Modular Inflatable Space Structures

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Abstract—**There is a growing need to develop a human focused exploration program and support infrastructure, including relay sites in deep space. One of the first targets will be cis-lunar space station, which is a strategic gateway towards permanent settlement of the Moon and Mars. A station in deep space will require structures with large surfaces, very high volume to mass ratio and high-packing efficiency. The transportation of bulky payloads to beyond low-earth orbits pose formidable cost and logistical challenges. This requires a paradigm shift in research towards methods to build and assemble low-mass, large and complex structures in space instead of transporting them from Earth and deploying them on-site. On-site additive construction and assembly methods hold promise, but they face a major challenge of still having to transport large and heavy robotic equipment required to perform complex construction. This paper presents an alternate and more feasible pathway in developing small structural units that can be quickly shaped and assembled with limited external support. Inflatable structures hold that promise as they are low-mass, can be quickly reshaped, inflated and rigidized into desired modular units that are assembled into large, complex structures. Our present work extends the inflatables concept to study modular, inflatable blocks assembled into pre-determined geometries. The inflatable building blocks would be assembled into communication relays, science instrument antennas, structures to hold solar panels and large reflectors. Our efforts aim to identify common desired structural design traits in these modular units to enable them to be multi-functional building blocks that can be assembled into more complex functional blocks. Our design methodology focuses on simplicity of deployment mechanisms and high-scalability over varying sizes. Finally, this paper will provide preliminary feasibility of the modular inflatable building block concept and analyze the applications of this technology towards assembly of large structures in deep space.**

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1. INTRODUCTION

There are plans to develop a human focused exploration program in deep space as a stepping-stone to return to the Moon and explore Mars. One such concept called Deep Space Gateway (Figure 1) outlines plans for building a space station in cis-lunar space. Such infrastructure would serve to further our existing capabilities in space. Some of these desired capabilities include high data-rate communication links in deep space, strategically located communication relays, large surfaces for energy collection, large science instruments such as telescopes and human habitats. While each of these applications would have specific design needs, there are common design traits for all these structures. They include large surface area to stowed volume ratios, high-packing efficiencies and structural reliability.

An increase in size of these space structures comes with increased complexity, reduced stowage efficiency and lower reliability. A credible strategy to scale up in size is to utilize a modular architecture, where a large superstructure is composed of modular building blocks. Research in this area is categorized into two strategies. The first, is termed as extra-vehicular assembly (EVA) [1] or extra-vehicular robotic assembly (EVR) [2] requiring an end-effector that is external to the structure itself. This includes robotic assembly of modular structural units also called digital material units [3] and additive robotic assembly using In-Situ Resource Utilization (ISRU) [4]. The second is to embed end-effectors into the structure that could then be controlled using actuation schemes [5].

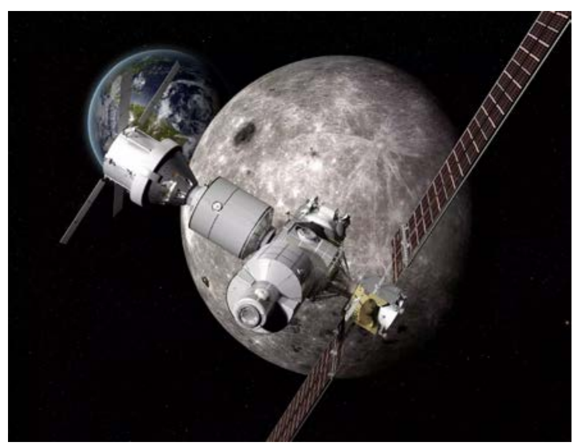

Figure 1. Boeing's Deep Space Gateway Concept.

These strategies are promising because the structural units can be compacted and have high redundancy. However, they need to carry the robotic equipment, which is bulky. Additionally, this equipment can be mechanically complex introducing multiple potential failure modes. These factors effectively bound the scalability and structural reliability of these systems.

In this paper, we propose a strategy that eliminates or minimizes the need for active end-effector elements and enable structural 'self-assembly'. Our strategy is to enable mechanical simple build blocks with high scalability. We propose the use of pneumatic inflatable modules which possess the ability to be passively activated and controlled without complex robotic end-effectors external or internal to the system. Methods for tuning the structural behavior of these modules are discussed using passively activated chemical sublimate powders [6]. We then go onto develop a method to characterize the reliability of such structures in deep space.

2. BACKGROUND

Pneumatic inflatables have been successfully applied for space structures since the 1950's [7]. Their mechanical simplicity and ability to be built into large low-mass structures has had renewed interest with Bigelow's inflatable habitat aboard the International Space Station (ISS) [8]. This section presents the background that serves as a starting point for our analysis.

Pneumatic Inflatable Modules - Structural Behavior

Inflatables are structurally complex due to their dynamic behavior since their structural properties show non-linear variations with scale [9]. The steady-state behavior of such structures is better understood and modelled and is the focus here. It is possible to linearly approximate inflatable membrane behavior reliably for smaller membrane thickness to area ratios [10]. This leads us to study smaller inflatable modules in the assembly of larger structures.

Based on the tensioned field theory [11], a scale tensile membrane gives rise to uncontrolled features such as wrinkle formation and regional membrane buckling. The structural behavior of an inflatable beam is characterized into pre-wrinkling and post-wrinkling phases. Wrinkle formation takes place instantly as a load is applied on thin pneumatic membranes. The membrane loses its load carrying ability once the wrinkle propagates through its circumference.

At this point, the membrane buckles and is unable to carry any load. Comer and Levy [12] modelled the bending moment of inflatable membranes using beam theory approximations. Their model as can be extended to include membrane thickness effects as described below:

$$\frac{M(x)}{pr^3} = \frac{\pi(2\pi - 2\theta_o + \sin 2\theta_o)}{4[(\pi - \theta_o)\cos\theta_o + \sin\theta_o]} \tag{1}$$

Where *M(x)* represents the net-bending moment developed in a simply supported cylindrical membrane of radius *r* and internal pressure *p*, θ_o is the critical buckling angle and is calculated based on the applied load *W*. Equation (1) can be used to model inflatable behavior using Euler – Bernoulli beam theory as described by the following equations:

$$\frac{d^2y}{dx^2} = \frac{M(x)}{EI_1}$$
$$\frac{d^2y}{dx^2} = \frac{M(x)}{EI_2} \tag{2}$$

Where *y* is the total deflection of the beam, *E* is the Young's modulus of elasticity of the membrane. I_1 and I_2 are moments of inertia before and after wrinkling respectively [13]. I_1 and I_2 are calculated as:

$$I_1 = \pi r^3 t$$
$$I_2 = r^3 t(\pi - \theta_o + (\sin 2\theta_o)/2) \tag{3}$$

The wrinkling behavior and thus load bearing capacity of these elements are proportional to the equilibrium pressure, *p,* inside them. We propose the use of sublimate powders as the source of pressure forming gas.

Passive membrane activation – Chemical Sublimates

Sublimate powders are known to undergo phase transformations from a solid into gas at phases close to their triple point. This state of a powder is described by ambient pressure and temperature. For a solid to convert into a gas, enough energy needs to be supplied to break the crystalline bond energies [14]. This energy is referred to as the sublimation enthalpy (ΔH_{sub}). The equipartition law [15] provides a reasonable approximation to calculating sublimation enthalpy as follows:

$$\Delta H_{sub}(p,T) = -U_{Lattice\_energy}(p,T) - 2RT \tag{4}$$

Here $U_{Lattice\ Energy}$ is the energy required for molecules to break their crystal lattice and convert to gas, *R* is the universal gas constant, *T* is temperature, *p* is the ambient pressure. In vacuum, ΔH_{sub} decreases dramatically and sublimation can be achieved isothermally [14]. Hence, these powders can be used to produce gas passively in vacuum.

Using Reynold's transport theorem [15], the mass flow rate of conversion from solid to gas is given as:

$$\frac{dm}{dt} = \alpha\sqrt{\frac{M}{2\pi RT}}(p_{eq} - p) \tag{5}$$

Here α is a material specific proportionality constant, M is the molecular mass, R is the gas constant and p_{eq} is the equilibrium vapor pressure of the sublimate.

Passive membrane pressure control

The sublimation process stops once ambient pressures approach the sublimate's natural vapor pressure at a given temperature as described below:

$$p_{eq} = \beta\sqrt{\frac{2\pi R}{M}}Te^{-\frac{\lambda}{RT}} \tag{6}$$

Here, β and λ are material specific constants. As a result, this excludes the requirement of an external active pressure controller, making the process simple and reliable

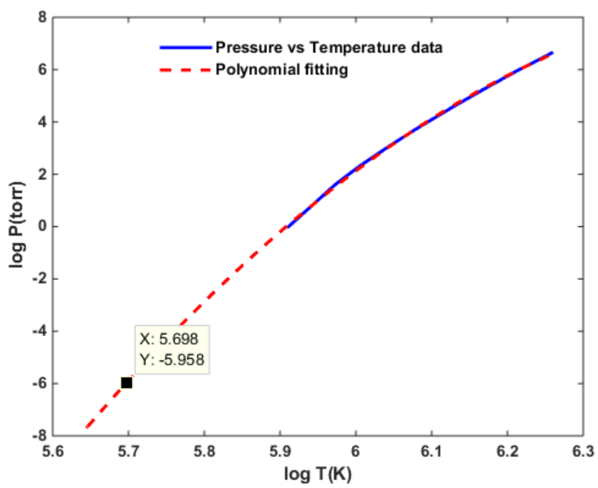

Figure 2. Equilibrium Pressure vs Temperature

Figure 2 shows a plot of equilibrium pressure given by (6) for benzoic acid. The results are extrapolated to find operating pressures at room temperature. The equilibrium pressure for benzoic acid was found to be 0.345 Pa at 25º C.

Reliability Assessment: Inflatable gas leakage

The greatest threat to pneumatic inflatables in space is from micrometeoroid impact. Standard ballistic equations [18] are used to develop equations that describe the damage due to micro-meteor impact. These equations use NASA's micrometeoroid-engineering model (MEMR2) [19] that includes direction probabilistic flux densities as a function of micrometeoroid mass and velocity distributions.

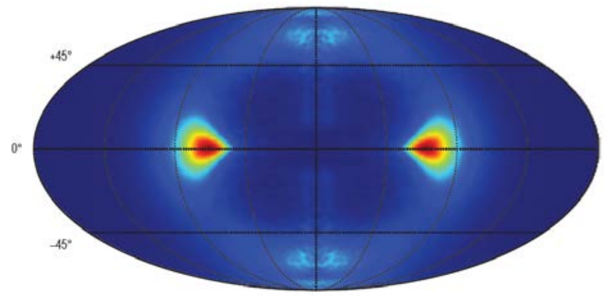

Figure 3. Interplanetary flux calculated at 1au using MEMR 2 [20]

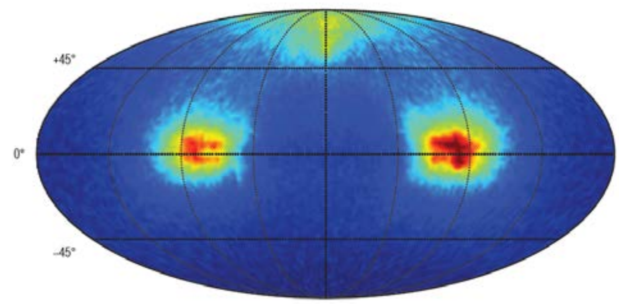

Figure 4. Interplanetary flux as measured by the Canadian Meteoroid Observation Radar (CMOR) at 1 AU [20]

The next section describes our method of designing composite inflatables with tunable modular sub- inflatables. We describe strategies to use inflatable structural properties and sublimate powders to develop composite structures. We investigate methods to develop stiffer assemblies that can deployed into pre-determined shapes. In addition, we develop methods to incorporate statistical meteoroid data with ballistic limit state equations. This is then used to understand the feasibility of such inflatable modules in outer space conditions.

3. METHODOLOGY

We begin with an analysis of the load-bearing and load transfer characteristics of inflatable beam elements. These units can be assembled in more than one spatial dimensions to yield an assembly of any arbitrary shape. The purpose of this analysis is to arrive at a basis for sizing such units that may then be used in increasingly complex designs.

Following this, we consider test assemblies of these inflatable units in one and two spatial dimensions. Inflatable pressure induced deflections are studied to understand passive shape control character of these structures. Sublimate powders exert equilibrium pressures in the range of 0.1 to 1 Pa. We base our calculations on Mylar membranes with parameters listed in the following table:

Table 1. Analysis parameters

Parameter	Value
Sublimate vapor pressure	0.1 to 1 Pa
Mylar thickness	20 µm
Young's Modulus	0.34 GPa

Finally, we develope a strategy to assess the reliability of such structures in space from the threat of micrometeoroid impact damage. NASA's MEMR 2 space environment model data is used for statistical quantification of mass and velocity distributions.

Modular Inflatables: Load bearing characteristics

An inflatable beam model is shown in Figure 5. The primary forces modelled on the inflatable beam include pressure induced axial force, pressure induced tensile hoop stress, external distributed tip loads and moments.

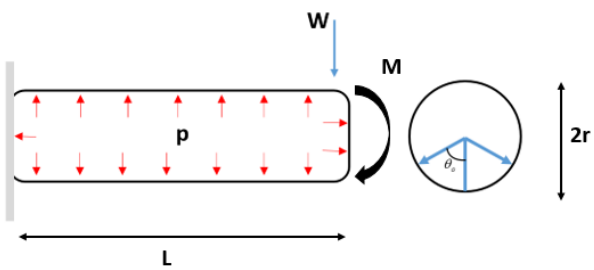

Figure 5. An inflatable beam model.

Equation (7) is solved for *θo* by varying loads acting on a single inflatable unit. In the limit, as *θo* approaches *π* radians, the module reaches it's theoretical load bearing capacity and is no longer able to act as a structural unit [16]

$$F(\theta_o) = \frac{\pi(2\pi - 2\theta_o + \sin 2\theta_o)}{4[(\pi - \theta_o)\cos\theta_o + \sin\theta_o]} - \frac{M(x)}{pr^3} \qquad (7)$$

Modular Inflatables: Structural assembly

Euler-Bernoulli beam theory approximations are extended to study assemblies of modular inflatable units in the *x* and *y*-dimensions as shown in Figures 6 and 7. In the case of a one dimensional assembly along the longitudinal axis as shown in Figure 6, the transverse forcess acting along each module and the hoop-stress generated in each module remain the same. The bending moment, however, changes with the addition of each module.

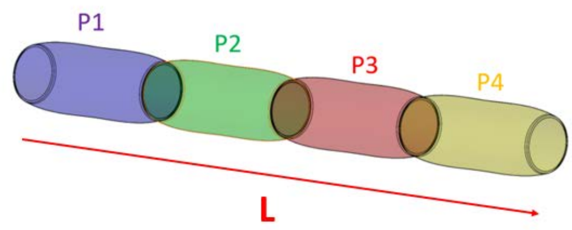

Figure 6. 1D composite inflatable assembled longitudinally.

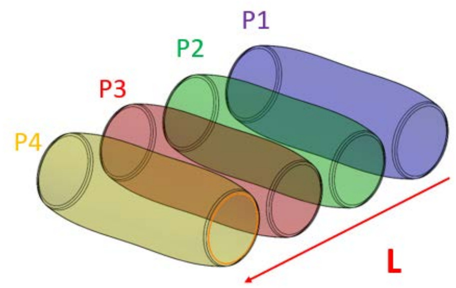

Figure 7. 1D composite inflatable assembled laterally.

To produce a stiff assembly, each module should be able to take on the increased bending moment offered by added modules. Figure 8 depicts contact loads:

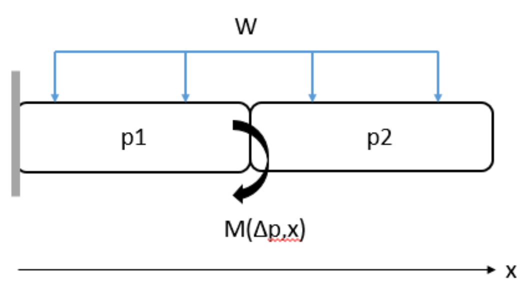

Figure 8. Interface loads – 1D longitudinal assembly.

External loads are now distributed instead of point loads and the tip load for each unit is now modified to include the pressure difference at the interface. Equation (7) is derived for each inflatable unit and is fed into the beam equation to solve for deflection as follows:

$$F(\theta_i) = \frac{\pi(2\pi - 2\theta_i + \sin 2\theta_i)}{4[(\pi - \theta_i)\cos\theta_i + \sin\theta_i]} - \frac{M(p_i, x)}{p_i r_i^3} \qquad (8)$$

The system of equations (9) is solved simultaneously to compute the total deflection in an assembly of *n* units.

$$\frac{d^2 y_i}{dx^2} = \frac{M_i(\Delta p_i, x)}{EI_i} \qquad (9)$$

In the case of one dimensional lateral assembly as shown in Figure 7, the interface conditions is shown in Figure 9.

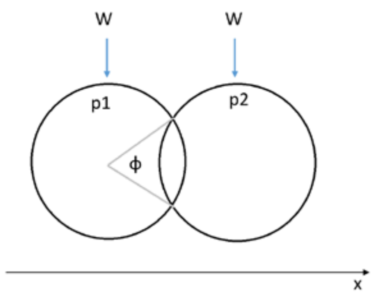

Figure 9. Interface loads – 1D lateral assembly.

As can be seen, the total surface area available to carry tensile hoop stresses is now less than the original area due to contact between the two modules [16]. The bending siffness in this case can now be reformulated as a function of contact angle φ and solved numerically to find the total deflection. Note that the tip load W remains the same.

Reliability Assessment –Inflatable modules

The sublimate of choice should be able to provide enough make-up gas in the event of punctures due to micrometeoroid penetration. Hence, the mass flow rate of gas into a unit must be greater than or equal to the flow out. This is described below:

$$\dot{Q}_{in} \geq \dot{Q}_{out} \tag{10}$$

Flowrate into the inflatable is computed as [17]:

$$\dot{Q}_{in} = \frac{\dot{M}RT}{mP_{eq}} \tag{11}$$

Where M is the mass flowrate, R is the universal gas constant, m is the molecular mass, T is the absolute temperature and P_{eq} is calculated using equation (6). The flowrate out of the inflatable is computed as the product of time averaged damage area A and molecular mobility as follows:

$$\dot{Q}_{out} = \left(\frac{\sum A_i p_i M_{tot}}{time}\right)\sqrt{\frac{kT}{2\pi m}} \tag{12}$$

P_i denotes the probability of successful penetration, k is Boltzmann's constant at temperature T and m is the gas's molecular mass. An impact equation is obtained for Mylar membranes using the hypervelocity ballistic impact equations [18] described below:

$$0.9^{\frac{2(nL-1)}{3}}\left(\frac{9m_M v_M{}^2}{\left(2\pi\rho_{mylar}\zeta_{mylar}\right)}\right)^{1/3} \geq \tau \tag{13}$$

Equation (13) shows the condition for successful penetration [19], where m_M represents meteoroid mass, v_M represents velocity, nL stands for number of membrane layers, ρ_{mylar} the density of Mylar, ζ_{Mylar} is the specific heat capacity of Mylar and τ is the thickness of the layer.

To compute the average impact probability P_i, the NASA MEMR 2 model [20] was used in equation (13). A circular orbit at an altitude of 370 km was analyzed using a commercial software package, STK, to obtain the spacecraft's state vectors. The state vectors were fed into the MEMR 2 model to obtain directionally average flux distributions as shown.

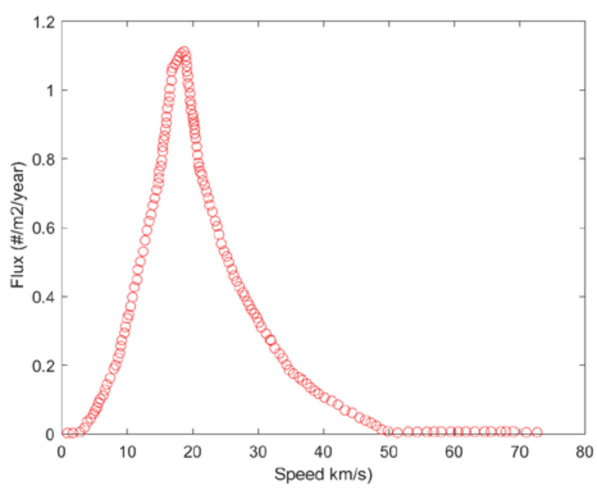

Figure 10. Micro-meteoroid flux distribution at 370 km

In the case of n inflatable modules covering the same area in space as a single large unit, the total probability of failure is written as follows:

$$P_{failure}(n) = \left(\frac{1}{n^2}\right)P_{failure}(1) \tag{14}$$

4. Results and Discussion

Modular Inflatables: Load bearing characteristics

Solutions to the non-linear equation (8) are plotted in Figure 11 against a test load of 1 N. In the limit, where the angle equals 180º, the membrane can no longer bear loads. Critical buckling angles against a tip load of 1 N show steady decrease with increasing pressure. However, as can be seen, the wrinkle region tends to travel longer along the length of the beam element. This suggests that the designed length of the inflatable would depend on the internal pressure created by the specefic sublimate powder used.

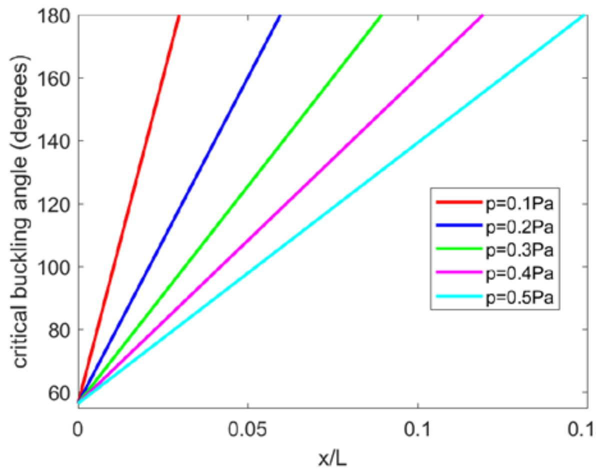

Figure 11. Critical buckling angles - single inflatable units.

Equation (1) relates the bending moments developed in areas where wrinkle formation starts to take place. Critical angles obtained earlier were used to compute the bending moment generated as a result of external loads.

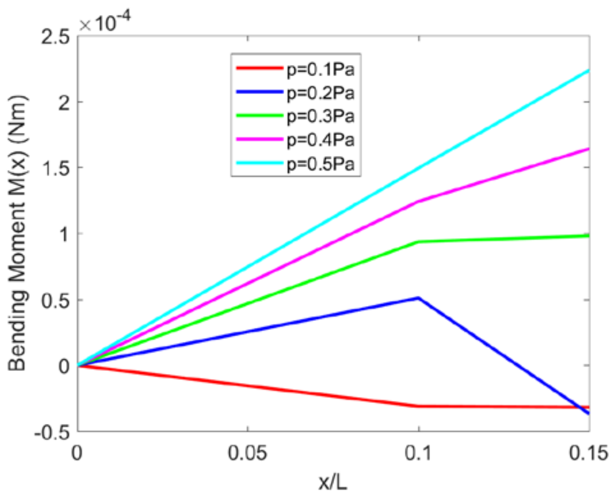

Figure 12. Bending moment variation – single inflatable units.

These results are extended for one dimensional longitudinal assemblies to understand their structural character.

Modular Inflatable Assembly: Load bearing characteristics

Figure 13 shows a plot similar to Figure 11. This plot shows the solution to the buckling angle equation for a one-dimensional assembly of two discrete modules assembled together. It can be observed that due to the distribution of external loads, the buckling of these membranes is 'delayed'.

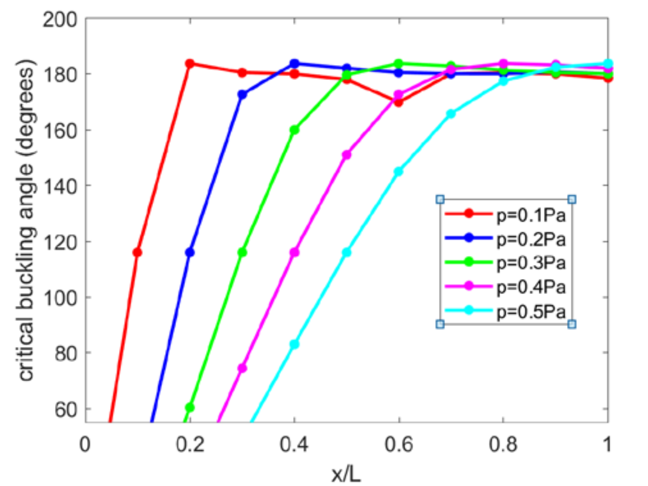

Figure 13. Critical buckling angles - modular inflatable assemblies

This shows their ability to carry higher loads than single inflatable units. Bending moments generated are plotted in Figure 14. A comparison between Figures 14 and 12 shows a much reduced bending moment in the case of the single inflatable.

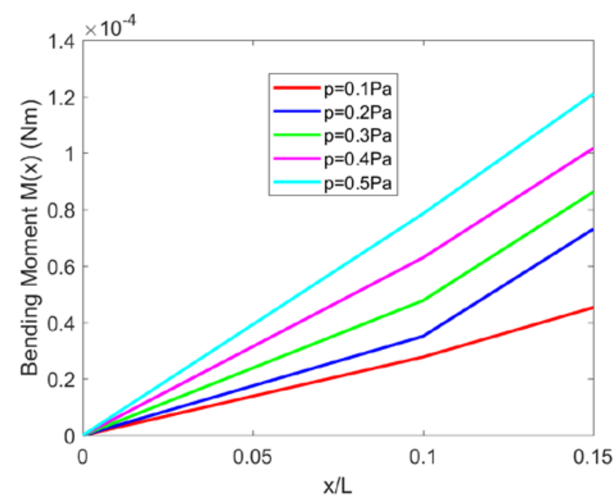

Figure 14. Bending moment variation - modular inflatable assemblies

It can be concluded from the above analysis, that a one dimensional assembly of modular inflatable units yeilds a stiffer structure as compared to single inflatable unit of the same overall size.

Modular Inflatable Assembly: deflection

The enhancement in stuffness in the case of composite inflatable assemblies is exhibited by increased resistance to external loads. The constitutive equation formulated in the Euler-Bernoulli form is numerically solved to obtain deflection as a function of applied loads [13].

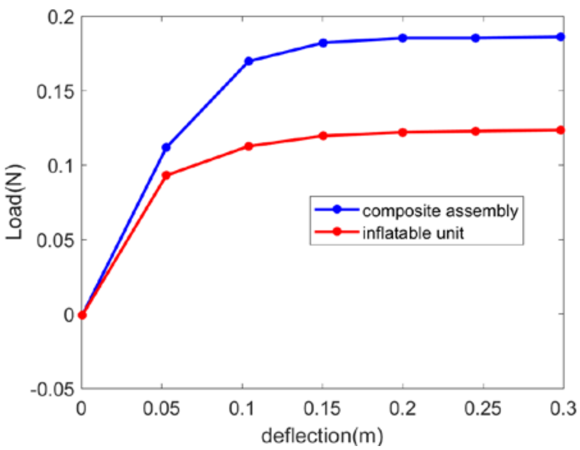

Figure 15. inflatable beams - deflection characteristics

Figure 15 shows the response of inflatable units and composite beams to external loads. We observe similar deflections for higher applied loads in the case of assembled composites. The above results show that large assemblies of small inflatable units can provide significant structural benefits over large inflatable units. Additionally, modulating the internal pressures in these units can lead to pre-deflected composites of desired curvatures.

Reliability Assessment –Inflatable modules

Directional flux data obatined from MEMR2 was averaged to obtain Figure 10. The generated data was used in equation (13) to compute the average penetration depth as plotted in Figure 16.

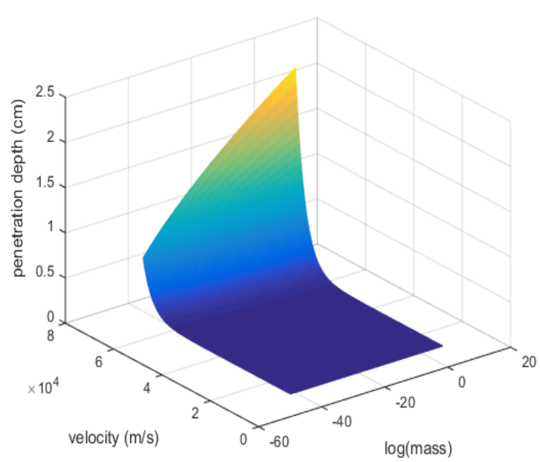

Figure 16. Penetration depth due to micrometeoroid impact

From the above plot, we observe that the penetration of meteoroids shows greater sensitivity to their velocity distributions. This is due to ballistic considerations made in the model. The penetration depths thus obtained can be used for computing average damage area distribution as described by Equation 12.

5. Composite Inflatable Assemblies

In this section, we look at the applying inflatable composite assemblies to large structures such as the next generation space station. Our approach has the potential to offer significant advantages over the proposed inflatable designs [8] in two key areas.

Most of the current inflatable technologies require a network of pneumatic mechanisms for inflatable activation. This limits the structures's scale and efficiency to much below its capacity while simultanously adding complexity and potential failure modes. Our approach of passive activation enables exploration of mechanically simple structural design concepts of much larger size.

Based on our analysis modultaing unit pressure by different powder combinations can potentially lead to structures of varying curvature and stiffness with minimal re-design and analysis. Figure 17 and 18 depict plausible composite assembly concepts

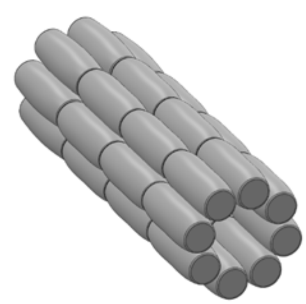

Figure 17. Tubular composite assembly

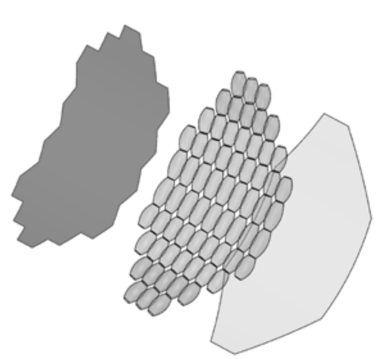

Figure 18. Re-enforced double curve assembly

Soft hinging and fastening concepts need to be incorporated into the design to facilitate complex assembly processes [21]. Enhancements to load bearing capacities can be facilitated using re-enforcing skins that can be incorporated into the stowage scheme.

6. CONCLUSIONS AND FURTHER WORK

The work presented in this paper shows preliminary feasibility of creating assemblies of pneumatic inflatable modules. Approximations to the steady-state behaviour of such modules using classical beam theory show higher stiffness and load bearing capabilties.

It can be concluded that chemical sublimate gas pressures can provide the needed tension for such structures. Additionally, since these powders can be activated using ambient conditions they do not require active end-effectors. This shows the potential scalability to large sizes without adding to mechanical complexity.Due to the sublimate gas being low pressure, there are limitations to their load bearing capacity. As shown in our analysis, this can mitigated to an extent through the usage of a combinations of inflatables with different powders producing different internal pressures. Further work is required to understand passive rigidization techniques to enhance the load bearing properties of these structures. An optimum sizing scheme will be required to ensure tuning of the structural properties.The ability for the sublimate to maintain a characteristic vapor pressures could enable design of superstructures with 'taut' and 'slack' regions. This property could be utilised to effect in-stu morphing into pre-determined shapes.

Further work is required to understand the extent to which such structures can be scaled-up in size without external supporting features. An extension to the present model is being developed to better characterize the interfacial interactions between inflatable units in an assembly.

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BIOGRAPHY

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