ROOF SYSTEMS BEHAVIOR

Progress Report

SIMPLE SPAN Z-PURLIN TESTS TO DETERMINE BRACE FORCE ACCUMULATION

by

Larry E. Curtis
and
Thomas M. Murray
Principal Investigator

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FEARS STRUCTURAL ENGINEERING LABORATORY
School of Civil Engineering and Environmental Science
University of Oklahoma
Norman, Oklahoma 73019

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CHAPTER I

INTRODUCTION

1.1 General

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 portion of the study reported here is limited to two topics:

1) Torsional brace force requirements for single span, multiple Z-purlin systems.

2) In-plane stiffness of such systems.

This report summarizes the results of twenty gravity load tests of 2, 6 and 7 purlin systems and nine stiffness tests of 2 and 7 purlin systems. The objective of the gravity load tests was to determine the magnitude of torsional brace forces in multi-purlin systems. The results are compared to data from 2 purlin tests and, hence, accumulation of brace force with increasing number of purlins is determined. These tests will henceforth be referred to as "accumulation" tests. The objective of the stiffness tests was similar to that of the accumulation tests, that is, to determine the system stiffness of multi-purlin systems as compared to two purlin systems.

For both test series, two span lengths were used: nominally 14 ft. and 22 ft. All purlins used in the tests were cold-formed Z-sections. Three material thicknesses were used: approximately 0.072, 0.088 and 0.099 in.

Two basic configurations were used for the accumulation tests: (a) All purlins facing in one direction with lateral restraint provided only by torsional braces attached to one purlin at a rafter location. (b) One half of the purlins facing one direction and the other half opposing with connection between the sets at the "ridge" at the nominal 1/3rd points of the purlin span. For the stiffness tests, only configuration (a) was used.

In the discussion that follows, terms conventionally used to describe a Z-purlin roof system will be used, e.g. eave purlin, ridge purlin, uphill and downhill purlins. It is assumed in these references that the roof system is constructed of Z-purlins with top flanges pointing toward the ridge of the roof on both slopes. However, all tests were conducted in a horizontal plane and an eave strut member was not used. Conventional roof panel without insulation was used in all but one test. A standing seam roof panel system without insulation was used in this test.

1.2 Accumulation Tests

The six configurations used in the accumulation test series are summarized as follows:

Test Series A/2.	14 ft. 0 in. simple span; two Z-purlins; gravity loading; torsional restraint on eave purlin at rafter; conventional panel.
Test Series A/7.	14 ft. 3½ in. simple span; seven Z-purlins; vacuum and gravity loading; torsional restraint on second "uphill" purlin at rafter locations; conventional panel.

Test Series B/2. — 22 ft. 3 in. simple span; two Z-purlins; gravity loading; torsional restraint on eave purlin at rafter locations; conventional panel.

Test Series B/6. — 22 ft. 3 in. simple span; six Z-purlins; gravity loading; torsional restraint on first or second uphill purlin; conventional panel.

Test Series B/6/6. — 22 ft. 3 in. simple span; 12 Z-purlins with six opposing six; gravity loading; conventional panel.

Test Series SS/6/6. — 22 ft. 3 in. simple span; 12 Z-purlins with six opposing six; gravity loading; panel deck and angle bracing between opposing purlin sets at the 1/3 points; standing seam panel; intermediate bracing at nominal 1/3 points.

A complete description of the various test setups and the testing procedure is found in Section 2.1. Test results are given in Section 3.1.

1.3 Stiffness Tests

The nine test configurations used for the stiffness tests are as follows. Torsional restraint was provided in all tests to one purlin at rafter locations.

Test S/2-T1. — 14 ft. 0 in. simple span; two Z-purlins; torsional restraint in tension; no gravity load; stiffness measured at the centerline; conventional panel.

Test S/2-C1. — 14 ft. 0 in. simple span; two Z-purlins; torsional restraint in compression; no gravity load; stiffness measured at the centerline; conventional panel.

Test S/2-T2. — 14 ft. 0 in. simple span; two Z-purlins; torsional restraint in tension; no gravity load; stiffness measured at outside quarter points; conventional panel.

Test S/2-C2. — 14 ft. 0 in. simple span; two Z-purlins; torsional restraint in compression; no gravity load; stiffness measured at the outside quarter points; conventional panel.

Test S/2-C2/99.	14 ft. 0 in. simple span; two Z-purlins; torsional restraint in compression; 99 plf gravity load; stiffness measured at the outside quarter points; conventional panel.
Test S/7-T1.	14 ft. 0 in. simple span; seven Z-purlins; torsional restraint in tension; no gravity load; stiffness measured at the centerline; conventional panel.
Test S/7-T1/99.	14 ft. 0 in. simple span; seven Z-purlins; torsional restraint in tension; 99 plf gravity load; stiffness measured at the centerline; conventional panel.
Test S/7-T2.	14 ft. 0 in. simple span; seven Z-purlins; torsional restraint in tension; no gravity load; stiffness measured at the outside quarter points; conventional panel.
Test S/7-T2/99.	14 ft. 0 in. simple span; seven Z-purlins; torsional restraint in tension; 99 plf gravity load; stiffness measured at the outside quarter points; conventional panel.

The test procedure and test setups are described in Section 2.2.

Test results are found in Section 3.2.

CHAPTER II

TEST DETAILS

2.1 Accumulation Tests

2.1.1 Test Components

Z-Purlins. The Z-purlins used for Test Series A and B were supplied by MBMA, and those for Test Series SS by Star Manufacturing Company, Oklahoma City, Oklahoma. All Z-purlins that were instrumented in a test setup were carefully measured and the dimensions recorded. Cross-sectional measurements are given in Table 1 with definitions in Figure 1. Table 2 shows cross-sectional properties and load and deflection data for the spans used in the tests assuming uniform loading. Properties were determined using AISI criteria with an assumed yield stress of 56 ksi.

Panels, Fasteners, Clips and Bolts. For Test Series A and B conventional panel, as shown in Figure 2, was used. The 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 connections. 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).

For Test Series SS, the standing seam panel as shown in Figure 3 was used. The sheet size was 24 in. in pansection width by 10 ft. in length and nominally 24 gage. The edges of each sheet section formed a 2 in. high box rib plus a 7/8 in. high seam. Sliding panel clips (Figure 4) were used to connect the roof to the panels. One 1/4 in. diameter by

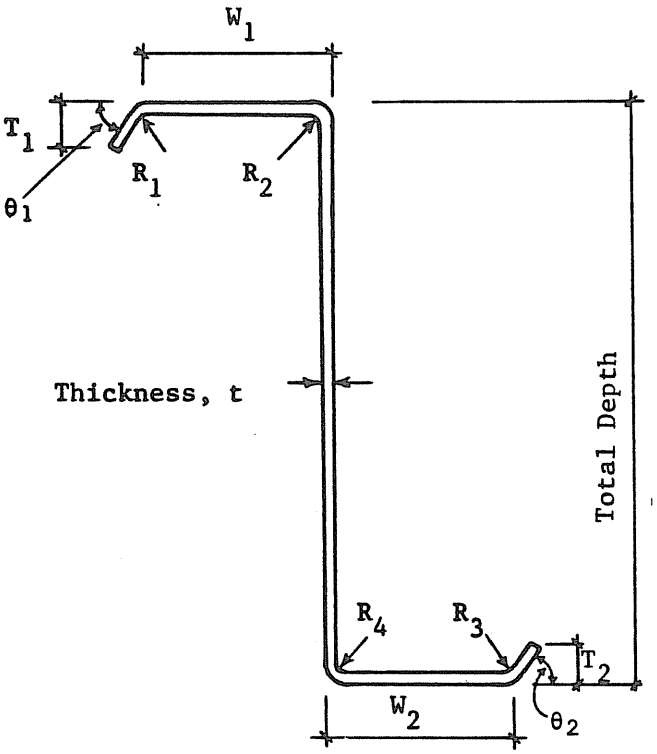


Figure 1. Cross-Section Measurements

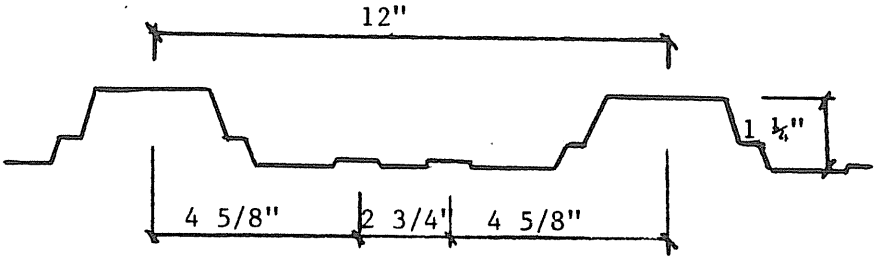


Figure 2. Conventional Panel Shape

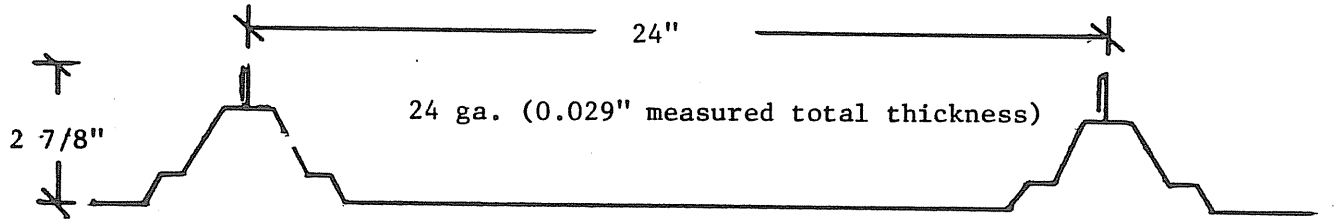


Figure 3. Standing Seam Panel Shape

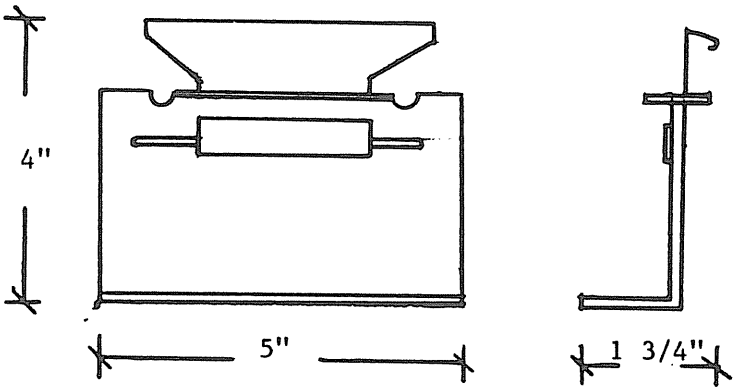


Figure 4. Panel Clip Detail

Table 1
Measured Z-Purlin Dimensions

Test Type	Purlin Location	Test	Total Depth (in.)	Thick-ness (in.)	Top Flange and Lip					Bottom Flange and Lip				
					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)
Acc	Ext.	A/2-1	8.16	0.076	2.40	0.56	0.50	0.22	45.0	2.52	0.38	0.50	0.22	39.0
Acc	Int.	A/2-1	8.15	0.075	2.40	0.53	0.50	0.22	43.0	2.44	0.40	0.50	0.22	37.0
Acc	Ext.	A/2-2	8.10	0.072	2.30	0.40	0.50	0.31	29.0	2.33	0.60	0.50	0.31	40.0
Acc	Int.	A/2-2	8.12	0.072	2.30	0.60	0.50	0.31	40.0	2.35	0.45	0.50	0.31	30.0
Acc	Ext.	A/2-3	8.15	0.074	2.40	0.42	0.50	0.28	30.0	2.40	0.67	0.50	0.28	28.0
Acc	Int.	A/2-3	8.30	0.073	2.42	0.35	0.50	0.28	28.0	2.47	0.70	0.50	0.28	41.0
Acc	2nd*	A/7	7.96	0.076	2.50	0.46	0.50	0.22	41.0	2.34	0.46	0.50	0.22	40.0
Acc	3rd*	A/7	7.98	0.076	2.45	0.48	0.50	0.22	39.0	2.32	0.46	0.50	0.22	38.0
Acc	Ext.	B/2	8.14	0.088	2.40	0.52	0.50	0.25	43.0	2.42	0.54	0.50	0.25	41.0
Acc	Int.	B/2	8.13	0.088	2.40	0.53	0.50	0.25	42.0	2.44	0.54	0.50	0.25	43.0
Acc	Ridge	B/6	8.05	0.088	2.30	0.58	0.38	0.22	45.5	2.48	0.51	0.38	0.22	42.0
Acc	Ridge	SS/6/6	7.87	0.099	2.75	0.60	0.50	0.28	41.0	2.92	0.70	0.50	0.28	46.0
Stiff	Ext.	S/2	8.10	0.072	2.30	0.40	0.50	0.31	29.0	2.33	0.45	0.50	0.31	40.0
Stiff	Int.	S/2	8.12	0.072	2.30	0.60	0.50	0.31	40.0	2.35	0.45	0.50	0.31	30.0

*Downhill

Table 2
Computed Z-Purlin Cross Sectional Properties

Test Type	Purlin Location	Test	Span (ft)	Gross			Strength			b_e (in.)	F_c (ksi)	F_t (ksi)	F_{bw} (ksi)	Moment Capacity (AISI)			1.67xAllowable		Deflection	
				I (in^4)	S_{t_3} (in^3)	S_{b_3} (in^3)	I (in^4)	S_{t_3} (in^3)	S_{b_3} (in^3)					M_c (ft.k)	M_t (ft.k)	M_w (ft.k)	M_u (ft.k)	W_u (lb/ft)	I (in^4)	Δ/ 100 plf
Acc	Ext.	A/2-1	14.000	11.047	2.745	2.721	11.047	2.745	2.721	2.104	33.600	33.600	31.648	7.686	7.619	7.736	12.723	475.867	11.047	0.316
Acc	Int.	A/2-1	14.000	10.814	2.693	2.664	10.814	2.693	2.664	2.105	33.600	33.600	31.537	7.539	7.459	7.561	12.457	465.924	10.814	0.323
Acc	Ext.	A/2-2	14.000	10.168	2.506	2.561	10.168	2.506	2.561	1.918	32.547	33.600	31.209	6.798	7.169	7.127	11.353	463.394	10.168	0.288
Acc	Int.	A/2-2	14.000	10.324	2.566	2.565	10.324	2.566	2.565	1.918	31.808	33.600	31.186	6.802	7.182	7.297	11.360	463.670	10.324	0.284
Acc	Ext.	A/2-3	14.000	10.924	2.672	2.739	10.924	2.672	2.739	2.046	32.693	33.600	31.412	7.280	7.670	7.582	12.157	454.694	10.924	0.319
Acc	Int.	A/2-3	14.000	11.294	2.680	2.814	11.294	2.680	2.814	2.067	33.600	33.600	31.107	7.504	7.880	7.512	12.532	468.724	11.294	0.309
Acc	2nd*	A/7	14.290	10.346	2.653	2.597	10.346	2.653	2.597	2.205	33.600	33.600	31.873	7.427	7.272	7.543	12.144	475.759	10.346	0.307
Acc	3rd*	A/7	14.290	10.401	2.659	2.605	10.401	2.659	2.605	2.155	33.600	33.600	31.851	7.446	7.294	7.554	12.180	477.185	10.401	0.306
Acc	Ext.	B/2	22.250	12.684	3.136	3.165	12.684	3.136	3.165	2.062	33.600	33.600	32.919	8.781	8.863	9.277	14.664	236.960	12.684	1.474
Acc	Int.	B/2	22.250	12.677	3.144	3.162	12.677	3.144	3.162	2.062	33.600	33.600	32.929	8.802	8.854	9.305	14.699	237.535	12.677	1.475
Acc	Ridge	B/6	22.250	12.224	3.044	3.097	12.224	3.044	3.097	1.992	33.600	33.600	33.007	8.523	8.673	8.962	14.233	230.007	12.224	1.529
Acc	Ridge	SS/6/6	22.250	14.676	3.721	3.835	14.676	3.721	3.835	2.371	33.600	33.600	33.600	10.419	10.737	11.369	17.400	281.178	14.676	1.274
Stiff	Ext.	S/2	14.000	10.168	2.506	2.561	10.168	2.506	2.561	1.918	32.547	33.600	31.209	6.798	7.169	7.127	11.353	463.394	10.168	0.288
Stiff	Int.	S/2	14.000	10.324	2.566	2.565	10.324	2.566	2.565	1.918	31.808	33.600	31.186	6.802	7.182	7.297	11.360	463.670	10.324	0.284

*Downhill

Note: Calculations based on σ_y = 56 ksi

1 in. long bolt was used to connect each clip to the purlin. The clip was securely fastened to the panel by the seaming operation.

2.1.2 Test Set-ups

Series A accumulation tests were performed using the test set-ups shown in Figures 5 and 6, Tests A/2 and A/7, respectively. Purlin spacing for both tests was 5 ft. 0 in.

In test set-up A/2, the purlins were bolted to knife edges through the bottom flange with 1/2 in. diameter bolts. These knife edges allowed free rotation at the supports. The knife edges were supported by rafter sections which in turn were supported by stub columns resting on the laboratory floor. Two 1/2 in. diameter rollers were inserted between the rafter sections and columns to allow for rafter section rotation. In test set-up A/7, similar construction was used except that the purlins were bolted directly to the flanges of built-up rafter sections.

Series B accumulation test set-ups (Figure 7) were constructed by first supporting two 60 ft. steel joists using the rafter sections previously mentioned. Purlins were then bolted to the joist chords through the bottom flange using 1/2 in. diameter bolts. Purlins were spaced at 4 ft. 9 in. For the opposed purlin test, approximately 2 ft. was left between the two ridge purlins for instrumentation workspace. In two of the B/2 tests, the previously described knife edge purlin supports were used. In the remaining tests, the purlins were bolted directly to the joist chords.

For test set-up B/6/6, restraint between the sets of purlins was provided at the ridge by two braces near the purlin span 1/3rd points. To accomplish this, four heavy angle sections were bolted to the appropriate panels and an instrumented brace was inserted between the pairs of

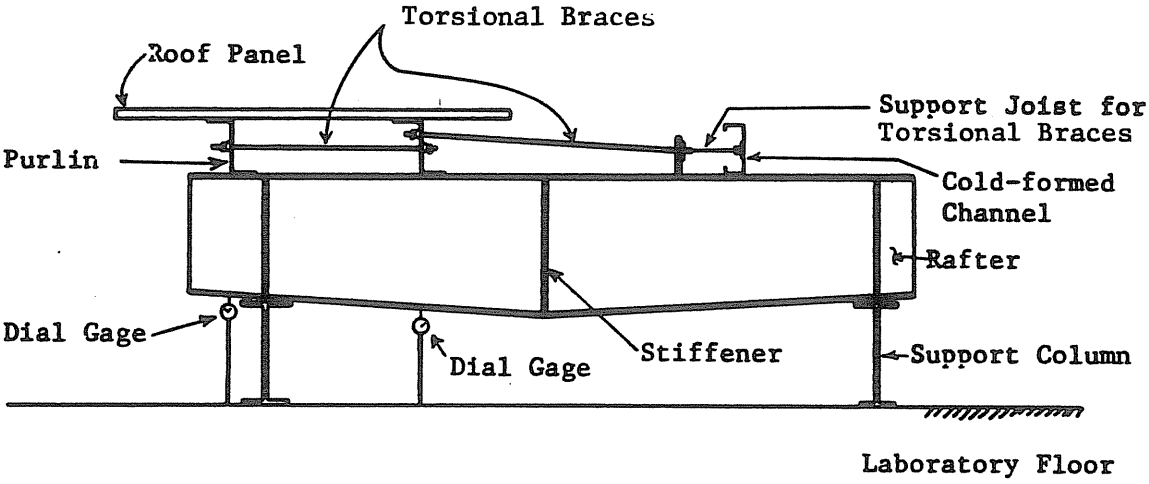
angles. A 10 kip capacity load cell formed part of each brace so that the load could be monitored. See Figure 7 for details.

The Series SS accumulation test set-up (Figure 8) was constructed similarly to test set-up B/6/6 except that two sets of bracing were used at the ridge. One set was attached to the panel as in the B/6/6 test set-up and the second was attached to adjacent purlin webs as shown in Figure 8. Both sets were instrumented so that forces could be measured at the four locations.

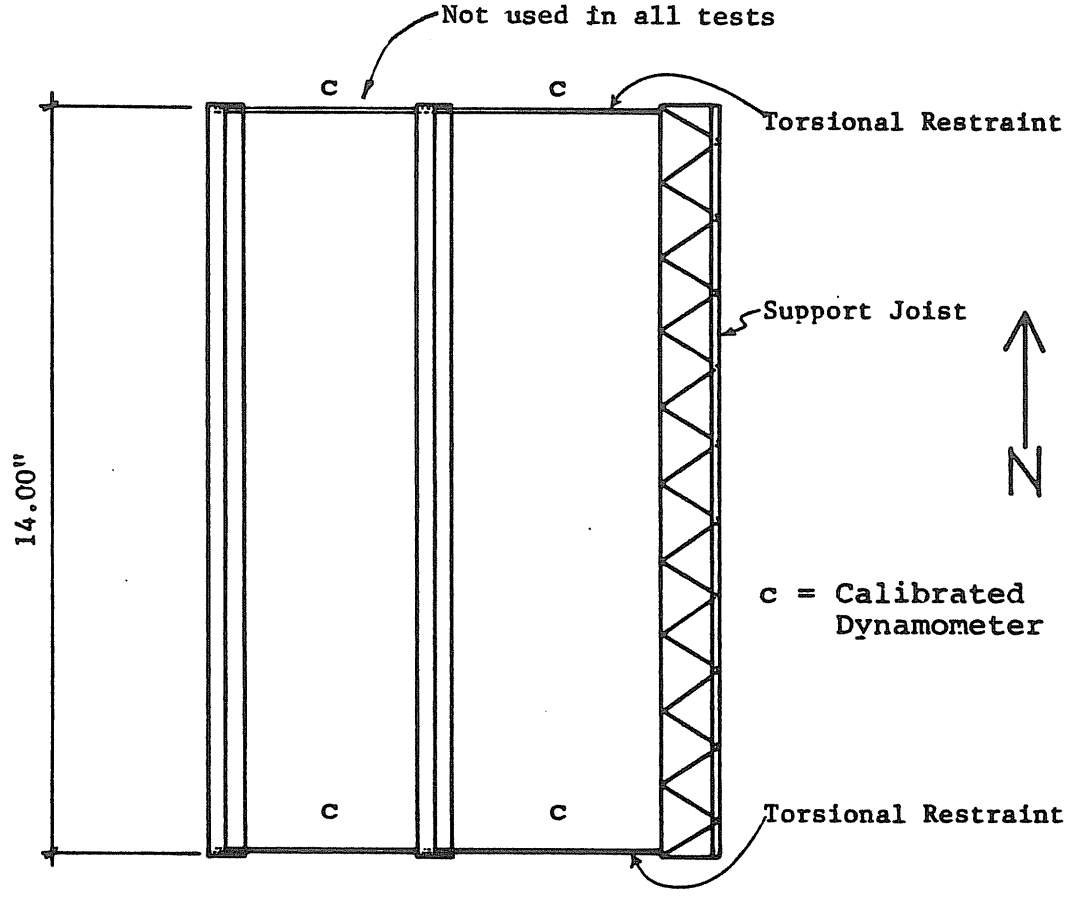
The torsional bracing used in all tests consisted of 3/4 in. diameter electrical conduit anchored to the supporting rafter section or joist. Nuts were welded into each end of the conduit and a 9 in. length of 1/2 in. diameter threaded stud was inserted. Holes were drilled at the proper location in the purlin webs and connection was made using "half moon" and flat washers together with a standard nut as shown in Figure 9. The washers and nuts were placed on the opposite side for a compression brace connection.

For all tests except Test Series A/2, the torsional restraint braces were connected from the purlin to a heavy stiffened angle as in Figure 9(a). For Test Series A/2 a standard 20 in. deep bar joist was used to react the 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 9(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 Series A and B conventional deck was connected to the purlins using self-drilling fasteners through the panel and the purlin



(a) Elevation of Test Set-up



(b) Plan View

Figure 5. A/2 Accumulation Test Set-up

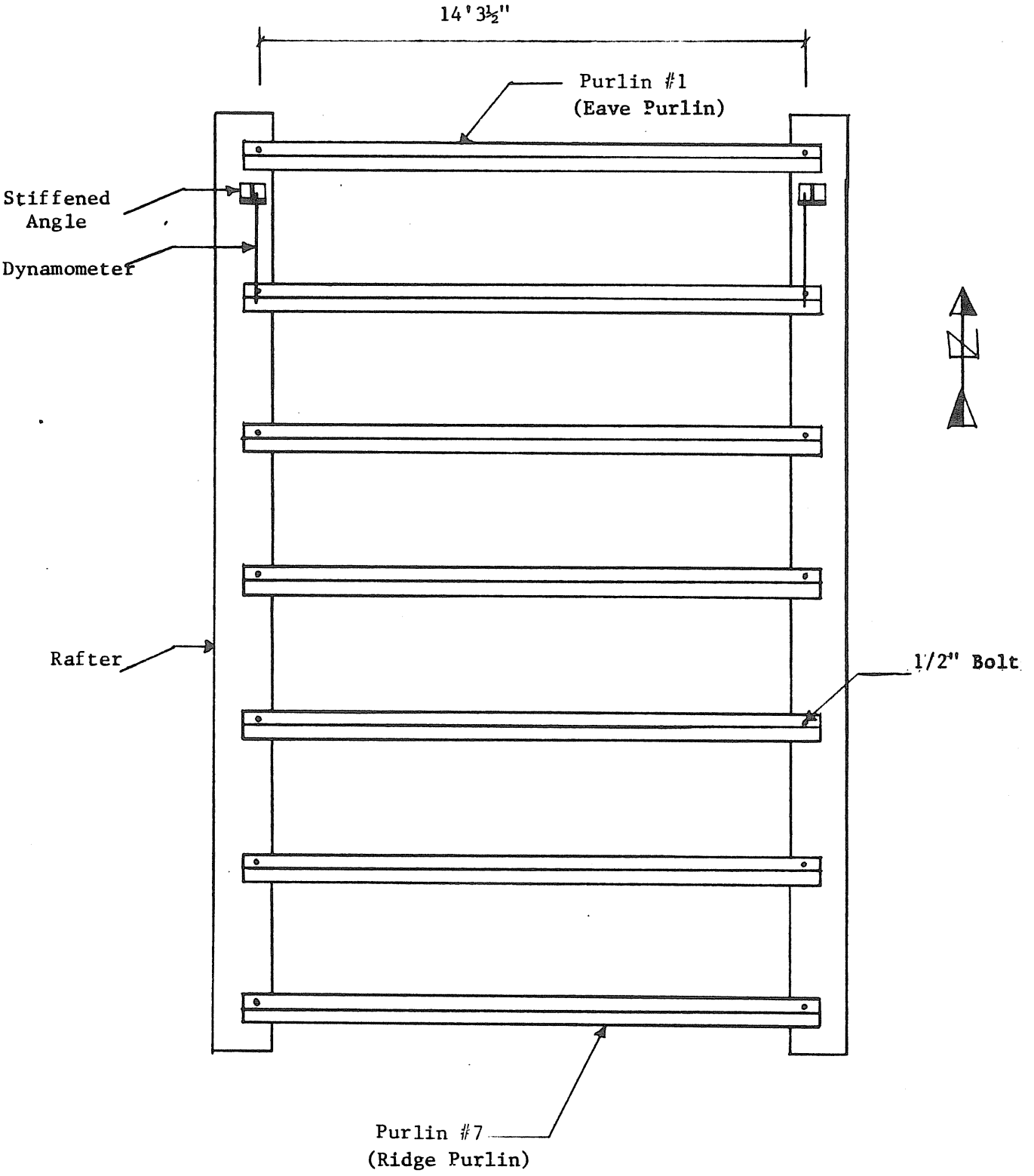
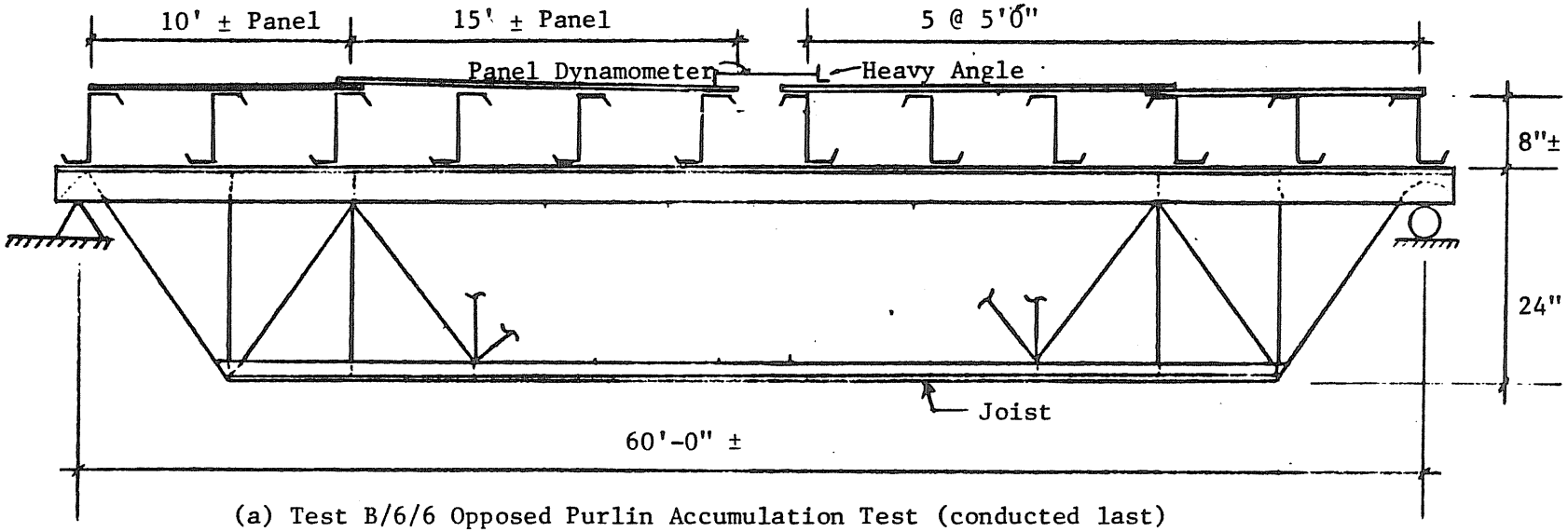
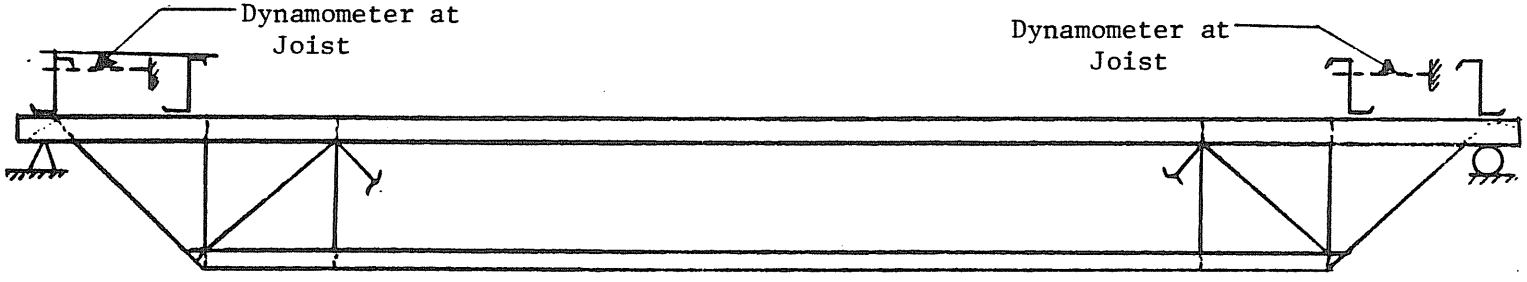


Figure 6. A/7 Accumulation Test Set-up

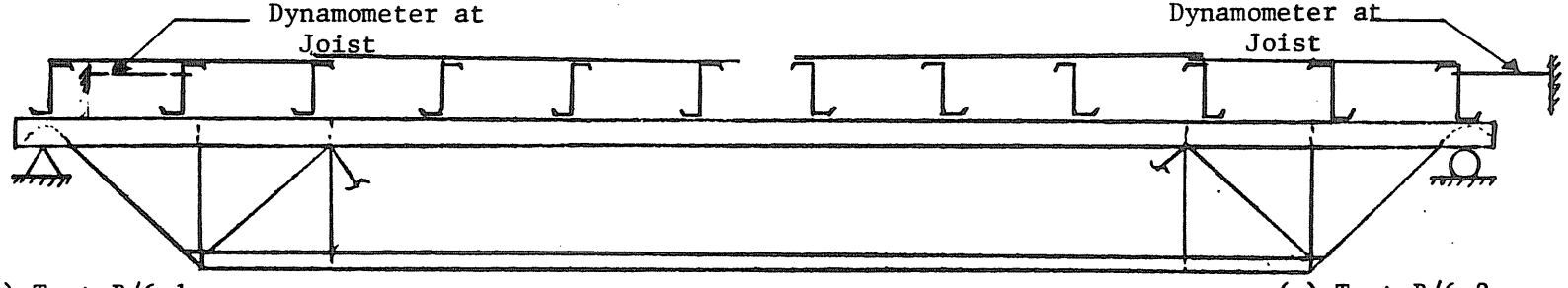


(a) Test B/6/6 Opposed Purlin Accumulation Test (conducted last)



(b) Test B/2-1&2

(c) Test B/2-3



(d) Test B/6-1

(e) Test B/6-2

Figure 7. Series B Test Set-ups

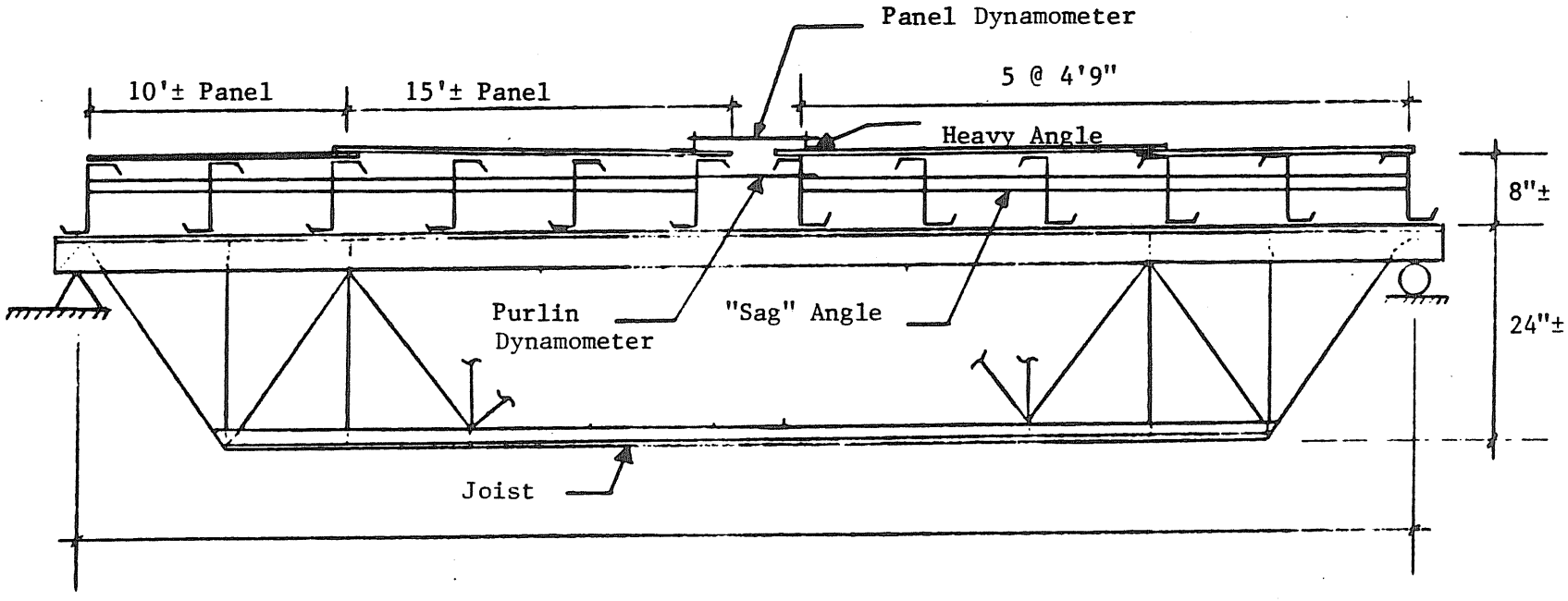
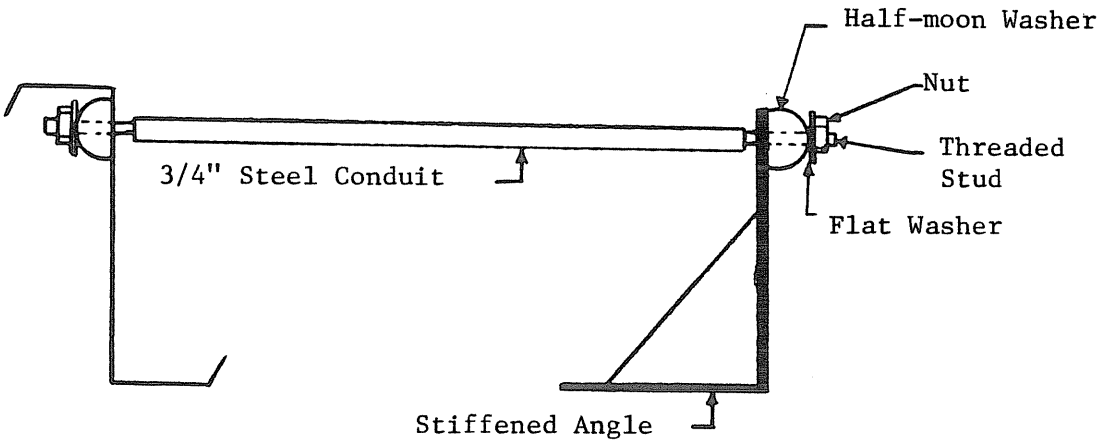
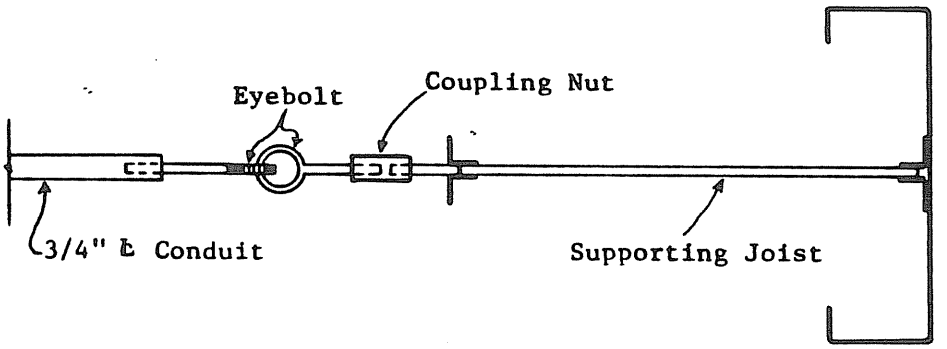


Figure 8. Series SS Test Set-up



(a) Tension Brace to Purlin Connection



(b) Brace Connection to Supporting Joist

Figure 9. Torsional Restraint Brace Connections

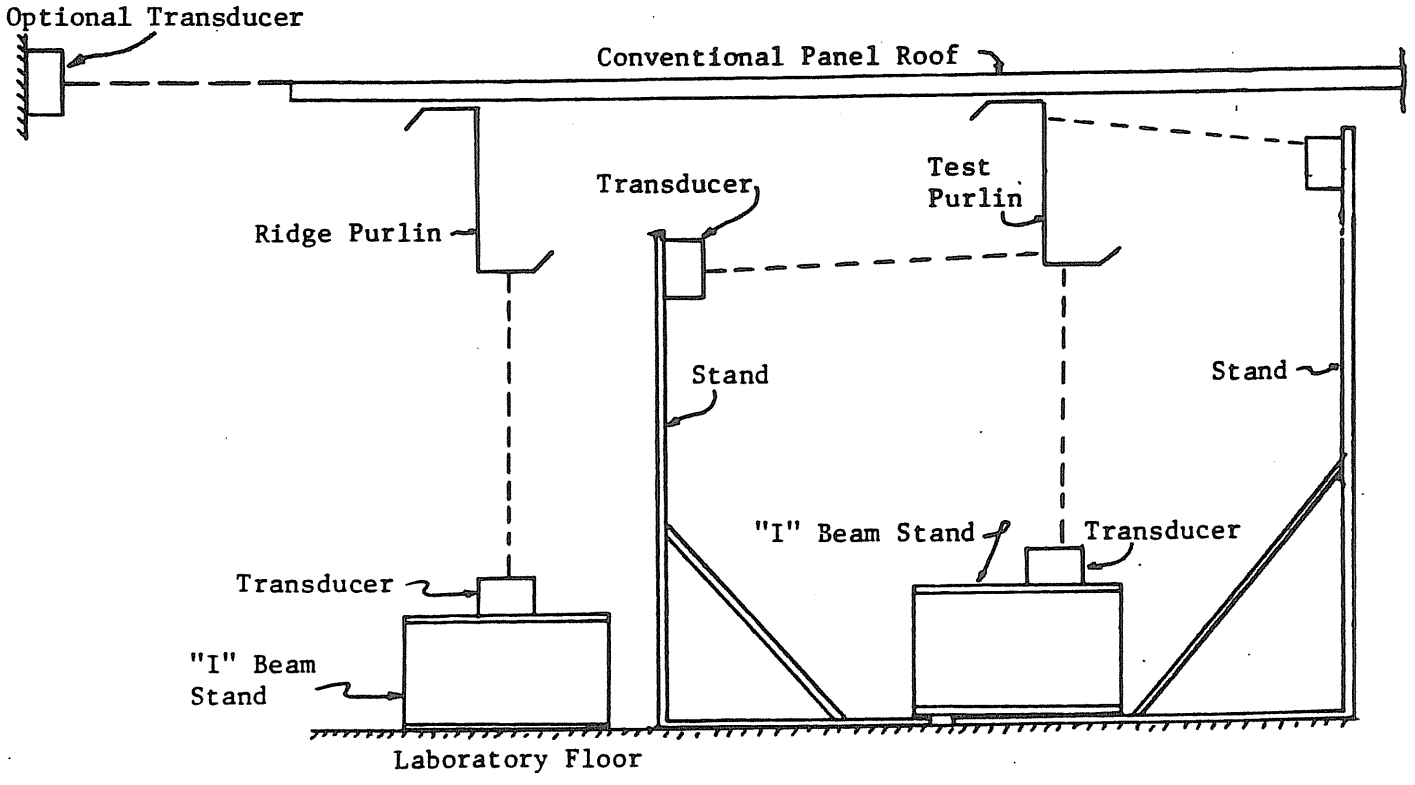


Figure 10. Typical Transducer Locations

top flange. For Series SS standing seam deck was connected to the purlins using 1/4 in. diameter bolts through the base of the clip and top flange of the purlin.

2.1.3 Instrumentation

Instrumentation consisted of calibrated dynamometers, dial gages, linear displacement transducers, and 10 kip capacity load cells. The calibrated dynamometers were typical torsional restraint braces with a full strain gage bridge installed at approximately the brace centerline. The braces were previously calibrated using a universal testing machine. The location of the dynamometers is shown in Figures 5, 6, 7, 8 and 10.

In each test, displacement transducers were used to measure vertical and horizontal movement of one or two purlins at the purlin span centerlines. Typically,vertical and the top and bottom flange horizontal deflections were measured at this location. A typical arrangement of transducers is shown in Figure 10. In some tests, the horizontal movement of the panel at this location was also measured. Additionally, for Test SS/6/6 the relative movement of the top flange of a ridge purlin at the supporting joist location was measured. Dial gages were used to measure similar movements at the eave purlins of Tests B/6, B/6/6 and SS/6/6.

Dial gages or displacement transducers were used to measure rafter and joist deflections at critical locations so that measured purlin vertical deflections could be corrected for support settlement.

Simulated live load was applied to the test systems using either concrete blocks (gravity loading) or suction (vacuum loading). For gravity loading, 33 ± 0.1 pounds solid concrete blocks were placed directly on the roof panel in a uniform pattern. The suction loading was applied to the system using a specially constructed vacuum chamber. The roof

system was first constructed in the chamber, then the entire assembly was sealed using polyethylene and duct tape and then suction applied using three pumps. The applied load was measured using a standard U-tube monometer and an electronic pressure sensing transducer.

2.1.4 Testing Procedure

At the beginning of each test approximately 25% of the total load was applied and then removed without data being recorded. Following this initial loading all dynamometers were "finger-tightened" and zero readings were recorded for all displacement transducers, dial gages and dynamometers. The system was then generally loaded in 33 plf per interior purlin increments, although certain tests were loaded in 16.5 plf per interior purlin increments. After each incremental load was applied and the system allowed to come to equilibrium, all instrumentation readings were recorded. The system was then loaded until sufficient data was recorded or until the maximum safe load of any member was reached. The first test in the A/2 series was the only test to failure.

2.2 Stiffness Tests

2.2.1 Test Components

Z-Purlins. The Z-purlins used for the stiffness tests were supplied by MBMA. Instrumented Z-purlins were measured carefully, and the recorded dimensions are found in Table 1. As in the accumulation tests, properties were determined using AISI criteria with an assumed yield stress of 56 ksi and are reported in Table 2.

Panels, Fasteners and Bolts. For all of the stiffness tests, conventional panel (Figure 2) was used. For the two purlin tests, the panel sheet size was 3 ft. by 10 ft. and nominally 26 ga., and for the seven purlin tests, the panel sheet size was 3 ft. by 15 ft. and nominally 26 ga. Self-drilling fasteners, No. 12 by 1 in., were used for both sheet-to-sheet and sheet-to-purlin connections. The fastener spacing was the same as used for the accumulation tests.

For both the two purlin and seven purlin tests, the purlins were bolted through the bottom flanges to the simulated rafters using 1/2 in. diameter bolts.

2.2.2 Test Set-up

The test set-ups used for the two purlin and seven purlin tests are shown in Figures 11 and 12, respectively. Construction of the test set-ups was identical to that described previously for the accumulation tests.

To transfer the horizontal load to the purlins, one end of a hydraulic ram was connected to a joist which was welded to the rafter sections. The other end of the ram was connected to a built-up H-section. Dynamometers were used to transfer the load from the H-section to the purlin. Details are shown in Figure 13. Two different configurations were used: (a) a dynamometer at the centerline of the purlin span or (b) dynamometers at the 1/4 points (excluding centerline) of the purlin span. The dynamometers were identical to those previously described for the accumulation tests.

The only external restraint provided to the purlins was by torsional restraint dynamometers connected to each end of one purlin at a

rafter location. The locations of these dynamometers are shown in Figures 11, 12 and 13. The connection details were as previously described for the accumulation tests.

2.2.3 Instrumentation

Instrumentation consisted of the calibrated dynamometers and various dial gages to measure vertical and horizontal deflections. Dial gages were placed at the load dynamometer-to-purlin connections to measure horizontal deflecion. Likewise they were placed near the top flange of the same purlins and directly over the rafter sections to measure purlin roll at this location. For the gravity load tests, dial gages were used to measure vertical centerline deflection of one purlin and to measure rafter deflection directly under this purlin so that corrections for support settlement could be made.

2.2.4 Testing Procedure

In each test, a horizontal force equal to approximately 25% of the maximum force was first applied. The system was then unloaded. The dynamometers were then "finger tightened" and zeroed and initial dial gage readings recorded. Gravity load was then added, if part of the test procedure. Horizontal load was then applied, generally in 100 lbs. increments per 1/4 point or centerline dynamometer, with dial gage readings recorded at all increments. The system was loaded until the load-deflection curve became significantly nonlinear or 1000 lbs at a dynamometer location was reached.

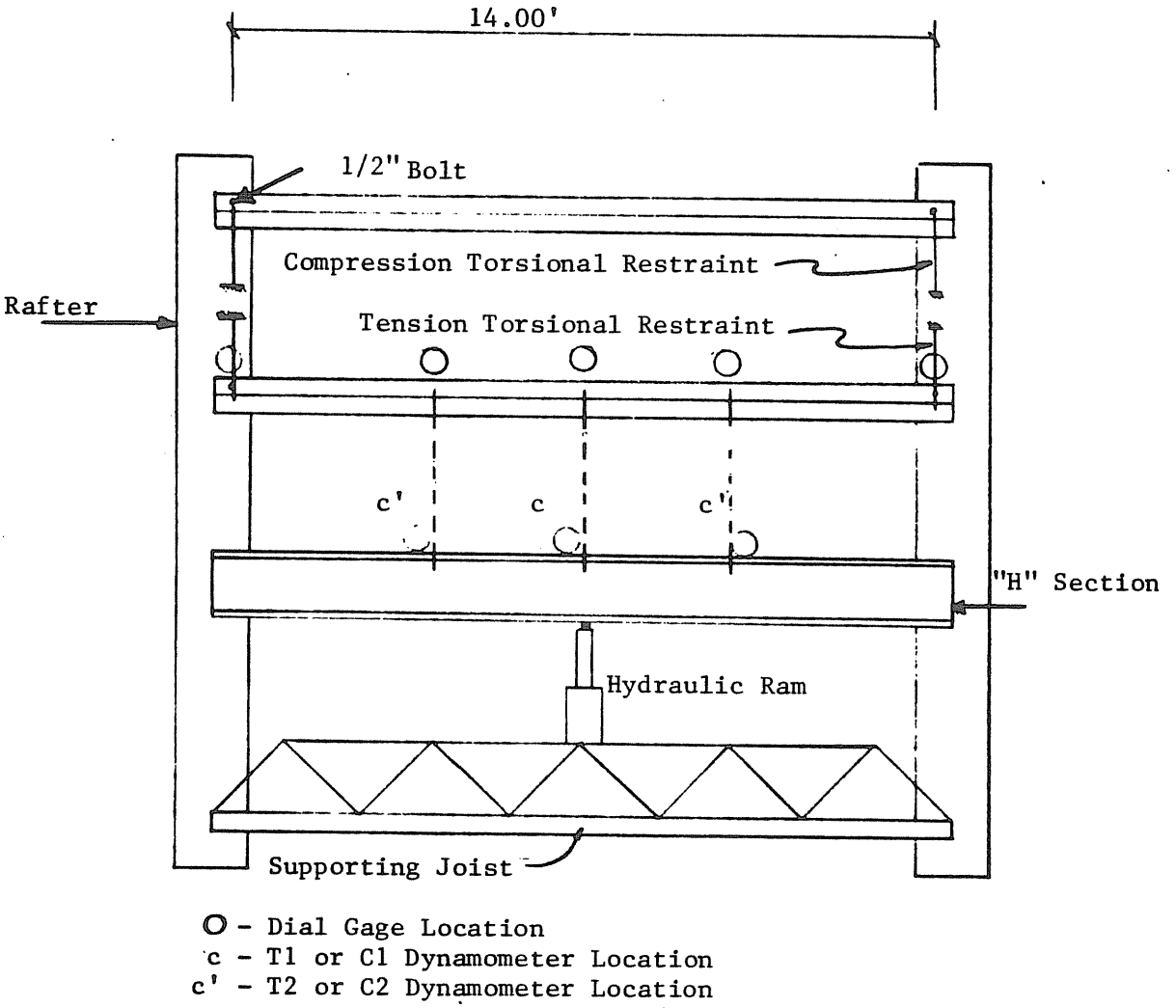


Figure 11. Two Purlin Stiffness Test Setup

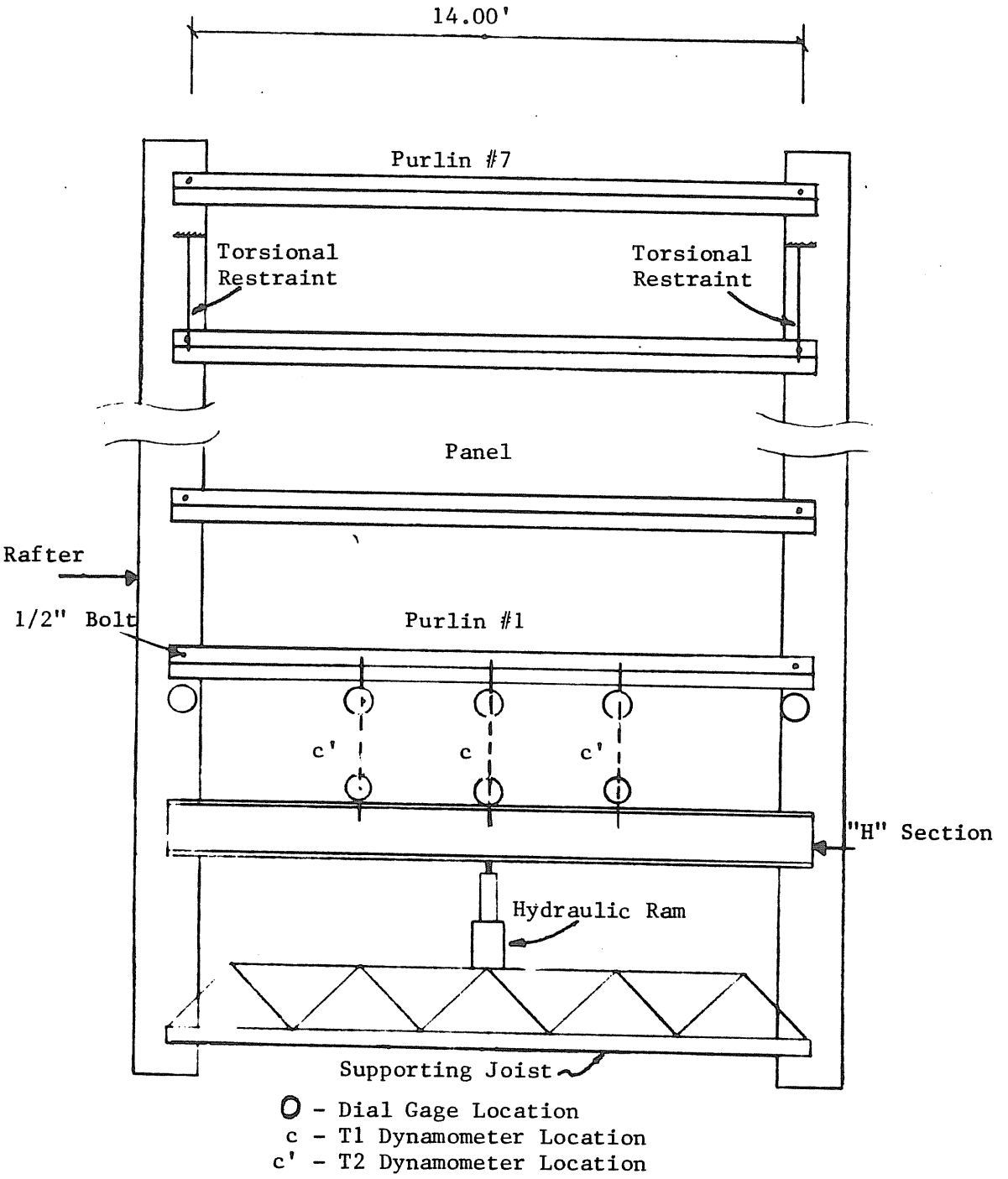


Figure 12. Seven Purlin Stiffness Test Setup

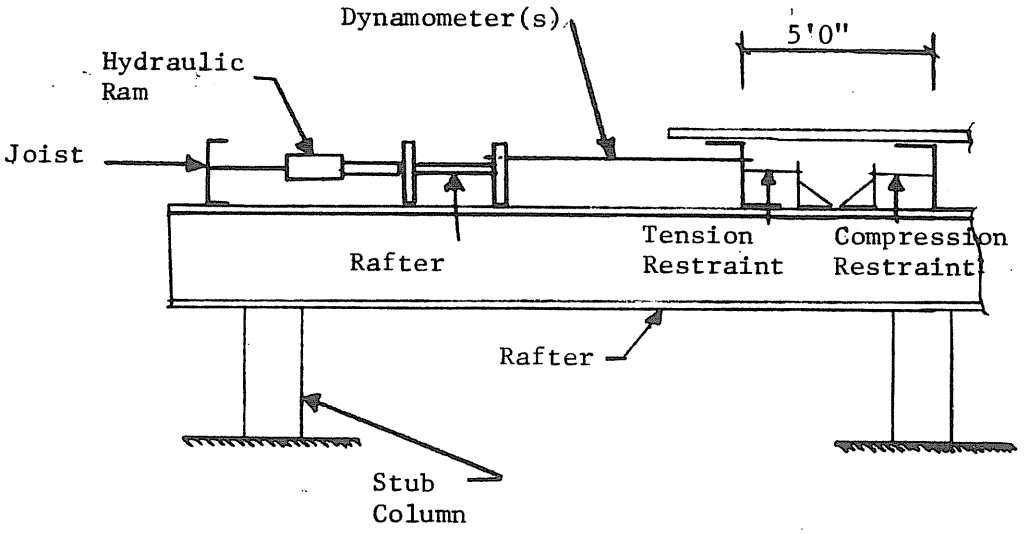


Figure 13. Stiffness Test Elevation

CHAPTER III

TEST RESULTS

3.1 Accumulation Tests Results

3.1.1 General

Test results consist of load versus deflection data and load versus brace force data. Load deflection data includes plots of simulated live load vs. vertical centerline deflection, load versus torsional restraint forces, and load versus lateral deflection of the top and bottom flanges of the simulated peak purlin at the centerline. The vertical deflection plots also include a theoretical deflection computed assuming constrained bending

$$\Delta = \frac{5wL^4}{384EI} \qquad (1)$$

where Δ = vertical centerline deflection, w = the applied uniform load, L = the span, I = the moment of inertia of the purlin with respect to the horizontal axis, and E = modulus of elasticity.

Results for Test Series A/2, A/7, B/2, B/6 and SS are found in Appendices A, B, C, D and E, respectively. A detailed test summary for each test is included in the appropriate appendix. Table 3 is a summary of brace force results for all accumulation tests. Gravity load was used for all tests except Series A/7 where suction was used. To provide data at corresponding load levels, linear interpolation was used to obtain the

Table 3
Summary of Series A and B Test Results

Test No.	Percent Brace Force at Given Load (plf)										
	16.5	33	49.5	66	99	132	165	198	231	264	280.5
A/2-1		14.5		13.1	13.2	13.2	13.5	14.3	15.2	17.7	19.2
A/2-2		19.4		17.0	15.6						
A/2-3		26.0		24.8	25.4	25.8	26.6				
A/7-0*		6.1		5.4	4.8	4.5	4.2	4.0	4.0		
A/7-1*		8.0		6.5	6.4	6.2	6.0				
A/7-3*		8.5		7.4	6.9	6.7	6.6	6.5			
A/7-4*		9.3		7.8	7.2	6.8	7.0	7.6			
A/7-7*		10.1		9.6	9.1	9.0					
B/2-1A		19.9		21.8	21.7						
B/2-1B		20.4		21.0	21.5						
B/2-2A		23.0		21.4	21.7						
B/2-2B		20.2		20.5	21.4						
B/2-3		21.6		21.7	22.2						
B/6-1		11.1		14.8	17.2						
B/6-2											
Load		13.1		14.1	16.2						
Unload		6.6		12.8	16.2						
B/6/6	22.4	19.8	20.6	19.8							

*Percent Brace Force Interpolated

results shown in Table 3 for Series A/7.

In the discussion that follows, percent brace force is defined as total of measured brace forces divided by the total vertical load supported by the purlins expressed in percent, that is

$$\% \text{ Brace Force} = \frac{\text{Total of Measured Brace Forces}}{\text{Total Vertical Load}} \times 100\% \qquad (2)$$

Also, "external purlin" refers to the purlin farthest from the support joist and "internal purlin" refers to the purlin nearest the support joist.

3.1.2 Test Series A/2 and A/7

Series A/2. The purpose of this series was to determine the magnitude of torsional brace forces required for two purlin, single span systems. Three tests were conducted. The maximum applied load in Test A/2-1 was 280.5 plf; in Test A/2-2, 99 plf; and in Test A/2-3, 165 plf. Span length was 14 ft. 0 in. for all tests and Test A/2-1 was conducted to failure (this is Test III of Reference 1).

Test results are found in Appendix A. For all tests, measured vertical deflections were greater than predicted by 5% to 20% (Figures A.5, A.12 and A.20). This finding is comparable to results reported in Reference 1.

Vertical loading in pounds per linear foot (plf) per purlin versus measured brace force at each torsional brace location is shown in Figures A.6, A.13 and A.21 for Tests A/2-1, -2 and -3, respectively. In Test A/2-3 dynamometers were installed between the purlins in the plane of the rafter web as shown in Figure A.16. Load versus brace force at this location is shown in Figure A.22.

In all tests, the measured brace forces tended to increase at an increasing rate with increase in vertical loading. From Table 3, it is

observed that the percent brace force decreased after the initial load increment and then began to increase after several increments. Further, substantial differences in percent brace force were recorded between the three tests, almost 100% between tests A/2-1 and A/2-3. No explanation was found for this difference.

Vertical loading versus midspan lateral displacement of top and bottom purlin flange locations or panel location are shown for the three tests in Figures A.7, A.14 and A.23. The results are typical when compared to similar plots found in Reference 1.

Series A/7. The purpose of this series was to determine the magnitude of torsional brace forces for seven purlin, single span systems and to monitor the lateral movement of midspan purlin and panel locations when such systems are gravity loaded. Five tests were conducted to determine brace forces and five tests were conducted to monitor horizontal movement of purlin and panel locations. All tests in the A/7 series were conducted at a span of 14.29 ft. The various tests were conducted using vacuum loading with Test A/7-7 repeated using gravity loading to verify that the loading method does not affect results. All tests in this series were essentially the same. Minor differences concerning measurement locations and modifications of the test setup are reported in the "Test Summary" sheets found in Appendix B. Test results are also found in Appendix B.

Tests A/7-0, -2, -3, -4 and -7 were conducted to measure restraint forces. The remaining tests were conducted to determine horizontal purlin and panel midspan movements. The tests to measure restraint forces are discussed first.

Vertical load versus vertical deflection of the first "downhill" purlin from the "ridge" purlin for Tests A/7-0, -2, -3 and -4 is shown in Figures B.5, B.8, B.11 and B.14, respectively. In all cases, measured vertical deflection exceeded the predicted deflections.

Vertical load versus vertical deflection for Test A/7-7 is shown in Figure B.22. For the gravity loading portion of this test, concrete blocks were placed on the panel starting from the eave end of the setup. Once each space between purlins was loaded to an equivalent purlin load of 99 plf, all data was recorded. Comparison with the vacuum loading portion of the test can only be made at full load (99 plf per purlin). As shown in Figure B.22, agreement at this load level is excellent.

Vertical loading versus brace force for Tests A/7-0, -2, -3, -4 and -7 are shown in Figures B.6, B.9, B.12, B.15 and B.23, respectively. Percent brace force at load increments of 33 plf per purlin are given in Table 3. Generally, the highest percentage was found for the first increment, with a relatively sharp decrease at the second increment (0.7% to 1.5%) and then a relatively constant percentage for the remaining increments. Figure 14 shows insignificant difference in brace forces (less than 5%) between the A/7-7 gravity and vacuum loadings.

From Table 3, the percent force varied from 10.1% to 4.0% depending on the test and loading increment. Also from Table 3, it is evident that the percent brace force increased with each repeated loading. Table 4 shows the percent increase in brace force at four load levels for each test with respect to the first test. The percent increase increases for each additional test reaching a maximum value of 100% at the 132 plf level of the last test. The only explanation found for this phenomenon

Table 4
Increase of Brace Force with Repeated Loading, A/7 Tests

Test	Increase of Brace Force (%)			
	33 plf	66 plf	99 plf	132 plf
A/7-0 *	0.0	0.0	0.0	0.0
A/7-1	31.1	20.4	33.3	37.8
A/7-3	39.3	37.0	43.8	48.9
A/7-4	52.5	44.4	50.0	51.1
A/7-7	65.6	77.8	89.6	100.0

*Base Test

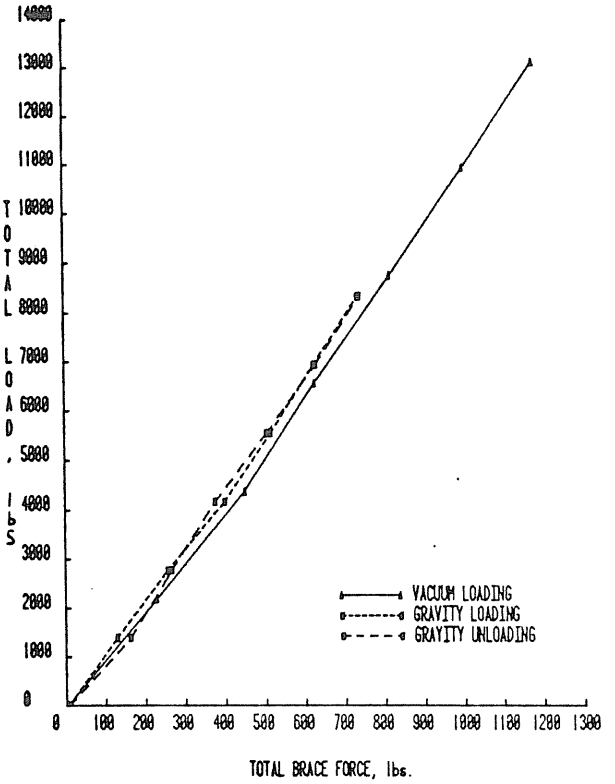


Figure 14. Comparison of Brace Forces from Gravity and Vacuum Loadings, Test A/7-7

is that the purlin web-to-rafter flange angle slightly decreased with each test loading causing an increase in brace force to maintain equilibrium.

Vertical loading versus lateral displacement of various top and bottom flange locations is shown in Figures B.7, B.10, B.13, B.16 and B.24 for Tests A/7-0, -2, -3, -4 and -7, respectively. In general, the lateral movements were consistent between tests. The erratic results shown in Figure B.24 were caused by the gravity loading procedure used for Test A/7-7. Figure B.25 shows results of the vacuum loading test.

Tests A/7-4 A, B and C, A/7-5 and A/7-6 were conducted to measure midspan lateral movement of various purlins at selected points on a cross-section and of panel movement. Torsional restraint forces were not measured in these tests. Load versus lateral displacement plots for the three tests are found in Appendix B. In these plots, purlin 1 is the "eave" purlin and purlin 7 is the "ridge" purlin (see Figure 6).

Tests A/7-4 A, B and C were conducted to measure panel movement near the top flange of the purlins. Measurements were made on purlins 1, 2, 5, 6 and 7 and results are shown in Figures B.17, B.18 and B.19. Results from the three tests are consistent, however, corresponding deflections increased for each subsequent test. In all tests, the deflection at purlin 2 was the largest and that at purlin 6 or 7 the smallest. Note that the torsional restraint braces were attached to purlin 2 (see Figure 6).

In Test A/7-5, lateral displacement of the bottom flange of purlins 1, 2, 5, 6 and 7 was measured. The results shown in Figure B.20 are consistent in that the bottom flange of all purlins moved in the uphill direction and the uphill purlins, except for purlin 6, moved more than the downhill purlins.

Test A/7-6 was configured similar to Test A/7-5 except that the displacement transducers were attached to the purlin webs as close as possible to the top flanges. Results are shown in Figure B.21. All purlins moved in the uphill direction, however, movements were not consistent between purlins in that uphill purlins moved less than downhill purlins. No explanation was found for this phenomenon.

3.1.3 Test Series B/2, B/6 and B/6/6

Series B/2. The purpose of this series was to determine the magnitdue of torsional brace forces required for two purlin, single span systems. The tests in this series are similar to the A/2 series; the primary difference being the span length, 22 ft. 3 in. versus 14 ft. 0 in. for the A/2 series.

Five tests were conducted. In each test, load was applied in 33 plf per purlin increments to 99 plf. Two additional load increments were applied in Test B/2-3. All tests were conducted with the purlins bolted to the simulated rafter top flanges; Tests B/2-1 and B/2-2 were repeated using knife supports between the purlin ends and the rafter flange. Only torsional braces were used in this series. Table 5 shows the various brace configurations. Tests B/2-1-A and -B used single braces connected to the interior (eave) purlin; Tests B/2-2-A and -B used braces between the purlins in addition to the interior purlin brace; and Test B/2-3 used a single torsional brace at each rafter connected to the exterior (ridge) purlin.

Test results are found in Appendix C and consist of a summary sheet, load versus vertical deflection, load versus brace forces, and load versus midspan lateral movement of the top and bottom purlin flanges and of the panel. Results are summarized in Table 5. (Results from an analytical model are also shown in Table 5. Discussion of the model will be

presented in a subsequent report).

For all tests, measured vertical deflections were greater (10% to 25%) than deflections predicted using the constrained bending assumption. No significant difference was found between the tests using the bolted connection and those using the knife edge connection.

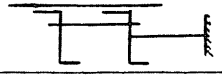
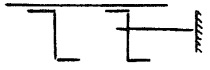
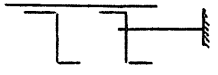
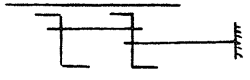
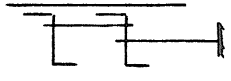
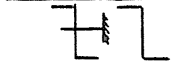
Brace forces increased approximately linearily with increasing vertical load as seen from the appropriate plot for each test, Appendix C. Table 5 shows the total brace force for each test at load increments of 33 plf, 66 plf and 99 plf. Results are consistent for the five tests. In Test B/2-2A, each torsional brace was pretensioned to 20 lbs prior to loading. Brace forces at the two additional load increments for Test B/2-3 are also shown in Table 5 under "Remarks".

Total brace force as a percentage of total supported load (both purlins) is shown in Table 3. For the five tests, the percent brace force is consistent, varying between 19.9% and 23.0% with an average value of 21.3%. Unlike results from the A/2, a decrease of percent brace force with increasing load was not found.

In general, the bottom flange of the instrumented purlin moved downhill at low loads (33 plf) and then reversed direction with a slight uphill displacement at 99 plf (see plots in Appendix C). Top and panel movements were uphill for all tests at all load levels, however, results are inconsistent between locations and tests, particularly at higher load levels.

Series B/6. The purpose of this test series was the same as for the A/7 series. Purlin span length was 22 ft. 3 in. and all purlin-to-rafter connections were bolted. Two tests were conducted: Test B/6-1 with

Table 5
Summary of Results from B/2 Tests

Test	Purlin to Rafter Connection	Brace Location	Total Brace Forces			Remarks
			33 plf	66 plf	99 plf	
Theory			439	878	1318	
B/2-1-A	Bolted		296	648	967	
B/2-1-B	Knife Edge		303	624	960	
B/2-2-A	Bolted		262 + 80 342	555 + 80 635	885 + 80 965	Forces were pretension to 20 lbs 2x20=40 lbs in two braces. Corrected brace force at 99: 885+80=965 lbs.
B/2-2-B	Knife Edge		300	610	955	
B/2-3	Bolted		321	645	991	at 132=1408 at 148.5=1680 Stopped at 148.5 plf because failure was near.

torsional braces connected to the eave purlin and Test B/6-2 with the braces connected to the first uphill purlin from the eave purlin. The southmost or ridge purlin was instrumented to measure midspan lateral and vertical deflections. Load was applied in 33 plf increments to 99 plf per interior purlin. One-half of these values was applied to the exterior (eave and ridge) purlins. Test results are found in Appendix D.

Measured vertical deflections are inconsistent with predicted values, see Figures D.4 and D.8. A possible explanation is secondary deflections caused by walking on the system during placement of the concrete blocks.

Brace forces as a function of uniform load are shown in Figures D.5 and D.9. It is obvious from these plots that the brace forces increased at an increasing rate with increased load. Total brace force as a percent of total supported load (all six purlins) at each load increment is shown in Table 3. The results are consistent between the tests during loading; less brace force was measured during unloading of Test B/6-2.

Lateral movement of the top and bottom flanges and panel at the midspan of the ridge purlin versus uniform load on that purlin is shown in Figures D.6 and D.10 for Tests B/6-1 and B/6-2, respectively. All movements are uphill with greater movement measured in Test B/6-2.

Test B/6/6. Test B/6/6 was conducted using the same test setup and purlins as were used for the Series B/6 Tests. An additional six purlins were added to the setup with the flanges in the second set opposing the flanges in the first set. Panel was installed over each set, but with a space at the ridge. Instrumented intermediate braces were installed at the 1/3rd points of the span at the ridge. These braces connected the roof sheets of each set (see Figure D.11). Load was applied

in 16.5 plf increments to 66 plf per interior purlin. One ridge purlin was instrumented to measure vertical and lateral displacements.

Vertical load versus vertical deflection of the instrumented purlin is shown in Figure D.12. Agreement with deflections computed using the constrained bending assumption is excellent.

Vertical load versus brace forces is shown in Figure D.13. Results are consistent between the braces. Total brace force as a percent of total vertical load on one purlin set (six purlins) is shown in Table 3. The percent brace force decreased with increasing load from 22.4% at 16.5 plf per interior purlin to 19.8% at 66 plf.

Measured lateral movements at midspan of the instrumented ridge purlin are shown in Figure D.14. Results are erratic, again possibly due to movements caused by walking on the system during loading.

3.1.4 Test Series SS

Test SS6/6 is similar to Test B/6/6 except that the previously described standing seam roof system was used and two sets of intermediate braces were installed at the ridge location. Two sets of six opposed purlins, spanning 22 ft. 3 in., were used. Four calibrated dynamometers were installed at the approximate 1/3rd points of the purlin span at the ridge. Two dynamometers connected the panels on opposite sides of the ridges and two connected the purlins at mid-web depth. One ridge purlin was instrumented at midspan to measure vertical and horizontal movements. The panel was instrumented to measure horizontal movement. The system was loaded in 33 plf increments to 66 plf per interior purlin. The panel dynamometers were then removed and the system unloaded in 33 plf increments. Test results are found in Appendix E.

Vertical load versus vertical midspan deflection of the instrumented ridge purlin is shown in Figure E.4. Deflections are generally greater than those predicted from constrained bending theory. The deflections increased after removal of the panel dynamometers.

Vertical load per interior purlin versus percent brace force (calculated as for Test B/6/6) is shown in Figure E.5 for the loading cycle and in Figure E.6 for the unloading cycle. The percent brace force was smaller at higher loads for both loading and unloading. The percent brace forces are summarized in Table 6. The total brace force during loading was approximately 25% of the total vertical load supported by one purlin set (6 purlins). Approximately 24% of the total brace force was supported by the panel dynamometers and the remaining 76% by the purlin dynamometers. Upon removal of the panel dynamometers, the total brace force decreased to 22.7%. This decrease was expected since the latter bracing system is less stiff than the former system.

Table 6
Brace Force Distribution in Test SS/6/6

Load	Brace Force (%)*		
	Deck	Angle	Total
33	5.7	19.7	25.4
66	6.1	17.8	23.9
66	-	22.7	22.7
33	-	20.6	20.6

*Brace force divided by total load on six purlins (one side) x 100%.

Horizontal displacements of the purlin flanges and panel at mid-span of one of the ridge purlins versus vertical loading are shown in Figures E.7, E.8 and E.9. The top flange and panel displacements are in the uphill direction and are larger at the 33 plf level than at the 66 plf level. The panel displacements are 2 to 2.5 times greater than the purlin displacements. Both the panel and purlin displacements increased upon removal of the panel dynamometers. Bottom flange displacements were also uphill and exceeded the top flange and panel displacements, indicating the purlin "rolled" toward the eave. This phenomenon can be explained by the torsional moment introduced by the panel at this location. Because of the clip used with the standing seam system, panel flexural rotations are amplified causing twisting of the purlin.

3.1.5 Comparison of A, B and SS Test Series

The following comparisons are drawn from the results of the A, B and SS series tests:

1. Comparing the percent brace force from Series A/2 and Series B/2 (Table 3), the percent brace forces for Series B/2 are significantly greater than for Series A/2 except for Test A/2-3. The difference is in the range of 5% to 7%, which means that the brace forces, as a percent of total vertical load, are 25% to 50% greater for the 22 ft. 3 in. span tests (B/2) as compared to the 14 ft. 0 in. span tests (A/2). Similar results are found when comparing percent brace forces found in the initial Tests of the A/7 Series to the Tests in the B/6 Series (Table 3).

2. Comparing percent brace force results from Series A/2 and A/7, it is evident that the percent brace force significantly decreases with increasing number of purlins (Table 3). Similar results were found for

the B/2 and B/6 Tests. The decrease for the A-Series was in the area of 50% and for the B-Series, 70%.

3. Results from the B/6 and B/6/6 Tests show that the stiffer the brace system the larger the brace force (Table 3). The brace system used for Series B/6 was torsional braces at the rafter line connected to the eave purlin. The average percent brace force for these tests during loading was approximately 14.5%. For Test B/6/6, the bracing system was two dynamometers connecting opposite ridge purlins at the 1/3rd point of the purlin span. The average percent brace force for this test was approximately 20.5% (Table 3).

4. A similar conclusion is reached when the results of Test B/6/6 and SS/6/6 during loading are compared. The average percent brace force for Test SS/6/6 with both panel and purlin dynamometers in place was 24.7% (Table 6). This restraint system is stiffer than that used in the B/6/6 Tests where the percent brace force was approximately 20.5%.

5. Comparison of Test SS/6/6 unloading with Test B/6/6 shows comparable percent brace forces (Tables 3 and 6), indicating that the standing seam system used in the SS/6/6 Test is as capable of carrying restraint forces as is the conventional system used in Test B/6/6.

6. In Test A/2-1, the only system loaded to failure, the percent brace force initially decreased with increasing vertical load and then increased near the failure load (Table 3). Table 3 shows that percent brace forces in Series A/7 consistently decreased with increasing load, however, the maximum vertical load in this series was only 79.6% of the failure load of Test A/2-1 (290.4 plf per purlin, p. A.1). The purlins used in Series A/7 are identical to those used in Test A/2-1.

7. In both the B/2 and B/6 series, brace forces increased slightly with increasing vertical load.

3.2 Stiffness Test Results

3.2.1 General

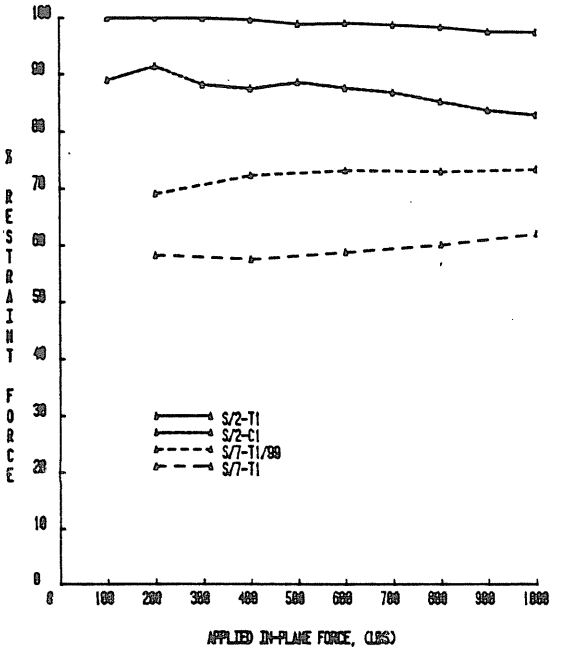
Tests to determine the in-plane stiffness of two and seven purlin roof systems (S/2 and S/7 Series, respectively) using conventional panel were conducted. All tests were at a span of 14 ft. 3 in. and the setups used were modifications of the A/2 and A/7 Test setups. Identical purlins and panels were used in the stiffness and A-Series Tests. Restraint was provided by torsional braces attached to one purlin at the rafter lines. Tests were conducted with the torsional restraint brace attached to both the eave purlin and the first uphill purlin from the eave purlin. Load was applied at either the midspan or quarter points (excluding the midspan) at the ridge purlin.

Test results consist of in-plane load versus vertical deflection, total restraint force and horizontal deflection. Results for the S/2 Series are found in Appendix F and those for the S/7 Series in Appendix G. Table 7 is a summary of the test results. A test designation S/2-T1 is to be interpreted as a two purlin stiffness test (S/2) with torsional restraint braces in tension (T) and with a single (1) in-plane point of load application, e.g. concentrated load at midspan and no applied gravity load on the system. A test designation S/7-C2/99, indicates a seven purlin stiffness test (S/7) with torsional braces in compression (C) and two (2) in-plane loads at the ridge purlin 1/4 points applied after a gravity load of 99 plf per interior purlin was placed on the system. Tension torsional restraint braces were attached to the first uphill purlin from the eave

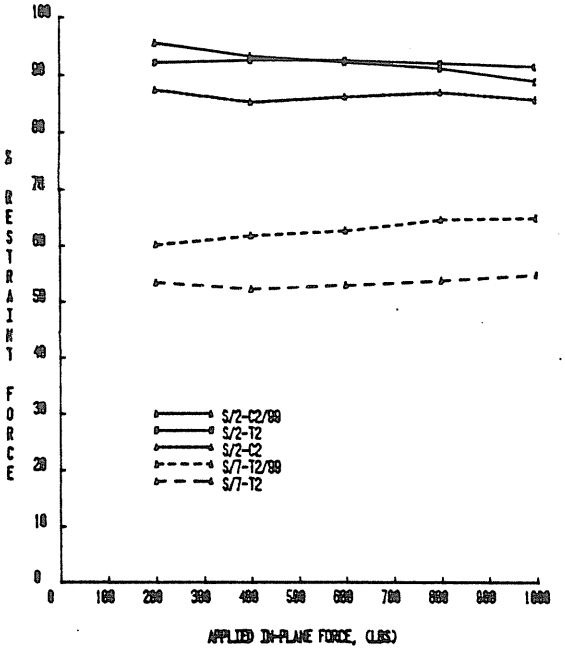
Table 7
Summary of Stiffness Test Results

Test	Brace Force and Stiffness at Given Load																			
	100		200		300		400		500		600		700		800		900		1000	
	Force (%)	K (lb/ft)	Force (%)	K (lb/ft)	Force (%)	K (lb/ft)	Force (%)	K (lb/ft)	Force (%)	K (lb/ft)	Force (%)	K (lb/ft)	Force (%)	K (lb/ft)	Force (%)	K (lb/ft)	Force (%)	K (lb/ft)	Force (%)	K (lb/ft)
S/2-T1*	103.7	1267	103.1	1227	99.9	1215	99.7	1316	98.9	1344	99.0	1396	98.7	1422	98.3	1457	97.5	1510	97.4	1518
S/2-T2*	-	-	92.1	1093	-	-	92.5	1105	-	-	92.5	1142	-	-	91.9	1125	-	-	91.3	1182
S/2-C1	89.0	1616	91.4	1521	88.2	1587	87.5	1618	88.6	1658	87.6	1713	86.8	1837	85.2	1812	83.7	1905	82.9	2050
S/2-C2	-	-	87.4	1570	-	-	85.2	1645	-	-	86.2	1631	-	-	86.9	1672	-	-	85.6	1698
S/2-C2/99	-	-	95.5	1968	-	-	93.2	2118	-	-	92.2	2203	-	-	91.0	2136	-	-	88.8	2116
S/7-T1*	-	-	58.3	2923	-	-	57.6	2868	-	-	58.8	2981	-	-	60.1	3114	-	-	62.1	3119
S/7-T1/99*	-	-	69.1	2871	-	-	72.3	2804	-	-	73.1	2896	-	-	72.9	2973	-	-	73.4	3046
S/7-T2*	-	-	53.4	2237	-	-	52.3	2053	-	-	53.0	2033	-	-	53.8	2049	-	-	54.8	2078
S/7-T2/99*	-	-	60.2	2727	-	-	61.8	2576	-	-	62.7	2526	-	-	64.6	2532	-	-	64.9	2551

* Two tests averaged

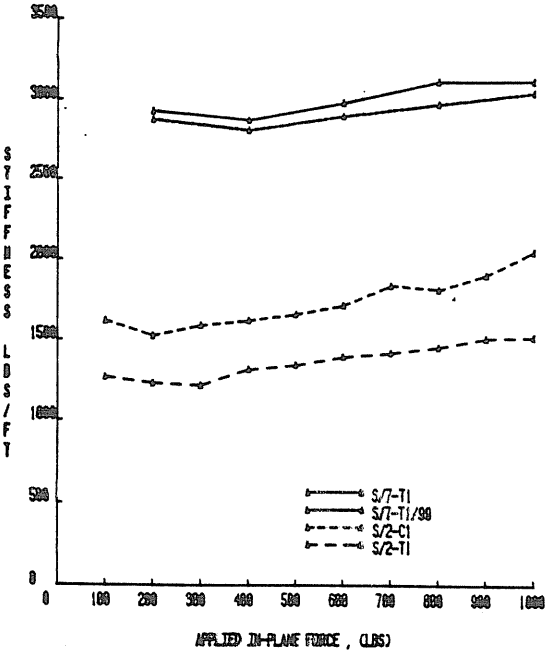


(a) Midspan Loading

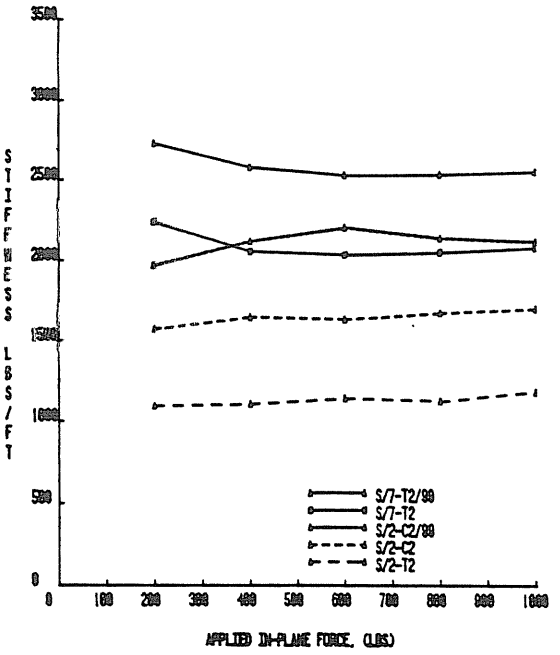


(b) Quarter Point Loading

Figure 15. Percent Restraint Force versus Applied In-Plane Force, Series S/2 and S/7



a) Midspan Loading



b) Quarter Point Loading

Figure 16. In-Plane Stiffness versus Applied In-Plane Force, Series S/2 and S/7

purlin (Figures F.1(a) and G.1) and compression braces were attached to the eave purlin (Figure F.1(b)).

3.2.2 Test Series S/2

Five tests were conducted in this series: two with tension torsional braces, two with compression torsional braces, and one with compression torsional braces and a gravity load of 99 plf per purlin. Of the tests without gravity load, one each was conducted with a single concentrated in-plane load and the second with two in-plane loads (1/4 points). The test with the additional applied gravity load used two concentrated loads. In some instances the tests were repeated. The maximum applied total in-plane force in every test was 1000 lbs.

From the various plots found in Appendix F, the relationship between applied force and in-plane horizontal displacement or total restraint force can be seen. From Table 7 and Figure 15, it is evident that the total restraint force at the torsional braces decreases with increasing in-plane force, more so for the test with additional gravity loading (S/2-C2/99). Percent restraint force is defined as total measured brace force divided by applied in-plane force times 100%. Stiffness on the other hand, increases with increasing in-plane force, again at a greater rate with the gravity load in place, Figure 16.

Comparing Figures 15(a) and (b) it is evident that the location of the restraint brace (T versus C braces) effects the restraint forces with more force developed when the braces are attached to the purlin at which the in-plane force is applied. However, on comparison of Figures 16(a) and (b), the compression brace systems are considerably stiffer. No explanation was found for the greater stiffness found in the test with the applied gravity loading.

3.2.3 Test Series S/7

Four tests were conducted in this series: two tests with single concentrated in-plane loads and two tests with two in-plane loads. One test of each type was conducted with 99 plf per interior purlin in place. All tests used tension type torsional restraint braces attached to the first uphill purlin from the eave purlin (Figure G.1).

Unlike the S/2 Tests, the total restraint force at the torsional braces increased with increasing applied horizontal force, Table 7 and Figure 15, however, the increase is slight. Total brace force was greater with the 99 plf gravity load in place.

For the S/7-T1 Tests, stiffness increased slightly for increasing in-plane force; for the S/7-T2 Tests, stiffness decreased slightly for increasing in-plane force. The stiffness decreased for the S/7-T1 Tests when the gravity load was in place and increased for the S/7-T2 Tests for the same situation.

Comparison of the S/2 and S/7 results shows a significant decrease in force at the torsional restraint braces when the system is increased from two purlins to seven purlins. For the two purlin system, the percent restraint force varied from 82.9% to 100%. (Table 7 shows 103.7% maximum which probably is due to instrumentation error). For the seven purlin systems, the percent brace force varied from 52.3% to 73.4%. Similarly stiffness increases. For the two purlin systems, stiffness varied from 1093 lb/ft to 2136 lb/ft. For the seven purlin systems, stiffness varied from 2033 lb/ft to 3119 lb/ft.

CHAPTER IV

SUMMARY AND SIGNIFICANT FINDINGS

A total of twenty gravity load and nine stiffness tests are reported here. The purpose of the gravity load tests was to determine restraint forces when torsional restraint braces are used to stabilize Z-purlin, conventional panel and standing seam roof systems and to determine accumulation effects of multi-purlin systems. The stiffness tests were conducted to determine in-plane stiffness and force transfer in two and seven purlin systems. The experimental results reported will be compared to analytical results at a later date as part of the total research effort.

Significant findings from this research are:

1. Measured vertical deflections of uniformly loaded, simple span Z-purlins exceeded predicted values, based on the constrained bending assumption, by 5% to 20%.

2. For all gravity load tests, the range of total force at the torsional braces as a percent of total vertical load stabilized by the braces ranged from 4.0% (Test A/7-0) to 26.6% (Test A/2-3).

3. From the results of 14 ft. 3 in. span tests, A-series, and the 22 ft. 0 in. tests; B-Series, a definite span effect was found. The range of percent brace forces for the A/2 series was 13.1% to 26.6% and that for the B/2 Series, 19.9% to 23.0%. The range for the A/7 Series Tests was 4.0% to 10.1% and for the B/6 Series, 11.1% to 17.2%.

4. Increasing the number of purlins in a system decreases the percent brace force. At 99 plf, the percent brace force from Test A/2-1 was 13.2% and for Test A/7-0, 4.8%. For Test B/2-1A the percent brace force was 21.7% and for Test B/6-1, 17.2%. Thus, direct accumulation of brace forces does not occur, e.g. the brace force required to stabilize six purlins is not three times that required to stabilize two purlins.

5. An increase in the stiffness of the bracing system increases the brace force. In Test B/6-1, at 66 plf, the brace force equaled 14.8% of the total vertical load; in Test B/6/6 the percent brace force was 19.8%. In Test B/6-1, torsional braces at the rafter lines were used; in Test B/6/6-1, only 1/3rd point intermediate braces were used. A decrease in brace force was also realized in Test SS/6/6 when the panel dynamometers were removed (Table 6).

6. Both the A/2 and A/7 test setups were retested several times. For both series, the initial loading was relatively high and subsequent loadings resulted in increased brace forces (Tables 3 and 4). The only explanation found for the phenomenon is that the angle between the rafter flange and the purlin web was decreased because of the initial loading and additional brace force was required to stabilize the system during the subsequent loadings because of the increased overturning moment due to increased eccentricity.

7. From Tests A/7-7, it was determined that gravity load testing using concrete blocks and testing using suction (vacuum chamber) gives identical results.

8. From results of the B/2 Series Tests, purlin support conditions (bolted directly to the rafter or knife edge) have little effect on the magnitude of brace forces (Table 5).

9. In the multi-purlin tests, it was observed that the ridge purlin tends to "roll" in the downhill direction. This phenomenon affects lateral displacement measurements. In future testing, it is recommended that the movement of the first downhill purlin from the ridge purlin be monitored.

10. From the in-plane stiffness tests, it was found that the percent of applied force resisted by the torsional braces decreases substantially as a function of the number of purlins between the applied in-plane force and the location of the restraint. At 1000 lb. applied force, 97.4% of the force in Test S/2-T1 was resisted by the torsional braces; in Test S/2-C1, 82.9%; and in Test S7/T1, 62.1%. Similar results were found for the quarter point tests (S/2-C2, etc.)

11. For all of the two purlin tests (S/2), brace force decreased with increasing in-plane force. For the seven purlin tests (S/7), the reverse was true (see Figure 15). For both series, force at the torsional braces was less for the quarter point tests (-C2 or -T2) than for the midspan tests (-C1 or -T1). When gravity load was applied, the in-plane force resisted by the torsional braces increased (Test S7-T1/99 versus Test S7-T1 and Test S7-C2/99 versus Test S7-C2, Figure 15).

12. From Figure 16, in-plane stiffness increased with increasing in-plane force for all two purlin tests. In-plane stiffness increased with increasing in-plane force for the seven purlin tests with midspan loading (Figure 16(a)) and decreased for 1/4 point loading (Figure 16(b)).

13. In-plane stiffness increased with increased number of purlins; the increase was much less than in direct proportion (Table 7).

This report is the third progress report concerning Z- and C-purlin supported roof systems. Subsequent reports will describe mathematical models to predict the phenomena observed in the testing described herein.

REFERENCES

1. Ghazanfari, A., and Murray, T.M., "Simple Span Z-Purlin Tests with Various Restraint Systems", Progress Research Report submitted to Metal Building Manufacturers Association, Research Division, Report No. FSEL/MBMA 82-01, February, 1982.

APPENDIX A

SERIES A/2 TEST RESULTS

TEST SUMMARY

Project: MBMA Roof System Behavior

Test No.: A/2-1

Test Date: April 29, 1982

Purpose: Basic test for assessing accumulation of restraint force.

Span(s): 14.625'

Thickness: 0.075" Moment of Inertia: 10.8 $in.^4$

Parameters: No intermediate braces

Torsional restraint at rafters only at internal purlin

Panel shear stiffness

Panel torsional restraint

Failure Load: 290.4 plf per purlin

Failure Mode: Vertical web buckling of internal purlin

Predicted Failure Loads:

Method AISI Constr. bending x 1.67 Load 466.0 plf

Method _____ Load _____

Method _____ Load _____

Discussion:

-Failure was by vertical web buckling of the internal purlin at the rafter location.

-Failure first occurred at the north rafter and the north half of the system collapsed.

-The external purlin rolled away from support joist at failure.

-Vertical deflections were 20-35% greater than predicted using the constrained bending assumption.

-At 165 plf, summation of internal brace forces equaled 13.5% of the total supported vertical load.

-At 264 plf, summation of internal brace forces equaled 17.7% of the total supported vertical load.

-Top flange lateral displacement exceeds bottom flange displacements but in the opposite direction.

-Maximum lateral displacement was 0.70 in.

-Strain gages were not installed.

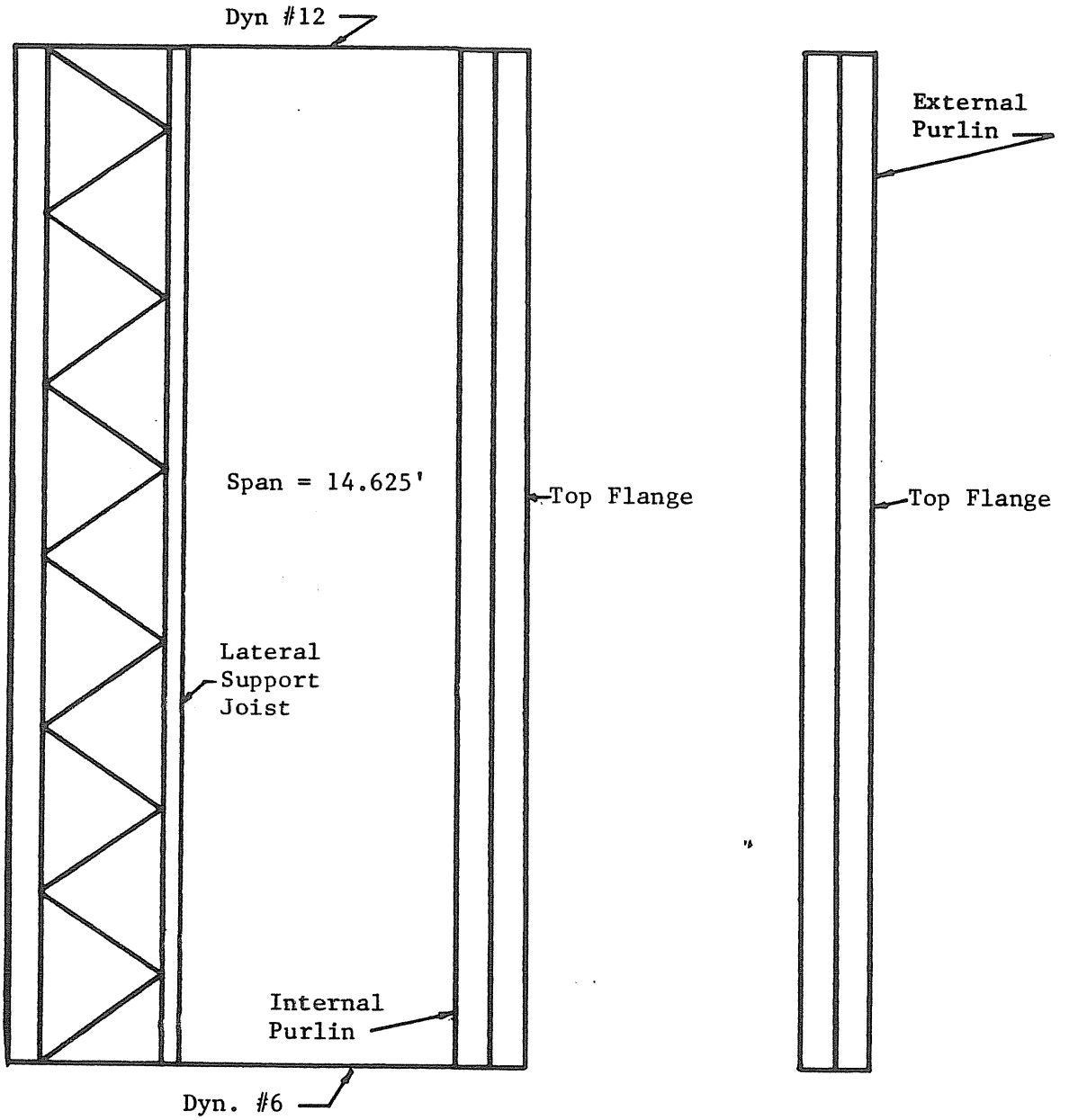
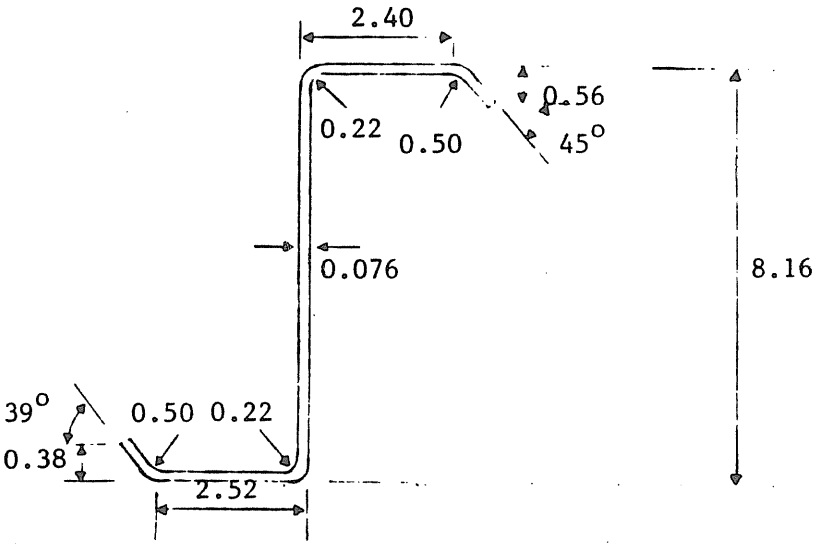
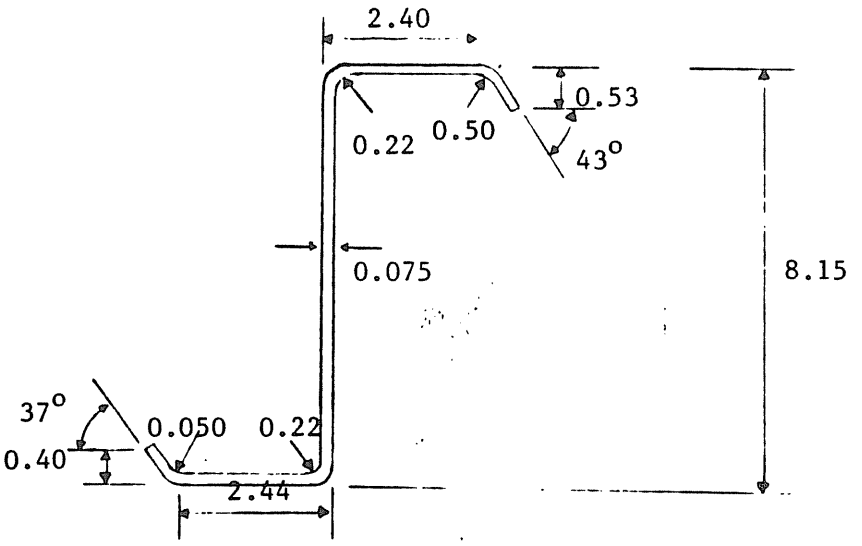


Figure A.1 Instrumentation Locations, Test A/2-1



External Purlin



Internal Purlin

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

```
A I S I   P U R L I N   A N A L Y S I S
              Z-SECTION
IDENTIFICATION: MBMA-A-1 (EXT. WEST 4/29/82)
```

	TOP	BOTTOM
FLANGE(in)	2.400	2.520
LIP(in)	0.560	0.380
LIP ANGLE(deg)	45.000	39.000
RADIUS L/F(in)	0.500	0.500
RADIUS F/W(in)	0.220	0.220

TOTAL DEPTH(in)	8.16
THICKNESS(in)	0.076
YIELD STRENGTH(ksi)	56

MOMENTS OF INERTIA(in^4)		SECTION MODULI(in^3) TOP	BOTTOM
GROSS=	11.047	2.745	2.721
STRENGTH=	11.047	2.745	2.721
DEFLECTION=	11.047		

BE=	2.104	in
FC=	33.600	ksi
FT=	33.600	ksi
FBW=	31.648	ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)

MC=	7.686	ft-k
MT=	7.619	ft-k
MW=	7.736	ft-k
MU=	12.723	ft-k (1.67*allowable)
SPAN =	14.625	ft.
UNIFORM LOAD=	475.867	plf (1.67*allowable)
DEFLECTION =	0.316	in./100plf

Figure A.3 AISI Purlin Analysis, Test A/2-1 External Purlin

```
A I S I   P U R L I N   A N A L Y S I S
              Z-SECTION
IDENTIFICATION: MRMA-A-1 (INT. EAST 4/29/82)

                          TOP              BOTTOM
FLANGE(in)              2.400              2.440
LIP(in)                 0.530              0.400
LIP ANGLE(deg)         43.000             37.000
RADIUS L/F(in)          0.500              0.500
RADIUS F/W(in)          0.220              0.220

TOTAL DEPTH(in)                 8.15
THICKNESS(in)                   0.075
YIELD STRENGTH(ksi)             56

                                          SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)              TOP                BOTTOM
GROSS=          10.814                   2.693               2.664
STRENGTH=       10.814                   2.693               2.664
DEFLECTION=     10.814
BE=    2.105  in
FC=   33.600  ksi
FT=   33.600  ksi
FBW=  31.537  ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)
           MC=      7.539  ft-k
           MT=      7.459  ft-k
           MW=      7.561  ft-k
           MU=     12.457  ft-k (1.67*allowable)
SPAN       =     14.625  ft.
UNIFORM LOAD=    467.124  plf (1.67*allowable)
DEFLECTION  =      0.323  in./100plf
```

Figure A.4 AISI Purlin Analysis, Test A/2-1 Internal Purlin

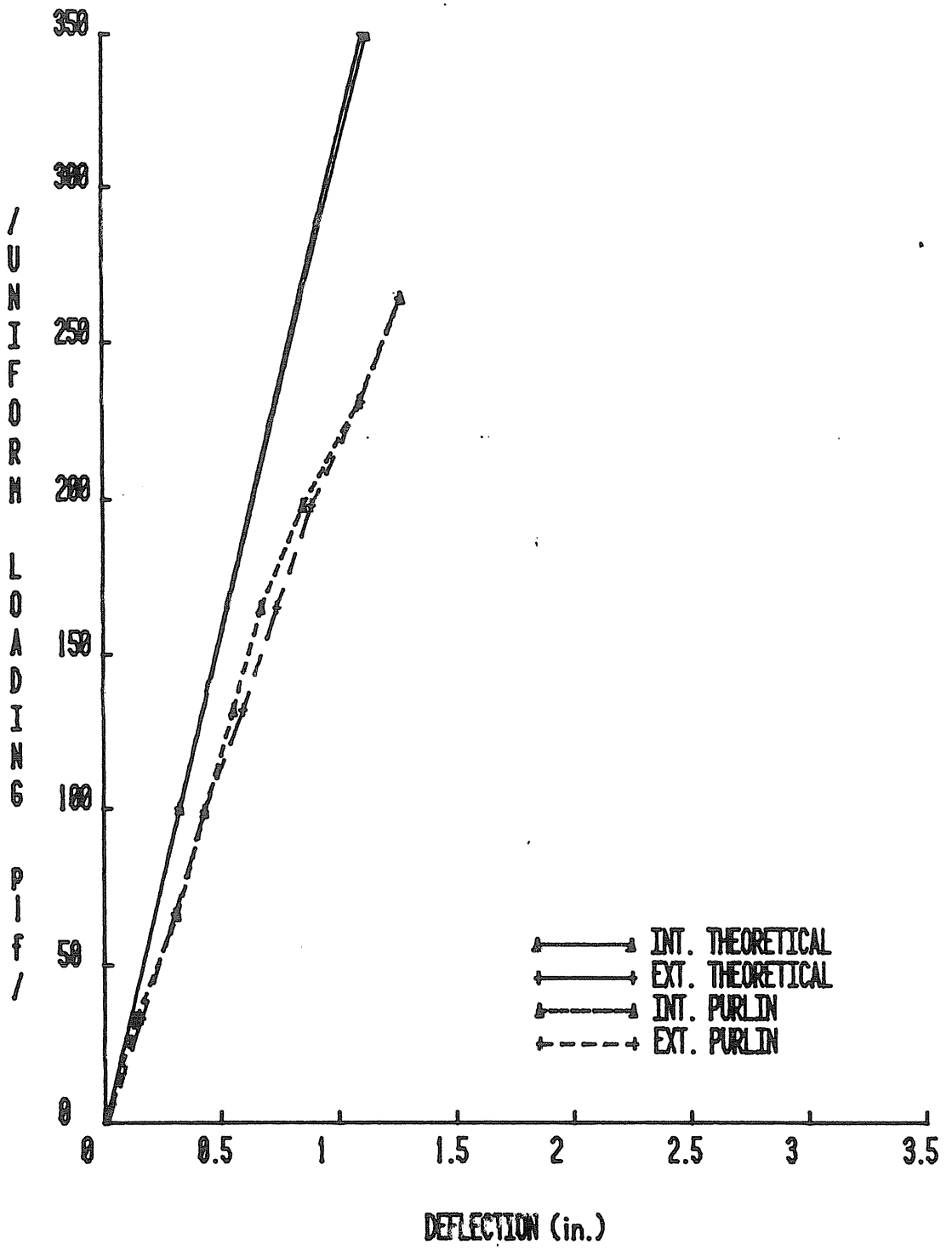


Figure A.5 Load vs. Vertical Deflection, Test A/2 -1

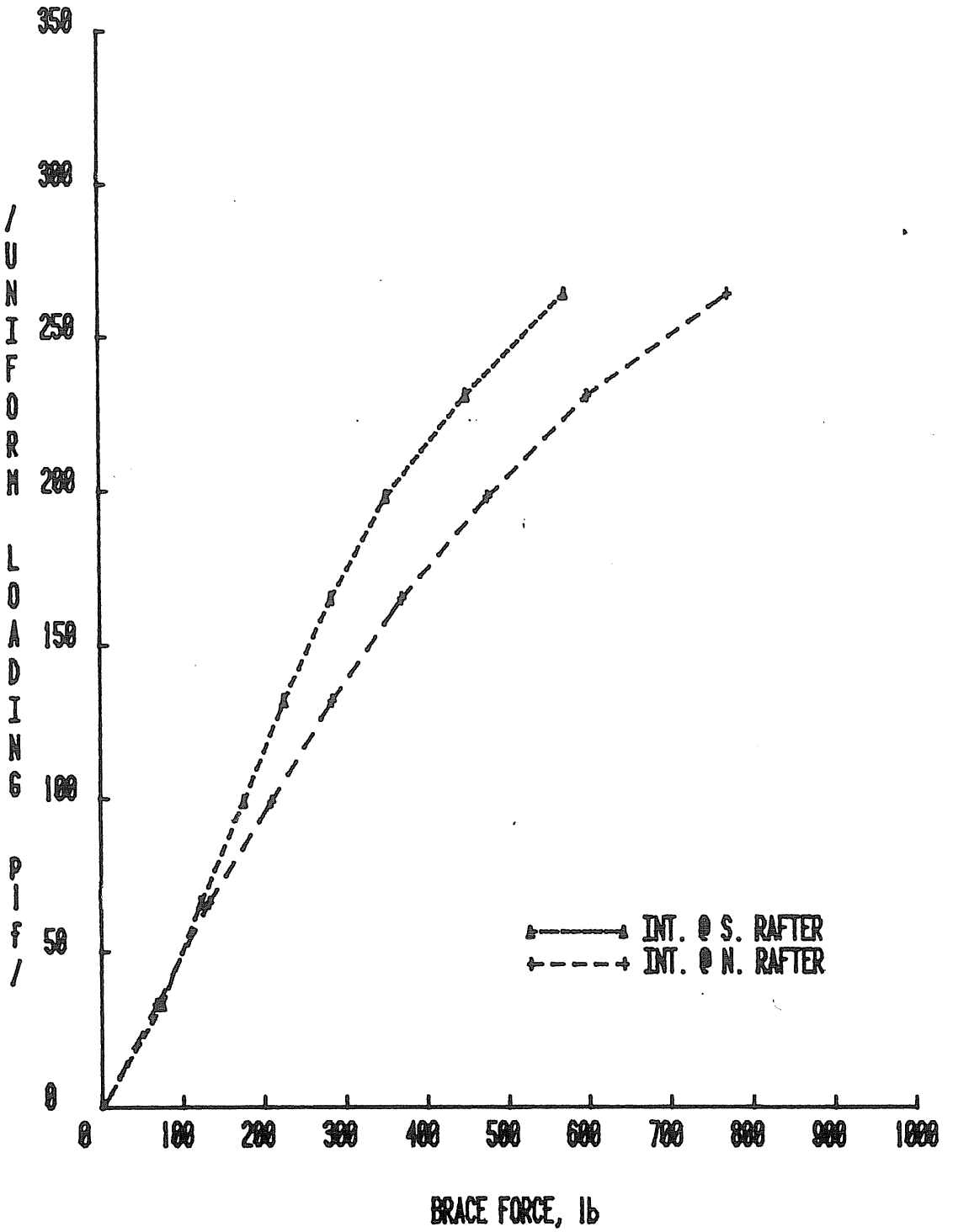


Figure A.6 Vertical Loading vs. Brace Forces, Test A/2-1

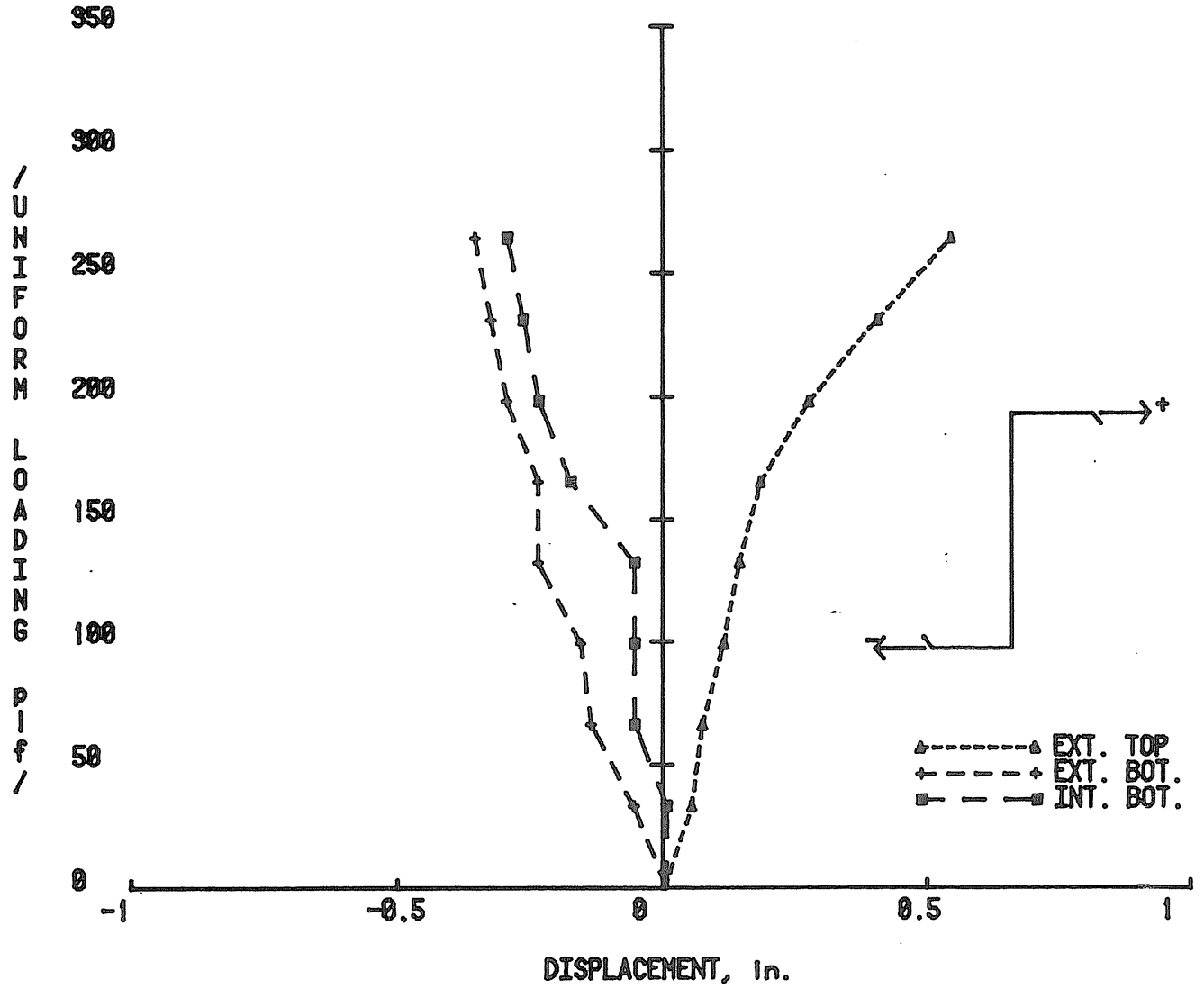


Figure A.7 Vertical Loading vs. Lateral Displacements, Test A/2-1"

TEST SUMMARY

Project: MBMA Roof System Behavior

Test No.: A/2-2

Test Date: July 29, 1982

Purpose: Base test for assessing accumulation of restraint force

Span(s): 14'-0"

Thickness: 0.072" Moment of Inertia: 10.17 in^4

Parameters: No intermediate braces

Torsional Restraint at rafters, only at internal purlin

Panel shear stiffness

Panel torsional restraint

Failure Load: Loaded to 99 plf per purlin

Failure Mode:

Predicted Failure Loads:

Method AISI Constr. Bending x 1.67 Load 463.4 plf

Method Load

Method Load

Discussion:

-Vertical deflections were about 6% greater than predicted from the constrained bending assumption for external purlin and 12% greater for internal purlin.

-Brace forces increased linearly with increasing vertical load.

-At 99 plf, summation of brace forces equaled 16% of total vertical load.

-Bottom flange lateral displacement exceeded top flange displacement, but in opposite direction.

-Maximum lateral displacement was less than .250 in. at 99 plf.

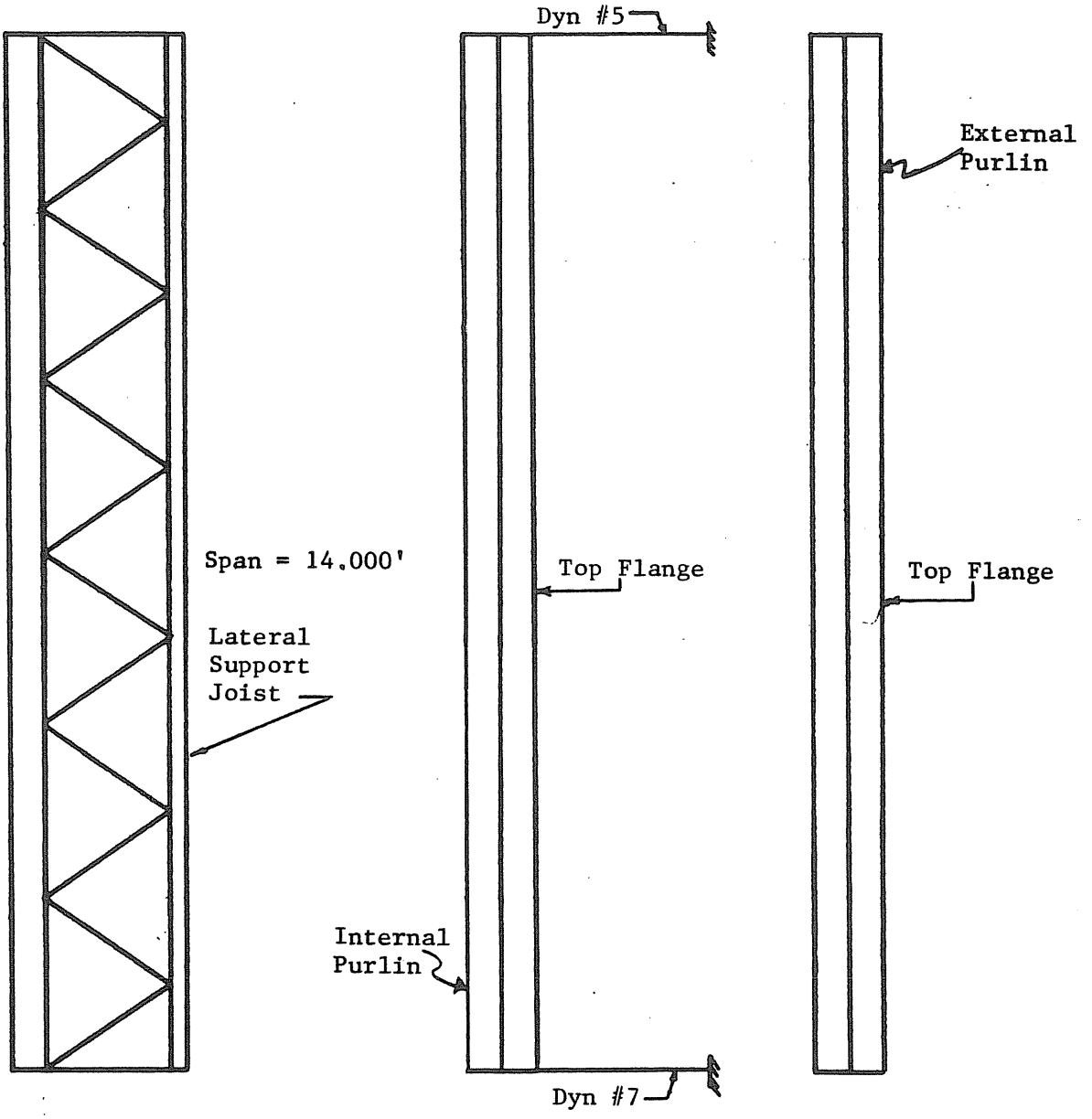
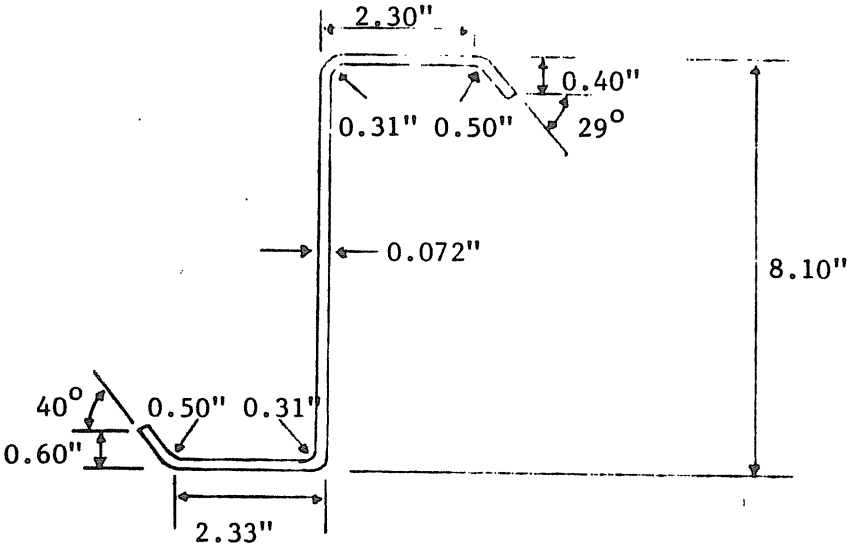
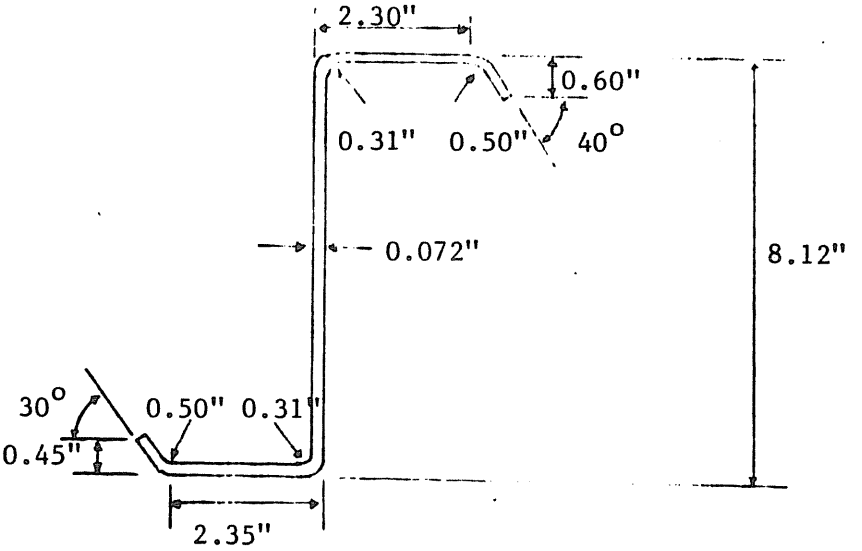


Figure A.8 Instrumentation Locations, Test A/2-2



External Purlin



Internal Purlin

Figure A.9 Measured Purlin Dimensions, Test A/2-2

```
A I S I  P U R L I N  A N A L Y S I S
              Z-SECTION
IDENTIFICATION: MBMA A/2-2 (WEST-EXT.) 7/29/82
```

	TOP	BOTTOM
FLANGE(in)	2.300	2.330
LIP(in)	0.400	0.600
LIP ANGLE(deg)	29.000	40.000
RADIUS L/F(in)	0.500	0.500
RADIUS F/W(in)	0.310	0.310

TOTAL DEPTH(in)	8.1
THICKNESS(in)	0.072
YIELD STRENGTH(ksi)	56

MOMENTS OF INERTIA(in^4)		SECTION MODULII(in^3) TOP	BOTTOM
GROSS=	10.168	2.506	2.561
STRENGTH=	10.168	2.506	2.561
DEFLECTION=	10.168		
BE= 1.918	in		
FC= 32.547	ksi		
FT= 33.600	ksi		
FBW= 31.209	ksi		

MOMENT CARRYING CAPACITY (AISI CRITERIA)

MC=	6.798	ft-k
MT=	7.169	ft-k
MW=	7.127	ft-k
MU=	11.353	ft-k (1.67*allowable)
SPAN =	14.000	ft.
UNIFORM LOAD=	463.394	plf (1.67*allowable)
DEFLECTION =	0.288	in./100plf

Figure A.10 AISI Purlin Analysis, Test A/2-2, External Purlin

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------------------------------------------------------------
A I S I  P U R L I N  A N A L Y S I S
              Z-SECTION
IDENTIFICATION: MBMA A/2-2 (EAST-INT.) 7/29/82
------------------------------------------------------------

                          TOP            BOTTOM
FLANGE(in)              2.300             2.350
LIP(in)                 0.600             0.450
LIP ANGLE(deg)         40.000            30.000
RADIUS L/F(in)          0.500             0.500
RADIUS F/W(in)          0.310             0.310

TOTAL DEPTH(in)                 8.12
THICKNESS(in)                   0.072
YIELD STRENGTH(ksi)             56

                                          SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)              TOP              BOTTOM
GROSS=          10.324                  2.566              2.565
STRENGTH=       10.324                  2.566              2.565
DEFLECTION=     10.324
BE=    1.918   in
FC=    31.808   ksi
FT=    33.600   ksi
FBW=   31.186   ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)
           MC=      6.802   ft-k
           MT=      7.182   ft-k
           MW=      7.297   ft-k
           MU=     11.360   ft-k (1.67*allowable)
SPAN         =     14.000   ft.
UNIFORM LOAD=    463.670   plf (1.67*allowable)
DEFLECTION   =      0.284   in./100plf
```

Figure A.11 AISI Purlin Analysis, Test A/2-2, Internal Purlin

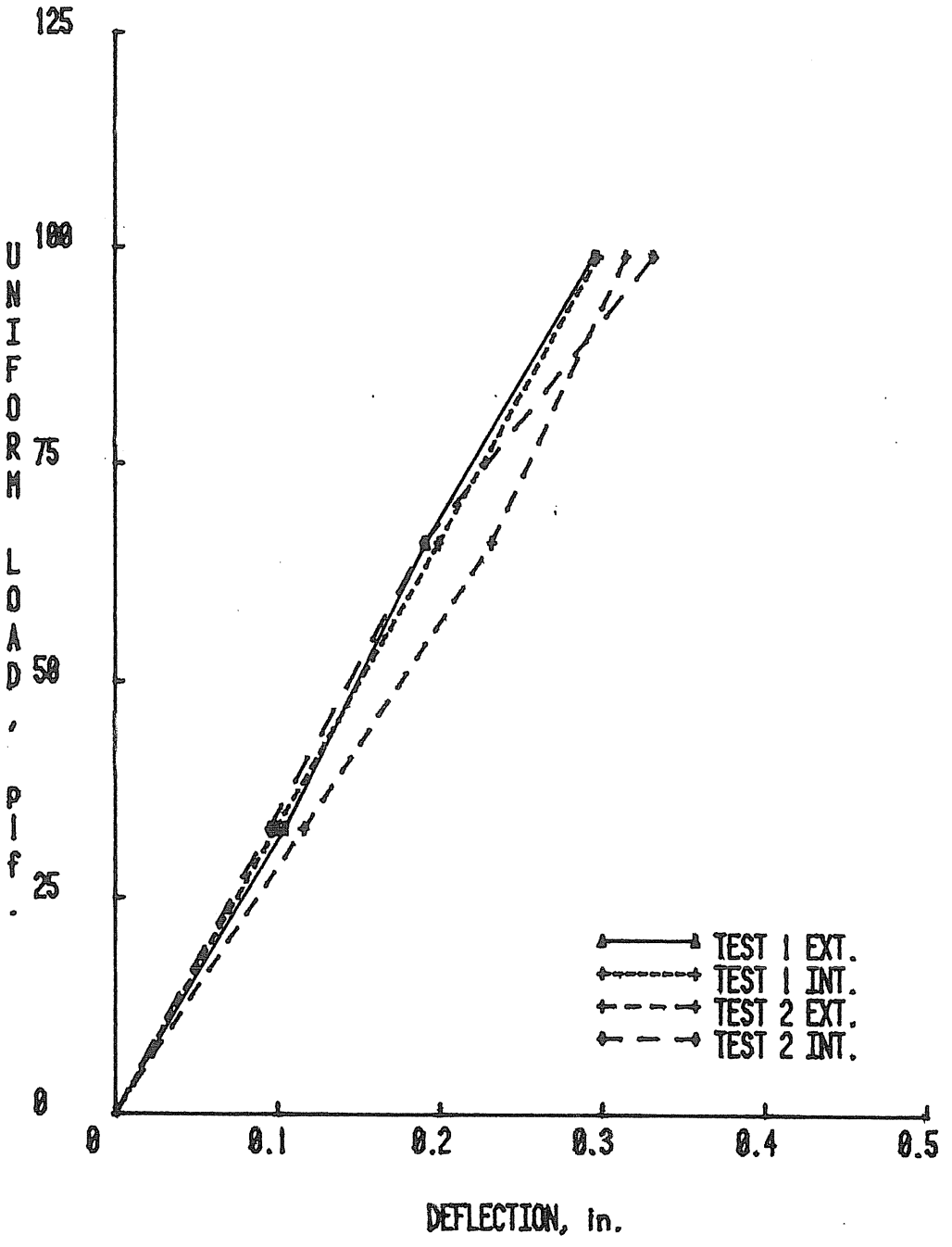


Figure A.12 Load vs. Vertical Deflection, Test A/2-2

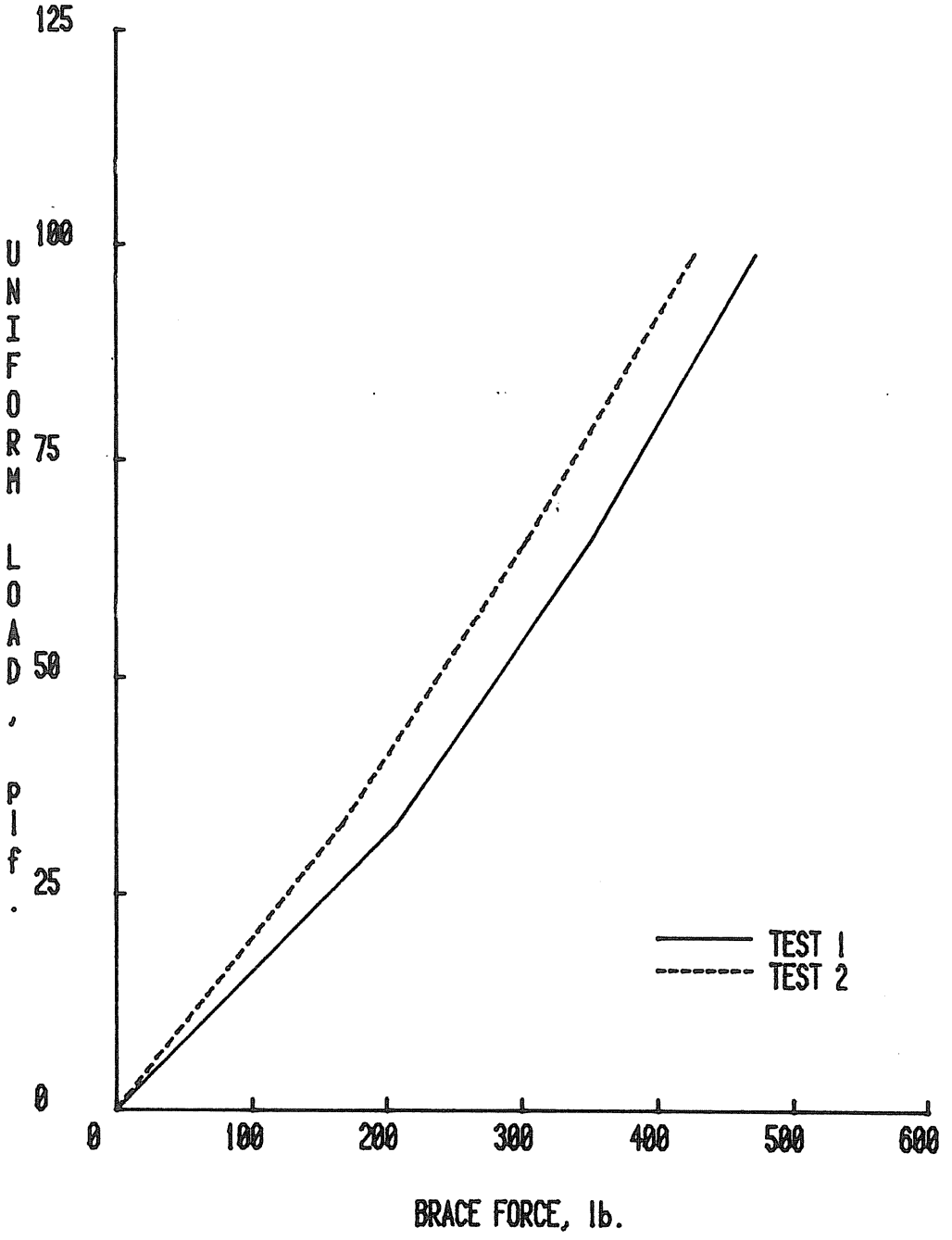


Figure A.13 Vertical Loading vs. Brace Force, Test A/2-2

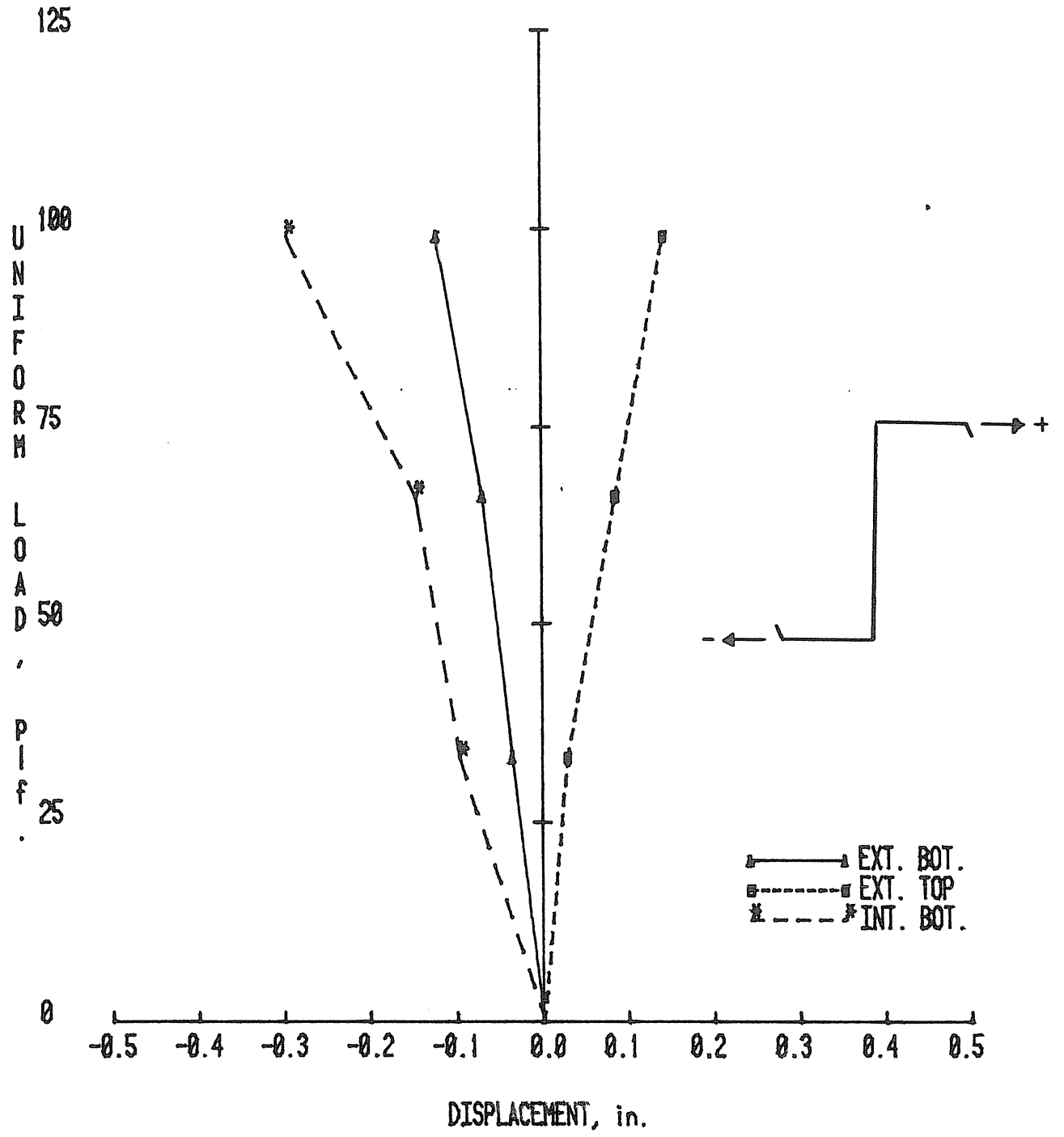


Figure A.14 Vertical Loading vs. Lateral Displacement, Test A/2-2-1

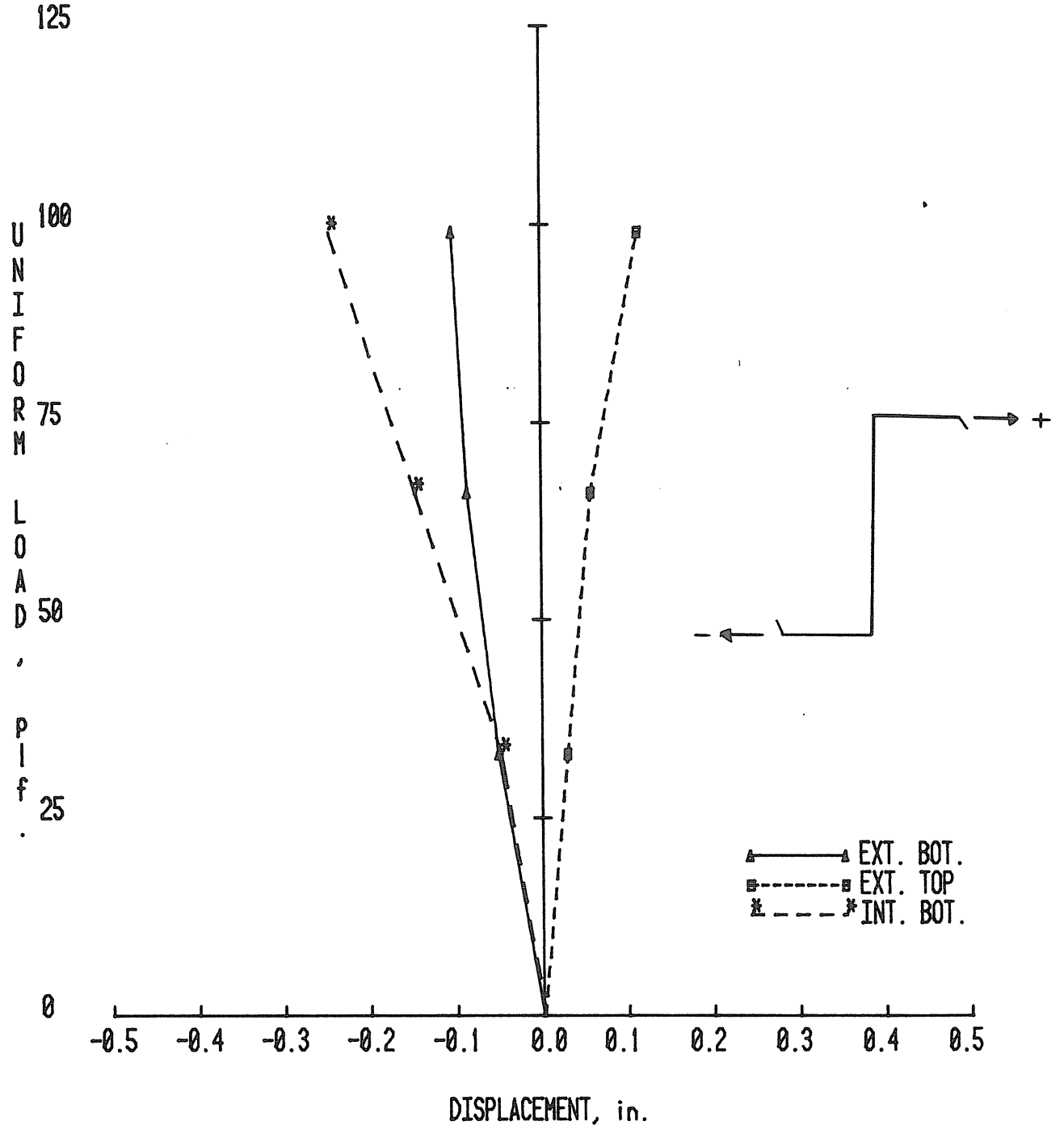


Figure A.15 Vertical Loading vs. Lateral Displacement, Test A/2-2-2

TEST SUMMARY

Project: MBMA Roof Systems Behavior

Test No.: A/2-3

Test Date: September 9, 1982

Purpose: Same as tests A/2-1, A/2-2

Span(s): 14.625'

Thickness: 0.073" Moment of Inertia: 10.9 $in.^4$

Parameters: Same as test A/2-1, A/2-2 except torsional braces were used for external and internal purlins.
Total 4 braces

Failure Load: Loaded to 165 plf per purlin

Failure Mode:

Predicted Failure Loads:

Method AISI Constr. Bending x 1.67 Load 454.7 plf

Method _____ Load _____

Method _____ Load _____

Discussion:

-Vertical deflections were about 20% greater than predicted from the constrained bending assumption for external purlin and 26% greater for internal purlin.

-Brace forces increased linearly with increasing vertical load.

-At 165 plf summation of external brace forces equalled 6.0% of total vertical load. Summation of internal brace forces equaled 19.3% of total vertical load.

-Top flange displacement exceeded bottom flange displacement, but in opposite direction.

-Maximum lateral displacement of purlin was less than .15 in. at 165 plf.

-Maximum lateral displacement of panel was 0.217 in. at 165 plf.

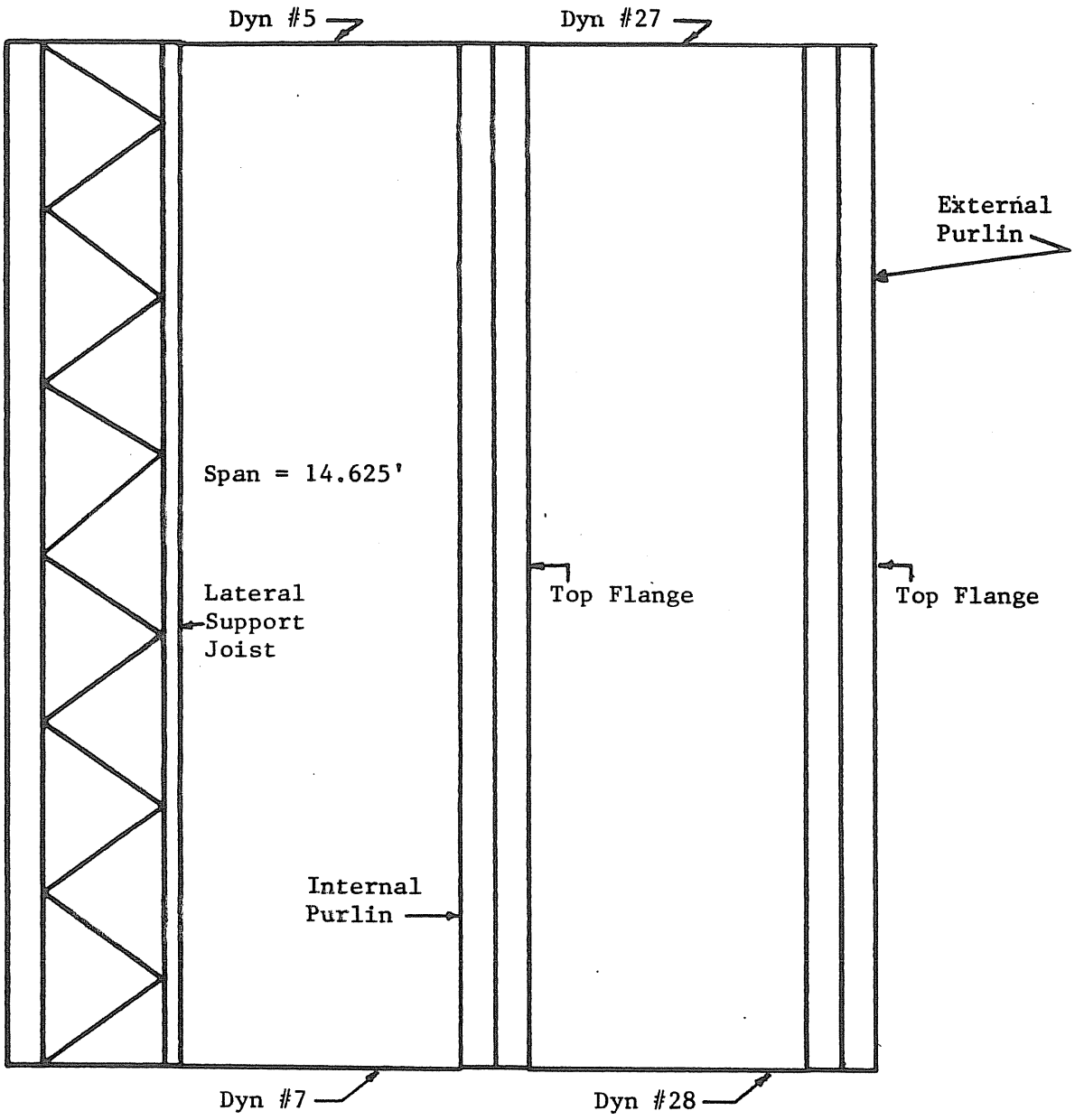
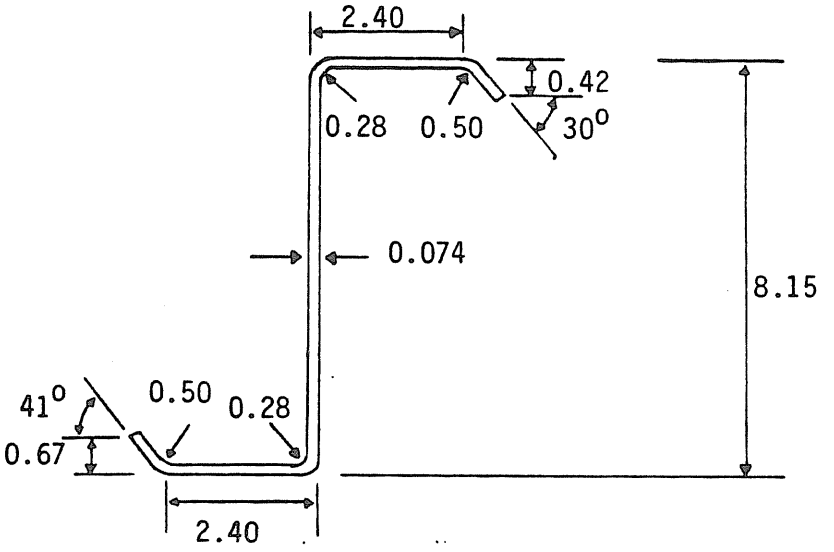
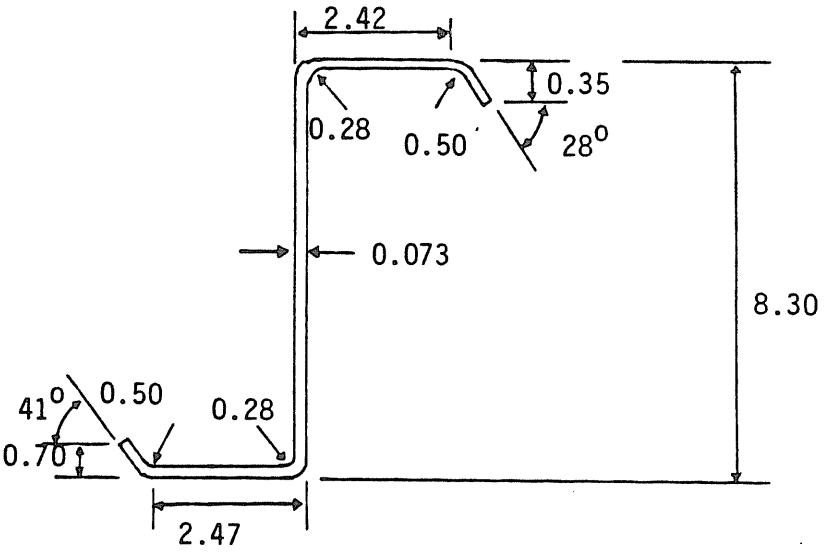


Figure A.16 Instrumentation Locations, Test A/2-3



External Purlin



Internal Purlin

Figure A.17 Measured Purlin Dimensions, Test A/2-3

```
A I S I   P U R L I N   A N A L Y S I S
              Z-SECTION
IDENTIFICATION: MBMA TEST-A/2-3 (EXT. 9/14/82)
```

	TOP	BOTTOM
FLANGE(in)	2.400	2.400
LIP(in)	0.420	0.670
LIP ANGLE(deg)	30.000	41.000
RADIUS L/F(in)	0.500	0.500
RADIUS F/W(in)	0.280	0.280

TOTAL DEPTH(in)	8.15
THICKNESS(in)	0.074
YIELD STRENGTH(ksi)	56

	MOMENTS OF INERTIA(in^4)	SECTION MODULII(in^3) TOP	BOTTOM
GROSS=	10.924	2.672	2.739
STRENGTH	10.924	2.672	2.739
DEFLECTION	10.924		

RE= 2.046 in
FC= 72.693 ksi
FT= 33.600 ksi
FBW= 31.412 ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)

MC=	7.280	ft-k
MT=	7.670	ft-k
MW=	7.582	ft-k
MU=	12.157	ft-k (1.67*allowable)
SPAN =	14.625	ft.
UNIFORM LOAD=	454.694	plf (1.67*allowable)
DEFLECTION =	0.319	in./100plf

Figure A.18 AISI Purlin Analysis, Test A/2-3 External Purlin

```
A I S I   P U R L I N   A N A L Y S I S
              Z-SECTION
IDENTIFICATION: MBMA TEST-A/2-3 (INT. 9/14/82)
```

	TOP	BOTTOM
FLANGE(in)	2.420	2.470
LIP(in)	0.350	0.700
LIP ANGLE(deg)	28.000	41.000
RADIUS L/F(in)	0.500	0.500
RADIUS F/W(in)	0.280	0.280

TOTAL DEPTH(in)	8.3
THICKNESS(in)	0.073
YIELD STRENGTH(ksi)	56

MOMENTS OF INERTIA(in^4)		SECTION MODULII(in^3) TOP	BOTTOM
GROSS=	11.294	2.680	2.814
STRENGTH=	11.294	2.680	2.814
DEFLECTION=	11.294		

```
BE=    2.067  in
FC=   33.600  ksi
FT=   33.600  ksi
FBW=  31.107  ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)
          MC=     7.504  ft-k
          MT=     7.880  ft-k
          MW=     7.512  ft-k
          MU=    12.532  ft-k (1.67*allowable)
SPAN        =    14.625  ft.
UNIFORM LOAD=   468.724  plf (1.67*allowable)
DEFLECTION  =     0.309  in./100plf
```

Figure A.19 AISI Purlin Analysis, Test A/2-3 Internal Purlin

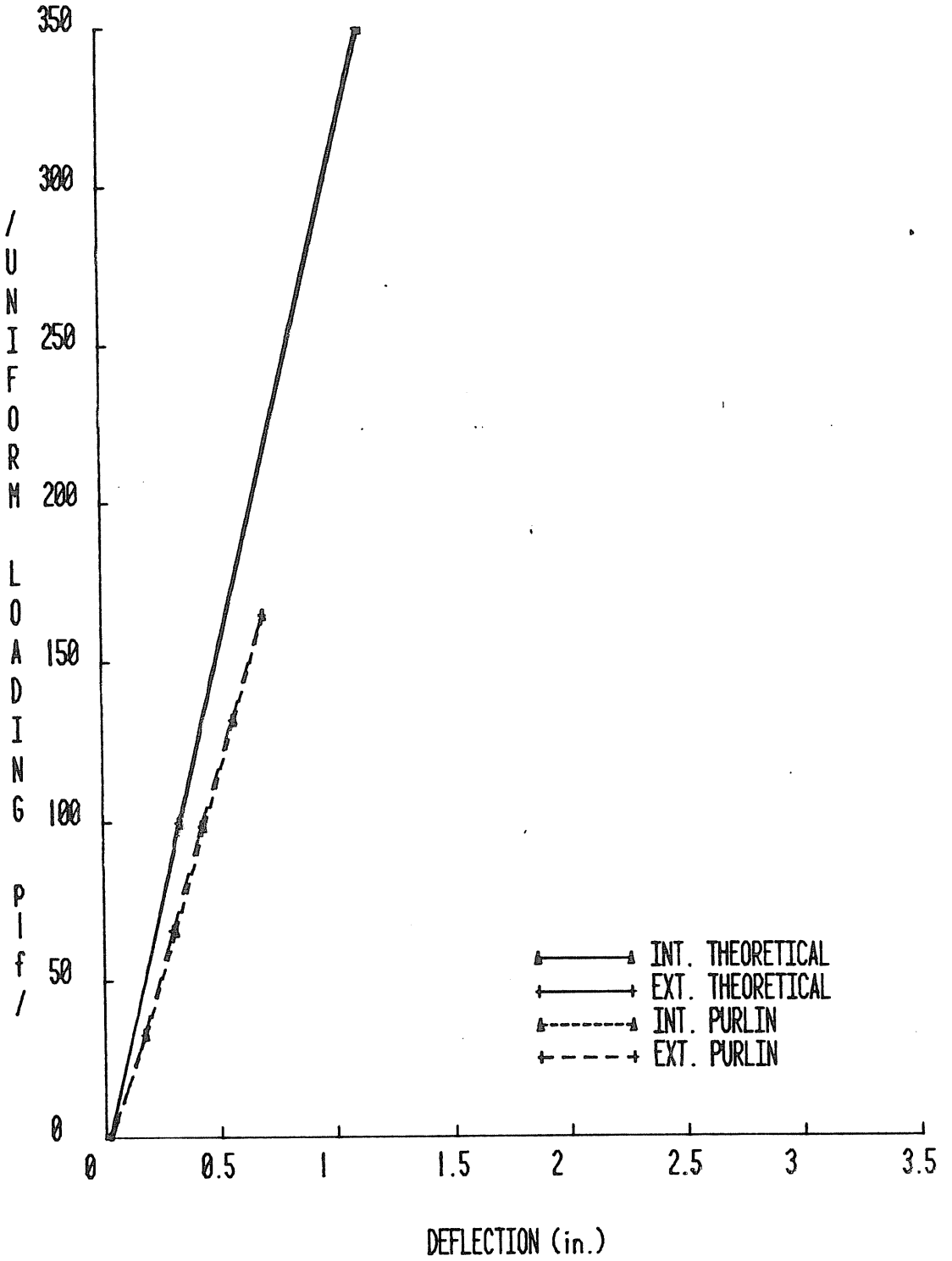


Figure A.20 Load vs. Vertical Deflection, Test A/2-3

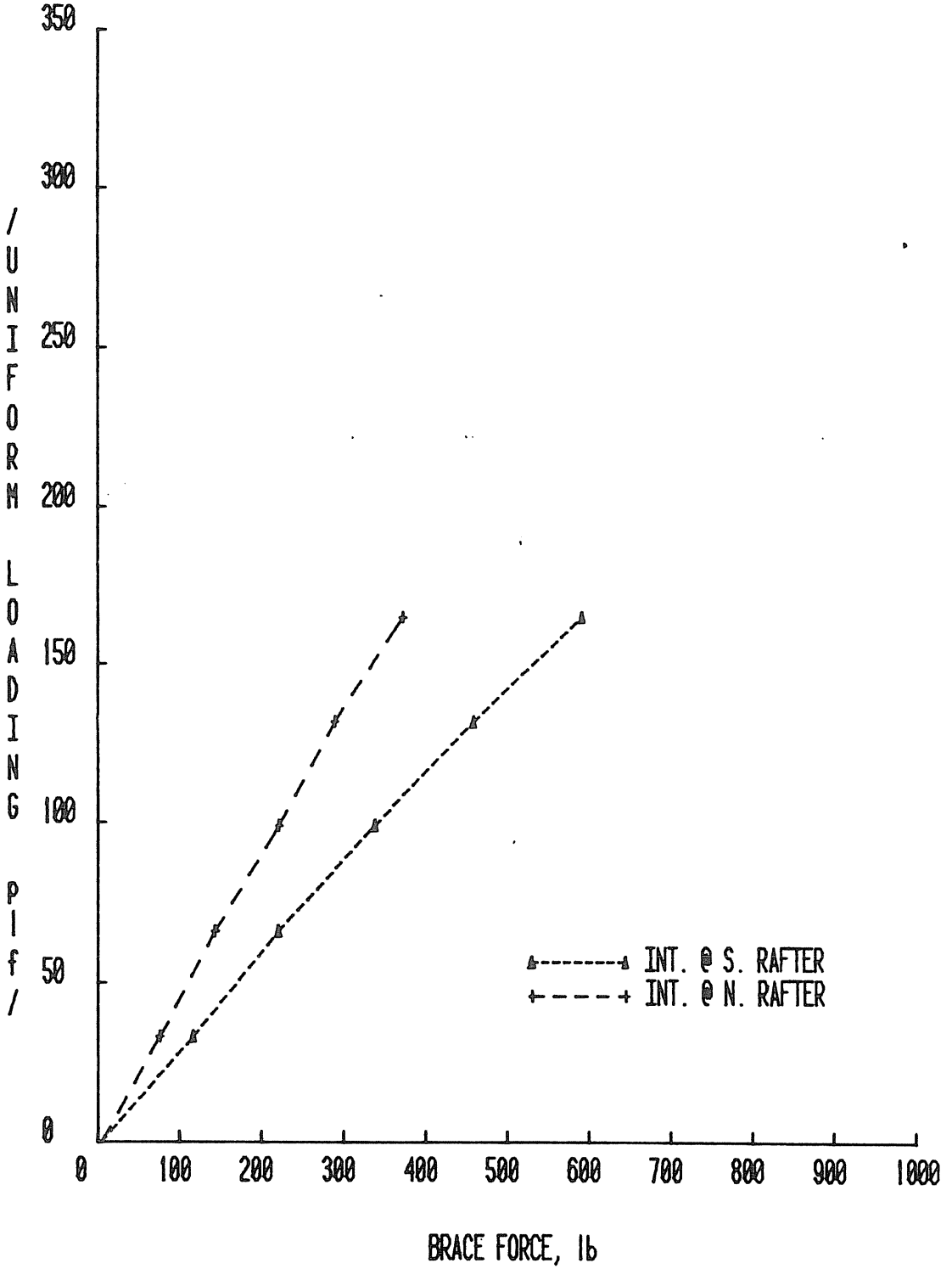


Figure A.21 Vertical Load vs. Internal Brace Forces, Test A/2-3

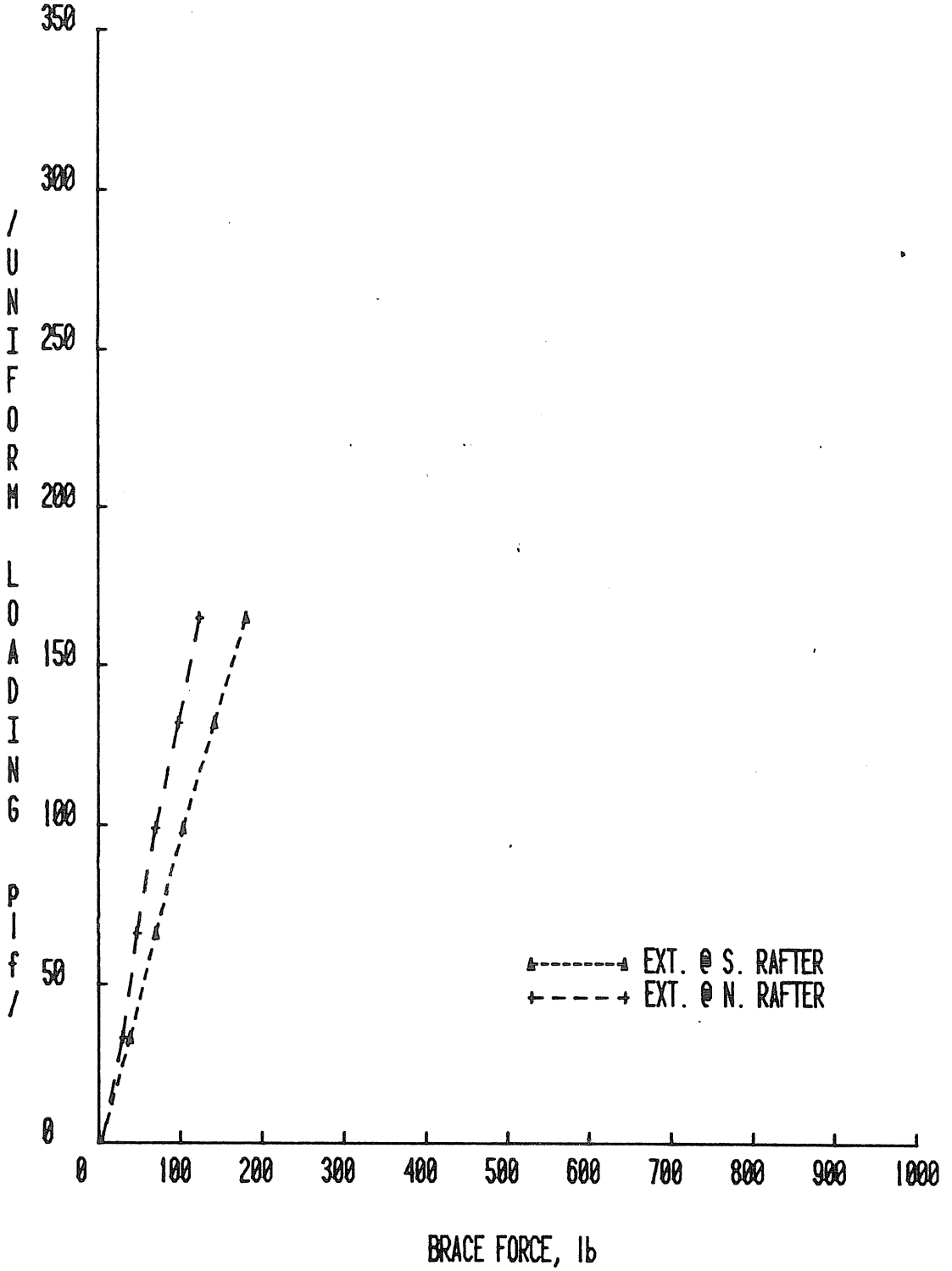


Figure A.22 Vertical Load vs. External Brace Forces, Test A/2-3

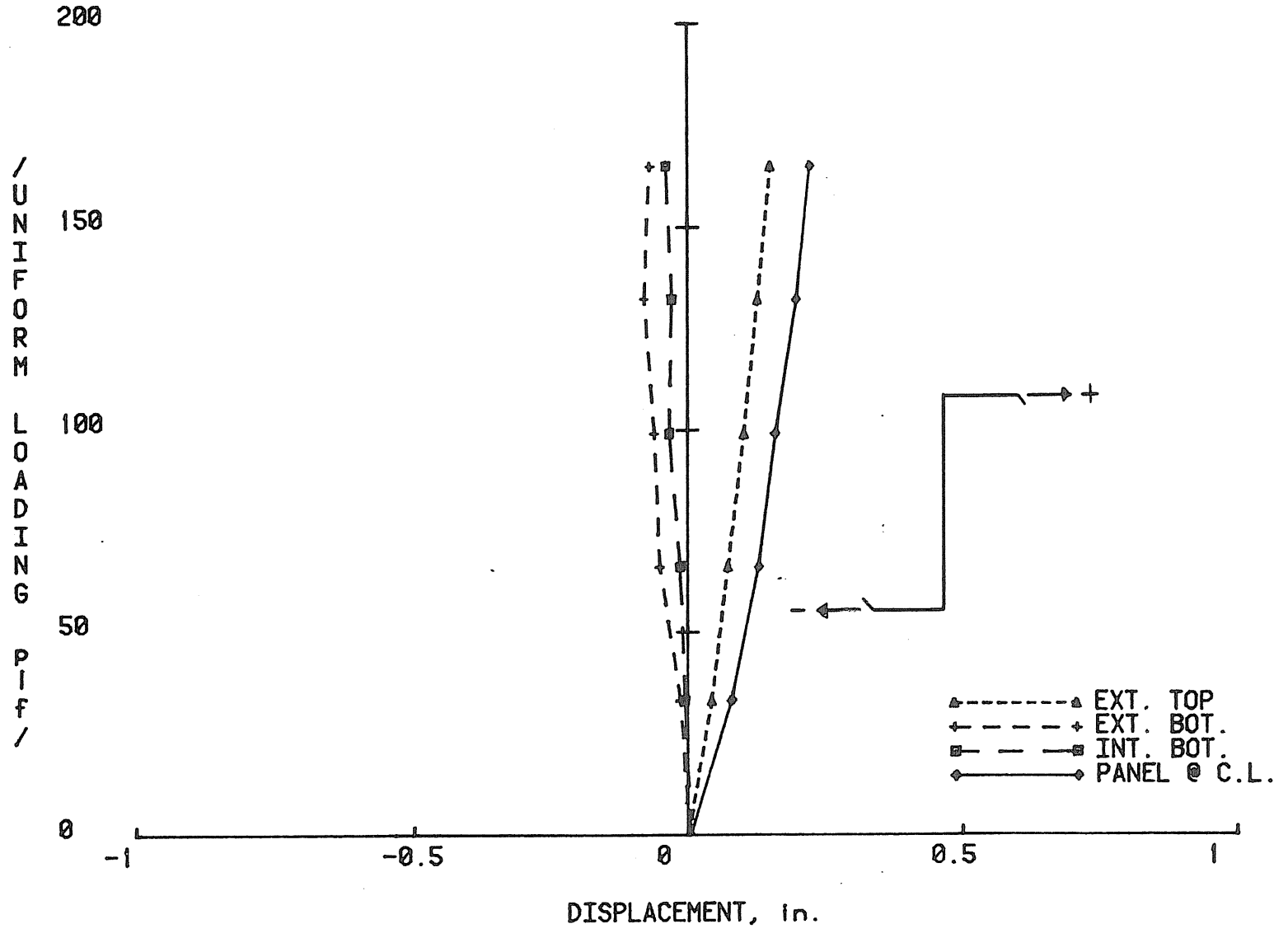


Figure A.23 Vertical Load vs. Lateral Displacements, Test A/2-3

APPENDIX B

SERIES A/7 TEST RESULTS

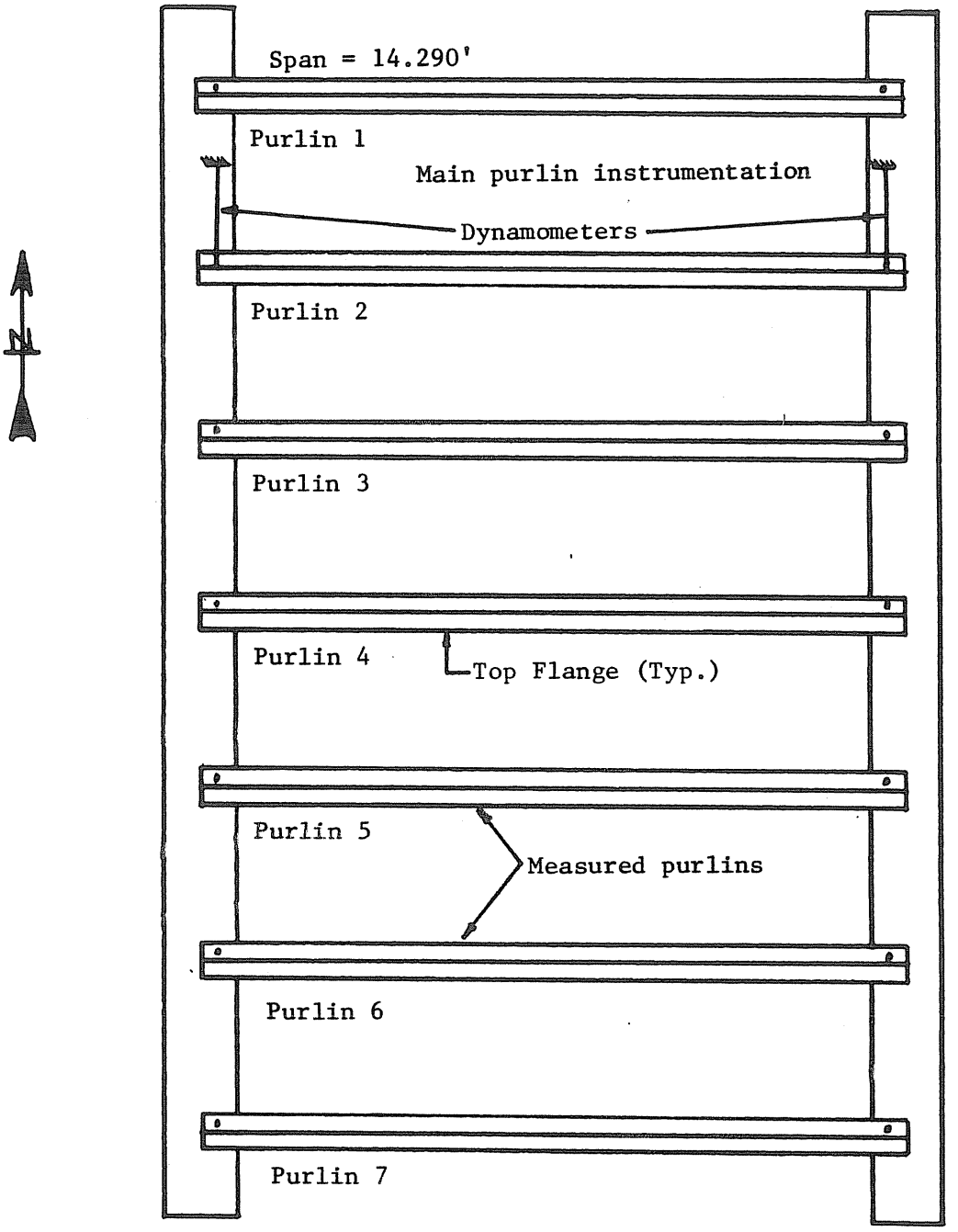
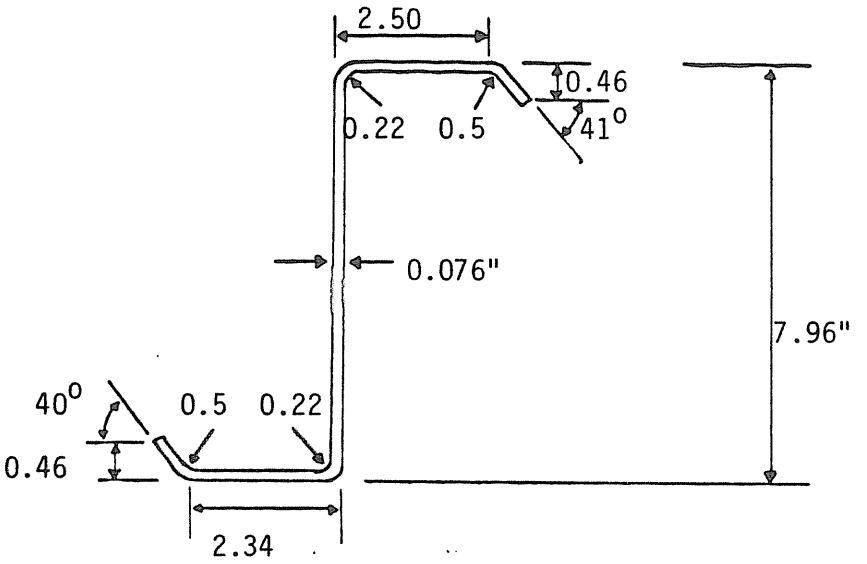
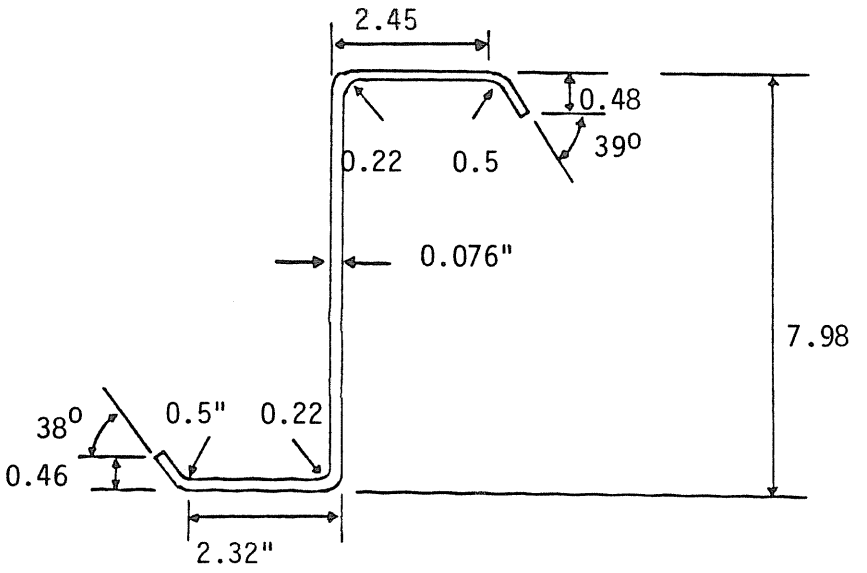


Figure B.1 Instrumentation Locations, Test A/7



a) Second Purlin from South



b) Third Purlin from South

Figure B.2 Measured Purlin Dimensions, Test A/7

```
---------------------------------------------------------
A I S I  P U R L I N  A N A L Y S I S
IDENTIFICATION: MBMA TEST A/7
---------------------------------------------------------

                          TOP             BOTTOM
FLANGE(in)              2.500              2.340
LIP(in)                 0.460              0.460
LIP ANGLE(deg)         41.000             40.000
RADIUS L/F(in)          0.500              0.500
RADIUS F/W(in)          0.219              0.219

TOTAL DEPTH(in)                 7.96
THICKNESS(in)                   0.076
YIELD STRENGTH(ksi)             56

                                              SECTION MODULII(in^3)
     MOMENTS OF INERTIA(in^4)                   TOP                BOTTOM
GROSS=          10.346                       2.653                2.597
STRENGTH=       10.346                       2.653                2.597
DEFLECTION=     10.346
RC=    2.205   in
FC=   33.600   ksi
FT=   33.600   ksi
FBW=  31.873   ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)
            MC=      7.427   ft-k
            MT=      7.272   ft-k
            MW=      7.543   ft-k
            MU=     12.144   ft-k (1.67*allowable)
SPAN          =     14.290   ft.
UNIFORM LOAD=    475.759   plf (1.67*allowable)
DEFLECTION    =      0.307   in./100plf
```

Figure B.3 AISI Purlin Analysis, Test A/7 , 2nd Purlin from South

```
---------------------------------------------------------
A I S I  P U R L I N  A N A L Y S I S
IDENTIFICATION: MBMA TEST A/7
---------------------------------------------------------

                          TOP              BOTTOM
FLANGE(in)              2.450              2.320
LIP(in)                 0.480              0.460
LIP ANGLE(deg)         39.000             38.000
RADIUS L/F(in)          0.500              0.500
RADIUS F/W(in)          0.219              0.219

TOTAL DEPTH(in)                 7.98
THICKNESS(in)                   0.076
YIELD STRENGTH(ksi)             56

                                        SECTION MODULII(in^3)
      MOMENTS OF INERTIA(in^4)          TOP              BOTTOM
GROSS=          10.401                2.659            2.605
STRENGTH=       10.401                2.659            2.605
DEFLECTION=     10.401
BE=    2.155  in
FC=   33.600  ksi
FT=   33.600  ksi
FBW=  31.851  ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)
            MC=      7.446  ft-k
            MT=      7.294  ft-k
            MW=      7.554  ft-k
            MU=     12.180  ft-k (1.67*allowable)
SPAN          =     14.290  ft.
UNIFORM LOAD=     477.185  plf (1.67*allowable)
DEFLECTION    =       0.306  in./100plf
```

Figure B.4 AISI Purlin Analysis, Test A/7, 3rd Purlin from South

TEST SUMMARY

Project: MBMA

Test No.: A/7-0

Test Date: 6/10/82

Purpose: Measure brace force accumulation --seven purlins

Span(s): 14.29'

Thickness: 0.076" Moment of Inertia: 10.401"^{4}

Parameters: Torsional restraint at rafters
Restraints in tension
Restraint braces attached to 2nd "uphill" purlin
Vacuum loading
Seven purlins at 5 ft. 0 in. o.c.

Failure Load:

Failure Mode:

Predicted Failure Loads:

Method Load

Method Load

Method Load

Discussion:

-Displacements were measured at centerline of purlins as follows:

a-Purlin 7: Horizontal top
b-Purlin 6: Horizontal top & bottom vertical
c-Purlin 1: Horizontal top

-Total brace force approximately same as for Test A/2

-Purlin webs not vertical at rafters.

-Top flange displacement not consistent especially between purlins 6 and 7.

-Purlin 6 deflected laterally the wrong way.

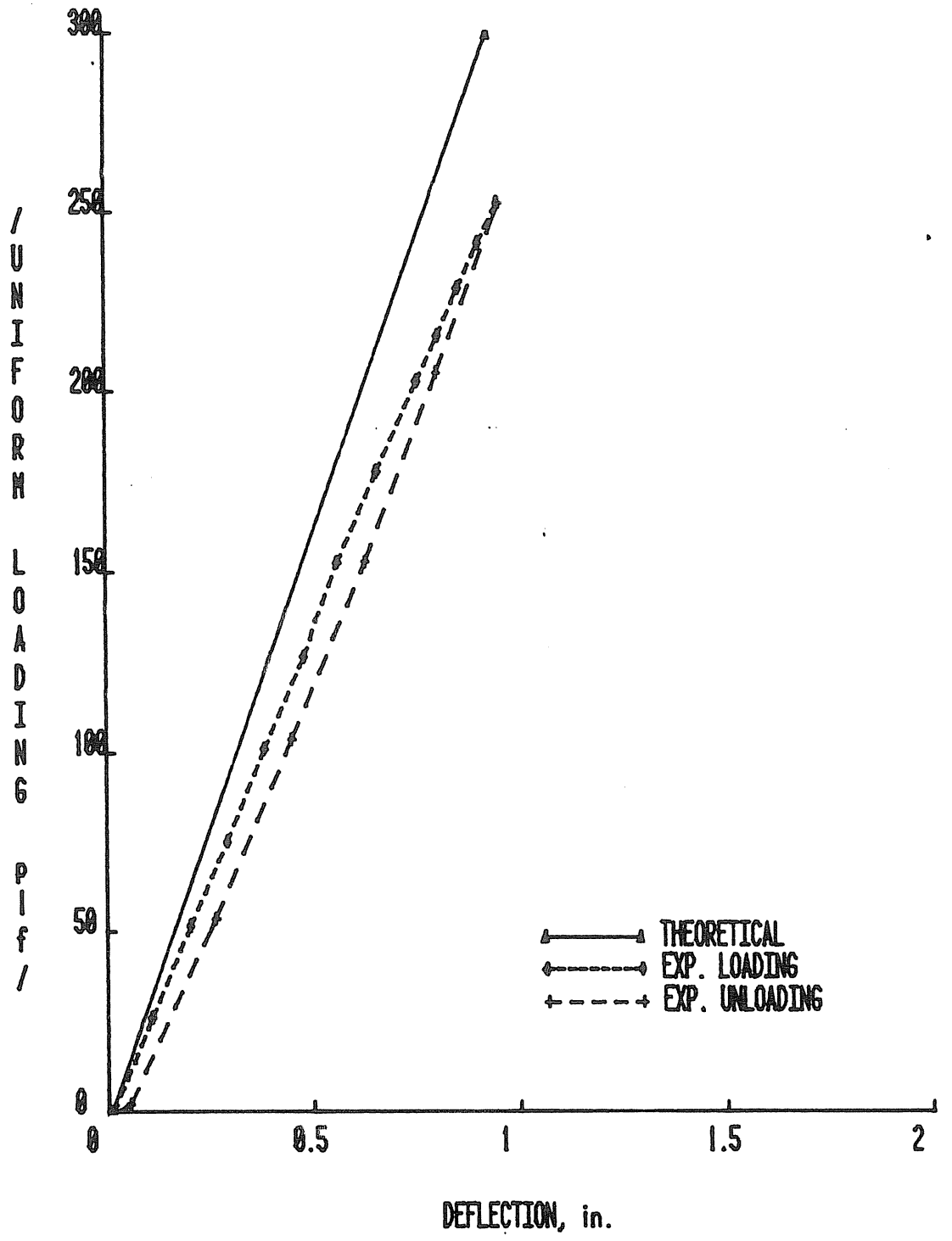


Figure B.5 Load vs. Vertical Deflection, Test A/7-0

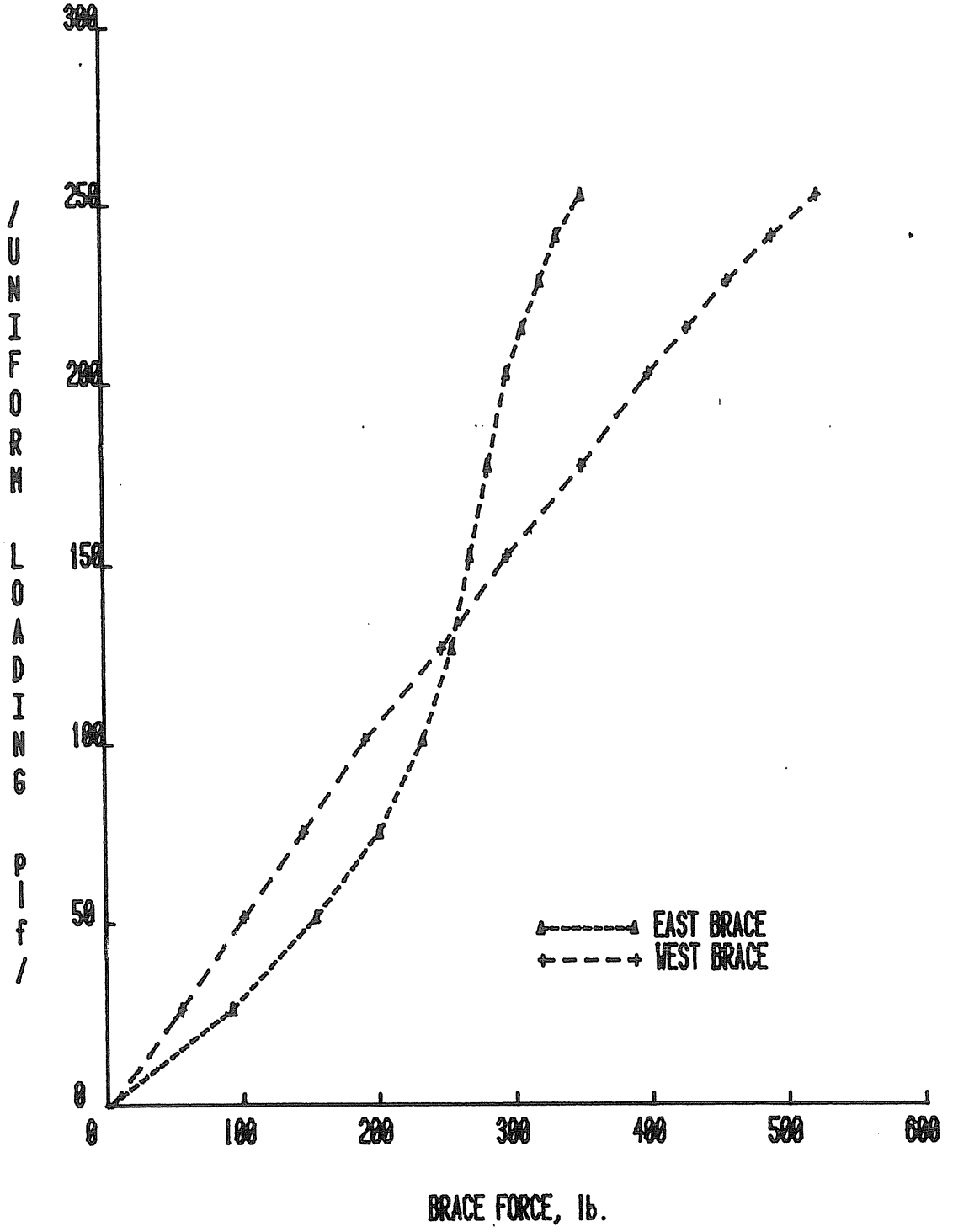


Figure B.6 Vertical Loading vs. Brace Force, Test A/7-0

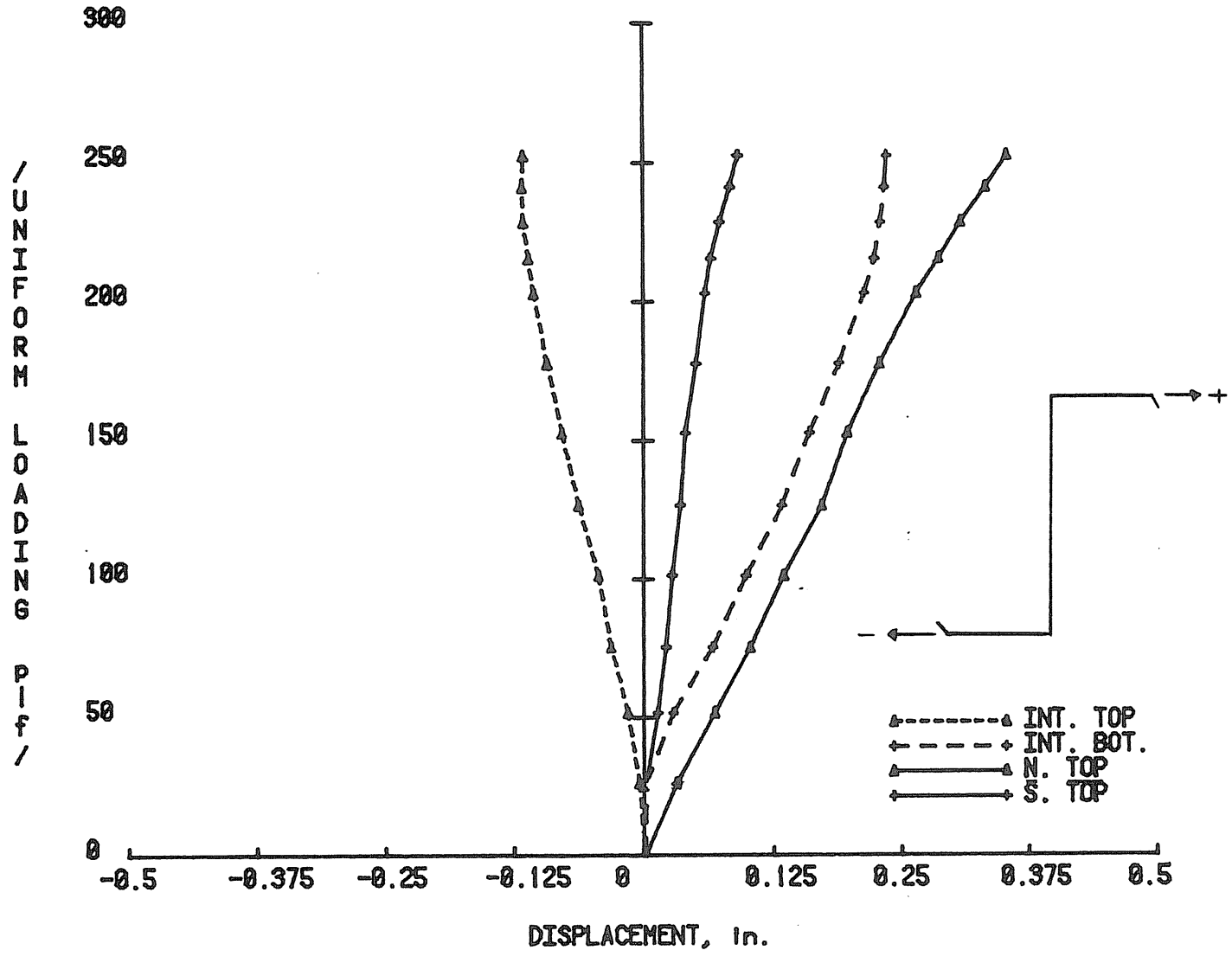


Figure B.7 Vertical Loading vs. Lateral Displacement, Test A/7-0

TEST SUMMARY

Project: MBMA

Test No.: A/7-2

Test Date: 6-25-82

Purpose: Measure brace force accumulation--seven purlin

Span(s): 14.29'

Thickness: 0.076" Moment of Inertia: 10.401"

Parameters: Torsional restraint at rafters
Restraints in tension
Restraint braces attached to 2nd "uphill" purlin
Vacuum loading
Seven purlins at 5 ft. 0 in. o.c.

Failure Load:

Failure Mode:

Predicted Failure Loads:

Method Load

Method Load

Method Load

Discussion:

-Repeat of Test A/7-0

-Results are approximately same.

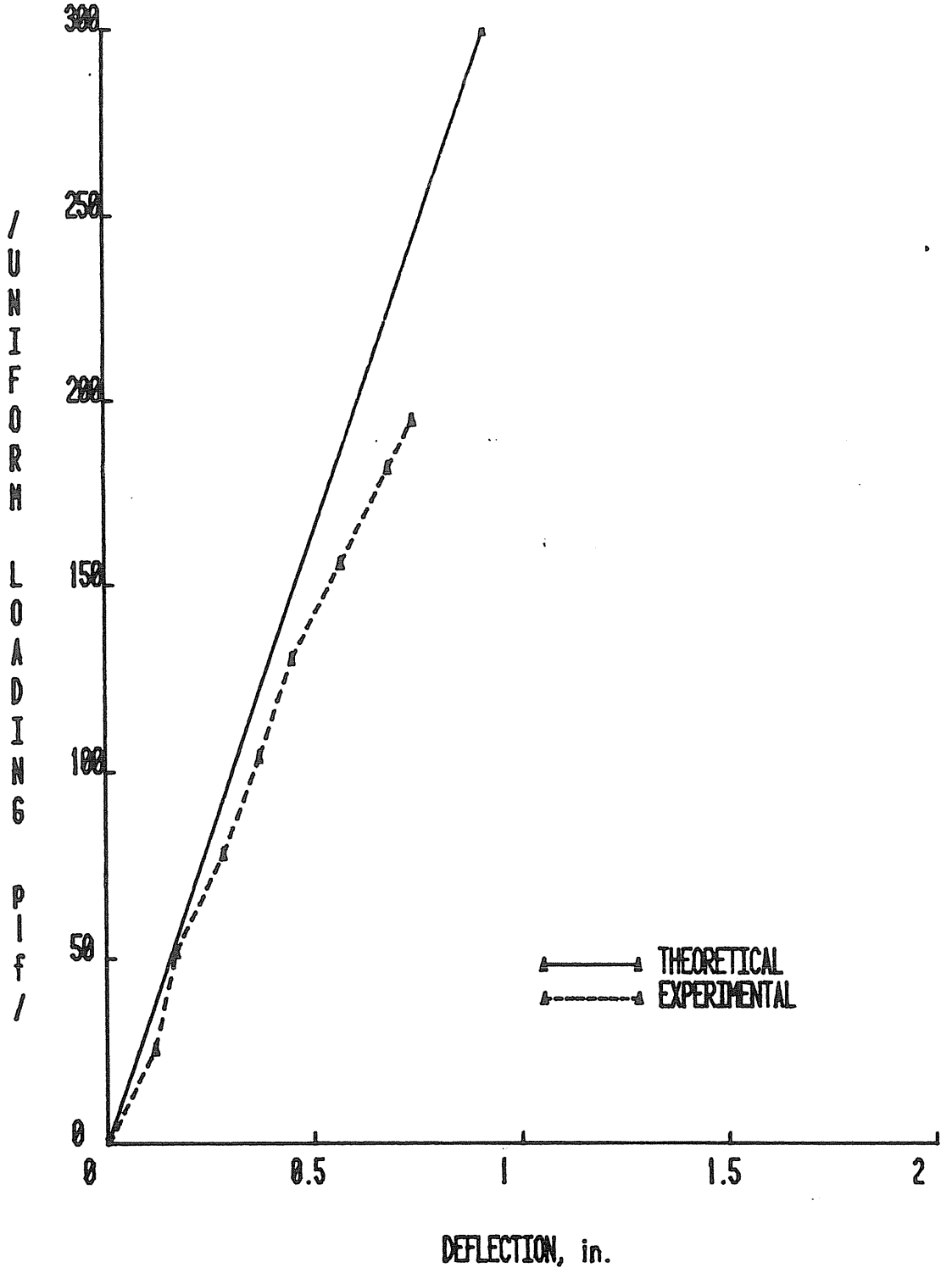


Figure B.8 Load vs. Vertical Deflection, Purlin 6, Test A/7-2

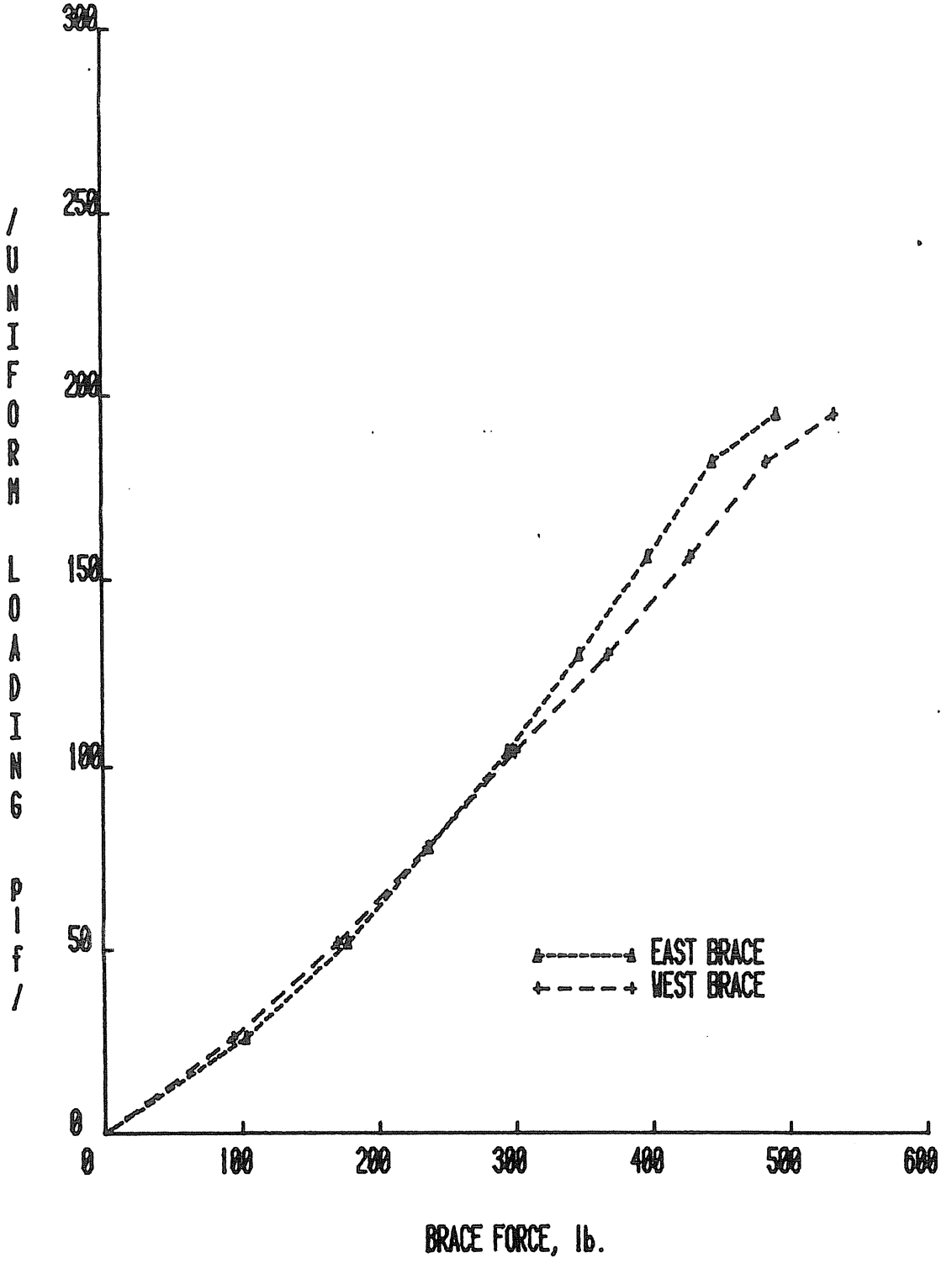


Figure B.9 Vertical Loading vs. Brace Force, Test A/7-2

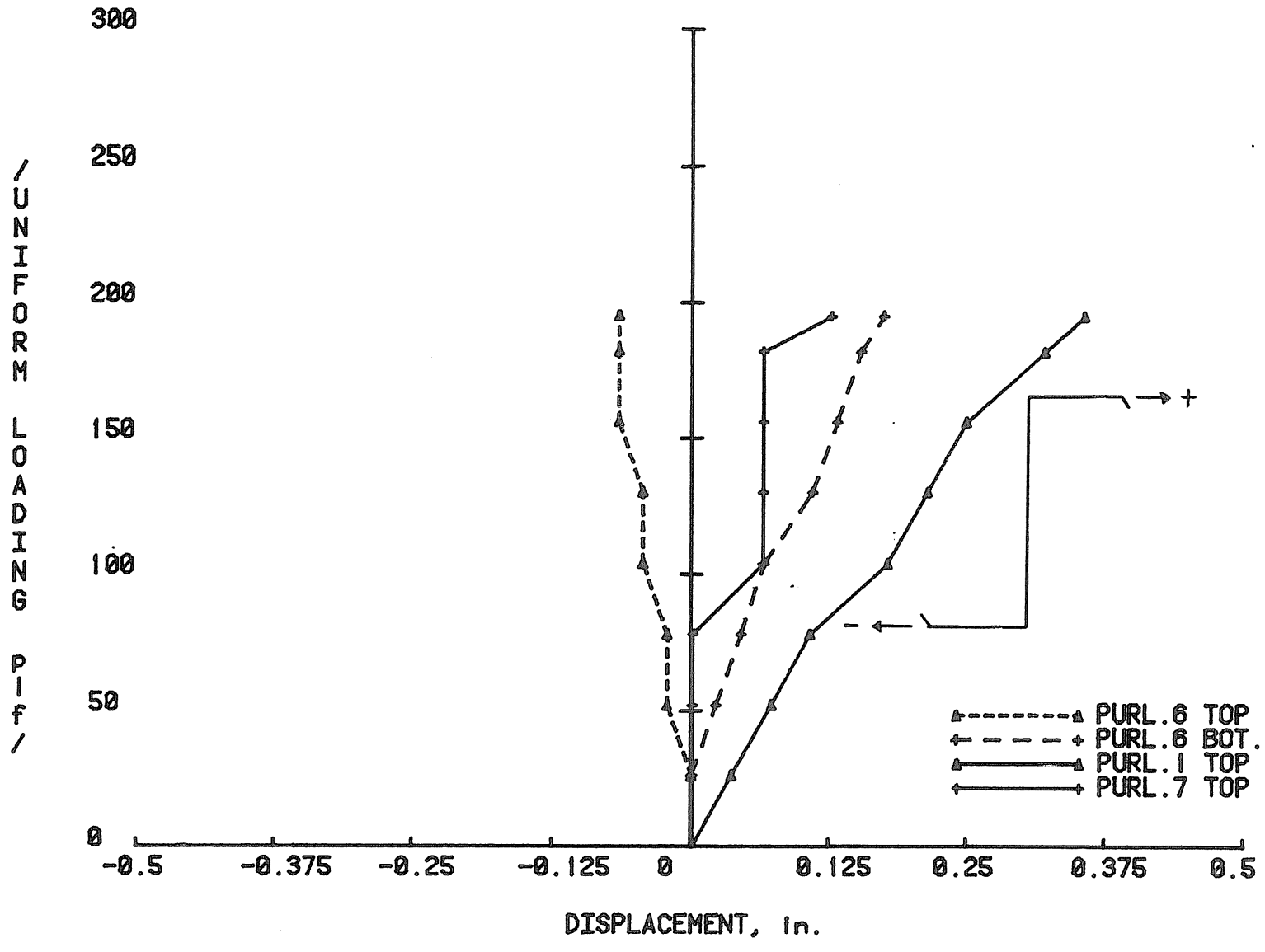


Figure B.10 Vertical Loading vs. Lateral Displacement, Test A/7-2

TEST SUMMARY

Project: MBMA

Test No.: A/7-3

Test Date: 6/28/82

Purpose: Measure brace force accumulation ; Measure lateral displacements

Span(s): 14.29'

Thickness: 0.076" Moment of Inertia: $10.401"^4$

Parameters: Torsional restraint at rafters

Restraints in tension

Restraint braces attached to 2nd "uphill" purlin

Vacuum loading

Seven purlins at 5 ft. 0 in. o.c.

Failure Load:

Failure Mode:

Predicted Failure Loads:

Method _____ Load _____

Method _____ Load _____

Method _____ Load _____

Discussion:

-Configuration same as A/7-0.

-Displacement transducers used to measure top flange displacement attached on web near top flange.

-Brace forces were found to be 20% larger than for test A/2.

-Lateral displacements were not consistent between purlins 6 and 7.

-Purlin 6 deflected in the wrong direction.

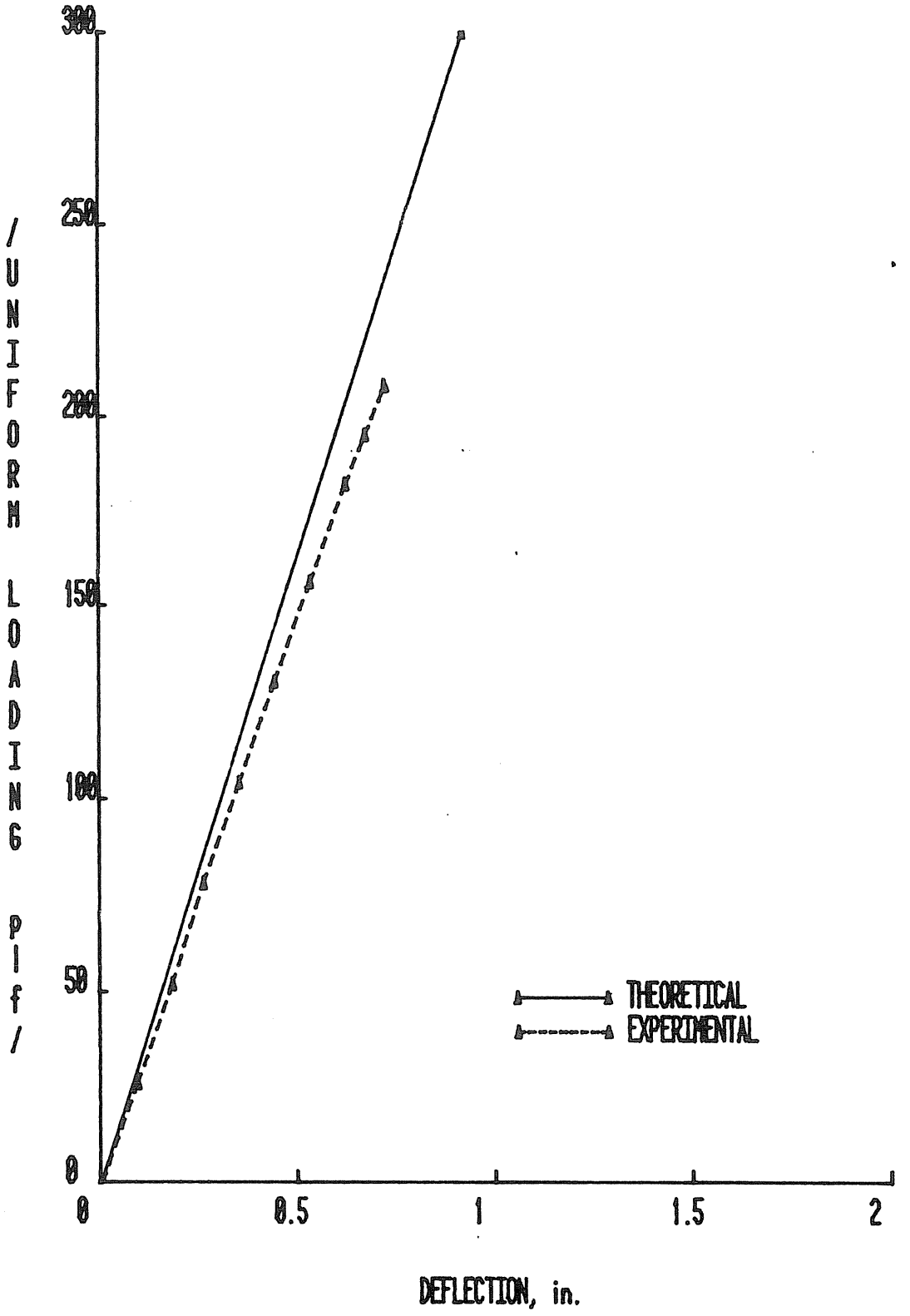


Figure B.11 Load vs. Vertical Deflection, Purlin 6, Test A/7-3

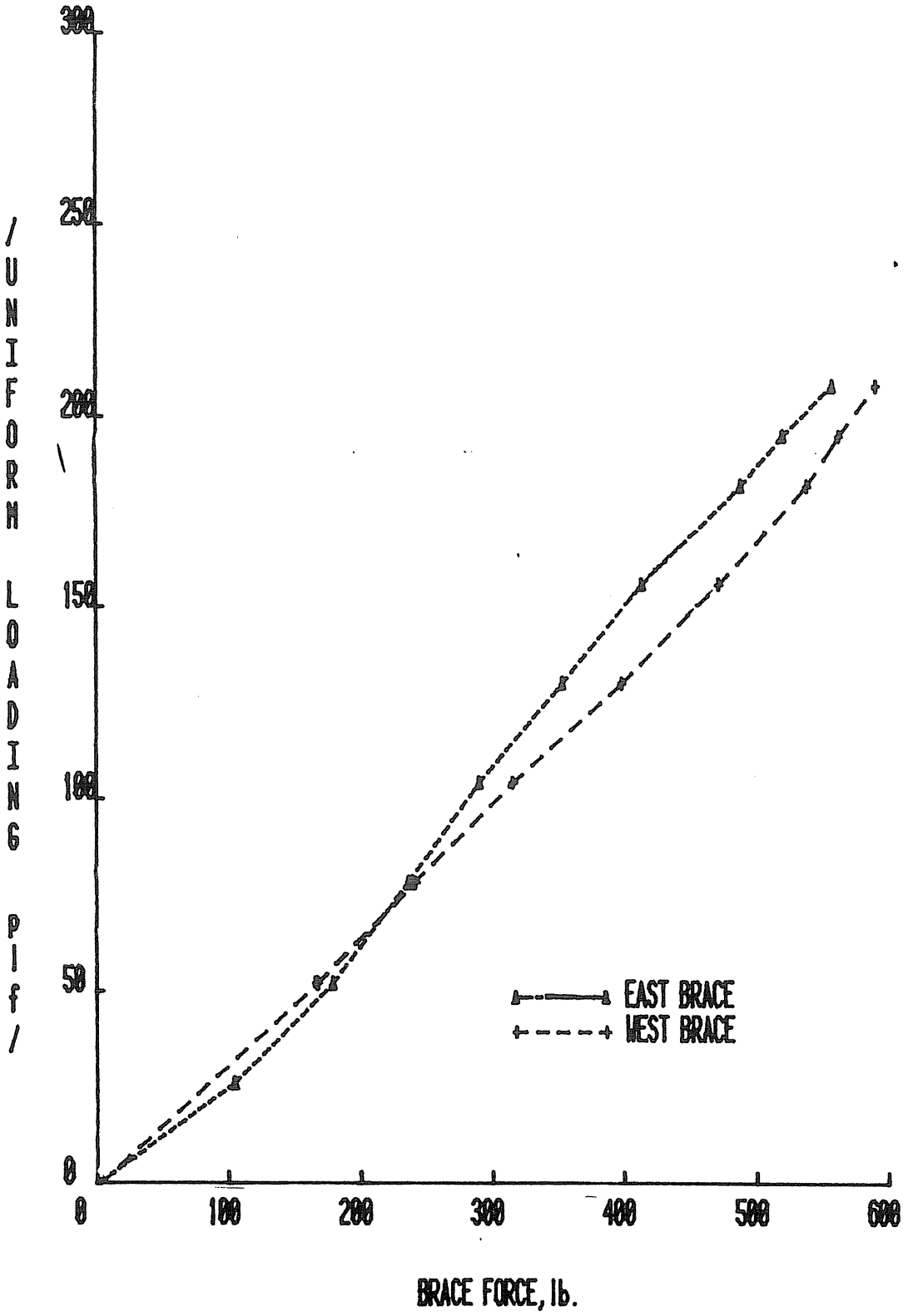


Figure B.12 Vertical Loading vs. Brace Force, Test A/7-3

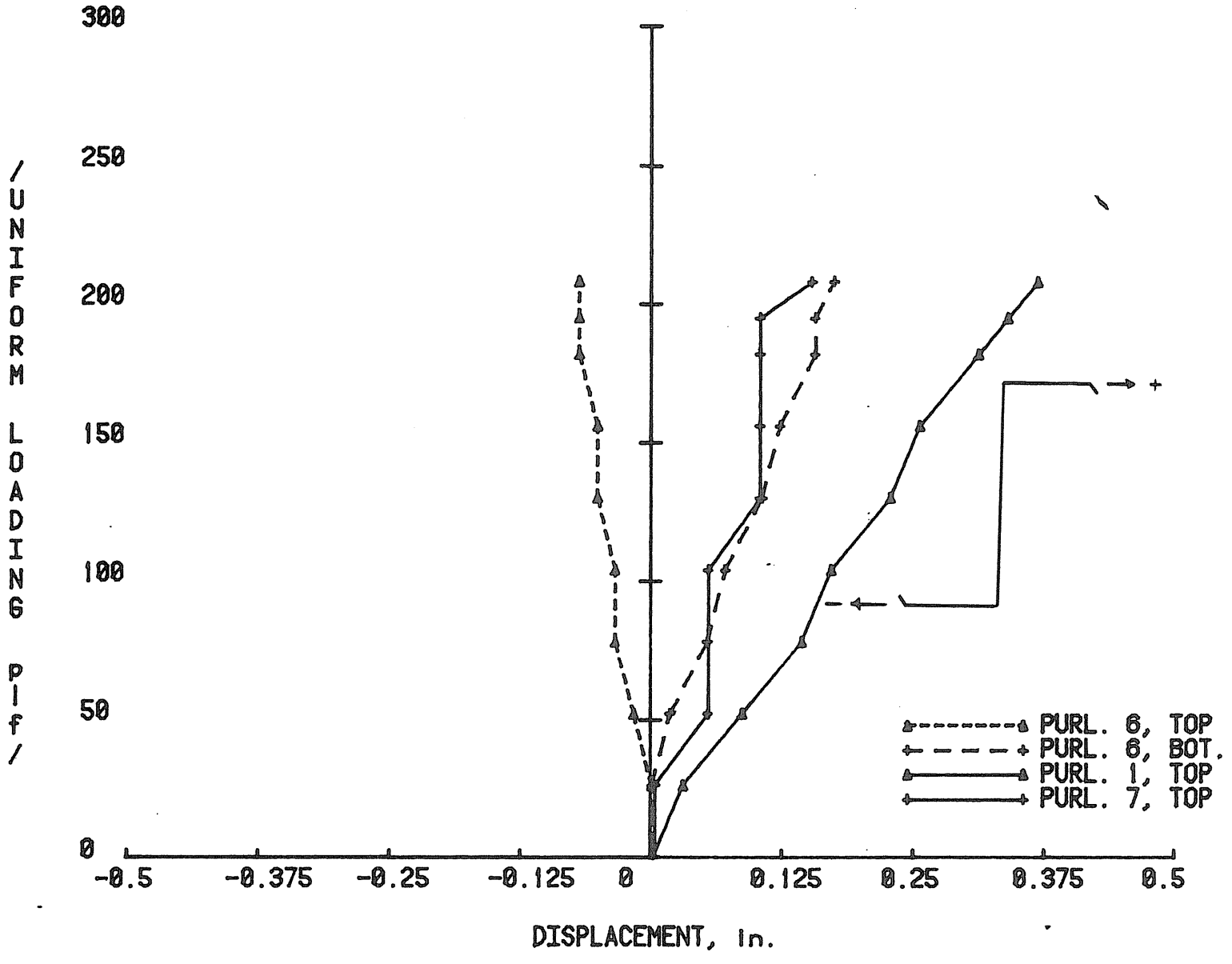


Figure B.13 Vertical Loading vs. Lateral Displacement, Test A/7-3

Project: MBMA

Test No.: A/7-4

Test Date: 7/6/82

Purpose: Measure brace force accumulation ; Measure lateral displacement

Span(s): 14.29'

Thickness: 0.076" Moment of Inertia: 10.401"^{4}

Parameters: Torsional restraint at rafters
Restraints in tension
Restraint braces attached to 2nd "uphill" purlin
Vacuum loading
Seven purlins at 5 ft. 0 in. o.c.

Failure Load:

Failure Mode:

Predicted Failure Loads:

Method Load

Method Load

Method Load

Discussion:

-Displacements were measured at centerline of purlins as follows:

a-Purlin 7: Horizontal top
b-Purlin 6: Horizontal top & bottom vertical
c-Purlin 1: Horizontal top

-Purlin webs were made vertical before starting test. After finishing testing all of the purlin tops leaned to the north. At this stage the east brace had 149 lb. tension force in it and the west brace 128 lb. Even after loosening the braces, the purlins were leaning northward.

-Brace force increased by a factor of 1.4 over the two-purlin test.

-During testing, all purlins deflected laterally to the south, with bottom flange displacement larger than top flange displacement by a factor of 2.6.

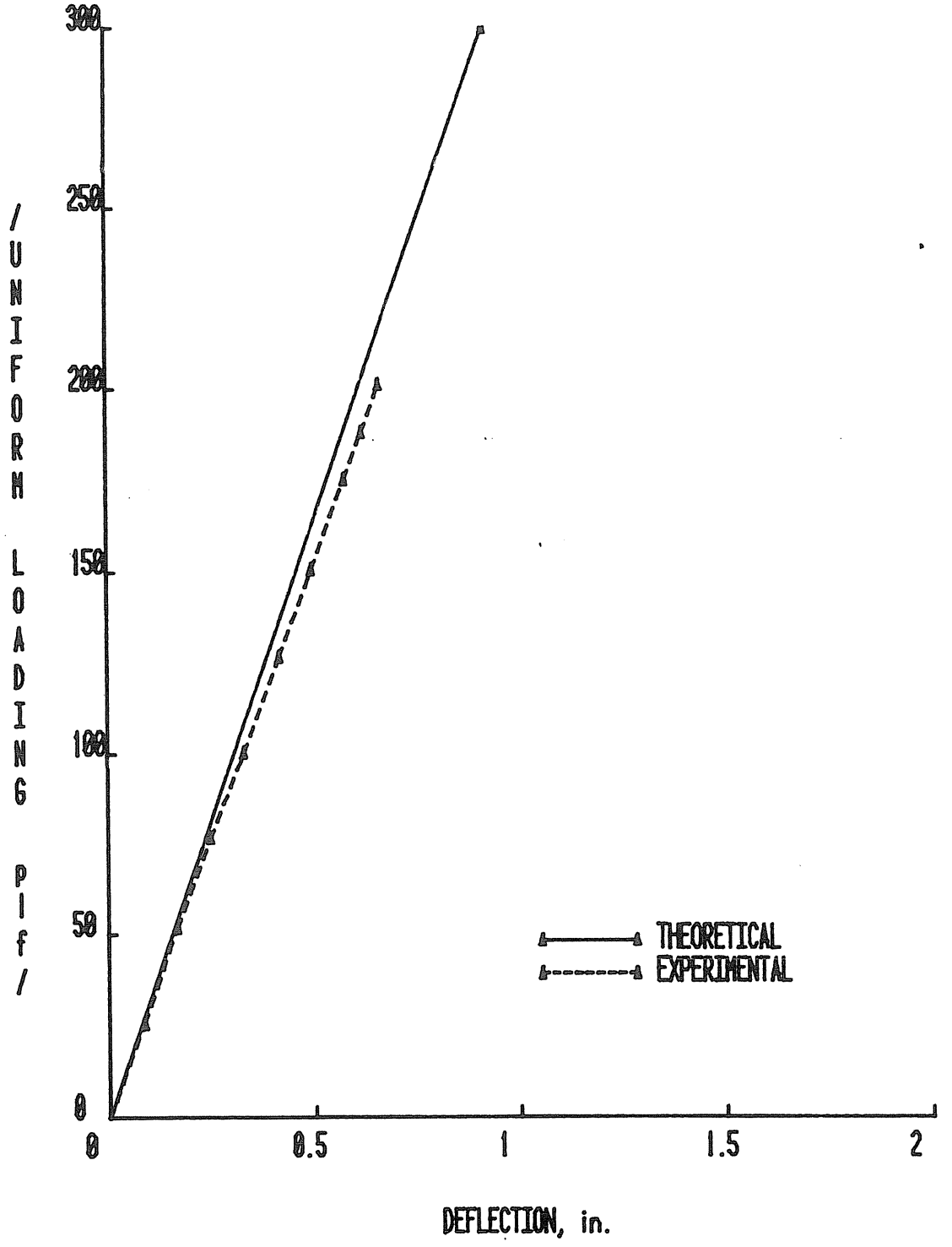


Figure B.14 Load vs. Vertical Deflection, Test A/7-4

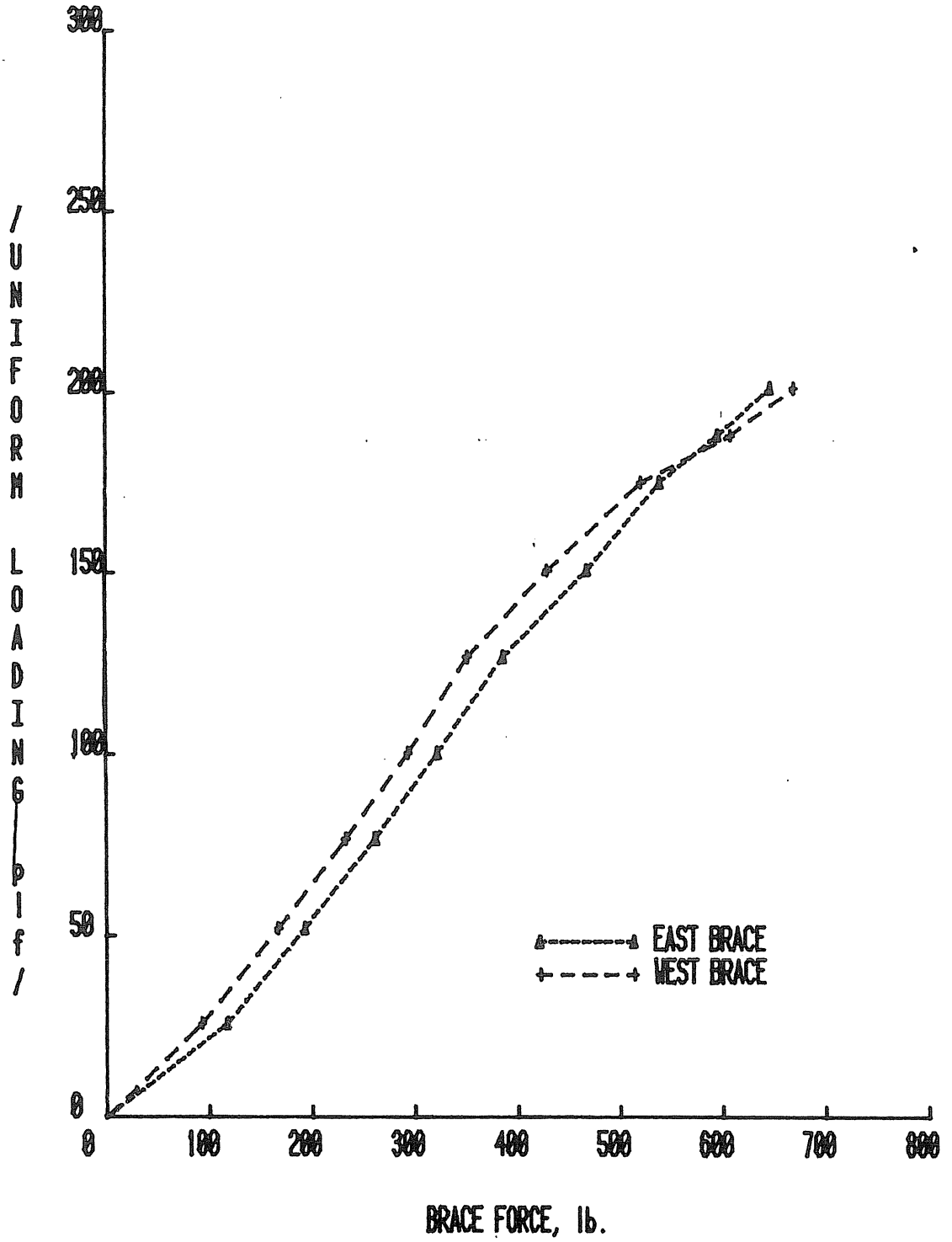


Figure B.15 Vertical Loading vs. Brace Force, Test A/7-4

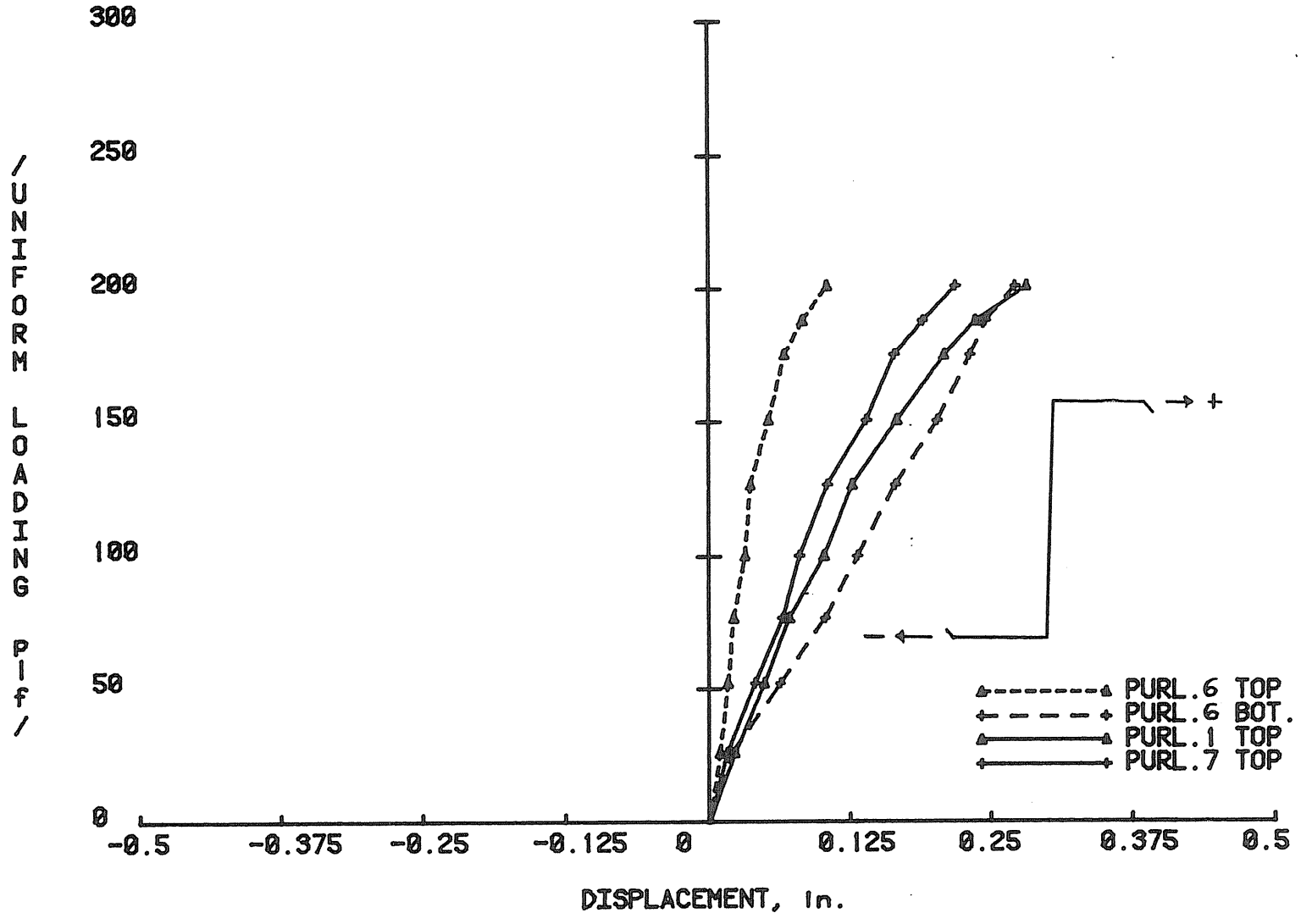


Figure B.16 Vertical Loading vs. Lateral Displacement, Test A/7-4

TEST SUMMARY

Project: MBMA

Test No.: A/7-4 A,B,&C

Test Date: 6/30/82

Purpose: Measure lateral displacements of panel

Span(s):

Thickness: Moment of Inertia:

Parameters: Torsional restraint at rafters
Restraints in tension
Restraint braces attached to 2nd "uphill" purlin
Vacuum loading
Seven purlins at 5 ft. 0 in. o.c.

Failure Load:

Failure Mode:

Predicted Failure Loads:

Method Load

Method Load

Method Load

Discussion:

-Configuration same as Test A/7-0.
-Displacement transducer attached to panels adjacent to top flange of purlins.
-Transducers were placed on the flange side of purlins 1 and 2.
-Transducers were placed on the web side on purlins 5, 6 and 7.
-Test was repeated 3 times -- A, B, C.
-Lateral displacements were found to be consistent in direction.
-Deflection of purlin 6 was very small.
-Brace forces were not measured.

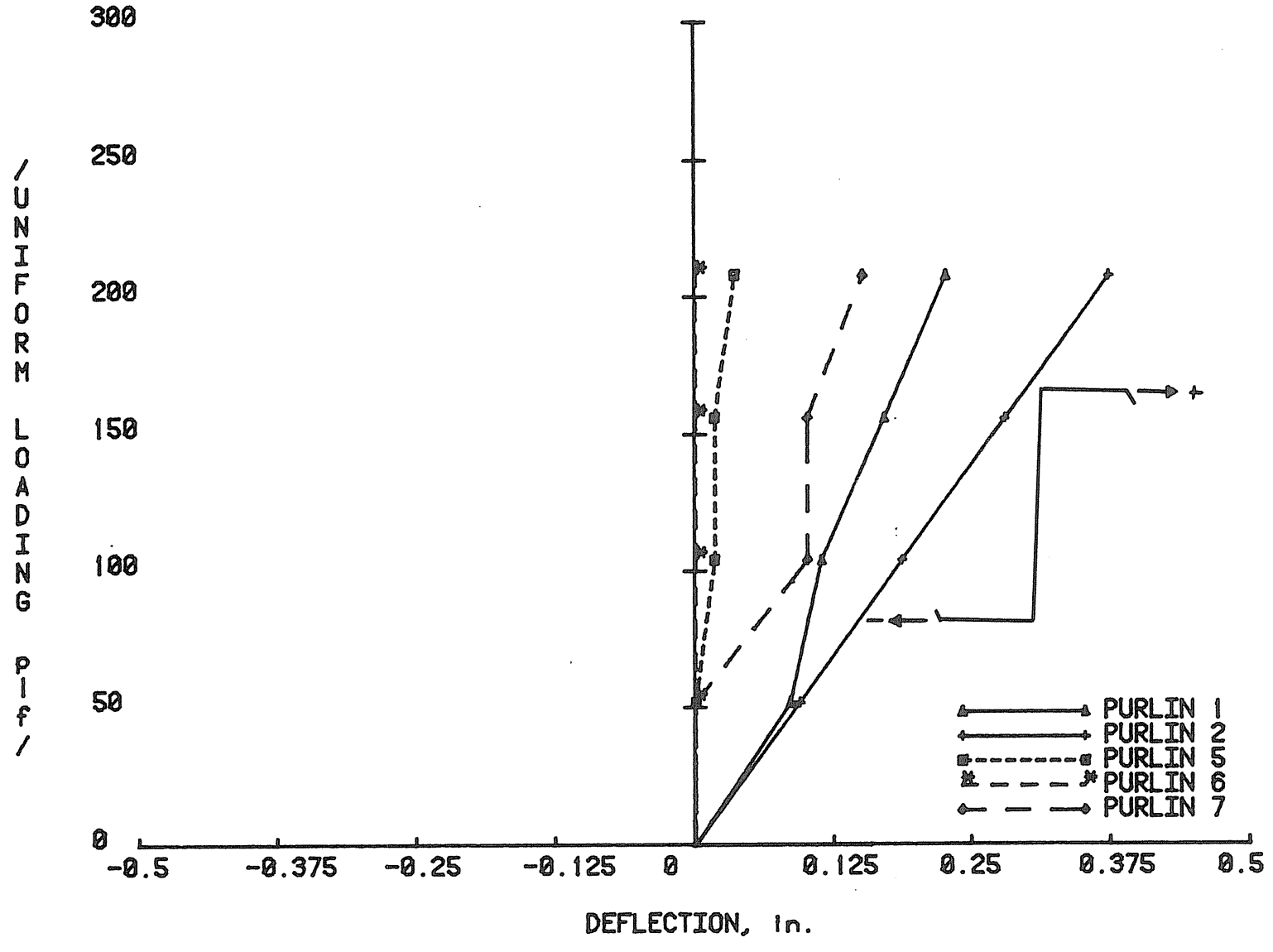


Figure B.17 Horizontal Deflection of Panels at Purlin Locations, Test A/7-4A

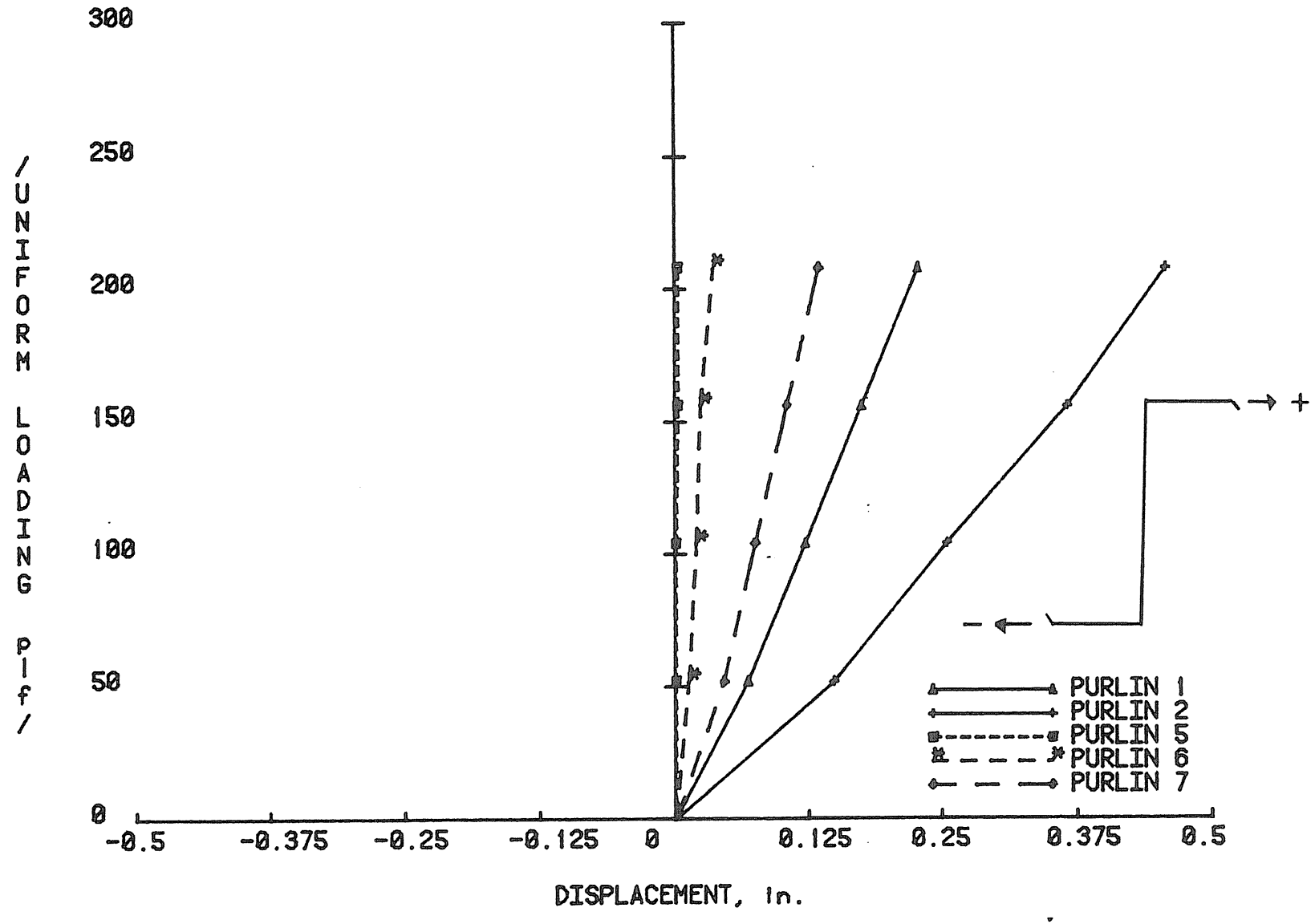


Figure B.18 Horizontal Deflection of Panels at Purlin Locations, Test A/7-4B

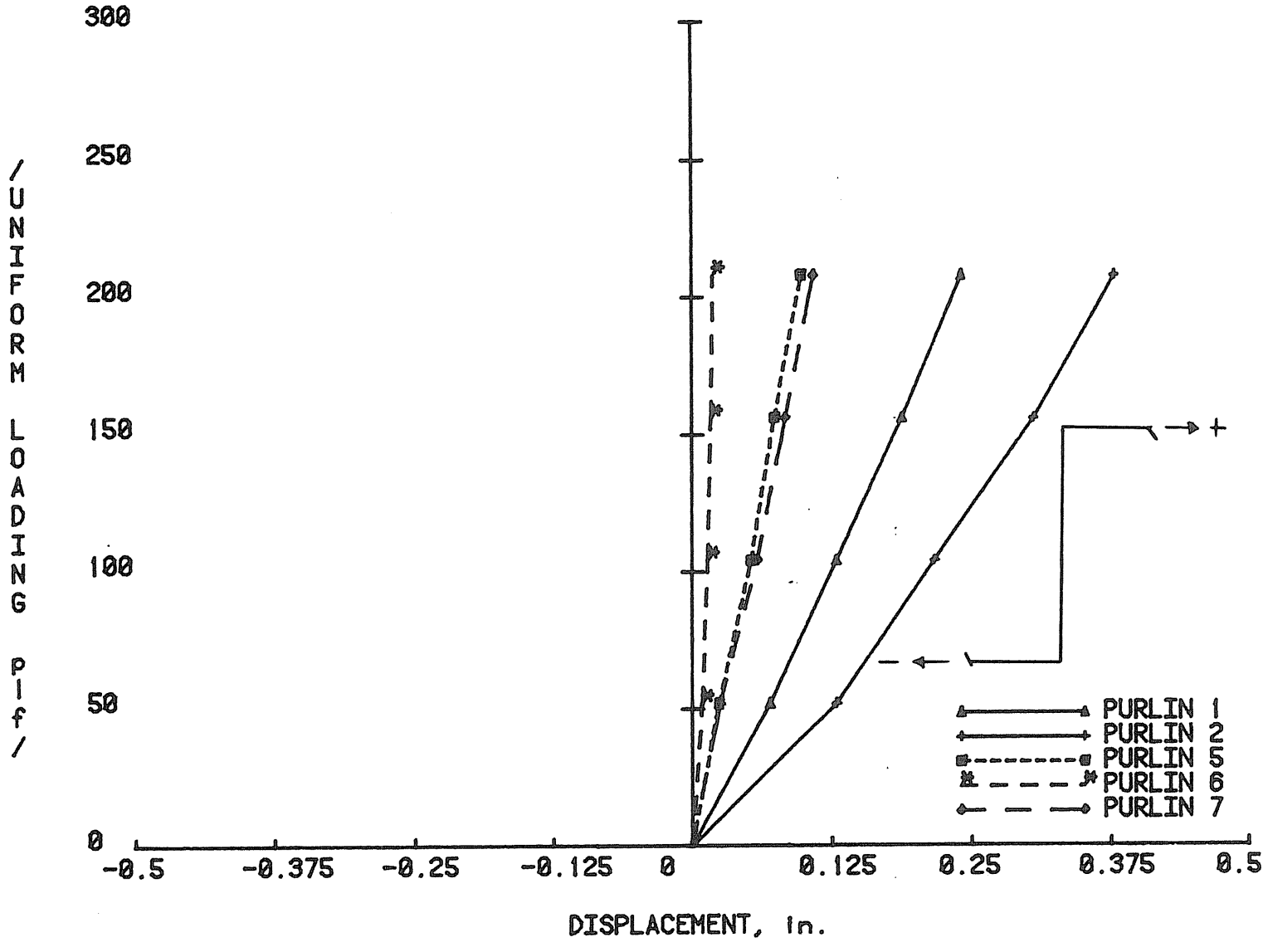


Figure B.19 Horizontal Deflection of Panels at Purlin Locations, Test A/7-4C

TEST SUMMARY

Project: MBMA

Test No.: A/7-5

Test Date: 6/30/82

Purpose: Measure lateral displacements of bottom flange.

Span(s):

Thickness: Moment of

Parameters: Torsional restraint at rafters
Restraints in tension
Restraint braces attached to 2nd "uphill" purlin
Vacuum loading
Seven purlins at 5 ft. 0 in. o.c.

Failure Load:

Failure Mode:

Predicted Failure Loads:

Method: Load

Method:

Method:

Discussion:

-Configuration same as Test A/7-0.

-Displacement transducers attached to web near bottom flange.

-Transducers were placed on the flange side of purlins 1 and 2.

-Transducers were placed on the web side of purlins 5, 6 and 7.

-Lateral displacements were found to be consistent in direction.

-Displacements were in the same direction as the top flange (Test A/7-4) and were found to be larger.

-Brace forces were not measured.

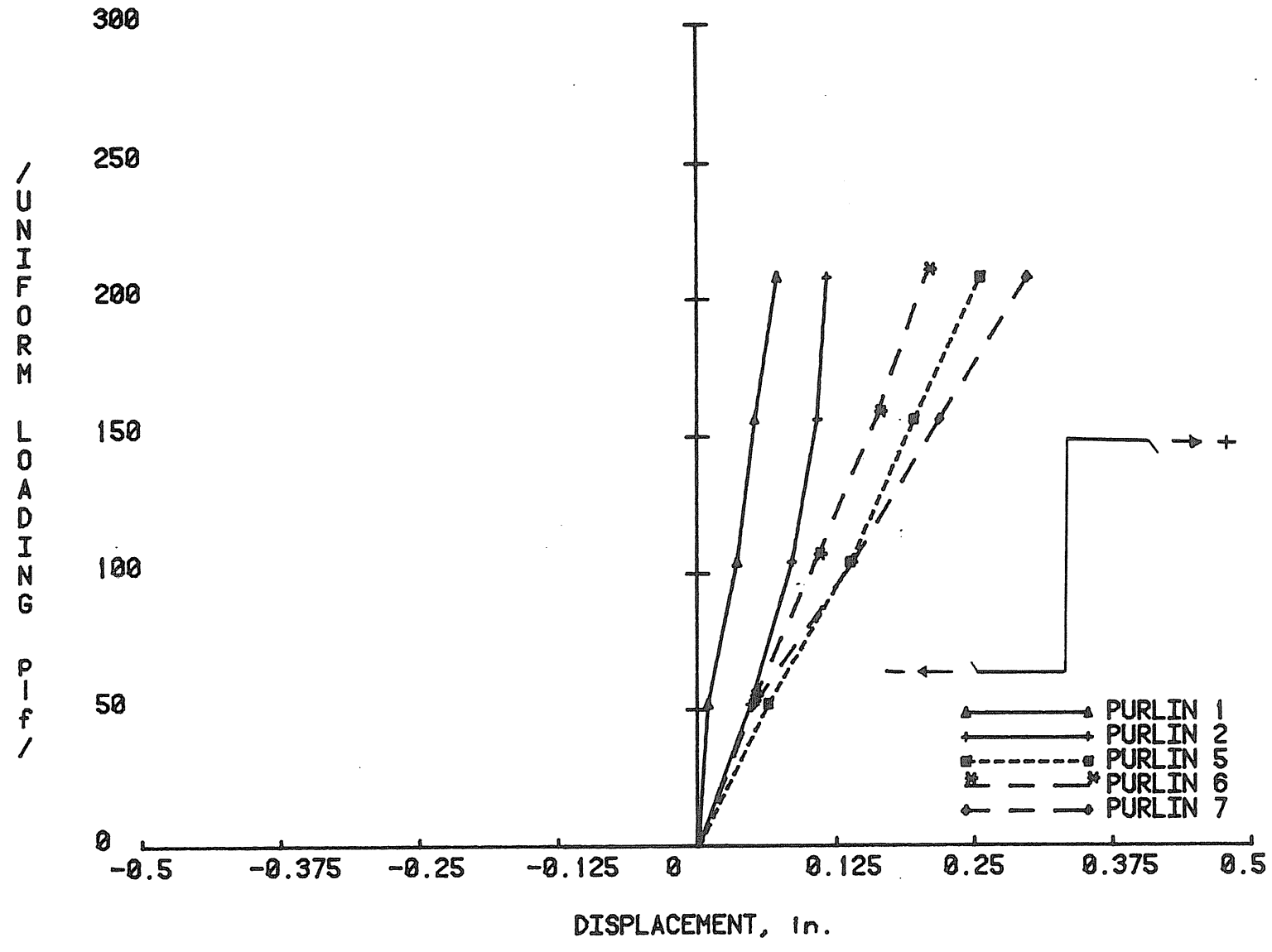


Figure B.20 Horizontal Displacement of Purlins, Test A/7-5

TEST SUMMARY

Project: MBMA

Test No.: Test A/7-6

Test Date: 6/30/82

Purpose: Measure lateral displacement of top flange

Span(s):

Thickness:

Parameters: Torsional restraint at rafters
Restraints in tension
Restraint braces attached to 2nd "uphill" purlin
Vacuum loading
Seven purlins at 5 ft. 0 in. o.c.

Failure Load:

Failure Mode:

Predicted Failure Loads:

Method

Method

Method

Discussion:

-Configuration same as Test A/7-0.
-Displacement transducers attached to purlin web near top flange.
-Transducers were placed on the flange side of purlin 1 and 2.
-Trnasducers were placed on the web side of purlins 5, 6 and 7.
-Lateral displacements were found to be consistent in direction.
-Brace forces were not measured.

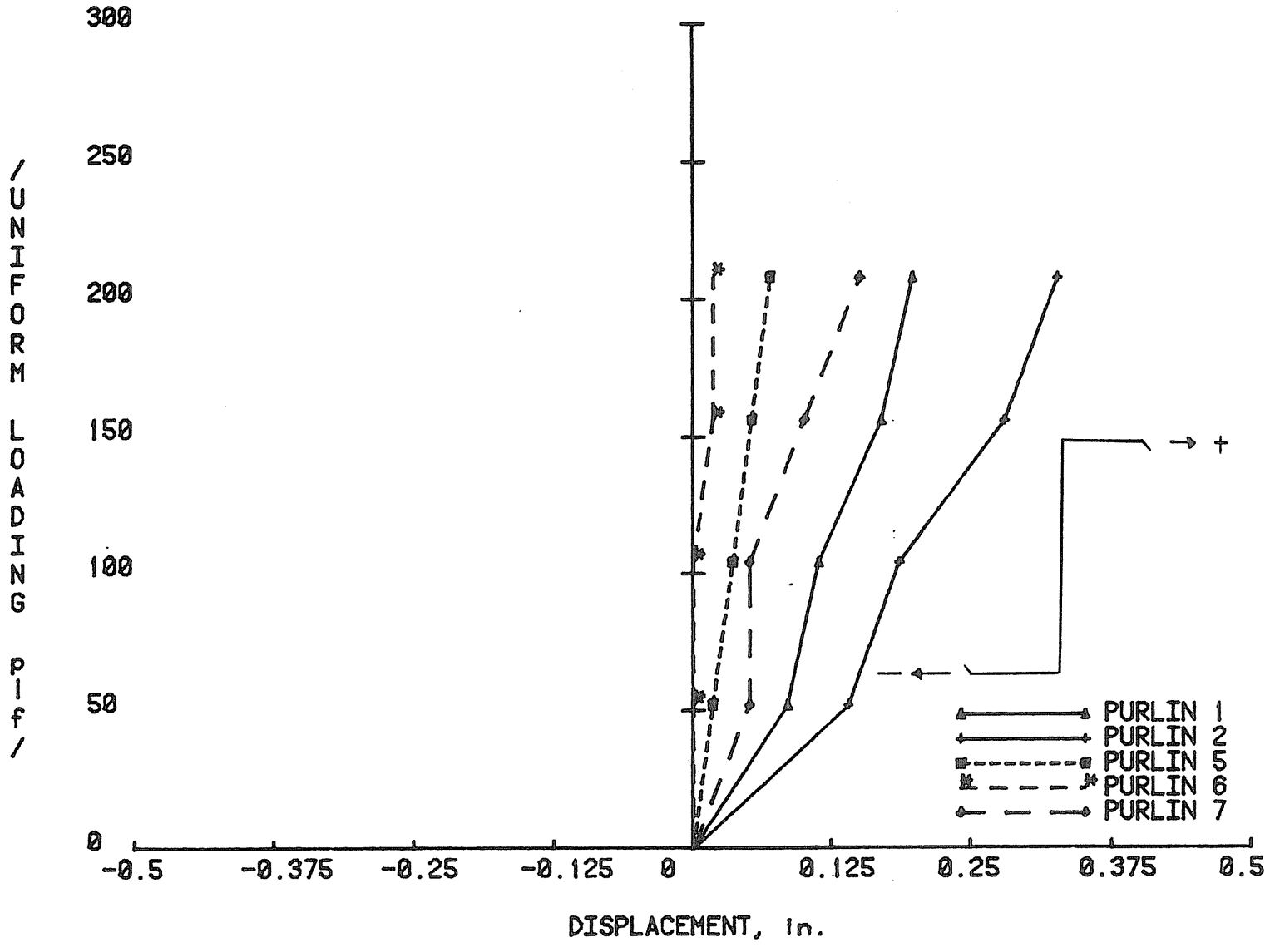


Figure B.21 Horizontal Top Displacement of Purlins, Test A/7-6

TEST SUMMARY

Project: MBMA

Test No.: A/7-7

Test Date: July 21, 1982

Purpose: Measure brace force accumulation for gravity and vacuum loading

Span(s): 14.29'

Thickness: .076" Moment of Inertia: 10.346"^{4}

Parameters: Torsional restraint at rafters
Restraints in tension
Restraint braces attached to 2nd "uphill" purlin
Vacuum loading
Seven purlins at 5 ft. 0 in. o.c.

Failure Load:

Failure Mode:

Predicted Failure Loads:

Method Load

Method Load

Method Load

Discussion:

Gravity Loading

-Gravity loading was applied in increments of 99 plf/5 ft. panel section.

-Gravity loading was from north to south and unloading from south to north.

-Brace forces increased approximately linearly with load increment.

-Vertical and lateral deflections were erratic because of loading sequence.

Vacuum Loading

-Brace forces varied linearly with load.

-Vertical deflections were approximately linear.

-Horizontal deflection was approximately linear.

Comparison

-At 99 plf per purlin over the entire test set-up, total brace force in the gravity test was 728 lb. and in the vacuum test 775 lb.

-Test results are considered to be identical for both types of loading.

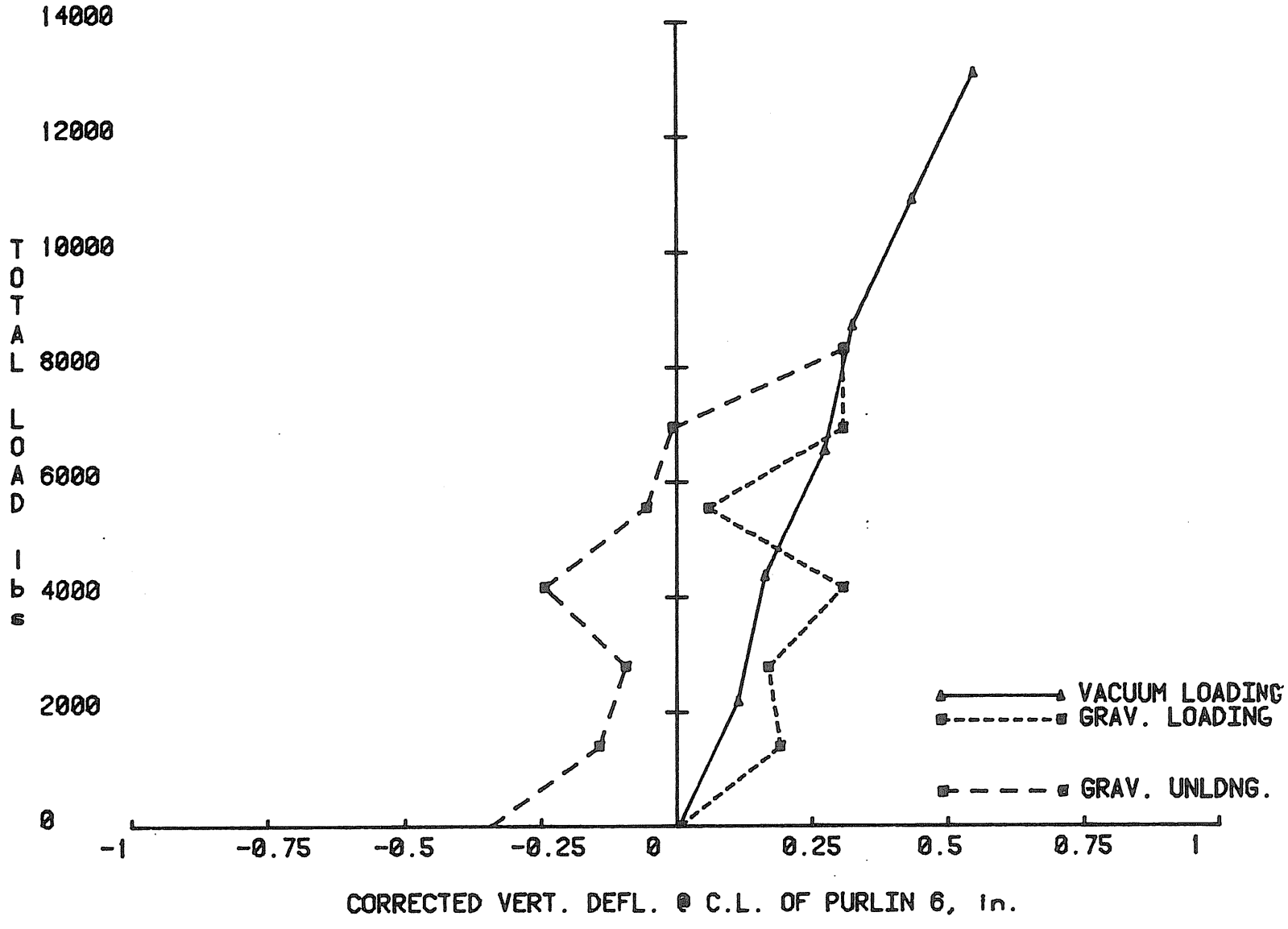


Figure B.22 Total Vertical Load vs. Vertical Deflection of Purlin 6, Test A/7-7

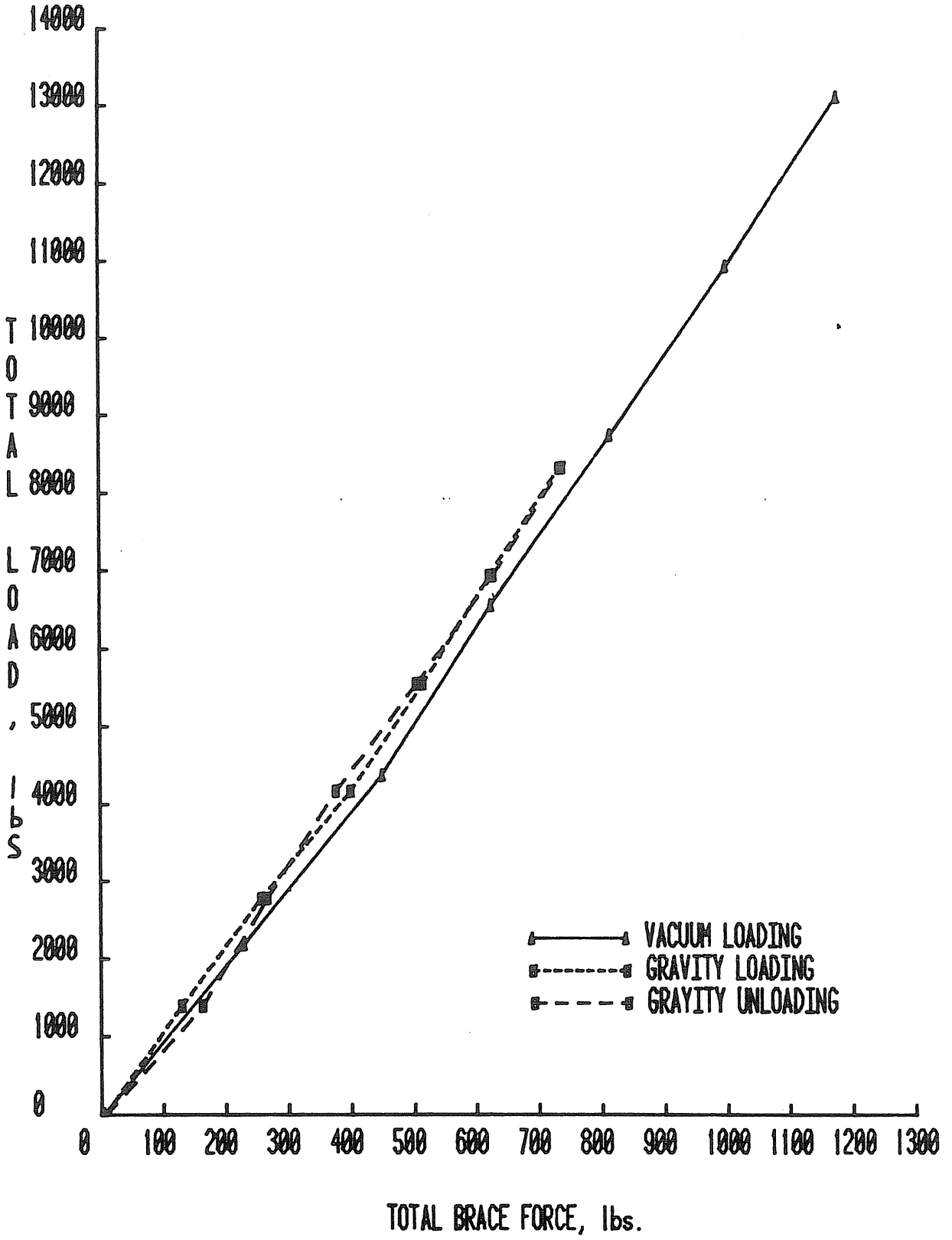


Figure B.23 Total Vertical Load vs. Total Brace Force, Test A/7-7

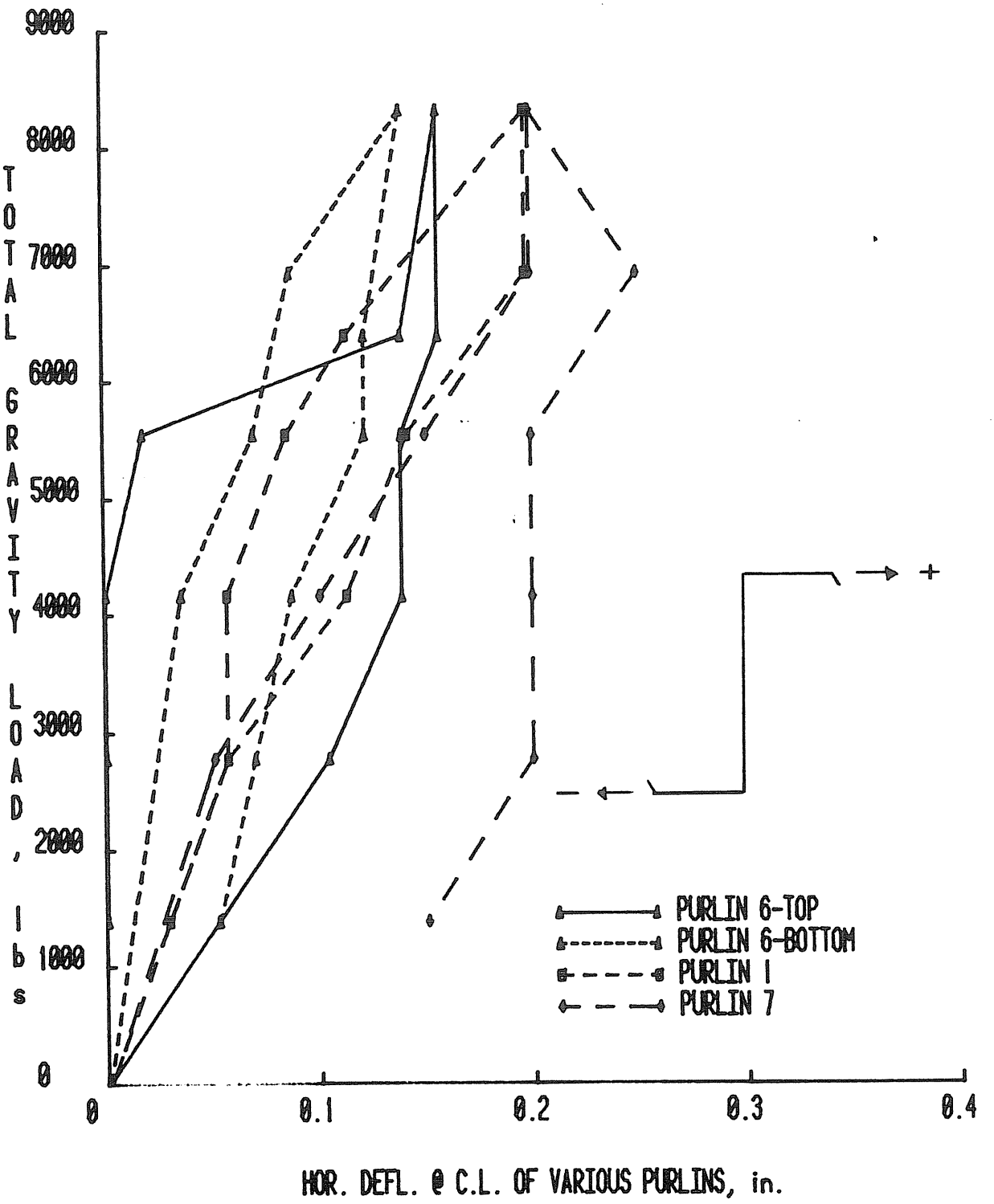


Figure B.24 Total Vertical Load vs. Horizontal Deflection, Test A/7-7 Gravity Loading

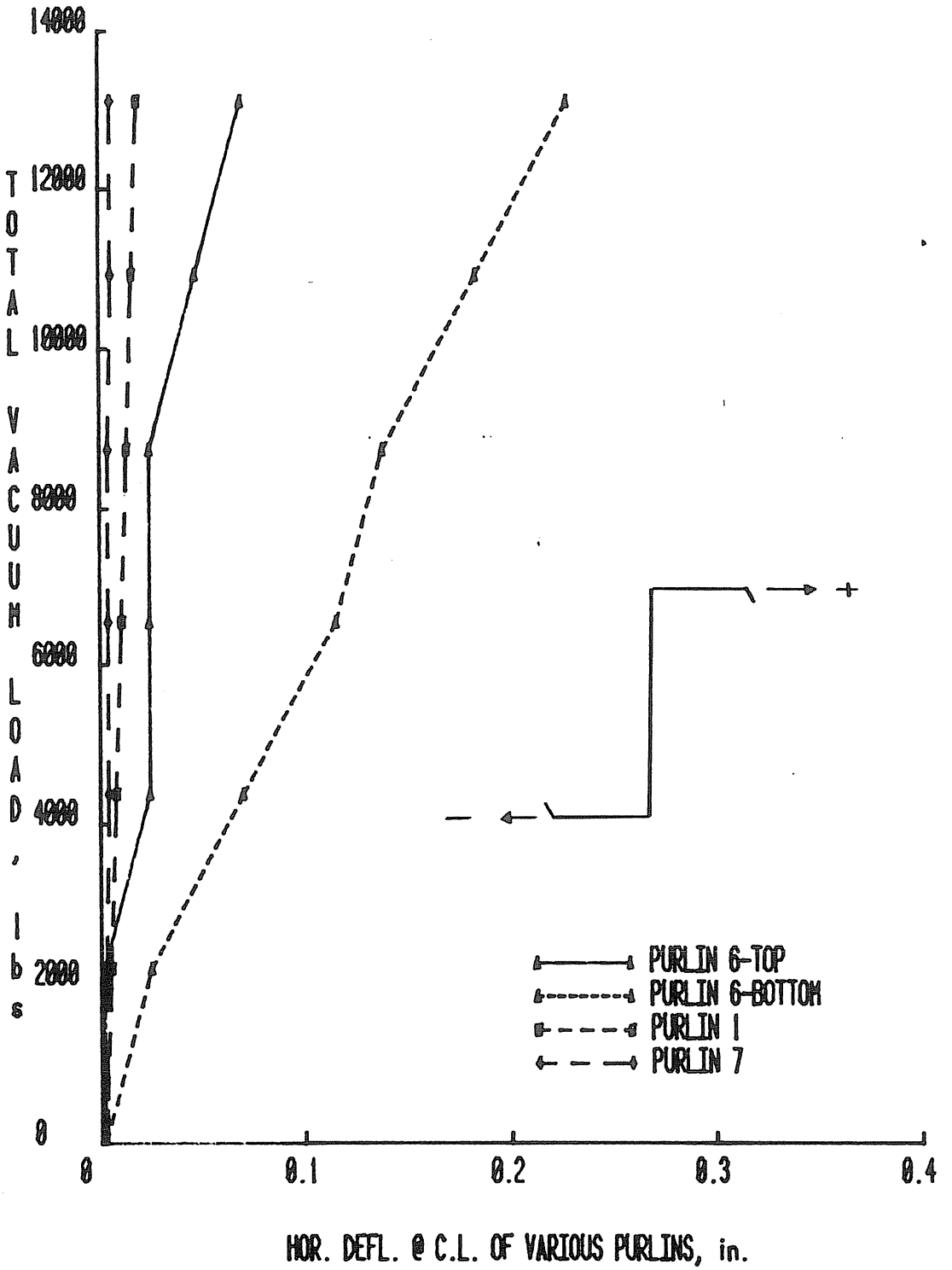
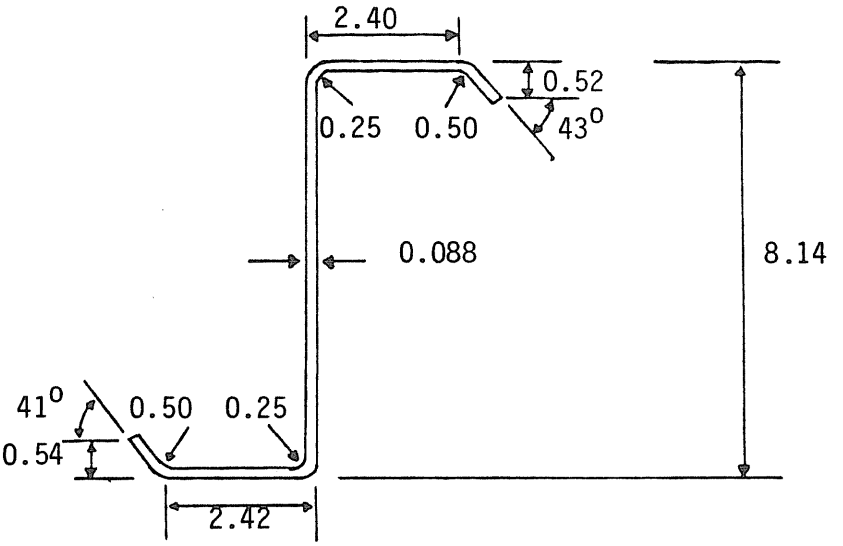


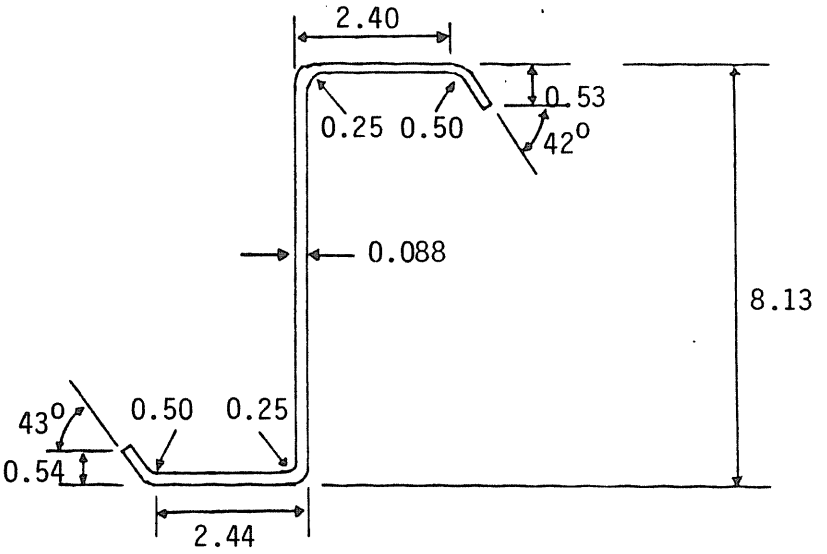
Figure B.25 Total Vertical Load vs. Horizontal Deflection, Test A/7-7 Vacuum Loading

APPENDIX C

SERIES B/2 ACCUMULATION TEST RESULTS



External Purlin (North)



Internal Purlin (South)

Figure C.1 Measured Purlin Dimensions, Test B/2

```
A I S I   P U R L I N   A N A L Y S I S
              Z-SECTION
IDENTIFICATION: MBMA TEST-B/2-1, S.PURLIN (SEPT 30,1982)
```

	TOP	BOTTOM
FLANGE(in)	2.400	2.440
LIP(in)	0.530	0.540
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)	8.13
THICKNESS(in)	0.088
YIELD STRENGTH(ksi)	56

MOMENTS OF INERTIA(in^4)	SECTION MODULII(in^3) TOP	BOTTOM
GROSS= 12.677	3.144	3.162
STRENGTH= 12.677	3.144	3.162
DEFLECTION= 12.677		

```
XL=    2.062  in
FC=   33.600  ksi
FT=   33.600  ksi
FBW=  32.929  ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)
            MC=     9.302  ft-k
            M1=     8.854  ft-k
            MW=     9.305  ft-k
            MU=    14.699  ft-k (1.67*allowable)
SPAN          =    22.250  ft.
UNIFORM LOAD=    237.535  plf (1.67*allowable)
DEFLECTION  =      1.475  in./100plf
```

Figure C.2 AISI Purlin Analysis, Test B/2, External Purlin

```
A I S I   P U R L I N   A N A L Y S I S
                Z-SECTION
IDENTIFICATION: MBMA TEST-B/2-1,N.PURLIN (SEPT 30,1982)
```

	TOP	BOTTOM
FLANGE(in)	2.400	2.420
LIP(in)	0.520	0.540
LIP ANGLE(deg)	43.000	41.000
RADIUS L/F(in)	0.500	0.500
RADIUS F/W(in)	0.250	0.250

TOTAL DEPTH(in)	8.14
THICKNESS(in)	0.088
YIELD STRENGTH(ksi)	56

	MOMENTS OF INERTIA(in^4)	SECTION MODULII(in^3) TOP	BOTTOM
GROSS=	12.684	3.136	3.165
STRENGTH=	12.684	3.136	3.165
DEFLECTION=	12.684		

BE=	2.062	in
FC=	33.600	ksi
FT=	33.600	ksi
FBW=	32.919	ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)

MC=	8.781	ft-k
MT=	8.863	ft-k
MW=	9.277	ft-k
MU=	14.664	ft-k (1.67*allowable)
SPAN =	22.250	ft.
UNIFORM LOAD=	236.960	plf (1.67*allowable)
DEFLECTION =	1.474	in./100plf

Figure C.3 AISI Purlin Analysis, Test B/2, Internal Purlin

TEST SUMMARY

Project: MBMA Roof Systems Behavior

Test No.: B/2-1-A, Sub Test I, bolted at supports

Test Date: September 30, 1982

Purpose: Sub test for assessing accumulation of restraint forces

Span(s): 22.25'

Thickness: 0.088 in. Moment of Inertia: 12.7 in^4

Parameters: No intermediate braces

Torsional restraint @ rafter only north purlin braced

Panel shear stiffness

Panel torsional restraint

Failure Load: Loaded to 99 plf

Failure Mode:

Predicted Failure Loads:

Method AISI Constr. bending x 1.67 Load 237.0 plf

Method _____ Load _____

Method _____ Load _____

Discussion:

-Vertical deflection was about 10% higher than predicted from the constrained bending assumption for south (external) purlin.

-Brace forces increased linearly with increasing vertical load.

-At 99 plf, east brace force was 21% greater than west brace force.

-At 99 plf, summation of brace forces equalled 22% of total vertical load.

-At 99 plf, lateral displacement of top and bottom flange were the same magnitude and the same direction, but smaller than panel lateral displacement.

-Maximum lateral displacement was .12 in. at 99 plf.

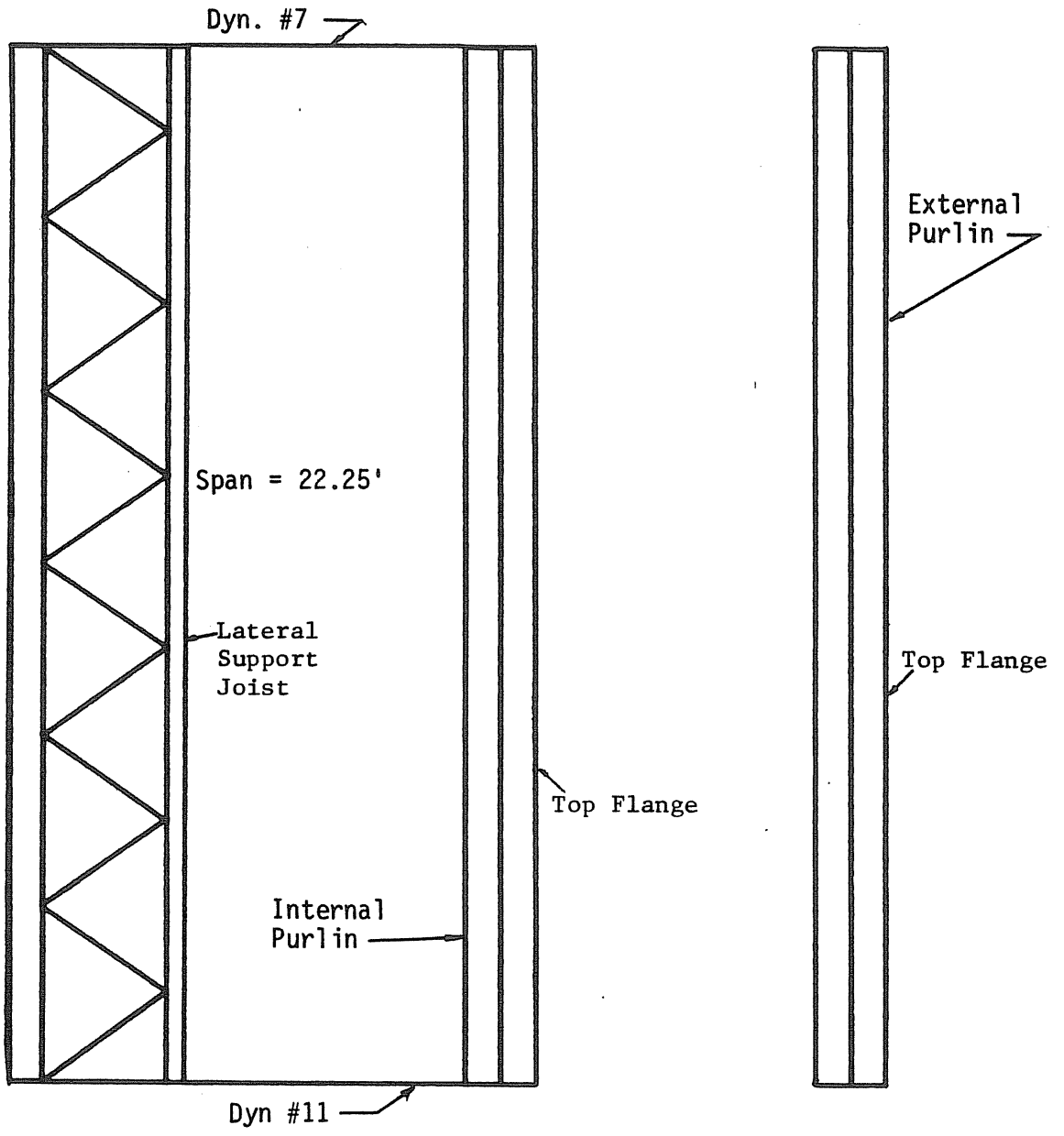


Figure C.4 Instrumentation Locations, Test B/2-1-A

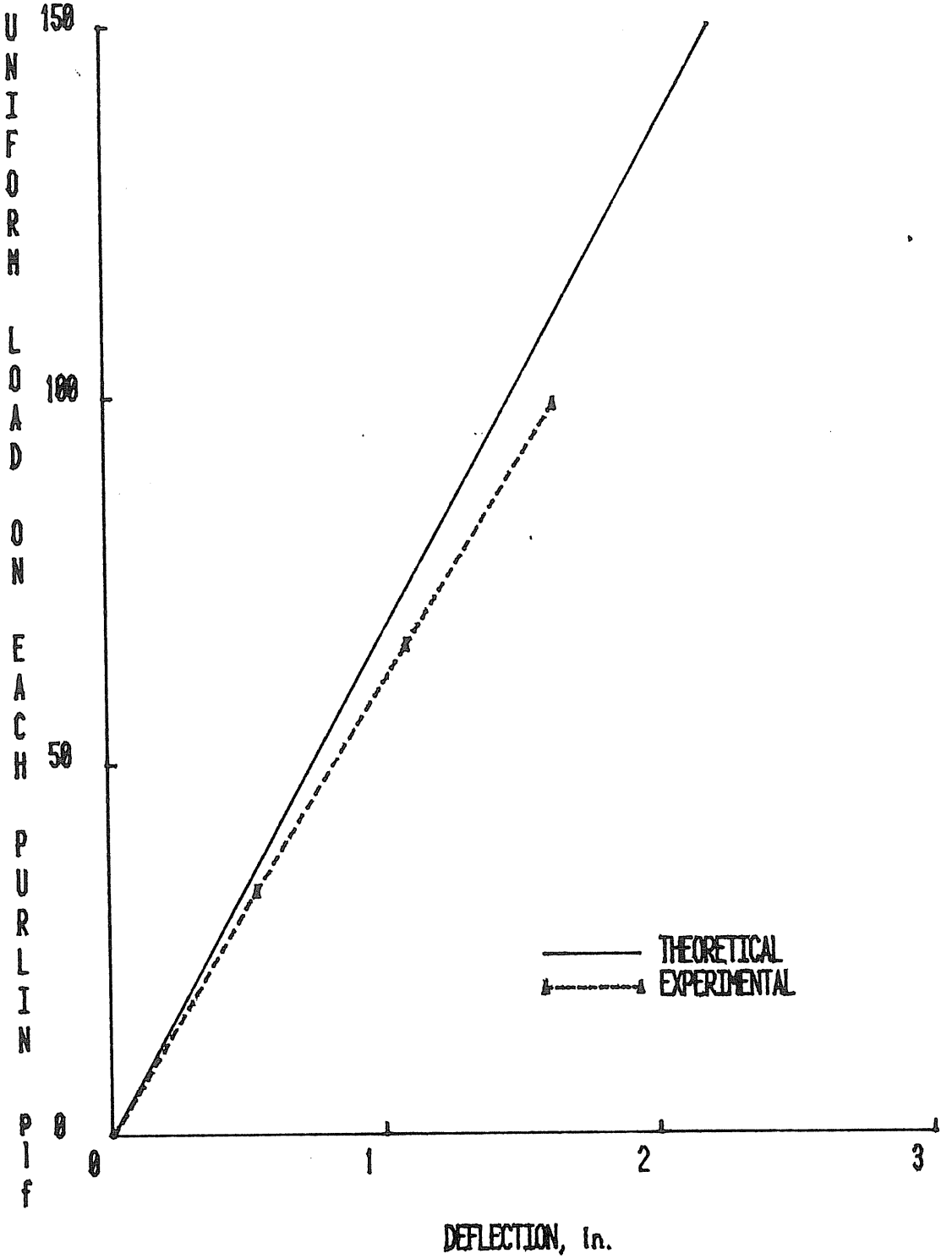


Figure C.5 Load vs. Vertical Deflection, Test B/2-1-A

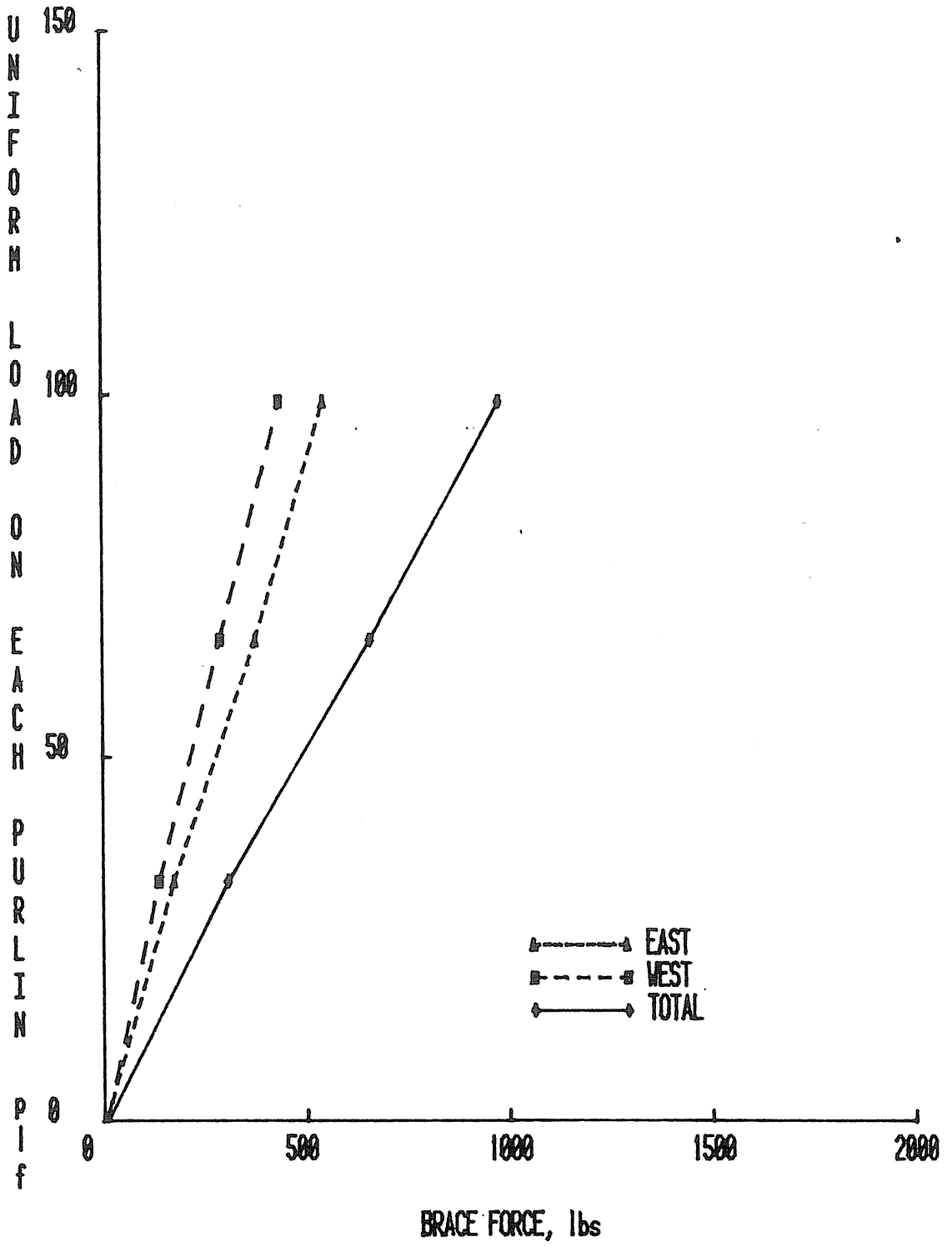


Figure C.6 Vertical Load vs. Brace Forces, Test B/2-1-A, Sub Test I

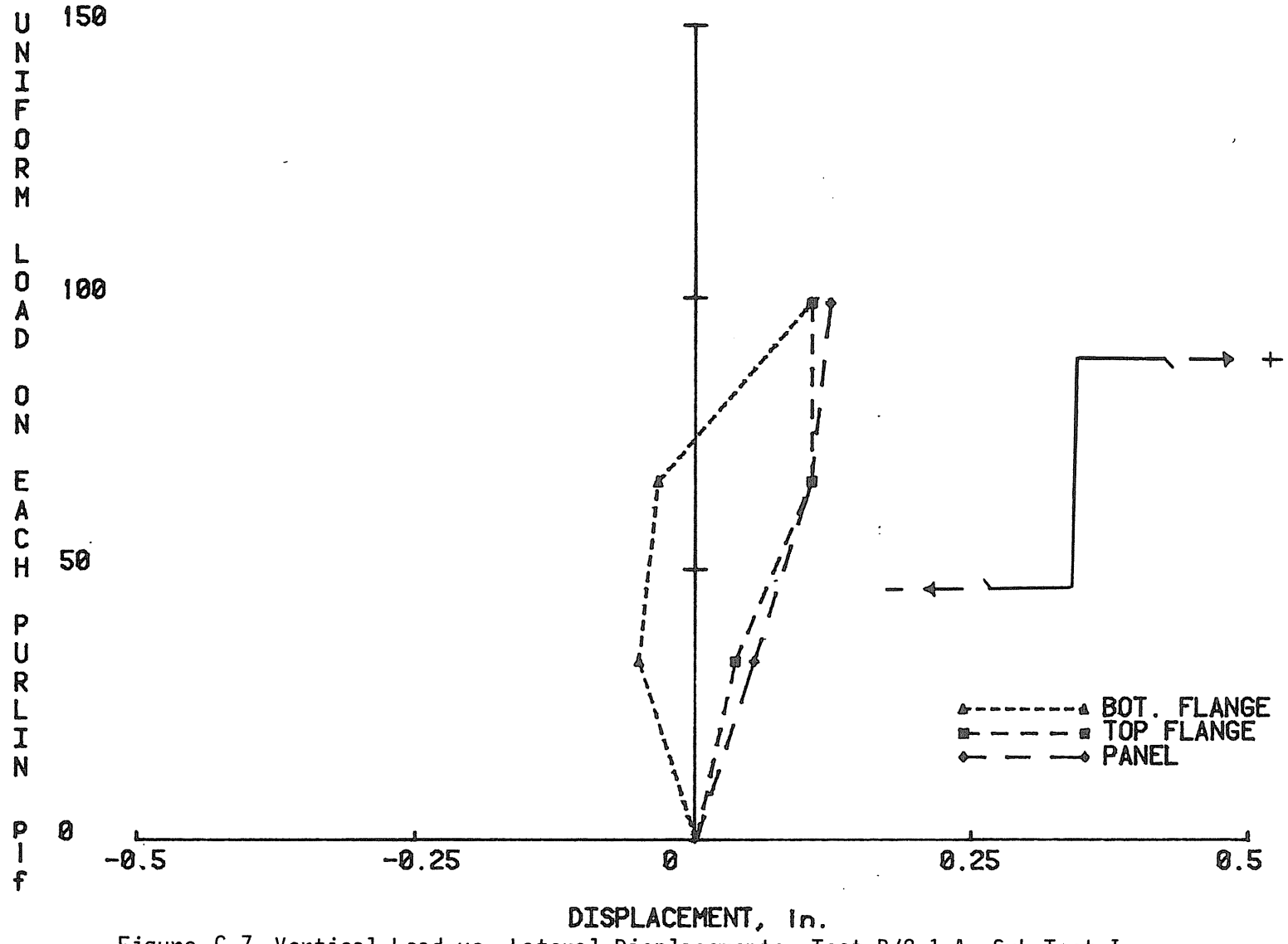


Figure C.7 Vertical Load vs. Lateral Displacements, Test B/2-1-A, Sub Test I

TEST SUMMARY

Project: MBMA Roof System Behavior

Test No.: B/2-1-B, Sub Test I (knife edge supports)

Test Date: October 5, 1982

Purpose: Sub Test for assessing accumulation of restraint forces & comparison of supports.

Span(s): 22.25'

Thickness: 0.088 in. Moment of Inertia: 12.7 in^4

Parameters: No intermediate braces

Torsional restraint @ rafter only north purlin braced

Panel shear stiffness

Panel torsional restraint

Failure Load: Loaded to 99 plf

Failure Mode:

Predicted Failure Loads:

Method AISI Constr. bending x 1.67 Load 237.0 plf

Method _____ Load _____

Method _____ Load _____

Discussion:

-Vertical deflection was between 20 to 25% higher than predicted from the constrained bending assumption for external purlin.

-Brace forces increased linearly with increased vertical load.

-At 99 plf, east brace force was 38% greater than west brace force.

-At 99 plf, summation of brace forces equalled 22% of total vertical load.

-At 99 plf, lateral displacement of top and bottom flange were roughtly of the same magnitude and opposite direction, but much smaller than panel lateral displacement.

-Maximum lateral displacements were -0.153" for the bottom flange, +0.094" for the top flange, and 0.339" for the panel.

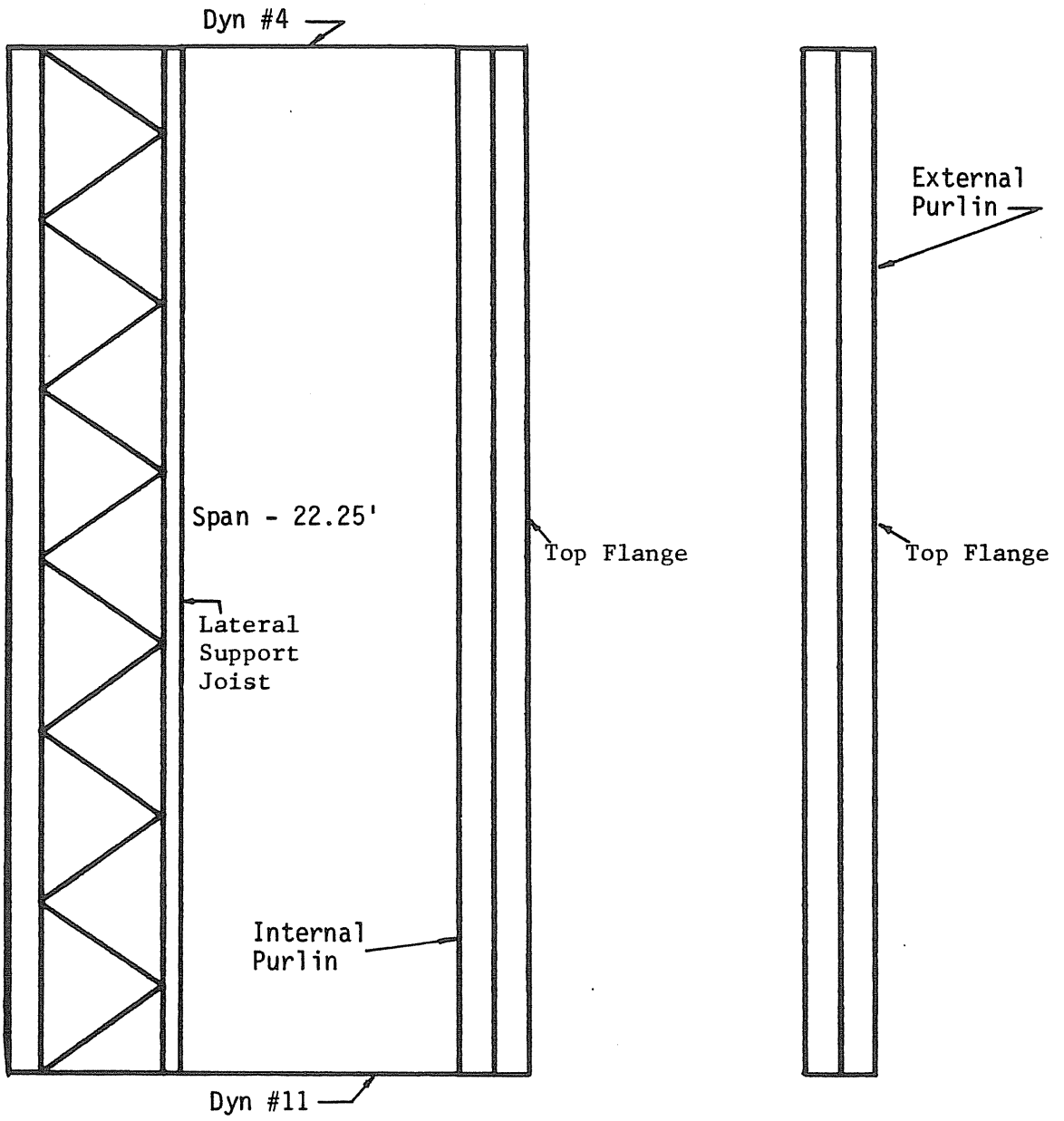


Figure C.8 Instrumentation Locations, Test B/2-1-B

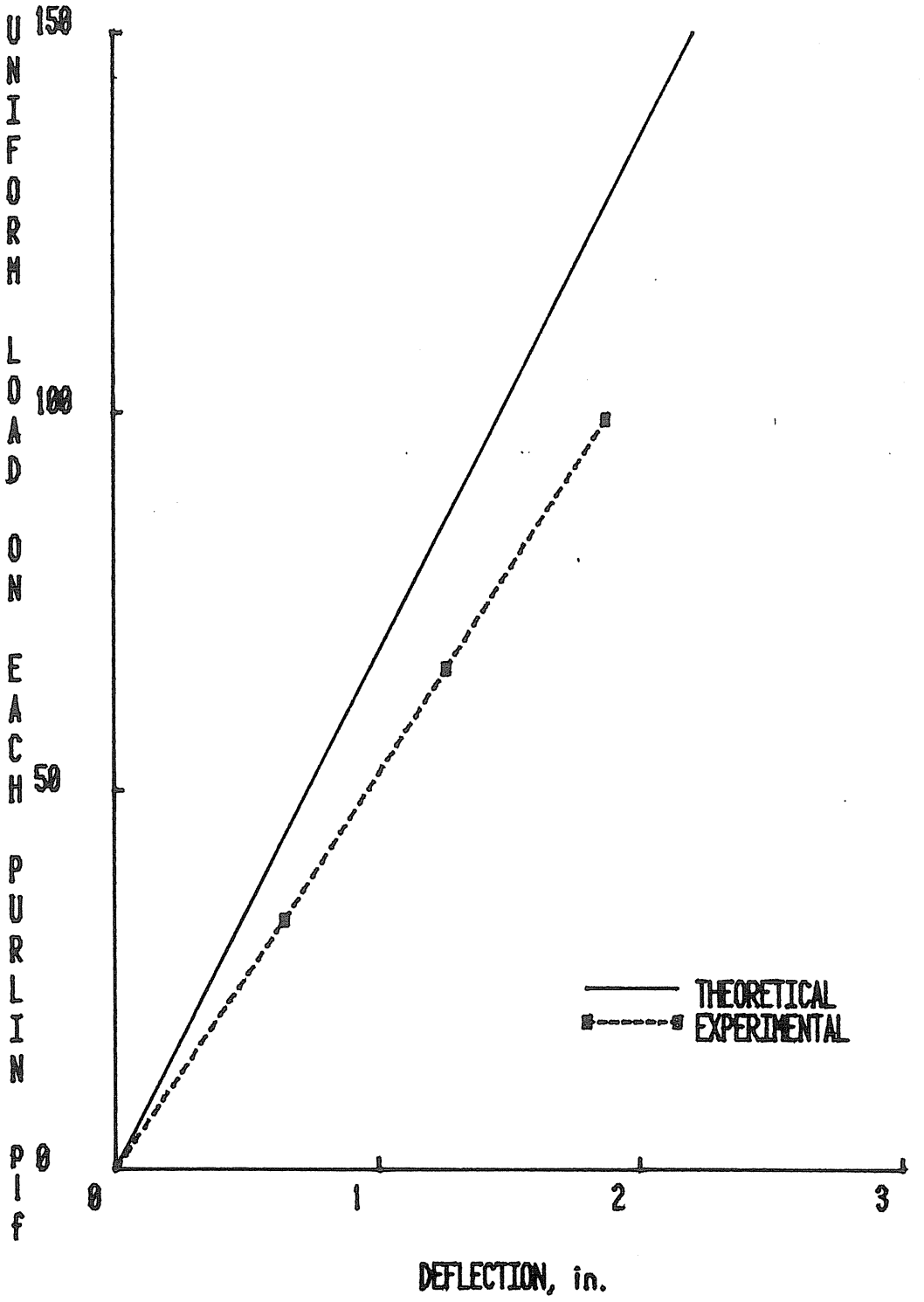


Figure C.9 Load vs. Vertical Deflection, Test B/2-1-B, Sub Test I

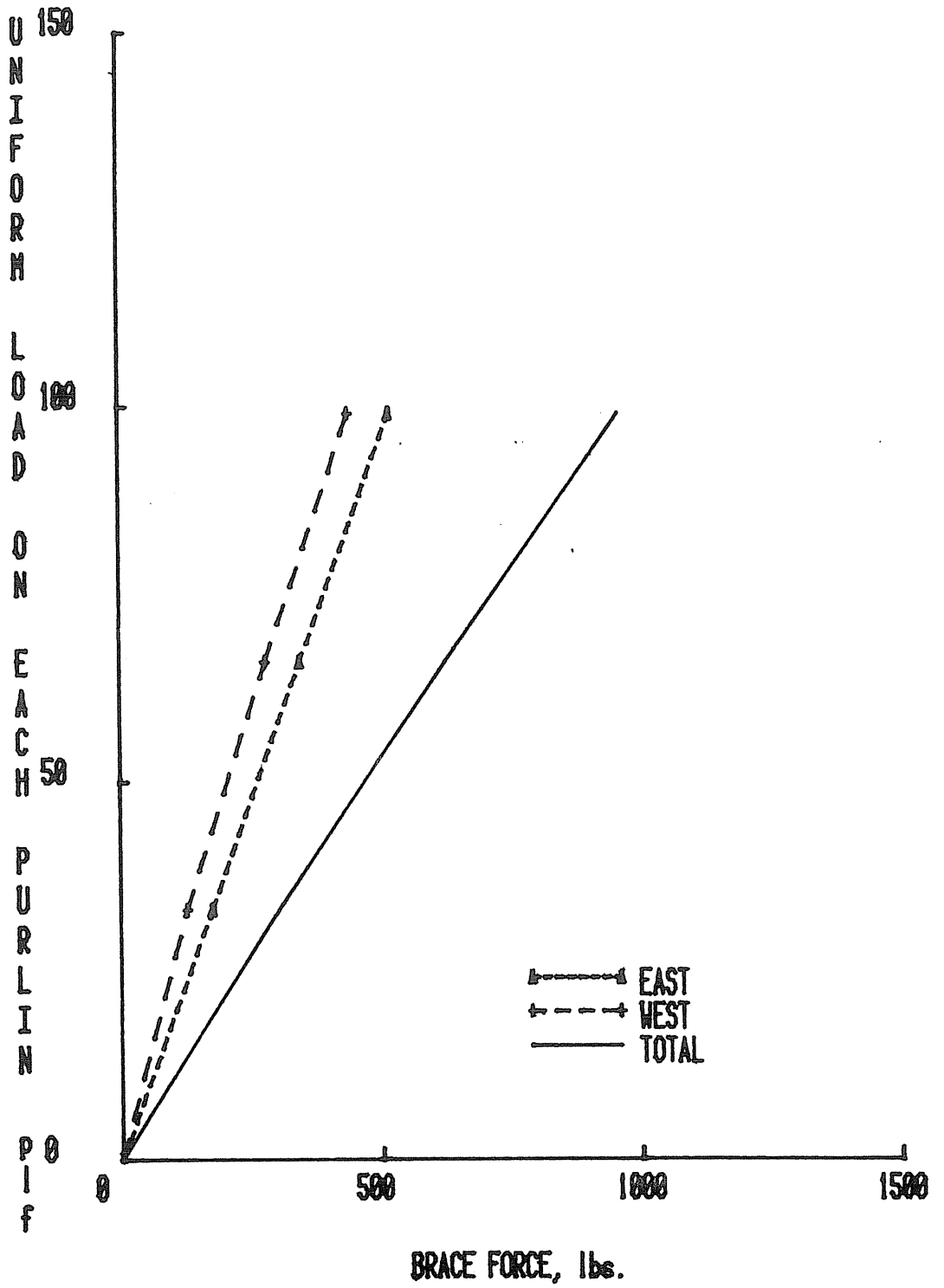


Figure C.10 Vertical Load vs. Brace Force, Test B/2-1-B, Sub Test I

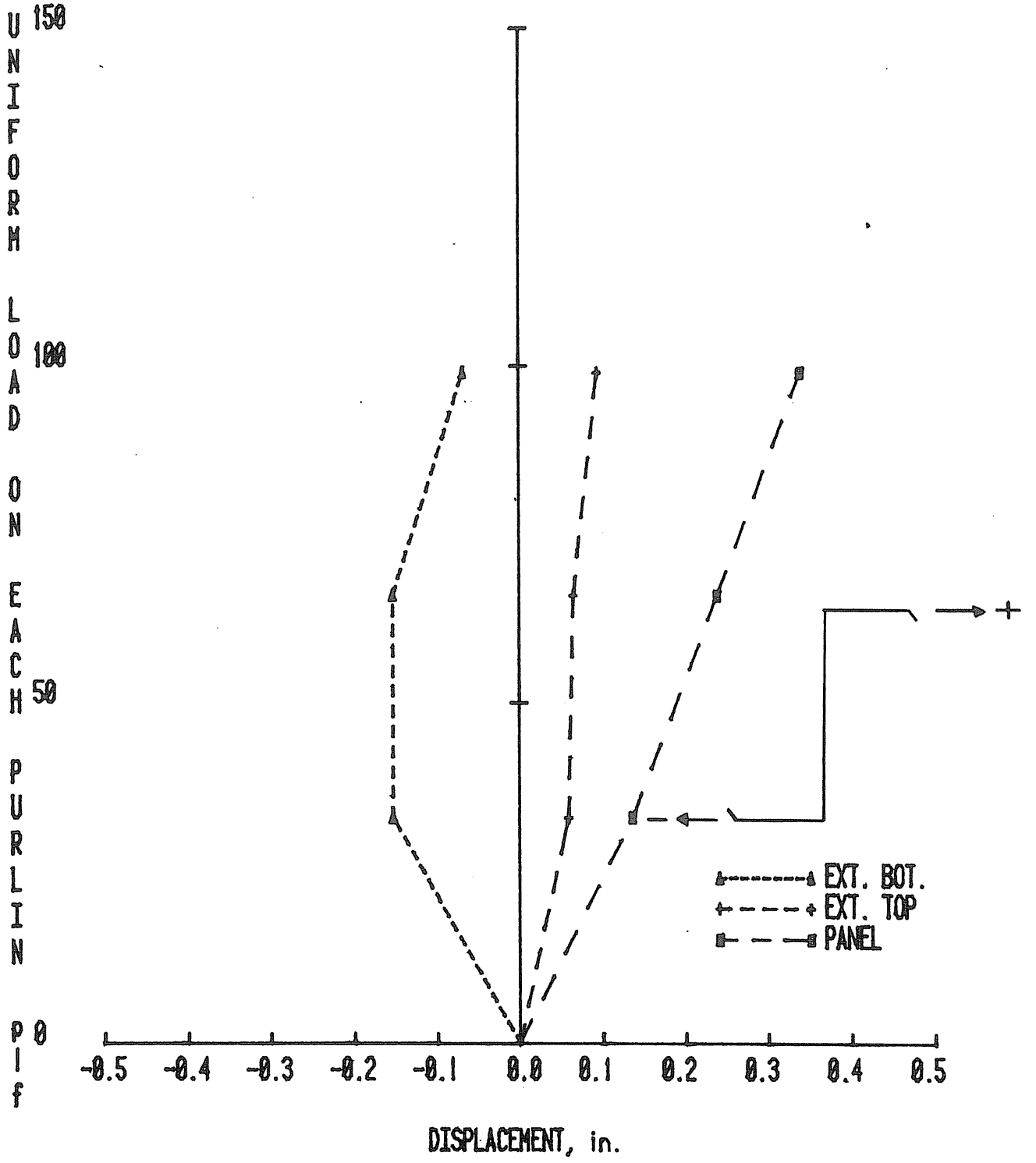


Figure C.11 Vertical Load vs. Lateral Displacement, Test B/2-1-B, Sub Test I

TEST SUMMARY

Project: MBMA Roof System Behavior

Test No.: B/2-2-A, Sub Test I, bolted at supports

Test Date: September 30, 1982

Purpose: Same as B/2-1, effect of more braces at rafters

Span(s): 22.25'

Thickness: Moment of Inertia:

Parameters: Same as Test B/2-1 except 4 torsional braces were used

Failure Load:

Failure Mode:

Predicted Failure Loads:

Method Load

Method Load

Method Load

Discussion:

-Vertical deflection was about 10% higher than predicted from the constrained bending assumption for south (ext.) purlin.

-Brace forces increased linearly with increasing vertical load.

-At 99 plf, summation of external brace forces equaled 6% of total vertical load. Summation of internal brace forces equaled 20% of total vertical load.

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

-Maximum lateral displacement was .202 in. at centerline of panel.

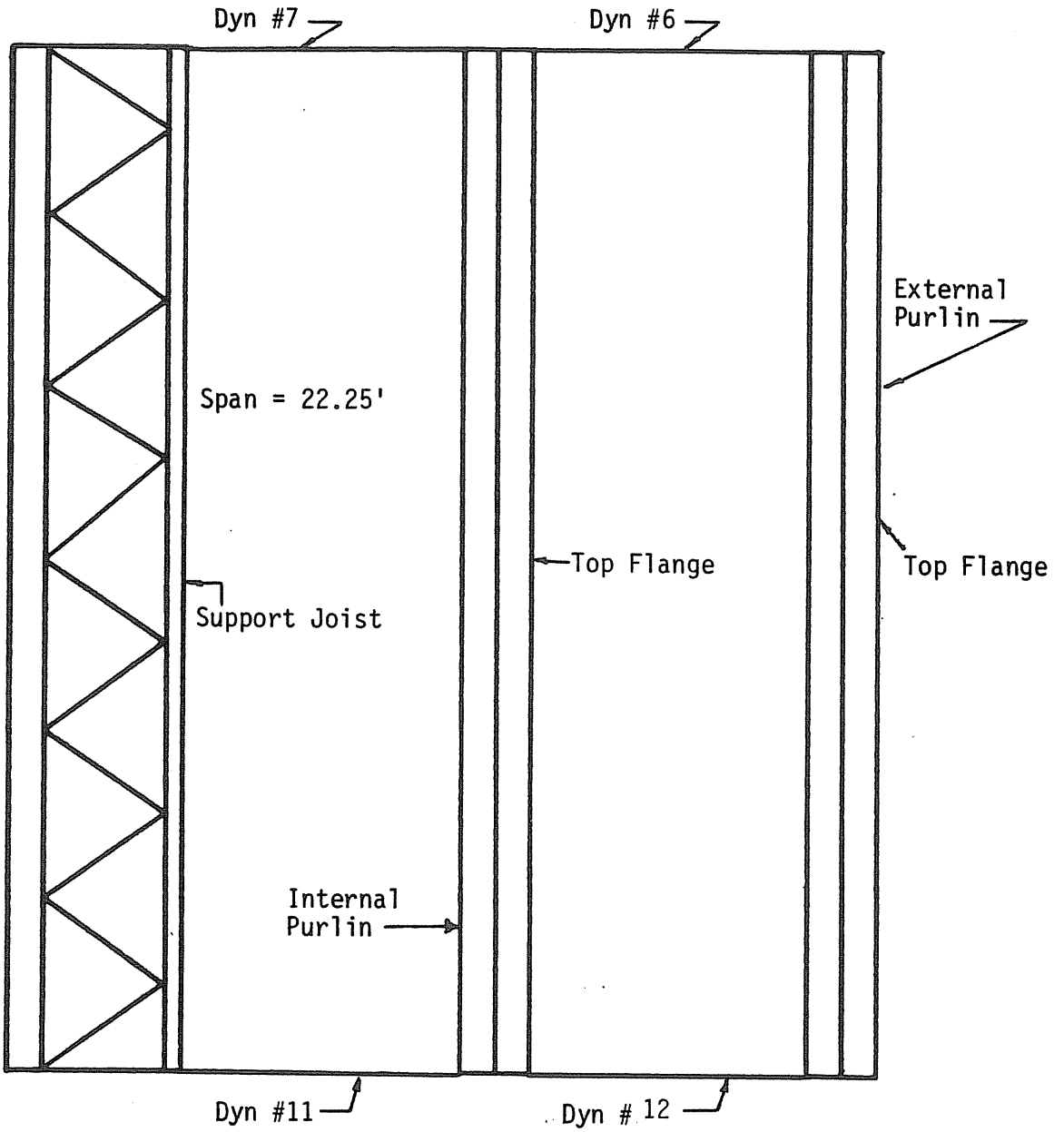


Figure C.12 Instrumentation Locations, Test B/2-2-A

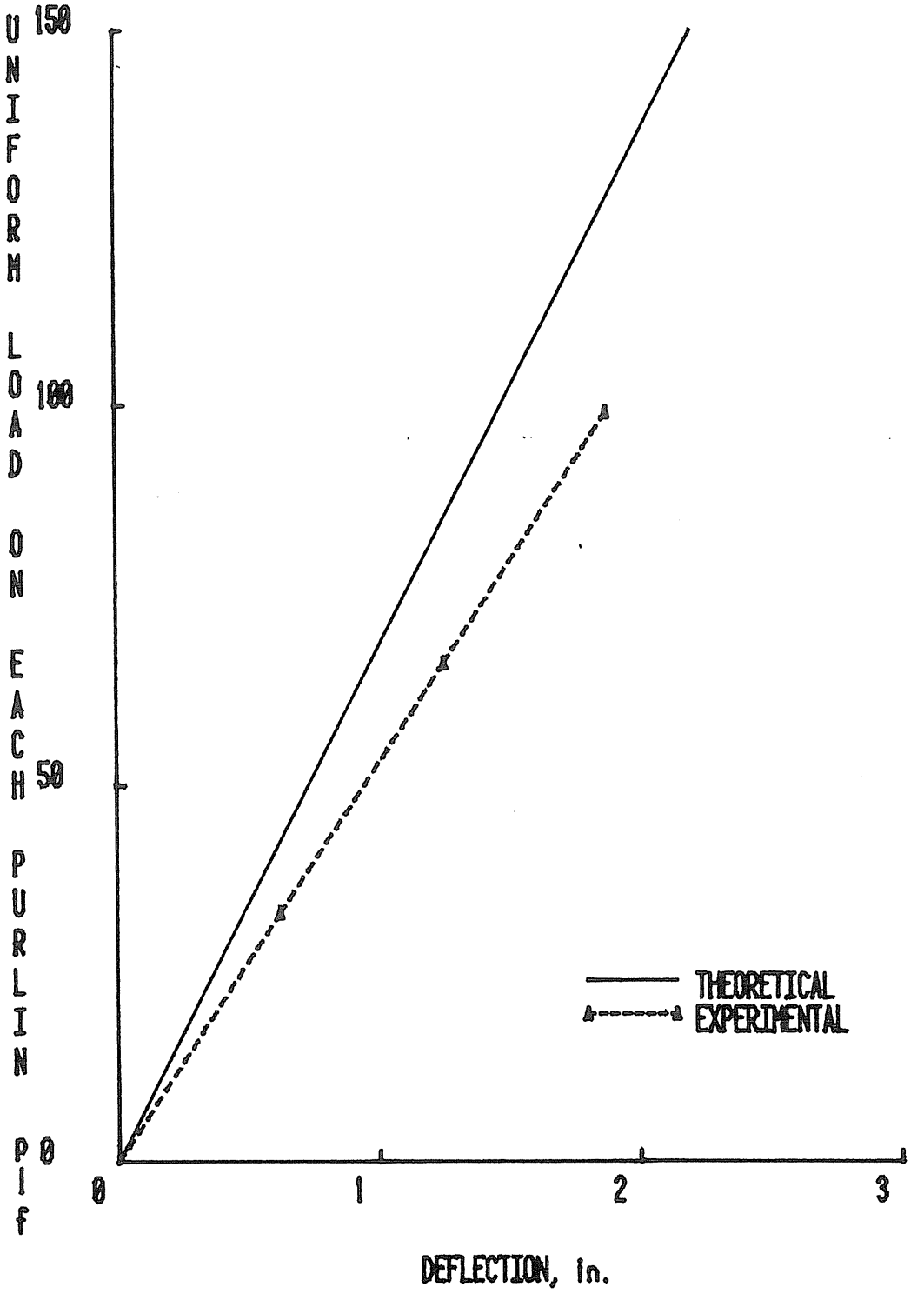


Figure C.13 Load vs. Vertical Deflection, Test B/2-2-A, Sub Test I

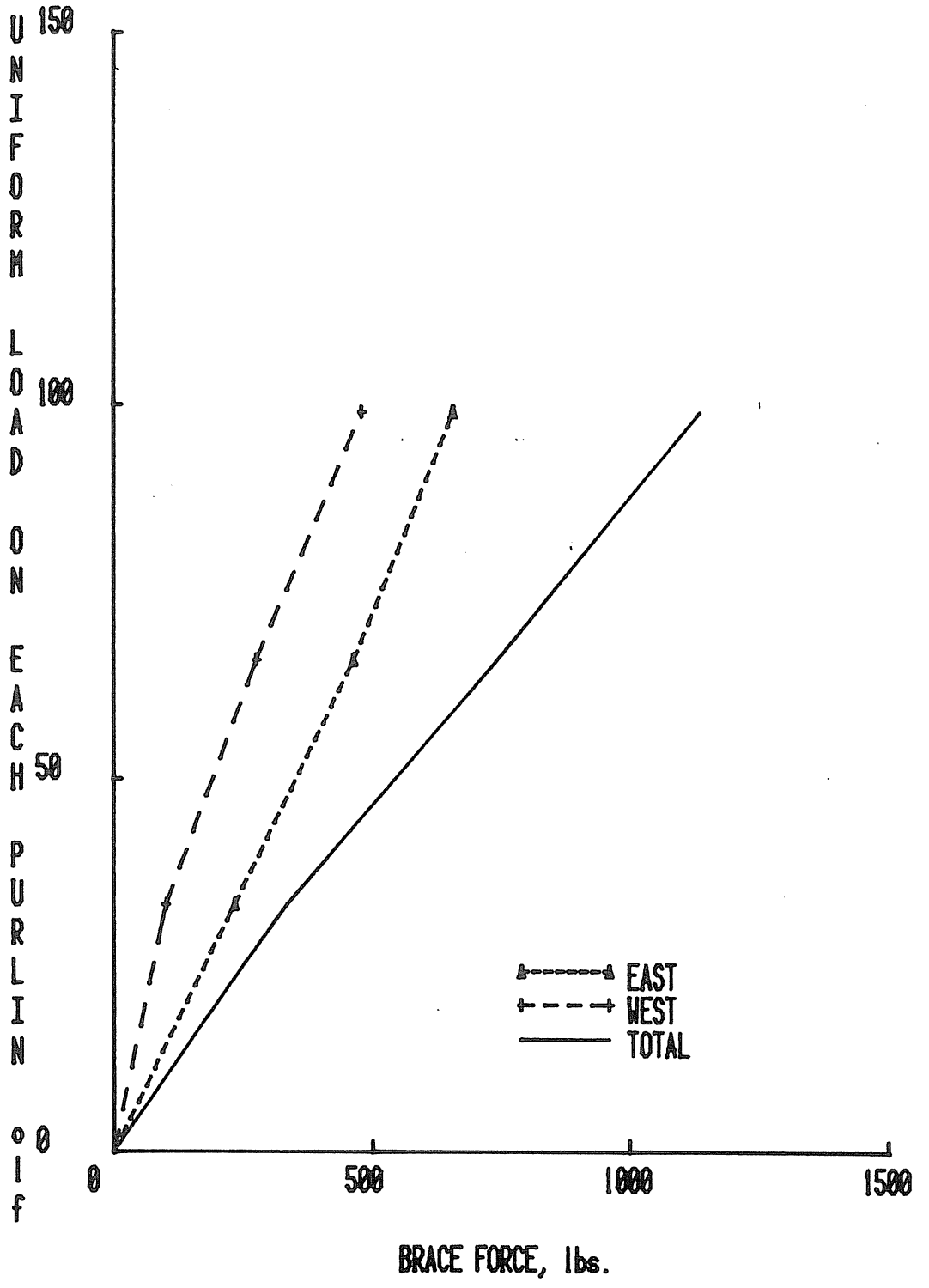


Figure C.14 Vertical Load vs. Brace Force, Test B/2-2-A, Sub Test I

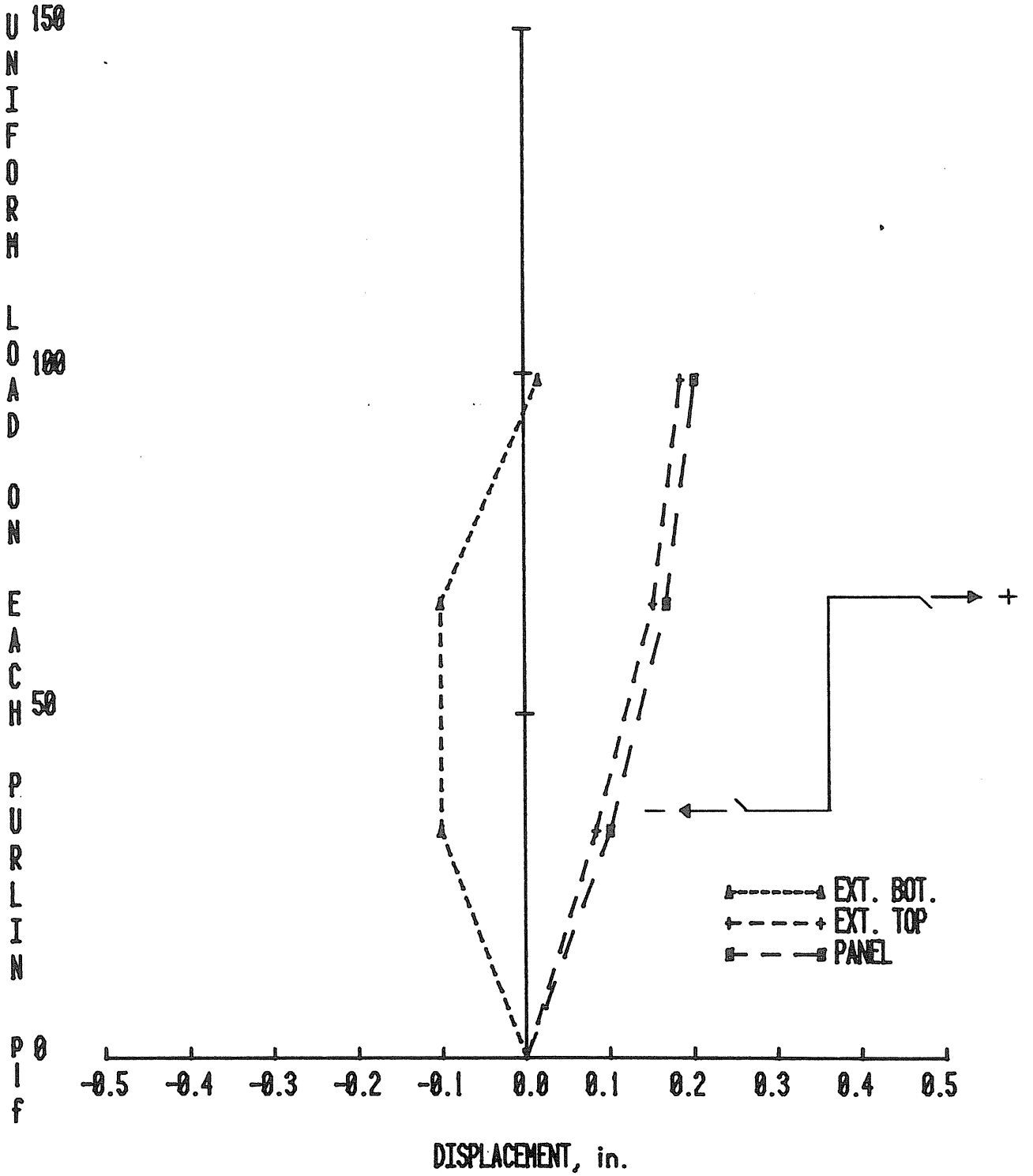


Figure C.15 Vertical Load vs. Lateral Displacement, Test B/2-2-A, Sub Test I

TEST SUMMARY

Project: MBMA Roof System Behavior

Test No.: B/2-2-B, Sub Test I, knife edge at supports

Test Date: October 1, 1982

Purpose: Same as Test B/2-1, effect of support conditions and more torsional braces.

Span(s):

Thickness: Moment of Inertia:

Parameters: Same as Test B/2-2-A

Failure Load:

Failure Mode:

Predicted Failure Loads:

Method Load

Method Load

Method Load

Discussion:

-Vertical deflection was about 10% higher than predicted from the constrained bending assumption for south (ext.) purlin.

-Brace forces increased linearly with increasing vertical load.

-At 99 plf, summation of external brace forces equaled 6% of total vertical load. Summation of internal brace forces equaled 22% of total vertical load.

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

-Maximum lateral displacement was .286 in. at panel centerline.

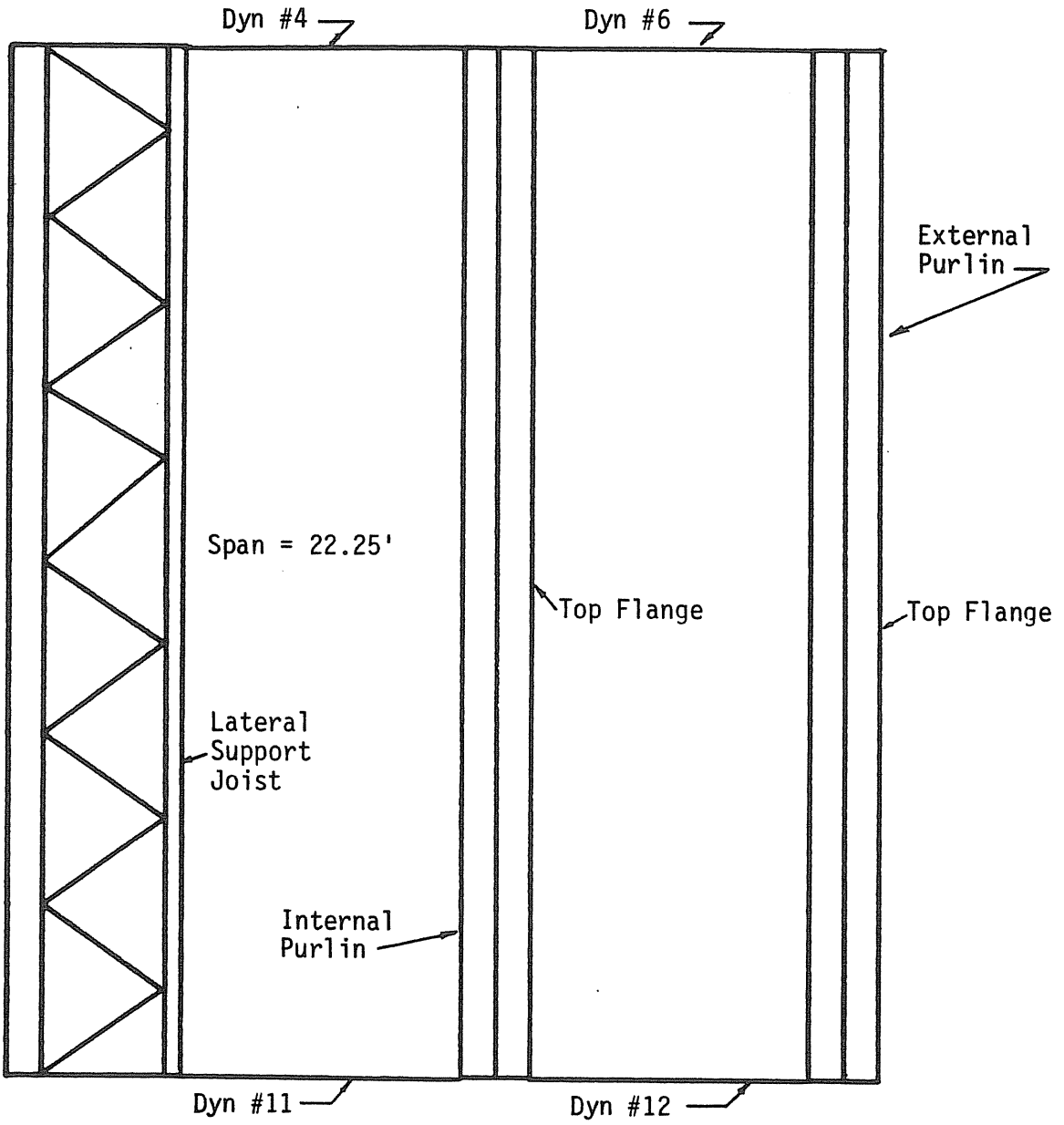


Figure C.16 Instrumentation Location, Test B/2-2-B

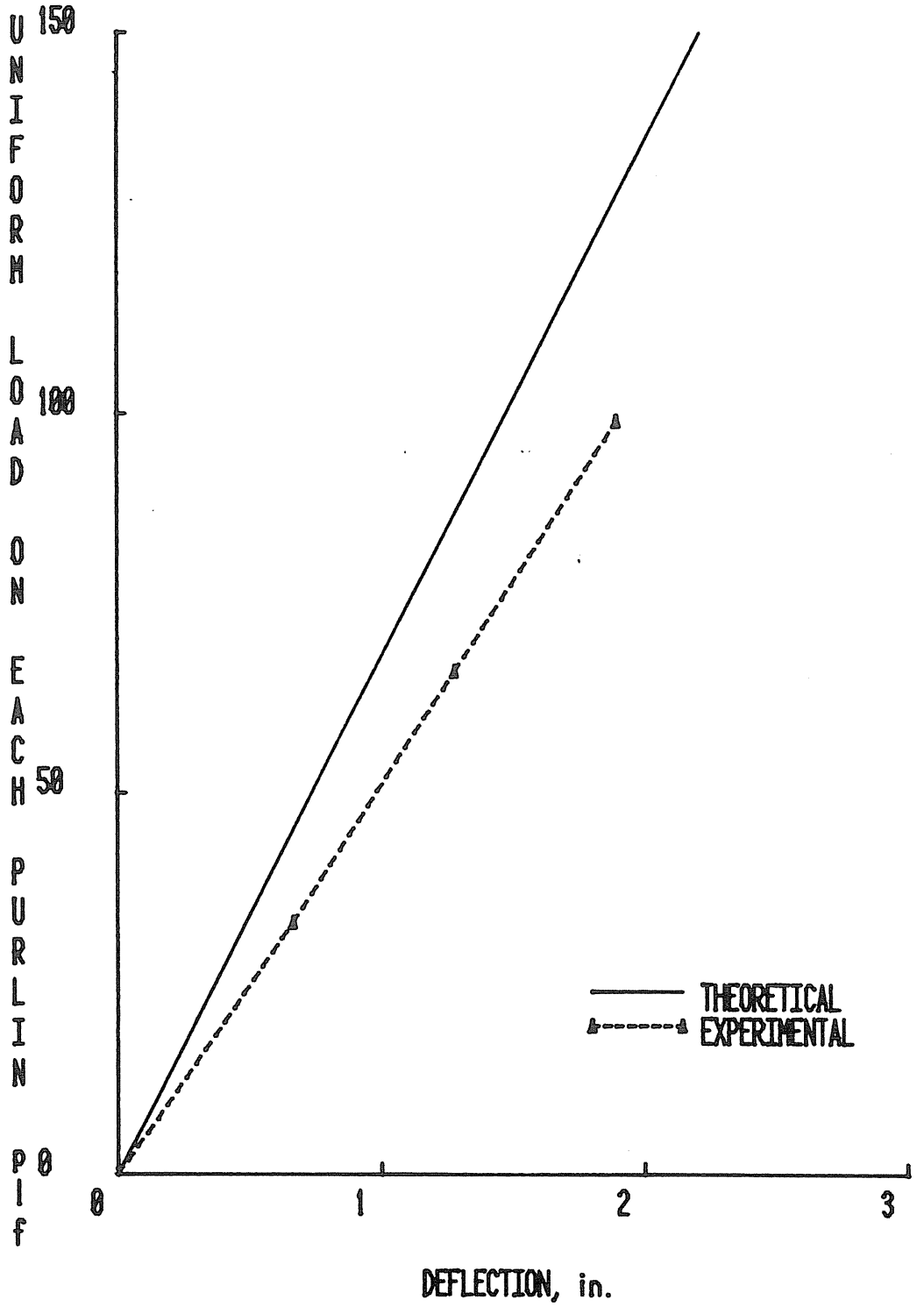


Figure C.17 Load vs. Vertical Deflection, Test B/2-2-B, Sub Test I

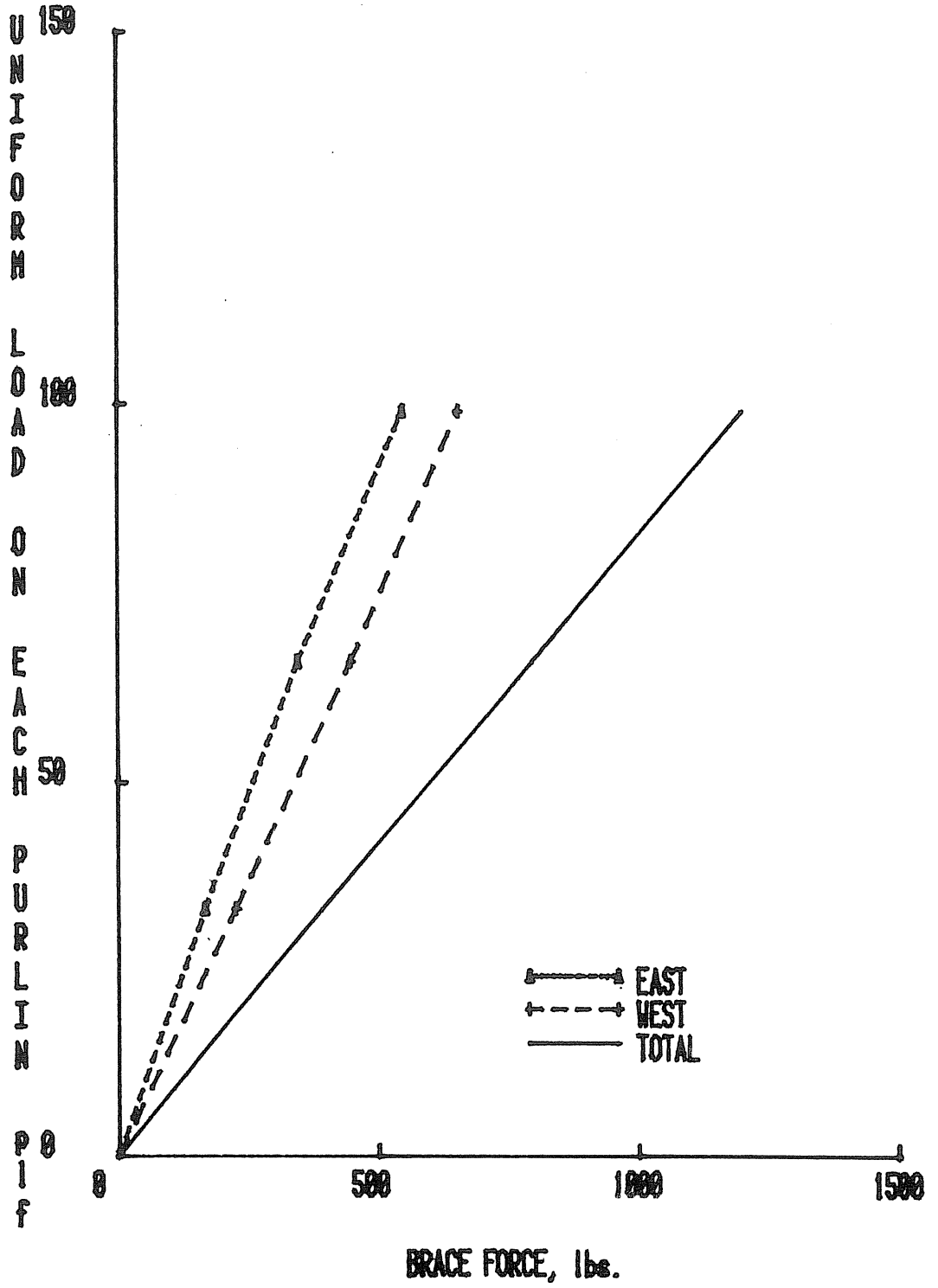


Figure C.18 Vertical Load vs. Brace Force, Test B/2-2-B, Sub Test I

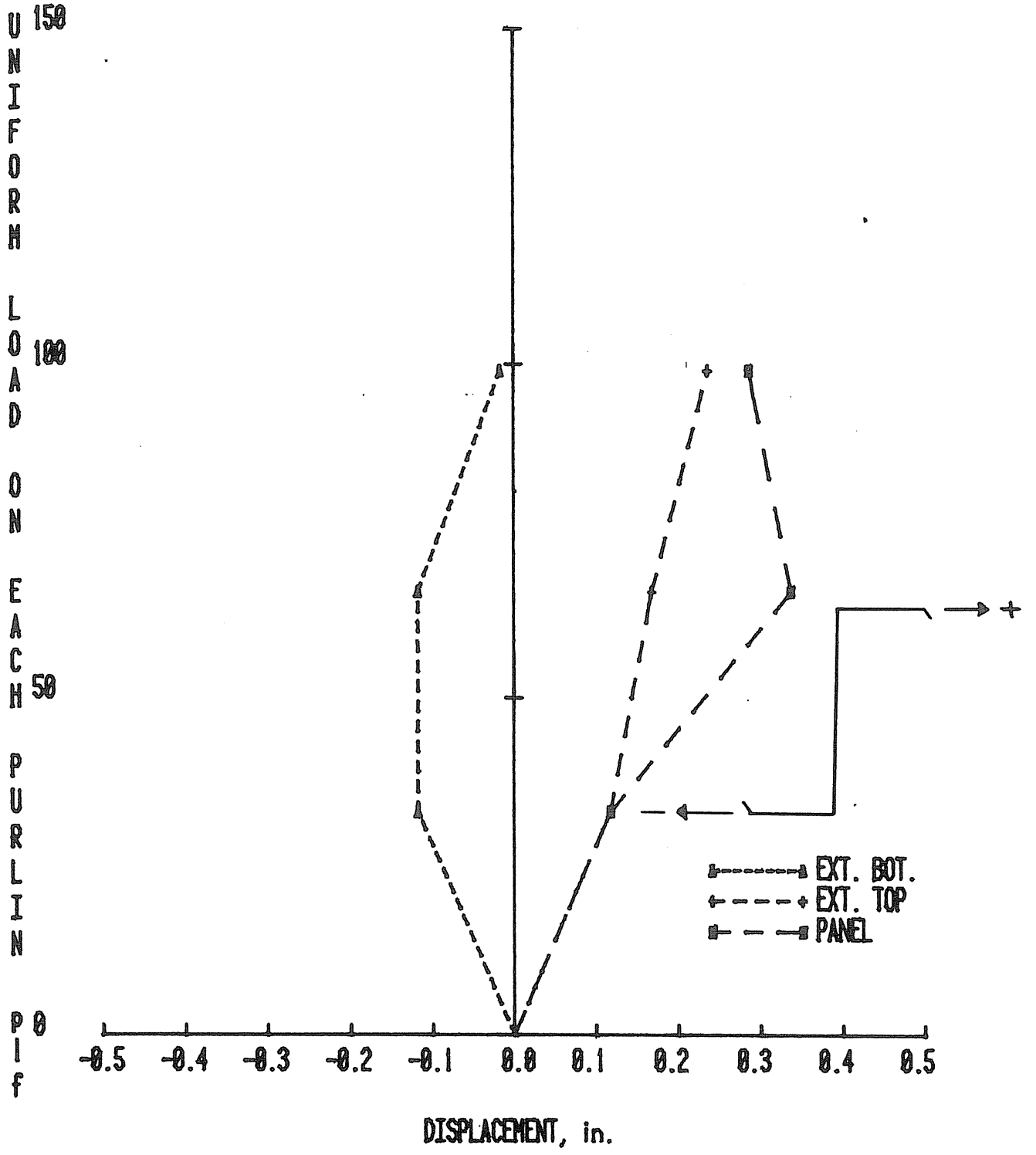


Figure C.19 Vertical Load vs. Lateral Displacement, Test B/2-2-B, Sub Test I

TEST SUMMARY

Project: MBMA Roof Systems Behavior

Test No.: B/2-3, Sub Test II

Test Date: October 5, 1982

Purpose: Sub test for assessing accumulation of restraint forces

Span(s): 22.25'

Thickness: 0.088" Moment of Inertia: 12.7 in^4

Parameters: No intermediate braces

Torsional restraint at rafters only south purlin braced.

Panel shear stiffness

Panel torsional stiffness

Failure Load: Loaded to 148.5 plf

Failure Mode:

Predicted Failure Loads:

Method AISI constr. bndg. x 1.67 Load 237.0 plf

Method Load

Method Load

Discussion:

-Vertical deflection was about 11-18% greater than predicted from the constrained bending assumption for south (ext.) purlin.

-Brace forces increased linearly with increasing vertical load up to 99 plf.

-At 99 plf, summation of brace forces equaled 23% of total vertical load.

-At 148.5 plf, summation of brace forces equaled 26% of total vertical load.

-Top flange lateral displacement exceeded bottom flange lateral displacement but in opposite direction.

-Maximum lateral displacement was 0.022 in. at 148.5 plf.

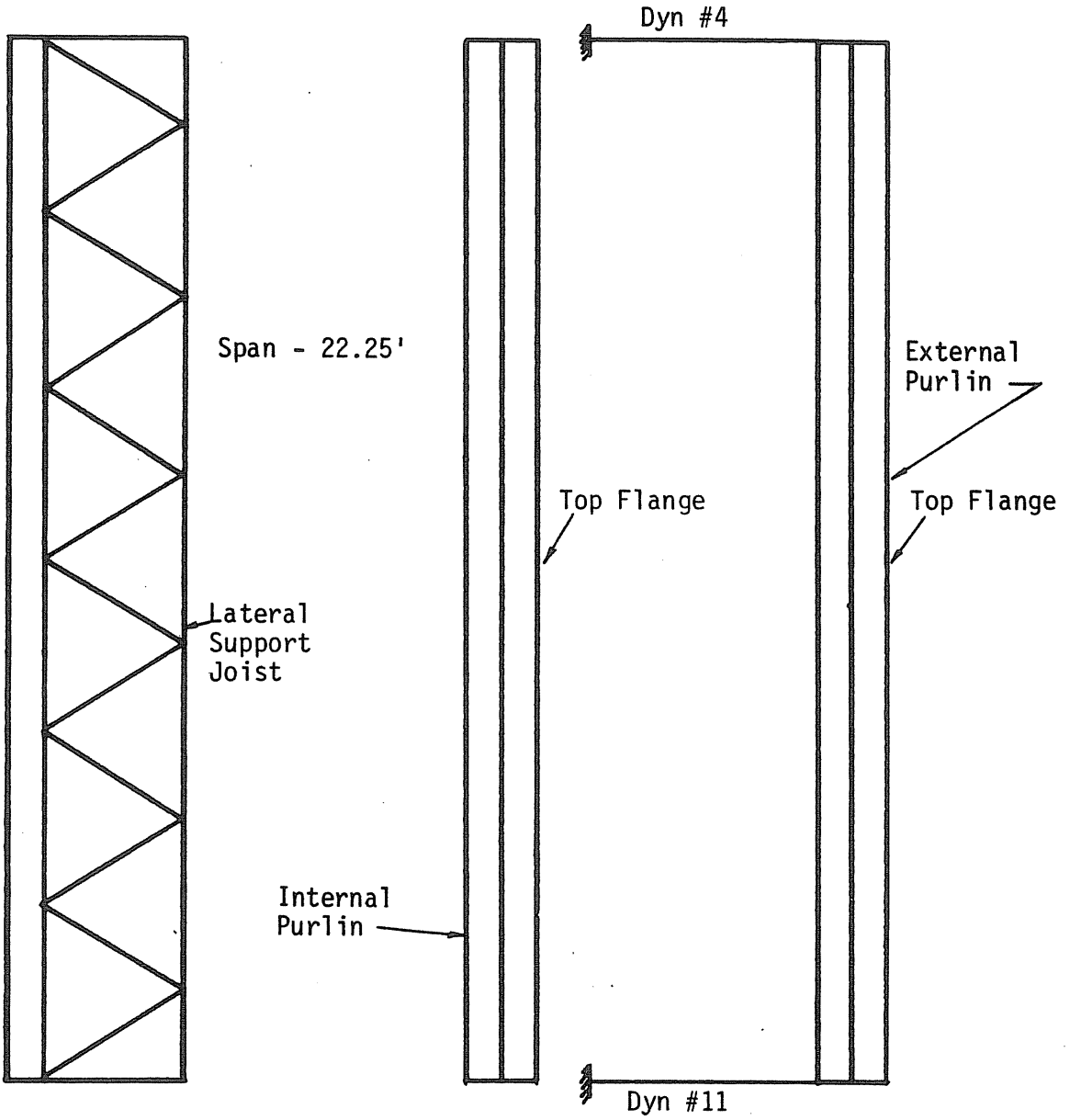


Figure C.20 Instrumentation Location, Test B/2-3

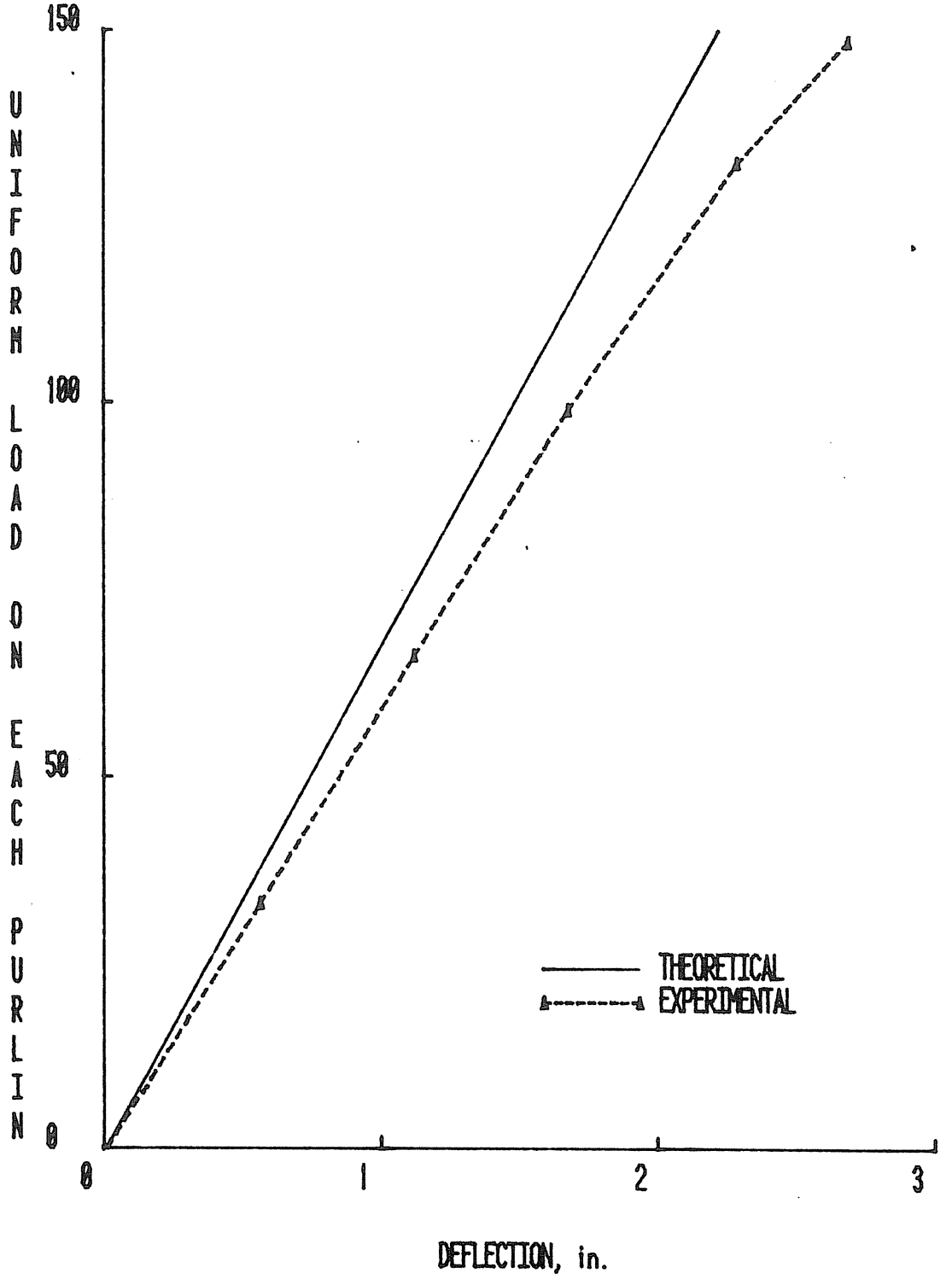


Figure C.21 Load vs. Vertical Deflection, Test B/2-3, Sub Test II

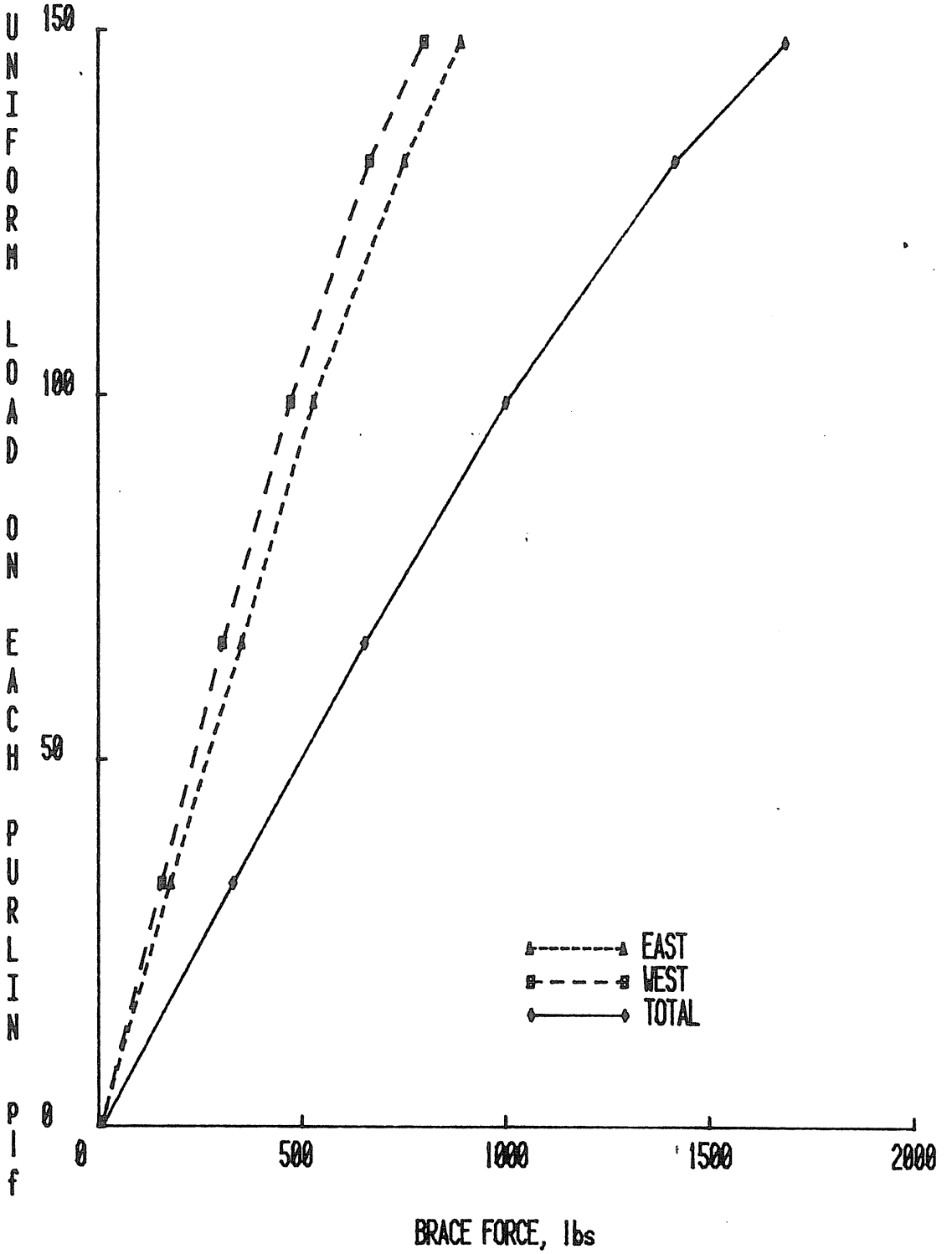


Figure C.22 Vertical Loading vs. Brace Forces, Test B/2-3, Sub Test II

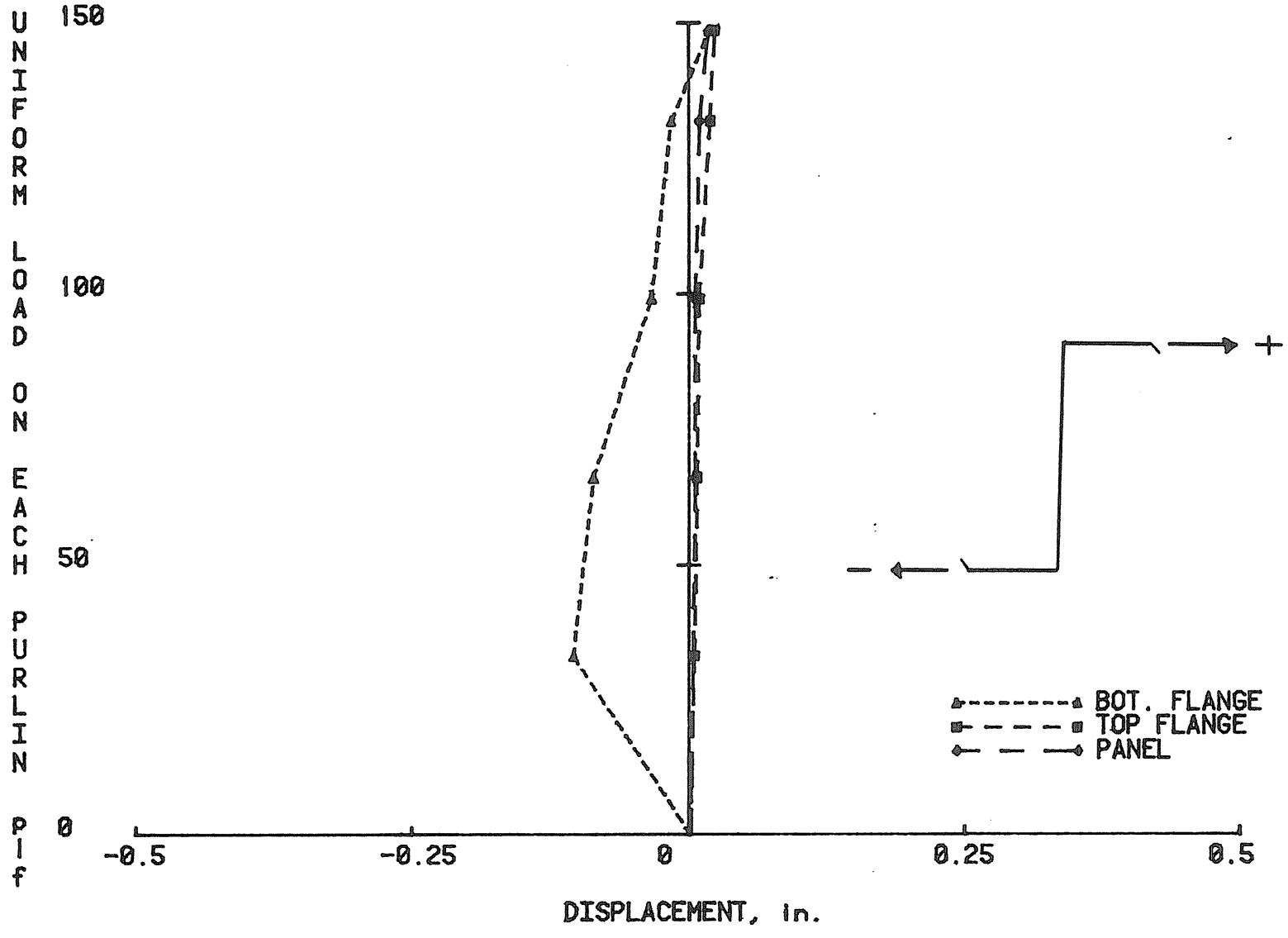
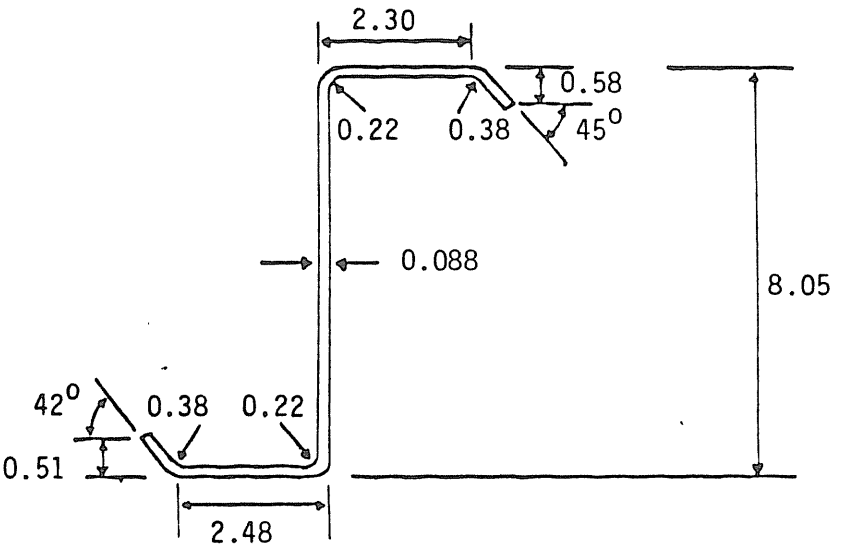


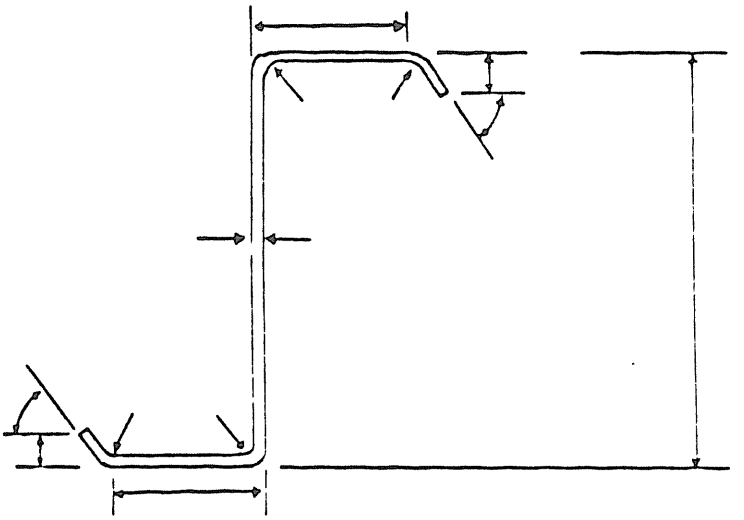
Figure C.23 Vertical Loading vs. Lateral Displacements, Test B/2-3, Sub Test II

APPENDIX D

B/6 ACCUMULATION TEST RESULTS



External Purlin (South)



Internal Purlin

Figure D.1 Measured Purlin Dimensions, Test B/6

```
A I S I   P U R L I N   A N A L Y S I S
                Z-SECTION
IDENTIFICATION: MBMA TEST B/6-1 (SOUTH PURLIN,EXT. 10//82)
```

	TOP	BOTTOM
FLANGE(in)	2.500	2.480
LIP(in)	0.580	0.510
LIP ANGLE(deg)	45.000	42.000
RADIUS I/F(in)	0.380	0.380
RADIUS F/W(in)	0.220	0.220

WEB DEPTH(in)	8.05
THICKNESS(in)	0.088
YIELD STRENGTH(ksi)	56

MOMENTS OF INERTIA(in^4)		SECTION MODULII(in^3) TOP	BOTTOM
GROSS=	12.224	3.044	3.097
STRENGTH=	12.224	3.044	3.097
DEFLECTION=	12.224		

```
RF=    1.992   in
FL=   56.000   ksi
FT=   56.000   ksi
FBW   53.007   ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)
            ML=     8.523   ft-k
            MT=     8.673   ft-k
            MW=     8.962   ft-k
            MU=    14.233   ft-k (1.67*allowable)
SPAN          =    22.250   ft.
UNIFORM LOAD=   230.007   plf (1.67*allowable)
DEFLECTION  =     1.529   in./100plf
```

Figure D.2 AISI Purlin Analysis, Test B/6, External Purlin

TEST SUMMARY

Project: MBMA Roof Systems Behavior

Test No.: B/6-1

Test Date: October 7, 1982

Purpose: Subtest for measuring accumulation of restraint forces.

Span(s): 22.25'

Thickness: 0.088" Moment of Inertia: 12.2 in^4

Parameters: No intermediate braces

Torsional restraint at rafters, only 2nd purlin from the north end.

Panel shear stiffness

Panel torsional stiffness

Failure Load: Loaded up to 99 plf on internal purlin

Failure Mode:

Predicted Failure Loads:

Method AISI constr. bndg. x 1.67 Load 230.0 plf

Method Load

Method Load

Discussion:

-Vertical deflection was about 6% greater than predicted from the constrained bending assumption for south (ext.) purlin

-Brace forces did not increase linearly with increasing vertical load.

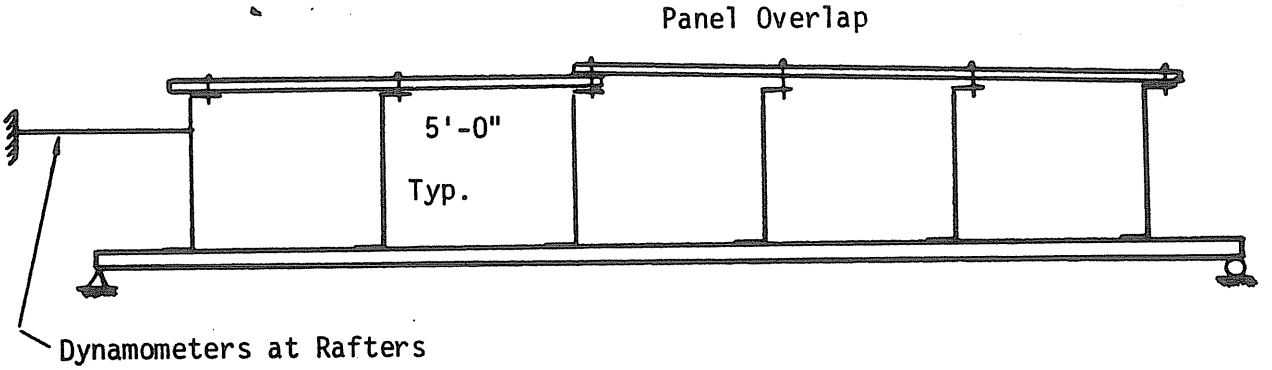
-At 33 plf on external purlin, summation of brace forces were 15% of total vertical load.

-At 49.5 plf on external purlin, summation of brace forces were 17% of total vertical load.

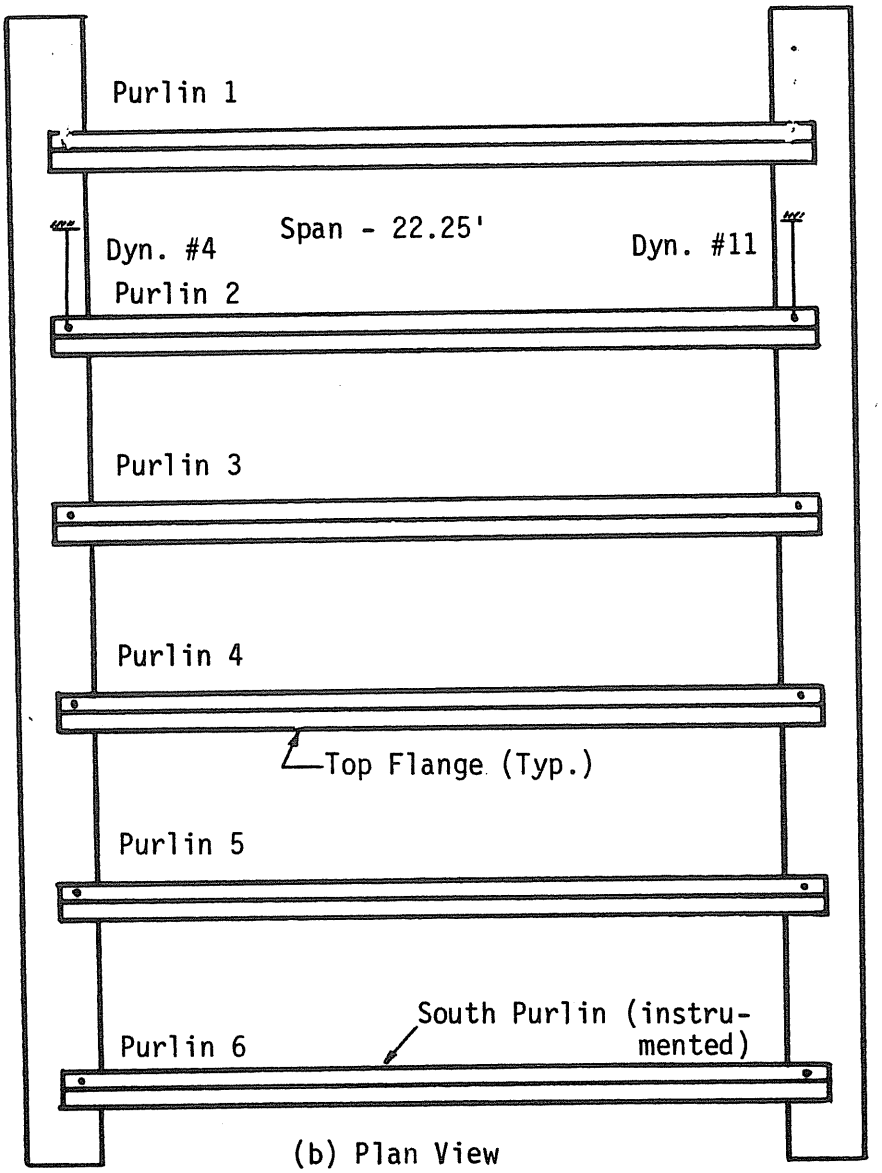
-At 49.5 plf on external purlin, east brace force was 16.3% greater than west brace force.

-Bottom flange lateral displacement of external purlin (south) exceeded top flange lateral displacement in the same direction.

-Maximum lateral displacement was .705 in. at 49.5 plf on external purlin.



(a) Side View



(b) Plan View

Figure D.3 Instrumentation Locations, Test B/6-1

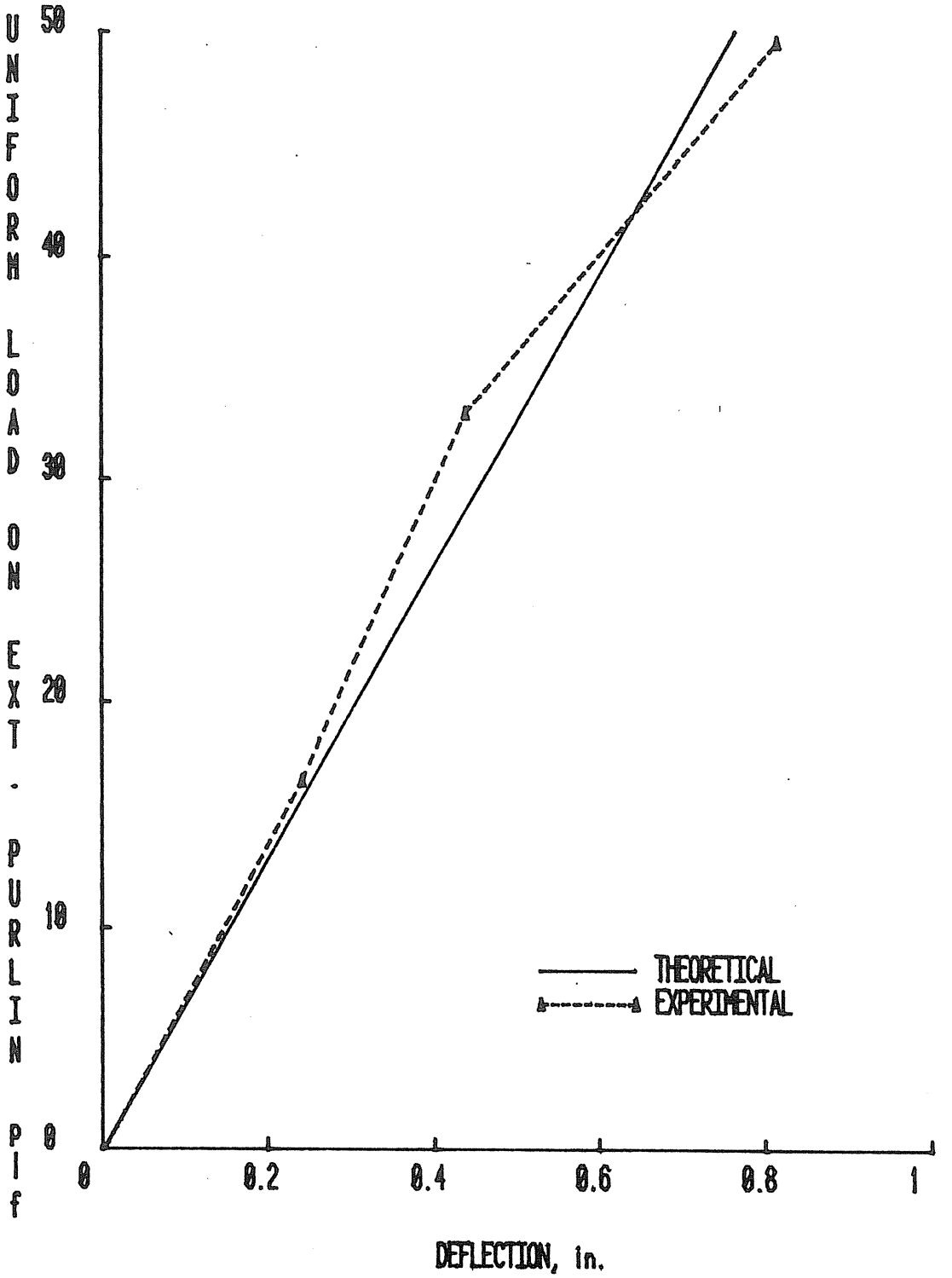


Figure D.4 Load vs. Vertical Deflection, Test B/6-1

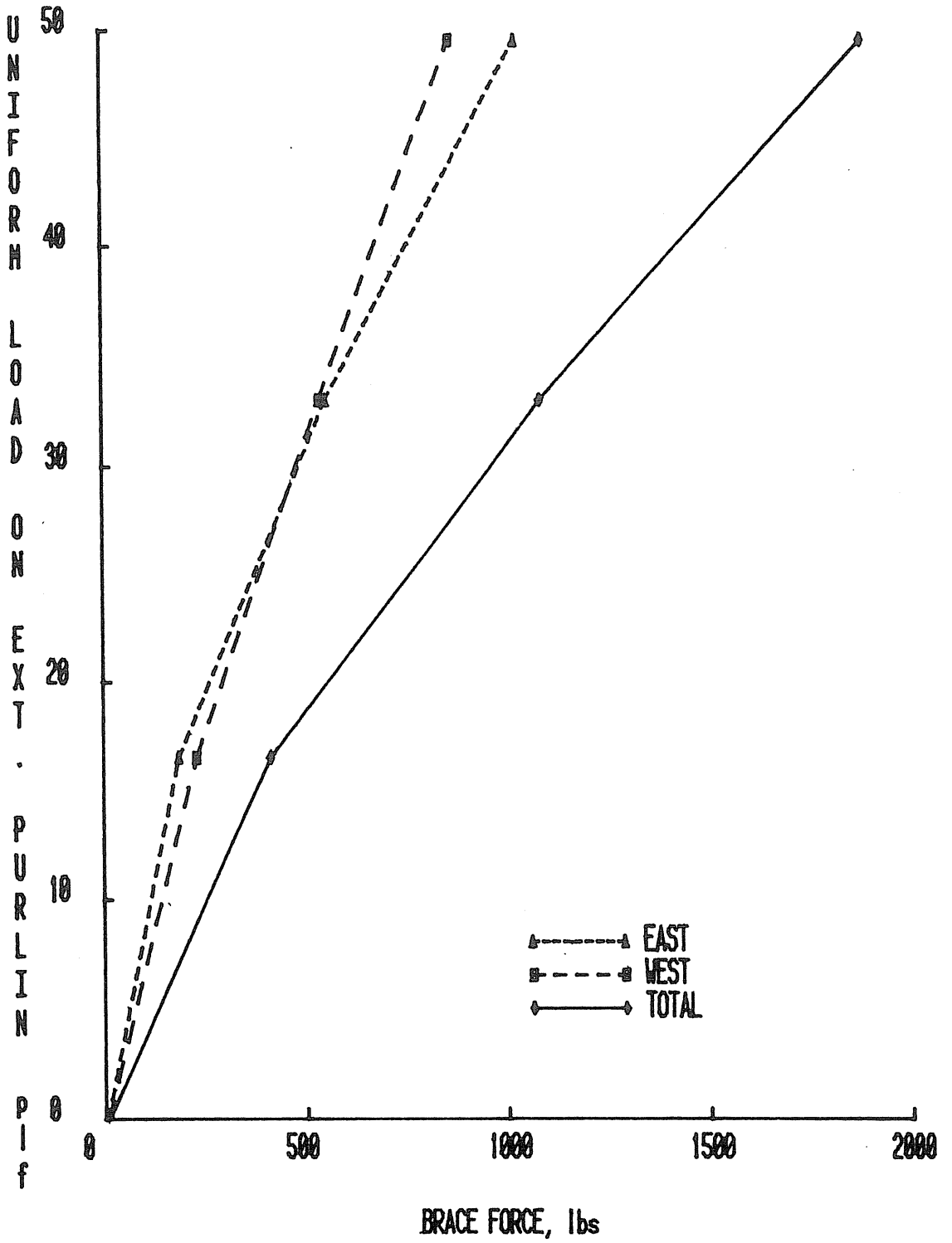


Figure D.5 Vertical Loading vs. Brace Forces, Test B/6-1

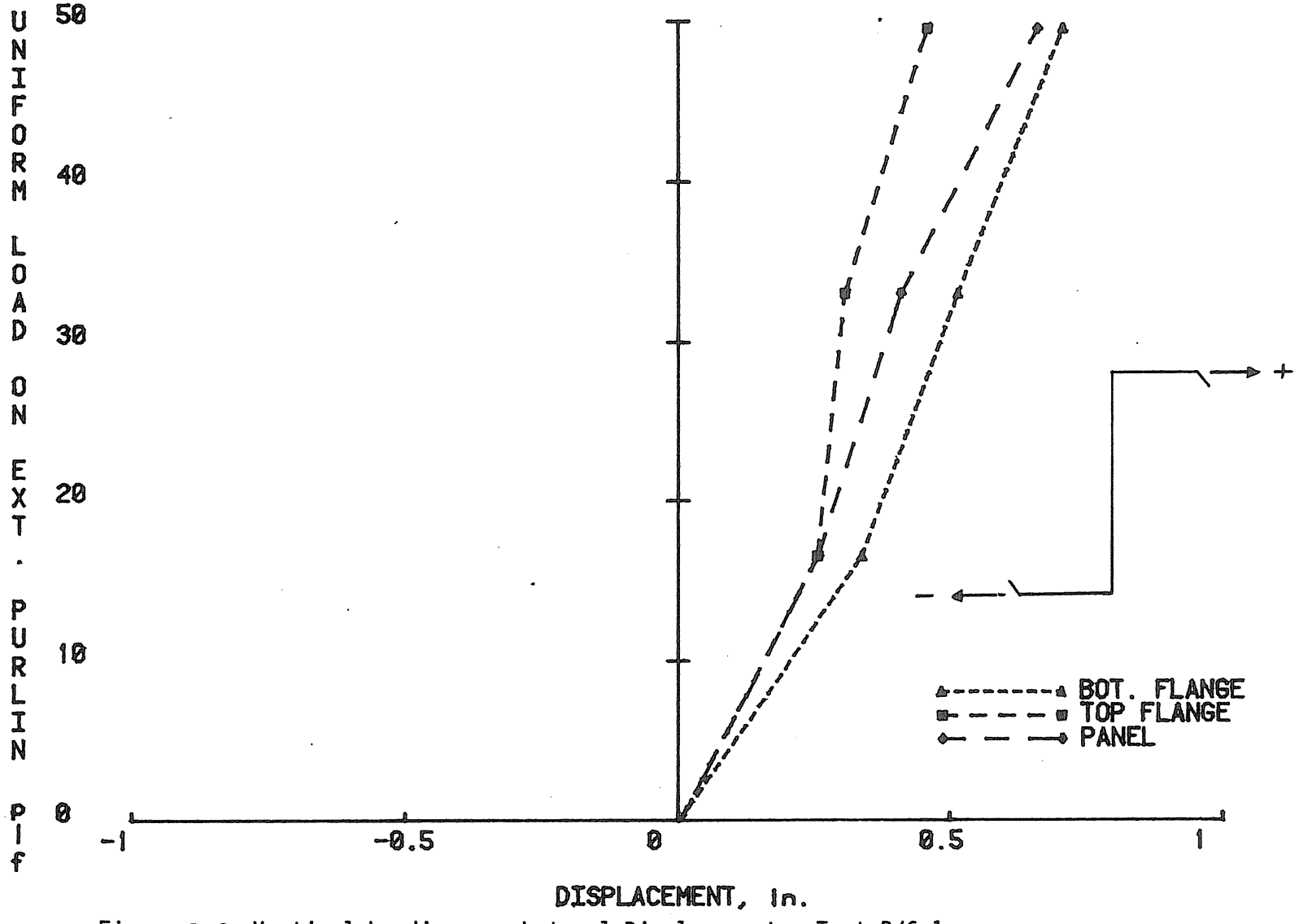


Figure D.6 Vertical Loading vs. Lateral Displacements, Test B/6-1

TEST SUMMARY

Project: MBMA Roof System Behavior

Test No.: Test B/6-2

Test Date: October 28, 1982

Purpose: Accumulation

Span(s): 22.25'

Thickness: 0.088" Moment of Inertia: 12.2 in^4

Parameters: No intermediate braces

Torsional restraint at rafters, only first purlin from the north end

Panel shear stiffness

Panel torsional restraint

Failure Load: Loaded up to 99 plf on internal purlins

Failure Mode:

Predicted Failure Loads:

Method AISI constr. bndg. x 1.67 Load 230.0 plf

Method Load

Method Load

Discussion:

-Vertical deflection was about 20% greater than predicted from constrained bending for the external (south) purlin.

-Brace forces increased with increasing the vertical load, but not linearly.

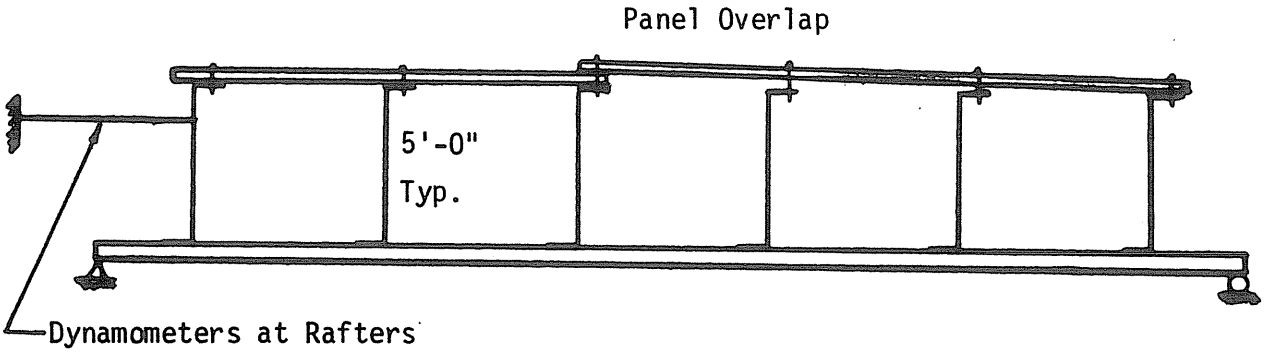
-At 49.5 plf on external purlin, east brace force was 36% greater than west brace force.

-At 33 plf on external purlin, summation of brace forces were 14.3% of total vertical load.

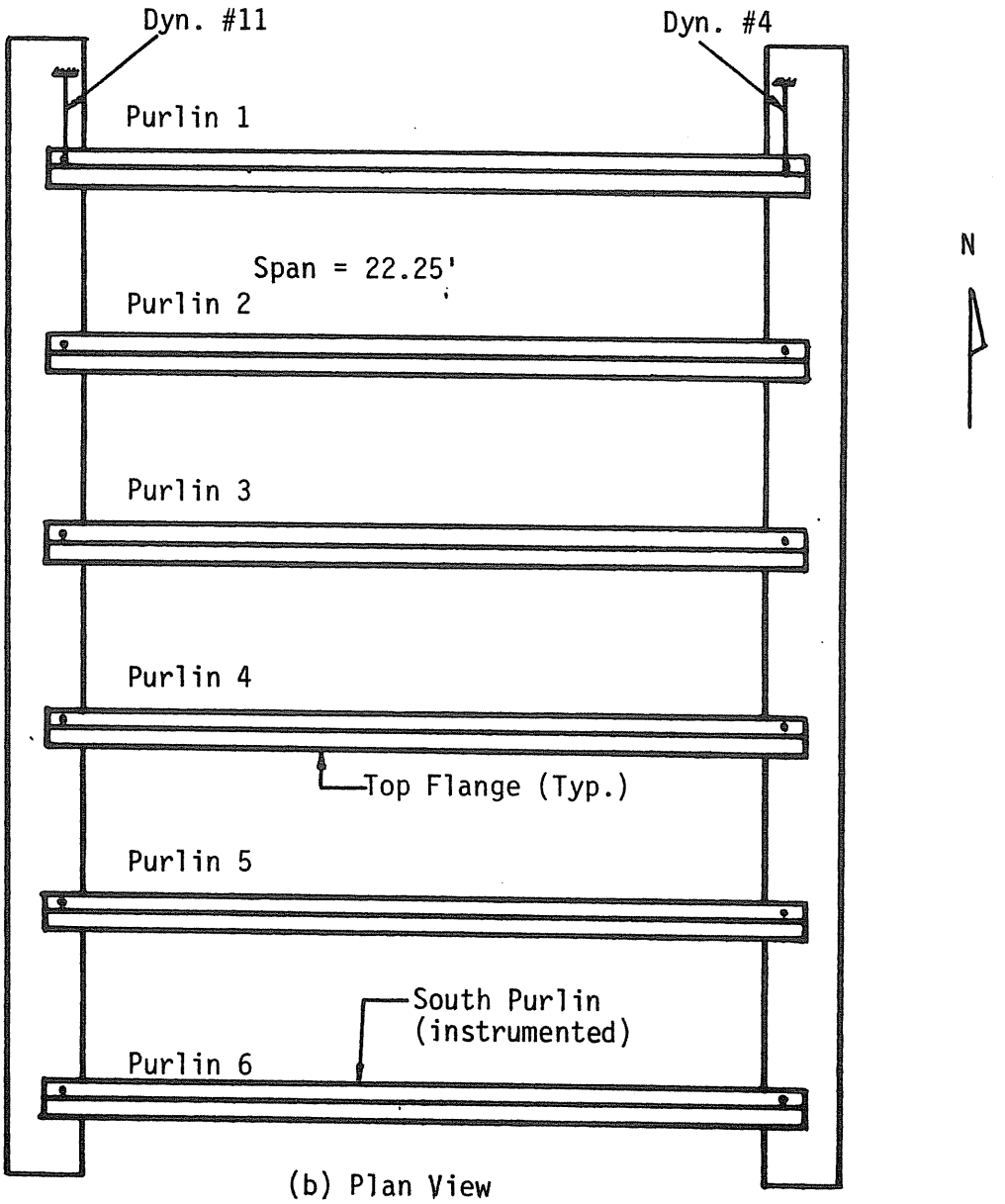
-At 49.5 plf on external purlin, summation of brace forces were 16.2% of total vertical load.

-Bottom flange lateral displacement of external purlin exceeded top flange lateral displacement in the same direction.

-Maximum lateral displacement was less than 1.1 in.



(a) Side View



(b) Plan View

Figure D.7 Instrumentation Locations, Test B/6-2

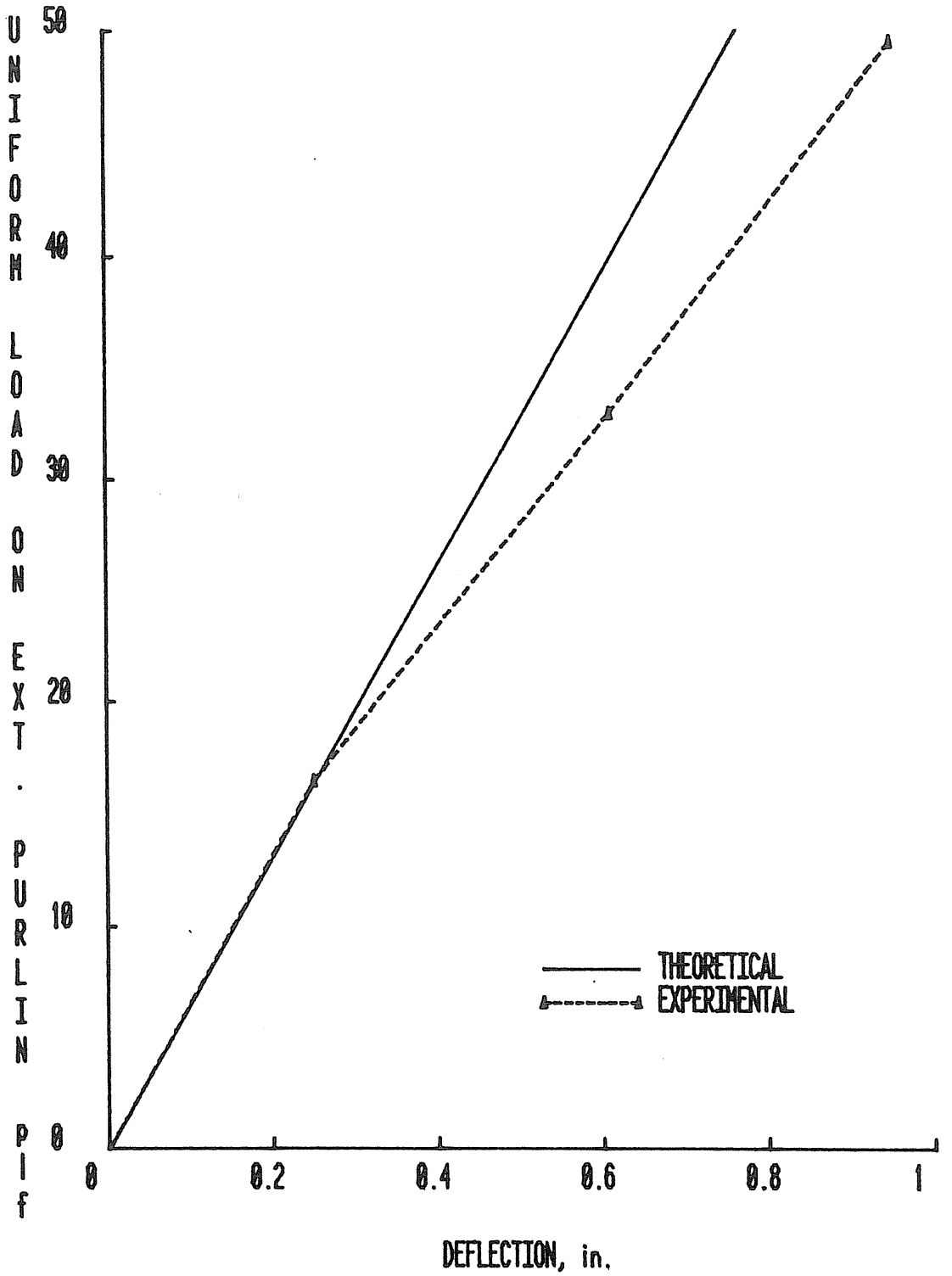


Figure D.8 Load vs. Vertical Deflection, Test B/6-2

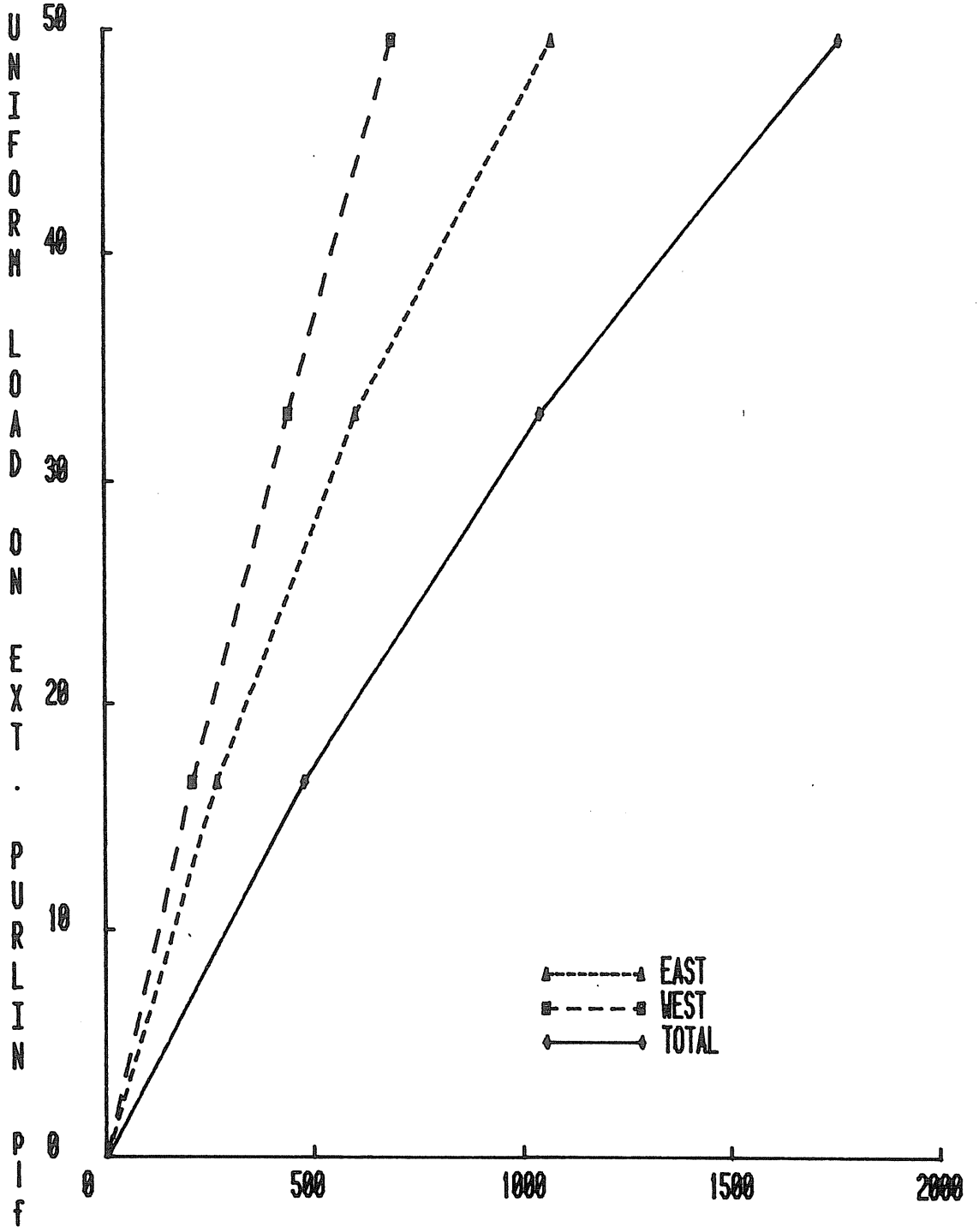


Figure D.9 Vertical Loading vs. Brace Forces, Test B/6-2

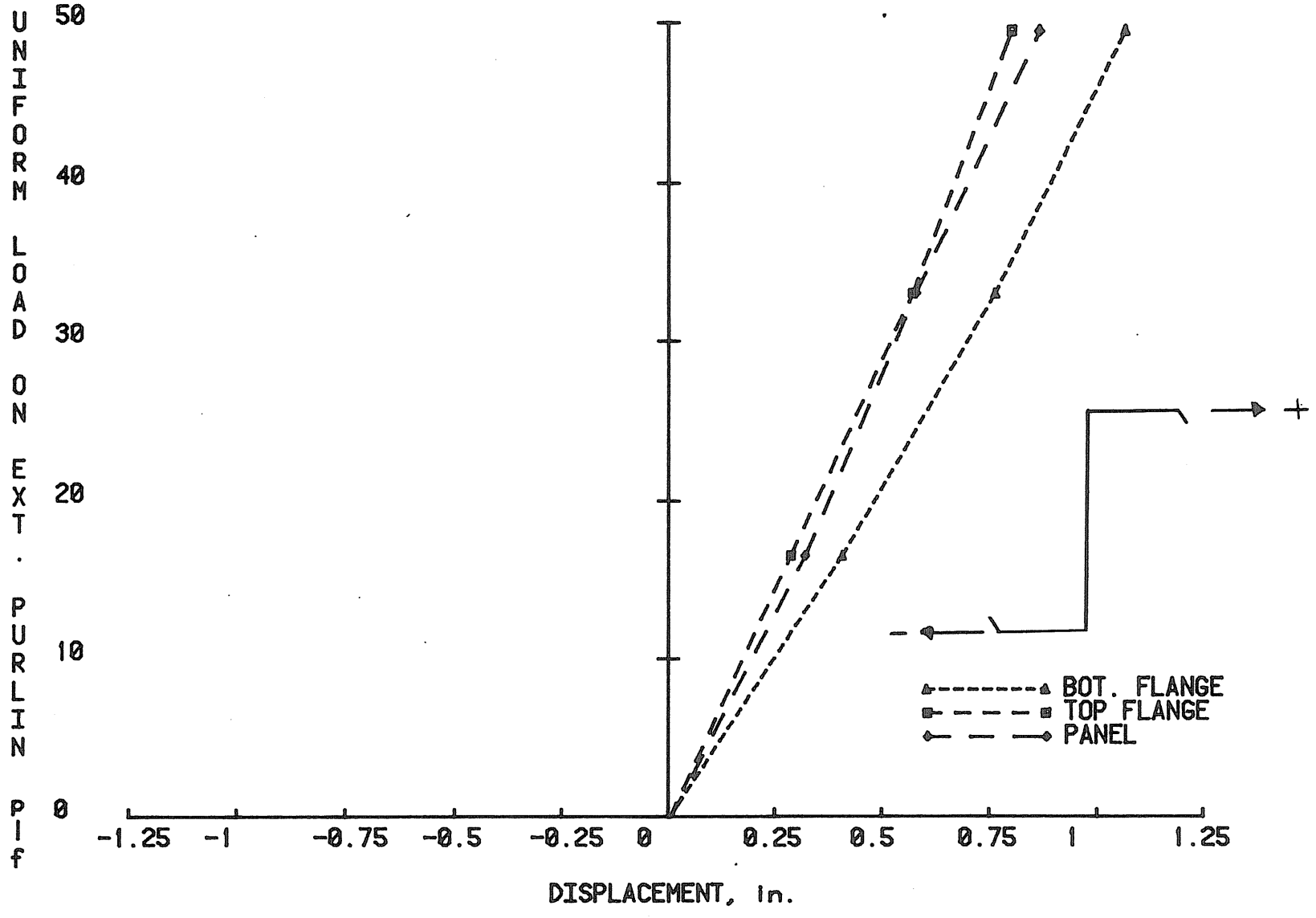


Figure D.10 Vertical Loading vs. Lateral Displacements, Test B/6-2

TEST SUMMARY

Project: MBMA Roof System Behavior

Test No.: B/6/6

Test Date: October 14, 1982

Purpose: Opposed purlin accumulation test

Span(s): 22.25'

Thickness: 0.088" Moment of Inertia: 12.2 in^4

Parameters: No intermediate braces
No torsional restraints
Panel shear stiffness
Panel torsional stiffness
1/3 pts. load cell between opposed purlins

Failure Load: Loaded to 66 plf on internal purlins

Failure Mode:

Predicted Failure Loads:

Method AISI const. bndg. x 1.67 Load 230.0 plf

Method _____ Load _____

Method _____ Load _____

Discussion:

-Vertical deflection was about the same as predicted from the constrained bending assumption for 6th purlin from north.

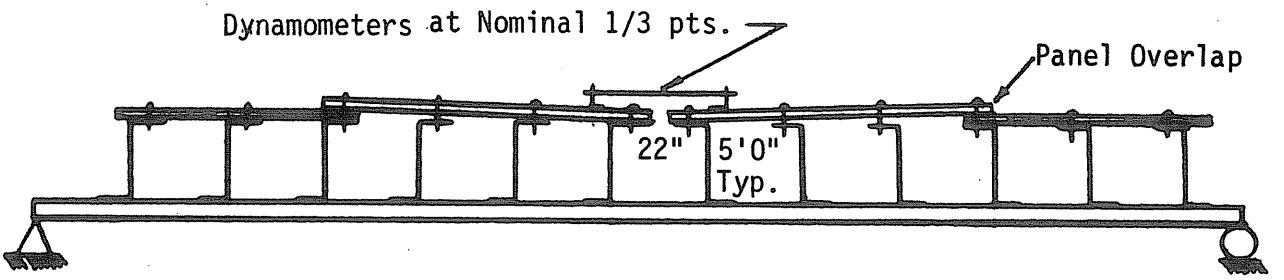
-Brace forces increased linearly with increasing vertical load.

-At 33 plf on external purlin, summation of brace forces equaled 20% of total vertical load.

-Top flange lateral displacement exceeded bottom flange lateral displacement.

-Maximum lateral displacement was 0.351 in. at 33 plf on external purlin.

-Purlins used in this test were identical to those used in Test B/6. See Figure D.1 for cross-section dimensions.



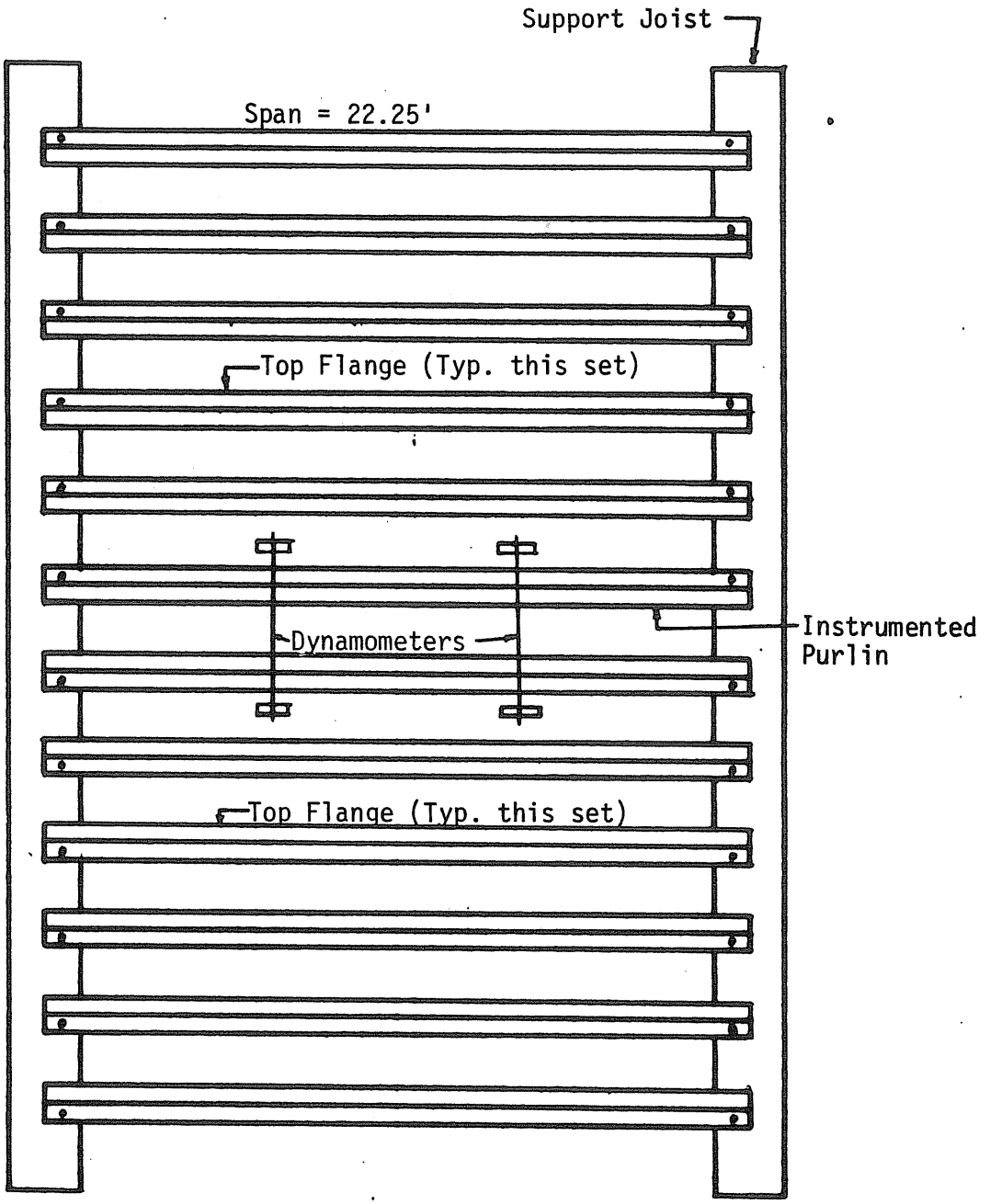


Figure D.11 Instrumentation Locations, Test B/6/6

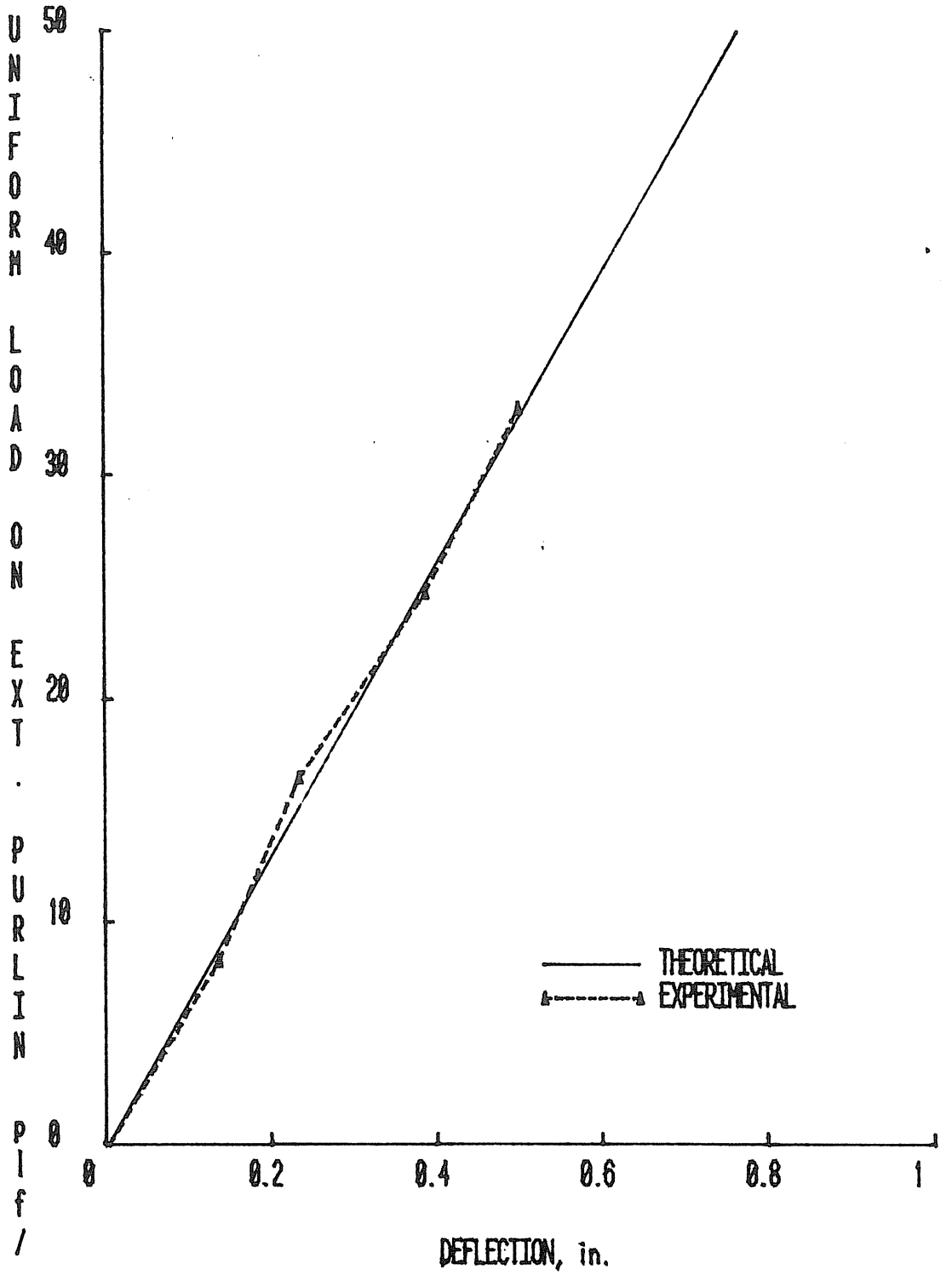


Figure D.12 Load vs. Vertical Deflection, Test B/6/6

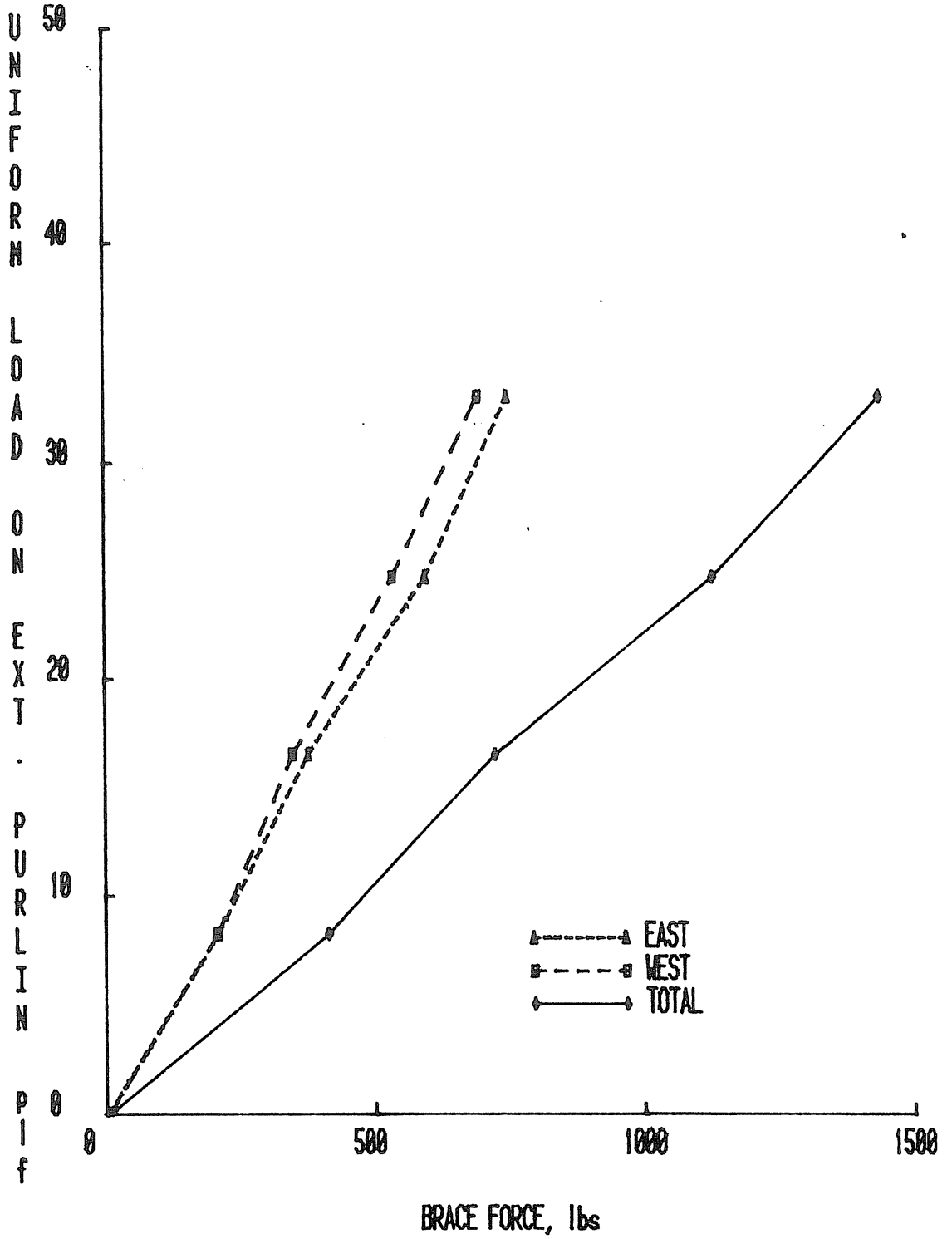


Figure D.13 Vertical Loading vs. Brace Forces, Test B/6/6

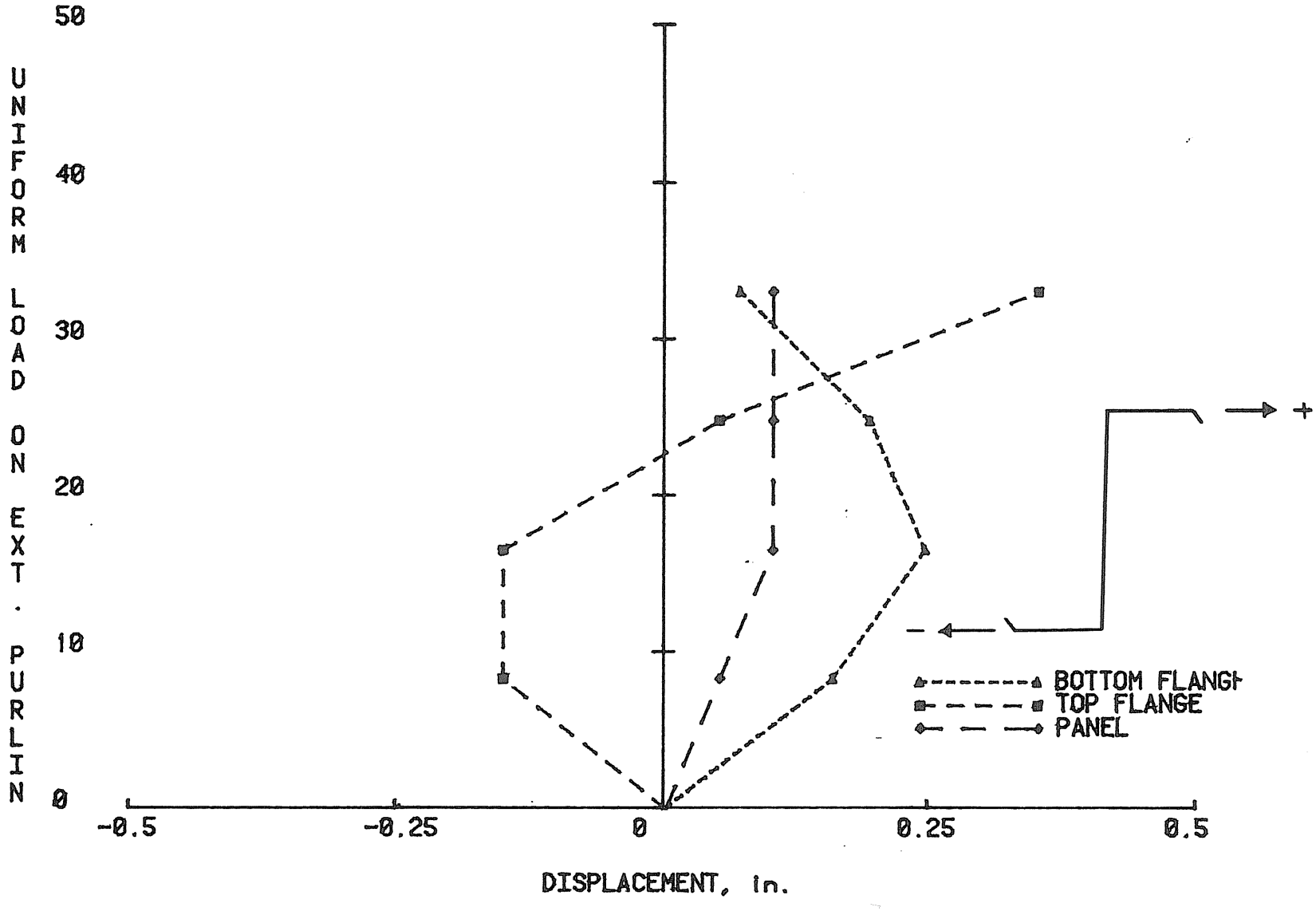


Figure D.14 Vertical Loading vs. Lateral Displacements, Test B/6/6

APPENDIX E

SERIES SS STANDING SEAM ACCUMULATION TEST RESULTS

TEST SUMMARY

Project: MBMA Purlins

Test No.: SS6/6-1 (Standing Seam)

Test Date: December 12, 1982

Purpose: Determine restraint requirements at ridge.

Span(s): 22 ft. 3 in.

Thickness: 0.099" Moment of Inertia: 14.676 in^4

Parameters: Two sets of 6 six purlins with flanges opposing.
Intermediate bracing at nominal 1/3rd pts.
Load cells between "ridge" purlins at nominal 1/3rd pts.
Dynamometers attached to panels at 1/3rd pts. for loading cycle only.

Failure Load: Not loaded to failure. 66 plf max.

Failure Mode:

Predicted Failure Loads:

Method AISI Purlin Analysis Load 281.178 plf

Method Load

Method Load

Discussion:
The test was conducted in the following manner:

1. The test set-up was preloaded to 16.5 plf and no data was taken.
2. The set-up was then loaded in increments of 33 plf to 66 plf/purlin with data recorded at each increment.
3. At 66 plf the deck braces were removed and data recorded.
4. The set-up was unloaded in 33 plf increments with data recorded at each increment.

-The % of brace force to the total load decreased with increased load both in loading and unloading.

-When the deck braces were removed the total brace force decreased from 1732.0 lb. to 1495.0 lb.

-Vertical centerline deflection was close to the theoretical prediction in both the loading and unloading cycles.

-Horizontal top flange deflection decreased with ~~increased~~ loading.

-Horizontal bottom flange deflection increased linearly with increased loading.

-In general, the "eave" purlins rolled toward the outside at the rafters.

-Horizontal movement of the panel was in the same direction as that of the "eave" purlin top flange. Panel horizontal displacement decreased with increased load in both the loading and unloading cases.

-During loading the panel braces carried considerably less of the load than did the purlin braces.

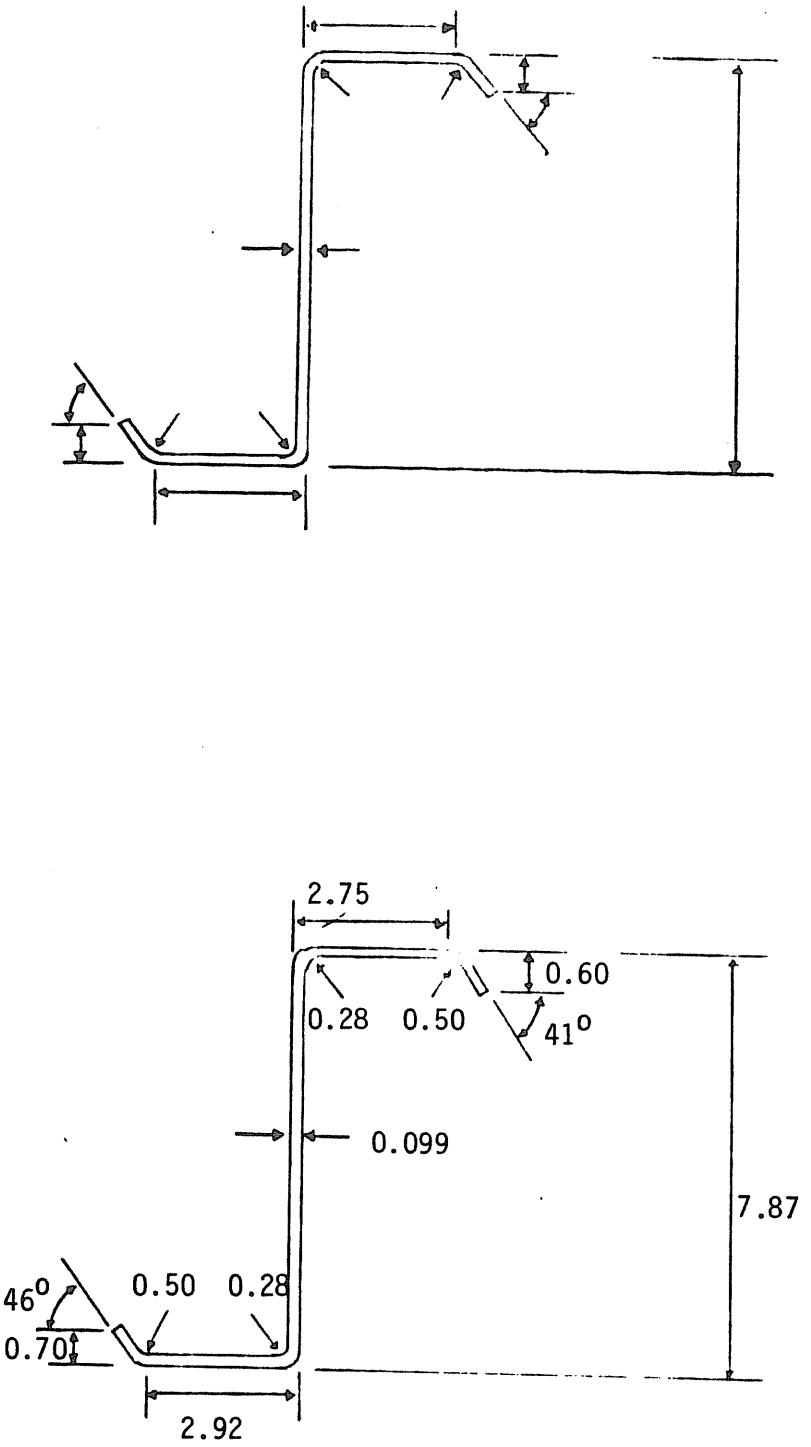


Figure E.1 Measured Purlin Dimensions, Test SS/6/6

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

IDENTIFICATION: MRMA [illegible]

	TOP	BOTTOM
FLANGE(in)	2.750	[illegible]
LIP(in)	0.600	0.600
LIP ANGLE(deg)	41.000	46.000
RADIUS L/F(in)	0.500	0.500
RADIUS F/W(in)	0.280	0.280

TOTAL DEPTH(in)	7.87
THICKNESS(in)	0.099
YIELD STRENGTH(ksi)	56

MOMENTS OF INERTIA(in^4)	TOP	BOTTOM
GROSS	14.676	[illegible]
STRENGTH=	14.676	[illegible]
DEFLECTION=	14.676	
RE	[illegible]	
FC	33.600	ksi
FT	33.600	ksi
FRW=	33.600	ksi

MOMENT CARRYING CAPACITY (AISI SPECIFICATION)

MC =	10.419	ft-k
MT =	10.737	ft-k
MW=	11.369	ft-k
MH=	17.400	ft-k [illegible]
SPAN =	22.250	ft.
UNIFORM LOAD =	281.178	plf [illegible]
DEFLECTION =	1.278	in. [illegible]

Figure E.2 AISI Purlin Analysis, Test SS/6/6

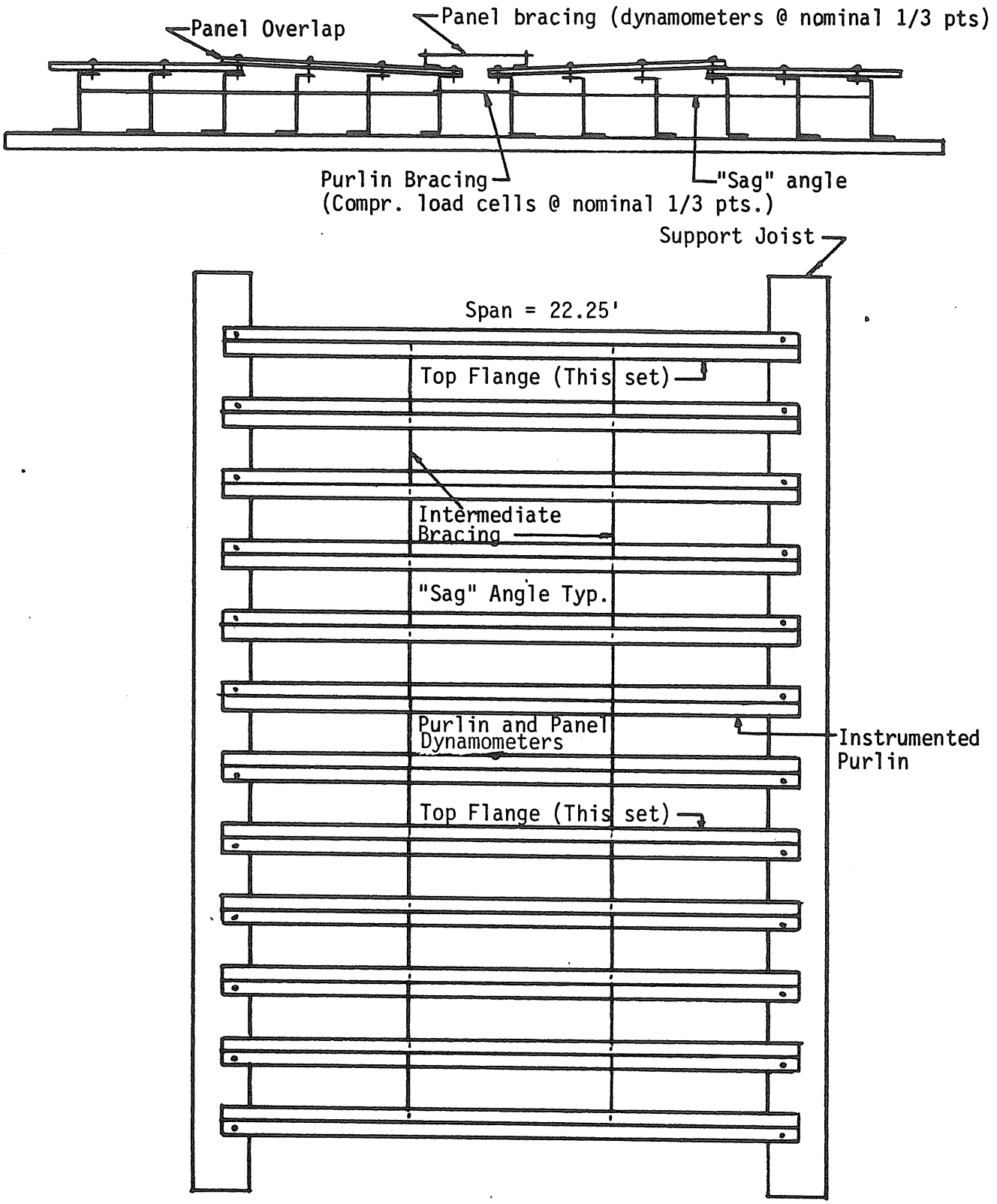


Figure E.3 Instrumented Locations, Test SS/6/6

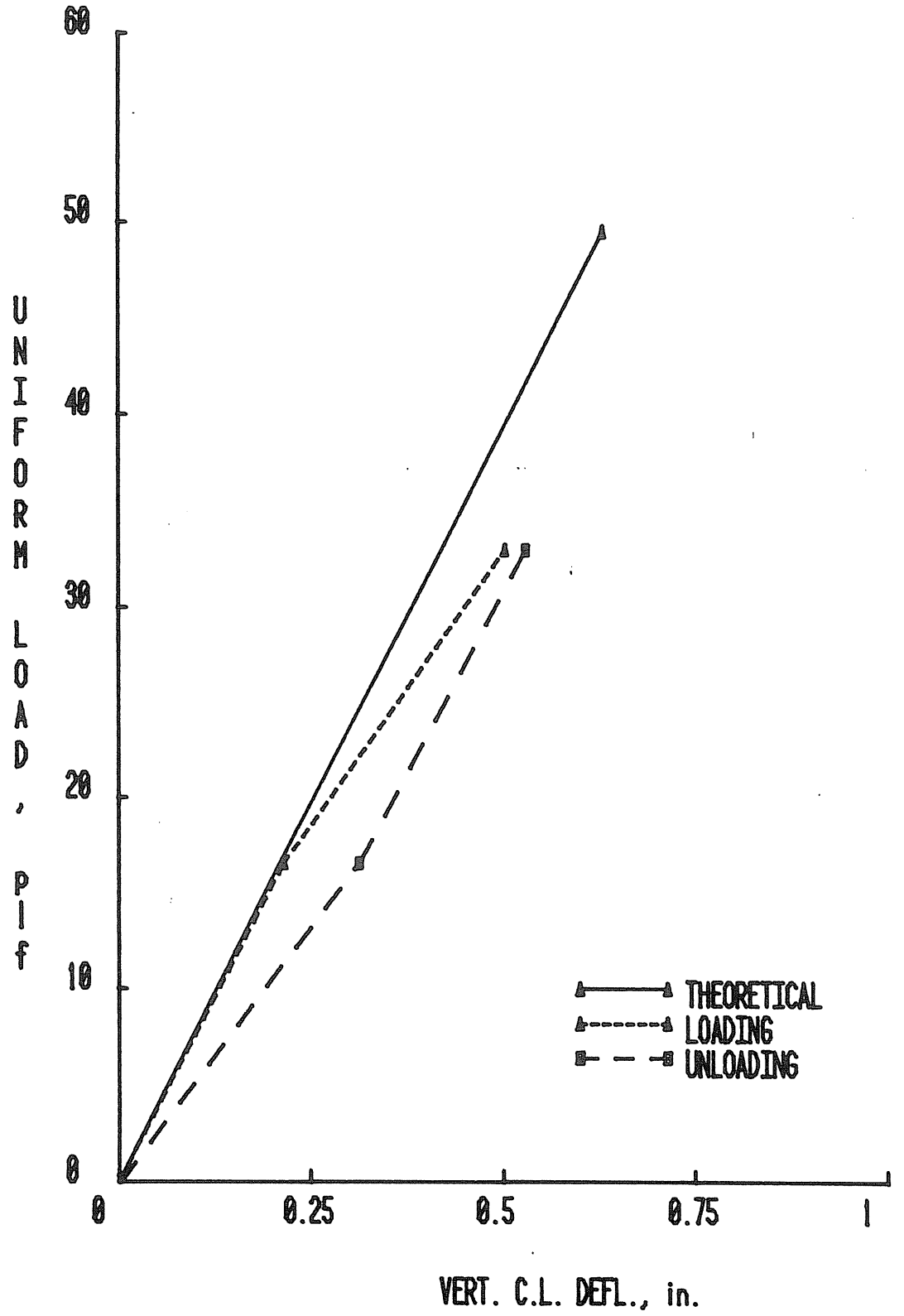


Figure E.4 Vertical Load vs. Vertical Deflection, Test SS/6/6

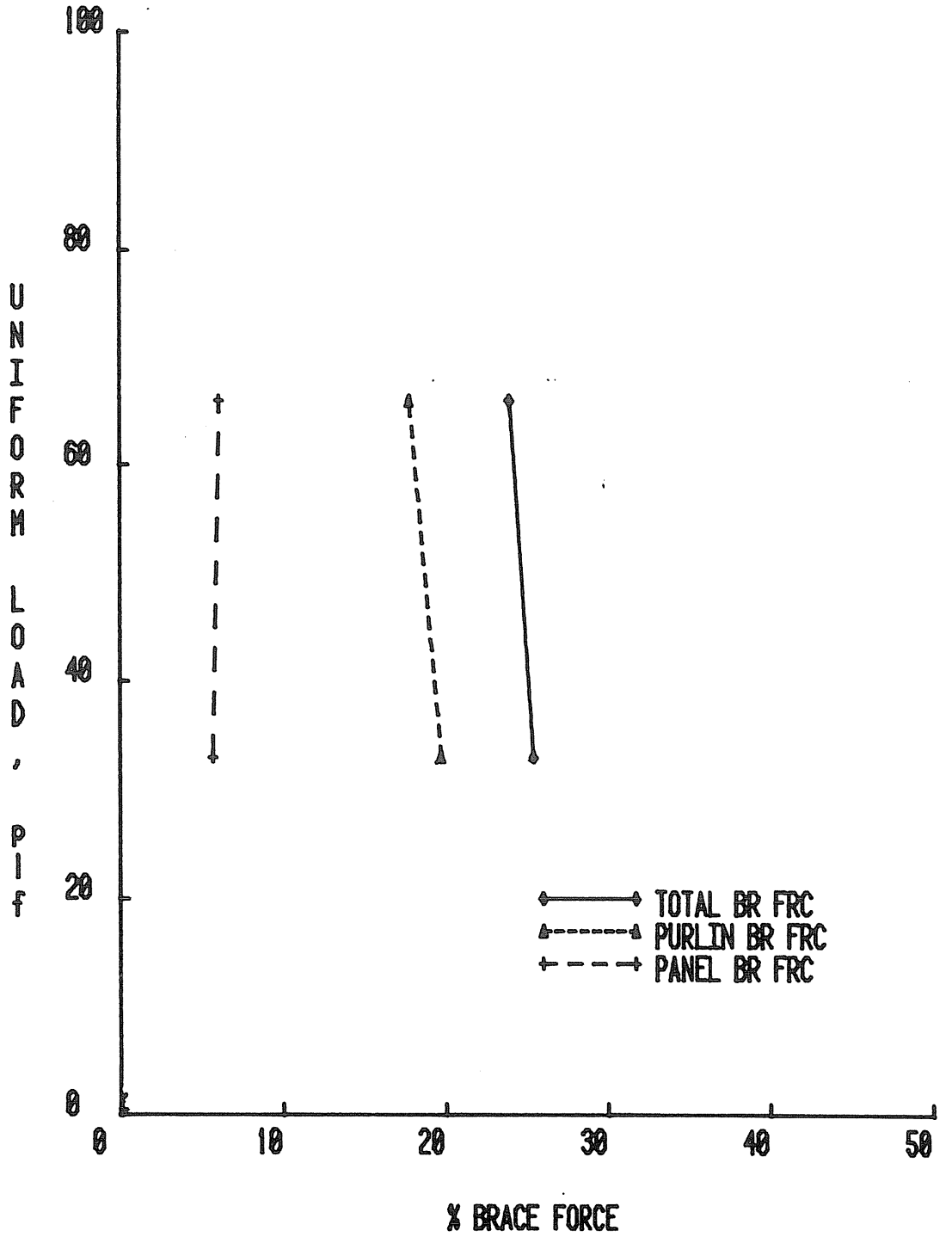


Figure E.5 Vertical Load vs. % Brace Force, Test SS/6/6 - Loading

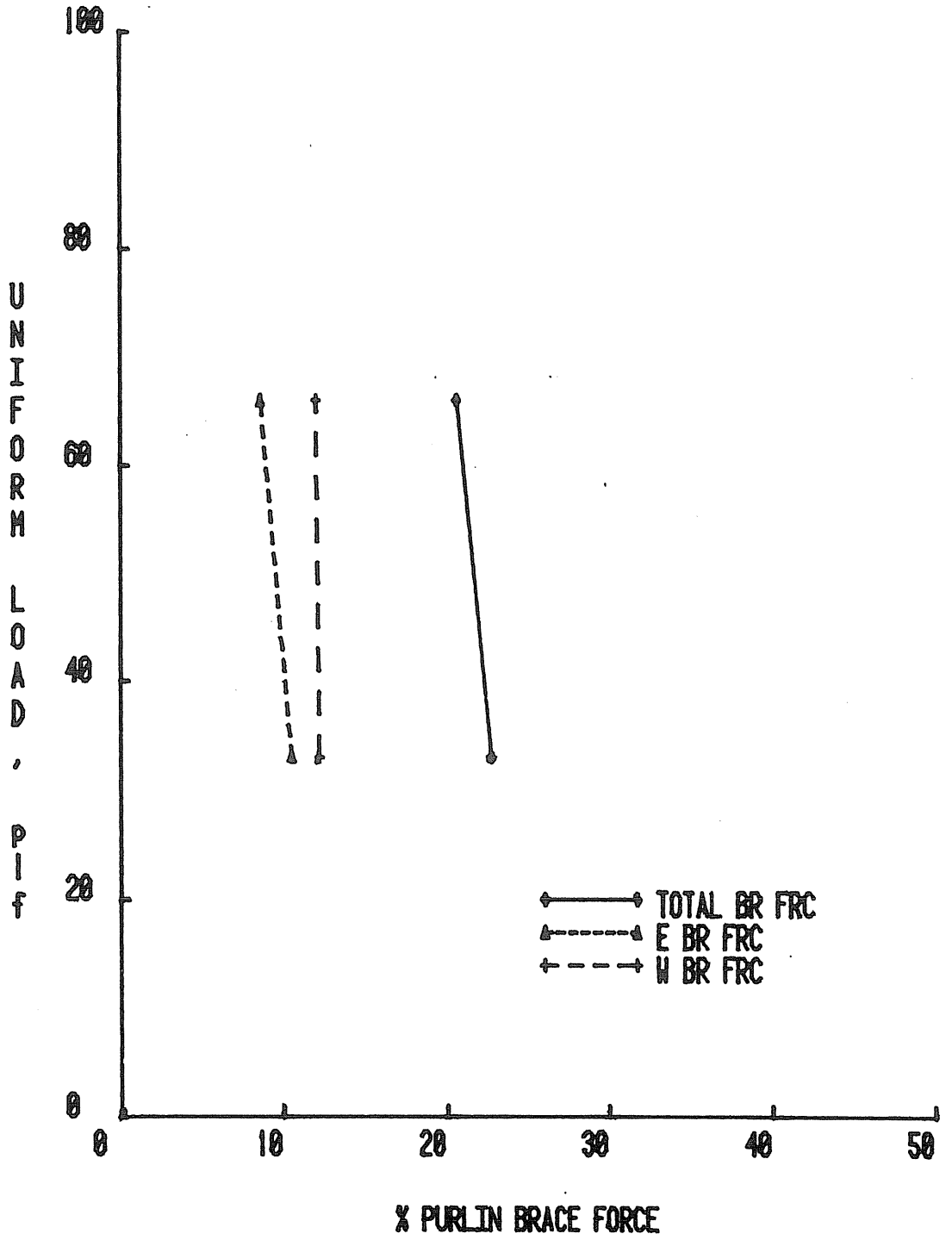


Figure E.6 Vertical Load vs. % Brace Force, Test SS/6/6 -Unloading

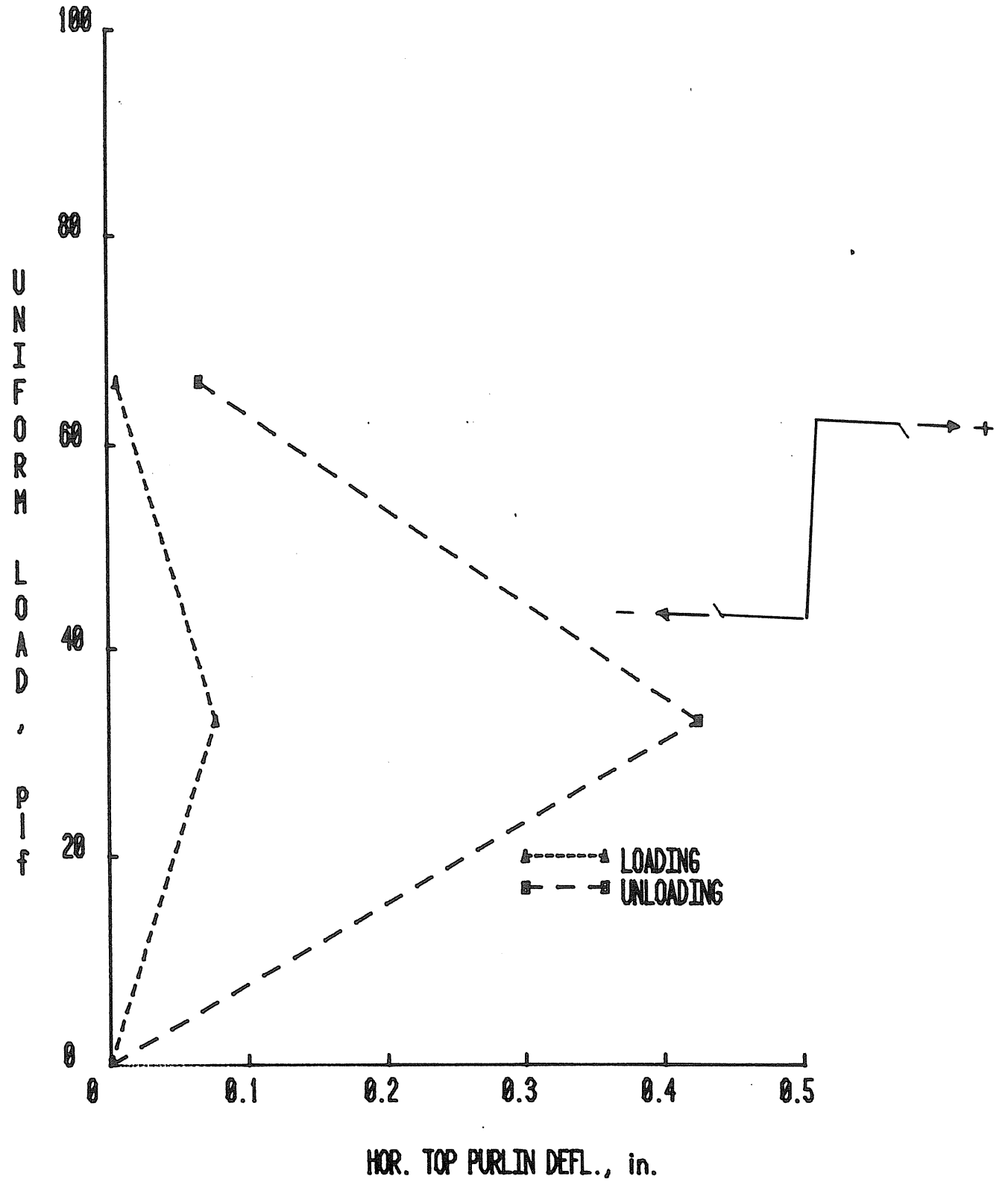


Figure E.7 Vertical Load vs. Horizontal Top Flange Purlin Deflection, Test SS/6/6

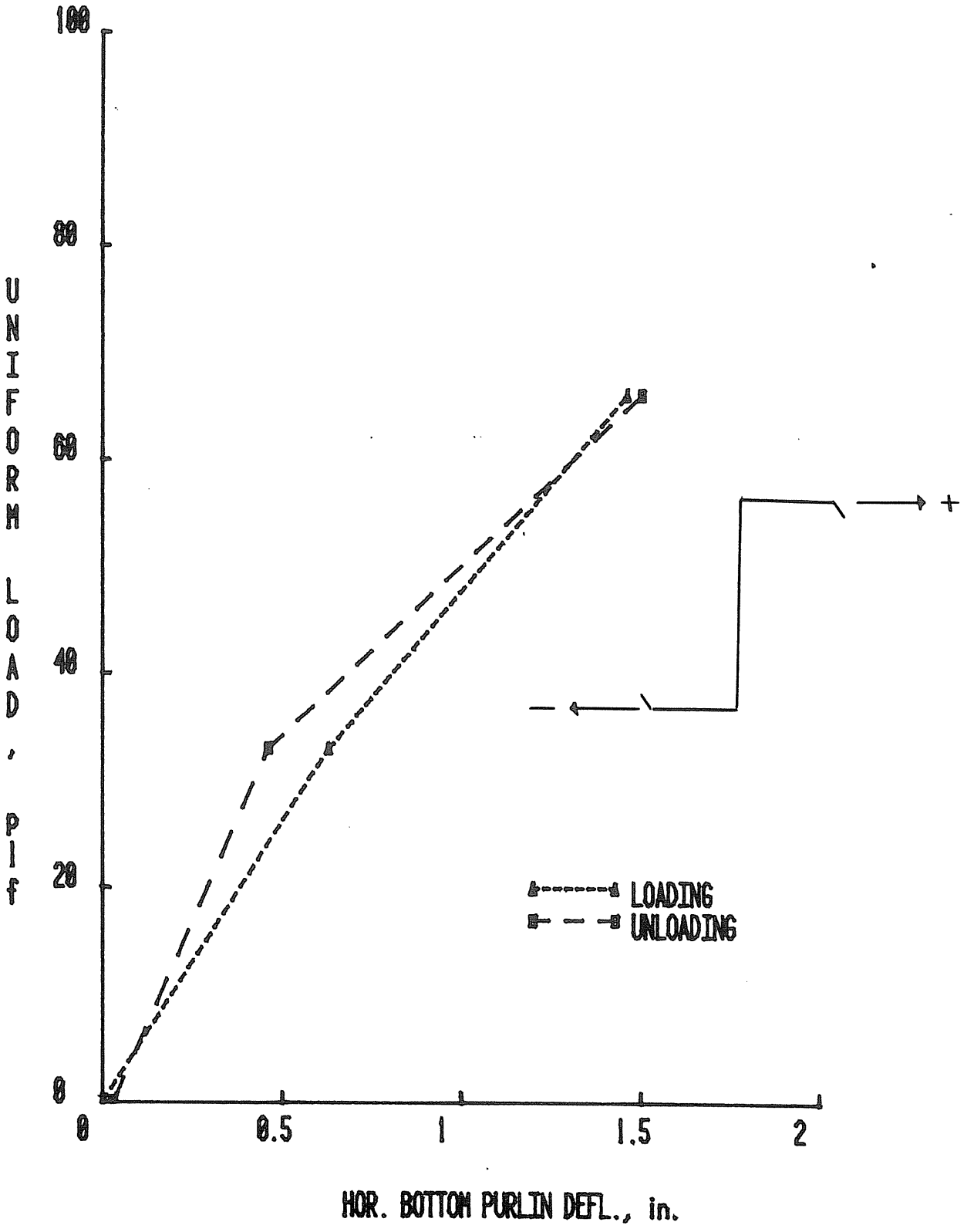


Figure E.8 Vertical Loading vs. Horizontal Bottom Flange Purlin Deflection, Test SS/6/6

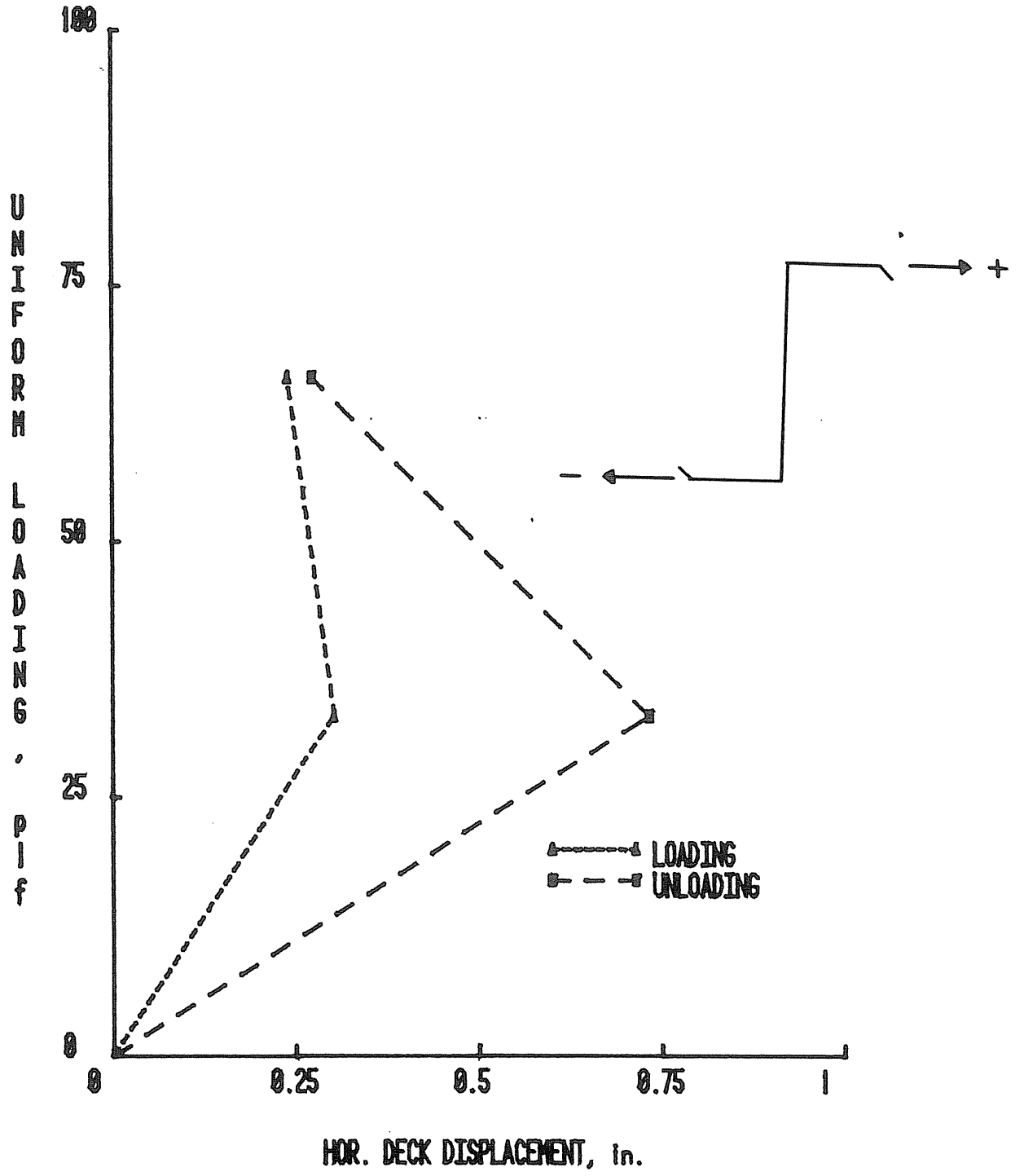
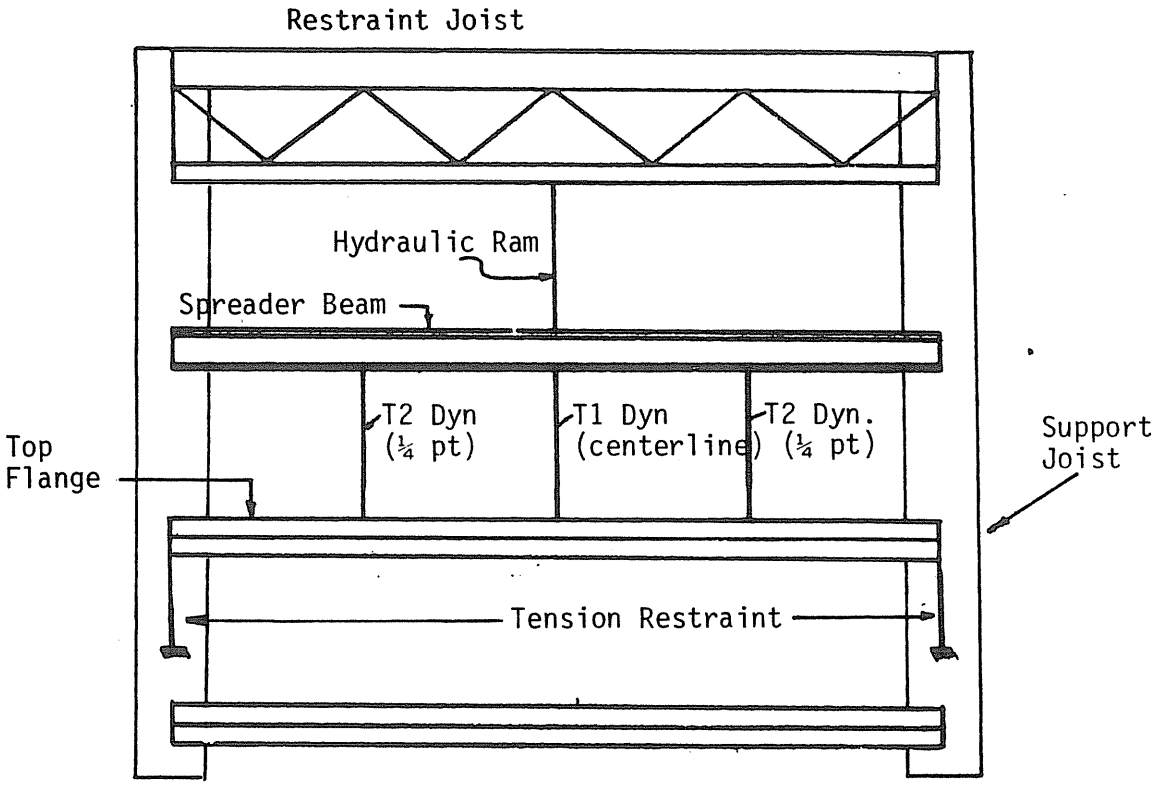


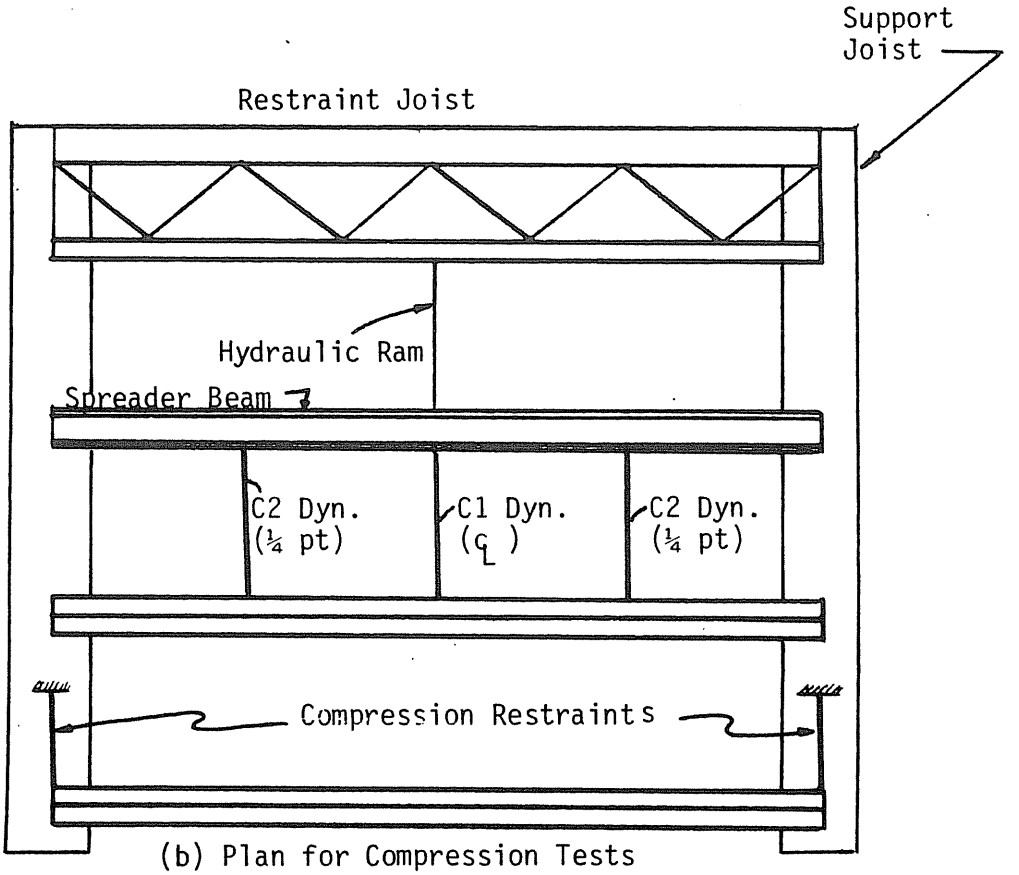
Figure E.9 Vertical Loading vs. Horizontal Panel Deflection, Test SS/6/6

APPENDIX F

S/2 STIFFNESS TEST RESULTS

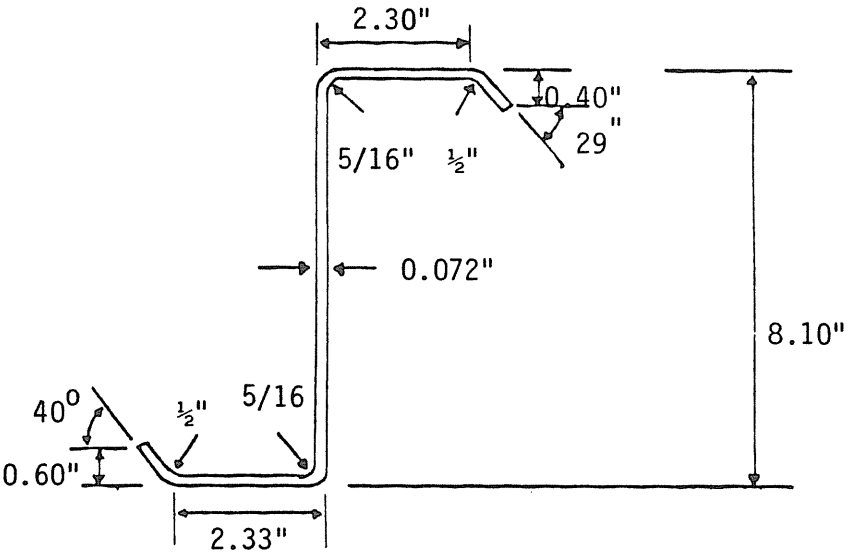


(a) Plan for Tension Tests

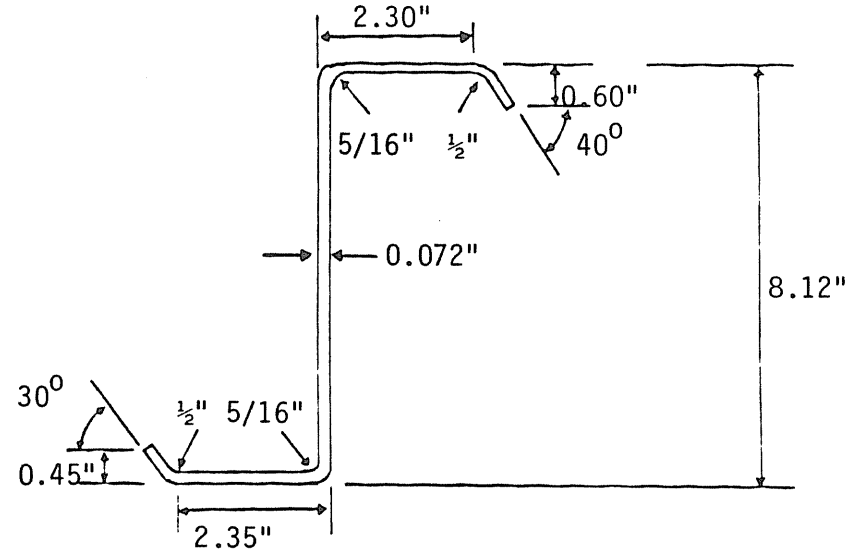


(b) Plan for Compression Tests

Figure F.1 Instrumentation Locations, Test S/2



External Purlin



Internal Purlin

Figure F.2 Measured Purlin Dimensions, Test S/2

```
A I S I   P U R L I N   A N A L Y S I S
              Z-SECTION
IDENTIFICATION: MBMA S/2    (WEST-EXT.) 7/29/82
```

	TOP	BOTTOM
FLANGE(in)	2.300	2.330
LIP(in)	0.400	0.600
LIP ANGLE(deg)	29.000	40.000
RADIUS L/F(in)	0.500	0.500
RADIUS F/W(in)	0.310	0.310

TOTAL DEPTH(in)	8.1
THICKNESS(in)	0.072
YIELD STRENGTH(ksi)	56

	MOMENTS OF INERTIA(in^4)	SECTION MODULII(in^3) TOP	BOTTOM
GROSS=	10.168	2.506	2.561
STRENGTH=	10.168	2.506	2.561
DEFLECTION=	10.168		

```
RF=    1.918   in
FC=   32.547   ksi
FT=   33.600   ksi
FBW=  31.209   ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)
          MC=     6.798   ft-k
          MT=     7.169   ft-k
          MW=     7.127   ft-k
          MU=    11.353   ft-k (1.67*allowable)
SPAN        =    14.000   ft.
UNIFORM LOAD=   463.394   plf (1.67*allowable)
DEFLECTION  =     0.288   in./100plf
```

Figure F.3 AISI Purlin Analysis, Test S/2 Exterior Purlin

```
A I S I  P U R L I N  A N A L Y S I S
              Z-SECTION
IDENTIFICATION: MBMA S/2     (EAST-INT.) 7/29/82

                          TOP          BOTTOM
FLANGE(in)              2.300           2.350
LIP(in)                 0.600           0.450
LIP ANGLE(deg)         40.000          30.000
RADIUS L/F(in)          0.500           0.500
RADIUS F/W(in)          0.310           0.310

TOTAL DEPTH(in)                 8.12
THICKNESS(in)                   0.072
YIELD STRENGTH(ksi)             56

                                      SECTION MODULII(in^3)
    MOMENTS OF INERTIA(in^4)          TOP          BOTTOM
GROSS=          10.324              2.566          2.565
STRENGTH=       10.324              2.566          2.565
DEFLECTION=     10.324
RE=    1.918   in
FC=   31.808   ksi
FT=   33.600   ksi
FW=   31.186   ksi

MOMENT CARRYING CAPACITY (AISI CRITERIA)
            MC=      6.802   ft-k
            MT=      7.182   ft-k
            MW=      7.297   ft-k
            MU=     11.360   ft-k (1.67*allowable)
SPAN          =     14.000   ft.
UNIFORM LOAD=    463.670   plf (1.67*allowable)
DEFLECTION    =      0.284   in./100plf
```

Figure F.4 AISI Purlin Analysis, Test S/2, Interior Purlin

TEST SUMMARY

Project: MBMA Roof System Behavior

Test No.: S/2-T1

Test Date: August 17, 1982

Purpose: In-plane stiffness and brace force: single load at centerline

Span(s): 14.00'

Thickness: .072" Moment of Inertia: $10.324"^4$

Parameters: Torsional restraint at rafters

Restraints in tension

Restraint braces attached to loaded purlin

Panel shear stiffness

Panel torsional restraint

Gravity Load: None

Predicted Failure Loads:

Method	AISI Purlin Analysis	Load	463.670 plf
Method		Load	
Method		Load	

Discussion:

Two tests were conducted with a maximum horizontal load at the centerline of 1000# being applied in each test. Torsional restraints were connected to the loaded purlin and were in tension.

Test 1

-The average stiffness was 1382.8 lb/in (10 readings)

-The average percent of total brace force to total applied load was 99.5% (10 readings)

-The maximum brace force was 959.7 lb. (N=492.89 lb, S=466.8 lb)

-The maximum centerline corrected horizontal deflection was 0.68 in. at maximum load

Test 2

-The average stiffness was 1351.7 lb/in (10 readings)

-The average percent of total brace force to total applied load was 99.8% (10 readings)

-The maximum brace force was 988.0 lb (N=523.4 lb, S=464.7 lb)

-The maximum centerline corrected horizontal deflection was 0.64 in. at max. load

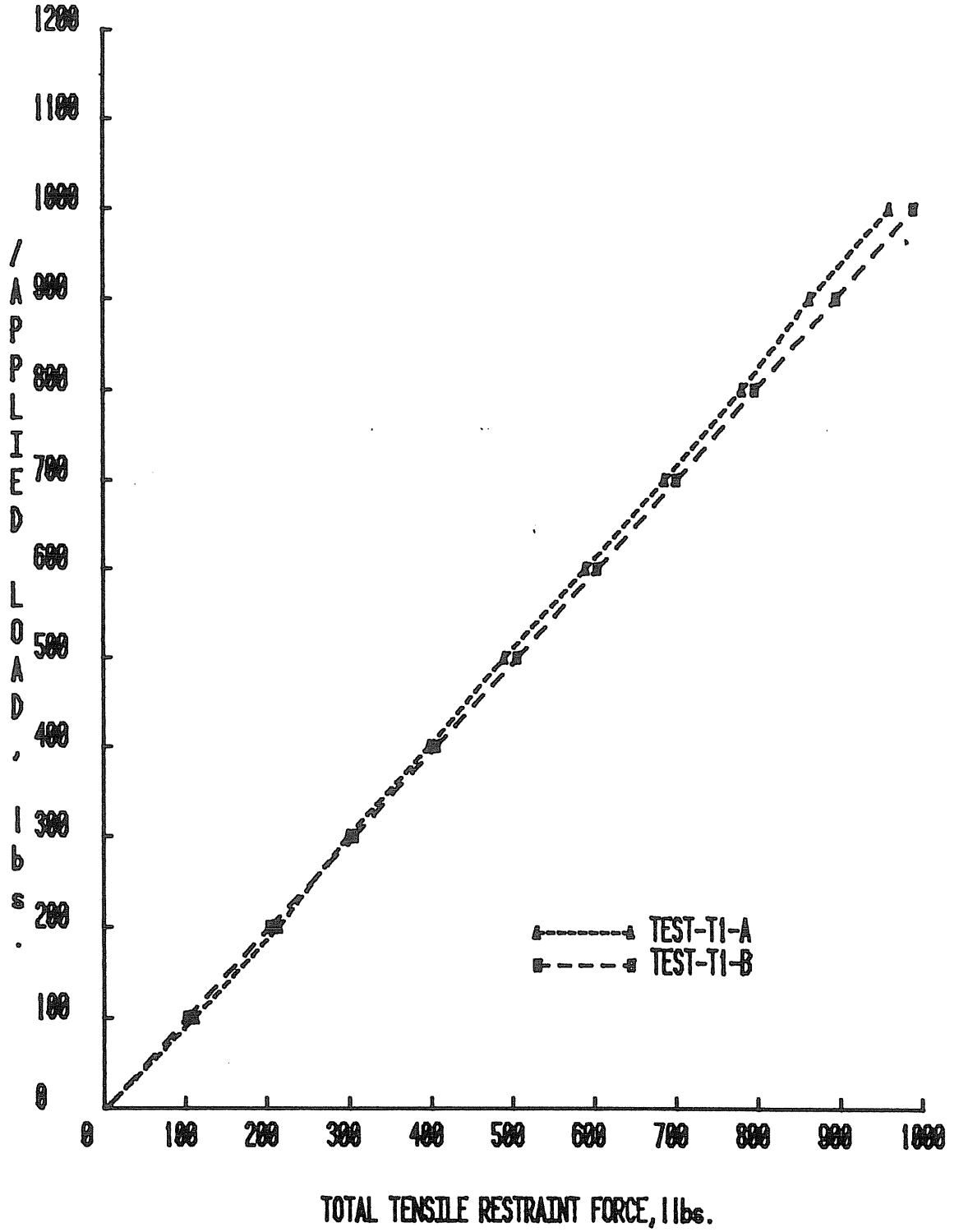


Figure F.5 In-plane Load vs. Total Restraint Force, Test S/2-T1

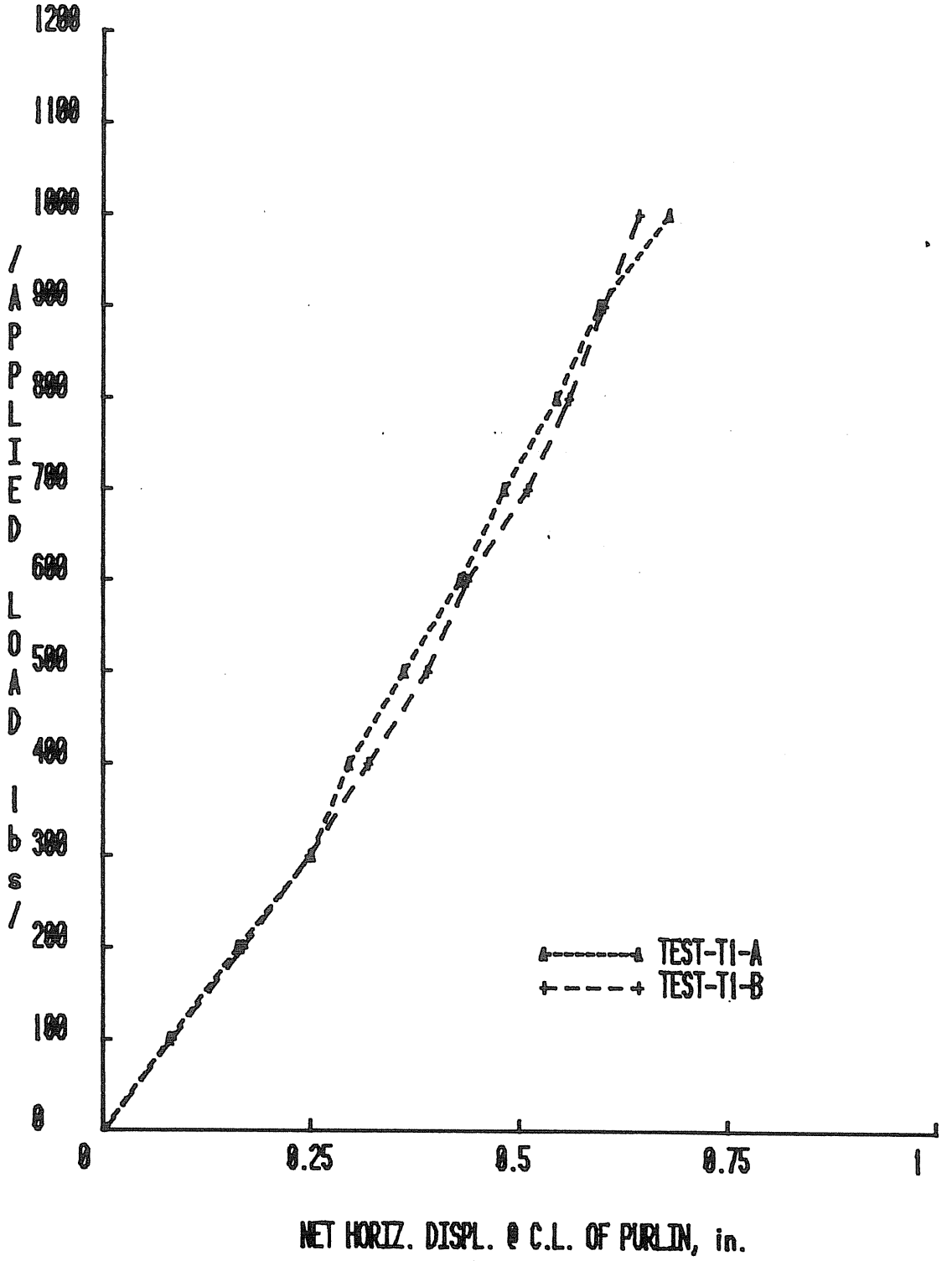


Figure F.6 In-plane Load vs. Horizontal Displacement, Test S/2 -T1

TEST SUMMARY

Project: MBMA Roof System Behavior

Test No.: S/2-T2

Test Date: August 17, 1982

Purpose: In-plane stiffness and brace force: loads at ¼ points

Span(s): 14.00'

Thickness: .072" Moment of Inertia: 10.324"^{4}

Parameters: Torsional restraint at rafters
Restraints in tension
Restraint braces attached to loaded purlin
Panel shear stiffness
Panel torsional restraint

Gravity Load: None

Predicted Failure Loads:

Method AISI Purlin Analysis Load 463.7 plf

Method _____ Load _____

Method _____ Load _____

Discussion:

Two tests were conducted. Torsional restraints were connected to the loaded purlins and were in tension.

Test 1

-The average stiffness (5 readings) for north ¼ point was 1132.9 lb/in., and for south ¼ point was 1212.8 lb/in.

-The average percent of total brace force to total applied load (5 readings) was 90.8%.

-The maximum total load applied was 975.3 lb.

-The maximum total brace force was 856.6 lb (N=432.0 lb, S=424.6 lb).

-The maximum ¼ point deflections were 0.45 in (N) and 0.38 in (S).

Test 2

-The average stiffness (5 readings) for north ¼ point was 1030.7 lb/in, and for south ¼ point was 1141.8 lb/in.

-The average percent of total brace force to total applied load (5 readings) was 93.4%.

-The maximum total load applied was 976.8 lb.

-The maximum total brace force was 925.4 lb (N=489.5 lb, S=435.9 lb).

-The maximum ¼ point deflections were 0.44 in (N) and 0.39 in. (S).

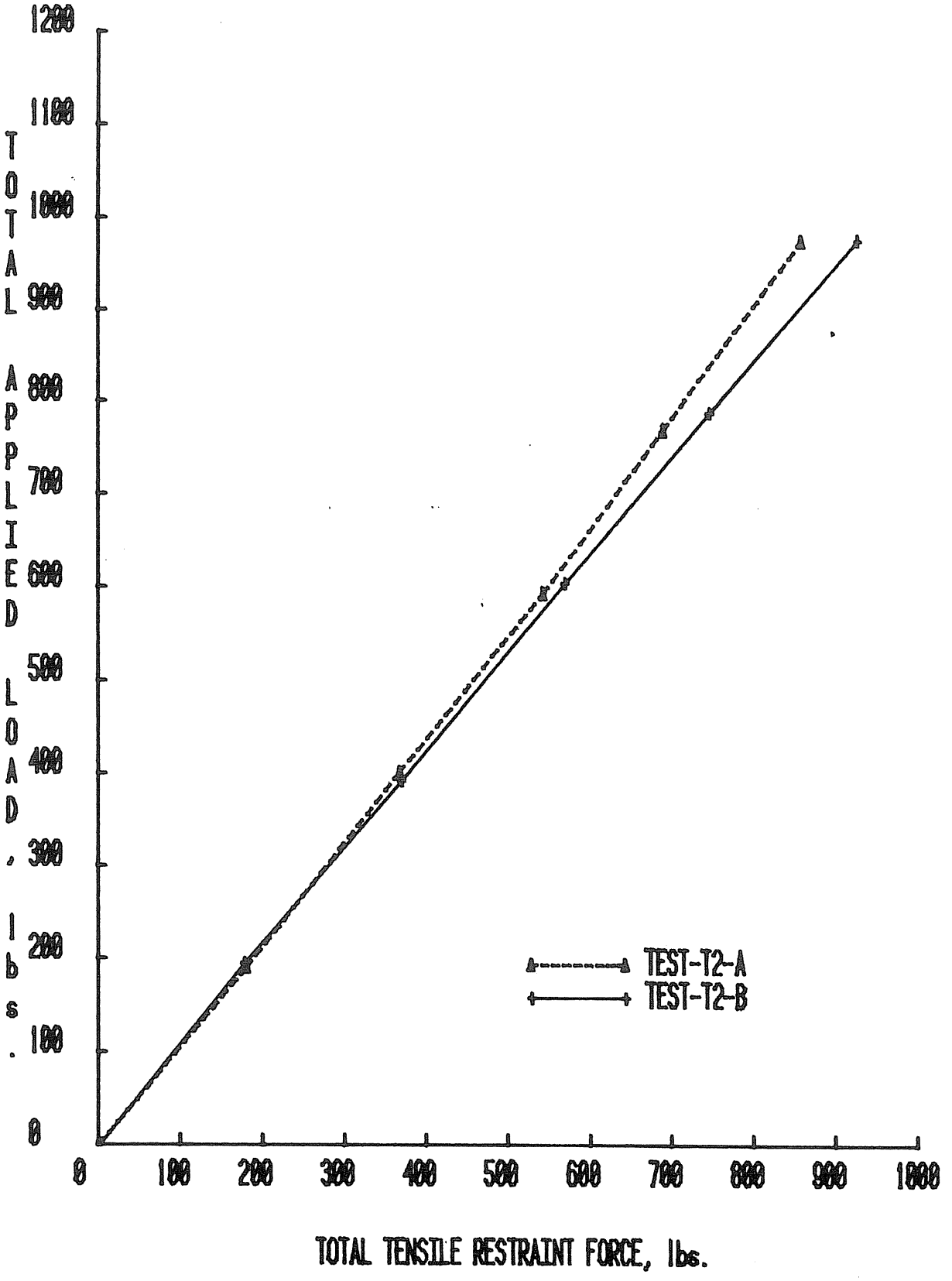


Figure F.7 In-plane Load vs. Total Restraint Force, Test S/2-T2

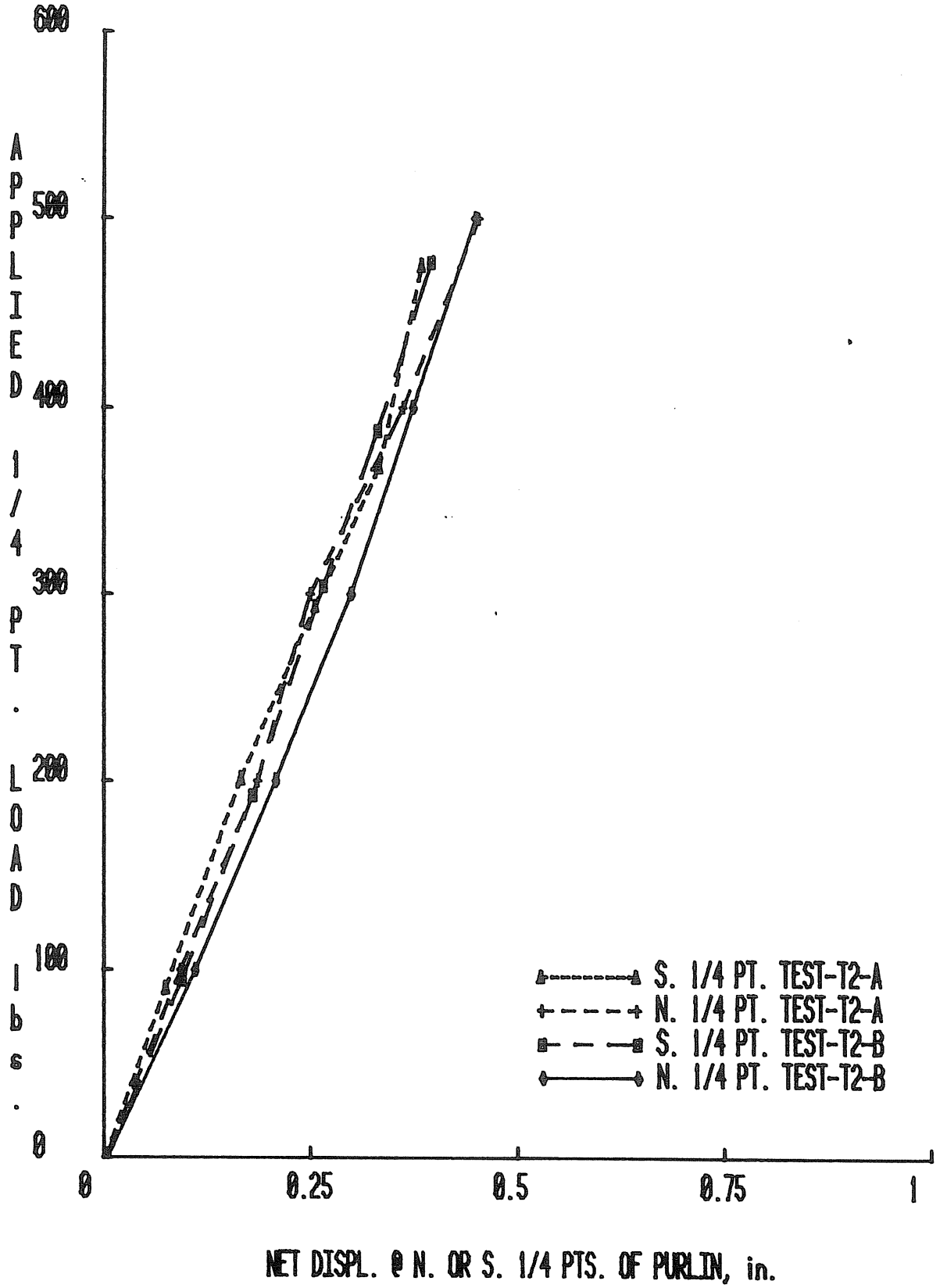


Figure F.8 In-plane Load vs. Horizontal Displacement, Test S/2-T2

TEST SUMMARY

Project: MBMA Roof System Behavior

Test No.: S/2-C1

Test Date: August 9, 1982

Purpose: In-plane stiffness and brace force: single load at centerline

Span(s): 14.00'

Thickness: .072" Moment of Inertia: $10.324"^4$

Parameters: Torsional restraint at rafters
Restraint in compression
Restraint braces attached to unloaded purlin
Panel shear stiffness
Panel torsional restraint

Gravity Load: None

Predicted Failure Loads:

Method AISI Purlin Analysis Load 463.7 plf

Method _____ Load _____

Method _____ Load _____

Discussion:

-One test was conducted with a maximum horizontal load of 1000 lb. Torsional restraints were connected to the unloaded purlin and were in compression.

-The average stiffness was (10 readings) 1731.7 lb/in.

-The average percent of total brace force to total applied load (10 readings) was 87.1%.

-The maximum brace force was 829.0 lb C.

-The maximum centerline corrected deflection was 0.49 in.

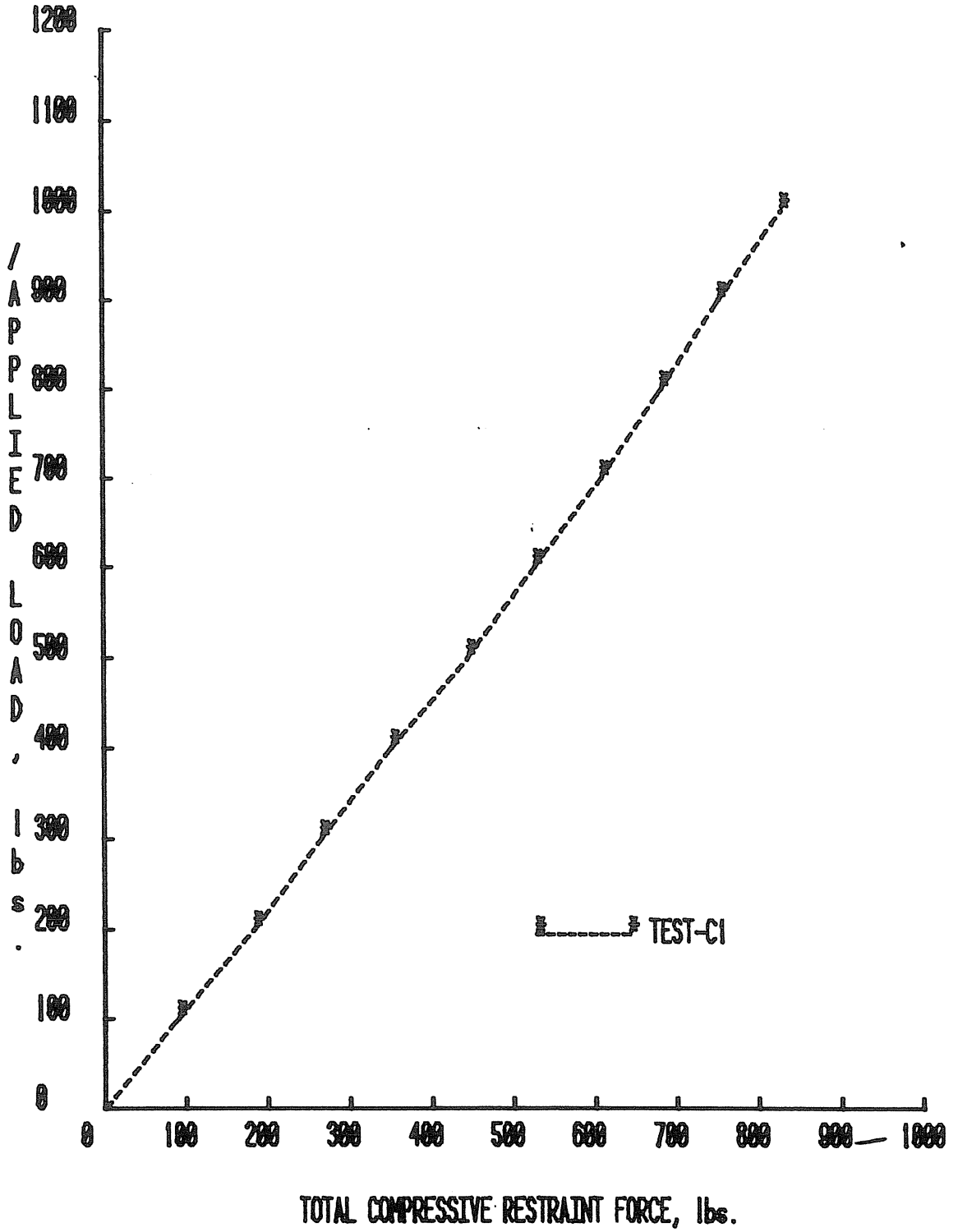


Figure F.9 In-plane Load vs. Total Restraint Force, Test S/2-C1

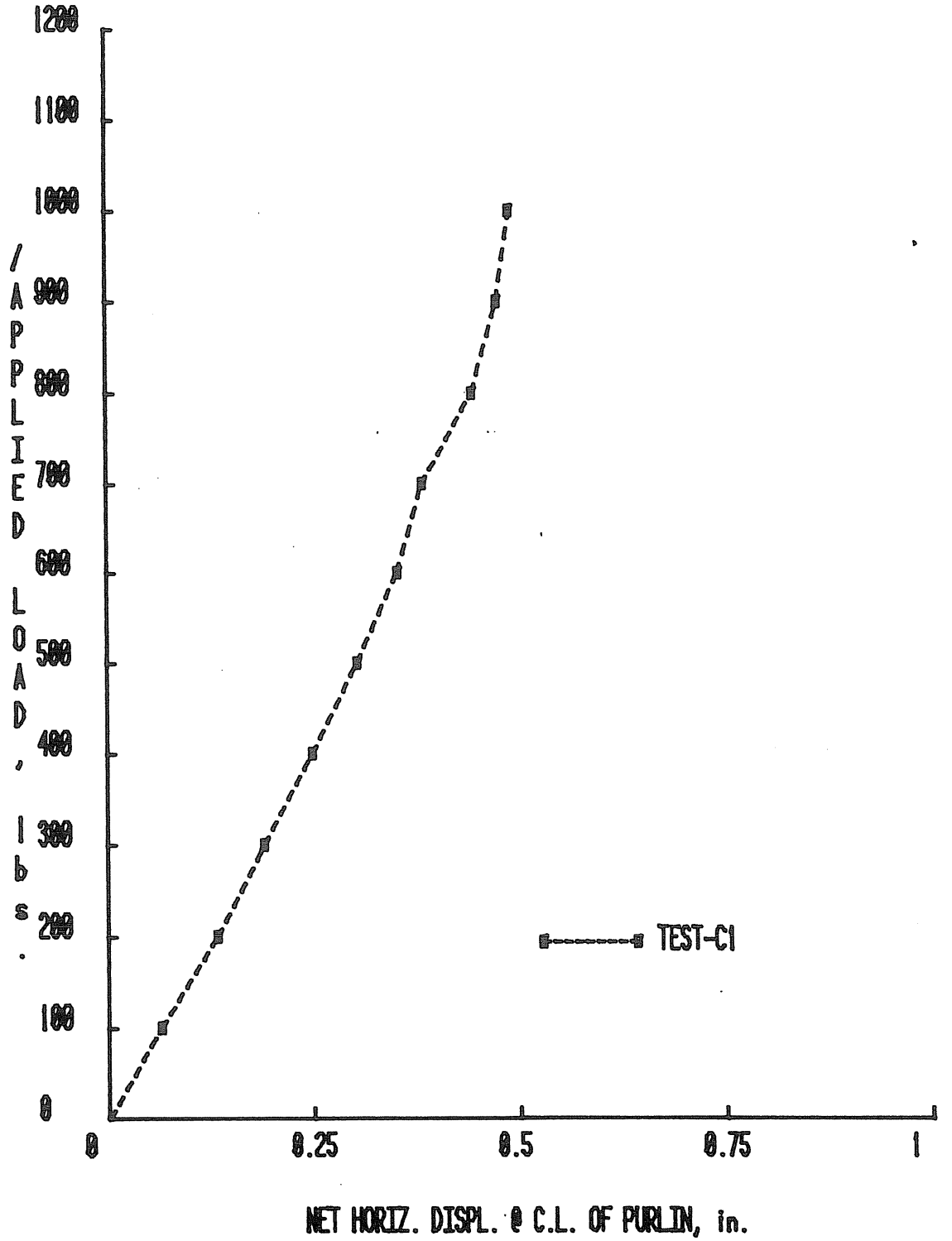


Figure F.10 In-plane Load vs. Horizontal Displacement, Test S/2-C1

TEST SUMMARY

Project: MBMA Roof System Behavior

Test No.: S/2-C2 & S/2-C2/99

Test Date: August 19, 1982

Purpose: In-plane stiffness and brace force: loads at ¼ points.

Span(s): 14.00'

Thickness: .072" Moment of Inertia: 10.324"^{4}

Parameters: Torsional restraint at rafters

Restraints in compression

Restraint braces attached to unloaded purlin

Panel shear stiffness

Panel torsional restraint

Gravity Load: 99 plf per purlin

Predicted Failure Loads:

Method AISI Purlin Analysis Load 463.7 plf

Method Load

Method Load

Discussion:

Test S/2-C2

-No gravity load.

-Torsional restraint braces in compression

-Torsional restraint braces at unloaded purlin.

-The average stiffness (5 readings) for north ¼ point was 1514.9 lb/in, and for south ¼ point was 1771.1 lb/in.

-The average % of total brace force to total applied load (5 readings) was 86.2%.

-The maximum total horizontal applied load was 931.9 lb.

-The maximum total brace force was 798.0 lb (N=399.5 lb and S=-398.6 lb).

-The maximum ¼ point corrected horizontal deflections were 0.3031" (N) and 0.2501" (S).

Test S/2-C2/99

-Tests identical to S/2-C2 were conducted with the purlins loaded to 99 plf per purlin.

Test 1

-The average stiffness (5 readings) for N ¼ point was 1962.6 lb/in and for S ¼ point was 2253.6 lb/in.

-The purlins were not straightened after the 99 plf/purlin was applied.

-The average percent of total brace force to total applied load (5 readings) was 92.1%.

-The maximum total load applied was 996.7 lb.

-The maximum total brace force was 885.0 (N=424.5 lb. and S=460.5 lb).

-The maximum ¼ point corrected horizontal deflections were 0.2461 in. (N) and 0.2291 in. (S).

Test 2

-The purlins were straightened after 99 plf/purlin was applied.

-The average stiffness (4 readings) for north ¼ point was 2933.5 lb/in. and for south ¼ point was 2470.3 lb/in.

-The average percent of total brace force to total applied load (4 readings) was 87.0%.

-The maximum total load applied was 790.6 lb.

-The maximum total brace force was 673.6 lb (N=291.1 lb. and S=382.4 lb).

-The maximum ¼ point corrected horizontal deflections were 0.1495 in. (N) and 0.1691 in. (S).

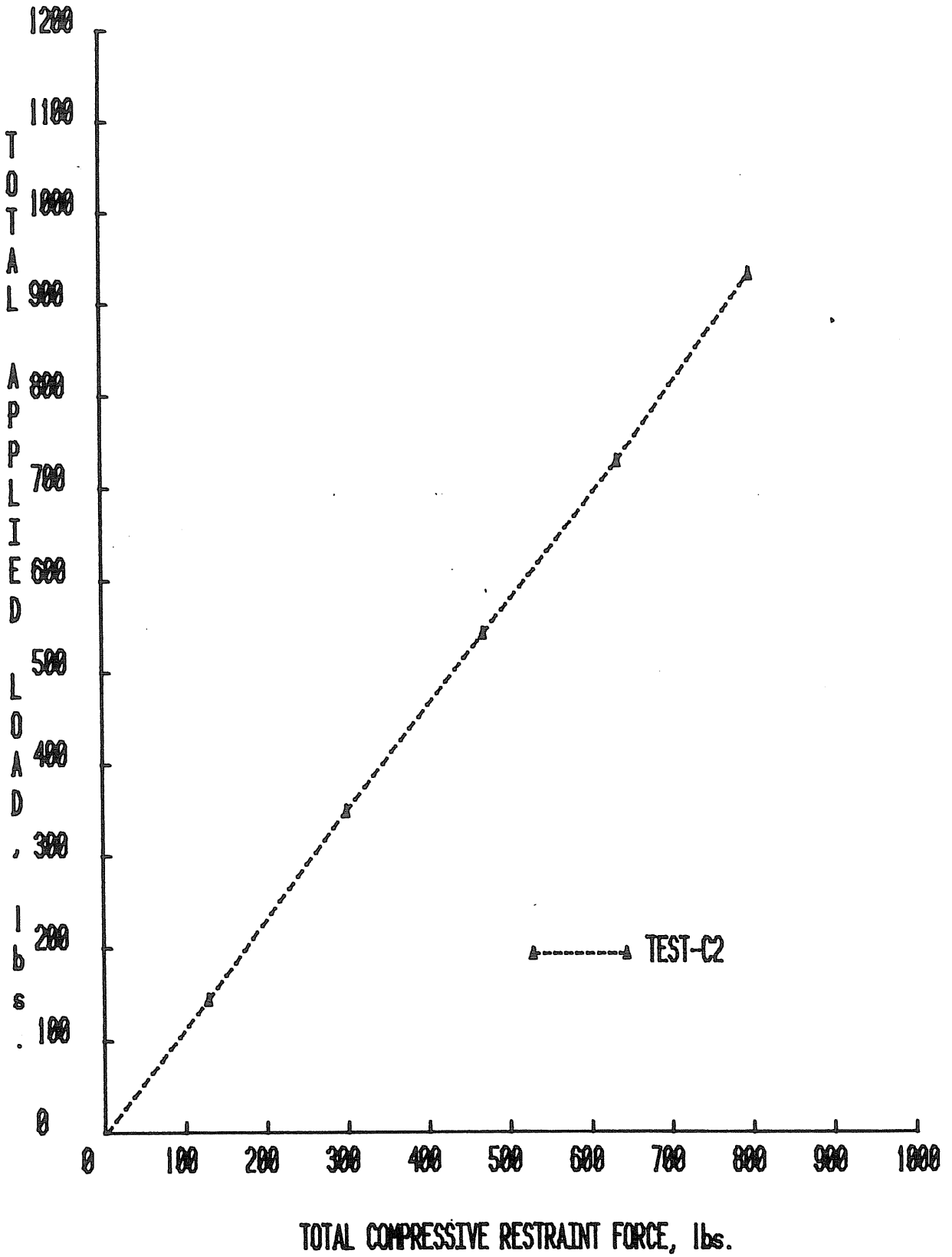


Figure F.11 In-plane Load vs. Total Restraint Force, Test S/2-C2

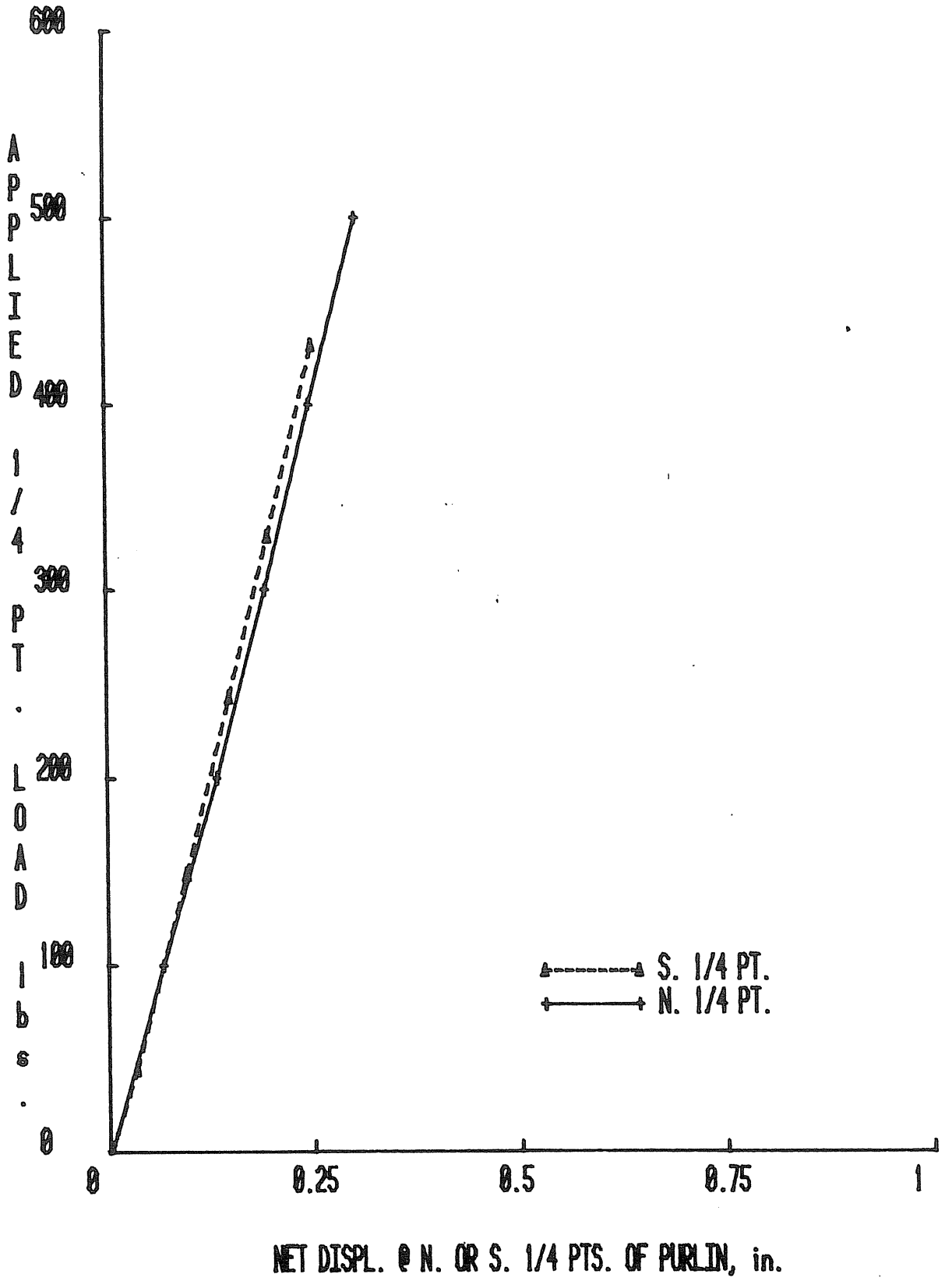


Figure F.12 In-plane Load vs. Horizontal Displacement, Test S/2-C2

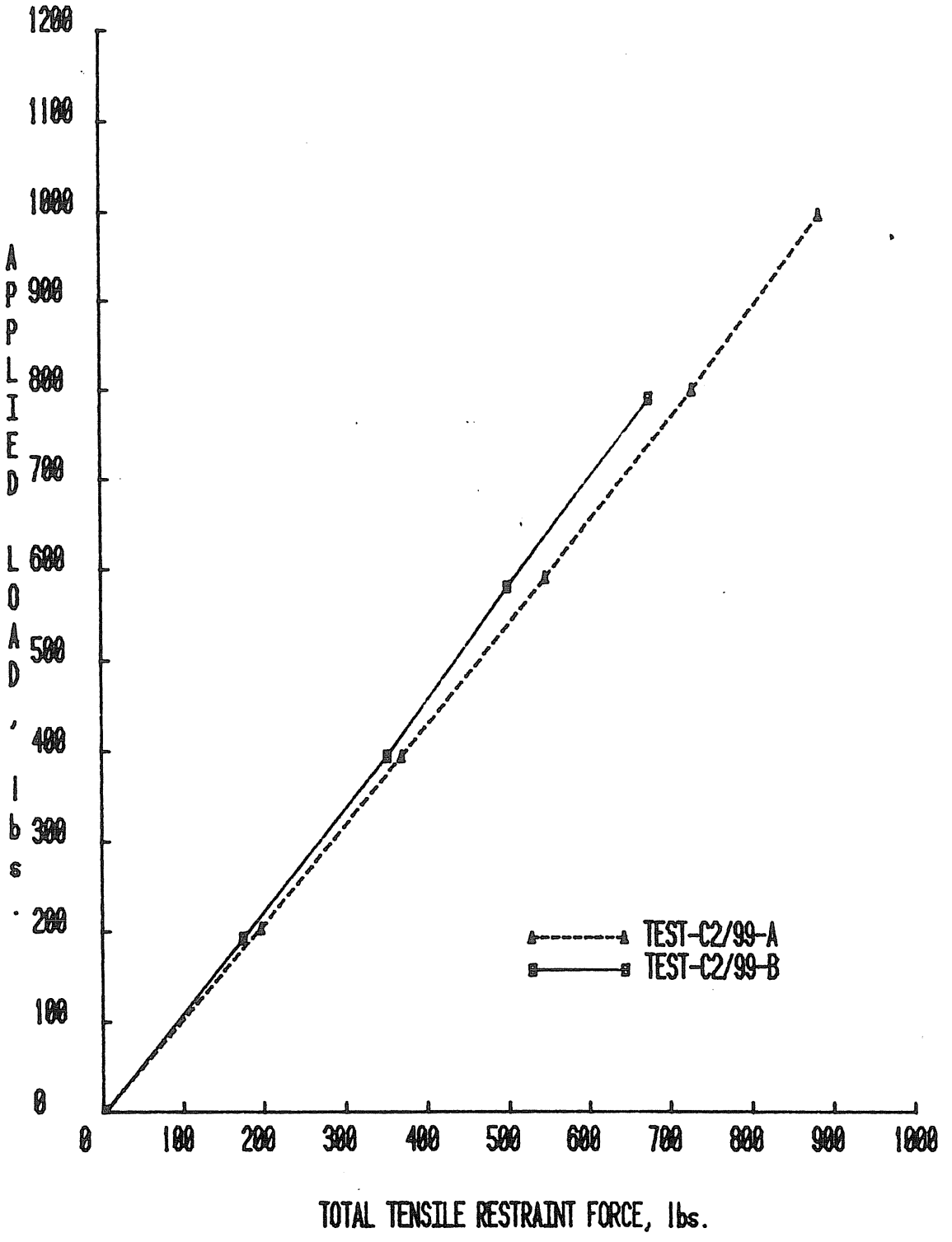


Figure F.13 In-plane Load vs. Total Restraint Force, Test S/2-C2/99

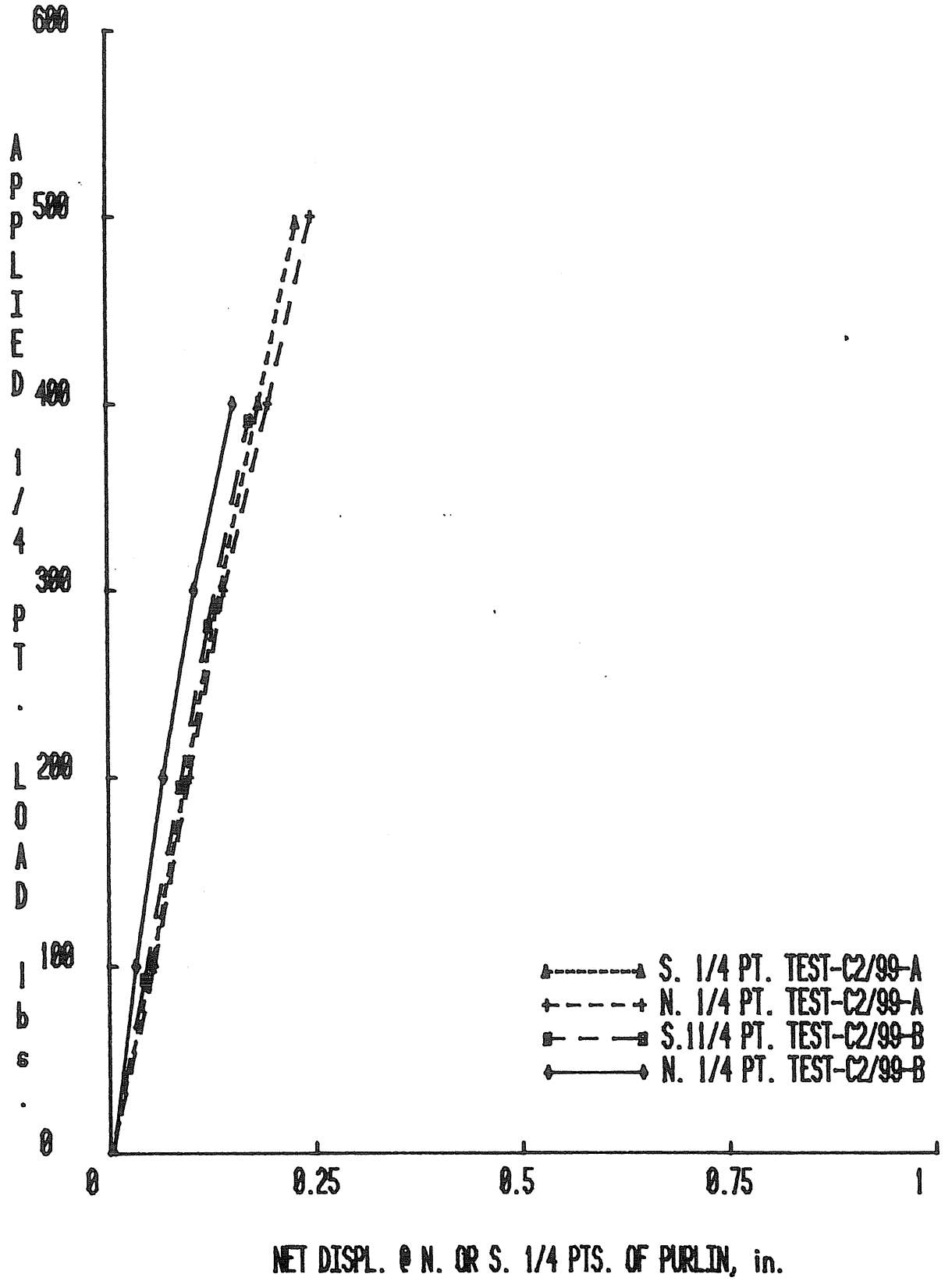


Figure F.14 In-plane Load vs. Horizontal Displacement, Test S/2-C2/99

APPENDIX G

SERIES S/7 STIFFNESS TEST RESULTS

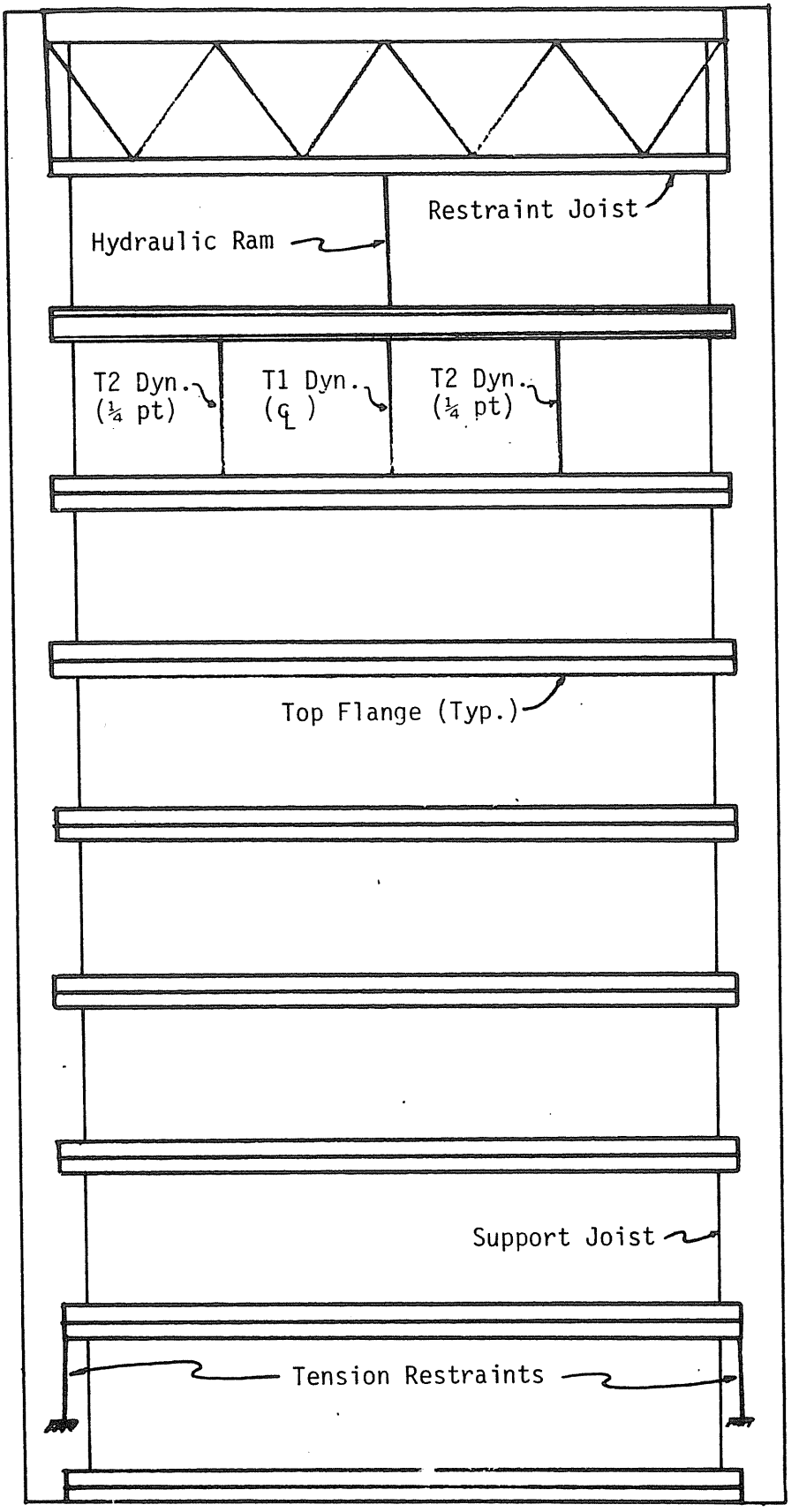


Figure G.1 Instrumentation Locations, Test S/7

TEST SUMMARY

Project: MBMA Roof System Behavior

Test No.: S/7-T1

Test Date: September 2, 1982

Purpose: In-plane stiffness and brace force: single load at centerline

Span(s): 14.00'

Thickness: _____ Moment of Inertia: _____

Parameters: Torsional restraint at rafters

Restraints in tension

Restraint braces attached to 6th purlin from applied load.

Panel shear stiffness

Panel torsional restraint

Gravity Load: None

Predicted Failure Loads:

Method _____ Load _____

Method _____ Load _____

Method _____ Load _____

Discussion:

Two tests were conducted. Torsional restraints were in tension and connected to 6th purlin from applied load.

Test 1

-The average stiffness (10 readings) was 2861.9 lb/in.

-The average percent of total brace force to total applied load (10 readings) was 60.6%.

-The maximum applied load was 1000#.

-The maximum brace force was 619.4 lb (E=347.3 lb and W=272.05 lb).

-The maximum centerline corrected deflection was 0.3417 in.

Test 2

-The average stiffness (8 readings) was 3155.2 lb/in.

-The average percent of total brace force to total applied load (8 readings) was 60.2%.

-The maximum applied load was 1500 lb.

-The maximum brace force was 959.2 lb (E=560.6 lb and W=398.6 lb).

-The maximum centerline corrected deflection was 0.5073 in.

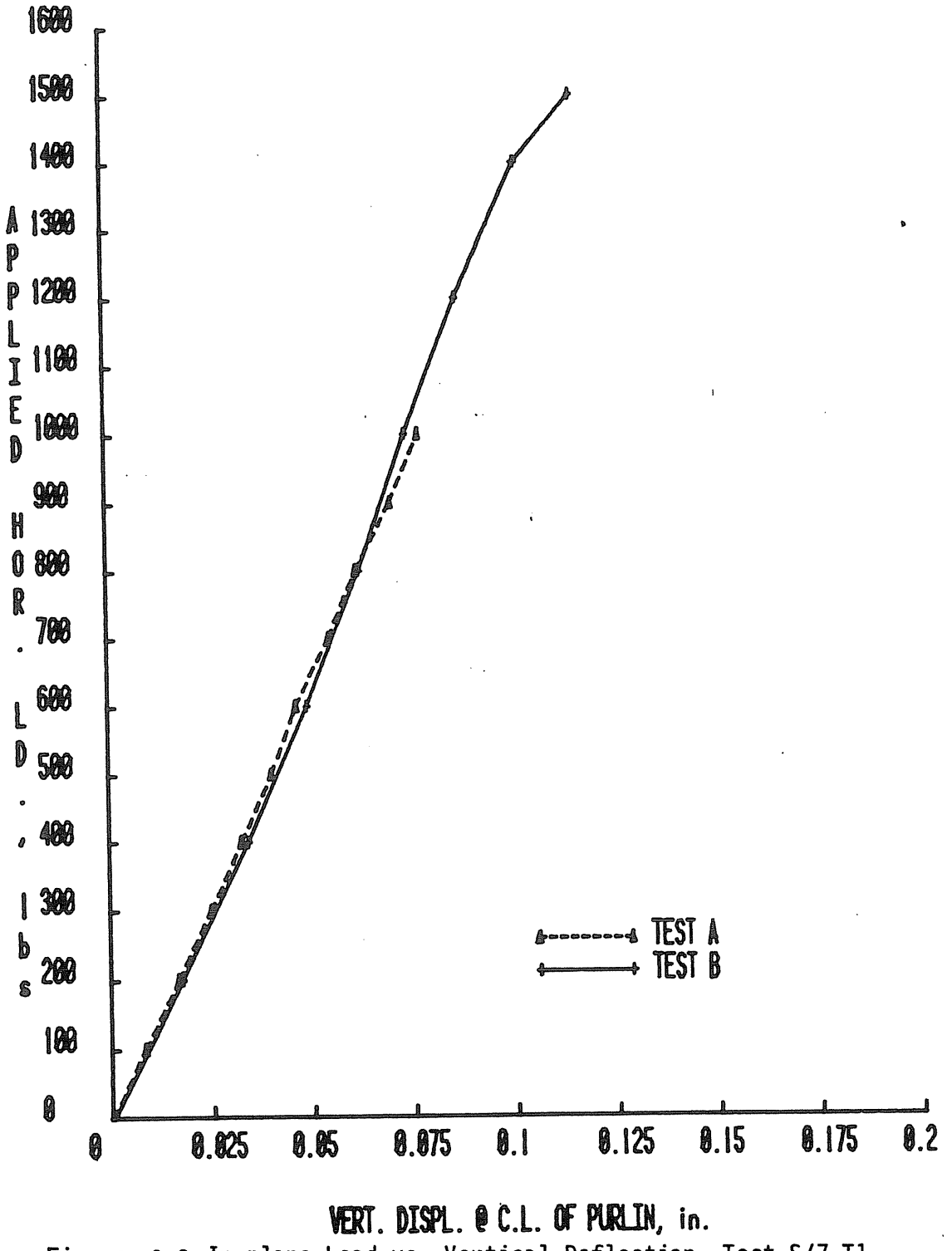


Figure G.2 In-plane Load vs. Vertical Deflection, Test S/7-T1

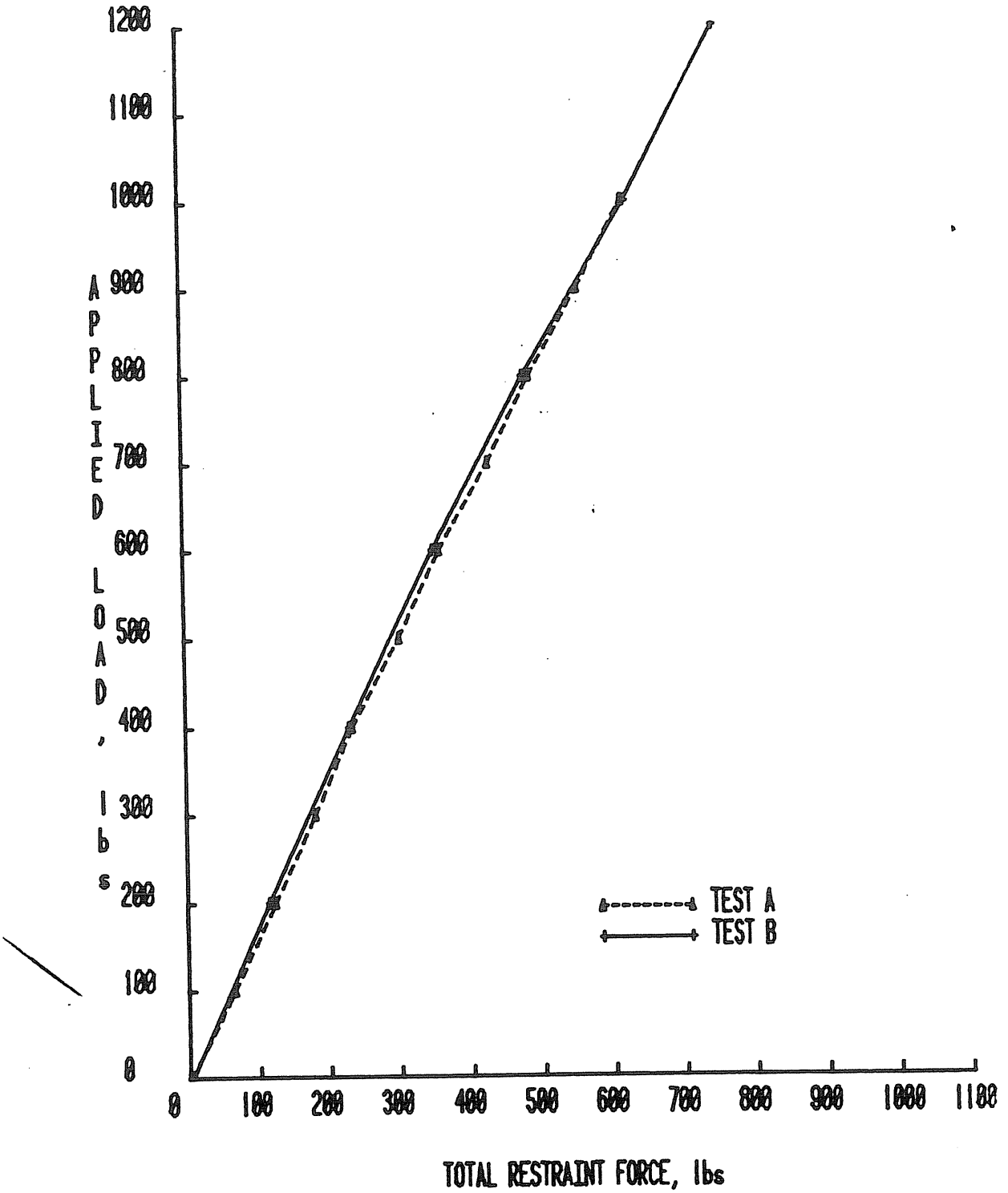


Figure G.3 In-plane Load vs. Total Restraint Force, Test S/7-T1

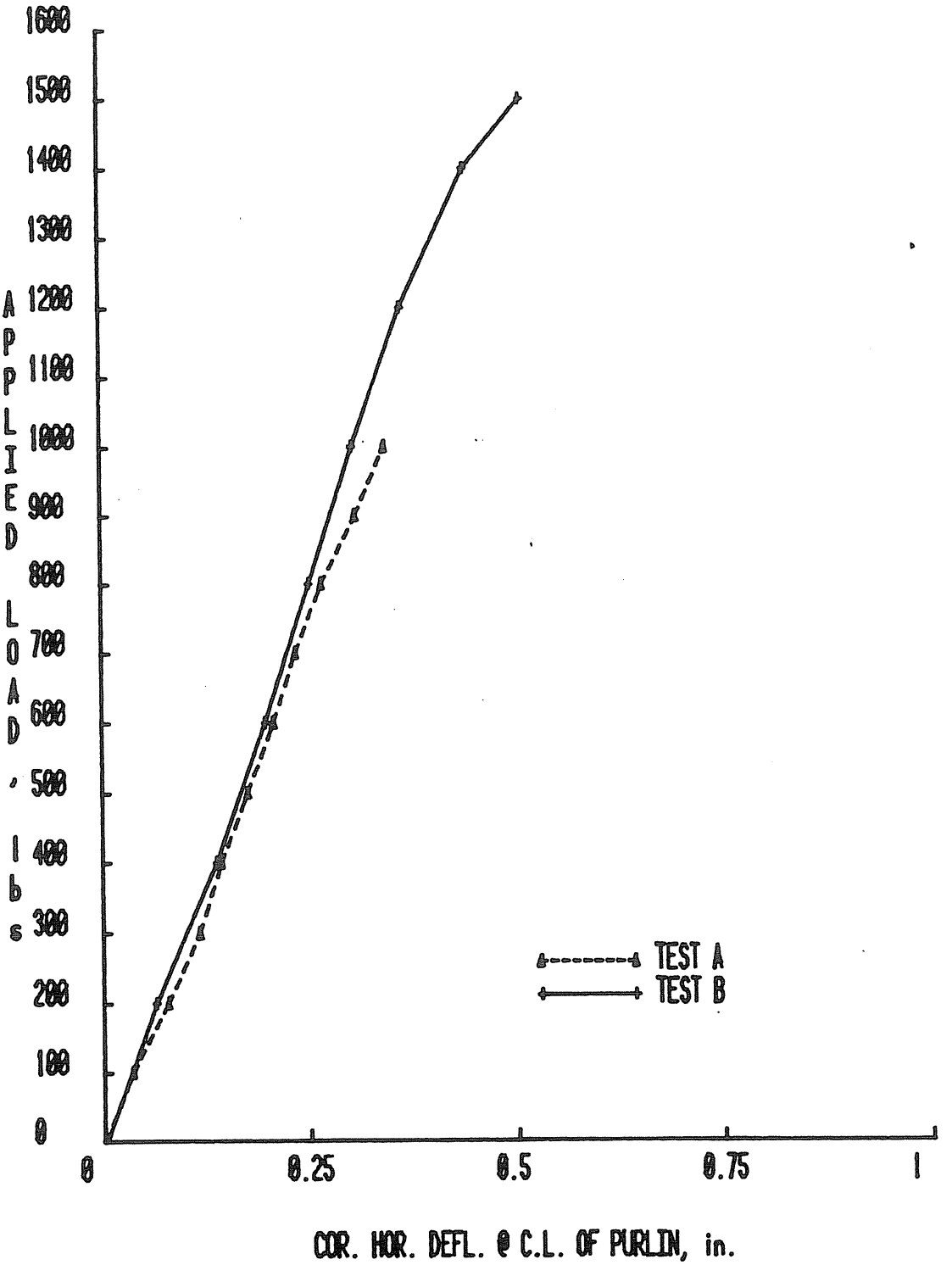


Figure G.4 In-plane Load vs. Horizontal Deflection, Test S/7-T1

TEST SUMMARY

Project: MBMA Roof System Behavior

Test No.: S/7-T1/99

Test Date: September 2, 1982

Purpose: In-plane stiffness and brace force: single load at centerline

Span(s): 14.00'

Thickness: _____ Moment of Inertia: _____

Parameters: Torsional restraint at rafters

Restraints in tension

Restraint braces attached to 6th purlin from applied load

Panel shear stiffness

Panel torsional restraint

Gravity Load: 99 plf per purlin

Predicted Failure Loads:

Method _____ Load _____

Method _____ Load _____

Method _____ Load _____

Discussion:
Two tests were conducted. Torsional braces were in tension and connected to the 6th purlin from applied load.

Test 1

-The average stiffness (8 readings) was 3124.9 lb/in.

-The average percent of total brace force to total applied load (8 readings) was 76.3%.

-The maximum applied load was 1300 lb.

-The maximum total brace force was 975.8 lb (E=566.7 lb, W=409.11 lb).

-The maximum centerline corrected deflection was 0.4021 in.

Test 2

-The average stiffness (8 readings) was 2884.7 lb/in.

-The average percent of total brace force to total applied load (8 readings) was 69.6%.

-The maximum total applied load was 1500 lb.

-The maximum total brace force was 1112.2 lb (E=585.0 lb, W=527.2 lb.)

-The maximum centerline corrected deflection was 0.4806 in.

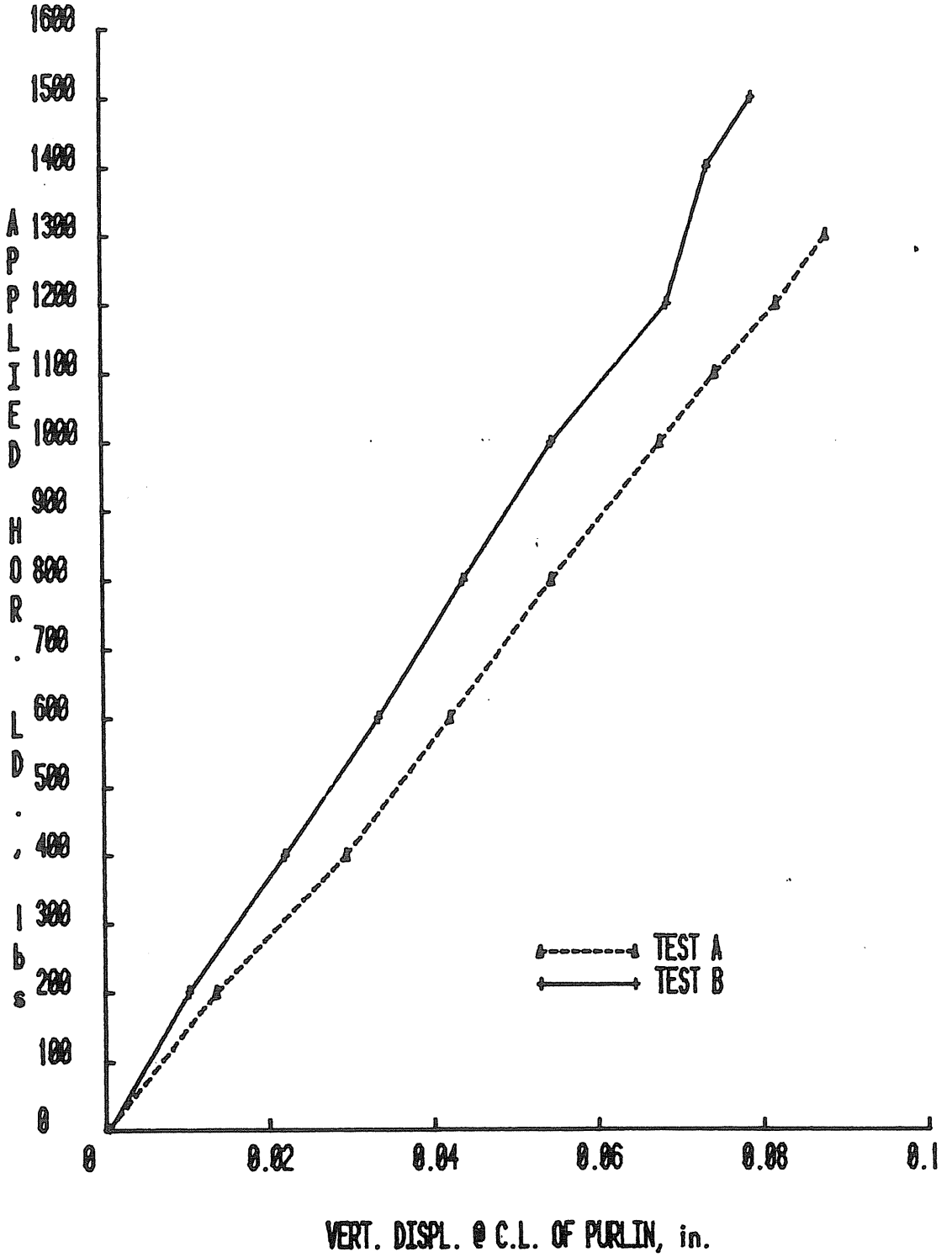


Figure G.5 In-plane Load vs. Vertical Deflection, Test S/7-T1/99

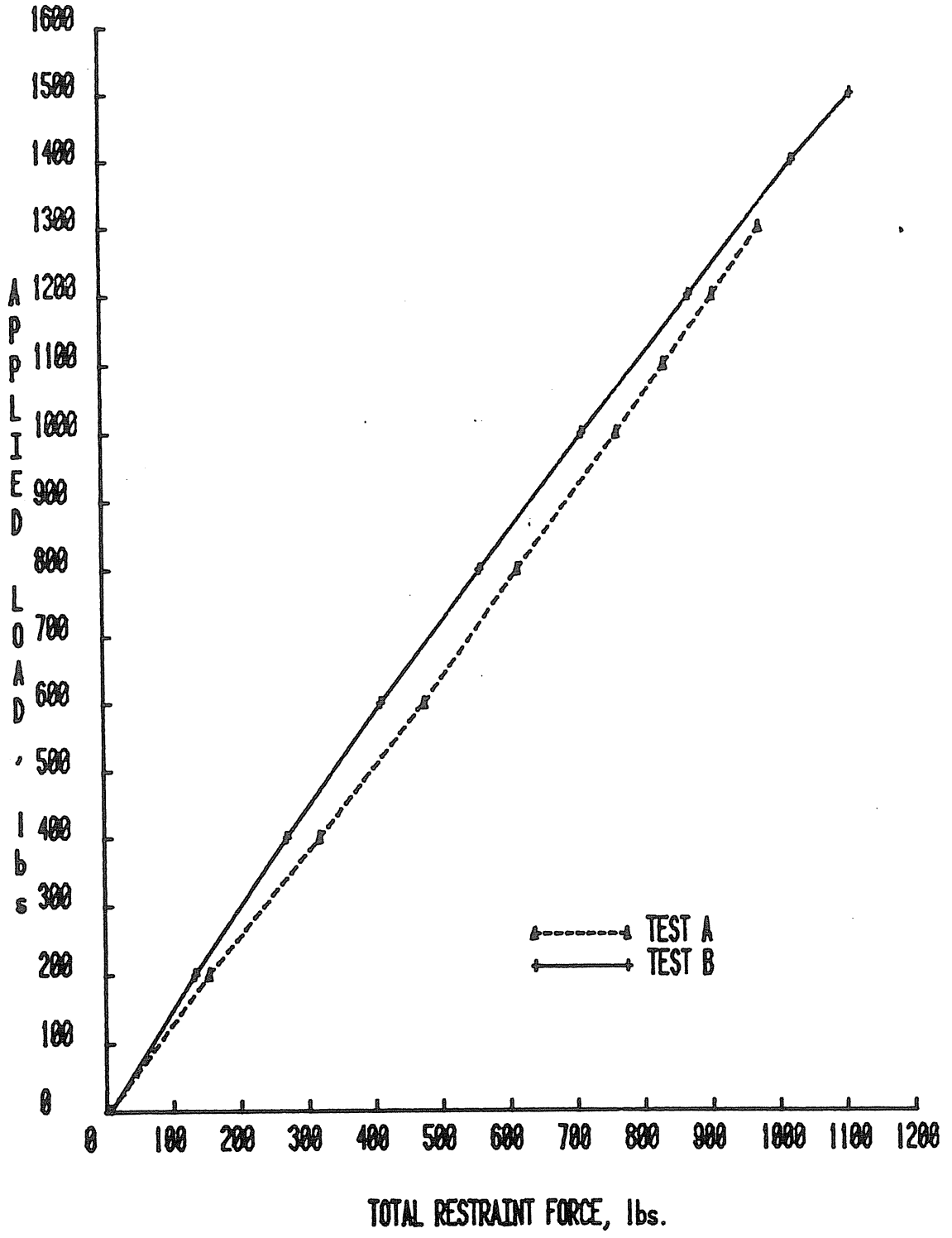


Figure G.6 In-plane Load vs. Total Restraint Force, Test S/7-T1/99

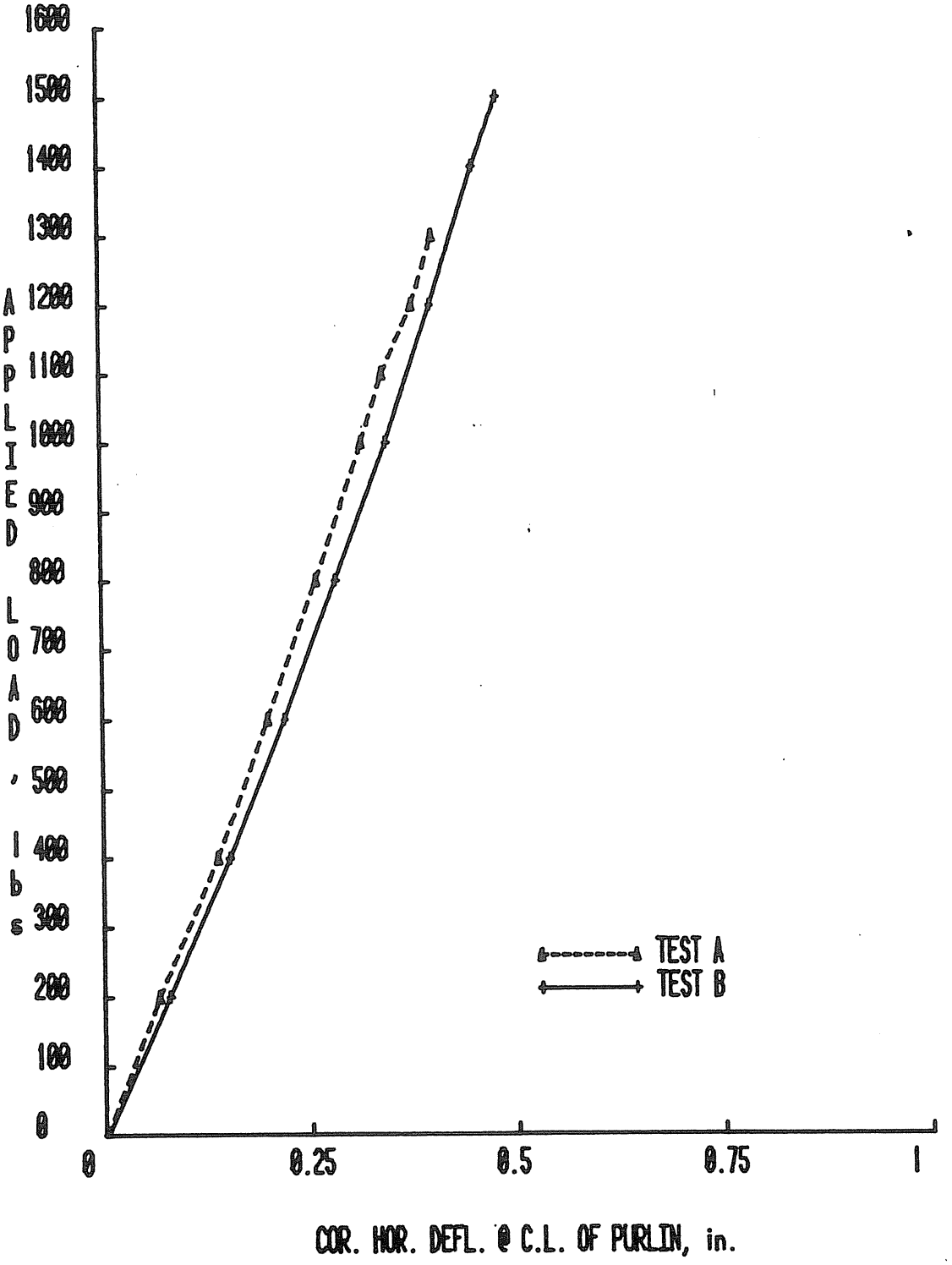


Figure G.7 In-plane Load vs. Horizontal Deflection, Test S/7-T1/99

TEST SUMMARY

Project: MBMA Roof System Behavior

Test No.: S/7-T2

Test Date: September 7, 1982

Purpose: Measure system stiffness of 7 purlin sys. @ ¼ pts (excl. ℄) & measure % brace force to total appl. force.

Span(s): 14.00'

Thickness: _____ Moment of Inertia: _____

Parameters: Torsional restraint at rafters

Restraints in tension

Restraint braces attached to 6th purlin from applied force.

Panel shear stiffness

Panel torsional restraint

Gravity Load: None

Predicted Failure Loads:

Method _____ Load _____

Method _____ Load _____

Method _____ Load _____

Discussion:
Two tests were conducted. Torsional braces were in tension and connected to the 6th purlin from the applied load.

Test 1

-The average stiffness (8 readings) for east ¼ pt. was 1954.2 lb/in. and for west ¼ pt. was 2391.8 lb/in.

-The average percent of total brace force to total applied load (8 readings) was 53.7%.

-The maximum applied load was 1643.8 lb.

-The maximum total brace force was 923.7 lb. (E=513.2 lb, W=410.54 lb).

-The maximum ¼ pt. deflection for east was 0.3998 in. and for west was 0.3665 in.

Test 2

-The average stiffness (9 readings) for east ¼ pt. was 1911.0 lb/in. and for west ¼ pt. was 2319.1 lb/in.

-The average percent of total brace force to total applied load (9 readings) was 55.9%.

-The maximum applied load was 1878.6 lb.

-The maximum total brace force was 1113.5 lb (E=606.6 lb and W=506.9 lb).

-The maximum ¼ pt. deflection for east was 0.4250 in. and west was 0.3960 in.

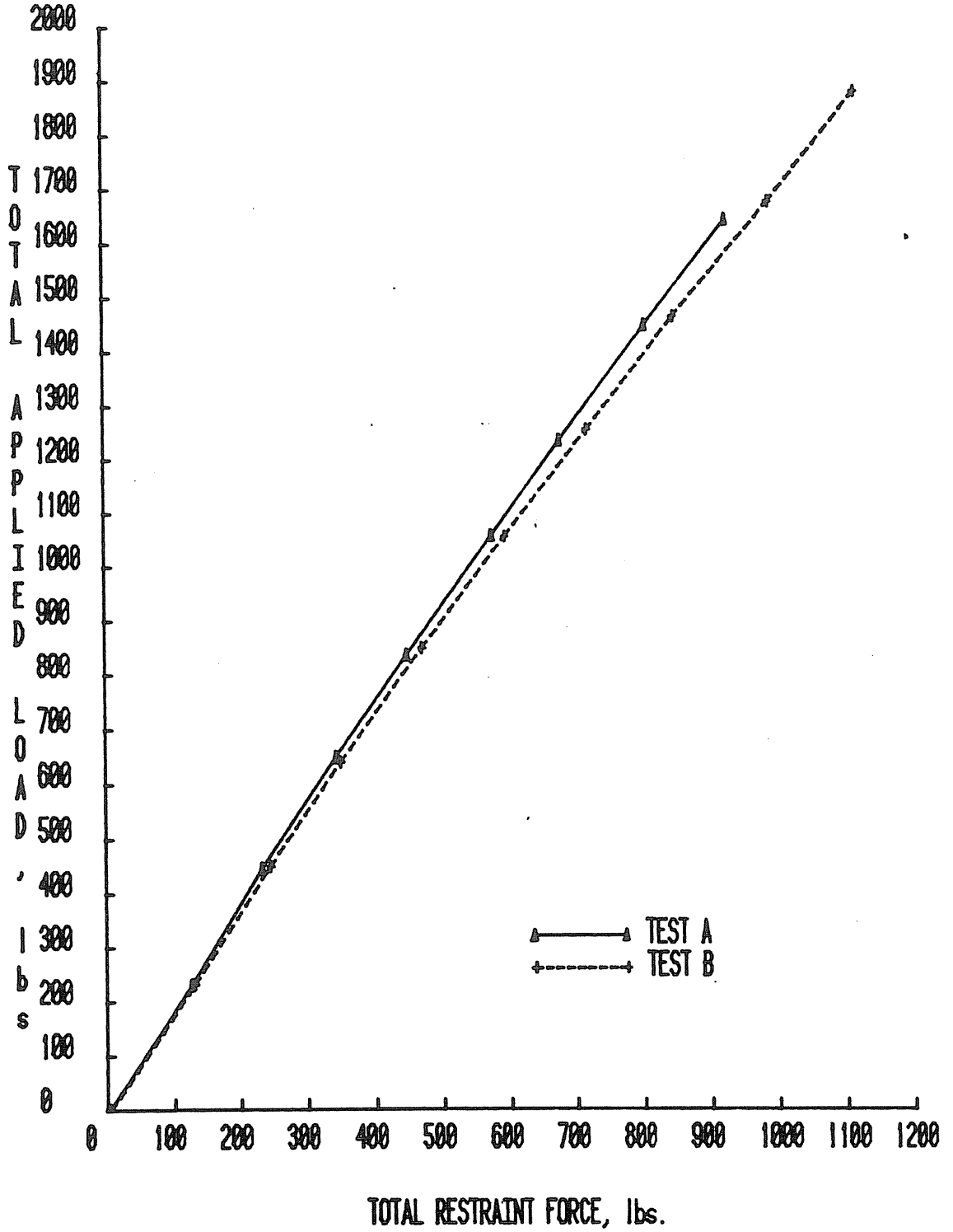


Figure G.8 In-plane Load vs. Total Restraint Force, Test S/7-T2

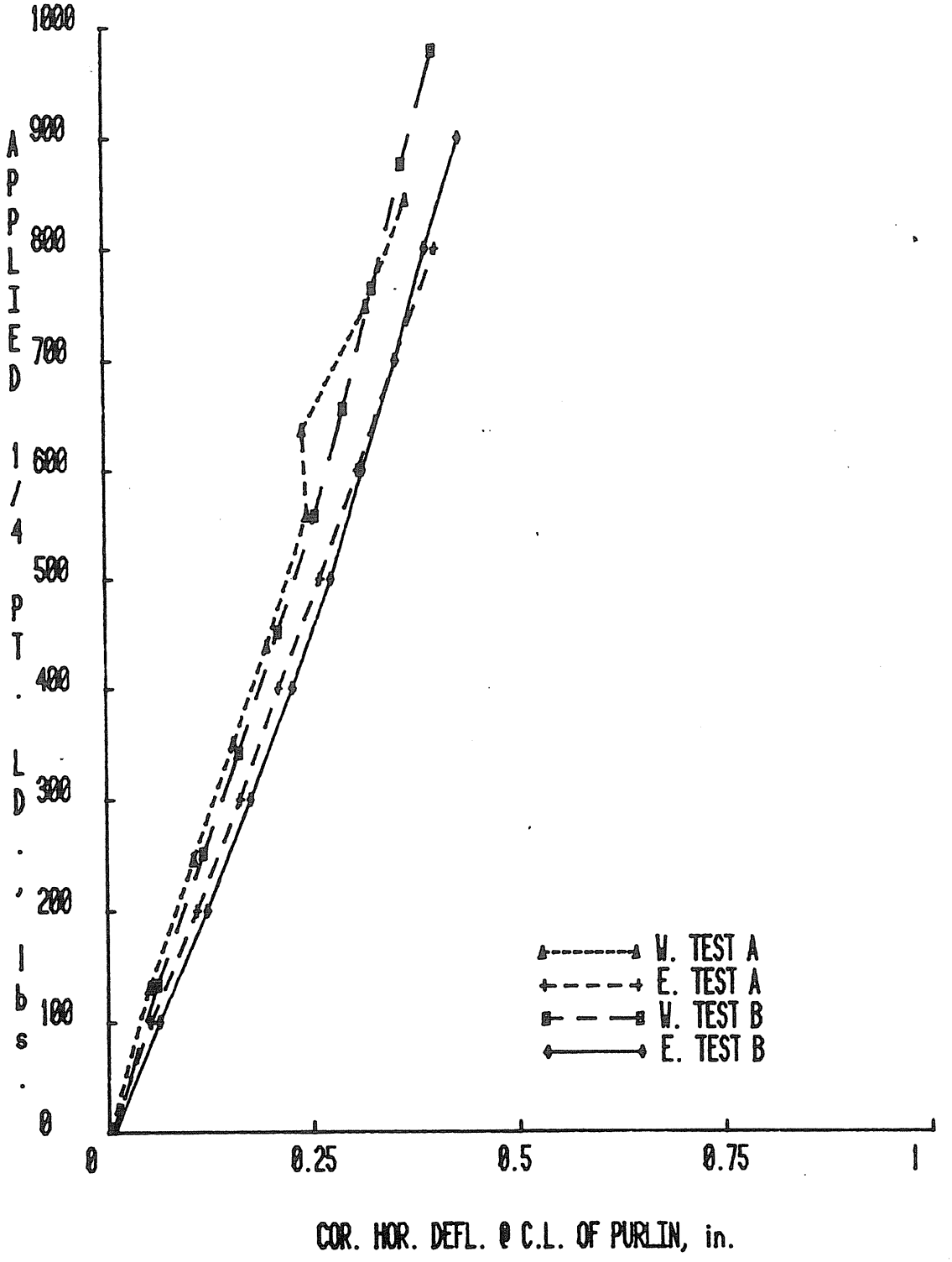


Figure G.9 In-plane Load vs. Horizontal Deflection, Test S/7-T2

TEST SUMMARY

Project: MBMA Roof System Behavior

Test No.: S/7-T2/99

Test Date: September 7, 1982

Purpose: Measure system stiffness of Z purlin sys. @ ¼ pts. (excl. ℄) & measure % brace force to tot. appl force.

Span(s): 14.00'

Thickness: _____ Moment of Inertia: _____

Parameters: Torsional Restraint at rafters

Restraints in tension

Restraint braces attached to loaded purlin

Panel shear stiffness

Panel torsional restraint

Gravity Load: 99 plf per purlin

Predicted Failure Loads:

Method No analysis run Load _____

Method _____ Load _____

Method _____ Load _____

Discussion:

Two tests were conducted.

Test 1

-The average stiffness (6 readings) for east ¼ point was 2341.5 lb/in. and west ¼ point was 2845.4 lb/in.

-The average percent of total brace force to total applied load (6 readings) was 63.8%

-The maximum applied load was 1272.06 lb.

-The maximum total brace force was 847.18 lb. (E=456.32 lb., W=390.86 lb).

-The maximum ¼ point deflection for east was .2481" and west was 390.86".

Test 2

-The average stiffness (7 readings) for east ¼ point was 2294.5 lb/in. and west ¼ point was 2828.8 lb/in.

-The average percent of total brace force to total applied load (7 readings) was 63.3%.

-The maximum applied load was 1475.23 lb.

-The maximum total brace force was 970.14 lb. (E=513.20 lb, W=456.94 lb).

-The maximum ¼ pt. deflection for east was .2954 in. and west was .2868 in.

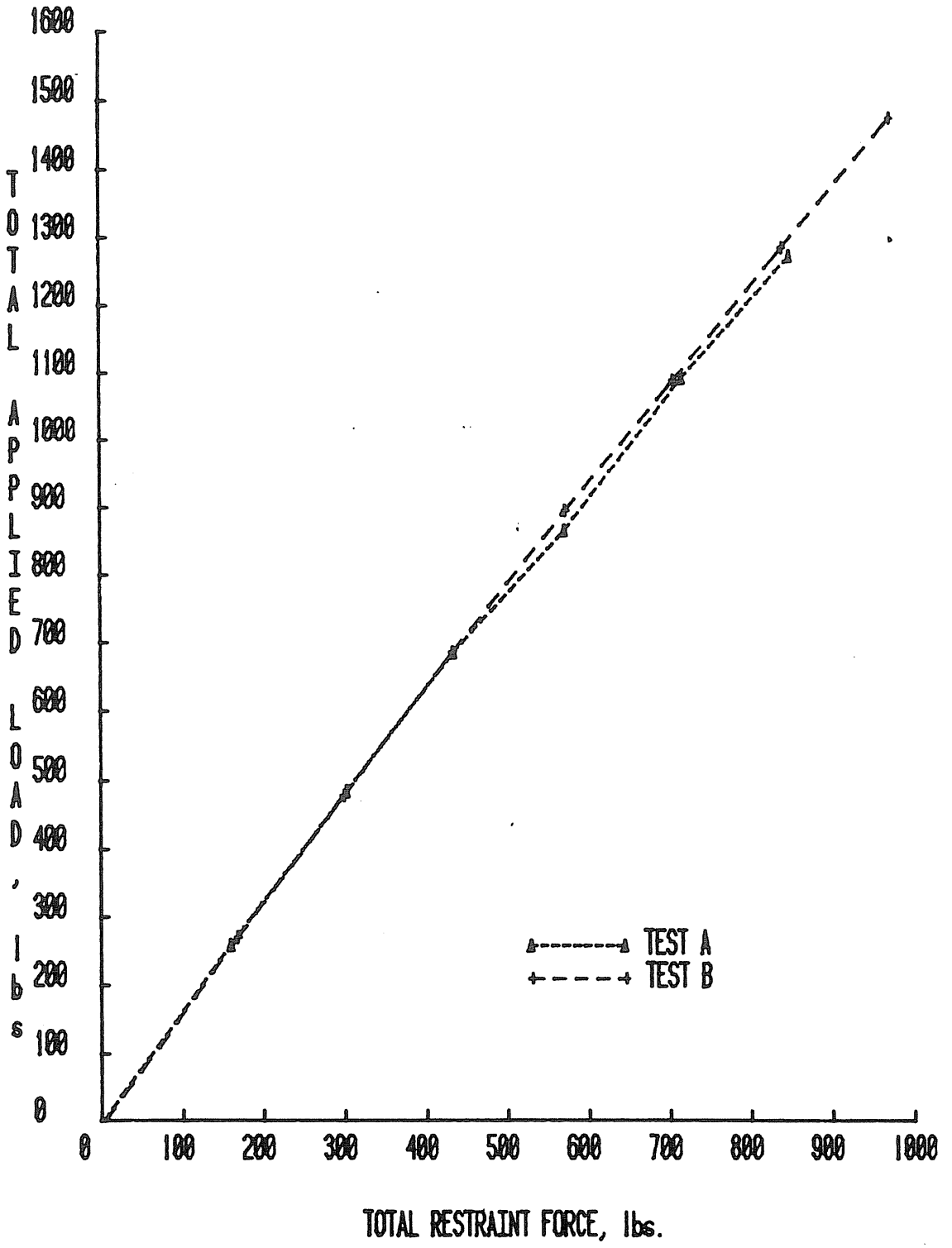


Figure G.10 In-plane Load vs. Total Restraint Force, Test S/7-T2/99

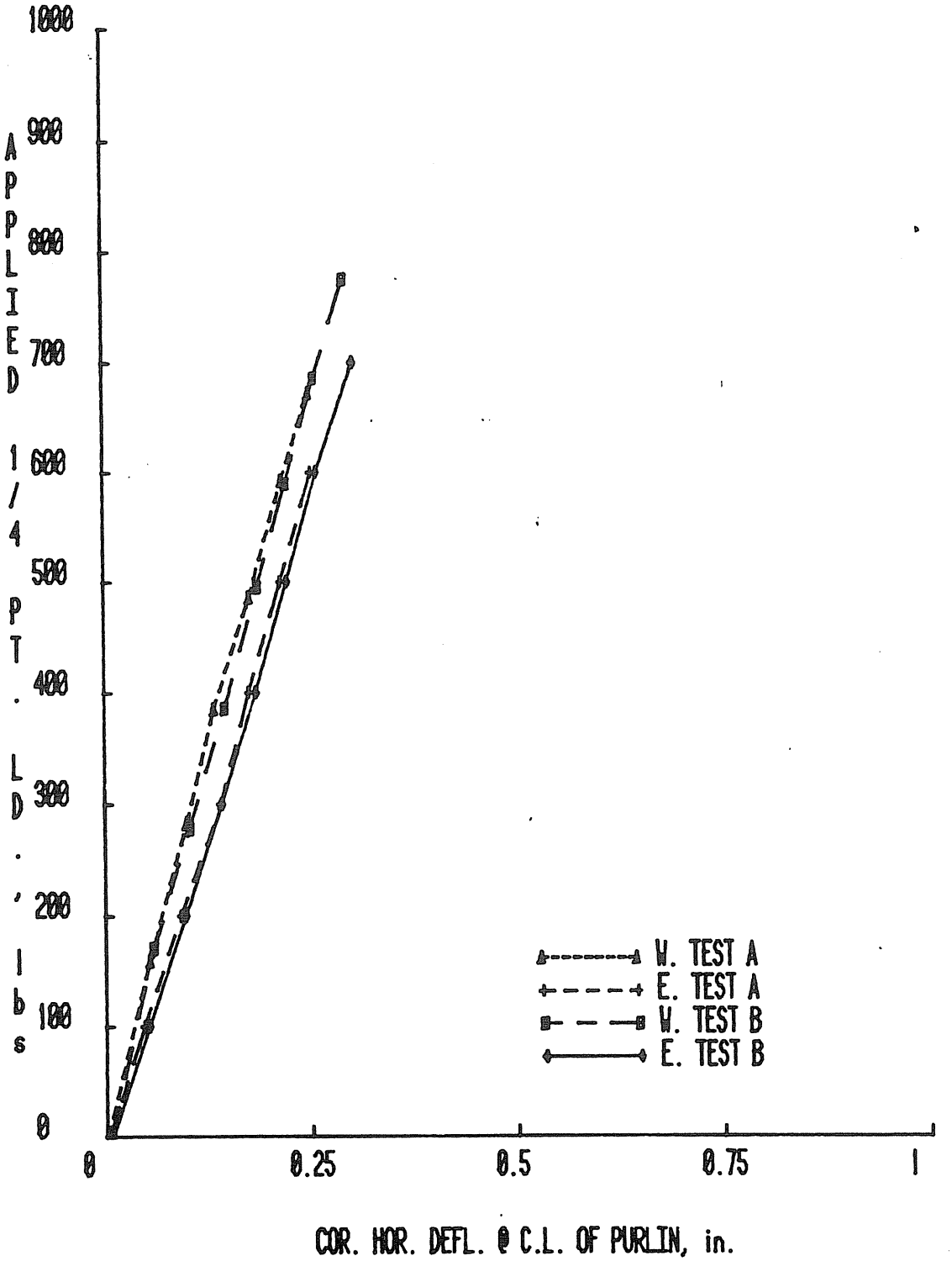


Figure G.11 In-plane Load vs. Horizontal Deflection, Test S/7-T2/99