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Review of Inflatable Booms for Deployable Space Structures: Packing and Rigidization

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Inflatable structures offer the potential of compactly stowing lightweight structures, which assume a fully deployed state in space. An important category of space inflatables are cylindrical booms, which may form the structural members of trusses or the support structure for solar sails. Two critical and interdependent aspects of designing inflatable cylindrical booms for space applications are i) packaging methods that enable compact stowage and ensure reliable deployment, and ii) rigidization techniques that provide long-term structural ridigity after deployment. The vast literature in these two fields is summarized to establish the state of the art.

I. Introduction

Inflatable space structures, or 'space inflatables', are promising candidates for a wide range of space applications. Distinguishing qualities include their low volume requirements when stored for launch, low system complexity and a simple deployment mechanism to form lightweight, large-scale space structures. Well-known inflatables missions include the Echo balloons launched by NASA in the 1960s [1], and the Inflatable Antenna Experiment (IAE) in the mid-1990s [2]. The relatively low Technology Readiness Level (TRL) of space inflatables does not reflect the extensive research and development that has taken place over the years, and inflatables remain a promising technology

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for a wide range of space applications. Of particular relevance are inflatable cylindrical structural elements, often referred to as booms; these can make up space trusses [3], support the reflector of an inflatable antenna [2], or form the structural framework for solar arrays [4] and solar sails [5].

Inflatable booms form part of a wider family of light-weight deployable structures, including rigid linked mechanisms such as the ATK ADAM masts [6], coilable thin shell members such as the STEM [7] or bi-stable composite booms [8], and telescopic masts [9]. The structural performance of a particular type of boom can be evaluated in a number of ways, including specific bending stiffness and buckling strength, or via a combined performance index [10]. A boom's performance at a system level must also be considered by taking into account the particular deployment method, and the specific mission requirements. Some of the main advantages inflatable booms have over their competitors include a high packaging efficiency with minimal stored strain energy, low system complexity, and a simple deployment mechanism.

While space inflatables solve many of the traditional problems in engineering space structures with regard to volume and mass minimisation, they come with their own set of challenges. These include finding efficient packing schemes, ensuring that the structure will deploy reliably and predictably, and enabling robust structural performance after deployment. Following deployment, space inflatables often undergo a rigidization process to provide long-term structural rigidity. This circumvents issues with punctures due to micro-meteorites or space debris, and negates the requirement to store supplementary inflation gas. A further challenge is the ground testing of large inflatable structures, which is complex and costly [11]. As a result of these challenges space inflatables have, for the most part, remained the subject of conjecture and experimentation, and have been employed in only a handful of (mostly experimental) missions.

This paper focuses on two key aspects of the design of inflatable booms for space structures: packing methods and rigidization techniques. A third important aspect is deployment control, which serves to improve reliability and predictability of deployment paths, reduce the reaction loads to the satellite during deployment, and thereby minimize the vibrations after deployment. An overview of deployment control techniques is provided by Grahne and Cadogan [12], and the subject is not covered in this review. Instead, attention is given to the inherent deployment characteristics of

different packing schemes.

The paper is laid out as follows. First, a series of boom packing techniques is described, which are categorized into coiling, folding and conical stowage methods. The discussion of boom folding methods is particularly broad, ranging from straightforward *z-folding* to more advanced origami patterns. Next, the review of rigidization techniques summarizes the vast literature on the subject, grouping the techniques by their mechanical, chemical or physical process of rigidization. A brief discussion concludes the review.

II. Boom Packing Methods

The choice of packing method is a crucial consideration in the design of inflatable booms for space structures. Foremost, the structure must be compactly stowed during launch, as may be quantified by the packing efficiency (the relative volume fraction of the stored configuration) or the deployment ratio (deployed/stowed boom length). The packing method determines the ventability of any residual air, as well as the strain energy stored in the stowed configuration; both affect the initial dynamics of the deployment. The boom deployment characteristics, in particular the predictability of the deployment path, are key in design and are also greatly influenced by the choice of packing method. When deployable booms form part of a larger inflatable structure, the packing methods must account for any extra loads during deployment from the overall structure, so that the deployment path avoids entanglement or other damage. Depending on the packing method, retardation mechanisms may be necessary to dissipate the kinetic and strain energy involved in the deployment. After deployment, the packing method still exerts its influence through residual creases, stresses, or material cracking at fold lines and vertices.

The required packing schemes may be determined by the purpose of the booms, and their role in the overall structural design. For example, Natori et al. [13] considered assemblies of wrapped membranes, using embedded inflatable booms for deployment; depending on their location within the wrapped membranes, the booms were necessarily either z-folded or spiral wrapped. Furthermore, in a combined deployment of inflatable booms, certain packing methods might be desirable to control deployment sequencing or improve the combined packing ratio.

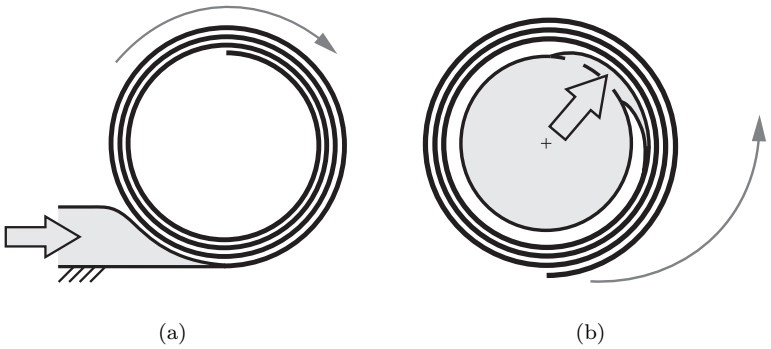


Fig. 1 The (a) coiling and (b) wrapping packing and deployment method.

In this section different stowage methods for inflatable booms for space structures are reviewed. The main categories are coiling/wrapping, folding and telescopic conical stowage. The packing scheme's effect on stowage, deployment and structural properties of the inflated booms are discussed, and the analysis methods are highlighted.

A. Coiling & Wrapping

A common stowage method is to first flatten the uninflated boom, before rolling it into a coil or wrapping it around a hub. In the 'coiled' configuration the inflation gas enters at the base of the boom and, as the boom is inflated, the coiled section is pushed along and unfurls. In the 'wrapped' configuration the gas enters from the hub, and the stowed boom swings out from the base during inflation; this configuration was used by Katsumata et al. [14] for embedding inflated booms in a wrapped membrane.

Steele and Fay [15] described the inflation of coiled cylinders with an analytical model, using experimental observations to provide a simple expression for the torque at the unrolling point, *i.e.* the transition between the unfurled and coiled configuration [16]. The coiled geometry was modelled as an archimedean spiral, which allows the inertia of the coiled section to be described as a function of deployment. Scenarios with constant internal pressure, and with pressure decreasing linearly with the volume (to simulate fixed-volume deployment) were analyzed. The use of retardation devices, such as velcro strips, was recommended to reduce the final unrolling velocity and resulting impact. In their analysis, the tube is supported on an infinite plane, rather than freely deployed in space. Fang and Lou [17] modelled the deployment of a self-rigidizable inflatable boom with embedded

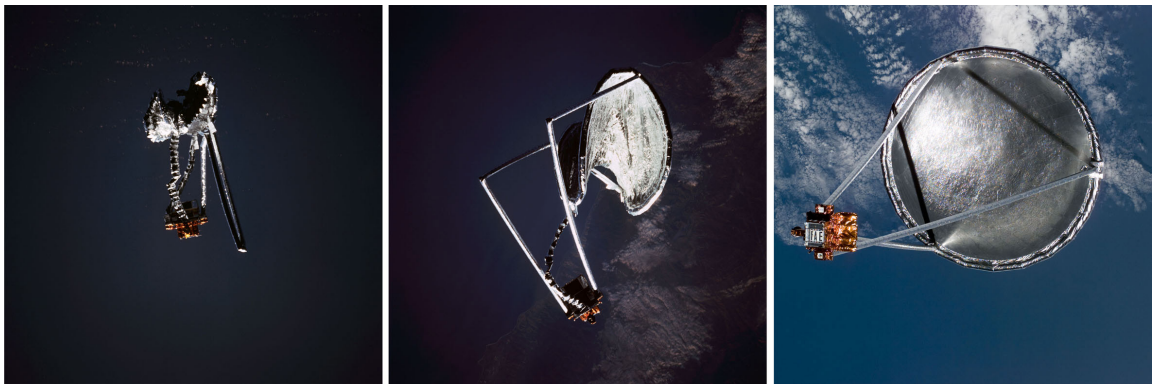
tape-springs [18], by representing the rolled boom as a system of rigid links connected by flexible rotational springs and dampers. Deployment studies of unrolling booms using finite element analysis have also been published, see *e.g.* Wang and Johnson [19].

The mechanics of coiling/wrapping the boom before inflation are subtle: due to the difference in coiling radius between the two sides of the flattened boom, it will locally buckle and wrinkle, and as the coiled diameter increases the coil may form a polygonal cross-section. The phenomenon is colloquially referred to as '50-pencing', after the Reuleaux Polygon used for the British 50 pence coin. As observed experimentally by Katsumata et al. [20], the local wrinkling and buckling can affect the deployment of the coiled booms by forming fold lines that pinch the tube, thereby limiting the flow of inflation gas. The deployment behavior of the coiled booms then shows similar instabilities as seen in *z-folded* tubes, as discussed in the next section. Satou and Furuya [21] also observed local buckling in the wrapping of membranes.

Coiling is a simple, effective and compact method to package an inflatable boom with minimal residual creases, and deployment is predictable in combination with simple retardation devices such as velco strips along the length. However, the method suffers from poor ventability of residual gas during launch, and connection to other components is complicated by the tip rotation. For the wrapped configuration, the boom must swing around its base during deployment, which could cause problems with entanglement.

B. Z-Folding

An important category of methods for packing cylindrical booms is the use of fold patterns. The simplest folding pattern is the '*z-fold*' (alternatively known as zigzag, concertina or accordion fold), whereby the boom is flattened before being simply folded back and forth at regularly spaced intervals at discrete lines or hinges. The discrete nature of the folding creates a discontinuous structure, where the airflow is restricted between sections, resulting in a structure sensitive to small changes in shape, with an unpredictable deployment path. The 28m long booms of the Inflatable Antenna Experiment (IAE) were folded this way before flight-testing; see Fig. 2(a). For the IAE it was intended to first deploy the booms mechanically to approximately the correct position before



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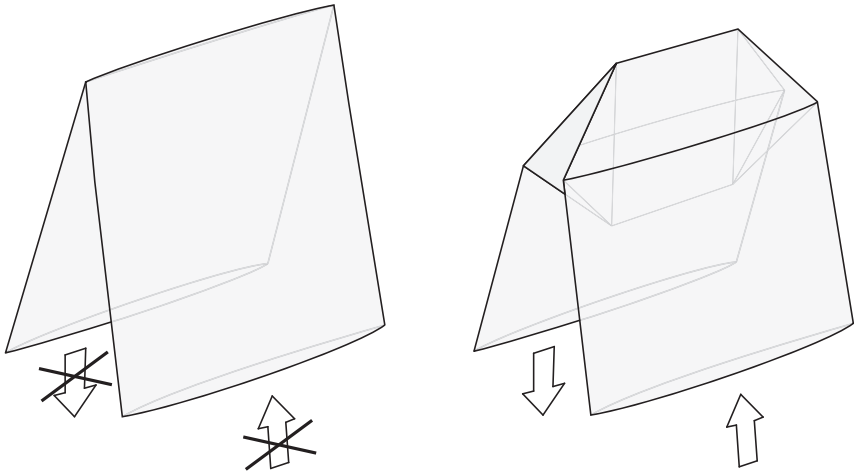


(b)

Fig. 2 Z-folded booms: (a) deployment of the Inflatable Antenna Experiment (IAE) (image credit: NASA); (b) a standard and a modified z-fold designed to facilitate gas flow (image after Katsumata et al. [20]).

releasing the inflation gas. Trapped residual air and strain energy stored in the folds, however, resulted in a premature and unpredictable, though ultimately successful, deployment [2, 22].

The z-folded boom is well studied, and Smith and Main [23] summarize several modelling efforts. Semi-analytical models have been developed to capture the dominant dynamic characteristics, where the assumption is that local bending effects, which initially exist as a result of the folding and later appear because of local buckling, dominate the overall deployment mechanism. This assumption results in a system of rigid links and non-linear hinges to model deployment [23, 24]. One of the fundamental challenges is the proper assignment of rotational spring stiffnesses to each hinge, which will depend on fold angle, pressurization and boom geometry. These can be determined

experimentally, or approximated by considering the bending stiffness of inflated cantilevers [25]. As summarized by Smith and Main [23], the analytical models indicate that the deployment of the z-folded boom is inherently unstable. This is supported by several finite element studies, *e.g.* Salama et al. [26], Wang and Johnson [19] and Katsumata et al. [20]. Miyazaki and Uchiki [27] compared finite element simulations of a single z-fold with micro-gravity experiments, and found close agreement.

A modification to the z-fold was proposed by Katsumata et al. [20], and replaces the single fold line with a number of additional folds that provide a small opening between the folded sections of the boom; see Fig. 2(b). Experiments showed a smoother inflation pressure and flow rate, as well as a more uniform deployment. In the finite element analysis, the conventional and modified z-folds were constructed by simulating the actual shaping operations. The resulting wrinkles and residual stresses in the stowed configuration played an important part in the inflation of the cylinder: the stored strain energy opens up the inner fold line, enabling a better flow of gas with fewer peaks in inflation pressure [20]. In summary, the modified z-fold provides an improved gas flow through the fold, at the expense of greater fold complexity and reduced packing efficiency.

Experiments, numerical simulations and flight-testing on the IAE have confirmed that the z-folding scheme is inherently unstable during deployment. A further drawback of z-folding is the poor ventability when folded: any residual air has to travel the length of the boom to be vented. Once launched into space, the trapped air exerts a pressure and will impart an initial velocity to the structure as it deploys, which must be included in any deployment modelling [19]. These problems are offset by the simplicity of the z-fold technique, as well as its space heritage. Furthermore, there are applications where z-folding is essential, such as for booms embedded along the perimeter of a spiral-wrapped membrane [13]. In these cases the modified z-fold may provide a more stable deployment [20], at the expense of more complex folds with higher residual stresses.

C. Origami Folding

A number of folding schemes for cylindrical booms have been proposed, based on origami patterns, which provide a promising method to compactly stow inflatable booms. Whereas z-folding

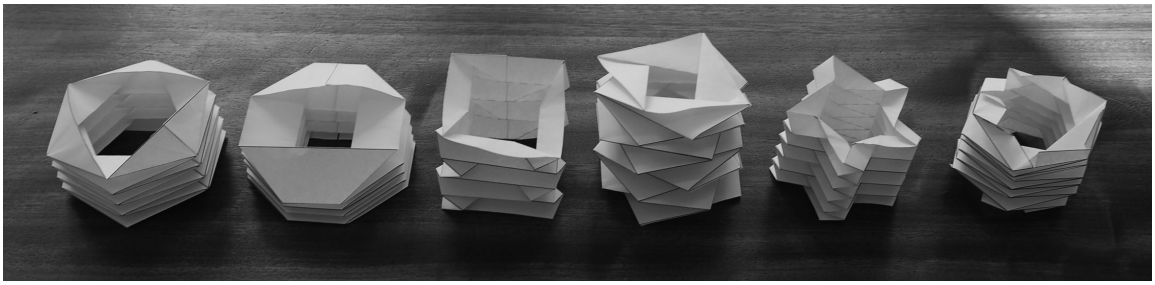


Fig. 3 Paper cylinders folded using fold patterns described in this section. From left to right: hexagonal Yoshimura pattern; tetragonal bellows fold; double-inversion bellows, with its derivative triangulated pattern; pentagonal Miura pattern; helically triangulated cylinder with hexagonal cross-section.

consists of simple parallel folds repeated along the length of the boom, origami patterns are more intricate and allow the booms to 'locally buckle' into the stowed configuration. Several examples of cylinders folded according to origami patterns described in this section are shown in Fig. 3. Unlike the z-folding, only single layers of membrane material are folded, and the open cross-section allows for good ventability of residual gas and assists in a uniform deployment. Furthermore, it is suited for rapid inflation as the deployment is driven by the inflation gas exerting a force on the distal end of the boom. First, several general concepts and challenges involved in engineering origami will be discussed, before reviewing proposed fold patterns.

a. Rigid Foldability & Material Deformation An important concept in applying origami to engineering, is the notion of 'rigid' origami. This assumes that the material does not bend or stretch between the fold lines, and can be modelled effectively as rigid panels connected by frictionless hinges [28]. A more relaxed definition is 'isometric' origami, where the material can bend but not stretch. Most fold patterns for stowing cylindrical booms cannot successfully be described using rigid origami, and therefore require material strains during the deployment. The degree of deformation of the facets during unfolding was shown to negatively impact the straightness of boom deployment [29].

The modelling of material deformation during the deployment of a folded cylinder has often been deliberately simple. For example, You and Kuribayashi [30] use a distortion factor: a simple geometric incompatibility between adjoining folding unit cells is taken as a measure of the deployment strain. Guest and Pellegrino [31] constructed 'triangulated' folded cylinders where the fold

lines were described by three helical patterns. They assumed that only one of the helices changes length during deployment, and its strain was taken as a measure of the total deformation. This approach was refined in [32]: by modelling the fold pattern as a pin-jointed bar framework (a fold line is represented by a bar, and a vertex by a pin-joint), any fold line could change length. The physical models discussed in that series of papers were constructed to have rigid panels connected by flexible hinges. When making similar folded cylinders from thin membranes, it is readily observed that the fold lines and facets may actually bend and twist during deployment. Capturing these deformations requires a more refined numerical modelling of the deployment, for example using the finite element method.

Interestingly, several of the fold patterns proposed for packing of cylindrical booms were in fact derived from stable inextensional post-buckling patterns of thin-walled cylinders under axial compression [33–35] or combined axial-torsional loading [36]. It is important to note that while the folded buckling states are inextensional, they are an isolated configuration and cannot fold or unfold without material strains: using these patterns for deployable booms will therefore necessitate some stretching of the material. This feature may also be used to advantage by designing multi-stable booms, which are undeformed in the stowed, a partly-deployed and fully inflated configuration [31, 37, 38].

b. Residual Creases Another area of interest is the effect of the residual creases on the mechanical properties of the inflated cylindrical boom. During deployment the material will have plastically deformed along its fold lines, leaving residual stresses and geometric imperfections in the cylinder. Research into the effect of creases on the properties of thin membranes [39–43] has shown that residual creases can reduce the effective modulus of the membrane by up to two orders of magnitude for low stress levels [40]; the stiffness will increase non-linearly as the folds are flattened out, and will approach the modulus of the constituent material for high strains. The folding can also result in micro-cracking along the fold lines, which will negatively affect the material properties. For example, in aluminium-polymer-aluminium laminates, cracking of the outer layers exposes the polymer to environmental radiation. Senda et al. [29] found that the stiffness, evinced by the natural frequency, of a rigidized (strain-hardened aluminium laminate) inflated folded boom was

reduced to about one-third compared to an unfolded boom; no analytical or numerical studies have been found to characterize this effect.

c. Material Thickness Research in engineering origami has primarily focused on the folding kinematics without taking into account any material thickness. However, some efforts have included the membrane thickness in the calculation of fold patterns for membrane wrapping [44, 45]. An important consideration is the thickness of a flat-folded vertex: this will be greater than the combined thickness of the layers due to finite curvature of the fold lines, as well as interaction of multiple fold lines at a vertex, and will therefore strongly affect the packing ratio of the folded booms. The stresses will also be highest at the vertices, with the risk of introducing pinhole punctures. The details of the folding behavior at the fold lines and vertices are currently not fully understood.

d. Stowed and Deployed Dimensions The geometry of the stowed configuration is key in attaining a high packing efficiency for the inflatable boom, and is determined by the choice of fold pattern. During deployment the outer diameter of the folded booms will vary: it may expand or contract to greater or lesser extent, depending on the fold pattern. For example, the fold patterns described by Sogame and Furuya [46] are purposely designed to expand both longitudinally and radially, and Kuribayashi [47] describes an origami pattern where the large change in radius was desirable for its application as a medical stent. For deployable booms in inflatable space structures an increase in radius may be desirable as it increases the bending stiffness of the boom after deployment, but also introduces challenges with connections to the satellite and other booms.

e. Fold Patterns A wide range of origami patterns has been proposed for folding cylinders. Often, the geometric differences are subtle, and the impact of the fold pattern on the boom deployment characteristics and material deformations remains largely unknown.

Nonetheless, some general geometric features are noteworthy. Firstly, the number of fold lines meeting at a vertex, *i.e.* the *degree* of a vertex. An origami vertex requires minimally 4 folds, but tessellations of degree-4 vertices rapidly become overconstrained and only a quirk of geometry enables folding [28, 48]. Higher-order vertices provide a greater degree of flexibility, but adding folds to a vertex increases the local strains and risk of pinhole punctures. Secondly, the basic elements of the fold pattern can either be tessellated to form a spiral along the length of the boom, or form a

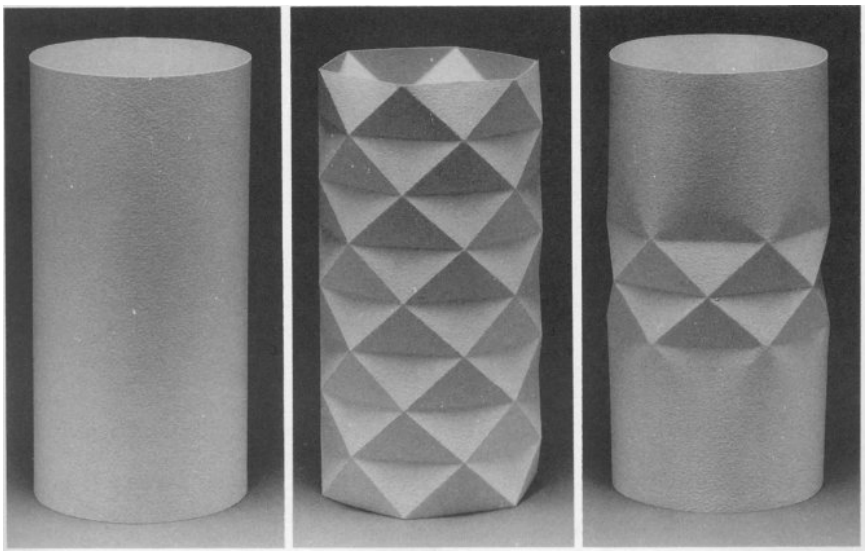
ring around the circumference that is repeated axially [49]. A helical pattern may have as benefit that deployment is coordinated along the length of the boom, rather than limited to individual sections, but also results in an axial twisting during deployment. Lastly, the packaging efficiency, stored strain energy and deployment characteristics are not only determined by the type of fold pattern, but also by the number of times a fold vertex is repeated around the circumference of the cylinder (*i.e.* the number of sides of the folded cylinder). These factors all contribute to the geometric richness of the origami patterns for inflatable cylinders, and the example fold patterns in this section have been selected to illustrate several of these variations. At present no consistent classification scheme exists for the origami fold patterns, and the boundaries between the presented categories are therefore necessarily blurred.

1. Yoshimura Pattern

The classic fold pattern associated with folded cylinders is the *Yoshimura* pattern; the fold pattern is shown in Fig. 4. Throughout this paper, when showing fold patterns, solid and dashed lines denote *mountain* and *valley* folds respectively, and the two axial edges would be joined to form the cylinders. The pattern is an inextensional post-buckling solution for axially compressed thin-walled cylinders [*e.g.* 33, 35]. It is, however, a stable configuration, and the booms thus cannot fold further without material strains. Similar patterns were found for axially compressed thin-walled cones [50]. Tsunoda et al. [51] studied the packing efficiency and micro-gravity deployment of inflatable booms using the Yoshimura pattern. The number of circumferential folds impacts the stowed height, as well as the strain energy stored in the folded boom. During deployment, the booms 'meandered' axially, but inflated uniformly. Senda et al. [29] showed that the hexagonal Yoshimura pattern does not compare well with other fold patterns in straight-line deployment, and requires large deformations of the fold lines and facets.

2. Bellows Folds

An important category of fold patterns for cylindrical booms is derived from the patterns used for folding bellows. Traditionally, bellows were designed to enable flexible motion over a limited range of motion, but they can be adapted to deploy from a flat to fully cylindrical configuration.



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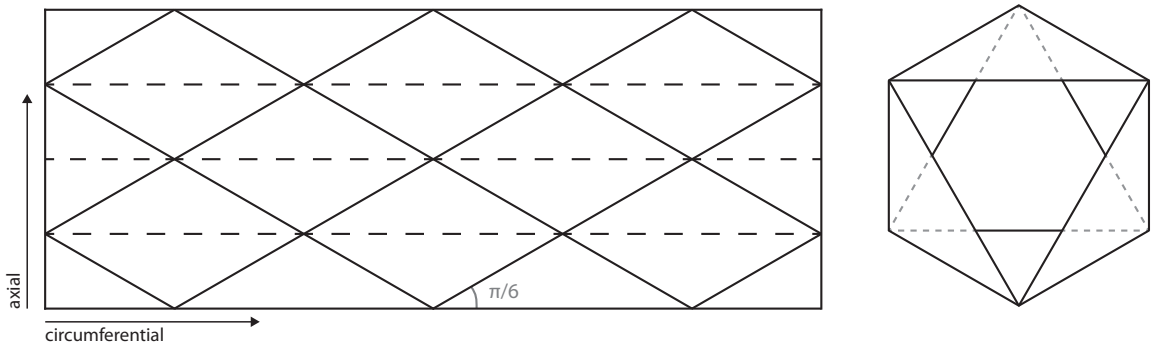
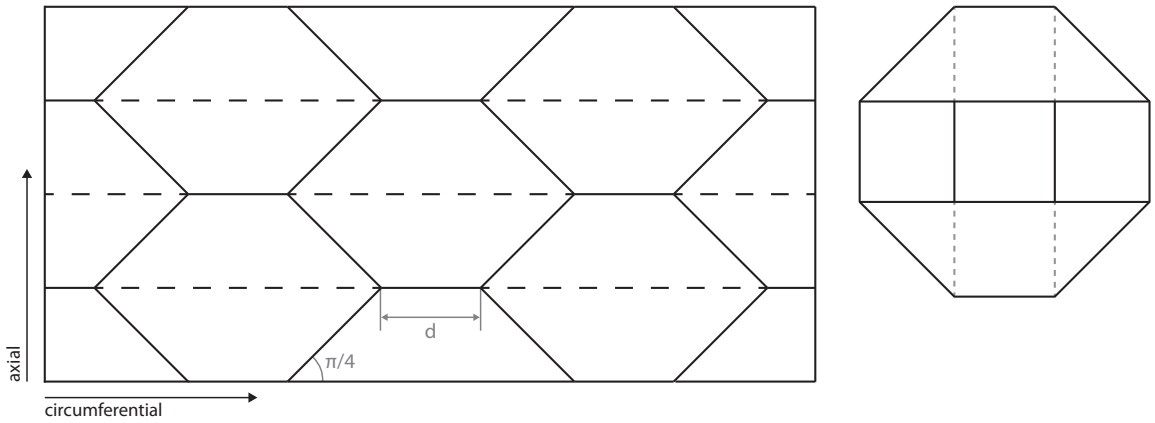


(b)

Fig. 4 The Yoshimura pattern: (a) approximation of the inextensional post-buckling geometry of an axially compressed thin-walled cylinder (image from Tarnai [35]); (b) fold pattern and cross-section of hexagonal Yoshimura pattern.

A classic bellows pattern is shown in Fig. 5(a); the pattern can be considered to derive from the *Yoshimura* pattern, by splitting the degree-6 vertices by a distance d. This fold pattern was used for the Tetragonal Accordion Deployment Control System (TADECS), an inflatable rigidizable boom for de-orbiting applications [52]; see Fig. 5(b). Lacour et al. [53] describes the fold geometry, which was selected for its minimal total fold length and interior space in its stowed configuration. An important novelty was the design of the deployment sequencing device: a strut with a clover-like device is placed inside the stowed cylinder, and during deployment the folds slide over the flexible petals, which snap back to retain the next folded layer.



(a)

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Fig. 5 A bellows pattern: (a) fold pattern and cross-section of a tetragonal bellows pattern, used for the (b) TADECS inflatable rigidizable boom for de-orbiting applications (images from Guenat and Le Couls [52]).

In Fig. 6 is shown the elementary unit of the bellows pattern, the '*reverse fold*'. A number of these folds are arranged around the circumference of the boom, with the resulting ring repeated along the length of the cylinder. In a stress-free stowed configuration of the cylindrical booms, the successive reverse folds must form a closed cross-section. As the bellows unfold (increasing dihedral fold angle $\alpha \in [0, \pi]$), the cross-section must deform to accommodate the change in enclosed angle $\beta \in [0, \pi - 2\varphi]$ of the reverse folds. The difference between the enclosed angle in fully-stowed and a partly-deployed state can be taken as a simple measure of the material deformation. While classic bellows patterns use single reverse folds at each corner, using two or more inversions can significantly reduce the average deformation during deployment [37, 54]. What is more, the use of multiple inversion enables the design of patterns that are stress-free in both the flattened, a partly-deployed, and fully inflated state; note that this does not include bending stresses along the fold

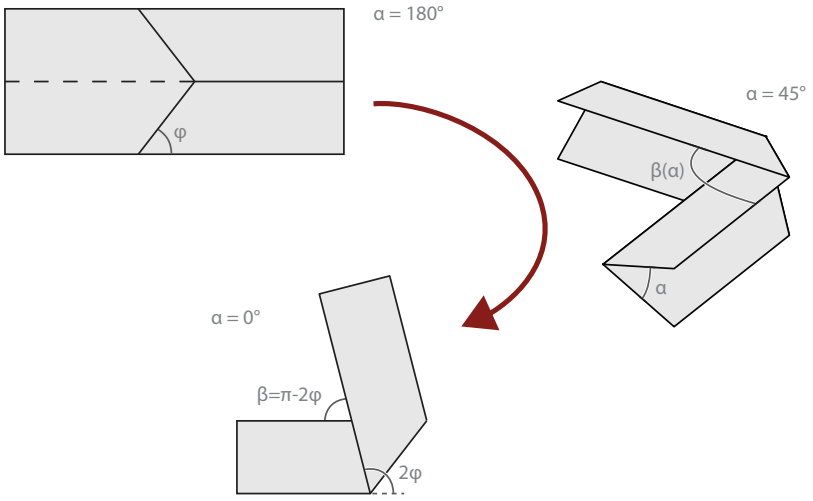
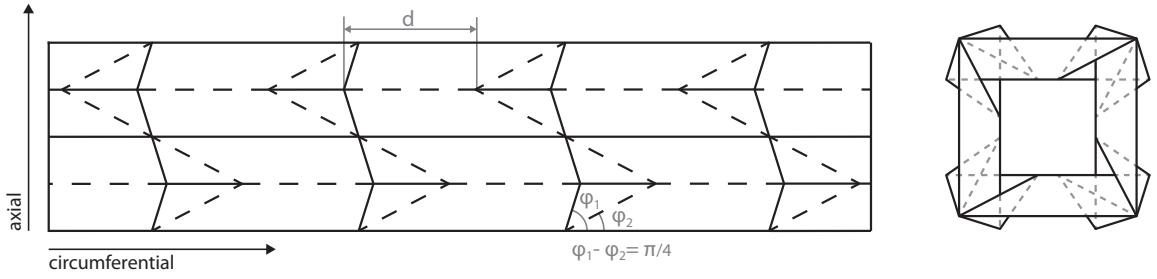


Fig. 6 Kinematics of a single reverse fold.

lines. Drawbacks of the use of multiple inversions include the increase in fold lines joining at the vertices, and the reduced packing efficiency due to the increased number of overlapping layers. The stowed height of the folded cylinder can be reduced by alternating the orientation of the fold pattern in successive layers, thereby offsetting the position of the flat-folded vertices; see Fig. 7(a). Shown are a fold geometry optimized by Kane [37] for a minimal mean deformation during deployment (fold pattern parameters: $\varphi_1 = 72.57°$, $\varphi_2 = 27.57°$). Kane [37] describes a wide range of modifications of the bellows patterns, including the triangulated cylinders formed by removing the spacing d between successive reverse folds; see Fig. 7(b). The triangulated cylinders will be discussed in detail in Section II C 4.

3. Miura Folds

This category of cylindrical folding patterns is derived from the classic planar *Miura-ori* pattern [55]: by varying the angles of the reverse folds from row to row, a global curvature is introduced. The use of these patterns for deployable structures was introduced by Sogame and Furuya [46], who described the geometry of the folded cylinders in their fully stowed configuration. Similar to the double-inversion bellows patterns, the convexity (*i.e.* mountain or valley fold assignment) of successive reverse folds is alternated. In the *Miura* patterns, however, they are separated into degree-4 vertices. The result is a star-shaped cross-section, which imparts the key feature that



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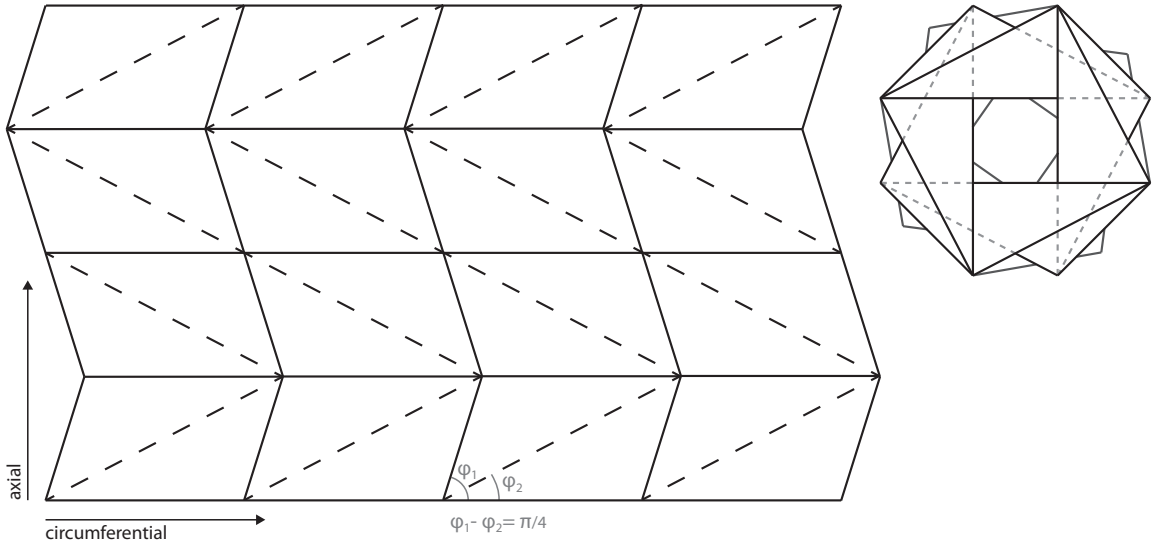

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Fig. 7 Variations of the double-inversion bellows fold pattern.

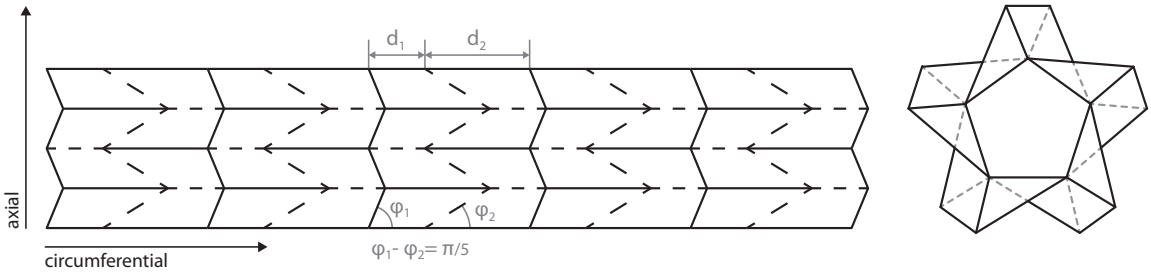


Fig. 8 A 5-sided cylindrical Miura fold pattern.

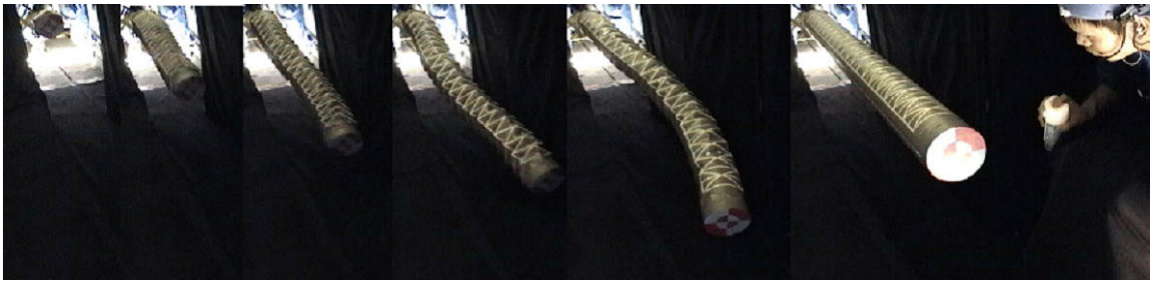
these booms expand both longitudinally and radially, and therefore have a negative Poisson's ratio. In Fig. 8 is shown a 5-sided cylindrical *Miura* pattern, with $\varphi_1 = 3/8\pi$ and $\varphi_2 = 7/40\pi$, where $d_1/d_2 = \sin(\varphi_1 - \pi/n) / \sin(\varphi_1 + \pi/n)$ to ensure no more than 4 layers overlap within each ring [46].

Senda et al. [29] studied the deployment characteristics of the *Miura* cylinders (there referred to as 'Star Shape Folding'). The tubes were made of aluminium laminate film, and were rigidized after

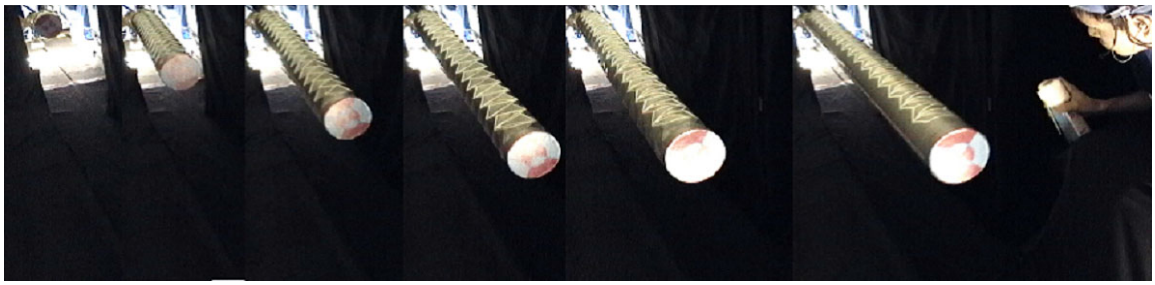
inflation by means of strain-hardening. Experiments were performed in a micro-gravity environment to study the deployment characteristics of various folding geometries, and determine the stiffness of the deployed and rigidized booms. The *Miura* cylinders were shown to have better straight-line deployment than those folded with the hexagonal Yoshimura pattern. This was ascribed to the amount of material deformation during deployment: in the Yoshimura cylinder the fold lines and facets deform significantly. It was argued that the star-shaped pattern provides an additional geometric parameter that can be tailored to synchronize the modules and expand the boom in a straight line. That link between the geometry and the deployment characteristics, however, was not fully elucidated. In fact, the patterns for the experiments were selected through trial and error. In their finite element analysis Senda et al. [29] studied the deformation of the folded boom subject to an applied internal pressure; the stiffness of the folds was modelled using a spring element. The Yoshimura cylinder was shown to be the hardest to deploy, and involved the highest stress concentrations. The stiffness of the rigidized booms, quantified by their fundamental vibrational frequency, was experimentally found to be effectively independent of the fold pattern. The measured frequencies were, however, decreased to between one and two-thirds of that of an unfolded cylinder; this may be due to residual creases, connection details at the base of the boom, and cracking of the thicker aluminium laminates at the creases.

4. Helically Triangulated

Among the best studied patterns is the helically triangulated cylinder; see Fig. 10. Guest and Pellegrino [31] first describe the geometric relationships of the triangulated cylinder, where it was assumed in the analysis that the folding is uniform throughout the cylinder, in contrast to experimental observations. By further assuming that only one type of fold line changes length, geometric arguments enabled the design of triangulated cylinders that are free of stresses in both their stowed and deployed state. It was shown that the deployment strains become smaller as the number of sides of the cylinder is increased; the trade-off is the packing ratio. Guest and Pellegrino [32] refined the analysis by introducing a pin-jointed truss model of all fold lines in the cylinder, whereby all lines undergo strain. It was shown that during axial compression, the boom



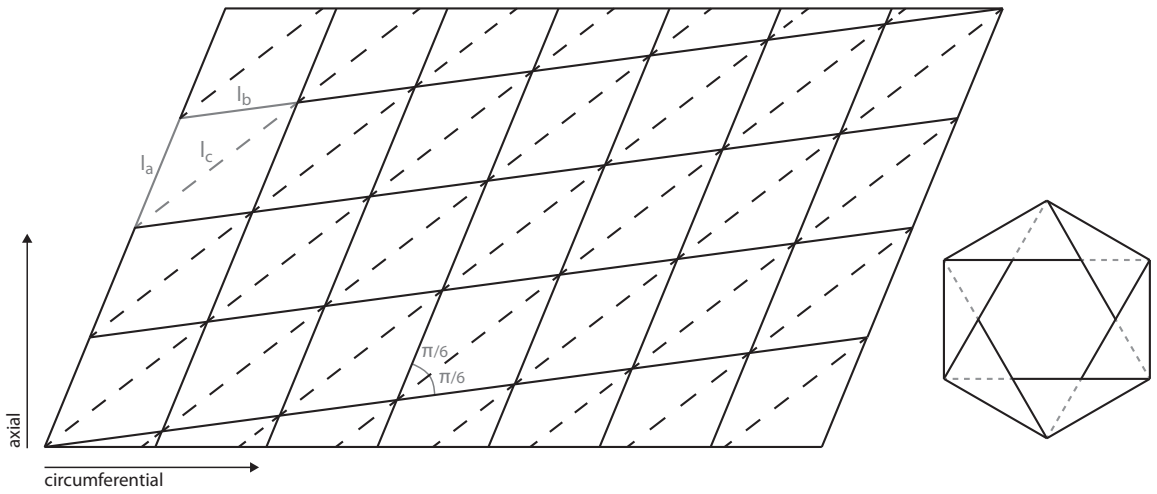
(a)



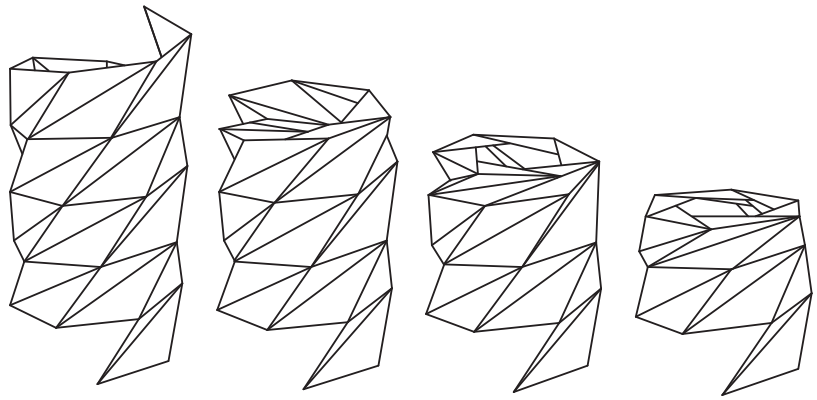
(b)

Fig. 9 Micro-gravity deployment tests of inflatable rigidizable booms, with (a) a hexagonal Yoshimura pattern, and (b) a pentagonal *Miura* pattern (images from Senda et al. [29]).

would collapse sequentially under a nominally constant load, in a manner similar to a propagating instability [56], as illustrated in Fig. 10(b). Further refinements were added to the numerical model in Guest and Pellegrino [57], including the effect of manufacturing imperfections and a rotational stiffness along the folding hinges, giving accurate simulations of the axial behavior of the cylinders. Note that the effects of the inflation gas exerting an internal pressure were not taken into account in the analysis. The studied triangulated cylinders had rigid facets with flexible hinge lines, which allowed for relatively compact mechanical models. However, for inflatable booms made of flexible membranes, the assumptions of straight fold lines will no longer hold. In a follow-up study by Barker and Guest [58], the inflation of annealed aluminium cylinders with a (non-helical) triangulated pattern was described; see Fig. 11. Here the orientation of successive folded layers was reversed, to avoid relative rotation of the ends during deployment. An important feature of the helically triangulated patterns is that the fully stowed cross-section is not necessarily a regular polygon, and that the vertices can therefore be offset with respect to each other in successive layers, reducing the stowed dimensions of the boom.



(a)



(b)

Fig. 10 The fold pattern (a) for a helically triangulated cylinder, and (b) its progressive collapse mechanism under an axial compressive load (image after Guest and Pellegrino [32]).

Many of the fold patterns discussed previously can be recognized in geometric studies such as Nojima [49], who described generalized flat-folding vertices and provided the closure conditions for the flat-folded stowed state. Most patterns can also be rotated to have the major fold lines oriented helically along the cylinder.

5. Rigid Origami Cylinders

Recent developments in the kinematics of rigid origami have led to the design of truly rigid-foldable tubes [59–61]. Unlike previously described folded cylinders, these can be folded continuously from a fully flattened to an extended configuration with only bending at discrete fold lines; see

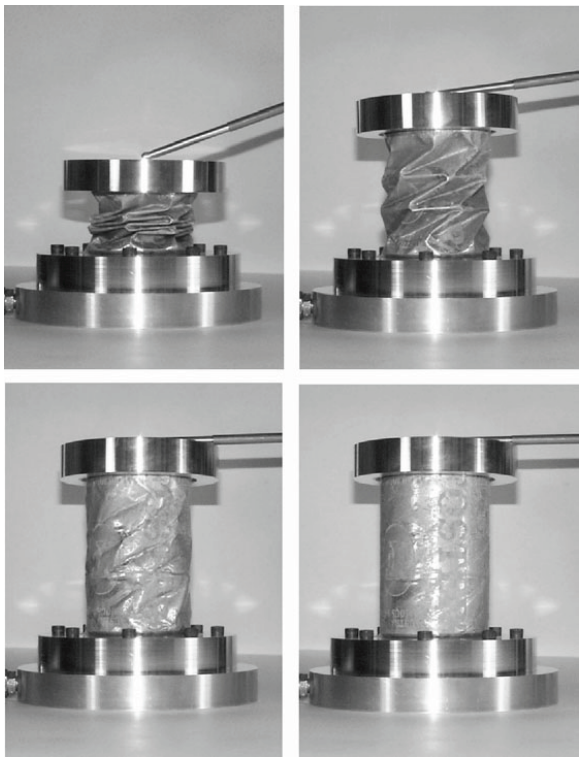


Fig. 11 Inflation of an aluminium triangulated cylinder (image from Barker and Guest [58]).

Fig. 12. A crucial consideration, however, is that the proposed cylinders contain vertices with non-zero Gaussian curvature (apices and saddle points). The folded tubes therefore cannot assume a purely cylindrical configuration without significant material strains, restricting their suitability for inflatable booms. Note that in the literature, the term 'rigid origami cylinders' may also refer to the manufacturing process, rather than the deployment. For example, Wang and Chen [62] and Wu [63] describe the rigid origami folding of a flat sheet into a pseudo-cylindrical surface; once joined at the edges, the cylinder will be rigid and non-foldable. The axial collapse of the cylinder can then be used for impact absorption, by dissipating energy during compression.

In summary, the use of origami fold patterns is a promising approach for storing inflatable cylinders. Advantages include compact stowage, good ventability, potential for straight deployment, and suitability for rapid deployment due to the open cross-section. Furthermore, the plastic deformation along the fold lines provides a resistive force during inflation. Challenges include accurate folding of the booms, the design of a transition from the fold pattern to a fixed connection, and quantifying the reduced strength after deployment due to residual creases and micro-cracking at the fold lines.

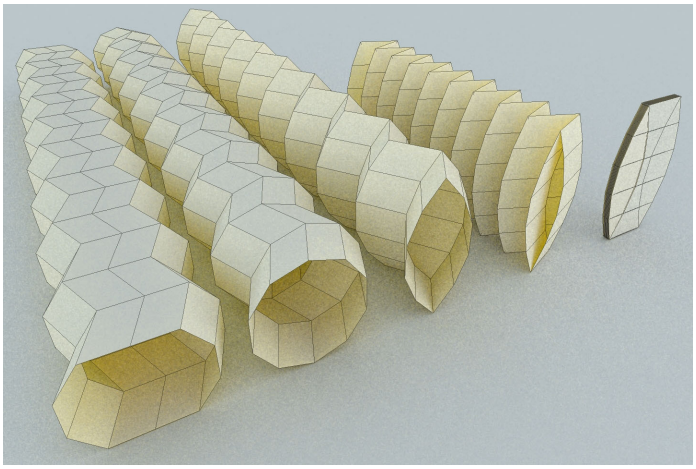


Fig. 12 A rigid-foldable cylinder (image from Tachi [59]).

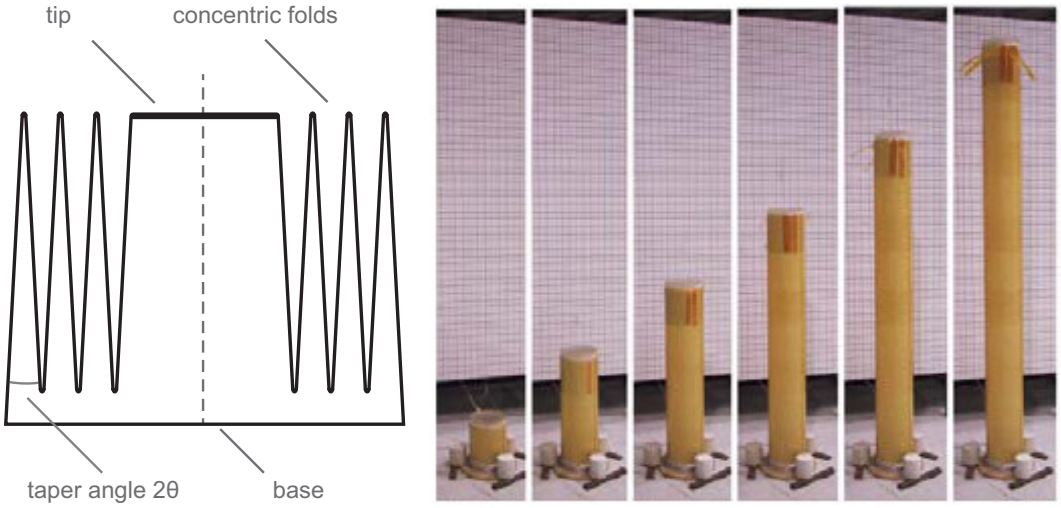
The geometric richness of the fold patterns and the relationship with the deployment characteristics and ultimate mechanical properties of the inflated booms is relatively unexplored.

Accurate modelling of the deployment dynamics is complex, as it must cover local mechanical effects such as wrinkling and plasticity, global effects such as shell buckling, as well as complex fluid-structure interaction. Experimental investigations will therefore be necessary to validate simplified modelling methods, and to advance the design and selection of suitable fold patterns.

D. Conical Folding

By introducing a slight taper, a conical boom is formed, which can be inverted and everted at regular intervals, to form a compact telescopic stowage configuration [64]; see Fig. 13. This approach is distinctly different from previously discussed packing methods, as the cross-section remains largely undeformed throughout stowage and deployment of the inflatable boom. Furthermore, folding does not take place at discrete locations along the boom, but instead the concentric folds will 'travel' through the material during deployment, dissipating energy through plastic deformation.

Inflatable conical booms were developed by L'Garde for the NASA In Space Propulsion (ISP) project [5, 66], and the concept was space-qualified on the Cibola Flight Experiment, in combination with a sub-T_g rigidization technique [67]. In order to improve the straightness of deployment, a mandrel can be placed at the narrow end of the conical boom, providing a stiff surface for the material to roll on [64, 65]. An alternative conical boom stowage method, referred to as the 'Goodyear



(a) (b)

Fig. 13 A conical boom is alternatingly folded along concentric folds, resulting in a compact telescopic stowed configuration. In the cross-sectional view (a) the boom has a conical taper angle θ and is axi-symmetric around the deployment axis. In (b) is shown the deployment through inflation of a telescopic conical boom (image from Palisoc et al. [65]).

deployment scheme', was mentioned by Johnson [68]. Here the inverted section is rolled onto a drum inside the boom, which provides a retardation force during deployment.

The precise mechanics of the conical boom deployment is not elucidated in the literature, and likely consists of a combination of effects. Veal et al. [64] note that the boom elongation is resisted by friction, which is reduced when inflation gas flows between the folds. The outermost folds experience the greatest longitudinal force, and will therefore deploy first. Another mechanism is profferred by Palisoc et al. [65], in which inflation presses the walls of the cylinder against the outer layer, so there is no relative motion between the folded layers, leaving the outer layer free to 'peel' away as the boom deploys. In either case the outer folds are most likely to deploy first. It is important to note that the deployment characteristics will depend on the amount of taper of the conical boom: for a large taper there will be no contact, and thus no friction, between the nested layers. Dynamic deployment of a strongly tapered conical boom with a single inversion was modelled using finite element analysis by Wang and Johnson [19]. The mechanics of the deployment observed depended on whether or not the inertia of the inflation gas was taken into account in the analysis. Similar dynamic deployments were reported in Li et al. [69] for conical booms with multiple inversions.

Importantly, the deployment mechanism is significantly different from the minimally tapered and quasi-statically deployed booms in Palisoc et al. [65].

The conical boom stowage method has several benefits: a controlled and straight deployment, a load carrying capacity during deployment, the ability to attach a membrane at multiple points along the boom length, good ventability of any residual air, and minimal initial deployment due to residual stresses. Veal et al. [64] also suggest that a tapered boom can reduce boom mass by as much as 40% without any loss in buckling strength, and that a tapered boom has a higher natural frequency than a cylindrical boom of same base radius; the mechanical characteristics of tapered inflatable booms are analyzed by Veldman [70]. One important consideration is that as the telescopic sections deploy, a plastic hinge travels through the material, which may result in undesired residual stresses and material damage.

III. Materials & Rigidization Techniques

Inflation gas can be relied upon to provide post-deployment structural rigidity for a finite period of time. Inevitably the inflation gas will escape through tiny imperfections in the inflatable skin such as pinholes that have appeared during manufacture, folding or deployment. The higher the inflation pressure, the faster this process will occur. Larger structures tend to require lower inflation pressures, perhaps only a few pascals, while smaller structures, especially strain rigidized booms, may require pressures of one bar or more. In larger structures, if inflation pressures are sufficiently low, the mean free paths of molecules in the gas will be long enough to make the probability of their encountering a hole so small that the requisite pressure will be maintained, perhaps only requiring occasional replenishment from extra stores of gas. Nevertheless, for the majority of missions lasting more than a few weeks, structural rigidity can only be maintained if the inflatable skin can be strengthened, or *rigidized*, following deployment. A variety of materials has been proposed for use in space inflatable rigidizable structures. This section describes some of the materials and rigidization techniques either used, or proposed for, use in inflatable rigidizable booms and truss structures.

Numerous reviews of inflatable rigidizable materials have been published to date: Cadogan [71],

Cadogan and Scarborough [72], Bernasconi and Reibaldi [73], May and Wereta [74], Forbes [75], Defoort et al. [76], Freeland et al. [77] and Lou and Feria [78]. The majority of these have been written by authors with a commercial industrial background. The proposed methods of categorizing inflatable rigidizable materials are equally numerous. In the following, materials are grouped by the particular methods used to rigidize them: UV setting resins (both solar and lamp cured), thermosetting resins, glass transition resins, gas cured resins, stretched metal laminates, evaporation/dehydration hardened materials, shape memory polymers, rigidizing foams, photalyzing film with wire frames, and embedded structural components.

There are several generally desirable characteristics of inflatable rigidizable booms that each rigidization method is able to address to a greater or lesser extent.

Stowage and Handling The ease of handling is important on the ground, as some specialized resin curing techniques make production, handling and storing laborious. The ease of stowage often depends on the thickness of materials, and the complexity of accompanying equipment such as thermal insulation blankets. Storage life is of key concern in missions in which deployment and rigidization are not scheduled to occur immediately after launch. Many rigidization techniques now exhibit storage lives of several years.

Rigidization Process The energy requirements for rigidization can vary from nothing for some passively cured resins, to a substantial sustained supply of energy as might be the case with thermally cured resins. Reversibility of a rigidization process can allow for more thorough ground testing of space hardware, as well as permitting missions with multiple deployment/stowing cycles. Outgassing (the release of a gas or vapor stored in the material, especially once in vacuum) generally must be kept to a minimum. The performance of rigidization techniques in this area varies widely. Uniformity of cure is a concern for many resin- and radiation-based rigidization methods. Uneven curing or drying can lead to uneven shrinkage and other distortions, changing the global shape of the structure. Rigidizability in a variety of thermal environments is a characteristic likely to increase the versatility of most missions.

Structural Performance The range of attainable deployed geometries can depend significantly

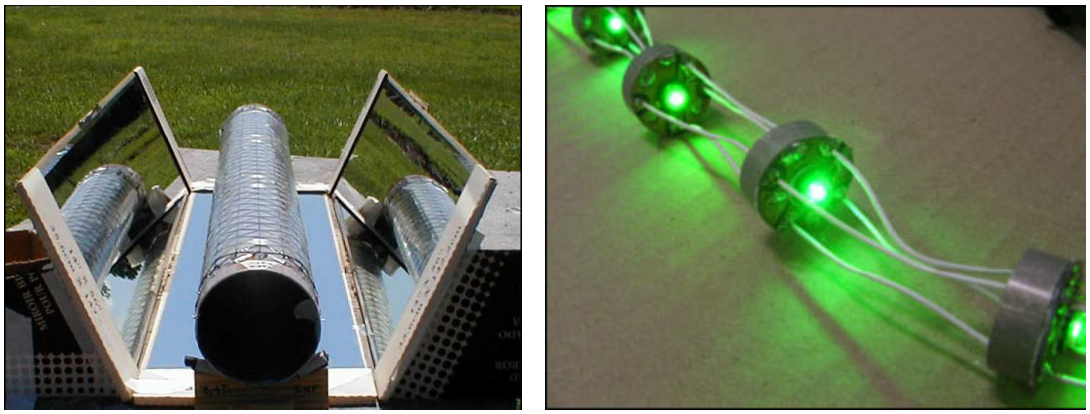
on the type of rigidization technique. Deployed structural properties also vary widely depending on the method chosen. Some composites can produce quite strong and rigid deployed structures, while for example stretched metal laminates are fundamentally limited in load bearing capacity. Resilience in the space environment is of key concern in missions which may span several years post-deployment. A low Coefficient of Thermal Expansion (CTE) is desired or required for structures supporting precise instruments such as optics, but can be less important for applications where a precise geometry is less crucial.

The suitability of a particular rigidization method for a given task must be assessed in terms of these characteristics.

A. UV-Setting Resins

Much early work in the field of UV-setting resins was performed by the US Air Force and the Hughes Aircraft Company [79, 80]. Later, the combination of a foam driven inflation followed by the UV hardening of a resin impregnated skin was examined [81, 82] (the intention being to use environmental UV radiation for curing). Later again, Adherent Technologies Inc. demonstrated the use of UV rigidization in inflatable isogrid booms, using both environmental [83], Fig. 14(a), and lamp-based [84] sources of radiation, Fig. 14(b). The use of internal lamps operating at various wavelengths in rigidizing pre-impregnated folded inflatable booms has been demonstrated [52, 85, 86]. Lamps have also been used to successfully cure a small non-inflatable gossamer structure during the parabolic flight of the FOCUS (First Orbital Curing Experiment of University Students) experiment [87]. The advantages of UV driven rigidization include long storage life, low outgassing and a wide variety of possible deployed shapes. Using solar radiation for curing allows for the possibility of a purely passive rigidization process, while the use of lamps allows for a more precisely controlled cure at the expense of greater system complexity and power consumption.

The choice of reinforcing fibers for use with UV-setting resins is limited, because for a full cure, UV radiation must penetrate to all layers of the rigidizable laminate, limiting the types of fibers that can be used, as well as the wall thickness of the structure. Many high tenacity fiber types, such as graphite, do not allow sufficient UV transmission. In addition, the polymer bladders used to contain



(a) (b)

Fig. 14 Rigidization of UV-cured resins using (a) solar radiation (image from Allred et al. [83]), and (b) a string of curing lamps (image from Mahias et al. [85]).

the inflation gas can also prevent critical wavelengths from reaching the rigidizable structure. The possibility of uneven curing and warping can be great when using environmental radiation as the curing agent. Finally, UV rigidization is irreversible, making the handling and ground testing of space hardware more difficult.

B. Thermosetting Resins

Thermally cured composites are particularly attractive candidate materials for space-rigidized inflatables because of the substantial heritage of similar composites for terrestrial applications, and because of the resulting high stiffness, high strength structure. Thermally cured resins are compatible with a wide range of reinforcing fibers, and can be used to create laminates with low out-gassing, good space resilience and a low CTE. The source of heat for curing can be either the sun [88–90], or a local source such as embedded heating elements [91, 92].

Thermally cured composites come with the added advantages of a passive rigidization process if using solar radiation, or a highly controlled curing process if using embedded heaters. There is almost no limit to the shape of the composite component of the inflatable booms: it can form the skin itself, or a rigid superstructure built around an inflatable bladder [93]. Thermosetting resins have traditionally suffered from relatively short storage lives, although formulations with storage lives of many years now exist [72]. It is also possible that the retention of heat could prove difficult

during deployment and curing, although the use of a multilayered insulation (MLI) blanket [71] can mitigate the problem. The cure process is irreversible, again making testing and handling of space hardware more difficult. Cure energies can be quite high, and if using solar radiation as the curing agent it can be difficult to ensure a uniform cure. The pre-deployment thermal environment must also be carefully controlled to prevent premature rigidization.

C. Glass Transition Resins

Many materials (including polymers) exhibit a change in state called a glass transition, which always occurs below the melting point, and is not a phase transition. Crystalline polymers generally consist of a portion which is purely crystalline, and a portion which is amorphous. While the crystalline component only loses its solid form during melting, the amorphous component undergoes a change in mobility at the glass transition temperature, T_g, resulting in a rubbery polymer. This property can be used to great advantage in inflatable booms by creating a structure which self rigidizes below a certain temperature once deployed.

L'Garde Inc. has made extensive use of sub-T_g resins in their boom designs [3, 5, 94–97], and notably in their 20m solar sail demonstrator [98, 99]; see Fig. 15. They have experimented with resins with T_g's of +50°C, +20°C, 0°C and -20°C [100]. L'Garde performed flight-tests of sub-T_g rigidizable Kevlar reinforced technology on the Cibola Flight Experiment [67]. Additional experimentation with sub-T_g resins has been performed by the United States Air Force (USAF), who developed the RIGEX boom [101] making use of sub-T_g resin, while ILC Dover has proposed the use of sub-T_g resins for a hexapod structure [102], and has also experimented with sub-T_g shape memory polymers (SMP) [4, 103–105]. SMPs mimic the behavior of shape memory alloys, and will naturally re-assume their pre-heating shape when heated above their T_g. This unusual behavior allows for more intricate self deploying structures than can be achieved using inflation alone.

While glass transition polymers are not generally as rigid as thermosetting resins, the reversibility of the rigidization process makes multi-deployment missions possible, and facilitates easy ground testing of components. Prior to deployment, composites making use of sub-T_g resins will usually have to be heated to ensure the necessary flexibility. Once full deployment has occurred, rigidiza-

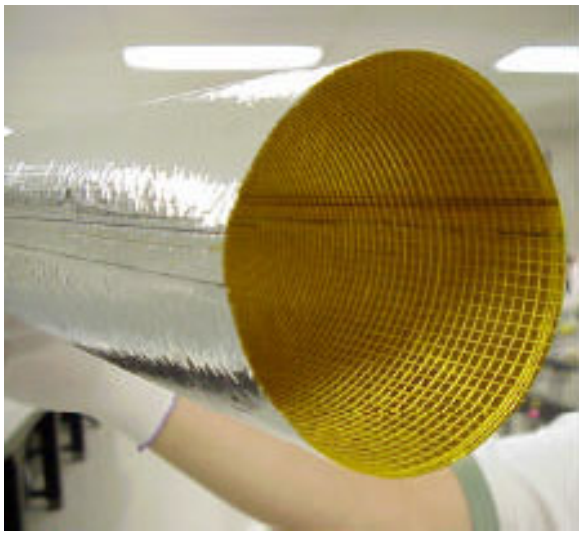


Fig. 15 Internal view of an inflatable boom with sub-T_g resin impregnated fibers running in hoop and axial direction (image from Lichodziejewski et al. [5]).

tion happens passively as the structure cools. A complicating feature of glass transition rigidized structures is the requirement to keep the deployed structure below T_g at all times, and will most likely require the use of an MLI blanket to protect the structure from solar radiation and other heat sources.

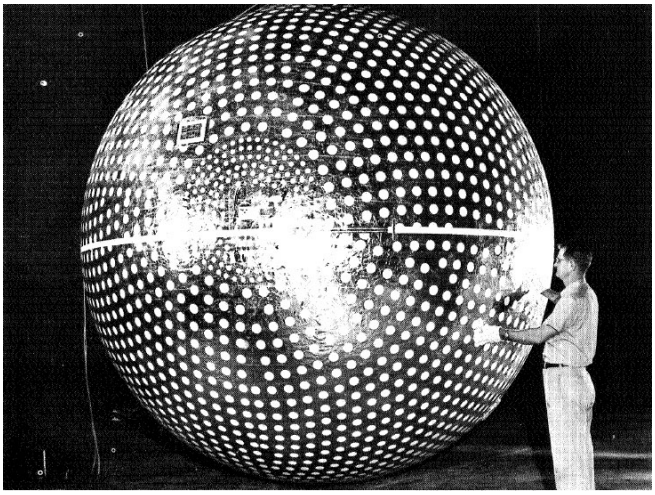
D. Stretched Metal Laminates

Stretched metal laminates have the most extensive heritage of deployment in space. Metal laminates consist of thin layers of ductile metals (usually aluminium) bonded to thin layers of polymers. Commonly used polymers are BoPET (Mylar®) and Kapton®. The metal component adds structural rigidity, while the polymer layer(s) act as a vapor barrier and improve toughness.

Metal-polymer laminates are used to form the skins of inflatable deployable structures. Once the structure is fully deployed, the internal pressure is increased until the metal component in the laminate slightly exceeds its yield stress; the polymer component remains elastic at all times. Once the inflation gas is vented or escapes, the pressure loading is removed and the structure attains a state of pre-stress in which the metal component is in compression and the polymer is in tension. Metal laminate structures gain their rigidity locally through strain hardening of the metal, and globally through the removal of imperfections (fold lines, creases) in the laminate surface during

yielding. The pre-stressing does, however, reduce the laminate's compression carrying capability. Different combinations of layers have been tried, including metal-polymer-metal, polymer-metal-polymer, and two-layer laminates [29, 106].

NASA began experimenting with metal laminates for space applications in the late 1950s [107], and later successfully launched aluminium-Mylar laminate spheres for passive communication tests and atmospheric density experiments: Explorer IX in 1961 [108], Explorer XIX in 1963 [109], see Fig. 16(a), and the larger Echo II in 1964 [1, 106, 110, 111]. L'Garde (with the sponsorship of NASA Langley) experimented with metal laminate inflatable booms [112], and improved the structural performance of their booms by spiral wrapping [113]; see Fig. 16(b). This wrapping reduces the hoop stress in the boom, allowing axial yielding to occur more fully (see Greschik and Mikulas [114] for a description of the effect of inflation on axial versus lateral creases in metal laminate cylinders). L'Garde has also launched a metal laminate sphere of its own [113]. EADS Astrium have employed a kapton-metal-kapton laminate inflatable boom in their proposed 'dihedral' wing de-orbiting device [115, 116], and Senda et al. [29] studied the inflation and rigidization of aluminium-laminate origami-folded cylinders.



(a)

(b)

Fig. 16 Strain-rigidization of metal-polymer laminates in (a) the Explorer XIX satellite [109], and (b) a z-folded spiral-wrapped boom (image from Lichodziejewski et al. [113]).

Stretched metal laminates have seen such extensive use because they are simple to manufacture and handle, rigidize predictably, have extremely low outgassing, can be stored almost indefinitely and

suffer few radiation effects (although the choice of polymer will affect this). The rigidization process is also largely reversible, with some degradation in structural performance with each subsequent deployment. The overall thickness of metal present in the laminate must be limited to roughly 100μm to prevent de-bonding. The thickness of metal is also generally required to be greater than that of the polymer to prevent auto-buckling after yielding [112]. These features limit the load carrying capacity of stretched metal laminates in general, and restrict their use to applications in which structural loads are minimal. Stretched metal laminate structures are also limited in the variety of shapes they can be used to form: only simple geometric shapes can be used if there is to be a uniform stress state throughout the structure. Inflation gas pressures must be carefully controlled during the yielding process if bursting is to be avoided. In particular for inflatable booms, the rigidization pressures will be greater than the pressure required for initial inflation of the structure, and more inflation gas will be necessary than for competing rigidization techniques.

E. Gas and vapor Cured Resins

Gas and vapor curing techniques for space inflatables received a lot of attention in the 1960s [79]. A variety of resins and catalysts has been proposed, including a water-setting resin impregnated fiber glass [117] and polyurethane polymers rigidized by volatile peroxide vapor [118]. Experiments have also been performed on polyurethane foam that rigidizes in a self-propagating reaction initiated by an aerosol delivered catalyst [119]. Gas curing also has been proposed as a supplement to thermosetting resins [120, 121].

The advantages of using a gas or vapor cured rigidizable structure include a passive curing process, and a wide variety of potential resin-fiber combinations. However, the method has been largely neglected in recent years because of the potential for outgassing of large quantities of hazardous catalyst. Overall laminate thickness is also likely to be limited if proper catalyst penetration is to be assured, and on-ground handling of vapor cured resins can be difficult, especially when using water-setting resins.

F. Solvent Boil-Off Rigidization

Inflatable structures making use of certain resins can be kept flexible by the use of softening solvents. The composite is covered in a vapor barrier to prevent evaporation of the solvent during storage. If sections of the barrier are made permeable to the solvent, and those same sections are folded or rolled up during storage, then rigidization will only occur after deployment. L'Garde experimented with Hydrogels when building the IRSS truss [122, 123], Fig. 17, which rigidizes via dehydration. Polyvinyl Alcohol (PVA) and even Gelatin have been proposed as suitable evaporation-rigidizable materials [79, 124, 125].

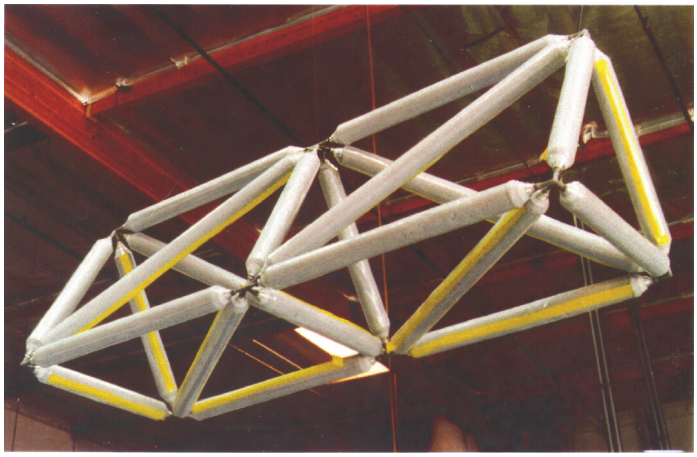


Fig. 17 IRSS truss using Hydrogel rigidization [123]. Image courtesy of L'Garde.

Solvent evaporation or boil-off rigidization appealed initially because of the simplicity of the process, the ready availability of suitable materials and the energy free rigidization step. The method's suitability for modern space applications is limited by the very large outgassing ($> 15\%$ total mass loss), and the likelihood of uneven drying and shrinkage.

G. Foam Rigidization

Foams have been proposed for space rigidization in a number of ways. Foam can be released from a central location, filling the structure and driving the deployment itself [126–128]; see Fig. 18. Alternatively, the interior walls of the structure can be pre-coated with material that foams either under the action of a catalyst, by heating [75, 129, 130], or simply in the presence of a vacuum [81]. Finally, thermoplastic foams that are pre-formed, stored and cooled on earth before heating above

the T_g in space which causes the foam to expand, have also been proposed [72].

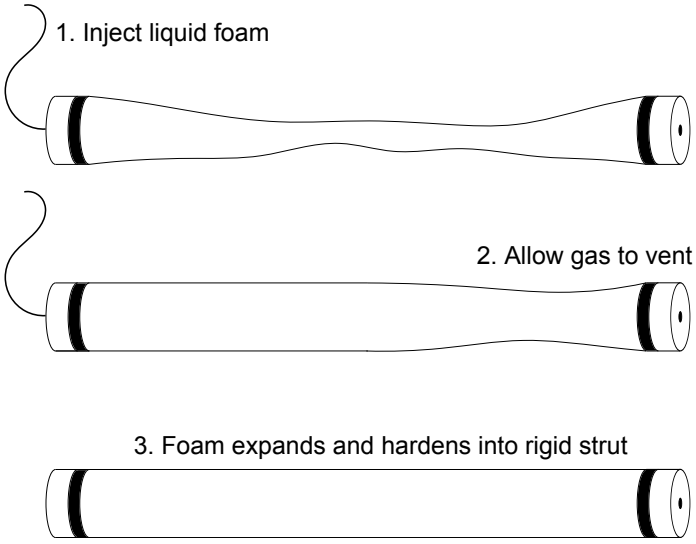


Fig. 18 Foam rigidization of a Kapton boom (figure after Griffith and Main [127]).

Foams that harden once deployed can add structural rigidity to their encasing booms or shells. There are fundamental difficulties in ensuring an even spread of foam during rigidization in space, and outgassing of foaming by-products could pose a problem. It has also been suggested that foams are unlikely to add to the structural performance of fiber reinforced composites in any meaningful way, although they may be appropriate for thin film or laminate booms [131].

H. Photolysable Structures

Possibly the most exotic inflatable rigidizing structures were the US Air Force's OV1-8 (Fig. 19) and AVL-802 (Gridsphere) experiments [132], launched in 1966 and 1971. Both types were spheres consisting of a thin film with an embedded wire mesh. On deployment the thin film acted as a bladder which drew the wire frame out into a spherical shape. The wire provided a rigid frame for the satellites. After a short while, the film photolysed (vaporized) under the effect of solar radiation, leaving behind the wire frame. What remained was a 'passive communication satellite', just as reflective to certain frequencies of EM radiation as a continuous sphere, but with much lower aerodynamic drag.

Fig. 19 The OV1-8 satellite with photolysable inflatable bladder embedded in a wire frame mesh (image credit: USAF).

I. Embedded Structural Components

In a last category of rigidization, the structural performance of the inflatable structure is derived from embedded components. NASA JPL has augmented metal laminate booms with tape springs to aid deployment and provide rigidization [17, 133, 134]. The increase in mass of the inflatable booms is offset by the structural performance, during and after deployment.

IV. Discussion

The development of space inflatables dates back to the dawn of spaceflight in the 1960s, and has been actively researched ever since. Despite this, the TRL of most space inflatable technologies has remained relatively low, with most flight missions limited to technology demonstrators, such as the IAE and the Cibola Flight Experiment. It is possible that the perceived risk of using inflatable structural components has outweighed the potential benefits. These benefits remain enticing, with a promise of high packaging efficiency, low system complexity, low cost and a simple deployment mechanism. Nonetheless, several factors have contributed to the limited uptake of space inflatables for flight missions.

Firstly, the deployment sequence of space inflatables is often unpredictable, and thereby seen to carry an inherent risk. Demonstrator missions such as the flagship IAE have unfortunately not

helped to improve this reputation. The predictability of deployment of inflatable booms can be significantly improved by introducing deployment control systems, at the expense of an increase in system complexity, and by careful design of the packaging method. In the last decade two promising packing methods have been explored: origami patterns, and conical-telescopic booms with concentric folds. The NASA Sunjammer mission [135] will include the deployment of inflatable conical-telescopic booms, which had previously been flight-tested on the Cibola Flight Experiment [67]. In Europe and Japan the focus has been on using origami patterns to stow inflatable booms, for example for an inflatable de-orbiting system under development by EADS Astrium [52, 115]. Deployment tests under micro-gravity conditions have demonstrated the potential of the origami folding approach [29].

Secondly, in order to ensure long-term structural performance of the space inflatable, the skin must be rigidized after inflation. This has proven to be a significant hurdle in raising the TRL of inflatable structures. Of the rigidization methods discussed in this paper, those that employ physical or mechanical means to rigidize (metal laminates and sub-T_g resins) have been used most frequently in space missions. The reason is in part historical. Strain rigidization of metal laminates was the method of choice for the NASA and US Air Force observation and passive communication balloon satellites in the 1960s. The relative success of these balloon missions gave metal laminates a head start on the TRL ladder. Sub-T_g resins have had some success in space, and will receive a boost with the launch of NASA's Sunjammer solar sail [135]. Rigidization methods that employ chemical means have, for the most part, remained the subject of research and experimentation. In addition to the undesirable complexity these methods add at a system level, this has occurred because of: high levels of outgassing of solvents or curing agents; lack of uniformity of cure for large or complicated geometries (particularly when using solar radiation to drive the cure); difficulty in handling pre-rigidized chemicals on the ground; short storage life of chemicals; large energy requirements for curing; and the limited skin thickness allowed in some cases for a thorough cure. Many of these problems have been overcome, but the TRL of the majority of these technologies remains low.

Perhaps another reason for the limited use of inflatables in space is the fact that the physical scaling laws for stiffness and strength appear to favour the design of larger rather than smaller

inflatable structures. This is further compounded by taking into account the mass and volume of the inflation system. In order to be competitive with alternative deployable structure technologies, the inflatable structures may have to be larger than any of those currently launched. This brings with it new challenges associated with ground-testing of these large inflatables.

Lastly, an important challenge of inflatable structures is attaining and maintaining a high accuracy of deployed shape. Recent developments in active shape and vibration control using embedded piezo-electric elements have promised improvements [136]. Nonetheless, it may have to be accepted that space inflatable are fundamentally not well suited for high precision applications. The surface accuracy required for reflectors or optical components exceeds the accuracy which can easily be obtained with inflatables. In addition, the CTE of inflatable rigidizable materials is often too great for such missions. Inflatables are, instead, more suitable for large deployable missions in which precise deployed geometry is not required. Therefore, solar sails, drag deorbiting devices, observation targets and deployable solar arrays are examples of applications which could see the use of inflatable structures in space expand in future years.

V. Conclusion

Inflatable space structures offer the promise of efficient packaging during launch, with subsequent deployment into large scale light-weight structures. Two of the key challenges in the design of space inflatables are the selection of a suitable packing scheme and rigidization method. The packing method must provide compact stowage, as well as reliable and predictable deployment dynamics. The post-deployment rigidization ensures the necessary structural stiffness for long-term space applications.

Cylindrical booms are an important category of inflatable space structures, as they form the basic elements in truss structures and are used as support structure for solar sails and solar arrays. A wide range of packing schemes for inflatable cylindrical booms has been reviewed. The classic z-folded booms suffer from unpredictable deployment, and coiled/wrapped booms complicate the possibility of interconnected booms. Alternatives are provided by the use of origami folding patterns, and telescopic conical booms. These advances in boom packing methods have potential for

predictable and rapid deployment, by virtue of the open cross-section in their stowed configuration. The conical boom technology has been flight-tested, but the use of origami fold patterns is currently at a low TRL. In particular, the link between fold pattern geometry and boom deployment characteristics is not sufficiently established.

The review of rigidization techniques has highlighted numerous chemical, physical and mechanical processes. No single candidate technique is without its benefits or limitations, but space heritage is limited to only few methods, such as stretched-metal laminates and sub-T_g resins. Challenges include: uneven curing, warping and distortion during curing or drying, unreliable action of the curing agent (solar radiation, inflation gas, foam, lamp radiation, heat) and requirements for complex supplementary equipment such as thermal blankets.

While the work documented in this paper clearly does not represent the entirety of research effort on inflatable booms, the authors have endeavoured to give a comprehensive picture of the field as it currently stands, and provide an introduction to the technologies and design considerations associated with inflatable booms for deployable space structures.

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