

**Static Test and Nonlinear Analysis of the Mast for
International Space Station Alpha Solar Array Wing**

C. C. Tang and A. J. Elliott
Lockheed Missiles & Space Company
Sunnyvale, California

and

Dr. M. L. Bowden and S. Robinson
AEC-Able Engineering Company, Inc.
Goleta, California

Abstract:

Static test and nonlinear analyses results are used to develop the on-orbit end-of-life (EOL) strength of the deployed mast for the International Space Station Alpha Solar Array wing. The fully deployed mast is a 108 feet long boom that is capable of supporting the solar array wing for on-orbit plume impingement loads and inertia loads induced by space station disturbances. A series of static structural tests are performed to characterize the mast. The test results are then used to validate a MSC/NASTRAN nonlinear finite element model of the mast. Nonlinear static analyses, using the test-validated finite element model, are performed to determine mast failure for a large number of load combinations and orientations. Based on these data and an understanding of the mast behavior in the nonlinear regime, two interaction strength formulas are developed to define the on-orbit EOL mast limit load capability for combined loads in two different orientations. The test program and nonlinear finite element analysis using MSC/NASTRAN SOL 106 (V67.7) are described in this paper.

1.0 Introduction

The International Space Station Alpha Solar Array wing is the largest solar array that has ever been designed for a spacecraft. The fully deployed mast, a 1296 inches long boom, is an important structural component of the solar array wing. It supports the solar blanket assemblies when subjected to on-orbit plume impingement loads and inertia loads induced by space station disturbances. The mast is not designed for ground operation without special supports.

A series of static tests are performed to characterize structural failure of the mast. It would be very expensive to rely solely on ground testing to determine the on-orbit end-of-life (EOL) mast failure strength for various combined loads in zero gravity environment. Therefore, test results are then used to validate a MSC/NASTRAN nonlinear finite element model of the mast. MSC/NASTRAN SOL 106 (Ref. 1) nonlinear static analyses, using the test-validated finite element model, are performed to determine mast failure loads for a large number of load combinations and orientations. Based on these results, and an understanding of the mast behavior in the nonlinear regime, two interaction strength formulas are developed to define the on-orbit EOL mast limit load capability for combined loads in two different orientations.

The solar array wing is part of the electrical power system for the International Space Station Alpha (ISSA) program. Rocketdyne is the subcontractor for ISSA photovoltaic modules, of which the solar array wings are a major component. Boeing is the prime contractor for the entire ISSA program. Lockheed Missiles & Space Company (LMSC) is the subcontractor responsible for the design, analysis, and manufacture of the solar array wing. AEC-Able Engineering Company, Inc. (ABLE) is a subcontractor to LMSC, providing the mast/canister subassembly for the solar array wing.

2.0 Mast Description

Mast Design Features

The mast is a four-sided structure which is designed to fold for storage in a canister (Figures 1 & 2). The geometry of the mast is based on units called "bays". The mast for space station solar array wing has 32 bays. The size of each bay is 30.4 inches by 30.4 inches by 40.5 inches (height). All bays are connected together to form a continuous structure from top to bottom. Individual bays open or close sequentially during mast deployment or retraction by the mast deployment mechanism. A typical bay is depicted in Figures 3. Major components for a bay are rigid batten, flex batten, longeron, diagonal, corner fitting, and elbow fitting.

At each end of a bay is a rigid frame, the rigid batten frame which controls the square cross section of the mast. Each rigid frame is shared by two neighboring bays (except for the bottom and top bays).

At the middle of a bay, there are four fiberglass flex battens which are in a post-buckled, "bow-shaped" configuration. When a bay is open, each batten acts as a compression spring pushing on

the mid-bay elbow joint; thus, inducing tension in the diagonal cables, and compression in the rigid battens.

Each longeron section has a hinge at each end. One end is hinged at the corner fitting; the other end is hinged at the elbow fitting. The hinges allow for 90 degrees of free rotation (from the longeron horizontal stacked position), when the bay is being deployed. Once rotational angle exceeds 90 degrees, the hinge acts as a rotational spring.

The mast is a mechanism during its deployment and retraction. Once all bays are erected, the mast behaves like an elastic truss-type structure with pre-loaded members, unless the applied load gets high enough to overcome this preload and the mast goes into a nonlinear regime.

Mast Load Paths

The mast is designed to have two load paths: one load path transmits axial and bending moment loads; the other load path transmits shear and torsion loads.

When axial load and bending moment are applied to the mast, the longerons are loaded in either tension or compression. Other components such as longeron axles, corner fittings, and elbow fittings are also involved in the load path in transferring tension/compression from one longeron to the next. It is the longeron axial buckling load that limits the ultimate capability in compression.

The load path for shear and torsion loads in the mast is more complicated because of the post-buckled flex battens. When shear and torsion (causing shear in each face of the mast) loads are applied, one diagonal in each face loads up while the other diagonal in the same face unloads. The compressive load on the flex battens remains constant at the flex batten post-buckled force. This shear/torsion load path continues to work as designed until an unloading diagonal goes slack, indicating that the applied load has forced the mast into the nonlinear regime. At that point, because the flex batten has such low stiffness in the post-buckled configuration (1.0 lb/in approximately), it will deflect under a small increase in shear load until secondary load paths are activated. Additional shear load is then transferred from one rigid batten frame to the next one mainly by bending in longerons that are not aligned to fold up. Because shear and torsion loads beyond the linear regime cause significant lateral displacement of elbow joints (due to additional flex batten bowing) and induce bending in longerons, the longeron axial buckling load capability is decreased. Therefore, the two load paths are no longer independent, and interaction between the axial, moment, shear, and torsion is expected for the mast loaded in the nonlinear regime.

3.0 Mast Static Test

Nine static tests were performed for the mast with various torsion/shear ratios. Five tests were conducted with the mast at a 0 degree orientation, and four tests with the mast at a 45 degree orientation. The torsion/shear ratios were chosen to cover an expected range of on-orbit plume impingement load combinations on the solar array wing.

3.1 Test Description and Setup

Tested Mast

Beginning-of-life (BOL) flex battens of the tested mast have a post-buckled strength of 46-lb force. Due to aging, EOL flex battens will exhibit a degraded post-buckled strength of 30 to 35-lb force. Due to schedule and cost constraints, it was not possible to install degraded flex battens in all 32 bays of the mast. Since the test shear load is applied to the mast tip, the maximum bending occurs theoretically at the mast base (bay 1). Flex battens in bottom 3 bays (bay 1 to 3) of the mast were replaced with degraded flex battens for static testing. The degraded flex battens have an averaged post-buckled strength of 30-lb force. The remaining 29 bays of the tested mast contain of BOL flex battens. The stiffness characteristics of the tested mast differ from those of a mast with degraded flex battens along the entire length, but with failure occurring within bottom 3 bays, the failure load is nearly the same.

The mast is tested in both the 0 degree and the 45 degree orientation. There is only one significant difference between orientations. In the 45 degree orientation tested mast, geometry correction cables are used to prevent unwanted flexing of the mast at the air-bearing support.

Mast Supports

The tested mast was deployed horizontally and was supported by an air-bearing support system at 9 locations near rigid batten frames. The test setup is depicted in Figure 4. The air-bearing support details are shown in Figures 5 and 6. The air-bearings slide freely on precision granite plates. A roller was mounted to the mast at each air-bearing support location with its center of rotation concentric with the mast center-of-gravity. The roller allows the support to compensate for lateral movement due to mast rotation, such that the contact point always remains directly underneath the mast center-of-gravity. The air-bearing supports accommodate mast translational and rotational displacements concurrently with negligible frictional effect.

Test Load Inputs

The method for applying load to the mast was through cables which run over pulleys and connect the mast tip-structure to weight trays, in which calibrated weights are placed. Because the shear load was applied at the tip of the mast, there was always a bending moment induced at the base equal to shear times mast length.

A constant axial compressive load of 150 lb was applied for all test cases. This was accomplished using a cable that runs the full length of the mast at its center from the load beam at the mast tip to a hole in the base fixture. Outside the base fixture, the cable ran over a pulley and connected to a suspended weight tray.

In the lower torsion/shear ratio test cases, a load beam mounted vertically on the mast tip allows the shear and torsion load to be physically coupled. A horizontal load cable attached along the load beam directly applied the shear load. The distance from the cable attached point to the center of the mast tip was the moment arm for torsion. A tower with pulleys was used to support the cable and

weight tray. In the higher torsion/shear ratio test cases, a dual tower system was necessary to load the mast. The shear load is applied at the center of the mast tip and torsion load is applied as a force couple, centered on the mast tip.

To protect the mast from damage, stops are positioned under the weight trays to prevent substantial mast travel when a failure occurs. At failure, the mast travel is limited and the buckled mast is captured in the strained position.

Load versus Deflection Graphing

Some of the test cases were intended to be terminated at 1.5 times the proportional limit load unless terminated earlier by reaching detrimental yield. In order to determine real-time status, a spreadsheet was used to update load vs. displacement graphs as each incremental load was applied. For each load step, the weights were added and both translational and rotational displacements at the mast tip were entered into the spreadsheet. The spread sheet automatically updated two graphs, shear vs. deflection and torsion vs. rotation.

Post-test Activities

After each test case, the mast was inspected for degradation and damage. The mast was examined for visual signs of yielded piece parts and diagonal wire tensions were checked. With all loads removed, the mast was twanged so that it oscillated approximately 5 inches to either side. When the oscillating stopped, the final position was compared to the original marking on the graph paper to ensure the mast returned to the original position. Occasionally a low-load stiffness check was performed. If the mast appeared to be compromised in some way, hardware was switched out to obtain a good mast for further testing.

3.2 Test Results

The mast test results are summarized in Table 1. All test cases, except test nos. 3 and 4a, were terminated at mast failure. Test nos. 3 and 4a were terminated at 1.5 times proportional limit. Also provided in Table 1 is the ratio of applied torsion to applied shear. This ratio remained constant during each test. The following general trends associated with mast failure behavior were observed:

- Mast tip load-deflection becomes nonlinear, when pre-tensioned diagonal wires of the mast go slack, indicating internal load redistribution. The non-linearity for mast tip rotation is more pronounced than for mast tip translation.
- Mast failure load is higher for 0 degree orientation than for 45 degree orientation.
- For the 45 degree orientation, mast fails with longeron elbows folding (movement of the elbow joint toward its original stacked position) for tests with torsion/shear ratio of 15.75 and higher. For the 0 degree orientation, the same trend exists but not as apparent.
- For the 45 degree orientation, mast fails with longeron elbows buckling (movement of the elbow joint in direction normal to its folding plane) for tests with torsion/shear ratio of 7.0 and lower. For the 0 degree orientation, the same trend exists but not as apparent.

- There is interaction between shear and torsion induced batten load and moment induced longeron load.

Figures 7 and 8 showed photographs of the failed mast for test nos. 8x and 4b respectively.

4.0 Mast Finite Element Model

A nonlinear MSC/NASTRAN finite element model is created for the fully deployed tested mast (without the air bearing supports) and is shown in Figure 9. The model geometry remains the same for the mast in both 0 degree and 45 degree orientations with the exception of geometrical correction cables. In the finite element model, the longerons and the battens are modeled using beam elements, the diagonal wires are modeled using rod elements, and the elbow fitting and corner fitting joints are modeled using spring elements to capture joint flexibility. Features of the finite element model, which are important for nonlinear large displacement analysis, are briefly described below:

- Nonlinear material property (Figure 10) is used to model the diagonal wires so they go slack when the compressive force exceeds the pre-tension force induced by the flex battens. The stiffness of the diagonal wire rises with increasing tension.
- Each post-buckled flex batten (elastic buckling) is idealized by two elements. One is a rod element with nonlinear axial property to capture the nonlinear load versus deflection relationship of the flex batten in its post-buckled configuration. The other is an elastic beam element, which does not have any axial stiffness, but possesses bending and torsion stiffness.
- Stiffness of stiff beams and springs are limited approximately to 3 orders of magnitude higher than that of neighboring elements, thus avoiding premature termination of numerical iteration in the nonlinear solution. In other words, "stiff" means stiff enough, but not too stiff to cause numerical problems.
- Each air-bearing support of the mast is modeled by introducing a support grid point at the mast center-of-gravity, the support grid is then connected to a support beam located at the rigid batten frame. The support grid is constrained only in the gravity direction, and is free to move in lateral directions and free to rotate. Therefore, the support grid always coincides with the position of the mast center-of-gravity, even after the mast undergoes large deflections and rotations; and the support reaction acts in perfect alignment with the resultant of the mast gravity load at the air-bearing support location. This precludes non-alignment between the direction of the support reaction and the resultant of the mast gravity load at the air-bearing support location and avoids inducing additional applied torsion for the mast. This idealization of the air-bearing support captures the intended function of the roller at the air-bearing support (see Figures 5 and 6).

The finite element model of the mast (excluding support structure) has 1582 grid points, and 7294 degrees of freedom.

Results of test no. 8x for the mast in the 45 degree orientation were chosen for initial test correlation with the finite element analysis result. The properties of the nonlinear diagonal wires and joint stiffness at elbow and corner fittings are fine-tuned such that the finite element model

would produce a match of mast tip deflections and rotations with results from test no. 8x. This finite element model was then used for all subsequent analyses.

5.0 Mast Nonlinear Analyses

Nonlinear Static Analysis

For a static nonlinear large displacement problem, MSC/NASTRAN SOL 106 (Ref. 2) solves a linearized system of equations for incremental displacement. The equation to solve at i-th iteration is:

$$[K_t] \{\Delta U^i\} = \{R^{i-1}\} \quad (1)$$

where $[K_t]$ is tangential stiffness matrix, which consists of the usual linear stiffness, stiffness due to large rotation, and geometrical stiffness (or differential stiffness) dependent on the initial stress level; $\{\Delta U\}$ is the incremental displacement; and $\{R\}$ is the residual load error vector. The iteration solution continues until $\{\Delta U\}$ and $\{R\}$ become negligible, which is signified by the convergence criteria.

Analysis of Test Cases

The finite element model described in Section 4.0 is used for analyzing 45 degree mast orientation test nos. 2x, 4x, 8x, and 9x; and 0 degree mast orientation test nos. 2c, 3, 4a, 4b, and 8. Analysis for each test case is typically carried out in several loading subcases. The first loading subcase uses thermal load to provide initial strain to the flex battens. This loading induces desired post-buckled force in the flex battens, tensile force in the diagonal wires; and also axial, shear, and moment in the longerons. The second loading subcase adds gravity and 150-lb axial compressive load to the mast. From the third loading subcase onward, shear and torsion are gradually added to the mast to simulate the test loading. Convergence criteria is based on error tolerances for displacement and work. Analysis failure load is defined as:

- The applied load at which the numerical solution fails to convergence; or
- The applied load when negative terms are encountered on the factor diagonal of stiffness matrix decomposition, and convergence solution is possible only after repeatedly neglecting differential stiffness. Negative terms indicate that the differential stiffness has introduced a structural instability.

The analysis results for all the test cases are summarized in Table 2. Also provided in Table 2 are the percent differences between analysis and test results. The difference is within 14 percent, which is quite good considering the complexity of the structure.

The mast tip displacement and rotation obtained from both test and analysis for selected test cases are provided in Figures 11 and 12. In general, mast tip displacements between test and analysis matched more closely than mast tip rotations between test and analysis; and matches of mast tip rotation between test and analysis are better for the 45 degree mast orientation than for the 0 degree

mast orientation, since the finite element model is tuned using the 45 degree mast orientation test no. 8x.

Nonlinear Buckling Analysis

To confirm that the analysis failure is indeed real structural instability (buckling), nonlinear buckling analysis is also performed using the restart feature in SOL 106 (Ref. 2). The eigenvalue problem for a nonlinear buckling analysis may be approximated by:

$$[K_n + \lambda\Delta K]\{\phi\} = \{0\} \quad (2)$$

with

$$\Delta K = K_n - K_{n-1}$$

where K_n and K_{n-1} are the stiffness matrices corresponding to the converged load steps n and $n-1$ in the vicinity of the instability.

Based on the virtual work principle, the critical buckling load is:

$$P_{cr} = P_n + \alpha\Delta P \quad (3)$$

with

$$\Delta P = P_n - P_{n-1}$$

and

$$\alpha = \frac{\lambda\{\Delta U\}^T [K_n + \frac{1}{2}\lambda\Delta K]\{\Delta U\}}{\{\Delta U\}^T \{\Delta P\}}$$

where

$$\Delta U = U_n - U_{n-1}$$

Matches between critical buckling analysis and nonlinear static analysis results are quite good for cases selected for investigation. The maximum difference is 4.2 percent among test nos. 2x, 8x, 9x, and 2c.

Analysis of On-Orbit Mast

The finite element model for the on-orbit mast with EOL degraded flex battens is obtained by replacing all flex batten elements with 35-lb force degraded flex battens. The geometrical correction cables and air bearing supports are removed. The gravity load effect is also removed from the loading subcases. A total of 18 cases with different ratios of torsion to shear and different mast orientations are analyzed to determine on-orbit mast failure loads. Six analysis cases are for the mast in 45 degree orientation; 7 analysis cases are for the mast in 22.5 degree orientation; and 5 analysis cases are for the mast in the 0 degree orientation. The predicted mast failure loads are summarized in Table 3. The on-orbit mast with 35-lb force degraded flex battens has a lower failure strength for high torsion/shear ratios than was obtained for the tested mast.

6.0 Mast Load Capability

Computed Longerons and Batten Loads

In order to develop the mast limit load capability from test and analysis data when subjected to combined loading, the mast is idealized as a pin-jointed truss type elastic structure so longeron and batten loads can be computed as follows:

The computed longeron load (L) is

$$L = \frac{A}{4} + \frac{M(\sin \theta + \cos \theta)}{2w} \quad (4)$$

and the computed batten load (B) is

$$B = \frac{V \cos \theta}{2} + \frac{T}{2w} \quad (5)$$

where A is 150 pounds axial compressive load, V is the applied shear, T is the applied torsion, M is the computed moment, and equals shear (V) times 1296 inches (length of mast from tip to base), w is width of the mast, which equals 30.4 inches, and θ is the mast orientation angle in degrees (the smallest angle between the shear or moment load vector and a major axis of the mast). Equations (4) and (5) transform a set of 4 applied loads into 2 internal load parameters, such that a 2-dimensional failure surface could be derived.

The computed batten load is a "nominal" load, and does not represent an actual compressive batten load, but serves as a load indicator of combined effects due to shear and torsion. The flex battens are always in a post-buckled configuration with a nearly constant post-buckled axial load. Flex battens provide a pre-tension load to mast diagonal wires so that all diagonal wires can carry externally applied shear and torsion loads when the mast operates within the linear regime.

Limit Load Factor

The mast limit load capability is obtained by dividing the failure load by a limit load factor. Considering that the finite element model tends to over-predict the mast failure load for the high shear case and to under-predict the mast failure load for the high torsion cases, and that longeron buckling is sensitive to joint imperfection, different factors are adopted to compute the mast limit load. The factors used for analysis-derived on-orbit EOL mast limit loads are:

- 1.98 for high shear cases;
- 1.80 for medium shear and torsion cases; and
- 1.65 for high torsion cases.

These factors include a contractually imposed factor of safety of 1.5 for test verified structures, and an additional factor was used to account for analysis and test variation.

Mast Limit Load Capability

The mast limit loads, in terms of computed longeron and batten loads, are provided in Tables 4 for the on-orbit EOL mast. These values are plotted in Figures 13 and 14 according to mast orientations (or load vector angles). Figure 13 illustrates the mast limit load as computed longeron load versus computed batten load for mast orientations of 22.5 to 45.0 degrees. Figure 14 illustrates the mast limit load as computed longeron load versus computed batten load for mast orientations of 0 to 22.5 degrees.

To reduce conservatism, two mast interaction strength formulas are developed for the on-orbit EOL mast with 35-lb force flex battens.

The first mast interaction strength formula is for the mast with an applied load vector angle larger than 22.5 degrees, and is expressed as:

$$(a) \quad \left(\frac{L}{1050}\right)^2 + \left(\frac{B}{26}\right)^2 \leq 1.0 \quad \text{and} \quad L \leq 1000$$

where L is the computed longeron load (in pounds), and B is the computed batten load (in pounds), from all applied loads, as defined in equations (4) and (5). The applied load vector angle is the smallest angle between the shear or moment load vector and a major axis of the mast. The value of 1000 pounds is the lower bound for longeron axial buckling with a knockdown factor. Formula (a) is graphically represented in Figure 13.

The second mast interaction strength formula is for the mast with an applied load vector angle equal to or less than 22.5 degrees, and is expressed as:

$$(b) \quad \left(\frac{L}{1350}\right)^2 + \left(\frac{B}{26}\right)^2 \leq 1.0 \quad \text{and} \quad L \leq 1000$$

where L and B are the same as for formula (a). Formula (b) is graphically represented in Figure 14.

7.0 Discussions

Because of the limited test scope, lack of instrumentation, and complexity of the mast structure, all intricacies of the mast nonlinear behavior are still not thoroughly understood. The nonlinear analysis did provide comparable failure loads for the tested mast. However, matches of mast tip torsion vs. rotation between test and analysis were not always satisfactory in the nonlinear range. Post-test study reveals that torsion vs. rotation is sensitive to pre-tension variation and nonlinearity in the diagonal wires.

8.0 Acknowledgments

The authors wish to thank: Jim Harrell and Shelly Briles for promptly coordinating the test program between LMSC and ABLE; and all members of the ABLE testing team for diligently completing tests on a tight schedule.

9.0 References

- [1] MSC/NASTRAN User's Manual, Version 67, The MacNeal-Schwendler Corporation, Los Angeles, CA, August 1991.
- [2] MSC/NASTRAN Handbook for Nonlinear Analysis (Draft), Version 67, The MacNeal-Schwendler Corporation, March 31, 1992.

Table 1: Mast Strength Test Summary

Test No.	Tor./Sh. Ratio (in)	Test Shear (lb)	Test Torsion (in-lb)	Test Moment (in-lb)	Failure Description and Comments
2x	7.0	53.6	377	69,465	Elbow buckled at bay 1. Failure within linear range
9x	15.8	50.6	797	65,588	Elbow folded at bay 3. Failure at the end of linear range
4x	28.7	45.2	1274	58,579	Elbow folded at bay 3. Failure at 1.25 proportional limit
8x	54.8	34.7	1895	44,945	Elbow folded at bay 3. Failure at 1.4 proportional limit
2c	7.0	74.3	523	96,330	Elbow buckled at bay 1. Failure at 1.5 proportional limit
4a	28.7	41.4	1185	53,693	Test terminated at 1.5 proportional limit. No failure
4b	28.7	57.0	1632	73,812	Repeatability check. Elbow folded at bays 2 & 3. Failure at 1.8 prop. limit
8	54.8	40.5	2218	52,522	Bottom elbow folded and top elbow buckled at bay 3 at 1.9 prop. limit
3	123.3	16.9	2089	21,863	Test terminated at 1.5 proportional limit. No failure

Notes:

- (1) Test number labeled with x indicates 45 deg. mast orientation; otherwise indicates 0 deg. mast orientation.
- (2) Mast axial compressive preload of 150 lb. is used for all tests.

Table 2: Analysis Results for the Tested Mast

Test No.	Tor./Sh. Ratio (in)	Analysis Axial preload (lb)	Analysis Failure Shear (lb)	Analysis Failure Torsion (in-lb)	Analysis Failure Moment (in-lb)	Percent Difference w.r.t. Test
2x	7.0	150	59.0	415	76,464	+10.1
9x	15.8	150	50.0	788	64,800	-1.2
4x	28.7	150	39.0	1117	50,544	-13.7
8x	54.8	150	31.0	1696	40,176	-10.7
2c	7.0	150	71.0	499	92,016	-4.4
4a	28.7	150	52.0	1490	67,392	N.A.
4b	28.7	150	52.0	1490	67,392	-8.8
8	54.8	150	37.5	2051	48,600	-7.4
3	123.3	150	21.8	2682	28,253	N.A.

Notes:

- (1) Percent difference with respect to (w.r.t.) test is defined as analysis shear minus test shear, times 100, then divided by test shear. Refer to Table 1 for test results.
- (2) N.A. means not applicable since mast was not tested to failure.

Table 3: Analysis Results for On-Orbit EOL Mast

Analysis Case No.	Tor./Sh. Ratio (in)	Analysis Axial preload (lb)	Analysis Failure Shear (lb)	Analysis Failure Torsion (in-lb)	Analysis Failure Moment (in-lb)	Mast Orientation Angle (deg.)
1x-ng	0.0	150	80.0	0.0	103,680	45.0
2x-ng	7.0	150	62.0	435.8	80,352	45.0
9x-ng	15.8	150	56.0	882.0	72,576	45.0
4x-ng	28.7	150	42.5	1217.6	55,080	45.0
8x-ng	54.7	150	30.7	1678.2	39,787	45.0
3x-ng	123.3	150	18.3	2250.2	23,717	45.0
1q-ng	0.0	150	77.0	0.0	99,792	22.5
2q-ng	7.0	150	65.0	456.9	84,240	22.5
9q-ng	15.8	150	53.8	846.6	69,725	22.5
4q-ng	28.7	150	46.5	1332.2	60,264	22.5
8q-ng	54.7	150	33.0	1805.1	42,768	22.5
3q-ng	123.3	150	18.5	2281.0	23,976	22.5
12q-ng	∞	150	0.0	2612.5	0.0	22.5
1-ng	0.0	150	85.3	0.0	110,484	0.0
2-ng	7.0	150	81.5	572.9	105,624	0.0
4-ng	28.7	150	53.0	1518.5	68,688	0.0
8-ng	54.7	150	31.5	1723.0	40,824	0.0
3-ng	123.3	150	18.4	2272.4	23,846	0.0

Notes:

- (1) Labeled -ng for analysis case number means zero gravity.
- (2) Mast orientation angle means the smallest angle between shear (or moment) load vector and a major axis of the mast.

Table 4: Limit Load Capability of the On-Orbit EOL Mast

Analysis Case No.	Limit Load Factor	Computed Batten Limit Load (lb)	Computed Longeron Limit Load (lb)	Mast Orientation Angle (deg.)
1x-ng	1.98	14.29	1236.92	45.0
2x-ng	1.98	14.69	962.87	45.0
9x-ng	1.80	19.06	958.68	45.0
4x-ng	1.80	19.47	732.59	45.0
8x-ng	1.65	23.31	583.61	45.0
3x-ng	1.65	26.35	357.06	45.0
1q-ng	1.98	17.96	1102.01	22.5
2q-ng	1.98	18.96	933.22	22.5
9q-ng	1.80	21.54	853.25	22.5
4q-ng	1.80	24.11	740.30	22.5
8q-ng	1.65	27.23	579.73	22.5
3q-ng	1.65	27.92	334.99	22.5
12q-ng	1.65	26.04	22.73	22.5
1-ng	1.98	21.53	936.70	0.0
2-ng	1.98	25.34	896.33	0.0
4-ng	1.80	28.60	648.46	0.0
8-ng	1.65	26.72	429.67	0.0
3-ng	1.65	28.23	260.43	0.0

Note: Mast orientation angle means the smallest angle between shear (or moment) load vector and a major axis of the mast.

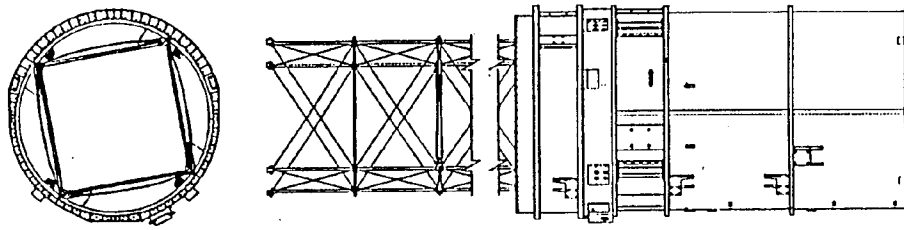


Figure 1: Mast-Canister Assembly

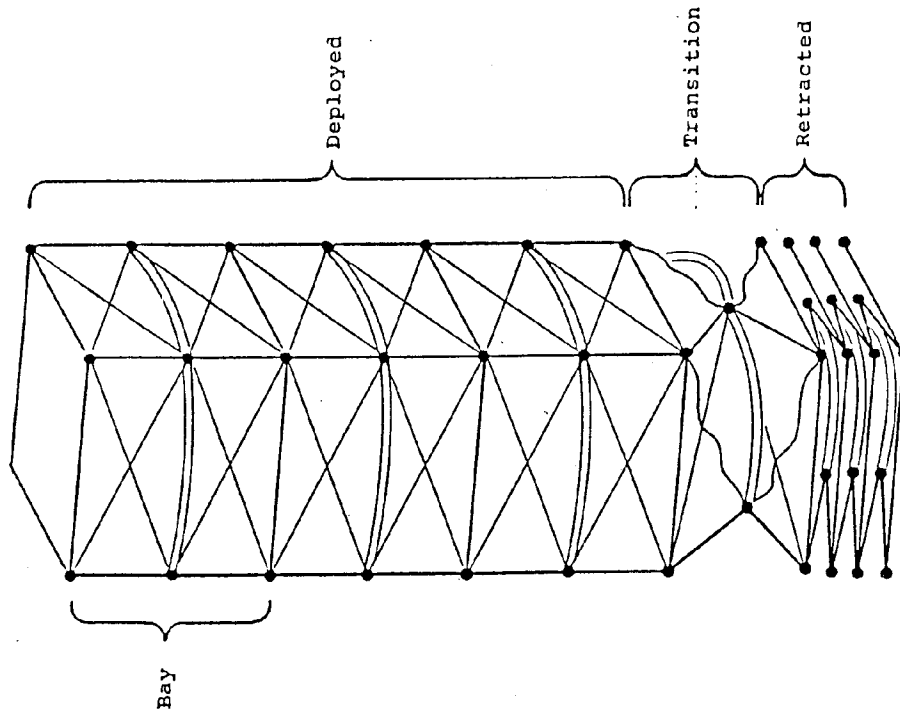


Figure 2: Mast Configuration

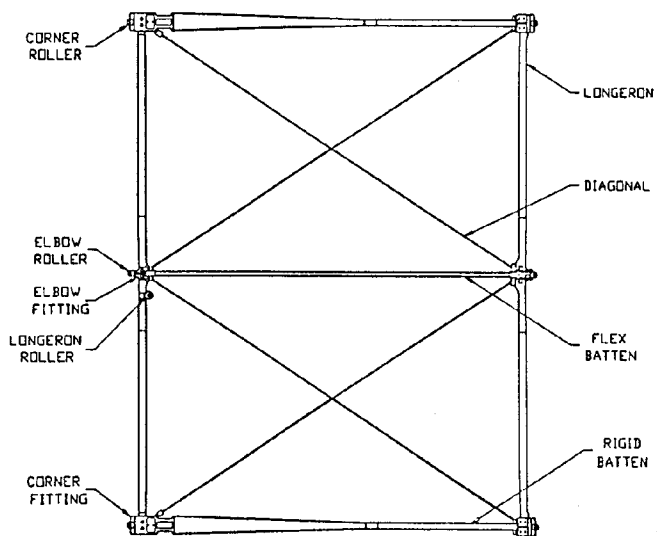


Figure 3: Mast Bay Component

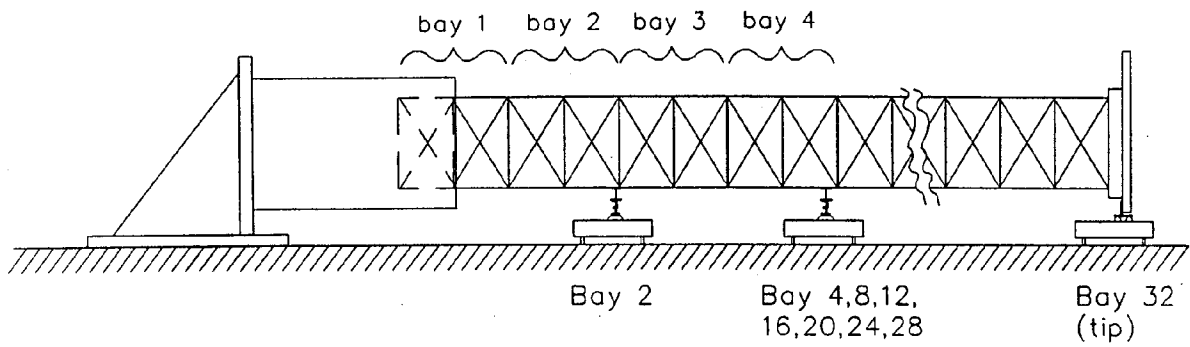


Figure 4: Mast Test Setup Showing Air-Bearing Support Locations

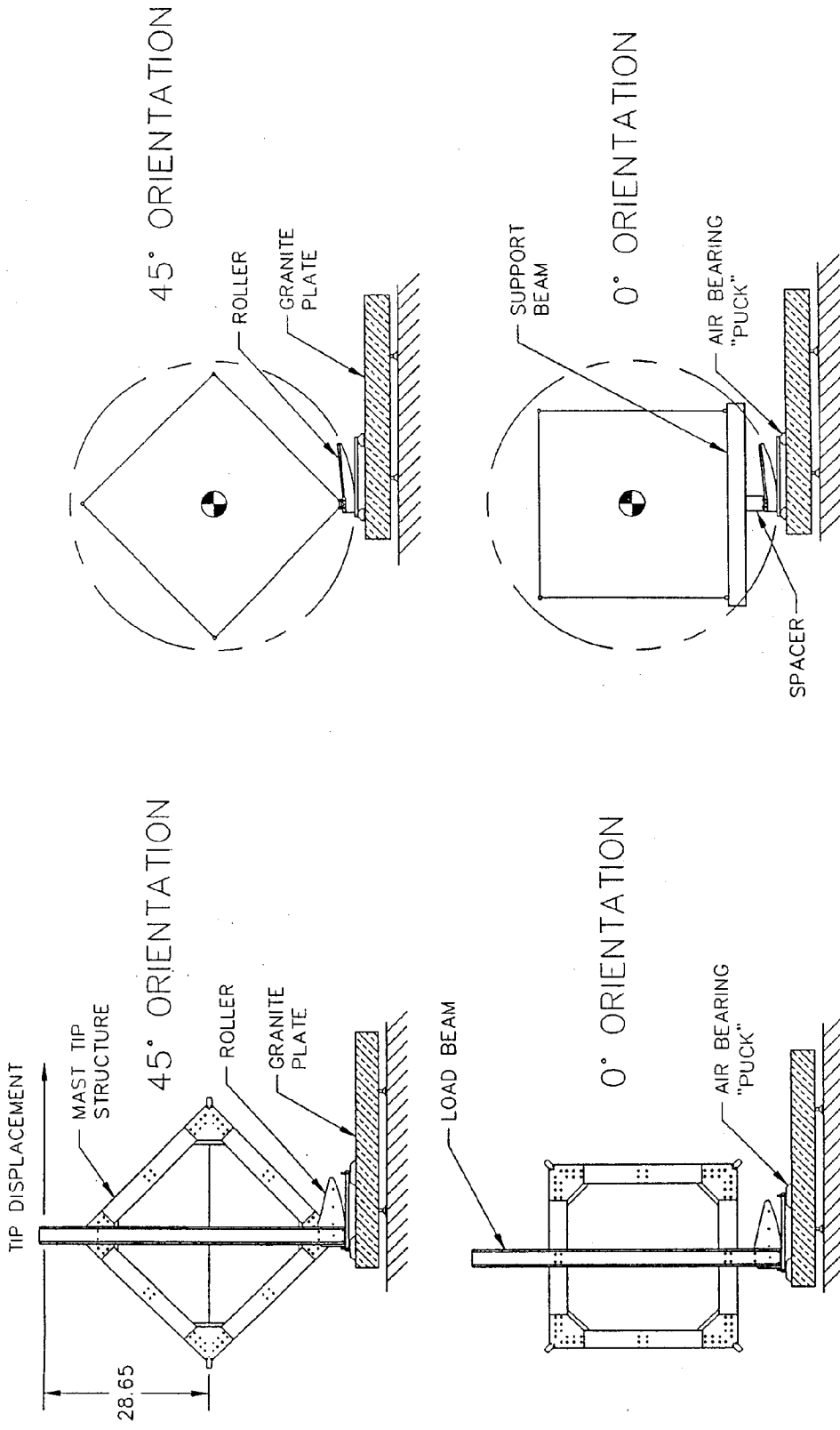
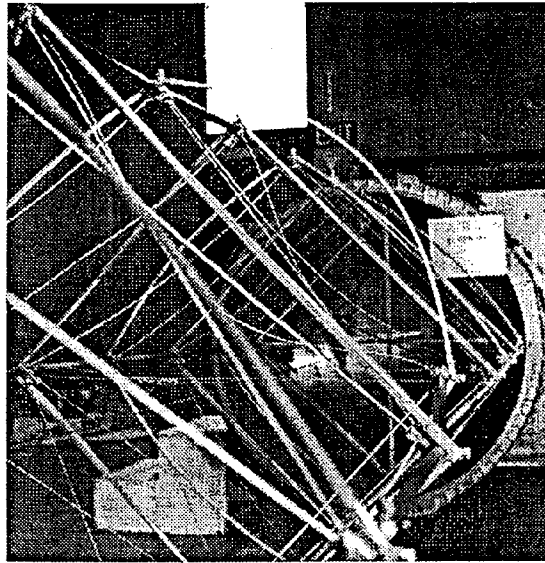


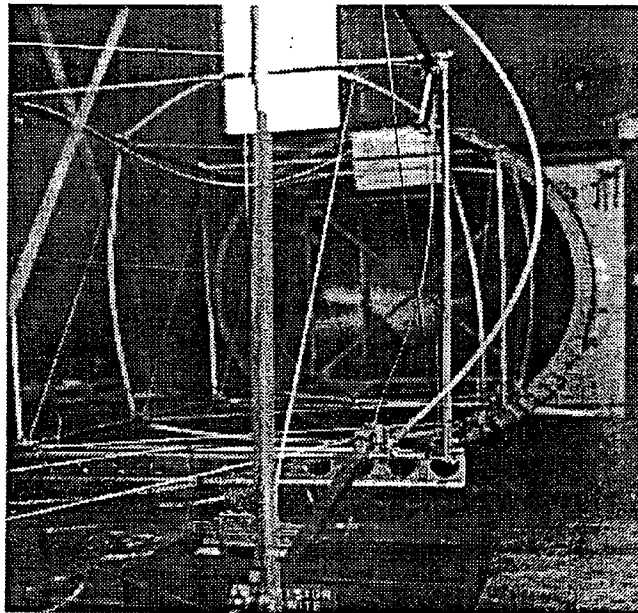
Figure 6: Typical Mast Support at Bays 2, 4, 8, 12, 16, 20, 24, and 28

Figure 5: Mast Tip Support at Bay 32



Folded compression-side (right side) elbow in bay 3

Figure 7: Failed Mast for Test No. 8x



Folded top-right elbow in bay 2 and folded bottom-right elbow in bay 3

Figure 8: Failed Mast for Test No. 4b

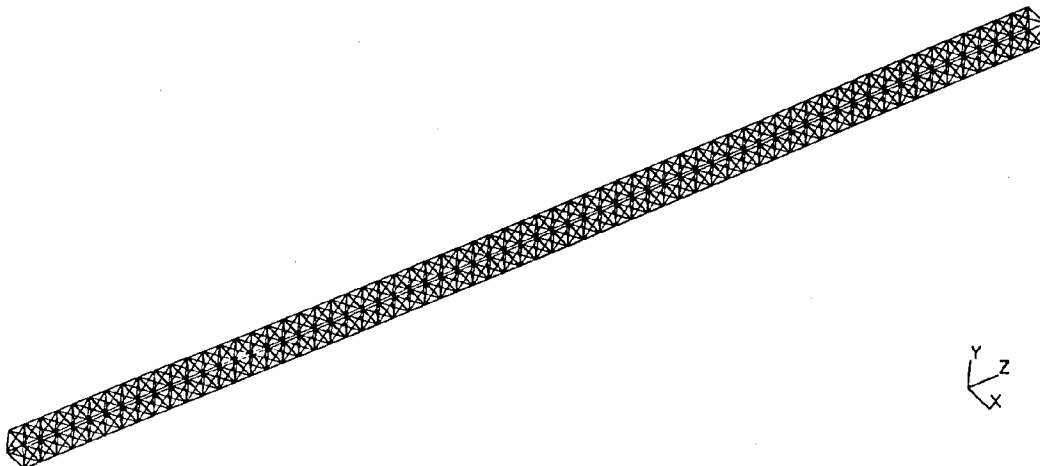


Figure 9: Finite Element Model of Deployed Mast

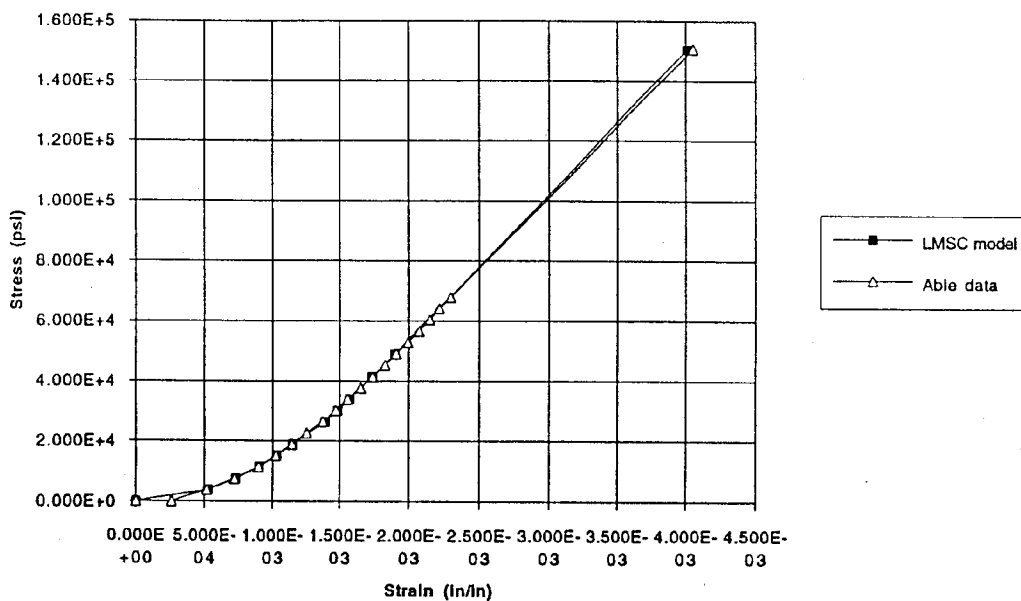


Figure 10: Diagonal Wire Tension Property

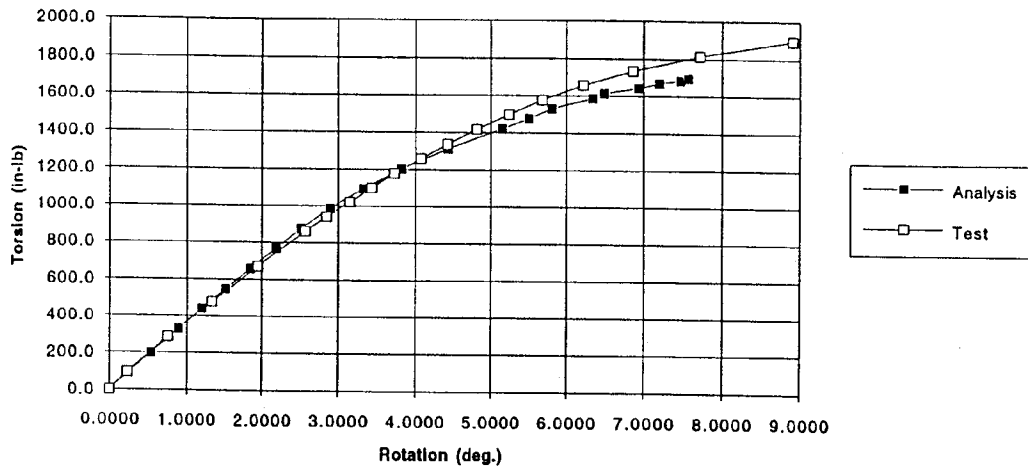
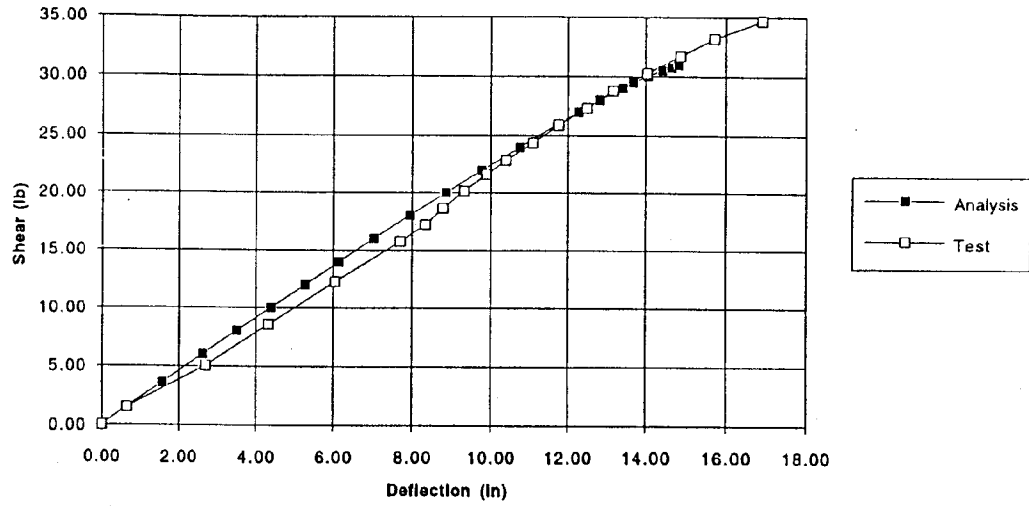


Figure 11: Mast Tip Load vs. Displacement for Test No. 8x

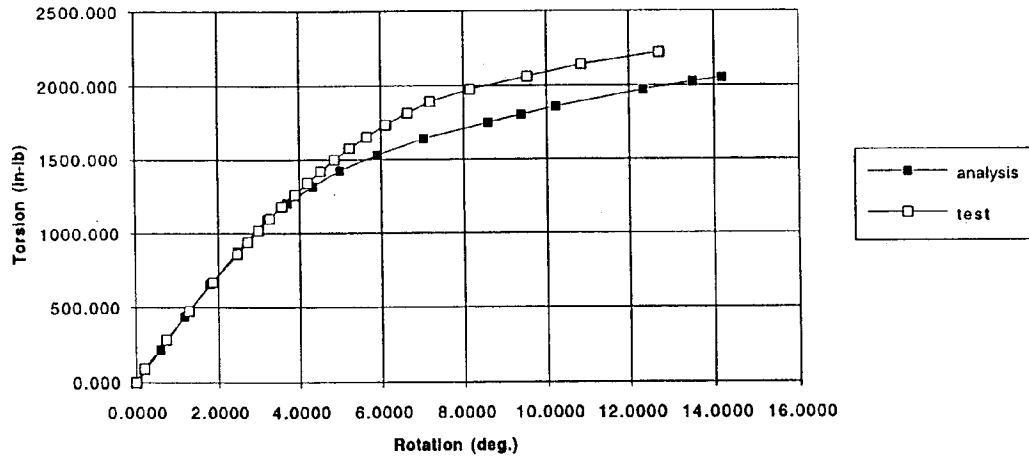
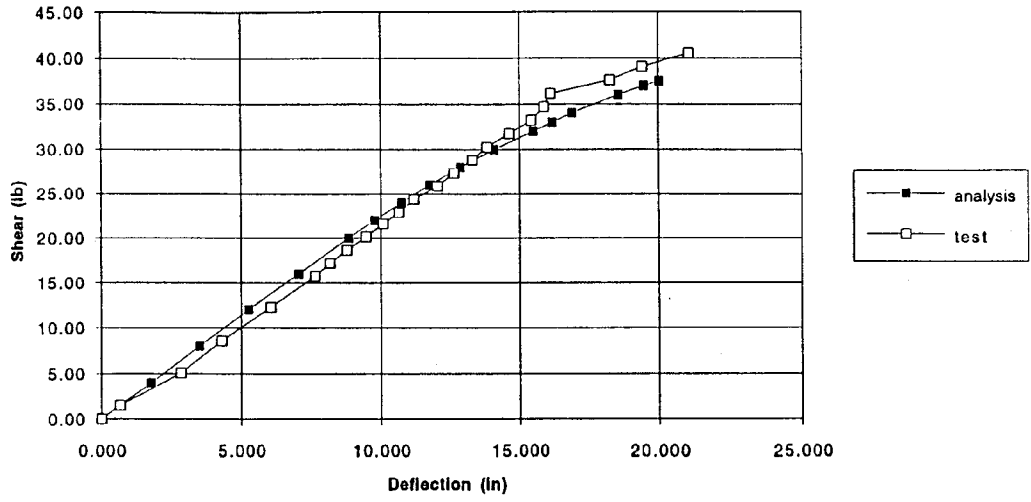


Figure 12: Mast Tip Load vs. Displacement for Test No. 8

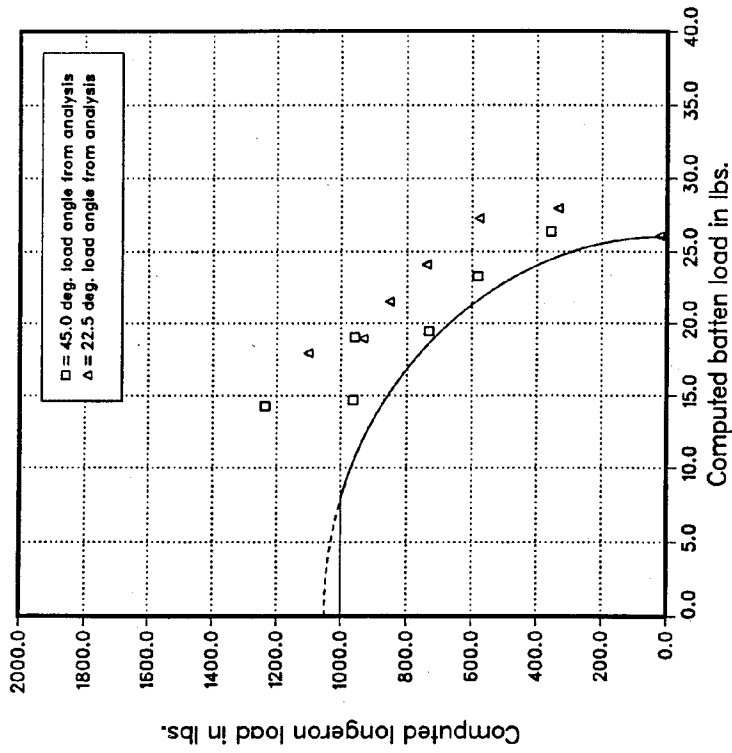


Figure 13: Mast Limit Load Capability
(for applied load vector angle
larger than 22.5 deg.)

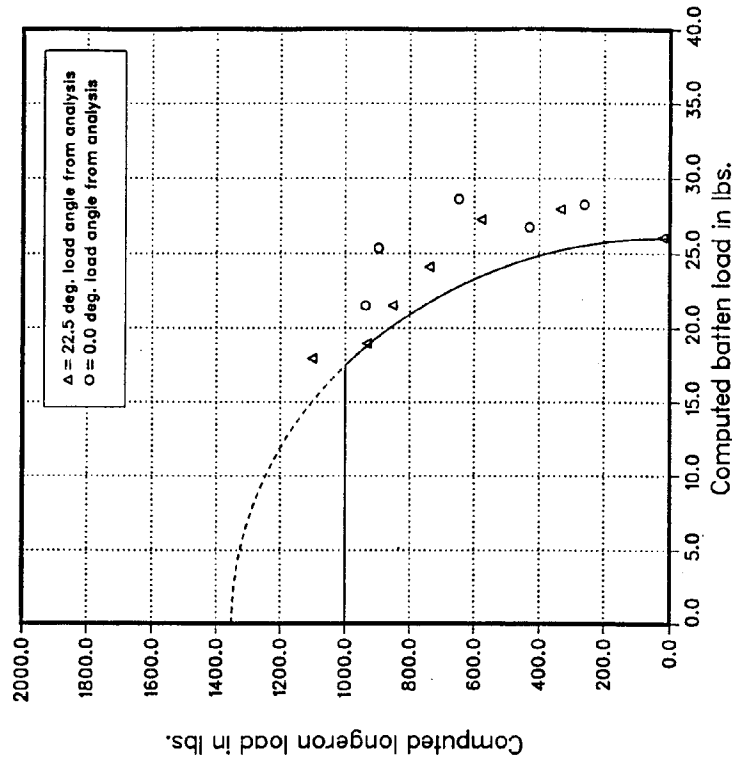


Figure 14: Mast Limit Load Capability
(for applied load vector angle
equal and less than 22.5 deg.)