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Deflection of Multicellular Inflatable Tubes for Redundant Space Structures

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A new concept of redundant space structures using multicellular inflatable elements is proposed, and the results of basic analyses on simple multicellular models are reported. Much effort has been devoted to methods for sufficiently hardening the inflatable elements in space to tolerate damage sustained from space debris, especially with respect to rigidization of a membrane; however, if the structures are redundant, they do not need to be as stiff and strong as those without redundancy. Deflections of two kinds of multicellular cantilever inflatable tubes are numerically investigated. First, nonrigidized tubes are analyzed by the modified Euler–Bernoulli beam theory. Second, rigidized tubes with slackening effects of the membrane are simulated using the modified nonlinear finite element method. The results show that multicellular tubes can be redundant against problems with pressurization and can be as stiff and as strong as monocellular models with less internal gas. In the multicellular rigidized inflatable tubes, maintaining a small amount of internal pressure is quite effective to prevent the deformation of the cross section, which causes a drop in stiffness and strength. Therefore, adopting a redundant system is effective both for rigidized and nonrigidized inflatable elements.

Nomenclature

a	=	constant
C	=	curvature of centerline of tube
C_0	=	constant
c	=	dimensionless curvature
d	=	diameter of cross section of inflatable tube
E	=	effective modulus of membrane
$\boldsymbol{f}$	=	outer force vector
h	=	parameter of membrane
h_p	=	height of square plate
I	=	second moment of area
L	=	length of inflatable tube
L_p	=	side length of square plate
M	=	moment
M_p	=	total mass of modularized plate without internal gas
m	=	dimensionless mass
$\boldsymbol{N}$	=	normal vector
N_m	=	maximum axial stress in membrane
N_0	=	minimum axial stress in membrane
n	=	number of division of each side of modularized plate
$\boldsymbol{n}$	=	unit normal vector
P	=	internal pressure of inflatable tube
r	=	radius of cross section of inflatable tube
s	=	ratio of length and height of square plate
t	=	thickness of membrane
V	=	volume of inflatable tube
W	=	tip load
x	=	distance from root end
$\boldsymbol{x}$	=	position vector of nodes
y	=	deflection of inflatable tube
ζ	=	dimensionless measure of change in radius
θ	=	angular position
κ	=	ratio of specific heat
ν	=	Poisson's ratio
ρ	=	density of membrane

Subscripts and Superscript

i, j, k	=	node numbers
m	=	triangle element number

Introduction

RECENT developments of electrical device technologies have enabled us to make smaller satellites at lower costs, whereas larger space structures are essentially required for satellites, such as large parabolic antennas, solar reflectors, or solar sails. Therefore, so-called gossamer spacecraft, or very large and ultralow mass space structures, have been extensively studied in recent years. According to Ref. 1, gossamer spacecraft fall into six categories: sails, strings (tethers), inflatables, lenses, meshes, and fields. Within these categories, inflatable structures have, in particular, generated wide interest for low-cost flight hardware.

Concepts of inflatable deployable space structures have been under development since the early 1960s, when the ECHO balloon satellites were successfully sent into orbit,[2–4] and some basic analyses for the structure design were made.[5] Since the mid-1990s, as requirements for larger space structures have increased, inflatable elements have come to the great attention of many researchers as promising space structure elements in the new century. Major advantages of using inflatable elements in space are their potentials of high packaging efficiency and lower fabrication cost. High deployment reliability is also expected due to being constructed with fewer mechanisms. In addition, structures with higher precision could be constructed by combining inflatable membranes and cable networks.[6]

However, inflatable elements essentially have two major problems.[7–9] First, environmental threats such as space debris or

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meteorites, atomic oxygen, and ultraviolet and radiation damage eventually result in leakage of the internal gas. Second, because of the high flexibility, free inflation deployment of inflatable elements could be very volatile. This problem was clearly evidenced by the orbital deployment of the Inflatable Antenna Experiment flown in May 1996 (Ref. 10). Therefore, some kinds of control are required for stabile deployment.

To ameliorate the first problem, leakage, much research has been done with respect to rigidization of a membrane after the deployment in space so that the elements can keep their shapes and stiffness even when they lose the internal pressure. As possible rigidization technologies, thermal/solar radiation cure, UV cure, metal yielding, foam rigidization, and other methods have been discussed,[7,9,11–14] however, there are still some difficulties in establishing practical technologies.

Inflatable elements discussed so far can be categorized into three types, according to the rigidization methods. The pressurized type has a nonrigidizable membrane and needs to maintain internal gas pressure over the life of the mission. The rigidized type has a rigidizable membrane, which can be rigidized after deployment in space and keeps its stiffness even when it loses the internal pressure during the mission life. Basically there are two methods for rigidization: chemical reaction and metal yielding. The foam-rigidized type is deployed and hardened by foam filled inside the enclosing membrane.

Many efforts have been devoted to harden sufficiently the inflatable elements to tolerate damages over the life of the mission. However, the authors believe there must be another approach. If the structures are redundant, or fail-safe, they do not have to be as stiff and strong as those without redundancy. In this paper, the authors propose a concept of redundant space structures using multicellular inflatable elements, and report the results of basic analyses on simple models. Two kinds of multicellular cantilever inflatable tubes have been studied to determine the fundamental physical characteristics of multicellular inflatable structures. The first is a pressurized type of multicellular tube and the second is a rigidized type of multicellular tube. Because a foam-rigidized type is considered to have less necessity to adopt redundancy, the authors do not discuss it in this paper.

Concepts of Redundant Space Structures Using Multicellular Inflatable Elements

Redundant Space Structures

The authors propose the concept of redundant space structures using multicellular inflatable elements. Although gossamer spacecraft including inflatables are very large and light, they are generally very vulnerable to damages. There are many environmental threats in space; in particular, the accumulation of man-made space debris in Earth orbits is getting worse year after year.[15] When we design gossamer spacecraft, adopting redundancy in the structures can be one solution to extend mission life. For instance, in tethers, one of the gossamer spacecraft, some redundant designs have been proposed and tested. Sheet-type tethers[16,17] and a multiline tether[18] are considered to be redundant against space debris damage and have longer lifetimes. The authors believe that in inflatables, structures can be also redundant.

Multicellular Inflatable Elements

A reflector structure using modularized inflatable elements supported by backup trusses has been proposed.[19,20] However, the authors theorize that whole structures could consist of only gossamer elements. As shown in Fig. 1, the authors introduce some concepts of beam structures, plate structures, and reflector structures consisting of modular inflatable elements. These designs can easily have structural redundancy, that is, even if some cells are punctured in space and lose internal pressure, the effect of the damage remains localized and does not harm the whole system. In addition, multicellular inflatable elements can maintain redundancy during their entire deployment in space. As discussed in the following section, the larger the structures become, the less mass disadvantages we have, even when number of cells increases.

Furthermore, by the modulaization of the structures, ground testing and manufacturing of large flexible elements can be made easier,

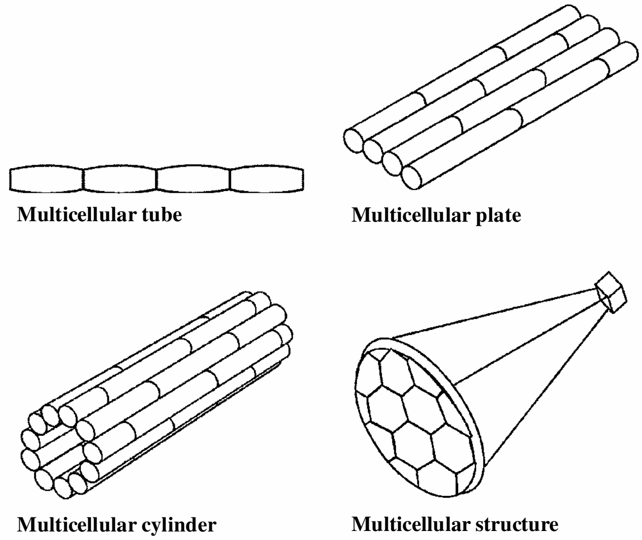


Fig. 1 Examples of multicellular inflatable elements.

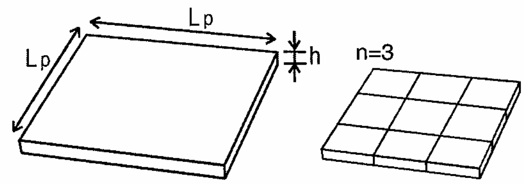


Fig. 2 Square inflatable plate.

as seen with the present deployment of modularized structures such as a modular mesh antenna with backup trusses.[21] Multicellular inflatable elements could also enable us to design stiffer inflatable structures with less gas: Relatively higher internal pressure is applied to the element where load is concentrated and less pressure where it is not. Furthermore, sequential and stabilized deployment could be possible, by inflating each cell one by one.

Comparison of Mass and Collision Probability

To determine the relations of mass and space debris damage probability to modularized inflatable structures, a simple square inflatable plate shown in Fig. 2 is considered. When we express $s = L_p/h_p$, the total mass M_p of the modular structure without internal gas is given by

$$M_p = 2L_p^2 t[(n + s + 1)/s]\rho \tag{1}$$

We define dimensionless mass m, which is

$$m = M_p \big/ 2L_p^2 t\rho = (n + s + 1)/s \tag{2}$$

With regard to collision probability, the rate of space debris damage into one cell of the structure is $1/n^2$ compared with monocellular inflatable plate, $n = 1$. Figure 3 shows the results of calculations of Eq. (2) and the relative collision probability $(1/n^2)$. With regard to mass, obviously as s becomes larger (or $L_p \gg h_p$), the effect of the increase of the number of cells becomes smaller; whereas the rate of failure decreases in inverse proportion to n^2.

Thus, the authors can conclude from this analysis that when inflatable plates with the same thickness are designed the larger structures have less mass disadvantage when the plate is modularized. On the other hand, modularizing the inflatable plate is quite effective to decrease the probability of puncture of a single inflatable cell. For inflatable structures, the collision probability can be directly proportional to lifetime. Figure 3 shows that slightly increasing the mass by modularization can increase the lifetime by a factor of 100. Moreover, the lifetime of modularized inflatables may be further increased because the effect of a single impact does not result in complete loss of structural performance. Therefore, the concept of redundant structures is significantly important for space inflatable structures design.

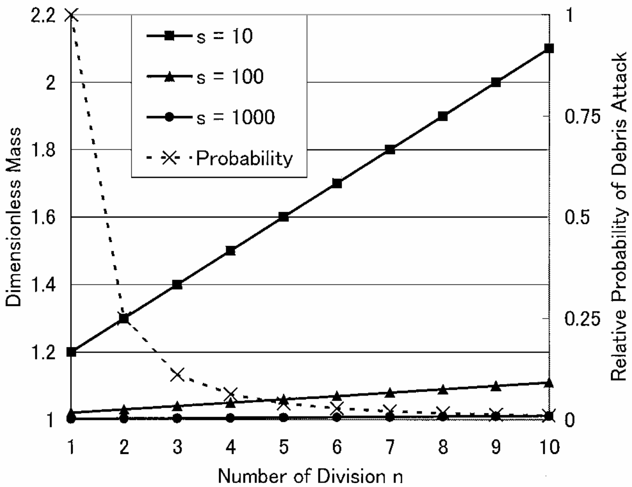


Fig. 3 Mass and collision probability.

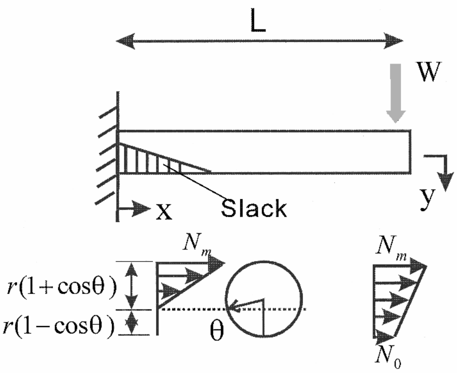


Fig. 4 Model of pressurized inflatable tube.

Fundamental Analysis of Cantilever Inflatable Tubes: Pressurized Type

Purpose of the Analysis

Simple models of inflatable elements, that is, cantilever inflatable tubes, are analytically investigated. Two kinds of multicellular models are studied: the pressurized type and the rigidized type. The purpose of these analyses is to learn the physical characteristics of inflatable elements and to obtain fundamental knowledge for multicellular inflatable structure design. The pressurized type is the first model discussed.

Modeling of a Pressurized Cantilever Inflatable Tube

The authors use Comer and Levy's model[22] for nonrigidized and pressurized inflatable tubes. Their analytical model[22] is similar to conventional Euler–Bernoulli beam theory, but the influence of wrinkles on a membrane is introduced. Figure 4 shows the model, whose radius of the cross section is r, length of the tube is L, and internal pressure is P. As the concentrated tip load W increases, the bending stress equilibrates the axial tension in the membrane on the concave side of the tube, and wrinkling begins in that region. The membrane wrinkles because a nonrigidized membrane is incapable of resisting compressive stresses. The model is also based on the assumption that the internal pressure maintains the circular shape of the cross section, and plane sections remain plane (Kirchhoff–Love's hypothesis). The angle θ in the slack region is given by

$$\frac{M(x)}{Pr^3} = \frac{\pi(2\pi - 2\theta + \sin 2\theta)}{4[(\pi - \theta)\cos\theta + \sin\theta]} \qquad (0 < \theta < \pi) \tag{3}$$

The second moment of area is given by

$$I = r^3 t(\pi - \theta + \sin 2\theta/2), \qquad \pi P r^3/2 < M < \pi P r^3$$

$$I = \pi r^3 t, \qquad M < \pi P r^3/2 \tag{4}$$

With the use of Eqs. (3) and (4), deformation of the tube is obtained by numerically solving the differential equation of the beam theory:

$$\frac{d^2 y}{dx^2} = -\frac{M(x)}{EI} \tag{5}$$

Main et al.[23] pointed out that the results of numerical analysis by this model correspond well to their experimental results if an effective modulus of membrane is used in the calculations instead of the cataloged Young's modulus.

The result of calculations on the usual monocellular inflatable tube model tells that, when moment M at the root of the tube exceeds the value of $\pi P r^3/2$, wrinkling occurs from the root, and the bending stiffness suddenly drops. Therefore, very high internal pressure is needed for this pressurized-type inflatable tube to avoid wrinkling and to maintain the stiffness.

Triple-Cellular Pressurized Cantilever Inflatable Tubes

As a simple model of multicellular inflatable structures, the authors analyze triple-cellular cantilever inflatable tubes (Fig. 5) using the equations described earlier. For numerical calculations, values in Tables 1 and 2 are used.

Figure 6 shows the load-deflection curves for models 1–5 in Table 1. Figure 6 shows that model 1, a triple-cellular tube, is as stiff as monocellular model 3, although the triple-cellular model has much less internal gas than that of model 3. The total volume of gas in model 1 is equal to that of monocellular model 4, which has much less stiffness than the triple-cellular tube, according to the curve shown in Fig 6.

Table 1 Pressures for triple-cellular tubes

Model	P_1, Pa	P_2, Pa	P_3, Pa
1	9000	6000	3000
2	9000	3000	3000
3	9000	9000	9000
4	6000	6000	6000
5	3000	3000	3000

Table 2 Physical values for the calculations

Parameter	Value
Length $L_1 = L_2 = L_3$	20 cm
Radius r	2 cm
Thickness of membrane t	20 μm
Young's modulus E	0.3 GPa

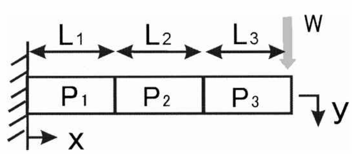


Fig. 5 Triple-cellular inflatable tube.

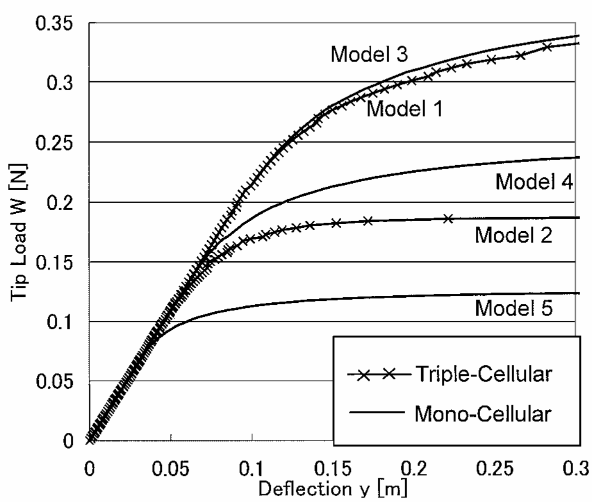


Fig. 6 Load-deflection curves for models 1–5.

Model 2 simulates a kind of pressurization problem. The middle cell was supposed to have 6000 Pa of internal pressure, but only the half of the pressure was provided. If the monocellular tube has the same trouble, it will be model 5. Figure 6 shows that model 2 is still stiffer than model 5.

From the analysis, the authors can say that multicellular inflatable structures have the possibilities of making stiffer structures with less gas and of realizing redundant, or fail-safe, systems.

Fundamental Analysis of Cantilever Inflatable Tubes: Rigidized Type

Modeling of a Rigidized Cantilever Inflatable Tube

The authors now analyze cantilever inflatable tubes with a rigidized membrane. The rigidized membrane is assumed to be isotropically rigidized and, thus, not subject to slackening or wrinkling. For the analysis, a finite element method (FEM) is used.

Finite elements of an inflatable tube are constructed by using the modified nonlinear FEM presented in Ref. 24. In this method, finite elements of geometrically nonlinear motion of a membrane are formulated, taking into account the slackening of the elements. The method's validity has been examined by convergence study; in addition, the analytical result was compared with experimental results to find they correspond well.[25] In the model shown in Fig. 7, the cylinder consists of quadrate elements, and triangle elements are used for the diaphragms. The cylinder is assumed to be successfully rigidized and not subject to slackening (plate elements), whereas the diaphragms are assumed to be nonrigidized membranes that create wrinkling. The number of divisions is 14 in the circumferential direction and 18 in the longitudinal direction. The boundary conditions at the root of the tube are fixed to all directions; in other words, the root remains a circular shape.

The effect of internal pressure is provided according to the following scheme. All elements are divided into triangles, then the volume of the tube V is given by

$$V = \frac{1}{6}\sum_m \left(\boldsymbol{x}_m^i \times \boldsymbol{x}_m^j\right) \cdot \boldsymbol{x}_m^k \tag{6}$$

where m is triangle element number, and i, j, and k are node numbers, as shown in Fig. 8. Because $PV^a = C_0$, the internal pressure P is obtained by

$$P = C_0 V^{-a} \tag{7}$$

The normal vector is

$$\boldsymbol{N} = \left(\boldsymbol{x}_m^j - \boldsymbol{x}_m^i\right) \times \left(\boldsymbol{x}_m^k - \boldsymbol{x}_m^i\right) = 2S\boldsymbol{n} \tag{8}$$

where S is the area of the triangle element and $\boldsymbol{n}$ is the unit normal vector. Finally, outer force $\boldsymbol{f}$, obtained by the following equation, is applied to each node of the element as the internal pressure:

$$\boldsymbol{f} = \tfrac{1}{3}\left(\tfrac{1}{2}P\boldsymbol{N}\right) = \tfrac{1}{6}P\boldsymbol{N} \tag{9}$$

In the following analysis, a is substituted by $\kappa = 1.30$, that is, adiabatic change is assumed inside the inflatable tube.

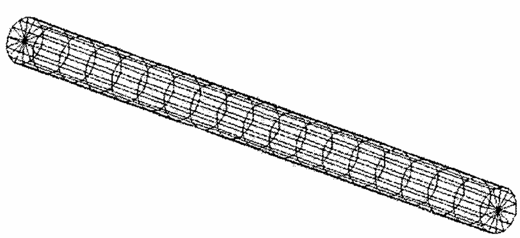


Fig. 7 Finite elements model.

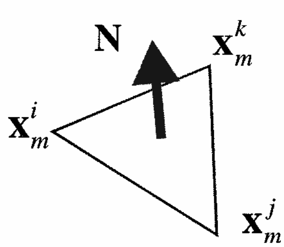


Fig. 8 Triangle element for pressure.

Monocellular Rigidized Cantilever Inflatable Tubes

First, simple monocellular rigidized cantilever inflatable tubes, shown in Fig. 9, are investigated. The physical values in Table 3 are used for the calculations. Figure 10 shows the simulation result when internal pressure $P = 0$. Figure 10a shows the tube when the tip load $W = 0.20$ N and the shape of the cross section of the midelement. Figure 10b shows the results when $W = 0.25$ N. It is found that the cross section becomes flatter as the tip load increases, and obviously the flatter the cross section is, the smaller the bending stiffness the tube has. This phenomenon, the decrement of bending stiffness because of flattening of the cross section, is called Brazier's effect (see Ref. 26). The analysis shows that when the internal pressure of the rigidized inflatable tube is very low, the bending stiffness drops because of this Brazier's effect. Because the imposed boundary conditions at the fixed end keep the section there circular, the flattening occurs at the middle of the tube, not at the root of the tube where the moment is largest.

According to Ref. 26, Brazier's effect in a tube of circular cross section can be expressed in the form

$$M = \left(2/\sqrt{3}\right)\pi Erth(c - 2c^3) \tag{10}$$

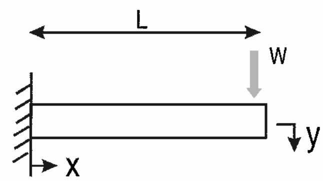
where $c = (\sqrt{3}/2)(r^2/h)C$ and $h = t/\sqrt{(1-\nu^2)}$ and

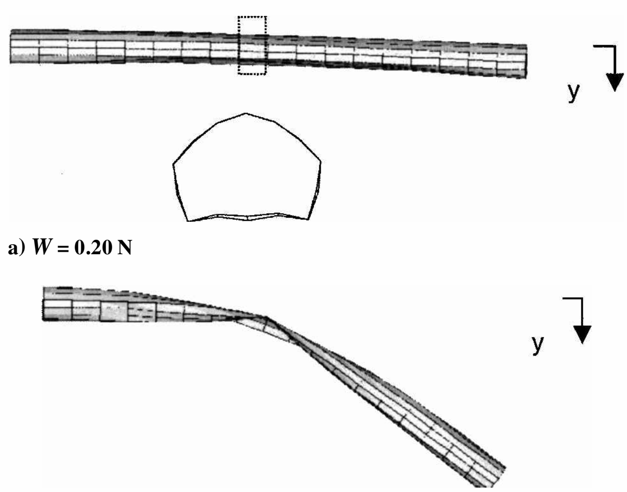
$$\zeta = \tfrac{4}{3}c^2 \tag{11}$$

Table 3 Physical values for the calculations

Parameter	Value
Length L	60 cm
Radius r	2 cm
Cylinder (aluminum foil)	
Thickness t_c	16.5 μm
Young's modulus E_c	3 GPa
Diaphragm (polyethylene)	
Thickness t_d	20 μm
Young's modulus E_d	0.3 GPa

Fig. 9 Model of monocellular rigidized inflatable tube.





a) $W = 0.20$ N

b) $W = 0.25$ N

Fig. 10 Deflection of rigidized inflatable tube.

Table 4 Pressures for models 1–4

Model	P_1, Pa	P_2, Pa	P_3, Pa
1	0	0	0
2	100	100	100
3	100	0	100
4	100	0	100

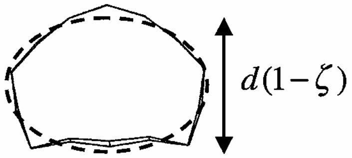


Fig. 11 Comparison of flattening cross section between Brazier's theory and finite element analysis.

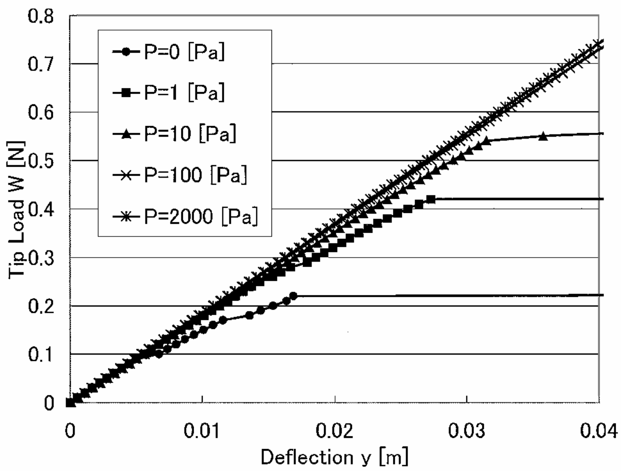


Fig. 12 Load-deflection curves for monocellular rigidized inflatable tube.

where c is the curvature of the center line of the tube, ν is Poisson's ratio of the membrane, and ζ is flattening ratio. From Eqs. (10) and (11), when $\nu = 0.30$ is substituted, the flattening of the cross section in the middle of the tube shown in Fig. 10a can be obtained as $\zeta = 0.329$. In Fig. 11, this result is compared with the result of finite element analysis. As can be seen, the two results correspond well.

Figure 12 shows the load-deflection curves of the monocellular rigidized inflatable tubes for various internal pressures. As can be seen Fig. 12, very small internal pressures, such as $P = 1$ or 10 Pa ($\sim 10^{-4} - 10^{-3}$ psi) have a considerable effect to keep the tubes stiff by avoiding Brazier's effect.

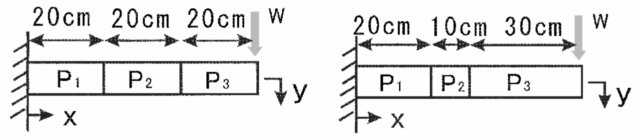
Some small jumps in deflection in the curves of $P = 0$ and 1 Pa are observed, which is caused by local deformation of the tube. Large jumps correspond to limit-point buckling.

In conclusion, even when the membrane of inflatable tubes is successfully rigidized, maintaining a very small amount of internal pressure can become quite effective to keep the elements stiff and strong over their lifetime.

Triple-Cellular Rigidized Cantilever Inflatable Tubes

The authors analyze triple-cellular rigidized cantilever inflatable tubes, similar to the pressurized type discussed before. Four models are considered, described in Table 4 and Fig. 13. The load-deflection curves for these models are shown in Fig. 14. Model 1 has no internal pressures; however, it becomes much stronger than the monocellular tube without internal pressure shown in Fig. 12 because polyethylene diaphragms instead of internal gas block Brazier's effect.

Model 3 simulated the trouble that the middle cell completely loses its internal pressure. When models 3 and 2 are compared, of course model 3 is weaker. However, model 3 is a little bit stronger than model 1, which has a total failure. As can be seen in Fig. 15, the flattening of the cross section occurs in the middle cell, which results in the limit-point buckling. The flattening of the cross section can be also seen at the root cell; however, the internal pressure ($P = 100$ Pa)



Models 1–3 Model 4

Fig. 13 Triple-cellular inflatable tube.

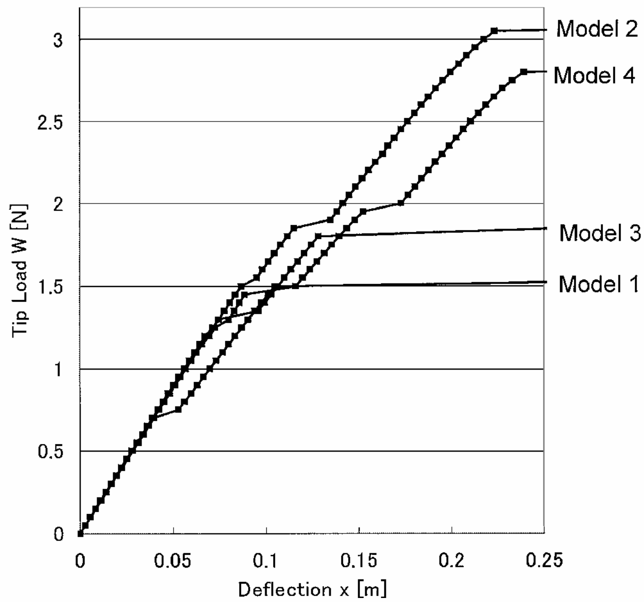


Fig. 14 Load-deflection curves for triple-cellular rigidized inflatable tube.

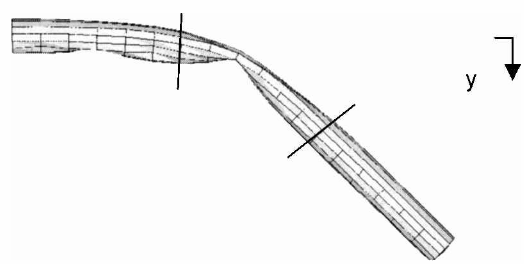


Fig. 15 Deflection of model 3 when W = 2.0 N.

prevents large flattening. Model 4 has a middle cell, which is half the length of that of model 3. Model 4 is stronger than model 3, almost as strong as complete model 2. Limit-point buckling occurs at the root cell in the model. Obviously having smaller cells realizes a higher redundant system.

From the results mentioned, the authors can conclude that multicellular tubes can maintain stiffness and strength to some extent even when some cells completely lose their internal pressure; the effect of the lost of pressure is small when the system is highly redundant.

Discussion of Redundant Inflatable Structures

Several physical characteristics of pressurized-type and rigidized-type inflatable tubes and the advantages of modularized structures are observed in the analyses. The bending stiffness of nonrigidizable and pressurized inflatable tubes is determined by slackening. Thus, rigidization of the membrane, to avoid slackening, considerably increases stiffness. However, even when the membrane of the tubes is successfully rigidized, if the internal pressure is lost, the tubes lose their stiffness and strength because of the resultant flattening of the cross section. As can be seen in Fig. 12, maintaining just a little pressure (approximately 1 Pa) is effective to prevent the flattening of the cross section and to maintain the stiffness and strength of the tube.

In the multicellular inflatable structures, even if there are some local depressurizations, the effects do not jeopardize the whole system. In addition, by adopting a multicellular design, tubes can be as stiff as monocellular structures, with much less internal gas. Therefore, the authors can say that redundant space structures using multicellular inflatable elements are quite promising structural concepts.

With the preceding discussion kept in mind, a new type of inflatable element is considered. This is a multicellular hybrid between the pressurized and the rigidized types. The multicellular hybrid type has a rigidizable membrane but maintains internal pressure over the life of the mission. The rigidized membrane does not need to be very stiff and the internal pressure does not need to be very high, compared with conventional inflatable design because both of the effects collaborate with each other.

Sublimating powder will provide the internal pressure. With its use, multicellular modules do not need complex pipelines for inflation. According to Ref. 7, sublimating inflation systems have been used since the ECHO balloon satellites in the 1960s. The operating principle for sublimation powders is to release the powder within the interior of the elements after orbital insertion. In space conditions, the powders will sublime into a gas that provides vapor pressures in the range of 10^{-1}–1 Pa. These powders provide self-pressure regulation if excess powder is carried and allowed to sublimate as make-up gas.

Conclusions

The concept of modularized space structures using multicellular inflatable elements is proposed, and deflections of simple multicellular cantilever tube models are investigated. Although inflatable elements are essentially vulnerable to damage, structures can be made redundant, or fail-safe, by consisting of modularized elements, that is, even if some cells are punctured and lose their internal pressure, the damage remains localized and does not harm the total system. Modularization of large structures also makes ground testing and manufacturing easier.

The analytical studies on cantilever inflatable tubes show that rigidization of a membrane is quite effective for maintaining stiffness because it avoids the wrinkling of the membrane, which causes a drop in stiffness. In the multicellular inflatable tubes, keeping just a little internal pressure is quite effective, even for rigidized inflatable elements, to prevent the deformation of the cross section, which would cause a drop in stiffness and strength. Therefore, adopting redundant systems is effective both for rigidized and nonrigidized inflatable elements.

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