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A novel multi-layer jamming (MLJ)-reinforced Tensairity beam for rapid construction in extreme environments

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Abstract

Variable stiffness concepts enable structural adaptation to diverse environments, categorized as smart materials or specialized configuration designs. Multi-layered jamming (MLJ) provides a rapid, reversible, and easily controlled actuation method. This study examines MLJ-based variable stiffness components for rapid construction and energy dissipation in civil engineering, focusing on an MLJ-reinforced Tensairity beam and construction procedure. The numerical model shows the structure's enhanced load-bearing capability post-vacuuming. During large deformation, energy dissipation via interlayer friction produces hysteresis loops, which may benefit to mitigate dynamic responses. While these techniques show promise, challenges exist concerning material limits, application boundaries, quantification, and precise shape control. They could also find utility in environments with confinement pressures like soil or water, expanding the potential applications.

Keywords: Variable stiffness concepts; multi-layer jamming (MLJ) system; multi-layer jamming (MLJ)-reinforced Tensairity beam, rapid construction; energy dissipation; inflatable structures; vibration control, finite element analysis (FEM).

1 Introduction

Variable stiffness components can adapt the structures' performance to various environments and application scenarios [1, 2], which finds diverse applications such as solar sails, satellite antennas, deployable wings, temporary buildings, and smart façade systems. These concepts generally fall into two categories: 1) using materials with inherent variable stiffness properties, such as smart materials like shape memory polymers (SMP) and magnetorheological elastomers (MRE); 2) employing simple materials but with specialized configuration designs, such as bending active systems, metamaterials, and jamming mechanisms.

Stiffness influences structural frequencies and is often linked to changes in damping ratios, affecting dynamic properties. Thus, dynamic performance variations induced by variable stiffness can be applied in semi-active structural control [3]. For instance, using shape memory polymer (SMP) for vibration control for adaptive structures and rigidization/reinforcement of inflatable structures for rapid construction. These components achieve stiffness and damping variations by thermally actuating the SMP between its glassy and rubbery states [4]. Through studying the responses of structures that integrated variable stiffness joints and sandwich panels under various loads, it has been demonstrated that activating these components during dynamic excitations can effectively mitigate the dynamic responses of structures, making them suitable for frames and trusses, as well as shell and plate structures [3].

Another exploration involves construction in extreme environments like extra-terrestrial or polar regions, which poses challenges due to harsh conditions, limited resources, transportation obstacles, and labour shortages. The lunar surface exemplifies such extreme conditions. Inflatable structures hold promise for lunar habitation modules, considering transportation, storage, construction, and reliability [5]. During transportation and construction phases, the skin should be flexible for folding, while being rigid during service to withstand loads. A variable stiffness membrane can adjust performance to meet the requirements of different stages. Rigidization technologies significantly enhance safety, durability, and repairability of inflatable structures [6]. Two methods have been proposed: SMP [7] and air pressure control [8]. Especially, multi-layered jamming (MLJ) achieved through vacuuming, offers a fast, reversible, and easily controlled actuation method initially proposed in soft robotics. MLJ can be used to reinforce the membrane. In theory, energy dissipation through inter-layer friction can occur during large deformation, resulting in a complete hysteresis loop. If designed to dissipate energy repeatedly with reversible shape changes, MLJ could also be utilized for vibration control.

This study examines MLJ-based variable stiffness components for rapid construction in extreme environments, focusing on an MLJ-reinforced Tensairity beam and construction procedure. As the structure inflates, it becomes buoyant, allowing it to float on water and interconnect with multiple units to form bridges, floating platforms, rafts, or lightweight roofs for temporary buildings.

This paper is arranged in six sections. Section 2 introduces the basic principles of Tensairity and MLJ systems. In Section 3, the design concept and construction process of an MLJ-reinforced Tensairity beam are proposed for easy transportation and rapid construction in wild or extreme environments. Sections 4 and 5 investigate the enhanced post-vacuuming effect using the MLJ system. The mechanical properties of the structure are explored using finite element analysis (FEA), verifying the structure’s feasibility and energy dissipation capabilities. Sections 6 and 7 discuss and conclude this study.

2 Basic principles

2.1 Tensairity

The Tensairity structural concept is based on the tensegrity principle of constructive separation of tension and compression in cables and struts. A fundamental Tensairity beam comprises three key parts: a cylindrical airbeam maintained at low pressure, a compression element tightly linked to the airbeam, and two cables wound in a spiral pattern around the airbeam with different helicity. The airbeam introduces pretension to the cables and offers continuous elastic support to the compression element, preventing structural instability and significantly reducing weight [9].

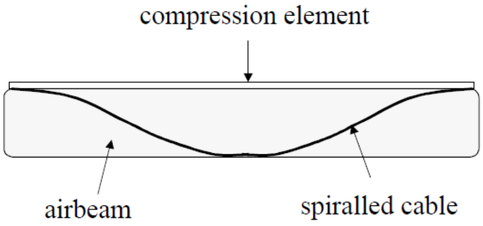

Figure 1. Basic elements of a Tensairity beam [9]

2.2 Multi-layer jamming (MLJ) system

The multi-layer jamming (MLJ) system is commonly used in flexible robots to enhance bending stiffness through vacuum utilization.

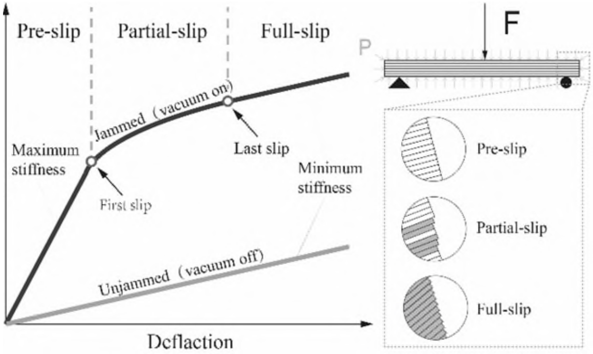

Figure 2. Principle of MLJ system [10].

This method leverages atmospheric pressure post-vacuuming to create confining pressure around the component, amplifying the shear force generated by interlayer friction. During the pre-slip stage, the MLJ beam exhibits maximum stiffness, transitioning to minimum stiffness when full sliding of each layer occurs. This minimum stiffness matches that of the system without vacuum, rendering the jamming effect ineffective in this scenario. Refer to Figure 2 [10] for an illustration of the MLJ principle.

3 Concept of a novel MLJ-reinforced Tensairity beam

3.1 Conceptual design

This paper proposes an innovative MLJ-reinforced Tensairity beam designed for easy transportation and rapid construction. By substituting the top compression element with an MLJ plate and replacing steel cables with aramid fiber spiralled ropes in the traditional Tensairity beam, this structure effectively merges the benefits of both Tensairity and MLJ systems. Before vacuuming, the MLJ plate is relatively flexible, allowing it to be easily rolled up and folded. Furthermore, the use of aramid fiber ropes instead of conventional steel cables simplifies anchoring, reduces weight, and improves durability, especially in wild and aquatic environments. This design facilitates the rolling and folding of the structure, saving space, and enabling easy transportation and rapid construction. Controlling the air pressure during both the vacuuming of the MLJ plate and the inflation of the airbeam allows for adjustments in structural stiffness. This structure is designed for flexibility and can be used by combining multiple units. It can be used as roofs, bridges, or waterborne air rafts. *Figure 3* shows the basic elements of the structure and an example of five units connected in parallel.

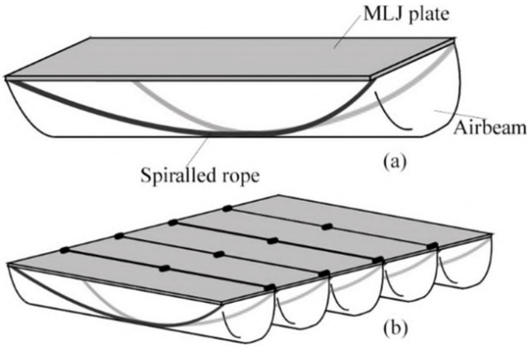

Figure 3. MLJ-reinforced Tensairity beam: (a)basic elements; (b)combination of five units

3.2 Construction process

The structure can be easily transported when rolled up and folded. Construction is straightforward, requiring only air pressure control. *Figure 4* illustrates the cyclic process of construction, service, and reuse with the following steps:

(1) **Unfolding:** Initially, the structure is unfolded and flattened.
(2) **Inflation:** The airbag is inflated and pressurized, stretching the aramid fiber ropes to generate pre-tension. In this case, the structure is essentially formed and the top MLJ plate is fully expanded.
(3) **Vacuumizing:** After vacuuming, the top compression element of the structure is formed, enhancing the load-bearing capacity.
(4) **Service:** During service, multiple units can be connected in parallel using simple methods such as ropes and buckles. This versatile structure is suitable for extreme environments, shelters, or temporary event structures. To further increase the load-bearing capacity and extend the service life, resin can be introduced in the MLJ plate after vacuuming to form FRP composite plate on the top. The air pressure in the airbeam can be regularly refilled, and the aramid fiber ropes, featuring easy connection mechanisms, can be swapped out when needed, which further enhances reparability.
(5) **Softening:** After service, the structure can be recycled for future use. The airbeam releases the gas, leading to its collapse. Subsequently, vacuum release softens of the top MLJ plate. Alternatively, the vacuum can be released first from the MLJ plate, followed by deflating the airbeam.
(6) **Folding:** Now that the structure is in a soft state, it can be rolled up as a whole and stored in a backpack or other bags for convenient transport and future assembly.

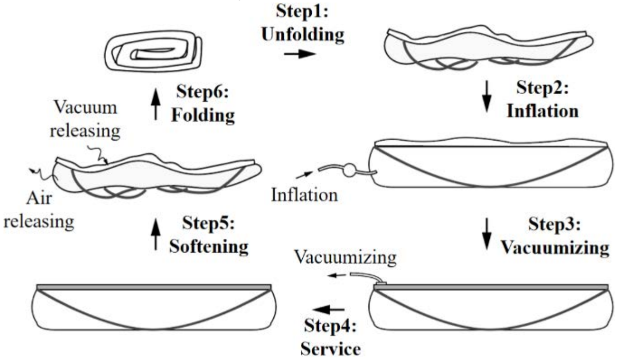

Figure 4. Construction process

4 Numerical model: post-vacuuming load bearing capability

4.1 FEM model

The studied structure is a slender simply supported beam, as shown in *Figure 5*. The vacuum effect is applied via a confining pressure P. Two simulations were conducted: (1) an MLJ beam and (2) an MLJ beam with continuous elastic support which simulates the pressure exerted by the airbeam. The beam has a total length of 500 mm, a width of 200 mm, and a thickness of 10 mm, made up of 10 layers, each 1 mm thick. The material is isotropic elastic with a modulus of 1700 MPa. The interlayer contacts are frictional with a friction coefficient of 0.5 [10].

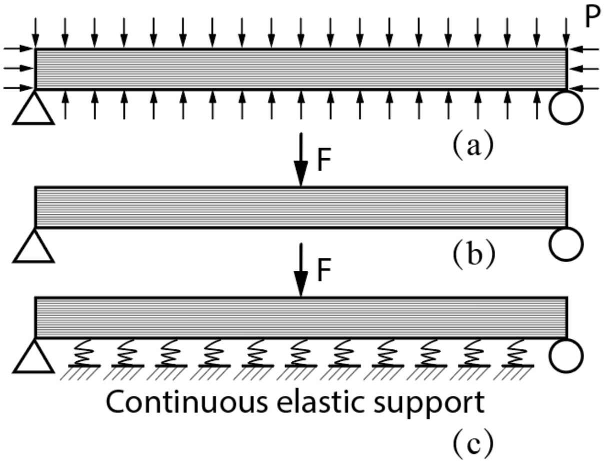

Figure 5. Two simulation models: (a) boundary condition; (c) loading an MLJ beam; (b) loading an MLJ beam with continuous elastic support

4.2 Full transient analysis: without and with continuous elastic support

During the simulation, the applied force F is increased from 0 to 1N with a constant speed, while the vacuum pressure P is maintained at constant values of 100kPa (fully vacuumed), 80kPa, 50kPa, 20kPa, and 0kPa (no vacuum condition). The results are demonstrated in *Figure 6*.

For an MLJ beam without continuous elastic support, vacuum pressure significantly enhanced the beam's load-bearing capacity. *Figure 6*(a) illustrates the Force vs. Deflection curves for different vacuum levels in a pure MLJ beam. When the vacuum pressure P increased from 20kPa to 100kPa, the midspan deflection under the same load decreased by 52% (from 201.8mm to 96.6mm). Due to the high flexibility of the layer material, the beam became unstable under large forces, leading to unconverged deformations. Notably, the structure without vacuum exhibited behaviour similar to that at 20kPa but failed to converge. In contrast, with elastic support, the beam exhibits improved stability. *Figure 6*(b) shows the variation in beam stiffness with the vacuum pressure. Here, beam stiffness is defined as:

$$BS = \delta \frac{F}{D} \tag{1}$$

where δ is a constant related to the beam's section area, material modulus, and selected section, and $\frac{BS}{\delta} = \frac{F}{D}$ is the stiffness indicator. The results indicate that a higher vacuum pressure increases beam stiffness. However, the shape of the Beam stiffness vs. Vacuum pressure curves varies with the external force F. Additionally, as the applied force increased, the overall beam stiffness decreased, and stiffness indicators spanned different orders of magnitude. Notably, larger forces result in greater stiffness variation across different vacuum pressures. For example, when the vacuum pressure increased from 20kPa to 100kPa, the stiffness variations at 0.1N, 0.5N, and 1N were 18.6%, 26.5%, and 108.9%, respectively. At 1N, the stiffness nearly doubled, leading to a 52% reduction in deflection. This variation occurs because different load levels caused the structure to transition through different sliding stages: no sliding, partially sliding, and full sliding. These transitions will be explained in more detail in *Figure 7* and Section 5.

For the MLJ beam with continuous elastic support, the Force vs. Deflection and Beam stiffness vs. Vacuum pressure curves, shown in *Figures 6*(c) and (d), exhibited trends that significantly differ from those observed without elastic support. The stiffness of the elastic support was set to 10^{-6} N/mm^3, estimated from a 200mm square cylinder airbeam with a 200Pa internal pressure-a setting primarily intended to maintain the airbeam's shape. Despite this low pressure, the midspan deflection decreased by up to 93%, demonstrating the airbeam's effectiveness in preventing instability within the system. Even without any

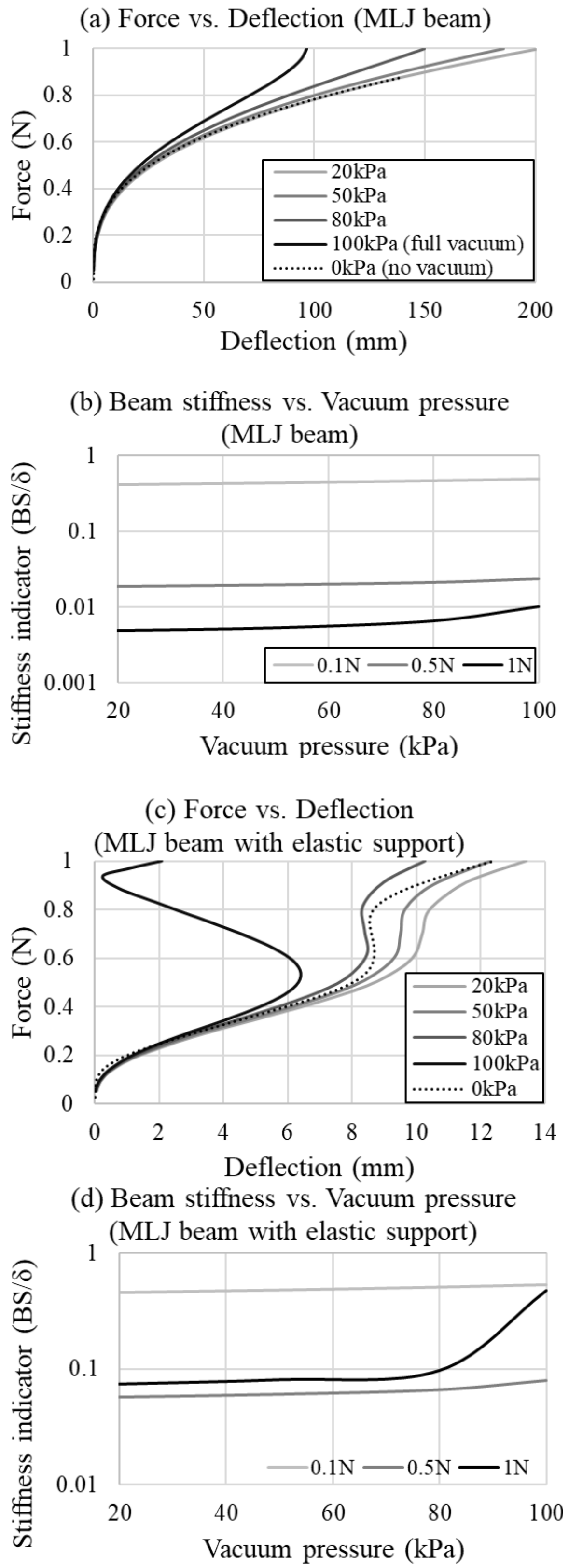

Figure 6. MLJ beam: (a) Force vs. Deflection; (b) Beam stiffness vs. Vacuum pressure; MLJ beam with continuous elastic support: (c) Force vs. Deflection; (d) Beam stiffness vs. Vacuum pressure

vacuum pressure, the deformation converged in a small level. When the applied force increased from 0 to 1N, the Force vs. Deflection curves deviated significantly from those of the beam without elastic support, likely due to differences in deformation modes. Additionally, the force level affected the deformation modes, but, at a given force level, higher vacuum pressure resulted in greater beam stiffness. Notably, at 1N with 100kPa vacuum pressure, the stiffness increased by 5.4 times compared to 20kPa. This highlights the superior reinforcement effect of the MLJ Tensairity system compared to a pure MLJ beam.

5 Potential dynamic behaviour

Theoretically, MLJ components have energy dissipation capabilities. These components undergo large deformations under large loads, causing sliding and friction between the flexible multi-layer materials. This interlayer friction dissipates energy, reducing dynamic responses such as acceleration and structural deformation. Throughout the energy dissipation process of the overall component deformation, the lower airbag provides continuous elastic support and undergoes compression. Upon load removal, by releasing vacuum and inflating the airbag, it rebounds, restoring the structural deformation. The structure can then return to service by reapplying vacuum to the top MLJ plate. As shown in *Figure 7*, the force-displacement curve of the MLJ component consists of three stages [11]:

(1) **$F \leqslant F_1$:** no relative sliding occurs between layers, resulting in high stiffness and a steep slope.

(2) **$F_1 < F \leqslant F_2$:** partial interlayer sliding occurs, reducing structural stiffness. With an increasing number of layers sliding, stiffness decreases further, leading to a lower slope in the second segment.

(3) **$F > F_2$:** full interlayer sliding occurs, resulting in low structural stiffness and significant deformation in the third segment. At this point, the structure's load capacity reaches its limit, and the component continues to deform, dissipating energy until the load cannot be further increased. During large deformation, energy dissipation via interlayer friction produces hysteresis loops, mitigating dynamic responses.

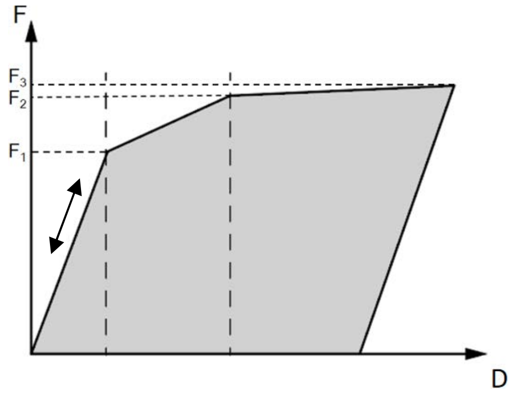

Figure 7. Force vs. displacement

6 Discussion

This paper introduces an innovative MLJ-reinforced Tensairity beam designed for easy transportation and rapid construction. By substituting the top compression element with an MLJ plate and replacing steel cables with spiralled aramid fiber ropes in the traditional Tensairity beam, this design effectively merges the advantages of both Tensairity and MLJ systems. The MLJ exhibits flexibility before vacuuming, allowing for easy rolling and folding. Moreover, the use of aramid fiber ropes simplifies anchoring, reduces weight, and improves durability, especially in wild and aquatic environments. This design streamlines the rolling and folding process, conserving space, and facilitating easy transportation and rapid assembly.

However, further research is needed to explore the structural properties, rigidization/reinforcement capabilities, and dynamic performance of the design. The following notes are made here:

- **Stiffness vs. strength:** Numerical simulations have demonstrated that the vacuum-based layer jamming system effectively enhances the load-bearing capacity of a flexible slender beam. In the proposed system, which incorporates a bottom airbeam, even a small elastic support significantly reduces the risk of instability, effectively leveraging the advantages of a Tensairity system. Notably, the response of no-vacuum condition (dashed curve in *Figure 6*(c)) did not follow the same trend as the curves for other pressure levels. This deviation suggests that the structural behaviour may be influenced by the stiffness ratio between the top MLJ plate and the bottom airbeam. This interaction could play a crucial role in the overall deformation and load-bearing capacity of the system and may be worth exploring further in future studies. Note that the initial stiffness under vacuum conditions was higher than in the absence of vacuum, and the pressure control mechanism proved to be both simple and responsive. This indicates that the layer-jamming mechanism effectively improves initial stiffness, supporting the concept of formwork-free self-shaping during early construction stages. However, further experimental validation is necessary to investigate the structural behaviour and failure modes at different load levels, particularly for larger structural applications.
- **Numerical model：** Numerical investigation presents significant challenges, particularly in modelling layer jamming and managing the high computational cost of multilayer structures. Simulation results are highly sensitive to boundary and contact conditions, these conditions should be carefully defined to accurately simulate jamming behaviour. Additionally, the complexity increases when accounting for anisotropic material properties and interactions between different materials and structural systems. In this study, a small simplified model was used, approximating the airbag as an elastic support and simulating vacuuming by applying confinement pressure. This model serves primarily to validate the concept and establish appropriate boundary and contact conditions. To advance toward practical civil structural applications, future research should extend the study to larger scales and stronger materials. Furthermore, for more complex conditions, advanced theoretical modelling is necessary to better predict structural behaviour, optimize simulations, and validate results through experimental testing.
- **Dynamic properties and energy dissipation：** The loading and unloading process of an MLJ beam can form a complete hysteresis loop. To fully utilize this for energy dissipation, further design optimization and experimental simulations are required for validation.
- **Application limits：** MLJ systems are mainly constructed from flexible materials and used in small-scale structures. However, the limits of

material stiffness and scale remain an open question. Exploring this issue can provide valuable insights for future designs, making it a key focus of our next theoretical study.

7 Conclusion

The MLJ-reinforced Tensairity beam facilitates easy transportation and construction, combining the advantages of both Tensairity and MLJ systems. The use of aramid fiber ropes eases anchoring, reduces weight, and enhances durability, particularly in rugged and aquatic environments. Its flexible design allows for interconnection with multiple units, making it suitable for various applications like bridges, floating platforms, rafts, or lightweight roofs for temporary buildings. It also holds promise for enhancing structural dynamic performance, but further validation is needed to refine its design and adaptability.

8 Acknowledgments

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References

[1] I. K. Kuder, A. F. Arrieta, W. E. Raither and P. Ermanni, "Variable stiffness material and structural concepts for morphing applications," *Progress in Aerospace Sciences,* vol. 63, pp. 33-55, 2013.

[2] R. D. Kornbluh, H. Prahlad, R. Pelrine, S. Stanford, M. A. Rosenthal and P. A. von Guggenberg, "Rubber to rigid, clamped to undamped: toward composite materials with wide-range controllable stiffness and damping," in *Smart Structures and Materials 2004: Industrial and Commercial Applications of Smart Structures Technologies*, vol. 5388, International Society for Optics and Photonics, 2004, July, pp. 372-386.

[3] Q. Wang, G. Senatore, K.M.B. Jansen, A. Habraken and P. Teuffel, "Seismic control performance of a 3-story frame prototype equipped with semi-active variable stiffness and damping structural joints," *Earthquake Engineering & Structural Dynamics,* vol. 50, no. 13, pp. 3379-3402, 2021.

[4] Q. Wang, G. Senatore, K.M.B. Jansen, A. Habraken and P. Teuffel, "Design and characterization of variable stiffness structural joints," *Materials & Design,* vol. 187, p. 108353, 2020.

[5] H. Qi, M. Yang, X. Zhang, Y. Zhang, B. Wu and J. Liu, “Review on the structural design and materials of covers for inflatable lunar habitat (in Chinese),” *Spacecraft Environment Engineering,* vol. 38, no. 6, pp. 715-722, 2021.

[6] M. Schenk, A. D. Viquerat, K. A. Seffen and S. D. Guest, "Review of inflatable booms for deployable space structures: packing and rigidization," *Journal of Spacecraft and Rockets,* vol. 51, no. 3, pp. 762-778, 2014.

[7] Q. Wang, P. Feng, K.M.B. Jansen and B. Charun, "A novel rigidizable inflatable lunar habitation system: design concept and material characterization," *Materials & Design,* vol. 246, p. 113289, 2024.

[8] Q. Wang, P. Feng and K.M.B. Jansen, "Designs of self-rigidizable inflatable habitats for construction in extreme environments," in *Proceedings of IASS Annual Symposia 2024*, Zürich, 2024.

[9] R. H. Luchsinger, A. Pedretti, P. Steingruber and M. Pedretti, "The new structural concept Tensairity: Basic principles," *Progress in structural engineering, mechanics and computation,* pp. 323-328, 2004.

[10] F. Caruso, G. Mantriota, L. Afferrante and G. Reina, "A theoretical model for multi-layer jamming systems," *Mechanism and Machine Theory,* vol. 172, p. 104788, 2022.

[11] B. Aktaş, Y. S. Narang, N. Vasios, K. Bertoldi and R. D. Howe, "A modeling framework for jamming structures," *Advanced Functional Materials,* vol. 31, no. 16, p. 2007554, 2021.