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Designs of self-rigidizable inflatable habitats for construction in extreme environments

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Abstract

Construction in extreme environments such as extra-terrestrial or polar regions poses challenges due to harsh conditions, limited resources, transportation obstacles, and labor shortages. The lunar surface exemplifies such extreme conditions. Inflatable structures have emerged as practical solutions for lunar habitation modules, considering transportation, storage, construction, and reliability [1]. Rigidization technologies significantly enhance safety, durability, and repairability of rigidized inflatable structures. This paper proposes two rigidization methods: shape memory polymer (SMP) and air pressure control, demonstrated through two self-rigidizable habitat designs. SMPs as a physical rigidization technology offer simplicity, reversibility, low energy requirements, and short maintenance time compared to thermal curing, allowing for ground testing and multiple applications [2, 3]. They also provide high compaction rates and flexible and simplified designs. Air pressure control, achieved through vacuum-based multi-layered jamming, offers a fast, reversible, and easily controlled actuation method initially proposed in soft robotics. This research has potential for multidisciplinary cooperation and development beyond lunar habitation modules. Lightweight and rigidizable inflatable structures find diverse applications, including solar sails, satellite antennas, deformable wings, deployable temporary buildings, and intelligent façade systems.

Keywords: inflatable habitats, rigidization methods, shape memory polymer (SMP), multi-layer jamming system, construction in extreme environments, variable stiffness components

1. Introduction

Adaptive structures, found in various applications such as aircraft, wind turbines, automobiles, antennas, and building structures, have the ability to adjust their shape in response to different operating conditions. This shape change allows for improved performance and the realization of new functionalities while also simplifying the construction process and reducing mass in designs [4]. For example, aircraft wings inspired by bird wings adapt to different flight conditions for better aerodynamic performance [5]. Similarly, in wind turbines, the size of the blades is increasing, and shape change through sophisticated control systems enables better load and stress control [6]. Buildings utilize shape morphing in adaptive façade systems to control direct daylight, natural ventilation, and heat exchange due to wind convection [7]. In civil structures, large shape changes can optimize load and stress control, resulting in efficient configurations with improved material utilization and lower energy consumption compared to conventional passive structures [8]. However, the concept of morphing presents inherent conflicting requirements, as there is a need for low stiffness to minimize actuation energy and high stiffness to support load-carrying capabilities. One promising solution is the integration of variable stiffness components into shape-changing structures [5, 9]. The existing variable stiffness concepts are generally grouped in four main directions: mechanism-driven, semi-active solutions, structural elasticity-related, and material engineering [5].

The paper explores the application of adaptive structures in extreme environments, like extra-terrestrial or polar locations, presenting challenges due to harsh conditions, limited resources, transportation obstacles, and labor shortages. The lunar surface exemplifies such extreme environments. Inflatable structures have emerged as practical solutions for lunar habitation modules, considering transportation, storage, construction, and reliability [1]. The adaptability of these structures to various processes requires soft materials for efficient folding and stowage, while also demanding high stiffness when inflated to enhance load-bearing capacity. As mentioned earlier, material engineering, including component material selection, composite design, and optimization, plays a key role in realizing the concept of variable stiffness [5]. Shape memory polymers (SMPs) are highlighted as a smart material with reversible deformation capabilities and potential for forming composite materials in morphing applications [5, 10]. Rigidization technologies are crucial for inflatable structures to address air leakage and enhance structural rigidity. Rigidized membrane structures can retain their shape even after punctures and air leakage, significantly improving safety, durability, and repairability. This paper proposes two rigidization methods for inflatable structures: shape memory polymer (SMP) and air pressure control. MP is described as a widely used physical rigidization technology due to its simplicity, reversibility, and low energy requirements. It allows for ground testing and multiple applications [2, 3]. In CASE A, SMP is used as a rigidization layer. The feasibility of this design is verified through static analysis. Moreover, the effect of SMP layer on structural dynamic performance is also discussed, as shown in Section 2. Instead, air pressure control, specifically multi-layered jamming (MLJ) achieved through vacuuming, offers a fast, reversible, and easily controlled actuation method initially proposed in soft robotics. This paper also proposes a design concept of a MLJ system applied to inflatable rigidization, referred to as CASE B in Section 3. In the end, Section 4 discusses and concludes this paper.

2. CASE A: SMP rigidization method

2.1. Design and construction process

This paper presents the concept of self-rigidizable lunar habitats, comprising an inner inflatable structure for astronaut living and research spaces, and an outer regolith layer (compacted regolith, regolith bags, or bricks [11]) serving as protection against radiation, temperature variation, and micrometeoroid impacts. The design focuses primarily on the restraint layer which bears the main tension load and utilizes a flexible AFRP that consists of Kevlar fiber and flexible epoxy resin. The SMP exhibits different states depending on its temperature relative to the glass transition temperature (T_g). In the glassy state, which occurs below T_g, the SMP is highly stiff with a modulus of approximately 1GPa. When the temperature exceeds T_g, the SMP enters a rubbery state, becoming more flexible with lower stiffness. The stiffness variation between these two states can reach up to 1000 times [12].

The construction process of rigidizable inflatable lunar habitats mainly includes four steps: inflation & expansion, rigidization, regolith coverage, and pressurization. In the rubbery state, the SMP allows for easy folding of the membrane, while in the glassy state, it maintains the folded shape securely, facilitating stowage and transportation. By actuating the SMP to the rubbery state, the membrane regains flexibility, enabling inflation and erection. Once the SMP re-enters the glassy state, it preserves the inflated shape, significantly increasing the stiffness of the inflatable structure. This reversible process of rigidization is made possible through the use of SMP. For structures requiring multiple deployments, after rigidization, the SMP can be activated above T_g, allowing the structure to be folded and reused, enabling a cycle of folding and inflation. In the case of inflatable lunar habitats, the rigidized inflatable structure is covered with a regolith layer, while the interior space is pressurized to 1atm to accommodate human activities.

2.2. Static analysis and dynamic property (frequency and damping): nonrigid vs. rigid

The effectiveness of the SMP rigidization method has validated through static analysis in our previous research [13]. A 6m diameter semi-sphere inflatable structure with a membrane comprised of a 10mm SMP layer and a 10mm AFRP restraint layer was proposed. The main material properties used are outlined in Table 1 [12]. The lunar inflatable habitat undertakes a uniform downward external pressure of P_2=8.1kPa generated from a 3m thick regolith layer and an internal pressure equivalent to atmospheric level (P_1=101 kPa) during normal operation (Figure 1).

Table 1. Main material properties [12]

	SMP nonrigid	SMP rigid	AFRP
Density (kg/m^3)	1050	1050	1451
Modulus (MPa)	1	1541	8543
Tensile strength (MPa)	-	40	151

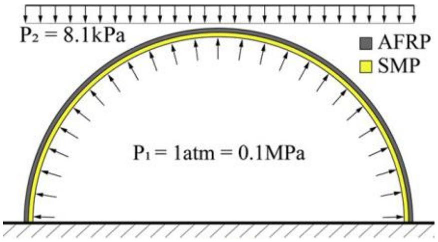


Figure 1: SMP-based semi-sphere inflatable habitat: support and loading conditions.

Under 1atm, after rigidization, the maximum deformation of the structure reduced by 23.6% (from 8.48 to 6.48mm), and AFRP stress dropped from 29.9 to 22.3MPa (reduced by 24.9%), as the rigid SMP layer took over some stress (4.73MPa). During punctures, internal pressure P_1 dropped to zero while external pressure P_2 remains constant, causing sudden buckling and converging failure due to excessive deformation, as shown in Figure 2(a). However, in the rigidized structure after air leakage, maximum deformation and SMP stress were limited to 8.47mm (Figure 2(b)) and 4.73MPa (Figure 2(c)), respectively. This clearly demonstrates the effectiveness of the rigidizable layer in preventing structural collapse when air leaking occurs.

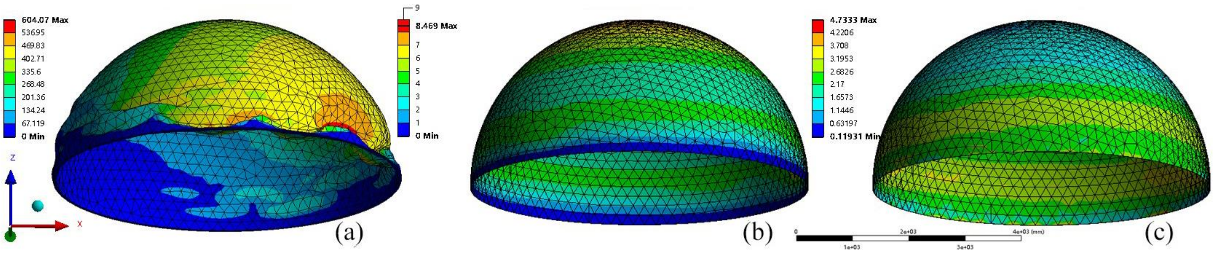
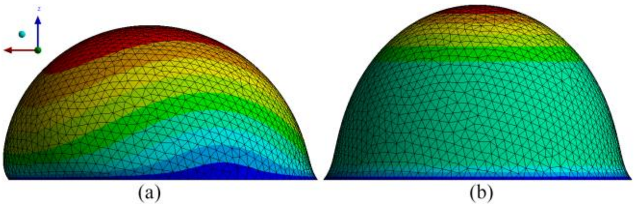


Figure 2. Semi-sphere inflatable habitat: (a) deformation at nonrigid (collapse occurs after air leakage) case; (b) and (c) deformation and SMP stress at rigid case (air leakage).

Additionally, this section also assessed the effect of rigidization layer on structural dynamic properties at nonrigid, rigid, and viscoelastic cases. The assessment extends to other non-pressurized inflatable lunar modules and Earth environments, considering cases with inner pressures of P1=1atm=101kPa and 0.2kPa. To maintain the shape of the inflatable module, a pressure difference of 0.2kPa is recommended based on the advice from DUOL Air Domes. The first mode corresponds to horizontal movement, while the second mode is characterized by vertical displacement, as shown in Figure 3. A full transient analysis is carried out to analysis the damping caused by viscoelastic effects in a free vibration test, wherein a ground displacement of 100mm is applied. To determine the damping ratio ζ, the displacement logarithmic decrement $\Delta = \ln\left(\frac{x(t)}{x(t+1)}\right)$ is applied to compute ζ through this formula:



$$\zeta = \frac{\Delta/2\pi}{\sqrt{1+(\Delta/2\pi)^2}} \quad (1)$$

Figure 3. Semi-sphere inflatable habitat: (a) first and (b)second modal shapes.

Table 2 reports the natural frequency and frequency shift, along with the damping variation observed when the SMP layer was actuated from the ambient temperature (25°C) to the transition temperature (65°C) of the structure, considering the causes of inner pressures P_1=101 and 0.2kPa. The frequency was computed with prestress. In general, the frequencies of all cases under 1 atm inner pressure are higher compared to those under 0.2 kPa inner pressure, which is attributed to the stiffening effect from inner pressure. When the SMP is within the viscoelastic range, the damping ratios have a further increase. This highlights that the presence of a rigidization layer increases the damping of the inflatable structure.

Table 2: Frequency, frequency shift, modal shape, and damping ratio at nonrigid, rigid, and viscoelastic cases

	Pressurized (P_1=1atm)			Non-pressurized (P_1=0.2kPa)		
	Nonrigid	Rigid (25°C)	Viscoelastic (65°C)	Nonrigid	Rigid (25°C)	Viscoelastic (65°C)
ω_1 (Hz)	45.3	53.5	45.7	44.8	53.2	45.4
ω_2 (Hz)	61.2	72.6	61.8	59.6	71.7	60.6
$S_{\omega1}$ (%)	-	18.1	0.9	-	18.8	1.3
$S_{\omega2}$ (%)	-	18.6	1.0	-	20.3	1.7
ζ (%)	2.2	3.6	4.4	2.2	3.3	4.1

3. CASE B: air pressure control

3.1. Concept of multi-layer jamming (MLJ) system

The second method involves air pressure control, which can increase the stiffness of inflatable structures through pressurization or vacuum. The multi-layer jamming (MLJ) system commonly used in flexible robots to enhance bending stiffness by utilizing vacuum. This relies on the atmospheric pressure, after vacuuming, increasing the interlayer shear force generated by friction, as shown in Figure 4 [14]. However, the use of this system is limited on the lunar surface due to vacuum environment. CASE B explores the potential application of this system in the rapid construction and shaping of terrestrial inflatable structures. This method offers significant advantages, including simple pneumatic control, fast control speed, reversible process, structural recovery, adjustable stiffness, and easy shaping.

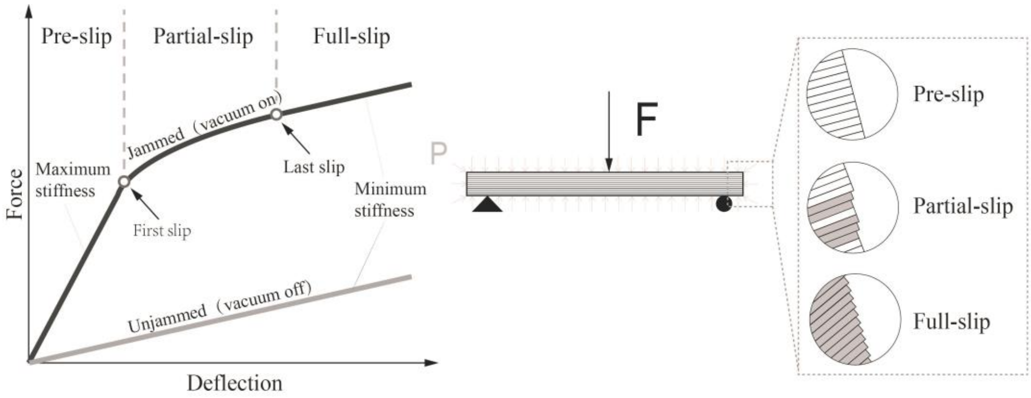


Figure 4. Principle of multi-layer jamming (MLJ) system [14].

3.2. Design and construction process

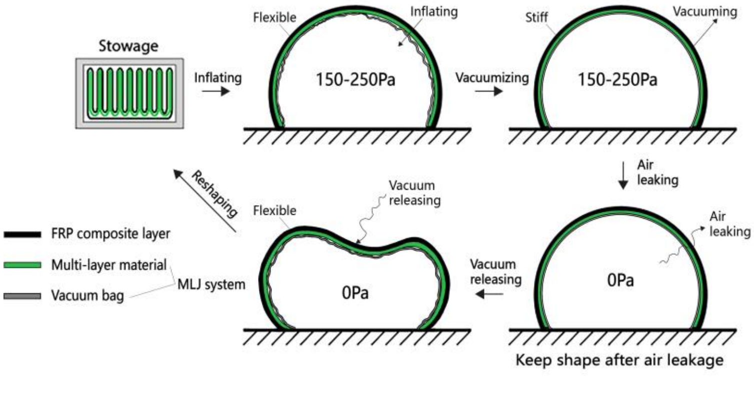


Figure 5: Transportation and construction circulation of an MLJ-rigidizable inflatable habitat: inflating (with 150-250Pa inner pressure), vacuuming, air leaking (releasing), vacuum releasing, and reshaping.

The rigidization process in an MLJ system is reversible. Figure 5 illustrates the steps involved in the transportation and construction circulation of an MLJ-rigidizable inflatable habitat, primarily including five steps: inflating (with 150-250Pa inner pressure), vacuuming, air leaking (releasing), vacuum releasing, and reshaping. During the inflation process, the inflatable structure takes shape with an inner pressure of 150-250Pa, and the membrane remains flexible. Once the membrane is vacuumed, incorporating the MLJ system, it becomes stiff. Even if the inner pressure drops to 0 after air leakage, the structure retains its shape. Releasing the vacuum allows the membrane to return to its flexible state, enabling it to be folded for stowage and transportation, facilitating multiple usages.

4. Discussion and conclusion

This paper proposes two conceptual designs of rigidizable inflatable habitats, demonstrating the feasibility of modifying material properties in SMP rigidization layers for different applications (transportation, construction, and service life). SMP rigidizable layers effectively prevent structural collapse and enhance dynamic performance of inflatable structures. This observation can also extend to the terrestrial extreme environments, such as polar and plateau. Without extra inner pressure, the structure solely maintains its shape under self-weight. However, the presence of additional loads, such as uniform downward snow loads in cold regions, can cause inflatable structures to collapse. Rigidization effectively mitigates this risk and ensures collapse prevention. Additionally, the potential of the MLJ system in collaboration with inflatable or other civil structures is worth exploring, although further experimental and numerical studies are needed to assess feasibility and applicability. However, several considerations should be noted:

- The conceptual structure, including openings and connections, requires further refined design, as different configurations significantly impact dynamic performance. The optimal arrangement of rigidization materials needs in-depth exploration, along with anchoring issues and boundary conditions in inflatable structures.
- Environmental differences between the Moon and Earth, such as gravity acceleration and internal pressure, must be considered. Certain Earth-designed structures, like the MLJ system, may not function on the Moon due to the lack of atmospheric confinement pressure on both sides of the layers. Similarly, unmanned aerial vehicles cannot operate on the Moon.
- The rigidization capability of the structures needs quantification in both design approaches. Balancing structural performance enhancement with increased weight caused by the addition of rigidization layers is crucial for achieving optimal design.
- Future studies should focus on thermal, radiation, and dynamic performances, considering the extreme lunar environment.

This research holds potential for multidisciplinary cooperation and development, extending beyond lunar habitation modules. Lightweight and rigidizable inflatable structures find diverse applications, including solar sails, satellite antennas, deformable wings, deployable temporary buildings, and intelligent façade systems.

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