ROOF SYSTEMS BEHAVIOR

Progress Report

SIMPLE SPAN Z-PURLIN TESTS WITH VARIOUS RESTRAINT SYSTEMS

by

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Research Division

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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 the Metal Building Manufacturers Association (MBMA). The purpose of this research is to develop criteria for the design of roof systems as opposed to individual structural components. The study is currently limited to cold-formed C- or Z-purlin supported "conventional" roof systems. A conventional system is defined as one consisting of a ribbed panel fastened to purlins at closely spaced intervals using self-drilling fasteners. Standing seam systems or systems not requiring secondary framing members (purlins) are not currently being considered in the research program.

As a starting point two assumptions are made:

(a) For design purposes, 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.

The first phase of the research is to determine the necessary lateral restraint so when assumptions (a) and (b) are used, an adequate factor of safety exists. 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 assumption (a) is valid or to prevent roll of C-purlins.

This first progress report summarizes the results of nine simple span Z-purlin tests conducted with the objectives of (1) determining the effect of intermediate lateral braces, torsional restraint braces at the rafter and combinations on Z-purlin strength, (2) determining the magnitude and distribution of required restraint forces and (3) obtaining data for use in developing design methodology for restraint systems. Each test consisted of 19 ft. 7½ in. simple span loading to failure of two Z-purlins. Four parameters were varied in the test series: intermediate bracing, torsional restraint at the rafter, panel shear stiffness (Q), and panel torsional restraint (F). Six combinations of the parameters were tested as shown in Table 1 with purpose and configuration as follows:

Test I. 19 ft. 7½ in. simple span; two Z-purlins; gravity loading; intermediate discrete braces and torsional restraint.

Purposes:

To determine the effect of intermediate discrete braces and of torsional restraint at the rafters on lateral movement. To determine the magnitude of these restraining forces. To serve as base data.

Table 1. Test Matrix

Parameter / Test	Intermediate Bracing @¼ Pt.	Torsional Restraint @ Rafter	Panel Shear Stiffness Q	Torsional Restraint F	Remarks
I	X	X	X	X	Base Test
II	X*	X	X*		Greased top Flg.
III		X	X	X	
IV	X		X	X	
V		X		X	No side lap fasteners
VI		X	X	X	Same as III except panel connections reinforced

*Intermediate braces @ 2'-0" o.c.

Configuration:

Intermediate braces at ¼ points; torsional restraint at the rafters.

Test II. 19 ft. 7½ in. simple span; two Z-purlins; gravity loading; continuous lateral restraint.

Purpose:

To measure the lateral force required to restrain Z-purlins if restraint is provided only at the compression flange. To determine the distribution of restraining forces when lateral restraint is provided.

Configuration:

The top flange of the Z-purlin was greased and panel to purlin fasteners were not installed. Sidelap fasteners were installed. Base angles fastened to the panel were used to prevent excessive horizontal movement of the panel assembly. Lateral support was provided by 11 sets of equally spaced intermediate braces attached to the compression portion of the web near the compression flange and anchored to an external support. This configuration approximates infinite panel shear stiffness, Q.

Test III. 19 ft. 7½ in. simple span; two Z-purlins; gravity loading; torsional restraint at the rafters.

Purpose:

To determine the magnitude of torsional restraining forces required at rafters.

Configuration:

Torsional restraint provided at the rafter locations; no other restraint provided.

Test IV. 19 ft. 7½ in. simple span; two Z-purlins; gravity loading; intermediate lateral restraint.

Purpose:

To determine the magnitude and distribution of intermediate restraining forces when no torsional restraint is provided at rafter.

Configuration:

Intermediate lateral braces were provided at the quarter points. No torsional restraint at the rafter was provided.

Test V. 19 ft. 7½ in. simple span; two Z-purlins; gravity loading; torsional restraint at the rafters; no side lap fasteners.

Purpose:

To determine the effect of panel shear stiffness on purlin strength.

Configuration:

Lateral restraint was provided at the rafters but no intermediate braces were used. Side lap fasteners were not installed so that the panel shear stiffness, Q, would be minimum.

Test VI. 19 ft. 7½ in. simple span; two Z-purlins; gravity loading; torsional restraint at the rafter; reinforced panel at the rafter.

Purpose:

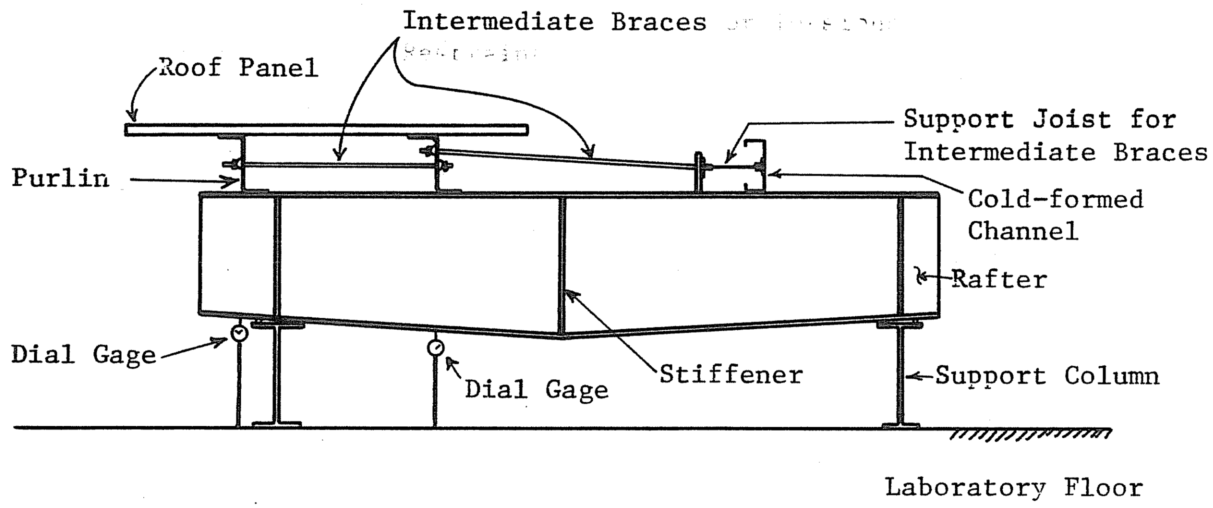
Same as Test III except near the rafter location side lap fasteners were doubled and the panel to purlin connection was reinforced to prevent premature panel shear failure.

Configuration:

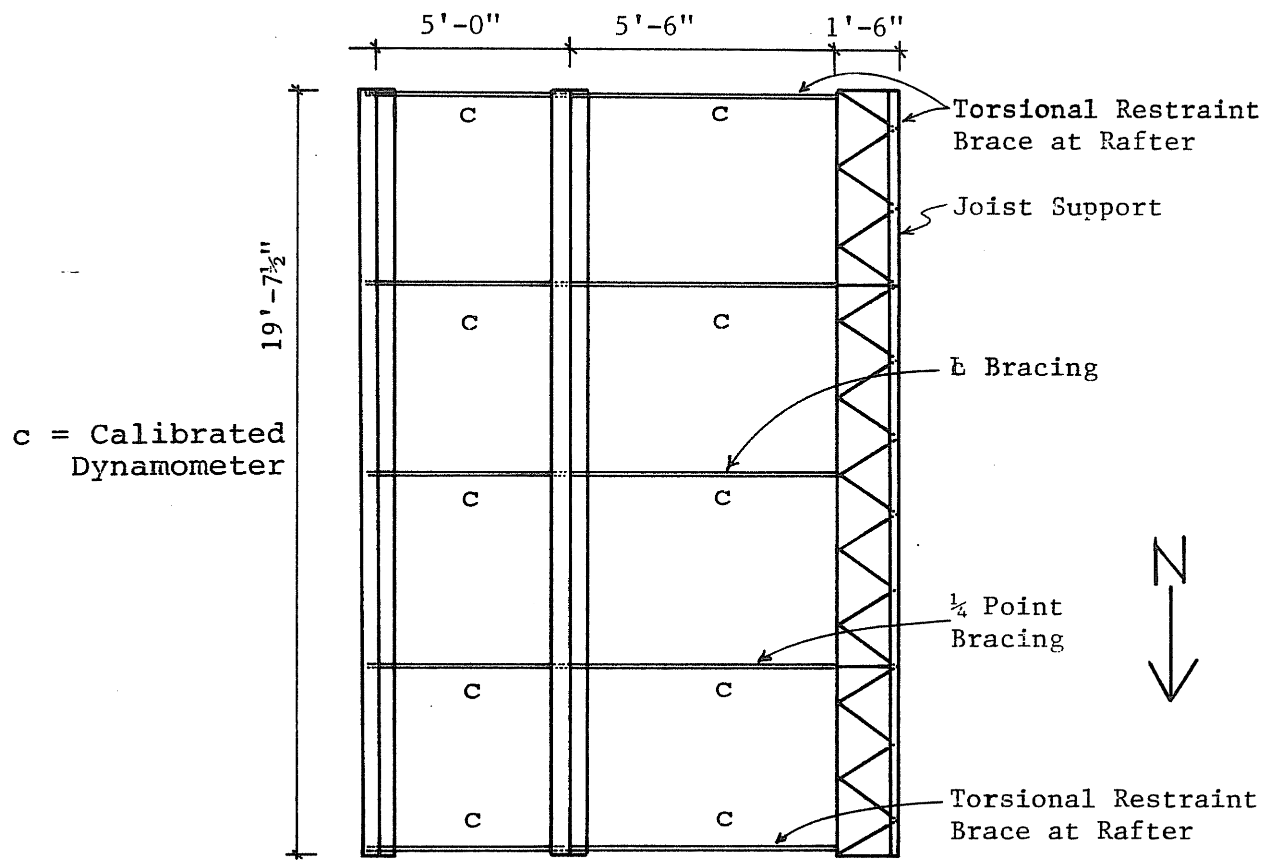
Same as Test III.

Details of the test set-up are shown in Figure 1. The purlins were supported by short sections of typical building rafters and simulated live load was applied using concrete blocks. The purlins were oriented with the top flanges facing in the same direction. Intermediate brace restraint and torsional restraint at the rafter was supplied using sections of steel tubing with threaded stud inserts. The braces were attached to the purlin as shown in Figures 1 and 4, and anchored to a relatively stiff structural member. The restraining member was a 20 in. deep standard open web steel joist with a cold formed C-section tack welded to the compression flange to prevent lateral buckling as shown in Figure 1. Four brace configurations were used in the test series. Figure 1(b) shows the location of intermediate quarter point braces and torsional restraint braces, Figure 1(c) shows the brace configuration to simulate infinite panel stiffness, Figure 1(d) shows the location of torsional restraint at the rafters and Figure 1(e) shows the configuration used for intermediate braces only.

The test purlins were all cold-formed from the same coil in a continuous operation. The test set-ups were constructed by laboratory personnel using standard industry procedures. Care was taken to ensure that the purlin webs were vertical before installation of the panel. The following is a complete description of the testing procedure and test results.

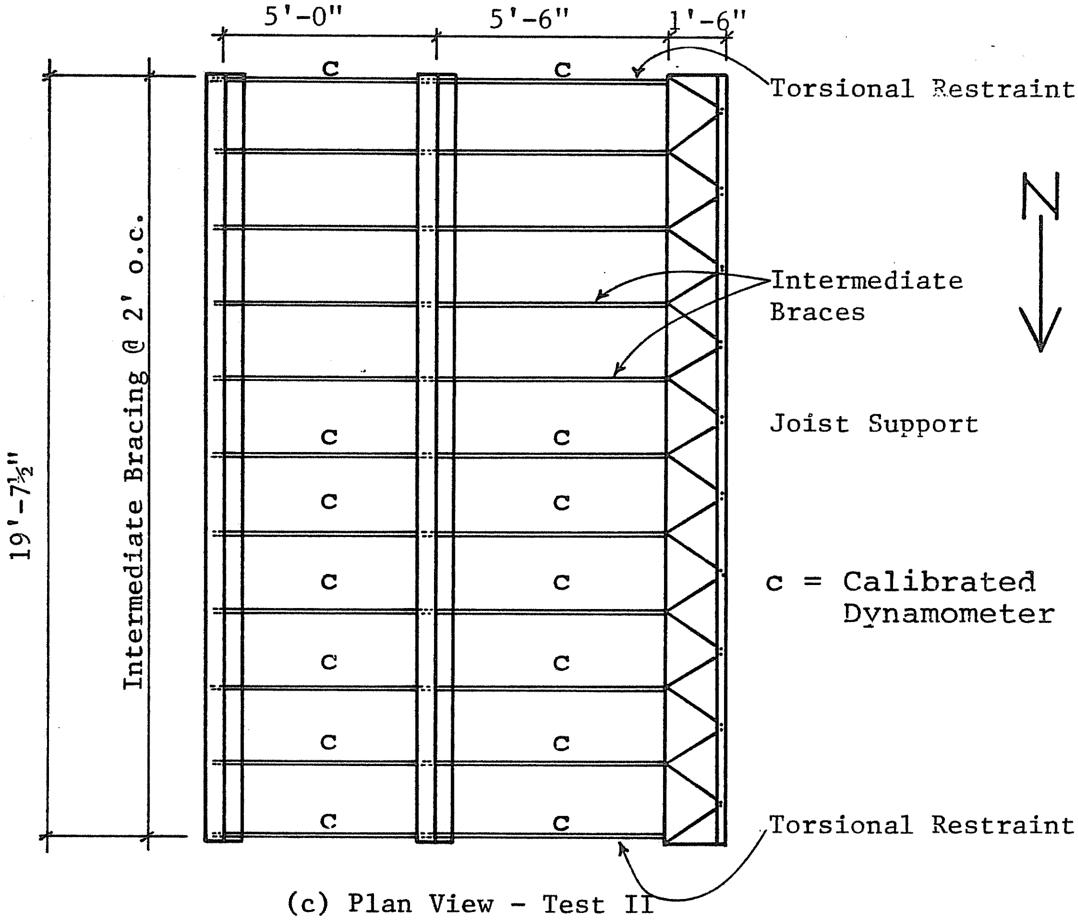


(a) Elevation of Test Set-up

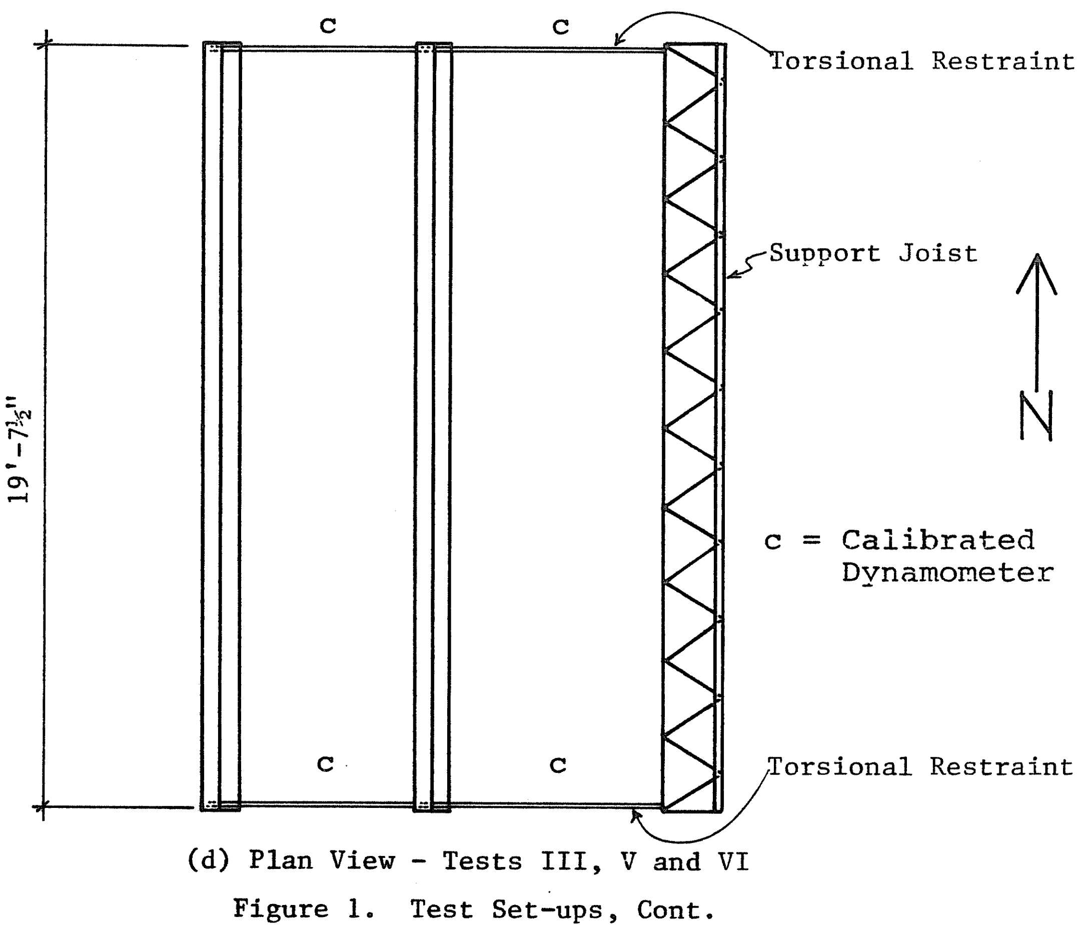


(b) Plan View - Test I

Figure 1. Test Set-ups

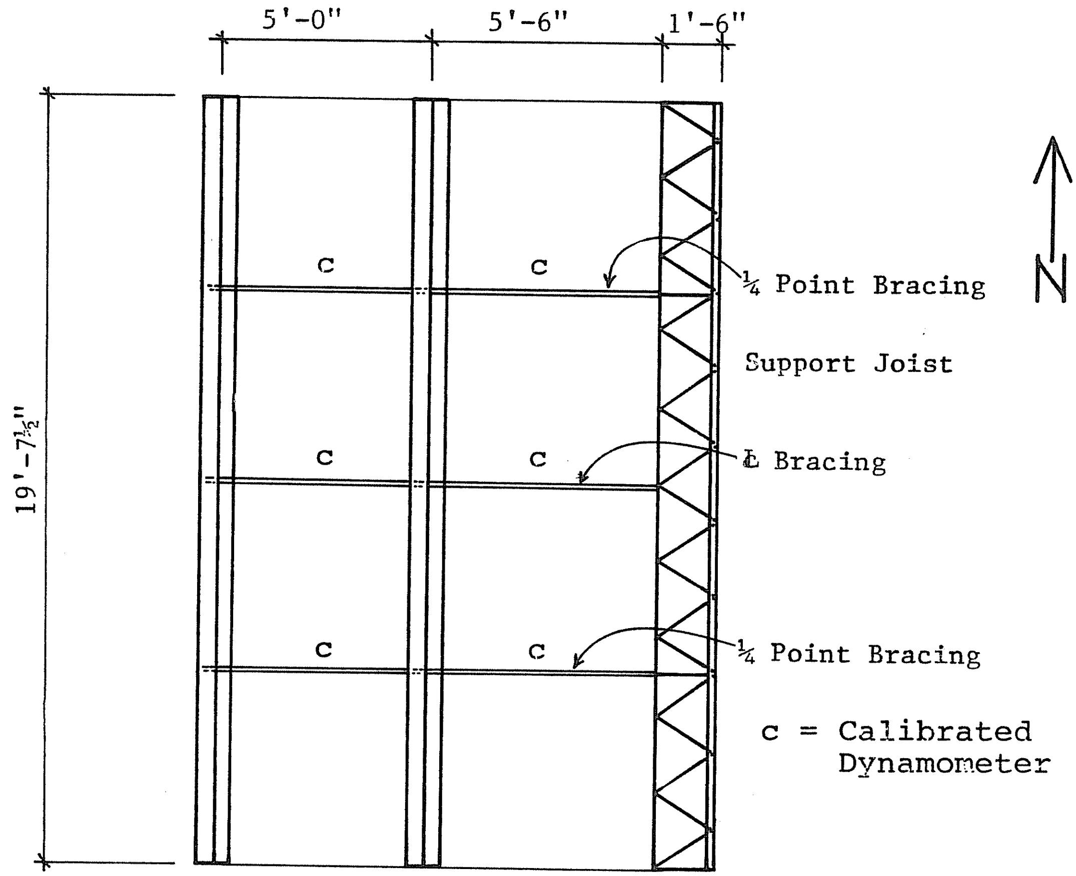


(c) Plan View - Test II



(d) Plan View - Tests III, V and VI

Figure 1. Test Set-ups, Cont.



(e) Plan View - Test IV

Figure 1. Test Set-ups, Cont.

CHAPTER II

TEST DETAILS

2.1 Test Components

Z-Purlins. The Z-purlins used for this test were supplied by MBMA. All Z-purlins were carefully measured and the dimensions are shown in Table 2. Table 3 shows cross-sectional properties and load and deflection data for a uniformly loaded simple span of 19 ft. 7½ in. calculated using AISI criteria with an assumed yield stress of 56 ksi. (Measured yield stress averaged approximately 58 ksi, Table 5.)

Panels and Fasteners. The panels were conventional panels with profile as shown in Figure 3. Sheet size was 3 ft. by 10 ft. and nominally 26 ga. Self-drilling fasteners, No. 12 by 1 in. were used for both sheet-to-sheet and sheet-to-purlin connection. Sheet-to-purlin fasteners were uniformly spaced at 12 inches on center and sheet-to-sheet fasteners were spaced at 30 in. on center (four per lap).

2.2 Test Set-up

General details of the test set-up are shown in Figure 1. To provide free rotation at the supports, the purlins were bolted to knife-edge bearings using ½ in. diameter machine bolts through the bottom flange of the purlin.

Table 2. Measured Z - Purlin Dimensions

Test No.		Total Depth (in.)	Thickness (in.)	Top					Bottom				
				W_1^* (in.)	T_1^* (in.)	R_1^* (in.)	R_2^* (in.)	θ_1^* (deg.)	W_2^* (in.)	T_2^* (in.)	R_3^* (in.)	R_4^* (in.)	θ_2^* (deg.)
I	W	8.12	0.093	2.50	0.50	0.468	0.281	44	2.56	0.50	0.468	0.281	44
	E	8.12	0.093	2.34	0.50	0.468	0.203	44	2.58	0.50	0.468	0.203	45
I-A	W	8.04	0.090	2.40	0.52	0.437	0.250	41	2.42	0.60	0.500	0.250	38
	E	8.06	0.090	2.36	0.56	0.500	0.250	43	2.42	0.51	0.437	0.250	44
II	W	7.96	0.090	2.40	0.50	0.500	0.218	43	2.50	0.46	0.500	0.218	43
	E	8.15	0.090	2.45	0.50	0.500	0.250	43	2.47	0.48	0.500	0.250	42
II-A	W	8.00	0.091	2.42	0.49	0.500	0.250	42	2.51	0.49	0.500	0.250	43
	E	7.96	0.086	2.50	0.47	0.500	0.219	45	2.46	0.47	0.500	0.218	42
II-B	W	7.90	0.087	2.34	0.45	0.500	0.250	43	2.43	0.48	0.437	0.250	44
	E	8.09	0.087	2.30	0.45	0.500	0.218	44	2.42	0.49	0.437	0.218	48
III	W	8.0	0.092	2.45	0.48	0.500	0.281	42	2.55	0.50	0.500	0.281	45
	E	8.14	0.090	2.55	0.46	0.437	0.250	43	2.50	0.48	0.437	0.250	42
IV	W	8.09	0.084	2.42	0.55	0.531	0.218	41	2.42	0.55	0.437	0.250	41
	E	8.10	0.086	2.38	0.55	0.500	0.218	42	2.38	0.62	0.500	0.250	42
V	W	7.95	0.091	2.45	0.48	0.500	0.250	43	2.48	0.49	0.500	0.250	44
	E	7.98	0.090	2.48	0.45	0.470	0.250	44	2.40	0.49	0.470	0.250	44
VI	W	8.13	0.087	2.40	0.48	0.500	0.218	44	2.41	0.50	0.437	0.218	44
	E	8.13	0.086	2.34	0.48	0.437	0.218	44	2.80	0.47	0.500	0.218	44

*See Fig. 2

Table 3. Z - Purlin Properties (F_y = 56 ksi, Span - 19.625')

Test No.		Gross I (in^4)	Gross S_t (in)	Gross S_b (in)	Strength I (in^4)	Strength S_t (in)	Strength S_b (in)	b_e (in)	F_e (ksi)	F_t (ksi)	F_{bw} (ksi)	Moment Cpcty. (AISI) M_c (Ft-k)	M_t (Ft-k)	M_w (Ft-k)	(1.67*allowable) M_u (Ft-k)	W_u (lb/Ft)	Deflection I (in^4)	Δ/100 plf (in)
I	W	13.43	3.33	3.36	13.43	3.33	3.36	2.13	33.60	33.60	33.36	9.33	9.41	10.08	15.58	323.57	13.43	0.843
	E	13.30	3.26	3.37	13.30	3.26	3.37	2.04	33.60	33.60	33.36	9.13	9.43	9.66	15.25	316.88	13.30	0.850
I-A	W	12.74	3.16	3.25	12.74	3.16	3.25	2.06	33.60	33.60	33.19	8.86	9.09	9.44	14.79	307.26	12.74	0.888
	E	12.55	3.16	3.14	12.55	3.16	3.14	2.02	33.60	33.60	33.17	8.84	8.80	9.43	14.69	305.18	12.55	0.901
II	W	12.26	3.10	3.13	12.26	3.10	3.13	2.09	33.60	33.60	33.27	8.68	8.76	9.23	14.52	301.70	12.26	0.922
	E	12.99	3.22	3.23	12.99	3.22	3.23	2.11	33.60	33.60	33.08	9.03	9.03	9.59	15.08	313.16	12.99	0.871
II-A	W	12.59	3.17	3.20	12.59	3.17	3.20	2.08	33.60	33.60	33.31	8.86	8.96	9.49	14.80	307.47	12.59	0.899
	E	11.78	2.99	2.99	11.78	2.99	2.99	2.19	33.60	33.60	32.91	8.39	8.37	8.80	13.98	290.35	11.78	0.960
II-B	W	11.37	2.89	2.93	11.37	2.89	2.93	2.00	33.60	33.60	33.06	8.09	8.20	8.60	13.51	280.66	11.37	0.995
	E	11.95	2.96	3.01	11.95	2.96	3.01	1.99	33.60	33.60	32.87	8.29	8.44	8.68	13.85	287.78	11.95	0.946
III	W	12.76	3.20	3.25	12.76	3.20	3.25	2.08	33.60	33.60	33.39	8.07	9.10	9.71	14.98	311.24	12.76	0.887
	E	13.02	3.24	3.23	13.02	3.24	3.23	2.21	33.60	33.60	33.09	9.07	9.05	9.64	15.11	313.90	13.02	0.869
IV	W	12.07	3.02	3.01	12.07	3.02	3.01	2.12	33.60	33.60	32.59	8.46	8.44	8.77	14.09	292.66	12.07	0.937
	E	12.26	3.06	3.06	12.26	3.06	3.06	2.07	33.60	33.60	32.77	8.56	8.58	8.93	14.29	296.91	12.26	0.923
V	W	12.38	3.14	3.16	12.38	3.14	3.16	2.14	33.60	33.60	33.36	8.79	8.86	9.36	14.69	305.08	12.38	0.913
	E	12.19	3.09	3.08	12.19	3.09	3.08	2.14	33.60	33.60	33.25	8.67	8.63	9.27	14.41	299.42	12.19	0.928
VI	W	12.33	3.06	3.07	12.33	3.06	3.07	2.09	33.60	33.60	32.84	8.57	8.59	8.96	14.32	297.44	12.33	0.918
	E	12.58	3.03	3.23	12.58	3.03	3.23	2.04	33.60	33.60	32.74	8.48	9.05	8.83	14.17	294.35	12.58	0.899

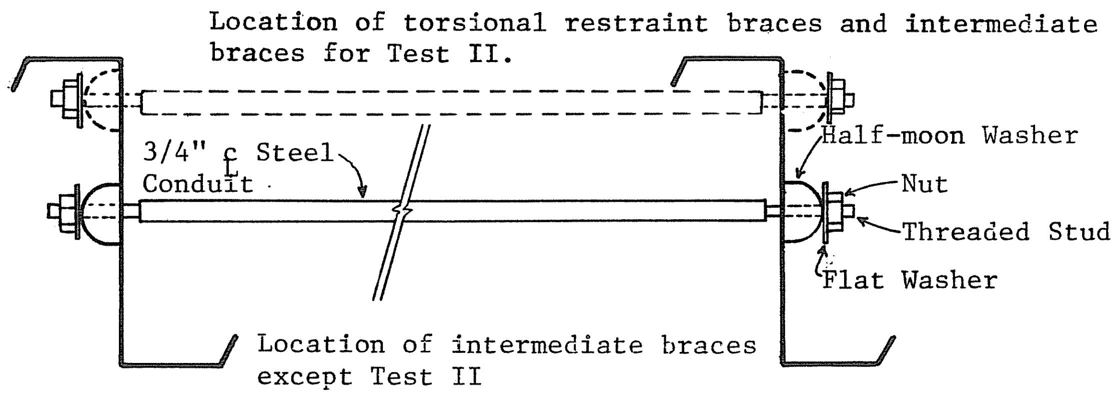
t = top
b = bottom
Note: All calculations are based on an assumed yield stress of 57 ksi. Measured yield stresses are slightly higher (Table 5).

The knife edge bearings were supported on rafter sections which in turn were supported on short column sections resting on the laboratory floor. Two ½ in. diameter rollers were inserted between the rafter sections and column to allow the rafter sections to rotate.

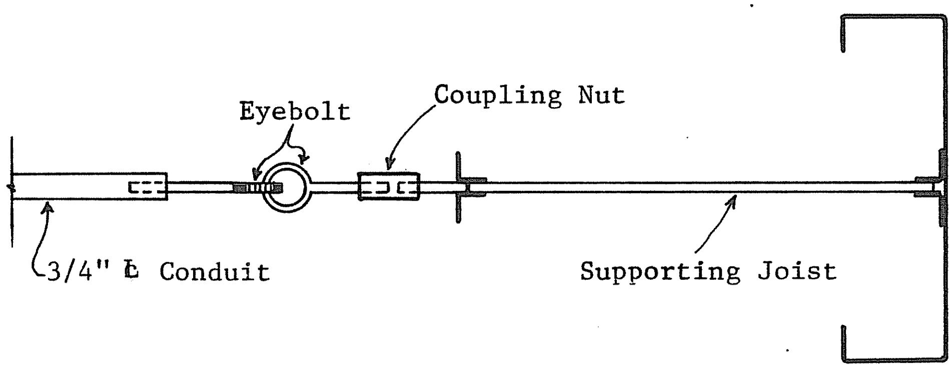
Intermediate and torsional restraint braces were fabricated from 3/4 in. diameter steel electrical conduit. Nuts were welded into each end of the conduit and a 9 in. length of ½ in. diameter threaded stud was inserted. Holes were drilled at the proper location in the purlin webs and connection was made using half moon and flat washers together with a standard nut as shown in Figure 4(a) for a tension brace connection. The washers and nuts were placed on the opposite side of the web for a compression brace connection.

A standard 20 in. deep bar joist was used to react the intermediate and torsional restraint brace forces. The joist was connected to one side of the rafters so that the plane of its web was horizontal. The brace connection to joist is shown in Figure 4(b). Two eye bolts were used to eliminate rotational restraint in the connection. The calculated stiffness of the supporting joist was 6.71 kips/in for a single concentrated force at midspan.

For all tests, the torsional restraint braces at the rafter locations were placed as near to the top flange as possible. Except for Test II, all intermediate braces were located at the web mid-depth. For Test II, the intermediate braces were placed at the same relative location as used for the torsional restraint braces. See Figure 4(a).



(a) Tension Brace to Purlin Connection



(b) Brace Connection to Supporting Joist

Figure 4. Intermediate and Torsional Restraint Brace Connections

For all tests except II, the panels were connected to the purlins using self drilling fasteners through the panel and the purlin top flange. For Test II, the top flange of each purlin was greased and the panels were laid directly on the flanges. Standard base angles were fastened to the panel on each side of the flanges with approximately ½ in. clearance to prevent the panel assembly from sliding off of the purlins. In all tests except V, adjacent panels were connected using side-lap fasteners. In Test V no side lap fasteners were installed. In Test VI, a base angle was placed parallel to the panel ribs at the rafter locations and bolted to the top flange of the purlins. Fasteners were installed at 6 in. on center through the panel and angle and side lap fastener spacing in the four outside laps was decreased to 6 in. on center.

2.3 Instrumentation

Instrumentation consisted of calibrated dynamometers, strain gages, dial gages, and linear displacement transducers. The calibrated dynamometers were typical intermediate or torsional restraint braces with a full strain gage bridge installed at approximately the brace centerline. The braces were then calibrated using a universal testing machine. Calibrated dynamometer locations are shown in Figures 1(b), (c), (d) and (e) for the various tests.

Strains near the midspan of the outside purlin (the

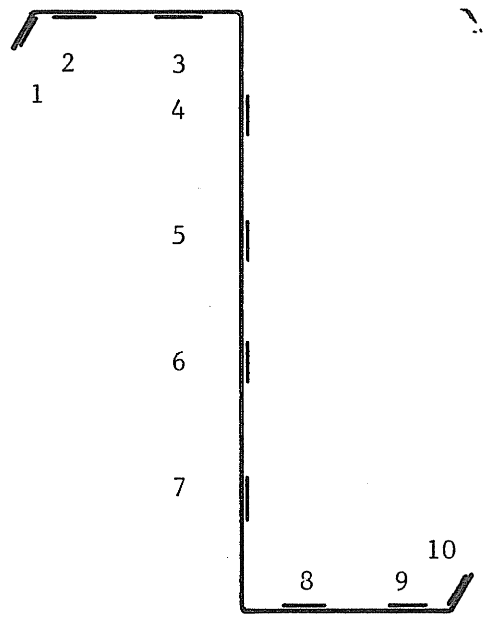


Figure 5. Location of Strain Gages

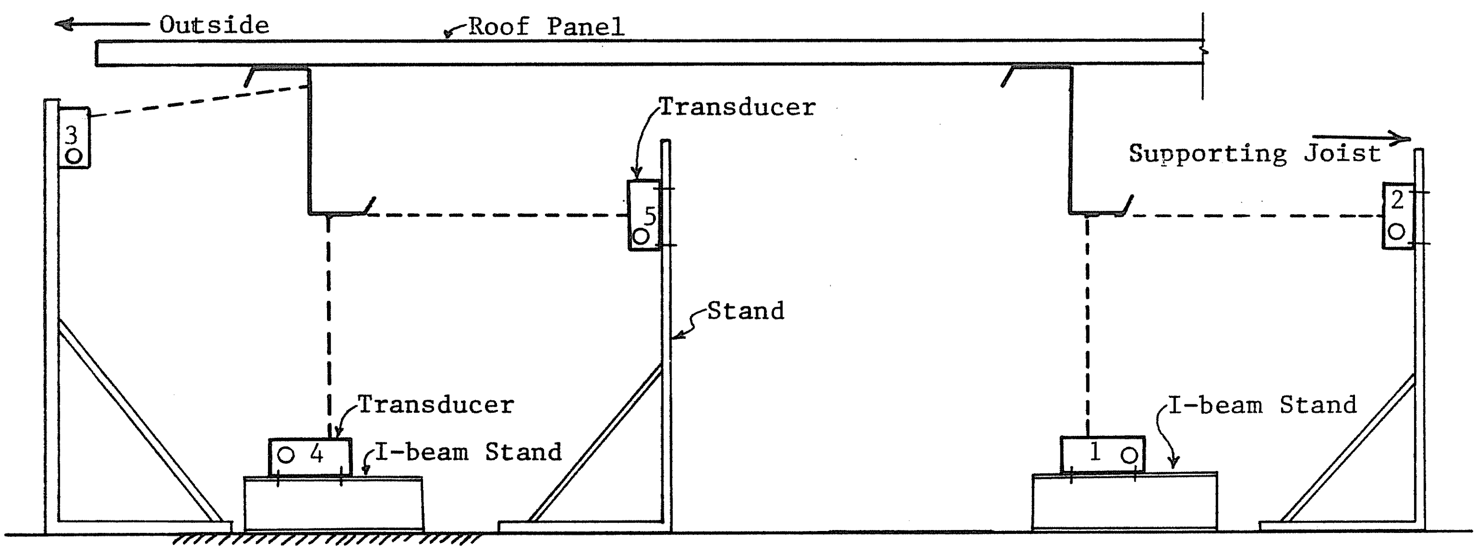


Figure 6. Location of Displacement Transducers

purlin farthest away from the supporting joist) were measured at 10 locations using strain gages. Figure 5 shows the location of the gages at the cross-section. One gage was installed on each lip, two gages on each flange, and four gages equally spaced along a vertical line on the web, one sided only.

Five linear displacement transducers were used to measure vertical and lateral displacement of the purlins. Two transducers were used to measure vertical deflection at the midspan of the purlins. Three transducers were used to measure lateral displacement, also at the midspan. As shown in Figure 6, two transducers measured horizontal displacement of the bottom flange and one transducer was used to measure horizontal displacement of the top flange of the outside purlin. Dial gages were placed directly underneath the joist support points on the rafter as shown in Figure 1(a). Data from these gages permitted a correction for girder deflection.

Gravity load was measured by the number of concrete blocks placed on the test purlins. Each block was known to weigh 33 ± 0.1 pounds.

2.4 Testing Procedure

At the beginning of each test, approximately 20% of the calculated load using the AISI criterion and constrained bending assumption was applied without recording any data and then removed. Following this initial loading, zero readings were recorded for all dynamometers, strain gages, displacement transducers and the dial gages. The system was then loaded in 16.5 plf increments. After each increment, readings of all instrumentation were recorded. The system was loaded until failure occurred and the failure mode and other observations recorded for each test.

2.5 Supplementary Tests

Coupon Tests. Standard tensile coupon tests were made from samples cut from typical purlin and panel material. Results from two tests of each material type are given in Section 3.8. Identical material was used in all tests.

Rotational Rigidity Tests. The rotational rigidity factor "F" of the panel to purlin connection used in the testing program was measured by personnel of the Butler Manufacturing Research Center, Grandview, Missouri. Two tests were conducted using the procedure described in the paper "Connection Strength in Thin Metal Roof Structures" by R.W. Haussler and R.F. Pabers published in the proceedings of the Second Specialty Conference on Cold-Formed Steel Structures, St. Louis, Missouri, October 1973. Material taken from the lot of purlins and panels supplied for the research program was used in the F-tests.

A schematic of the test set-up is shown in Figure 7. For each test a length of panel was supported at one end with solid hardwood blocks contoured to match the cross-section of the test panels and clamped between two support channels.

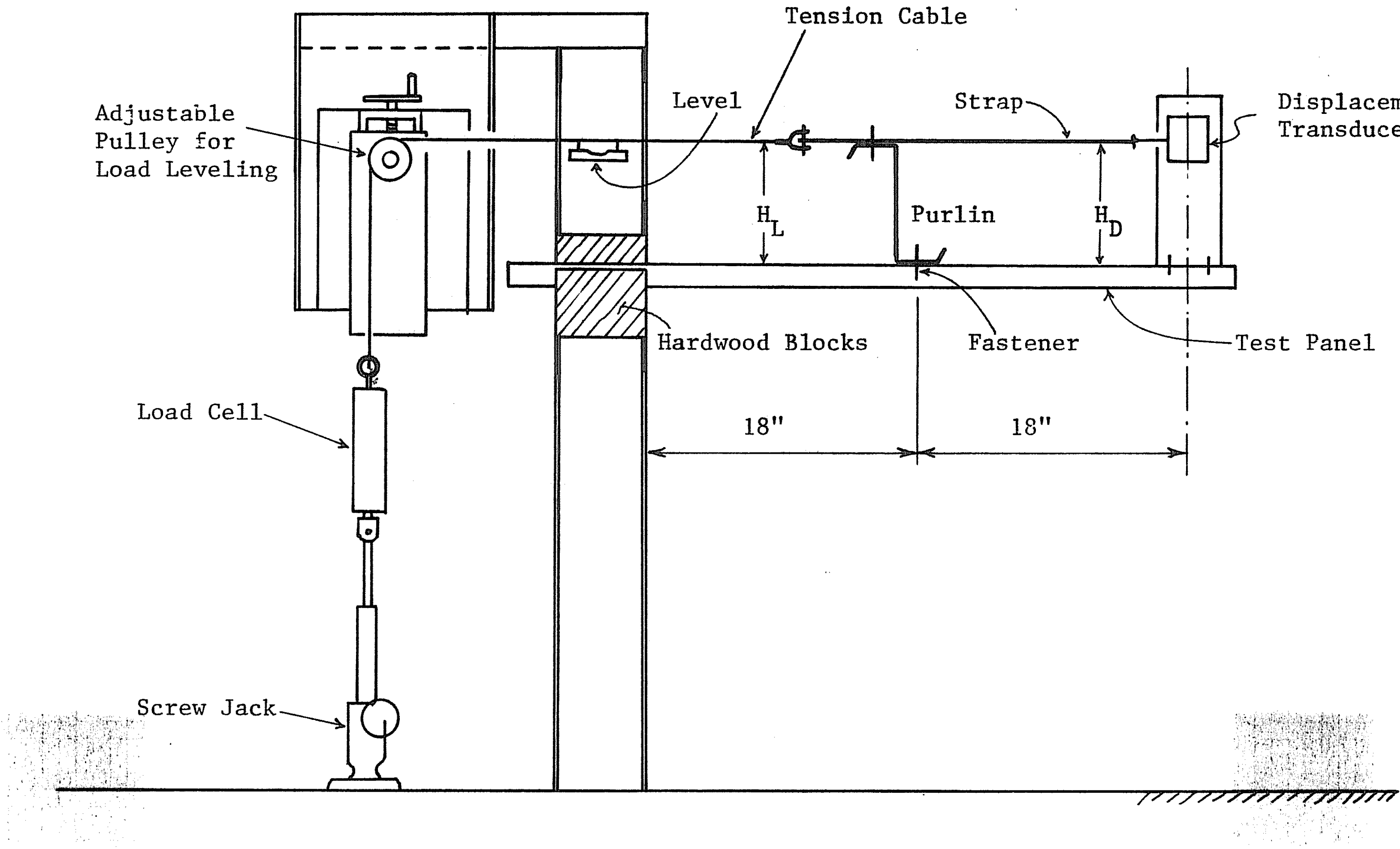


Figure 7. F-Test Set-up

At midlength of the cantilever, a Z-purlin was attached using self-drilling fasteners at 12 in. on center. Near the free end a displacement transducer was attached to the panel. A thin flexible steel strap was then attached between the purlin flange opposite the panel and the transducer measuring cable. Load was applied using a motor driven screw jack and a tension cable connected to the purlin flange as shown in Figure 7. Vertical adjustment of this cable was made to ensure load application parallel to the horizontal axes of the test panel. The load was monitored using a calibrated load cell.

Load was applied in increments to cause approximately 0.50 in. of lateral deflection at the purlin flange. The load was held constant for a time period of 1-3 minutes at each load increment to obtain equilibrium. The load was increased until either panel buckling or severe panel deformation occurred.

The rotational rigidity factor "F" was determined from

$$F = \frac{P \cdot H_L}{\tan^{-1} \frac{\Delta}{H_D}} \qquad (2)$$

where P = applied load per unit width of panel, H_L = load height (see Figure 7), H_D = displacement transducer height (see Figure 7) and Δ = horizontal displacement of the purlin flange. For units of inches and pounds, F has the unit lb-in/in/radian. Results are given in Section 3.8.

Diaphragm Tests. Diaphragm tests (Q-tests) were not completed in time for inclusion in this progress report.

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 deflection of top and bottom flanges of the outside purlin and the bottom flange of the inside purlin. The vertical deflection plots also include theoretical deflection as computed assuming constrained bending.

$$\Delta = \frac{5wL^4}{384EI} \tag{1}$$

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. Simulated live load vs. intermediate brace or torsional restraint brace forces for at least one half of the span are also included.

Results for Tests I to VI are found in appendices A through E, respectively. Table 4 is a summary of results and a detailed description of each test is found in the appropriate appendix.

Table 4. Summary of Test Results

Test No.	AISI/Constrained Bending (plf)	Actual Failure Load (plf)	Failure Mode	Remarks
I	316.9	219.9	Local buckling of flange and/or web.	Initial failure was end bearing; purlins were repaired.
I-A	305.2	226.1	Local buckling of flange and/or web.	
II	310.7	132.0	Purlins rolled over.	Intermediate brace restraint system failed.
II-A	290.3	135.3	Purlins rolled over.	Several intermediate braces carried no load.
II-B	280.7	188.2	Tension flange lateral buckling	Outside two intermediate braces in compression.
III	311.2	193.6	Center portion of the purlin rolled.	Panel to purlin connection failed near support.
IV	292.6	231.0	Local buckling of the flange and/or web.	North end of the purlins were rolled toward west, (Fig. 1(d))
V	299.4	191.9	Purlins rolled.	Panel to purlin connection failed near supports.
VI	294.3	230.0	Local buckling of the top flange and/or web.	Panel to purlin connection was reinforced.

Note: If failure occurred during a laod increment, the failure load was calculated assuming the partial increment was uniformly distributed. Symmetry of loading was maintained during the application of load increments.

In the discussion of test results that follows, "exterior" or "external" refers to the purlin farthest from the lateral support joist and "interior" or "internal" refers to the purlin closest to the support joist. Only the exterior purlin was strain gaged.

3.2 Test Series I

The purpose of this series was to provide base data for comparison to all remaining tests. The test configuration consisted of intermediate braces at midspan and quarter points, and torsional restraint braces at the rafters. Test I was first conducted using a span of 20 ft. 0 in. center-to-center of rafter webs. Premature failure was caused by web crippling at the knife edge bearings. Subsequently, the span was reduced to 19 ft. 7½ in. to obtain a larger bearing length at each end. The purlins were then repaired and the test repeated. Failure occurred at 219.9 plf by local buckling of the flange and/or web approximately 1 ft. from the midspan. Using the AISI criteria and the constrained bending assumption, the predicted failure load was 316.9 plf.

To verify that the repaired purlins did not affect test results, the test was repeated as Test I-A. Failure occurred at 226.1 lbs. per linear ft. again by local buckling of the flange and/or web approximately 1 ft. from the midspan. The predicted failure load was 305.2 lbs. per linear ft.

Test summary sheets found in Appendix A describe in detail the test results. In both tests, the measured vertical deflection exceeded the predicted values with the internal purlin deflecting more than the external purlin, Figures A.5 and A.16. Brace forces were somewhat erratic, except at midspan, for Test I possibly due to the repaired ends, Figures A.6 to A.8. Brace forces were consistent for Test I-A, Figures A.17 to A.19. The largest forces were measured at the rafter (torsional restraint braces) and the smallest at midspan, Figure A.20. Strains were only measured for Test I. The distribution varied from the constrained bending assumption, Figures A.9 and A.10.

For Test I-A, exterior and interior brace forces at midspan and at the ¼ points were essentially equal. The ratio of interior to exterior brace forces at the rafter was near 4.0. Total brace force as a percentage of supported vertical load was approximately 20% for the exterior purlin and 40% for the interior purlin.

3.3 Test Series II

The purpose of this series was to measure the restraint required if the top flange of both purlins was continuously supported. Test Summary sheets in Appendix B detail the results for three tests: II, II-A, and II-B. Test II was terminated at 132 plf because of failure of the lateral support joists. Test II-A was conducted with all intermediate and torsional restraint braces placed so that only tension could be resisted (see Figure 4(a)). The outside (nearest the rafters) four braces went slack under light loading. Failure occurred at 135.3 plf due to the inability of the web to restrain lateral movement of the tension flange.

Test II-B was conducted only after it was determined which braces would be in tension and which in compression (by trial and error). Failure occurred at 188.2 plf due to tension flange buckling. Measured vertical deflections were very close to predicted values, Figure B.27. Brace forces at the rafters were in compression (Figure B.28), near zero at the first inside locations (Figure B.29) and in tension for the remaining locations to the midspan (Figures B.31 to B.34). The distribution along the purlins is plotted in Figures B.35 and B.36. Strains were only measured in Test II and were found not to vary with the constrained bending assumption, Figures B.11 and B.12.

The ratio of exterior to interior brace forces at a transverse location varied considerably along the span (see Test Summary sheet). Summation of brace forces as a percent of supported vertical load was approximately 17% for the exterior purlin and 39% for the interior purlin.

3.4 Test III

This test was conducted to determine the magnitude of required torsional restraining forces at the rafter. A Test Summary sheet is included in Appendix C. Failure occurred when the center portion of the purlins rolled at a load of 193.6 plf. Subsequent investigation showed that the failure was caused by tearing of the panel in shear at fastener locations near the rafters. Measured vertical deflections of the exterior purlin agreed with predicted values; interior purlin deflections were greater than predicted (Figure C.5). Good to excellent agreement exists between brace forces at opposite rafters, Figure C.6. Measured strains were relatively consistent with the constrained bending assumption, Figure C.7.

The ratio of interior to exterior braces forces varied from approximately 2.0 to near 4.0. The total brace force as a percent of supported vertical load varied from approximately 10 to 30%. Near failure the maximum brace force exceeded 900 lb.

3.5 Test IV

Test IV was conducted to determine the magnitude of intermediate brace forces when torsional restraint is not supplied at the rafter. Test results are shown in Appendix D. Failure occurred at 231.0 plf and was caused by local flange and/or web buckling near midspan. As shown in Figure D.5, good agreement was obtained between predicted and measured vertical deflections. Comparison of Figures D.6 and D.7 shows that the brace forces at the north ¼ point were significantly greater than at the south ¼ point. Figure D.9 shows the distribution of brace forces along the span.

Measured strains did not conform to the constrained bending assumption as shown in Figures D.11 and D.12. Tension was measured in the top lip and the top flange was found to have fully yielded at the failure load.

The ratio of interior to exterior brace forces at a transverse location varied from less than 1.0 to more than 2.5. Summation of exterior brace forces as a percent of supported load was approximately 25% and varied from less than 30% to approximately 50% for the interior braces.

3.6 Test V

Test V was conducted to determine the lack of panel stiffness on purlin performance. The test configuration was the same as Test III except sidelap fasteners were not installed. Failure occurred at 191.9 plf becuase of tearing of the panel at fastener locations near the rafters (vs. 193.6 plf for Test III). Measured vertical deflections were in good agreement with predicted values, Figure E.5. Measured brace forces at the rafter locations were consistent, Figure E.6. Measured strains did not conform to the constrained bending assumption, Figures E.7 and E.8.

Total brace force as a percent of the supported load was approximately 25% at the exterior purlin and 50% at the interior purlin. The ratio of interior to exterior brace forces at a location varied from less than 1.5 to approximately 2.5.

3.7 Test VI

Test VI was identical to Test III except the panel to purlin connection and sidelap connections were reinforced near the rafters as described above. Results are shown in Appendix F. Failure was by local buckling of the flange and/or web near midspan at a load of 230.0 plf versus 193.6 for Test III. Figure F.5 shows good agreement between measured and predicted vertical deflection. Comparison of Figure F.6 and F.7 shows consistency between brace forces at opposite ends of the span. Strains were not measured in this test.

Summation of brace forces as a percent of supported vertical load was near 10% for the exterior purlin and near 40% for the interior purlin.

3.8 Results of Supplementary Tests

Coupon Tests. Coupon test results from two samples each of purlin and panel material are given in Table 5. The average yield stress for the two purlin samples was 58.0 ksi. It is noted that the computed properties shown in Table 5 are based on a yield stress of 56 ksi.

Rotational Rigidity Tests. Results from two rotational rigidity tests (F-tests) are shown in Figure 8 as applied load versus deflection and in Figure 9 as F versus deflection.

Table 5. Tensile Coupon Test Results

Material Location	Test No.	Thickness (in.)	Width (in.)	Yield Stress (ksi)	Ultimate Stress (ksi)	Elongation %
Purlin	1	0.0920	0.498	58.93	68.32	30.0
	2	0.0917	0.501	57.03	68.56	30.5
	Avg.			57.98	68.44	30.2
Panel	1	0.0179	0.497	62.95	66.54	30.0
	2	0.0179	0.497	62.05	66.54	30.0
	Avg.			62.50	66.54	30.0

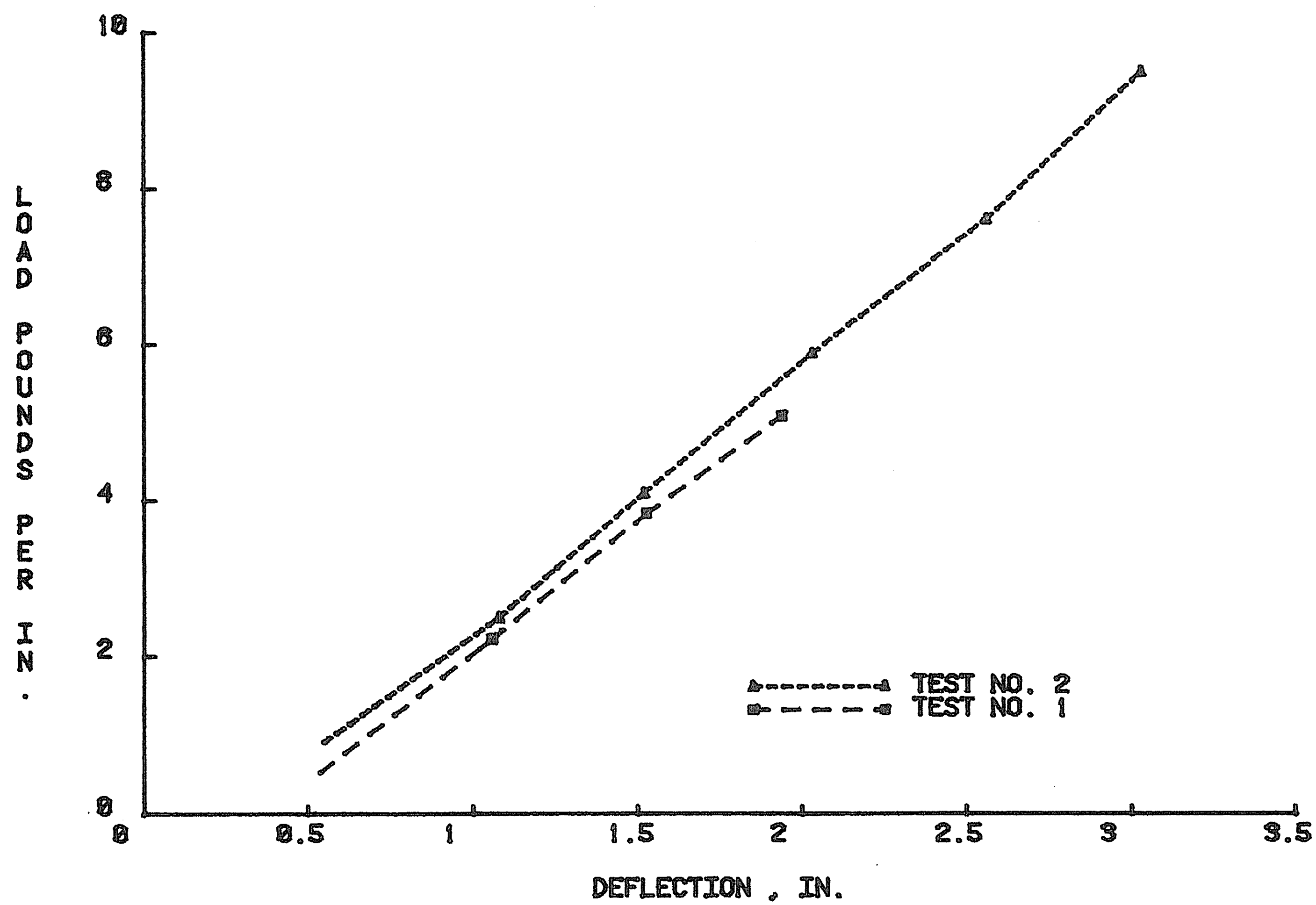


Figure 8. Load vs. Deflection Relationships from F-Tests

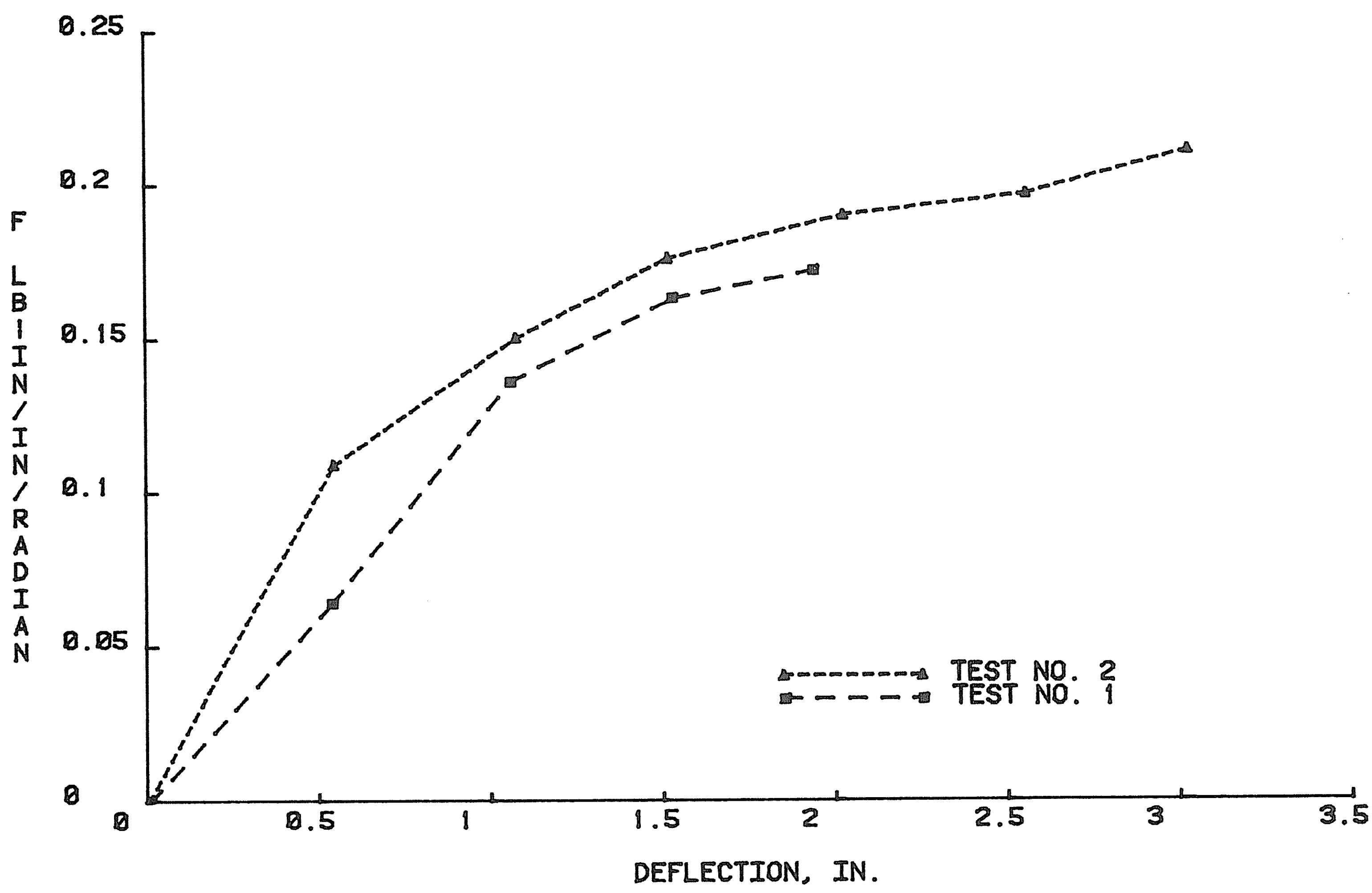


Figure 9. F vs. Deflection

CHAPTER IV

SUMMARY AND OBSERVATIONS

Nine simple span, gravity loaded Z-purlin tests were conducted to investigate the effects of various restraint systems on purlin strength and to determine the magnitude and distribution of restraint forces. A summary of the test results is found in Table 4. Comparison of results at 99 and 165 plf per purlin is given in Table 6 and 7, respectively.

The following observations are made as a result of this test program:

1. The actual failure load for any test did not exceed 80% of the predicted failure load using current AISI provisions increased by 1.67 to account for the implied factor of safety. In tests where elements of the cross-section buckled locally (Tests I, I-A, IV and VI), the compression lip was observed to straighten toward the plane of the compression flange before failure occurred. It must be noted that significant changes in predicted failure load can result from small changes in the assumed lip length.

2. The constrained bending assumption for estimating

Table 6. Comparison of Results at 99 plf per Purlin

Test No.	Inter-mediate Bracing	Torsional Restraint	Shear Stiff-ness	Torsional Stiffness	Midspan Vertical Deflection Exterior (in.)	$\frac{\Delta m}{\Delta c}$	Measured Restraint Force as a % of Support Load		Lateral Displace-ment of Top Flange (Exterior) (in.)	Max. Stress	
							Exterior One Purlin	Interior Two Purlin		Tension (ksi)	Comp. (ksi)
I	yes	yes	yes	yes	0.96	1.14	NA	NA	0.46	18.1	19.2
I-A	yes	yes	yes	yes	0.89	1.00	16.7	38.6	0.04	NA	NA
II	yes	yes	yes*	no	1.02	1.18	NA	NA	0.10	19.0	20.0
II-A	yes	yes	yes*	no	0.81	0.85	NA	NA	0.13	NA	NA
II-B	yes	yes	yes*	no	1.00	1.02	18.0	29.0	0.05	NA	NA
III	no	yes	yes	yes	0.85	0.99	15.5	48.5	0.01	18.1	17.5
IV	yes	no	yes	yes	0.96	1.03	21.0	31.0	0.15	18.8	41.1
V	no	yes	no	yes	0.98	1.07	24.5	48.5	0.05	27.9	17
VI	no	yes	yes	yes	0.89	0.98	8.0	33.9	0.11	NA	NA

Note: Δm = measured deflection for exterior purlin

Δc = constrained bending deflection for exterior purlin

N.A. = not measured, invalid or erratic

* = provided by intermediate braces at 2'-0 o.c.

Table 7. Comparison of Results at 165 plf

Test No.	Inter-mediate Bracing	Torsional Restraint at Rafter	Shear Stiff-ness	Torsional Stiffness	Midspan Vertical Deflection Exterior (in.)	$\frac{\Delta m}{\Delta c}$	Measured Restraint Force as a % of Support Load		Lateral Displace-ment of Top Flange (Exterior) (in.)	Max. Stresses	
							Exterior One Purlin	Interior Two Purlin		Tension (ksi)	Comp. (ksi)
I	yes	yes	yes	yes	1.53	1.09	NA	NA	0.46	30.0	31.2
I-A	yes	yes	yes	yes	1.51	1.02	18.9	41.8	0.05	NA	NA
II	yes	yes	yes*	no	NA	NA	NA	NA	NA	NA	NA
II-A	yes	yes	yes*	no	NA	NA	NA	NA	NA	NA	NA
II-B	yes	yes	yes*	no	1.53	0.93	17.0	39.0	0.09	NA	NA
III	no	yes	yes	yes	1.42	0.99	20.3	57.1	0.08	56.0	56.0
IV	yes	no	yes	yes	1.66	1.07	21.1	37.3	0.29	32.4	46.3
V	no	yes	no	yes	1.72	1.12	23.4	52.9	0.372	37.0	28.6
VI	no	yes	yes	yes	1.49	0.98	8.7	34.9	0.17	NA	NA

Note: Δm = measured deflection for exterior purlin

Δc = constrained bending deflection for exterior purlin

NA = not measured, invalid or erratic

* = provided by intermediate braces at 2'-0 o.c.

deflections ($5wL^4/384EI$) is adequate for design. From Tables 6 and 7, the ratio of measured to predicted vertical deflection ranged from 0.85 to 1.18 at 99 plf per purlin and from 0.93 to 1.12 at 165 plf per purlin.

3. At 99 plf per purlin, measured restraining force as a percentage of supported load (single purlin loading for exterior braces and two purlin loading for interior braces) varied from 8.0 to 24.5% for exterior purlins and 17.5 to 48.5% for interior purlins (Table 6). At 165 plf per purlin, measured restraining force as a percentage of supported load varied from 8.7 to 23.4% for exterior purlins and 19.2 to 57.1% for interior purlins (Table 7). The large difference between exterior and interior total brace forces indicates that the panel assembly carries relatively more force than the exterior braces.

4. Results from Test II-B may lend credence to the contention that brace forces partially accumulate over a slope. Figures B.31 and B.37 show that when continuous intermediate restraint is supplied (as from an eave or from resistance of the opposite slope), part of the restraining system is in tension and part in compression. The total restraint forces in Test II-B were 18.0 and 29.0% at 99 plf per purlin and 17.0 and 39.0% at 165 plf per purlin as compared to slightly higher precentages for other tests. However, Test I results, Figure A.20, tend to contradict this conclusion. Further study is recommended.

5. The magnitude of brace forces can be significantly affected by the angle between the web and lower flange, especially at the rafter location. Figure D.9, for instance, shows considerable difference between the magnitude of intermediate forces at opposite ends of the same purlin. It was observed in this test, that the angle between the web and lower flange varied from 90°.

6. Little difference in purlin strength was found for practical bracing configurations: Test I-A, 226.1 plf; Test IV, 231 plf; and Test VI, 230 plf. (The failure mode for Test III was independent of purlin strength.)

7. From Test III results, it is evident that panel-to-purlin connection strength is a design consideration at least for simple span purlins.

8. From Test V (no sidelap fasteners), either shear stiffness (Q) has little effect on strength or sidelap fasteners do not contribute to shear stiffness. Note that the failure was caused by tearing of the panel at fasteners near the rafter. Further study is recommended.

APPENDIX A

TEST I RESULTS

TEST SUMMARY

Project: MBMA Roof System Behavior

Test No.: I

Test Date: November 24, 1981

Purpose: Base Test

Span(s): 19.625'

Thickness: 0.093" Moment of Inertia: 13.3 in^4

Parameters: Intermediate bracing @ ¼ pt.

Torsional restraint @ rafter

Panel shear stiffness

Panel torsional restraint

Failure Load: 219.9 plf

Failure Mode: Local buckling of flange and/or web near midspan

Predicted Failure Loads:

Method AISI Constr. BendingX1.67 Load 316.9 plf

Method ____ Load ____

Method ____ Load ____

Discussion:

Two tests were conducted:

1. Span 20'-0"

   -Bearing failure occurred at the north end at 132 plf.

   -Vertical deflections were 20-30% greater than predicted from constrained bending assumption.

   -Failed portion of purlin was repaired by cutting and welding new end.

2. Span 19'-7½"

   -Local buckling of the flange and/or web occurred at 219.9 plf approximately 1 ft. from the centerline.

   -Vertical deflections were 10-15% greater than predicted. Deflections of the west purlin (nearer the lateral support joist) were greater.

   -Measured intermediate brace forces were erratic especially near repaired end.

   -Brace forces seem to increase linearily with increasing load.

-Ratio of exterior to interior brace forces at centerline varied from 1.92 to 2.71, at south ¼ point from 1.23 to 1.68 and at south rafter from 6.88 to 2.44 (Data for north ¼ point and rafter is not considered to be valid.)

-At 66 plf, summation of external braces forces equaled 29.7% of vertical load on external purlin. Summation of internal brace forces equaled 47.7% of total vertical load.

-At 198 plf, summation of external brace forces equaled 42.3% of total vertical load.

-Stress distribution from measured strains approximates constrained bending.

-Stresses increased linearily with loading.

-Top flange lateral displacements exceeded bottom flange displacements.

-Maximum lateral displacement was less than 0.5 in.

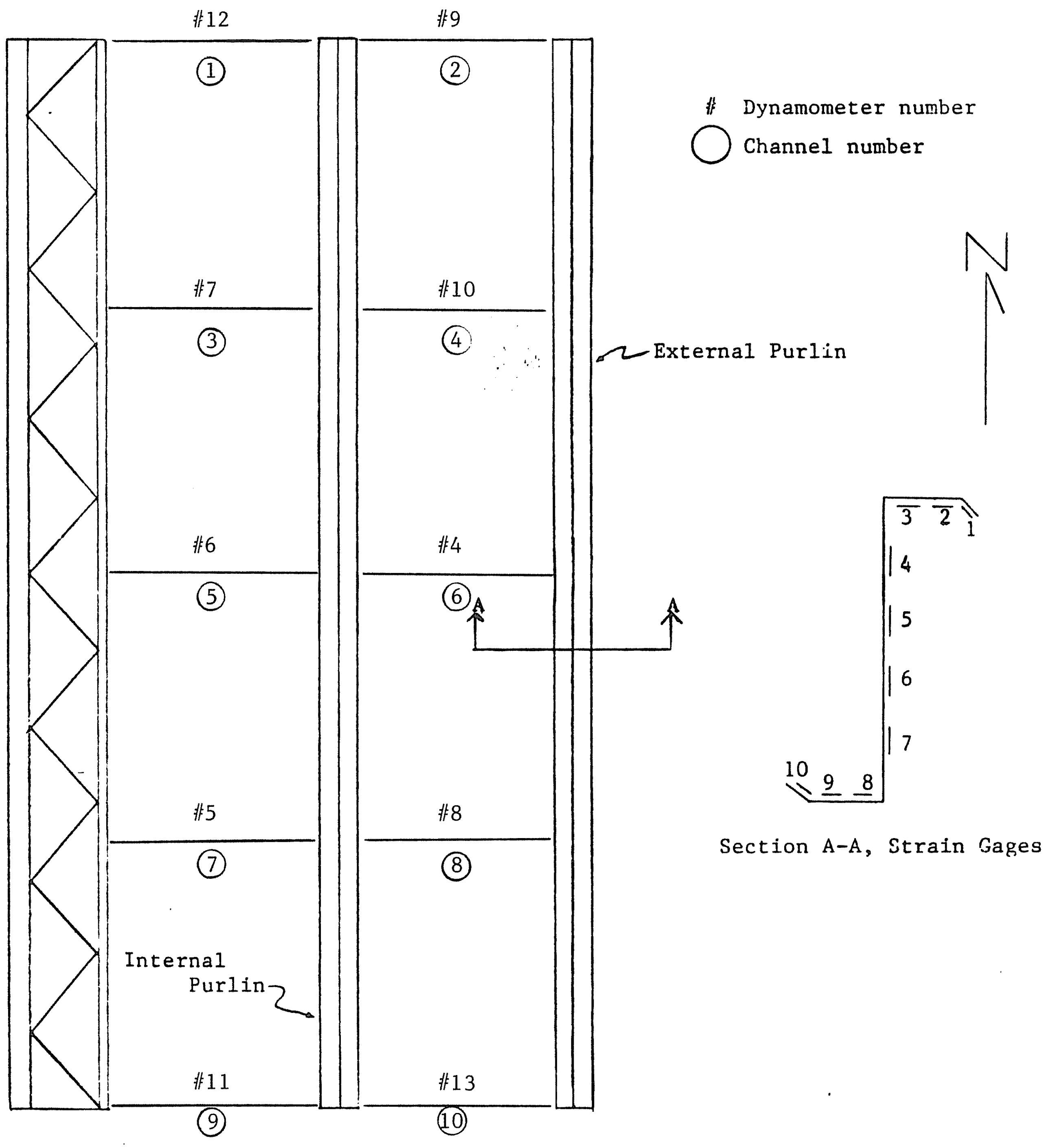
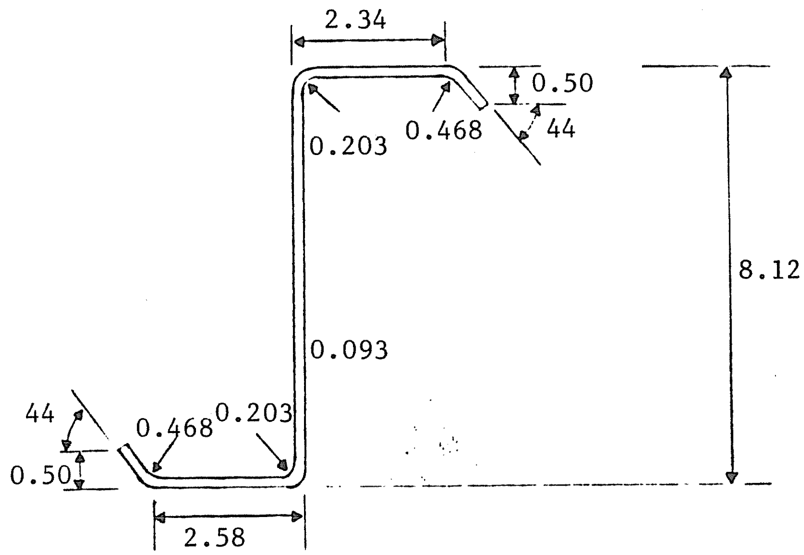
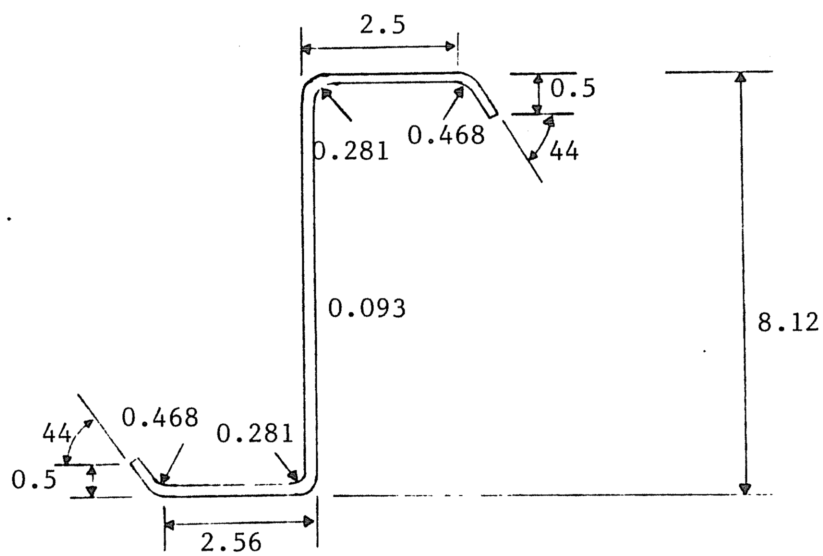


Figure A.1 Instrumentation Location, Test I



External Purlin



Internal Purlin

Figure A.2 Measured Purlin Dimensions, Test I

```
---------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: MBMA-I-W 11/24/81
---------------------------------------------------------
                        TOP             BOTTOM
FLANGE(in)             2.500             2.560
LIP(in)                0.500             0.500
LIP ANGLE(deg)        44.000            44.000
RADIUS L/F(in)         0.468             0.468
RADIUS F/W(in)         0.281             0.281

TOTAL DEPTH(in)                8.12
THICKNESS(in)                  0.093
YIELD STRENGTH(ksi)            56
                                              SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)            TOP              BOTTOM
GROSS=         13.426                   3.331             3.359
STRENGTH=      13.426                   3.331             3.359
DEFLECTION=    13.426
BE=    2.126   in
FC=    33.600   ksi
FT=    33.600   ksi
FBW=   33.363   ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)
          MC=      9.328   ft-k
          MT=      9.406   ft-k
          MW=     10.081   ft-k
          MU=     15.578   ft-k (1.67*allowable)
SPAN         =    19.625   ft.
UNIFORM LOAD=    323.575   plf (1.67*allowable)
DEFLECTION   =     0.843   in./100plf
```

Figure A.3 AISI Purlin Analysis, Test I West Purlin

```
----------------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: MBMA-I-E 11/24/81
----------------------------------------------------------------
                          TOP              BOTTOM
FLANGE(in)               2.340              2.580
LIP(in)                  0.500              0.500
LIP ANGLE(deg)          44.000             45.000
RADIUS L/F(in)           0.468              0.468
RADIUS F/W(in)           0.203              0.203

TOTAL DEPTH(in)                 8.12
THICKNESS(in)                   0.093
YIELD STRENGTH(ksi)             56
                                        SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)          TOP              BOTTOM
GROSS=         13.304                 3.263             3.369
STRENGTH=      13.304                 3.263             3.369
DEFLECTION=    13.304
BE=     2.044  in
FC=    33.600  ksi
FT=    33.600  ksi
FBW=   33.363  ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)
             MC=        9.135   ft-k
             MT=        9.433   ft-k
             MW=        9.662   ft-k
             MU=       15.255   ft-k (1.67*allowable)
SPAN           =       19.625   ft.
UNIFORM LOAD=         316.881   plf (1.67*allowable)
DEFLECTION   =          0.850   in./100plf
```

Figure A.4 AISI Purlin Analysis, Test I East Purlin

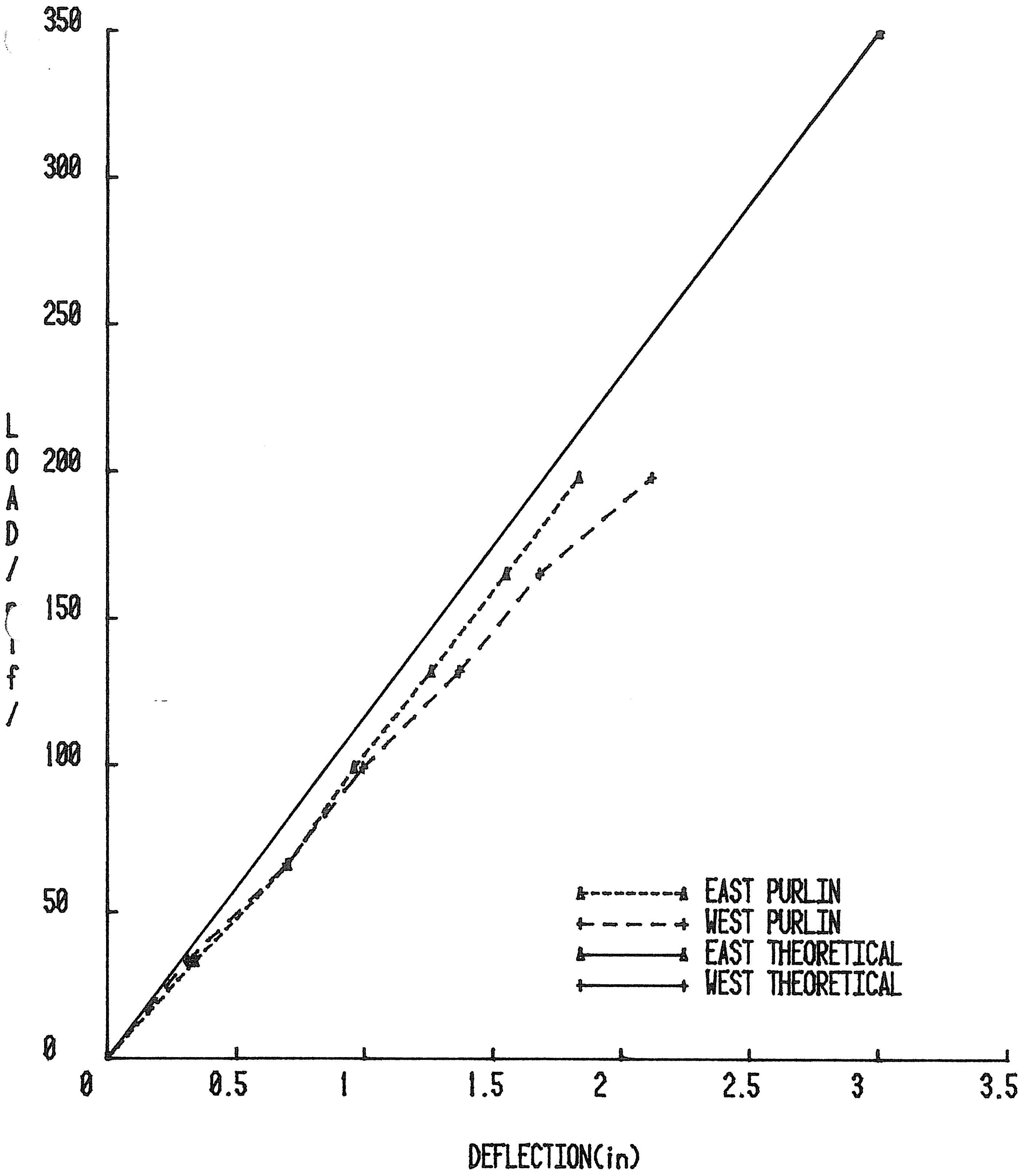


Figure A.5 Load vs. Vertical Deflection, Test I

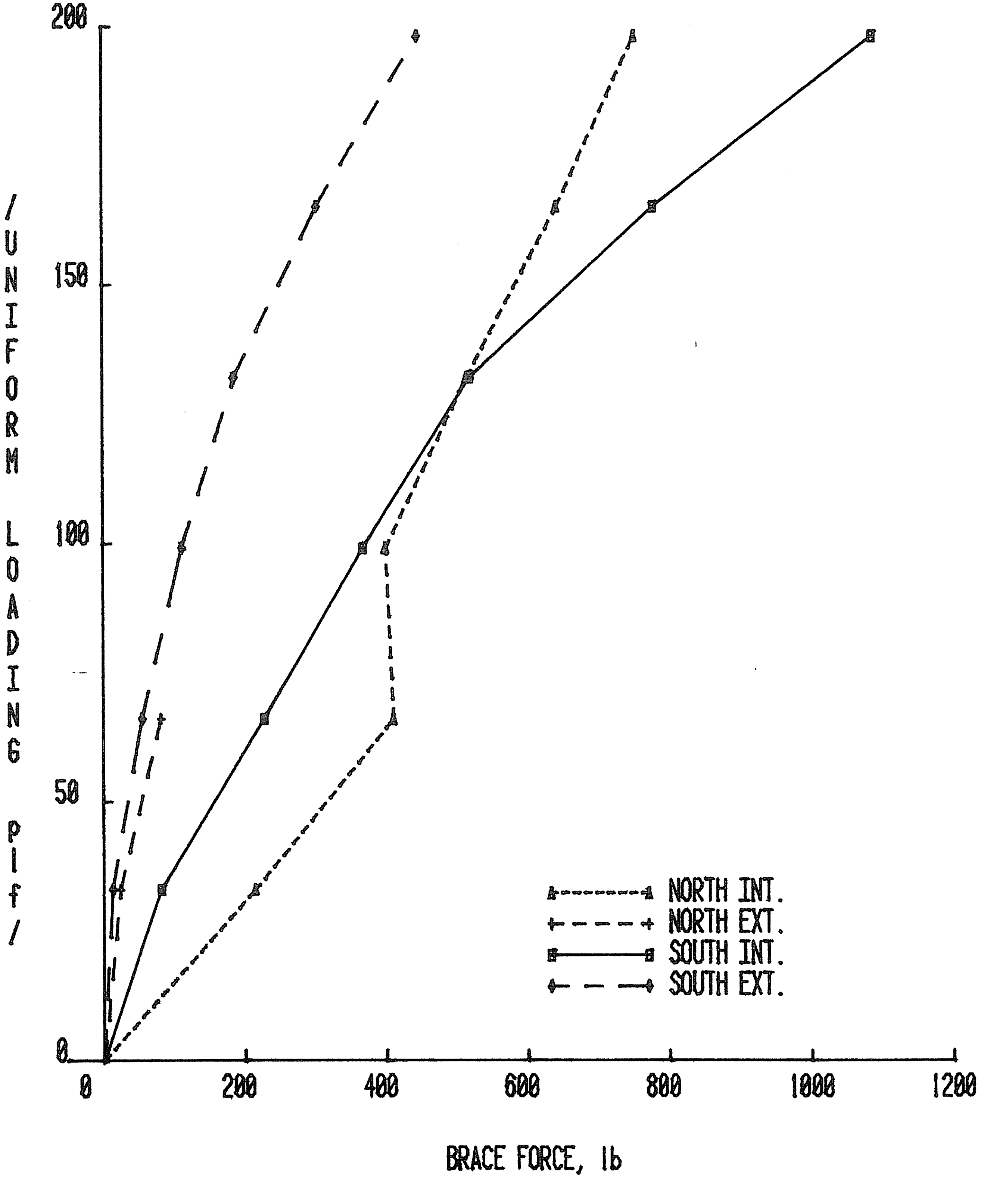


Figure A.6 Vertical Loading vs. Brace Force at Rafter, Test I

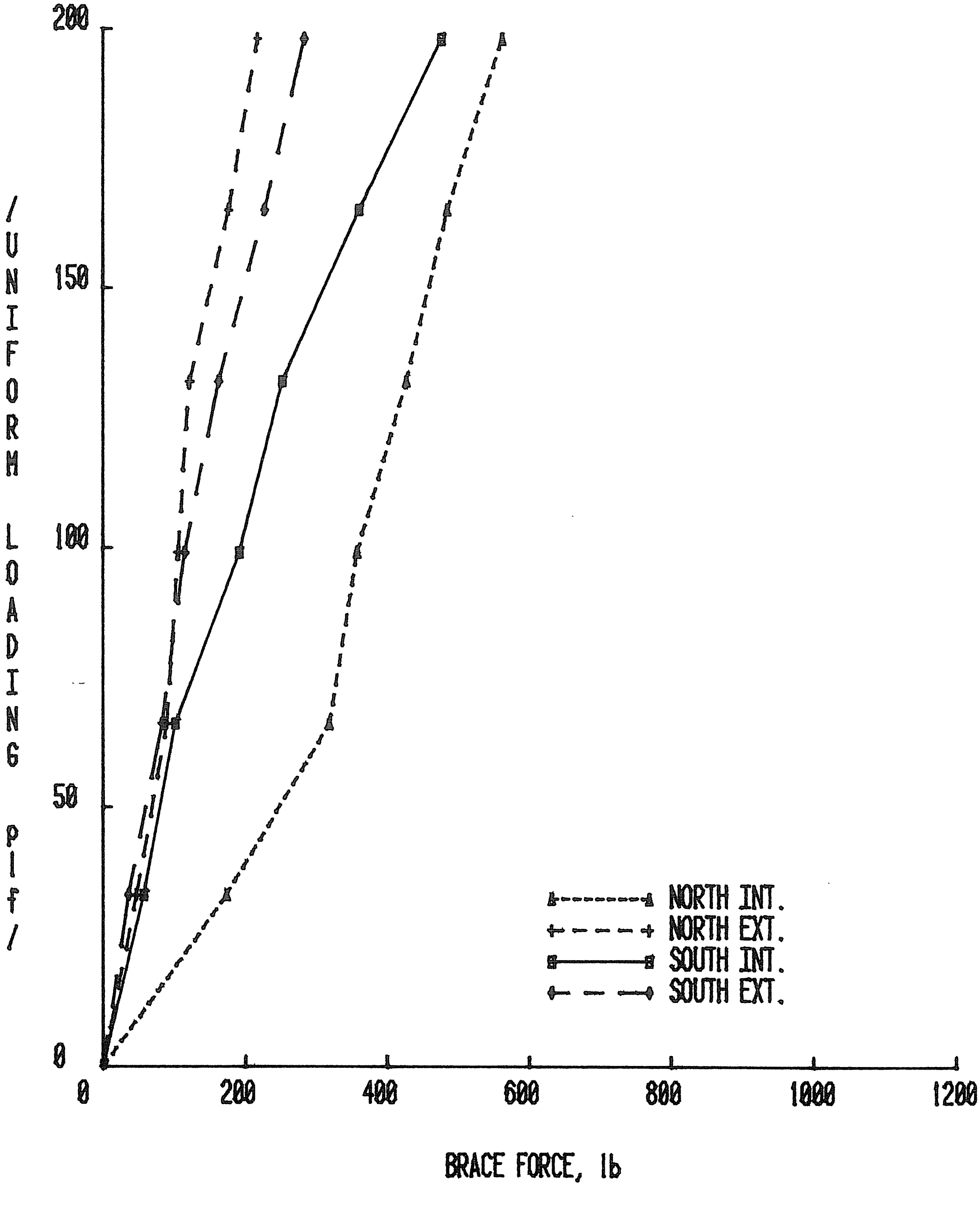


Figure A.7 Vertical Loading vs. Brace Force at ¼ Points, Test I

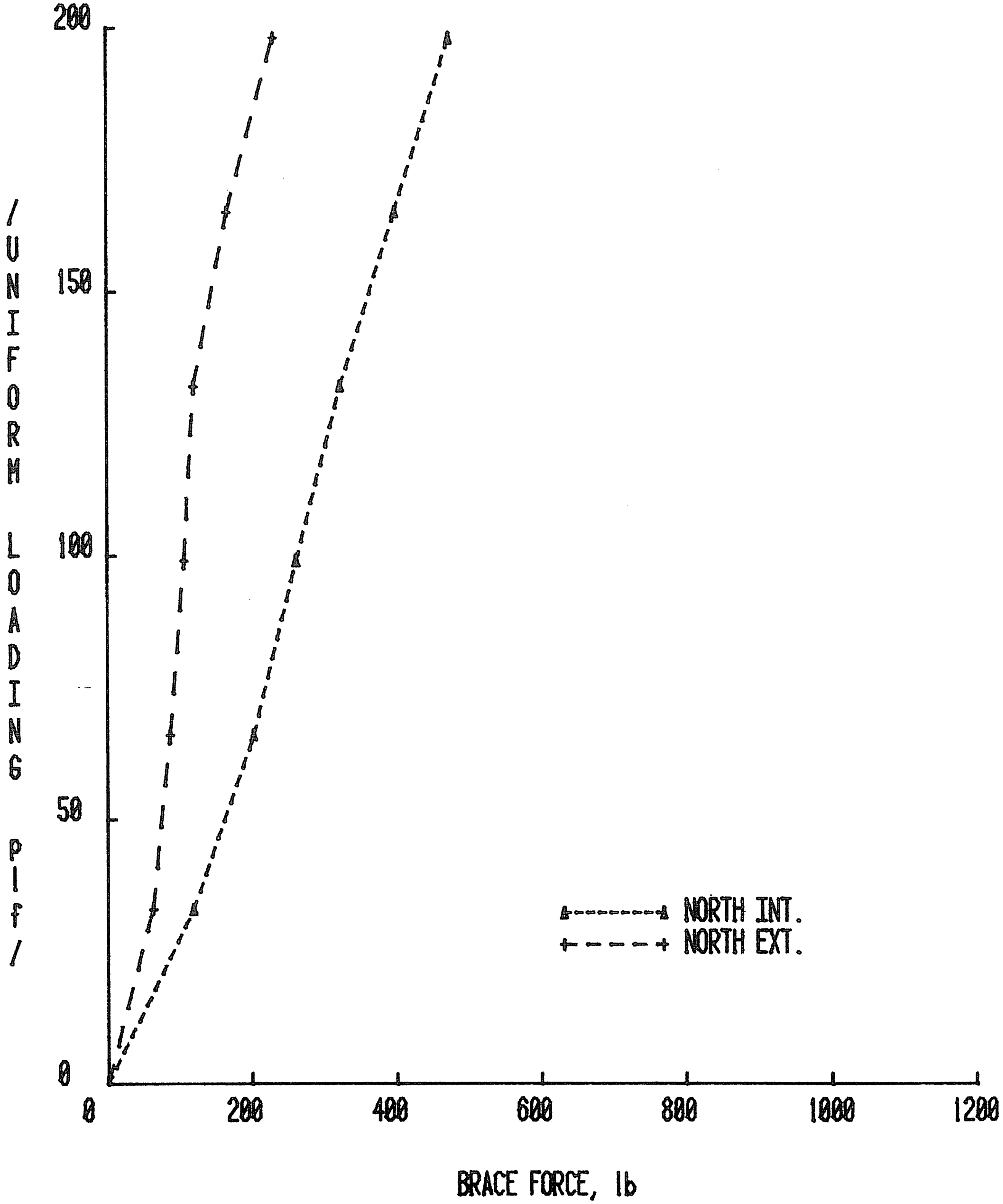


Figure A.8 Vertical Loading vs. Brace Force at Midspan, Test I

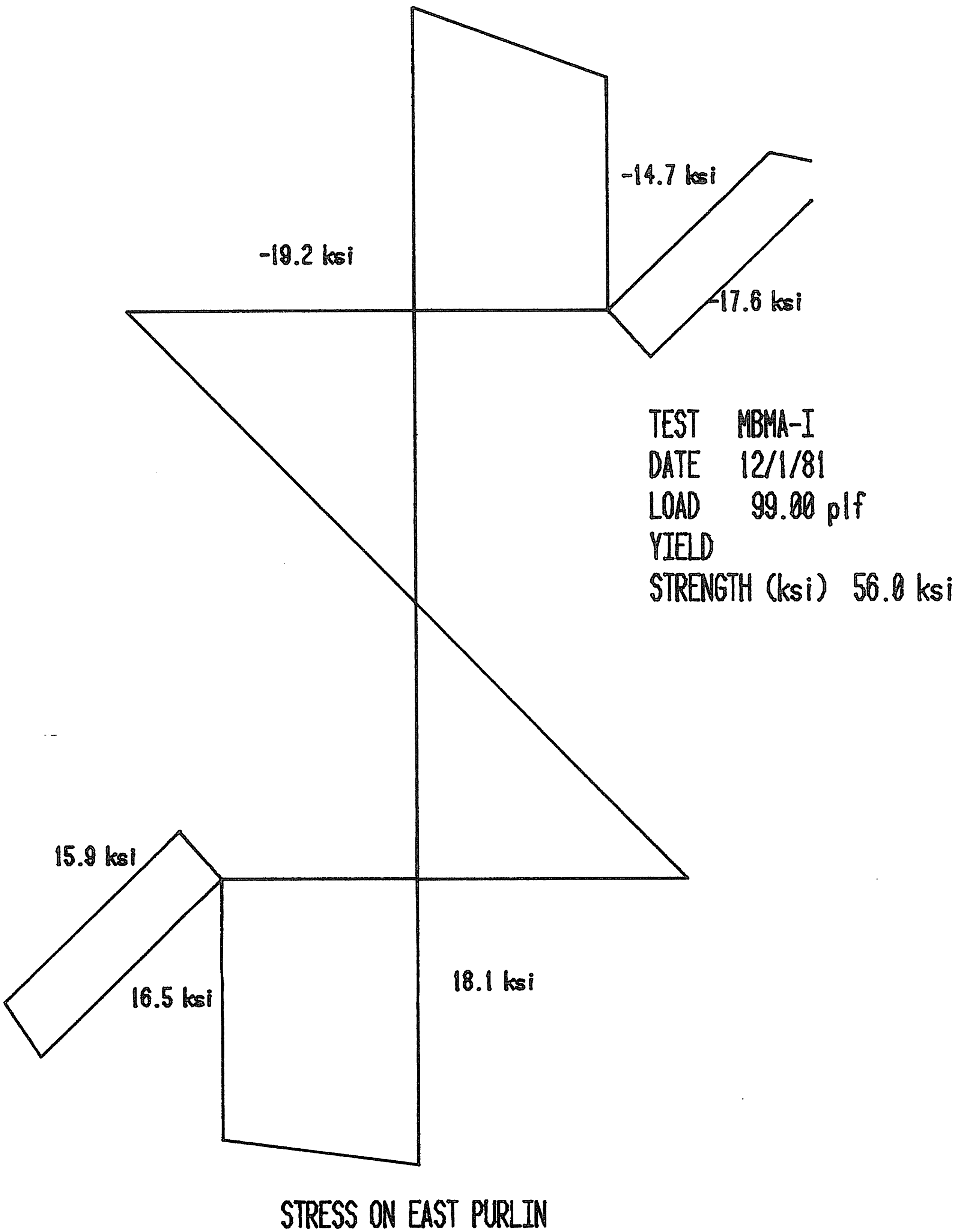


Figure A.9 Stress Distribution at 99 plf, Test I

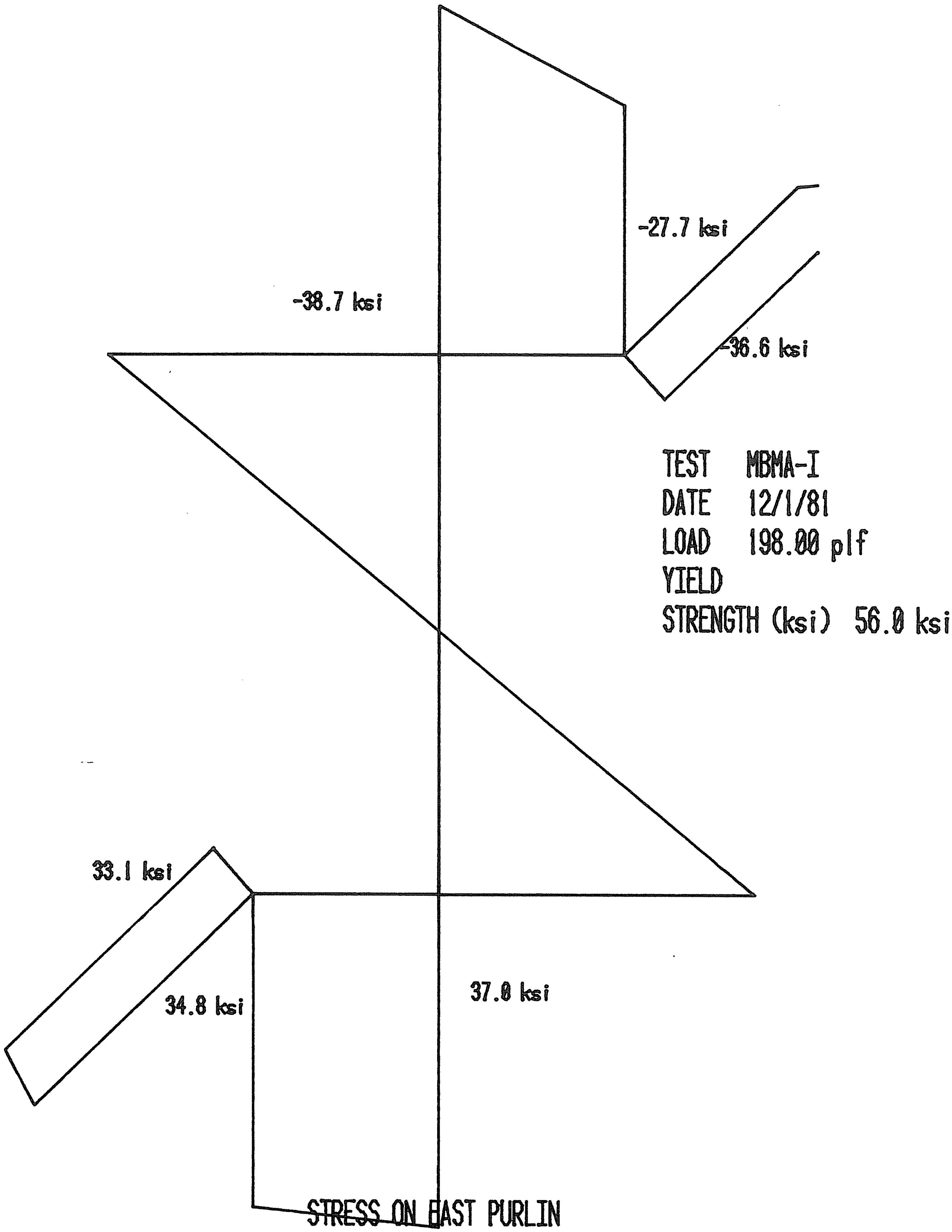


Figure A.10 Stress Distribution at 198 plf, Test I

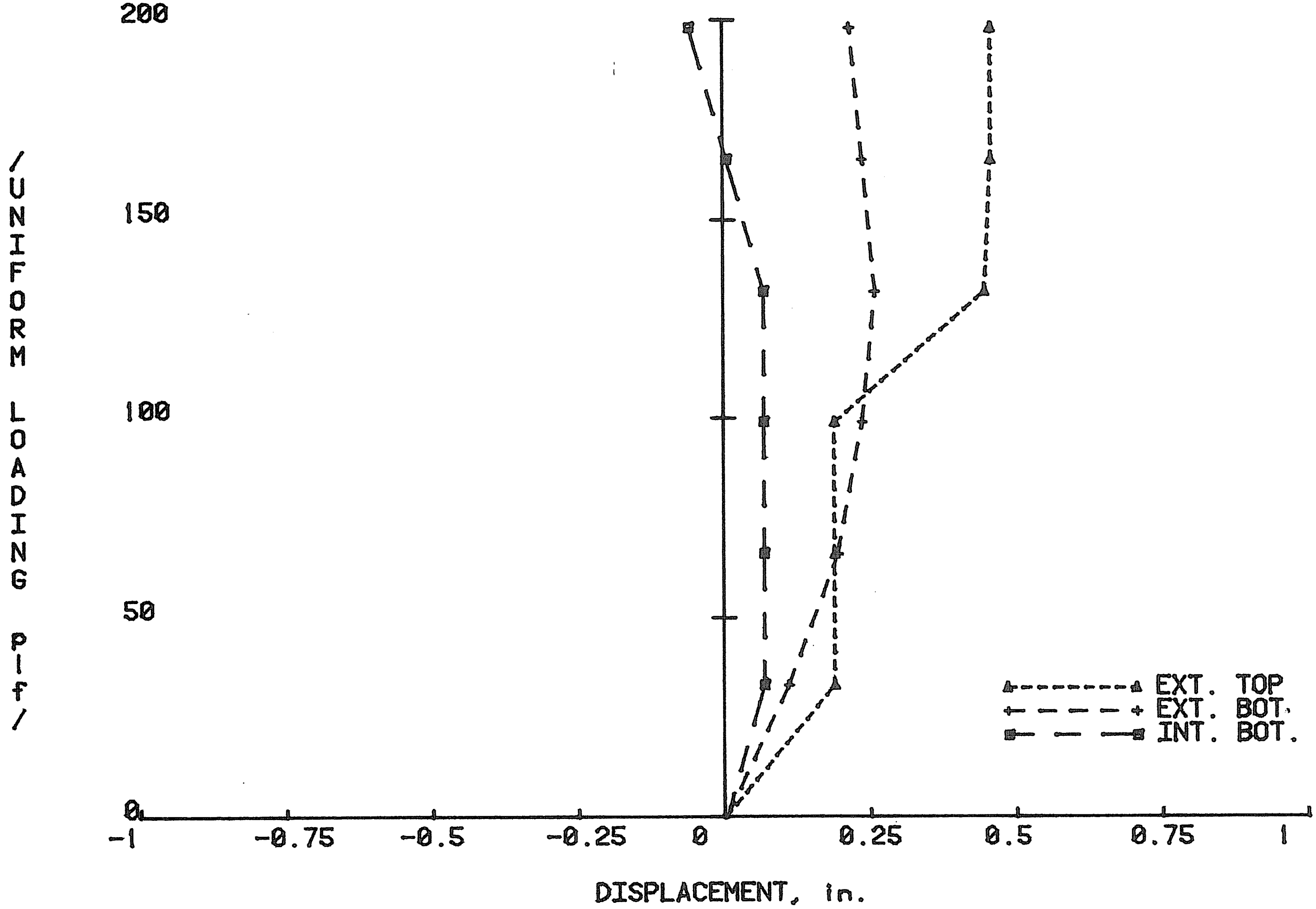


Figure A.11 Vertical Loading vs. Lateral Displacements, Test I

TEST SUMMARY

Project: MBMA Roof System Behavior

Test No.: I-A

Test Date: December 9, 1981

Purpose: Base test

Span(s): 19.625'

Thickness: 0.090" **Moment of Inertia:** 12.6 in^4

Parameters: Intermediate bracing @ ¼ pt.

Torsional restraint @ rafter

Panel shear stiffness

Panel torsional restraint

Failure Load: 226.1 plf

Failure Mode: Local buckling of flange and/or web near midspan

Predicted Failure Loads:

Method AISI constrained bending Load 305.2 plf

Method ____ Load ____

Method ____ Load ____

Discussion:

- -Local buckling of the flange and/or web occurred at 226.1 plf approximately 1 ft. from the midspan.
- -Vertical deflections were 15-28% greater than predicted from the constrained bending assumption for west purlin (nearer the lateral support joist), and 5-15% for the east purlin.
- -Measured internal brace forces @ N. rafters were 80% greater than N. external brace forces @ 181.5 plf.
- -Brace forces seem to increase linearly with increasing load.
- -The ratio of exterior to interior brace forces @ the centerline varied from 0.90 to 0.91, @ the south ¼ pt. from 0.52 to 0.72, @ the north ¼ pt. from 0.34 to 0.82, @ the south rafter from .28 to 0.36 and @ the north rafter from 4.1 to 24.10.
- -At 66 plf, summation of external brace forces equaled 20% of total vertical load on external purlin. Summation of internal brace forces equaled 40% of total vertical load.
- -At 214.5 plf summation of external brace forces equaled 23% of total vertical load and summation of internal brace forces equaled 47% of total vertical load.
- -Bottom flange lateral displacements exceeded top flange displacements.
- -Maximum lateral displacement was less than 0.3 in.

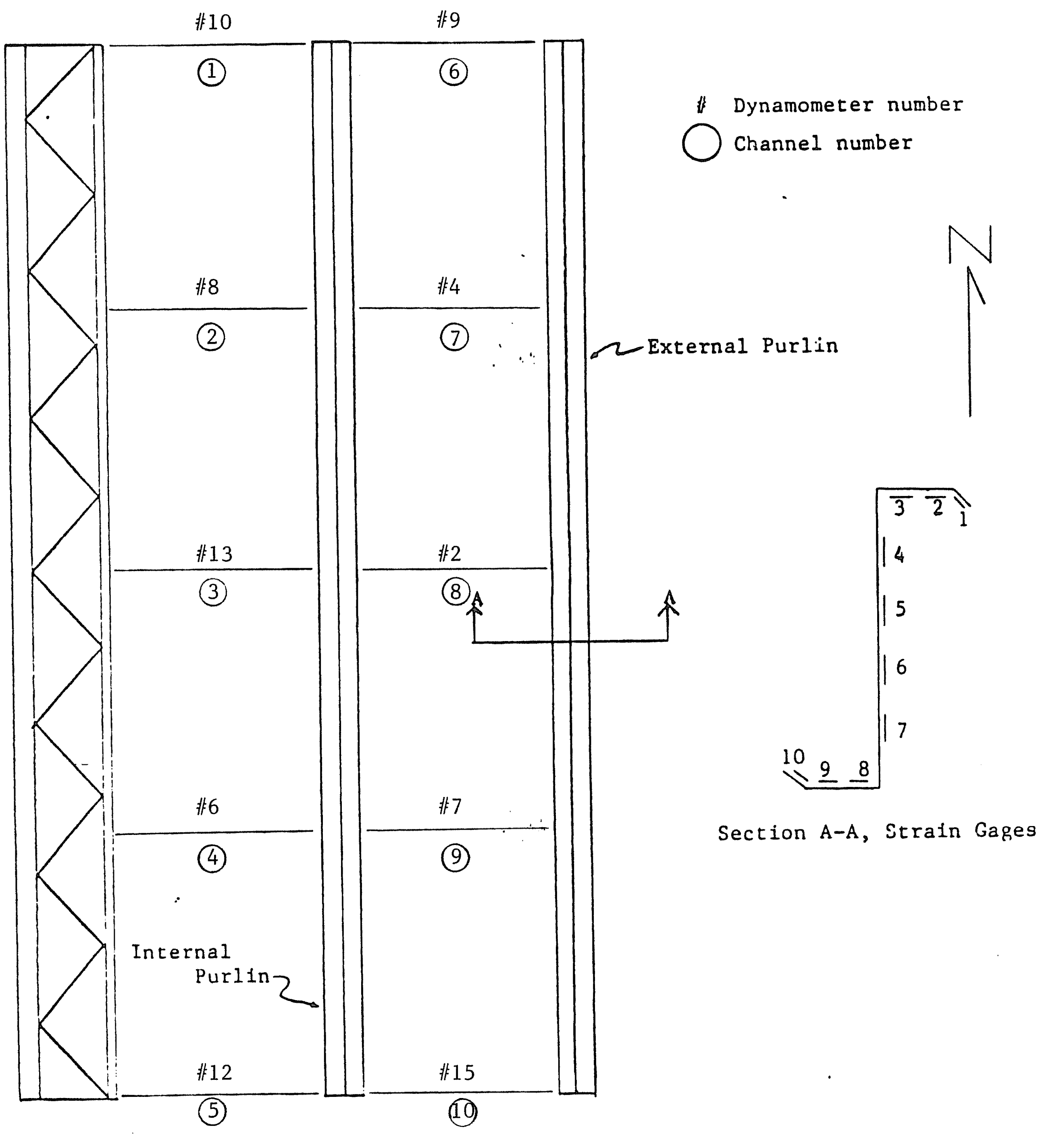
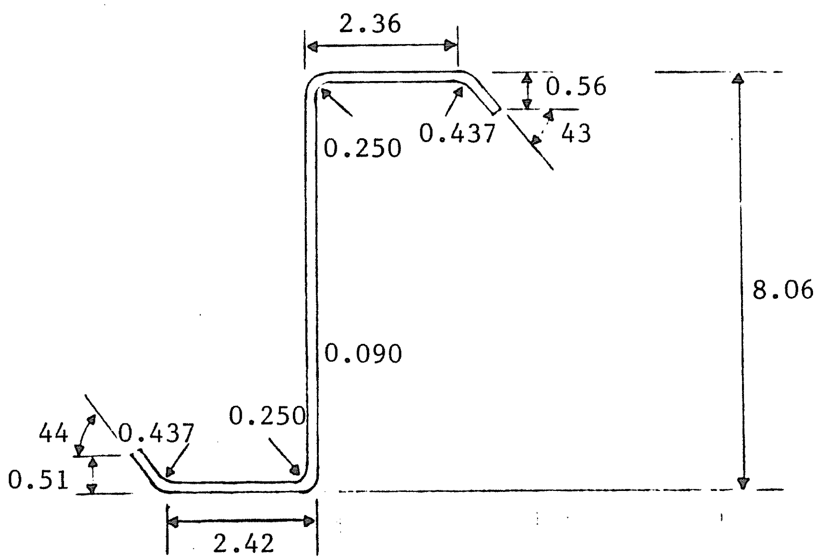
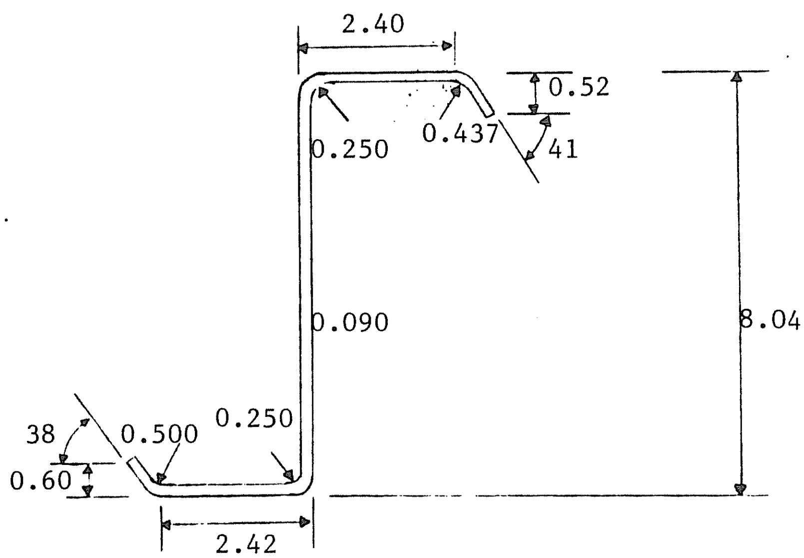


Figure A.12 Instrumentation Location, Test I-A



External Purlin



Internal Purlin

Figure A.13 Measured Purlin Dimensions, Test I-A

```
---------------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: MBMA TEST-I-A WEST PURLIN
---------------------------------------------------------------
                      TOP            BOTTOM
FLANGE(in)           2.400            2.420
LIP(in)              0.520            0.600
LIP ANGLE(deg)      41.000           38.000
RADIUS L/F(in)       0.440            0.500
RADIUS F/W(in)       0.250            0.250

TOTAL DEPTH(in)             8.04
THICKNESS(in)               0.09
YIELD STRENGTH(ksi)         56
                                 SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)      TOP             BOTTOM
GROSS=          12.739            3.163            3.247
STRENGTH=       12.739            3.163            3.247
DEFLECTION=     12.739
BE=     2.060   in
FC=     33.600  ksi
FT=     33.600  ksi
FBW=    33.190  ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)
            MC=      8.858   ft-k
            MT=      9.093   ft-k
            MW=      9.441   ft-k
            MU=     14.792   ft-k (1.67*allowable)
SPAN         =      19.625   ft.
UNIFORM LOAD=      307.261   plf (1.67*allowable)
DEFLECTION   =       0.888   in./100plf
```

Figure A.14 AISI Purlin Analysis, Test I-A Interior Purlin

```
-------------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: MBMA TEST-I-A EAST PURLIN
-------------------------------------------------------------
                      TOP             BOTTOM
FLANGE(in)           2.360             2.420
LIP(in)              0.560             0.510
LIP ANGLE(deg)      43.000            44.000
RADIUS L/F(in)       0.500             0.440
RADIUS F/W(in)       0.250             0.250

TOTAL DEPTH(in)            8.06
THICKNESS(in)              0.09
YIELD STRENGTH(ksi)        56
                                 SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)      TOP             BOTTOM
GROSS=         12.551            3.157             3.142
STRENGTH=      12.551            3.157             3.142
DEFLECTION=    12.551
BE=    2.020   in
FC=    33.600   ksi
FT=    33.600   ksi
FBW=   33.171   ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)
          MC=      8.840   ft-k
          MT=      8.798   ft-k
          MW=      9.427   ft-k
          MU=     14.692   ft-k (1.67*allowable)
SPAN        =     19.625   ft.
UNIFORM LOAD=    305.177   plf (1.67*allowable)
DEFLECTION  =      0.901   in./100plf
```

Figure A.15 AISI Purlin Analysis, Test I Exterior Purlin

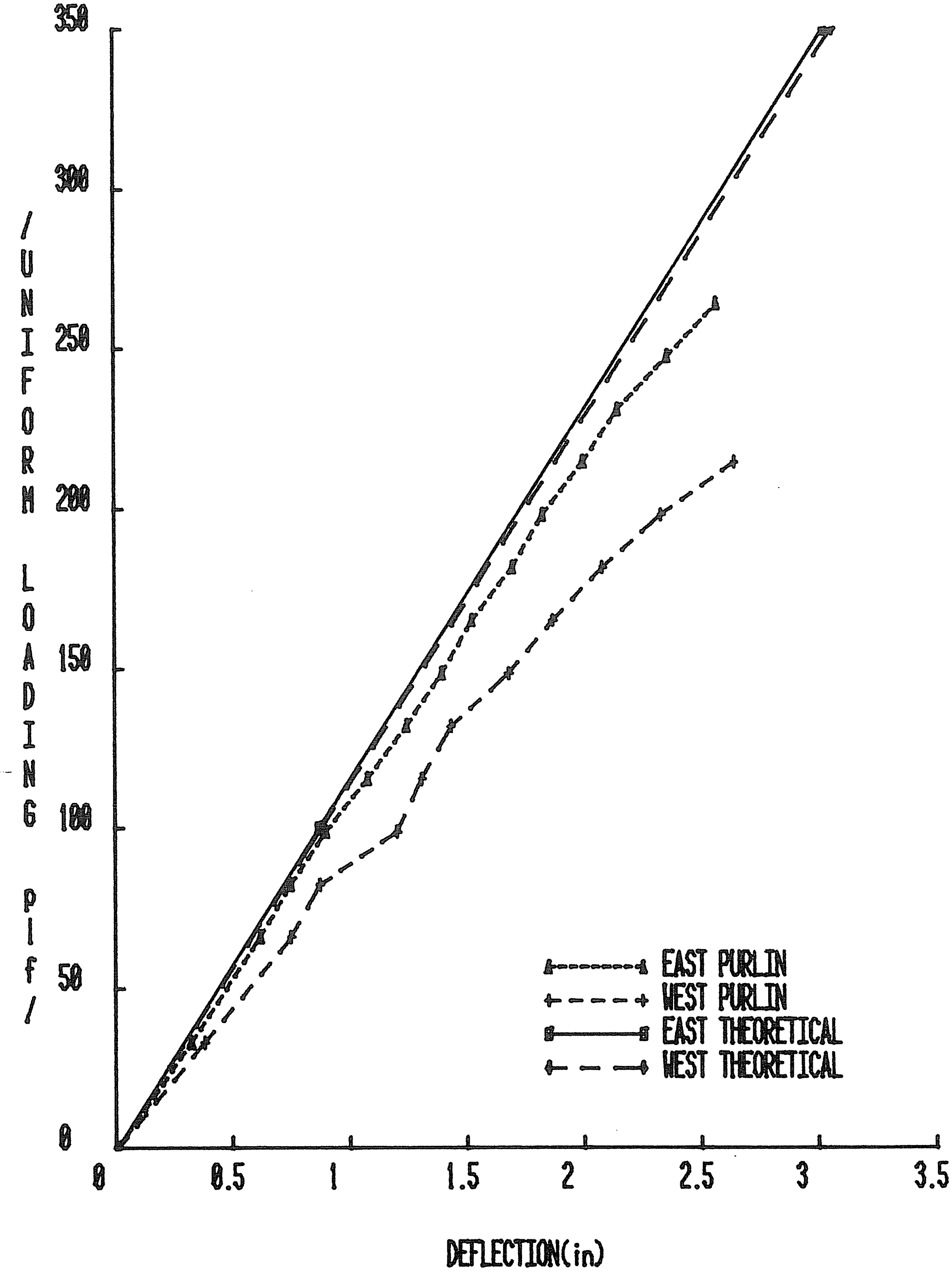


Figure A.16 Load vs. Vertical Deflection, Test I-A

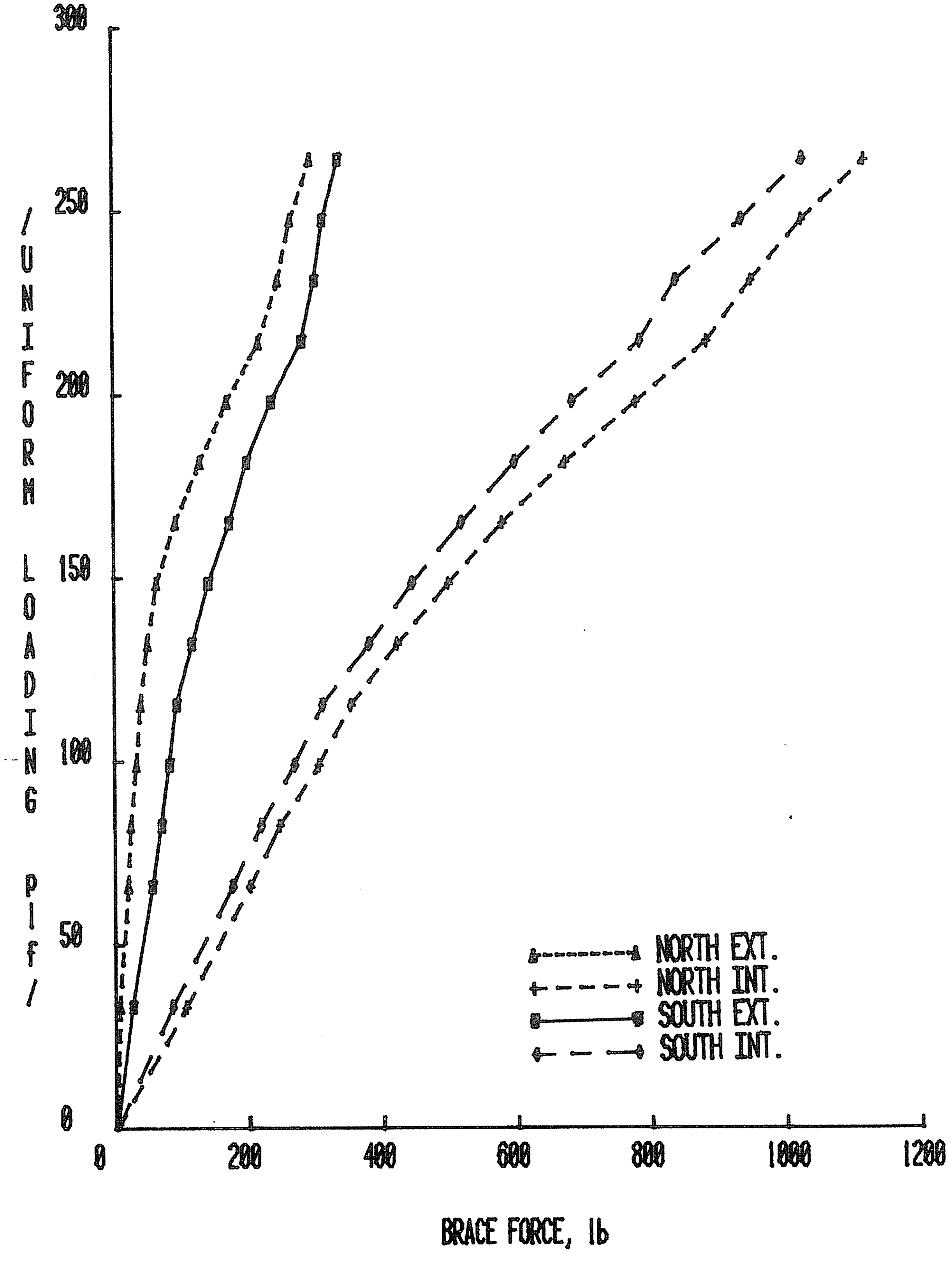


Figure A.17 Vertical Loading vs. Brace Force at Rafter, Test I-A

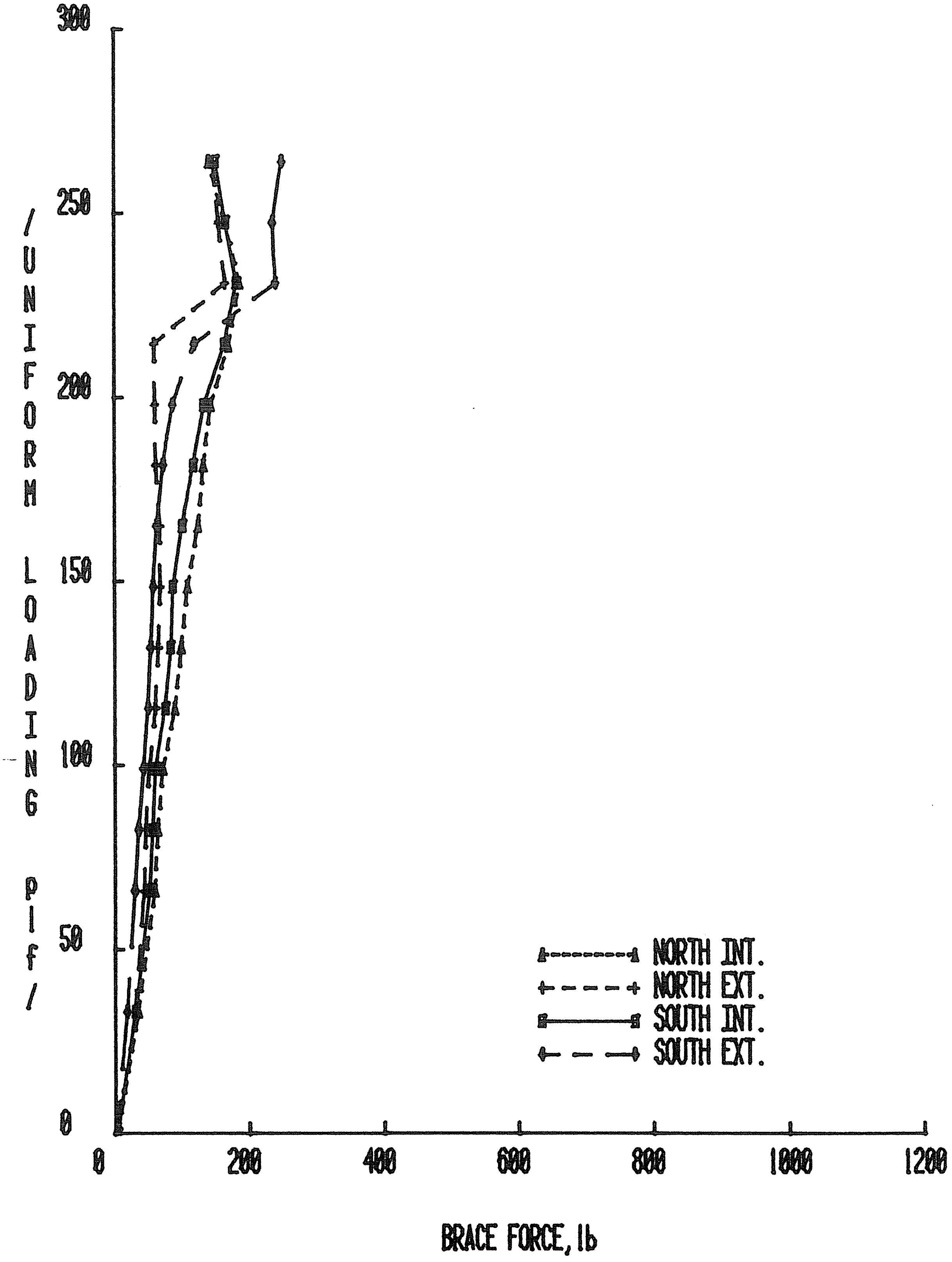


Figure A.18 Vertical Loading vs. Brace Force at ¼ Points, Test I-A

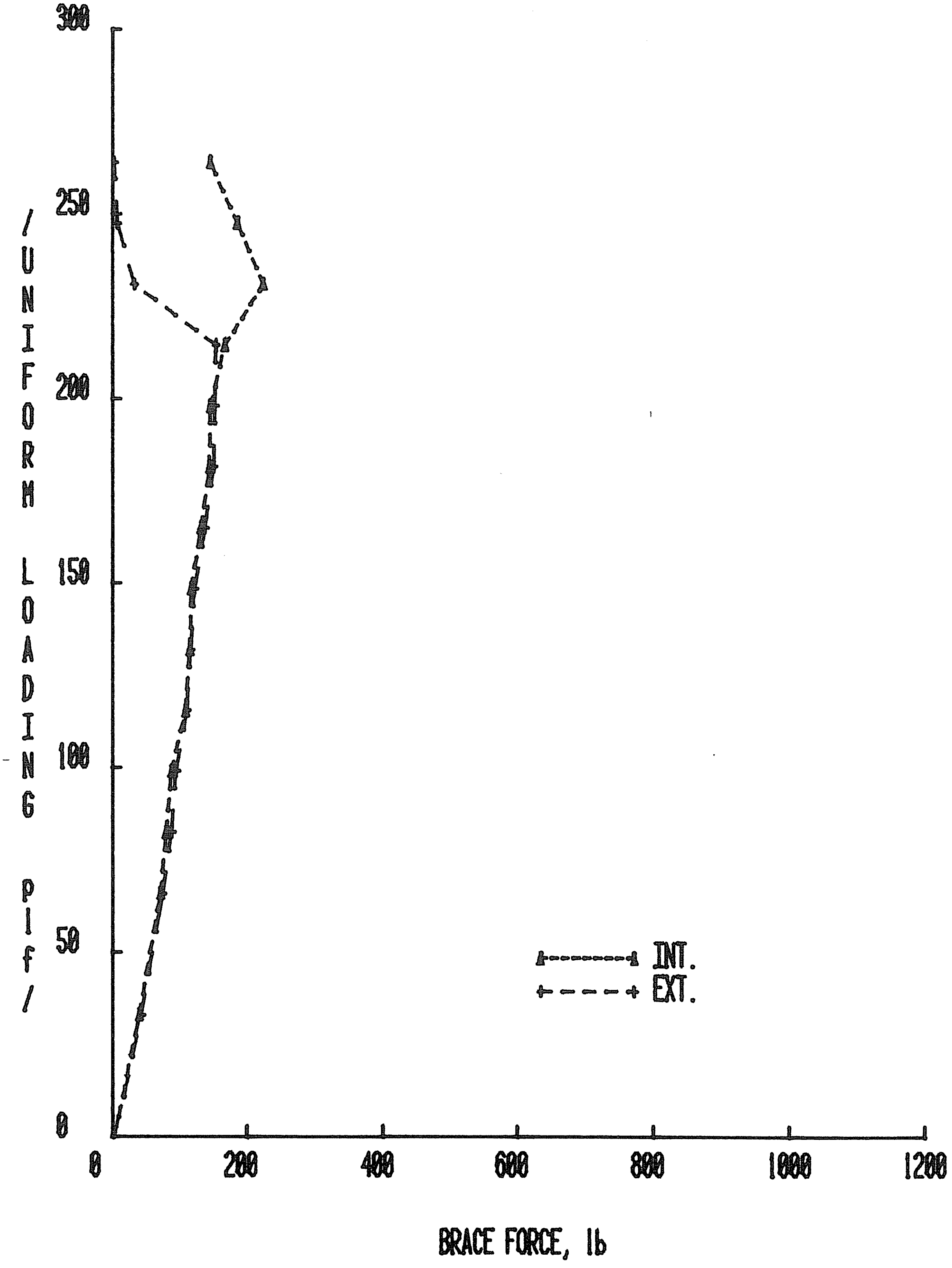


Figure A.19 Vertical Loading vs. Brace Force at Midspan, Test I-A

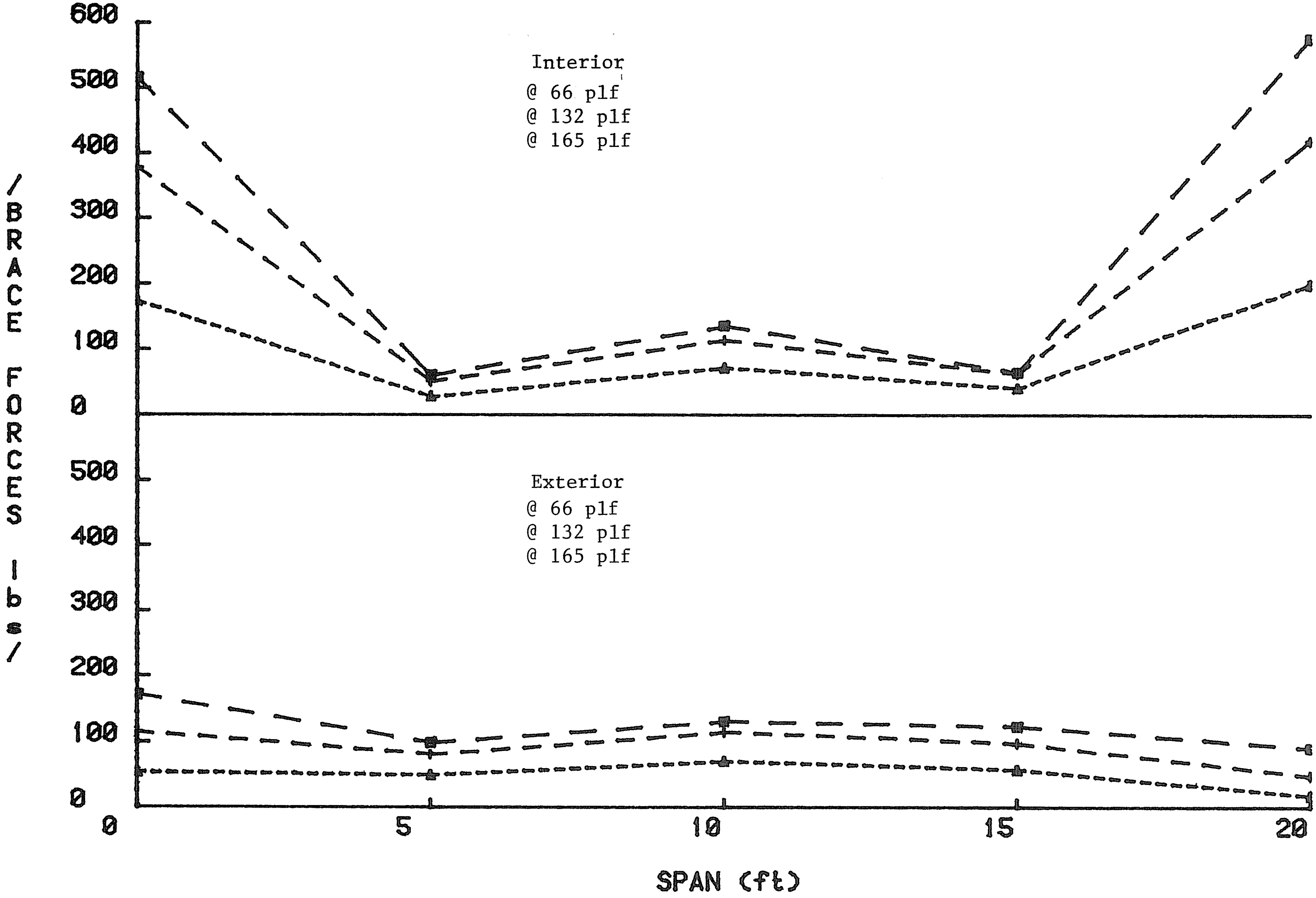


Figure A.20 Distribution of Brace Forces Along Purlin, Test I-A

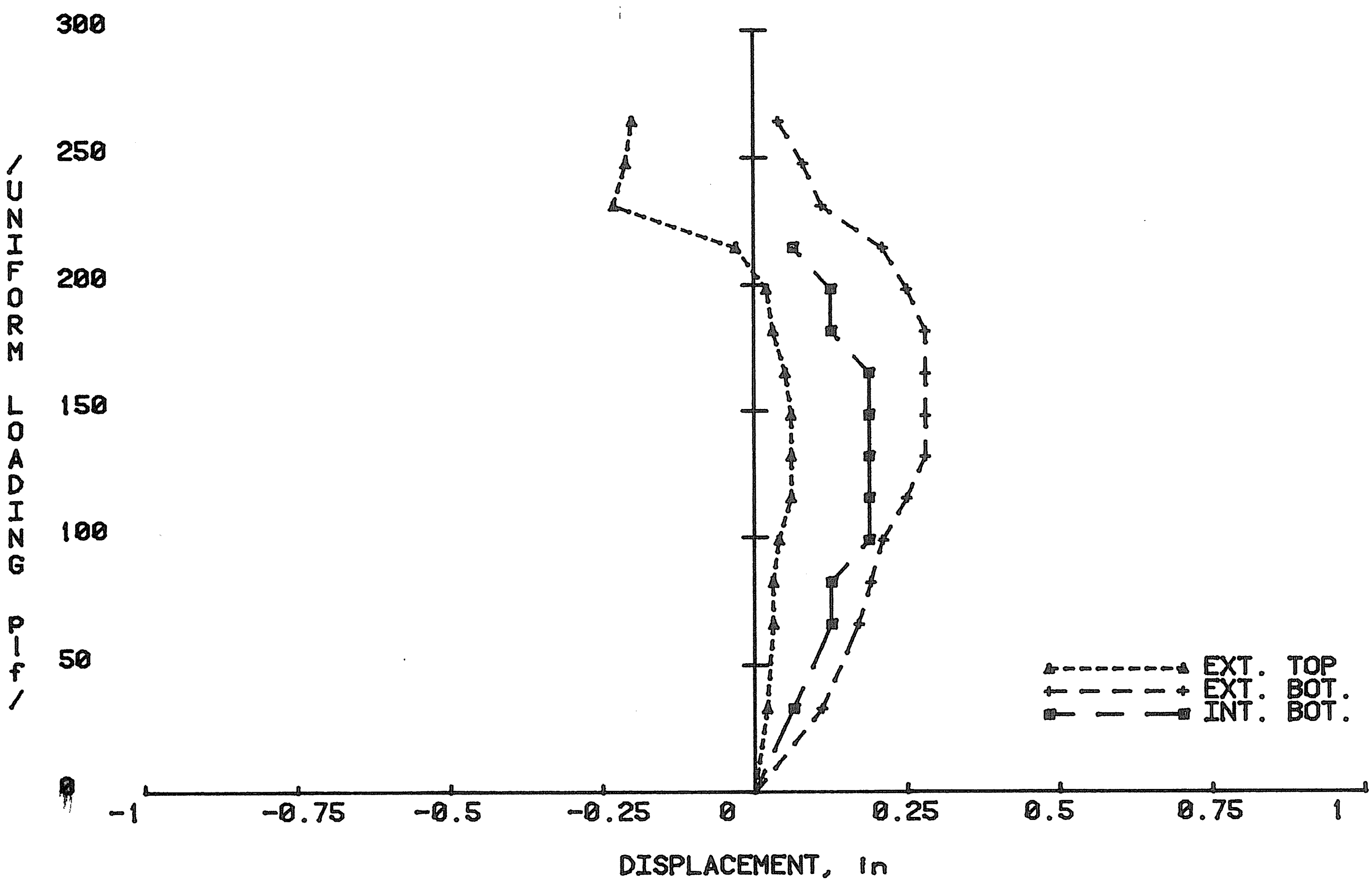


Figure A.21 Vertical Loading vs. Lateral Displacement, Test I-A

APPENDIX B

TEST II RESULTS

TEST SUMMARY

Project: MBMA Roof System Behavior

Test No.: II

Test Date: December 3, 1981

Purpose: Determine restraint forces required for compression flange restraint only.

Span(s): 19.625'

Thickness: 0.090" Moment of Inertia: 12.265 in^4

Parameters: Intermediate bracing @ 2'-0" O.C.

Torsional restraint @ rafter

No panel shear stiffness (greased top flange)

No panel torsional stiffness

Shear stiffness provided by intermediate braces

Failure Load: 132.0 plf

Failure Mode: Purlins roller over due to failure of lateral support joist.

Predicted Failure Loads:

Method	AISI constrained bending	Load	x 1.67. 301.7 plf
Method		Load	
Method		Load	

Discussion:

-Lateral buckling of the compression flange joist occurred at a load of 132.0 plf.

-When the intermediate brace restraint system failed, the purlins rolle over.

-Vertical deflections were 13-17% greater than predicted. Deflection of west purlin (nearer the lateral support joist was greater).

-Brace forces within 4' of midspan seemed to increase linearly with increasing load.

-Ratio of interior to exterior brace forces @ centerline varied from 2.46 to 8.10, @ 2' from centerline 1.52 to 5.26, @ 4' from centerline 1.70 to 3.01, @ 6' from centerline 1.1 to 1.84; between 8' from centerline and the rafters some of the brace forces were in compression (the test set-up did not permit measurement of compressive brace forces).

-Stresses increased linearly with loading.

-Bottom flange lateral displacements exceeds top flange displacement.

-Maximum lateral displacement was less than 0.6 in.

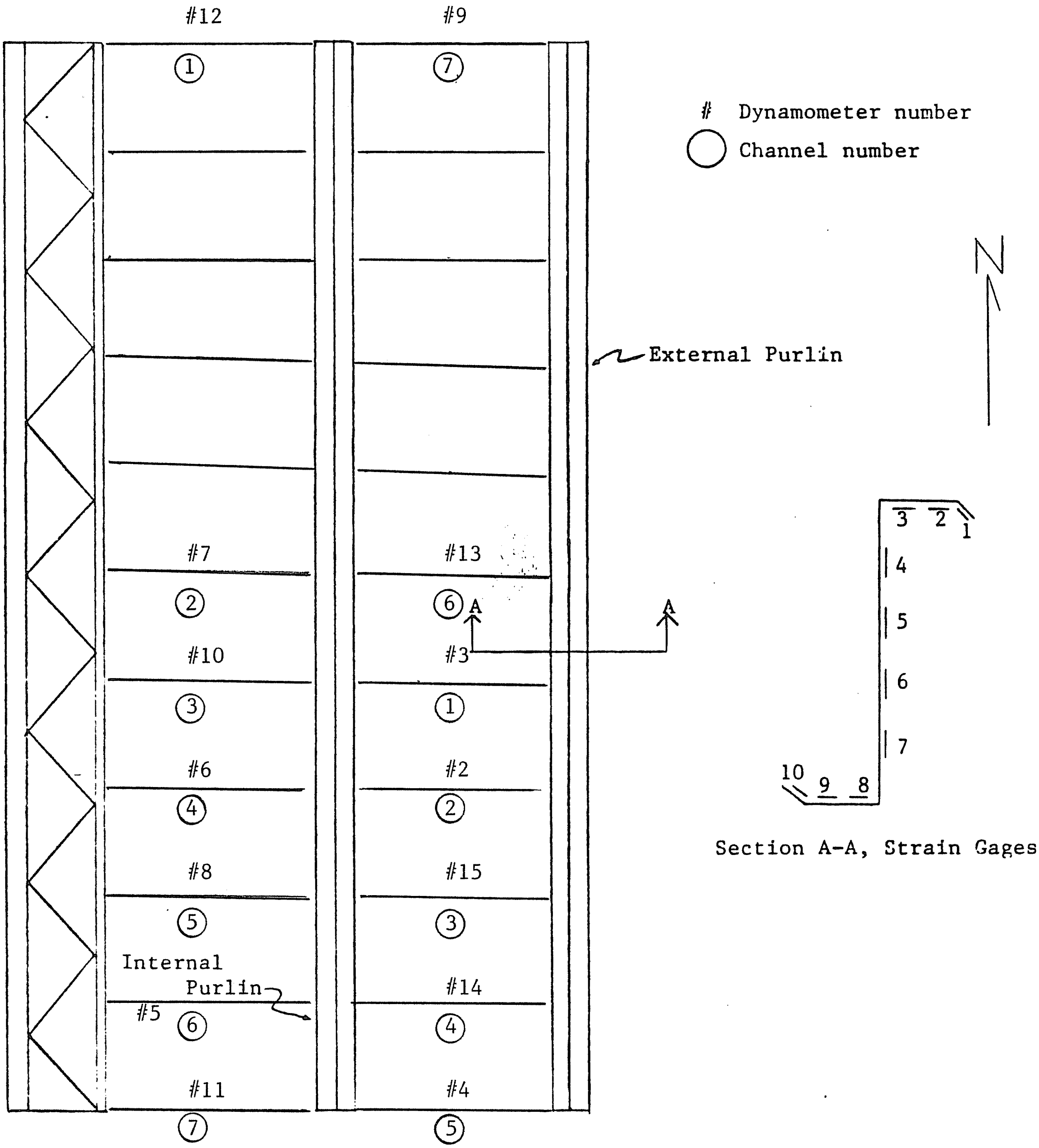
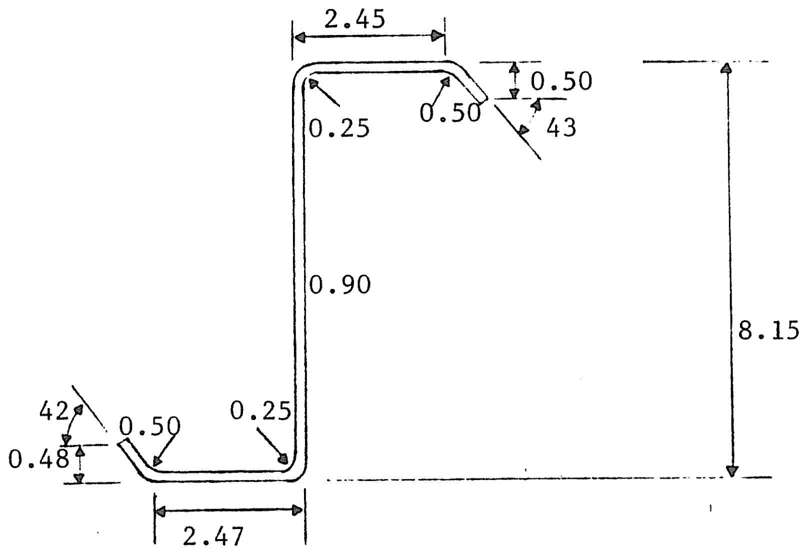
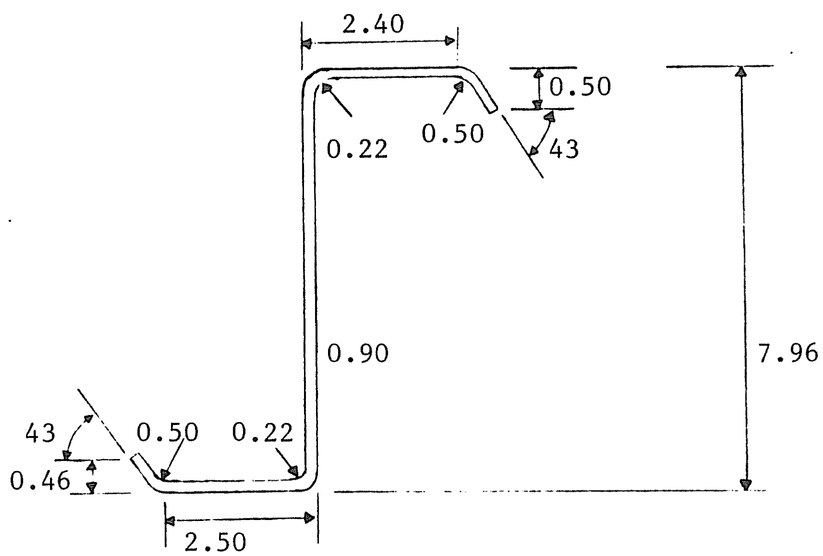


Figure B.1 Instrumentation Location, Test II



External Purlin



Internal Purlin

Figure B.2 Measured Purlin Dimensions, Test II

```
------------------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: MBMA-II-W 11/25/81
------------------------------------------------------------------
                          TOP            BOTTOM
FLANGE(in)              2.400            2.500
LIP(in)                 0.500            0.460
LIP ANGLE(deg)         43.000           43.000
RADIUS L/F(in)          0.500            0.500
RADIUS F/W(in)          0.219            0.219

TOTAL DEPTH(in)                7.96
THICKNESS(in)                  0.09
YIELD STRENGTH(ksi)            56
                                       SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)           TOP              BOTTOM
GROSS=         12.264                  3.106             3.127
STRENGTH=      12.264                  3.106             3.127
DEFLECTION=    12.264
BE=    2.091   in
FC=    33.600   ksi
FT=    33.600   ksi
FBW=   33.266   ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)
             MC=       8.697  ft-k
             MT=       8.756  ft-k
             MW=       9.228  ft-k
             MU=      14.524  ft-k (1.67*allowable)
SPAN           =      19.625  ft.
UNIFORM LOAD=        301.692  plf (1.67*allowable)
DEFLECTION   =         0.922  in./100plf
```

Figure B.3 AISI Purlin Analysis, Test II West Purlin

```
-------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: MBMA-II-E 11/25/81
-------------------------------------------------------
                      TOP            BOTTOM
FLANGE(in)           2.450            2.470
LIP(in)              0.500            0.480
LIP ANGLE(deg)      43.000           42.000
RADIUS L/F(in)       0.500            0.500
RADIUS F/W(in)       0.250            0.250

TOTAL DEPTH(in)             8.15
THICKNESS(in)               0.09
YIELD STRENGTH(ksi)         56
                                 SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)      TOP             BOTTOM
GROSS=         12.996            3.224             3.226
STRENGTH=      12.996            3.224             3.226
DEFLECTION=    12.996
BE=    2.110  in
FC=    33.600  ksi
FT=    33.600  ksi
FBW=   33.085  ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)
          MC=       9.028  ft-k
          MT=       9.032  ft-k
          MW=       9.591  ft-k
          MU=      15.076  ft-k (1.67*allowable)
SPAN         =     19.625  ft.
UNIFORM LOAD=     313.156  plf (1.67*allowable)
DEFLECTION   =      0.871  in./100plf
```

Figure B.4 AISI Purlin Analysis, Test II East Purlin

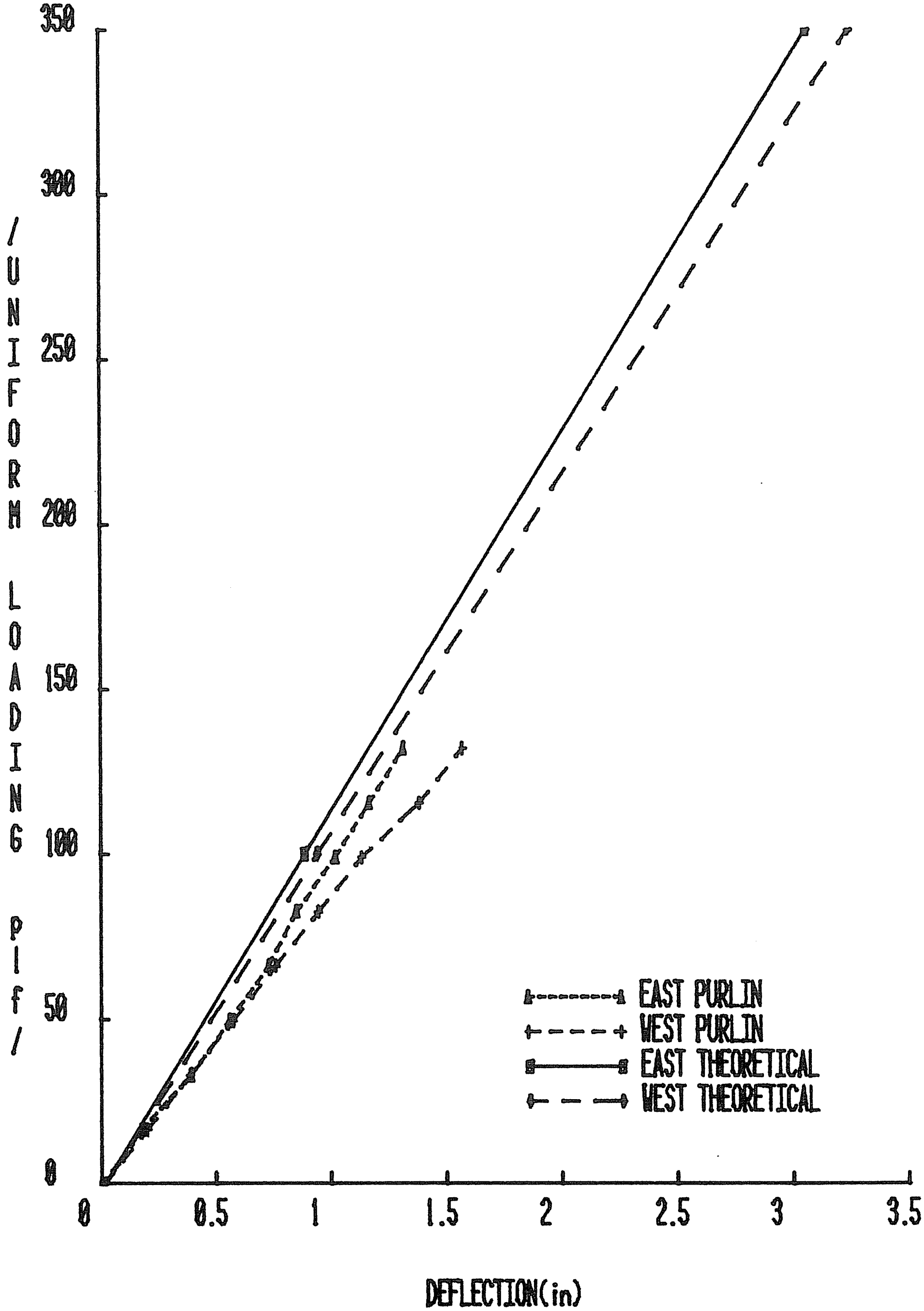


Figure B.5 Load vs. Vertical Deflection, Test II

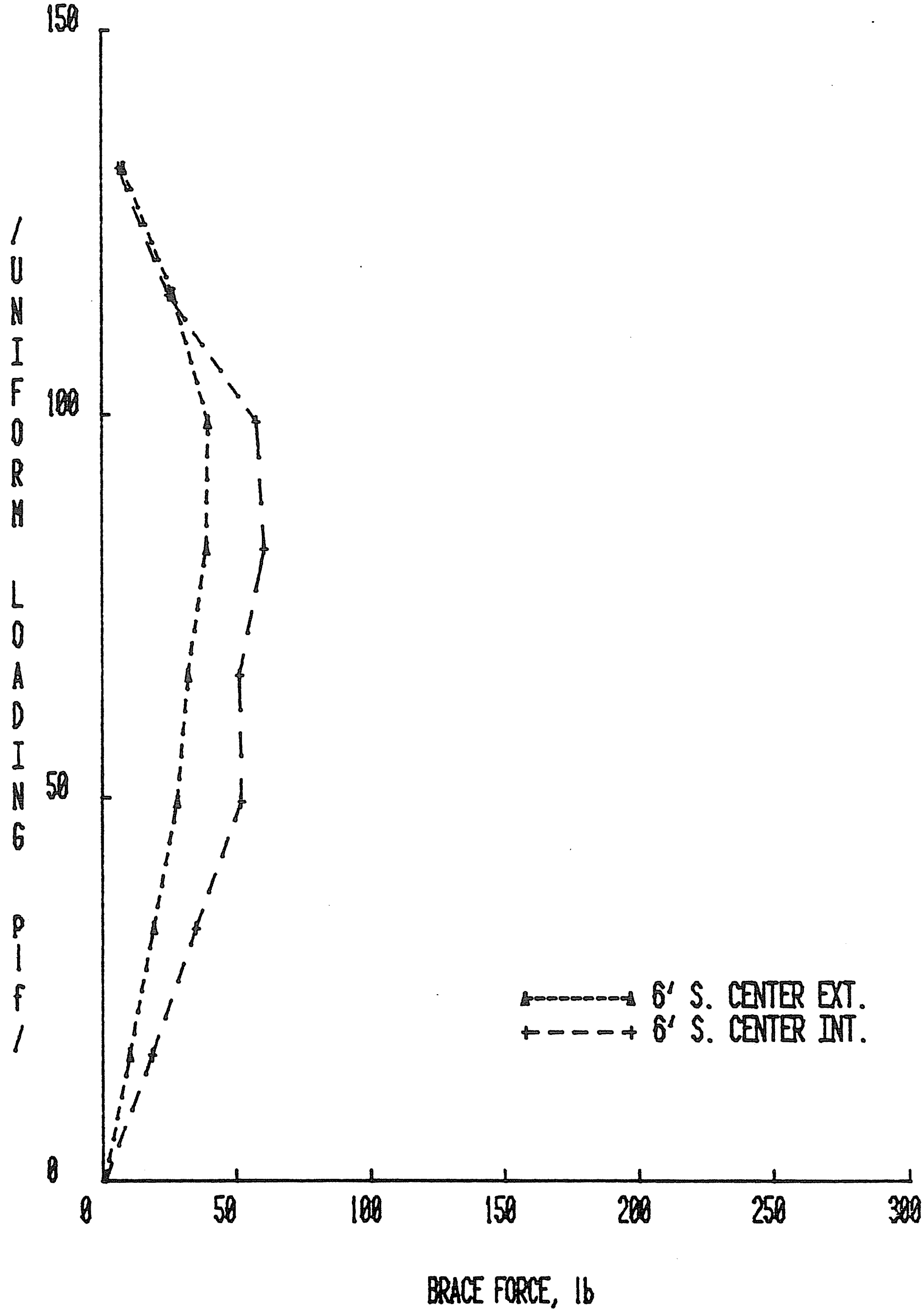


Figure B.6 Vertical Loading vs. Brace Force 6' From Midspan, Test II

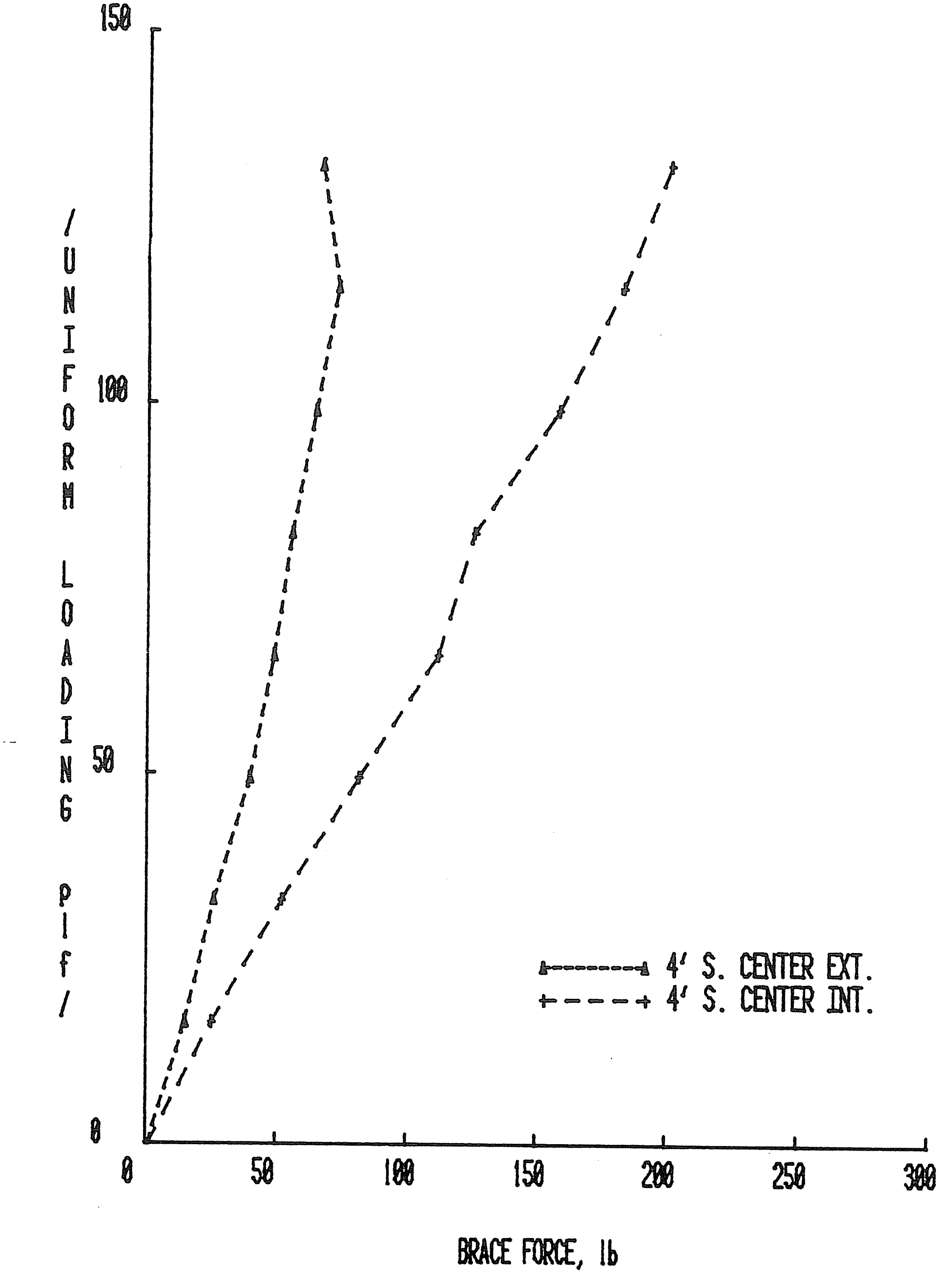


Figure B.7 Vertical Loading vs. Brace Force 4' From Midspan, Test II

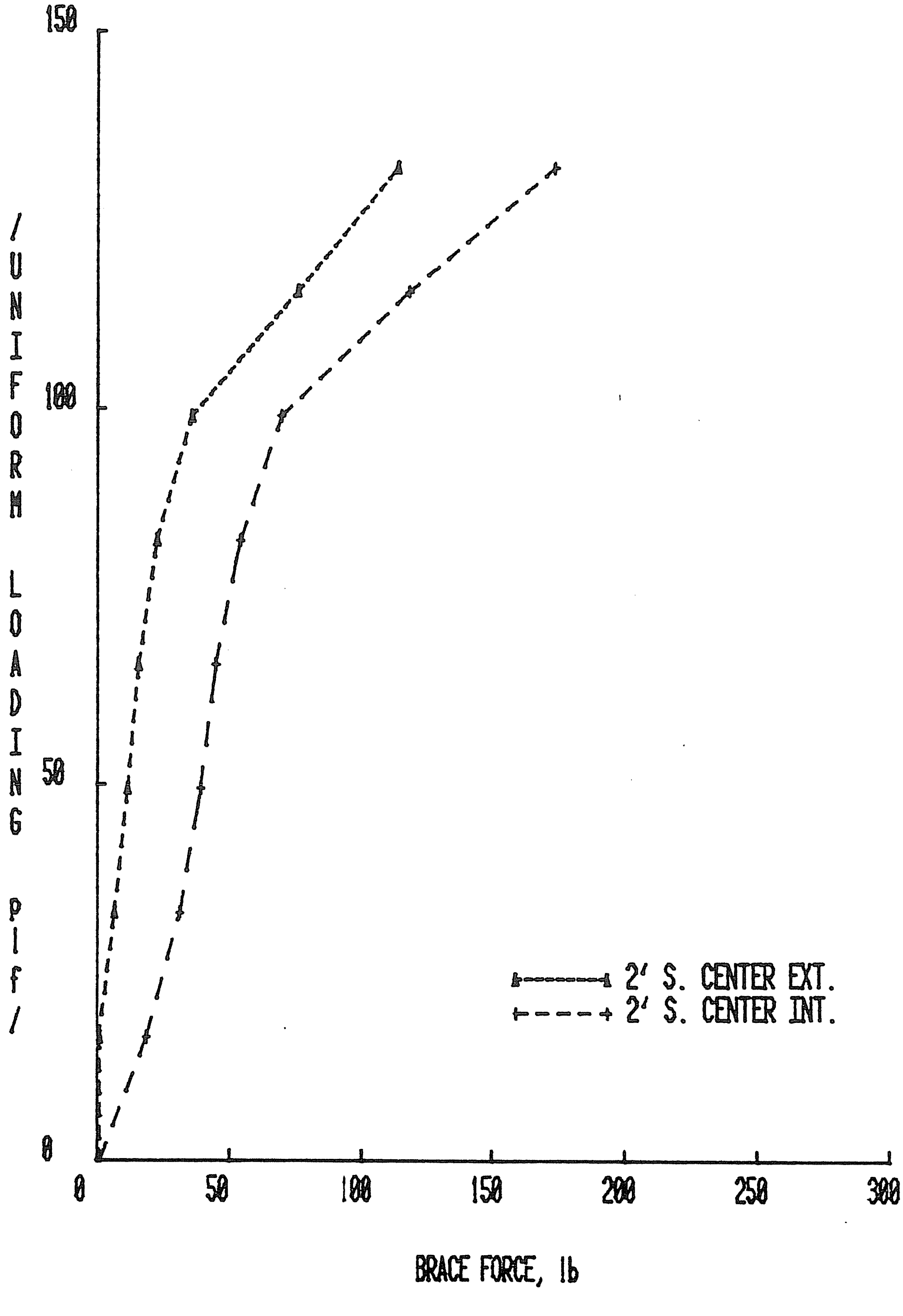


Figure B.8 Vertical Loading vs. Brace Force 2' From Midspan, Test II

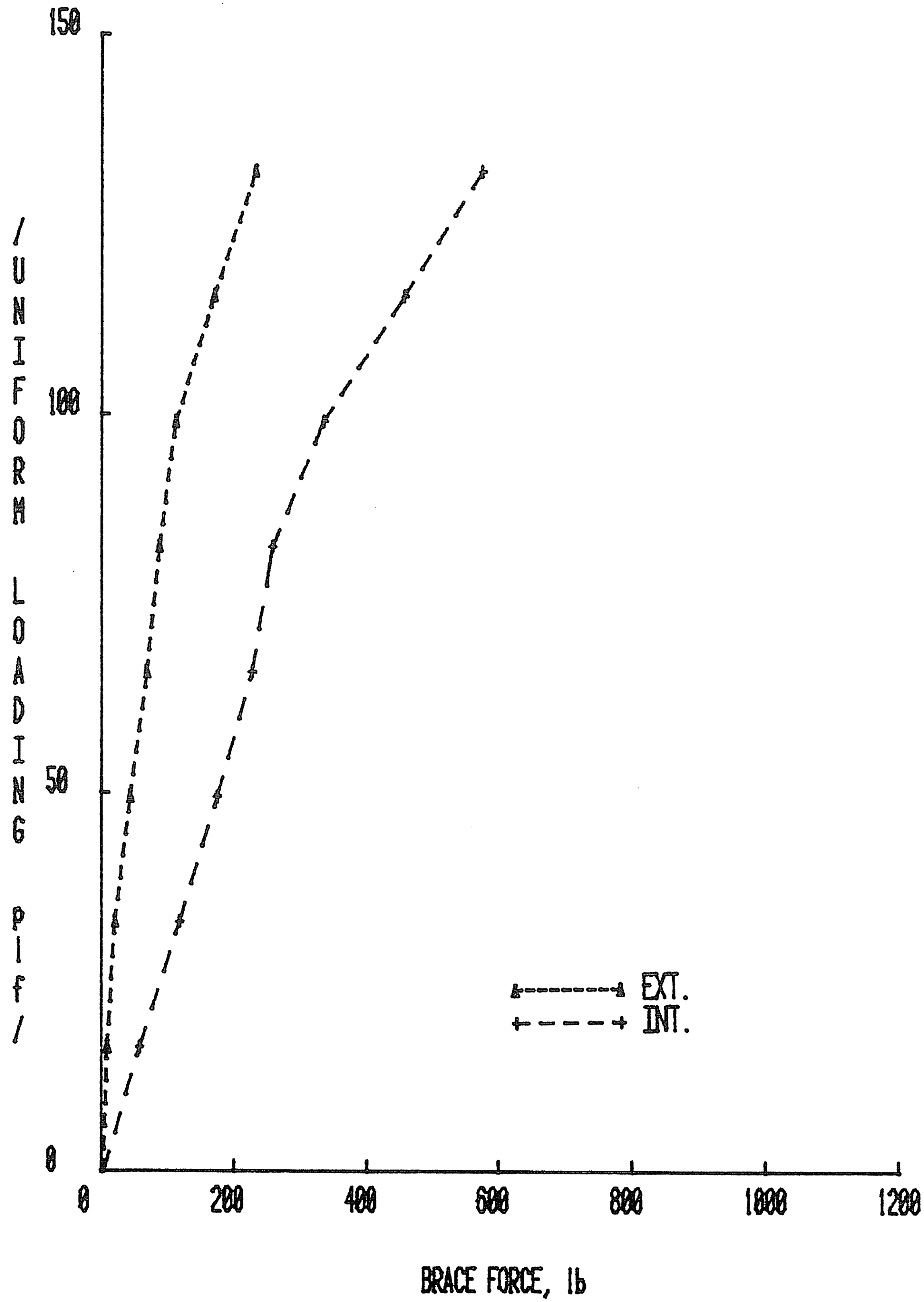
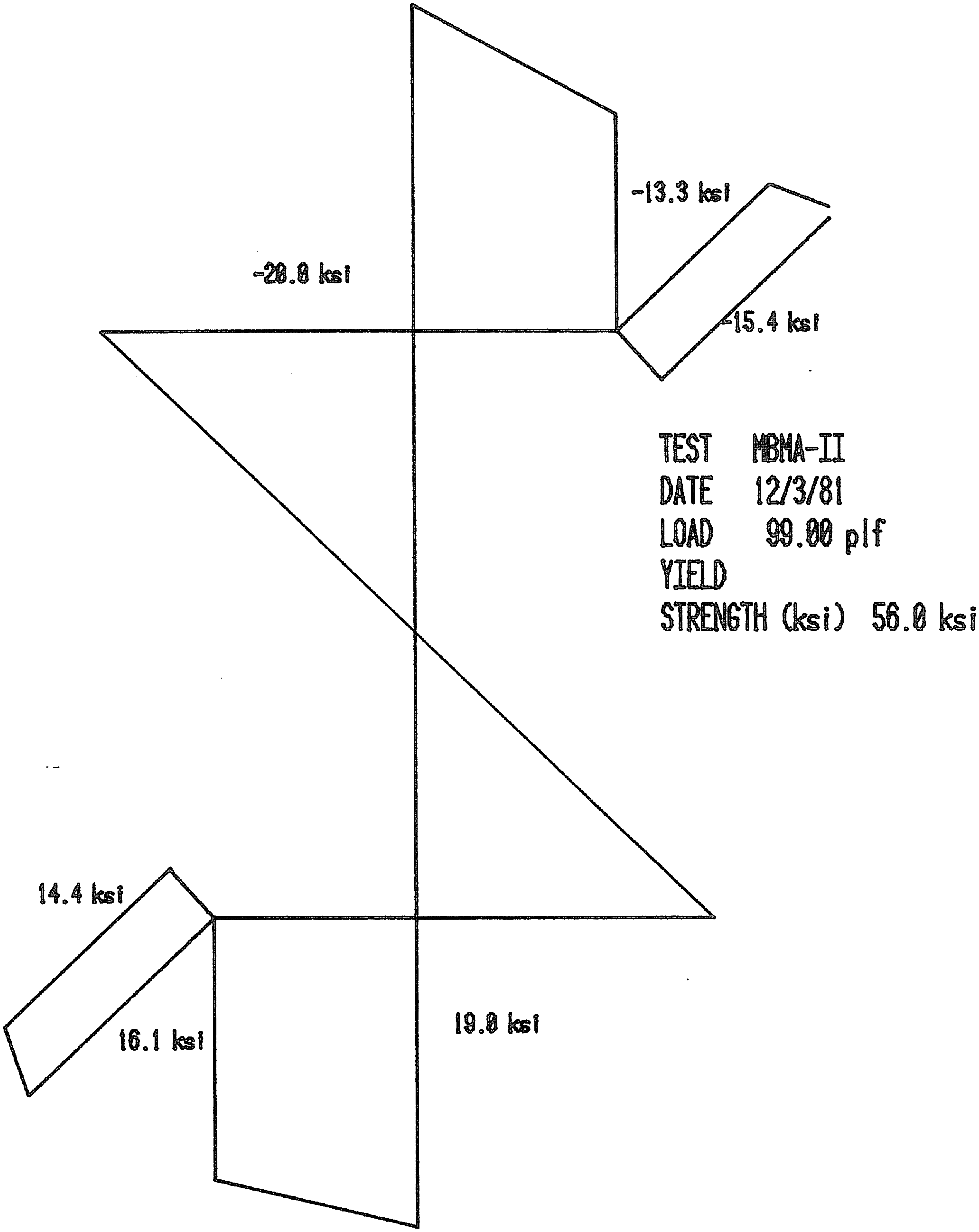


Figure B.9 Vertical Loading vs. Brace Force at Midspan, Test II



B.10 Stress Distribution at 99 plf, Test II

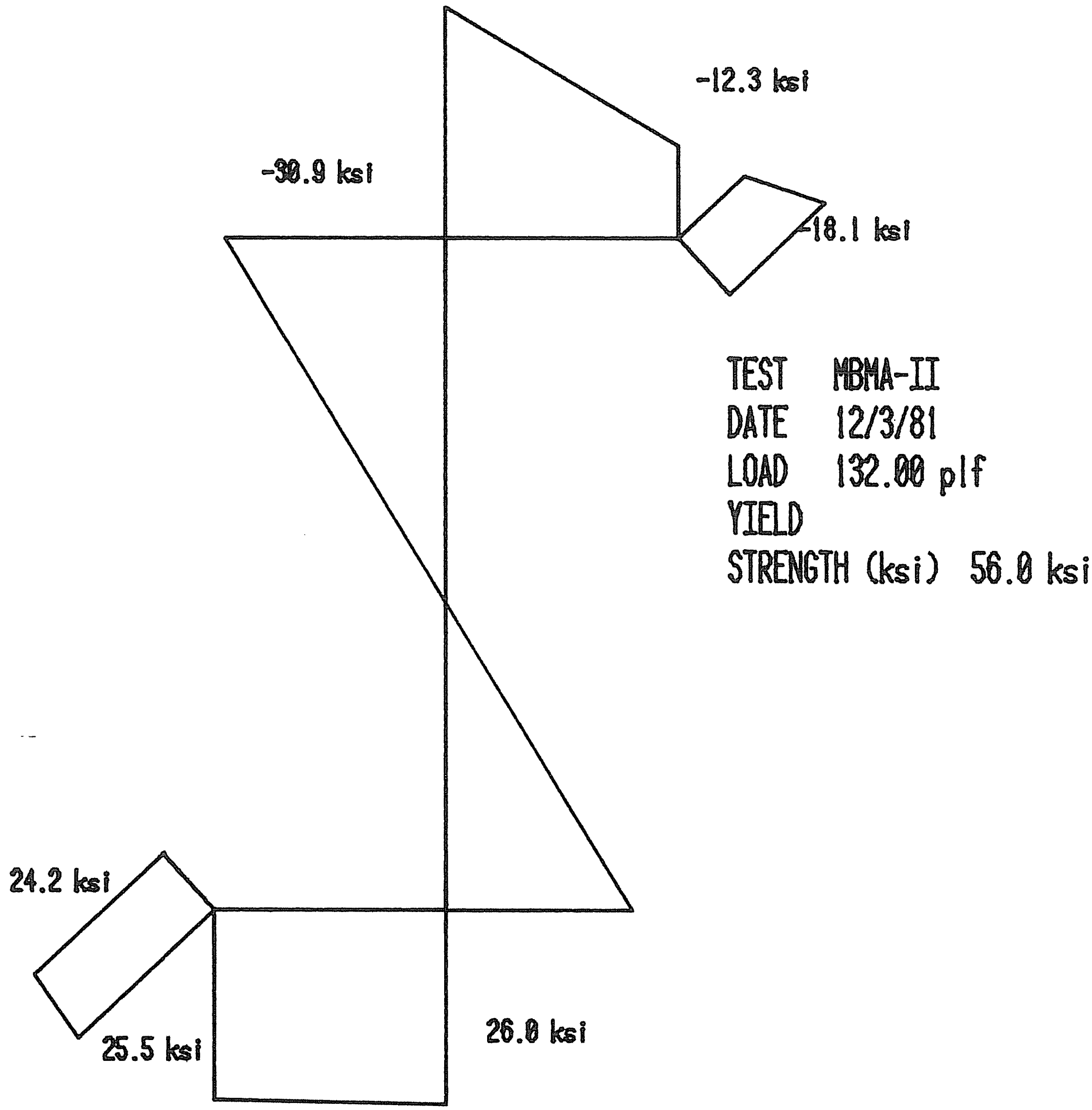


Figure B.11 Stress Distribution at 132 plf, Test II

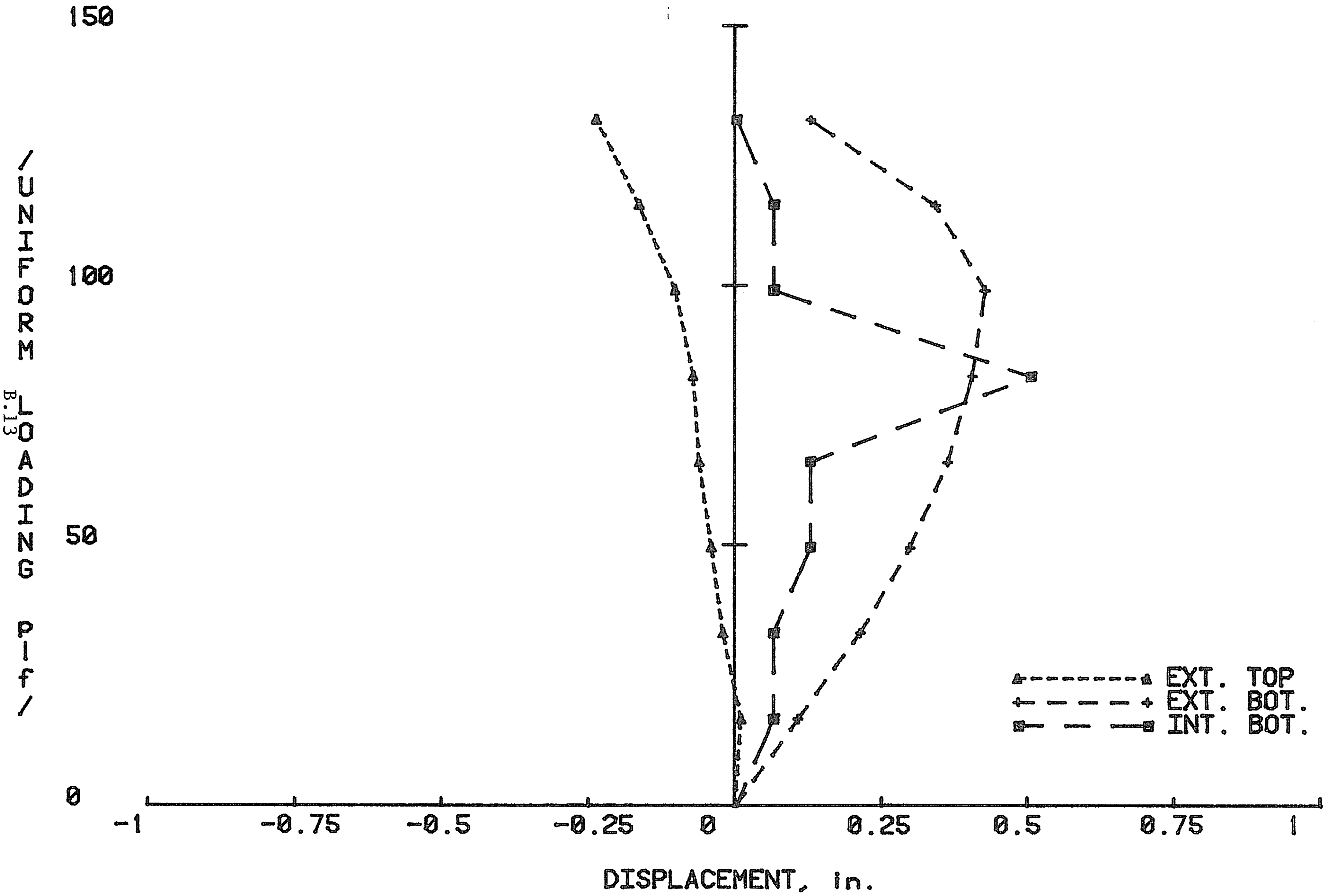


Figure B.12 Vertical Loading vs. Lateral Displacements, Test II

TEST SUMMARY

Project: MBMA Roof System Behavior

Test No.: II-A

Test Date: December 10, 1981

Purpose: Determine restraint forces required for compression flange restraint only.

Span(s): 19.625'

Thickness: 0.086 Moment of Inertia: 11.782 in^4

Parameters: Intermediate bracing @ 2'-0" O.C.

Torsional restraint @ rafter

No panel shear stiffness (greased top flange)

No panel torsional stiffness

Shear stiffness provided by intermediate braces

Failure Load: 135.3 plf

Failure Mode: Buckling of tension flange

Predicted Failure Loads:

x 1.67.

Method AISI constrained bending Load 290.3 plf

Method ____ Load ____

Method ____ Load ____

Discussion:

-Failure occurred at 135.3 plf due to the inability of the web to restrain lateral movement of the tension flange.

-Several intermediate braces and the torsional braces @ rafters were in compression at all loads.

-Vertical deflection was 15-26% greater than predicted from the constrained bending assumption for west purlin (nearer the lateral brace joist). For the east purlin deflections were very close to the constrained bending assumption up to 115.5 plf and 30% greater @ 132 plf.

-Maximum lateral displacement of the tension flange before failure was 1.85 in.

-Bottom flange lateral displacement exceeded top flange lateral displacement.

-Brace forces @ centerline increased linearly with increasing load up to 115.5 plf.

-Brace forces @ 2' and 4' from centerline increased linearly with increasing load up to 115.5 plf.

-Braces near the rafters were in compression. The test set-up was modified to measure compressive forces and the test repeated (Test IIB).

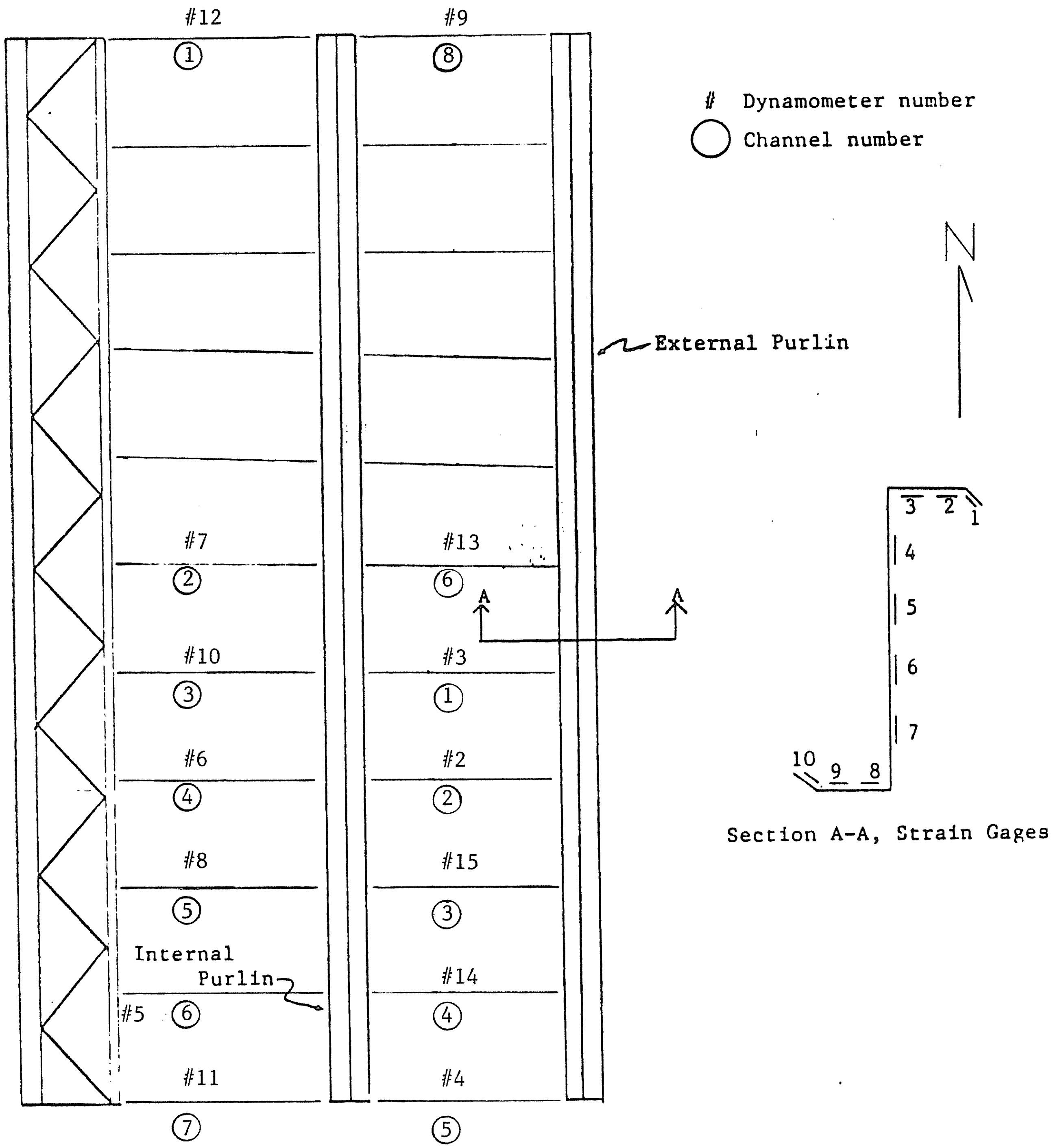
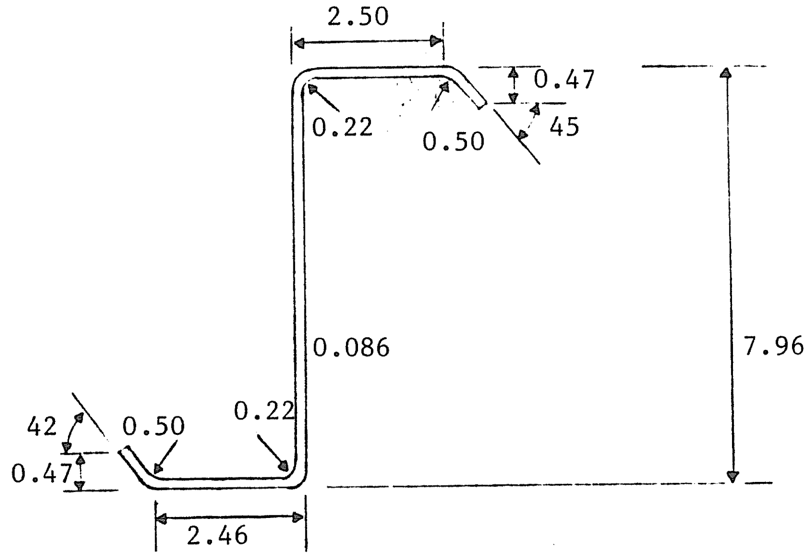
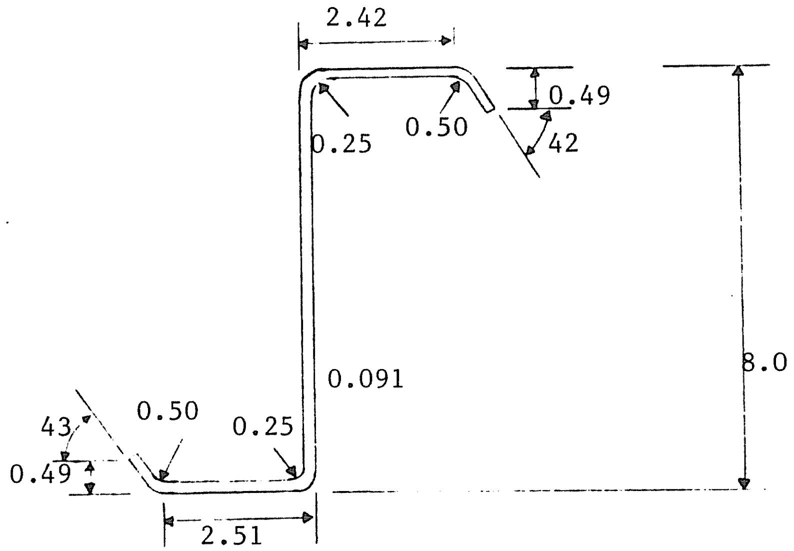


Figure B.13 Instrumentation Location, Test II-A



External Purlin



Internal Purlin

Figure B.14 Measured Purlin Dimensions, Test II-A

```
-----------------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: MBMA-II-A-WEST 12/10/81
-----------------------------------------------------------------
                         TOP            BOTTOM
FLANGE(in)              2.420            2.510
LIP(in)                 0.490            0.490
LIP ANGLE(deg)         42.000           43.000
RADIUS L/F(in)          0.500            0.500
RADIUS F/W(in)          0.250            0.250

TOTAL DEPTH(in)              8
THICKNESS(in)                0.091
YIELD STRENGTH(ksi)          56
                                         SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)         TOP                BOTTOM
GROSS=          12.589              3.166                3.201
STRENGTH=       12.589              3.166                3.201
DEFLECTION=     12.589
BE=    2.079   in
FC=    33.600   ksi
FT=    33.600   ksi
FBW=   33.311   ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)
          MC=       8.864  ft-k
          MT=       8.964  ft-k
          MW=       9.493  ft-k
          MU=      14.802  ft-k (1.67*allowable)
SPAN          =    19.625  ft.
UNIFORM LOAD=     307.467  plf (1.67*allowable)
DEFLECTION    =     0.899  in./100plf
```

Figure B.15 AISI Purlin Analysis, Test II-A West Purlin

```
---------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: MBMA-II-A-EAST 12/10/81
---------------------------------------------------------
                     TOP             BOTTOM
FLANGE(in)          2.500             2.460
LIP(in)             0.470             0.470
LIP ANGLE(deg)     45.000            42.000
RADIUS L/F(in)      0.500             0.500
RADIUS F/W(in)      0.219             0.219

TOTAL DEPTH(in)            7.96
THICKNESS(in)              0.086
YIELD STRENGTH(ksi)        56
                                   SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)       TOP               BOTTOM
GROSS=         11.782              2.996              2.989
STRENGTH=      11.782              2.996              2.989
DEFLECTION=    11.782
BE=    2.195   in
FC=    33.600  ksi
FT=    33.600  ksi
FBW=   32.914  ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)
          MC=       8.388   ft-k
          MT=       8.370   ft-k
          MW=       8.803   ft-k
          MU=      13.978   ft-k (1.67*allowable)
SPAN          =    19.625   ft.
UNIFORM LOAD=     290.355   plf (1.67*allowable)
DEFLECTION   =      0.960   in./100plf
```

Figure B.16 AISI Purlin Analysis, Test II-A East Purlin

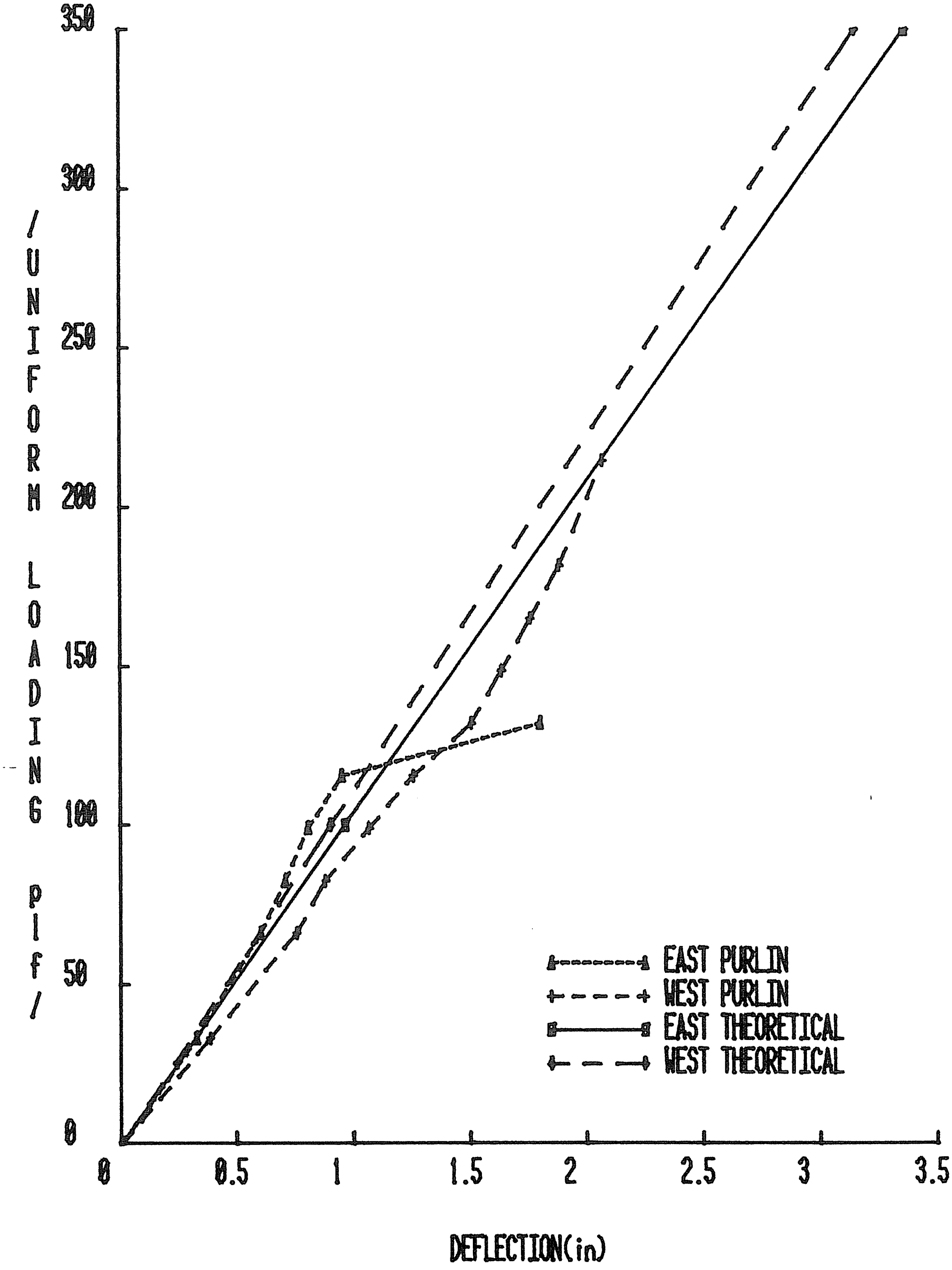


Figure B.17 Load vs. Vertical Deflection, Test II-A

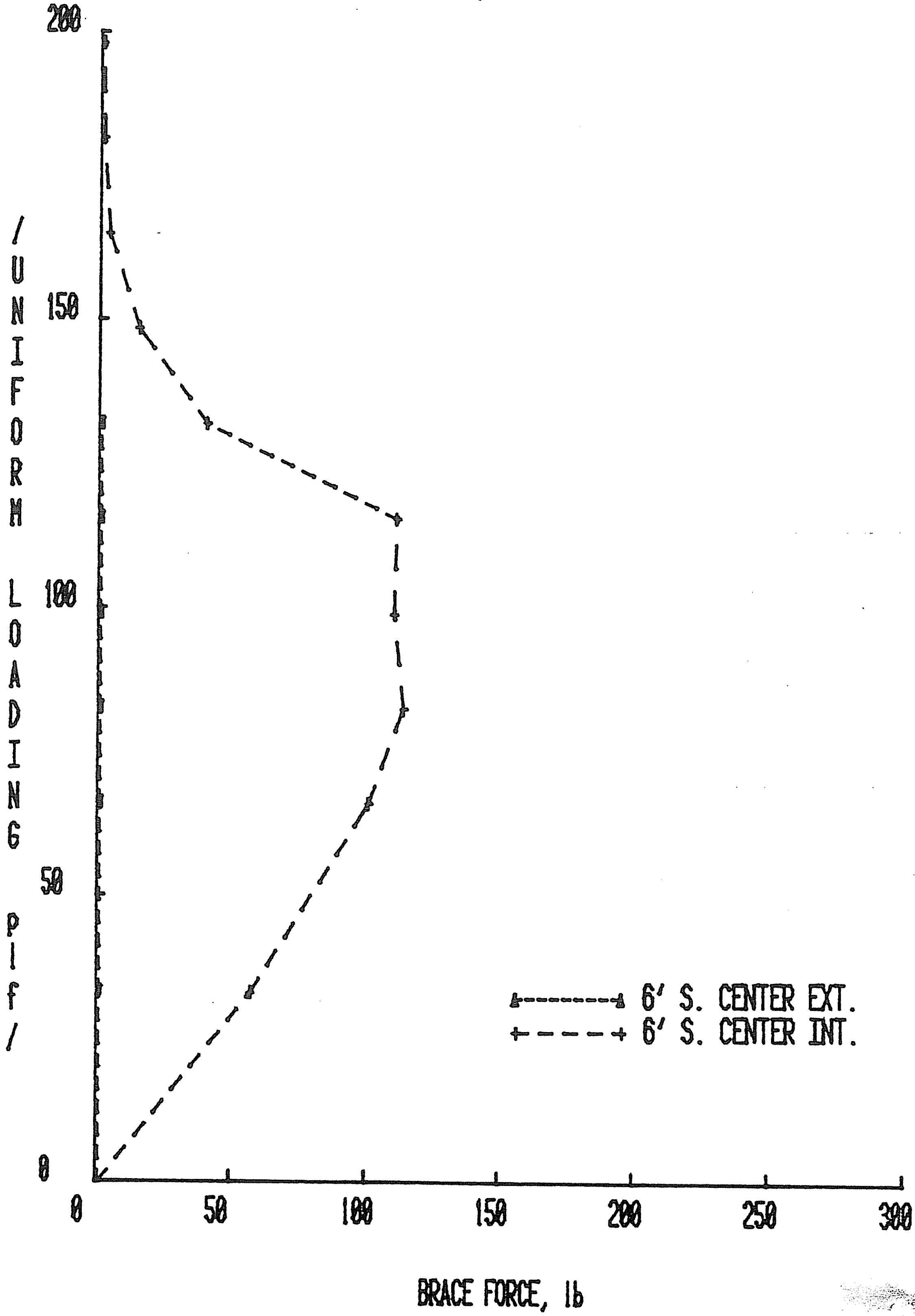


Figure B.18 Vertical Loading vs. Brace Force 6' From Midspan, Test II-A

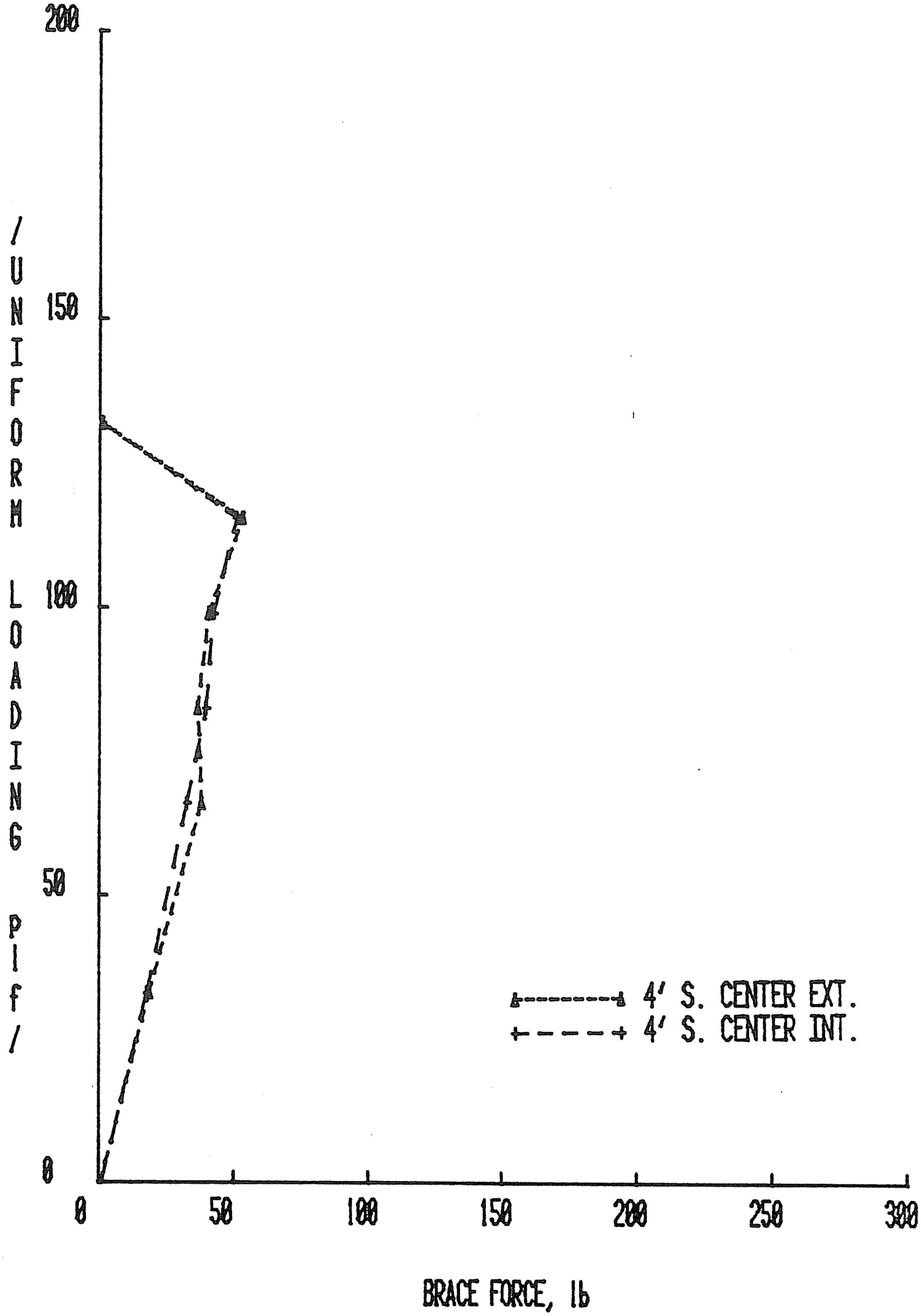


Figure B.19 Vertical Loading vs. Brace Force 4' From Midspan, Test II-A

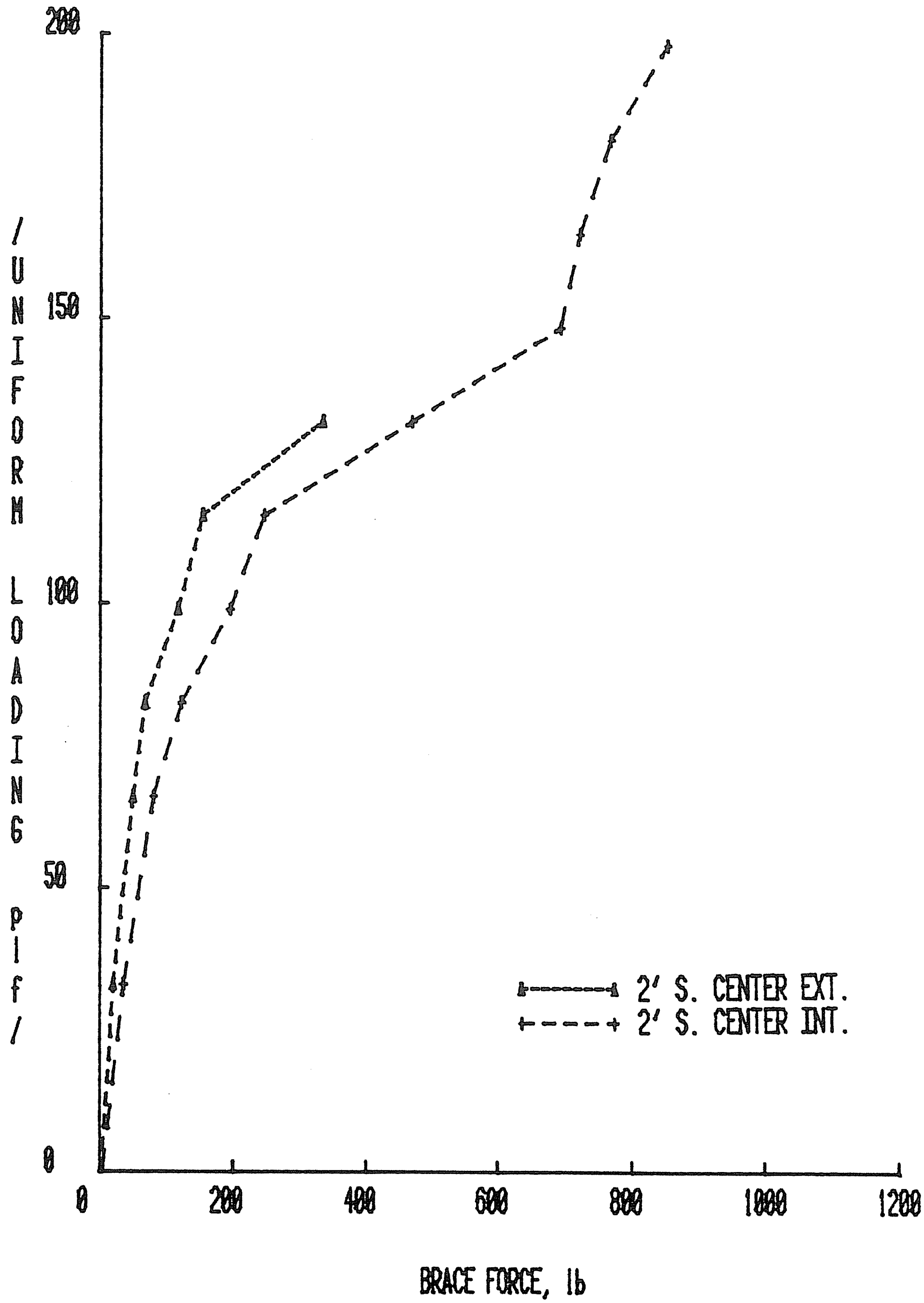


Figure B.20 Vertical Loading vs. Brace Force 2' From Midspan, Test II-A

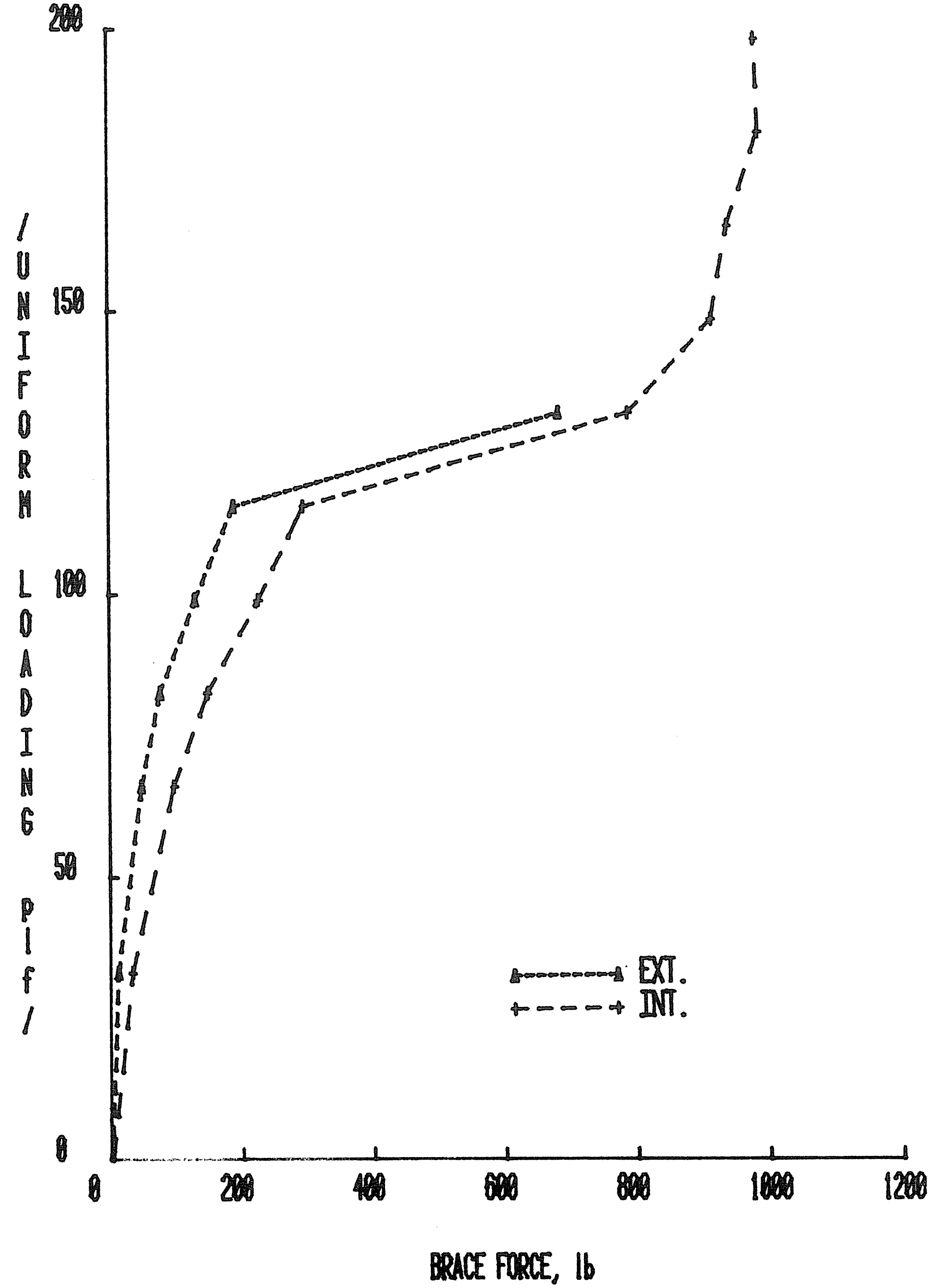


Figure B.21 Vertical Loading vs. Brace Force at Midspan, Test II-A

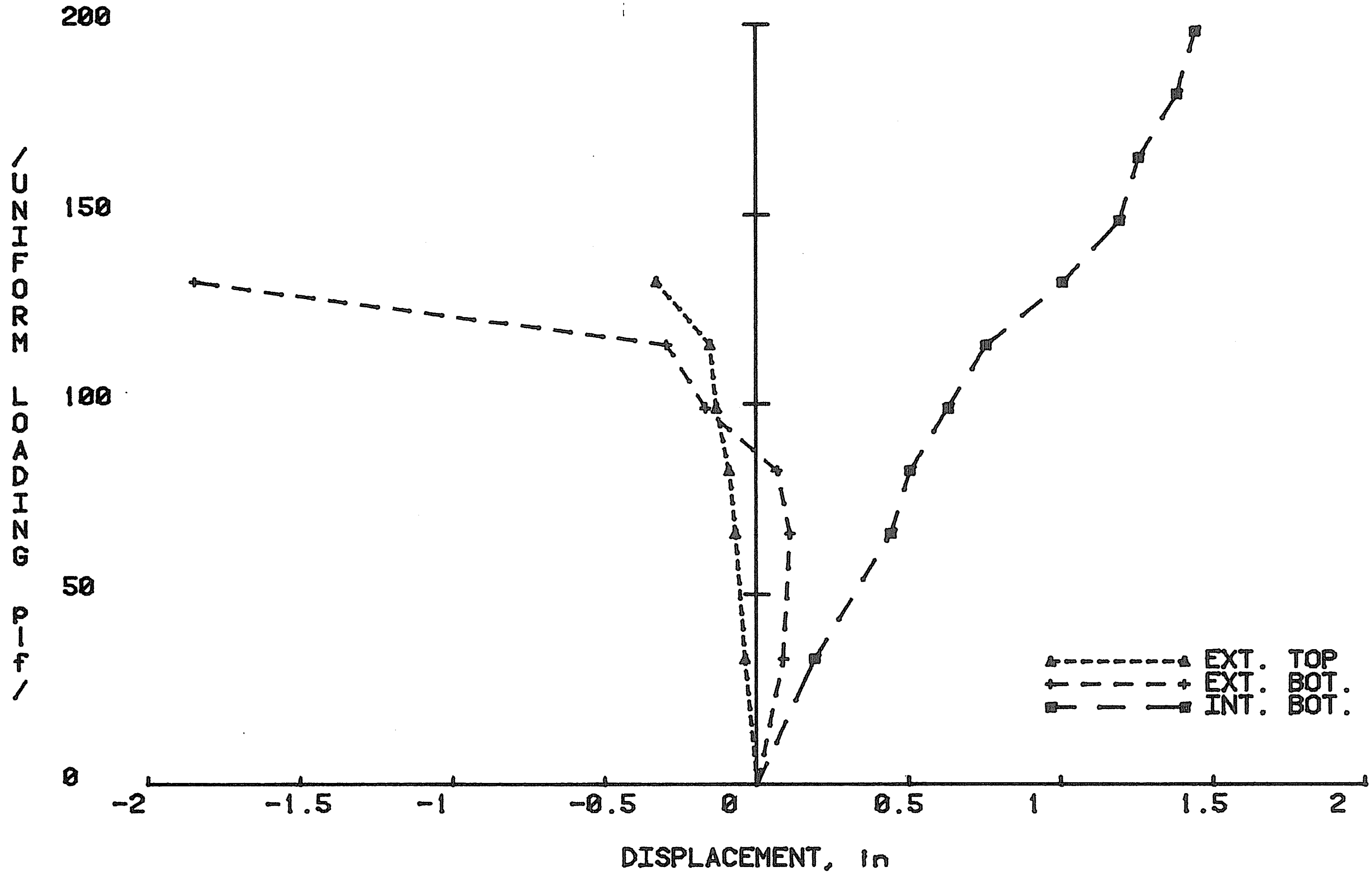


Figure B.22 Vertical Loading vs. Lateral Displacement, Test II-A

TEST SUMMARY

Project: MBMA Roof System Behavior

Test No.: II-B

Test Date: December 21, 1981

Purpose: Determine restraint forces for compression flange restraint only.

Span(s): 19.625'

Thickness: 0.087" Moment of Inertia: 11.4 in^4

Parameters: Intermediate bracing @ 2'-0" o.c.

Torsional restraint @ rafters

No panel shear stiffness (greased top flange)

No panel torsional stiffness

Shear stiffness provided by intermediate braces

Failure Load: 188.2 plf

Failure Mode: Buckling of tension flange.

Predicted Failure Loads:

Method AISI constrained bending x 1.67. Load 280.7 plf

Method ______ Load ______

Method ______ Load ______

Discussion:

- -Failure occurred at 188.2 plf due to the inability of the web to restrain lateral movement of the tension flange.
- -Torsional restraint braces and the adjacent intermediate braces were in tension at all load levels.
- -Vertical deflection was about 10% greater than predicted from the constrained bending assumption.
- -For the east purlin (nearer the lateral support joist); west purlin deflection was very close to predicted.
- -Brace forces increased linearly with increasing vertical load.
- -The ratio of internal to external brace forces @ centerline varied from 1.37 to 2.06; @ north rafter from -3.61 to 38.87, @ south rafter from 1.86 to 4.70 @2' north of centerline from 1.25 to 1.65 and @ 4' north of centerline from 1.25 to 2.09.
- -Stresses increased linearly with loading.
- -At 66 plf, summation of external brace forces equaled 14% of total vertical load on external purlin. Summation of internal brace forces equaled 28% of total vertical load.
- -At 181.5 plf, summation of external brace forces equaled 19% of total vertical load and internal brace forces equaled 37.5% of total vertical load.
- -Bottom flange lateral displacement exceeded top flange displacement.
- -Maximum lateral displacement was less than 0.70 in. before failure.

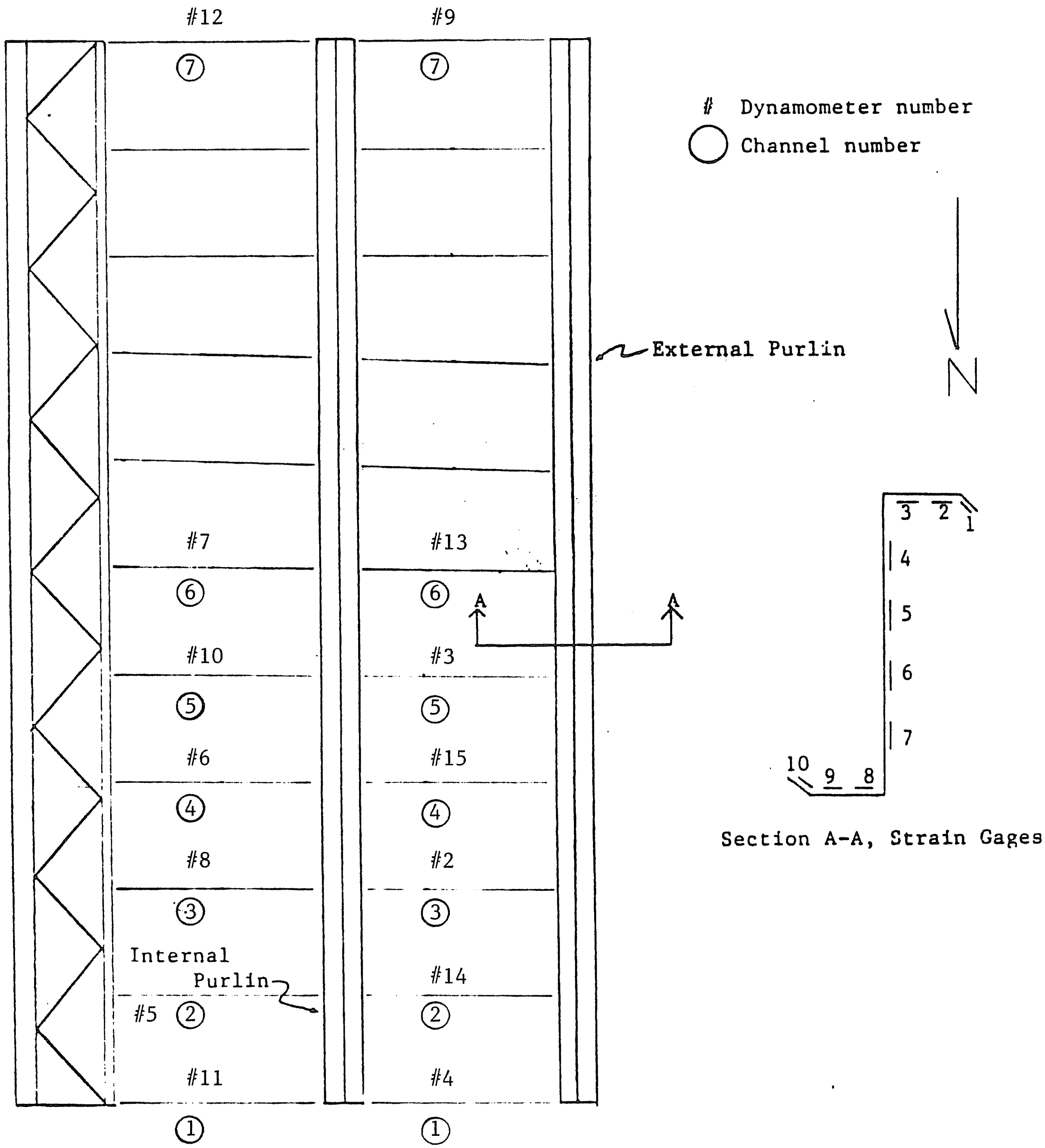
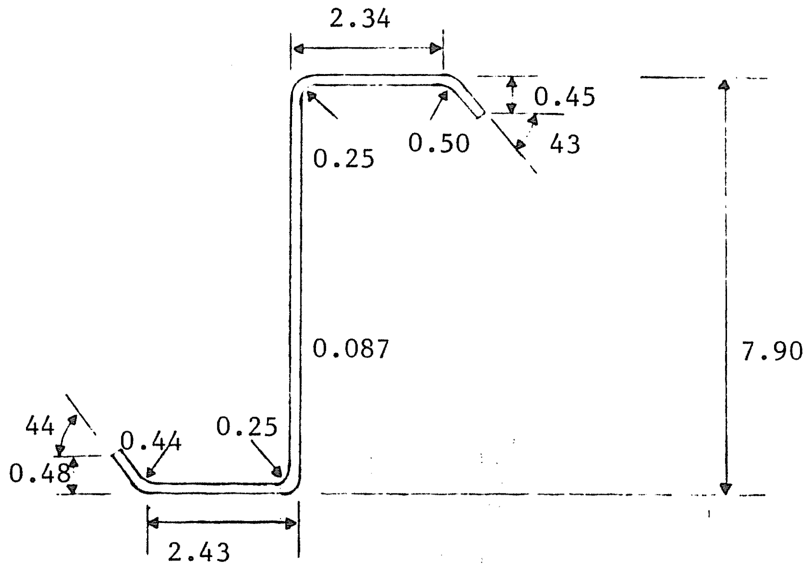
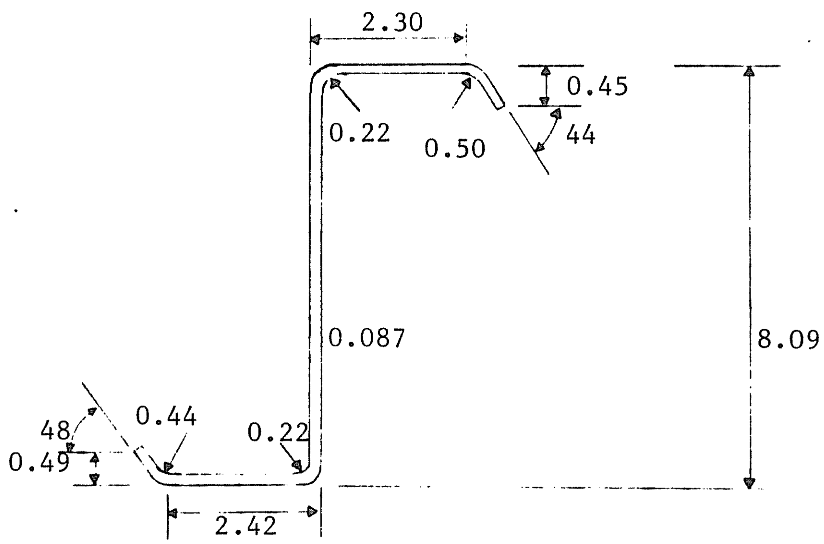


Figure B.23 Instrumentation Location, Test II-B



External Purlin



Internal Purlin

Figure B.24 Measured Purlin Dimensions, Test II-B

```
-----------------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: MBMA TEST-II-B (12/21/81) WEST PURLIN
-----------------------------------------------------------------
                          TOP            BOTTOM
FLANGE(in)               2.340            2.430
LIP(in)                  0.450            0.480
LIP ANGLE(deg)          43.000           44.000
RADIUS L/F(in)           0.500            0.438
RADIUS F/W(in)           0.250            0.250

TOTAL DEPTH(in)               7.9
THICKNESS(in)                 0.087
YIELD STRENGTH(ksi)           56
                                    SECTION MODULII(in^3)
    MOMENTS OF INERTIA(in^4)         TOP              BOTTOM
GROSS=        11.368               2.890             2.931
STRENGTH=     11.368               2.890             2.931
DEFLECTION=   11.368
BE=     2.003   in
FC=    33.600   ksi
FT=    33.600   ksi
FBW=   33.064   ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)
          MC=      8.091   ft-k
          MT=      8.205   ft-k
          MW=      8.604   ft-k
          MU=     13.512   ft-k (1.67*allowable)
SPAN        =     19.625   ft.
UNIFORM LOAD=    280.662   plf (1.67*allowable)
DEFLECTION  =      0.995   in./100plf
```

Figure B.25 AISI Purlin Analysis, Test II-B West Purlin

```
-----------------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: MBMA TEST-II-B (12/21/81) EAST PURLIN
-----------------------------------------------------------------
                          TOP              BOTTOM
FLANGE(in)               2.300              2.420
LIP(in)                  0.450              0.490
LIP ANGLE(deg)          44.000             48.000
RADIUS L/F(in)           0.500              0.438
RADIUS F/W(in)           0.219              0.219

TOTAL DEPTH(in)                8.09
THICKNESS(in)                  0.087
YIELD STRENGTH(ksi)            56
                                         SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)          TOP               BOTTOM
GROSS=          11.955                2.963              3.013
STRENGTH=       11.955                2.963              3.013
DEFLECTION=     11.955
BE=     1.994   in
FC=     33.600   ksi
FT=     33.600   ksi
FBW=    32.877   ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)
          MC=       8.296   ft-k
          MT=       8.436   ft-k
          MW=       8.682   ft-k
          MU=      13.855   ft-k (1.67*allowable)
SPAN        =      19.625   ft.
UNIFORM LOAD=     287.785   plf (1.67*allowable)
DEFLECTION  =       0.946   in./100plf
```

Figure B.26 AISI Purlin Analysis, Test II-B East Purlin

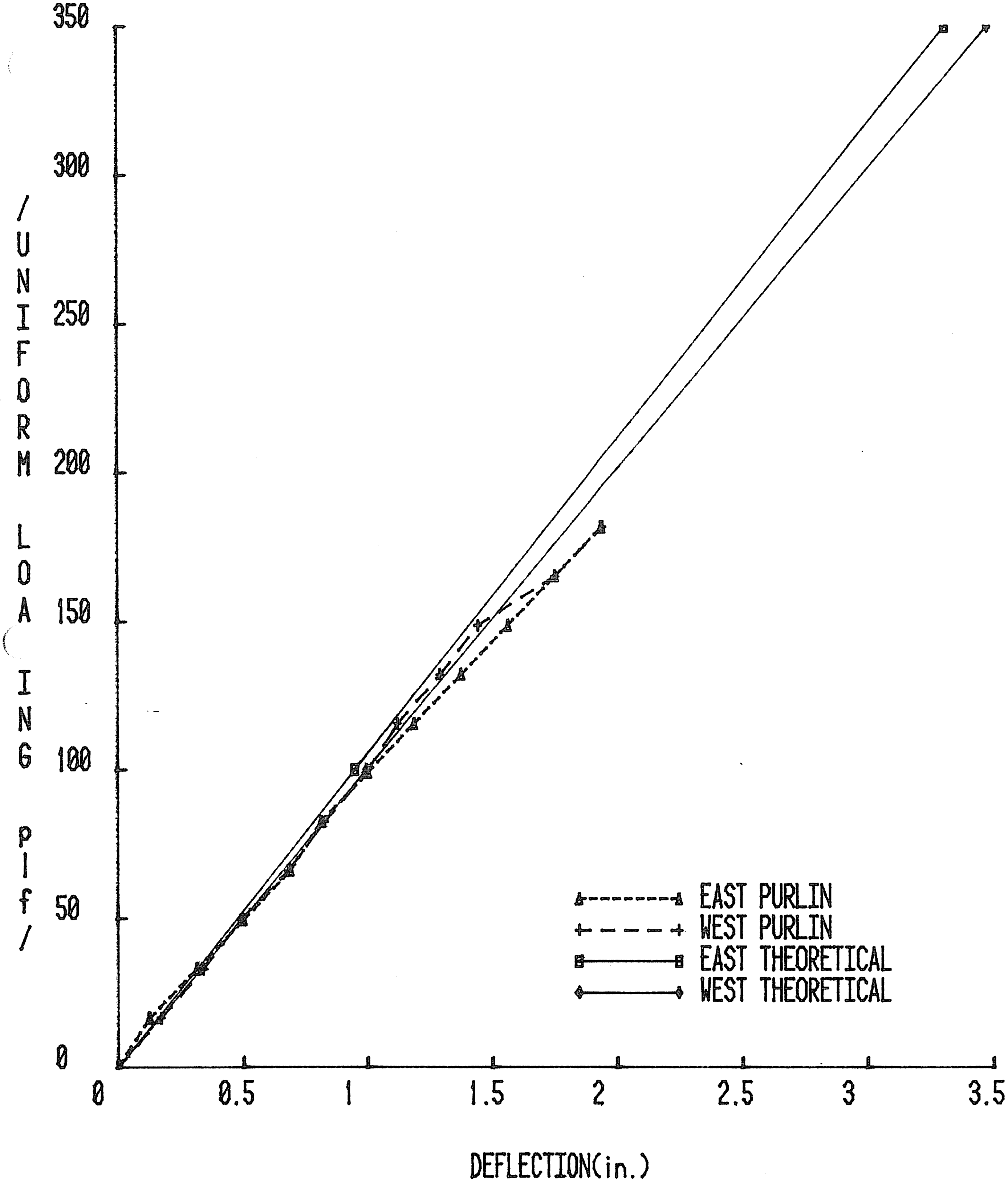


Figure B.27 Load vs. Vertical Deflection, Test II-B

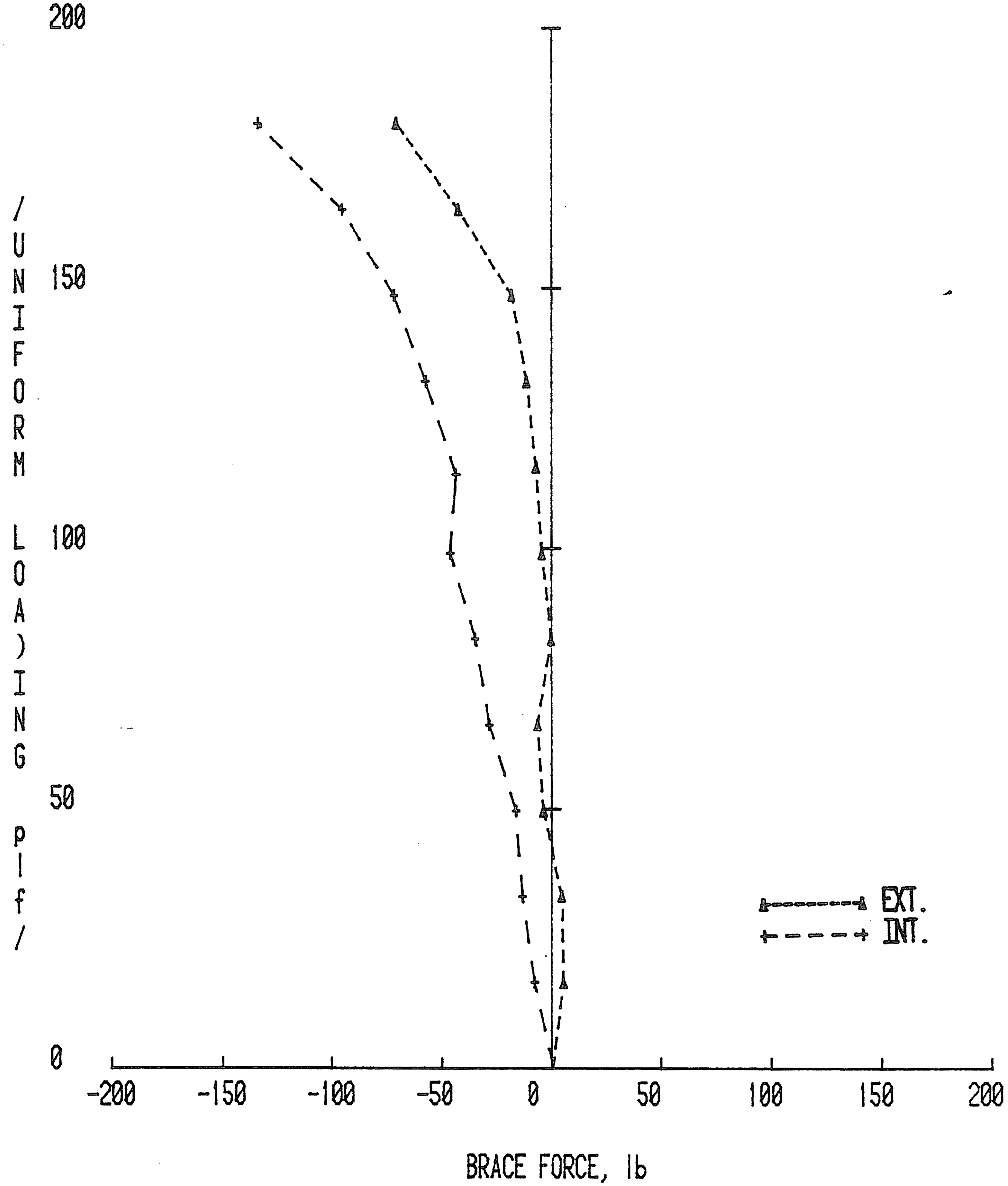


Figure B.28 Vertical Loading vs. Brace Force @ North Rafter, Test II-B

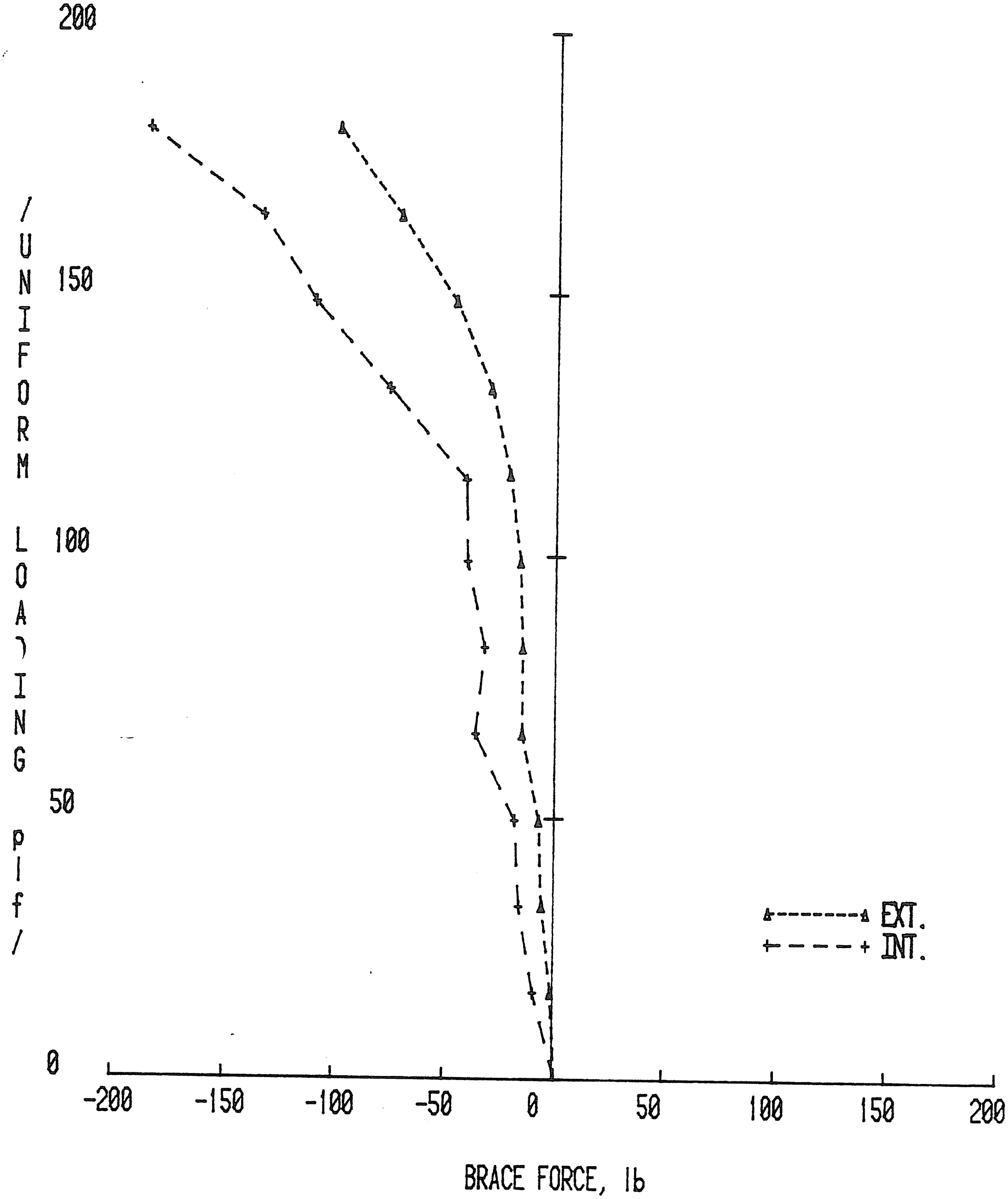


Figure B.29 Vertical Loading vs. Brace Force @ South Rafter, Test II-B

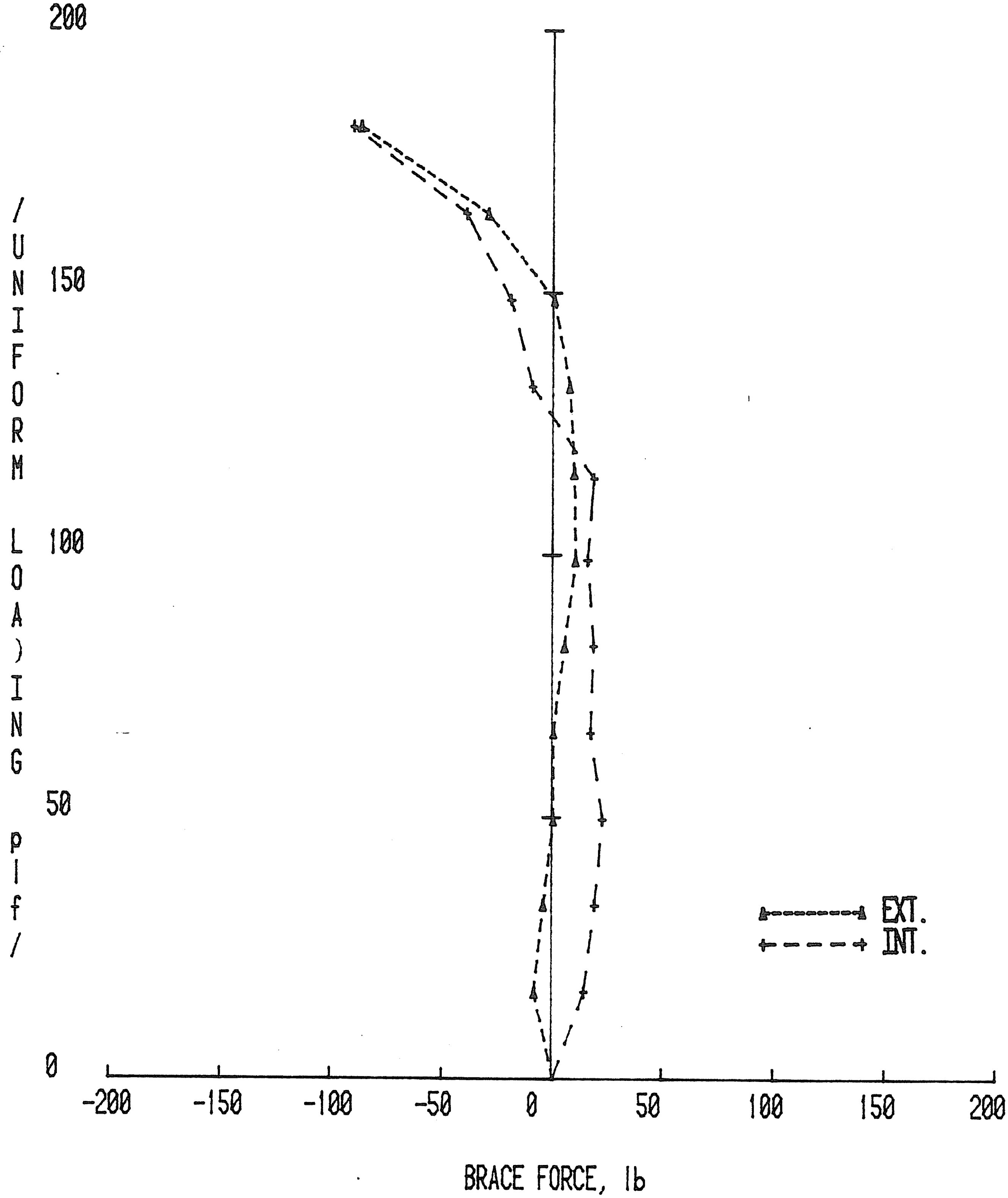


Figure B.30 Vertical Loading vs. Brace Force 8' From Midspan, Test II-B

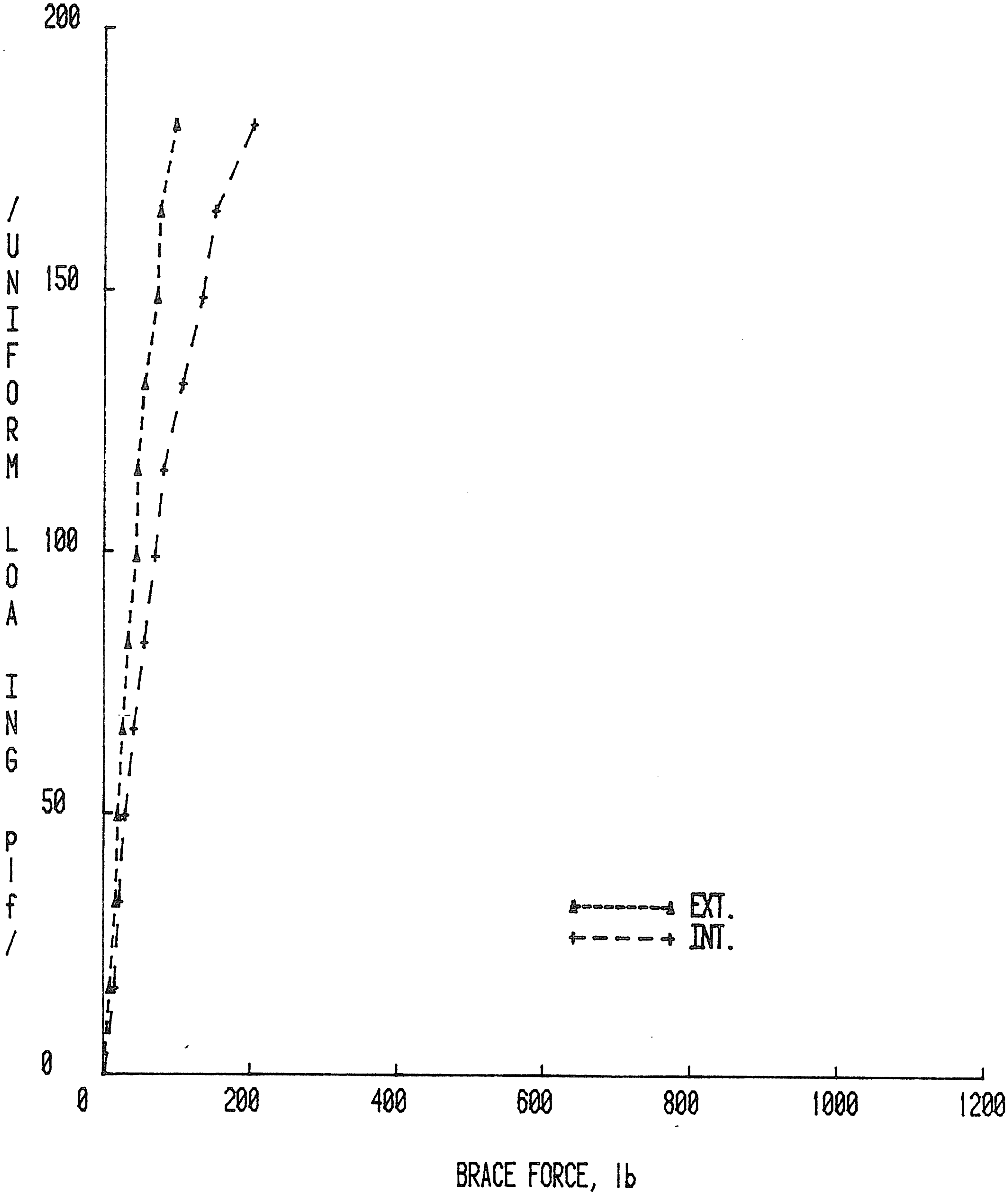


Figure B.31 Vertical Loading vs. Brace Force 6' From Midspan, Test II-B

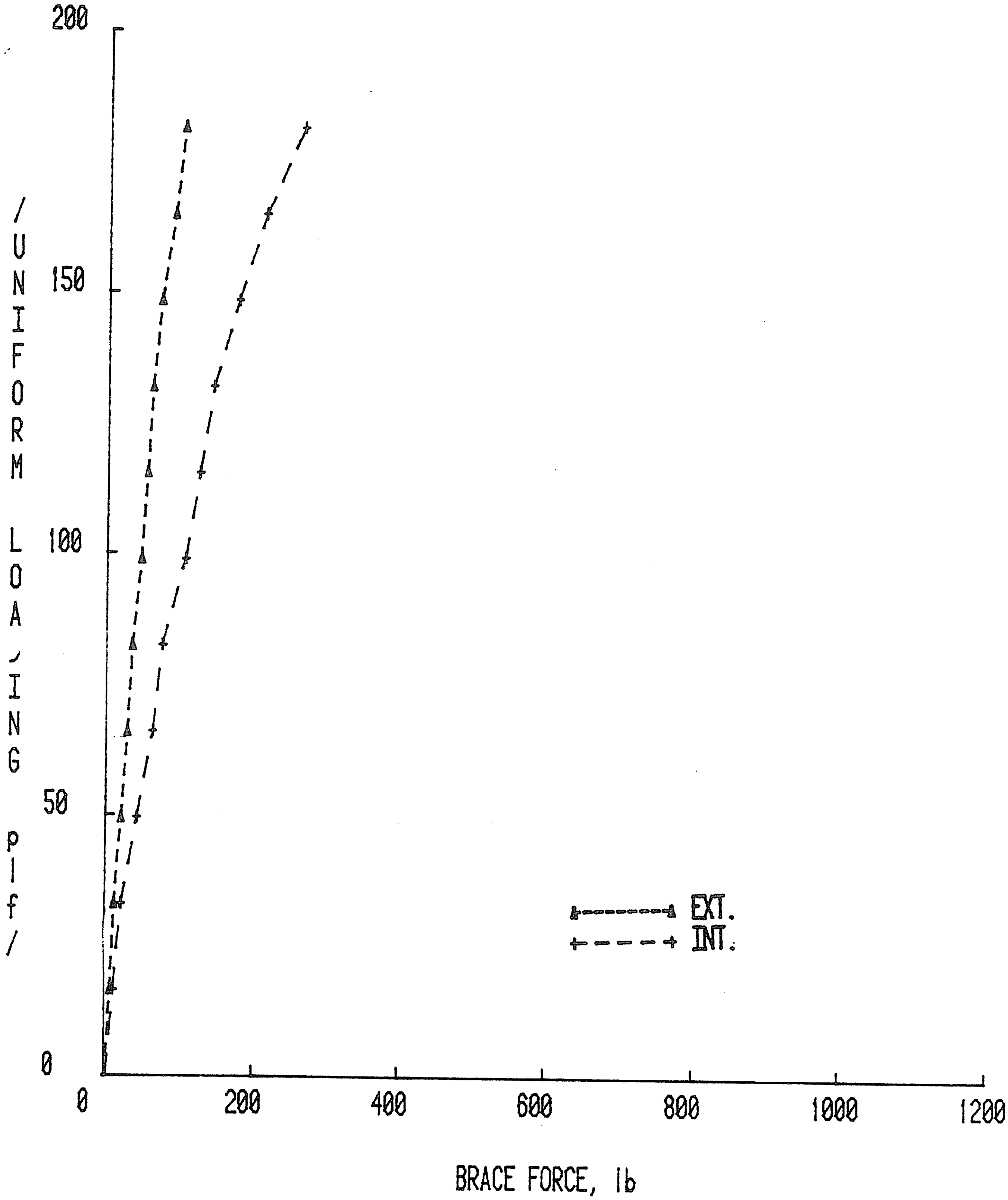


Figure B.32 Vertical Loading vs. Brace Force 4' From Midspan, Test II-B

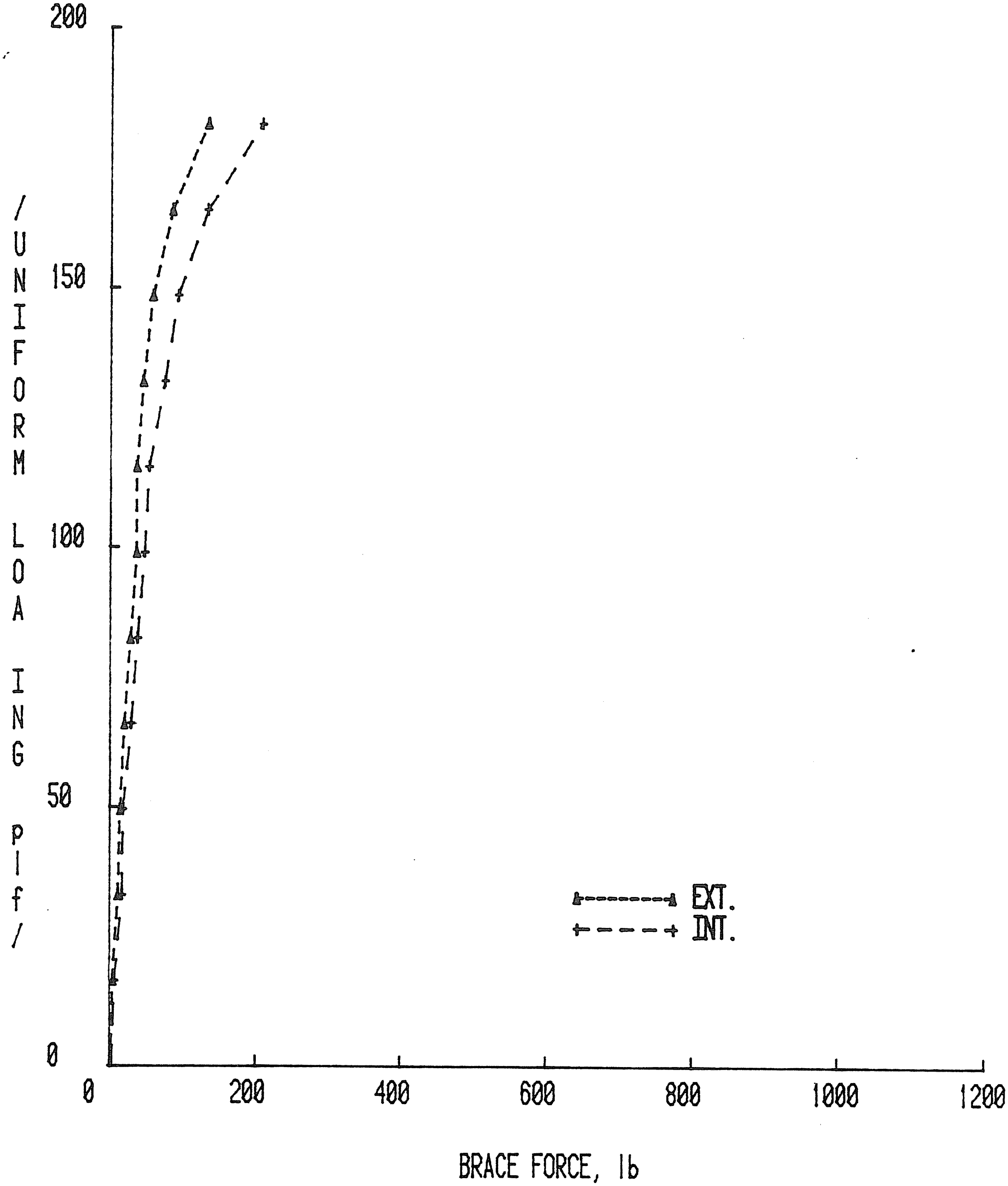


Figure B.33 Vertical Loading vs. Brace Force 2' From Midspan, Test II-B

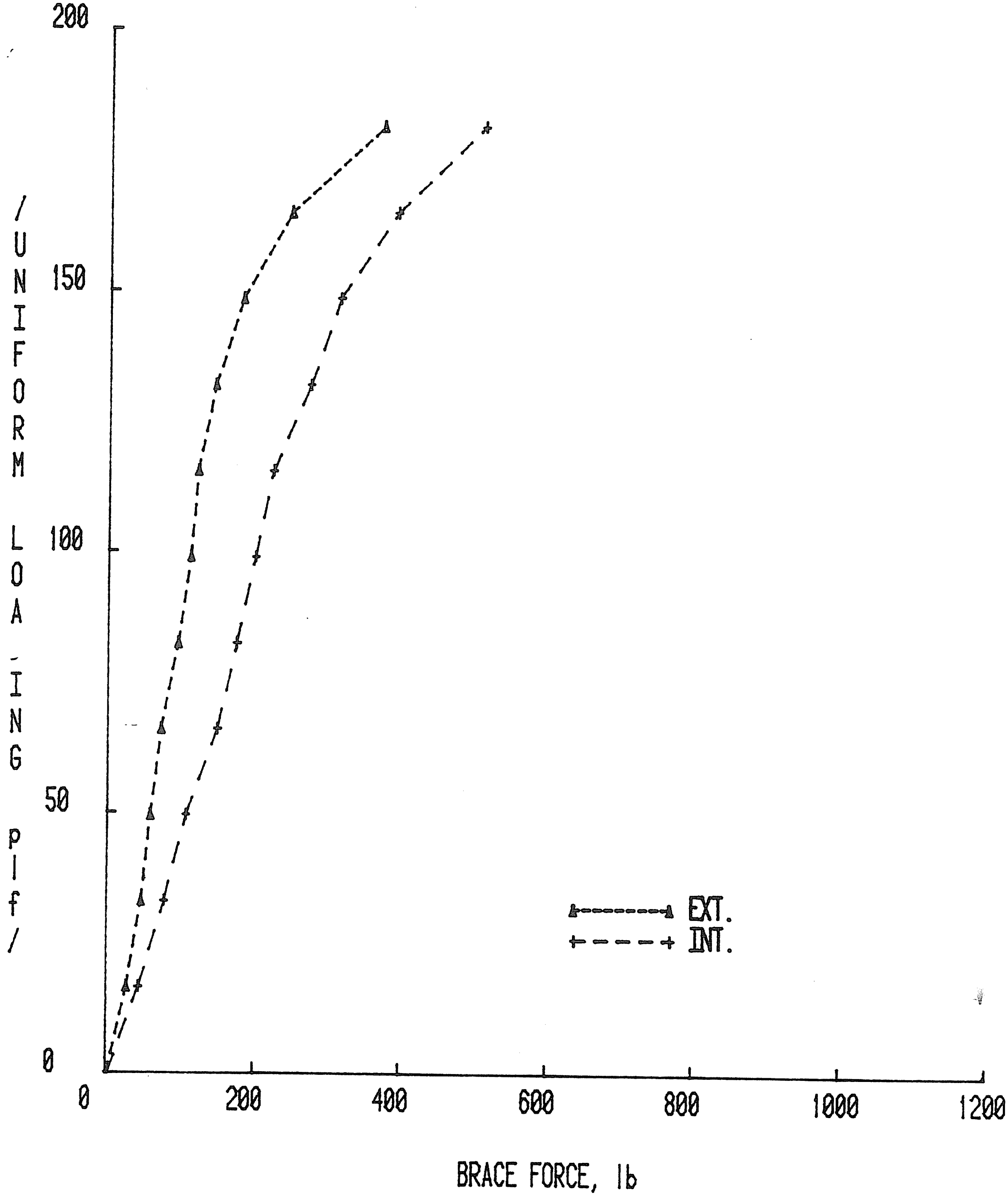


Figure B.34 Vertical Loading vs. Brace Force @ Midspan, Test II-B

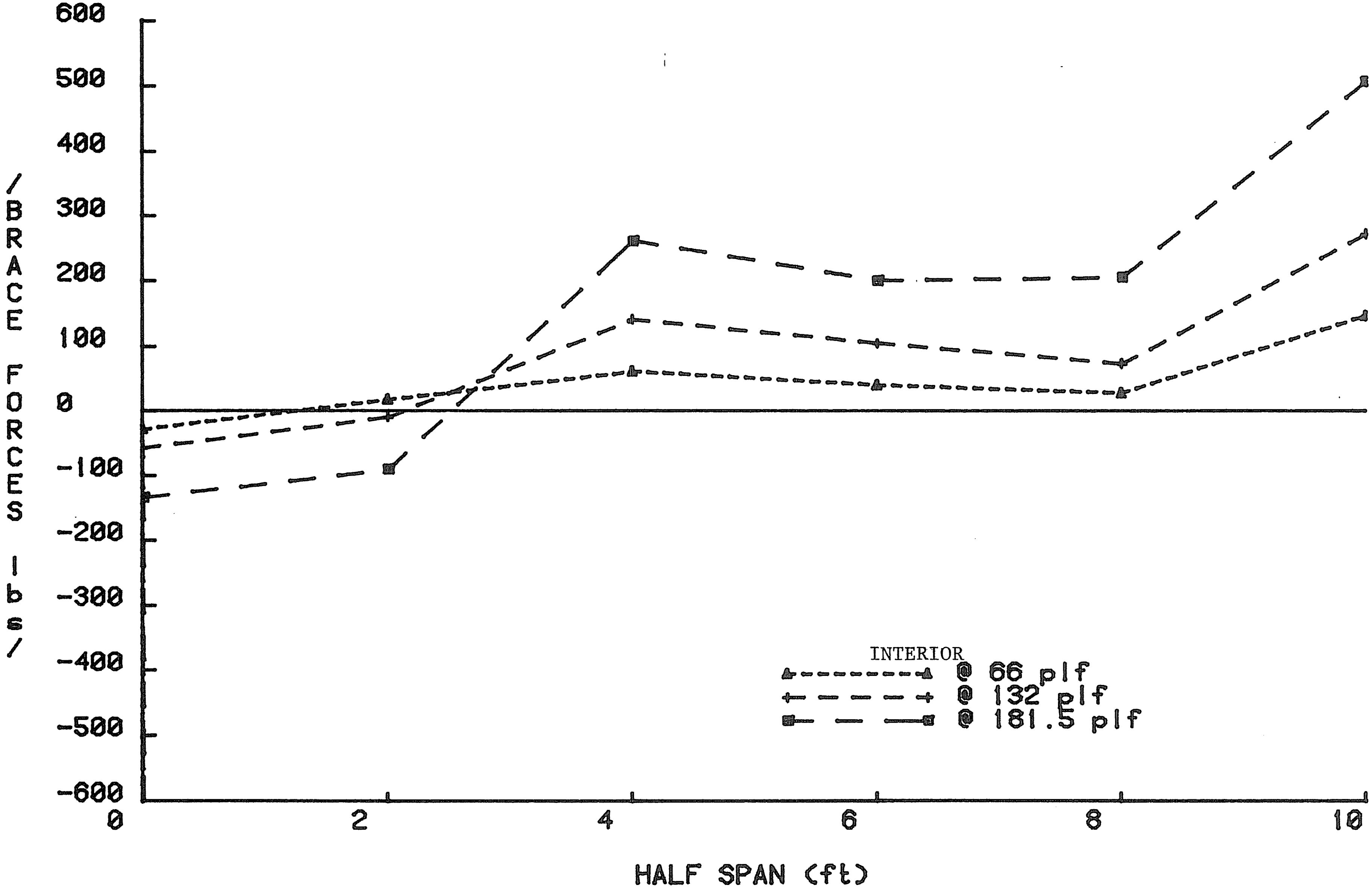


Figure B.35 Distribution of Intermediate Brace Forces Along Span at Interior Purlin, Test II-B

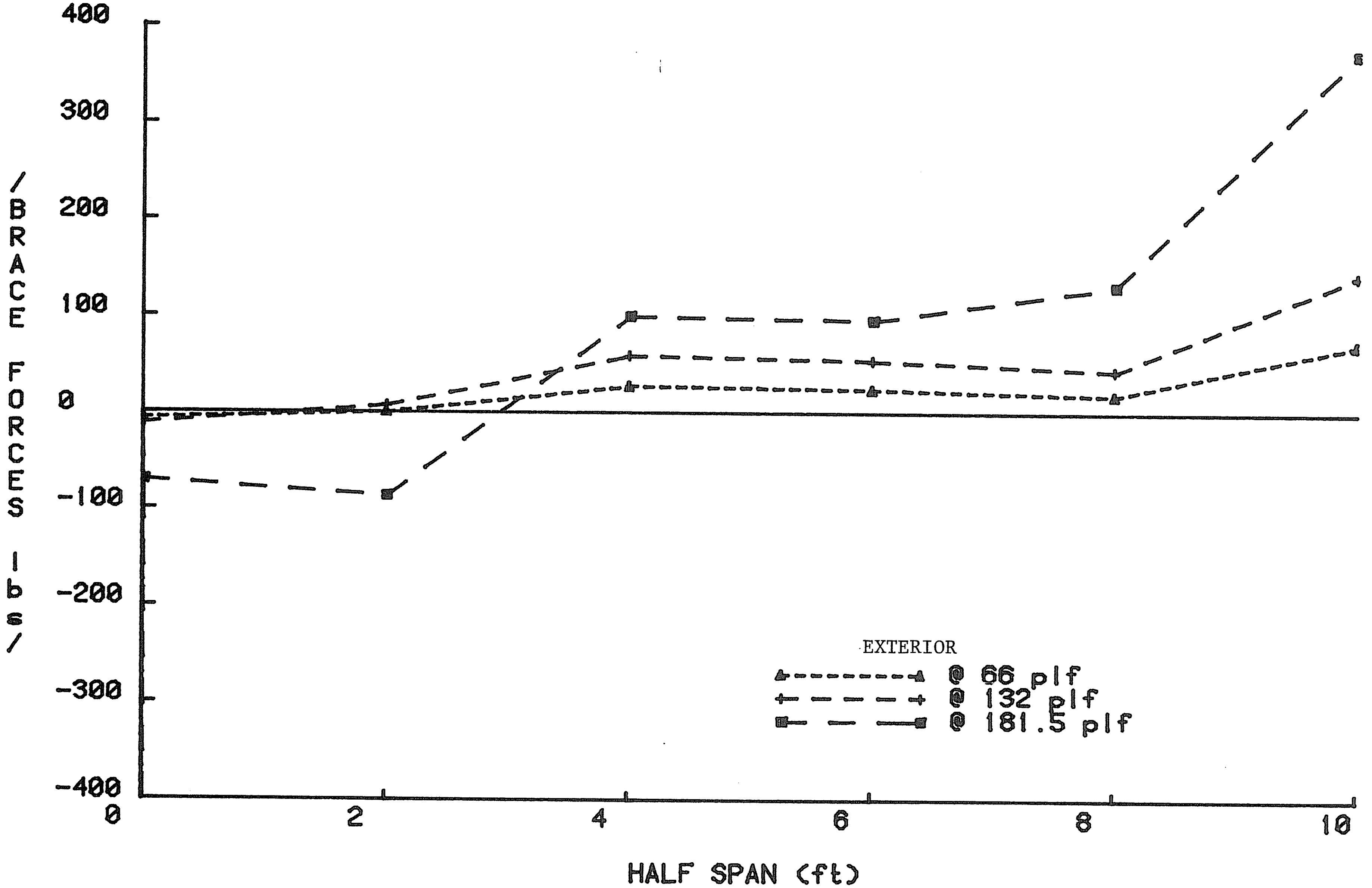


Figure B.36 Distribution of Intermediate Brace Forces Along Span Between Purlins, Test II-B

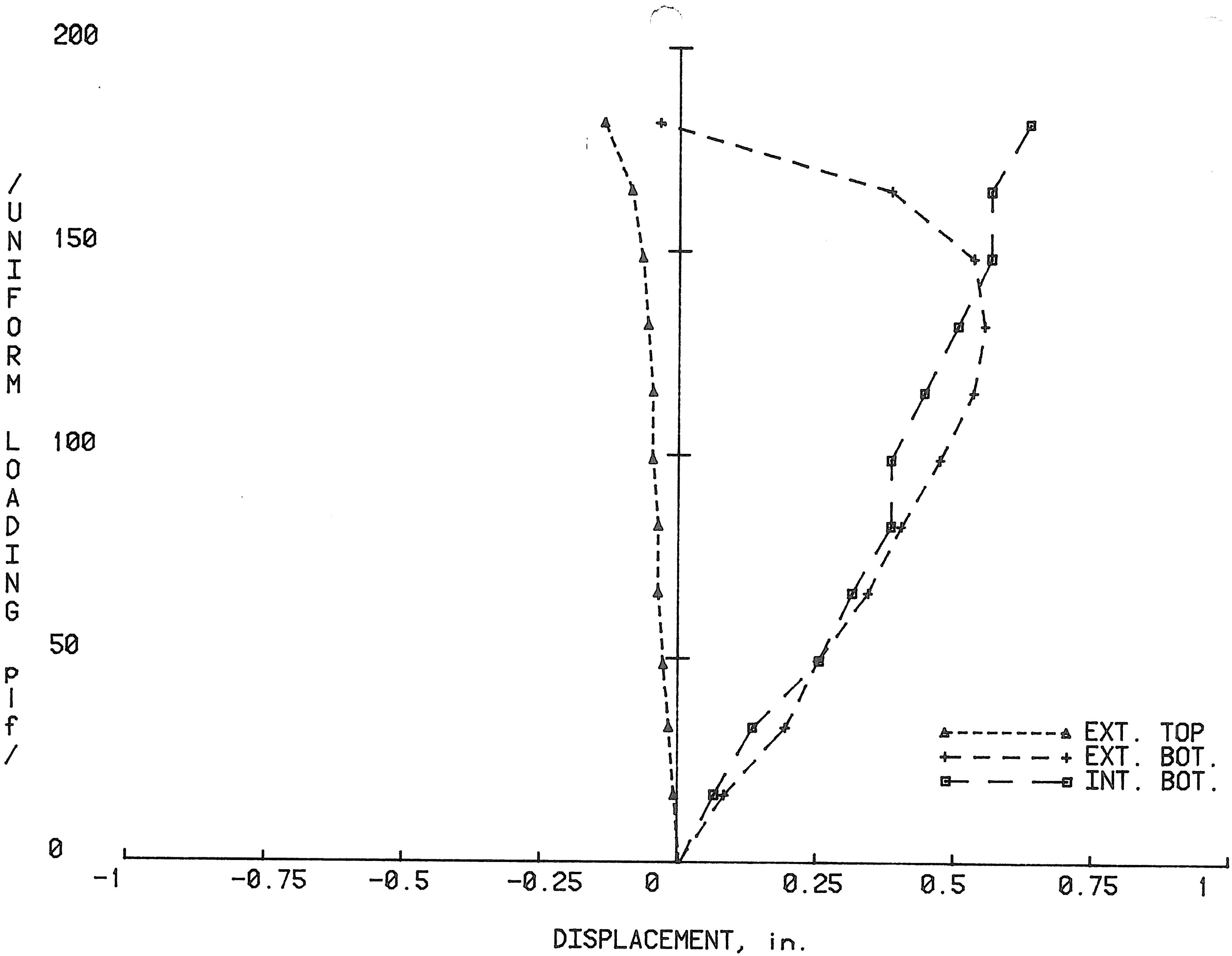


Figure B.37 Vertical Loading vs. Lateral Displacements, Test II-B

APPENDIX C

TEST III RESULTS

TEST SUMMARY

Project: MBMA Roof System Behavior

Test No.: III

Test Date: November 25, 1981

Purpose: To determine the magnitude of torsional restraining forces required @ rafters.

Span(s): 19.625'

Thickness: 0.092" Moment of Inertia: 12.758 in^4

Parameters: No intermediate braces

Torsional restraint @ rafter

Panel shear stiffness

Panel torsional restraint

Failure Load: 193.6 plf

Failure Mode: Center portion of purlins rolled toward east @ 193.6 plf

Predicted Failure Loads:

Method AISI constrained bending Load x 1.67. 311.2 plf

Method Load

Method Load

Discussion:

-Panel to purlin connection failed near support; panel failed in shear at fastener location.

-East purlin (nearer the lateral support joist) vertical deflections were very close to prediction. West purlin vertical deflections were approximately 20% greater than predicted.

-Measured torsional restraint forces were consistent. Forces at internal locations were almost identical. External forces varied a maximum of 10%.

-Braces forces increased at an increasing rate.

-Ratio of interior to exterior brace forces varied from 3.31 to 3.72 for the north end and 2.45 to 2.90 for the south end.

-At 66 plf, summation of external brace forces equaled 13.4% of vertical load on external purlin and 19.8% at 165 plf. Summation of internal brace forces equaled 21.9% of total vertical load.

-At 165 plf, summation of external brace forces equaled 19.8% and internal equaled 28.0%.

-Stress distribution from measured strains approximates constrained bending.

-Stresses increased linearily with loading.

-Bottom flange lateral displacements were greater than and in opposite direction of top flange lateral displacements indicating twisting of the purlin.

-Maximum lateral displacement was less than 0.4 in.

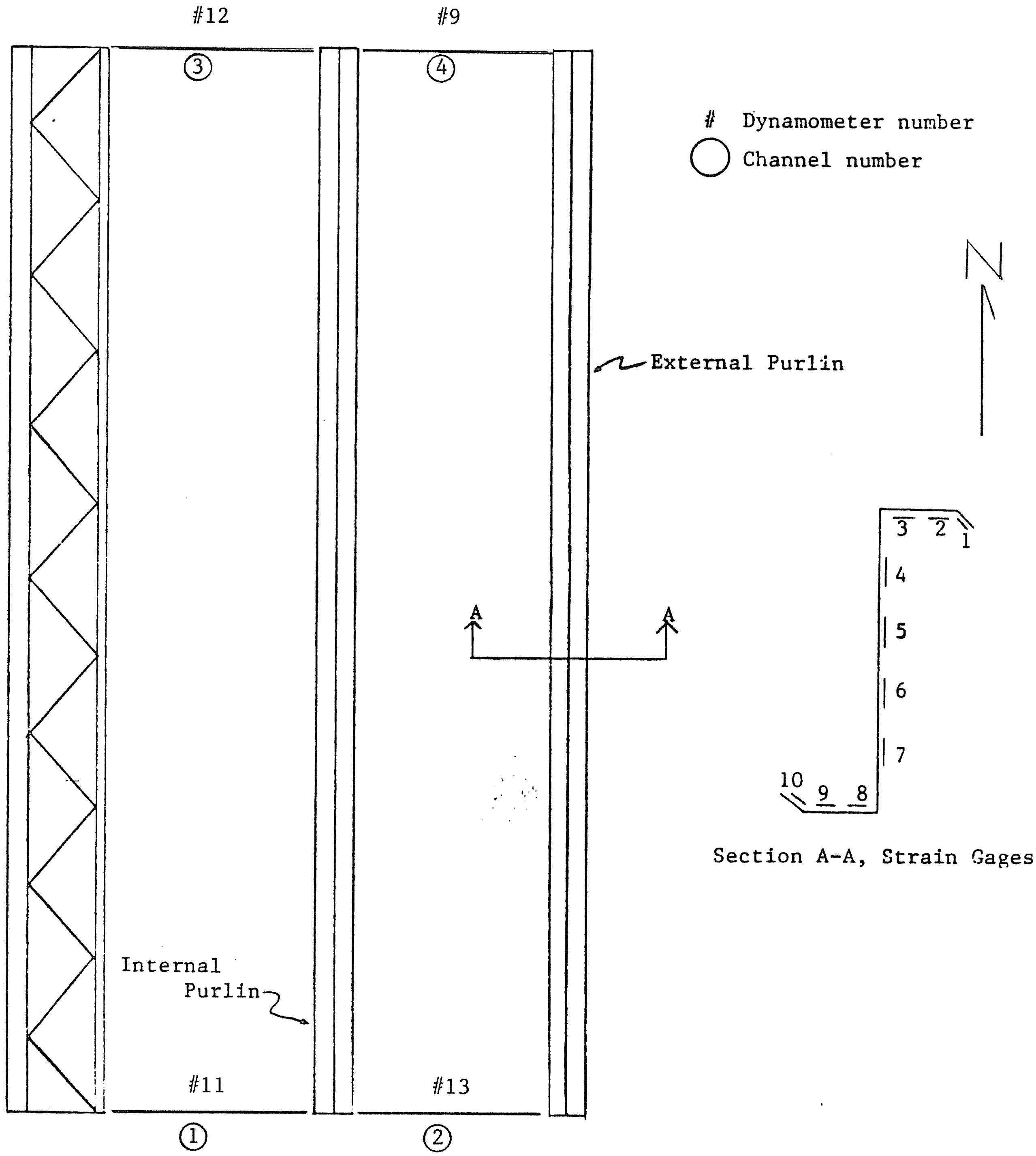
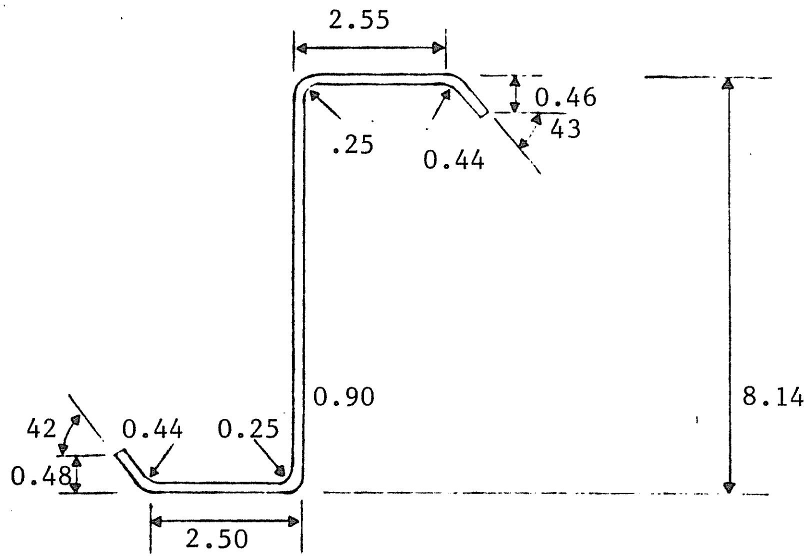
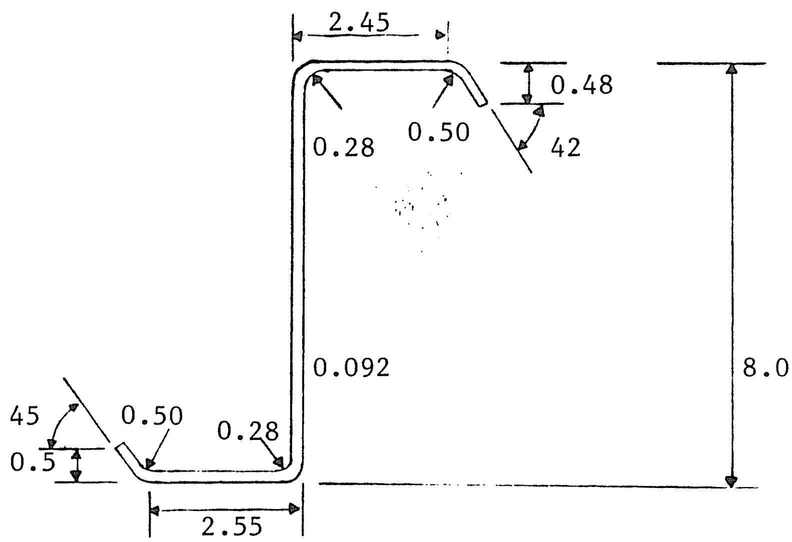


Figure C.1 Instrumentation Location, Test III



External Purlin



Internal Purlin

Figure C.2 Measured Purlin Dimensions, Test III

```
--------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: MBMA-III-W 11/24/81
--------------------------------------------------------
                         TOP              BOTTOM
FLANGE(in)              2.450              2.550
LIP(in)                 0.480              0.500
LIP ANGLE(deg)         42.000             45.000
RADIUS L/F(in)          0.500              0.500
RADIUS F/W(in)          0.281              0.281

TOTAL DEPTH(in)               8
THICKNESS(in)                 0.092
YIELD STRENGTH(ksi)           56
                                         SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)           TOP               BOTTOM
GROSS=         12.758                  3.204              3.249
STRENGTH=      12.758                  3.204              3.249
DEFLECTION=    12.758
BE=    2.077   in
FC=    33.600   ksi
FT=    33.600   ksi
FBW=   33.393   ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)
             MC=       8.972   ft-k
             MT=       9.098   ft-k
             MW=       9.715   ft-k
             MU=      14.984   ft-k (1.67*allowable)
SPAN           =      19.625   ft.
UNIFORM LOAD=        311.242   plf (1.67*allowable)
DEFLECTION     =       0.887   in./100plf
```

Figure C.3 AISI Purlin Analysis, Test III West Purlin

```
---------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: MBMA-III-E 11/24/81
---------------------------------------------------------
                      TOP             BOTTOM
FLANGE(in)           2.550             2.500
LIP(in)              0.460             0.480
LIP ANGLE(deg)      43.000            42.000
RADIUS L/F(in)       0.440             0.440
RADIUS F/W(in)       0.250             0.250

TOTAL DEPTH(in)             8.14
THICKNESS(in)               0.09
YIELD STRENGTH(ksi)         56
                                   SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)        TOP           BOTTOM
GROSS=         13.021              3.238          3.232
STRENGTH=      13.021              3.238          3.232
DEFLECTION=    13.021
BE=     2.210   in
FC=    33.600   ksi
FT=    33.600   ksi
FBW=   33.095   ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)
          MC=       9.067   ft-k
          MT=       9.049   ft-k
          MW=       9.638   ft-k
          MU=      15.112   ft-k (1.67*allowable)
SPAN         =     19.625   ft.
UNIFORM LOAD=     313.906   plf (1.67*allowable)
DEFLECTION   =      0.869   in./100plf
```

Figure C.4 AISI Purlin Analysis, Test III East Purlin

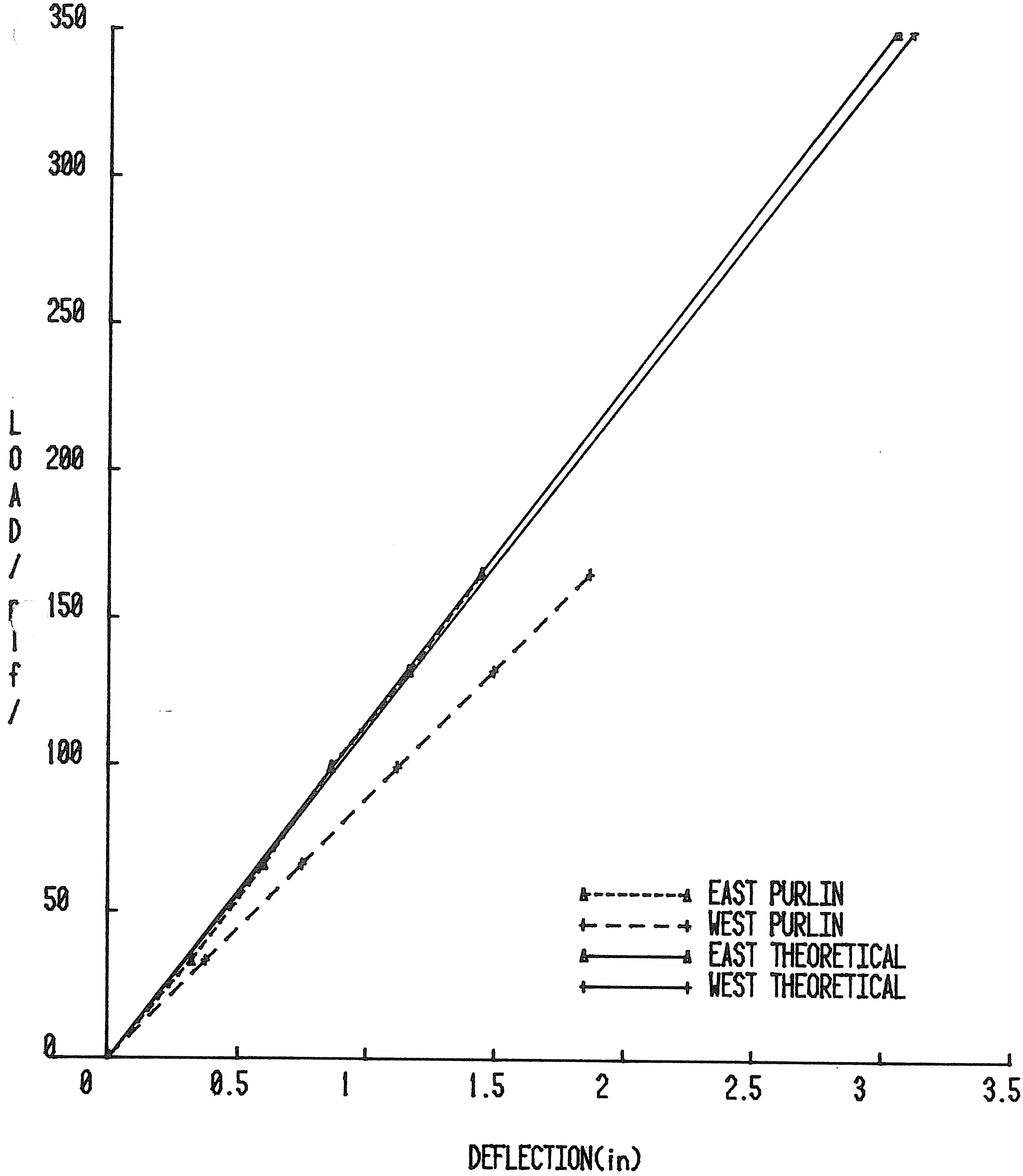


Figure C.5 Load vs. Vertical Deflection, Test III

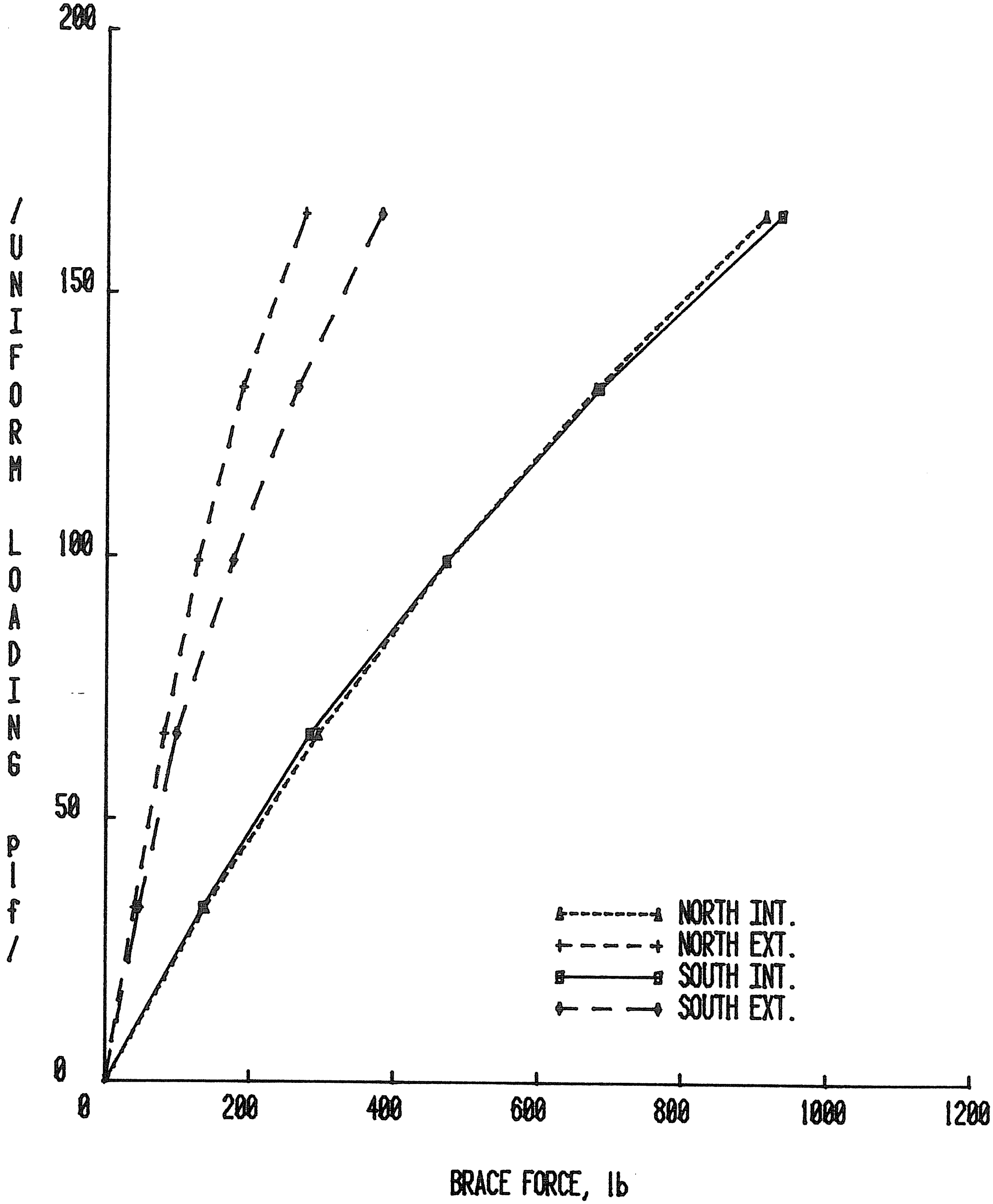


Figure C.6 Vertical Loading vs. Brace Force at Rafter, Test III

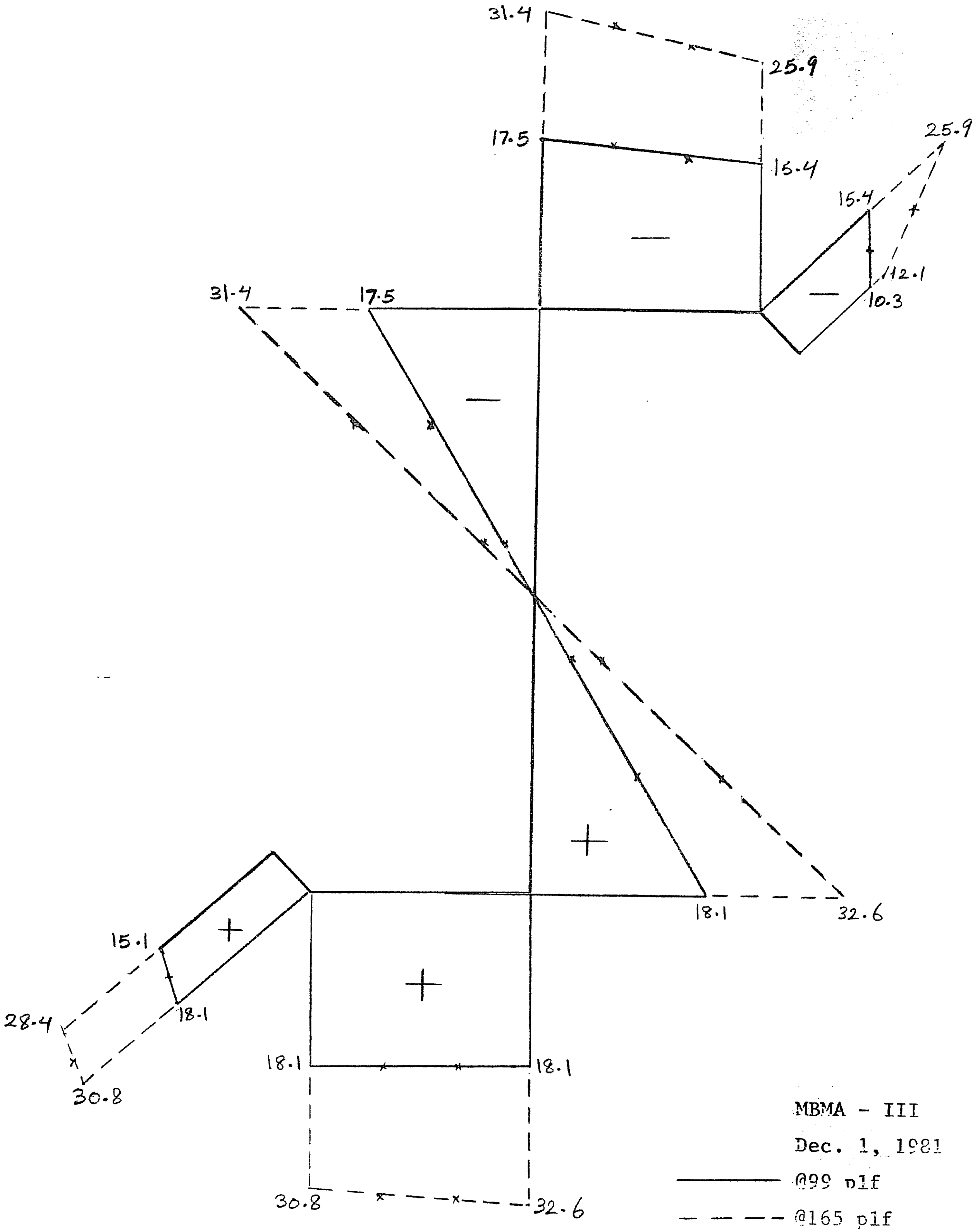


Figure C.7 Stress Distribution, Test III

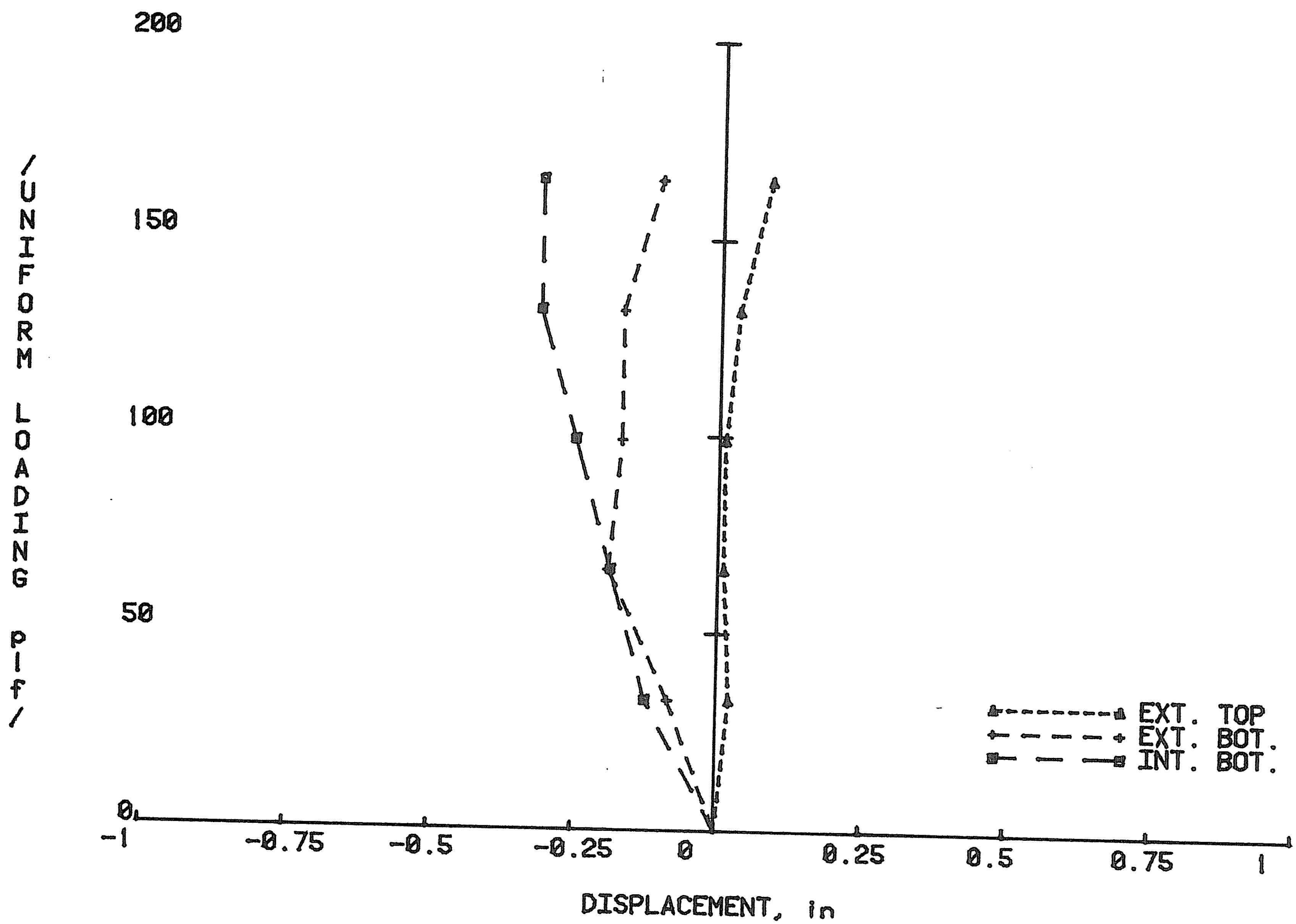


Figure C.8 Vertical Loading vs. Lateral Displacements, ~~Test~~ III

APPENDIX D

TEST IV RESULTS

TEST SUMMARY

Project: MBMA Roof System Behavior

Test No.: IV

Test Date: January 5, 1982

Purpose: Determine torsional restraint forces for ℄ and ¼ pt. intermediate bracing.

Span(s): 19.625'

Thickness: 0.084 Moment of Inertia: 12.0 in^4

Parameters: Intermediate bracing @ ¼ pt.

No torsional restraint @ rafters

Panel shear stiffness

Panel torsional restraint

Failure Load: 231.0 plf

Failure Mode: Local buckling of flange and/or web near midspan.

Predicted Failure Loads:

Method AISI const. bending x 1.67 Load 292.6 plf

Method ___ Load ___

Method ___ Load ___

Discussion:

- Failure occurred at 231.0 plf due to local buckling of the flange and/or web approximately 1' from midspan.
- The north end of the purlins tended to roll toward the west causing longer forces in the north braces.
- Vertical deflections were 6-16% greater than predicted from constrained bending for the east purlin (nearer the lateral support joist), and 3-21% for the west purlin.
- Brace forces increased linearly, except @ north ¼ point for loads greater than 99 plf.
- Stress distribution from measured strains approximates constrained bending, and indicates yielding occurred @ the web top flange junction @ 231 plf.
- Stress increased linearly with loading.
- Ratio of internal to external brace forces @ centerline varied from 1.37 to 1.87; @ north ¼ pt. from 0 to 2.59 and @ south ¼ pt. from 1.24 to 2.55.
- Summation of internal and external brace forces @ 66 plf are 30% and 23% of total vertical load, respectively, and @214.5 plf, are 47% and 24% of the total vertical load.
- Top flange lateral displacement exceeded bottom flange displacement but in opposite directions.
- Maximum lateral displacement was less than 0.6 in.

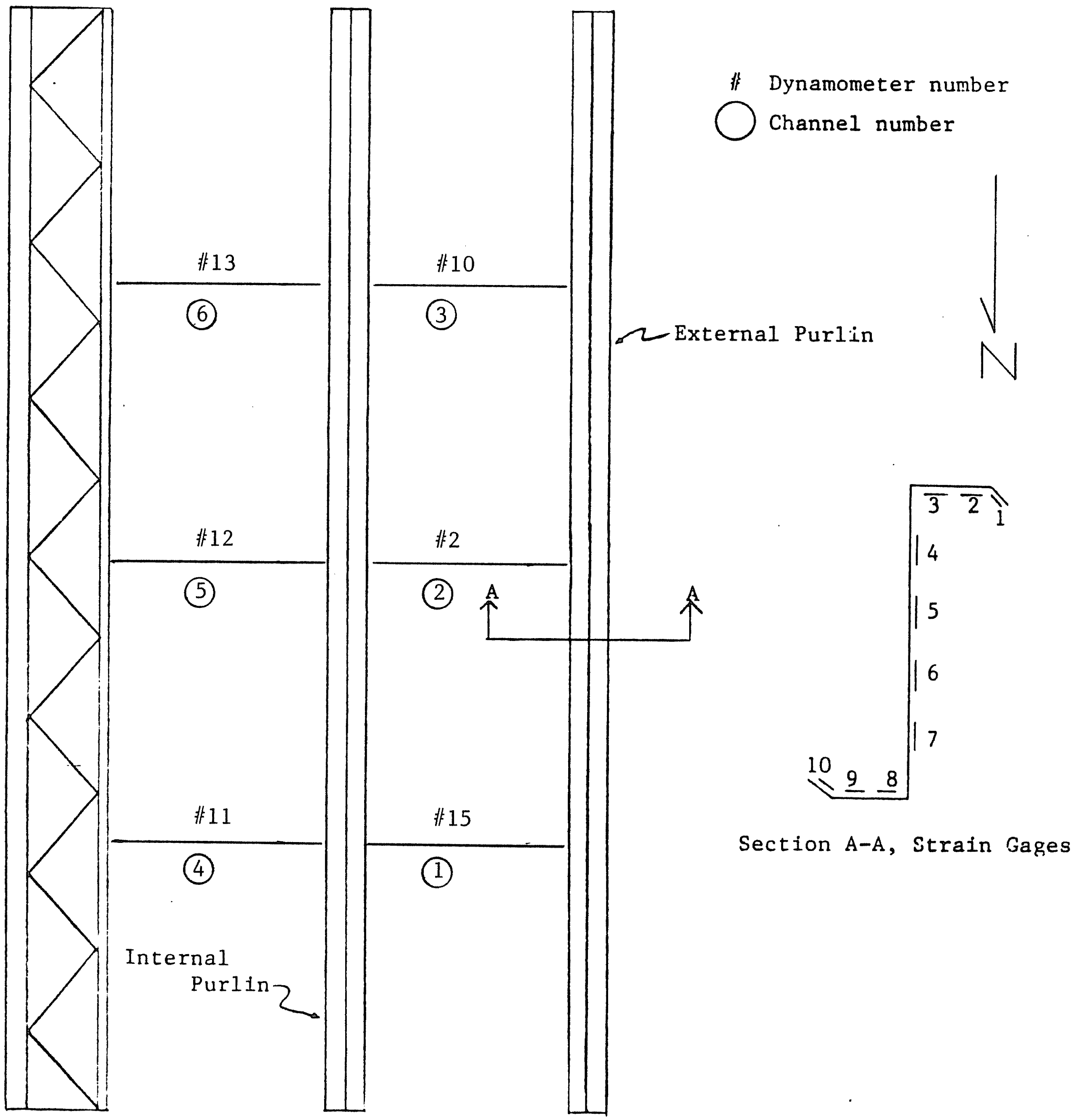
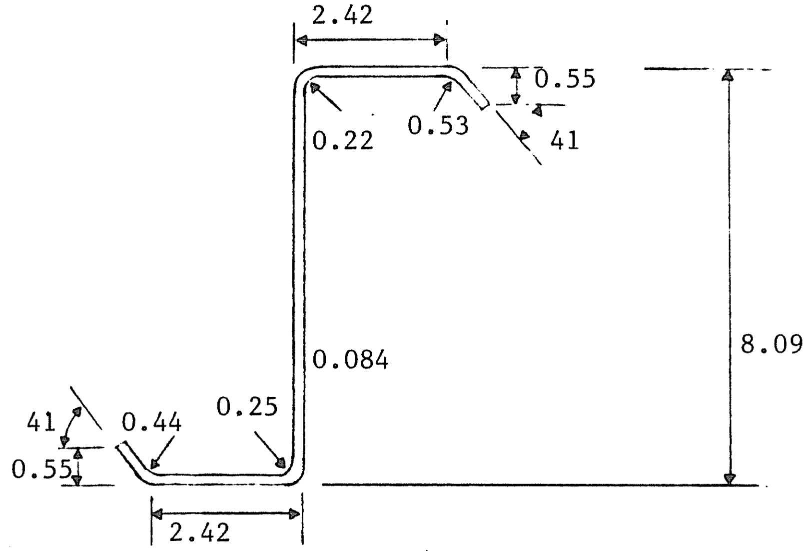
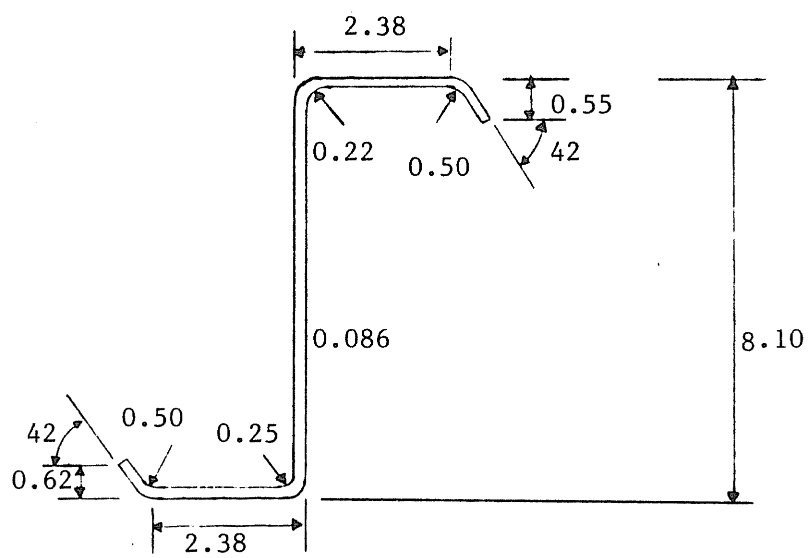


Figure D.1 Instrumentation Location, Test IV



External Purlin



Internal Purlin

Figure D.2 Measured Purlin Dimension, Test IV

```
--------------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: MBMA-IV-W1/5/82
--------------------------------------------------------------
                          TOP              BOTTOM
FLANGE(in)               2.420              2.420
LIP(in)                  0.550              0.550
LIP ANGLE(deg)          41.000             41.000
RADIUS L/F(in)           0.531              0.438
RADIUS F/W(in)           0.219              0.250

TOTAL DEPTH(in)                  8.09
THICKNESS(in)                    0.084
YIELD STRENGTH(ksi)              56
                                           SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)          TOP                  BOTTOM
GROSS=          12.075                3.020                 3.013
STRENGTH=       12.075                3.020                 3.013
DEFLECTION=     12.075
BE=     2.117   in
FC=     33.600   ksi
FT=     33.600   ksi
FBW=    32.594   ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)
           MC=        8.456   ft-k
           MT=        8.437   ft-k
           MW=        8.774   ft-k
           MU=       14.089   ft-k (1.67*allowable)
SPAN         =       19.625   ft.
UNIFORM LOAD=       292.658   plf (1.67*allowable)
DEFLECTION   =        0.937   in./100plf
```

Figure D.3 AISI Purlin Analysis, Test IV West Purlin

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

IDENTIFICATION: MBMA-IV-E1/5/82

	TOP	BOTTOM
FLANGE(in)	2.380	2.380
LIP(in)	0.550	0.550
LIP ANGLE(deg)	42.000	42.000
RADIUS L/F(in)	0.500	0.500
RADIUS F/W(in)	0.219	0.250

TOTAL DEPTH(in)	8.1
THICKNESS(in)	0.086
YIELD STRENGTH(ksi)	56

	MOMENTS OF INERTIA(in^4)	SECTION MODULII(in^3) TOP	SECTION MODULII(in^3) BOTTOM
GROSS=	12.262	3.057	3.063
STRENGTH=	12.262	3.057	3.063
DEFLECTION=	12.262		

BE= 2.075 in

FC= 33.600 ksi

FT= 33.600 ksi

FBW= 32.775 ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)

MC=	8.559	ft-k
MT=	8.578	ft-k
MW=	8.932	ft-k
MU=	14.294	ft-k (1.67*allowable)
SPAN =	19.625	ft.
UNIFORM LOAD=	296.911	plf (1.67*allowable)
DEFLECTION =	0.923	in./100plf

Figure D.4 AISI Purlin Analysis, Test IV East Purlin

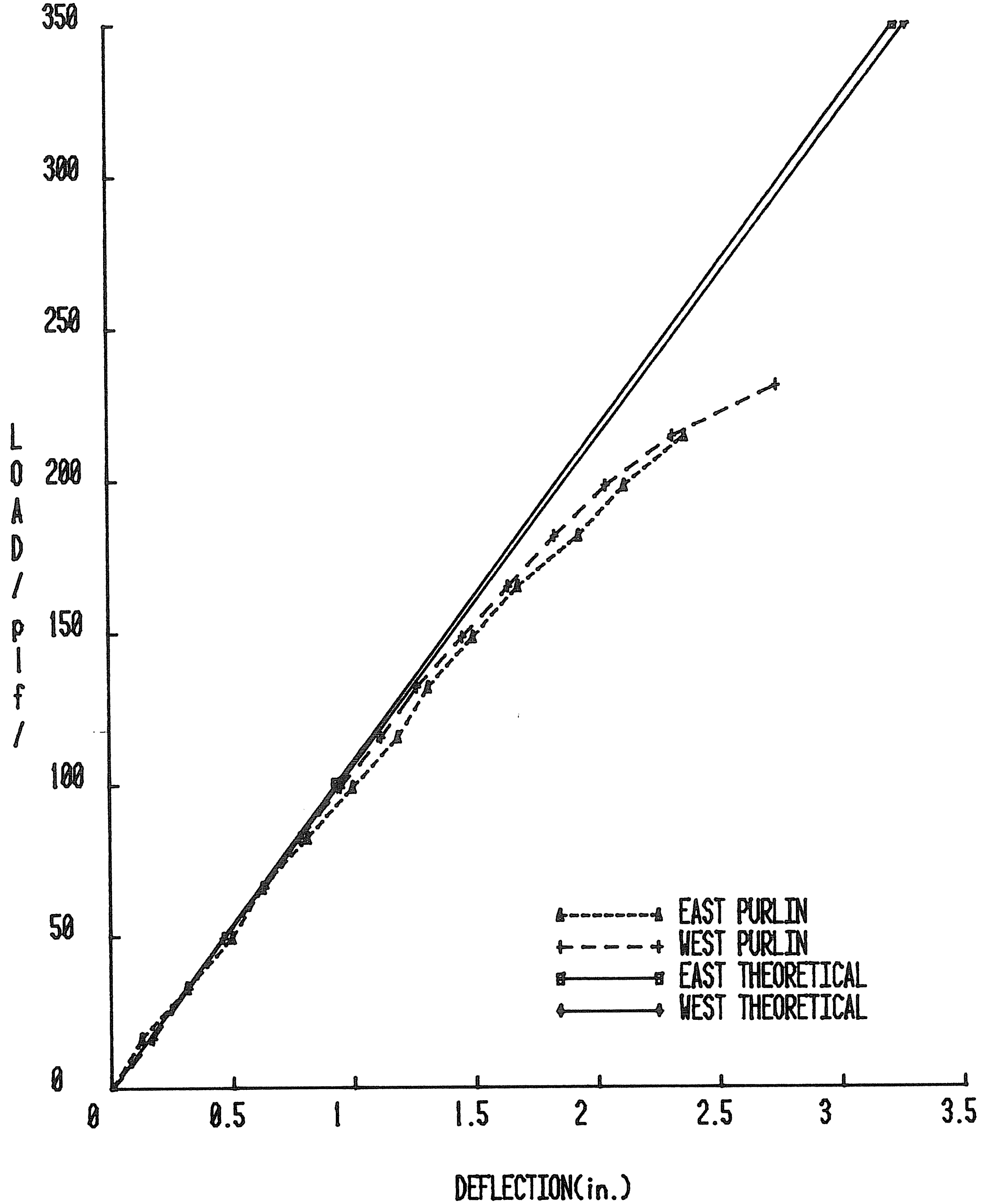


Figure D.5 Load vs. Vertical Deflection, Test IV

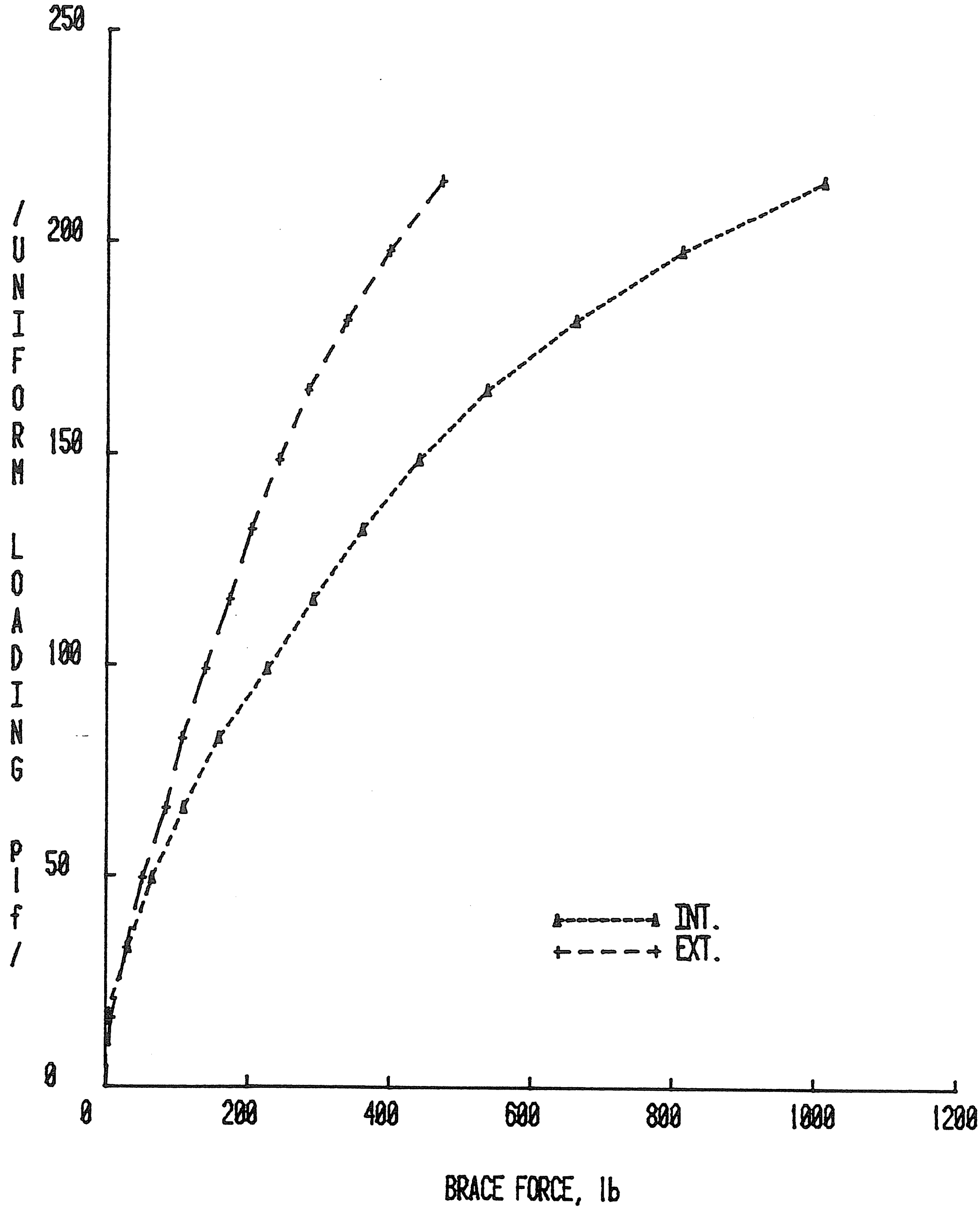


Figure D.6 Vertical Loading vs. Brace Force at North ¼ Points, Test IV

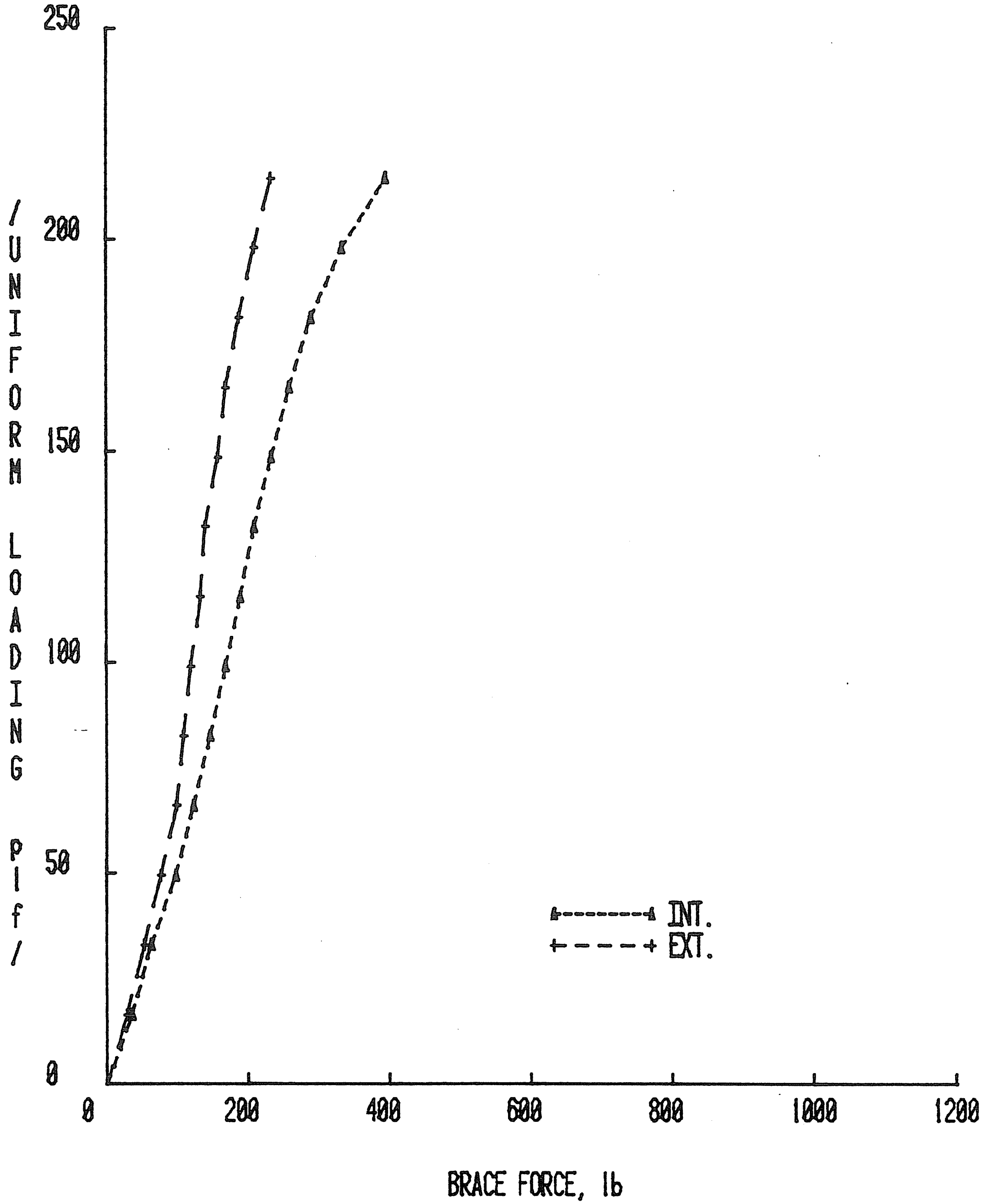


Figure D.7 Vertical Loading vs. Brace Force at South ¼ Points, Test IV

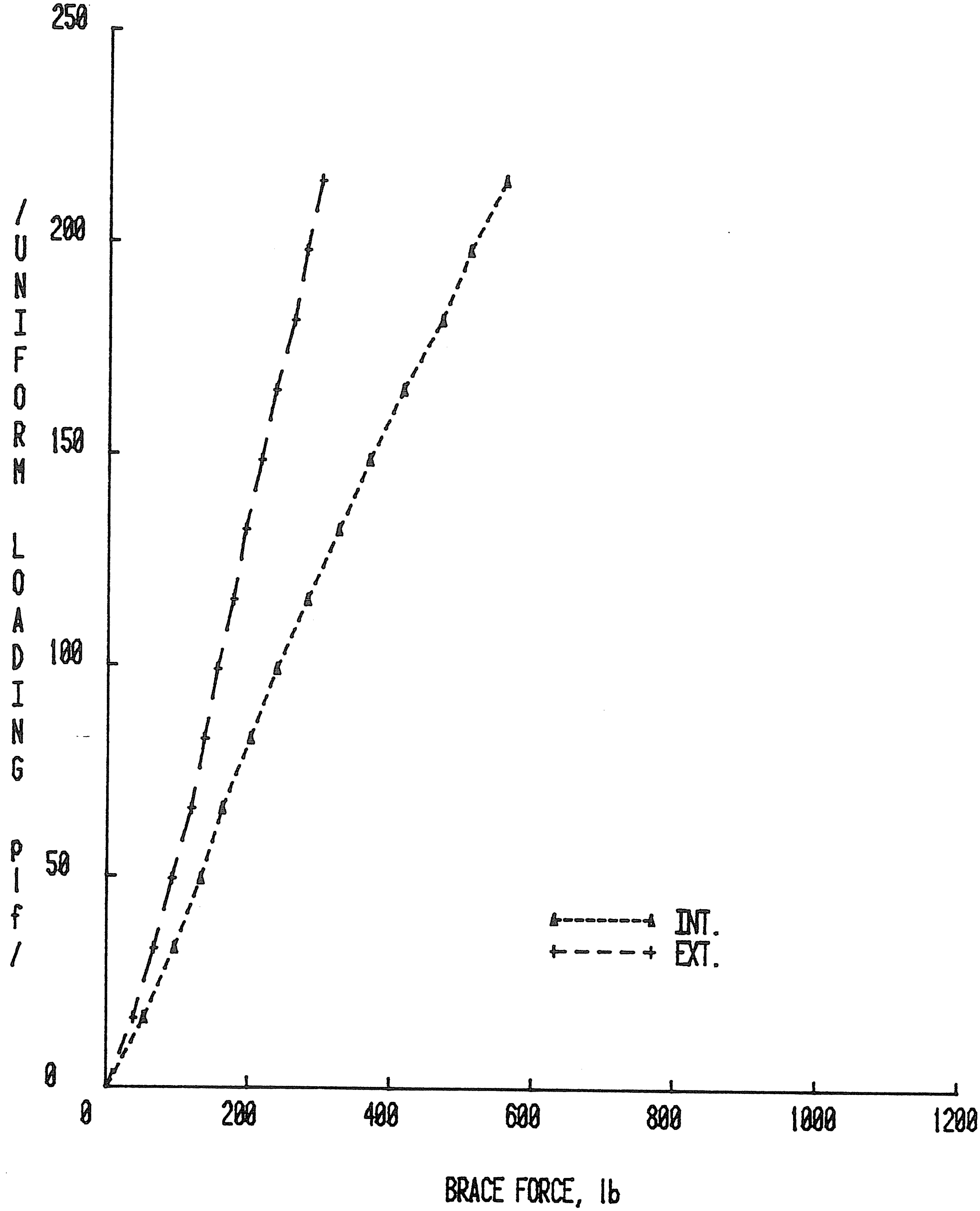


Figure D.8 Vertical Loading vs. Brace Force at Midspan, Test IV

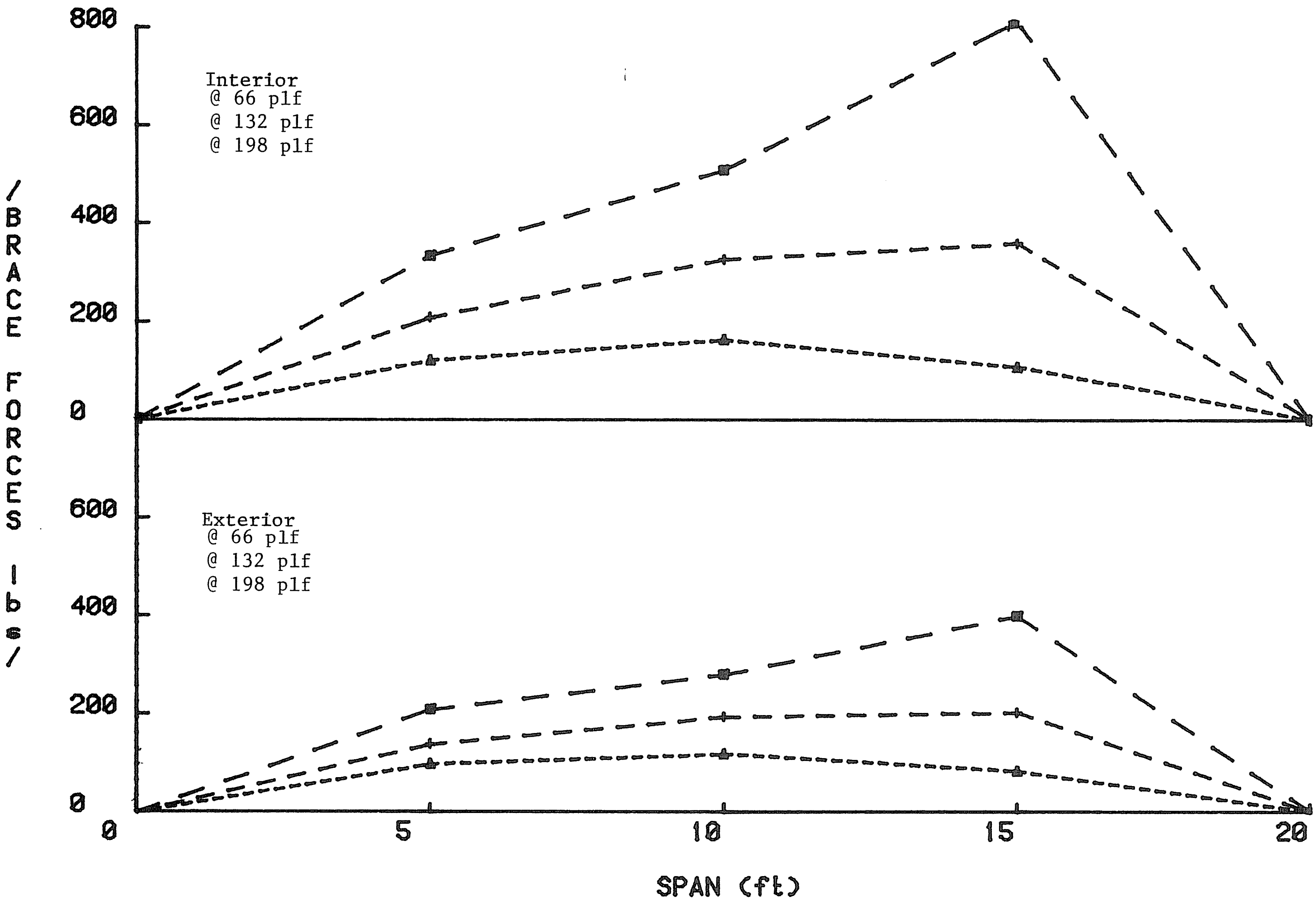


Figure D.9 Distribution of Brace Forces along the Span

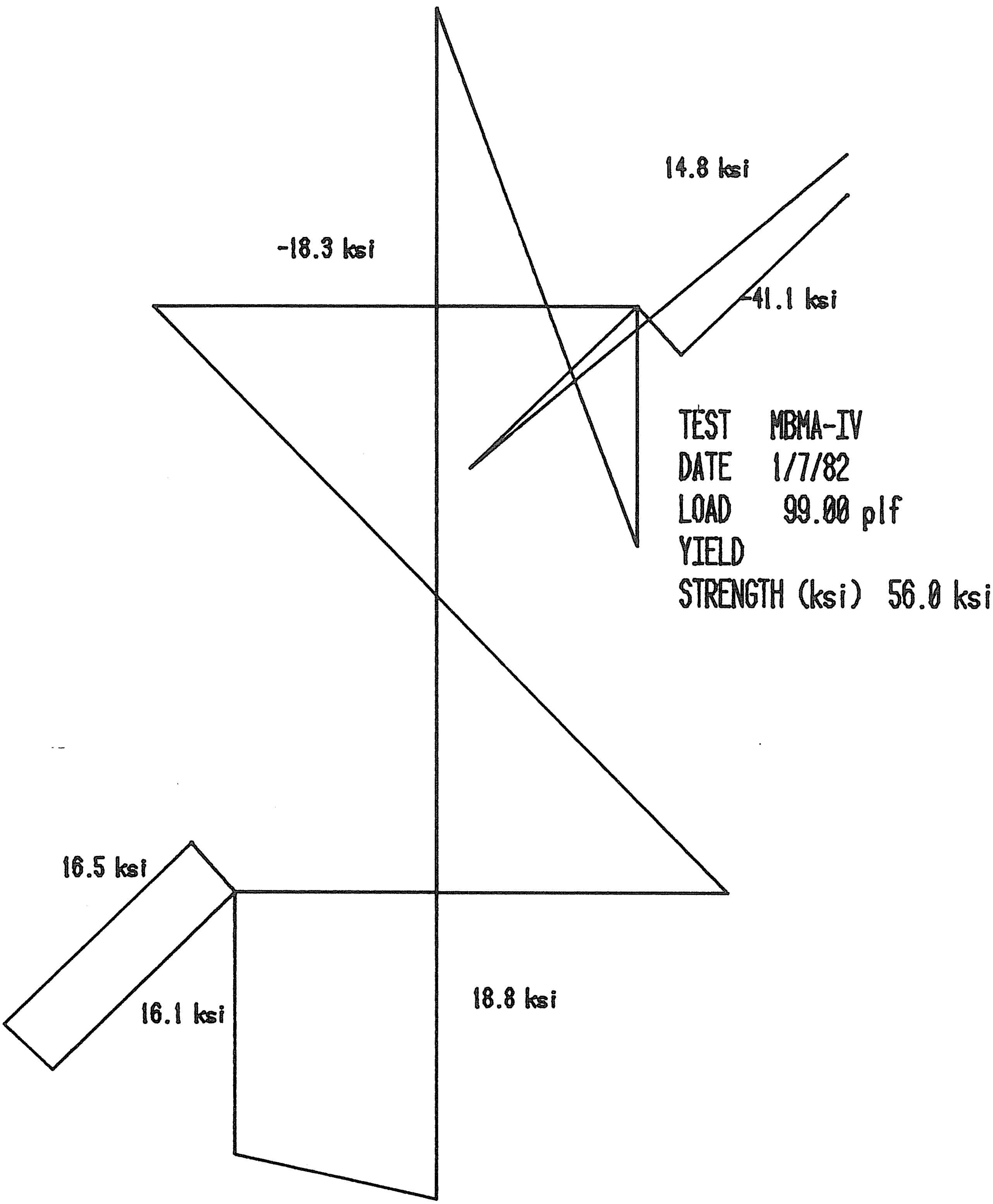


Figure D.10 Stress Distributions at 99 plf, Test IV

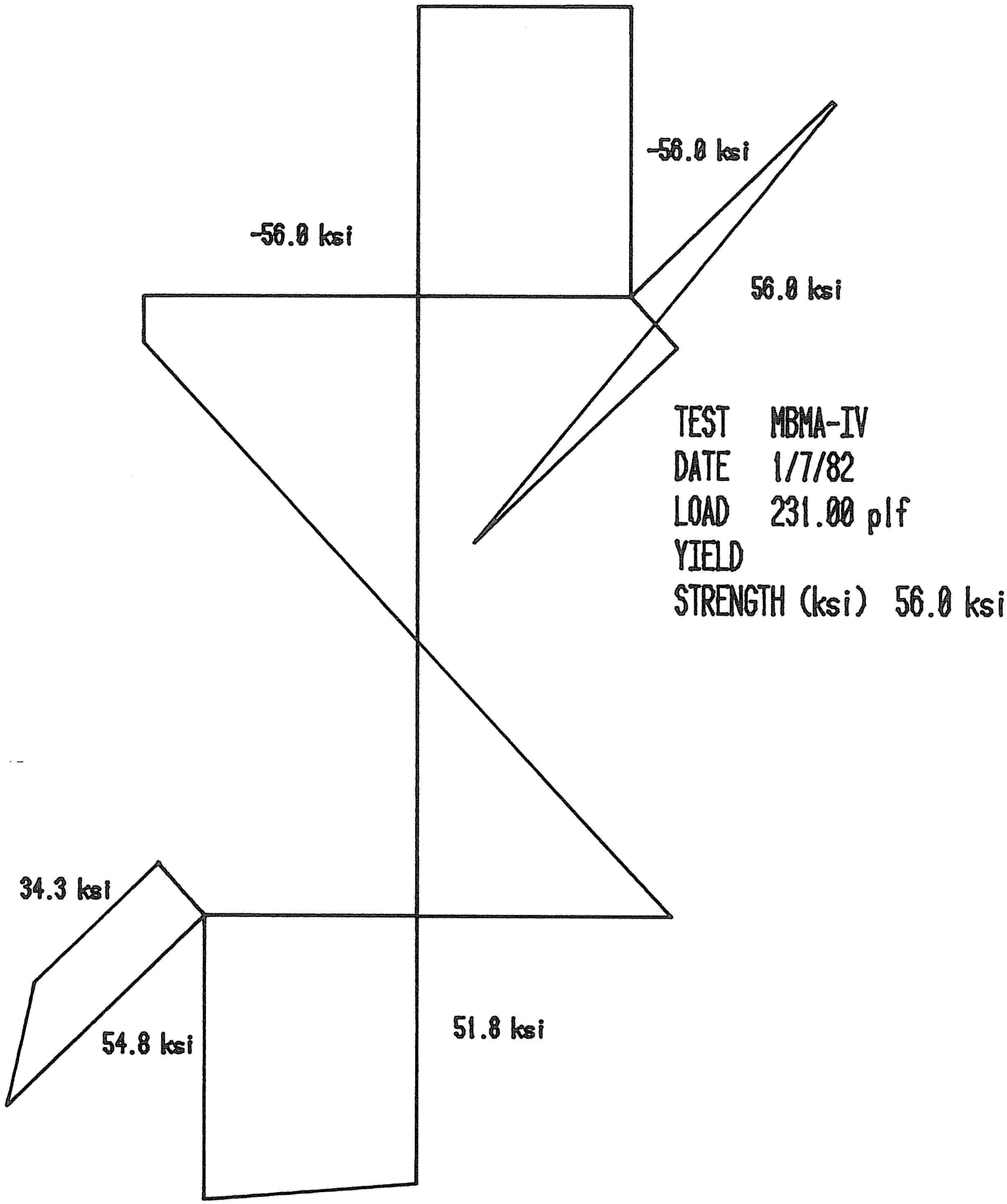


Figure D.11 Stress Distributions at 231 plf, Test IV

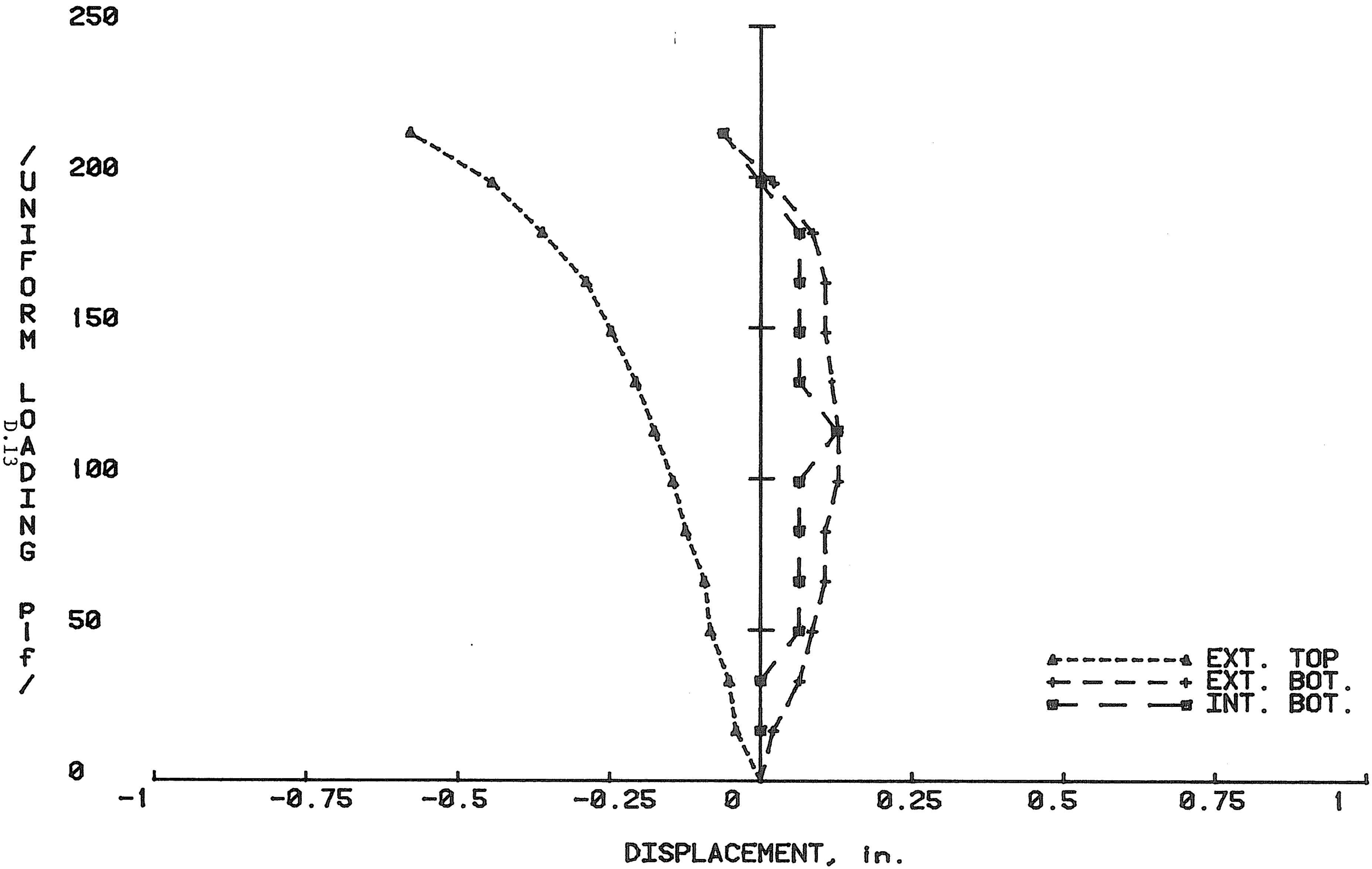


Figure D.12 Vertical Loading vs. Lateral Displacements, Test IV

APPENDIX E

TEST V RESULTS

TEST SUMMARY

Project: MBMA Roof System Behavior

Test No.: V

Test Date: December 3, 1981

Purpose: To determine the effect of no panel shear stiffness.

Span(s): 19.625'

Thickness: 0.090 Moment of Inertia: 12.186

Parameters: No intermediate braces

Torsional restraint at rafter

No panel shear stiffness; no sidelap fasteners

Panel torsional restraint

Failure Load: 191.9 plf

Failure Mode: Failure of panel to purlin connection near rafter support.

Predicted Failure Loads:

Method AISI Constr. bending x 1.67 Load 299.4 plf

Method ____ Load ____

Method ____ Load ____

Discussion:

- Panel to purlin connection failed near the support; panel failed in shear at fasteners.
- Vertical deflections were 14-24% greater than predicted from constrained bending assumptions for the west purlin (nearer the lateral support joist), and 4-11% greater for east purlin.
- Brace forces increased linearly with the increased loading.
- Stress distribution measured from strain readings approximated constrain bending distribution.
- Stresses increased linearly with increased load.
- The ratio of internal to external brace forces was 1.39 to 2.43 at the north rafter and 1.85 to 2.10 at the south rafter.
- Summation of brace forces @ 66 plf was 28% of vertical load at the external purlin and 50% of vertical load at the internal purlin.
- At 165 plf, the brace forces are 23% of total vertical load at the external purlin and 53% of vertical load at the internal purlin.
- Lateral displacement of the bottom flange exceeded the top flange but in the opposite direction.
- Maximum lateral displacement was less than 0.5 in.

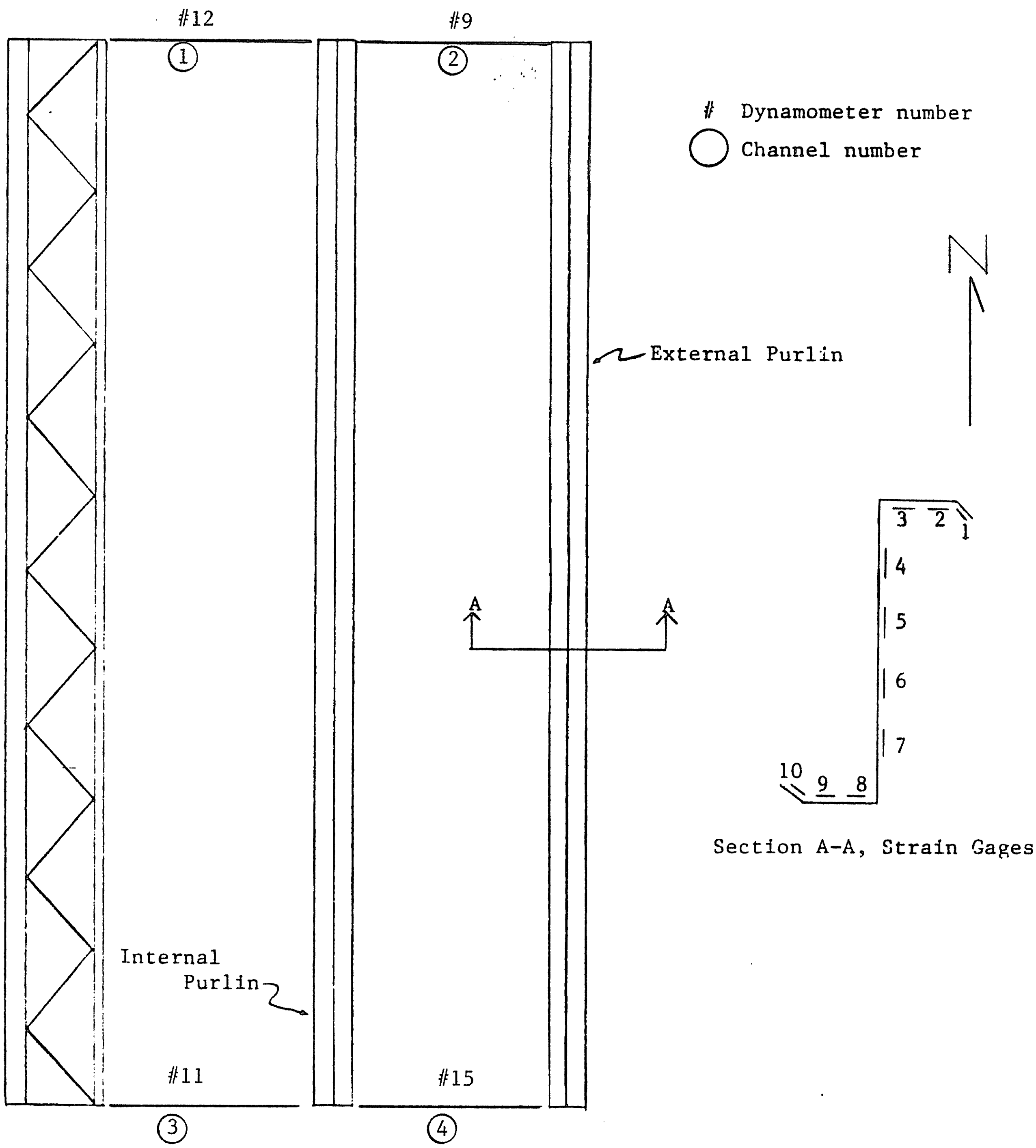
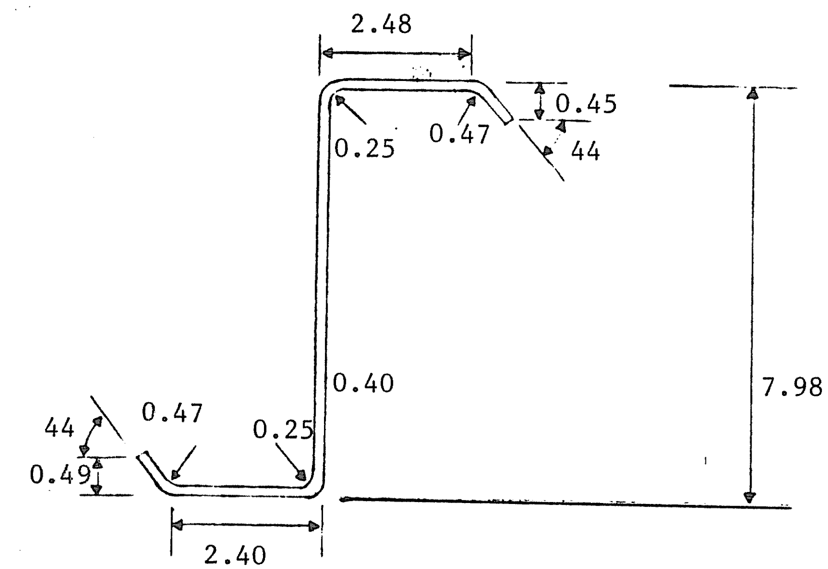
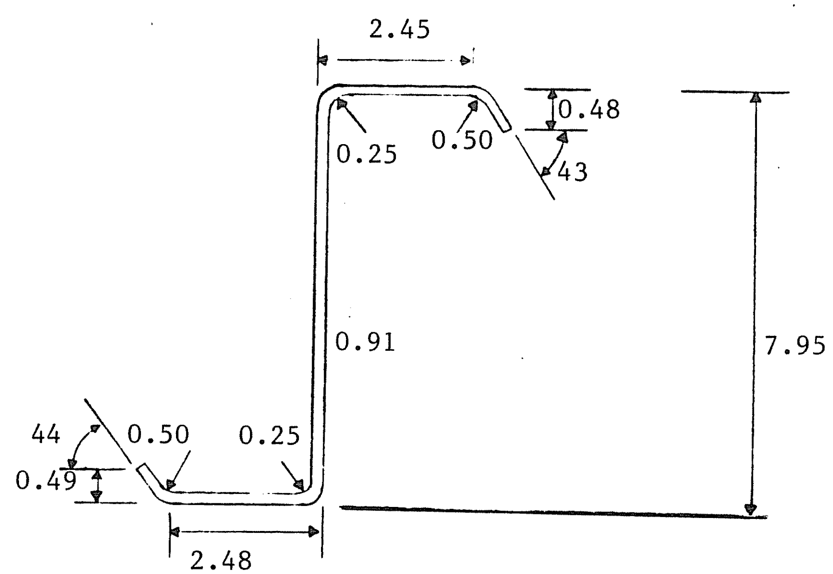


Figure E.1 Instrumentation Location, Test V



External Purlin



Internal Purlin

Figure E.2 Measured Purlin Dimensions, Test V

```
-------------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: MBMA-V-W 12/3/81
-------------------------------------------------------------
                      TOP             BOTTOM
FLANGE(in)           2.450             2.480
LIP(in)              0.480             0.490
LIP ANGLE(deg)      43.000            44.000
RADIUS L/F(in)       0.500             0.500
RADIUS F/W(in)       0.250             0.250

TOTAL DEPTH(in)             7.95
THICKNESS(in)               0.091
YIELD STRENGTH(ksi)         56
                                      SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)          TOP              BOTTOM
GROSS=        12.366                  3.140             3.155
STRENGTH=     12.366                  3.140             3.155
DEFLECTION=   12.366
BE=    2.109   in
FC=    33.600  ksi
FT=    33.600  ksi
FBW=   33.358  ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)
           MC=      8.791   ft-k
           MT=      8.833   ft-k
           MW=      9.435   ft-k
           MU=     14.680   ft-k (1.67*allowable)
SPAN         =     19.625   ft.
UNIFORM LOAD=     304.937   plf (1.67*allowable)
DEFLECTION   =      0.915   in./100plf
```

Figure E.3 AISI Purlin Analysis, Test V West Purlin

```
---------------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: MBMA-V-E 12/3/81
---------------------------------------------------------------
                       TOP              BOTTOM
FLANGE(in)           2.480               2.400
LIP(in)              0.450               0.490
LIP ANGLE(deg)      44.000              44.000
RADIUS L/F(in)       0.470               0.470
RADIUS F/W(in)       0.250               0.250

TOTAL DEPTH(in)             7.98
THICKNESS(in)               0.09
YIELD STRENGTH(ksi)         56
                                    SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)          TOP              BOTTOM
GROSS=        12.186                 3.095              3.083
STRENGTH=     12.186                 3.095              3.083
DEFLECTION=   12.186
BE=    2.140   in
FC=    33.600   ksi
FT=    33.600   ksi
FBW=   33.247   ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)
          MC=       8.667   ft-k
          MT=       8.632   ft-k
          MW=       9.271   ft-k
          MU=      14.415   ft-k (1.67*allowable)
SPAN        =      19.625   ft.
UNIFORM LOAD=     299.418   plf (1.67*allowable)
DEFLECTION  =       0.928   in./100plf
```

Figure E.4 AISI Purlin Analysis, Test V East Purlin

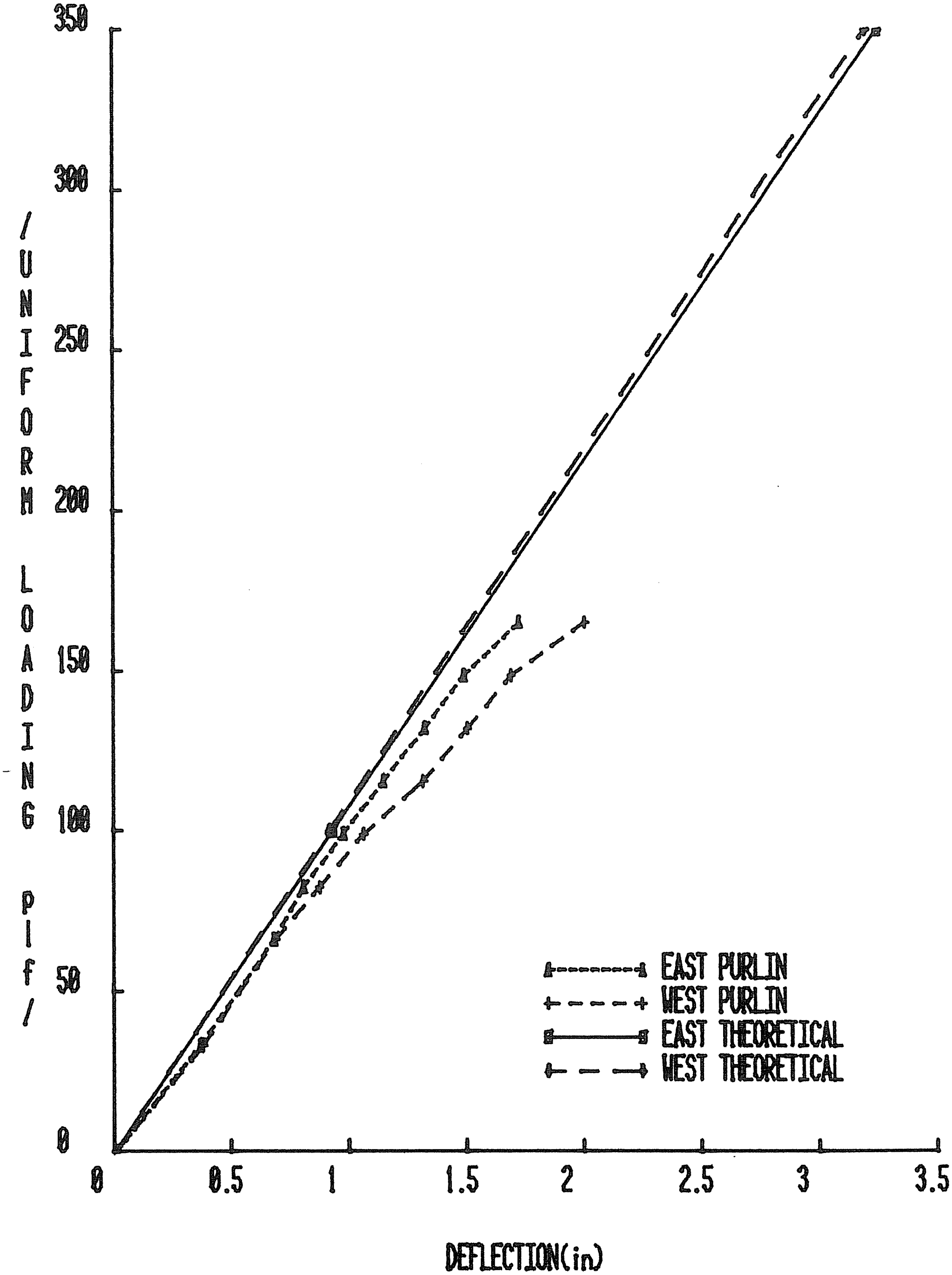


Figure E.5 Load vs. Vertical Deflection, Test V

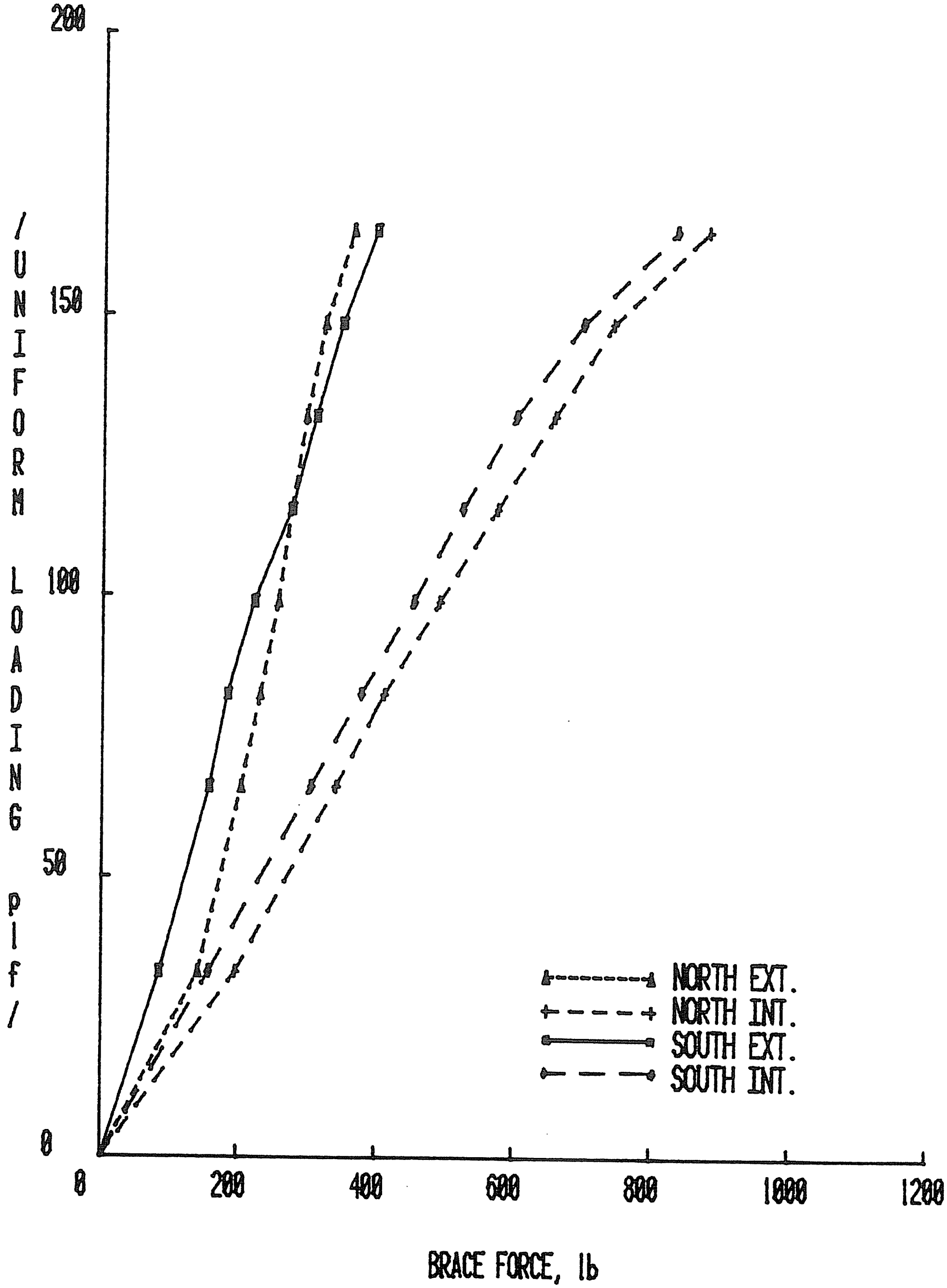


Figure E.6 Vertical Loading vs. Brace Force at Rafter, Test V

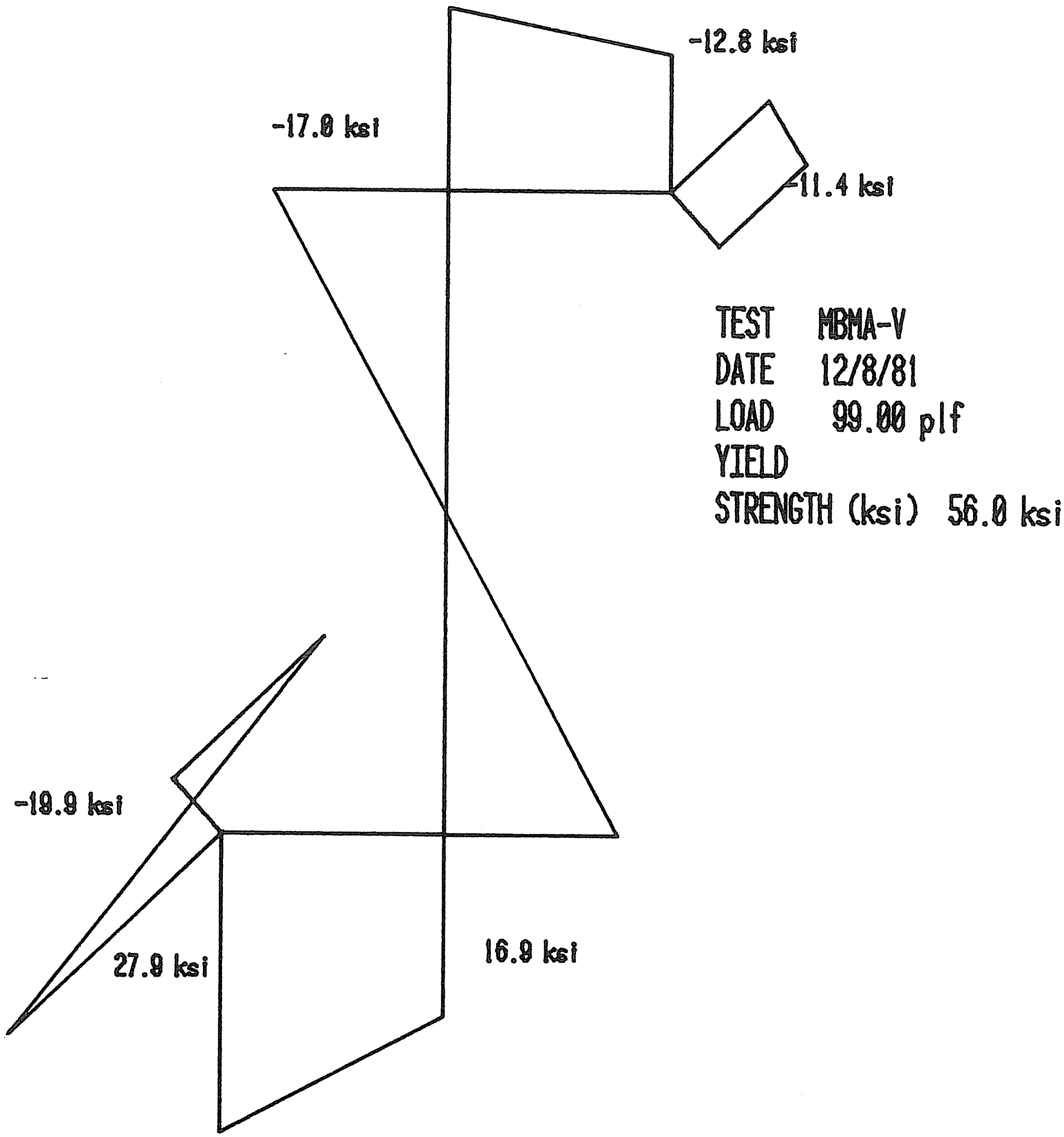


Figure E.7 Stress Distribution at 99 plf, Test V

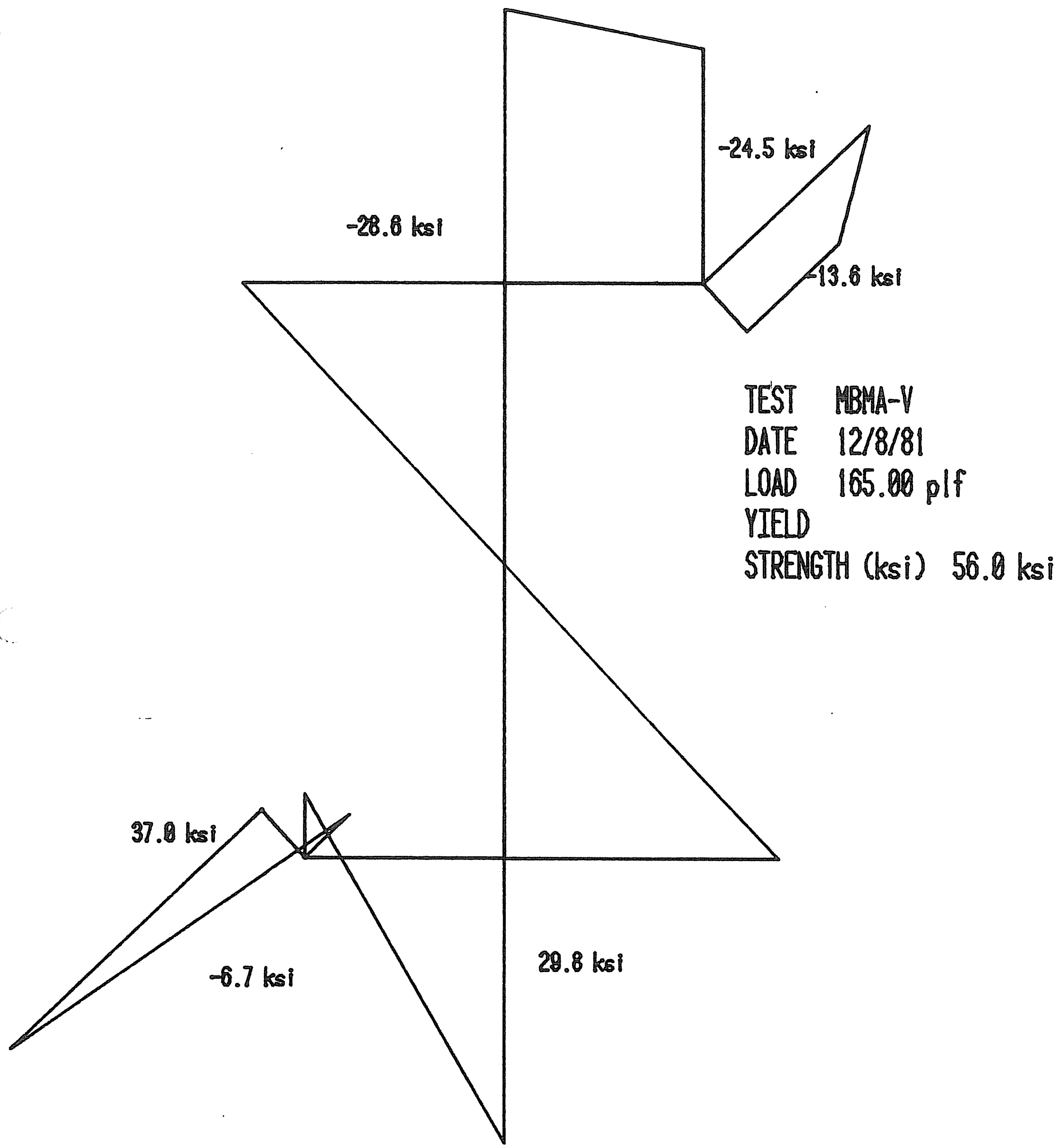


Figure E.8 Stress Distribution at 165 plf, Test V

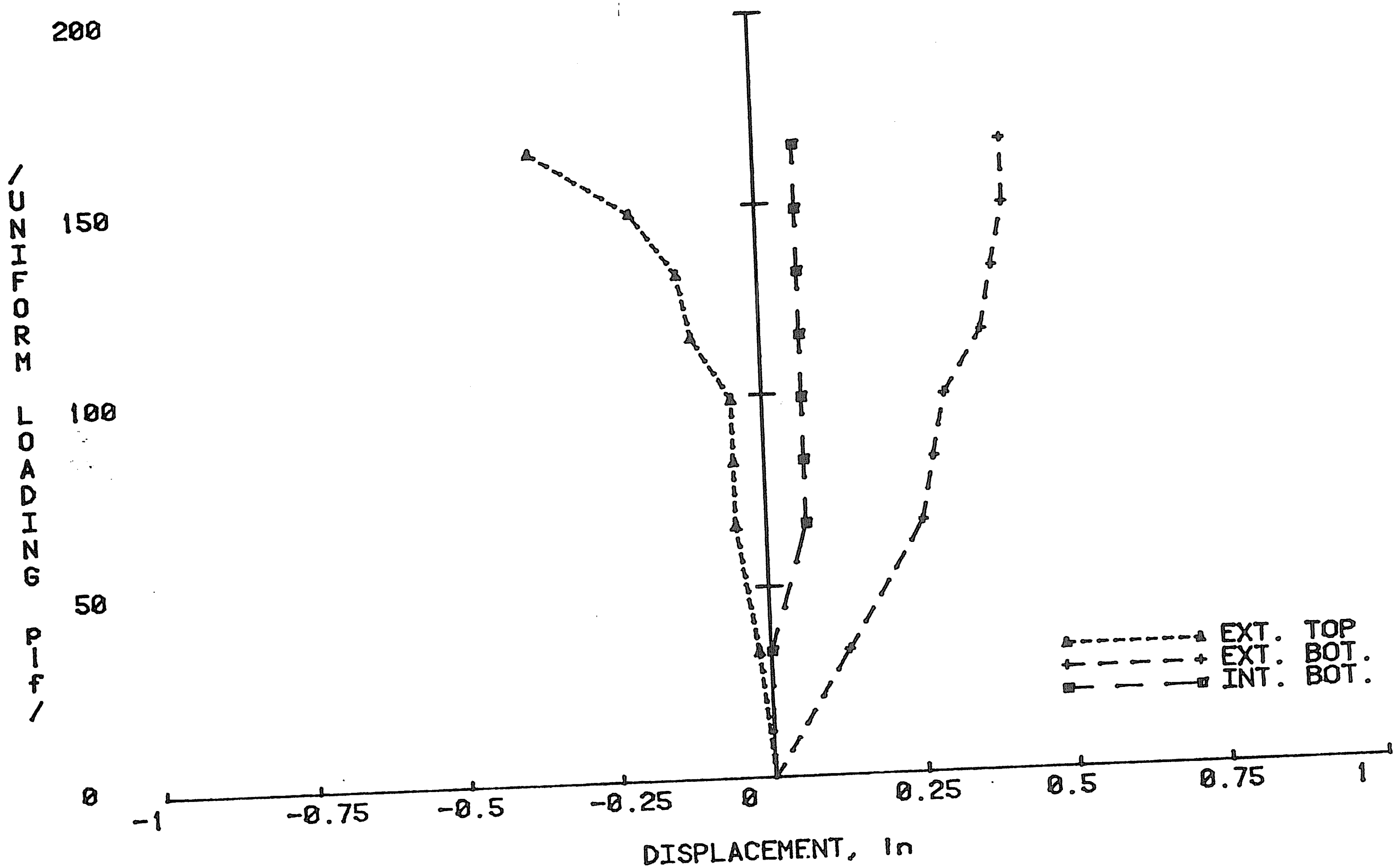


Figure E.9 Vertical Loading vs. Lateral Displacements, Test V

APPENDIX F

TEST VI RESULTS

TEST SUMMARY

Project: MBMA Roof System Behavior

Test No.: VI

Test Date: December 23, 1981

Purpose: To determine the magnitude of torsional restraining forces required @ the rafters

Span(s): 19.625'

Thickness: 0.086" Moment of Inertia: 12.3 in^4

Parameters: The same as test III except panel to purlin connection was reinforced.

Failure Load: 230.0 plf

Failure Mode: Local buckling of the top flange and/or web.

Predicted Failure Loads:

Method AISI constr. bending Load 294.3 plf

Method Load

Method Load

Discussion:

-Panel to purlin connection was reinforced by angles at outside edges of panel perpendicular to purlins.

-Identical to Test III in all other respects.

-Vertical deflection was 10-31% higher than the constrained bending assumption for the east purlin (nearer to the lateral support joist), but for the west purlin vertical deflection was very close to predicted.

-Ratio of internal to external brace forces were 2.81 to 3.37 for the north rafter and 4.42 to 12.21 for the south rafter.

-Summation of brace forces @ 66 plf was 8% of total vertical load for the external joist and 33% for the internal purlin.

-At 231 plf the ratios were 11% and 40% of total vertical load for exterior and interior purlins, respectively.

-Brace forces increased linearly with increasing load.

-Lateral displacement of the bottom flange exceeded the top flange.

-Maximum lateral displacement was 0.70 in.

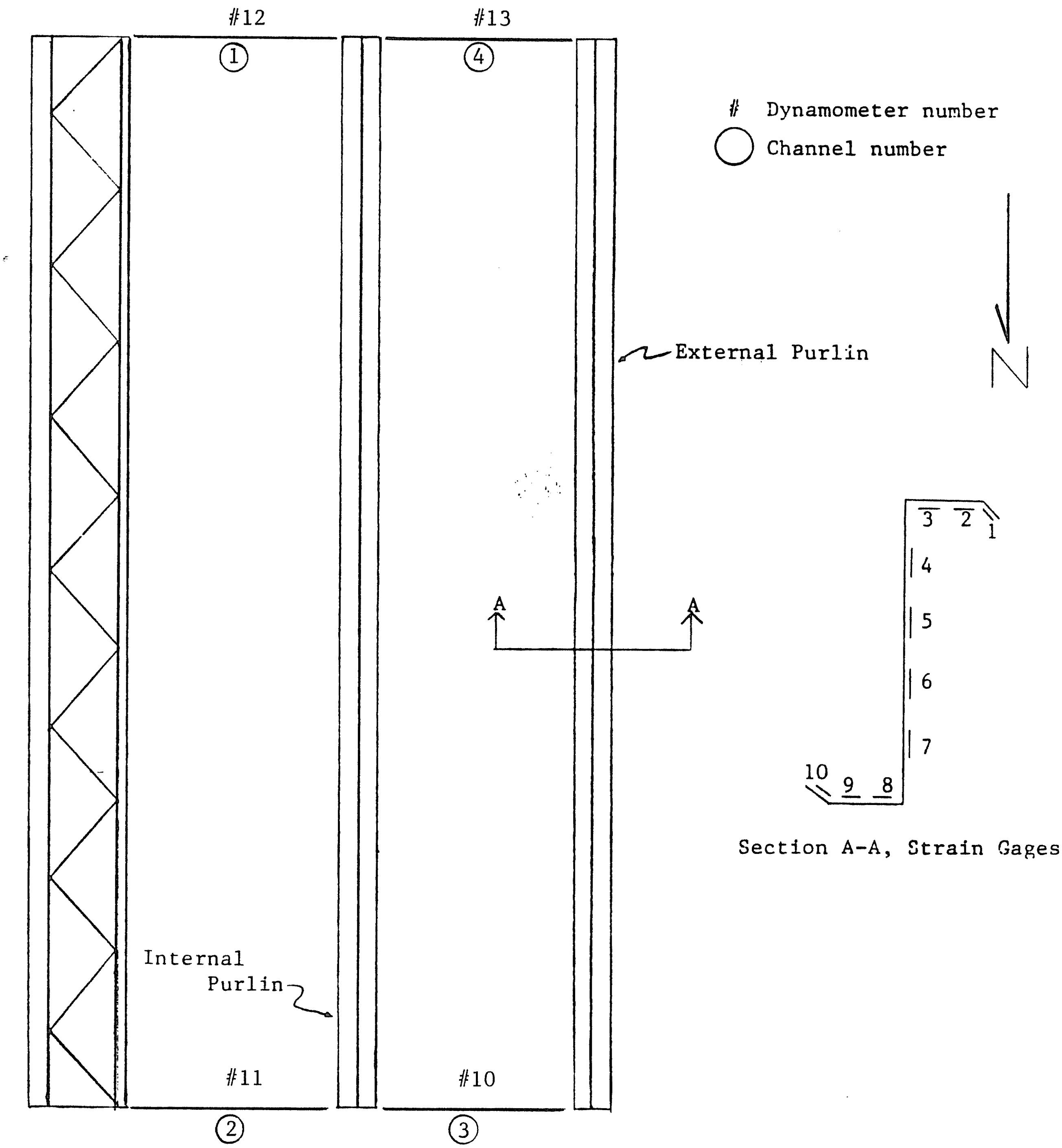
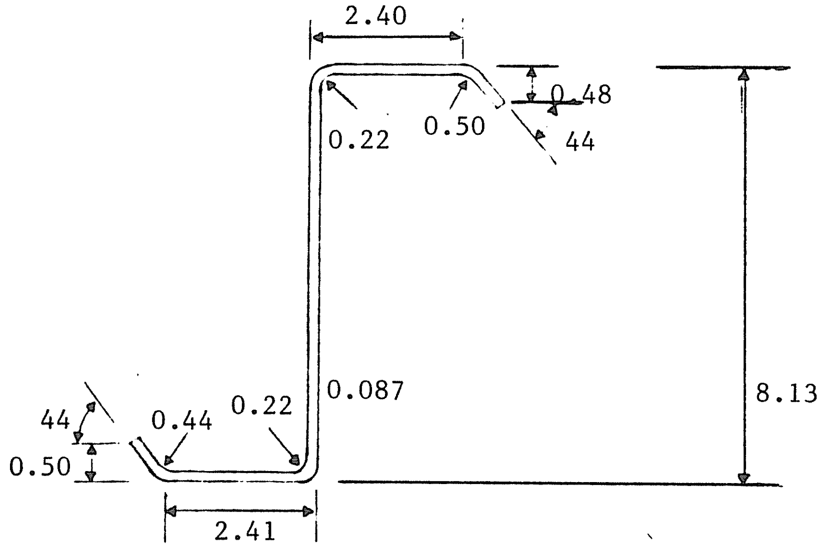
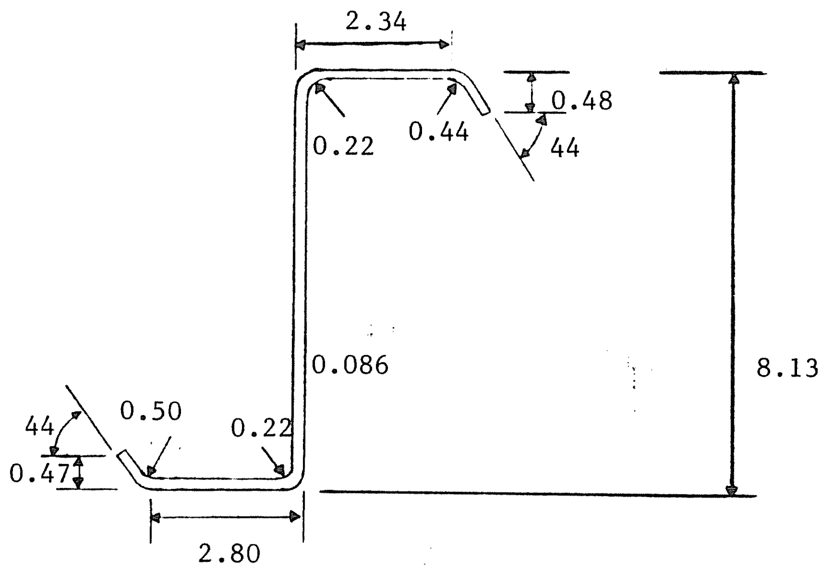


Figure F.1 Instrumentation Location, Test VI



External Purlin



Internal Purlin

Figure F.2 Measured Purlin Dimensions, Test VI

```
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: MBMA-VI-W(EXT) 12/23/81
```

	TOP	BOTTOM
FLANGE(in)	2.400	2.410
LIP(in)	0.480	0.500
LIP ANGLE(deg)	44.000	44.000
RADIUS L/F(in)	0.500	0.438
RADIUS F/W(in)	0.219	0.219

TOTAL DEPTH(in)	8.13
THICKNESS(in)	0.087
YIELD STRENGTH(ksi)	56

	MOMENTS OF INERTIA(in^4)	SECTION MODULII(in^3) TOP	BOTTOM
GROSS=	12.327	3.062	3.068
STRENGTH=	12.327	3.062	3.068
DEFLECTION=	12.327		

BE= 2.094 in
FC= 33.600 ksi
FT= 33.600 ksi
FBW= 32.838 ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)

MC=	8.575	ft-k
MT=	8.590	ft-k
MW=	8.964	ft-k
MU=	14.320	ft-k (1.67*allowable)
SPAN =	19.625	ft.
UNIFORM LOAD=	297.445	plf (1.67*allowable)
DEFLECTION =	0.918	in./100plf

Figure F.3 AISI Purlin Analysis, Test VI West Purlin

```
--------------------------------------------------------------
A I S I   P U R L I N   A N A L Y S I S
IDENTIFICATION: MBMA-VI-E(INT) 12/23/81
--------------------------------------------------------------
                        TOP              BOTTOM
FLANGE(in)             2.340              2.800
LIP(in)                0.480              0.470
LIP ANGLE(deg)        44.000             44.000
RADIUS L/F(in)         0.438              0.500
RADIUS F/W(in)         0.219              0.219

TOTAL DEPTH(in)               8.13
THICKNESS(in)                 0.086
YIELD STRENGTH(ksi)           56
                                   SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)       TOP               BOTTOM
GROSS=         12.582              3.031              3.232
STRENGTH=      12.582              3.031              3.232
DEFLECTION=    12.582
BE=    2.035   in
FC=    33.600   ksi
FT=    33.600   ksi
FBW=   32.745   ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)
          MC=      8.486   ft-k
          MT=      9.051   ft-k
          MW=      8.826   ft-k
          MU=     14.171   ft-k (1.67*allowable)
SPAN        =     19.625   ft.
UNIFORM LOAD=    294.351   plf (1.67*allowable)
DEFLECTION  =      0.899   in./100plf
```

Figure F.4 AISI Purlin Analysis, Test VI East Purlin

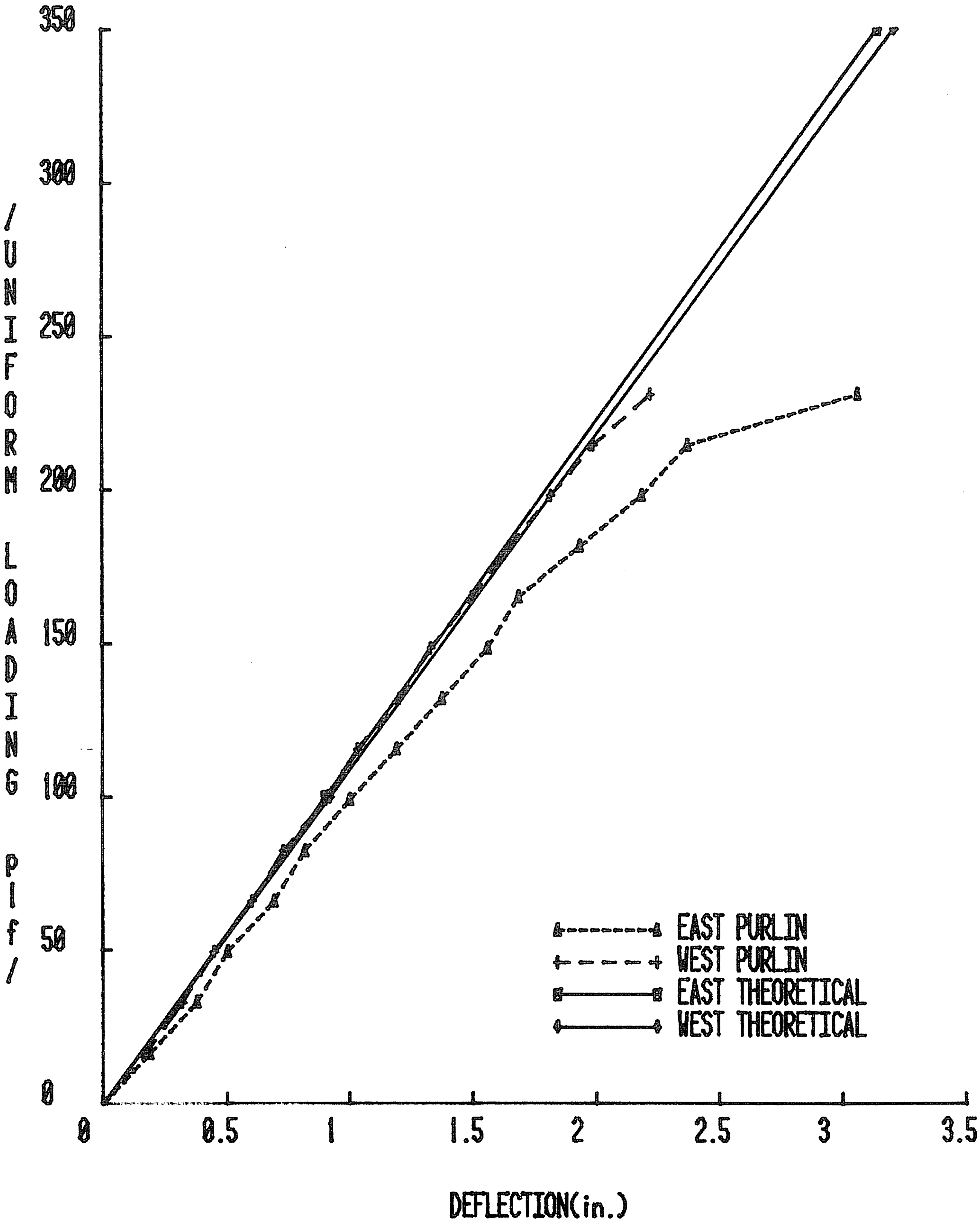


Figure F.5 Load vs. Vertical Deflection, Test VI

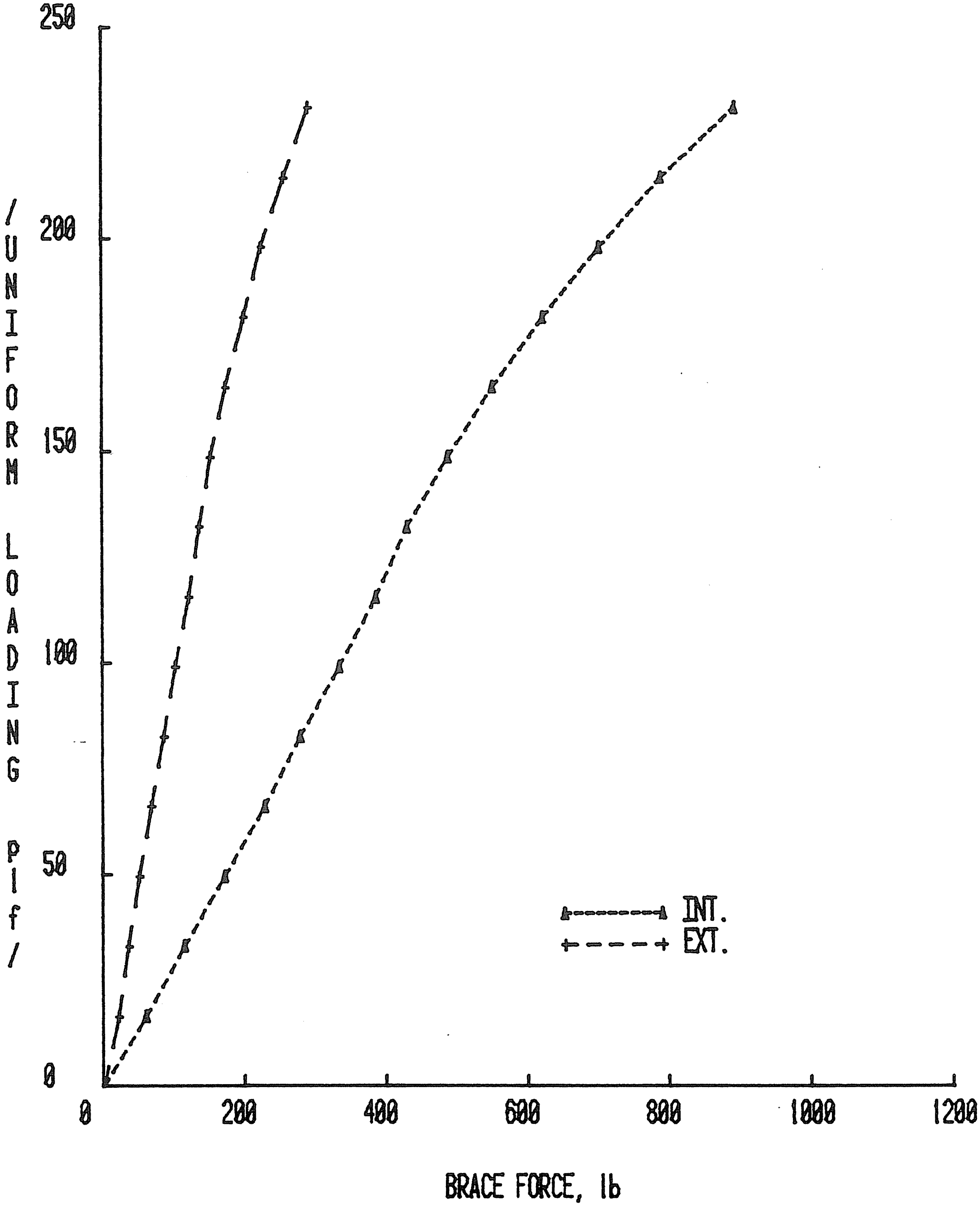


Figure F.6 Vertical Loading vs. Brace Force at North Rafter, Test VI

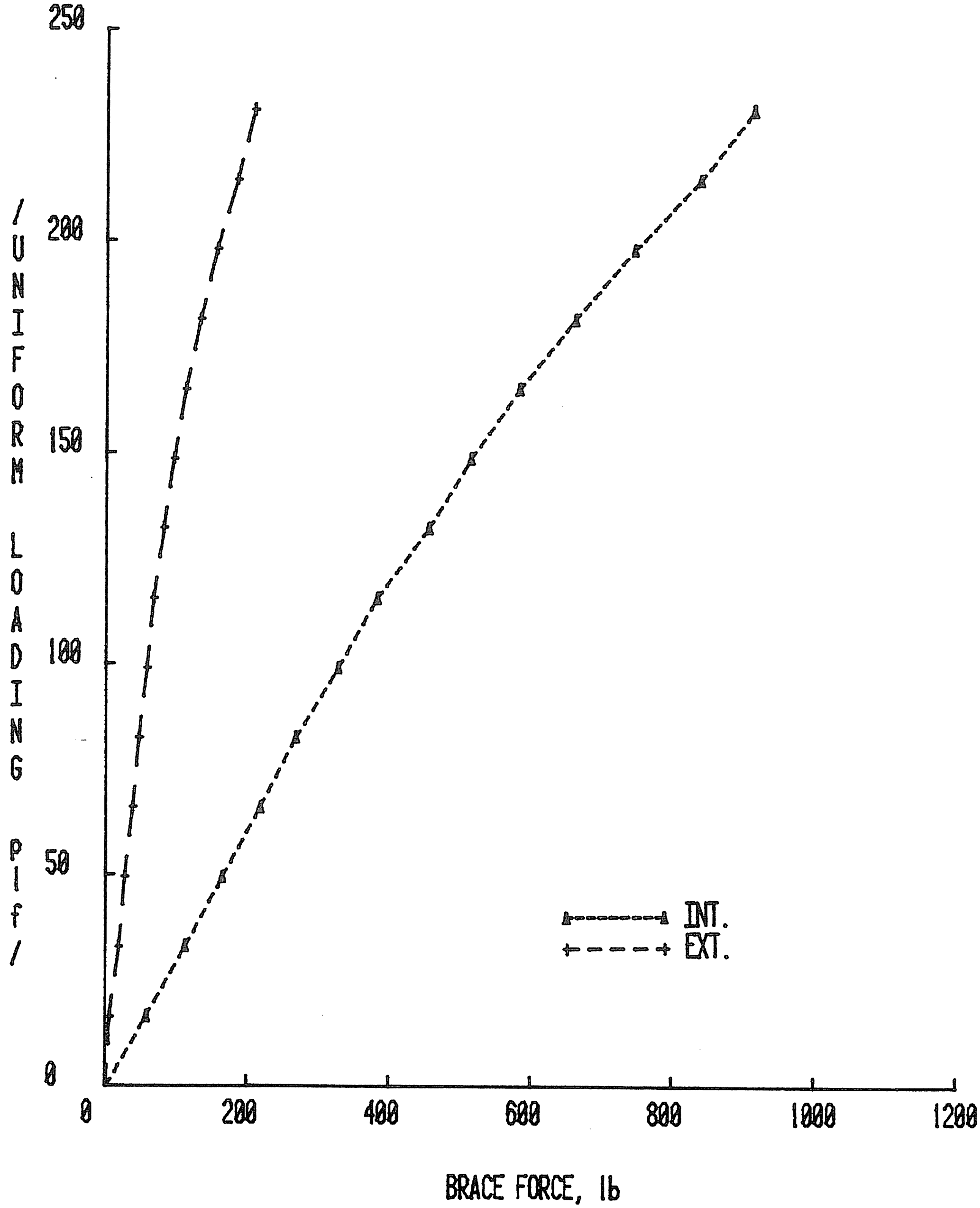


Figure F.7 Vertical Loading vs. Brace Force at South Rafter, Test VI

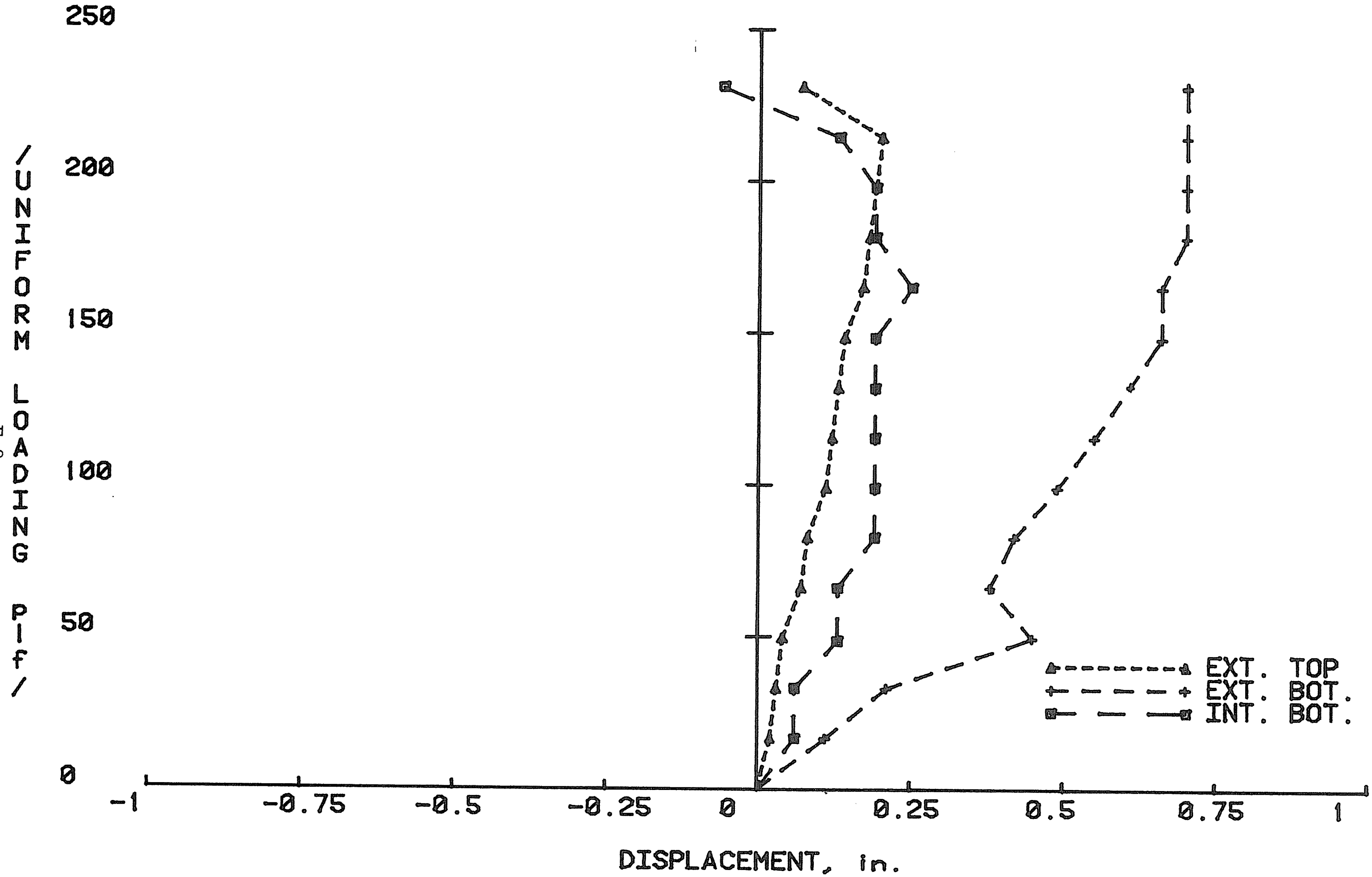


Figure F.8 Vertical Loading vs. Lateral Displacements, Test VI