Building Structures on the Moon and Mars: Engineering Challenges and Structural Design Parameters for Proposed Habitats

Ramesh B. Malla, Ph.D., F. ASCE, A.F. AIAA
Professor
Department of Civil and Environmental Engineering
University of Connecticut, Storrs, CT 06269
(E-Mail: MallaR@engr.uconn.edu**)**

Presented at the
Breakout Panel Session- Theme C - Habitats (Preparation and Architecture)

RETH Workshop- Grand Challenges and Key Research Questions to Achieve Resilient Long-Term Extraterrestrial Habitats
Purdue University; October 22-23, 2018

UCONN UNIVERSITY OF CONNECTICUT

Civil & Environmental engineering

What is Structural Resiliency?

- Minimization of direct and indirect losses from hazards through enhanced resistance and robustness to extreme events, as well as more effective recovery strategies.

- Characterized by four traits:
  - Robustness
    - Ability to maintain critical functions in crisis
  - Resourcefulness
    - Ability to effectively manage crisis as it unfolds
  - Rapid Recovery
    - Reconstitute normal operations quickly and effectively
  - Redundancy
    - Backup resources to support originals

Per: National Infrastructure Advisory Council, 2009

Hazard Sources & Potential Lunar Habitats

Potential Hazard Sources

- Impact (Micrometeorite, Debris)
- Hard Vacuum
- Extreme Temperature
- Seismic Activity
- Low Gravity
- Radiation
  - Galactic Cosmic Rays (GCR)
  - Solar-Emitted Particles (SEP)

"Bessel Crater" - https://www.lpi.usra.edu/science/kiefer/Education/SSRG2-Craters/craterstructure.html

Available Habitat Types

- Inflatable Membrane
- Rigid-Frame Structure
- Hybrid Frame-Membrane Structure
- Subsurface Variants

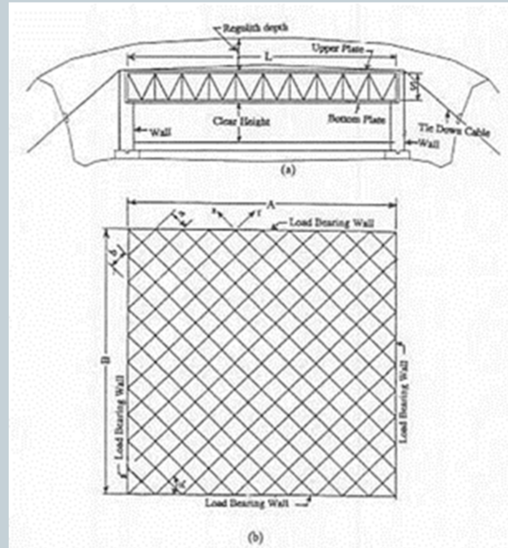


FIG. 1. Proposed Braced Double-Skinned Roof Structure for Lunar Base: (a) Cross-Sectional View; (b) Plan View

Malla, et al. (1995)

Comparison of Surface Conditions

Mass and Gravity

Moon
Mass = 7.35×10^{22} kg
Diameter = 2,160 miles; 3,476 kilometers
Gravity = ~1.62 m/s2 (about 1/6th the gravitational field of the Earth)

Mars
Mass = ~6.42×10^{23} kg
Diameter = 4,222 miles; 6,787 km
Gravity = ~3.68 m/s2 (about 1/3rd the gravitational field of the Earth)

Earth
Mass = ~5.98×10^{24} kg
Diameter = 7,926 miles; 12,756 km
Gravity = ~9.81 m/s2

Diurnal Cycle

Moon
Lunar day is 27.322 Earth days long (27 days, 7 h, and 43 min. - the same as its period of revolution around the Earth)

Mars
Martian day is 24 hours, 37 minutes (1.026 Earth days) long, known as sol

Earth
24 hours

Temperature Extremes

Moon
-233° C to 123° C (-387.4° F to 253.4° F; 40.15 K to 396.15 K)

Mars
-140° C to 20° C (-220° F to 68° F; 133.15 K to 293.15 K)

Earth
-89° C to 58° C (-128° F to 136.4° F; 184.15 K to 331.15 K)

Comparison of Surface Conditions

Atmosphere

Moon
0.0000000101 kPa (Hard Vacuum, no atmosphere/no weather)

Mars
0.7-0.9 kPa (Mostly carbon dioxide with small amounts of other gases)

Earth
101.325 kPa (14 psi)

Soil/Rock

Moon
Very powdery and abrasive with high density at increased depth
Small to large rocks

Mars
Very find powder on surface
May have frozen soil at depth

Impact Analysis: Hybrid Frame-Membrane Habitat

- Malla, R. B., & Gionet, T. G. (2013)
- Large deformation non-linear finite element frequency, static, and dynamic analyses
- Prestressing:
  - Internal Pressure (14 psi)
  - External Temperature Differential (-233 to 133 °C)
- Dynamic Analysis Results-
  - Dynamic response at or near point of impact. Away from the point of impact, the displacement and stress results are primarily a cause of the static loads (Regolith Shielding & Internal Pressure).

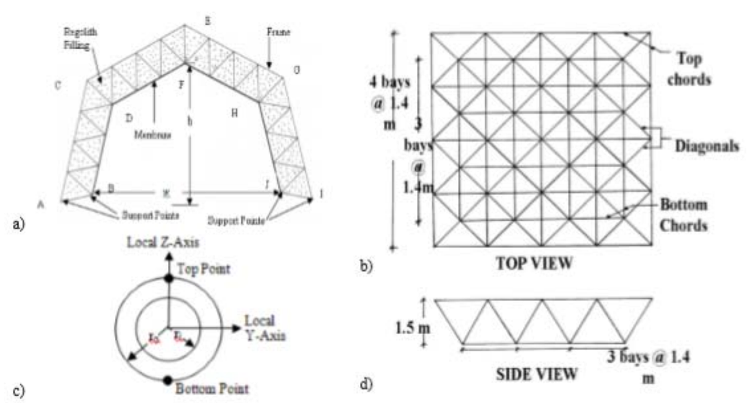
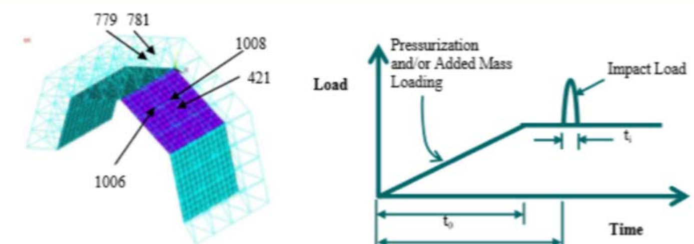


Figure 1. **Proposed structure.** *a) Front view; b) Top view; c) Frame member cross-section with top and bottom of cross section marked; and d) Side view.*



781: Midspan of outer chord and point of impact
779: Joint of outer chord
1008: Midspan of inner chord
1006: Joint of inner chord
a) 421: Central node of membrane panel

Figure 4. **Finite element model with key nodes and loading diagram.** *a) Finite element mesh model of the structure with some key nodes identified; b) Scheme used to apply pressurization, added mass, and impact loads.*

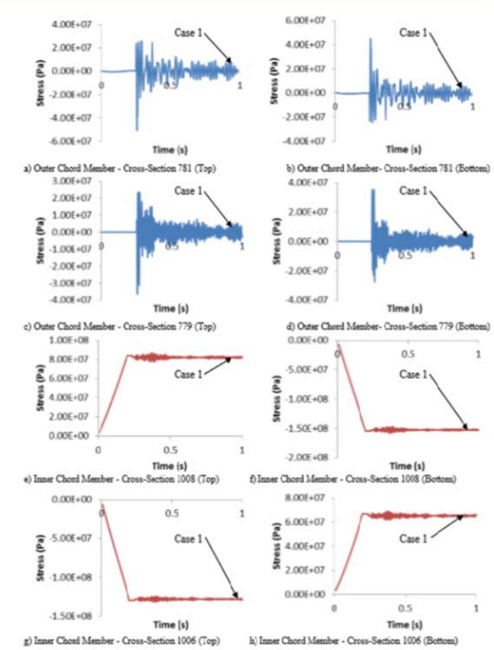
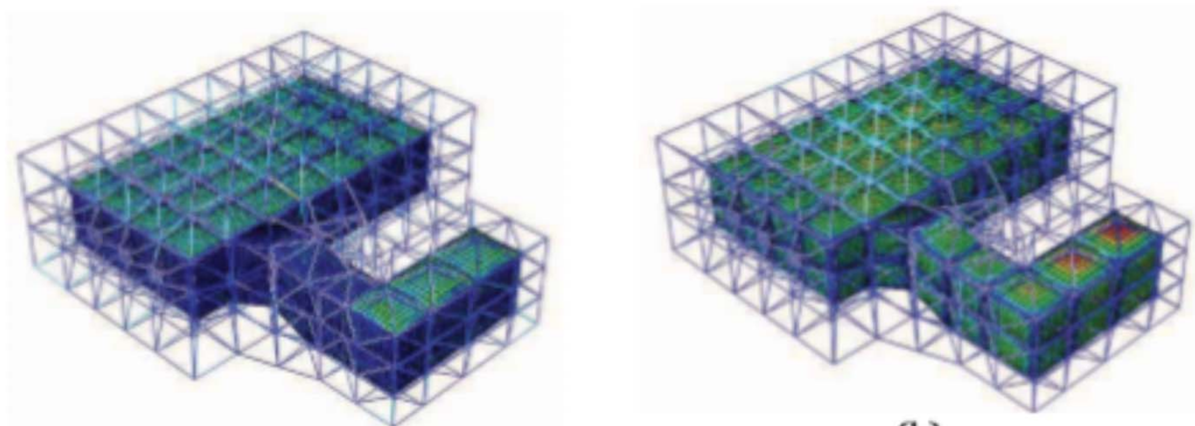


Figure 7. Stress time history at the top and bottom of various frame members' cross-section for temperature case 1. *a) Cross-section 781 (top); b) Cross-section 781 (bottom); c) Cross-section 779 (top); d) Cross-section 779 (bottom); e) Cross-section 1008 (top); f) Cross-section 1008 (bottom); g) Cross-section 1006 (top); h) Cross-section 1006 (bottom).*

Effects of Temperature Gradients on the Design of a Frame-Membrane Lunar Habitat

- K. Brown & R. B. Malla (2015)
- 1 meter thick regolith shield
- Runge-Kutta method Shielding Surface Temperature Determination (-170.75 to 113.95 °C)
- High daytime temperature = Nodal expansion
- Low nighttime temperature = Nodal contraction
- Added mass of regolith shield reduced both the stress and deflection magnitudes throughout the structure.



(a)

(b)

Figure 5. Rectangular habitat stress

Table 6. Habitat Stresses and Nodal Deflections with temperature effects

Section	Chord	Yield Stress	Max. Stress		Safety Factor		Max. Displacement	
			Day	Night	Day	Night	Day	Night
Main Habitat	Inner	503 MPa	269 MPa	290 MPa	1.87	1.73	25.75 mm	25.15 mm
	Diagonal		326 MPa	299 MPa	1.54	1.68	26.23 mm	22.49 mm
	Outer		309 MPa	276 MPa	1.63	1.82	27.41 mm	20.20 mm
	Membrane	2.92 GPa	368 MPa	370 MPa	7.93	7.89	56.87 mm	56.22 mm
Airlock Structure	Inner	503 MPa	218 MPa	239 MPa	2.30	2.10	17.90 mm	17.36 mm
	Diagonal		314 MPa	292 MPa	1.60	1.72	19.20 mm	17.42 mm
	Outer		338 MPa	301 MPa	1.49	1.67	20.65 mm	13.04 mm
	Membrane	2.92 GPa	411 MPa	413 MPa	7.10	7.07	56.10 mm	54.72 mm

Regolith Temperature Determination

Governing Thermodynamic Equation

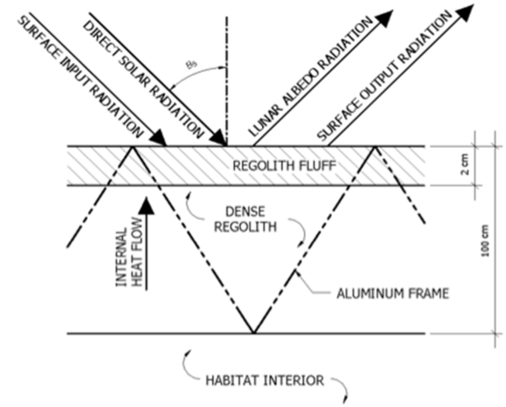
- If a structure radiates heat outward with a defined heat input, a thermodynamic differential equation of heat flow through the structure exists.

$$kV\frac{\partial^2 T(X,t)}{\partial X^2} - Mc\frac{\partial T(X,t)}{\partial t} = \dot{q}_{out}(X,t) - \dot{q}_{in}(X,t)$$

Steady State Temperature

- Equating input and output radiation.

$$\dot{q}_{in}(X,t) = \dot{q}_{out}(X,t)$$



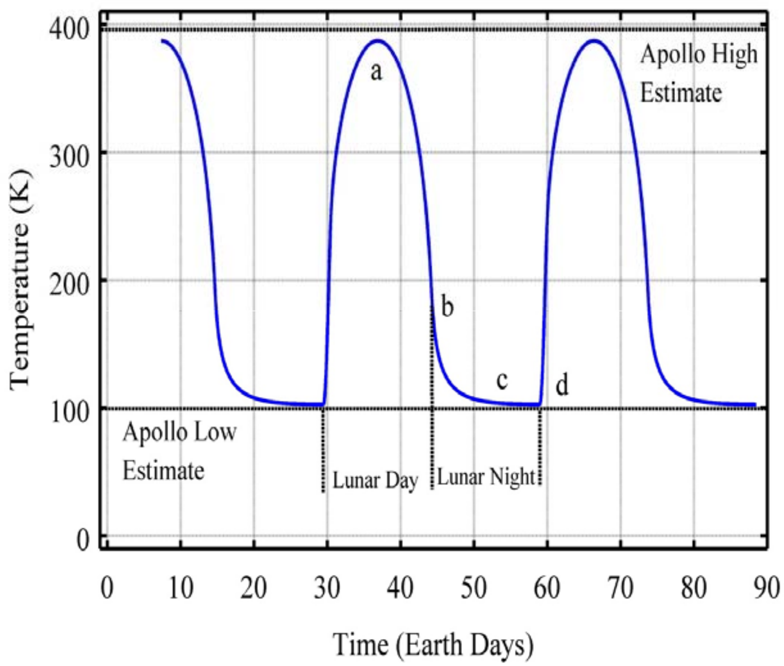
Nomenclature

$\dot{q}_{out}$	Heat output
$\dot{q}_{in}$	Heat input
M	Mass of regolith
V	Volume of regolith
T	Temperature of regolith
X	Depth within regolith
k	Thermal conductivity
c	Specific heat of regolith

Malla, R. B., & Brown, K. M. (2015)

Regolith Temperature Determination

Lunar Surface Temperature



- These results compare very well with previous studies and with experimental data from Apollo 15 and 17 missions.

- General equation simplified to consider variation with time only.
- Solved using 4th order Runge-Kutta techniques.

$$-Mc\frac{\partial T(t)}{\partial t} = \dot{q}_{out}(t) - \dot{q}_{in}(t)$$

$$\dot{q}_{in}(t) = \dot{q}_s + \dot{q}_i$$

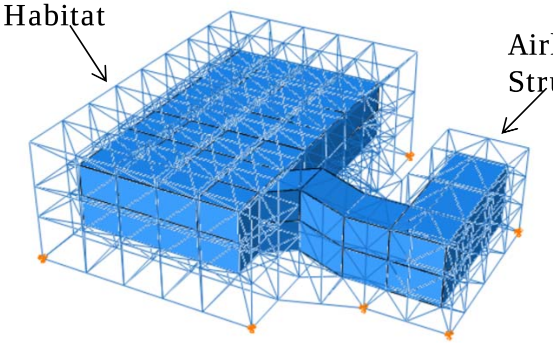
$$\dot{q}_{out}(t) = \dot{q}_{nbb} + \dot{q}_r$$

Lunar Cycle Temperatures

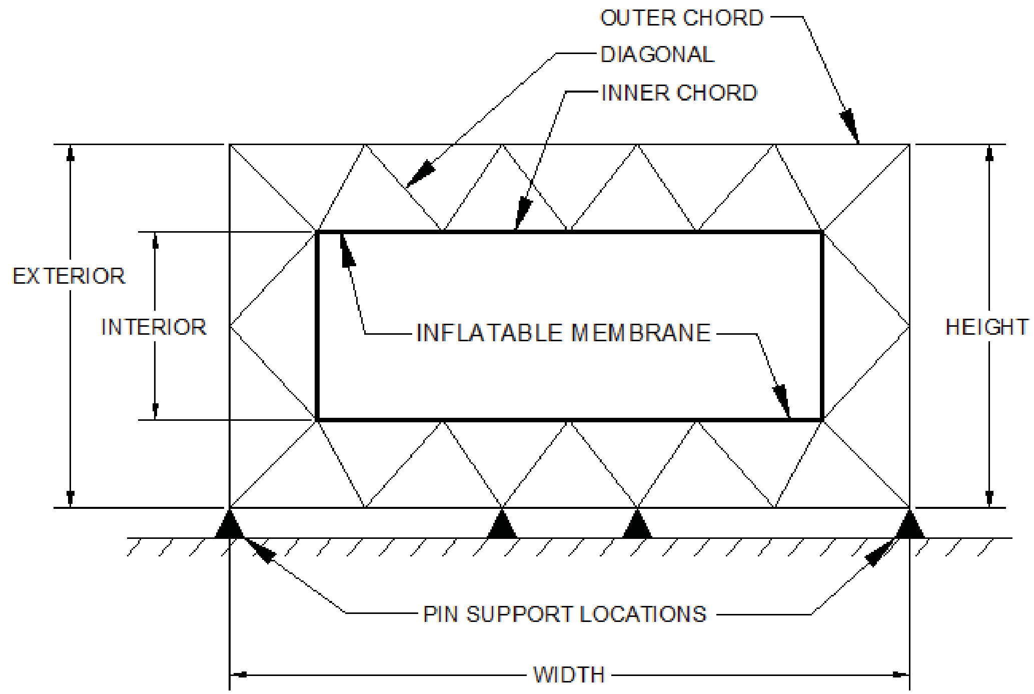
- Mid-day: 387 K (Steady State)
- End of day: 186 K
- Mid-night: 105 K
- Night Minimum: 102 K

Malla, R. B., & Brown, K. M. (2015)

Frame-Membrane Habitat Design Concept



Interior Dimensions	Main Habitat	Airlock
Height	2.13 m	2.13 m
Width	5.75 m	1.8 m
Length	10.0 m	5.4 m
Floor Area	57.5 m^2	9.72 m^2
Volume	122.7 m^3	20.7 m^3



Malla, R. B., & Brown, K. M. (2015)

Future Habitat Design Considerations

O'Donnell and Malla (2017)

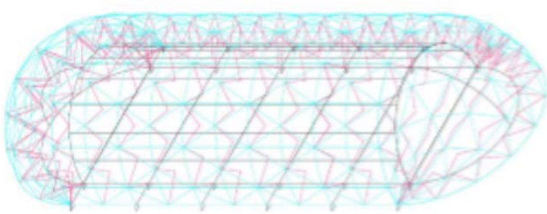


Figure 7. Semi-Circular Habitat

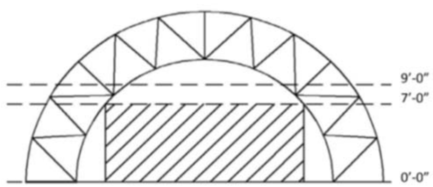


Figure 14. Section View of Frame-Membrane Structure Modification 3

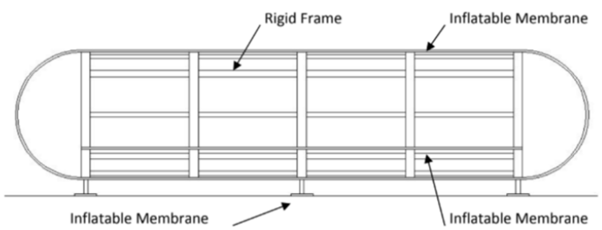


Figure 17. Section of Horizontal Cylinder

- Hazard analysis on additional habitat geometries
- Effect of extreme temperature variations on metallic truss members
- Interfaced sensor equipment for system failure detection
- Physical effects of secondary radiation on shielding material
- Automated habitat construction

Acknowledgment and References

Acknowledgments:

-NASA /Steckler Space Colonization Research and Technology Development grant -NASA EPSCoR
-NASA/Connecticut Space Grant Consortium -Hamilton Sundstrand Space Systems, Inc.

References:

- Brown, K. M., & Malla, R. B. (2015). Effects of Temperature Gradients on the Design of a Frame-Membrane Lunar Habitat. Earth and Space 2014. doi:10.1061/9780784479179.071
- Malla, R. B., & Brown, K. M. (2015). Determination of temperature variation on lunar surface and subsurface for habitat analysis and design. *Acta Astronautica*, *107*, 196-207. doi:10.1016/j.actaastro.2014.10.038
- Malla, R. B., & Gionet, T. G. (2013). Dynamic Response of a Pressurized Frame-Membrane Lunar Structure with Regolith Cover Subjected to Impact Load. Journal of Aerospace Engineering, 26(4), 855-873. doi:10.1061/(asce)as.1943-5525.0000187
- Malla, R. B., Adib-Jahromi, H. R., & Accorsi, M. L. (1995). "Simplified Design Method for Braced Double-Skinned Structure in Lunar Application," ASCE J. of Aerospace Engineering, Vol. 8, No. 4., pp 189-195.
- O'Donnell, Fiona A. and Malla, R. B. (2017)."Lunar Environmental and Construction Challenges and a Proposed Semi-Circular Frame Membrane Habitat", 55th AIAA Aerospace Sciences Meeting, AIAA SciTech Forum, (AIAA 2017-1446)

THANK YOU