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Development and Construction of Operational Modules for Planetary Habitat Research

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The Inflatable Lunar/Mars Habitat (ILMH) located at the University of North Dakota is an operational planetary base concept equipped with a rover and two NDX-2AT space suits. The ILMH is used to conduct planetary analog missions for up to 3 crew members. Four additional modules will be added to the ILMH under a NASA EPSCoR grant. The additional modules will allow crew members to grow plants, conduct additional extravehicular activities (EVA), perform analysis on geologic samples, and maintain human exercise and performance. The additional modules are designed to mimic feasible extraterrestrial architecture, with the purpose of being tested and optimized on Earth. This paper will describe the structural engineering challenges of designing an extraterrestrial habitat for terrestrial use, from concept to design and fabrication. Initial designs were developed by calculating individual component stresses and reactions. Full scale models were structurally verified using Solidworks Simulation. The result is a habitat suited for extraterrestrial analog simulations in which a crew of three can perform isolated missions for a period of months. The data obtained from the missions will apply to plant production, exercise and human performance, EVA, and geology. The data can help determine the optimal design of a habitat for upcoming missions to settle extraterrestrial bodies.

Nomenclature

A'	=	area of the top portion of the members cross-sectional area
B	=	boom area
b	=	skin width
c	=	perpendicular distance from the neutral axis to a point farthest away from the neutral axis
E	=	modulus of elasticity
EI	=	flexural rigidity
I	=	moment of inertia about the neutral axis
I_{yy}	=	area moment of inertia with respect to the y-axis
I_{yz}	=	product moment of area
I_{zz}	=	area moment of interial with respect to the z-axis
M	=	bending moment
μ_s	=	static friction coefficient
Q	=	moment of the area A' about the neutral axis
q	=	shear flow
σ	=	normal stress
t	=	width of members cross-sectional area measured at the point where τ is to be determined
τ	=	shear stress
t_D	=	skin effective thickness
V	=	shear force
v	=	deflection
w	=	distributed load

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I. Introduction

Planetary habitat concepts have become an area of considerable investigation as extraterrestrial settlement missions attract the attention of the space community. The design must support crew physiological and psychological needs while maintaining minimal mass and volume requirements. The design of such a system poses a unique engineering challenge. Primarily, the habitat must mimic any feasible space architecture. Subsequent activities and methods of data collection must also correlate with extraterrestrial exercises.

The ILMH was designed to be capable of using in situ Martian or Lunar resources for radiation shielding and has structurally sound infrastructure in the event of depressurization. The pressurized system of the habitat, space suits, rover, airlocks, and connecting structures are used for various analog simulations of up to four crew members. In compliance with the current preferences for planetary habitat architecture, the additional modules with be cylindrical in shape. The modules will be connected by an enclosed walkway that originates at the ILMH. Previous research has determined operational requirements for various procedures to be accomplished in planetary habitats. The habitat system will contain an area in which plants are grown for research as well as those grown for crew consumption. For extended duration missions, equipment for exercise and tracking human performance must be included. A planetary habitat would also need a facility where the crew members would prepare for EVA's. There must be a separate facility for sample return processing to mitigate possible contamination.

Creating habitat structures designed for extraterrestrial use is difficult because the testing must be done on Earth. While cylindrical modules may be sufficient for extraterrestrial habitation, they are not ideal in 1-g conditions. The unconventional geometry of the modules necessitates creative engineering solutions that are effective. In addition to the volume requirements imposed by launch vehicle payload restrictions, the modules must minimize material usage. For the additional modules, top level requirements dictate they must be cylinders 22.97 feet (7 meters) in length with a 9.84-foot (3 meter) diameter. All modules must connect to the walkway, thus the height of the doorway and floor from the ground is the same throughout the system. Each module must have an entrance and an exit with a pathway of no less than 28 inches due to fire safety regulations.

II. Purpose

The purpose of this paper is to identify initial human habitation in space concepts that can be simulated on Earth for use in analog simulations of extraterrestrial crewed missions. The unique nature of a space exploration mission must be replicated to the highest degree possible to obtain accurate physiological and psychological responses from the crew. These concepts will be translated to performance requirements necessary for the structural design of the additional modules. Structural analysis will be performed to verify the module designs. Accepted designs will be translated to specifications for fabrication. Finally, the modules will be integrated with the existing ILMH. The ILMH is an advanced architectural concept for possible use on the surfaces of the Moon and Mars.[1] It is a hybrid inflatable design that has an internal rigid frame surrounded by an inflatable bladder. The bladder can be inflated to a partial pressure allowing astronauts to enter and build the internal elements without spacesuits. The internal elements consist of the internal space frame composed of interlocking hub and strut elements. Interior architectural elements are mounted to the completed interior frame. These include wall and floor panels, life support equipment, and storage racks. The ILMH at the University of North Dakota includes airlocks, connecting structures, spacesuits, and pressurized rover interfaces to create a facility capable of simulating a conceptual planetary habitat base.

III. Problem Statement

The ILMH additions for Earth analog missions must be developed to meet the following requirements:

1) All structures must simulate conceptual planetary habitat architecture.
2) The structures must support gravity loads.
3) The structures must support crew and payload loads.
4) The habitat architecture should maximize usable volume.
5) The habitat architecture should minimize structural mass.
6) The structures must be designed to withstand an outdoor environment.
7) Satisfactory human performance requirements must be identified and integrated into the habitat architecture.
8) The habitat architecture must be designed to accommodate anticipated experimental procedures used during habitat analog missions.

IV. Preliminary Analysis

The Plant Production, Extra Vehicular Activity, Exercise and Human Performance, and Geology Modules were designed with respect to their individual requirements. Development began with the Plant Production Module due to its distinct configuration requirements and corresponding anticipated weight. All structural materials are aluminum and welded. The floor, rib, and stringer structural design of the Plant Production Module was adopted as the standard for the remaining modules general structural design. A safety factor of 1.5 was applied to the aluminum structure for an allowable stress of 33 MPa.

A. Plant Production Module

Previous research at UND has determined an optimal arrangement of plant production components. For a crew of four, it was suggested that a planting area of 40 - 50 square meters is sufficient to provide the vegetarian portion of the crew's diet. This research emphasized attaining minimal hardware mass as well as reducing the geometric distance from the light source to the plant leaves. Thus, the Plant Production Module requirements state the module should have a planting area 6 meters (19.67 ft.) long three levels high to produce 70% of the crew's vegetarian diet. This was reduced by a meter to lessen the workload on the crew during isolation missions, thus the planting area is sufficient to support 40% of the vegetarian diet for four crew members. The shelves are designed in accordance with proposed extraterrestrial greenhouse concepts. Vertical segmentation of the shelves is 22.30 inches to allow for uninhibited tending of the crop. Furthermore, the shelf trays must be removable to adjust for plant growth as the distance between the light source and plant leaves increases. Removable light panels are connected to the shelves with chains and clips. The clips can be moved from link to link to adjust the distance between light source and plant leaf as the plants age.

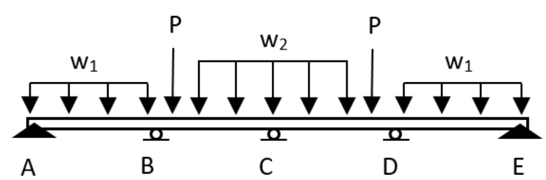

Figure 1. Plant Module Load Distribution. *Modeled as a simple beam for simplicity.*

The Plant Production Module posed the greatest engineering challenge due to the anticipated weight of plant materials and water. Preliminary analysis began with understanding how the loads of the plant biomass, water, crew, and surrounding material were distributed along the cross-sectional area of the floor. An estimated 400 grams (0.88 lb.) of plant biomass would reside in each planting area. The water was expected to add 0.4 gal/ft^2 to the planting areas.[2] A distributed load along the walkway was representative of the crew and was estimated to be 170.78 kg (376.5 lbs.).[2] Additional weight from the aluminum shelf frame was estimated to be 40.6 kg (89.5 lb.). The shelf planting area is made of aluminum with an estimated mass of 3.887 kg (8.569 lb.) per 1 meter (3.28 ft.) section. The total mass of the wooden floor distributed along the walkway was estimated to be 99.87 kg (220.2 lb.). The resulting load distribution is shown in Figure 1.

The load distribution was simplified to a simple beam. The simple beam was cut into 4 segments for added simplicity. Equations (1), (2), and (3) were used to determine the resulting shear and bending moments on each segment. The previous segment results are used in the following segment, moving from point A to point E.

$$EI\frac{d^4v}{dx^4} = w(x) \tag{1}$$

$$EI\frac{d^3v}{dx^3} = V(x) \tag{2}$$

$$EI\frac{d^2v}{dx^2} = M(x) \tag{3}$$

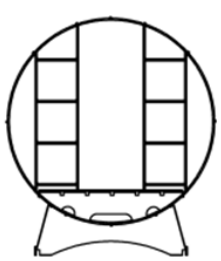

Figure 2. Floor Support Structure.

The maximum moment was found to be 0.076 kNm at point C. The beam to lay along the cross-section of the module was designed to the factor of safety allowable stress calculated with Eqn. (4). The maximum moment, along with the flexure formula and the section modulus, Eqns. (5) and (6) respectively, are used to determine the cross-sectional shape of the beam.

$$F.S. = \frac{\sigma_{failure}}{\sigma_{allow}} \tag{4}$$

$$\sigma_{max} = \frac{Mc}{I} \tag{5}$$

$$S = \frac{M_{\max}}{\sigma_{allow}} \tag{6}$$

It was determined that the beam supporting the live loads of the module and shelf hardware must have a section modulus of 2.3 mm^3 (0.00357 in^3). The section modulus can then be used to determine cross-sectional dimensions for simple shapes due to the relationship in Eqn. (7). To ensure the proper cross-sectional area is chosen, the shear formula, Eqn. (8), is used to check if the allowable shear stress is exceeded.[3]

$$S_{required} = \frac{I}{c} \tag{7}$$

$$\tau_{allow} \geq \frac{V_{\max} Q}{It} \tag{8}$$

Subsequent beams were designed for the floor support in the same manner. However, upon discussion with the manufacturer, it was decided the floor design would be difficult to fabricate with the materials on hand. Therefore, the floor support structure was modified to be an aluminum sheet with a flanged end to support the floor seen in Figure 2.

A value of interest was the maximum moment along the length of the module. This moment is used to determine the design of the stiffeners that must be used to reinforce the module. This was done by simplifying the load distribution to a simple beam. A distributed load exists along the entire length of the module consisting of the weight of the aluminum structure. The middle 5 meters added a second distributed load, consisting of the aluminum shelves and live plant masses. The maximum moment was found to be 3.5 meters (11.48 ft.), or halfway, along the length of the module with a value of 909753 Newton-meters (670999 pound-force-foot).

Due to the cylindrical geometry, the skin encircling the module must be stiffened with structural members. Each plant shelf is mounted to a rib, or frame, which in turn is mounted to stringers fixed to the skin, which is 0.039 inches (1 mm) thick. The stringers can be simplified to concentrations of area called booms that have the same cross-sectional area as the stringers. Between booms, the normal stress varies along the segment of skin. The piece of skin is replaced by booms on either side so that the same force and moment on the skin is on the booms. Using this method, it is assumed the booms take all of the normal stresses and the skin takes all of the shear stress. The normal stress is calculated using Eqns. (9) and (10). The boom area is represented by Eqn. (11).

$$I_{zz} = I_{yy} = \sum_{i=1}^{n} z_i^2 B_i \tag{9}$$

$$\sigma_x = \left(\frac{M_y I_{zz} - M_z I_{yz}}{I_{zz} I_{yy} - I_{yz}^2} \right) z + \left(\frac{M_z I_{yy} - M_y I_{yz}}{I_{zz} I_{yy} - I_{yz}^2} \right) y \tag{10}$$

$$B_1 = \frac{t_D b}{6}\left(2 + \frac{\sigma_2}{\sigma_1}\right) + \frac{t_D b}{6}\left(2 + \frac{\sigma_n}{\sigma_1}\right) \tag{11}$$

Equations (9), (10), and (11) are used to solve for the number of stringers, *n*, needed at the location of the maximum moment along the module. The location of each stringer was determined assuming the module skin is ineffective in bending so that the stringers would amass the total bending moment. Arbitrary values of the number of stringers along the circumference of the skin were chosen and the net I_{yy} was computed considering the stringers to be lumped masses. The number of stringers must distribute the stress so that the value is less than the allowable stress. Using this method, the number of stringers needed was found to be a minimum of 28.

In summary, the structure of the modules is as follows. A cylinder, 275.5 inches in length and 118.1 inches in diameter with a thickness of 0.039 inches is designated as the skin of the module. The skin is internally welded to 30 stringers with a 1 x 1 x 1/8 inch geometry. The stringers are in turn welded to circular frames, or ribs, with a geometry of 2 x 1 x 1/8 inches. All modules have 4 ribs equally spaced along the length of the module except the Plant Module. Resting on each rib is a floor support with a curved bottom portion to fit the curvature of the ribs, shown in Figure 2. The curved floor supports are 83.46 inches wide, 17.7 inches in height, ¼ inch thick, and top portion of these floor supports shall be bent at a 90 angle to a horizontal position. From the top of the flange, five 2 x 2 inch cuts will be made through the front plate. To conserve material, rounded cuts with a 4-inch radius will be cut from the front plate. Floor joists 275.59 inches long will be 2 x 2 x 1/8 inch tubing and will be placed in the floor support extruded cuts. A 1-inch-thick wooden floor will be placed on top of the floor supports and joists. The distance from the ground to the bottom of the door is 39.53 inches. The distance from the bottom of the cylinder to the floor is 20.5 inches. The door will be 30 inches wide and 72 inches in height.

The Plant Production Module has ribs to stiffen each end of the module, and at every shelf junction to provide a mount for the shelf frames. The frame for the shelves consists of 3 sets of rods. The two vertical rods will be mounted to the top of the floor joists on one end and secured to the circular ring on the other end. Due to the circular module, the vertical rods are two different heights: 80.41 inches and 95.82 inches. Horizontal rods will span the 22.63 inches between the vertical rods, creating a platform to rest the shelf on. The shelf is a 0.787-inch-thick sheet with flanges along the length. To complete the frame, a set of vertical rods are mounted to the next channel beam 31 inches away. The shelves will continue in the same manner for 196.5 inches. The shelf rod geometry is 1 x 1 x 1/8 inch thick. To stiffen the joint where the shelf frame meets the floor joists, vertical stiffeners with a 1.5 x 1.5 x 1/8 inch geometry are welded to the floor joists and ribs.

B. EVA Module
The general structure for the floor support, ribs, and stringers was maintained in the EVA module. The EVA module contains an aluminum airlock 0.6 inches (1.5 mm) thick with two rear-entry suitports and a door. The suit port concept requires the airlock be installed at an angle of 24° from the vertical. Keeping with extraterrestrial requirements, the airlock extends from the floor to the skin of the module to prevent contamination. The upper half of the airlock is installed at an angle with an extruded portion remaining vertical to house the doorframe. Two suitports are installed on the angled portion. The suitports must be 22.33 inches wide and 27.25 inches tall to allow a crew member to easily pass through. The airlock is stiffened with structural members of 1.5 x 1.5 x 1/8 inch cross-sectional geometry framing the suitports. The joint between the vertical and angled sections of the airlock is stiffened with a 2 x 1 x 1/8 inch structural member. The supporting structure of the suitports is designed to withstand 400 lbs., the weight of two crew members entering the analog space suits. The suits are attached to the exit surface of the airlock to permit rear entry. Due to the complex distribution of stresses from the suit ports to the surrounding skin and beams, a Solidworks simulation was performed to validate the structural integrity of the airlock. The design of the airlock was developed so a person entering a suit through the suit port would be able to do so unaided.

C. Exercise and Human Performance and Geology Modules
The general structure for the floor support, ribs, and stringers was maintained in the Exercise and Human Performance and Geology Modules. The structural design for the Exercise and Human Performance and Geology modules is most similar, both of which contain a sheet metal partition with a door. The location of the partition varies depending on the size and position of equipment in the two modules. In the Exercise and Human Performance Module, the partition serves as a wall where a crew member can privately be evaluated. The Geology Module partition serves as an airlock, where destructive experiments on sample return missions can be conducted without contamination concerns. Additional structural analysis is unnecessary for these modules because they are expected to hold the lightest load.

V. Structural Analysis

A. Plant Production Module
The Plant Production Module contains 5 meters (16.4 ft.) of shelves, leaving a meter at each end for data logging and water storage. In the 5 meter long sections there are six sets of shelves three levels high. The area below the bottom shelf is also used for planting areas. Each planting area contains a metal tray that is flanged on the front and back ends to securely fit in the frame. Each tray can be removed to accommodate new configurations. The metal trays were designed to accommodate 21.36 pounds-force. Figures 3 and 4 present drawings of the module. All dimensions are in inches. Figure 6 is a representation of the fully configured module. Added to the curved sheet metal floor joists are beams running the length of the module. They mount to the square extrusion in the curved floor joist and are welded. Additional vertical

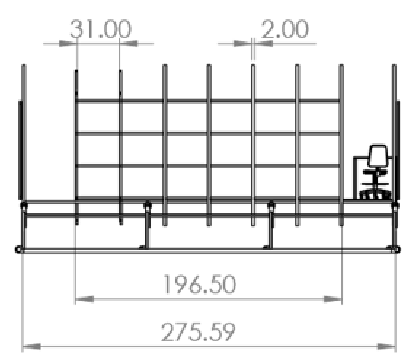

Figure 3. Plant Module right view.

tubing supports the beams. Each floor joist is mounted to a rib. A total of nine ribs span the module. Besides the two ribs on either end, each rib is mounted along its inner diameter to a shelf frame, a curved floor joist, and the vertical tubing to support the floor beams. The outer diameter of the ribs are mounted to the stringers, which are mounted to the skin. There is a total of 30 stringers encircling the ribs. Both ends of the module are capped with sheet metal and include a doorframe.

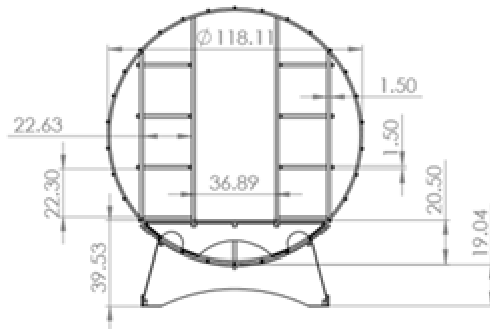

Figure 4. Plant Module front view.

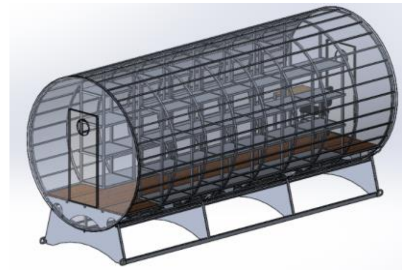
Figure 5. Plant Module

The module was built and tested in Solidworks. The module was tested under maximum loads, i.e. shelves full of plants and water (37.5 lbs./tray) with three crew members inside. An additional load of 1187.5 lbs. from the fiberglass insulation wrapped around the outer diameter of the metal module was also added. The results showed the module was sufficiently designed to withstand the expected loads. Figures 6, 7, 8, and 9 show the maximum stress along the beams, the stress on the floor joists, the maximum deflection in the module, and the maximum strain.

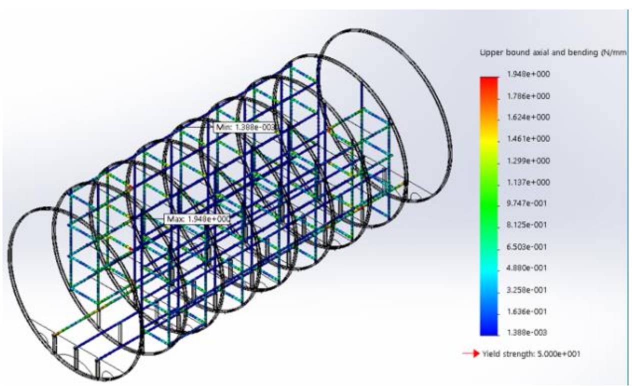
Figure 6. Maximum Beam Stress. *Maximum stress value of 1.948e+00 MPa.*

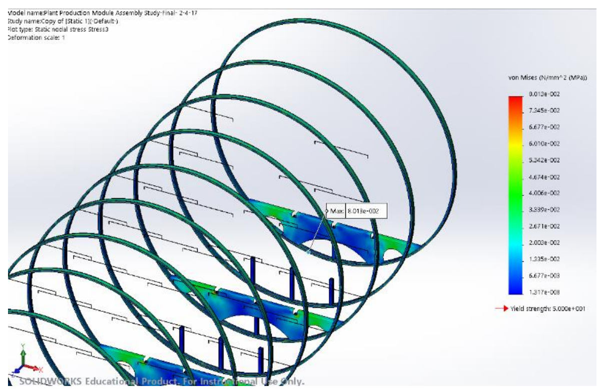
Figure 7. Maximum Stress. *Maximum stress on the floor joists is 8.013e-002 MPa.*

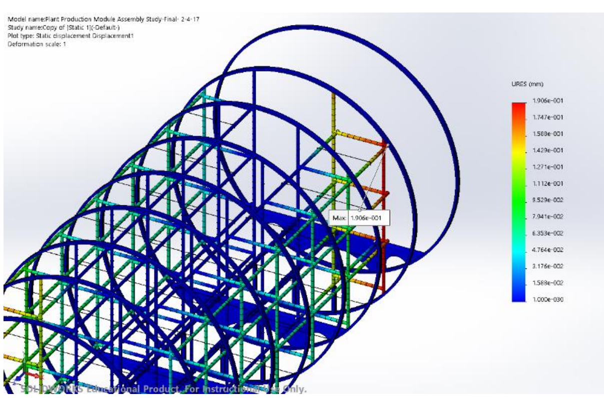
Figure 8. Maximum Displacement. *Maximum displacement value of 1.906e-001 mm.*

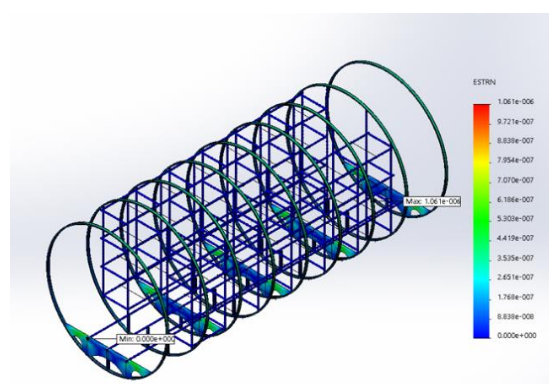
Figure 9. Maximum Strain. *Maximum strain value of 1.061e-006 Equivalent Strain.*

B. EVA Module

The EVA module contains an aluminum sheet metal airlock, with the upper half bent at a 24-degree angle. The airlock is supported by beams without interfering with any crew members attempting to get into a suit. The airlock and suitport configuration is critical for human performance. The crew members must be able to enter and exit the suits unaided. Therefore, the distance from the floor to the suitport must be high enough that a person doesn't have to crouch uncomfortably but low enough that the crew member can touch the ground when putting their legs into the boots of the suit. A handlebar runs across the top of the airlock to help the crew members get into and out of the suits. The handlebar is a specific distance from the suitports to ensure it can be reached while remaining a helpful aid. Additionally, the suitports cannot be too close together nor too close to the edges so that the crew member stepping through the suitport is not encumbered by the structure. Finally, a vertical door is installed in the airlock so that the suits can be periodically cleaned. This adds complexity to the slanted airlock.

The suitports are made of steel and are attached to the outer face of the airlock. They have a mechanism that allows the crew member to detach themselves from the suitport once they are securely in the space suit. On the inner face, additional steel plates stiffen the area of the airlock that has be removed to permit a crew member to climb through. Structural members are mounted to the inner slanted surface of the airlock and to the outer vertical surfaces. The configuration was designed with a 400-lb. load applied to the suitports to simulate two crew members getting into spacesuits at the same time. Figures 10 and 11 present drawings of the module. All dimensions are in inches. Figure 12 presents a model of the fully configured module.

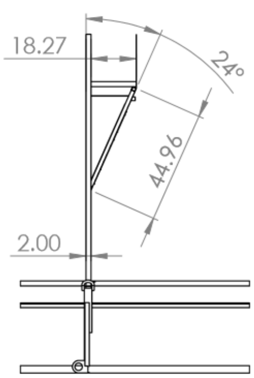

Figure 10. EVA Right View.

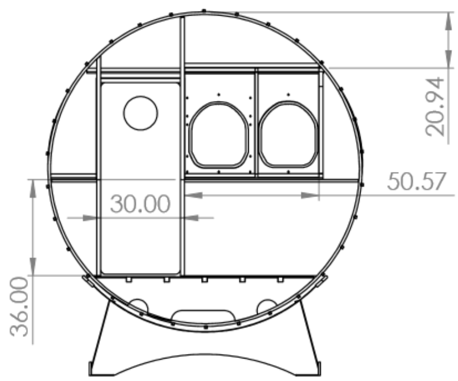

Figure 11. EVA Front View.

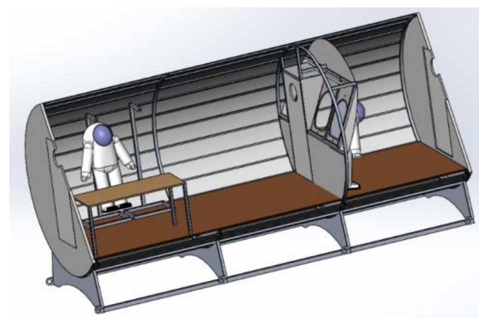

Figure 10. EVA Right View. **Figure 11. EVA Front View.** **Figure 12. EVA Module.**

The EVA Module airlock suitport was tested under the load of one crew member in one suitport, 200 lbs. A steel sheet was added to the inner face of the suitport to further stiffen the angled airlock section. Figures 13, 14, 15, and 16 show the maximum stress along the beams, the stress on the airlock, the maximum deflection of the airlock, and the maximum strain.

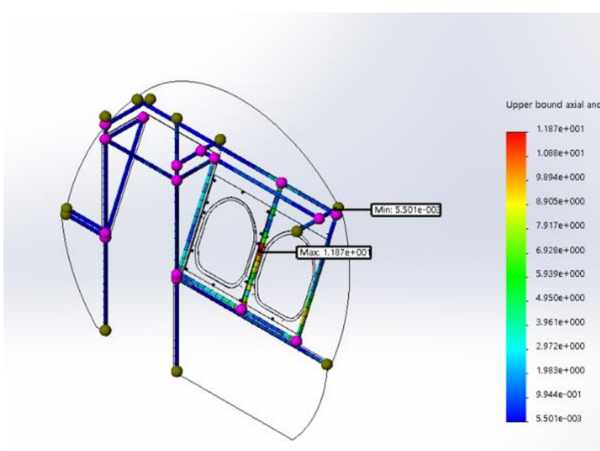

Figure 13. Maximum Beam Stress.
Maximum stress value of 1.187e+001 MPa.

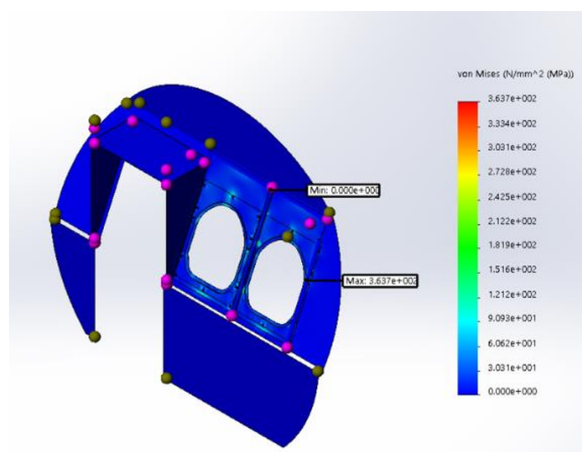

Figure 14. Maximum Stress.
Maximum stress value of 3.637e+002 MPa. This stress is along the bolts and can be ignored. The surrounding stress σ=1.516e+002 is on the steel plates σ_{yield}=250 MPa

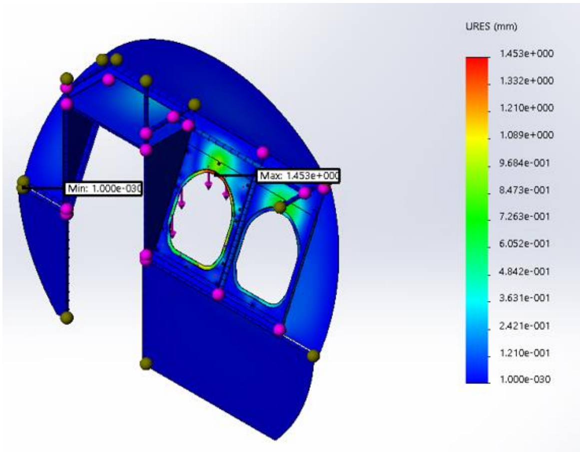

Figure 15. Maximum Displacement. *Maximum displacement value of 1.453 mm.*

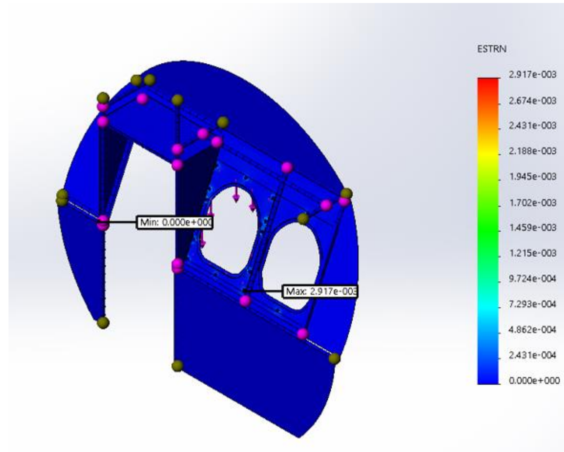

Figure 16. Maximum Strain. *Maximum strain value of 2.917e-003 Equivalent Strain.*

C. Saddles

The final design consideration was the saddles that the modules will rest on. Due to the curved nature of the modules, the sling where the module rests is also curved. Additionally, the sling has slightly rounded edges to prevent ripping or tearing of the module fabric. The sling is mounted to the top of the curved supports, which are flanged at the bottom to rest on the ground. Connecting the four segments are beams running along the outer diameter of the module and along the ground. Hooks are added to either end of the saddles so they can be moved. The saddles are aluminum with nylon straps that lay over the top of the module and fix to the saddles on either side. The saddles were designed using minimal materials and were tested under the maximum loads, i.e. the weight of the Plant Production Module. Figures 17, 18, and 19 show the maximum stress, displacement, and strain on the saddles under the weight of the Plant Production Module which is 6,890 pounds-force.

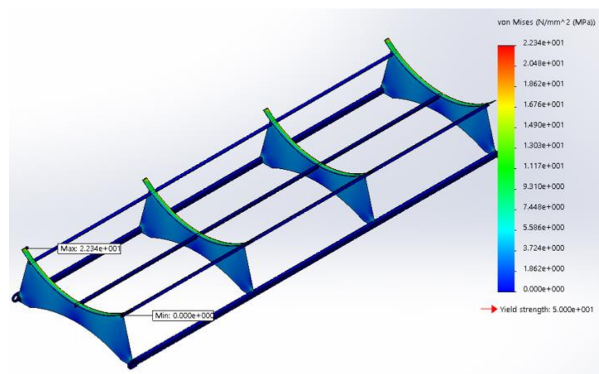

Figure 17. Maximum Stress.
Maximum stress value of 2.234e+001 MPa

Of interest was the possibility of strong winds or gusts affecting the stability of the modules. Some research has been done regarding flow over cylindrical bodies with a plane boundary, but none addressed the gap ratio from the ground to cylinder of the modules. Thus, some preliminary analysis was done to determine at what wind speed an empty module would slip and tip. In order to tip the module, the moment about the edge of the module must be greater than the moment about the center of mass. Equations (12) and (13) are solved for the wind force required to tip an empty module weighing 5689.6 lbs. The center of mass was calculated in Solidworks.

$$M_g = F_g x \tag{12}$$

$$M_{wind} = F_{wind} y \tag{13}$$

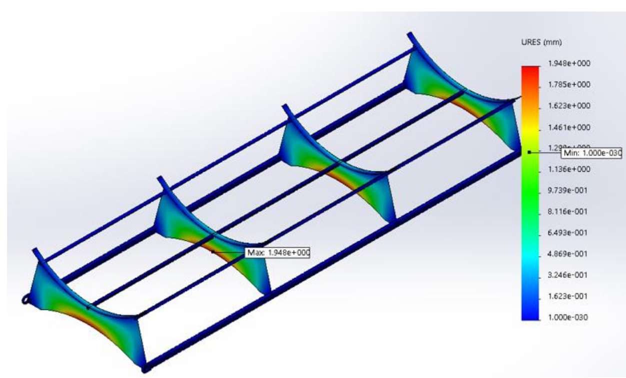

Figure 18. Maximum Displacement.
Maximum displacement value of 1.948e+00 mm.

The wind force to tip the module is estimated to be 46.6 mph. Generally, wind poses a danger to structures once speeds get up to 35 mph with structural damage occurring around 58 mph so this estimated value seemed acceptable. Equation (14) is used to calculate the force required to slide the module. The static friction coefficient of grass is estimated to be $\mu_s = 0.2$.

$$F_f = \mu_s F_g \tag{14}$$

The wind force to cause the module to slip is estimated to be 26.3 mph. It is important to note that these values only describe situations where the wind is directly perpendicular to the side of the module. It is more realistic that the wind would hit the module at an angle, thus the wind speed to tip or slide the module would likely be larger.

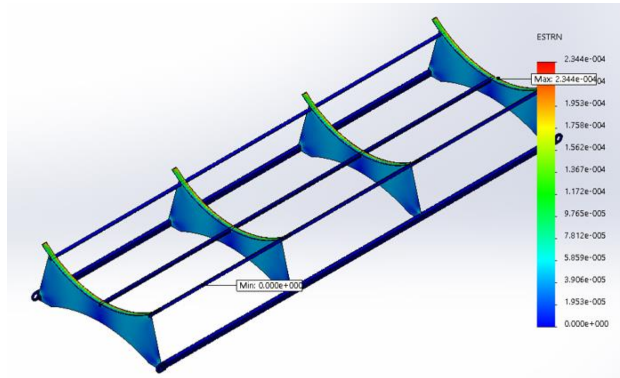

Figure 19. Maximum Strain.
Maximum strain value of 2.344-004 Equivalent Strain

VI. Fabrication and Integration

Once each module was fabricated, they were moved to the ILMH to begin the integration process. Figure 20 represents the modeled ILMH with the four additional modules. Fabrication was done locally allowing for daily updates on the status of the modules. Figures 21, 22 a and b, and 23 are images of the Plant Production Module, EVA Module, Geology Module after fabrication. The Plant Production Module is completed. The EVA Module is in the final stages of integration with only some minor tasks left to be resolved. Both the Geology and Exercise and Human Performance Modules are in the initial stages of integration. Figure 24 is an image of the status of the project.

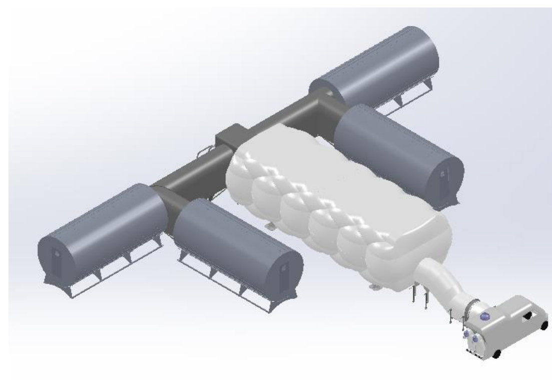

Figure 20. Habitat concept.

Figure 21. Plant Production Module.
Adjustable lights emit wavelengths conducive to plant growth.

Figure 22. EVA Module. a) Front. b) Back.

Figure 23. Geology Module.

Figure 24. Habitat at the University of North Dakota.

VII. Conclusion

A habitat has been developed at the University of North Dakota under a NASA EPSCoR grant for the purpose of conducting long-duration isolation extraterrestrial analog missions. This paper presents the structural design and development of an extraterrestrial habitat for use on Earth. Specifically, how these unique structures can be designed and developed for terrestrial use. Components within the curved geometry can be configured to maximize volume and minimize mass, which will be imperative for any future space architecture. These structures can be sufficiently stiffened for terrestrial testing so that the optimal configuration can be achieved before humans are ready for planetary missions. Habitable requirements for humans with respect to psychology and physiology can be simulated to collect data for future use. Future work will consist of extending the walkway to the other side of the ILMH to connect the Exercise and Human Performance and Geology Modules. Insulation and fabric will cover the walkway to create a tunnel from the ILMH to the four modules. Recommendations for the future include stress sensors on the saddles to monitor their response to environmental effects of wind and terrain changes and the corresponding weight distribution shifts.

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