Viscoelastic Effects in Metal-Polymer Laminate Inflatable Structures

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A 1 m long inflatable-rigidizable mast was developed as a payload for InflateSail: a 3U CubeSat technology demonstration mission. The thin-walled cylindrical mast consists of an aluminum-polymer laminate, and long-term structural performance is ensured through strain-rigidization: the packaging creases are removed through plastic deformation of the aluminum plies. During ground tests it was observed that after rigidization the internal pressure dropped more rapidly than could be accounted for by leakage of inflation gas alone. It was hypothesized that viscoelastic behaviour of the laminate material causes a further, time-dependent (order of seconds), increase in cylinder diameter, with a corresponding drop in internal pressure. Additional experiments revealed an increase in diameter, including large visco-elastic shear in the adhesive of the lap joint. This was not found to be sufficient to fully account for the observed reduction in pressure. An increase in temperature of the gas during inflation, with subsequent cooling down to ambient is thought to cause the additional pressure drop.

Nomenclature

L	cylinder length [m]	T	temperature of inflation gas [K]
V	cylinder volume [m^3]	γ	gas adiabatic index
r	cylinder radius [m]	σ	stress [Pa]
t	laminate thickness [m]	ε_θ	hoop strain [-]
P	inflation gas pressure [Pa]	τ	time [s]

I. Introduction

The InflateSail satellite is a CubeSat technology demonstration mission for an end-of-life satellite deorbiting system.[1,2] The deorbiting system comprises two deployable structures: a 1 m long inflatable-rigidizable cylindrical mast and a 10 m^2 drag sail supported by bistable CFRP deployable booms; see Figure 1. It is envisaged that the InflateSail payload could, in future, be attached to larger host satellites before launch, and then deployed at the end of the satellite's life. The gossamer drag sail increases the host satellite's aerodynamic drag, thereby accelerating its orbital decay. The inflatable mast provides an offset between the center-of-mass of the host satellite and the center-of-pressure of the gossamer sail, which facilitates passive attitude stabilization and thereby maximizes the presented drag area.[3] The proposed drag deorbiting system would enable satellites to comply with the 25 year deorbiting guidelines.[4]

The focus of this paper is the inflatable-rigidizable cylinder developed for InflateSail, which functions as a lightweight deployable structural member supporting the drag sail. The 1 m long and 90 mm diameter cylindrical mast is folded down using an origami pattern to a packaged height of approximately 65 mm.[2]

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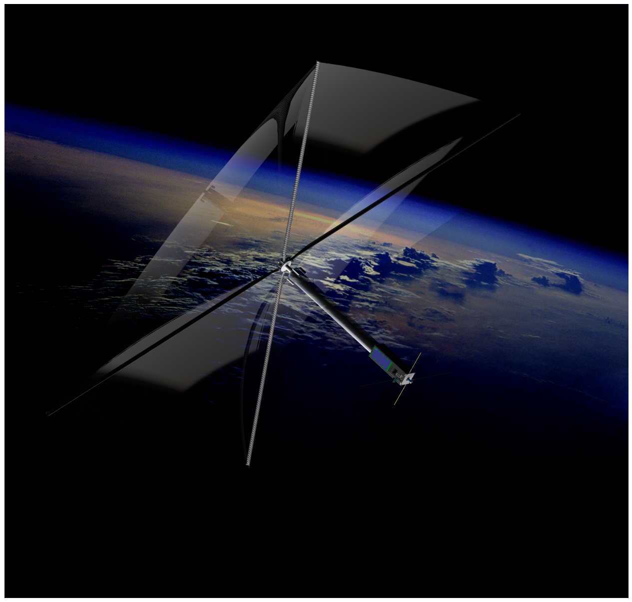


Figure 1. InflateSail deploys two structures from a 3U CubeSat: a 1 m long inflatable cylindrical mast, and a 10 m^2 drag augmentation sail supported by four CFRP booms. [Background image: NASA]

A Cool Gas Generator (CGG) provides long-term storage of the inflation gas.[5] The inflatable cylinder is constructed of a thin metal-polymer laminate. Following deployment, the residual creases are removed by plastically deforming the metal plies in the laminate in a process referred to as strain-rigidization.[6,7,8] The metal plies provide structural stiffness while the polymer plies increase toughness and tear-resistance.

Metal-polymer laminates have been a recurring choice for inflatable rigidizable space structures since Echo II was launched in 1964. The mechanical rigidization process allows the inflatable skin to be stored for many years before deployment without significant degradation. The lack of any curing process makes the rigidization simple and reliable. Drawbacks include an upper limit in wall thickness (and hence deployed structural strength and stiffness) based on the maximum thickness of metal which can be folded and unfolded without significant damage occurring.

During qualification deployment tests, it was observed that the inflatable test cylinders would experience a small, but marked and repeatable drop in pressure in the seconds following the full deployment and rigidization of the deployable inflatable.[1] This effect was in addition to the leakage of inflation gas from the mast; the InflateSail design includes an additional internal bladder to aid airtightness, but this proved not to be sufficient to completely eradicate small leaks in the system. The additional pressure drop was initially attributed to viscoelastic behaviour in the polymer ply, but this paper presents a follow-up investigation into the likely causes of the pressure drop.

A. Deployment Inflation Pressure

Figure 2 shows the pressure trace of a pressure-controlled deployment of the inflatable mast, performed under ambient conditions with pressurized air. After an initial pressure spike, a low inflation pressure sufficed to deploy the mast. Once the cylinder was fully extended, the pressure rapidly increased to achieve strain-rigidization where the laminate skin was plastically deformed to remove the creases. A controller maintained the inflation pressure at 50 kPa, and the air inlet valve was opened when the internal pressure dropped below a threshold value. Upon closer inspection, the ‘saw-tooth’ profile of the internal pressure after full extension showed a more rapid drop in pressure than could be accounted for by leaking of inflation gas, and successive pressure drops were found to become progressively more gradual. Assuming that the final drop in pressure was exclusively the result of leaking inflation gas, the leak rate could be subtracted from the earlier ‘saw-tooth’ curves to reveal a marked drop in pressure over a period of several seconds after achieving the rigidization pressure.

In the InflateSail Flight Model, the inflation system comprises a (CGG)[5,1] which provides a fixed quantity

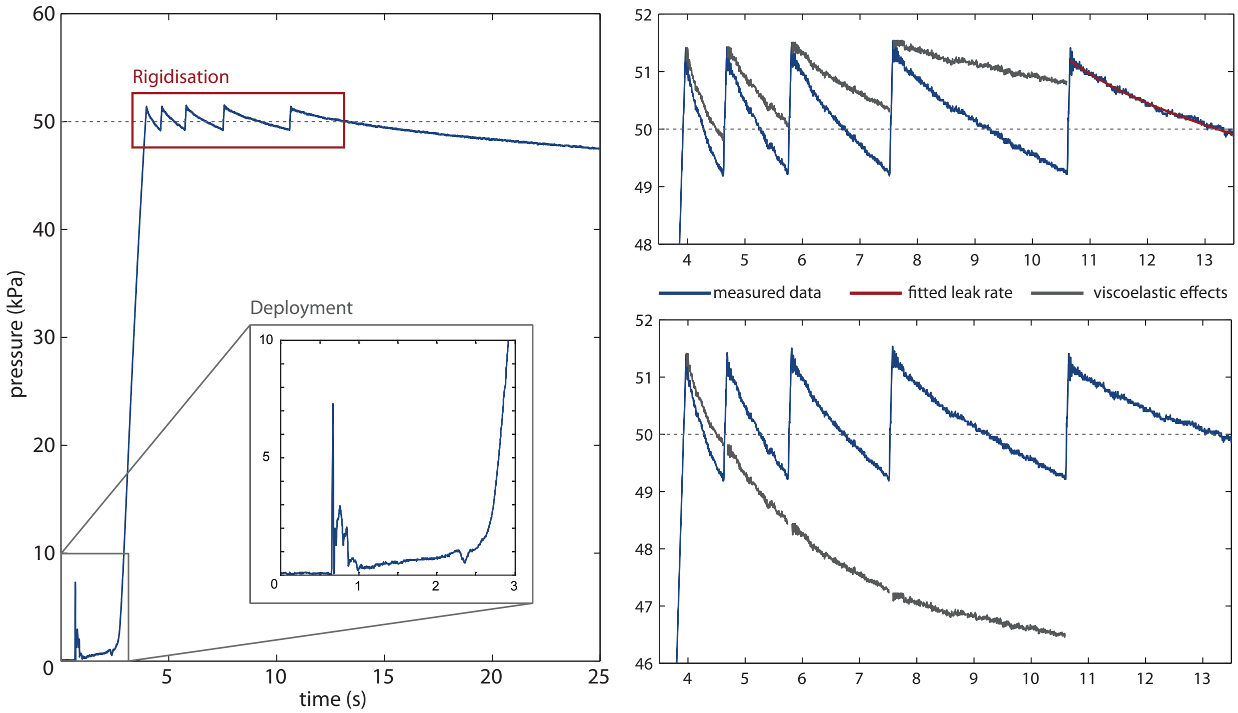


Figure 2. Pressure trace during pressure-controlled inflation of the deployable cylinder (left). The 'saw-tooth' profile of the pressure after full extension is believed to be a result of leakage as well as viscoelastic effects in the laminate material. Subtracting the leak rate from the measured data shows the pressure drop due to the time-dependent effects.

of N_2 inflation gas. A qualification cylinder deployment using a CGG was performed inside a vacuum chamber; the pressure trace is shown in Figure 3. After a small pressure spike the inflatable cylinder deployed rapidly (within approx. 0.5 s). After attaining its maximum inflation pressure, a sharp drop in pressure can again be observed, transitioning into a gradual loss of pressure due to leaking of inflation gas. After a minute a release valve was opened, venting the remaining inflation gas into the vacuum chamber.

B. Inflation Pressure Drop Hypotheses

In order to account for the marked drops in inflation pressure, a number of explanations were hypothesized:

- *viscoelastic effects in laminate* – as a first approximation it is assumed that the aluminum plies of the laminate do not exhibit time-dependent behaviour, and behave perfectly elastic-plastic. It was hypothesized that the polymer ply (Mylar) creeps, increasing the cylinder diameter, and thereby reducing the internal pressure. Additionally, the flattening of the creases could be time-dependent due to viscoelasticity of the polymer at the fold lines.

- *viscoelastic effects in the adhesive joint* – a single lap joint seals the cylinder, using a Pressure Sensitive Adhesive (PSA) transfer tape (3M 966; 10 mm wide, 60 μm thick). A low shear modulus of the adhesive was expected to account for a modest increase in cylinder radius.

- *thermodynamic effects* – no significant temperature variations were observed with the embedded temperature sensors, but drops in temperature could account for some of the observed pressure drops.

The viscoelastic behaviour of the laminate material was considered to be the most promising explanation for the decrease in inflation pressure. The cylinder diameter was not measured directly during the ambient or vacuum chamber (Figures 2,3) inflation experiments. However, over-inflation tests to approximately 100 kPa showed large plastic deformations, resulting in auto-buckling after depressurization; see Figure 4.

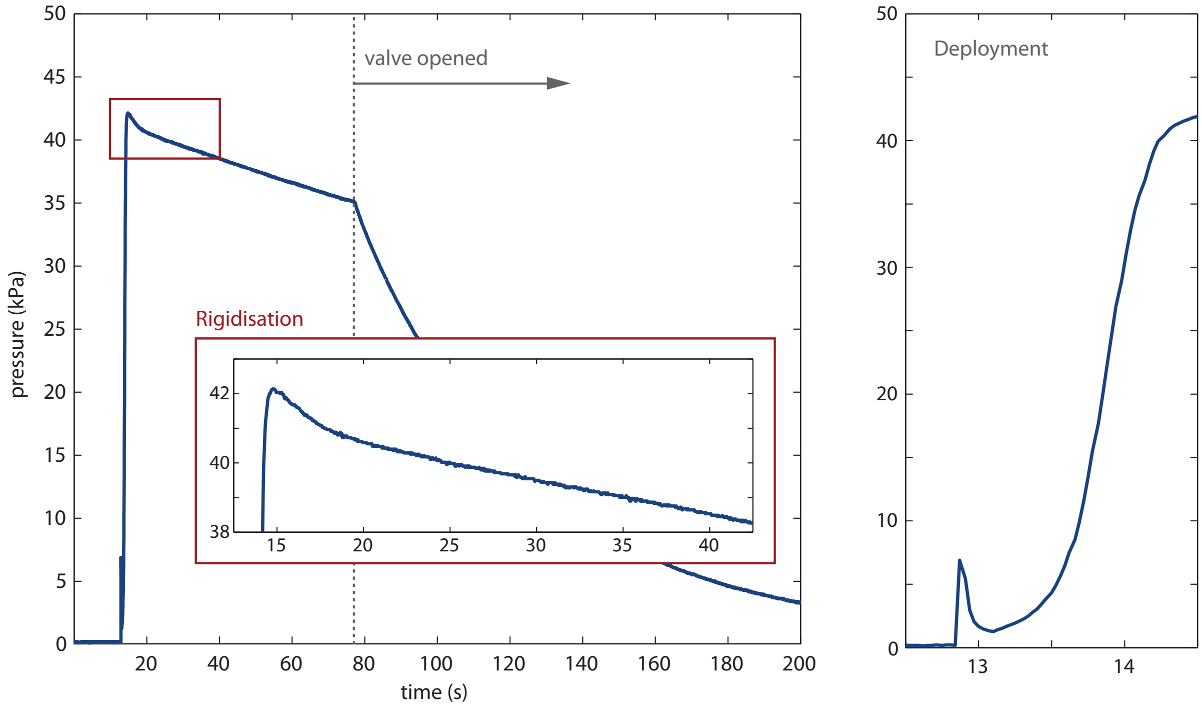


Figure 3. Pressure trace of a fixed-mass inflation of the deployable cylinder using a CGG. A rapid pressure drop can be observed shortly after peak inflation pressure is reached, which after a few seconds transitions into a gradual loss of pressure due to leaking of inflation gas.

C. Material Definition

A number of different two and three ply metal-polymer laminates were considered for use in the InflateSail flight mission. The laminate selected was a three ply aluminum-BoPET (Mylar)-aluminum material, with a total thickness of approximately 45 μm made up of plies of nominally equal thickness; see Figure 5. The toughness of the laminate material protects the cylinder from over-inflation, and it has been observed to survive pressures up to 100 kPa, despite the onset of yield in the metal plies occurring at the "rigidization" pressure of approximately 50 kPa.[2] Although BoPET (Biaxially-oriented Polyethylene Terephthalate) is a semi-crystalline polymer known for its high resistance to creep, it does still exhibit a degree of viscoelastic behaviour.[9,10]

As an illustrative example, an inflation pressure of 70 kPa in a cylinder of radius 45 mm and skin thickness 45 μm generates a hoop stress of 70 MPa across the three plies of the laminate. Immediately after a rapid inflation, the much higher stiffness of the metal plies causes them to carry the majority of this load. If the total thickness of metal in the laminate is assumed to be 26 μm, not including the polymer ply or adhesive, then the stress acting on the metal plies is 120 MPa. Subsequent yielding in the metal plies increases the strain in the polymer ply, causing it to carry a greater share of the total loading.

The 3M 966 10 mm wide, 60 μm thick PSA transfer tape was chosen because because of its low outgassing properties, resistance to high temperatures, and relatively high shear strength. No information about the viscoelastic properties of the adhesive has been found.

II. Analysis

A. Pressure-Strain Relationship

After subtracting estimated leak rate, it was assumed that the remaining δP is due *to a volume change* of the cylinder, through plastic and/or viscoelastic deformation of the laminate. The expansion can be assumed to be either *isothermal* or *adiabatic*, providing bounds to the required volume change.

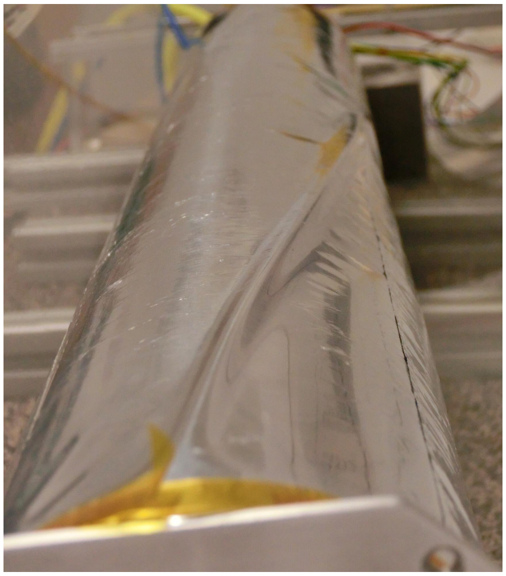


Figure 4. Auto-buckling of cylinder afer depressurization from 100 kPa inflation pressure, showing significant plastic deformation in hoop direction.

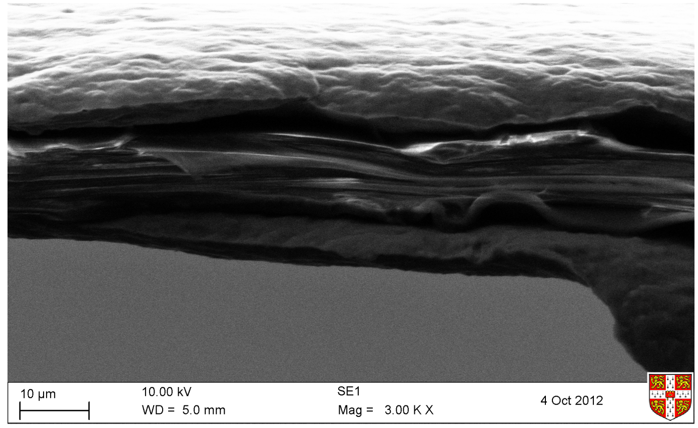


Figure 5. SEM image of the InflateSail laminate material.

Isothermal It could be assumed that the gas temperature in the cylinder remains constant during the expansion process. From the ideal gas law we find:

$$PV = \text{constant} \tag{1}$$

Linearising around the initial inflation presure P_i we find:

$$\frac{\delta P}{P_i} = -\frac{\delta V}{V_i} \tag{2}$$

With the volume $V_i = L\pi r_i^2$ can express the volumetric strain as:

$$\frac{\delta V}{V} = \frac{\delta L}{L} + 2\frac{\delta r}{r_i} \tag{3}$$

Adiabatic Alternatively, it could be assumed that the initial expansion is too rapid (order of seconds) for the gas temperature the equilibrate with the ambient temperature. This leads to the expression for adabiatic expansion:

$$PV^{\gamma} = \text{constant} \tag{4}$$

where γ is the adiabatic index. For air at ambient temperature, $\gamma \approx 1.4$. Linearisation leads to:

$$\frac{\delta P}{P_i} = -\gamma\frac{\delta V}{V_i} \tag{5}$$

Furthermore, it is assumed that the increase in the volume of the cylinder δV is due *only to a radial expansion* and therefore $\delta L = 0$. For analysis of rigidisation, the laminate deformation is approximated as perfectly plastic ($\nu = 0.5$) which results in a constant cylinder length.[8] Therefore:

$$\frac{\delta P}{P_i} = -\gamma\frac{\delta V}{V_i} \approx -2\gamma\frac{\delta r}{r_i} = -2\gamma\varepsilon_\theta \tag{6}$$

where $\gamma = 1$ for isothermal and $\gamma = 1.4$ for adiabatic expansion, and ε_θ is the effective hoop strain.

After subtracting the assumed leak rate in the ambient inflation, shown in Figure 2, the cumulative drop in pressure from 51.4 kPa to 46.5 kPa would require a hoop strain of 4.8% (isothermal) or 3.4% (adiabatic), after having reached the initial inflated volume. It is important to note that a cylinder pressurised with a fixed quantity of gas at an initial pressure of approximately 50 kPa would not experience as great a pressure drop.

B. Short term response of polymer plies

The response of a Kelvin-Voigt material to the application of a sudden stress at time $\tau = 0$ is:

$$\epsilon(\tau) = \frac{\sigma_0}{E}\left(1 - e^{-\lambda\tau}\right) \tag{7}$$

A Standard Linear Solid (SLS) model may have to be considered to enable modelling of relaxation effects.

III. Evaluation of pressure drop hypotheses

The cause of the rapid pressure drops was hypothesised to be viscoelastic behaviour of the polymer ply in the laminate material. Two sets of experiments were performed to study this effect: inflation experiments on cylinder samples where the cross-sectional diameter was monitored, and tensile tests on samples of the laminate material.

A. Inflation Experiments

A series of inflation tests was done on shorter cylinder samples (0.5 m long). The inflation was pressure controlled, and the diameter of the cylinder was measured using contactless distance gauges (Micro-Epsilon optoNCD 2300); see Figure 6. The cylinders were initially inflated to a pressure of approximately 5 kPa, to provide a reference diameter. Next, the cylinder was rapidly pressurised to 70 kPa. The pressure was held for approximately 30 s, with extra air released into the cylinder if the pressure fell below a threshold value, after which the air was vented from the cylinder. The inflation tests were performed on the laminate material selected for flight (Al/Mylar/Al) as well as an alternative laminate (Al/Kapton/Al). This alternative laminate was known to have a lower yield stress, so the maximum inflation pressures used were lower when testing with this laminate (between 45 and 50 kPa).

Figure 6. Experimental setup for inflation tests, with two contactless laser distance gauges to measure the change in cylinder diameter. The seam is facing upwards, to enable image tracking of the expansion of the seam.

After initial inflation experiments, it was discovered that the seam expanded significantly. This had not previously been observed in post-inflation inspections of the cylinder, as it was found to recover elastically. To quantify the effect, the seam was filmed using a video camera and the extension was measure using the Matlab Vision toolbox.

Pressure measurements from two inflation experiments on cylinders made of the flight laminate material are shown in Figure 7. In both experiments the time-dependent 'saw tooth' behaviour was observed. The loss of pressure after the last top-up was assumed to be entirely due to air leaking from the cylinder. This was subtracted from the earlier measurements to reveal the cumulative drop in pressure due to the time-dependent behaviour. A very similar pattern was observed for the two cylinders, showing repeatability of the behaviour, and in both cases the cumulative pressure drop was approximately 9.6 %. A hoop strain of 4.8 % would therefore be required to account for the pressure drop only due to changes in diameter of the boom.

Figure 8 shows the change in diameter measured in laminate cylinders made from the two different test materials. In each case the previously uninflated cylinders were rapidly inflated to their target pressure (70 and 50 KPa respectively), and that pressure was held constant for a period of time. The inflation gas was

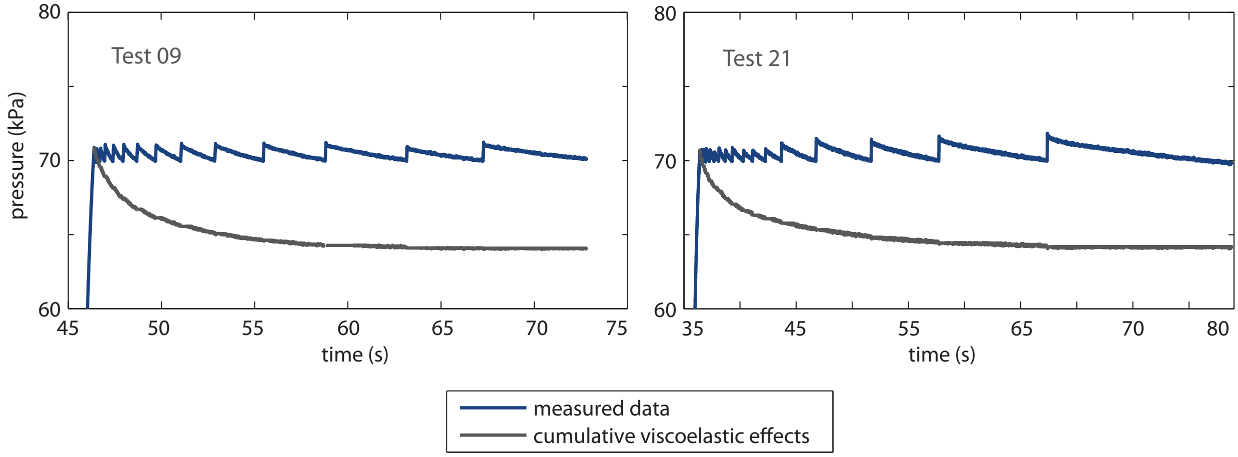
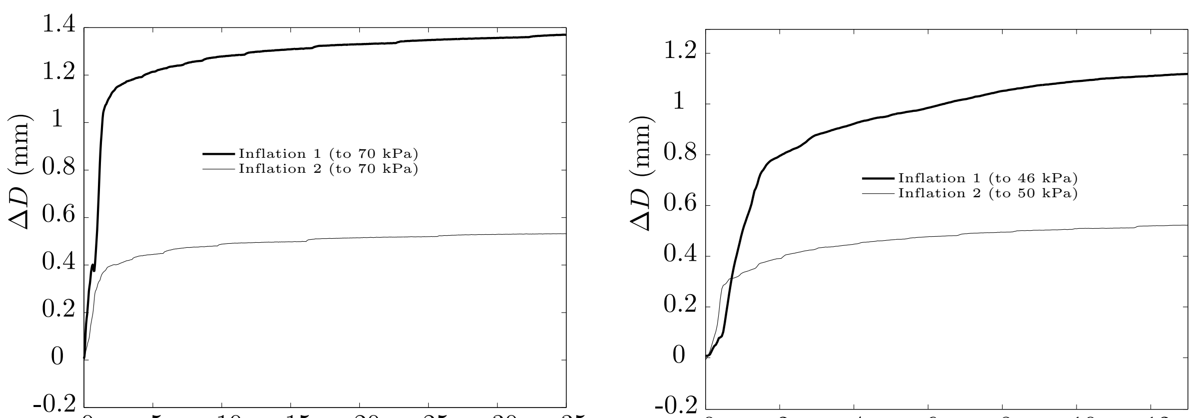


Figure 7. Pressure measurements for two inflation tests on the flight model laminate with target pressure of 70 kPa. The estimated leak rate, based on the final decay curves, was substracted to reveal the cumulative pressure drop due to time-dependent effects.

then released and the cylinders allowed to relax for a number of minutes. During this time the seams were observed to return fully to their original displacements. However, in both cases the diameter of the cylinders was permanently increased by the yielding of the laminate materials. Taking the increased diameter as reference, the diameter change during a second inflation process was monitored. In both laminate samples it can be seen that this second inflation does not lead to such a substantial change in diameter, and was observed to be fully recoverable. Both the initial and subsequent inflation tests show significant time dependence. The time dependence in the initial inflations is attributed to a combination of viscoelastic effects in the shearing of the seam, and in the laminate skin itself during its yielding process. The variation with time observed during second and subsequent inflations, however, is thought to be due primarily to the shearing of the seam.

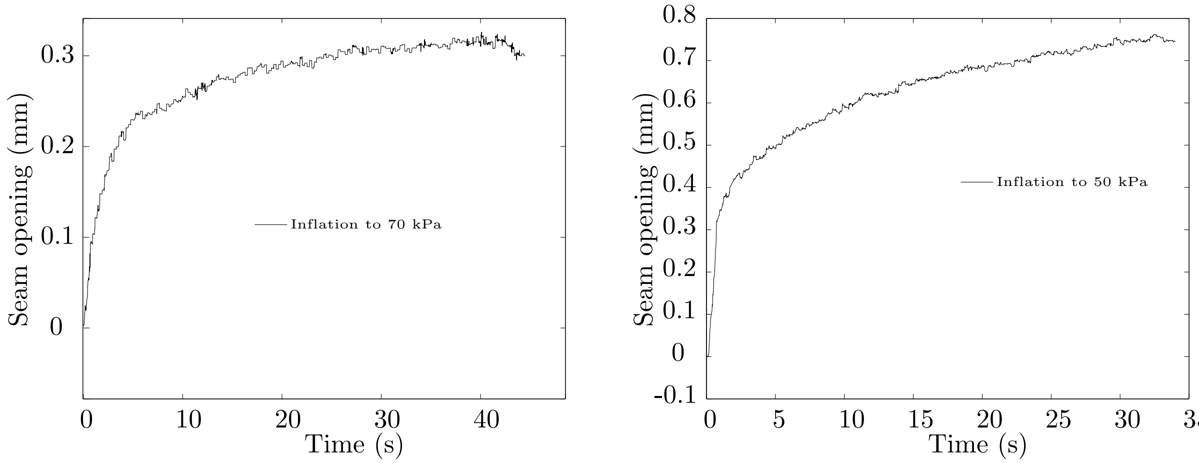


(a) Al/Mylar/Al laminate

(b) Al/Kapton/Al laminate

Figure 8. Change in diameter of inflatable laminate cylinders following rapid inflation

The effect of the shearing of the seam was isolated by filming the seams of various cylinders during the inflation process, and post-processing using the Matlab Vision toolbox. Typical results are shown in Figures 9 and 10. This analysis highlighted two interesting features. First, the extent to which the seam shears appears to be dependent on the particular laminate used, and second, the shear displacement of the seam is recoverable and repeatable. The material dependence is likely due to the surface properties of the laminates; effort was made to keep the laminates clean, but no surface treatment was done before applying the adhesive. It was noted with some surprise that the 0.3 mm (0.7 mm for the non-flight laminate)shear deformation of the 60μm thick adhesive appeared to be elastically recoverable.



(a) Al/Mylar/Al laminate (b) Al/Kapton/Al laminate

Figure 9. Hoop expansion of seam following rapid expansion

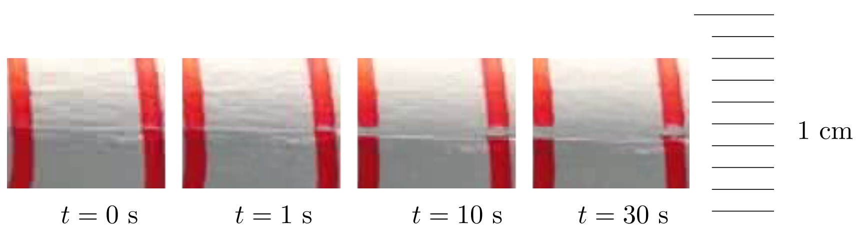


Figure 10. The shearing of the seam from the experiment shown in Figure 9(b)

For the Al-Mylar-Al laminate, a change in cylinder diameter of approximately 1.4 mm was measured after pressurisation, which corresponds to a hoop strain of $\varepsilon_\theta \approx 1.5\%$. This is a combination of elastic, plastic and viscoelastic strains of the laminate as well as viscoelastic shear of the seam. Even if the entire change in cylinder diameter was attributed to time dependent effects, this would only account for a 3 % pressure drop.

B. Material Characterisation

In addition to the inflation experiments, a series of tensile tests were performed on the laminate material to gain insight into their time-dependent behaviour. Determining the mechanical properties of the laminate material has proven to be unexpectedly challenging, due to non-linear behaviour as a result of non-flatness of the material and unreliability of measurements of cross-head displacements of the tensile testing machine.[11] In the design process, the yield stress of the laminate material therefore had to be estimated from the stress-strain curves, as the 0.2% proof stress could not be accurately determined. The required rigidization pressure was validated experimentally through non-destructive testing of the cylinder stiffness.[1]

Analysis of the laminate materials use for the NASA Echo II project had previously revealed viscoelastic behaviour of the material.[9,10] The tensile tests on the InflateSail laminate were performed using a Shimadzu tensile testing machine, with a video extensometer to provide contactless strain measurement. A speckle pattern was applied to a small patch of masking tape, and applied to the laminate material; these provided reference markers for the video gauge software. Trial tests on Aluminium foil samples verified that the cross-head displacements could not be reliably used for strain measurement of the laminate material. The test protocol involved loading the samples beyond the yield point, before unloading and reloading, to check against the elastic modulus of Aluminium.

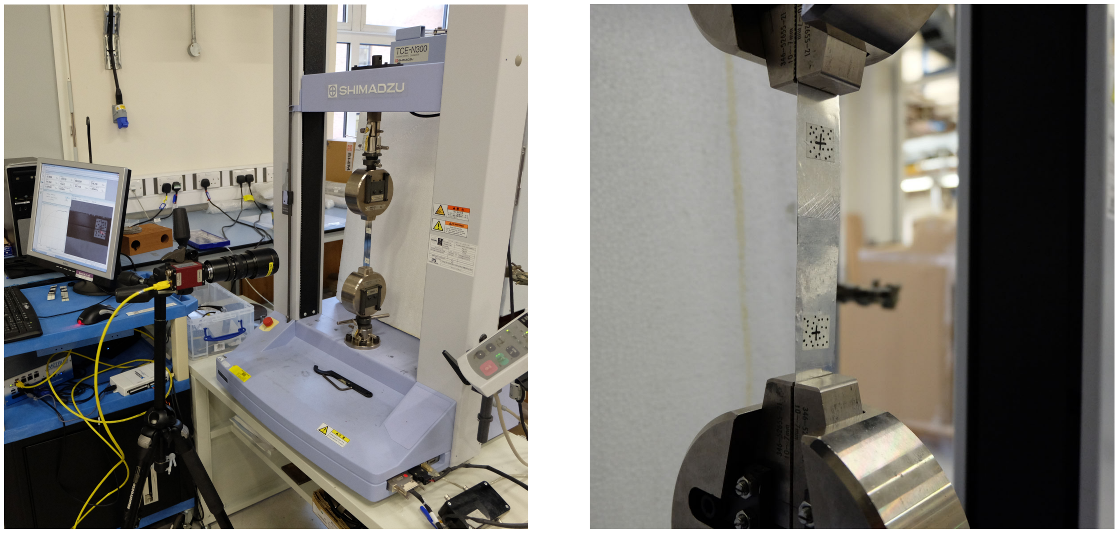


Figure 11. Laminate sample in tensile testing machine, with video gauge.

For the creep tests, the objective was to rapidly increase the load to the target value before holding it constant for approximately 1000 s; see Figure 12. The target loads are the Von Mises equivalent laminate stresses for inflation pressures of 50, 60 and 70 kPa. The Shimadzu control software did not allow rapid loading, and instead ramped the load until the desired value was reached (in the tests shown, 99% of the target load was reached within 15 seconds). The ramp-up period exceeded the time scales of the rapid depressurisation observed in the inflation experiments, but short term viscoelastic behaviour of laminate could be estimated from the longer term data.

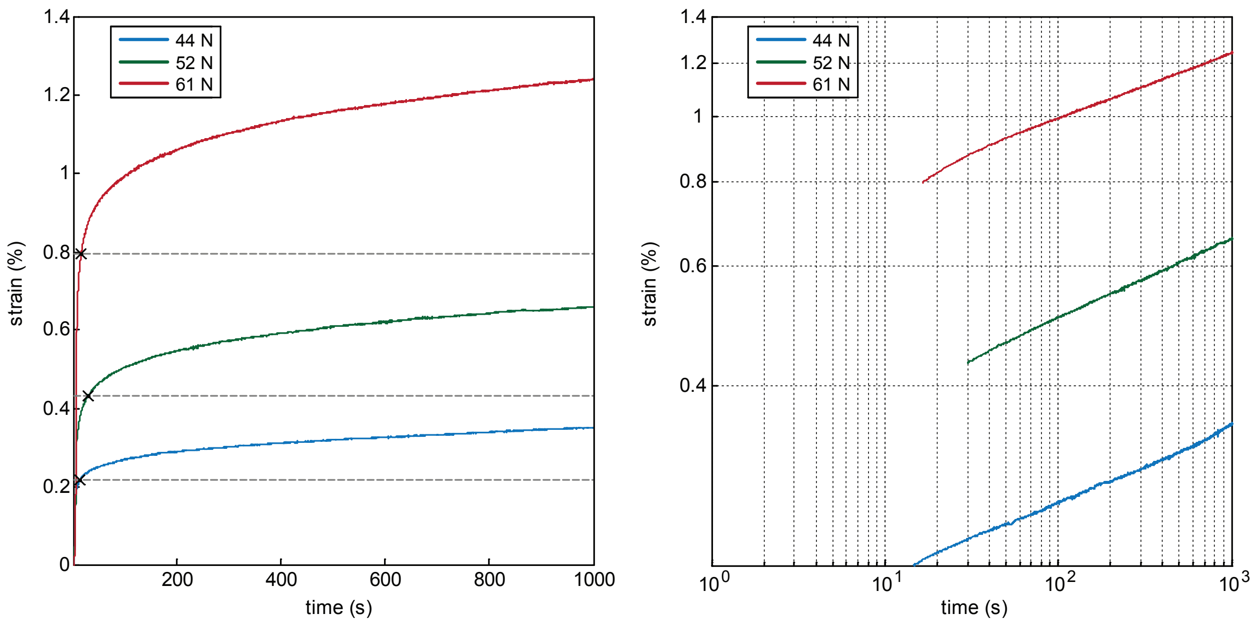


Figure 12. Creep test results for laminate strips, on linear and log-log axes. Dashed horizontal lines indicate the point at which 99% of the target load was attained. The creep time constants for the different target loads are nominally equal (as evinced by the slope of the graphs on log-log scales).

IV. Conclusion

This investigation into the viscoelastic effects present in a metal-polymer laminate inflatable mast was motivated by the observed rapid drop in pressure following inflation tests. The InflateSail deployment and rigidization processes are driven by the release of a fixed quantity of gas. A thorough understanding of the mechanics of the laminate material and seam is required to be able to predict the final laminate skin stress which can be achieved with a given quantity of inflation gas.

The experimental results presented here indicate that the laminate material and the adhesive in the lap joint which seals the cylinder, both display viscoelastic behaviour. This results in a time-dependent change in diameter of the cylinder after reaching maximum inflation pressure. The shearing of the seam is greater than anticipated, but is a repeatable process, showing very similar behaviour between inflations. The viscoelastic behaviour of the laminate does not fully recover following inflation due to the permanent deformation of the metal plies.

The large shear deformation of the seam has led to a modification of the InflateSail Concept of Operations, as it presents the risk of a higher likelihood of rupture than had previously been allowed for. InflateSail is equipped with a release valve for venting the inflation gas after deployment and rigidization, and this will now be opened earlier than originally planned. The InflateSail mast will remain pressurised less than 15 seconds, in order to minimise the risk of rupture due to viscoelastic shearing of the seam. Furthermore, inflation will be avoided at elevated temperatures, as that would have a detrimental effect on the shear stiffness and strength of the adhesive in the lap joint.

The magnitude of the time-dependent drop in pressure could only partially be explained by the measured increase in cylinder diameter. An explanation for the discrepancy is sought in a gradual temperature drop of the inflation gas, which is presumed to have increased during the rapid inflow of gas during inflation. A more complete thermodynamic model, and measurement of the temperature of the inflation gas inside the cylinder would form part of future work.

V. Acknowledgements

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