INFLATABLE RIGIDISABLE MAST FOR END-OF-LIFE DEORBITING SYSTEM

A. Viquerat\textsuperscript{1}, M. Schenk\textsuperscript{1}, B. Sanders\textsuperscript{2}, and V. Lappas\textsuperscript{1}

\textsuperscript{1}Surrey Space Centre, University of Surrey, GU1 7XH, Guildford, United Kingdom (V.Lappas@surrey.ac.uk)
\textsuperscript{2}CGG Safety & Systems, Westelijke Randweg 25, 4791 RT, Klundert, The Netherlands (Berry.Sanders@cggss.com)

ABSTRACT

An inflatable-rigidisable cylindrical mast was developed as part of the InflateSail technology demonstration mission. The light-weight deployable mast is inflated using a Cool Gas Generator (CGG). To ensure long-term structural performance after deployment, the boom is rigidised by removing the residual creases in the aluminium-laminate skin material through strain-rigidisation. The 1 m long and 90 mm diameter mast is folded using an origami pattern, and in its stowed configuration takes up 63 mm of height in the InflateSail CubeSat structure. The benefits of this folding method include minimal material deformation during deployment, a compact stowed configuration, and an open cross-section to accommodate the rapid release of inflation gas. Deployment tests showed a repeatable deployment, with minimal deviation from the intended straight path. Post-deployment vibration experiments established the efficacy of strain-rigidisation in recovering the stiffness of the deployed boom. Experiments were also performed on fully rigidised booms to determine their bending and compression strengths.

Key words: inflatable mast; dynamic characterisation.

1. INTRODUCTION

This paper presents the design and testing of a cylindrical inflatable mast, intended as the support structure for a 10 m\textsuperscript{2} drag deorbiting sail used in the InflateSail 3U CubeSat – one of the technology demonstrators of the QB50 mission. If the mission is successful, the inflatable mast and drag sail combination could be used as a light-weight modular deorbiting system for much larger host satellites. In its deployed state the inflatable mast has a length of approximately 1 m and a diameter of 90 mm. Its purpose is to clear the deorbiting sail from any appendages on the host craft and to provide passive attitude stabilisation through the offset between the sail centre of pressure and satellite centre of mass. The inflatable mast is folded using an origami pattern, and in its stowed configuration occupies no more than 63 mm of height in a CubeSat. The skin of the cylinder is an aluminium-polymer laminate, and the inflation system consists of two small Cool Gas Generators (CGGs). Only one CGG is required to deploy and rigidise the boom, with the second included for redundancy.

The inflatable rigidisable mast has been designed for a long in-orbit lifetime prior to deployment (> 15 years). Because the strain rigidisation process of aluminium-polymer laminates requires no chemical reaction or softening solvents, and because CGGs have been demonstrated to retain stores of gas for many years in space, this system is well suited for forming structural components in deorbiting or other long duration missions. Other advantages of the system include its simplicity (no moving parts), its fundamentally lightweight nature, and the ready adaptability of the design to much larger structures.

In this paper we describe details of the design and testing of the inflatable system. A description of the system design shows how the inflatable mast fits in the overall InflateSail concept. The boom membrane material, folding method and inflation system are then described in further detail, before presenting the results of the Engineering
2. SYSTEM DESIGN

The InflateSail satellite is a drag deorbiting demonstration mission, built on a 3U CubeSat platform. In its launch configuration approximately 1U is dedicated to the bus electronics (EPS, OBC, ADCS, and communications) and the remaining 2U is divided between the inflatable mast and deorbiting sail payloads.

A single deployable panel opens at one end of the satellite, and the inflation of the boom pushes out the sail deployment mechanism to position it away from the body of the satellite. This “jack-in-the-box” deployment method avoids some of the complexity of a multi-panel opening design, and results in a satellite with solar cells facing in multiple directions. However, this approach requires a more complicated internal structure consisting of very smooth inwards-facing walls, and a linear guide system to allow the top of the inflatable to move inside the satellite structure without twisting or rotating.

The 10 m² sail deployment mechanism is derived from the system described in Fernandez et al. [2], while the inflatable mast was developed specifically for InflateSail.

2.1. Inflatable Mast Subsystem

The inflatable mast consists of a cylindrical boom with two end fittings, an inflation system, and facilities to feed wires through the mast to the sail deployment system. An exploded view of the subsystem is shown in Figure 2 and a break-down of all components is presented in Figure 3.

- **cylindrical boom** The inflatable cylindrical boom is constructed from an aluminium-polymer laminate (see Section 3), with an internal Mylar bladder to improve airtightness. The 1 m long boom is folded using an origami pattern (see Section 4), and fully stowed occupies merely 63 mm in height; see Figure 4.

- **end fittings** The end fittings ensure an airtight connection to the boom, and provide a feed-through for the wiring. The bottom end fitting also contains an inlet (2x) for the inflation gas, a pressure sensor, and a solenoid valve. The normally-open valve vents air during launch ascent, and provides controlled venting of the inflation gas after the boom deployment. The pressure sensor monitors the internal boom pressure during inflation.

- **inflation system** The N₂ inflation gas is stored using Cool Gas Generators (CGG); see Section 5. A dual CGG setup is used for redundancy, and provides the option of topping up the internal pressure in case of unexpected leaks.

3. MEMBRANE MATERIAL

The inflatable booms are constructed of a thin aluminium-polymer laminate: the aluminium layers provide structural stiffness after deployment, while the polymer layer increases toughness.

3.1. Strain Rigidisation

The creases introduced during the folding process will affect the mechanical properties of the boom once it is deployed. The residual creases can significantly reduce the effective material stiffness by deforming as a plastic hinge [5], and the boom strength will decrease due to imperfections which trigger local buckling. In order to recover the stiffness and strength of the inflatable boom, the creases will therefore be removed using strain rigidisation. This is achieved by increasing the pressure in the cylinder until the aluminium layer in the skin deforms plastically, thereby permanently flattening the creases; see Figure 5.
For a pressurised thin-walled cylinder (wall thickness $t$, radius $R$ and gauge pressure $p$) the longitudinal and hoop stress in the material can be found simply from equilibrium:

\[
\sigma_l = \frac{pR}{2t} \quad (1)
\]
\[
\sigma_h = \frac{pR}{t} = 2\sigma_l \quad (2)
\]

Assuming a plane stress Von Mises yield criterion, the pressure required to plastically deform the material is given by

\[
p_y = \sqrt{\frac{4}{3}} \frac{\sigma_y t}{r} \quad (3)
\]

where $\sigma_y$ is the yield stress of the material. At the point of yield the plastic deformations are constrained by the bi-axial stress state in the thin-walled cylinder. In fact, it is straightforwardly shown that (to first approximation) the cylinder will only deform plastically in the hoop direction, and will not elongate axially [1, 4]. The minimum inflation pressure required to effectively remove the fold creases is determined by the yield stress of the material; see Equation 3. A greater inflation pressure will further flatten the creases, but at the expense of using more inflation gas. Furthermore, after the pressure is released the elastic recovery of the polymer layers will result in residual stresses in the aluminium layer, which may lead to auto-buckling. This was in fact observed in some inflation tests where the booms were overinflated, and a permanent longitudinal crease was formed after depressurisation.
3.2. Mechanical Properties

The laminate material used for the EM tests consists of three layers: two 14.5 μm aluminium layers sandwich 16 μm of Mylar and adhesive. The thickness of the layers was measured from a micrograph of the cross-section. The mechanical properties of the laminate material directly affect the performance of the inflatable boom in its deployed state. The elastic modulus determines the boom stiffness (although any residual creases will significantly lower the effective modulus [5]) and the flexural rigidity affects the boom strength as it buckles locally under compression or bending loads.

Measuring the mechanical properties of the thin laminate films proved to be challenging. The tests were performed using a standard Instron tensile testing machine, and an effective elastic modulus of 15–25 GPa was found for the laminate. This implies a Young’s modulus of 20–35 GPa for the aluminium layers, which is significantly lower than the expected value of 70 GPa. What is more, literature suggests that some thin aluminium foils may exhibit unusually low elastic moduli [6, 10]. The source of the low measured elastic modulus is being investigated, and until the issue has been resolved a standard value of 70 GPa is assumed for the analysis. The yield stress is more reliably found, and was estimated to be approximately 50 MPa for the laminate material.

The flexural rigidity was measured using the heavy elastica method [6, 12]. By measuring the deflection of a cantilevered strip of laminate under gravity, the flexural rigidity can be estimated. The aluminium-polymer laminate was found to have a flexural rigidity of 5.6·10^{-4} Nm. This allowed the Young’s modulus of the aluminium foil layers to be estimated at 68 GPa, supporting the hypothesis of unidentified error sources in the tensile tests.

4. BOOM FOLDING METHOD

Several methods for compactly folding inflatable cylindrical booms have been developed [9]. For the InflateSail project the inflatable boom will be folded using an origami pattern. Here the developable cylindrical surface is formed into flat facets separated by fold lines; the facets pop through into the cylindrical form at the end of inflation. A primary reason for the selection of an origami pattern for packing the inflatable boom is the open cross-section in the stowed configuration. This allows for rapid dispersal of the inflation gas from the CGG, and enables fast deployment of the boom. Moreover, origami booms have been shown to combine compact stowage with straight-line deployment [10].

4.1. Fold Pattern Selection

The family of origami patterns selected for folding the inflatable boom is described in Schenk et al. [8]. The current base-line pattern is shown in Figure 6, and is fully defined by its geometric parameters \( n = 5, \phi_1 = 67^\circ, H/R = 0.67 \) and \( R = 90 \text{ mm} \). The repeating layer is therefore 60.3 mm in height, fixing the boom length to integer multiples of this value.

The geometric richness of the origami patterns enabled various design trade-offs. The primary selection criterion was the minimisation of material deformation during deployment, which was shown to be linked to straightness of the boom deployment [10]. The deployment strains are characterised by the number of circumferential folds \( n \) and the reverse fold angle \( \phi_1 \) [8]. A combination was selected which minimises material deformation for the initial deployment phase, while providing a second undeformed configuration at approximately 70 % deployment. Decreasing the bay height of the pattern \((H/R)\) reduces the tip rotation during deployment, but will also result in a greater number of folds in the boom membrane. In turn, this increases the packaged height and might impact the mechanical properties of the deployed boom by leaving more residual creases in the boom membrane. In the selected pattern, only four folds meet at each vertex, helping to minimize the risk of pin-hole punctures due to the high local curvatures at the vertices (the inflatable bladder was later added to the design, to ensure airtightness of the inflatable boom). In its stowed configuration the boom is circumscribed by a 90 mm diameter circle, preventing the folded boom from protruding beyond the end fittings, and the large internal space (≥ 35 mm inscribed circle) accommodates the solenoid valve used to vent the inflation gas after deployment.

4.2. Manufacturing Process

The origami folding of the inflatable boom is challenging: the limited boom diameter precludes manually supporting the material from the inside, and the aluminium-polymer laminate does not allow reversal of folds. A novel manufacturing method (see Figure 7) was therefore developed:

I) First, the cylindrical boom is assembled. The bladder and aluminium-laminate are cut from flat sheets and wrapped around a cylindrical mandrel before being sealed using transfer tape. The end fittings are then attached, taking care to ensure accurate alignment of the fitting so the boom deploys straight from the CubeSat.

II) A stiff plastic sheet is scored with the desired fold pattern, and manually folded so the creases become flexible. The folded plastic sheet is then flattened, wrapped around the pressurised boom, and held in place using masking tape.

III) The pressure inside the cylindrical boom is lowered by opening the solenoid valve, and the pressure is automatically maintained at a set value. The pressure should be high enough to press the laminate material flush against the plastic mandrel, but low
Figure 6: The fold pattern selected for the inflatable boom (left), with the cross-sectional view of its fully folded configuration (right). The fold pattern is fully defined by its geometric parameters $n = 5$, $\varphi_1 = 67^\circ$, $H/R = 0.67$ and $R = 45$ mm. In its fully stowed configuration the diameter of the circumscribed circle is 90 mm, and the open cross-section is at least 35 mm in diameter.

Figure 7: Manufacturing and folding process: I) assembly of cylindrical boom, II) the plastic master sheet wrapped around a pressurised boom, III) gradual folding of boom while maintaining a low internal pressure, IV) removal of mandrel to reveal the origami-folded boom.

Figure 8: A 105 cm long boom folded to approximately 6 cm (the allowed vertical height for the folded boom in InflateSail).
enough to allow the boom to be gradually folded, using the plastic mandrel as a guide.

IV) After folding the boom the plastic sheet is removed and the boom compressed is to its stowed dimensions; see Figure 8.

5. INFLATION SYSTEM

In laboratory tests inflation of the deployable mast has been achieved using compressed air. However, the flight model of InflateSail will be inflated using a Cool Gas Generator (CGG) developed by TNO and CGG Safety and Systems BV, both located in The Netherlands. The Cool Gas Generator is an innovative way of storing gas by chemically binding it in a solid propellant. After ignition a self-sustained reaction passes through the grain and releases the gas at ambient temperature. The remainder of the propellant is left behind in the CGG.

Two types of Cool Gas Generator have been tested in space. Four CGGs, each producing 40 litres of nitrogen at 1 bar and 273 K, have been on board the ESA PROBA-2 satellite since 2009 [7], and eight miniaturised CGGs, each producing 0.15 litres of nitrogen at 1 bar and 273 K [11], have been flying on board the Delfi n3XT satellite since November 2013. To date, two generators on board of each satellite have been fired with excellent results.

The CGG designed for InflateSail is of a completely new design, and produces 3.2 normal litres of nitrogen gas (3.9 ± 5% g). One of the main goals has been to avoid a pyrotechnic classification. To this end the CGG is equipped with an innovative resistance wire igniter, developed by TNO. Another innovation is the use of stainless steel as a construction material, instead of titanium (used for the other space qualified CGGs). Stainless steel is easier to machine and has lower material cost, but is also slightly heavier than titanium. Furthermore, the CGG is designed to be modular: its length can be adjusted to decrease or increase the amount of gas produced, without changing the ignition system or the aft part of the CGG with the gas exit. Due to these unproven innovative features, two CGGs are mounted on board InflateSail for redundancy reasons.

The CGG itself is cylindrical with a diameter of 16 mm and a length of 90 mm (including flying leads); see Figure 9. The igniter is mounted on the top, while the gas outlet is at the bottom. The CGGs will be mounted in the satellite by a clamp band. A ring on the circumference of the CGG can be used to fix the CGG inside the clamp band. After the ignition signal is given, the igniter will be powered and after a few seconds the CGG will start releasing gas. The CGG propellant is isolated from the outside atmosphere by means of a breaking foil, which ruptures when sufficient pressure is built up. The burning profile is such that 90% of the gas will be released in about 6 seconds, with 99% within 60 seconds after activation. The InflateSail boom is inflated directly from the CGG, and no further gas flow control is implemented.

The rapid release of inflation gas was an important design driver for the design of the inflatable boom, and the selection of the origami folding method to stow the boom.

6. DEPLOYMENT TESTING

To verify the functionality of the InflateSail design, a dimensionally accurate engineering model of the satellite was constructed, and numerous deployment tests have been performed: both in ambient conditions (Figure 11) and in vacuum (Figure 12). These tests were also used to verify the repeatability of the folding process, the airtightness of the deployed boom, the manner of the deployment (twisting or rotation once outside the body of the satellite), and the effect of the seam on the straightness of the deployed boom.

6.1. Feasibility of Design

Functional tests have confirmed that it is possible to construct and fold aluminium-polymer laminate booms of 1 m length and compress them to a height of approximately 6 cm (Figure 8) including end fittings. The boom has never been observed to fail to exit the satellite body and deploy to its full length. The walls of the satellite
and two linear guides constrain the deploying boom to push almost straight out. The inflation pressure required to push the top of the inflatable out of the satellite has been observed to be relatively small ($\leq 5$ kPa). Any slight hindrance to deployment is quickly overcome by the resulting build-up of pressure in the boom. Consider that, at a final inflation pressure of 55 kPa, the inflation gas exerts a force of 350 N on the end fittings.

6.2. Airtightness and Inflation Pressure Margin

One of the key challenges in designing an inflatable strain-rigidised structure is balancing the requirements of high skin flexibility, resilience at high inflation pressures, and airtightness. An initial fitting design achieved the first two of these requirements, but suffered from a lack of airtightness. A second design iteration which sealed the bladder and laminate separately (see Section 2) sufficiently addressed this remaining issue. A vacuum deployment test (Figure 12) afforded a good opportunity to assess the airtightness in the space environment. Consecutive tests at an inflation pressure of 55 kPa showed an average leak rate of 0.35 mg/s and 0.52 mg/s (of air) respectively. It is difficult to isolate the precise source of leaks, with the skin-fitting interface, the gas inflow pipe, the pressure sensor attachment, and the skin itself all being potential locations for leaks.

An initial rapid, but slight, drop in pressure is observed after the boom is deployed to its full length. This is attributed to creep in the polymer layer of the laminate, which results in further deformation of the boom material and thereby a small drop in internal pressure.

A potential source of catastrophic failure is skin rupture and burst. Numerous test specimens have been inflated to 100 kPa with no ruptures observed. For a target rigidisation pressure in the range of 50–60 kPa, this represents at least a 65% over-inflation safety margin. Note that booms over-inflated to this extent display obvious permanent plastic deformation, and often auto-buckle following the release of the inflation gas; see Section 3.1.

6.3. Straightness of Deployment

The linear guides inside the satellite constrain the top of the inflatable to a single degree of freedom on its way out of the satellite. Once outside, the boom is free to twist and rotate. The selected fold pattern was found to have an almost imperceptible twist of the tip during deployment. The effect of gravity makes it difficult to gauge how straight the locus of the boom tip will be in orbit, but using a helium balloon to counteract the effect of gravity on the inflatable top fitting (Figure 11) allows the boom...
as many degrees of freedom as possible in ground testing. During these balloon tests the boom tip was not observed to deviate greatly from the satellite longitudinal axis while inflating.

6.4. Effect of the Seam

A 10 mm longitudinal seam joins the flat laminate sheet into a cylinder, and is positioned to avoid passing through any vertices of the fold pattern. This seam increases the stiffness of the boom skin locally. Once the boom has reached its full length there is a brief period in which the bladder and all layers of the laminate skin stretch elastically as the inflation pressure increases. During this stage the higher longitudinal stiffness of the seam causes a small incompatibility between the longitudinal strain of the seam and the rest of the skin. This effect is short lived, and has not been observed to affect the straightness of the deployed boom or cause any damage to the inflatable. At the onset of plastic deformation, longitudinal strain ceases to increase (as described in Section 3.1), and no further incompatibility between the seam and the skin occurs.

7. POST-DEPLOYMENT TESTING

7.1. Vibration Testing

The stiffness of the deployed and rigidised inflatable is a key parameter of interest, in particular its bending stiffness \( EI \). The bending stiffness of a deployed and strain-rigidised boom can be estimated by determining the natural frequency of the boom. If it is assumed that the base of the inflatable boom is clamped while the top is free to move, the stiffness of the boom can be estimated as:

\[
EI = \frac{\omega_n^2 L^3 (m_{tip} + 0.242672 \cdot m)}{3} \tag{4}
\]

where \( \omega_n \) is the frequency of the first mode of the boom in radians/sec, \( L \) its length, \( m \) the mass of the boom and \( m_{tip} \) is a concentrated mass at the tip of the boom. A "pristine" uncreased boom with the properties described in Section 3.2 has a theoretical stiffness of \( EI = 583 \text{ Nm}^2 \) with a natural frequency of 12.9 Hz.

Experiments were performed to determine the natural frequency of the boom following inflation to a range of pressures. Three booms with a length of 1027 mm (total length of 1050 mm including end fittings) were constructed and folded; see Figure 8. The mass of the membrane material and top fitting were measured to be 36.2 g and 229 g respectively. The dynamics of the inflatable mast is therefore dominated by the mass of the end fitting, as follows from Equation 4. The sample booms were folded and stowed in the CubeSat mock-up (see Figure 4), before being inflated and deployed to a pressure of 10 kPa. The samples were vented down to atmospheric pressure, and a miniature accelerometer was attached to the top. The frequency response of the boom tip was analysed using an impact hammer. The vibration characteristics of all three samples was tested following inflation and venting cycles from 10 kPa to 70 kPa at 10 kPa intervals. Beyond 70 kPa the laminate skin undergoes large plastic deformations, and the risk of burst increases. The effect of air damping was neglected because of the low frequencies and velocities involved. The structural damping of Sample 1 was estimated by performing a frequency sweep using a small shaker and force transducer. The results of all vibration tests are given in Table 1.

The seam locally stiffens the boom, meaning that the lowest frequency of vibration is likely to occur in a plane orthogonal to that defined by the seam and the central axis of the boom ("minor axis bending"). The natural frequencies of vibration of the three boom samples in this plane are shown in Figure 13. There is an obvious trend in each of the samples in which the stiffness of the booms increases rapidly with inflation pressure initially, which then slows as the pressure increases further beyond the theoretical rigidisation stress of approx. 55 kPa. Only a fraction of the theoretical bending stiffness is recovered (< 50%), even after inflation to 70 kPa. It is, however, possible to attain a natural frequency greater than half of the theoretical maximum. Sample 1 exhibited notably lower frequencies, and it is thought that this may be due to the damage caused to the boom by repeated attachment and detachment of the shaker attachment.

![Figure 13: The natural frequency (minor axis bending) of the three samples determined using impact tests. For each pressure increment, the boom was pressurised then allowed to deflate fully before beginning the frequency tests.](image)

7.2. Strength Testing

A series of simple loading experiments were performed to estimate the failure strength of the deployed and rigidised mast (following inflation to 70 kPa for the vibration tests). Only bending and compression tests were administered, with failure in tension not being considered
Table 1: Summary of frequency test results. The dual-axis accelerometer placed on the top fitting of the boom allowed the free vibration to be resolved into two components: one in the plane formed by the seam and the central axis of the boom (“major axis”), and a second plane orthogonal to this (“minor axis”). The damping ratio, $\zeta$, estimates for Sample 1 were derived from shaker tests. It is possible that these shaker tests slightly damaged the boom, resulting in the lower stiffness observed in the sample.

<table>
<thead>
<tr>
<th>Pressure (kPa)</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$f_{n1}$ (Hz)</td>
<td>$EI$ (Nm$^2$)</td>
<td>$\zeta$ (-)</td>
</tr>
<tr>
<td>10</td>
<td>major 3.9</td>
<td>minor 3.7</td>
<td>52 0.027</td>
</tr>
<tr>
<td></td>
<td>minor 3.7</td>
<td>minor 3.7</td>
<td>52 0.027</td>
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<td>minor 4.7</td>
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<td>82 0.040</td>
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<td></td>
<td>minor 7.0</td>
<td>minor 7.0</td>
<td>182 0.078</td>
</tr>
</tbody>
</table>

Table 2: Summary of boom loading tests. To assess the repeatability of the rigidisation process, each sample was subjected to a number of tests to failure, being re-inflated and allowed to vent before each test. The compression failure load includes an additional 2.2 N due to the weight of the top cap.

<table>
<thead>
<tr>
<th>Boom</th>
<th>Failure Moment (Nm)</th>
<th>Compression Failure Load (N)</th>
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<tbody>
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<td>45.1</td>
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<td>Sample 3</td>
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<td>43.6</td>
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8. DISCUSSION AND CONCLUSION

Intended as a structural component in an end-of-life de-orbiting system, an inflatable-rigidisable mast has been developed for the InflateSail technology demonstration mission. The inflatable structure combines an inherently low system mass with a simple deployment mechanism. A Cool Gas Generator (CGG) provides long-term storage of the inflation gas by chemically binding it to a solid propellant. For InflateSail the CGG is expected to release its 3.9 g of N$_2$ inflation gas within approximately 6 seconds. This rapid inflation was an important design driver for the inflatable mast.

The cylindrical boom is folded using an origami pattern, which can accommodate the rapid inflation by
virtue of its open cross-section in its stowed configuration. Deployment experiments with the engineering model demonstrated a reliable and straight boom deployment. The inflatable booms are made of an aluminium-polymer laminate; after deployment the residual creases are removed from the membrane by means of strain-rigidisation. Post-deployment dynamic characterisation experiments showed successful recovery of the boom stiffness, demonstrating the efficacy of the strain-rigidisation method in ensuring long-term structural performance.

Much of the design validation has been experimental, with theoretical analysis hampered by difficulties in accurately measuring the material properties of the laminate, and the challenge of accounting for the residual creases in any stiffness and strength calculations on the boom. Nonetheless, the test results validated the concept of an origami-folded inflatable boom with strain-rigidisation of an aluminium-polymer laminate, and the PFM for Inflate-Sail is currently under development.

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