Deployment Analysis of the Olympus Astromast and Comparison with Test Measurements

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An analytical procedure is presented to predict deformations and member loads of a coilable, deployable, continuous-longeron space mast (Astromast) in the transition zone from stowed to deployed configuration. A nonlinear, three-dimensional, finite-element model is set up to represent each truss member and the initial prestress of the deployed mast. By applying an appropriate loading procedure, the mast is forced into its characteristic helical transition zone. In this zone, the truss elements are highly loaded and the coiling of the longerons is initiated for the mast-stowed configuration. The geometry change of the mast from the deployed state into the coiled configuration is computed with the large strain/displacement nonlinear finite-element program LARSTRAN. The analytical results are verified by test measurements on a demonstration mast model. There is good agreement between the analytical results and test measurements.

Introduction

THE Olympus solar array deployment system employs a continous-longeron Astromast.[1] The latter is stowed in a canister with a motor and guide rails for actuating the deployment and retraction of the solar blanket. The highest stressing occurs in the canister compartment where the mast changes from a straight deployed configuration into a coiled state. Design improvements were implemented in the development and qualification phase of the deployment system. The impact of the improvements on the mast performance was considered only by test, due to the fact that understanding and predicting the mast deformation and stress in the transition section between the coiled longerons and the straight mast (Fig. 1) cannot be readily obtained by analysis.

In analyzing the transition zone, difficulties arise due to the large deformations occurring in combination with the geometric and material nonlinearities, large strains, action of diagonal members in tension only, special hinge conditions at the batten-frame longeron interface (Fig. 1), and prestress state of the deployed mast. As a result of the prestress, the battens are in a postbuckling state and exhibit a strong nonlinear force displacement relationship.

Analytical investigations for the mast deployment are presented and the verification of the computed results with test measurements is considered.

General Methodology

The evaluation procedure adopted is to analyze the transition section by an incremental large-displacement technique and to check the computed results with the test deformation measurements where possible. Since the Olympus mast hardware was not available for this type of testing, a similar demonstration model was employed to verify the applied methodology by test. The proved methodology was then applied to the Olympus mast for deriving the deformations and member loads. To generate the transition zone in the analysis, it was necessary to start with a deployed straight mast (where the initial prestressing conditions are known) and to apply the appropriate loads to force the mast in the transition zone. The loading procedure in the computation was determined by the loading sequence in the demonstration model.

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Test Measurements

To support and check the analysis, the test measurements outlined in this section were performed.

Generation of Transition Zone

The Astromast demonstration model is a continuous longeron mast 3 m long without the canister deployment device. The battens and longerons are made of unidirectional glass fiber-reinforced plastic (GFRP) and the diagonal cables of steel. Also, on the Olympus Astromast, the diagonal are very thin GFRP rods, which exhibit a cable-like behavior since they do not withstand substantial compressive loading. The plates on both ends of the mast are pin jointed to the longerons, allowing the longeron to lie horizontally on the aluminum disk the after the coiling of the mast. See Fig. 2.

To investigate the onset of the transition zone only, a mast section of 10 bays has been considered, with an end plate on one end and clamped longerons on the other such as that on the canister-deployed mast version. To stow the straight deployed mast, the following procedure is employed: first, torsion is applied at the end plate, causing a release of pretension of the three diagonals per bay over the whole mast length. Further torsion leads to "torsional buckling" of the single bays, starting in the mast middle and progressing toward the ends. During this operation, the mast diameter is substantially decreased in the respective bays.

The torsion can be increased up to a point where all bays over the whole mast length, except the first and last, are twisted and a sudden "snap through" of the pin-jointed longerons occurs at the end plate. This "snap-through" effect is accompanied by an intermediate mast length reduction, because the longerons change from an almost vertical position at the end plate to a "coiling" position. Applying compressive loading relieves the applied torsion moment and initiates a movement of mast twist toward the pin-jointed end and an untwisting of the bays at the opposite end. This indicates the forming of the transition zone, which assumes its full length when the mast can be sustained in its deformed state under pure compressive load and with the longeron in contact on the end plate over a full bay length. In this configuration, three mast bays at the clamped end are returned to their initial prestressed, straight condition. No relative twist of the longerons with respect to the batten triangles has been noticed in the transition zone, except near the coiled part. In this area, the variation in longeron bending due to the change in mast diameter is partially coupled with the in-plane batten triangle deformation.

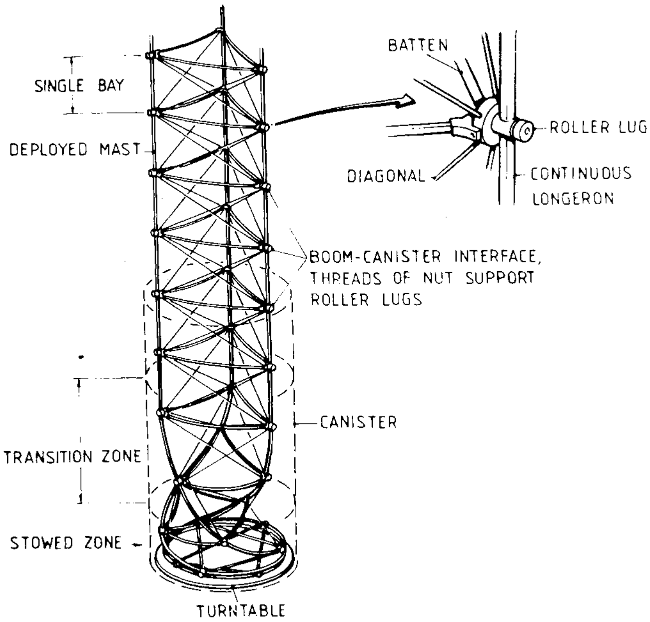

Fig. 1 Astromast transition section.

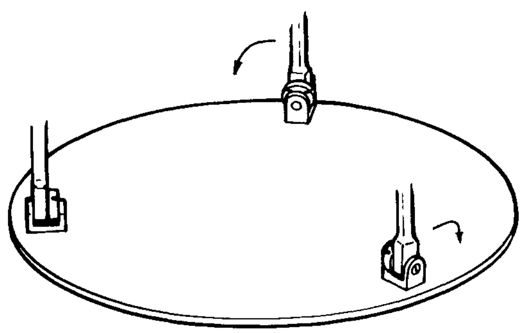

Fig. 2 End plate boundary condition.

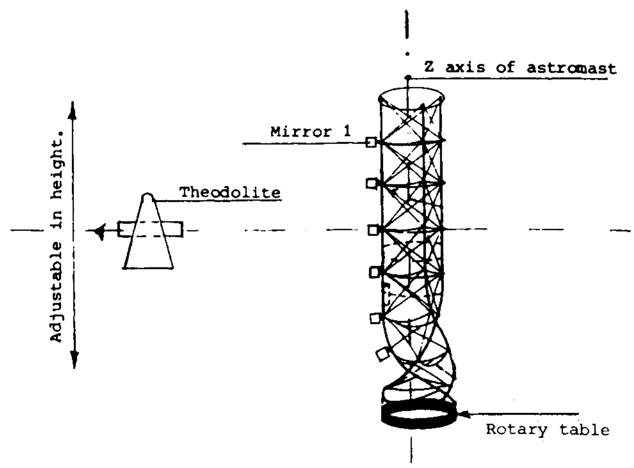

Fig. 3 Measuring setup.

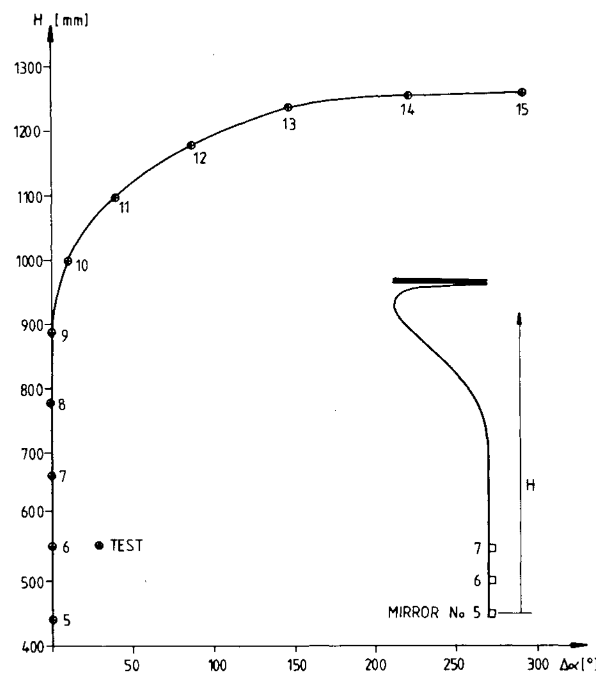

Fig. 4 Angular displacement of longeron in the transition zone.

Deformation Measurements

The length and the shape of the transition zone was determined by test for comparison with the analytical results. Fifteen cubic mirrors, equipped with alignment targets, were attached to the longeron hinge points to determine their exact position (Fig. 3). The Astromast was mounted vertically on a rotary table with the upper end plate held in a free rotating fixture. This fixture was adjustable in height to apply the necessary compressive loading. The rotary table was equipped with an angular readout to determine the angular displacement of the hinges in the transition zone. An optical tooling bar carrying a theodolite with an alignment laser was mounted at a fixed distance in front of the rotary table. The vertical position of the mirrors was measured on a ruler mounted beside the rotary table.

With this setup, the vertical distance of the longeron hinge points in the transition zone and their angular positions were measured with respect to the straight part of the mast. Figure 4 shows the angular displacement of the hinge points over the mast height. The transition zone consists of six twisted bays with an overall length of 370 mm. The mast diameter variation over the height (Fig. 5) was determined by measuring the sides of each triangular plane.

The measurements show that the mast diameter variation causes a maximum compression of the battens in the transition zone. These measurements were employed to define the range of interest in which the batten compression test determined the load displacement characteristics.

Batten Characteristic

The battens are in a postbuckling state when moving through the transition zone and they exhibit a strong nonlinear behavior. Since their load deformation characteristic strongly influences the shape of the transition zone, a good representation of their performance is necessary in the analytical model.

One triangular batten frame was cut at the yokes and the single battens were mounted on a special test rig with the same built-in offset of the original mast. With this test setup, the batten compressive load was measured from a straight shape to its maximum deformation in the transition zone. The measured force displacement curve (Fig. 6) shows a steep nonlinear load increase at the beginning, followed by an almost constant load when the batten has reached its postbuckling state. This is valid for the whole range of deformations considered in the transition zone. When releasing the compression, a curve with the same characteristics (slightly shifted) was measured in a similar manner.

Young's Modulus Test

The Young's modulus of the actual GFRP material was measured in a tensile test with a batten specimen. The measured value was employed in the analytical model.

Torsional Stiffness of the Longeron

A torsion test according to the German Standard DIN 53447 was performed to measure the torsional stiffness of the unidirectional GFRP longerons. The test specimen employed was a single bay long longeron. Up to 10 deg of torsion, a linear elastic behavior was exhibited, followed by a nonlinear behavior with increasing "creep" effects. The measured elastic torsional stiffness GJ is employed to derive an appropriate St. Venant torsion constant for the analysis, where the shear modulus G is calculated from Young's modulus and Poisson's ratio using the equation,

$$G = E/2(1+V) \qquad (1)$$

By this approach, the actual torsional stiffness of the longerons can be introduced in the analysis, as the program does not allow input of an arbitrary shear modulus in the employed beam elements.

Analytical Approach

A nonlinear mathematical model of the demonstration mast was set up for the analysis of the transition zone using the large strain/displacement finite-element program LARSTRAN.[2] The deployed mast configuration is first considered with prestressing conditions known from the mast geometry. To form the transition zone, the same loading procedure that was determined by qualitative measurements on the demonstration mast is applied to the mathematical model. Torsion and compression, applied by an incremental large-displacement technique, forces the model to coil up at one mast end. The transition zone assumes its full length when the model can be sustained in its deformed state under pure compressive load.

Mathematical Model

The mathematical model consists of 10 single laced bays and is considered sufficient for representing the transition zone (Fig. 7). The given mast radius $r = 88.6$ mm corresponds to the demonstration mast geometry with unloaded straight battens.

The longerons are represented by beam elements with six degrees of freedom (dof) and the battens and diagonals by truss elements. Each batten and diagonal is idealized by one element, whereas the longerons consist of six elements per bay length.

The beam element BECOS provided by the program element library is a two-nodal point linear elastic (small-strain) element.[3] Thus, the longeron nonlinearities due to large strain were not considered in the present model. The linear performance of the longeron was verified by tests for a twist up to 10 deg. The batten element FLA2S is a two-nodal point elastic large-strain truss element that allows to input any arbitrary linear and nonlinear behaviour. These element properties allow a good representation of the measured batten characteristics.

For the diagonals, the special nonlinear features of the two-nodal point FLA2 rod element were employed to introduce the prestress loads of the deployed mast configuration and to eliminate the stiffness of the diagonal string elements when subjected to compressive loads in the deployment.

Longeron, batten, and diagonal geometric data and material properties are given in Table 1.

To simulate the deployed mast side, the longerons are idealized with cantilevered fixed boundary conditions at one mast end. At the other end, the longerons have pin-joint connections to a fictitious stiff end plate. The stiff end plate condition is introduced by fixing the initial longeron position (dof x, y, z) relative to each other, while allowing for longeron rotation (two axes only) and simultaneous overall movement of the three end points.

Since the batten and diagonals are idealized by truss elements, no local longeron torsion can be transferred at the hinge points. On the actual Astromast, a transfer of longeron torsion into overall torsion or bending of the batten triangle is possible, but can be found only during the test near the coiled-

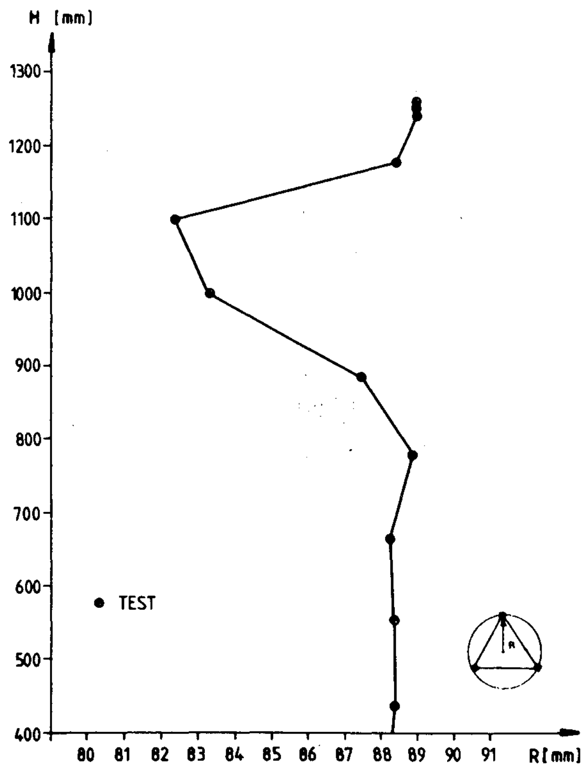

Fig. 5 Mast radius variation in the transition zone.

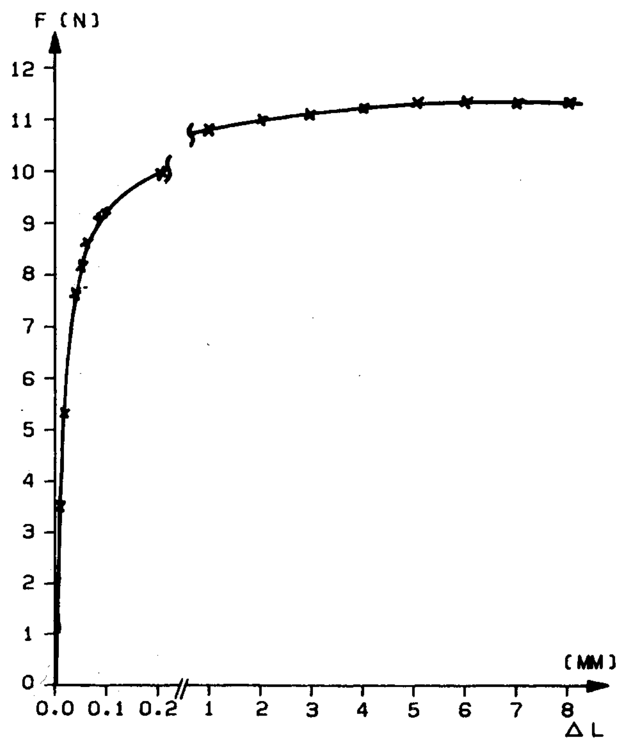

Fig. 6 Batten load-deflection characteristic.

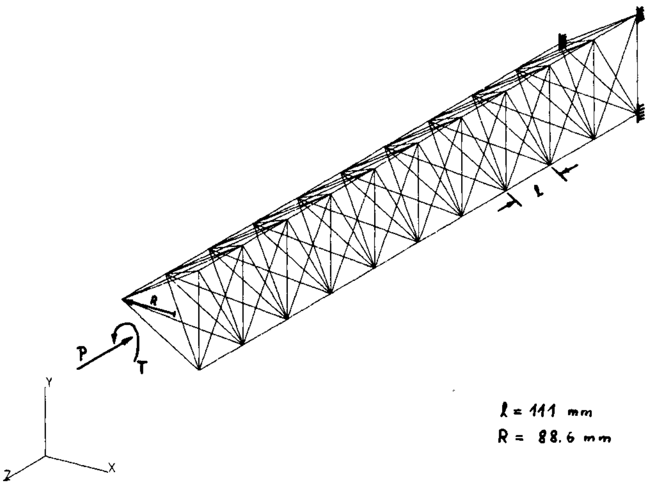

Fig. 7 Ten-bay Astromast model.

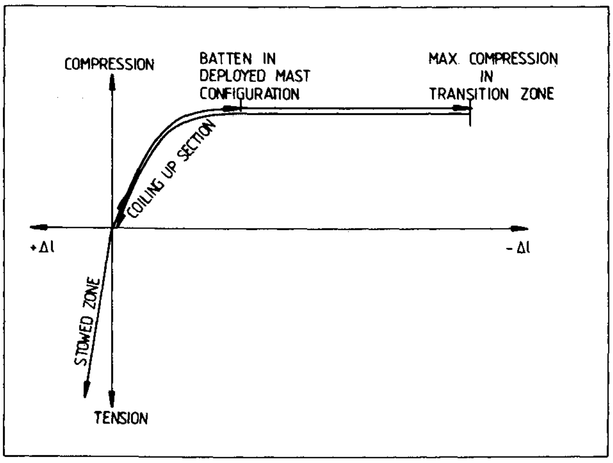

Fig. 8 Batten load cycle in transition zone.

up section. As a result, this effect on the transition zone is assumed to be negligible. Therefore, a more refined representation of the hinge connection was not implemented at this stage of the analytical investigation. Also, the effect of the diagonals acting with a varying offset on the lonerons, when moving through the transition zone, was not considered with the simplified hinge model.

Implementation of Batten Characteristic

Since the FLA2S element permits the idealization of any arbitrary linear and nonlinear elastic behavior, the measured batten performance during all phases of the coiling procedure was introduced with a single element. The idealized behavior included the change from unloaded straight shape into the postbuckling state in the deployed mast configuration, as well as the transfer through the transition zone. It also represented the tensioned state in the stowed section.

By employing values for the Young's modulus corresponding to the strain rate, a fully reversible nonlinear behavior under compression that followed the measured batten curve was introduced. When the element began to act in tension, the linear elastic tensile Young's modulus represented its stress/strain behavior. The programmed performance over the whole load cycle in the transition zone is shown in Fig. 8. A single-batten mathematical model was employed to check the programmed element performance before introduction in the complete mast model.

Table 1 Geometries data and material properties of mathematical model

Properties	Longeron	Batten	Diagonal
Cross section, mm^2	Circular, 7.06	Circular, 2.83	Circular, 0.5027
Diameter, mm	3	1.9	0.8
Linear elastic Young's modulus, MPa	3.387×10^4	3.387×10^4	2.1×10^5
Poisson's ratio	0.3	0.3	0.3
Element type	BECOS	FLA2S	FLA2

Applied Load Cases

Before applying the previously described loading procedure to generate the transition zone, the initial deployed configuration with its internal prestressing state had to be computed since the mathematical model geometry represented a nonprestressed mast state.

Deployed Mast

The prestressed configuration was computed by introducing a constraint length on the diagonals that was developed with a reduction from 88.6 to 88.04 mm in the geometry of the mast radius. This corresponded to a batten transfer from a straight to a postbuckling state. Since a stepwise application of the contraint length was not possible in the employed program and the introduction with a single computational load step was too large for the batten characteristic change from a straight to a postbuckling state, the following approach was considered: The prestress loads in the deployed configuration were introduced with initial strains in the diagonal elements and with external loads in the direction of the diagonals. The external loads were reduced stepwise to simulate the deployed physical constraints.

The following pretension loads were computed for the single truss members of the deployed configuration: −7.8 N longeron, −10.8 N batten, and 6.68 N diagonal.

Mast Torsion

As a first step in generating the transition zone, torsion is applied at one mast end. The torsion is introduced by moving the three longeron hinge points incrementally via a prescribed displacement on a circular line (x-y plane) while, at the same time, allowing the free mast length reduction (z direction). As in the test, the torsion first causes an unloading of the prestress in the three diagonals per bay over the entire mast length that is accompanied by a corresponding load increase in the three remaining members. Since the diagonal members act only in tension, their action is eliminated in the analysis when they are in compression. Further end torsion yields to "torsional buckling" of the single bays, starting in the middle of the mast (Fig. 9) and progressing toward the ends of the mast (Fig. 10). The mast twist is accompanied by strong mast diameter reduction and related batten compression.

Altogether, 223 torsional load steps were computed with an overall twist of 390 deg. At this point, the program failed with a singularity in the solution, indicating an unacceptable large change in the mast length for a very small increase in applied torsion. This effect arises at the "snap-through" point of the longeron at the end plate.

Mast in Compression and Guided Hinge Torsion

To overcome the singularity in the solution, the dof definition at the end-plate side had to be changed. The applied end-plate torsion, prescribed by the x-y displacements of the longeron points, was stopped at 390 deg by suppressing the x,y dof. The previously free axial displacement (z direction) was changed to a prescribed motion simulating the mast compression. The rotational dof at the longeron pin joints with the end

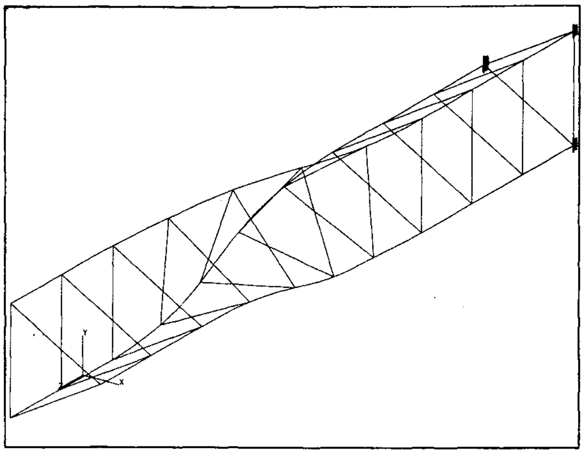

Fig. 9 Mast torsion at 60 deg.

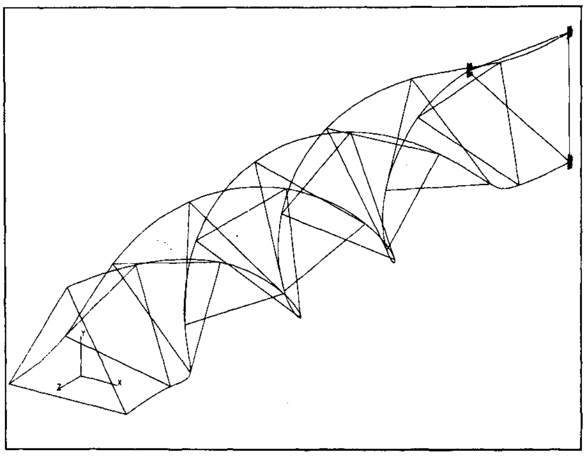

Fig. 10 Deformed mast before "snap through."

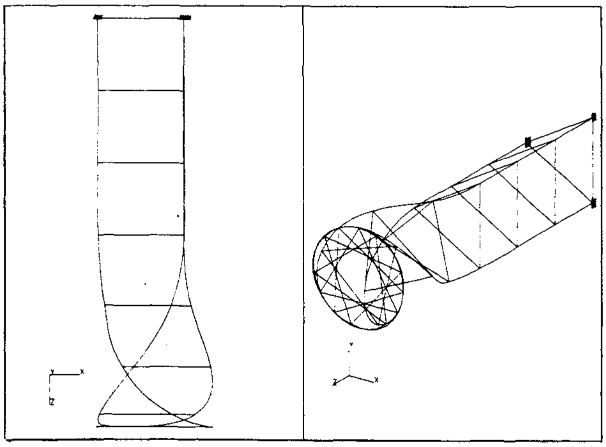

Fig. 11 Computed transition zone.

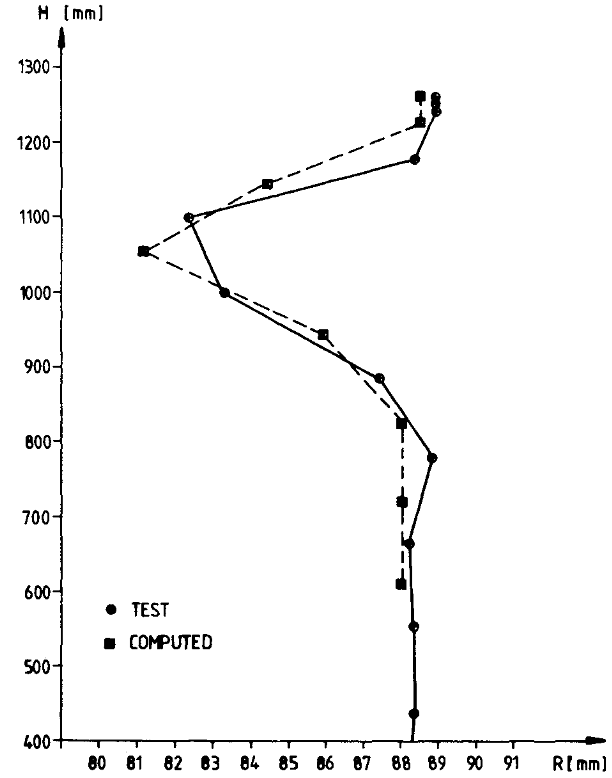

Fig. 12 Measured/computed mast radius in the transition zone.

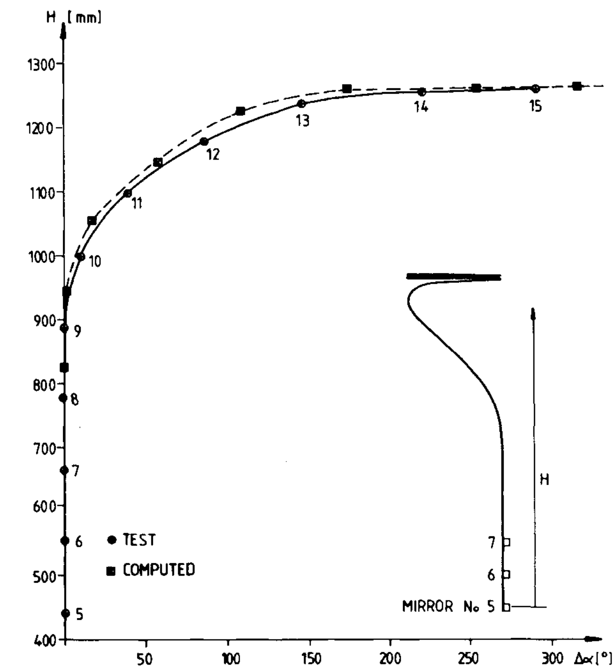

Fig. 13 Measured/computed angular displacement in the transition zone.

plate were also prescribed, where a sudden "snap through" toward a coiling configuration was noticed in the test.

The incremental mast compression with simultaneous hinge rotation generated a controlled collapse of the longerons at the end plate. During this process, the applied torsion was continuously reduced and there was a movement of the twisted mast sections toward the pin-jointed end and an untwisting of the bays at the opposite end. This indicated the formation of a transition zone that assumed its full length when the mast was sustained in its deformed state under a pure compressive load. See Fig. 11. The longeron contact with the end plate was represented in the analysis by restricting the corresponding longeron points in the mast axis. The analysis showed a mast diameter reduction at the beginning of the transition zone, followed by an increase to the unprestressed diameter in the wound section. This section was characterized by tensioned battens and unloaded diagonals.

The final part of the transition zone generation was performed with 46 incremental load steps.

Comparison of Analytical and Test Results

The general character and shape of the computed and measured transition zone are in good agreement, as determined by visual comparisons of deformation plots and evaluation of computed member loads. Specifically, there is good agreement for the following characteristics:

1) Unloading of three of the six diagonals per bay over the whole transition zone.

2) Variation of the mast diameter with an intermediate minimum value.

3) Increase in the mast diameter in the coiling section.

4) Tensioning of the battens in the stowed zone.

5) Unloading of all diagonals near and in the stowed zone.

The following peculiarities, which are in agreement with the test measurements, appeared clearly in the analytical model simulating the transition zone:

1) Release of three pretensioned diagonals per bay over the whole mast length under little torsion.

2) Mast twist initiates in the middle portion of the mast.

3) Mast twists in all bays before the hinged longerons collapse at the end plates.

4) "Snap through" of longerons at the pin-jointed end plate hinges.

5) The mast twist moves toward the end plates when the transition zone is formed.

6) Straightening of the mast bays at the clamped end and return of the mast to the pretensioned stated when the hinged longerons are coiled at the end plate.

Figure 12 compares the measured and computed radius variation of the mast in the transition zone. A comparison of the measured and computed angular displacement of the longeron hinge points is given in Fig. 13. The difference in overall mast length (20%) and angular position of the hinge points might arise due to the simplified idealization in the model for the hinges between the batten triangles and the longerons and, possibly, due to nonlinear performance effects in the longeron. The latter are under further investigation. In the idealization of the Olympus mast model, coupling of the longeron torsion with the overall torsion of the batten triangles is considered in the hinge connection. Results for the modified analytical model are under evaluation.

For the test mast, the following loads were computed for the truss member at the hinge points:

1) Longeron: compressive load (about three times higher than the prestress load in the deployed configuration), shear loads, bending moments, and torsion moment.

2) Diagonal: tension load (about four times higher than the prestress load in the deployed configuration).

3) Batten: compressive loads.

The computed loads in the mast members are employed to define the load levels for mast component test and to improve confidence for the mast design. For better comparison of analysis and test and visualization of the mast deformation (especially in the transition zone), a film has been produced for animated motion of actual mast deformations and computed incremental displacements.

Conclusion

The employed analytical procedure verified by test measurements has proved the ability to predict deformations and member loads in the transition zone of the Astromast. Also, the process of forming the transition zone is well represented in the analysis. The member loads derived for the test mast indicate the loads trend for the Olympus mast. Results for the latter are still under evaluation. The presented methodology can be employed to evaluate material properties, geometry, and truss member parametric modifications.

References

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