

A Deployable Stiffened Biconvex Mast

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Deployable structures are a common spacecraft configuration feature. Deployables are used to configure spacecraft inertia properties, provide expanded antenna aperture and solar array area, or to provide separation between spacecraft components. Lightsat design would be especially enhanced by small size lightweight deployable structures. A review of the state of the art of deployable structures has been conducted and shows that these devices can be divided into two categories: one, rollable mast of the stem, bistem, or stacer types; and two, folding trusses. The rollable masts are generally of open section and susceptible to thermal excitation. Folding trusses are not available in small size. To address these design challenges, a rollable closed section biconvex mast was design, constructed, and experimentally evaluated. The mast was constructed of composites to obtain high stiffness and low weight and to exploit the relative ease with which a shaped cross section can be fabricated. The mast has a lenticular cross section that can be flattened to allow it to be stowed around a drum. Once on orbit, the mast is unrolled and opens up to the lenticular cross section. A novel stiffener has also been developed which increases the capability of the section. Design characteristics and test results are presented.

Introduction

Deployable masts, when incorporated into small satellite design, can provide design characteristics which belie their small launch weight and volume. Deployable masts allow small satellites to incorporate large antenna apertures into their design, provide large separation between components of the spacecraft, or allow the inertia properties to be configured for gravity gradient attitude stabilization.

Most current work on masts in the U.S. is on the development of the structures for the space station. Furthermore, a literature search found no reference to using masts in small satellite design. It is quite possible that no concerted effort has been made to optimize a mast for small sat application. The desired design parameters for small satellite application are small stowing volume, low cost, simplicity, and light weight. The deployed mast should have a high capability section with high bending rigidity, good buckling stability, and good torsional rigidity.

The purpose of this research was to design and build a test section of a deployable mast with an internal stiffener. This research included the following phases:

a) a literature search to determine the state of the art of deployable structures and to determine if any work has been done to

optimize masts for small satellite application.

b) selection of a type of mast to investigate and brainstorming to develop ideas to improve on existing designs.

c) fabrication of a section of mast.

d) design, fabrication and testing of an internal stiffener.

The Biconvex Mast

Because a literature search revealed no deployable masts applicable to small satellite design, the first step was to determine which type of mast would be appropriate for small satellites. The biconvex mast was chosen because it is simple and easy to manufacture, (factors that lead to low cost, a very desirable criteria for small satellites) and it was a closed section beam, so it would not be subject to the thermal excitation that open section masts are subject to.

The biconvex mast is made up of a pair of flexible, thin composite shells. The shells are formed using a mold. The halves of the tube are bonded at the edges by epoxy adhesive. The tube can be flattened and rolled up around a drum into a small volume. Once freed it springs back to its original shape behaving like a closed section beam.

Reference [1] demonstrates the stowing concept, which is depicted in Fig. 1.

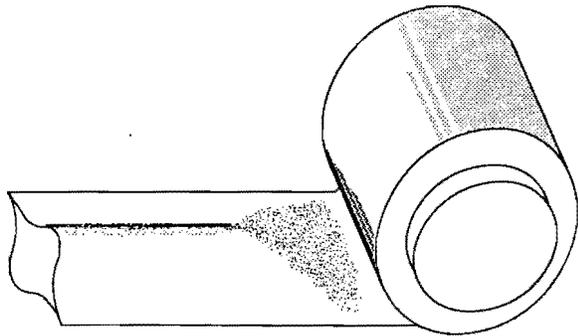


Fig. 1 The Biconvex Mast

These masts are commonly manufactured from copper beryllium (CuBe) or Carbon Fiber Reinforced Plastics (CFRP). Once deployed on orbit this mast has good torsional properties and its buckling strength is of the order of a cylindrical mast.

Because it is susceptible to buckling in its transition region between stowed and deployed states, previous designs have used a supported transition region. [1] Recent work in this area has been done in Europe under contract to ESA. [2&3]. A major portion of this contract was the development of the continuous manufacturing method needed to construct masts of unlimited length. ESA has built an 8 m mast of this type that was flown on the Ulysses space probe.

The section shape is defined by several parameters: the radius r , the angle ϕ , the flat shoulders size b , and the thickness t . ESA selected the following values for their design:

$\phi = 1.3 \text{ rad} = 75 \text{ deg}$ Due to all around stiffness and strength optimization

$b = 0.3 r$ Due to shear stress level optimization in the interface between both tube halves

$t = 0.008 r$ To keep the flattening strains low enough to avoid long term viscoelastic properties degradation

To define the biconvex mast stowing size, the stowing drum radius, R , is also defined and optimized. ESA has taken for the optimum value for R ,

$$R = 3.2 r = 400 t$$

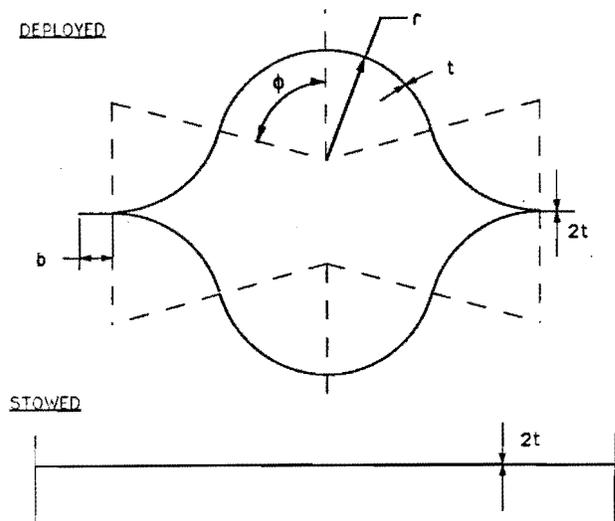


Fig. 2 Cross Section of Biconvex Mast

Accordingly, the overall size of the mast is defined by selecting t .

The dimensions of the mast section fabricated for this research were dictated by the material available which was CFRP composed of unidirectional plies each with a thickness of 0.005 inches. Each half of the mast was fabricated of two layers, one in the 0 deg direction, the other in the 90 degree direction. The mast section properties are:

$$\begin{aligned} t &= 0.01 \text{ in} \\ b &= 0.375 \text{ in} \\ r &= 1.25 \text{ in} \\ R &= 4 \text{ in} \\ \phi &= 64.3 \text{ deg} \end{aligned}$$

The material properties of the CFRP material are:

$$\begin{aligned} E_x &= 24.6 \times 10^6 \text{ lb/in}^2 \\ E_s &= 1.02 \times 10^6 \text{ lb/in}^2 \\ E_y &= 1.21 \times 10^6 \text{ lb/in}^2 \\ \nu &= 0.28 \end{aligned}$$

The CFRP used is a low temperature cure thermoset, which means it needs pressure and temperature to cure it. The mold was fabricated from ash wood which was waterjet cut to the desired shape. The composite shape was obtained by curing the composite layup on the shaped mold. Two shaped sections were fabricated using the mold and curing the composite in an autoclave to get the desired stress free configuration. The two edges were then bonded together.

The ability of the mast to roll up and deploy was demonstrated. The mast was

flattened and rolled around an eight inch diameter drum and then released. The mast rolled and deployed satisfactorily.

Stiffener Design

A significant thrust of this research has been fabricating a stiffener for the mast that will still allow it to be rolled and stowed. The idea for the stiffener came from an examination of the biconvex mast, which revealed that the capability of this section could be improved by either pulling the flat edges together or pushing the curved edges apart.

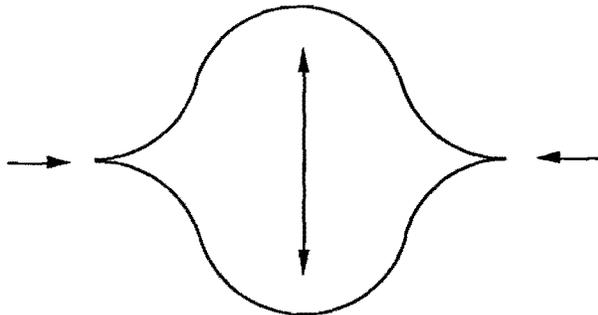


Fig. 3 Section Reinforcement

This idea then led to the idea that since the lenticular profile of the mast flattens and rolls nicely yet still has strain energy stored in it to return it to its curved shape, a stiffener could be fabricated out of this same shape only rotated 90 degrees so that it ran longitudinally. This stiffener would push the curved edge outward, increasing the bending rigidity and the buckling stability.

This design has three components, the curved sections, a sliding insert and an anchoring frame. The curved sections are narrow pieces of the the same profile as the mast itself, so they have the tendency to

maintain their curved shape. The curved sections are bonded to the outside of the anchoring frame on one end and the sliding insert on the other. The stiffener also has midplane symmetry. Fig. 4 illustrates the configuration of a short section of stiffener.

The sliding insert is used to pull the curved sections flat for stowing and tension is maintained to keep the curved sections flat. Once the mast is unrolled, the insert is released and deployed. The anchoring frame and sliding insert are latched in the deployed position to prevent the curved sections from sliding flat under loading, which provides additional structural integrity. Once deployed the curved sections will give support to the outer profile, increasing bending stiffness and resistance to buckling. Note that the stiffener can be stowed with the basic mast so that deployment can be ground tested.

Analytical Results

The predicted bending stiffness of the base mast was computed. For isotropic materials bending stiffness is defined by the product EI , where E is the Young's Modulus and I is the section's moment of inertia. However, because composites are not isotropic, EI is not defined. To obtain the parameter that is comparable for a composite beam, F.K. Chang's method for obtaining the bending stiffness for a composite beam was used. [4]. The analysis predicts bending stiffness from numerical integration that is based on section geometry, material orientation and material properties. For the fabricated mast, the parameter D is:

$$D = 1.19E6 \text{ lb-in}^2$$

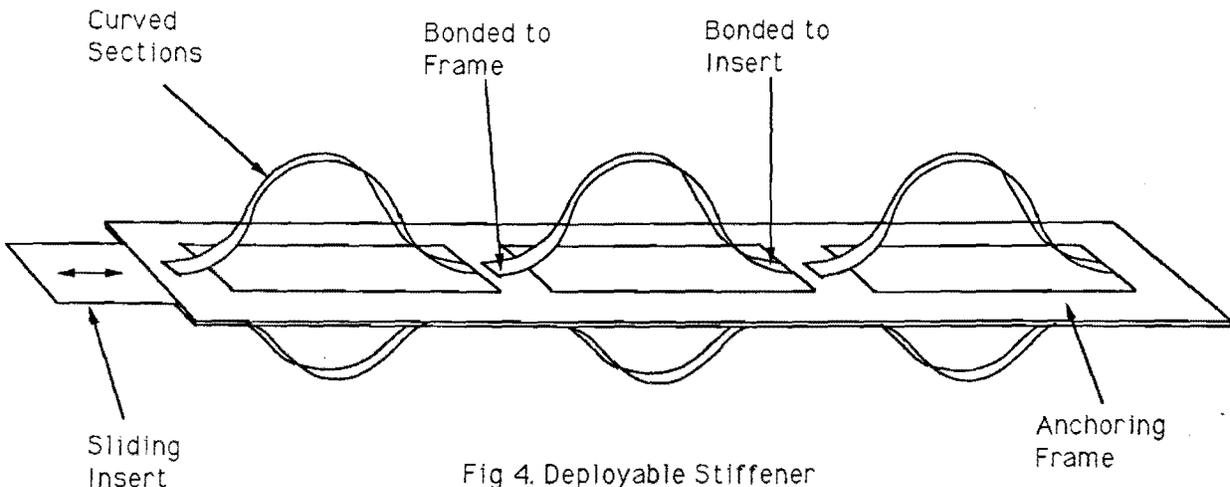


Fig 4. Deployable Stiffener

Analytical methods to determine the expected increase in bending rigidity for the stiffened mast are not available so an experimental comparison must be made to yield conclusions on the impact of the stiffener on bending rigidity.

This mast was tested as a cantilevered beam. Fig. 5 shows the test configuration.

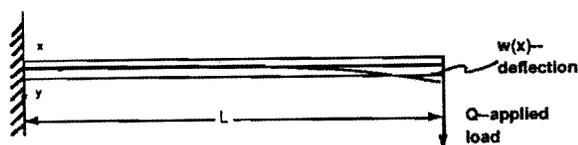


Fig. 5 Test Configuration

Test Results

For a perfectly cantilevered beam, under a static load Q, the deflection w is

$$w = \frac{Q x^3}{6 D}$$

From the experimentally measured deflections, w at station x, the stiffness parameter, D, can be determined and the results are presented in Table 1.

	Bending Stiffness, D
Basic Mast	1770 lb-in ²
Stiffened Mast	3075 lb-in ²

Table 1. Experimental Bending Stiffness

The value for the bending stiffness is, however 0.1% of what is predicted analytically. There are two possible reasons for this. One, the theory used in the analysis is for long beams, and the test sample was just barely twice as long as it was wide. The second and more serious problem was the test setup. Since the beam mast was quite stiff, flexibility in clamping affected the test results. To see if these effects were present a polynomial curve was fit to the data, however, the results were inconclusive.

The stiffened mast has twice the stiffness of the basic mast, it weighs 1.71 times more and the stiffness to weight ratio is essentially the same.

	Stiffness/Weight	Weight/length
Basic Mast	1.87E5	9.5E-3 lb/in
Stiffened Mast	1.89E5	16.3E-3 lb/in

Table 2. Performance Parameter Comparison

Recommendations for Further Study

Additional development work on the stiffener will undoubtedly lead to a decrease

in the weight of the stiffener while maintaining its ability to strengthen the section.

Furthermore, because the overall size of the mast is a function of the thickness of the shell, making this composite mast smaller had not been possible in the past. However, new ultrathin composite material has been developed, where t = 0.001 in rather than the t = 0.005 in used in this investigation. This could lead to masts of r=0.25, 0.50, 0.75, 1.0 in versus the r=1.25 of this mast.

This decrease in size will yield a corresponding decrease in weight and stowing size, which is illustrate in Table 3.

t	Number of plies	r	R, stowing radius	Weight/length
0.002	2	0.25 in	0.80	3.39E-4
0.004	4	0.50	1.60	1.357E-3
0.006	6	0.75	2.40	3.052E-3
0.008	8	1.00	3.20	5.426E-3

Table 3. Mast Characteristics Based on Material Thickness

In the future longer sections of mold could be cast using composite mold material which is in fact superior to using aluminum as a mold. This is because the composite mold material has a similar coefficient of thermal expansion to the CFRP that is molded on it. This method also avoids the machining costs incurred with an aluminum mold.

References

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