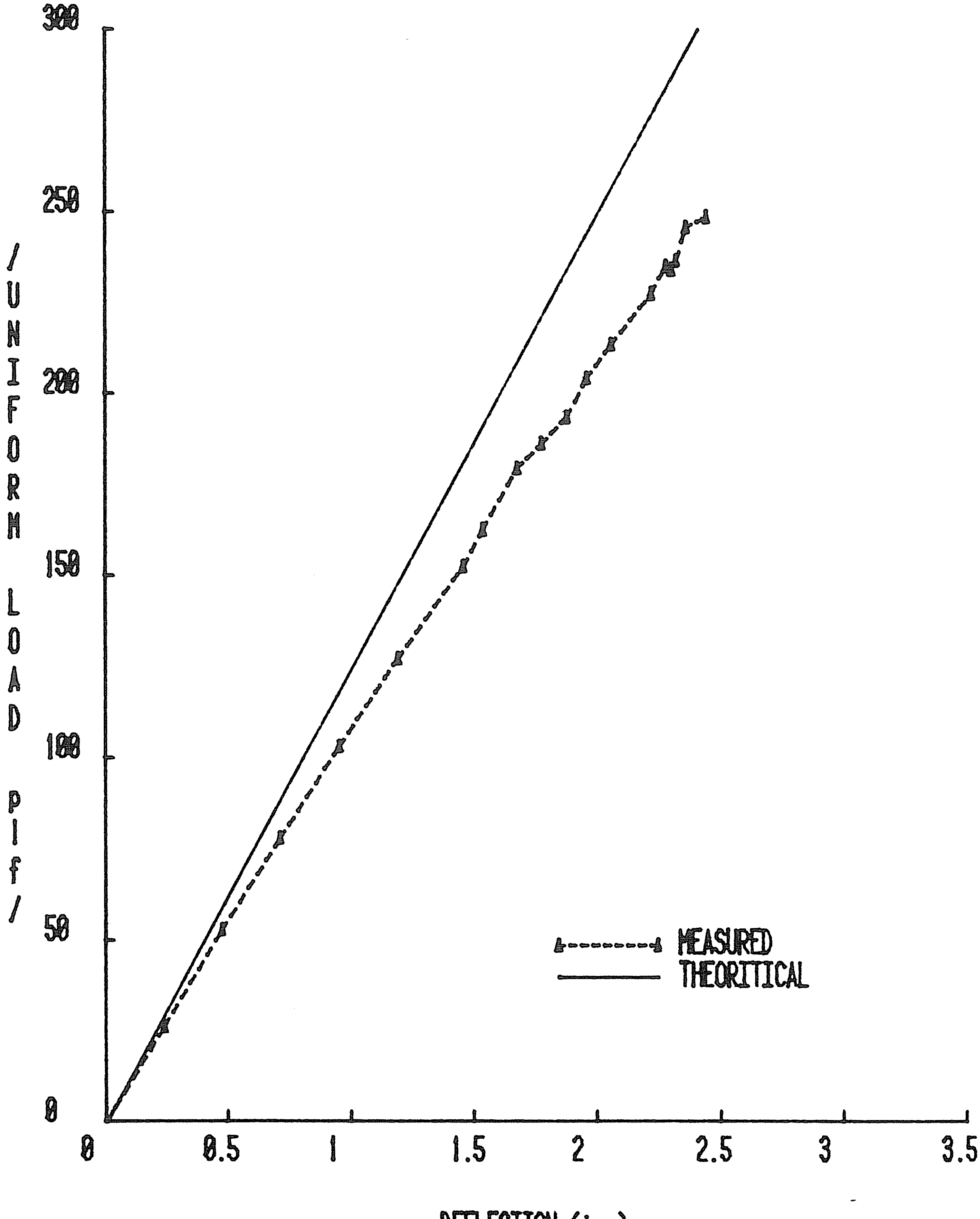


Figure D.26 Load vs. Vertical Deflection, Test 4-D

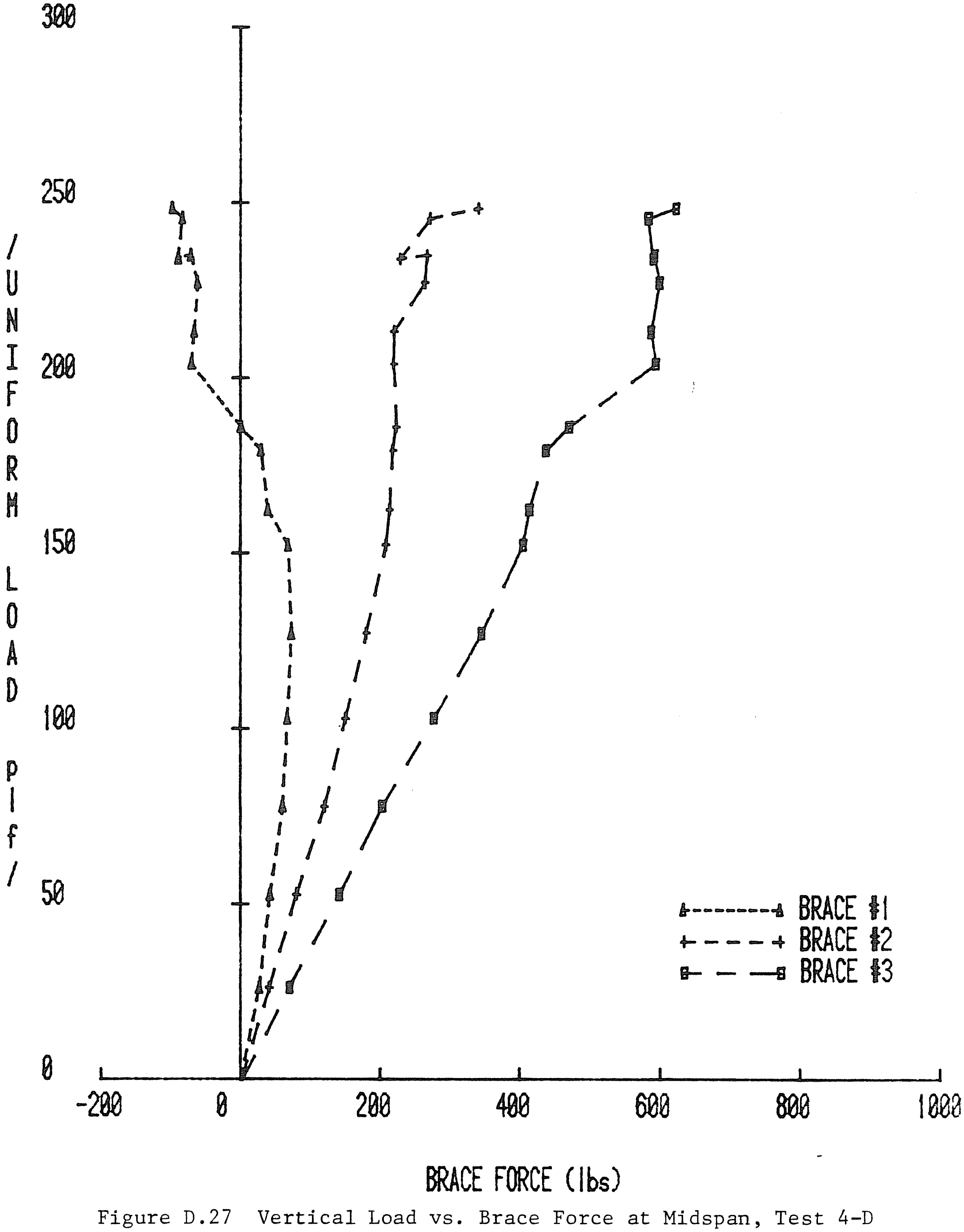


Figure D.27 Vertical Load vs. Brace Force at Midspan, Test 4-D

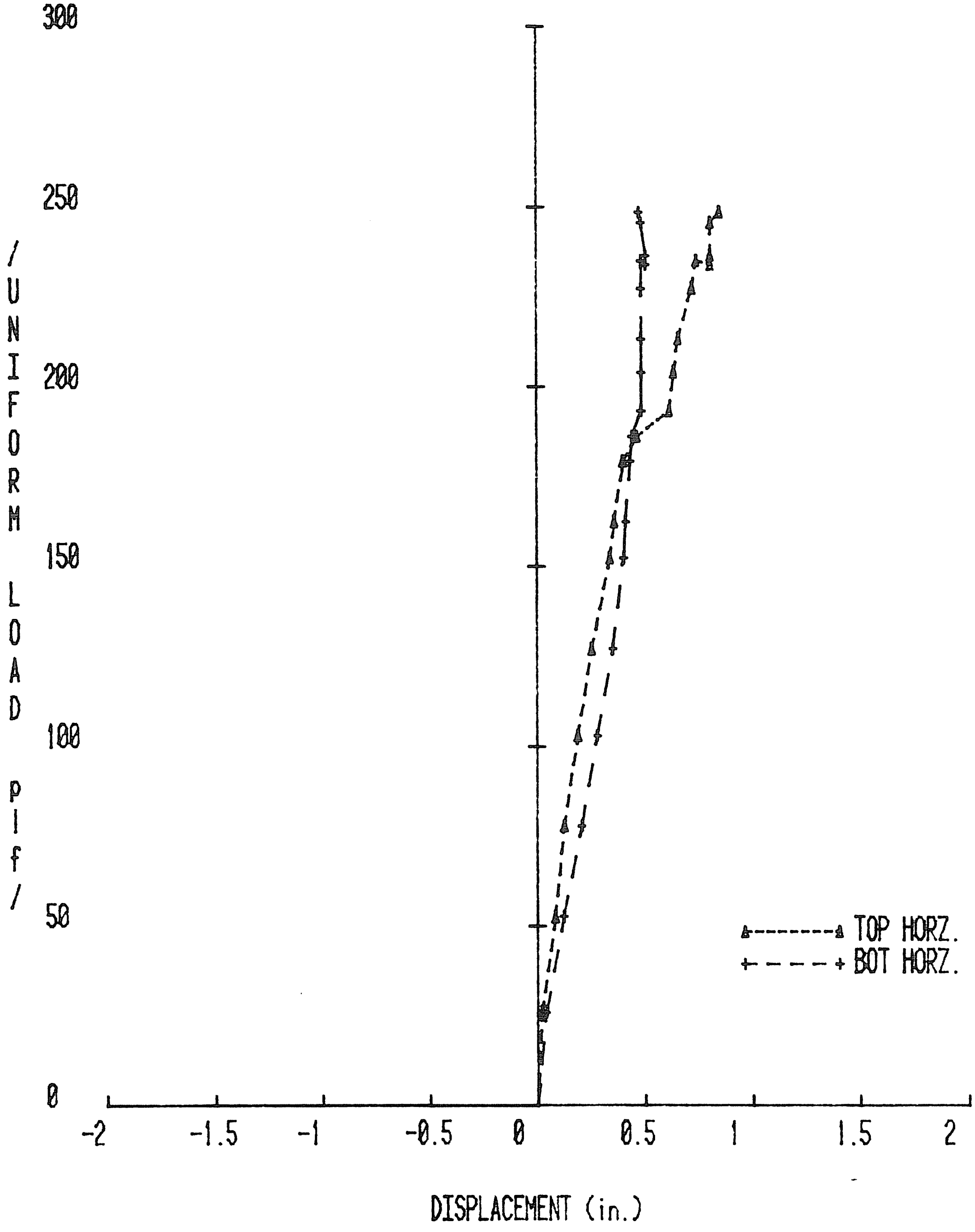


Figure D.28 Vertical Load vs. Lateral Displacements, Test 4-D

TEST SUMMARY

Project: Star Manufacturing Company

Test No.: 4E

Test Date: November 25, 1981

Purpose: Adequacy of clips as lateral braces

Span(s): Single span 20'-0"

Thickness: 0.099 in. Moment of Inertia: 15.08 in^4

Parameters: No intermediate braces

Clips installed

No insulation

Spacing 4'-10"

Failure Load: 246.3 plf

Failure Mode: Lateral buckling

Predicted Failure Loads:

Method ______ Load ______

Method AISI Constrained Bending Load 348.8 plf w/F.S. = 1.67

Method ______ Load ______

Discussion:

-Failure occurred due to lateral buckling of the top flange at 246.3 plf.

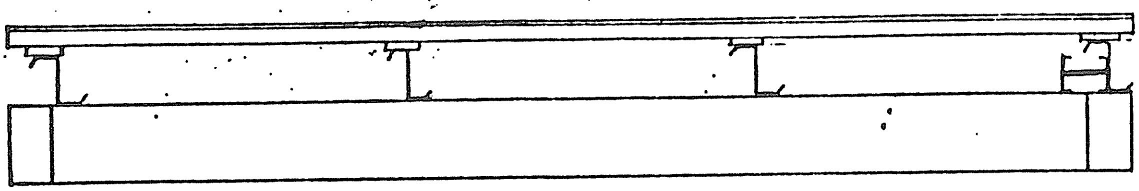
-Vertical displacements of the test purlin were 10-15% greater than predicted by constrained bending until near failure when the displacement increased at a rapid rate.

-No strain measurements were made.

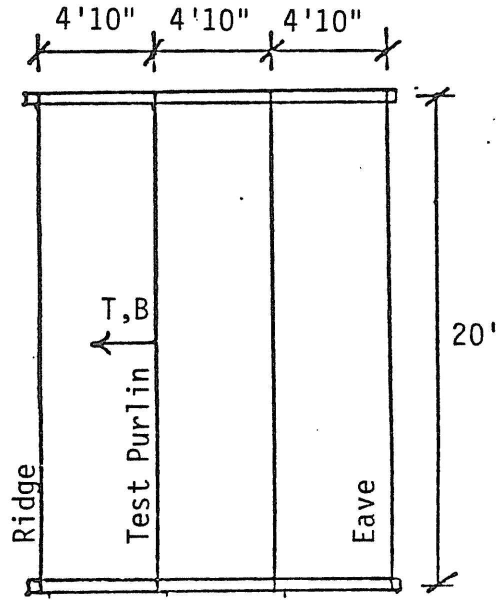
-Horizontal displacement of the top flange increased in "jumps" at 35.4 and 41.6 psf indicating slip due to breaking of friction at the clips.

-Maximum centerline lateral deflection of the test purlin top flange exceeded 1 in.

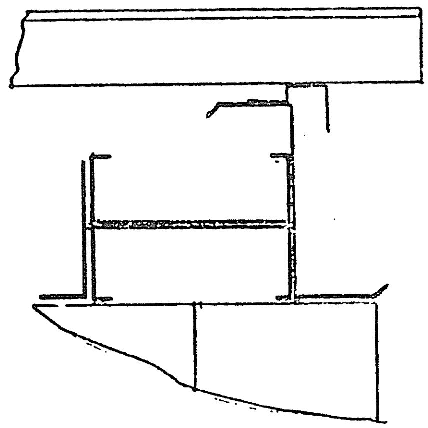
-Lateral deflections of the top and bottom flanges were in the same direction with the top flange showing more deflection than the bottom.



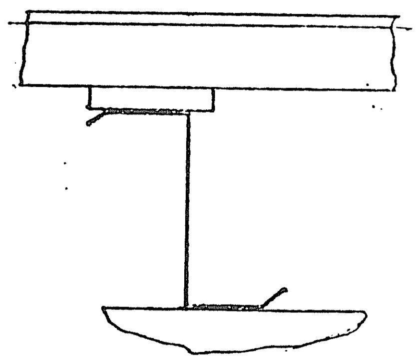
(a) Elevation of Test Set-Up



(d) Plan View



(b) Eave



(c) Typical Purlin

- Measured Displacement
T - Top
B - Bottom
⊗ - Strain Gaged Cross-Section
c - Calibrated Dynanometer
--- Intermediate Brace

Figure D.29 Instrumentation Location, Test 4-E

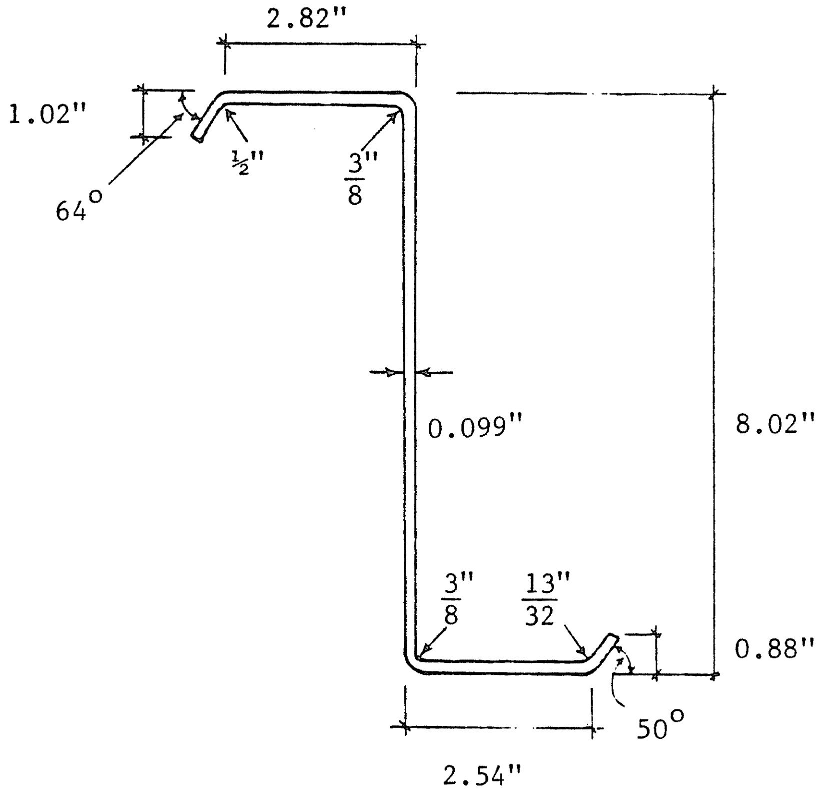


Figure D.30 Measured Purlin Dimensions, Test 4-E

```
AISI PURLIN ANALYSIS
IDENTIFICATION: STAR PURLIN TEST 4-E

                      TOP          BOTTOM
FLANGE(in)           2.820          2.540
LIP(in)              1.020          0.880
LIP ANGLE(deg)      64.000         50.000
RADIUS L/F(in)       0.500          0.406
RADIUS F/W(in)       0.375          0.375

TOTAL DEPTH(in)              8.02
THICKNESS(in)                0.099
YIELD STRENGTH(ksi)          57.9
                                         SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)         TOP              BOTTOM
GROSS=           15.082               3.890            3.730
STRENGTH=        15.082               3.890            3.730
DEFLECTION=      15.082
BE=     2.346   in
FC=     34.740   ksi
FT=     34.740   ksi
FBW=    34.740   ksi
```

Figure D.31 AISI Cross-Section Analysis, Test 4-E

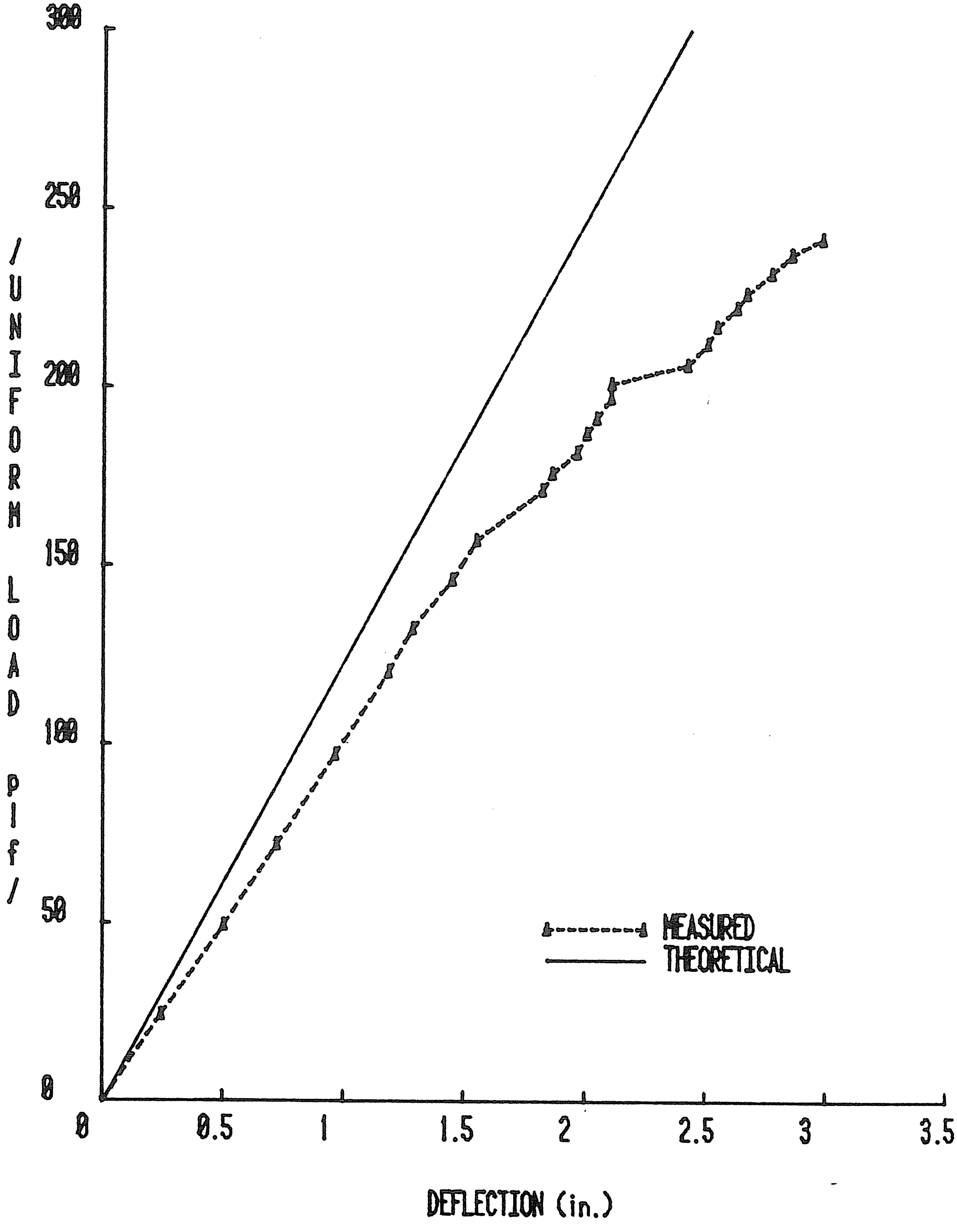


Figure D.32 Load vs. Vertical Deflection, Test 4-E

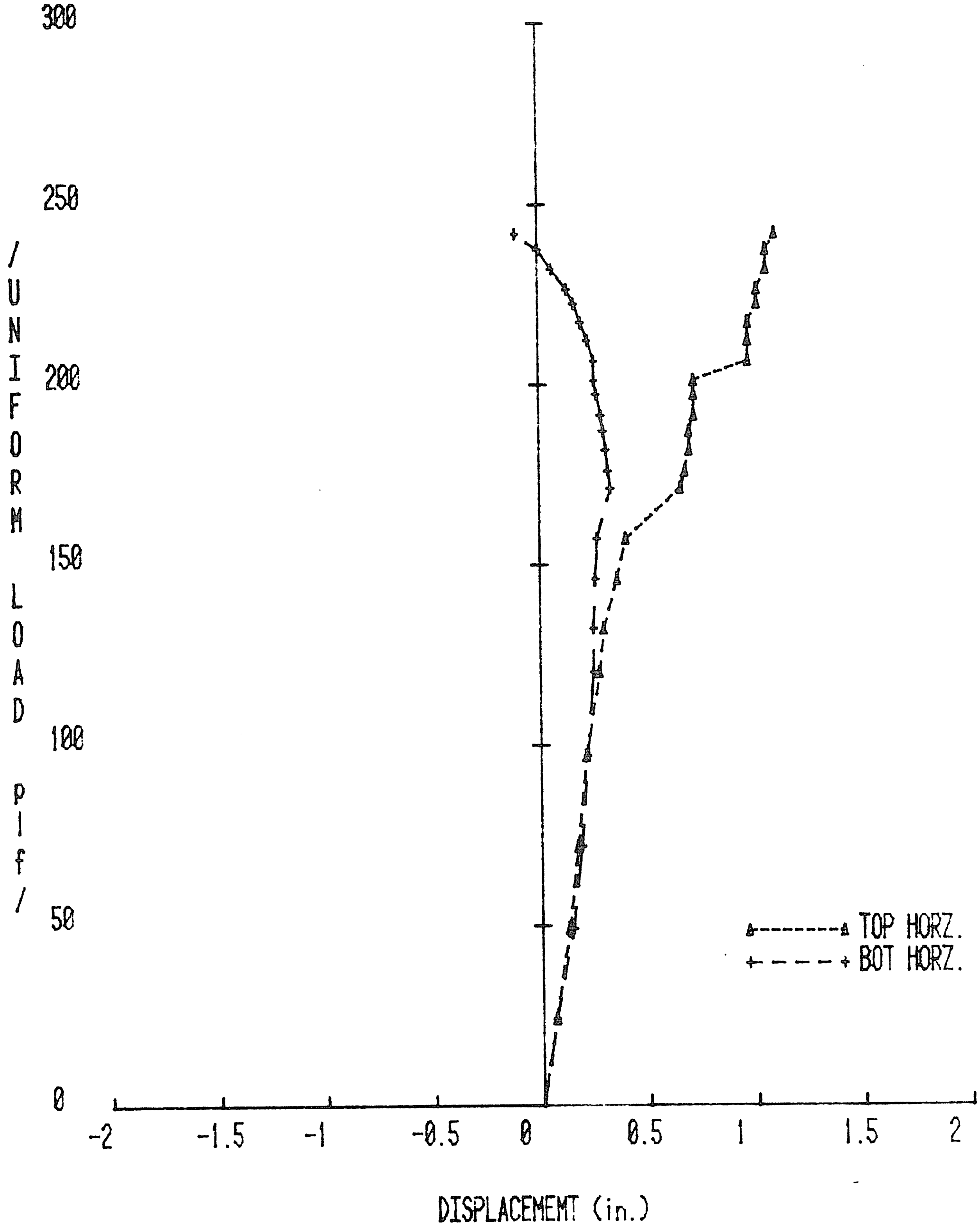


Figure D.33 Vertical Load vs. Lateral Displacements, Test 4-E

APPENDIX E

TEST SERIES V RESULTS

TEST SUMMARY

Project: Star Purlin Study

Test No.: 5-A

Test Date: April 22, 1982

Purpose: Star Standard Brace System

Span(s): 3 @ 20' = 60'

Thickness: .066 & .055 Moment of Inertia: $I_x = 9.947\ in^4$ & $I_x = 8.310\ in^4$

Parameters: Standard Braces @ 1/3 pts.

Clips are in place

No Insulation

Spacing 4'9"

Failure Load: 251.3 plf

Failure Mode: Compression flange buckling @ north span

Predicted Failure Loads:

Method Star Load 273 plf

Method AISI Constrain Load 310.6 plf

Method Load

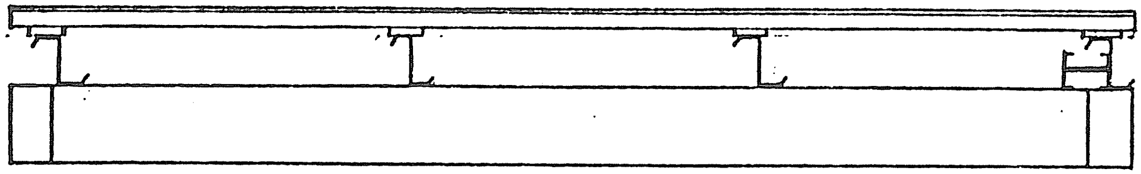
Discussion:

- Failure occurred by compression buckling just outside the lap at the north interior support.
- Web crippling was also observed at the south exterior support.
- The load-deflection curve showed very good agreement with that predicted by stiffness analysis and assuming constrained bending.
- The failure was clearly marked by an increase in the deflection with no increase in load.
- The Star Manufacturing Company design program predicted a failure load of 273 plf. The AISI constrained bending failure load predicted was 310.6 plf.
- The plot of the experimental stress distribution on the cross-section did not compare well with constrained bending assumptions. At failure load the stress plot indicated buckling of the compression flange and lip.
- At 20.7 psf (working load) the ratio of brace forces was: 1:2.08:3.59 for the exterior row of the exterior bay; 1:1.24:1.96 for the interior row of the exterior bay; 1:2.77:4.22 for the north row of the interior bay; and 1:2.53:4.07 for the south row of the interior bay. The ratio of tributary areas was 1:3:5.
- At 52.8 psf (failure load) the ratio of brace forces was: 1:2.70:5.94 for the exterior row of the exterior bay; 1:1.67:2.57 for the interior row of the exterior bay; 1:3.15:5.32 for the north row of the interior bay; and 1:2.77:5.07 for the south row of the interior bay. The ratio of tributary areas was 1:3:5.

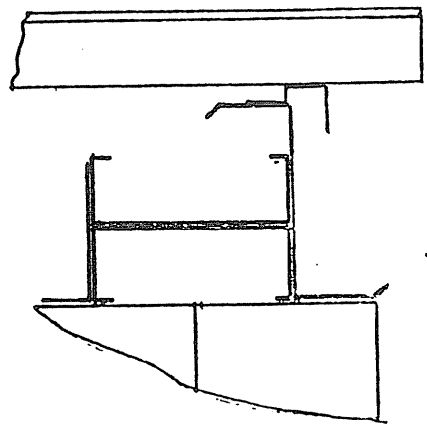
-At 20.7 psf (working load) the brace forces as a percentage of stabilized vertical load were 26%, 14% and 14% for the exterior bay and 15%, 13% and 12% for the interior bay from the ridge to eave.

-At 52.8 psf (failure load) the brace forces as a percentage of stabilized vertical load were 18%, 13% and 16% for the exterior bay and 14%, 14% and 15% for the interior bay from the ridge to eave.

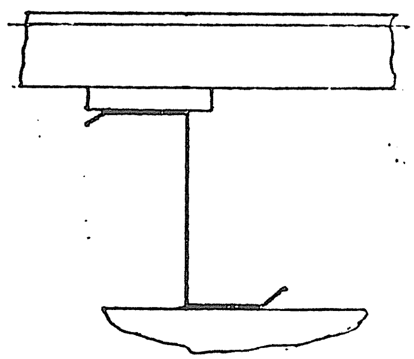
-The top and bottom flanges moved laterally in the same direction. The lateral displacements for the top and bottom flanges were approximately the same up to failure at which point the top flange moved more than the bottom flange.



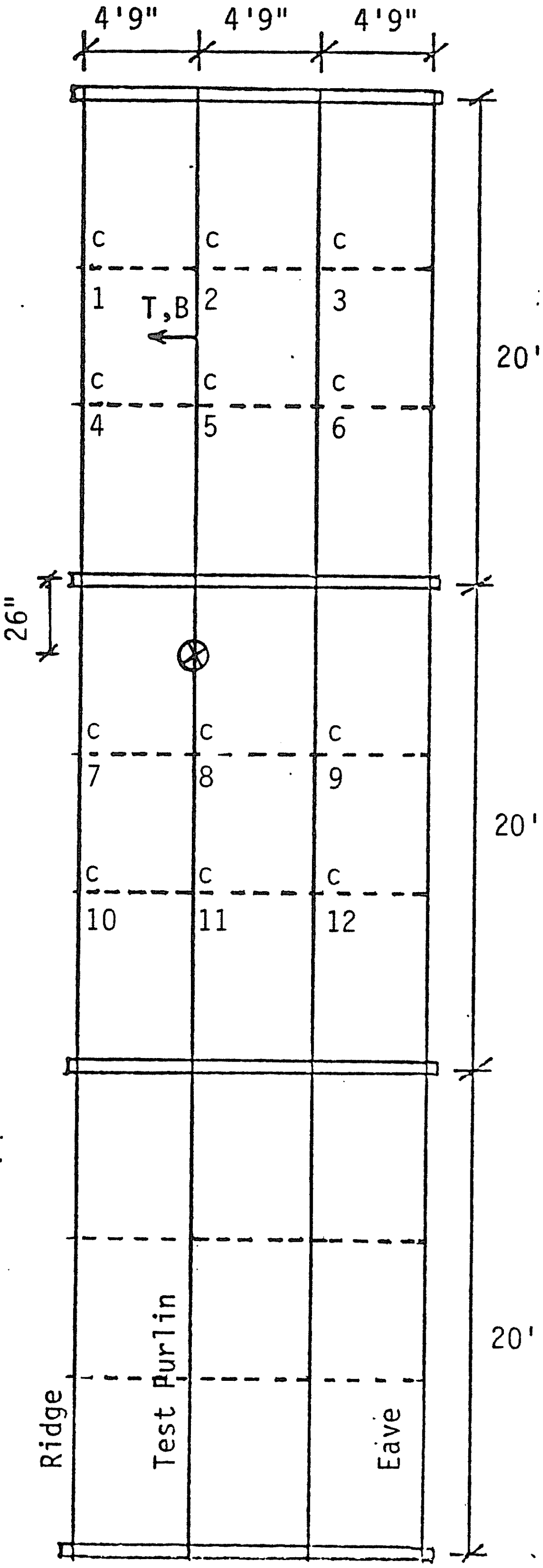
(a) Elevation of Test Set-Up



(b) Eave



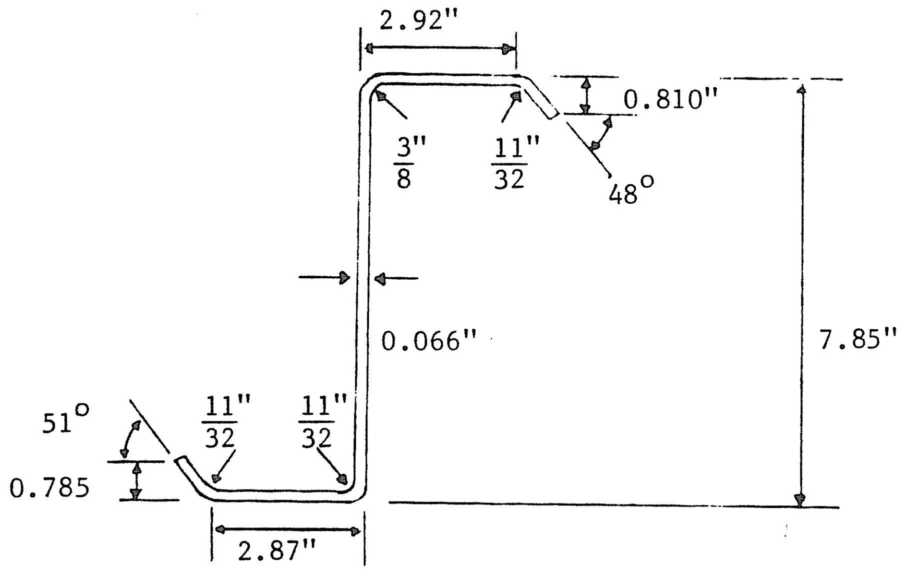
(c) Typical Purlin



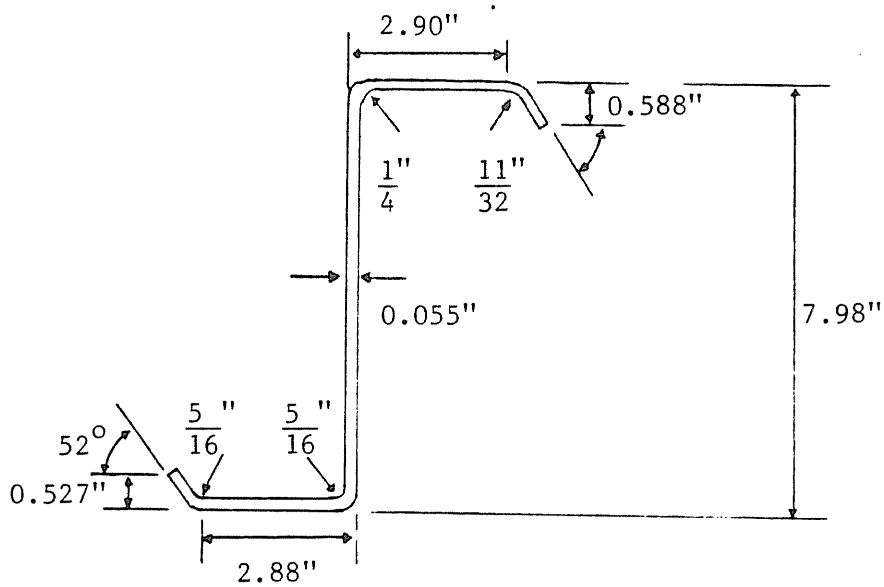
(d) Plan View

← - Measured Displacement
T - Top
B - Bottom
⊗ - Strain Gaged Cross-Section
c - Calibrated Dynanometer
--- Intermediate Brace

Figure E.1 Instrumentation Location, Test 5-A



North Span



Center Span

Figure E.2 Measured Purlin Dimensions, Test 5-A

A I S I P U R L I N A N A L Y S I S
IDENTIFICATION: STAR PURLIN TEST 5-A NORTH

	TOP	BOTTOM
FLANGE(in)	2.920	2.870
LIP(in)	0.800	0.785
LIP ANGLE(deg)	48.000	51.000
RADIUS L/F(in)	0.344	0.344
RADIUS F/W(in)	0.375	0.344

TOTAL DEPTH(in)	7.85
THICKNESS(in)	0.066
YIELD STRENGTH(ksi)	61

	MOMENTS OF INERTIA(in^4)	SECTION MODULII(in^3) TOP	BOTTOM
GROSS=	9.938	2.573	2.535
STRENGTH=	9.694	2.470	2.512
DEFLECTION=	9.938		

BE= 2.235 in
FC= 29.751 ksi
FT= 36.600 ksi
FBW= 32.921 ksi

Figure E.3 AISI Cross-Section Analysis, Test 5-A

A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: STAR PURLIN TEST 5-A CENTER

	TOP	BOTTOM
FLANGE(in)	2.900	2.880
LIP(in)	0.588	0.527
LIP ANGLE(deg)	48.000	52.000
RADIUS L/F(in)	0.344	0.313
RADIUS F/W(in)	0.250	0.313

TOTAL DEPTH(in)	7.98
THICKNESS(in)	0.055
YIELD STRENGTH(ksi)	63.9

MOMENTS OF INERTIA(in^4)		SECTION MODULII(in^3) TOP	BOTTOM
GROSS=	8.310	2.112	2.083
STRENGTH=	7.697	1.867	2.025
DEFLECTION=	8.035		

BE= 1.907 in
FC= 33.967 ksi
FT= 38.340 ksi
FBW= 31.481 ksi

Figure E.4 AISI Cross-Section Analysis, Test 5-A

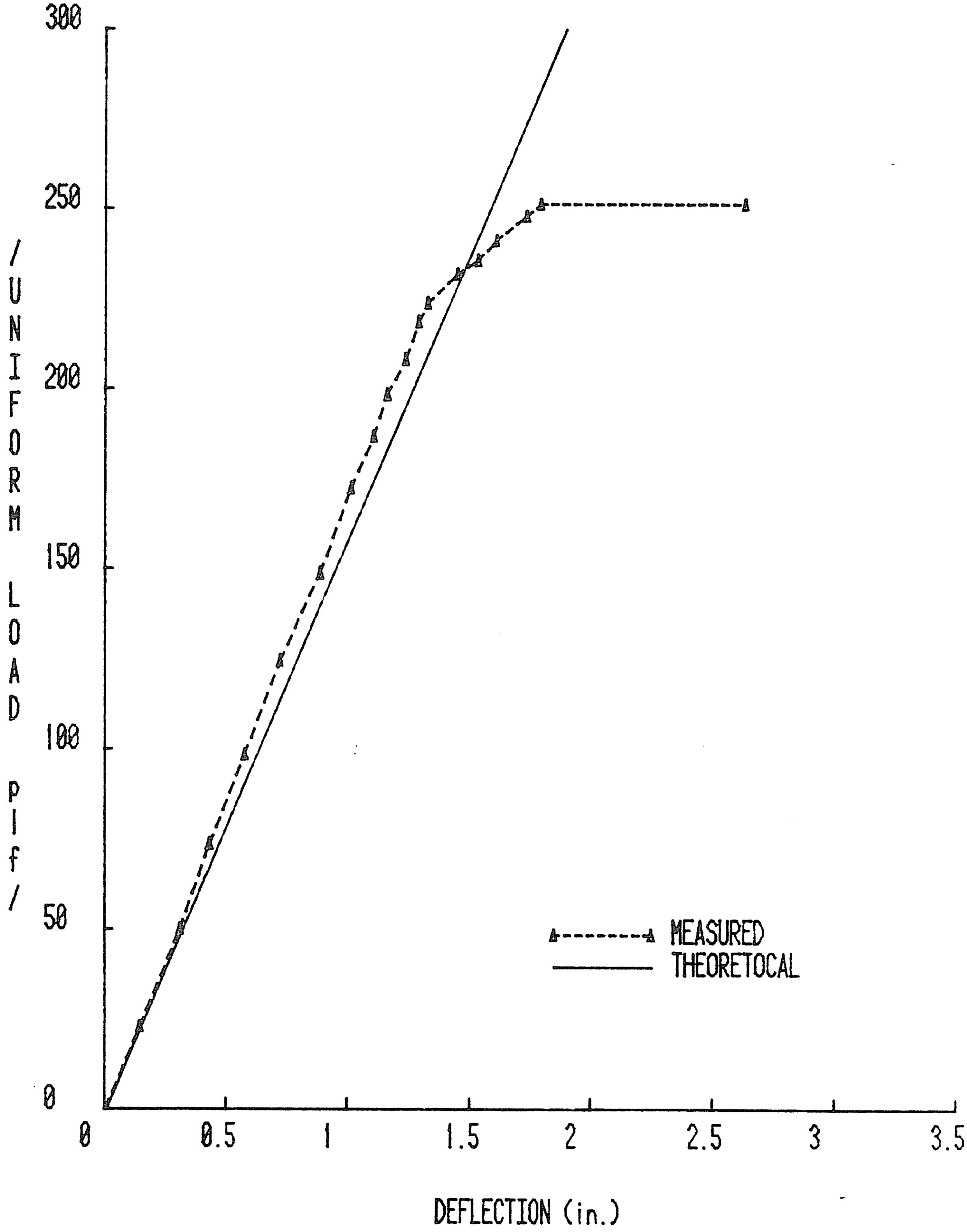


Figure E.5 Load vs. Vertical Deflection, Test 5-A

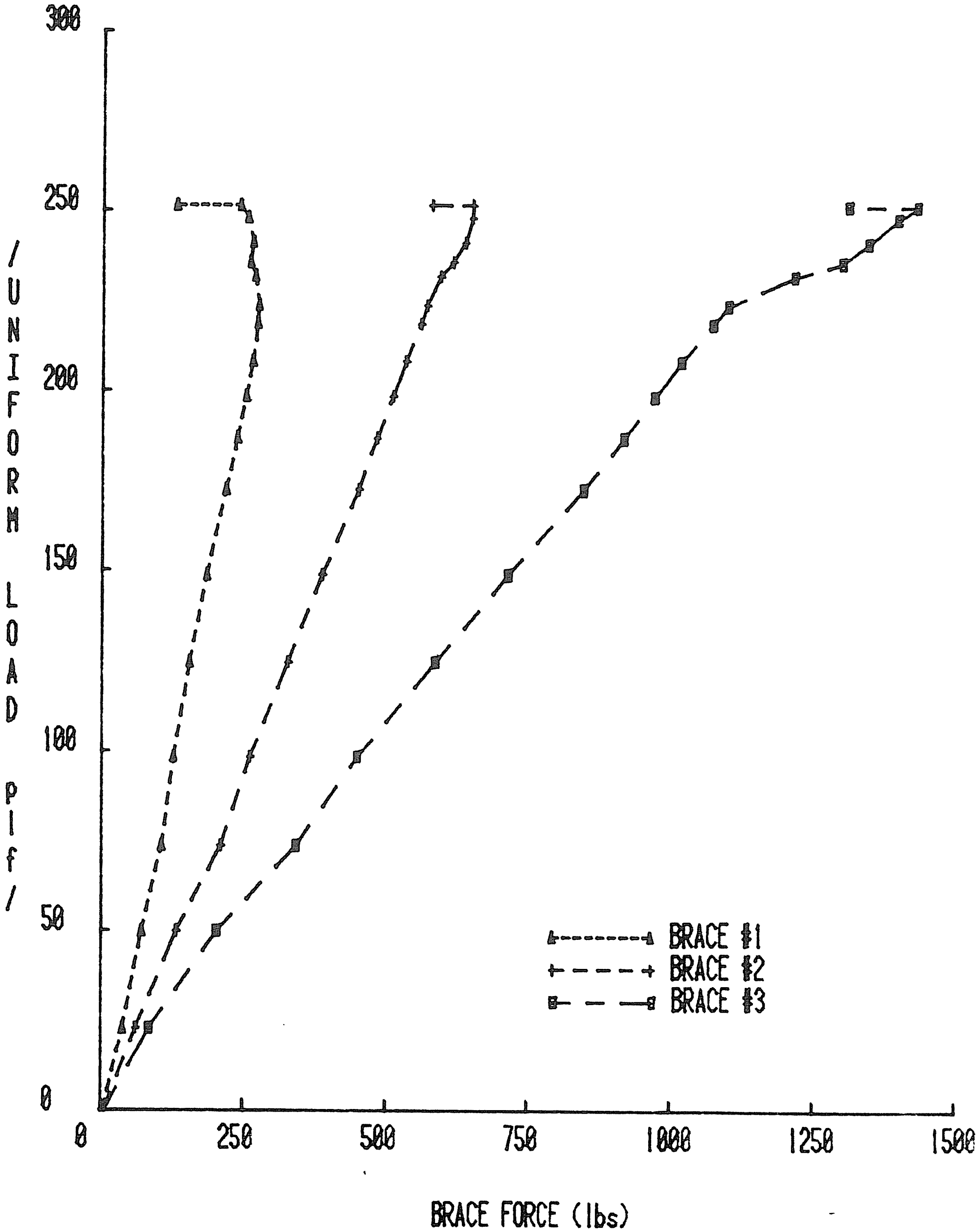


Figure E.6 Vertical Load vs. Brace Force at Exterior 1/3rd Point of North Span, Test 5-A

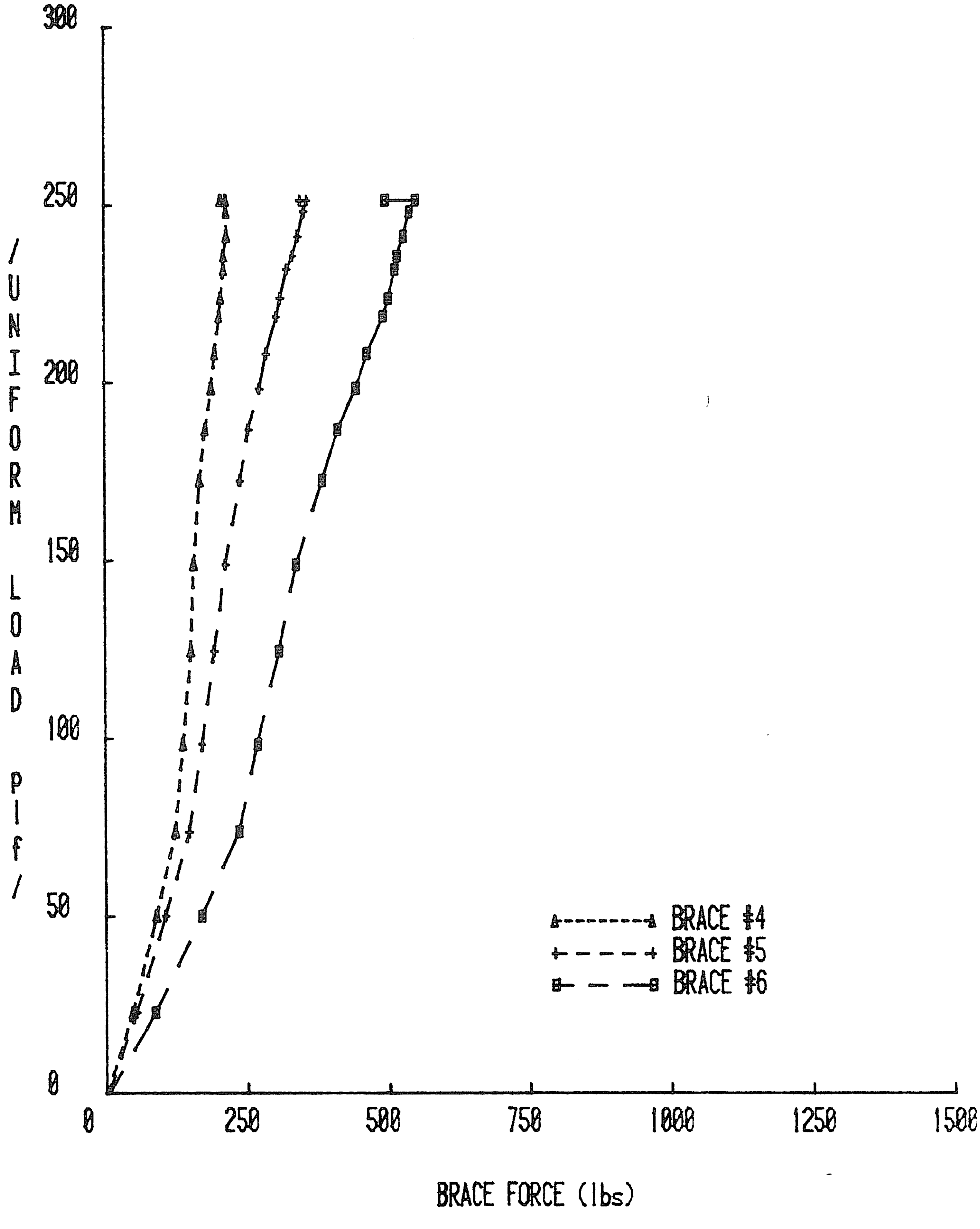


Figure E.7 Vertical Load vs. Brace Force at Interior 1/3rd Point of North Span, Test 5-A

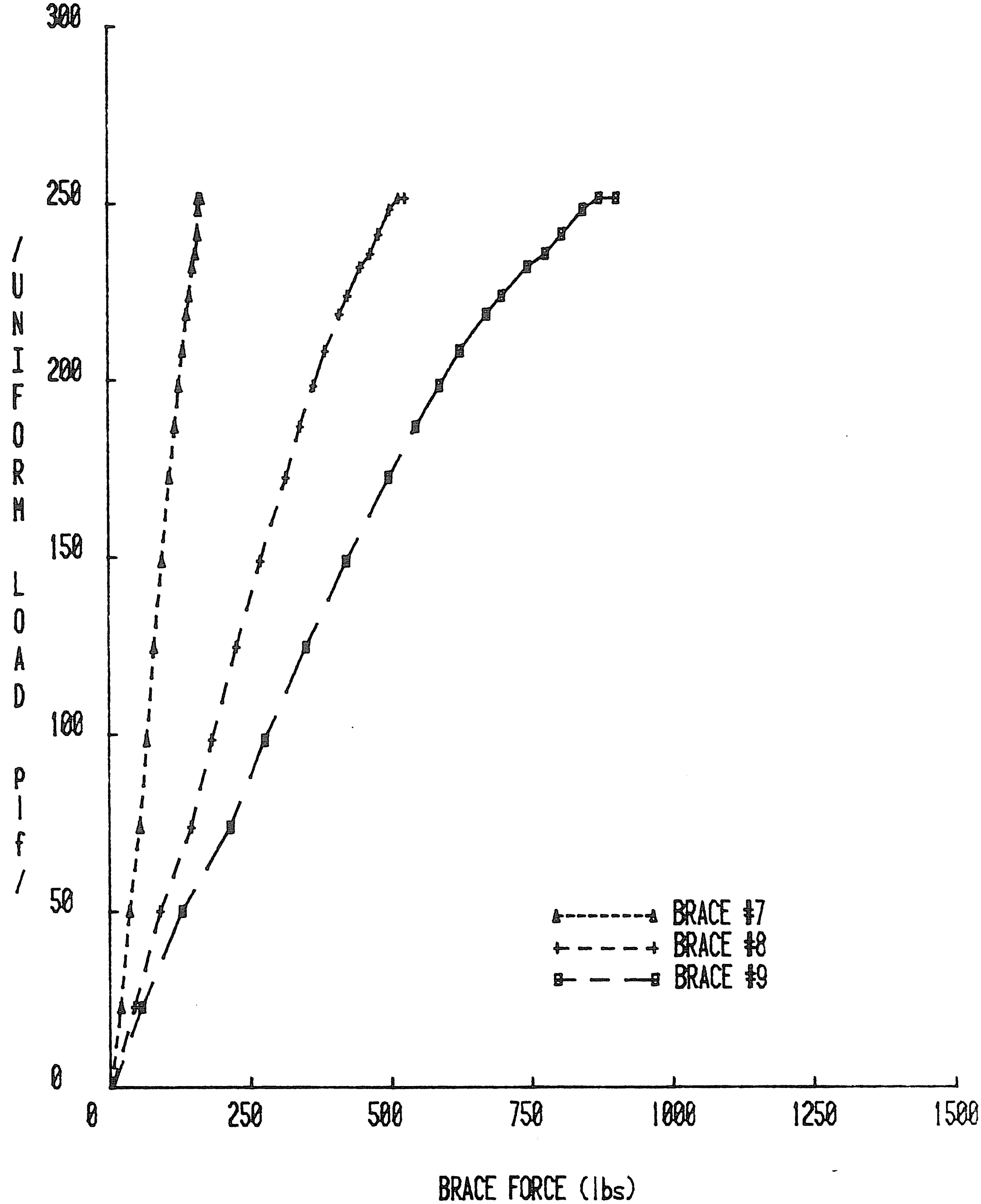


Figure E.3 Vertical Load vs. Brace Force at North 1/3rd Point of Center Span, Test 5-A

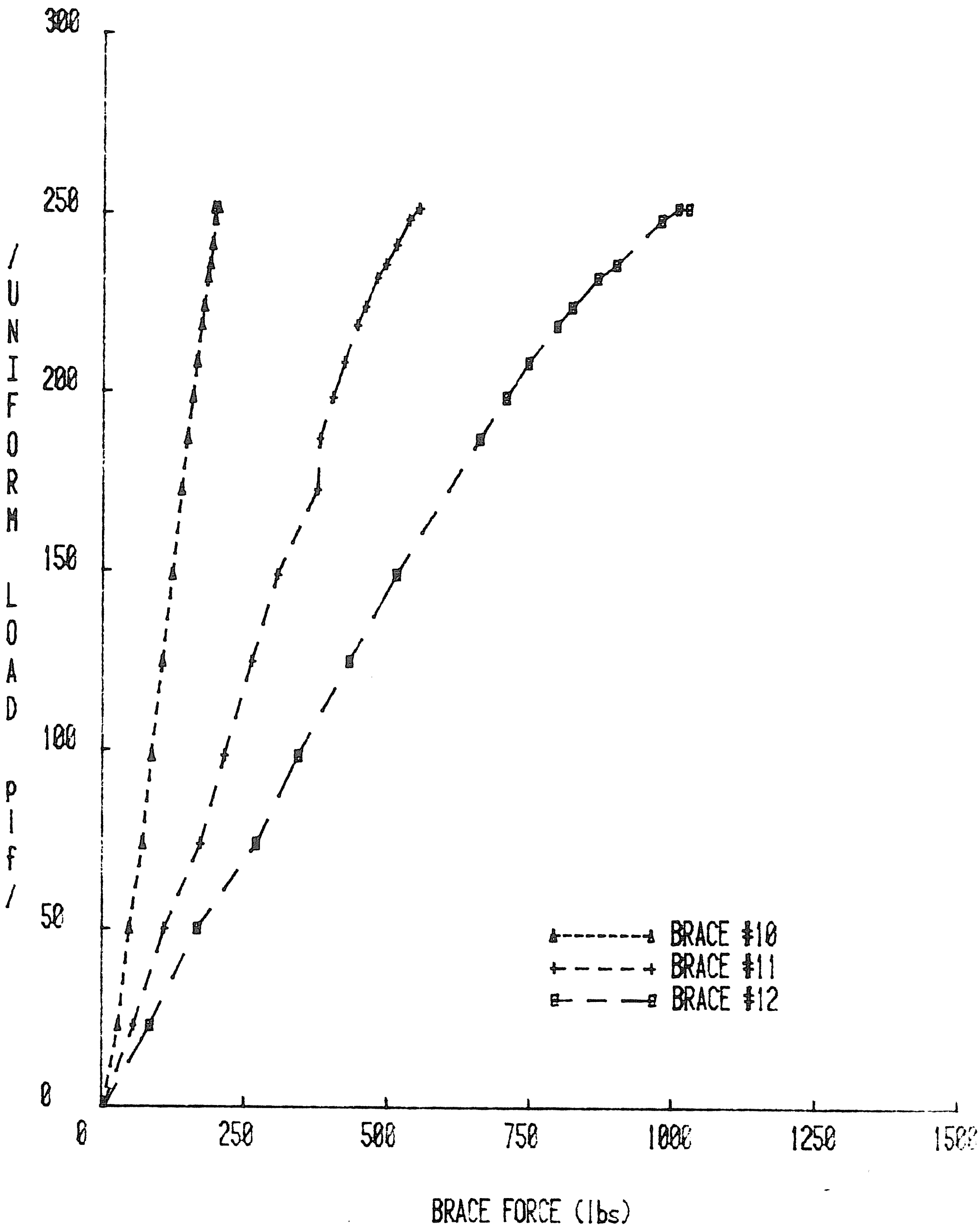


Figure E.9 Vertical Load vs. Brace Force at South 1/3rd Point of Center Span, Test 5-A

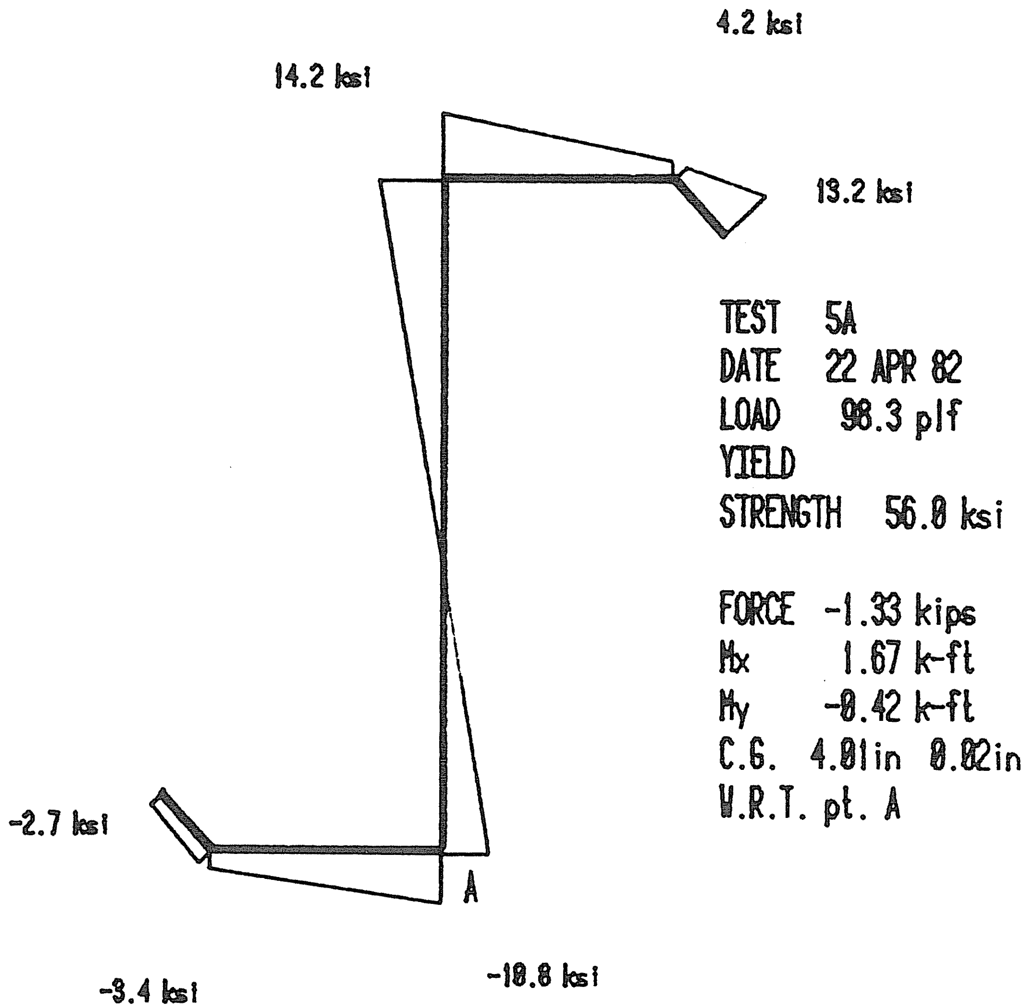


Figure E.10 Stress Distribution at 98.3 plf, Test 5-A

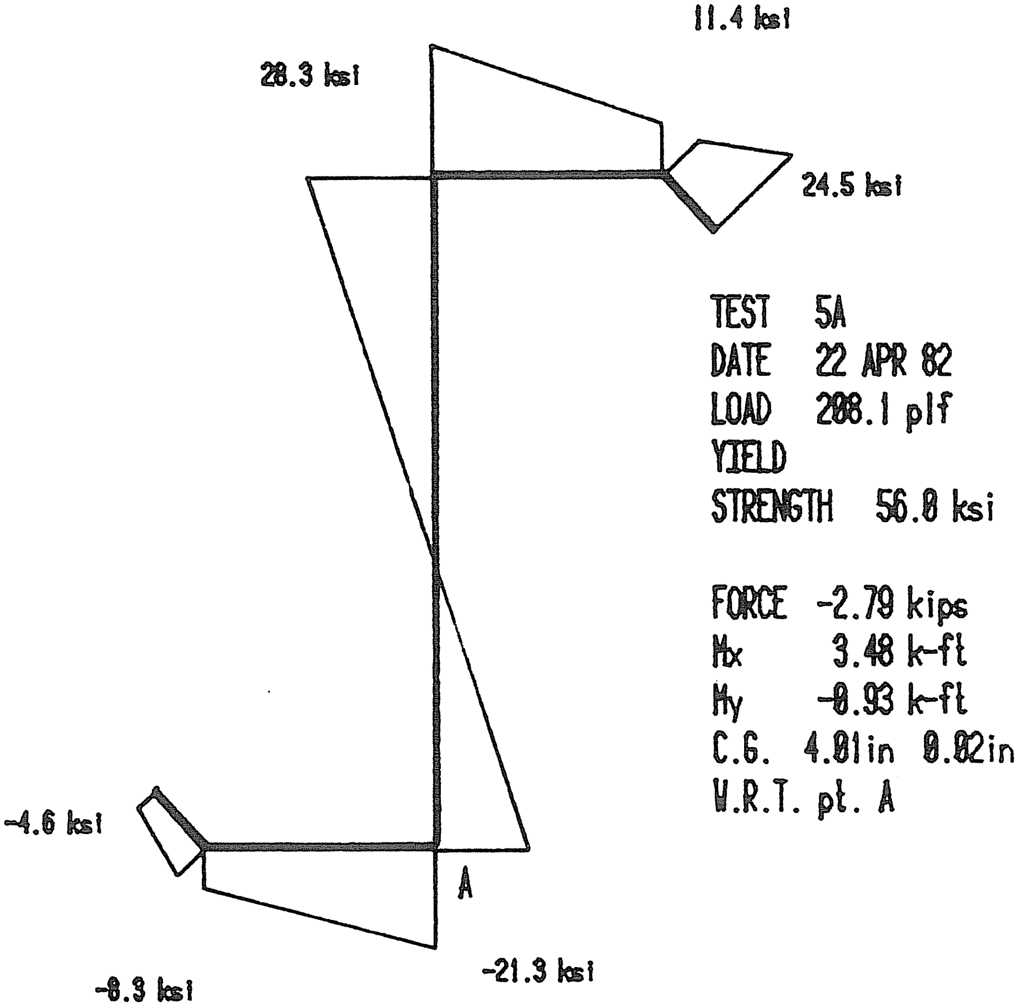


Figure E.11 Stress Distribution at 208.1 plf, Test 5-A

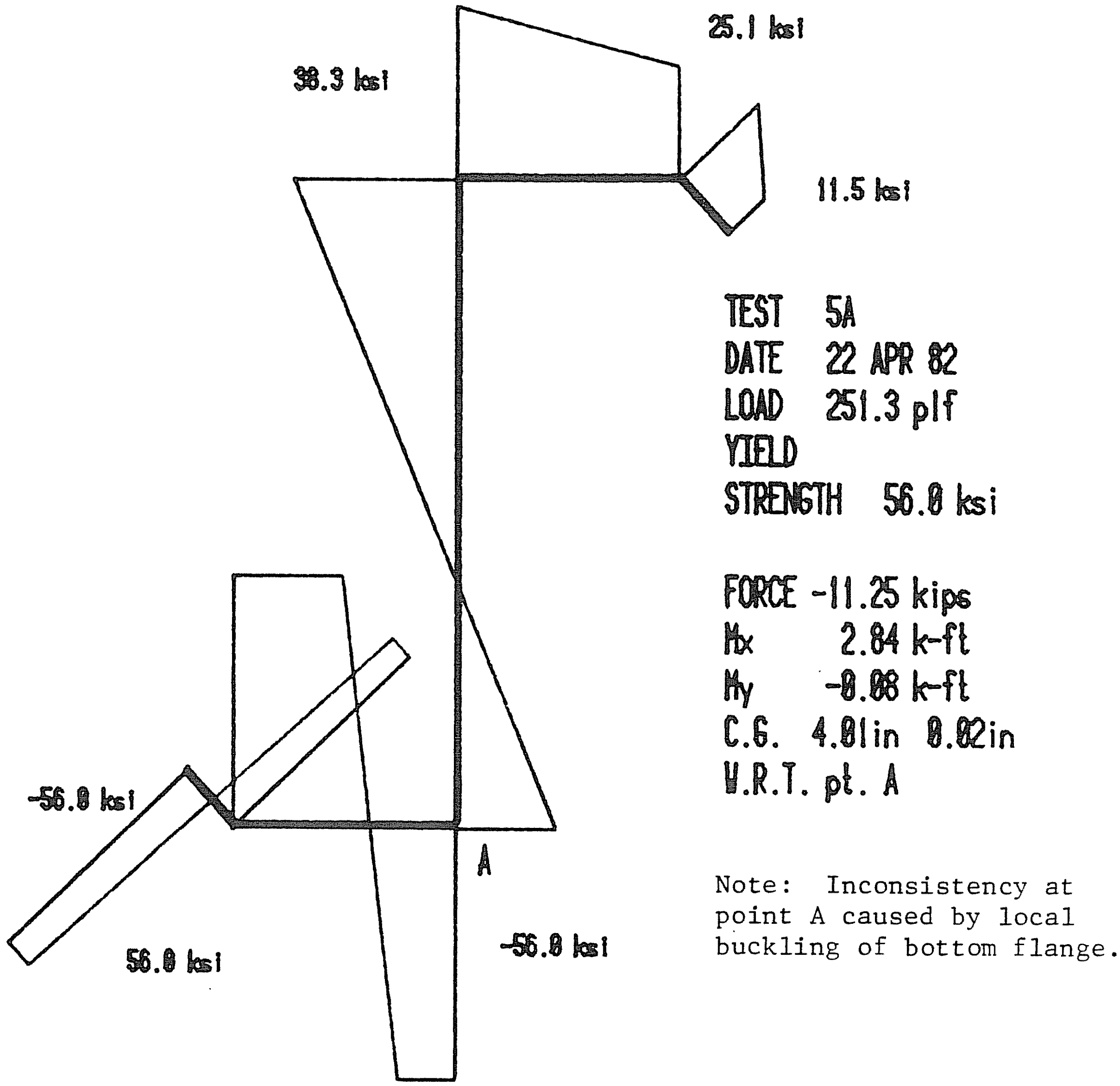


Figure E.12 Stress Distribution at 98.3 plf, Test 5-A

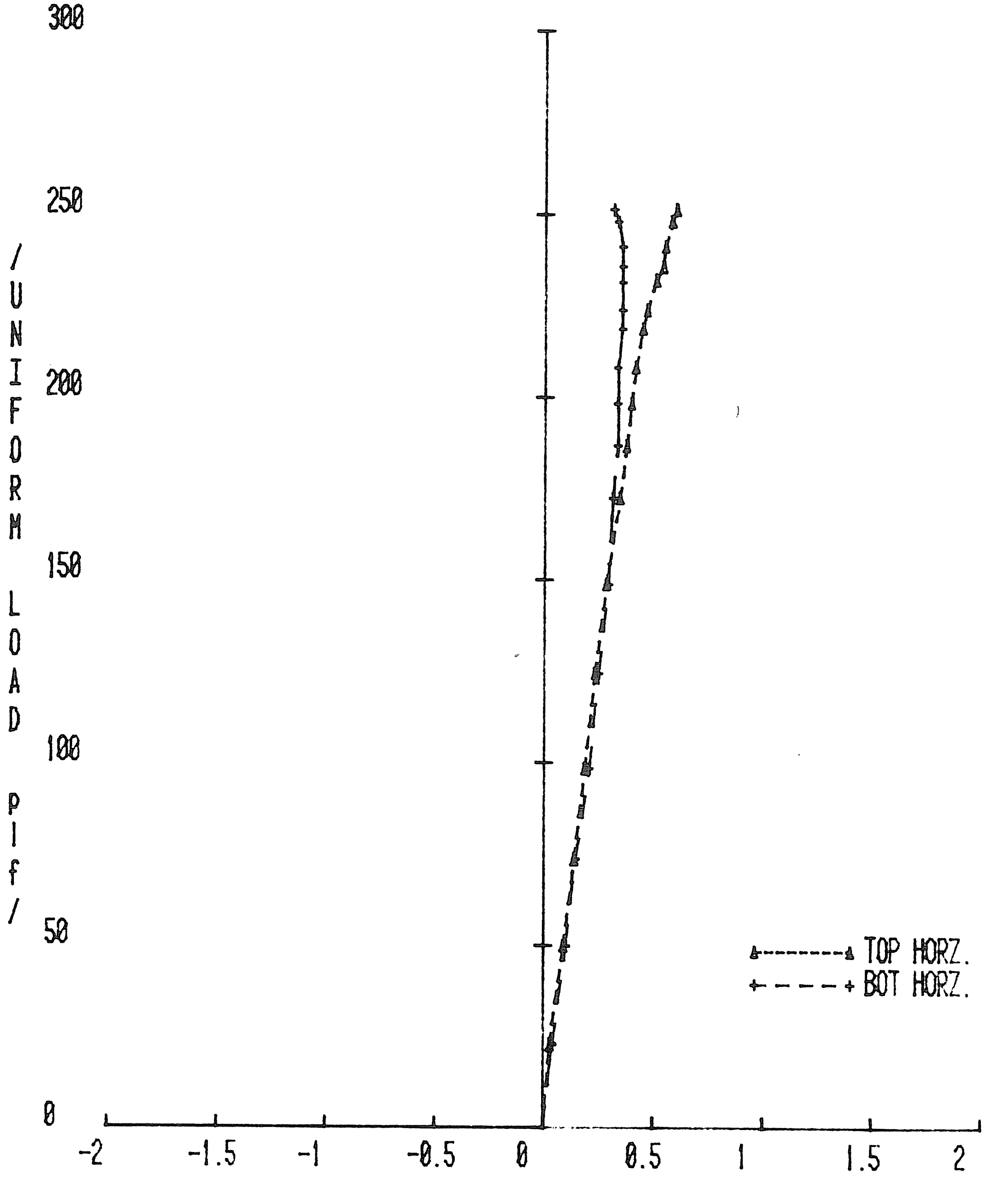


Figure E.13 Vertical Load vs. Lateral Displacements, Test 5-A

TEST SUMMARY

Project: Star Manufacturing Company

Test No.: 5-B

Test Date: May 17, 1982

Purpose: Center line brace only

Span(s): 3 @ 20' = 60'

Thickness: .055 & .059 Moment of Inertia: 10.02 in^4 & 8.658 in^4

Parameters: Internal braces @ ℄

Clips in place

No insulation

Spacing @ 4'9"

Failure Load: 190.5 plf

Failure Mode: Web crippling at north exterior support

Predicted Failure Loads:

Method Star	Load 203 plf
Method AISI Constrained	Load 375.9
Method	Load

Discussion:

- Failure occurred well above design load by web crippling. However, the load-deflection curve showed a nonlinear change before the web crippling occurred.
- The load deflection curve began to show a nonlinear change after a load of 141.6 plf was obtained.
- The Star Manufacturing Company's predicted failure load was 6% higher than the test failure load.
- The AISI predicted constrained bending failure load was 96% higher than the test failure load.
- The experimental stress distribution looked like an unconstrained bending distribution.
- From stiffness analysis (constrained bending) the moment at 123.5 plf was 3.29 k-ft while the experimental moment measured from strain gages was 2.44 k-ft.
- The moment about the y axis was -0.42 k-ft.
- The brace forces in the exterior bay are higher than those in the interior bay.
- At 19.8 psf (working load) the ratio of brace forces was 1:2.10:2.30 for the exterior bay and 1:2.10:2.75 for the interior bay. The ratio of tributary areas was 1:3:5.
- At 40.11 psf (failure load) the ratio of brace forces was 1:1.48:1.84 for the exterior bay and 1:2.83:4.06 for the interior bay.

-When tributary area is considered it is evident that the brace forces did not accumulate in proportion to tributary area after the first two purlins.

-At 19.8 psf (working load) the brace forces as a percentage of stabilized vertical load were 16%, 12% and 8% from the ridge to eave of the exterior bay and 9%, 7% and 5% from the ridge to eave of the interior bay. At 40.11 psf (failure load) the brace forces as a percentage of stabilized vertical load were 22%, 11% and 8% from the ridge to eave of the exterior bay and 7%, 7% and 6% from the ridge to eave of the interior bay.

-As the purlins approached failure the top flange lateral displacement increased in magnitude and the bottom flange changed its direction and began to move in the same direction as the top flange.

-The maximum lateral displacement was 1.16 in. for the top flange and 0.917 in. for the bottom flange.

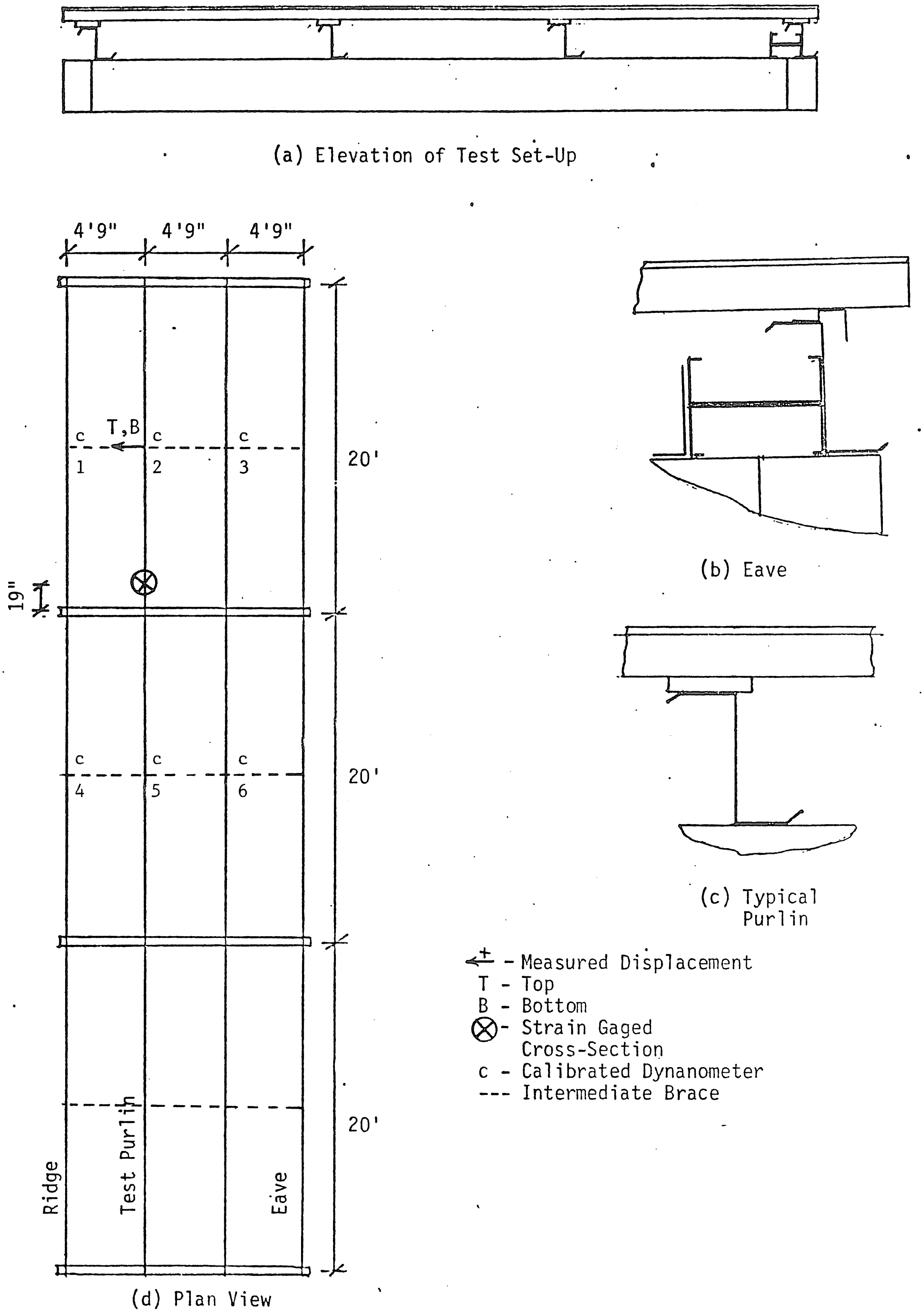
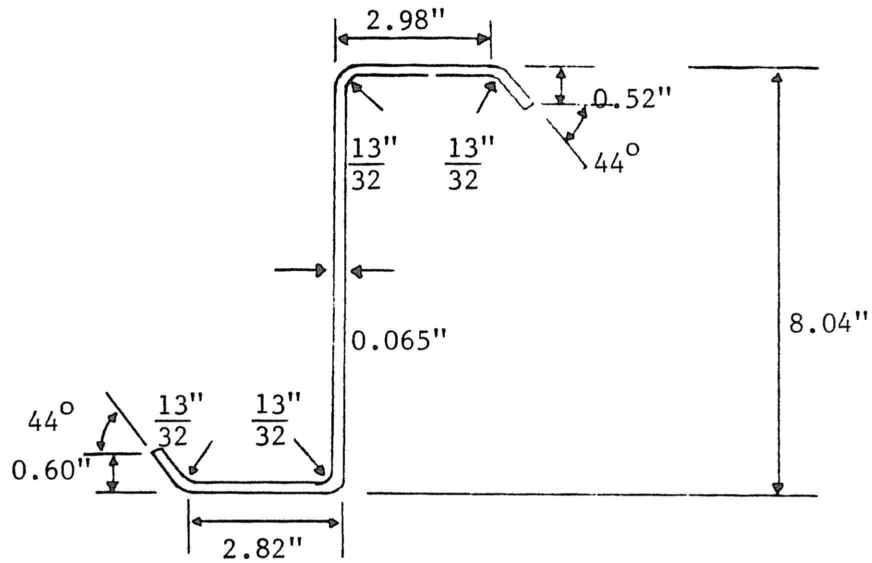
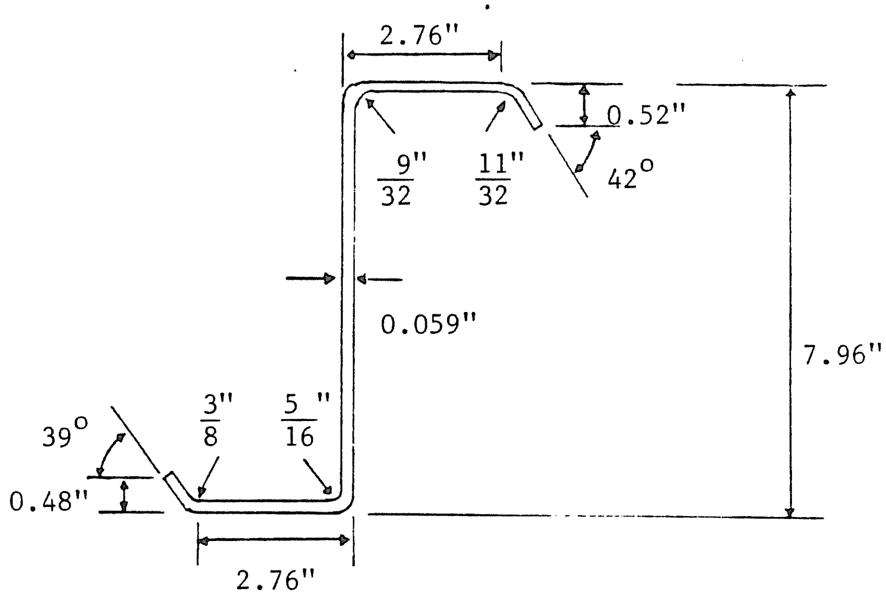


Figure E.14 Instrumentation Location, Test 5-B



North Span



Center Span

Figure E.15 Measured Purlin Dimensions, Test 5-B

A I S I   P U R L I N   A N A L Y S I S

IDENTIFICATION: STAR PURLIN TEST 5-B NORTH

	TOP	BOTTOM
FLANGE(in)	2.980	2.820
LIP(in)	0.520	0.600
LIP ANGLE(deg)	44.000	44.000
RADIUS L/F(in)	0.406	0.406
RADIUS F/W(in)	0.406	0.406

TOTAL DEPTH(in)	8.04
THICKNESS(in)	0.065
YIELD STRENGTH(ksi)	51.4

MOMENTS OF INERTIA(in^4)		SECTION MODULII(in^3) TOP	SECTION MODULII(in^3) BOTTOM
GROSS=	10.020	2.523	2.503
STRENGTH=	9.694	2.391	2.473
DEFLECTION=	10.020		

BE= 2.197 in

FC= 30.840 ksi

FT= 30.840 ksi

FBW= 28.168 ksi

Figure E.16 AISI Cross-Section Analysis, Test 5-B

```
-----------------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: STAR PURLIN TEST 5-B CENTER
-----------------------------------------------------------------
                        TOP              BOTTOM
FLANGE(in)            2.760               2.760
LIP(in)               0.520               0.480
LIP ANGLE(deg)       42.000              39.000
RADIUS L/F(in)        0.344               0.375
RADIUS F/W(in)        0.281               0.313

TOTAL DEPTH(in)                7.96
THICKNESS(in)                  0.059
YIELD STRENGTH(ksi)            58.7
                                          SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)         TOP                 BOTTOM
GROSS=           8.658               2.191                2.193
STRENGTH=        8.259               2.031                2.155
DEFLECTION=      8.589
BE=     1.999   in
FC=     32.496  ksi
FT=     35.220  ksi
FBW=    30.422  ksi
```

Figure E.17 AISI Cross-Section Analysis, Test 5-B

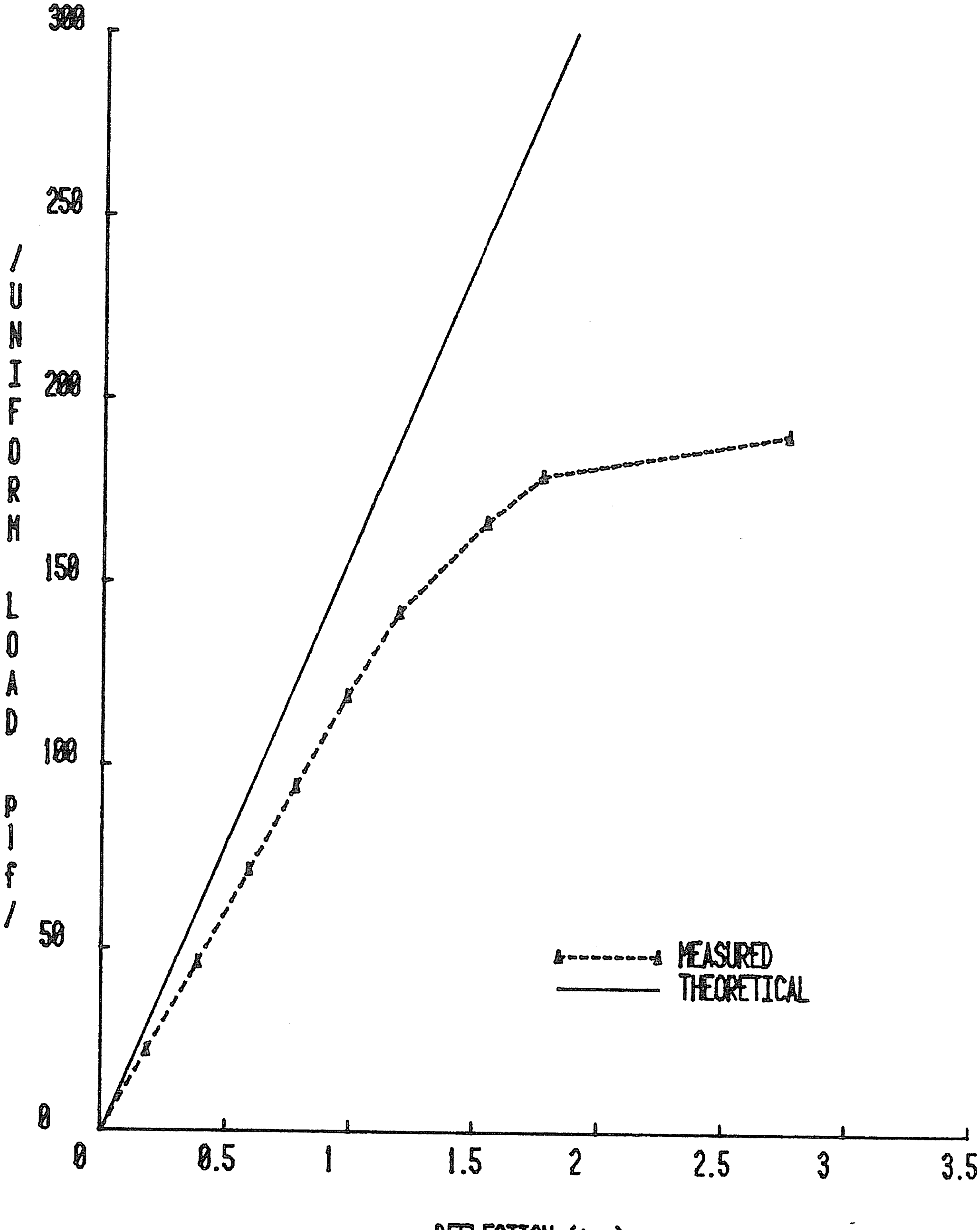


Figure E.18 Load vs. Vertical Deflection, Test 5-B

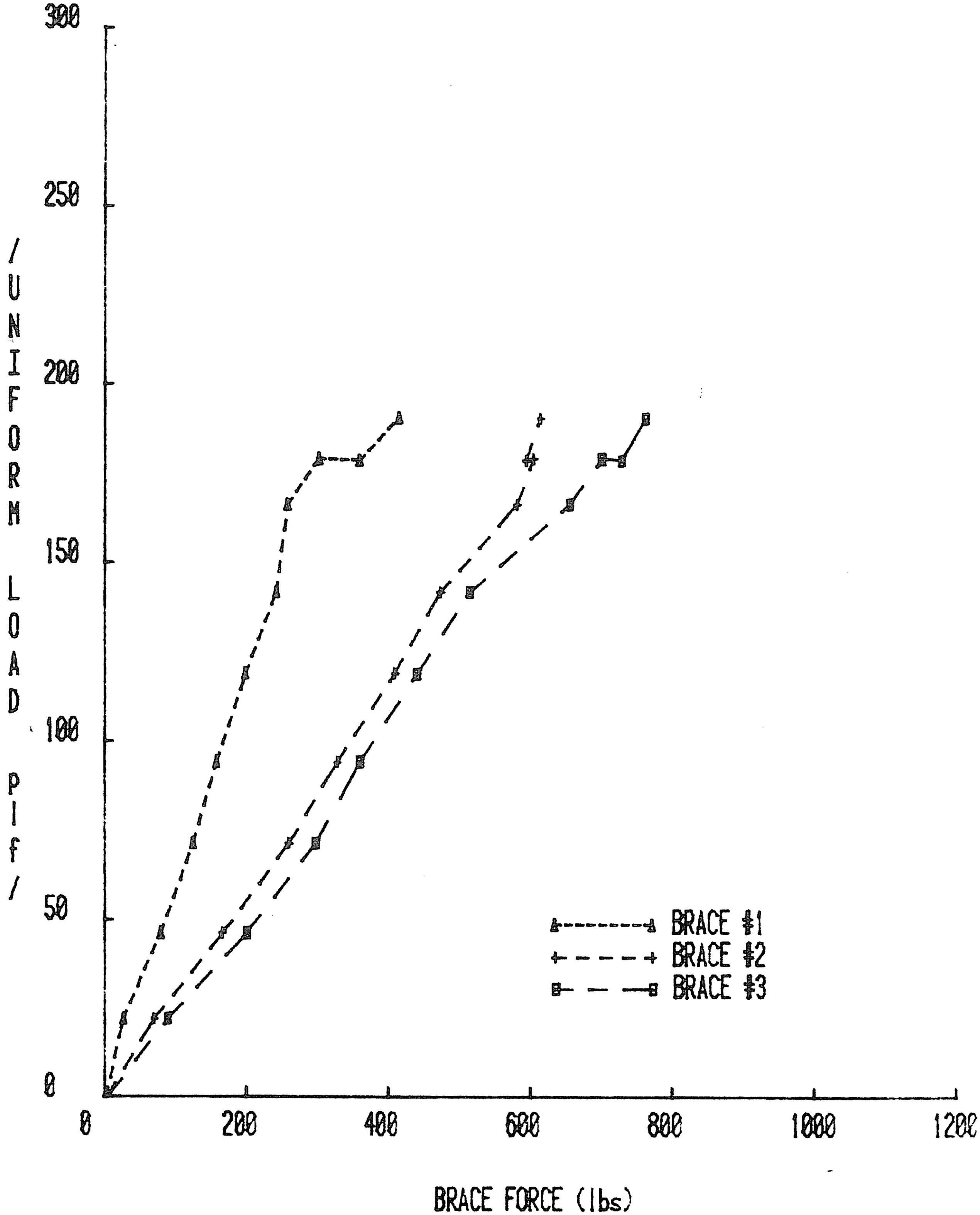


Figure E.19 Vertical Load vs. Brace Froce at Midspan of North Span, Test 5-B

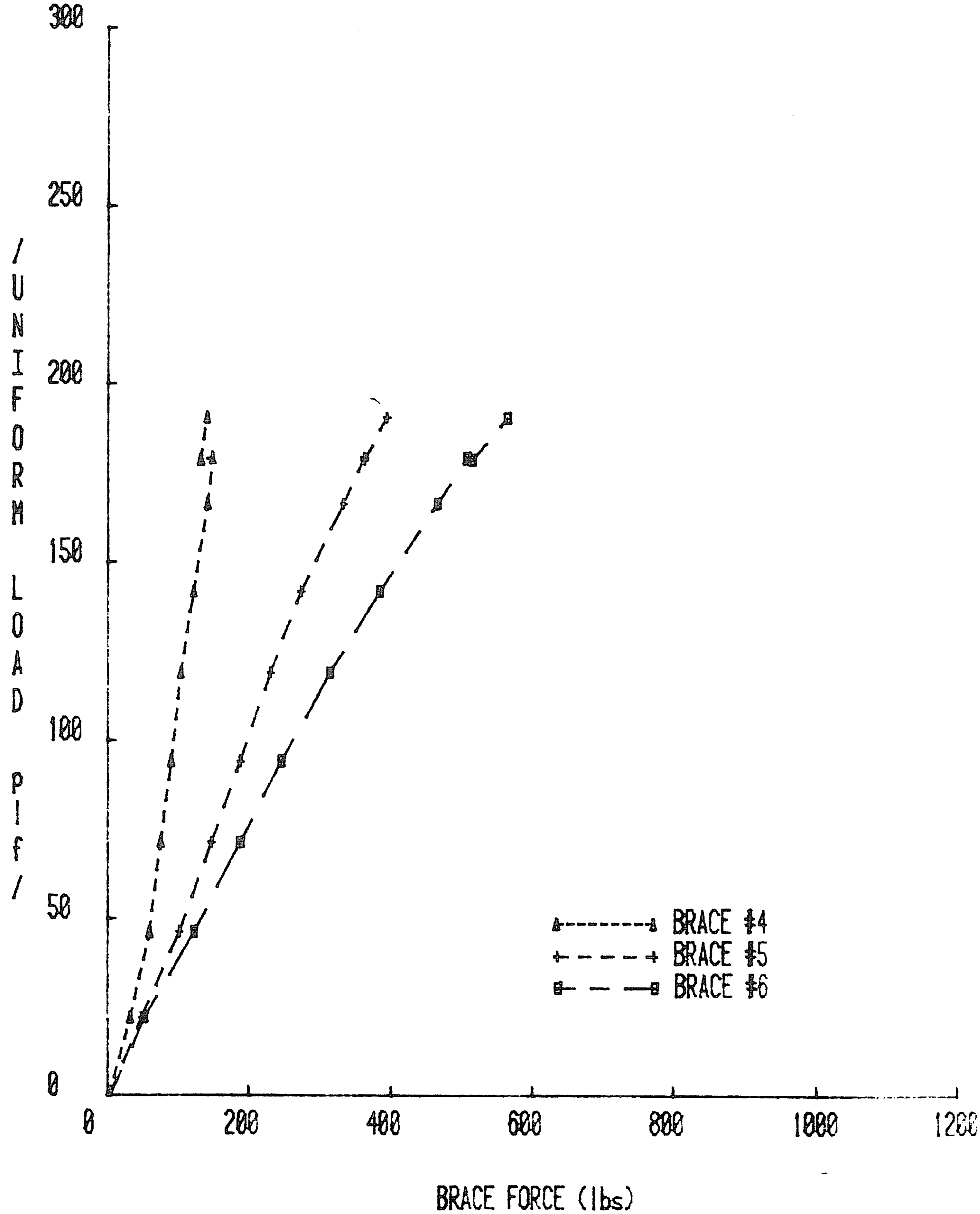


Figure E.20 Vertical Load vs. Brace Force at Midspan of Center Span, Test 5-B

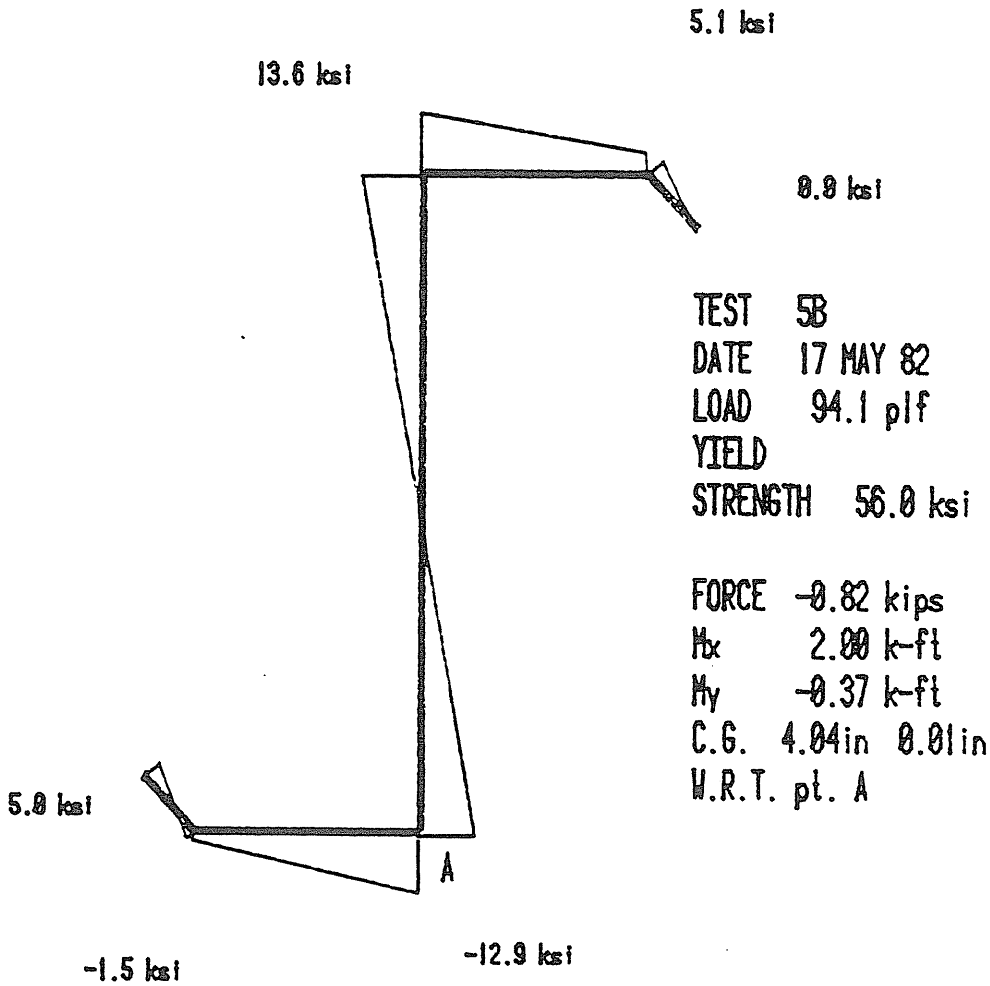


Figure E.21 Stress Distribution at 56 plf, Test 5-B

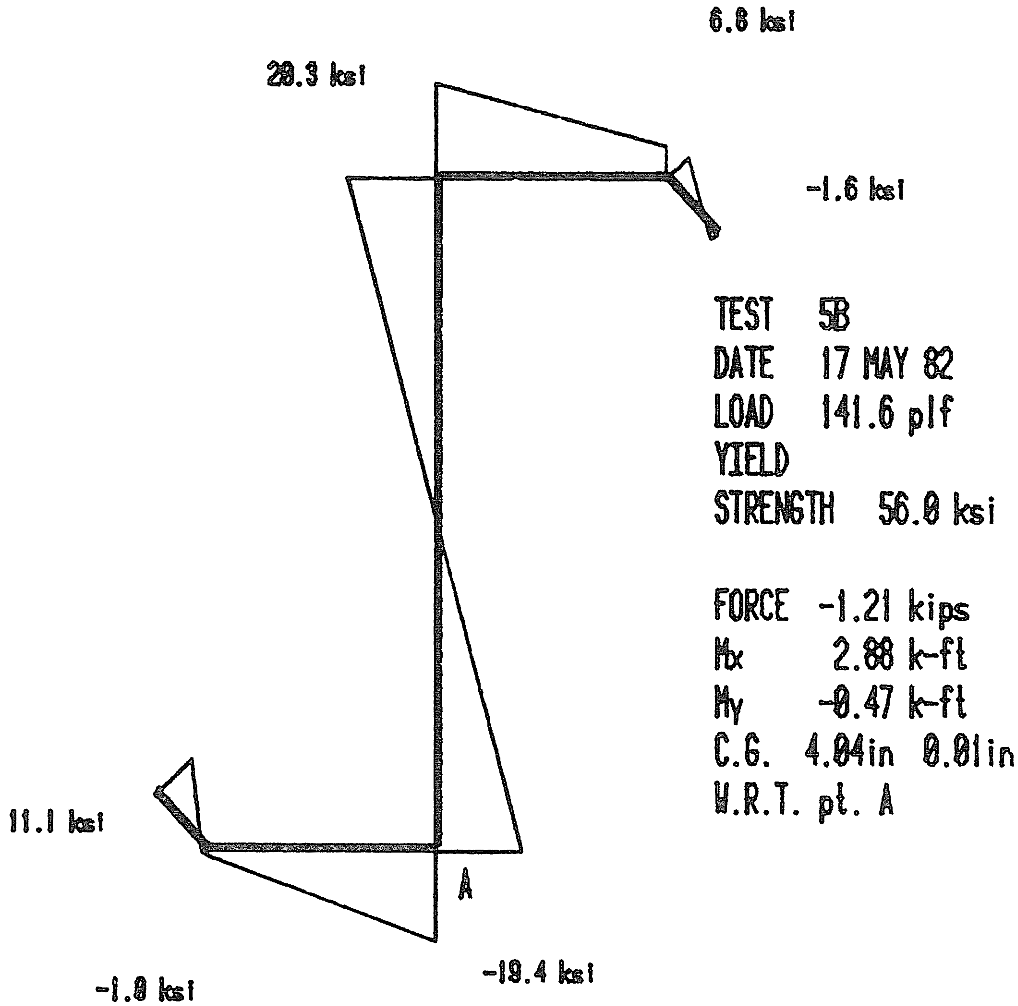


Figure E.22 Stress Distribution at 141.6 plf, Test 5-B

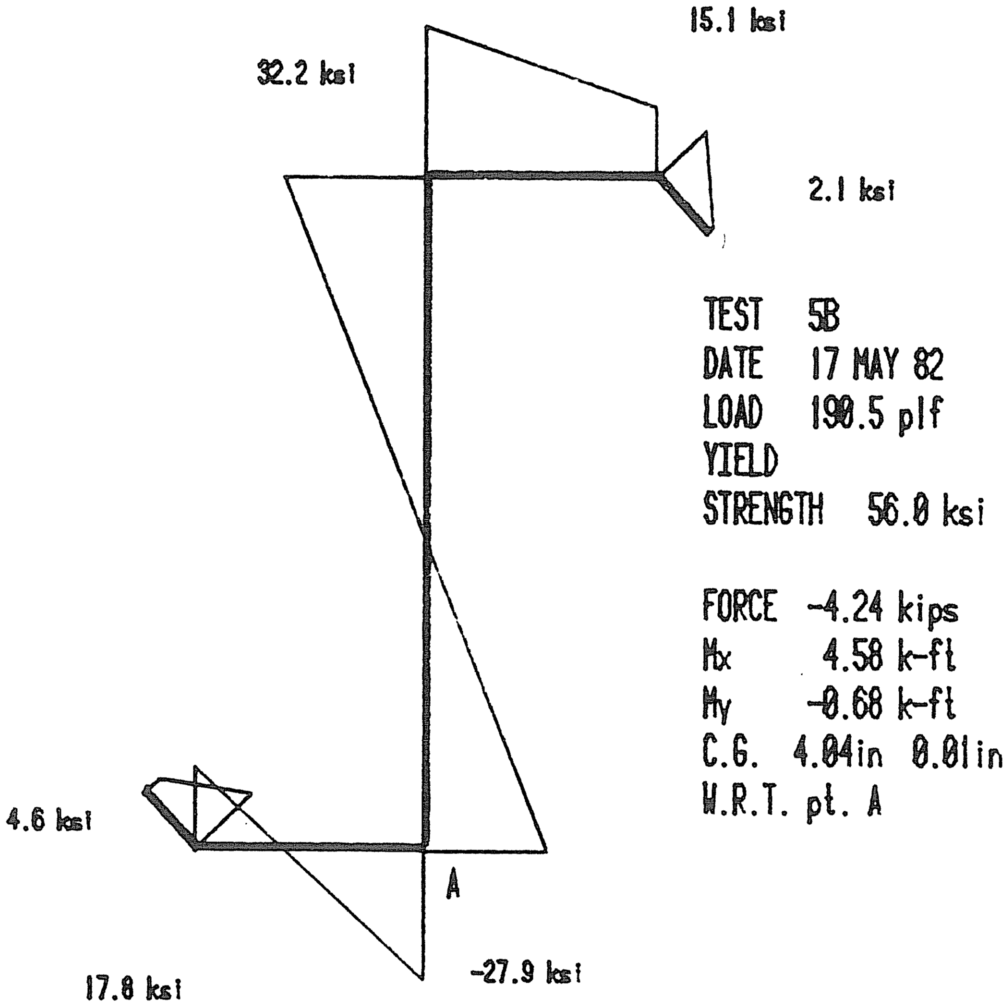


Figure E.23 Stress Distribution at 190.5 plf, Test 5-B

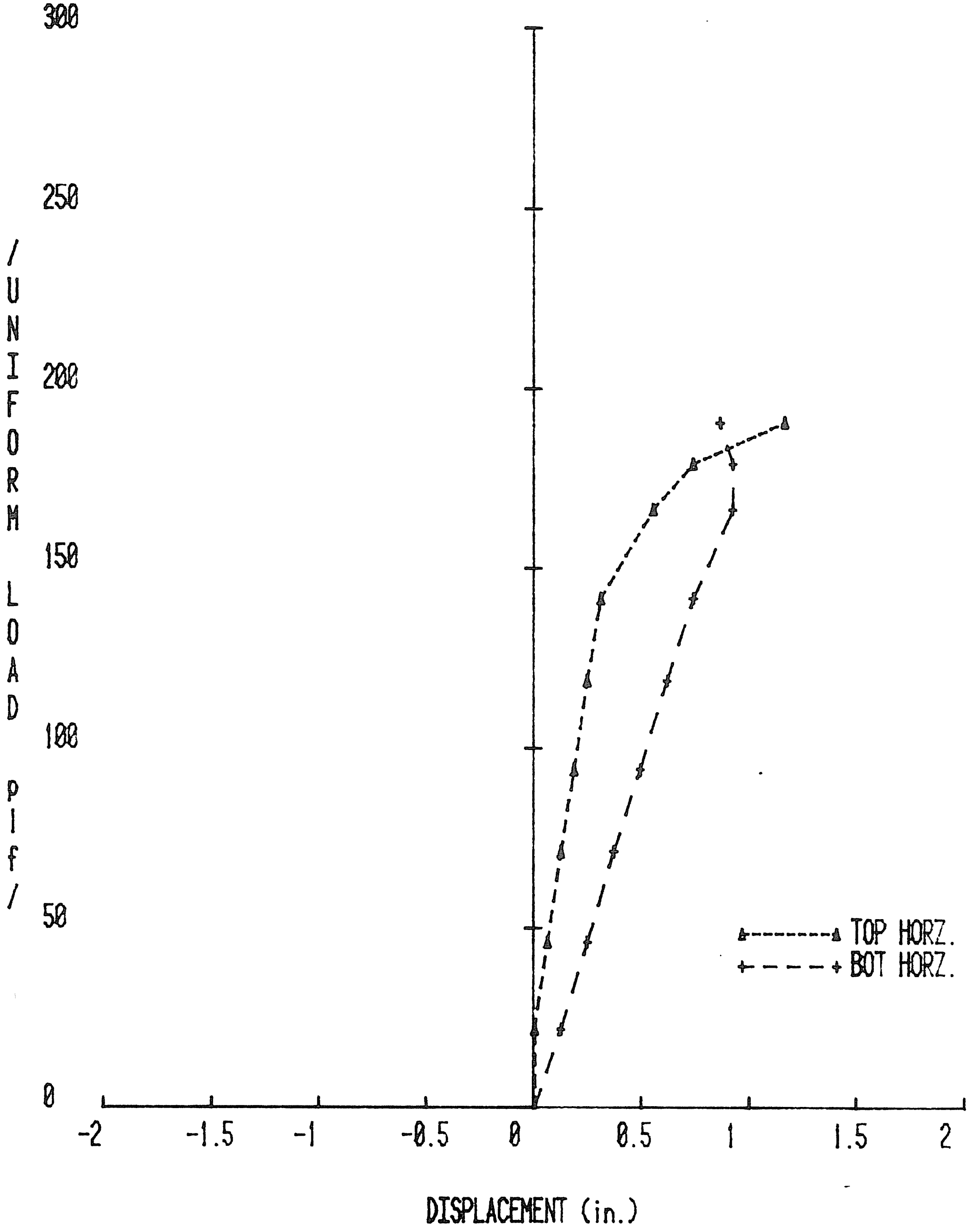


Figure E.24 Vertical Load vs. Lateral Displacements, Test 5-B

APPENDIX F

TEST SERIES VI RESULTS

TEST SUMMARY

Project: Star Manufacturing Company

Test No.: 6-A

Test Date: 2/18/82

Purpose: Test w/only ℄ bracing

Span(s): 3 @ 20'

Thickness: Outside 0.084" Inside 0.064" Moment of Inertia: I=13.499 in^4, I=9.837 in^4, I=12.565 in^4

Parameters: Intermediate Braces @ ℄

Clips in place

No insulation

Spacing 4'-9"

Strain Gages 3" outside of lap.

Failure Load: 259.4 lb/ft

Failure Mode: Lateral buckling of the ridge purlin

Predicted Failure Loads:

Method		Load	
Method	Star	Load	385 plf
Method	AISI Constrained x 1.67	Load	432.2 plf
Method		Load	

Discussion:

- The failure of the ridge purlin was due to a lack of bracing. The intermediate brace at the centerline was not attached properly. The bracing given to the purlin from the deck was not enough to restrain the purlin.
- The experimental deflections were much higher than predicted curve.
- From the experimental stress plot it was determined that the test was no good due to a lack of bracing.
- At 37 psf the brace forces in the interior span as a percentage of stabilized vertical load were: 11.4%, 5.9%, and 6.5% and at 53 psf they were 13.6%, 7.1% and 7.2%.
- At 37 psf the ratio of brace forces in the interior span was: 1:1.55:2.88 and at 53 psf 1:1.57:2.66 in the direction of ridge to eave. The ratio of tributary area was 1:3:5.
- At 37 psf the brace forces in the interior span as a percentage of stabilized vertical load were 11.4% and 12.2% with the ridge brace force not taken. At 53 psf they were 9.2% and 11.5% in the direction of ridge to eave with the ridge brace force not taken.
- The lateral displacement of the test purlin was about 1 in at the top flange. The top and bottom flanges moved in the same direction.

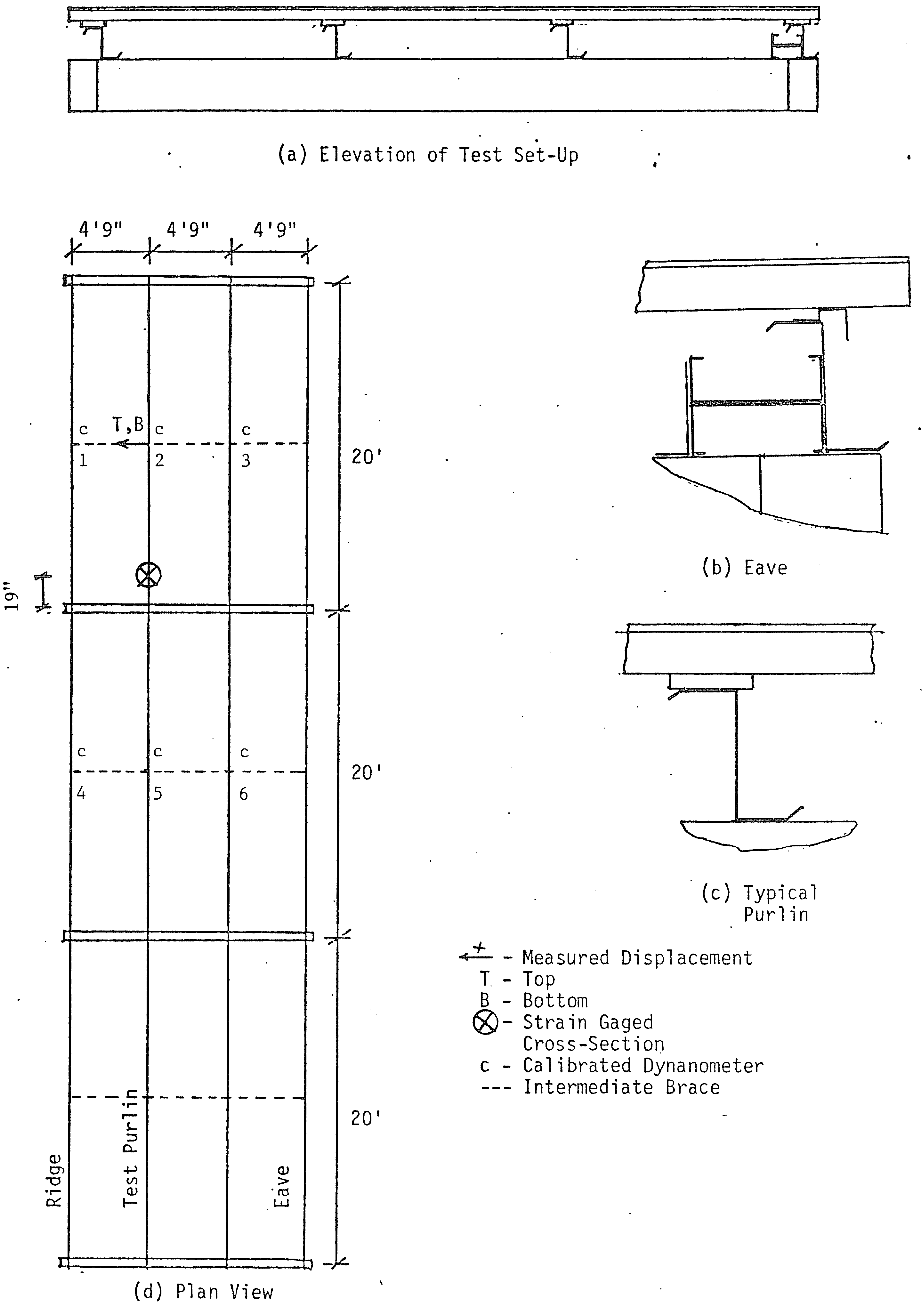


Figure F.1 Instrumentation Location, Test 6-A

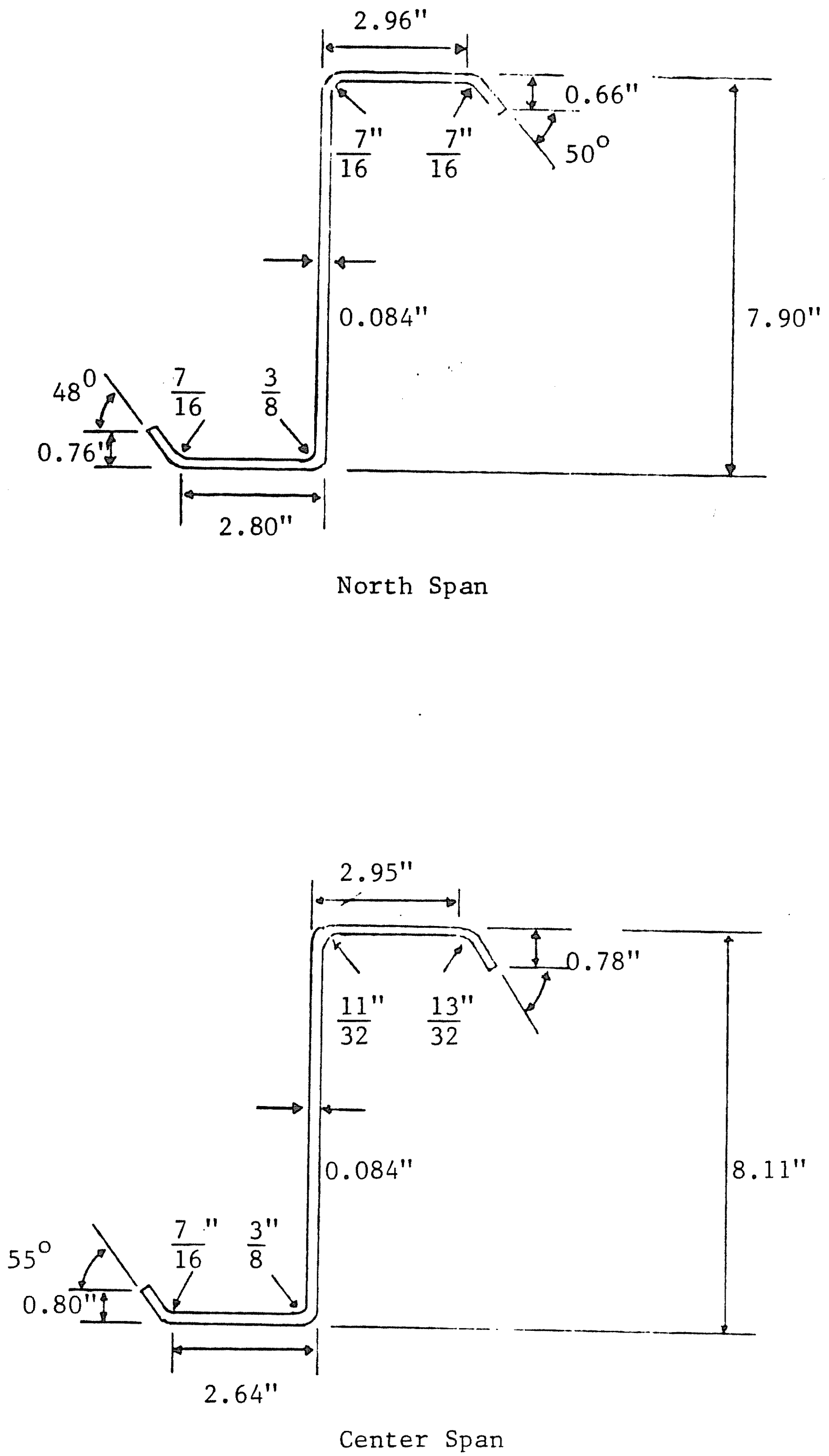


Figure F.2 Measured Purlin Dimensions, Test 6-A

A I S I P U R L I N A N A L Y S I S
IDENTIFICATION: STAR PURLIN TEST 6-A NORTH

	TOP	BOTTOM
FLANGE(in)	2.960	2.800
LIP(in)	0.660	0.760
LIP ANGLE(deg)	50.000	48.000
RADIUS L/F(in)	0.438	0.375
RADIUS F/W(in)	0.438	0.375

TOTAL DEPTH(in)	7.9
THICKNESS(in)	0.084
YIELD STRENGTH(ksi)	51.6

	MOMENTS OF INERTIA(in^4)	SECTION MODULII(in^3) TOP	SECTION MODULII(in^3) BOTTOM
GROSS=	12.534	3.225	3.190
STRENGTH=	12.534	3.225	3.190
DEFLECTION=	12.534		

BE=	2.439	in
FC=	30.960	ksi
FT=	30.960	ksi
FBW=	30.501	ksi

Figure F.3 AISI Cross-Section Analysis, Test 6-A

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-----------------------------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: STAR PURLIN TEST 6-A CENTER
-----------------------------------------------------------------------------
                         TOP              BOTTOM
FLANGE(in)             2.950               2.640
LIP(in)                0.780               0.800
LIP ANGLE(deg)        52.000              55.000
RADIUS L/F(in)         0.406               0.438
RADIUS F/W(in)         0.344               0.375

TOTAL DEPTH(in)                8.11
THICKNESS(in)                  0.064
YIELD STRENGTH(ksi)            57
                                        SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)           TOP                BOTTOM
GROSS=          10.177                 2.577               2.483
STRENGTH=        9.827                 2.434               2.451
DEFLECTION=     10.177
BE=     2.200   in
FC=    30.220   ksi
FT=    34.200   ksi
FBW=   30.433   ksi
```

Figure F.4 AISI Purlin Analysis, Test 6-A

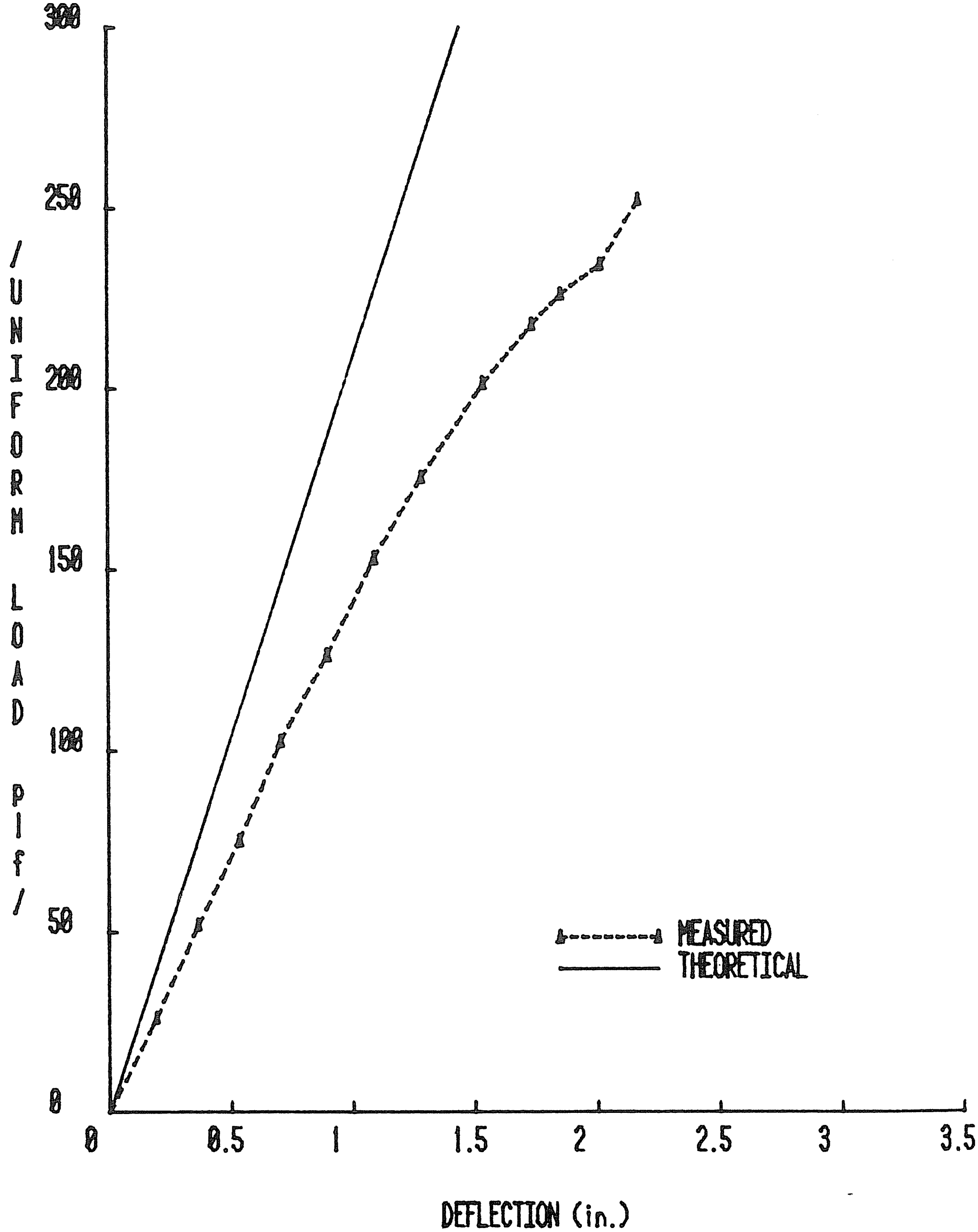


Figure F.5 Load vs. Vertical Deflection, Test 6-A

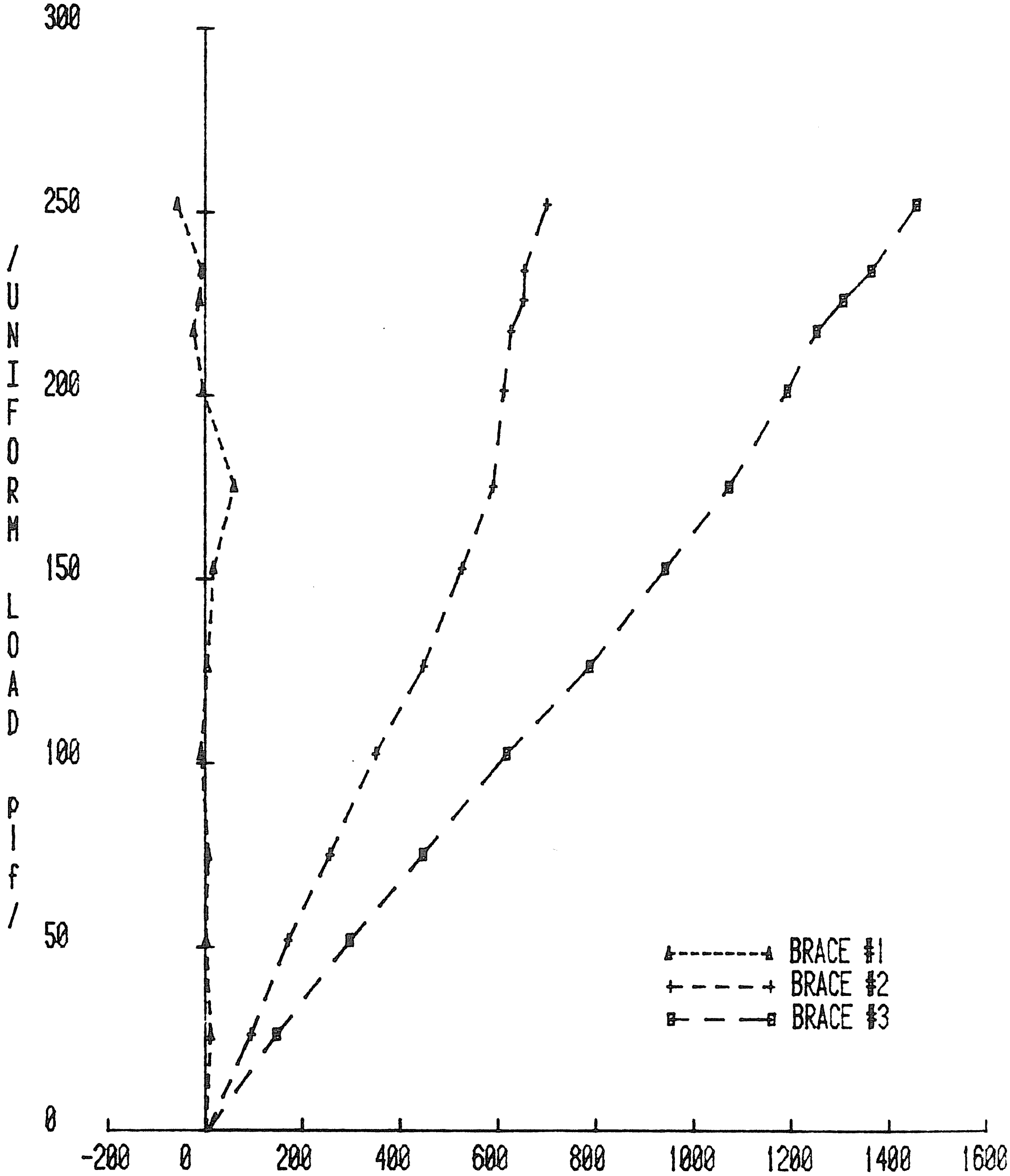


Figure F.6 Vertical Load vs. Brace Force at Midspan, Test 6-A Center Span

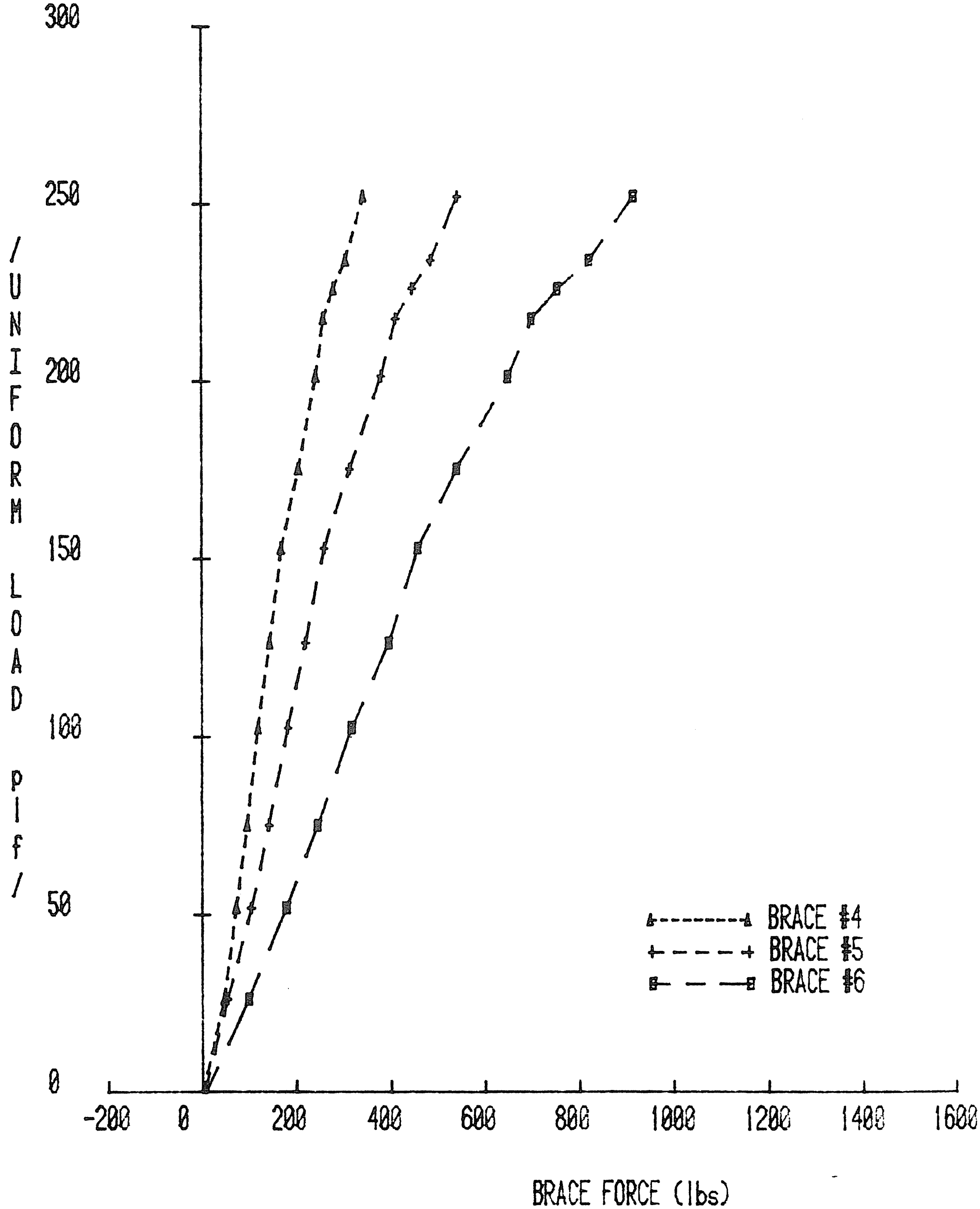


Figure F.7 Vertical Load vs. Brace Force at Midspan, Test 6-A Center Span

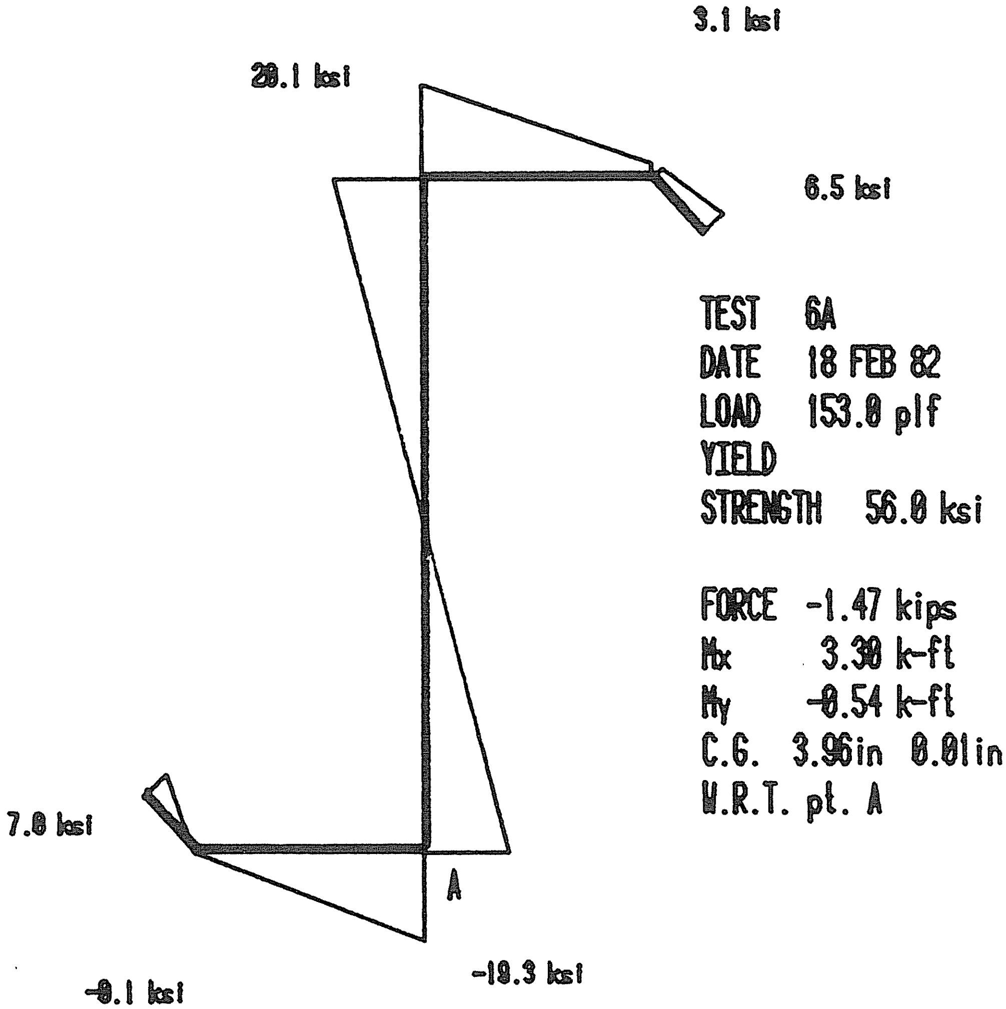


Figure F.8 Stress Distribution at 153 plf, Test 6-A

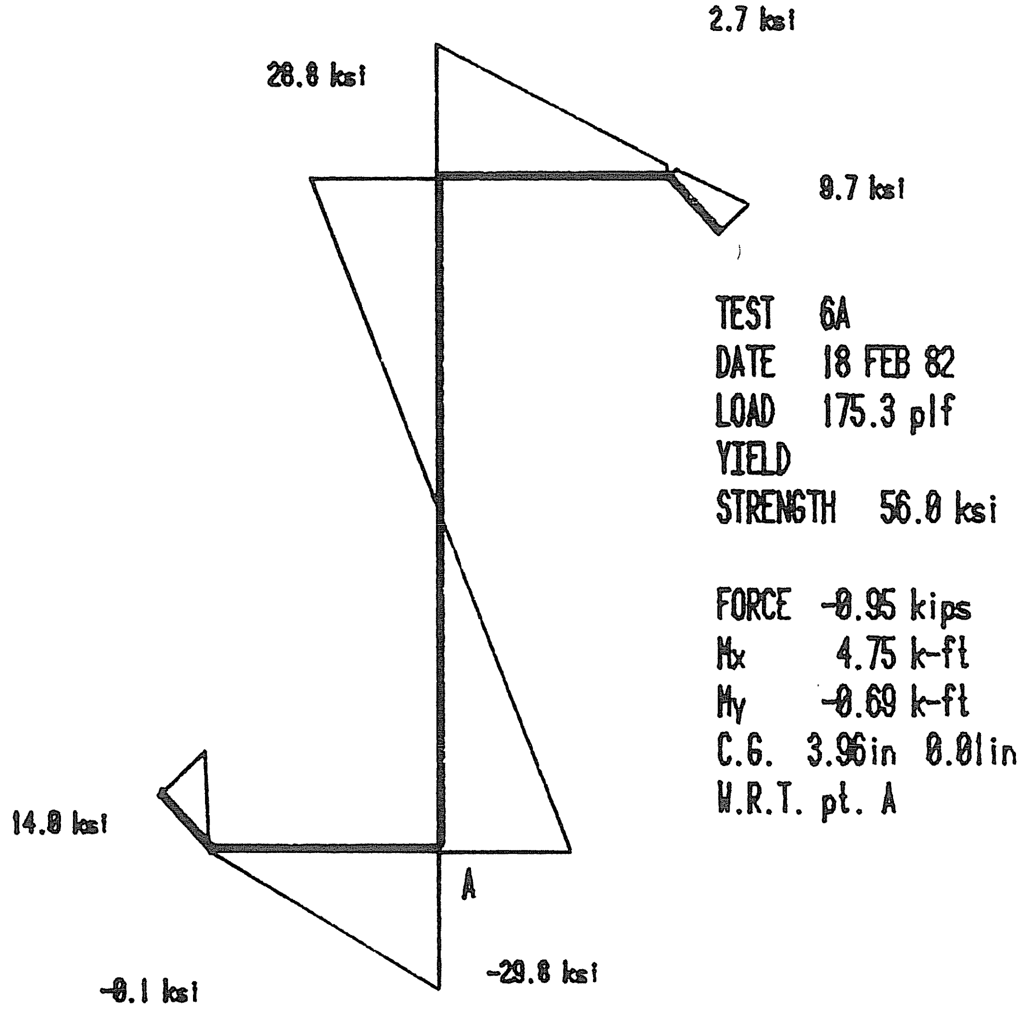


Figure F.9 Stress Distribution at 175.3 plf, Test 6-A

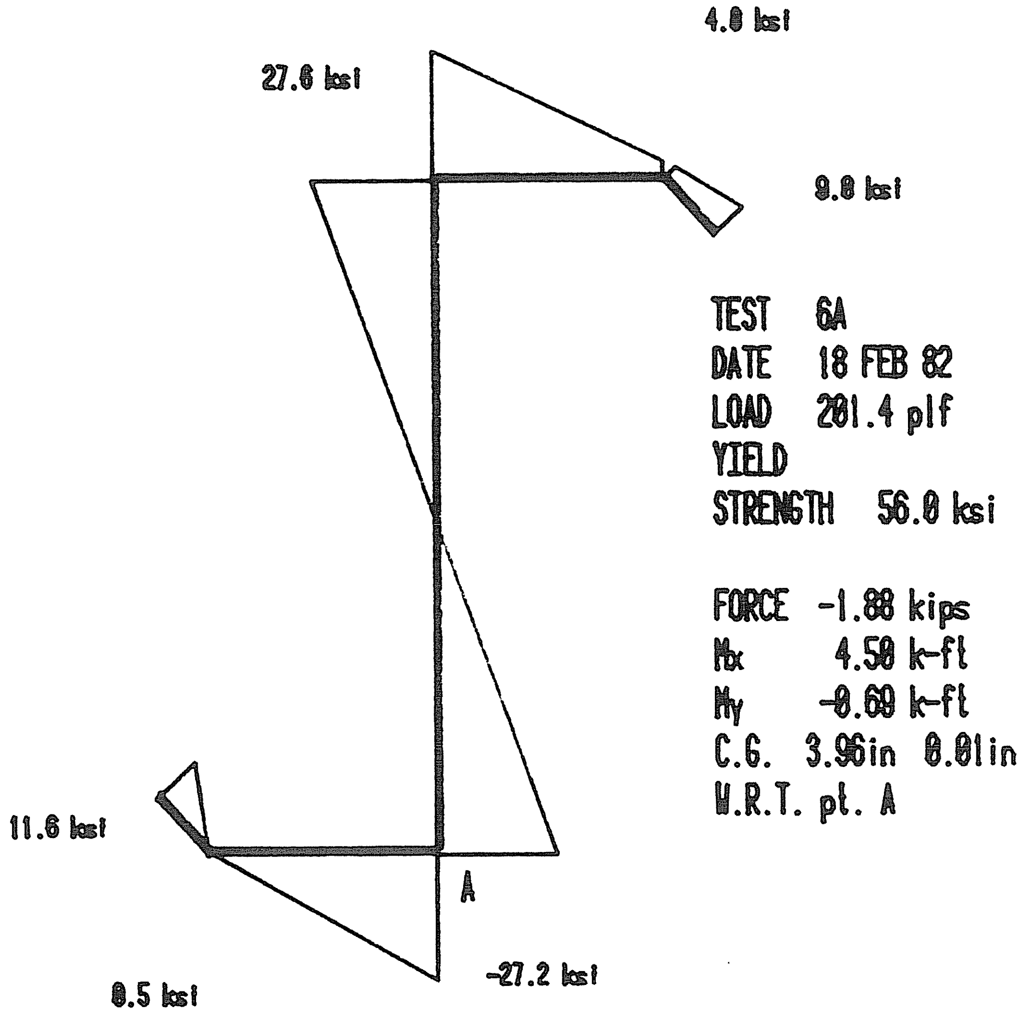


Figure F.10 Stress Distribution at 201 plf, Test 6-A

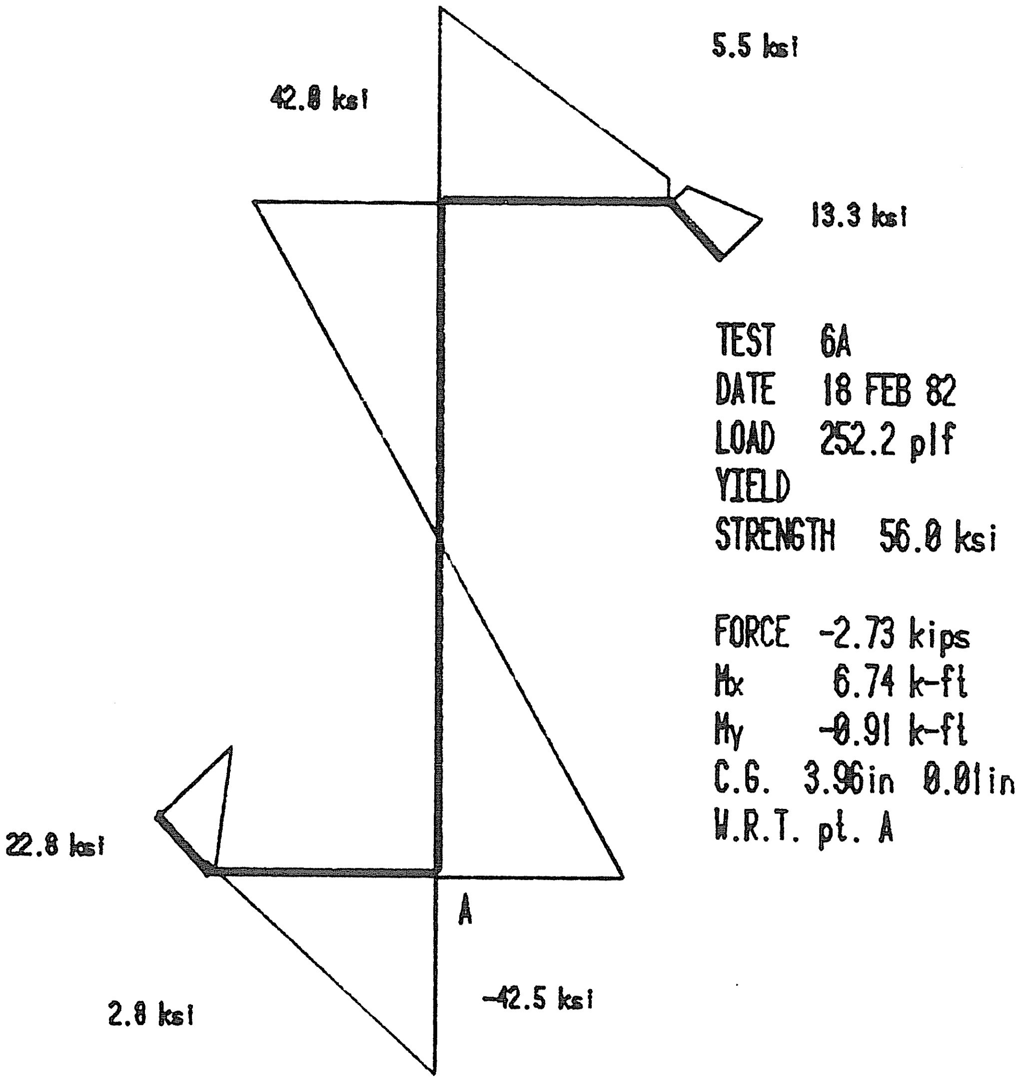


Figure F.11 Stress Distribution at 252.2 plf Test 6-A

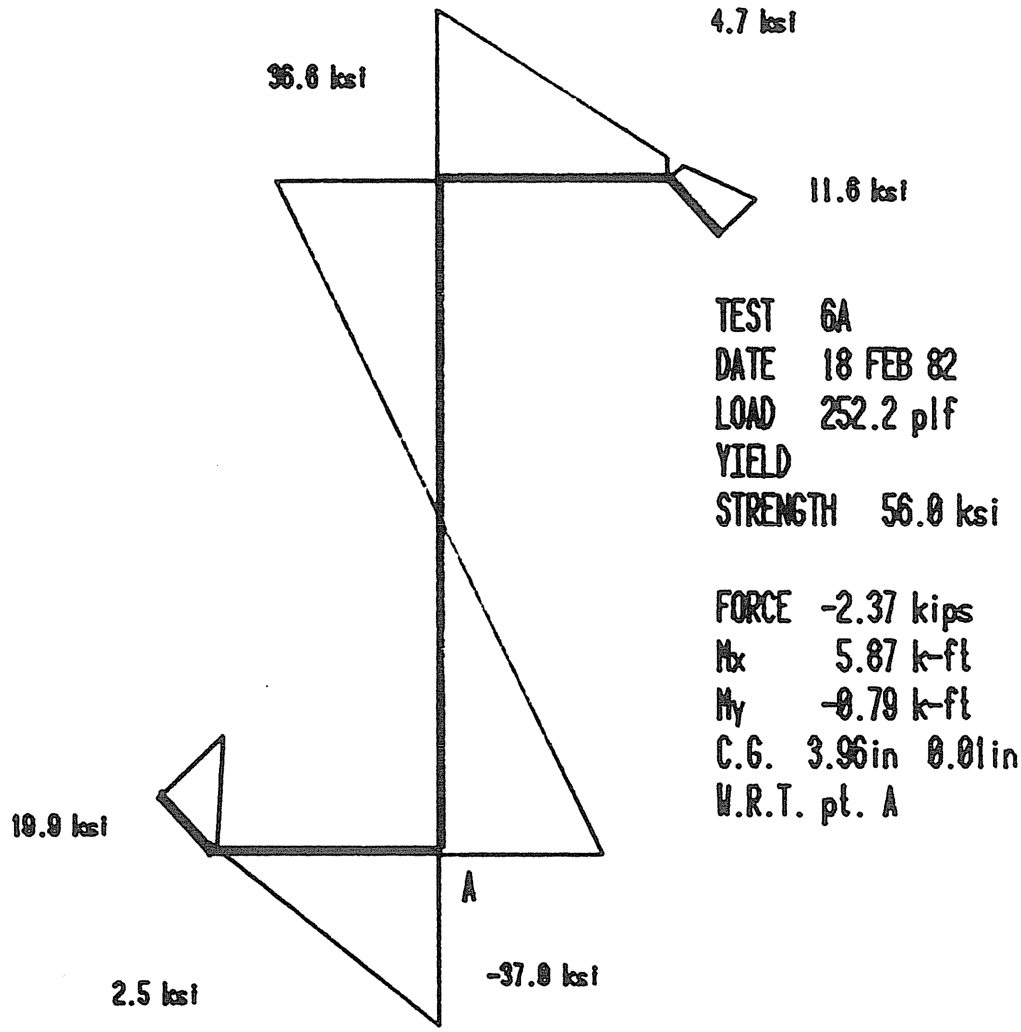


Figure F.12 Stress Distribution at 252.2 plf Failure, Test 6-A

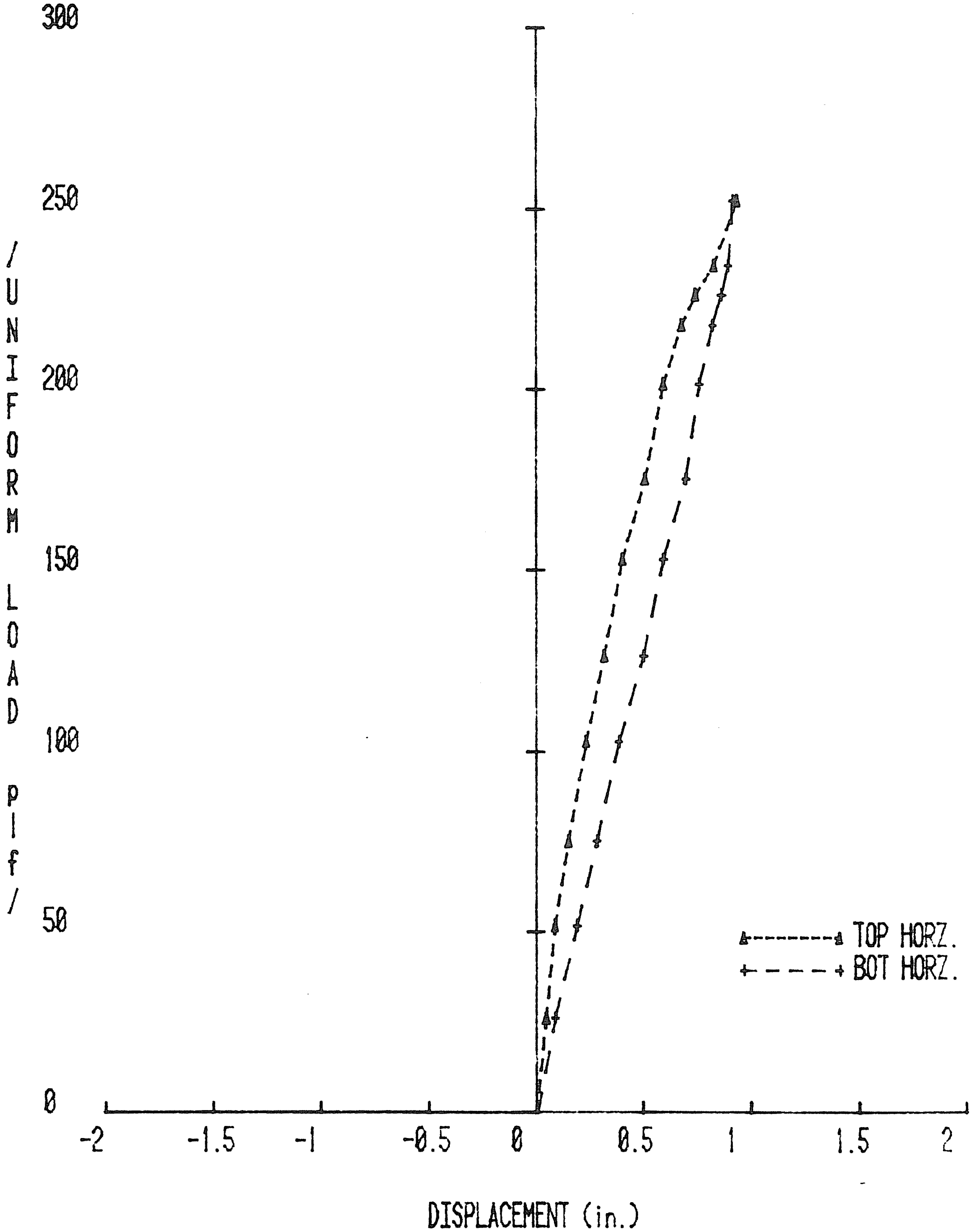


Figure F.13 Vertical Load vs. Lateral Displacements, Test 6-A

TEST SUMMARY

Project: Star Manufacturing Company

Test No.: 6B

Test Date: March 8, 1982

Purpose: Adequacy of single brace at midspan

Span(s): 3 @ 20'

Thickness: .080 & .066 Moment of Inertia: $I_x = 12.595''^4$, $I_x = 9.829''^4$

Parameters: Intermediate braces at ℄

Clips installed

No insulation

Spacing 4' 9"

Failure Load: 284.5 plf

Failure Mode: Local buckling

Predicted Failure Loads:

Method	Load
Star Manufacturing	290 plf
AISI (Cont. Bracing)	436.0 plf

Discussion:

- Failure occurred by local buckling of the bottom (compression flange) in the interior span immediately outside the lap. Buckling of the compression flange in the outside bay at midspan followed.
- Measured vertical deflections were greater than theoretical predictions.
- The moment of inertia of the eave purlin was 79.6% of that of the test purlin. It was not possible to determine if the eave purlin failed first.
- The strain gages, which were mounted 3" from the end of the lap on the north outside purlin, did not indicate yield strain near failure.
- Stress plots indicate unconstrained bending.
- At 37 psf, the brace forces in the interior spans as a percentage of stabilized vertical load were 9.1%, 5.6%, and 5.1% in the direction of ridge to eave and at 60 psf they were 11.7%, 5.9% and 4.3%.
- At 37 psf the brace forces in the exterior span as a percentage of stabilized vertical load were 14.2%, 9.1%, 9.2% and at 60 psf they were 14.3%, 8.3% and 7.7% in the direction of ridge to eave.
- For the intermediate brace location in the exterior span at 37 psf, the ratio of brace forces was 1.0:1.92:3.24 and at 60 psf the ratio was 1.0:1.73: 3.34. The ratio of tributary areas was 1:3:5.
- At 37 psf, the ratio of brace forces at the intermediate brace location in the interior span was 1.0:1.84:2.81 and at 60 psf the ratio was 1.0:1.53: 2.24. The ratio of the tributary areas was 1:3:5.

-Lateral displacement of the lower flange of the test purlin at midspan of the exterior span was 1.70 in. near failure. The top flange lateral displacement was less than .5 in.

-The top and bottom moved laterally in the same direction.

-At 240 plf, slippage of the horizontal displacement transducer at the top flange may have occurred.

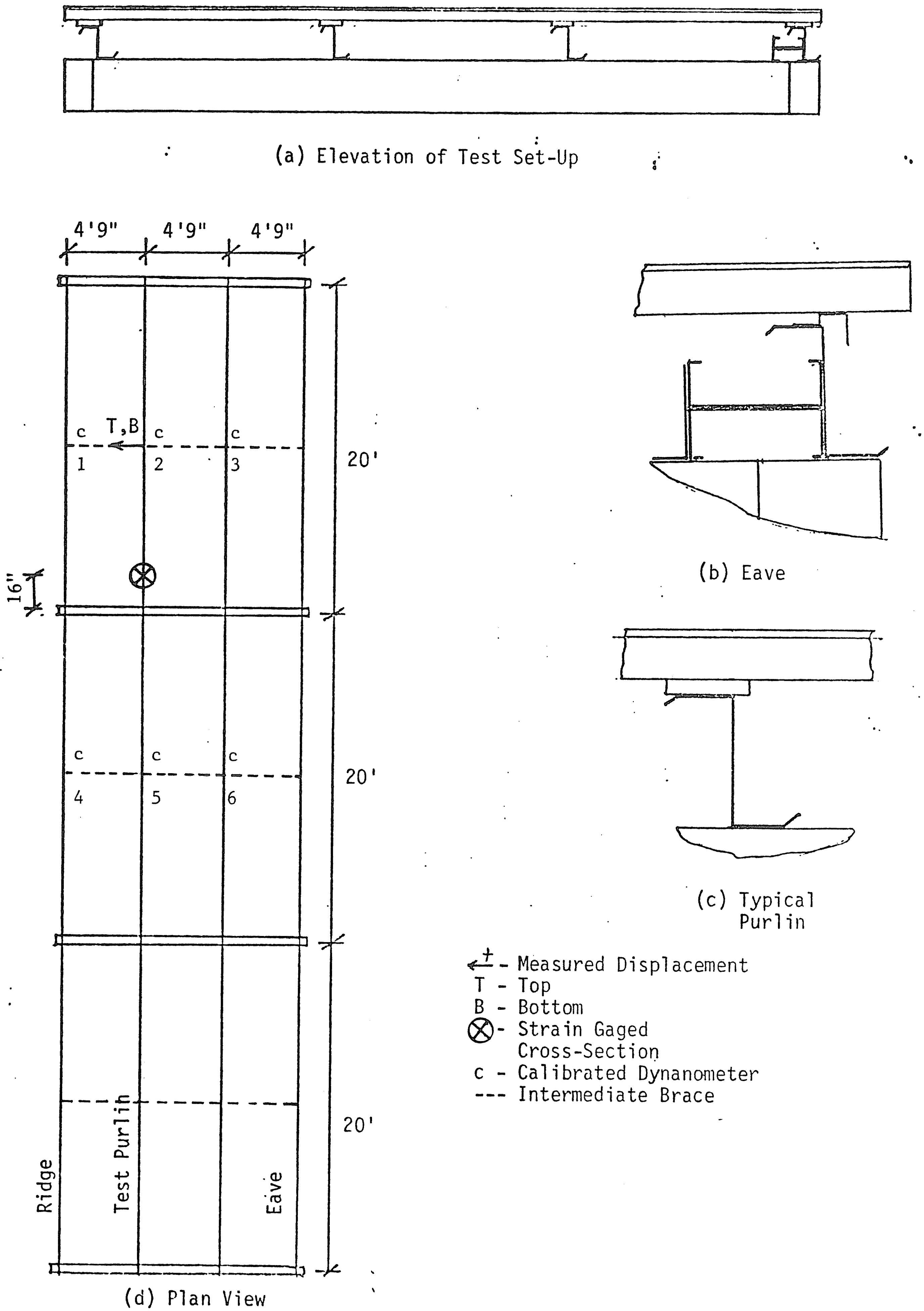
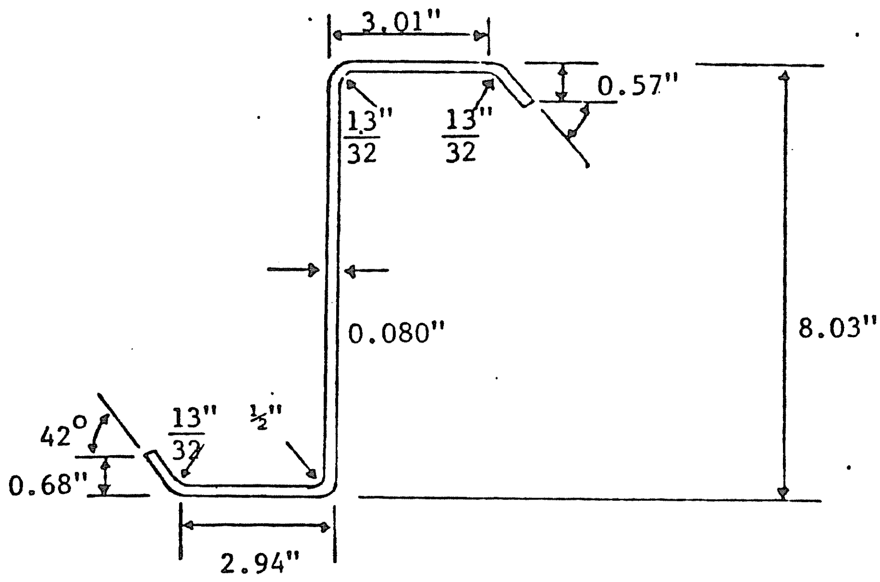
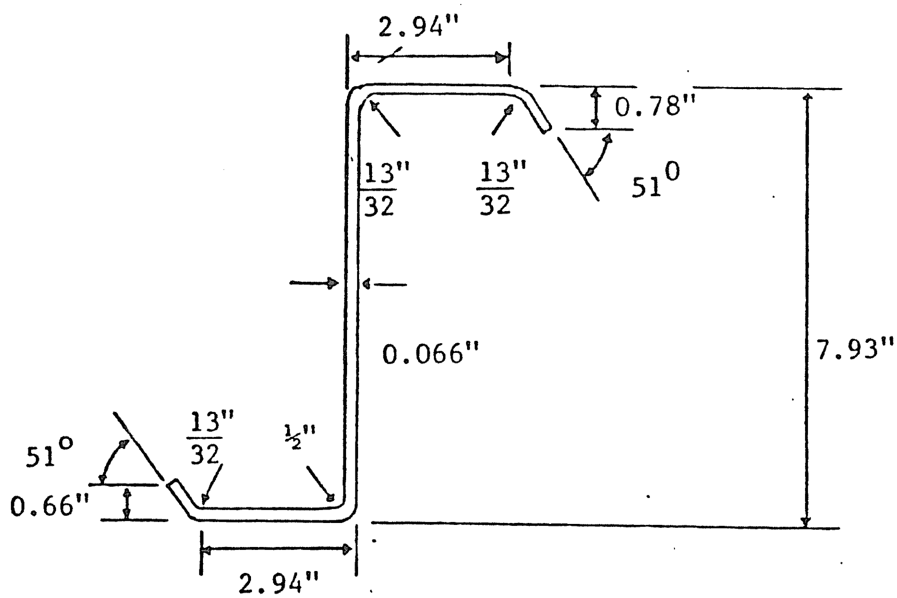


Figure F.14 Instrumentation Location, Test 6-B



North Span



Center Span

Figure F.15 Measured Purlin Dimensions, Test 6-B

A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: STAR PURLIN TEST 6-B NORTH

	TOP	BOTTOM
FLANGE(in)	3.010	2.940
LIP(in)	0.570	0.680
LIP ANGLE(deg)	41.000	42.000
RADIUS L/F(in)	0.406	0.406
RADIUS F/W(in)	0.406	0.500

TOTAL DEPTH(in)	8.03
THICKNESS(in)	0.08
YIELD STRENGTH(ksi)	53.4

MOMENTS OF INERTIA(in^4)		SECTION MODULII(in^3) TOP	BOTTOM
GROSS=	12.595	3.149	3.188
STRENGTH=	12.524	3.120	3.182
DEFLECTION=	12.595		

BE= 2.468 in
FC= 32.040 ksi
FT= 32.040 ksi
FBW= 30.937 ksi

Figure F.16 AISI Cross-Section Analysis, Test 6-B

A I S I   P U R L I N   A N A L Y S I S

IDENTIFICATION: STAR PURLIN TEST 6-B CENTER

	TOP	BOTTOM
FLANGE(in)	2.940	2.710
LIP(in)	0.780	0.660
LIP ANGLE(deg)	51.000	51.000
RADIUS L/F(in)	0.406	0.406
RADIUS F/W(in)	0.406	0.500

TOTAL DEPTH(in)	7.93
THICKNESS(in)	0.066
YIELD STRENGTH(ksi)	59.3

MOMENTS OF INERTIA(in^4)		SECTION MODULII(in^3) TOP	SECTION MODULII(in^3) BOTTOM
GROSS=	9.829	2.553	2.449
STRENGTH=	9.559	2.438	2.424
DEFLECTION=	9.829		

BE= 2.197 in

FC= 31.262 ksi

FT= 35.580 ksi

FBW= 32.045 ksi

Figure F.17 AISI Purlin Analysis, Test 6-B

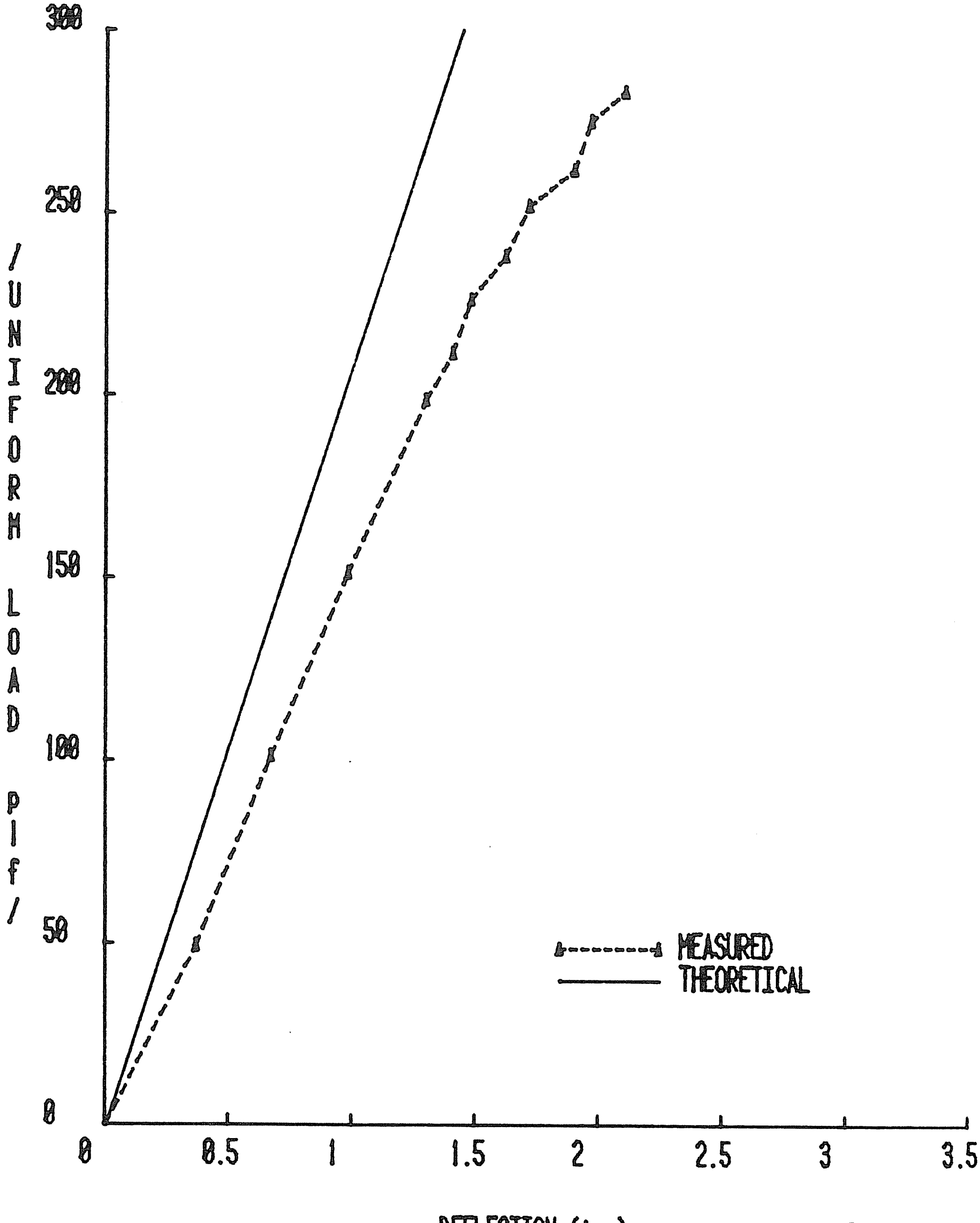


Figure F.18 Load vs. Vertical Deflection, Test 6-B

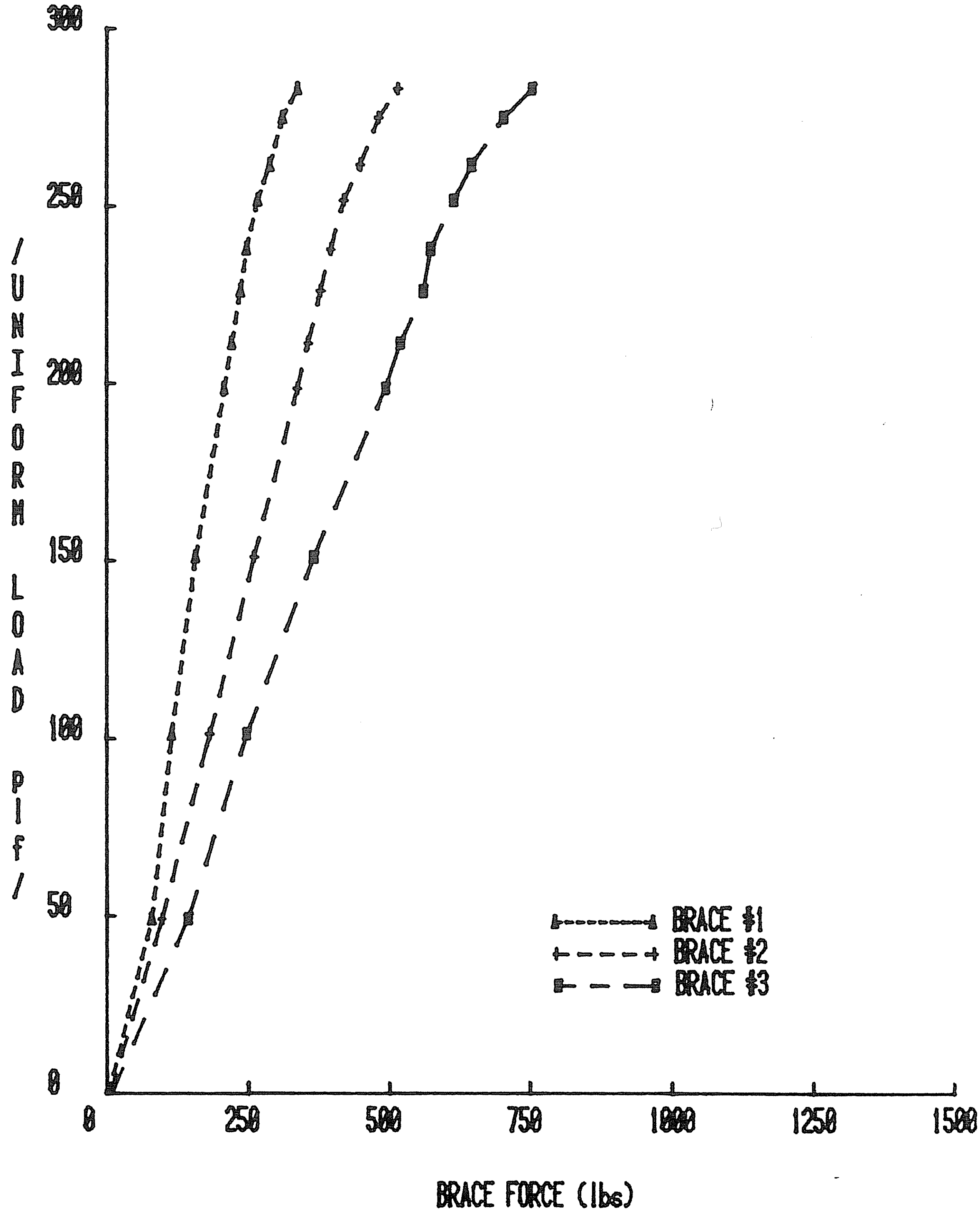


Figure F.19 Vertical Load vs. Brace Force at Midspan, Test 6-B North Span

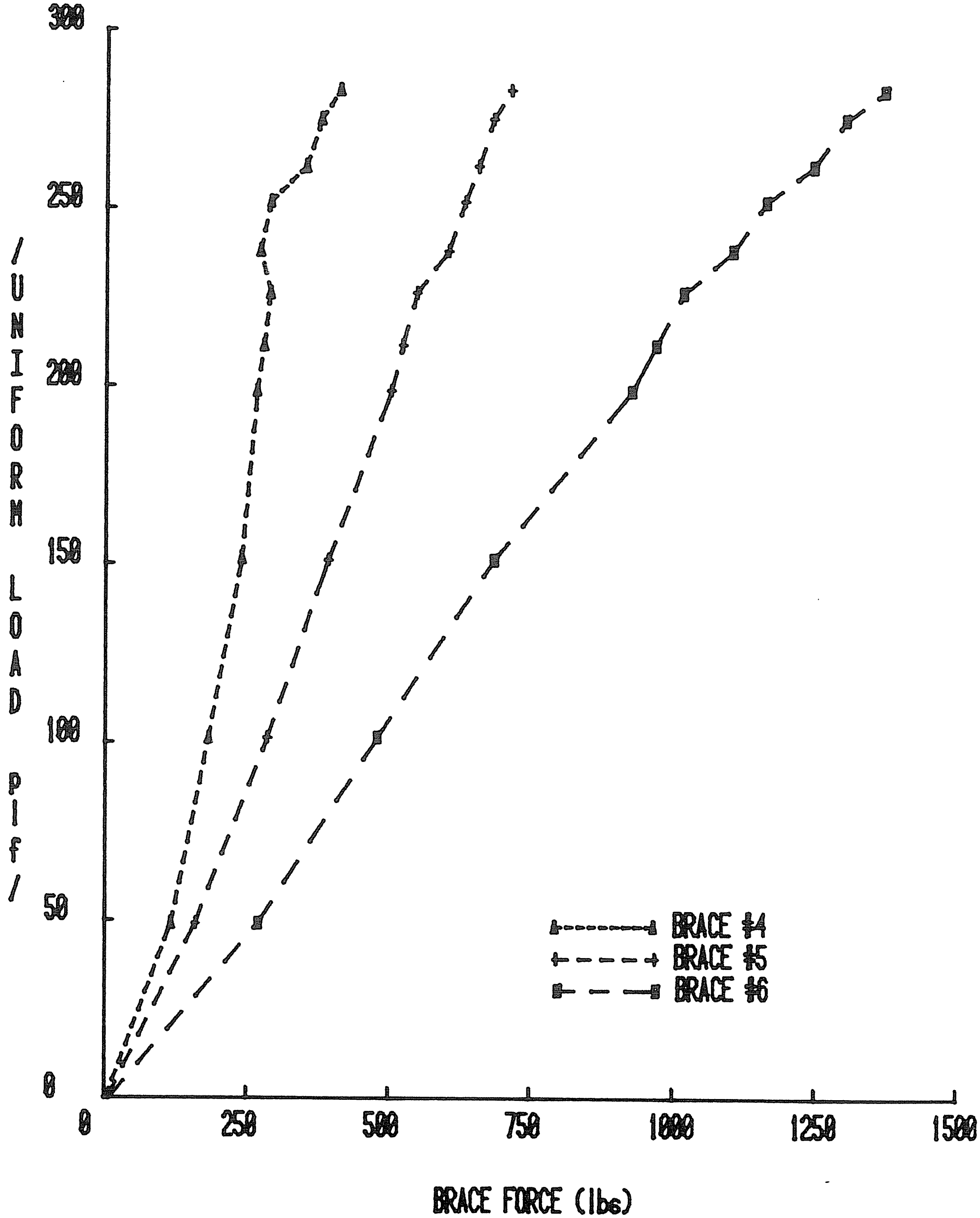


Figure F.20 Vertical Load vs. Brace Force at Midspan, Test 6-B Center Span,

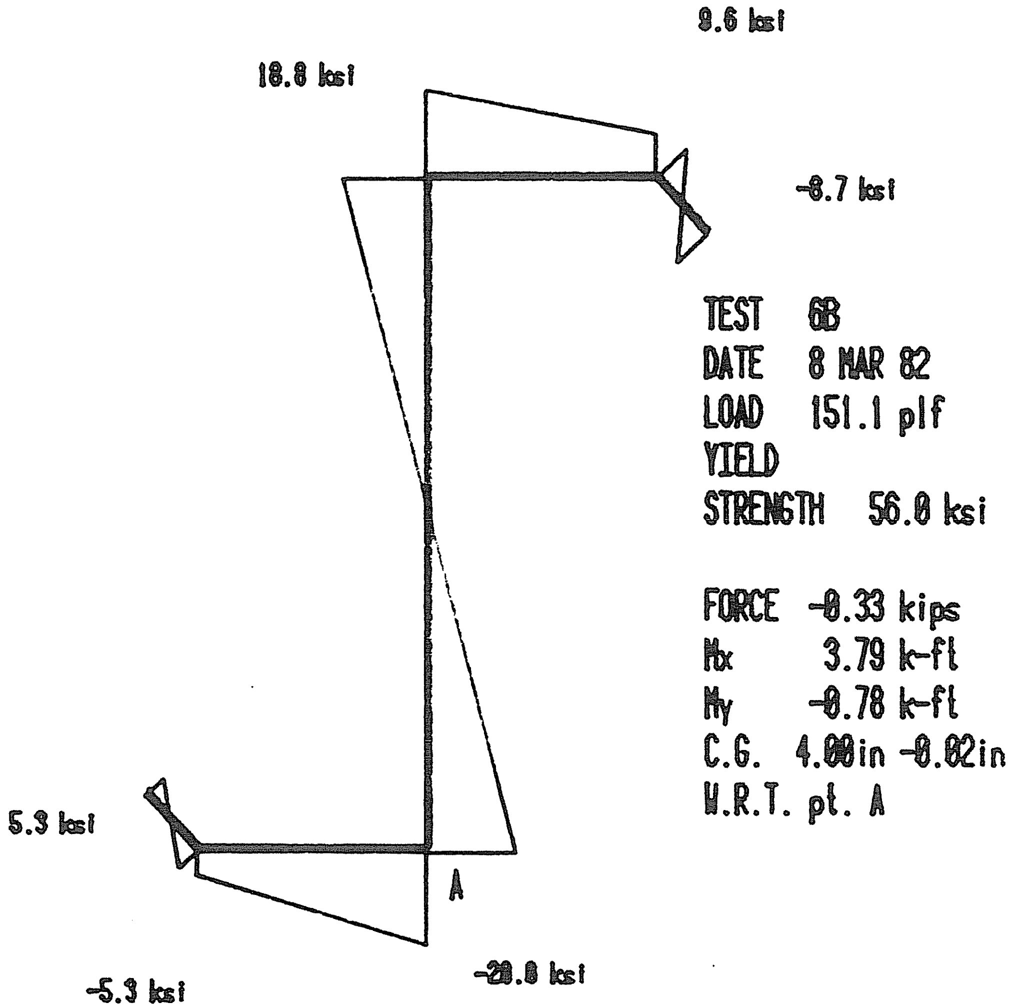


Figure F.21 Stress Distribution at 151.1 plf, Test 6-B

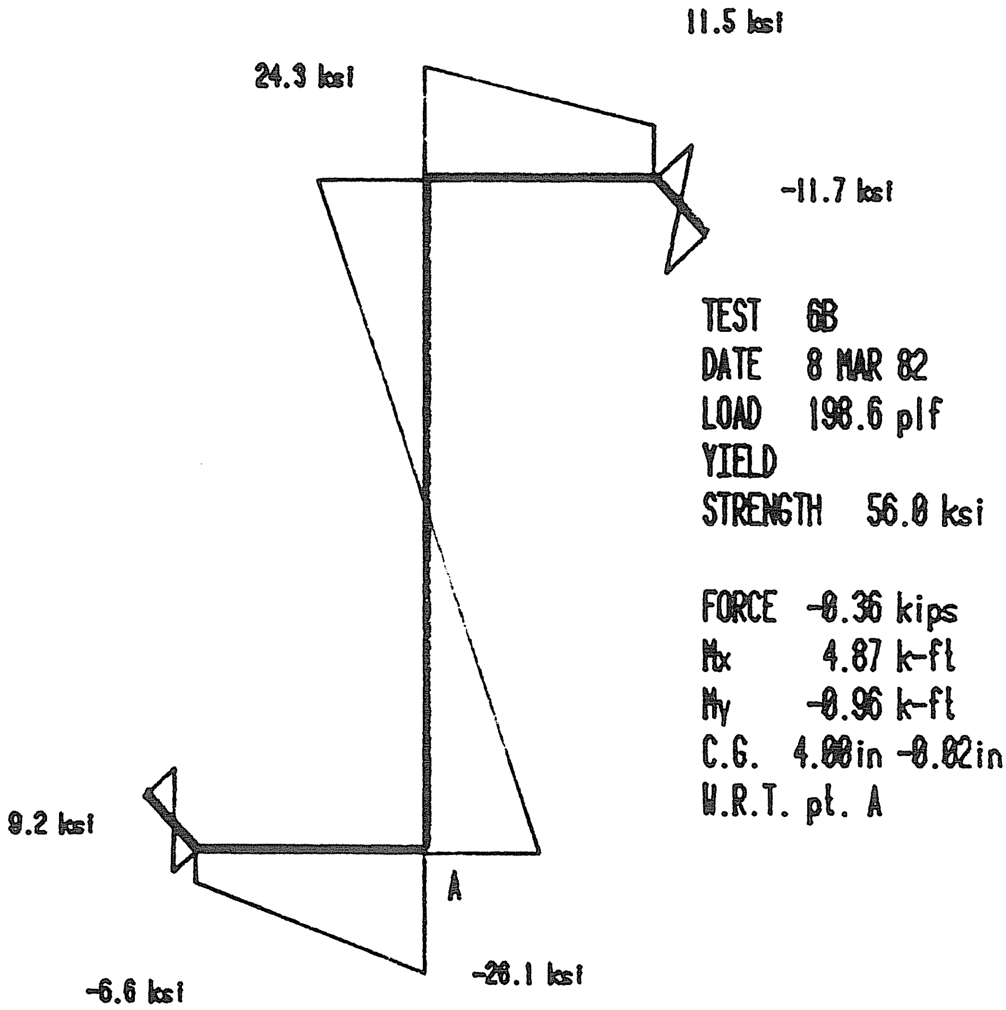


Figure F.22 Stress Distribution at 198.6 plf, Test 6-B

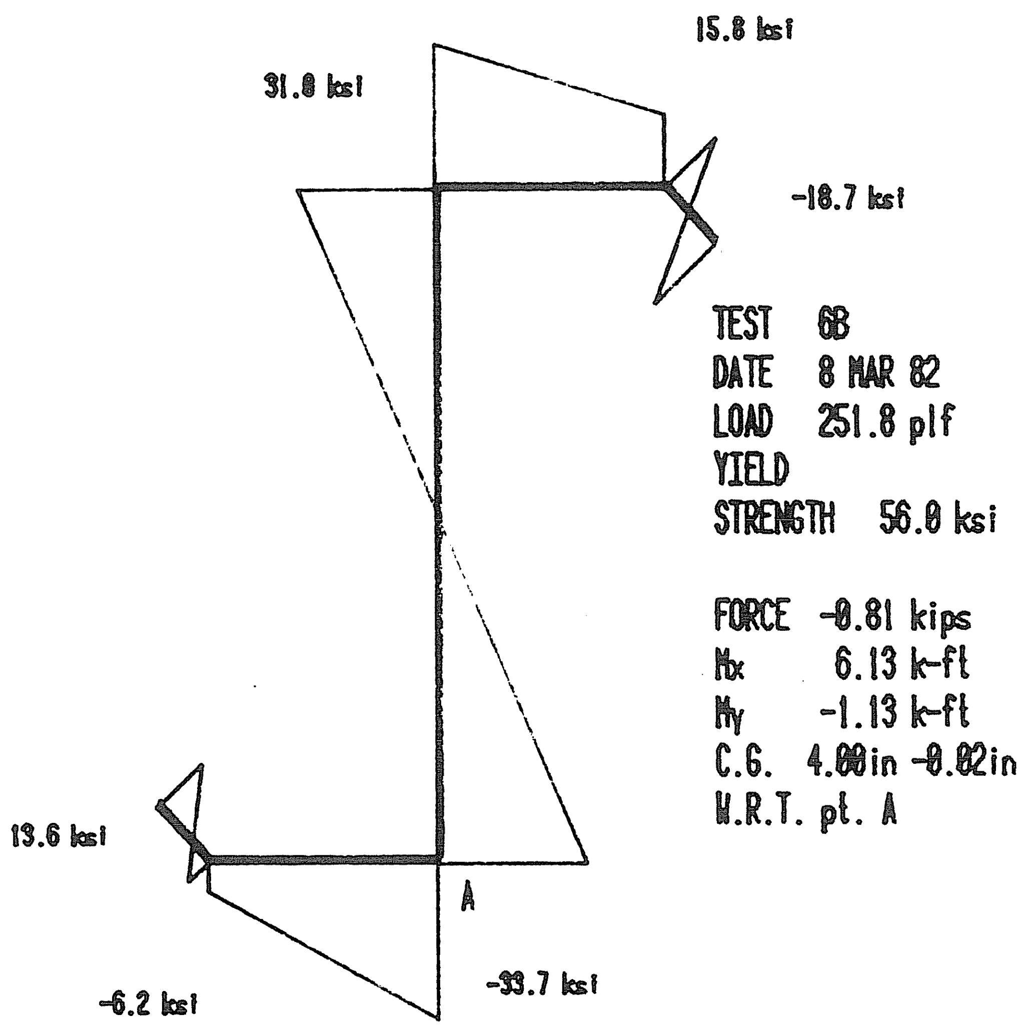


Figure F.23 Stress Distribution at 251.8 plf, Test 6-B

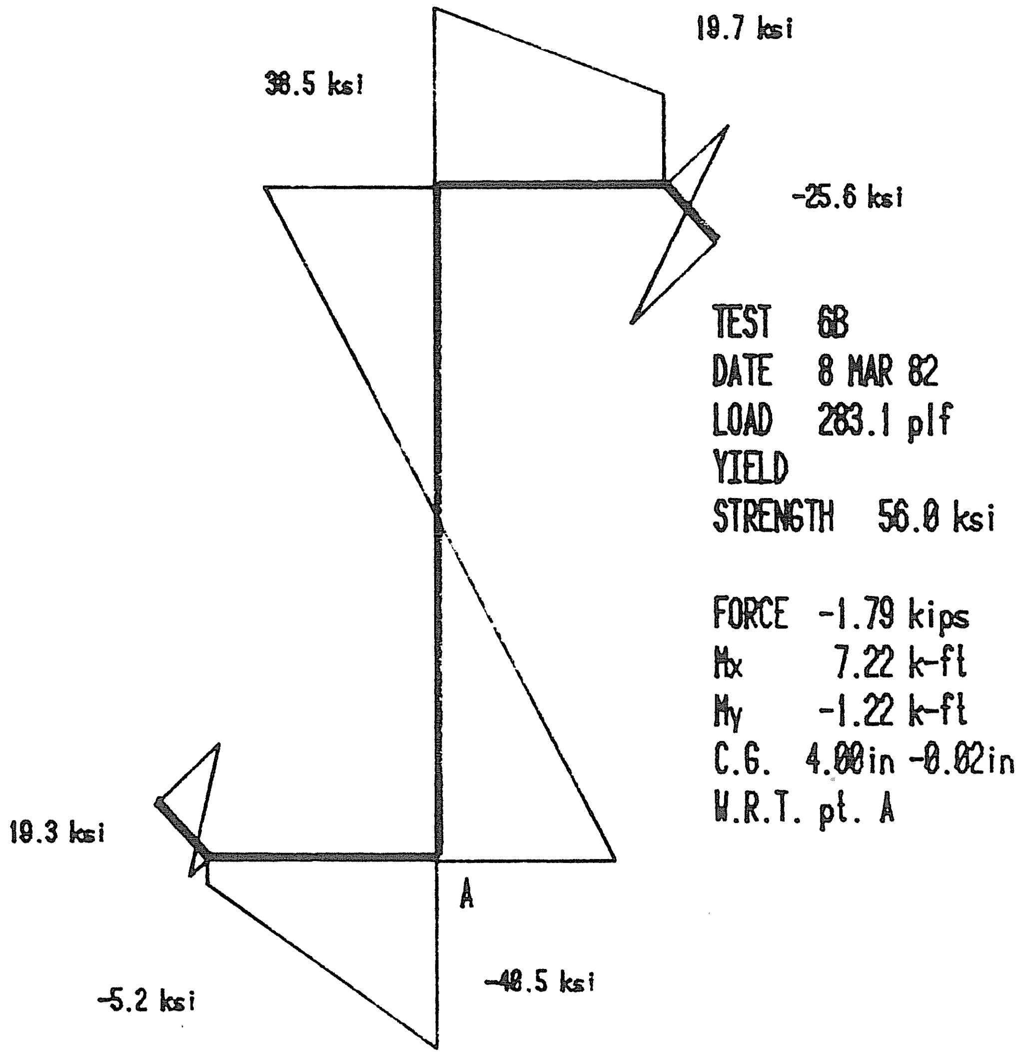


Figure F.24 Stress Distribution at 283.1 plf, Test 6-B

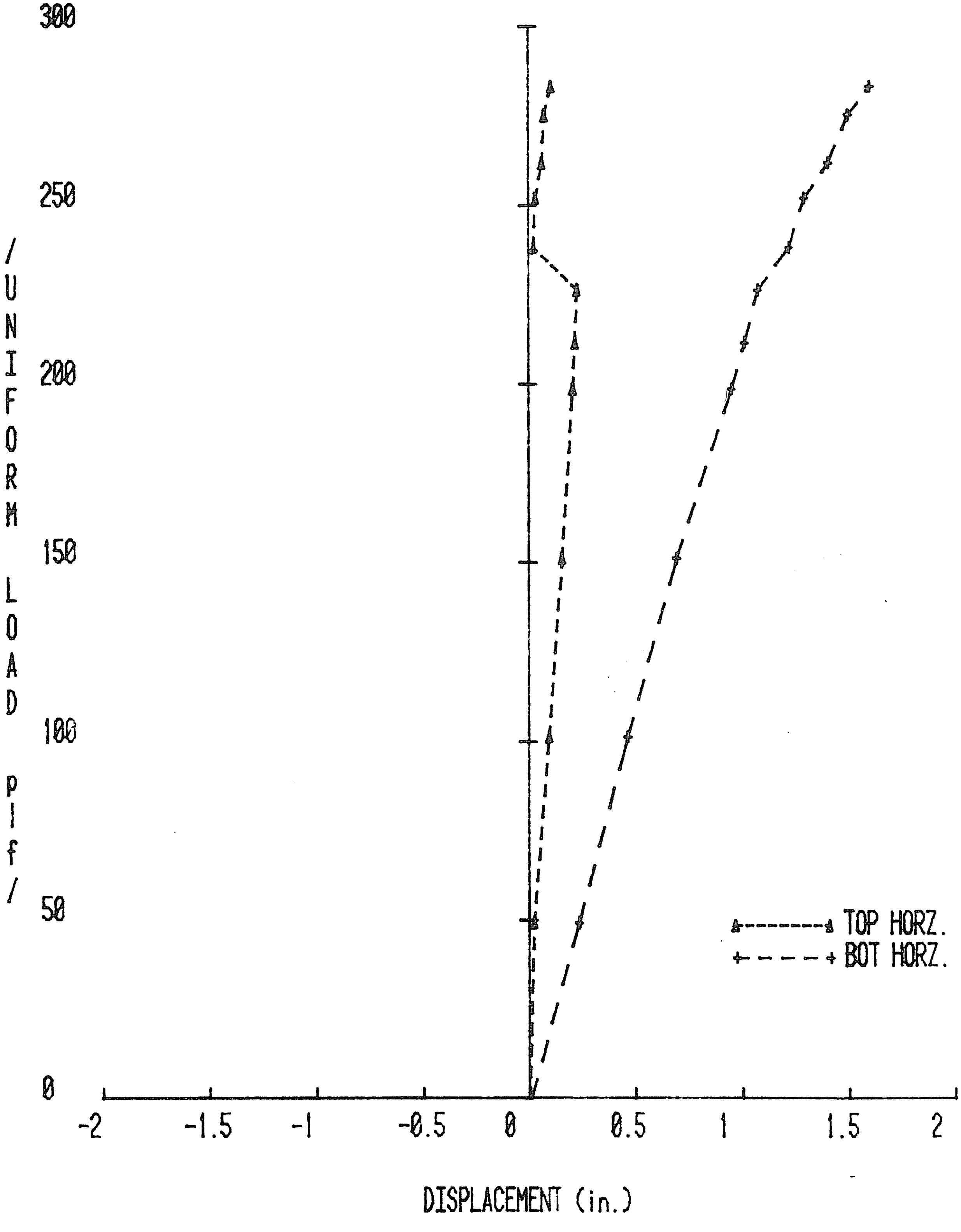


Figure F.25 Vertical Load vs. Lateral Displacements, Test 6-B