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Preliminary Analysis of the 30-m Ultraboom Flight Test Article

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Future NASA missions require long, ultra-lightweight booms to enable solar sails, large sunshields, and other gossamer-type spacecraft structures. The space experiment discussed in this paper will flight validate the non-traditional ultra lightweight rigidizable, inflatable, isogrid structure utilizing graphite shape memory polymer (GR/SMP) called UltraBoom™. The focus of this paper is the analysis of the 3-m ground test article. The primary objective of the mission is to show that a combination of ground testing and analysis can predict the on-orbit performance of an ultra lightweight boom that is scalable, predictable, and thermomechanically stable.

Nomenclature

E	=	Tow Young's Modulus
ρ	=	Tow Density
$\alpha_{Isogrid}$	=	Coefficient of thermal expansion
a	=	Axial node spacing
A	=	Total area of axial tows
b	=	Width of an elliptical tow
D	=	Diameter of circular tow
E_e	=	Effective Modulus
H	=	Circumferential axial tow spacing
I	=	Isoboom moment of inertia
k	=	Number of K-tows
L	=	Length of tube
n	=	Number of axial tows
r	=	Radius of boom
t	=	Thickness of elliptical tow
t_e	=	Effective thickness
ν	=	Effective Poisson's ratio
ρ_e	=	Effective Density
J_x	=	Nonstructural mass polar moment of inertia
L_x	=	Location of nonstructural mass
M_x	=	Mass of nonstructural mass
t_w	=	Thickness of "MLI"
ρ_w	=	Density of "MLI"

The opinions expressed herein are the authors' own and do not necessarily reflect those of NASA, Caltech or the Jet Propulsion Laboratory.

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I. Introduction

FUTURE NASA missions require long, ultra-lightweight booms to enable solar sails, large sunshields, and other gossamer-type spacecraft structures. The Ultra Lightweight Isogrid Boom Space Experiment shown in Figure 1 will flight validate the non-traditional ultra lightweight rigidizable, inflatable, isogrid structure utilizing graphite shape memory polymer (GR/SMP) called *UltraBoom*™. The focus of this paper will be on the analysis of the 3-m ground test article tested during the study phase of the ST-8 mission. The primary objective of the mission is to show that a combination of ground testing and analysis can predict the on-orbit performance of an ultra lightweight boom that is scalable, predictable, and thermomechanically stable.

The UltraBoom is a precision ultra lightweight deployable space structure that utilizes graphite shape memory composite and isogrid structural design to achieve high-deployed volume to packed volume ratio and high structural stiffness to mass ratio, respectively. The current design meets the requirements set by the New Millennium Program technical objectives. The use of graphite shape memory composite allows the flight system to be packed and deployed on the ground prior to launch. Preliminary packing and deployment test showed a packing factor less than 5, which is better than the required packing factor of less than 10. The transition temperature of the graphite shape memory polymer, which is critical for packing and deployment, can be tailored to meet on-orbit mission requirements. The utilization of isogrid tubular boom in structural design provides flexibility in optimizing the stiffness to mass ratio. The prototype has demonstrated a minimum bending stiffness of 2000 N-m^2 with a linear density of 70 g/m, which is better than the required 1000 N-m^2 bending stiffness and 75 g/m linear density.

A thorough analytical investigation complemented the testing done during the Study Phase. The focus of the analytical modeling during this phase of the project was two-fold: to fully replicate the test data from the 3-m engineering test article, and to predict the performance of the boom when later operated in both a "relevant environment" and the laboratory environment, during future testing. The combination of analysis and experiment, as shown in Figure 2, advances the Technology Readiness Level (TRL) of Ultraboom technology to prepare it for use on future NASA missions. The effects of air, temperature, and gravity on the dynamics of the boom were quantified by comparing the laboratory and environmental tests. For reliability, the boom's properties must be predictable from basic mechanical modeling.

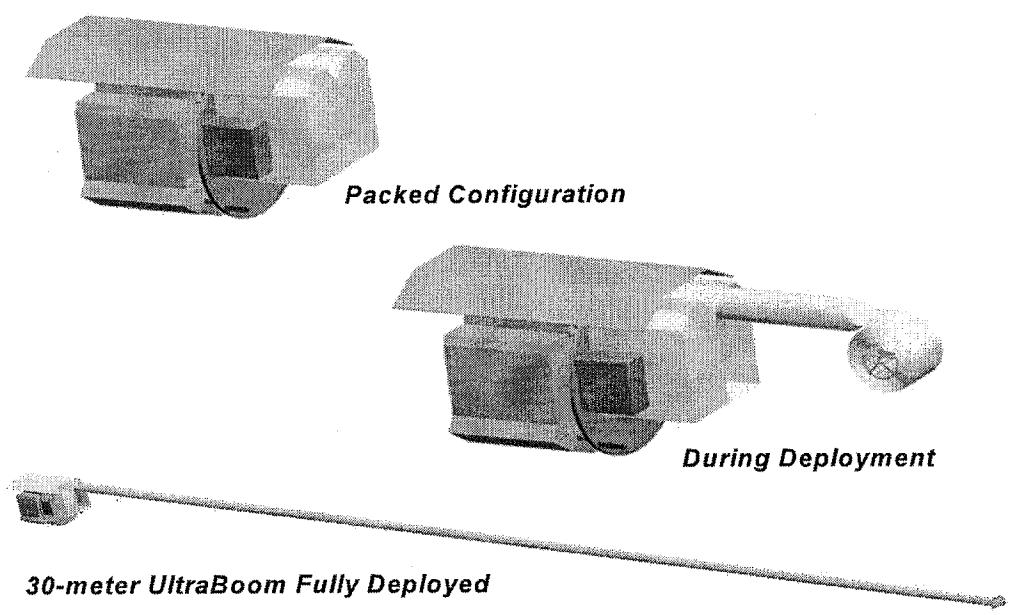

Figure 1. Ultra Lightweight Isogrid Boom Space Experiment Flight System.

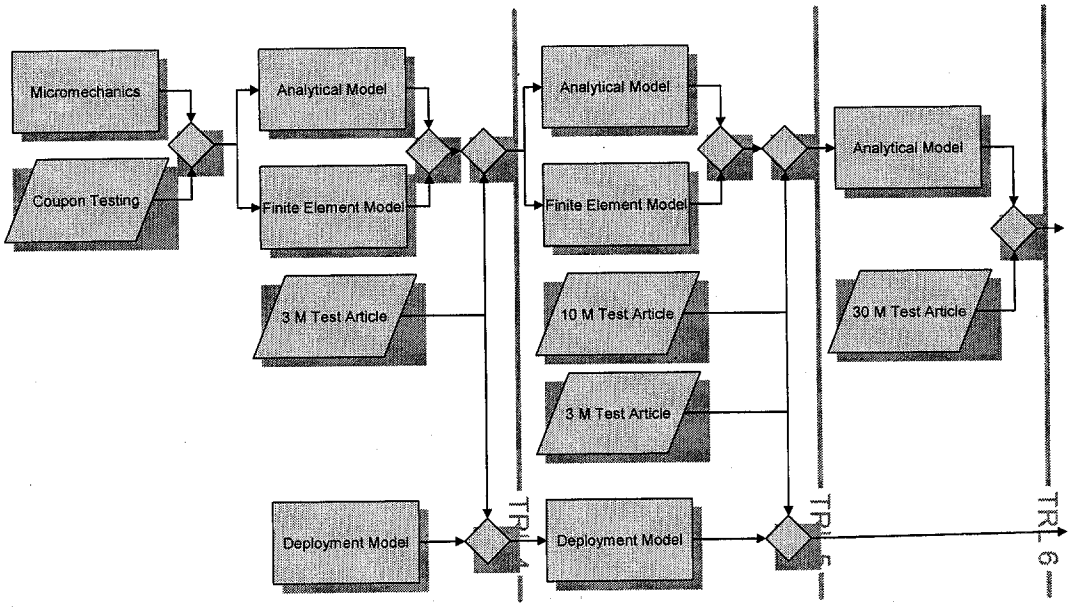

Figure 2. By combining analysis and experimentation, the Ultraboom's Technology Readiness Level can be readied for mission use.

II. Equivalent Isogrid Properties

Recent analysis using micromechanical models of the tow behavior, combined with knowledge of the Isogrid geometry, indicate that the thermomechanical performance of the booms can be analytically predicted. While tow test data will be used to determine accurate laboratory material properties, and serve as the input for the analytical models, experience shows that tow properties should be predictable using micromechanics.

The manufactured tows have a fiber volume fraction of approximately 50%. Using micromechanics, the modulus was estimated as 1.537×10^{11} Pa (22 Msi). This value was used along with the measured tow dimensions for all flight predictions. However the 3-m laboratory test boom shown in Figure 3 had significant bowing (Figure 4) of the axial tows which decreases their effective modulus. The effective modulus was estimated using Timoshenko's well-known knockdown factor for bowed axial members,

$$E_{eff} = \frac{E}{1 + 0.5(g / r_{tow})^2}$$

where g is the amount of bow. For the 3-m test article, measurements were made at over 90 locations to establish an average bow of 0.52-mm. With a tow radius of 0.42-mm, this leads to an effective modulus of 83.2 GPa (12 Msi).

For this effort, the primary analytical model approximates the complex mechanics of the isogrid column as a linear, cantilevered beam. Using the tow properties determined from analysis or testing, an equivalent cylindrical boom model can be derived.

The equivalent boom model will be derived by first determining the properties of an isogrid tow from micromechanics or testing. The modulus E and the geometry are then used to define an equivalent thin-walled cylindrical cross section in terms of axial modulus, mass, and weight. For UltraBoom tows, the cross section is elliptical. Denoting the major and

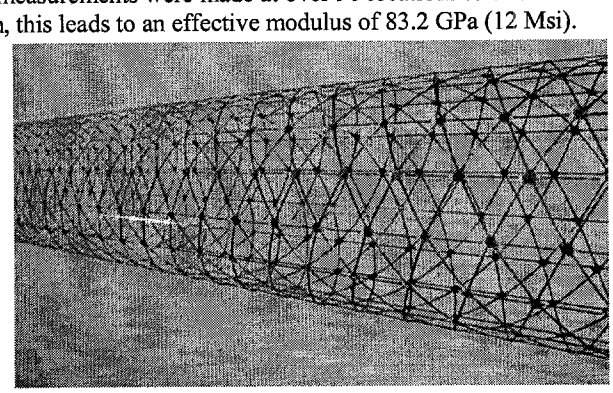

Figure 3. UltraBoom™ with Membranes Removed to Show Basic Composite Structure.

minor axes as b and t respectively, the area and moment of inertial of the tow are:

$$A_{tow} = \frac{\pi t b}{4} \qquad I_{tow} = \frac{\pi b t^3}{64}$$

Following the approach of Mikulas, we define the equivalent rectangle with the same moment of inertia and area having a thickness and width of

$$t_r = \sqrt{\frac{\pi}{12}}t \qquad b_r = \sqrt{\frac{3\pi}{4}}b$$

respectively. The effective wall thickness, modulus, and density become

$$E_e = E\frac{b}{h} \qquad t_e = t_r \qquad \rho_e = 3\frac{b_r}{h}\rho_{tow} + \rho_{mli}\frac{t_{mli}}{t_e}$$

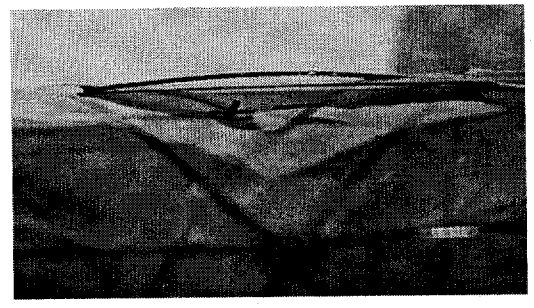

Figure 4. Bowing of the Axial Tows of the tested Ultraboom Column resulting from oversizing the boom bladder.

where the subscript "mli" refers is the non-loadbearing thermal protection system and inflation bladder (nonstructural mass), "h" is the axial tow spacing, and Poisson's ratio is 1/3. From these equivalent cylindrical properties, the performance of the boom can be predicted. Detailed nonlinear finite element models of the boom mechanics were used to verify the linear analysis. NASTRAN models of the boom were built treating the individual tows as beam elements of a cylindrical truss. Using these equivalent cylindrical boom properties, the response of the 3-m Ground Test article and 30-m flight test article can be predicted.

III. 3-m Ground Test Article

The configurations of the 3-m ground test articles are shown in Figure 5. Testing was conducted to characterize the structural mechanics and dynamics to assure the boom technology can meet 30-m flight length with scalability to 100-m, stiffness of 1000 N-m^2, and a mass of less than 0.075 kg/m. Gravity introduces tension on the boom when

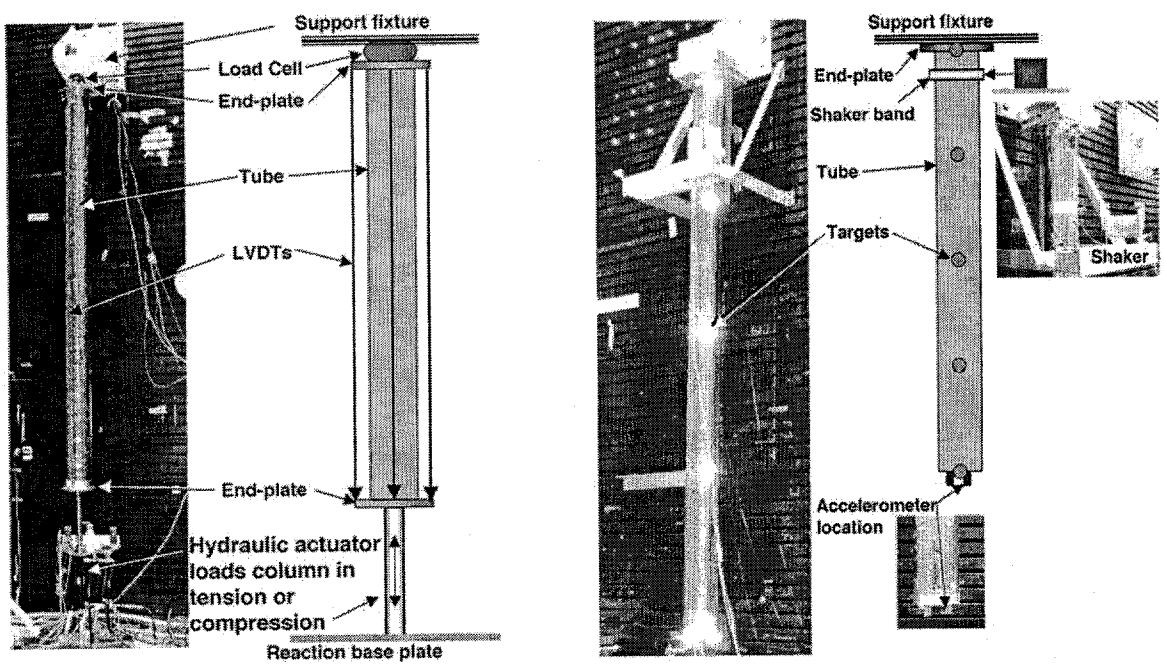

Figure 5. Static (left) and Dynamic (right) test set up of the 3-m Ground Test Article at LaRC.

supported in the vertical position, and this effect was investigated using more detailed analytical models. No significant effect was found. In addition, no model exists for boom damping, so empirical curve fits must be used.

Two 3-m booms subjected to packaging and deployment were provided to Langley by ILC for testing to verify column structural characteristics including verifying the column's bending stiffness (EI). The first column (z-folded packaging) suffered a premature failure under loading due to a severe fold condition as described in the previous section. The test data from those tests are not presented because the results are in question due to the failure. The second column was tested successfully for axial tension, cantilever bending, and cantilever dynamics. Axial compression was not completed since the column was damaged by laboratory handling prior to compression testing. The static and dynamics tests were performed in Langley's Inflatable/Deployable static test cell and 16-m vacuum chamber. Results are tabulated in Table 1. More details can be found in the companion paper[5].

Analysis was performed on the boom for each of these tests. Results are presented in the proceeding subsections. Note that NASTRAN numerical results were also performed on similar Isogrid booms, to validate this analytical approach. These models will not be included herein. Numerical values for all quantities used in the analysis are denoted in the Appendix.

Table 1. Average Structural Characterization Ground Test Results

	EA N	EI N-m^2	Frequency-Hz w/o mass w/ mass	Frequency-Hz w/o mass w/ mass	Frequency-Hz w/o mass w/ mass
STATIC					
Tension (0-35 N)	4.02E+05				
Tension (52-98 N)	4.74E+05				
Bending on-fold		1122			
Bending off-fold		1117			
DYNAMICS					
Ambient Lab on fold		1385	2.047 1.844	14.95 14.88	18.19 18.09
Ambient Lab off fold		1429	2.078 1.875	15.09 15.08	18.39 18.09
Ambient in Chamber off fold		1138	1.859	15.45	17.36
Vacuum in Chamber off fold		1237	1.938	16.48	20.94

A. Axial Response

Given a tube with the equivalent wall thickness and modulus, the axial response of the boom can be calculated as

$$\delta = \frac{PL}{E_e 2\pi r t_e}$$

For the analysis at hand, this relationship allows predictions of the tow modulus to be made from measurements of the tow geometry, force applied and deflections. These results were used to determine the EA values in Table 1. The analytical prediction was $3.4\text{x}10^5$ N. Given the bowing of the tube discussed in Section III, a reasonable approximation to the test article response was found.

A second quantity of interest is the tube buckling behavior. Three different buckling mechanisms can initiate compressive failure of the boom: global Euler buckling of the tube, local Euler buckling of a rib, or crippling of the surface. Since the Ultraboom was effectively isotropic walls, standard buckling formulae can be used. Due to damage to the boom during handling these predictions could not be empirically validated.

Table 3. Buckling predictions for 3-m Test Article

Global Euler	Local Euler	Crippling		
$P_{ge} := \frac{\pi^3 r^3 \cdot E_e \cdot t_e}{L^2}$	$P_{le} := \frac{n\pi^2 I_{tow} \cdot E}{a^2}$	$\phi := \frac{-1}{16} \cdot \sqrt{\frac{r}{t_e}}$	$\gamma := 1 - 0.901\left(1 - e^{\phi}\right)$	$P_{cr} := \frac{2 \cdot \pi \cdot \gamma \cdot E_e \cdot t_e^2}{\sqrt{3 \cdot \left(1 - \nu_e^2\right)}}$
1530 N	444 N		50.1 N	

B. Cantilever Bending

The second test condition was the cantilever bending test. Using the effective modulus and moment of intertia, the deflection due to a nomal tip force, P_e, can be calculated as

$$w := \frac{P_e \cdot L^3}{3E_e \cdot I_e}$$

For the test article a value of 1.13 in/lbf was calculated. However as the boom deflects, the tip mass applies a moment to the boom as well. Solution of the problem was carried out using results from Roark[6]. A difference of less than 0.5% was found. Thus the formula above was used to determine the effective modulus from the testing. Results in Table 2 show reasonable agreement with the predicted modulus of the tow, 1394 N-m^2.

C. Cantilever Vibration

The final analysis area was the cantilever vibration of the boom. If the boom is assumed to be a cantilever beam with tip mass, the bending mode is estimated using:

$$\omega_{bending} := \frac{1}{2 \cdot \pi} \cdot \sqrt{\frac{3 \cdot E_e \cdot I_e}{\left[0.24\left(2 \cdot \pi \cdot r \cdot t_e \cdot \rho_e\right) \cdot L^4\right] + Mx_1 \cdot L^3}}$$

which results in a predicted first mode of 2.031 Hz. However, the tip mass has a significant inertia which is not accounted for in this formula. Thus a Raleigh-Ritz analysis was undertaken to determine its effect. Two approaches were used: using clamped-free mode shapes for admissible functions[4] and using a combination of clamped-pin and clamped-slider mode shapes[4] as quasi-comparison functions[3]. Often quicker convergence can be obtained with quasi-comparison functions. For the test configuration, convergence was better with the clamped free functions due to the small effect the tip inertia has on the boom. In fact, the predicted frequency with inertia agreed to three decimal places to the effect predicted above. Hence the results were used to calculate the experimental EI values in Table 2. Agreement in the ambient conditions is remarkable. In Vacuum much lower values were found.

IV. Conclusion

Simple analysis methods have been shown effective for analysis of the Ultraboom 3-m ground test article. Correction of the effective modulus predicted by micromechanics to account for quilting (or bowing) of the tows allowed for predictions of tube performance. More detailed comparisons are not to be expected given the manufacturing defect in the test article. Future comparisons (on improved specimens) should be undertaken to further validate these analysis techniques.

Appendix A. Numerical Values Used in the analysis

E	=	153.7 GPa	r	=	90.17 mm
ρ	=	1470 kg/m3	t	=	0.81 mm
$\alpha_{Isogrid}$	=	5×10^{-7}	J_x	=	Nonstructural mass polar moment of inertia
a	=	65 mm	L_x	=	3 m
A	=	0.63 mm^2	M_x	=	0.81 kg
b	=	0.99 mm	t_w	=	0.127 mm
h	=	57 mm	ρ_w	=	2.34×10^3 kg/m^3
k	=	24			
L	=	3 m			
n	=	10			

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