

KINEMATICS-DRIVEN DEPLOYMENT ANALYSIS OF AN INFLATABLE LUNAR HABITAT WITH NONLINEAR MEMBRANE RESPONSE

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Abstract

Inflatable lunar habitats offer launch-volume efficiency but couple mechanism dynamics to a highly compliant restraint layer. This paper isolates deployability from subsequent pressurization and links three models: a FEMAP finite-element model of the complete habitat for static material screening; an MSC Adams multibody model of a three-ring, two-stage module for joint forces, work and power; and a geometrically and materially nonlinear LS-DYNA model of the dry Kevlar K300T2 restraint layer. Linear, half-cosine and quintic minimum-jerk laws are assessed for synchronized and staged motion under equal-global-time and equal-local-stroke-time criteria. At equal local time, staging reduces peak mean absolute force by 22.6 – 30.6%, cumulative mechanical work by 30.4 – 33.3%, and peak power by 59 – 63%. For the minimum-jerk case, the selected deployability-affected membrane area falls from 14.86% to 9.53% of nominal lateral area. Staging is therefore beneficial only when allowed a longer global maneuver, showing that motion smoothness, timing and membrane response must be co-designed.

1 INTRODUCTION

Expandable softgoods habitats can provide a larger habitable volume per launch volume than an equivalent rigid shell, but their structural function is distributed among a multilayer structure composed of a bladder, restraint, thermal and protective layers. TransHab and later NASA developments established the feasibility of large layered inflatables and the need for full-scale structural testing [1,2,3]. Certification studies further show that human-rated softgoods require a building-block approach, statistically supported knock-down factors and explicit treatment of material variability [4]. These issues become more severe for surface-based habitats because deployment must also interact with the ground, mechanisms and lunar gravity. Recent reviews classify lunar and Martian habitat concepts by architecture, material and construction strategy and identify deployable/inflatable solutions as mass-efficient but validation-intensive [1]. A related safety study emphasizes the risk of assigning packing, deployment and pressure retention to an insufficiently separated structural function [5]. The present work therefore treats deployment before inflation: only the structural restraint layer and the frame-guide mechanism are retained in the dynamic models. Pressure qualification, gas-barrier performance and the complete multilayer stack are outside the current study. The geometry originates from the authors' conceptual pressurized lunar habitat, for which a

cylindrical configuration was selected after geometric, static, thermal and habitability trade-offs [6]. The contribution is a kinematics-driven, multi-model assessment that connects: (i) full-structure static screening, (ii) actuator demand from a multibody representation and (iii) nonlinear dry-fabric deformation under the same prescribed motions. Thin membranes may develop localized slack and wrinkles through geometric instability, making a large-deformation finite-element treatment essential [9,10]. Table 1 positions the analysis relative to the literature base.

Table 1: Literature basis and resulting modelling decisions.

Source	Established point	Decision in this work
Kennedy [2]	TransHab architecture and structural tests	Retain a layered-habitat context
Valle et al. [3]	Softgoods design, analysis and test hierarchy	Separate structural restraint from other layers
Jones [4]	Certification depends on tests, variability and factors	Treat the model as pre-qualification
Siviero et al. [5]	Safety-critical functions and material risks	Decouple deployment from inflation

Source	Established point	Decision in this work
Caiazzo et al. [1,6]	Environmental review and cylindrical baseline	Adopt the previously screened habitat
Wong; Vatankehagh hadim [9,10]	Wrinkling and support-motion coupling	Use geometrically nonlinear shell analysis

2 HABITAT CONCEPT AND MODEL CHAIN

2.1 Static structural screening in FEMAP

The reference habitat consists of a cylindrical softgoods shell with a hemispherical endcap, eight internal rectangular rings, and a carbon-fibre floor with its support structure. The complete FEMAP model was subjected to a 1 atm pressure load. Five dry woven restraint candidates (see Tab. 2) from the project material catalogue have been compared using consistent geometry, boundary conditions and shell representation. The catalogue thickness, rather than a fitted laminate thickness, was used for this screening; the fibres are non-impregnated dry fabrics and are not treated as a resin-matrix composite.

$$\sigma_{\theta} = \frac{pR}{t}, \quad \sigma_x = \frac{pR}{2t} \quad (1)$$

For a cylindrical membrane, Eq. 1 provides the hoop and axial sizing references. Introducing safety factor SF and a restraint efficiency $\eta = 0.80$ gives the minimum thickness in Eq. 2. For Kevlar K300T2, $SF = 4$ gives 0.28 mm , below the 0.42 mm catalogue thickness used in the finite-element comparison. This calculation is a screening check; discontinuities at rings and endcaps are resolved by the FEMAP model rather than by membrane theory.

$$t_{req} = SF \cdot \frac{pR}{\eta \sigma_u} \quad (2)$$

Table 2: Dry-fabric catalogue data used in the static screen.

Material	Mass/area (g/m ²)	σ_u (MPa)	E (GPa)	t (mm)
Kevlar K300T2	300	2930	102.0	0.42
Vectran V200T2	200	3200	100.0	0.21
Zylon Z300T2	300	5800	270.0	0.42
CF50/Vectran50	200	3716	151.8	0.21
CF61/Aramid39	210	3850	179.0	0.25

Table 3: FEMAP response under 1 atm pressure differential.

Material	ucyl (mm)	uend (mm)	σ_{cyl} (MPa)	σ_{end} (MPa)
Kevlar K300T2	2.164	0.864	180	101
Vectran V200T2	11.02	3.95	679	385
Zylon Z300T2	2.00	0.73	341	92
CF50/Vectran 50	7.09	2.60	682	385
CF61/Aramid 39	5.06	1.86	571	323

According to Tab.3, Zylon gives the smallest displacement but the project trade also weights stress distribution, durability, availability and technology maturity. Kevlar K300T2 was consequently retained as the engineering compromise: its full-structure cylinder displacement is 2.164 mm and its average cylinder stress is 180 MPa .

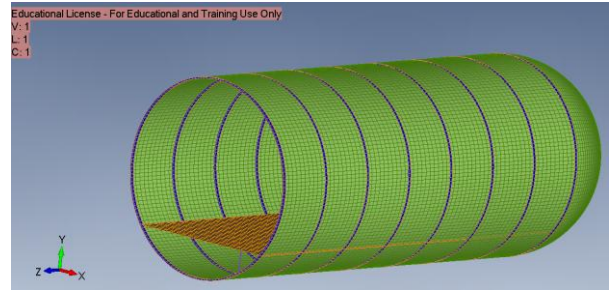


Figure 1: FEMAP finite-element model of the complete cylindrical habitat used for static screening.

2.2 Deployment module and information transfer

The modularity of the deployable structure has a radius of $R = 1600 \text{ mm}$ and total undepleted length of $L = 2000 \text{ mm}$. Three rigid frames are initially located at $0, 1000$ and 2000 mm , so each undepleted inter-ring span is $L_{span} = 1000 \text{ mm}$. The two telescopic deployable mechanism have a stroke of $\Delta = 500 \text{ mm}$. The modularity preserves the frame spacing and fabric span relevant to deployment while excluding the floor, secondary softgoods and pressure. Lunar gravity is included in the multibody model. Table 4 summarizes the analysis chain. FEMAP selects geometry and dry restraint material; MATLAB generates consistent kinematics; the same kinematic family is prescribed in MSC Adams and LS-DYNA. Adams's actuator forces are evaluated rather than imposed back into LS-DYNA.

Table 4: Purpose and information flow of the three numerical models.

Model	Representation	Inputs	Outputs
FEMAP FE	Complete habitat	1 atm; material candidates	Static stress, displacement, selection
MSC Adams MBD	3 rings; 2 prismatic stages	Lunar gravity; prescribed $q(t)$	Joint force, work, power
LS-DYNA FE	Dry Kevlar cylindrical span	Large motion; nonlinear table	u , strain, energy, affected area

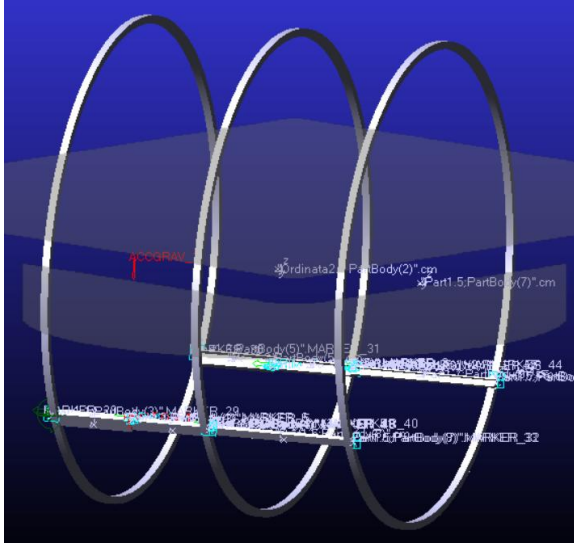


Figure 2: MSC Adams habitat's modularity with three frames and the telescopic guide system.

3 PRESCRIBED DEPLOYMENT KINEMATICS

3.1 Motion laws

For each stage, normalized time is $s = \tau/T_{loc}$ on $0 \leq s \leq 1$ and closure is $q = \Delta f(s)$. Three laws are screened: linear, half-cosine and quintic minimum jerk (QMJ). The QMJ polynomial is the standard zero-velocity, zero-acceleration endpoint trajectory [8].

$$f_{lin}(s) = s \quad (3)$$

$$f_{cos}(s) = \frac{[1 - \cos(\pi s)]}{2} \quad (4)$$

$$f_{QMJ}(s) = 10s^3 - 15s^4 + 6s^5 \quad (5)$$

$$q = \Delta f, \quad \dot{q} = (\Delta/T_{loc})f', \quad \ddot{q} = (\Delta/T_{loc}^2)f'' \quad (6)$$

For the linear law, the in-stroke velocity is constant but jumps instantaneously between zero and Δ/T_{loc}

at the stroke boundaries. In an ideal analytical description, this velocity discontinuity produces impulsive endpoint acceleration; therefore, the linear law is retained only as a baseline. The half-cosine law has zero endpoint velocity, providing a continuous transition in position and velocity. However, its acceleration is finite and non-zero at both endpoints, so the trajectory is not acceleration-continuous when connected to a stationary phase. The QMJ law has both zero velocity and zero acceleration at the stroke boundaries. It therefore provides a C^2 -continuous transition between motion and hold phases, avoiding artificial velocity or acceleration discontinuities in the flexible-structure analysis.

Table 5: Kinematic-law properties for a single 500-mm stroke.

Law	Endpoint velocity	Endpoint acceleration	Implication
Linear	jump	impulsive	Baseline only
Half-cosine	zero	non-zero	Smooth velocity
QMJ	zero	zero	C^2 transition

3.2 Strategies and timing criteria

Synchronized motion commands both stages simultaneously. Staged motion commands stage 1 inserts a stabilization pause of $0.10T_{loc}$ and then commands stage 2; opening reverses the order. The monitored absolute positions are $x_2 = x_{2,0} - d_2$ and $x_3 = x_{3,0} - d_1 - d_2$, with $x_{2,0} = 1000 \text{ mm}$ and $x_{3,0} = 2000 \text{ mm}$. Hence the distal ring accumulates both closures. The equal-global-time criteria, named *criterion A* imposes equal global closure/opening time; staged local strokes must therefore be faster. The equal-local-stroke-time criteria, named *criterion B* imposes equal local stroke time; staged motion then takes longer globally. A reference velocity of 10 mm/s has been chosen as the upper limit; a consequent reference time of 240 s has been used. Table 6 gives the resulting cycle durations.

Table 6: Timing definition for the 200-s reference analysis.

Crit.	Strategy	T_{loc} (s)	Pause (s)	Closure (s)	Cycle (s)
A	Staged	114.29	11.429	240	600
A	Sync.	240	0	240	600
B	Staged	240	24	504	1128
B	Sync.	240	0	240	600

Table 7: Peak local velocities and finite accelerations.

Case	Linear v (mm/s)	Cosine v (mm/s)	QMJ v (mm/s)	QMJ a (mm/s ²)
A-staged	4.375	6.872	8.203	0.2210
A-sync.	2.083	3.272	3.906	0.0501
B-staged	2.083	3.272	3.906	0.0501
B-sync.	2.083	3.272	3.906	0.0501

Table 7 reports actuator-level quantities. During synchronized deployment, the distal-frame velocity and finite acceleration are twice the corresponding local actuator values because the distal position depends simultaneously on d_1 and d_2 . During staged deployment, only one actuator moves at a time, and the distal-frame kinematic quantities therefore coincide with the active local actuator values. The highest prescribed local actuator velocity is 8.2031 mm/s for the staged QMJ case under Criterion A, which remains below the selected reference limit of 10 mm/s.

4 MULTIBODY ACTUATOR-DEMAND ANALYSIS

4.1 MSC Adams model and metrics

The three frames are modelled as rigid bodies connected by two actuated translational joints, representing the two telescopic deployment stages. The first joint controls the motion of the intermediate frame, whereas the second joint contributes to the motion of the distal frame. Since the distal frame is affected by both telescopic stages, its absolute displacement includes the contributions of both joint motions. The axial forces calculated at the two translational joints are used to evaluate the actuator demand. At each time step, the absolute joint forces are averaged and the maximum value reached during the complete simulation is defined as the peak mean absolute force. The mechanical power associated with joint j is calculated as:

$$P_j(t) = |F_j(t) \cdot \dot{q}_j(t)| \quad (7)$$

where $F_j(t)$ is the axial joint force and $\dot{q}_j(t)$ is the corresponding actuator velocity. The total mechanical power is obtained by summing the contributions of the two joints. Its maximum value defines the peak total power, whereas the cumulative mechanical work corresponds to the area under the total power-time curve. Stage 2 consistently requires a higher force because it moves a larger equivalent mass and carries the contribution associated with the distal frame.

4.2 Force, work and power results

Tables 8 to 10 report the Criterion-B values at the precision available from the MSC Adams postprocessing. The reductions are calculated relative to the synchronized case of the same law. Criterion A is intentionally not mixed into these tables because its global time budget is different at the actuator level.

Table 8: Peak mean absolute force at equal local stroke time (Criterion B).

Law	Sync. (N)	Staged (N)	Reduction
Linear	≈ 31	≈ 24	22.6%
Half-cosine	≈ 44	≈ 31	29.5%
QMJ	≈ 49	≈ 34	30.6%

Table 9: Cumulative mechanical work at equal local stroke time (Criterion B).

Law	Sync. (J)	Staged (J)	Reduction
Linear	≈ 56	≈ 39	30.4%
Half-cosine	≈ 65	≈ 44	32.3%
QMJ	≈ 72	≈ 48	33.3%

Table 10: Peak total mechanical power at equal local stroke time (Criterion B).

Law	Sync. (W)	Staged (W)	Reduction
Linear	≈ 0.117	≈ 0.048	59.0%
Half-cosine	≈ 0.260	≈ 0.101	61.2%
QMJ	≈ 0.350	≈ 0.131	62.6%

At equal local time, staging reduces all the three actuation metrics. The power reduction is the largest (59 – 63%) because simultaneous motion superposes the power demand of both stages. Within either strategy, QMJ has the largest peak power for the selected duration. Thus, an endpoint-smooth trajectory protects the flexible model from kinematic discontinuities but is not automatically the lowest-power command.

5 NONLINEAR MEMBRANE ANALYSIS IN LS-DYNA

5.1 Dry-fabric model and convergence

The LS-DYNA model uses (i) dry Kevlar K300T2 for the cylindrical fabric segment and (ii) frame-driven boundary motion. Large deformation is enabled and the woven restraint response is introduced through a tabulated nonlinear orthotropic law. Independent tests on Kevlar 49 fabric show nonlinear, direction-dependent tension, strain-dependent transverse contraction and nonlinear in-plane shear [7], supporting a tabulated fabric representation rather than a single isotropic

modulus. The stress-strain curve for the fabric material has been added in the solve. Maximum transverse displacement $u_{\perp}$ is used as a global convergence indicator for the mesh sensitivity analysis. For time sample k and a small denominator regularization δ , the relative difference between two meshes i and j is $\frac{100|u_{\perp i} - u_{\perp j}|}{\max(|u_{\perp j}|, \delta)}$. Table 11 shows the mean and maximum error of the mesh sensitivity analysis.

Table 11: Mesh-convergence statistics for maximum transverse displacement.

Mesh pair	Elems. i	Elems. j	Mean error	Max. error
1 $\rightarrow$ 2	127500	255000	6.4%	15.9%
2 $\rightarrow$ 3	255000	582500	0.8%	5.5%

5.2 Closure ratio and membrane-response metric

The imposed closure is normalized by the undeployed inter-ring span, $r = \Delta/L_{span}$. Here $\Delta = 500 \text{ mm}$ and $L_{span} = 1000 \text{ mm}$ at the beginning of the maneuver. Across the screened configurations, maximum transverse deflection rises rapidly at low r and then approaches a lower-sensitivity regime. This trend is represented phenomenologically by Eq. 8; in order to interpret the response.

$$w(r) = w_{\infty}[1 - \exp(-kr)] \quad (8)$$

The final configurations are additionally compared through an affected-area indicator. In LS-PrePost, elements satisfying the same transverse-displacement selection operation are activated and their current surface area A_{aff} is measured. With the nominal cylinder lateral area $A_0 = 2\pi RL = 20.106 \text{ m}^2$, the percentage is

$$\eta_{aff} = 100 A_{aff}/A_0 \quad (9)$$

This definition quantifies the selected affected surface, not wrinkle wavelength or amplitude, and remains dependent on the displacement threshold. It is therefore reported as a comparative indicator using an identical selection for the synchronized and staged cases.

Table 12: Final affected area for QMJ deployment under Criterion B.

Strategy	$A_{aff} \text{ (m}^2\text{)}$	η_{aff}	Change vs sync.
Sync.	2.98724	14.857%	Baseline
Staged	1.91557	9.527%	-35.87%

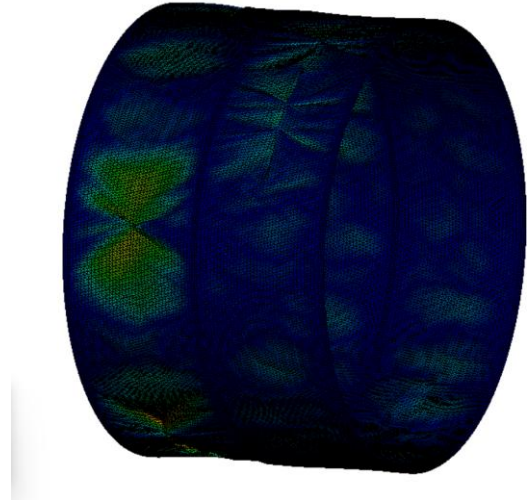


Figure 3: Final QMJ synchronized configuration under Criterion B; contours display transverse YZ displacement ($u_{\perp}$).

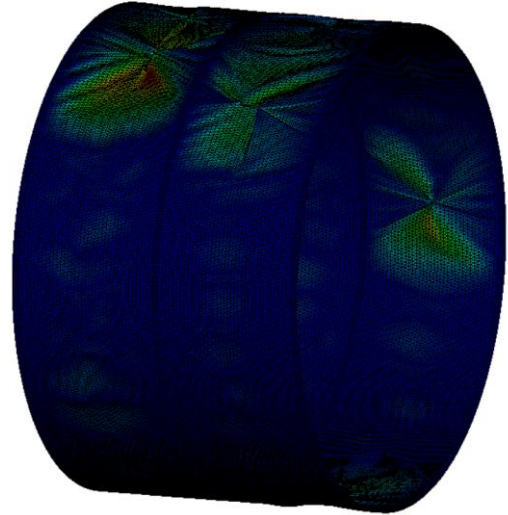


Figure 4: Final QMJ staged configuration under Criterion B; contours display transverse YZ displacement ($u_{\perp}$).

Sequential QMJ motion reduces the selected affected area from 2.987 m^2 to 1.916 m^2 , i.e. the 35.87% in relation to the synchronized deployment. The result is consistent with reduced simultaneous forcing and with the staged redistribution of slack; it does not by itself establish a reduction in local peak strain.

6 DISCUSSION AND CONCLUSION

The combined FEMAP/MSC Adams/LS-DYNA methodology separates three complementary aspects of the habitat design. FEMAP establishes the full-structure static baseline and supports the

selection of dry woven Kevlar K300T2. MSC Adams evaluates the forces, work and power required by the telescopic deployable mechanism while LS-DYNA captures the geometric and material nonlinearities of the unpressurized fabric during deployment. The results show that the advantage of staged deployment depends on the adopted timing criterion. Under Criterion B, where both strategies have the same local stroke time, staging reduces peak mean absolute force from 22.6% to 30.6%, cumulative mechanical work from 30.4% to 33.3% and peak power from 59% to 63%. For the QMJ law, the affected membrane area also decreases from 14.857% to 9.527% of the nominal lateral area. However, the staged close-hold-open cycle increases from 600 s to 1128 s. Under Criterion A, the same global duration requires the staged local stroke to be completed in 114.29 s, increasing its kinematic severity. QMJ remains the preferred law for nonlinear membrane analysis because its velocity and acceleration vanish at the motion boundaries, although it does not provide the lowest peak power at fixed duration. Future work will focus on manufacturing a scaled prototype of the aforementioned habitat's modularity. The prototype will be used to reproduce the staged and synchronized deployment sequences and experimentally measure joint forces, ring motion and fabric deformation. These tests will validate the interaction between prescribed kinematics and nonlinear structural dynamics before extending the analysis to the complete pressurized habitat.

REFERENCES

1. Caiazzo, A., Casaburo, A., Petrone, G., De Rosa, S. & Franco, F. (2026). Structures for extraterrestrial habitat: A review. *Acta Astronautica* 238, 471–493. <https://doi.org/10.1016/j.actaastro.2025.10.029>
2. Kennedy, K.J. (2000). Inflatable Habitats Technology Development. In *Mars Greenhouses: Concepts and Challenges*, NASA/TM-2000-208577, pp. 64–76.
3. Valle, G.D., Litteken, D.A. & Jones, T.C. (2019). Review of Habitable Softgoods Inflatable Design, Analysis, Testing, and Potential Space Applications. *AIAA SciTech 2019 Forum*, AIAA 2019-1018. <https://doi.org/10.2514/6.2019-1018>
4. Jones, T.C. (2018). Structural Certification of Human-Rated Inflatable Space Structures. *2018 IEEE Aerospace Conference*, pp. 1–13. <https://doi.org/10.1109/AERO.2018.8396616>
5. Siviero, A., Delpiano, D., Castagneri, D., Amoikon, S., Demaria, L. & Davies, R. (2024). Structural Design and Safety Critical Conditions Analysis on Composite and Modern Materials Applied in Construction of Inflatable Modules for Lunar and Martian Bases. *75th International Astronautical Congress*, IAC-24, D3,2A,4, x88273, pp. 73–86. <https://doi.org/10.52202/078374-0009>
6. Caiazzo, A., Petrone, G., Casaburo, A., De Rosa, S. & Franco, F. (2026). Conceptual Structural Design of a Pressurized Inflatable and Deployable Habitat Optimized for Lunar Surface Missions. *Materials Research Proceedings* 69, 1278–1282. <https://doi.org/10.21741/9781644904251-221>
7. Zhu, D., Mobasher, B. & Rajan, S.D. (2011). Characterization of Mechanical Behavior of Kevlar 49 Fabrics. In T. Proulx (Ed.), *Experimental and Applied Mechanics*, Vol. 6, pp. 377–384. Springer. https://doi.org/10.1007/978-1-4614-0222-0_46
8. Flash, T. & Hogan, N. (1985). The coordination of arm movements: An experimentally confirmed mathematical model. *The Journal of Neuroscience* 5(7), 1688–1703. <https://doi.org/10.1523/JNEUROSCI.05-07-01688.1985>
9. Wong, Y.W. & Pellegrino, S. (2006). Wrinkled membranes. Part III: Numerical simulations. *Journal of Mechanics of Materials and Structures* 1(1), 63–95. <https://doi.org/10.2140/jomms.2006.1.63>
10. Vatankehaghadim, B. & Damaren, C.J. (2021). Nonlinear deployment dynamics and wrinkling of a membrane attached to two axially moving beams. *Journal of Spacecraft and Rockets* 58(6), 1714–1732. <https://doi.org/10.2514/1.A34962>
11. Miyazaki, Y. (2006). Wrinkle/slack model and finite element dynamics of membrane. *International Journal for Numerical Methods in Engineering* 66(7), 1179–1209. <https://doi.org/10.1002/nme.1588>