Surface-Based Lunar Habitats with Inflatable and Deployable Features: A Conceptual Design and Numerical Feasibility Study

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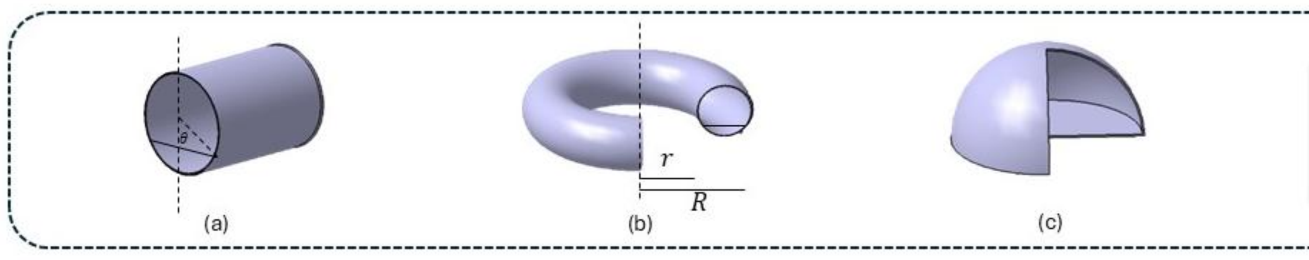
ABSTRACT

Inflatable and deployable structures are increasingly recognized as a promising solution for long-duration lunar surface missions, where mass efficiency, compact stowage, and rapid deployment are critical design drivers. This work presents the conceptual design and a preliminary numerical feasibility study of a surface-based inflatable and deployable lunar habitat. Several geometric configurations are initially investigated to identify the solution minimizing structural mass for an equivalent habitable volume. A cylindrical architecture is selected due to its favorable mass efficiency, one-dimensional deployment simplicity, and inherent modularity while preserving continuous curvature. The analyzed habitat consists of a fabric restraint layer made of aluminized Kapton Kevlar (AKK), sized with a safety factor of four, coupled with a carbon-fiber-reinforced composite floor designed to support astronaut and internal equipment loads. Habitability aspects are preliminarily assessed through a digital mock-up, enabling the simulation of astronaut presence and representative operational activities. A finite element model of the fully-deployed structure is developed to verify the analytical sizing and assess structural feasibility under the pressurization load. Modal analyses are performed to define an appropriate pressurization time profile, avoiding dynamic coupling with the first structural natural frequency. Subsequent transient dynamic analyses confirmed the absence of resonant behavior and provided element stress–strain time histories. Finally, the deployment kinematic is investigated through a multibody model, allowing the definition of stiffness and damping characteristics of the mechanisms to ensure a robust and controlled habitat deployment.

SCHEME

➢ Geometry-Driven Preliminary Design Framework



Step 1: Starting geometric configurations

(a)

$$r = r_{int} + t$$
$$\theta = \pi - 2\text{asin}(-\frac{h}{r_{int}})$$
$$A_h = \pi r^2 - \left[\frac{\pi r^2 \theta}{2\pi} - rh\cos(\alpha)\right]$$
$$L = \frac{V_h}{A_h}$$

(b)

$$r = k \cdot 1.6 + t$$
$$R = r + 1.6$$
$$\theta = \pi - 2\text{asin}(-\frac{h}{r_{int}})$$
$$A_h = \pi r^2 - \left[\frac{\pi r^2 \theta}{2\pi} - rh\cos(\alpha)\right]$$
$$V_h = A_h \cdot 2\pi r^2 \rightarrow imposed$$

(c)

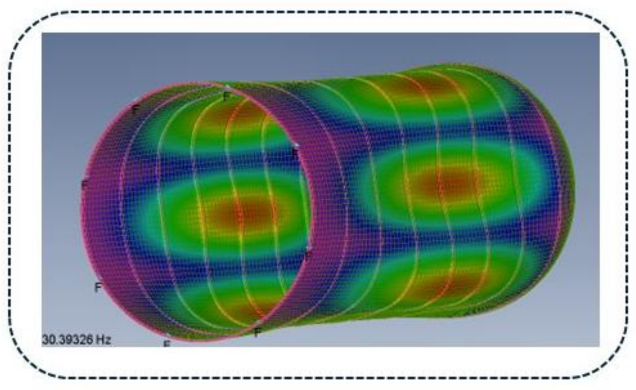
$$V_h = \frac{2}{3} \cdot \pi \cdot R_{int}^3$$
$$R_{ext} = R_{int} + t$$
$$V_{ext} = \frac{2}{3} \cdot \pi \cdot R_{ext}^3$$
$$R_{int} = [3\, V_h / 2\pi]^{\frac{1}{3}}$$

Step 2: Geometric characteristics equations

Configuration	Radius [m]	Length [m]	Rotation distance [m]	Habitable V. [m³]	Stowed V. [m³]	Total V. [m³]
(a)	1.6	7.0	-	50.0	8.1	58.1
(b)	1.6	-	2.1	105.1	15.0	120.1
(c)	2.879	-	-	50.2	0	50.2

Step 3: Results

➢ Pipeline for modal identification and time-frequency evaluation of pressurization profiles



1. Ramp load

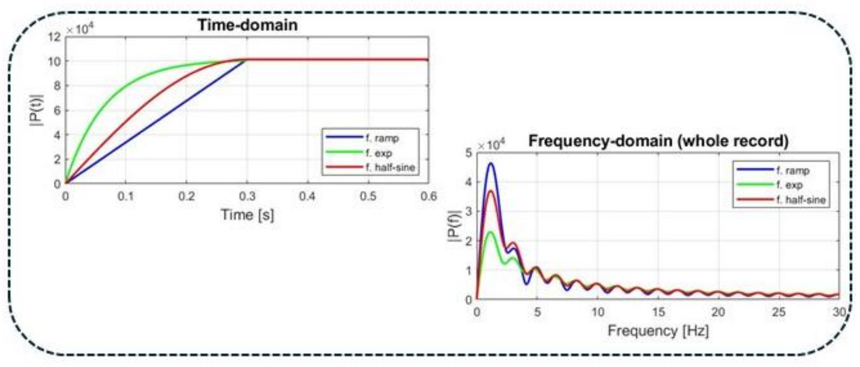
$$\begin{cases} P(t) = p_0 \frac{t}{t_r} & t \in [0, t_r] \\ P(t) = p_0 & t > t_r \end{cases}$$

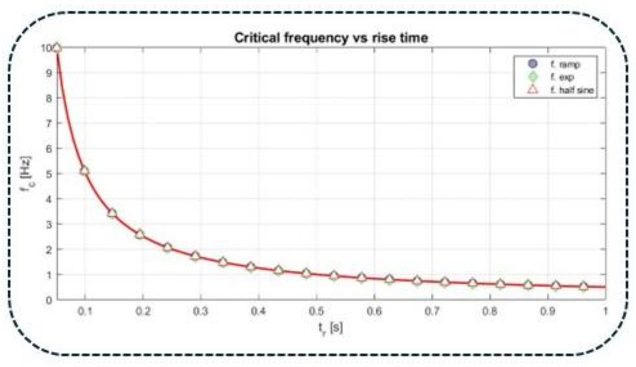
2. Exponential load

$$\begin{cases} P(t) = p_0(1 - e^{-\alpha t}) & t \in [0, t_r] \\ P(t) = p_0 & t > t_r \end{cases}$$

3. Half-sine load

$$\begin{cases} P(t) = p_0 \sin\left(\frac{\pi}{2}\frac{t}{t_r}\right) & t \in [0, t_r] \\ P(t) = p_0 & t > t_r \end{cases}$$





CONCLUSIONS

•**Conceptual Design:** A hollow cylindrical configuration was selected as the lightest geometry capable of enclosing a 50 m³ habitable volume. The Hemispherical end-cap was adopted due to its more uniform stress distribution and reduced load transmission. The optimized floor position was set at 20% of the module diameter.

•**Habitability assessment:** The assessment included two 95th-percentile ANSUR digital mannequins; both able to perform representative operational tasks, including object grasping, sitting, walking, and overhead reach.

•**Overall numerical analyses:** Static analysis finds peak stresses of 22.62% of the material yield strength, with average displacements of 9 mm for the restrain layer and 7 mm for the floor. Modal analysis identified the first structural natural frequency at 30.39 Hz, while the selected exponential pressurization profile exhibited significant frequency content only up to 12 Hz. Transient dynamic analyses confirmed the absence of resonant coupling between the structure and the applied load. Preliminary kinematic analyses indicate a stable and controlled deployment behavior.

RESULTS

Configuration	Shell mass [kg]	Floor mass [kg]	Total mass [kg]	% T. mass increase compared to (a)
(a)	101	103	**204**	-
(b)	170	190	**360**	52
(c)	67	151	**218**	5

Tab1. Preliminary mass comparison of the three configurations under investigation

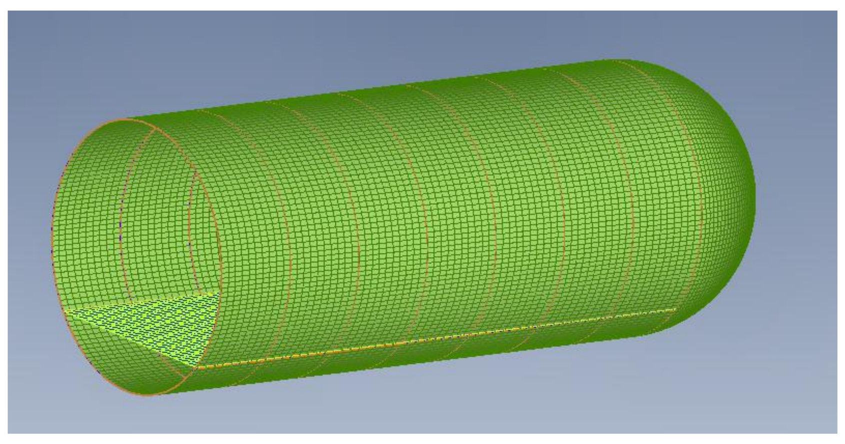


Fig1. Finite element implementation of the lunar fully-deployed surface-based habitat design.

Geometry	Hollow cylinder + Hemispherical endcap
Shell mass [kg]	101
Floor mass [kg]	103
Rings mass [kg]	128
Total mass [kg]	**332**

Tab2. Summary of the selected structural configuration

Fig2. Isometric rendering of the fully deployed pressurized inflatable habitat, showing two digital mannequins and operational equipment placeholders (NX-SIEMENS).

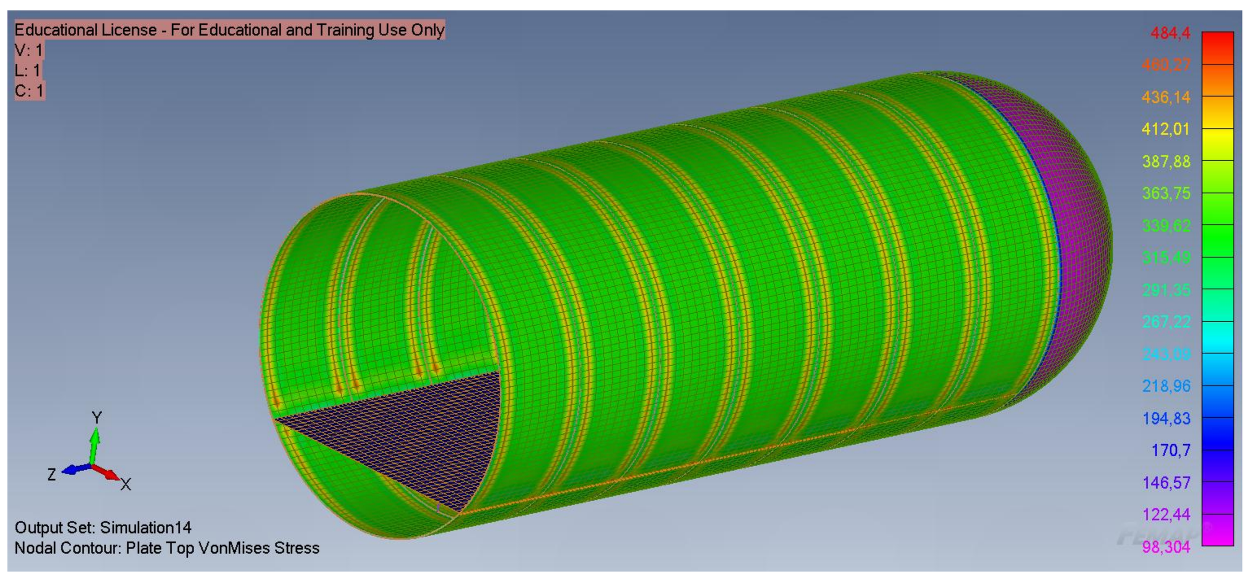
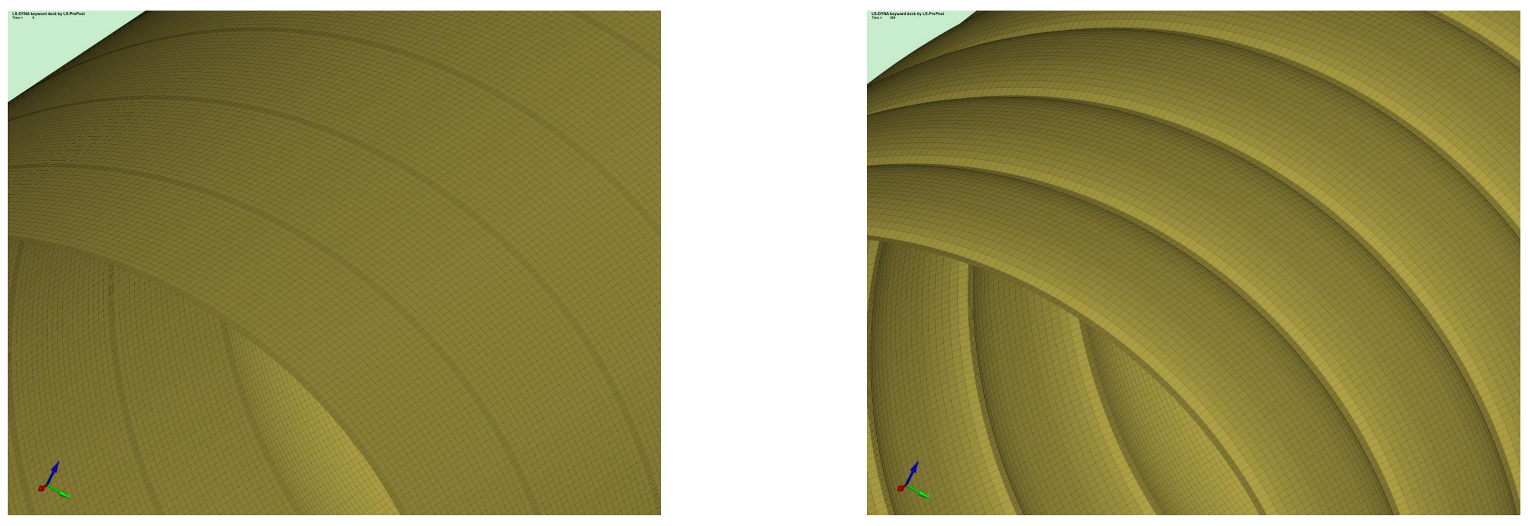
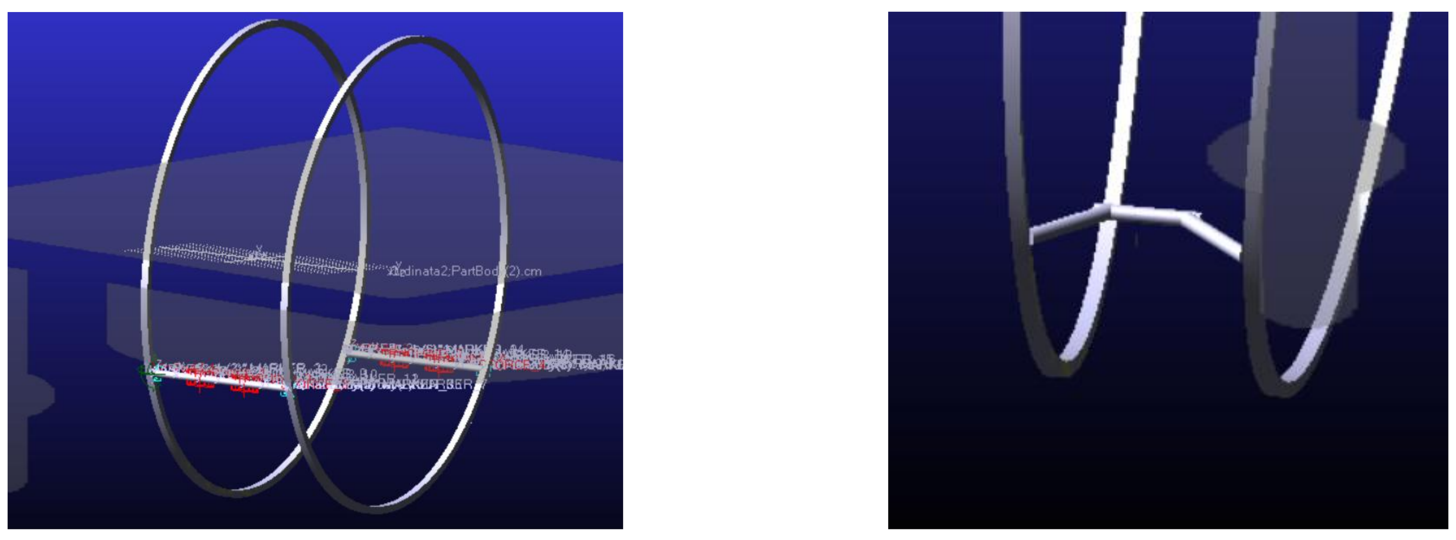


Fig3. Static analysis showing the Von Mises stress distribution on the fully-deployed habitat (FEMAP).



(a) (b)

Fig4. Dynamic analysis visualizing a portion of the fully-deployed habitat: (a) pre-inflation configuration, (b) post-inflation configuration (LS-PrePost).



(a) (b)

Fig5. Preliminary multibody kinematic model of the habitat deployment: (a) global system configuration and (b) detail of the ring-to-ring connection (ADAMS MCS).

ACKNOWLEDGMENT

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Ref:
⌘ Caiazzo, Alfonso, et al. "Structures for extraterrestrial habitat: A review." Acta Astronautica (2025), https://doi.org/10.1016/j.actaastro.2025.10.029. [Online]
⌘ Caiazzo, Alfonso, et al. "Conceptual Structural Design of a Pressurized Inflatable and Deployable Habitat Optimized for Lunar Surface Missions." CEAS-AIDAA, 1-4 Dec., Turin (2025) [Under Review]

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