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

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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 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].

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Inflatable booms form part of a wider family of lightweight deployable structures, including rigid-link mechanisms such as the ATK ADAM (ABLE Deployable Articulated Mast) [6], coilable thin shell members such as a STEM (Storable Tubular Extensible Member) [7] or bistable 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.

Although space inflatables solve many of the traditional problems in engineering space structures with regard to volume and mass minimization, 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 micrometeorites 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.

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 and Wrapping

A common stowage method is to first flatten the uninflated boom, before rolling it into a coil or wrapping it around a hub; see Fig. 1. 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 modeled 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] modeled 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 for example 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 Velcro 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

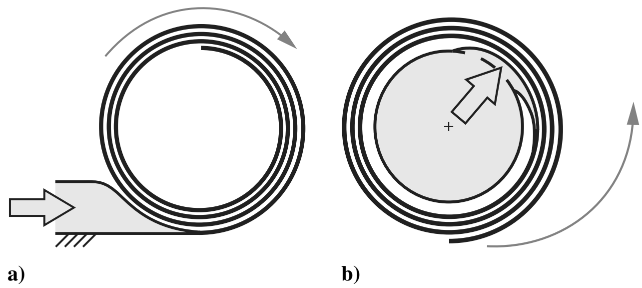


Fig. 1 The a) coiling, and b) wrapping packing and deployment method.

deployment path. The 28-m-long booms of the IAE were folded this way before flight testing; see Fig. 2a. For the IAE, it was intended to first deploy the booms mechanically to approximately the correct position before 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].

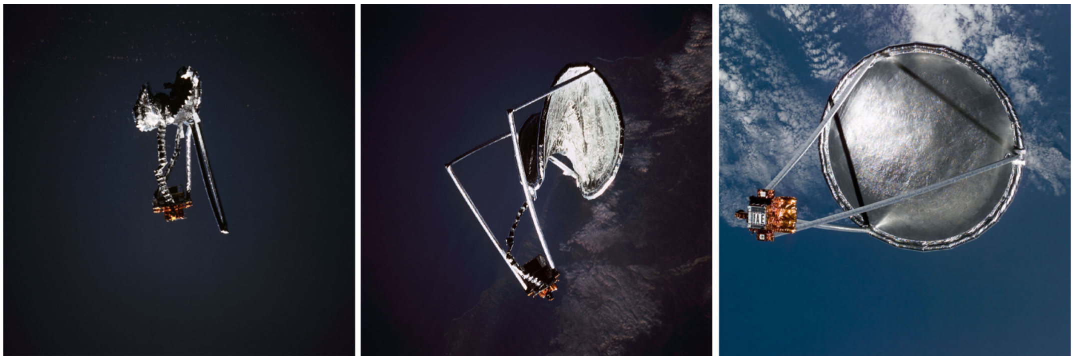
The z-folded boom is well studied, and Smith and Main [23] summarize several modeling efforts. Semi-analytical models have been developed to capture the dominant dynamic characteristics, where the assumption is that local bending effects, which initially exist as a result of the folding and later appear because of local buckling, dominate the overall deployment mechanism. This assumption results in a system of rigid links and nonlinear 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 microgravity 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. 2b. 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 modeling [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



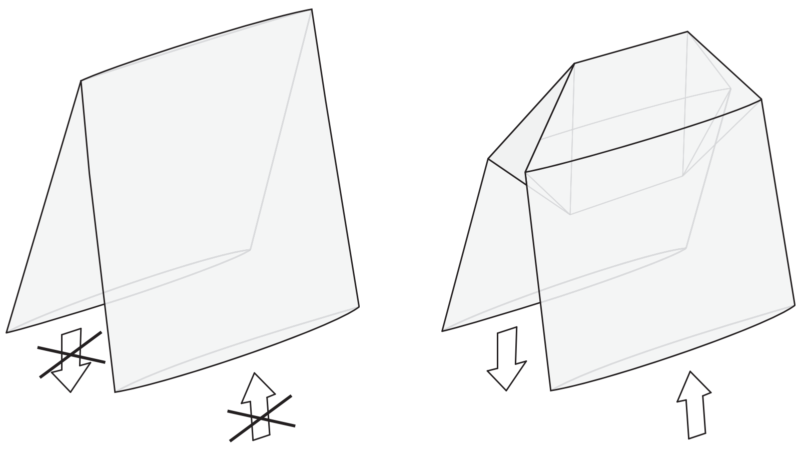


Fig. 2 *Z*-folded booms: a) deployment of the IAE (image credit: NASA); and b) a standard and a modified *z*-fold designed to facilitate gas flow (image after Katsumata et al. [20]).

method to compactly stow inflatable booms. Whereas z-folding 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.

1. Rigid Foldability and 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 modeled 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 modeling 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 modeling 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 modeling 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 postbuckling 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 multistable booms, which are undeformed in the stowed configuration, a partly deployed, and fully inflated configuration [31,37,38].

2. 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 nonlinearly as the folds are flattened out, and will approach the modulus of the constituent material for high tensile strains. The folding can also result in microcracking along the fold lines, which will negatively affect the material properties. For example, in aluminum–polymer–aluminum 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 aluminum 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.

3. 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.

4. 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 because it increases the bending stiffness of the boom after deployment, but it also introduces challenges with connections to the satellite and other booms.

5. 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.

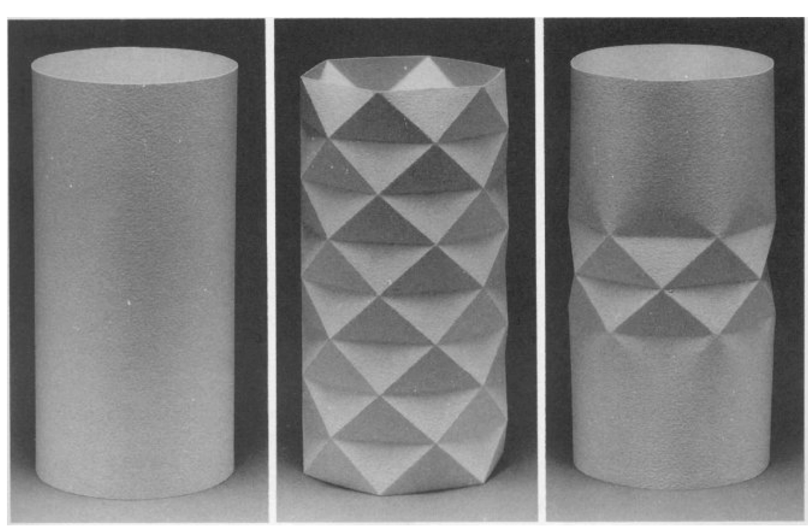
Fig. 3 Paper cylinders folded using the patterns described in this section; from left to right in the order of appearance in the article.

Nonetheless, some general geometric features are noteworthy. First, the number of fold lines meeting at a vertex (i.e., the degree of a vertex). An origami vertex requires minimally four 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. Second, 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. Last, 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.

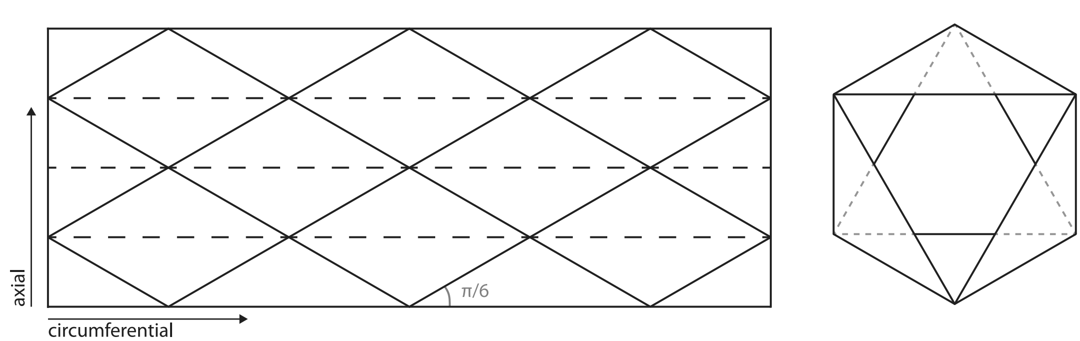
a. Yoshimura Pattern.—The classic fold pattern associated with folded cylinders is the Yoshimura pattern; the fold pattern is shown in Fig. 4. (Throughout this paper, when showing fold patterns, solid and dashed lines denote mountain and valley folds, respectively, and the two axial edges would be joined to form the cylinders.) The pattern is an inextensional postbuckling 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 microgravity 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.

b. 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. A classic bellows pattern is shown in Fig. 5a; 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 deorbiting applications [52]; see Fig. 5b. Lacour et al. [53] describe the fold geometry, which was selected for its minimal total fold length and available interior space in its stowed configuration. An important novelty was the design of the deployment sequencing device: a strut with a cloverlike 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.

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



a)



b)

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

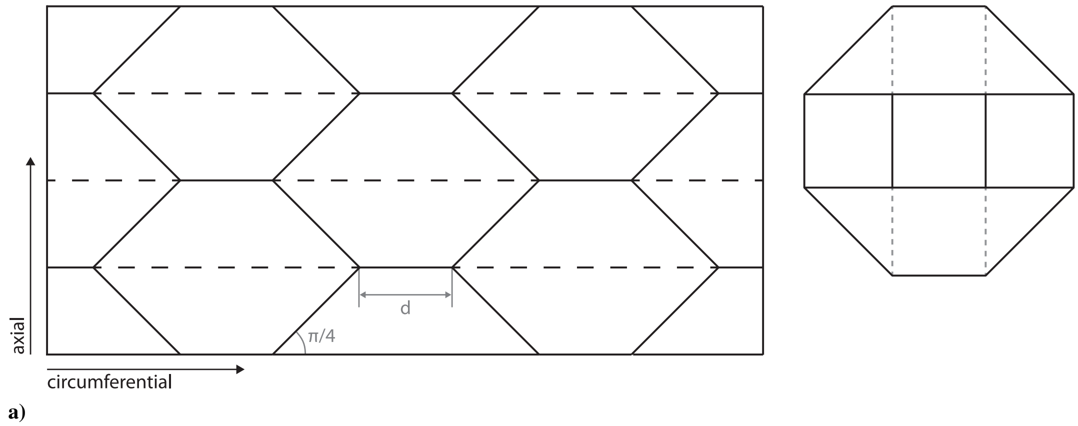


Fig. 5 A bellows pattern: a) fold pattern and cross section of a tetragonal bellows pattern, used for the b) TADECS inflatable rigidizable boom for deorbiting applications (images from Guenat and Le Couls [52]).

$\alpha \in [0, \pi]$), the cross section must deform to accommodate the change in enclosed angle $\beta \in [\pi - 2\varphi, \pi]$ of the reverse folds. The difference between the enclosed angle in the fully stowed state and a partly deployed state can be taken as a simple measure of the material deformation. Although 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 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. 7a. Shown are a fold geometry optimized by Kane [37] for a minimal mean deformation during deployment (fold pattern parameters: $\varphi_1 = 72.57$ deg, $\varphi_2 = 27.57$ deg). 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. 7b. The triangulated cylinders will be discussed in detail in Sec. II.C.4.

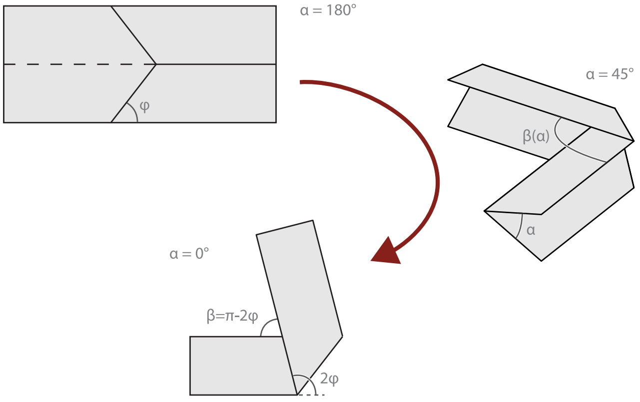


Fig. 6 Kinematics of a single reverse fold.

c. 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 these booms expand both longitudinally and radially and therefore have a negative Poisson's ratio. In Fig. 8 is shown a five-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 that no more than four 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 aluminum laminate film and were rigidized after inflation by means of strain hardening. Experiments were performed in a microgravity environment to study the deployment characteristics of various folding geometries (see Fig. 9) 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 modeled using a spring element. The Yoshimura cylinder was shown to be the hardest to deploy and involved the highest stress concentrations. The stiffness

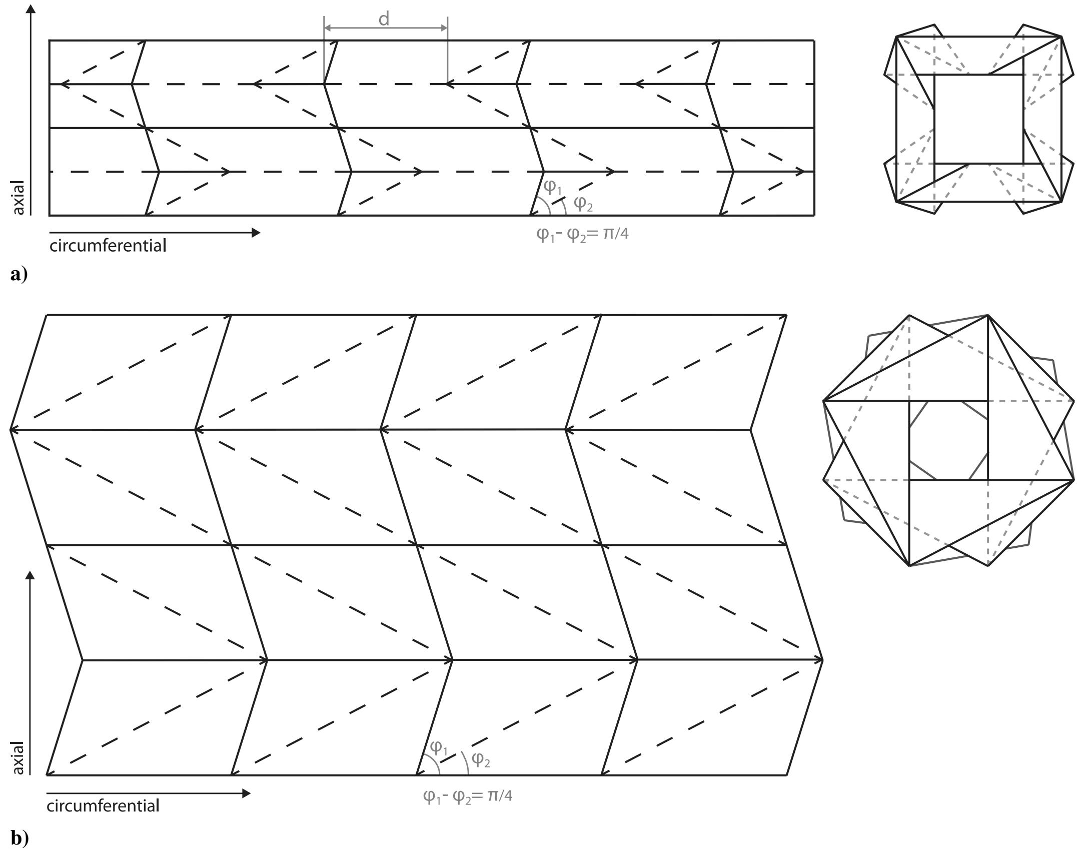


Fig. 7 Variations of the double-inversion bellows fold pattern.

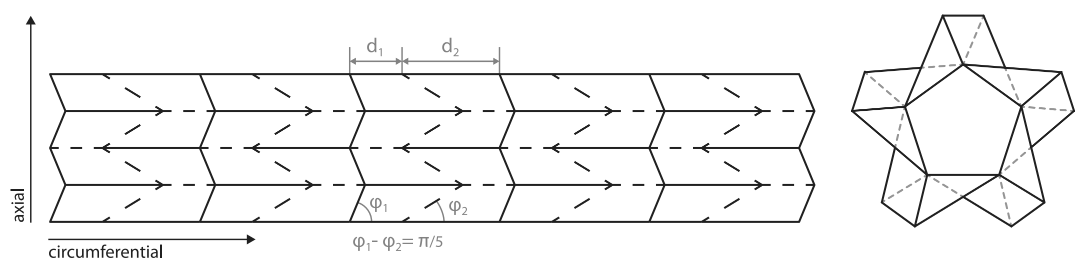


Fig. 8 Five-sided cylindrical Miura fold pattern.

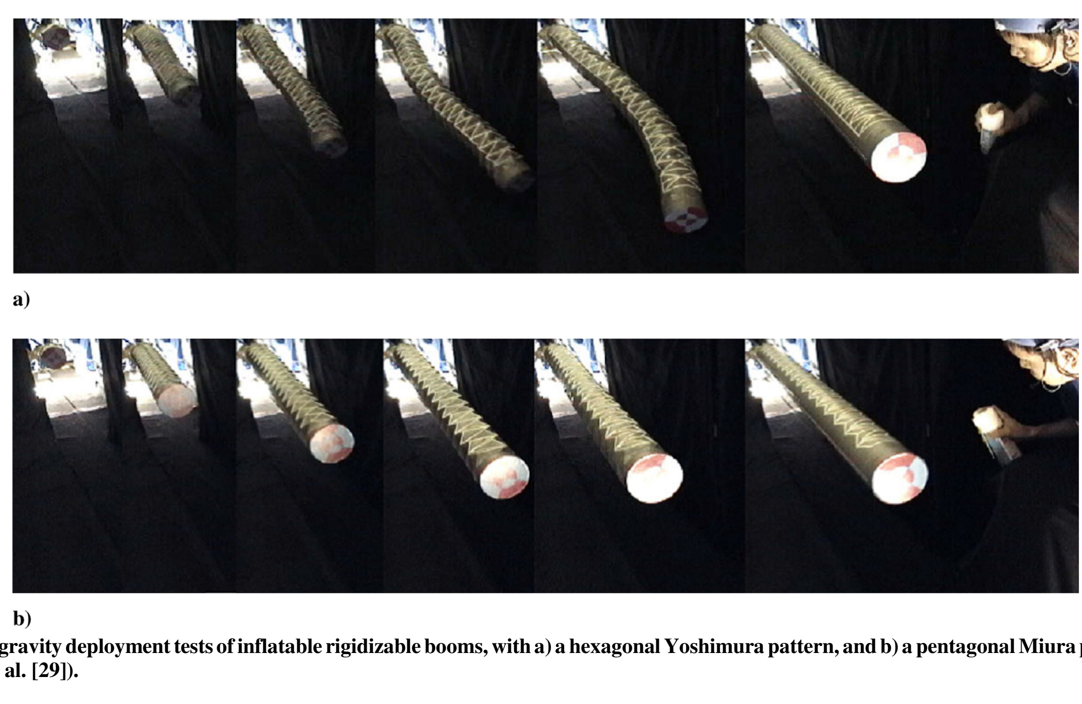


Fig. 9 Microgravity deployment tests of inflatable rigidizable booms, with a) a hexagonal Yoshimura pattern, and b) a pentagonal Miura pattern (images from Senda et al. [29]).

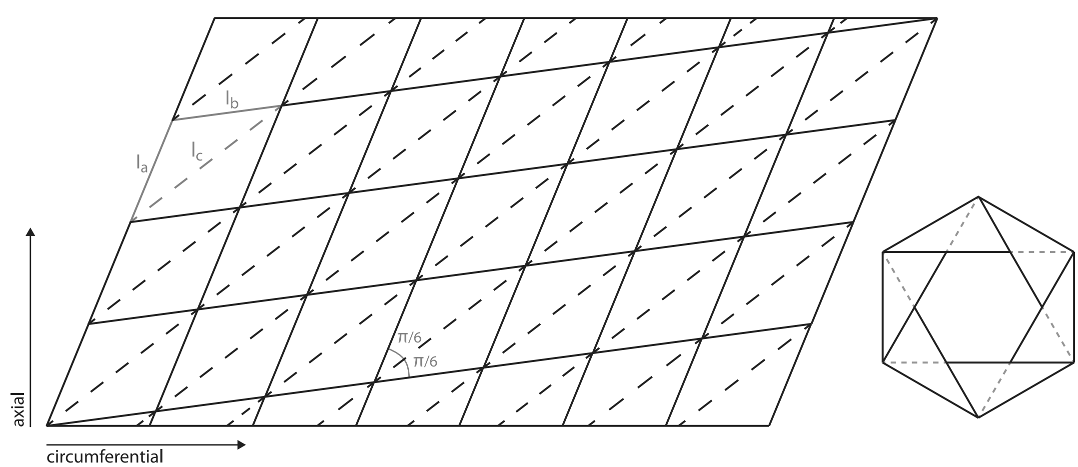
of the rigidized booms, quantified by their fundamental vibrational frequency, was experimentally found to be effectively independent of the fold pattern. The measured frequencies were, however, decreased to between 1 and $2/3$ of that of an unfolded cylinder; this may be due to residual creases, connection details at the base of the boom, and cracking of the thicker aluminum laminates at the creases.

d. 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 tradeoff 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 would collapse sequentially under a nominally constant load, in a manner similar to a propagating instability [56], as illustrated in Fig. 10b. 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 aluminum cylinders with a (nonhelical) 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 the vertices can therefore be offset with respect to each other in successive layers, reducing the stowed dimensions of the boom.

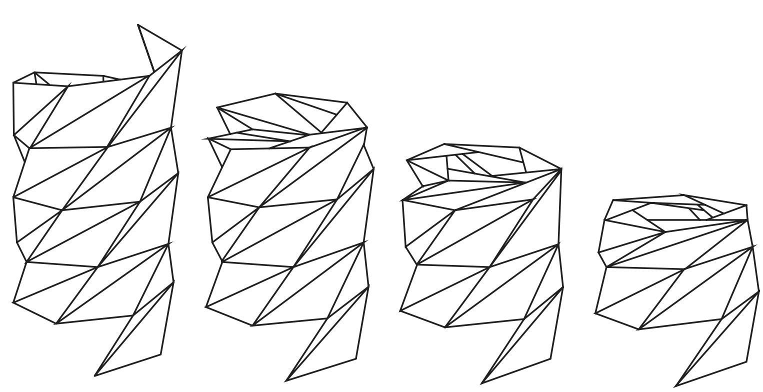
Many of the fold patterns discussed previously can be recognized in geometric studies such as Nojima [49], who described generalized flat-folding vertices and provided the closure conditions for the flat-folded stowed state. Most patterns can also be rotated to have the major fold lines oriented helically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

e. 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. 12. A crucial consideration, however, is that the proposed cylinders contain vertices with nonzero 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 pseudocylindrical surface; once joined at the edges, the cylinder will be rigid and nonfoldable. 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



a)



b)

Fig. 10 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]).

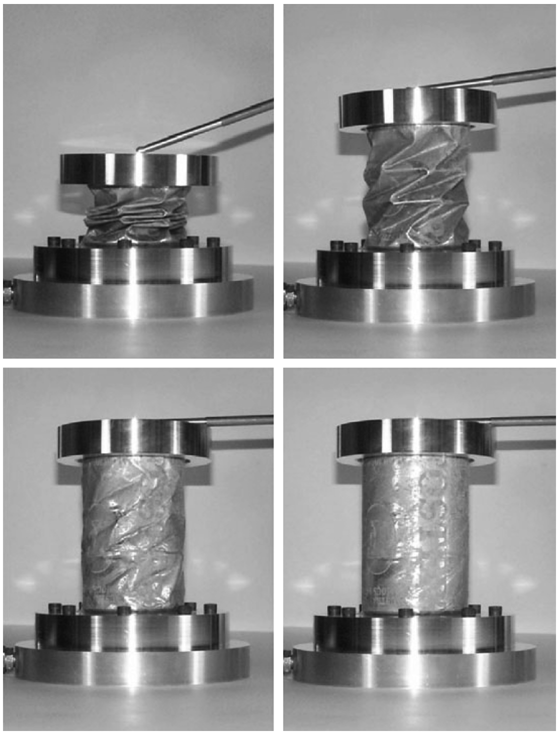


Fig. 11 Inflation of an aluminum triangulated cylinder (image from Barker and Guest [58]).

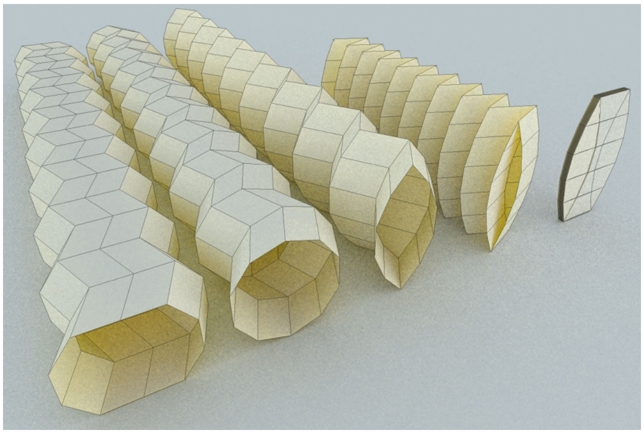


Fig. 12 Rigid-foldable cylinder (image from Tachi [59]).

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 microcracking at the fold lines. 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 modeling of the deployment dynamics is complex because it must cover local mechanical effects such as wrinkling and plasticity, global effects such as shell buckling, and complex fluid–structure interaction. Experimental investigations will therefore be necessary to validate simplified modeling 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 project [5,66], and the concept was space-qualified on the Cibola Flight Experiment, in combination with a sub-T_g rigidization technique [67]. 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 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 proffered by Palisoc et al. [65], in which inflation presses the walls of the cylinder against the outer layer, and 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

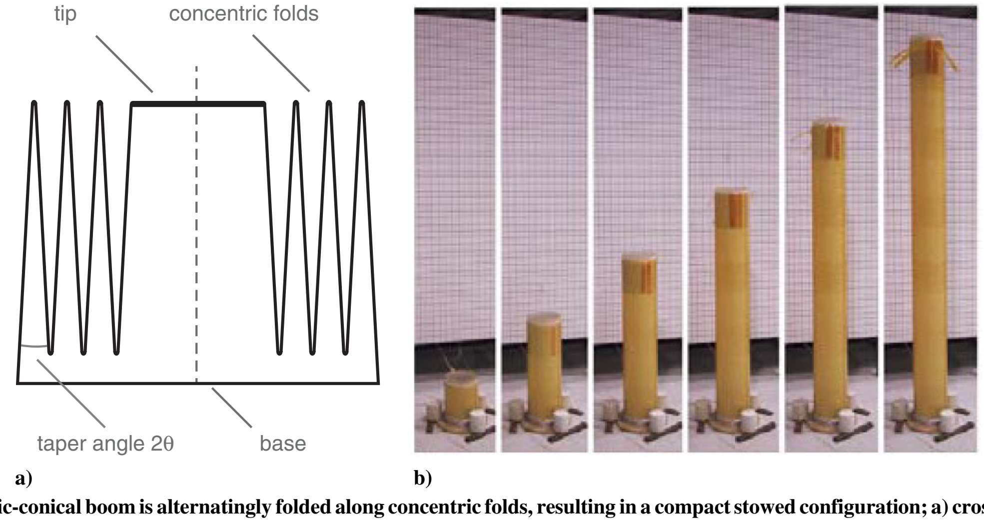


Fig. 13 A telescopic-conical boom is alternatingly folded along concentric folds, resulting in a compact stowed configuration; a) cross-sectional view, and b) inflation of a telescopic-conical boom (image from Palisoc et al. [65]).

be no contact, and thus no friction, between the nested layers. Dynamic deployment of a strongly tapered conical boom with a single inversion was modeled 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 and 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 1 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 have 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: Ultraviolet (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 that 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. Ultraviolet Setting Resins

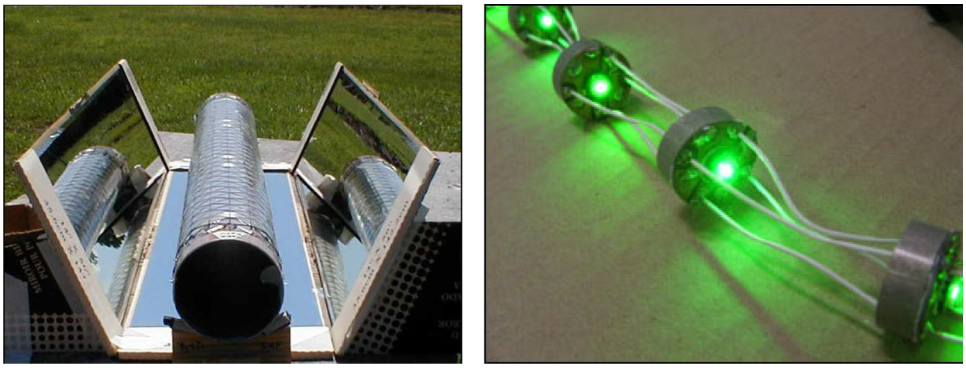
Much early work in the field of UV-Setting Resins was performed by the U.S. Air Force and the Hughes Aircraft Company [79,80]. Later, the combination of a foam-driven inflation followed by the UV hardening of a resin impregnated skin was examined [81,82] (the intention being to use environmental UV radiation for curing). Later again, Adherent Technologies Inc. demonstrated the use of UV rigidization in inflatable isogrid booms, using both environmental [83] (Fig. 14a) and lamp-based [84] sources of radiation (Fig. 14b). The use of internal lamps operating at various wavelengths in rigidizing preimpregnated 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 (from "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 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 outgassing, 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



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]).

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 predeployment 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 that is purely crystalline and a portion that is amorphous. Although 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 that 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 20 m solar sail demonstrator [98,99]; see Fig. 15. They have experimented with resins with values of T_g of $+50$, $+20$, 0, 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 U.S. 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 (SMPs) [4,103–105]. SMPs mimic the behavior of shape memory alloys and will naturally reassume their preheating shape when heated above their T_g. This unusual behavior allows for more intricate self-deploying structures than can be achieved using inflation alone.

Although glass transition polymers are not generally as rigid as thermosetting resins, the reversibility of the rigidization process makes multiple-deployment missions possible and facilitates easy ground testing of components. Before 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, rigidization 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 aluminum) 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 prestress 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 prestressing 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 aluminum–Mylar laminate spheres for passive communication tests and atmospheric density experiments: Explorer IX in 1961 [108], Explorer XIX in 1963 [109] (see Fig. 16a), and the larger Echo II in 1964 [1,106,110,111]. L'Garde (with the sponsorship of NASA Langley Research Center) experimented with metal laminate inflatable booms [112] and improved the structural performance of their

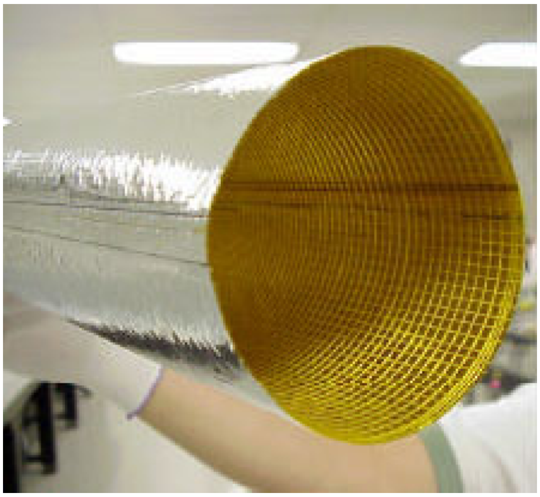


Fig. 15 Internal view of an inflatable boom with sub-T_g resin impregnated fibers running in the hoop and axial directions (image from Lichodziejewski et al. [5]).

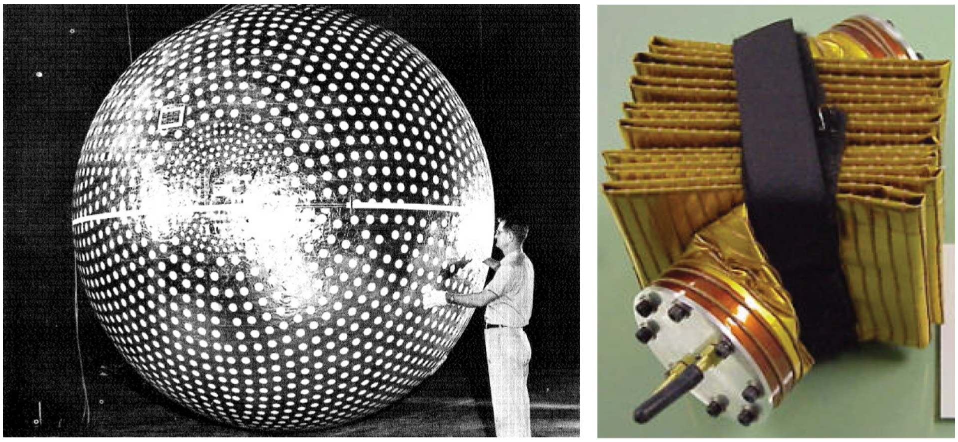


Fig. 16 Strain rigidization of metal-polymer laminates in a) the Explorer XIX satellite [109], and b) a z-folded spiral-wrapped boom (image from Lichodziejewski et al. [113]).

booms by spiral wrapping [113]; see Fig. 16b. 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 deorbiting device [115,116], and Senda et al. [29] studied the inflation and rigidization of aluminum-laminate origami-folded cylinders.

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 100 μm to prevent debonding. The thickness of the metal is also generally required to be greater than that of the polymer to prevent autobuckling 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 Boiloff 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 (Inflatable Rigidizable Space Structure) IRSS truss [122,123], Fig. 17, which rigidizes via dehydration. Polyvinyl alcohol and even gelatin have been proposed as suitable evaporation-rigidizable materials [79,124,125].

Solvent evaporation or boiloff 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 precoated 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 preformed, stored, and cooled on Earth before heating above the T_g in space, which causes the foam to expand, have also been proposed [72].

Foams that harden once deployed can add structural rigidity to their encasing booms or shells. There are fundamental difficulties in

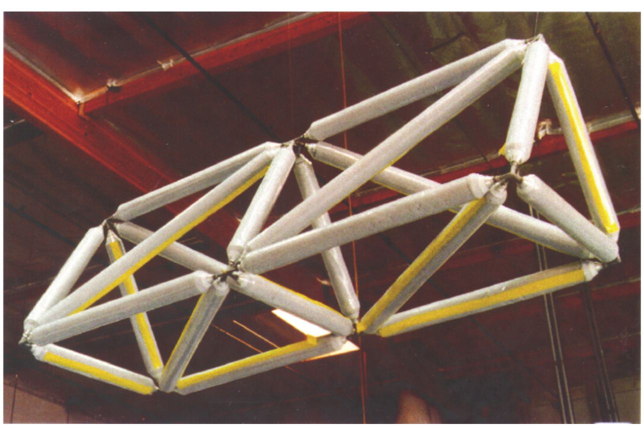


Fig. 17 IRSS truss using Hydrogel rigidization [123]. Image courtesy of L'Garde.

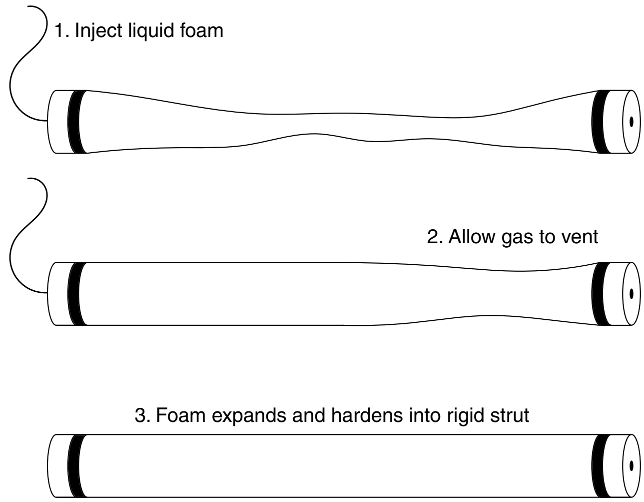


Fig. 18 Foam rigidization of a Kapton boom (figure after Griffith and Main [127]).

ensuring an even spread of foam during rigidization in space, and outgassing of foaming byproducts 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 U.S. 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 that drew the wire frame out into a spherical shape. The wire provided a rigid frame for the satellites. After a short while, the film photolyzed (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 electromagnetic radiation as a continuous sphere, but with much lower aerodynamic drag.

I. Embedded Structural Components

In the last category of rigidization, the structural performance of the inflatable structure is derived from embedded components. NASA Jet Propulsion Laboratory 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.

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

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.

First, the deployment sequence of space inflatables is often unpredictable and is 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 deorbiting system under development by EADS Astrium [52,115]. Deployment tests under microgravity conditions have demonstrated the potential of the origami folding approach [29].

Second, 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 U.S. 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 prerigidized 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 favor 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. 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.

Last, 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 piezoelectric 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 that 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 that could see the use of inflatable structures in space expand in future years.

V. Conclusions

Inflatable space structures offer the promise of efficient packaging during launch, with subsequent deployment into large-scale lightweight 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 because 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.

Although the work documented in this paper clearly does not represent the entirety of research effort on inflatable booms, the authors have endeavored 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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Reference

[1] Pezdirtz, G. F., "Erectable Space Structures—ECHO Satellites," NASA N62-12545, 1962.

[2] Freeland, R. E., Bilyeu, G. D., Veal, G. R., Steiner, M. D., and Carson, D. E., "Large Inflatable Deployable Antenna Flight Experiment Results," *Acta Astronautica*, Vol. 41, Nos. 4–10, 1997, pp. 267–277. doi:10.1016/S0094-5765(98)00057-5

[3] Guidanean, K., and Lichodziejewski, D., "An Inflatable Truss Structure Based on New Sub-Tg Polyurethane Composites," *43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, AIAA Paper 2002-1593, April 2002.

[4] Cadogan, D. P., Lin, J. K., and Grahne, M. S., "Inflatable Solar Array Technology," *37th AIAA Aerospace Sciences Meeting and Exhibit*, AIAA Paper 1999-1075, Jan. 1999.

[5] Lichodziejewski, D., Derbès, B., West, J., Belvin, K., and Pappa, R., "Bringing an Effective Solar Sail Design Toward TRL 6," *39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, AIAA Paper 2003-4659, July 2003.

[6] Douglas, M. V., "Module for an Articulated Stowable and Deployable Mast," U.S. Patent 5,267,424 , 1993.

[7] Rimrott, F. P. J., and Fritsche, G., "Fundamentals of STEM Mechanics," *Proceedings of the IUTAM-IASS Symposium on Deployable Structures: Theory and Applications*, edited by Pellegrino, S., and Guest, S. D., Kluwer Academic, Dordrecht, The Netherlands, Sept. 1998, pp. 321–333.

[8] Iqbal, K., Pellegrino, S., and Daton-Lovett, A., "Bi-Stable Composite Slit Tubes," *IUTAM-IASS Symposium on Deployable Structures: Theory and Applications*, edited by Pellegrino, S., and Guest, S. D., Kluwer Academic, Dordrecht, The Netherlands, Sept. 1998, pp. 153–162.

[9] Thomson, M. W., "Deployable and Retractable Telescoping Tubular Structure Development," *Proceedings of the 28th Aerospace Mechanisms Symposium*, Cleveland, OH, May 1994, pp. 323–338.

[10] Murphey, T. W., "Booms and Trusses," *Recent Advances in Gossamer Spacecraft*, edited by Jenkins, C. H. M., Vol. 212, Progress in Astronautics and Aeronautics, AIAA, Reston, VA, 2006, pp. 1–44.

[11] Pappa, R. S., Lassiter, J. O., and Ross, B. P., "Structural Dynamics Experimental Activities in Ultralightweight and Inflatable Space Structures," *Journal of Spacecraft and Rockets*, Vol. 40, No. 1, 2003, pp. 15–23. doi:10.2514/2.3934

[12] Grahne, M. S., and Cadogan, D. P., "Deployment Control Mechanisms and Packaging Methodologies for Inflatable and Membrane Structures," *Gossamer Spacecraft: Membrane and Inflatable Structures Technology for Space Applications*, edited by Jenkins, C. H. M., Vol. 191, Progress in Astronautics and Aeronautics, AIAA, Reston, VA, 2000, pp. 417–431.

[13] Natori, M. C., Katsumata, N., and Yamakawa, H., "Membrane Modular Space Structure Systems and Deployment Characteristics of Their Inflatable Tube Elements," *51st AIAA Structures, Structural Dynamics, and Materials Conference*, AIAA Paper 2010-2909, April 2010.

[14] Katsumata, N., Fujii, R., Natori, M. C., and Yamakawa, H., "Membrane Space Structure Models with Inflatable Tubes," *Proceedings of the 27th International Symposium on Space Technology and Science*, Tsukuba, Japan, Paper 2011-c-38, July 2009.

[15] Steele, C. R., and Fay, J. P., "Inflation of Rolled Tubes," *Proceedings of the IUTAM-IASS Symposium on Deployable Structures: Theory and Applications*, edited by Pellegrino, S., and Guest, S. D., Kluwer Academic, Dordrecht, The Netherlands, Sept. 2000, pp. 393–403.

[16] Fay, J. P., and Steele, C. R., "Forces for Rolling and Asymmetric Pinching of Pressurized Cylindrical Tubes," *Journal of Spacecraft and Rockets*, Vol. 36, No. 4, 1999, pp. 531–537. doi:10.2514/3.27196

[17] Fang, H., and Lou, M., "Deployment Study of a Self-Rigidizable Inflatable Boom," *Journal of Spacecraft and Rockets*, Vol. 43, No. 1, 2006, pp. 25–30. doi:10.2514/1.3283

[18] Seffen, K. A., and Pellegrino, S., "Deployment Dynamics of Tape-Springs," *Proceedings of the Royal Society of London A*, Vol. 455, No. 1983, 1999, pp. 1003–1048. doi:10.1098/rspa.1999.0347

[19] Wang, J. T., and Johnson, A. R., "Deployment Simulation Methods for Ultra-Lightweight Inflatable Structures," NASA TM-2003-212410, 2003.

[20] Katsumata, N., Natori, M. C., and Yamakawa, H., "Folding and Deployment Analyses of Inflatable Structures," *Proceedings of the 28th International Symposium on Space Technology and Science*, Paper 2011-c-38, Okinawa, Japan, June 2011.

[21] Satou, Y., and Furuya, H., "Mechanical Properties of Wrapping Fold Wrinkles in Large Space Membrane," *Proceedings of the 28th International Symposium on Space Technology and Science (28th ISTS)*, Paper 2011-c-32, Okinawa, Japan, June 2011.

[22] Freeland, R. E., Bilyeu, G. D., and Veal, G. R., "Development of Flight Hardware for a Large, Inflatable-Deployable Antenna Experiment," *Acta Astronautica*, Vol. 38, No. 4–8, 1996, pp. 251–260. doi:10.1016/0094-5765(96)00030-6

[23] Smith, S. W., and Main, J. A., "Modeling the Deployment of Inflatable Space Structures," *Gossamer Spacecraft: Membrane and Inflatable Structures Technology for Space Applications*, edited by Jenkins, C. H. M., Vol. 191, Progress in Astronautics and Aeronautics, AIAA, Reston, VA, 2000, pp. 203–237.

[24] Breukels, J., and Ockels, W., "Analysis of Complex Inflatable Structures Using a Multi-Body Dynamics Approach," *49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, AIAA Paper 2008-2284, April 2008.

[25] Main, J., Peterson, S., and Strauss, A., "Beam-Type Bending of Space-Based Inflated Membrane Structures," *Journal of Aerospace Engineering*, Vol. 8, No. 2, 1995, pp. 120–125. doi:10.1061/(ASCE)0893-1321(1995)8:2(120)

[26] Salama, M., Kuo, C. P., and Lou, M., "Simulation of Deployment Characteristics of Inflatable Structures," *AIAA Journal*, Vol. 38, No. 12, 2000, pp. 2277–2283. doi:10.2514/2.896

[27] Miyazaki, Y., and Uchiki, M., "Deployment Dynamics of Inflatable Tube," *43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, AIAA Paper 2002-1254, April 2002.

[28] Wu, W., and You, Z., "Modelling Rigid Origami with Quaternions and Dual Quaternions," *Proceedings of the Royal Society A*, Vol. 466, No. 2119, 2010, pp. 2155–2174. doi:10.1098/rspa.2009.0625

[29] Senda, K., Oda, T., Ohta, S., Igaras, Y., Watanabe, A., Hori, T., Ito, H., Tsunoda, H., and Watanabe, K., "Deploy Experiment of Inflatable Tube Using Work Hardening," *47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, AIAA Paper 2006-1808, May 2006.

[30] You, Z., and Kuribayashi, K., "Expandable Tubes with Negative Poisson's Ratio and Their Application in Medicine," *Origami 4: 4th International Meeting of Origami Science, Mathematics and Education*, edited by Lang, R. J., A K Peters, Natick, MA, 2009, pp. 117–127.

[31] Guest, S. D., and Pellegrino, S., "The Folding of Triangulated Cylinders, Part 1: Geometric Considerations," *Journal of Applied Mechanics*, Vol. 61, No. 4, 1994, pp. 773–777.

[32] Guest, S. D., and Pellegrino, S., "The Folding of Triangulated Cylinders, Part 2: The Folding Process," *Journal of Applied Mechanics*, Vol. 61, No. 4, 1994, pp. 778–783.

[33] Miura, K., "Proposition of Pseudo-Cylindrical Concave Polyhedral Shells," Inst. of Space and Aeronautical Science, Rept. 442, Univ. of Tokyo, Tokyo, 1969.

[34] Johnson, W., Soden, P. D., and Al-Hassani, S. T. S., "Inextensional Collapse of Thin-Walled Tubes Under Axial Compression," *Journal of Strain Analysis for Engineering Design*, Vol. 12, No. 4, 1977, pp. 317–330. doi:10.1243/03093247V124317

[35] Tarnai, T., "Folding of Uniform Plane Tesselations," *Origami Science & Art, Proceedings of the 2nd International Meeting of Origami Science and Scientific Origami*, edited by Miura, K., Seian Univ. of Art and Design, Otsu, Shiga, Japan, Nov.–Dec. 1994, pp. 83–91.

[36] Hunt, G. W., and Ario, I., "Twist Buckling and the Foldable Cylinder: An Exercise in Origami," *International Journal of Non-Linear Mechanics*, Vol. 40, No. 6, 2005, pp. 833–843. doi:10.1016/j.ijnonlinmec.2004.08.011

[37] Kane, N. R., "Mathematically Optimized Family of Ultra Low Distortion Bellow Fold Patterns," U.S. Patent 6,054,194 , 2000.

[38] You, Z., and Cole, N., "Self-Locking Bi-Stable Deployable Booms," *47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, AIAA Paper 2006-1685, May 2006.

[39] MacNeal, R. H., and Robbins, W. M., "Tensile Properties of a Tape with a Transverse Crease," Astro Research Corp., ARC-R-241, Santa Barbara, California, 1967.

[40] Murphey, T. W., "The Constitutive Modeling of Thin Films with Random Material Wrinkles," *19th AIAA Applied Aerodynamics Conference*, AIAA Paper 2001-1347, June 2001.

[41] Papa, A., and Pellegrino, S., "Systematically Creased Thin-Film Membrane Structures," *Journal of Spacecraft and Rockets*, Vol. 45, No. 1, 2008, pp. 10–18. doi:10.2514/1.18285

[42] Woo, K., Nandurkar, K., and Jenkins, C., "Effective Modulus of Creased Thin Membranes," *Journal of Spacecraft and Rockets*, Vol. 45, No. 1, 2008, pp. 19–26. doi:10.2514/1.29282

[43] Hayase, R., Kamemura, H., Inoue, S., and Miyazaki, Y., "A Study on Mechanical Model of Crease of Membrane," *Proceedings of the 28th International Symposium on Space Technology and Science*, Paper 2011-c-31, Ginowan City, Japan, June 2011.

[44] Guest, S. D., and Pellegrino, S., "Inextensional Wrapping of Flat Membranes," *Proceedings of the 1st International Conference on Structural Morphology*, edited by Motro, R., and Wester, T., Montpellier, France, Sept. 1992, pp. 203–215.

[45] Watanabe, H., Natori, M. C., Okuizumi, N., and Higuchi, K., "Folding of a Circular Membrane Considering the Thickness," *ISAS Proceedings of 14th Workshop on Astrodynamics and Flight Mechanics 2004: A Collection of Technical Papers*, 2005, pp. 19–24.

[46] Sogame, A., and Furuya, H., "Conceptual Study on Cylindrical Deployable Space Structures," *Proceedings of the IUTAM-IASS Symposium on Deployable Structures: Theory and Applications*, edited by Pellegrino, S., and Guest, S. D., Kluwer Academic, Dordrecht, The Netherlands, Sept. 2000, pp. 383–392.

[47] Kuribayashi, K., "A Novel Foldable Stent Graft," Ph.D. Thesis, Univ. of Oxford, Oxford, England, U.K., 2004.

[48] Tachi, T., "Generalization of Rigid Foldable Quadrilateral Mesh Origami," *Journal of the International Association for Shell and Spatial Structures*, Vol. 50, No. 3, 2009, pp. 173–179.

[49] Nojima, T., "Modelling of Folding Patterns in Flat Membranes and Cylinders by Origami," *JSME International Journal Series C*, Vol. 45, No. 1, 2002, pp. 364–370. doi:10.1299/jsmec.45.364

[50] Coppa, A. P. A., "Family of Rigid Shell Structures, Self-Deployable from Folded Configurations of Small Initial Volume," *9th AIAA/ASME Structures, Structural Dynamics and Materials Conference*, AIAA Paper 1968-0359, April 1968.

[51] Tsunoda, H., Senbokuya, Y., and Watanabe, M., "Deployment Characteristics Evaluation of Inflatable Tubes with Polygon Folding Under Airplane Microgravity Environment," *Space Technology*, Vol. 25, Nos. 3–4, 2005, pp. 127–137.

[52] Guenat, H., and Le Couls, O., "Ultra-Light Structures: Status of Development and Potential Applications," *ESA Techno/Innovation Days*, 2010.

[53] Lacour, D., Defoort, B., Peypoudat, V., and Gautrias, C., "Control Device for Deployment of Inflatable Structures," U.S. Patent 7,740,203 , 2010.

[54] Schenk, M., Kerr, S. G., Smyth, A. M., and Guest, S. D., "Inflatable Cylinders for Deployable Space Structures," *Proceedings of the 1st International Conference Transformables 2013*, Seville, Spain, Sept. 2013.

[55] Miura, K., "Method of Packaging and Deployment of Large Membranes in Space," Inst. of Space and Astronautical Science, Rept. 618, Tokyo, 1985.

[56] Kyriakides, S., "Propagating Instabilities in Structures," *Advances in Applied Mechanics*, Vol. 30, 1993, pp. 67–189. doi:10.1016/S0065-2156(08)70174-1

[57] Guest, S. D., and Pellegrino, S., "The Folding of Triangulated Cylinders, Part 3: Experiments," *Journal of Applied Mechanics*, Vol. 63, No. 1, 1996, pp. 77–83. doi:10.1115/1.2787212

[58] Barker, R. J. P., and Guest, S. D., "Inflatable Triangulated Cylinders," *Proceedings of the IUTAM-IASS Symposium on Deployable Structures: Theory and Applications*, edited by Pellegrino, S., and Guest, S. D., Kluwer Academic, Dordrecht, The Netherlands, Sept. 2000, pp. 17–26.

[59] Tachi, T., "One-DOF Cylindrical Deployable Structures with Rigid Quadrilateral Panels," *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009*, edited by Domingo, A., and Lazaro, C., Polytechnic Univ. of Valencia, Valencia, Spain, Sept.–Oct. 2009, pp. 2295–2305.

[60] Miura, K., and Tachi, T., "Synthesis of Rigid-Foldable Cylindrical Polyhedra," *Journal of the International Society for the Interdisciplinary Study of Symmetry (ISIS-Symmetry)*, Special Issue for the Festival-Congress, Gmünd, Austria, 2010, pp. 204–213.

[61] Yasuda, H., Yein, T., Tachi, T., Miura, K., and Taya, M., "Folding Behaviour of Tachi-Miura Polyhedron Bellows," *Proceedings of the Royal Society A*, Vol. 469, No. 2159, 2013, Paper 20130351. doi:10.1098/rspa.2013.0351

[62] Wang, K., and Chen, Y., "Folding a Patterned Cylinder by Rigid Origami," *Origami 5: 5th International Meeting of Origami Science, Mathematics, and Education*, edited by Wang-Iverson, P., Lang, R. J., and Yim, M., CRC Press, Boca Raton, FL, 2011, pp. 265–276.

[63] Wu, W., "Rigid Origami: Modelling, Application in Pre-Folded Cylinders and Manufacturing," Ph.D. Thesis, Univ. of Oxford, Oxford, England, U.K., 2010.

[64] Veal, G., Palisoc, A., and Derbès, W., "Deployable Inflatable Boom and Methods for Packaging and Deploying a Deployable Inflatable Boom," U.S. Patent Application 6,786,456 , 2004.

[65] Palisoc, A. L., Redell, F. H., and Andersen, G., "Deployment and Structural Support of Space Membrane Optics System Using Rigidizable Conical Booms," *Proceedings of the 9th Biennial ASCE Aerospace Division International Conference*, American Society of Civil Engineers, 2004, pp. 946–953.

[66] Garbe, G. P., Wie, B., Murphy, D., Ewing, A., Lichodziejewsi, L., Derbès, B., Campbell, B., Wang, J., Taleghani, B., Canfield, S. L., Beard, J. W., and Peddieson, J., "Solar Sail Propulsion Technology Development," *Recent Advances in Gossamer Spacecraft*, Vol. 212,

Progress in Astronautics and Aeronautics, edited by Jenkins, C. H. M., AIAA, Reston, VA, 2006, pp. 191–261.

[67] Caffrey, M., Katko, K., Nelson, A., Palmer, J., Robinson, S., Roussel-Dupre, D., Salazar, A., Wirthlin, M., Howes, W., and Richins, D., "The Cibola Flight Experiment," *Proceedings of the 23rd Annual AIAA/USU Conference on Small Satellites*, Paper SSC09-III-6, Aug. 2009.

[68] Johnson, C. E., "A Study on the Use of an Antenna/Homing Guide for Lunar Base Communication/Navigation Systems," NASA CR-88688, 1966.

[69] Li, B., Tan, D., Yang, Z., and Wen, J., "Deployment Simulation and Comparison of Inflatable Antenna Beam with Different Folded Configurations," *International Journal of Applied Electromagnetics and Mechanics*, Vol. 33, Nos. 3–4, pp. 1513–1527, 2010.

[70] Veldman, S. L., "Design and Analysis Methodologies for Inflated Beams," Ph.D. Thesis, Delft Univ. of Technology, Delft, The Netherlands, 2005.

[71] Cadogan, D. P., "Rigidization Mechanisms and Materials," *Gossamer Spacecraft: Membrane and Inflatable Structures Technology for Space Applications*, edited by Jenkins, C. M., Vol. 191, Progress in Astronautics and Aeronautics, AIAA, Reston, VA, 2000, pp. 257–475.

[72] Cadogan, D. P., and Scarborough, S. E., "Rigidizable Materials for Use in Gossamer Space Inflatable Structures," *42nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, AIAA Paper 2001-1417, April 2001.

[73] Bernasconi, M. C., and Reibaldi, G. G., "Inflatable, Space-Rigidized Structures: Overview of Applications and Their Technology Impact," *Acta Astronautica*, Vol. 14, 1986, pp. 455–465. doi:10.1016/0094-5765(86)90146-3

[74] May, C. A., and Wereta, A., "Process Identification Study for Space Cured Composite Structures," NASA CR-158942, 1978.

[75] Forbes, F. W., "Expandable Structures for Space Applications," U.S. Air Force Aero Propulsion Lab., AD0607541, Wright-Patterson Air Force Base, OH, 1964.

[76] Defoort, B., Peypoudat, V., Bernasconi, M. C., Chuda, K., and Coqueret, X., "Recent Advances in the Rigidization of Gossamer Structures," *Textile Composites and Inflatable Structures*, Vol. 3, Computational Methods in Applied Sciences, Springer, Dordrecht, The Netherlands, 2005, pp. 259–283.

[77] Freeland, R. E., Bilyeu, G. D., Veal, G. R., and Mikulas, M. M., "Inflatable Deployable Space Structures Technology Summary," *Proceedings of the 49th International Astronautical Congress*, International Astronautical Federation, Melbourne, Australia, Paper IAF-98-I.5.01, Sept.–Oct. 1998.

[78] Lou, M. C., and Feria, V. A., "Development of Space Inflatable/Rigidizable Structures Technology," *Proceedings of the IUTAM-IASS Symposium on Deployable Structures: Theory and Applications*, edited by Pellegrino, S., and Guest, S. D., Kluwer Academic, Dordrecht, The Netherlands, Sept. 1998, pp. 251–259.

[79] Keller, L. B., and Schwartz, S., "Rigidization Techniques for Integrally Woven Composite Constructions," Hughes Aircraft, ML-TDR-64-299, Culver City, CA, 1964.

[80] Schwartz, S., and Bagby, J., "Rigidized Inflatable Solar Energy Concentrators," NASA CR-254, 1964.

[81] Lester, D., Warner, M., and Blair, M., "Foam Inflated Rigidized Structures for Space Applications," *Proceedings of the 1993 Joint Army Navy NASA Air Force (JANNAF) Propulsion Meeting*, Vol. 2, JANNAF Interagency Propulsion Committee, Nov. 1993, pp. 243–251.

[82] Lester, D. M., and Cannon, D. M., "Foam Inflated Rigidized Truss Structure Developed for an SRS Technologies Solar Concentrator," Thiokol Corp., AD-A409527, Brigham City, UT, 1996.

[83] Allred, R. E., Hoyt, A. E., McElroy, P. M., Scarborough, S., and Cadogan, D. P., "UV Rigidizable Carbon-Reinforced Isogrid Inflatable Booms," *43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, AIAA Paper 2002-1202, April 2002.

[84] Hoyt, A. E., Harrah, L. A., Allred, R. E., and McElroy, P. M., "Rigidization-on-Command ROC Resin Development for Lightweight Isogrid Booms with MLI," *Proceedings of the 33rd International Conference on Environmental Systems (ICES)*, Paper ICES-2003-01-2342, Vancouver, BC, Canada, 2003.

[85] Mahias, R., Defoort, B., Mille, M., Coqueret, X., and Langlois, S., "Polymerization of Composite Materials in Free Space Environment," *Proceedings of the 11th International Symposium on Materials in Space Environment*, Paper IAC-04-I.5.08, Aix en Provence, France, Sept. 2009.

[86] Defoort, B., Lacour, D., and Le Couls, O., "Assembly of Prepregs for Producing Structures, for Example Ones Which Deploy Through Inflation," U.S. Patent Application 20,100,166,988 , 2010.

[87] Reiss, P., Breunig, E., Zimmerhakl, P., Newie, N., and Zeiner, A., "Investigating New Space Structures with the Focus Experiment," *Proceedings of 20th ESA Symposium on European Rocket and Balloon Programmes and Related Research*, Hyre, France, May 2011.

[88] Reibaldi, G. G., and Bernasconi, M. C., "QUASAT Program: The ESA Reflector," *Acta Astronautica*, Vol. 15, No. 3, 1987, pp. 181–187. doi:10.1016/0094-5765(87)90018-X

[89] Woods, A. R., and Bernasconi, M. C., "The OUR-Space Peace Sculpture: Introducing a Cultural Dimension into the Space Environment," *Proceedings of the 40th Congress of the International Astronautical Federation*, Paper IAA-89-673, Malaga, Spain, Oct. 1989.

[90] Veldman, S. L., and Vermeeren, C. A. J. R., "Inflatable Structures in Aerospace Engineering—An Overview," *Proceedings of the European Conference on Spacecraft Structures, Materials and Mechanical Testing*, European Space Agency, Noordwijk, The Netherlands, Nov.–Dec. 2000, pp. 93–98.

[91] Cadogan, D., Grahne, M., and Mikulas, M., "Inflatable Space Structures: A New Paradigm for Space Structure Design," *Proceedings of the 49th International Astronautical Congress*, Paper IAF-98-I.1.02, Melbourne, Australia, Sept.–Oct. 1998.

[92] Sandy, C. R., "Next Generation Space Telescope Inflatable Sunshield Development," *IEEE Aerospace Conference Proceedings*, Vol. 6, IEEE Publ., Piscataway, NJ, March 2000, pp. 505–519.

[93] Sarles, S. A., and Leo, D. J., "Consolidation of U-Nyte Epoxy-Coated Carbon-Fiber Composites via Temperature-Controlled Resistive Heating," *Journal of Composite Materials*, Vol. 42, No. 24, 2008, pp. 2551–2566. doi:10.1177/0021998308097197

[94] Lichodziejewski, D., Cravey, R., and Hopkins, G., "Inflatably Deployed Membrane Waveguide Array Antenna for Space," *44th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics, and Materials Conference*, AIAA Paper 2003-1649, April 2003.

[95] Lichodziejewski, D., Derbès, B., Reinert, R., Belvin, K., Slade, K., and Mann, T., "Development and Ground Testing of a Compactly Stowed Scalable Inflatably Deployed Solar Sail," *45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, AIAA Paper 2004-1507, April 2004.

[96] Redell, F. H., Lichodziejewski, D., Kleber, J., and Greschik, G., "Testing of an Inflation-Deployed Sub-Tg Rigidized Support Structure for a Planar Membrane Waveguide Antenna," *46th AIAA Structures, Structural Dynamics and Materials Conference*, AIAA Paper 2005-1880, April 2005.

[97] Johnson, L., Young, R. M., and Montgomery, E. E., "Recent Advances in Solar Sail Propulsion Systems at NASA," *Acta Astronautica*, Vol. 61, Nos. 1–6, 2007, pp. 376–382. doi:10.1016/j.actaastro.2007.01.047

[98] Lichodziejewski, D., Derbès, B., and Mann, T., "Vacuum Deployment and Testing of a 4-Quadrant Scalable Inflatable Rigidizable Solar Sail System," *46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, AIAA Paper 2005-2122, April 2005.

[99] Mann, T., Behun, V., Lichodziejewski, D., Derbès, B., and Sleight, D., "Ground Testing a 20-Meter Inflation Deployed Solar Sail," *47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, AIAA Paper 2006-1707, May 2006.

[100] Redell, F. H., and Lichodziejewski, D., "Power-Scalable Inflation-Deployed Solar Arrays," *45th AIAA Structures, Structural Dynamics and Materials Conference*, AIAA Paper 2004-1572, April 2004.

[101] Moeller, C. R., "Design and Ground-Testing of an Inflatable-Rigidizable Structure Experiment in Preparation for Space Flight," M.S. Thesis, U.S. Air Force Inst. of Technology, Wright-Patterson Air Force Base, OH, 2005.

[102] Adetona, O., Keel, L. H., Horta, L. G., Cadogan, D. P., Sapna, G. H., and Scarborough, S. E., "Description of New Inflatable/Rigidizable Hexapod Structure Testbed for Shape and Vibration Control," *43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, AIAA Paper 2002-1451, April 2002.

[103] Cadogan, D. P., Lin, J. K., and Grahne, M. S., "The Development of Inflatable Space Radar Reflectarrays," *40th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, AIAA Paper 1999-1517, April 1999.

[104] Lin, J. K. H., Sapna, G. H. III, Cadogan, D. P., and Scarborough, S. E., "Inflatable Rigidizable Isogrid Boom Development," *43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, AIAA Paper 2002-1297, April 2002.

[105] Cadogan, D. P., Scarborough, S. E., Lin, J. K., and Sapna, G. H. III, "Shape Memory Composite Development for Use in Gossamer Space Inflatable Structures," *43rd AIAA/ASME/ASCE/AHS/ASC Structures,*

Structural Dynamics, and Materials Conference, AIAA Paper 2002-1372, April 2002.

[106] Staugaitis, C. L., and Kobren, L., "Mechanical and Physical Properties of the Echo II Metal-Polymer Laminate," NASA TN-D-3409, 1966.

[107] O'Sullivan, W. J., "Self Supporting Space Vehicle," U.S. Patent 2,996,212 , 1961.

[108] Keating, C. V., and Woerner, G. M., "Temperature Control of the Explorer IX Satellite," NASA TN-D-1369, 1962.

[109] "NASA Facts: Explorer XIX, the Air Density Satellite," NASA, 1964.

[110] Bahiman, H., "Postlaunch Structural Analysis of ECHO II Satellite," NASA TN-D-3170, 1966.

[111] James, T. G., "Effect of Electron Irradiation on Some Properties of the Echo II Laminate," NASA TN-D-2207, 1964.

[112] Friese, G. J., Bilyeu, G. D., and Thomas, M., "Initial '80s Development of Inflated Antennas," NASA CR-166060, 1983.

[113] Lichodziejewski, D., Veal, G., and Derbs, B., "Spiral Wrapped Aluminum Laminate Rigidization Technology," *43rd AIAA Aerospace Sciences Meeting and Exhibit*, AIAA Paper 2002-1701, April 2002.

[114] Greschik, G., and Mikulas, M., "On Imperfections and Stowage Creases in Aluminum-Rigidized Inflated Cylinders," *37th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, AIAA Paper 1996-1332, April 1996.

[115] Peypoudat, V., and Le Couls, O., "Satellite Air Brake Wing Structure," U.S. Patent Application 20,090,218,448 , 2009.

[116] Depuy, C., and Le Couls, O., "Gossamer Technology to Deorbit LEO Non-Propulsion Fitted Satellite," *Proceedings of the 40th Aerospace Mechanisms Symposium*, NASA Kennedy Space Center, FL, May 2010, pp. 301–308.

[117] Nelms, F. W., "Vacuum Deployment of a Large Expandable Aerospace Shelter," Aerospace Environmental Facility, Arnold Engineering Development Center, AEDC-TR-66-123, U.S. Air Force Systems Command, Arnold Air Force Station, TN, 1966.

[118] Rochon, R., Clark, R. C., Hanssen, N. S., and McKillip, W. J., "Aerospace Expandable Structures and Maintenance Support Devices," Vol. 1, GCA Corp. and Archer Daniels Midland Co., AFAPL-TR-65-40, Minneapolis, MN, 1965.

[119] Hanny, J. F., Lankston, L. R., Jones, J. W., and Scott, J. C., "Chemical Rigidization of Expandable Structures," National Cash Register Co., AFAPL-TR-66-53, Dayton, Ohio, 1966.

[120] Bernasconi, M. C., and Rits, W. J., "Inflatable, Space-Rigidized Support Structures for Large Spaceborne Optical Interferometer Systems," *Acta Astronautica*, Vol. 22, 1990, pp. 145–153. doi:10.1016/0094-5765(90)90016-E

[121] Bernasconi, M. C., and Kotacka, K., "Inflatable Foldable Structure and Method of Manufacturing Foldable Structures," U.S. Patent 5,044,579 , 1991.

[122] Derbès, B., "Case Studies in Inflatable Rigidizable Structural Concepts for Space Power," *37th Aerospace Sciences Meeting and Exhibit*, AIAA Paper 1999-1089, Jan. 1999.

[123] Guidanean, K., and Williams, G. T., "An Inflatable Rigidizable Truss Structure with Complex Joints," *39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, AIAA Paper 1998-2105, April 1998.

[124] Keller, L. B., Schwartz, S. S., Olevitch, A., and Allinikov, S. A., "Space Rigidized Resin Fiberglass Sandwich Materials," *Journal of Spacecraft*, Vol. 3, No. 4, 1966, pp. 513–518.

[125] Russell, I. W., and Hanssen, N. S., "Application of a Gelatin Resin System to Aerospace Expandable Sandwich Structures," GCA Corp., AFAPL-TR-65-84, Minneapolis, MN, 1965.

[126] Grossman, G., and Williams, G., "Inflatable Concentrators for Solar Propulsion and Dynamic Space Power," *Journal of Solar Energy Engineering*, Vol. 112, No. 4, 1990, pp. 229–236. doi:10.1115/1.2929928

[127] Griffith, D. T., and Main, J. A., "Structural Modeling of Inflated Foam-Rigidized Aerospace Structures," *Journal of Aerospace Engineering*, Vol. 13, No. 2, 2000, pp. 37–46. doi:10.1061/(ASCE)0893-1321(2000)13:2(37)

[128] Tinker, M. L., and Schnell, A. R., "Foam Rigidized Inflatable Structural Assemblies," U.S. Patent Application 7,735,265 , 2010.

[129] Schwartz, S., "Delayed Action, Foam-in-Place Polyurethane for Use in Aerospace Environment," U.S. Air Force, ASD-TDR-62-416, 1963.

[130] Jouriles, N., and Welling, C. E., "Development of a Predistributed Azide Base Polyurethane Foam for Rigidization of Solar Concentrators in Space," NASA CR-235, 1965.

[131] Schnell, A. R., Leigh, L. M., Tinker, M. L., and McConnaughey, P. R., "Deployment, Foam Rigidization, and Structural Characterization of Inflatable Thin-Film Booms," *43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, AIAA Paper 2002-1376, April 2002.

[132] "Spacecraft—Details: OV1-8," NASA National Space Science Data Center, 2012, http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1966-063A [retrieved 28 Jan. 2014].

[133] Huang, J., Fang, H., Lopez, B., and Lou, M., "The Development of Inflatable Array Antennas," *AIAA Space 2003 Conference and Exposition*, AIAA Paper 2003-6320, Sept. 2003.

[134] Fang, H., Quijano, U., Knarr, K., Huang, J., and Lovick, R., "Experimental and Analytical Studies of a Large In-Space Deployable Dual-Band Membrane Reflectarray Antenna," NASA Interplanetary Network Progress Rept. 42-169, 2007.

[135] Chafer, C., "Commercial Solar Sail Applications: Overview and Update on NASA's Sunjammer Mission," *Proceedings of the 3rd International Symposium on Solar Sailing* CD-ROM, University of Strathclyde, Glasgow, Scotland, June 2013.

[136] Tarazaga, P. A., Inman, D. J., and Keats Wilkie, W., "Control of a Space Rigidizable Inflatable Boom Using Macro-Fiber Composite Actuators," *Journal of Vibration and Control*, Vol. 13, No. 7, pp. 935–950, 2007. doi:10.1177/1077546307078757

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