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Feasibility Study of Inflatable Structures for a Lunar Base

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The design of a structure on the moon requires addressing a host of issues not encountered on Earth. A modular inflatable structure consisting of thin membranes of composite material integrated with supporting columns and arches is proposed. An initial linear analysis of the structure is briefly reviewed. The actual response of an inflatable membrane is nonlinear and, hence, a nonlinear numerical analysis of the stresses and displacements was undertaken. Results indicate that an inflatable structure is a feasible concept for a lunar structure.

Nomenclature

E = modulus of elasticity, MPa
h = membrane thickness, cm
q = transverse (pressure) load, kPa
w = transverse membrane deflection, cm
x,y = Cartesian coordinates, cm
ϕ = stress function, cm^2
σ_1, σ_2 = membrane principal stresses, MPa
σ_{vm} = von Mises stress, MPa

Introduction

A HUMAN-TENDED outpost on the moon that will evolve into an operational base is a crucial stepping stone in the expansion of humanity into space. A lunar base is one of the prime objectives of the U.S. space program and has been proposed in numerous studies in recent years. The establishment of a human-tended base on the moon was recommended by the National Commission on Space Report[1] in 1986 as a national mission, by the Ride Report[2] in 1987 as one of the four initiatives needed to ensure U.S. leadership in space in the 21st century, and in the 1988 studies of the NASA Office of Exploration[3] as the case study for human exploration of space. On July 20, 1989, the 20th anniversary of the first human landing on the moon (Apollo 11), President Bush called for a permanent human return to the moon before 2010, to be followed by a manned mission to Mars. A long-term plan for human expansion into space and the establishment of a lunar base was outlined in 1989 in the NASA 90-Day Report,[4] and further recommended by the Augustine Report[5] in 1990. The Stafford Report[6] in 1991 proposed four space architectures, all of which include different levels of lunar base development.

The design of a lunar structure requires addressing a host of issues that are not encountered on Earth. A structure on the moon must protect its inhabitants from the harsh lunar environment and as a result unconventional structural concepts must be explored. The primary lunar environmental conditions to be considered for a structure include 1) an atmosphere that is essentially a vacuum; 2) no weather conditions; 3) gravity of 1/6 g; 4) surface temperature variations from $-173°C$ ($-279°F$) during the lunar night to 127°C (261°F) during the lunar day,[7] resulting in a 300°C (540°F) temperature gradient; 5) harmful solar flare protons and galactic cosmic rays such as HZE particles (high charge-Z and high energy-E particles); 6) meteoroid and micrometeoroid impact; 7) minimal seismic activity; and 8) specific regolith (lunar soil) properties at the selected site.

Several concepts for lunar structures have been proposed. During the early stages of the Apollo program, cylindrical vessels standing vertically were suggested.[8] In the late 1960s, a concept involving buried cylindrical tanks connected together to form a complete lunar colony was proposed.[9] This was followed by an approach that consisted of buried cylindrical modules laid end to end.[10] Post-Apollo designs include a shielded shallow arch[11] and a large spherical structure.[12] Concepts involving a fabric dome stiffened with a structural foam[13] and a multilevel concrete base[14] have recently been proposed. Interconnected modules made from lunar concrete[15] and a mobile habitat[16] are another two recent ideas. A discussion on the architectural attributes of pressurized volumes for use in space can be found in Ref. 17, and a review of several lunar base concepts is given in Ref. 18.

Requirements for the design of a lunar structure are 1) a low ratio of volume to usable floor area, 2) light transportation weight, 3) expandability, 4) small stowage volume, 5) modularity, 6) durability, 7) safety, 8) reliability, and 9) short construction time with minimal extravehicular activity. Constraints on the cost of transportation, materials, construction time, construction equipment, and architectural requirements must also be accounted for.

Inflatable structures are suited for a lunar base in view of their unique features. The primary loading on the membranes of an inflatable structure in the lunar environment is the internal pressure. This pressure induces only tensile stresses for properly designed structures. These stresses make the most efficient use of material strength since there are no stability problems associated with tension. Membrane materials typically have a low density and are flexible and, therefore, transportation costs (i.e., low stowage volume and weight), construction time, and the amount of construction equipment required are reduced when compared with traditional Earth-bound construction materials (e.g., concrete, metals, or wood). Attributes of expandability, low ratio of volume to usable floor area, and modularity can be incorporated into the design of an inflatable structure. In addition, the structure can be tested for constructability and pressure containment on Earth prior to the actual construction on the moon.

The loads applied on the membranes of an inflatable structure consist of 1) the pressure of an internal atmosphere, selected to be 69 kPa (10 psi); 2) the dead load (gravity load) induced by the structural material weight; and 3) a gravity

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load of 7.8 kPa (1.1 psi) [regolith density = 1.75 g/cm^3 (3.39 $slug/ft^3$)[7]] from a layer of regolith of 2.74 m (9 ft) for radiation shielding,[19] micrometeoroid protection,[7] and thermal insulation.[7]

Initial Analysis

A concept for an inflatable structure in a lunar habitat was initially set forth in 1988 by Vanderbilt et al.[20] and refined in 1990 by Nowak et al.[21] This concept is based on a structure comprised of identical inflatable modules. A module consists of the following structural components: 1) four wall membranes, 2) a roof and a floor membrane, 3) four inflatable columns with footings, and 4) four solid arches. A photograph of a physical model (scale 1:80) of this inflatable structure concept, including a simulated regolith cover and a cutaway, is shown in Fig. 1.

A module of 6.1 × 6.1 × 3.0 m (20 × 20 × 10 ft; $l \times w \times h$) was selected based on the size of a typical office and/or living room in terrestrial structures. A radius of curvature of the roof membrane of 6.1 m (20 ft) was chosen based on a compromise between reducing wasted internal volume (a low radius) and lowering the induced stresses (a higher radius). This approach meets requirements 1-5. It also has the attributes of a minimal number of structural components to facilitate manufacturing and the ability to isolate a pressure loss within a module with the use of interior pressure sealing partitions.

Columns with a radius of 30.5 cm (12 in.) are assumed based on typical radii of cylindrical columns in terrestrial structures. The membrane material in these columns holds the roof down and acts in tension when the structure is pressurized. In the event of a pressure loss, the inflated columns support the solid arches and act in compression.

Solid arches are integrated with the roof membranes to stabilize the structure, limit the roof deformations, and support the gravity loads in the event of a pressure loss. One method for rigidizing the arches is to fill a membrane sleeve with a structural foam that solidifies after mixing two chemical compounds. The tensile and compressive strengths of this solid foam are 10.9 MPa (1.6 ksi) and 19.7 MPa (2.9 ksi), respectively.[22]

Kevlar 49, a material widely used in space applications, which can be woven into a membrane with a tensile yield strength of 690 MPa (100 ksi),[23] was chosen as the membrane material for the case study. Initial calculations for the thicknesses of the roof and column membranes were conducted based upon the linear elastic response of a pressurized sphere and cylinder, respectively.

Thicknesses of 0.30 mm (0.012 in.) for the roof membrane and 1.93 mm (0.076 in.) for the column membrane were found to be structurally adequate.[21] Closed-form solutions for the stresses in the wall membrane, whose geometry is nonspherical with a varying radius of curvature, have not yet been developed. Initially, the wall membrane thickness is assumed to be the same as the roof membrane since the geometries and loadings are similar for both membranes. Since closed-form solutions for the arches have not yet been developed, the arch radius and membrane sleeve thickness are assumed to be the same as those of the column. These initial results indicate that thin membranes can contain the internal pressure in an inflatable structure on the moon.

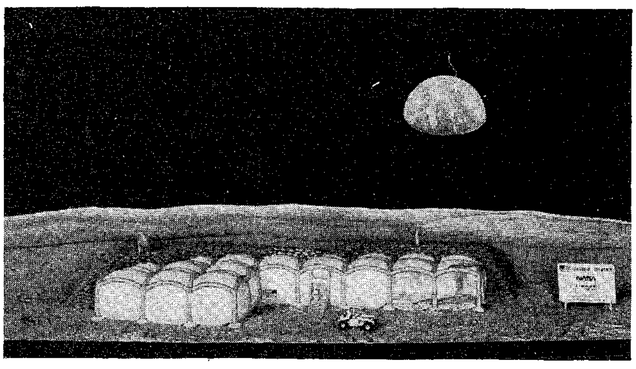


Fig. 1 Physical model (scale 1:80) of the proposed inflatable structure.

Nonlinear Analysis

A nonlinear analysis of the module was undertaken to verify the initial results and/or modify the structure accordingly. Required results from this analysis are the displacements of the members to ensure that there are no excessive deformations, and the von Mises stresses in the material to verify that the material does not yield. The von Mises stresses are defined as[24]

$$\sigma_{vm} = \sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2} \qquad (1)$$

Membranes are thin sheets of material formed into the desired geometry of the structure. They only transmit loads in the plane of the material. Any resistance through transverse bending and shear is negligible. The structural behavior of membranes is governed by the following set of coupled partial differential equations[25]

$$\nabla^4\phi = \left(\frac{\partial^2 w}{\partial x \partial y}\right)^2 - \left(\frac{\partial^2 w}{\partial x^2}\right)\left(\frac{\partial^2 w}{\partial y^2}\right) \qquad (2)$$

and

$$-\frac{q}{Eh} = \frac{\partial^2 \phi}{\partial y^2}\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 \phi}{\partial x^2}\frac{\partial^2 w}{\partial y^2} - 2\frac{\partial^2 \phi}{\partial x \partial y}\frac{\partial^2 w}{\partial x \partial y} \qquad (3)$$

To perform a structural analysis for the actual stresses and deformations, these equations must be solved. Very few closed-form solutions exist for the response of membrane structures due to the nonlinearity of Eq. (2). Iterative numerical solution techniques are employed to overcome this difficulty. It is important to note that the solutions for the deformations and stresses are nonlinear even if the material remains linear and elastic under the applied loads.[25]

Two approaches that involve specifying the geometry of the structure can be applied to perform a numerical analysis of membrane structures. The first approach is to describe the initial or unstressed geometry and then to proceed with the analysis. This approach is desirable from a fabrication viewpoint. A second approach is to define the final or stressed geometry before conducting the analysis. In this case, the initial shape for fabrication is found from the analysis, but may be impractical to fabricate. Consequently, the first approach is utilized.

Solution Technique

The finite element method (FEM) was chosen as the numerical technique since it is the most developed and offers the best tools for analyzing a nonlinear structure. A finite element software package, ABAQUS,[26] capable of analyzing nonlinear membrane structures with 3- and 4-node membrane elements and solids with 8-node solid elements was utilized.

The FEM requires the geometry of the discretized structure (a FEM mesh) as input. Results from a structural analysis are only as accurate as the description of the FEM mesh since errors accumulate during the incremental solutions. To minimize these errors, a computer program (GEOMM) was written to generate the FEM mesh of the structure for a wide variety of shapes as input to ABAQUS.

An analysis was performed on one isolated module to determine the induced stresses and deformations from the induced loads. The effects of the stresses and deformations caused by an adjacent module, as occur in an internal module, are not yet addressed. As a result, the computational effort is greatly

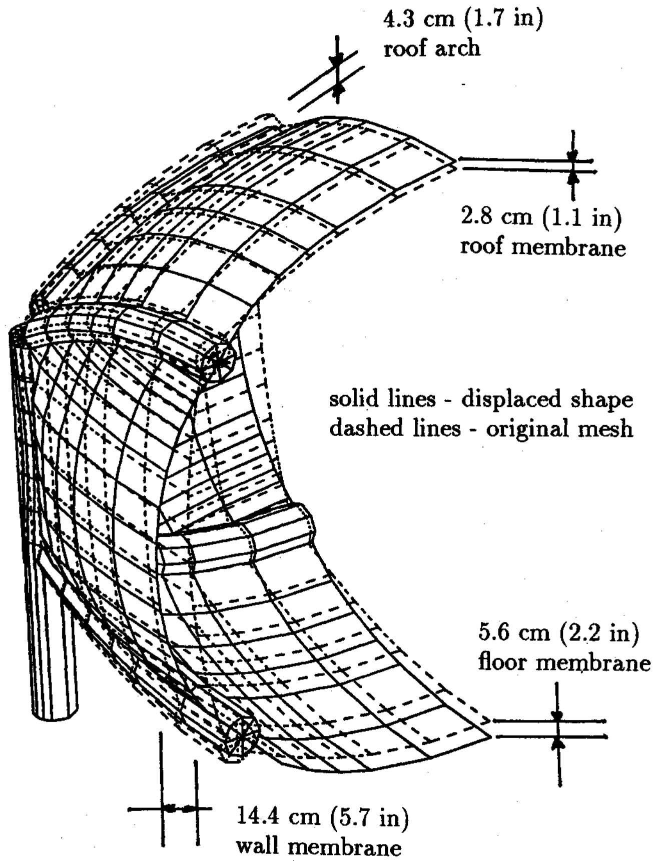
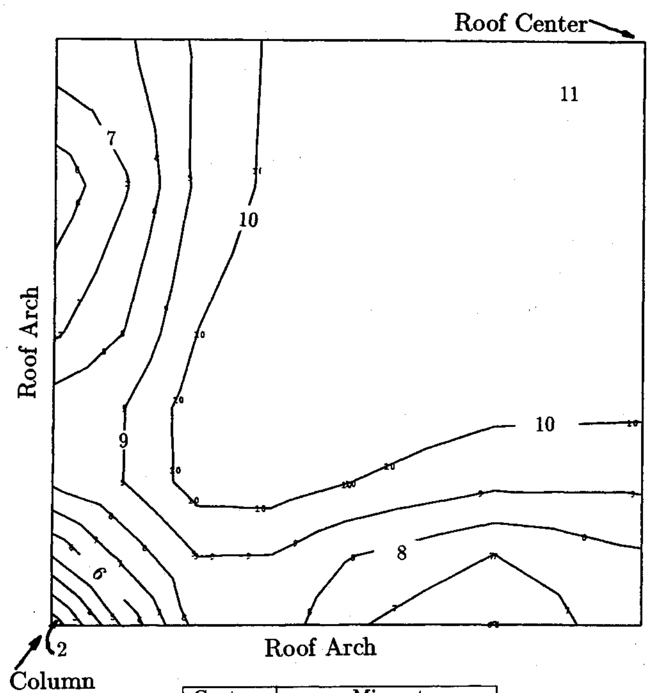


Fig. 2 FEM mesh and displaced shape (magnified 3x) of one-quarter of a module.



Contour	von Mises stress	
	% of yield	MPa (ksi)
1	40	276 (40.0)
2	45	311 (45.0)
3	50	345 (50.0)
4	55	380 (55.0)
5	60	414 (60.0)
6	65	449 (65.0)
7	70	483 (70.0)
8	75	518 (75.0)
9	80	552 (80.0)
10	85	587 (85.0)
11	90	621 (90.0)

Fig. 3 Stress contours of the quarter-roof membrane.

reduced when compared to an analysis of several interconnected modules. One-fourth of a module was analyzed due its symmetry. The FEM mesh of the quarter-module is shown as dashed lines in Fig. 2.

Results

Input for the nonlinear structural analysis consisted of the same loadings, geometries, and material properties used in the initial analysis. Data for FEM meshes were generated using the GEOMM code.

Roof Membrane

The maximum tensile stress in the roof membrane was 9% lower than that obtained in the linear analysis. A contour plot of the von Mises stresses shown in Fig. 3 displays stress variations within the quarter-roof membrane. At the center of the roof, stresses reached a maximum value of 627 MPa (91 ksi) or 91% of the tensile yield stress. At the corner of the roof, the membrane is not allowed to deform due to the intersecting arches and, therefore, stresses are reduced there. This is advantageous since connection detailing is complicated if high stresses exist.

Floor-Wall Intersection

Excessive stresses and deformations were revealed with the original concept at the intersection of the floor and wall membranes since there were no arches there. Solid arches similar to those at the roof were incorporated to alleviate these problems.

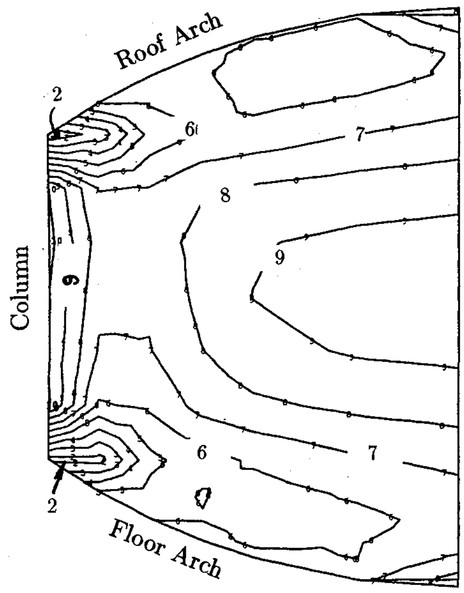
Solid Arches

The solid arches were modeled with the properties of the solid foam,[22] but neglected the strength of the membrane sleeve. The resulting stresses were approximately 50% below the material strength of the foam. To make more efficient use of the material, the radius of the arches was reduced from 30.5 cm (12 in.) to 22.9 cm (9 in.). Subsequent computations indicated no stress concentrations, a maximum tensile stress of 7.2 MPa (1.1 ksi), and a maximum compressive stress of 6.3 MPa (0.9 ksi). These stresses are less than the strengths of the foam. Hence, solid foam arches with a smaller radius have adequate strength under the induced loads.

Columns

Results for the columns revealed excessive localized stresses and deformations. These are caused by the wall membrane tensile forces acting on the column, which changed the column cross section from circular to oval. In view of these excessive stresses and deformations, the inflatable column concept is not feasible. One solution is to replace the inflated columns with solid foam columns similar to the solid arches. This modification was introduced since the solid arches had no excessive deformations under loading conditions similar to the columns.

An analysis with a solid column with the same radius as the solid arch yielded maximum tensile and compressive stresses of 2.7 MPa (0.4 ksi) and 8.3 MPa (1.2 ksi), respectively. These stresses, which are less than the capacity of the solid foam, are caused by the bending of the column from the wall membrane tensile loads. It should be pointed out that the buckling capacity of the column is 717 kN (163 kip) which is much higher than the 88 kN (20 kip) induced compressive column load. Hence, a solid foam column can resist the induced loads.



Contour	von Mises stress	
	% of yield	MPa (ksi)
1	30	207 (30.0)
2	38	262 (38.0)
3	46	317 (46.0)
4	54	373 (54.0)
5	62	428 (62.0)
6	70	483 (70.0)
7	78	538 (78.0)
8	86	593 (86.0)
9	94	649 (94.0)
10	102	704 (102.0)

Fig. 4 Stress contours of the half-wall membrane.

Wall Membrane

Compressive stresses were revealed at two locations where "wrinkles" developed since membranes cannot resist these stresses. To eliminate these wrinkles, tensile stresses must be induced. Higher tensile stresses can be obtained by stiffening the membrane. This membrane stiffening was achieved by increasing the radius of curvature at the locations of the wrinkles.

A subsequent analysis revealed that the material was overstressed by 50%. To decrease these stresses, the wall membrane thickness was increased by 50% to 0.45 mm (0.018 in.). Further computation resulted in the stress contours shown in Fig. 4. The maximum stress, occurring at the center of the wall membrane, had a magnitude of 690 MPa (100 ksi) or 100% of the yield stress. Thus, a wall membrane with an increased thickness and modified geometry is adequate for the induced loads.

Displacements

The displaced shape of the pressurized module is shown as solid lines in Fig. 2. These displacements are magnified by a factor of 3 for clarity. A maximum displacement of 14.4 cm (5.7 in.) occurred outward at the center of the wall membrane. Upward displacements of 2.8 cm (1.1 in.) were found at the center of the roof membrane. At the center of the roof arch there was a downward displacement of 4.3 cm (1.7 in.) caused by the wall membrane pulling on the arch. The floor membrane displaced 5.6 cm (2.2 in.) downward at the center. All displacements occur only during the pressurization of the module and remain constant when the structure is in use, thus, they are considered acceptable.

Concluding Remarks

An initial linear analysis indicated that an inflatable structure for a lunar base can be made from thin membranes. To account for the actual behavior of membrane structures, a nonlinear analysis was conducted. Results from this nonlinear analysis revealed that several significant modifications to the initial structure were necessary. These modifications included a stiffened wall membrane to eliminate wrinkles, a thicker wall membrane to reduce stresses, a floor arch to eliminate excessive deformations, a solid column to reduce localized stresses and deformations induced in an inflatable column, and smaller arch and column radii to make more efficient use of material. Subsequent results indicate that the induced stresses are below the strength of currently available materials and resulting displacements were within tolerable limits. An inflatable structure thus appears to be feasible for use in the lunar environment.

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References

[1]*Pioneering the Space Frontier*, Report of the National Commission on Space, Bantam, New York, 1986, p. 140.

[2]Ride, S. K., "Leadership and America's Future in Space," Report to the Administrator, NASA, Washington, DC, Aug. 1987.

[3]"Exploration Studies Technical Report FY 1988 Status," Vol. I, II, NASA TM 4075, NASA Office of Exploration, Washington, DC, Dec. 1988.

[4]"Report of the 90-Day Study on Human Exploration of the Moon and Mars," NASA, Washington, DC, Nov. 1989.

[5]Augustine, N. R. (ed.), "Report of the Advisory Committee on the Future of the U.S. Space Program," Superintendent of Documents, U.S. Government Printing Office, Washington, DC, Dec. 1990.

[6]Stafford, T. P. (ed.), "America at the Threshold—Report of the Synthesis Group on America's Space Exploration Initiative," Superintendent of Documents, U.S. Government Printing Office, Washington, DC, May 1991.

[7]Heiken, G. H., Vaniman, D. T., and French, B. M., *Lunar Sourcebook, A User's Guide to the Moon*, Cambridge Univ. Press, London, 1991, Chap. 2.

[8]"Initial Concept of Lunar Exploration Systems for Apollo: Systems Considerations," NASA CR-55734, Vol. 2, The Boeing Co., Seattle, WA, 1963.

[9]Johnson, R. W., "The Lunar Colony," *Journal of Science*, Vol. 5, No. 2, 1969, pp. 82–88.

[10]Duke, M. B., Mendell, W. W., and Roberts, B. B., "Strategies for a Permanent Lunar Base," *Lunar Bases and Space Activities in the 21st Century*, edited by W. W. Mendell, Lunar and Planetary Science Inst., Houston, TX, 1985, pp. 57–68.

[11]Land, P., "Lunar Base Design," *Lunar Bases and Space Activities in the 21st Century*, edited by W. W. Mendell, Lunar and Planetary Science Inst., Houston, TX, 1985, pp. 363-373.

[12]Yin, P. K., "Structural Design of an Inflatable Lunar Habitat," *Engineering, Construction, and Operations in Space II, Proceedings of Space 90*, edited by S. W. Johnson and J. P. Wetzel, Vol. 1, ASCE, New York, 1990, pp. 520–528.

[13]Chow, P. Y., and Lin, T. Y., "Structures for the Moon," *Engineering, Construction, and Operations in Space, Proceedings of Space 88*, edited by S. W. Johnson and J. P. Wetzel, ASCE, New York, 1988, pp. 362–374.

[14]Lin, T. D., Senseney, J. A., Arp, L. D., and Lindbergh, C., "Concrete Lunar Base Investigation," *Engineering, Construction, and Operations in Space, Proceedings of Space 88*, edited by S. W. Johnson and J. P. Wetzel, ASCE, New York, 1988, pp. 146–155.

[15]"Lunar Base Concept," Shimizu Corp., Space Concept Office, 16-1 Kyobashi 2-chrome, Chou-ku, Tokyo 104.

[16]Griffin, B. N., "A Mobile Habitat for Early Lunar Exploration," International Academy of Astronautics, Paper 91-628, 42nd Con-

gress, International Astronautical Federation, Montreal, Canada, Oct. 1991.

[17]Roberts, M., "An Introduction to Pressurized Volumes in Space," *Engineering, Construction, and Operations in Space II, Proceedings of Space 90*, edited by S. W. Johnson and J. P. Wetzel, Vol. 2, ASCE, New York, 1990, pp. 1132–1141.

[18]Kennedy, K. J., and Cerinele, M. P., "Habitation and Human Systems for the 90 Day Study," NASA Johnson Space Center, Houston, TX, 1991.

[19]Silberberg, R., Tsao, C. H., Adams, J. H., Jr., and Letaw, J. R., "Radiation Transport of Cosmic Ray Nuclei in Lunar Material and Radiation Doses," *Lunar Bases and Space Activities of the 21st Century*, Lunar and Planetary Inst., Houston, TX, 1984, pp. 663–669.

[20]Vanderbilt, M. D., Criswell, M. E., and Sadeh, W. Z., "Structures for a Lunar Base," *Engineering, Construction and Operations in Space, Proceedings of Space 88*, edited by S. W. Johnson and J. P. Wetzel, ASCE, New York, 1988, pp. 352–361.

[21]Nowak P. S., Criswell, M. E., and Sadeh, W. Z., "Inflatable Structures for a Lunar Base," *Engineering, Constructions and Operations in Space II, Proceedings of Space 90* (Wilmington, DE), edited by S. W. Johnson and J. P. Wetzel, ASCE, New York, 1990, pp. 510–519.

[22]Lampo, R., "Structural Property Goals for Low-Density Structural Foams and Composites for Expedient Military Applications," U. S. Army Corps of Engineers, Construction Engineering Research Lab., M-85/19, Champaign, IL, 1985.

[23]"Kevlar Product Information," DuPont Corp., 1986.

[24]Nadai, A., *Theory of Flow and Fracture of Solids*, McGraw-Hill, New York, 1950, Chap. 3.

[25]Leonard, J. W., *Tension Structures, Behavior and Analysis*, McGraw-Hill, New York, 1988, Chap. 5.

[26]ABAQUS, Hibbitt, Karlsson and Sorensen, Inc., Providence, RI, 1989.

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