JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 39, No. 5, September–October 2002

Self-Rigidizable Space Inflatable Boom

Michael Lou* and Houfei Fang†
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109-8099
and
Lih-Min Hsia‡
California State University at Los Angeles, Los Angeles, California 90032

Development of inflatable structures for space applications has progressed rapidly in the past few years. Noticeable advances have been achieved in several key technology areas, such as system concepts, analysis tools, material selection and characterization, and inflation deployment control. However, many challenges remain to be overcome before the inflatable structures can be actually incorporated into space flight systems. One of these challenges is the development of suitable in-space rigidization methods, and many researchers in the space inflatables community are currently working toward this goal. The concept and development of a new type of space inflatable/self-rigidizable structures, called the spring-tape-reinforced aluminum laminate booms is described. Analysis and test results related to buckling capability, effects of stowage, modal characteristics, and dynamic responses of spring-tape-reinforced aluminum laminate booms are presented and discussed.

Nomenclature

E	=	modulus of elasticity
I	=	moment of inertia
L	=	length
M_{beam}	=	mass of the beam
M_{mass}	=	lumped mass

Introduction

SPACE inflatable structures technology is one of the emerging technologies that can potentially revolutionize the design of large space structural systems. There is great interest in near-term space applications of inflatable structures and in the possibility of enabling several breakthrough missions in the more distant future. In fact, many future NASA missions must use space inflatable structures to meet their launch volume and mass goals. This is especially true for missions that will employ flight hardware components and systems of relatively large in-orbit configurations. These include radar antennas, solar arrays, sunshades, solar concentrators, and telescope reflectors. At present, these hardware components and systems commonly use mechanically deployed structures to meet their launch volume constraints. Compared to mechanically deployed structures, space inflatable structures have many distinct advantages, such as much lighter weight, higher packaging efficiency, lower life-cycle costs, simpler design with fewer parts, and higher deployment reliability. In 1997, NASA embarked on a technology development program to advance the inflatable technology and make it available to 21st-century space missions. Since that time, important technological advancements in space inflatable structures, particularly in the areas of controlled deployment, material characterization, and analysis and simulation tools, have been achieved. However, space rigidization of inflatable structures continue to be a major technical challenge and must be adequately addressed before space inflatables can be actually applied to future missions.

For space applications, the desired features for space rigidization include 1) being lightweight and easily adaptive to high-efficiency packaging; 2) being compatible with existing controlled deployment schemes; 3) requiring no, or very low, space power or curing agent; 4) producing no, or very low, in-orbit outgassing or contamination; 5) having predictable postrigidization configuration accuracy; 6) being adaptive to standard ground handling procedures and schedules (e.g., if a curing agent is needed, it must have a long enough shelf life in ambience to accommodate flight system integration, launch preparation, and possible launch delays); and 7) having a reversible rigidization process such that the rigidization process and postrigidization configuration of the flight unit can be checked out and then repackaged for launch. At this time, many space rigidization methods are being studied and developed. These methods include stretched aluminum laminate, hydro-gel rigidization, open-cell foam, and various polyester resins that are curable by space cold, heat, UV, or infrared (IR). Of all known space rigidization methods, only the one that uses stretched aluminum laminate is judged to possess all of the aforementioned desired features. Additionally, the space rigidization method of using stretched aluminum laminates also has two more important advantages: 1) This method uses the rigidization pressure from the inflation system that is already needed for deployment. 2) Both of the component materials, aluminum and Kapton®, of a typical aluminum laminate have long heritages of space applications. However, the stretched aluminum laminate rigidization method has two major shortcomings, low load-carrying capability and local failure modes. Because, due mainly to packaging constraints, only a very thin (no more than 0.1-mm) soft aluminum layer can be incorporated in the laminate, the inflatable/rigidizable booms made of stretched aluminum laminates buckle under very low axial loading due to local crippling. Local crippling is a failure mode induced primarily by surface and/or embedded imperfections in the boom walls that can vary from one boom to another, even though they are of the same design. Before the stretched aluminum laminate method can become the preferred space rigidization method for inflatable structures, the load-carrying capability must be improved and the local failure mode be eliminated.

Spring-Tape-Reinforced Aluminum Laminate Booms

During the past several years, the Jet Propulsion Laboratory (JPL), California Institute of Technology, has been continuously engaged in performing research related to space inflatable structures, including long space-rigidizable booms made of stretched aluminum laminates. It was during such an effort that the concept of a new kind of self-rigidizable space inflatable structure, identified as spring-tape-reinforced aluminum laminate booms, was invented.[1]

Received 26 June 2001; revision received 4 February 2002; accepted for publication 18 April 2002.

*Principal Engineer, Mechanical Systems Engineering and Research Division. Associate Fellow AIAA.
†Senior Engineer, Mechanical Systems Engineering and Research Division. Member AIAA.
‡Professor, Department of Mechanical Engineering. Member AIAA.

A typical spring-tape-reinforced aluminum laminate boom consists of a tube that is formed with aluminum laminate sheet and seamed by Kapton tape and two end caps. Figure 1 shows the cross section of the aluminum laminate tube. To keep the boom straight after the inflation deployment, a dummy seam is placed on the opposite location (180 deg apart) of the real seam. Four spring tapes are attached to the inside wall of the tube in the axial direction. At this time, commercially available stainless steel measuring tapes, commonly known as carpenter tapes, are used. With a wall thickness of about 0.1 mm, a spring-tape-reinforced aluminum laminate boom can be easily flattened, rolled up (or folded up), and deployed by a relatively low inflation pressure. The buckling capability of a spring-tape-reinforced aluminum laminate boom is significantly improved by the high modulus of elasticity and curved cross-sectional profile of the spring tapes. The length of a spring-tape-reinforced aluminum laminate boom can consequently be significantly increased. Note that spring tapes are very effective in resisting inward buckling, and the aluminum laminate wall is very stable in resisting outward buckling. Therefore, these two components effectively complement each other in resisting local crippling of the boom. In addition, unlike the nonreinforced aluminum laminate booms, a spring-tape-reinforced aluminum laminate boom relies on the reinforcing tapes, not prestrain induced by high internal pressure, to attain its postdeployment stiffness. The required inflation pressure for a spring-tape-reinforced aluminum laminate boom is relatively low (usually less than 5 psi) and that, in turn, reduces the load requirements for its seam.

Buckling Test and Analysis

The axial buckling capability of a spring-tape-reinforced aluminum laminate boom has been investigated in a previously reported research effort.[2] A brief summary is given here for the sake of completeness.

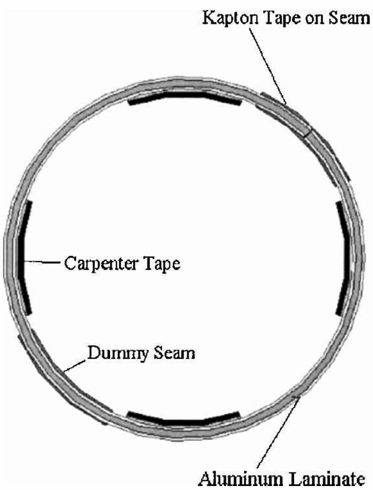

Fig. 1 Cross section of a typical spring-tape-reinforced aluminum laminate boom.

Seven spring-tape-reinforced aluminum laminate booms samples were designed, fabricated, and buckling tested. These booms were 7.62 cm in diameter and 5 m in length. The boom walls were made of an aluminum laminate that consists of a 0.0762-mm-thick 1145-O aluminum sheet with 0.0254-mm-thick polyester films bonded on both sides. The reinforcement tapes were steel carpenter measuring tapes (commercial-grade tapes). The nominal weight of each boom specimen (excluding the end caps) was slightly less than 0.9 kg. Table 1 shows the results from buckling tests conducted on these sample booms with pin–pin end conditions.

Because the seven sample booms were numbered in accordance with the order in which they were fabricated, the differences in the buckling loads were mainly due to improvements in boom fabrication and assembly, including better straightness and adhesive tapes. As the fabrication/assembly of booms improved from specimen 1 to 7, the corresponding Euler buckling load of the boom was asymptotically approaching the theoretical value of 75.2 kg as predicted by analysis. Figure 2 shows the finite element model and the buckling analysis result of the spring-tape-reinforced aluminum laminate boom. This model is composed of 4802 nodes. Aluminum laminate sheets were simulated by 2364 plate elements. Carpenter tapes with aluminum laminate sheets were simulated by 2364 laminate elements. End caps were simulated by 96 elements. Because this model is used to analyze the characteristic of the boom after it is deployed and rigidized, there is no internal pressure involved in this model. From Fig. 2, one can observe that the failure mode is an Euler buckle.

The buckling load predicted by the finite element analysis is 75.2 kg (167 lb), compared to the best first-time buckling test result of 74.3 kg (165.2 lb). The percentage difference between the analytical prediction and test result is

$$\xi = 1 - \frac{\text{test result}}{\text{analysis result}} = 1 - \frac{165.2}{167} = 1\% \tag{1}$$

One question that still needs to be answered is what percentage of buckling load increase is induced by the addition of reinforcement. Without the reinforcement, the buckling load of a thin-walled boom is very unpredictable. However, we found some buckling test results

Table 1 First-time buckling test results

Boom number	Buckling load, kg	Buckling type
1	53.1	Euler
2	51.3	Euler
3	60.8	Euler
4	67.3	Euler
5	60.5	Euler
6	61.4	Euler
7	74.3	Euler

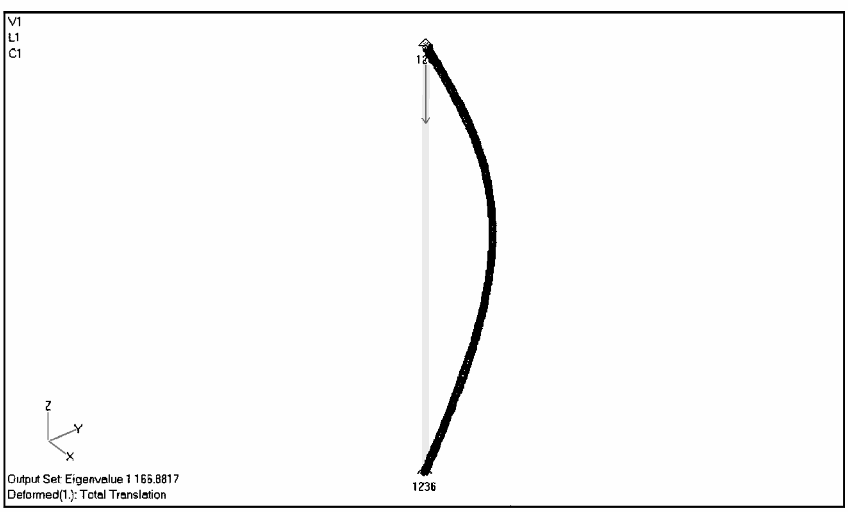

Fig. 2 Finite element model and buckling analysis of a spring-tape-reinforced aluminum laminate boom.

Table 2 Buckling test results of unreinforced booms

Boom number	Buckling load, kg
1	11.6
2	13.7
3	15.1

Table 3 Comparisons between reinforced and unreinforced aluminum laminate booms

Parameter	Reinforced	Unreinforced
Average buckling loads, kg	61.2	13.5
Length, m	5	0.46
Aluminum thickness, mm	0.076	0.076
Aluminum diameter, mm	76.3	102
Boundary condition	Pin–pin	Fixed–fixed

of an unreinforced aluminum laminate boom in the literature[3] that can be used for comparison with the buckling capability of a reinforced aluminum laminate boom. The unreinforced boom was made of 0.076-mm-thick aluminum shell, the length was only 0.46 m, and the diameter was 102 mm. The boundary condition was fixed–fixed. Table 2 gives the buckling test results of unreinforced aluminum laminate booms. Table 3 gives the comparisons between reinforced and unreinforced aluminum laminate booms. From Table 3, one can see that the buckling capability of the reinforced boom increased to 4.5 times that of the unreinforced boom, whereas the length increased to 10.9 times, and the diameter decreased to 0.75 times, that of the unreinforced boom.

Stowage and Redeployment Tests

To study the packaging efficiency and stowage effect of spring tape-reinforced aluminum laminate booms, a series of stowage and redeployment test were performed on booms 3 and 4. For stowage, the booms were flattened and rolled up on a mandrel with a diameter of 16.5 or 30.5 cm before inflation deployment. Figure 3 shows the process of a typical inflation deployment. The deployment control technique using Velcro strips was employed.

Test Description

A description of the test follows:

1) Before being tested for the first time, both booms 3 and 4 were inflated for 5 min at 34.5 kPa before testing. The buckling loads are 61.3 kg for boom 3 and 67.9 kg for boom 4.

2) After the buckling tests, both booms were flattened and tightly rolled up on mandrels. A 16.5-cm-diam mandrel was used for boom 3, and a 30.5-cm-diam mandrel was used for boom 4.

3) After five days in storage, boom 3 was first unrolled. After the boom was unrolled, we found wrinkles along the edge in some areas. Figure 4 shows a closeup of these wrinkles. These wrinkles may have been caused by the boom not being perfectly straight to begin with, and the problem may have been further compounded by the imperfect process of rolling up.

There are two terminologies that need to be defined here. When the boom is rolled up, one side of the boom faces the mandrel and is compressed (Fig. 5). This surface will be designated as the compressed surface and the opposite surface as the stretched surface.

After the boom was inflated at 34.5 kPa for 5 min, these edge wrinkles almost disappeared. At this time, some bigger wrinkles appeared on the stretched surface. Figure 6 shows these wrinkles. One explanation for these wrinkles is that the stretched surface was elongated during the rollup. Inflation tends to straighten the boom and induce these wrinkles. These wrinkles could be one of the causes of the buckling load decay.

After inflation, boom 3 was tested twice. The first test result was 41.7 kg, and the second test result was 40.5 kg. The boom was inflated at 34.5 kPa for 5 min between two tests.

After the two tests, we kept the boom inflated at 34.5 kPa for 2.25 h. We noticed that 30–40% of the wrinkles were removed. We repeated the buckling test again, and the result was 42.6 kg. Keeping the boom pressurized for some time apparently helped to remove wrinkles and to straighten the boom. As a result, the buckling load increased.

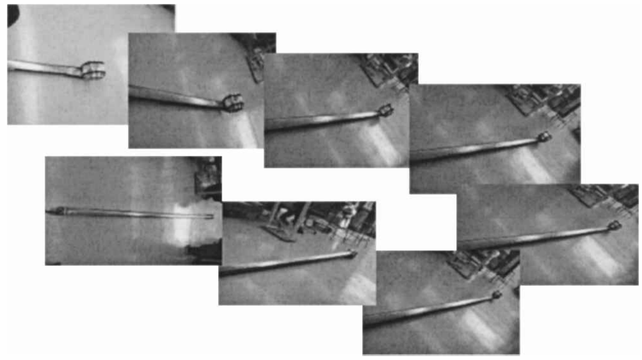

Fig. 3 Inflation deployment of a 5-m spring-tape-reinforced boom.

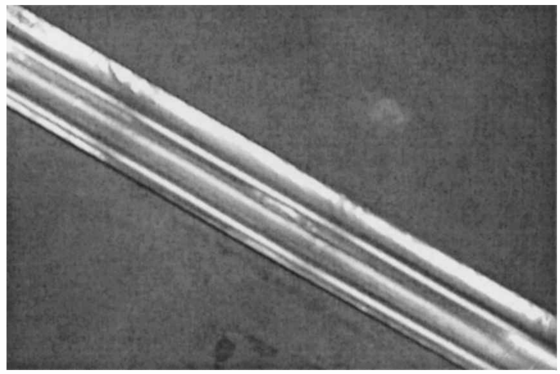

Fig. 4 Wrinkles on boom 3.

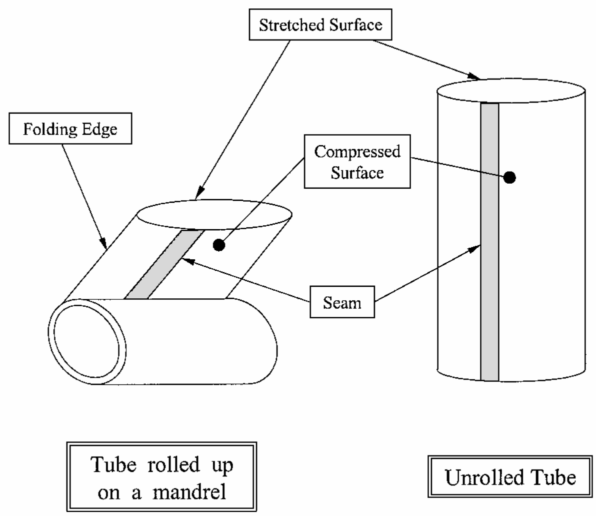

Fig. 5 Terminologies.

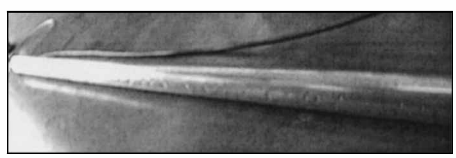

Fig. 6 Wrinkles on boom 3, after inflation.

Boom 4 was also unrolled and tested on the same day. Figure 7 shows boom 4 after inflation. One can also see bigger wrinkles on the stretched surface of the boom, but they were not as severe as on boom 3.

Two buckling tests were conducted. Buckling loads of 47.9 and 46.1 kg were recorded, respectively.

Test Results and Discussion

The poststowage buckling test results are summarized in Table 4. In Table 4 first-time load refers to the first-time buckling load

Table 4 Buckling test results of redeployed booms

Boom number	Test number	Buckling load, kg	Inflation time, min
3	1	61.3 (first time)	5
3	2	41.7 (rolled up)	5
3	3	40.5 (rolled up)	5
3	4	42.6 (rolled up)	135
4	5	67.9 (first time)	5
4	6	47.9 (rolled up)	5
4	7	46.1 (rolled up)	5

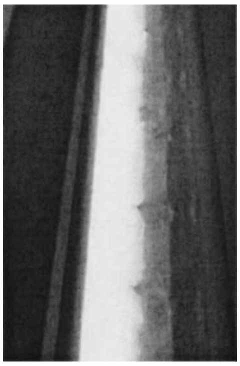

Fig. 7 Boom 4, after inflation.

recorded before the booms are rolled up. Inflation time refers to the time that the booms were left pressurized.

We observed that the buckling load decreased each time we repeated the test on the same boom, except for test 4 on boom 3, when the boom was kept pressurized for an extended period of time.

When tests 2 and 3 are compared for boom 3, note that buckling load was reduced by 1.2 kg. Under the assumption that the same thing would have happened if the boom were never rolled, the percent reduction of the load on boom 3 due to roll up (on a 16.5-cm mandrel) is

$$\frac{61.3 - 41.7 - 1.2}{61.3 - 1.2} = 31\%$$

Applying the same reasoning for boom 4, we find that the percent reduction of the load on boom 4 due to roll up (on a 30.5-cm mandrel) is

$$\frac{67.9 - 47.9 - 1.8}{67.9 - 1.8} = 27\%$$

Comparing tests 3 and 4, we find that the percent increase of the load due to continuous pressurization of the boom is

$$\frac{42.6 - 40.5 + 1.2}{40.5 - 1.2} = 8\%$$

From these test data, we can make the following observations:

1) After a boom is rolled up for stowage and later unrolled, its resistance to buckling is reduced. During the rollup, the aluminum skin on the outside of the boom is stretched, whereas the skin on the inside of the boom is compressed. After the boom is unrolled and inflated, the uniform internal pressure causes the outside surface of the boom to wrinkle. This may be the primary reason for the decrease in buckling resistance.

2) The wrinkles along the edges of the flattened boom are more easily removed by inflation pressure than the wrinkles on the surfaces.

3) The diameter of the mandrel appears, at least in the range of 16.5–30.5 cm, not to affect the buckling load of the redeployed boom significantly.

4) Keeping the redeployed boom under inflation pressure noticeably improved its buckling capability.

Dynamic Test and Analysis

Dynamic characteristics of a 5-m spring-tape-reinforced aluminum laminate boom have been analyzed and test verified. The boom also has a 0.0762-mm aluminum laminate wall and is 7.62 cm in diameter. The boundary condition of the boom is fixed (top)–free (bottom).

Table 5 First three global frequencies obtained from test and analysis

First global frequency	Second global frequency	Third global frequency
	Test	
1.46 Hz	11.30 Hz	34.31 Hz
	Analysis	
1.47 Hz	11.54 Hz	34.21 Hz
	Differences	
0.7%	1.3%	0.3%

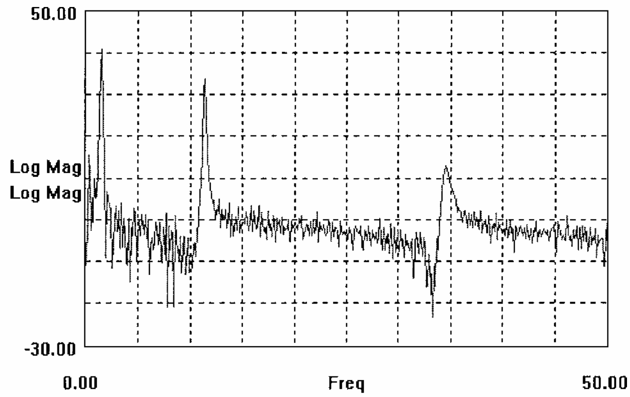

Fig. 8 Typical frequency response spectrum.

Dynamic Test Results

Figure 8 gives a typical frequency response spectrum obtained from dynamic testing of the spring-tape-reinforced aluminum laminate boom. The input excitation and output response are both measured and recorded at the lower (free) end of the boom. The first three resonant frequencies are obtained as 1.46, 11.30, and 34.31 Hz.

Dynamic Analysis

A high-fidelity finite element model has also been assembled for the boom sample used in the dynamic testing. This model is composed of 4802 nodes. Aluminum laminate sheets were simulated by 2364 plate elements. Carpenter tapes with aluminum laminate sheets were simulated by 2364 laminate elements. End caps were simulated by 96 elements. Figure 9 shows the finite element model used for dynamic analysis of the spring-tape-reinforced aluminum laminate boom.

The finite element analysis predicted the first three global frequencies at 1.47, 11.54, and 34.21 Hz. Table 5 compares the analytical predictions with the results of actual dynamics testing. The maximum difference is only 1.3% for the second mode frequency.

Figures 10–12 show the first three global modes. This finite element model produced 11 modes between 0 and 34.5 Hz. Because of symmetry, mode 1 is identical to the mode 2, which is the first global mode. Mode 3 is identical to the mode 4, which is the second global mode. The 11th mode is identical to the 12th mode, which is the third global mode. There are six local modes between the second global mode and the third global mode. Mode shapes of these local modes are represented by Figs. 13–18.

Simulation of a Spring-Tape-Reinforced Aluminum Laminate Boom

In an attempt to reduce modeling and computational efforts, the feasibility of modeling a spring-tape-reinforced aluminum laminate boom by the use of beam elements, instead of laminate and solid elements, was investigated. This effort was based on the following basic data of a spring-tape-reinforced aluminum laminate boom: The weight of the boom is 0.9 kg, the weight of the end cap is

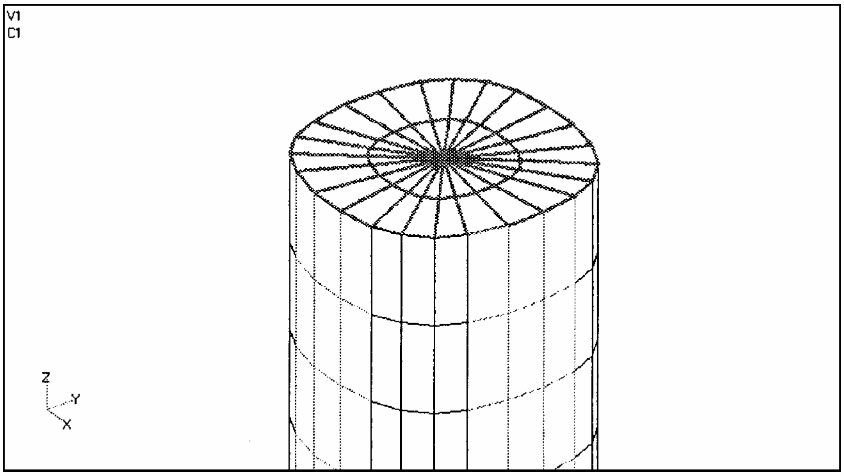

Fig. 9 Dynamic analysis finite element model.

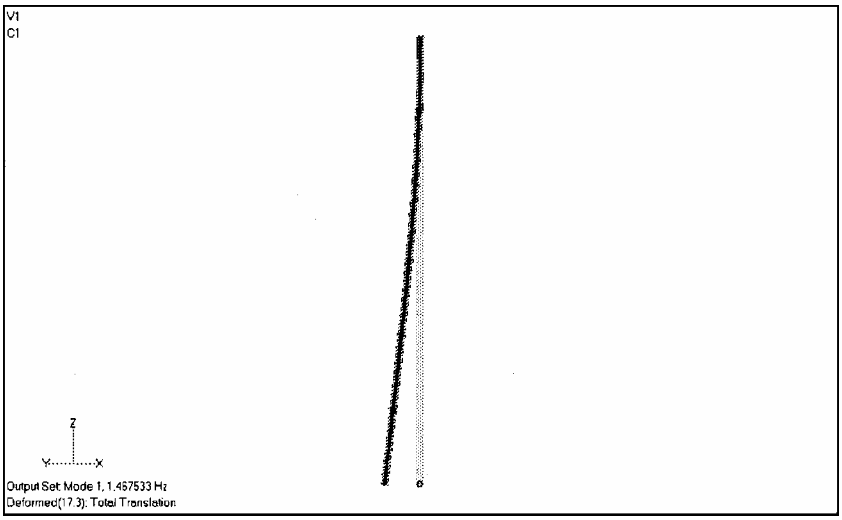

Fig. 10 First global mode shape.

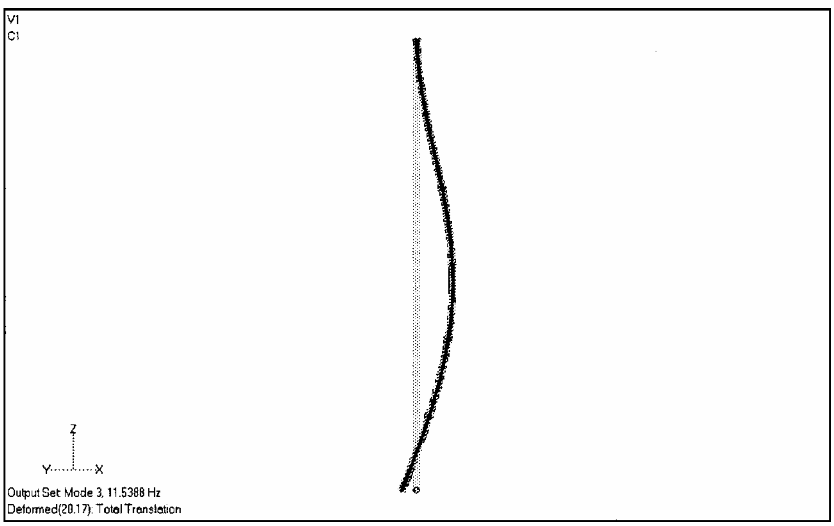

Fig. 11 Second global mode shape.

0.366 kg, and the length of the boom is 5 m. The first frequency, as predicted by finite element analysis, is 1.4675 Hz.

The fundamental frequency of a slender beam with concentrated mass (end cap) at one end and the other end fixed can be calculated[4] by the equation

$$f_1 = \frac{1}{2}\sqrt{\frac{3EI}{L^3(M_{\text{beam}} + 0.24M_{\text{mass}})}} \tag{2}$$

Based on the given data, the value of EI (i.e., the product of Young's modulus and moment of inertia) of the beam is calculated to be $2061\ \text{N}\cdot\text{m}^2$ ($718{,}102\ \text{lb}\cdot\text{in.}^2$).

A new finite element model was created. This model is composed of beam elements with a length of 5 m and an EI of $2061\ \text{N}\cdot\text{m}^2$. At the bottom of the beam, there is a 0.366-kg lumped mass that is used to represent the end cap. The top of the beam is fixed, and the bottom of the beam is free. The first three natural frequencies

Table 6 Frequencies of laminate element model and beam element model

Element type	First global frequency	Second global frequency	Third global frequency
Laminate	1.47 Hz	11.54 Hz	34.21 Hz
Beam	1.46 Hz	11.62 Hz	35.26 Hz
Difference	0.7%	0.7%	3.1%

and mode shapes are calculated. Table 6 gives the first three global frequencies calculated by the use of laminate elements and beam elements.

The first and second natural frequencies of these two models are very close. The third natural frequencies of these two models are different by more than 3%. One reason is that, during the first and second modes, the cross section of the laminate element model does not change noticeably (Figs. 19 and 20). However, for mode 3, one

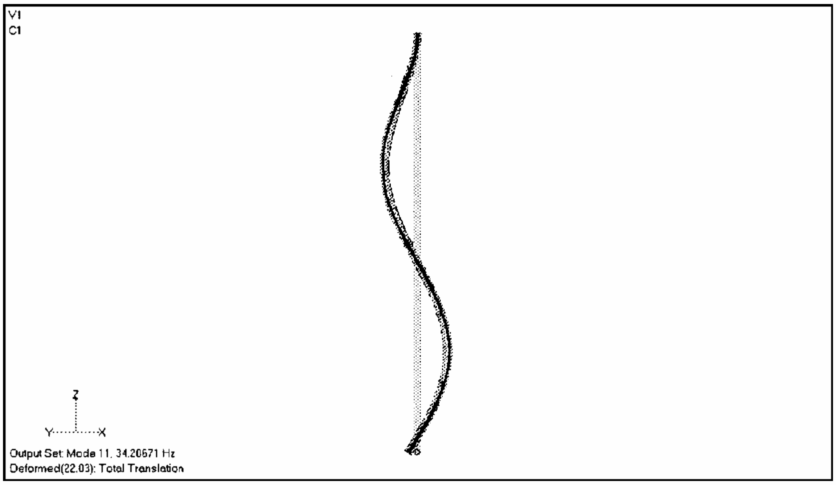

Fig. 12 Third global mode shape.

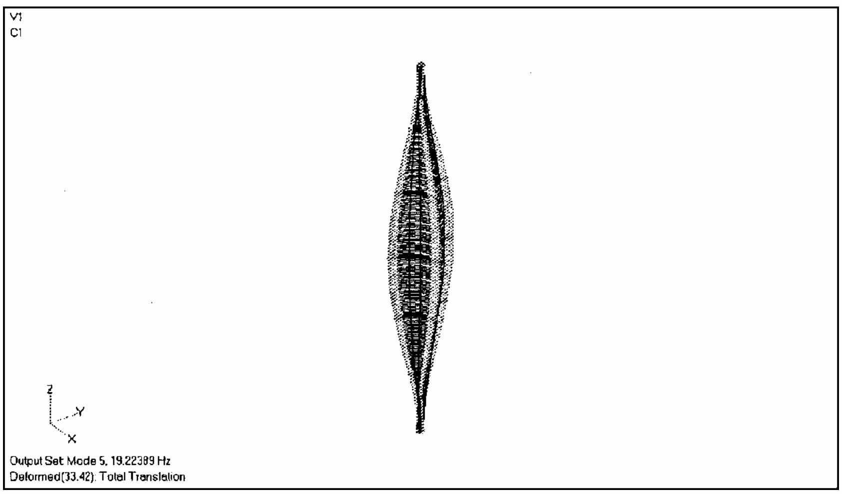

Fig. 13 Fifth mode.

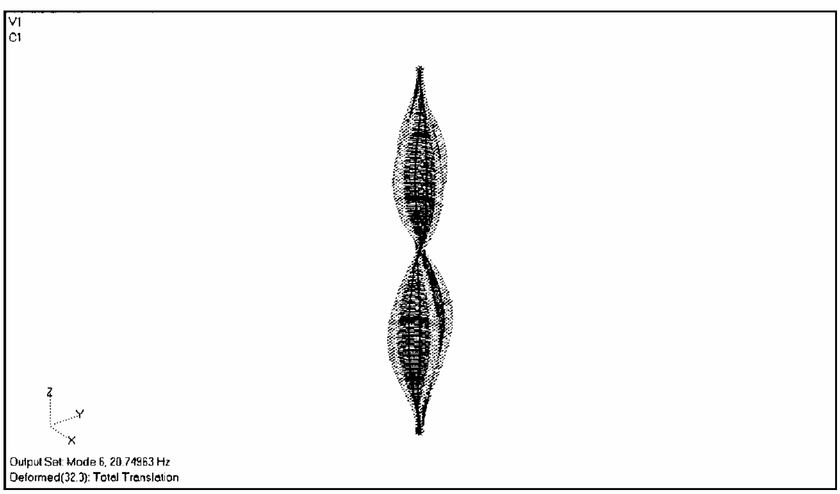

Fig. 14 Sixth mode.

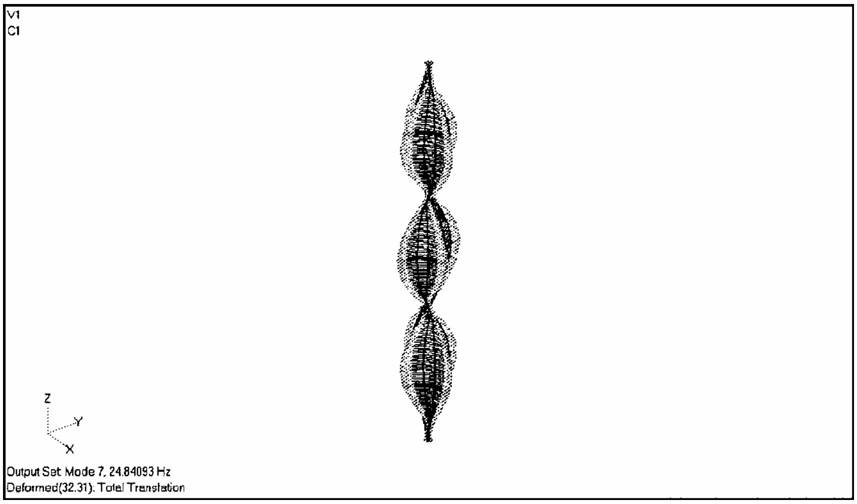

Fig. 15 Seventh mode.

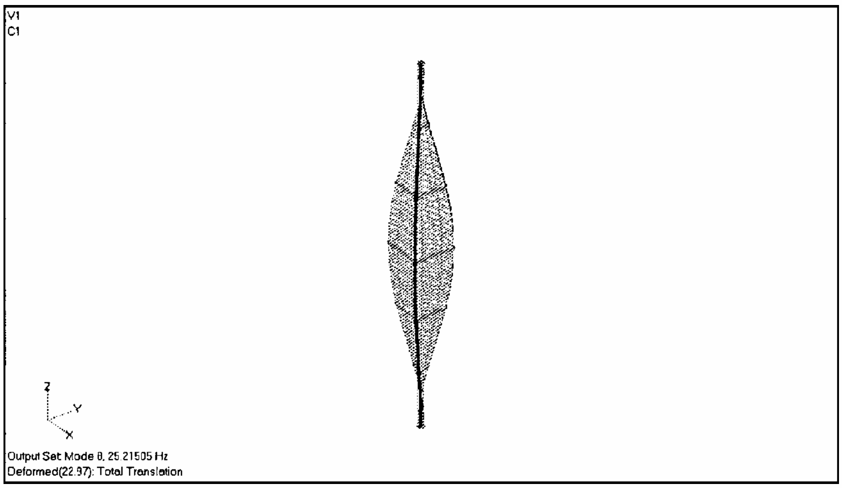

Fig. 16 Eighth mode.

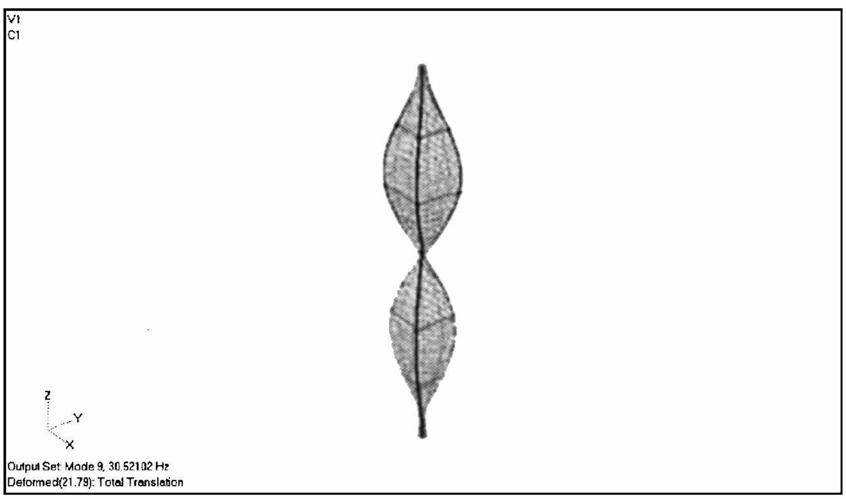

Fig. 17 Ninth mode.

can see from Fig. 21 that the cross section of the boom has obviously changed from a circular shape. Therefore, the beam element model should not be used to calculate high-frequency characteristics.

Extension of Boom Length and Capability

From an assessment of the load-carrying requirements of potential space applications of spring-tape-reinforced aluminum laminate booms, the maximum boom length is estimated to be about 10 m. This estimate is based on the assumption that the boom is made of commercially available carpenter tapes, which put an arbitrary limit on the boom diameter of 7.62 cm.

To extend this maximum useful boom length, we are considering the concept of clustered booms. A clustered boom is formed by structurally joining three, four, or more individual spring-tape-reinforced aluminum laminate booms together. A preliminary analytical study has been conducted, which showed that a clustered boom yields significantly higher buckling strength than a single spring-tape-reinforced aluminum laminate boom. It is believed that

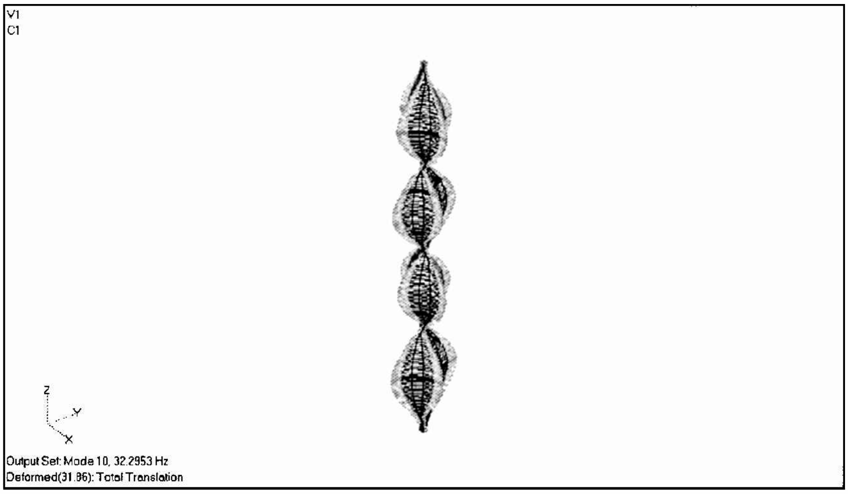

Fig. 18 Mode 10.

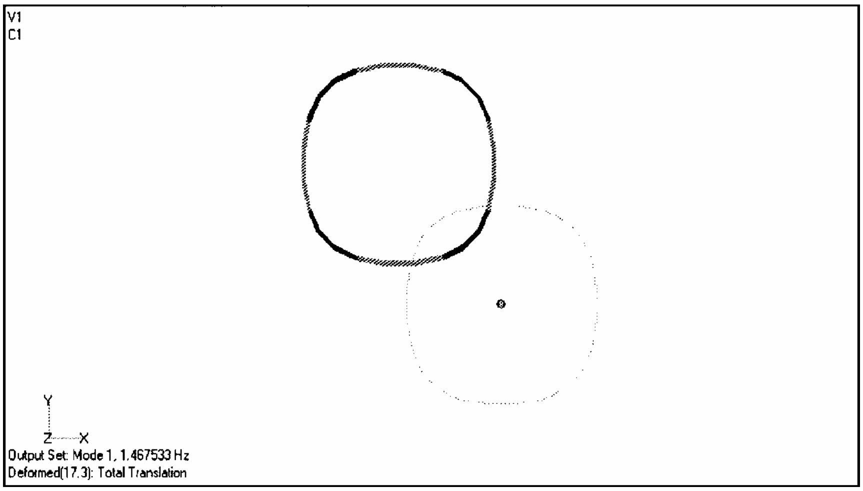

Fig. 19 Deformed cross section of the first mode.

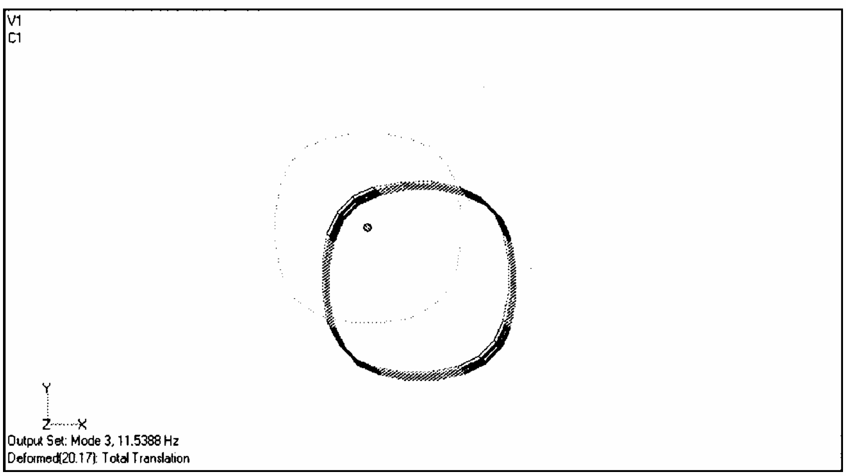

Fig. 20 Deformed cross section of the second mode.

the clustered booms can reach a length of over 50 m. Inflation deployment of clustered booms is also inherently stable, and the need for adding deployment control devices may be eliminated. However, there remain many practical issues for the design and fabrication of clustered booms that need to be resolved. These include the joining of booms, packaging schemes, and deployment mechanisms.

Other design improvements for enhancing structural integrity and the load-carrying capability of spring-tape-reinforced aluminum laminate booms that are currently being considered are 1) the addition of circumferential reinforcements, 2) improved laminate materials, 3) larger boom diameters, and 4) longitudinal reinforcing tapes made of fiberglass/epoxy composite, graphite/epoxy composite, titanium, or other high-toughness materials. In addition, a new generation of modeling and analysis tools is also being developed specifically for space inflatable and rigidizable structures, including spring-tape-reinforced aluminum laminate booms. For example, see Ref. 5.

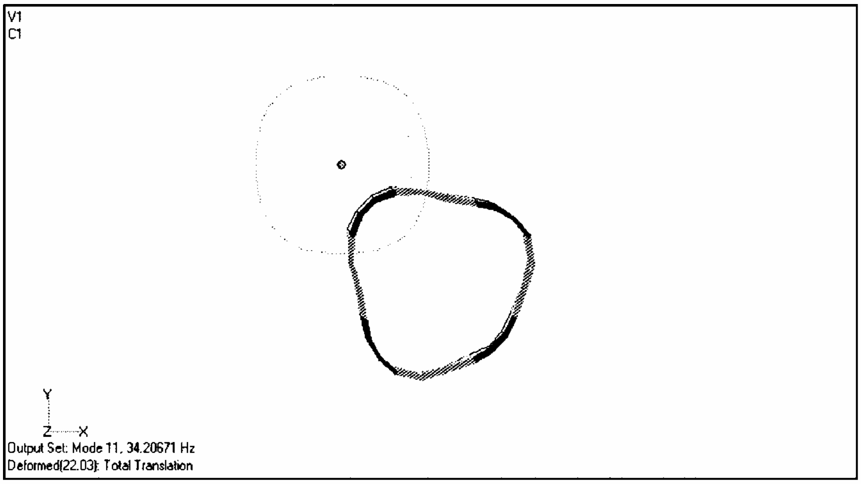

Fig. 21 Deformed cross section of the third mode.

Summary

The spring-tape-reinforced aluminum laminate booms represent a new and innovative type of space inflatable and rigidizable structure. Through the development process, including design, analysis, fabrication, assembly, and testing, many distinct advantages of the spring-tape-reinforced aluminum laminate booms have been identified and demonstrated. These include 1) simplicity of design, 2) self-rigidizability in space, 3) high load-carrying capability, 4) high packaging efficiency, 5) failure by Euler buckling (which is easy to predict) instead of local crippling, 6) low inflation deployment pressure requirements, 7) space-qualified materials with negligible outgassing and contamination, and 8) reversibility for repeated ground testing.

Acknowledgments

The work described was performed at Jet Propulsion Laboratory, California Institute of Technology. The authors thank Pierre Leung, Grigor Kerdanyan, and Joel Rodriguez, all of California State University at Los Angeles, for their contributions to this research effort.

References

[1] Fang, H., and Lou, M., "Tape-Spring Reinforcements for Inflatable Structural Tubes, *NASA Technical Briefs*, Vol. 24, No. 7, 2000, p. 58.

[2] Lou, M., Fang, H., and Hsia, L., "A Combined Analytical and Experimental Study on Space Inflatable Booms," Inst. of Electrical and Electronics Engineers, IEEE Paper 12.0411, March 2000.

[3] Friese, G. J., Bilyue, G. D., and Thoms, M., "Initial '80s Development of Inflatable Antennas," NASA CR 166060, Jan. 1983, p. 65.

[4] Blevins, R. D., *Formulas for Natural Frequency and Mode Shape*, Krieger, Malabar, FL, 1979, p. 124.

[5] Yang, B., Lou, M., Ding, H., and Fang, H., "Buckling Analysis of Tape-Spring Reinforced Inflatable Struts," AIAA Paper 2000-1725, April 2000.

J. Lassiter
Guest Editor