A Cellular Backshell Concept for a Planetary Entry Vehicle

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The development of an alternative, novel backshell concept to replace the traditional approach for the backshell of a planetary entry vehicle, was initiated in this study. The motivation was to determine if the novel concept, with the potential to provide significant improvements compared to the traditional approach, would be feasible. In initiating this effort, two cellular-type structures were chosen for evaluation. Preliminary structural finite element analysis models of just a single backshell panel were created for both a traditional design and the cellular concepts. Structural results revealed similar behavior for all the models. Although these initial results predicted higher mass values for the cellular structures, eventually adding more variables to the cell structure to further tailor the cellular concept, may significantly lower the mass predicted, and is justification for further study. Additionally, a novel approach to the thermal protection system of the cellular structures was proposed that included the use of advanced thermal blanket insulation. Thermal sizing analysis was performed for a simplified planetary entry heating condition producing a preliminary thermal design. However, further development and testing will be needed to determine if the proposed novel thermal protection approach, in conjunction with the cellular structure, would be an attractive alternative candidate backshell concept for future planetary entry vehicles.

I. Introduction

THE aeroshell of a planetary entry vehicle is designed to carry structural loads while protecting the structure and vehicle contents from severe aerodynamic heating occurring during planetary entry. Traditional aeroshell designs include the use of thermal protection system (TPS) materials on the outermost surface of the vehicle. Typically, these TPS materials are bonded to the underlying structure and designed to reduce heat transfer to the structure. Consequently, the TPS protects the underlying structure from being exposed to excessive elevated temperatures that degrade structural performance. The use of TPS bonded to honeycomb sandwich structure (HSS) as a lightweight means of providing sufficient bending stiffness dates back to Apollo [1]. State-of-the-art (SOA) capsule shaped vehicles continue to follow the same design approach, including the Mars Science Laboratory [2], Space-X Dragon spacecraft [3], and the Orion crew module currently being developed by NASA [4].

The aeroshell is composed of a heatshield and backshell. As an example, an illustration of the aeroshell components for NASA Orion Crew Module is shown in Fig. 1. Ablative TPS materials have been used on the heatshield surface where exposure to the most severe aerodynamic heating occurs due to the heatshield being the windward surface. Alternatively, insulative TPS has been used on the backshell where, although the heating is still high, the heating is not as severe as on the heatshield, due to the backshell being leeward. Depending on the mission trajectory and vehicle system configuration, the most severe structural loads can occur on either the heatshield or backshell.

NASA has been developing alternative heatshield concepts to meet the demands of future planetary missions requiring larger payloads. Examples include the work NASA is performing developing a Hypersonic Inflatable Aerodynamic Decelerator (HIAD) concept [5] and hot structure heatshields [6]. The hot structure heatshield approach

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integrates the functions of thermal protection and structural load carrying by utilizing structural material on the outermost surface of the vehicle that can withstand the high temperatures while carrying structural loads.

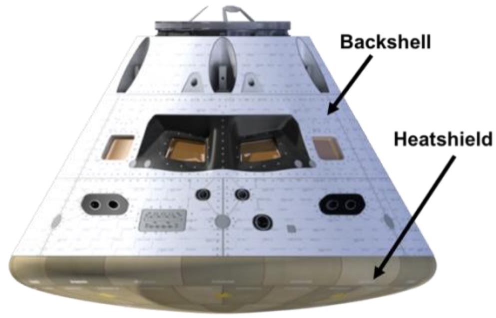
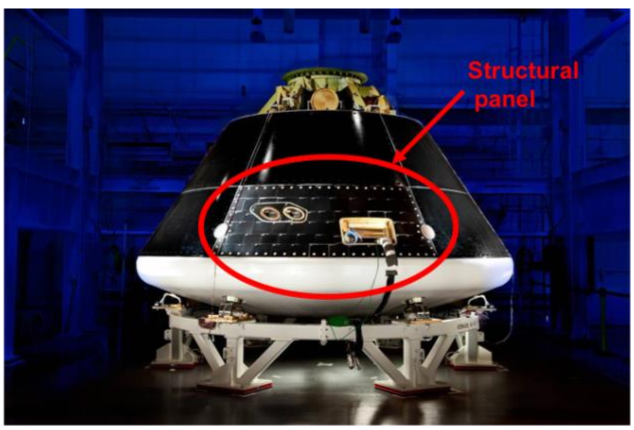
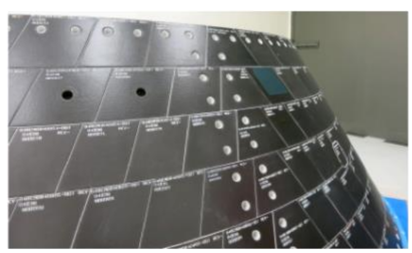


Fig. 1 Image of aeroshell components on NASA Orion Crew Module.

Unlike the heatshield, to our knowledge, the use of alternative concepts have not be recently explored for the backshell. Where hot structure could be considered for use on the backshell, the advantages would not be as significant as with the heatshield, since the current approach did not require ablative TPS, due to aeroheating on the backshell being less severe. Consequently other approaches should be considered to reduce the mass of the backshell as the desire for larger capsules with 10-m diameters has become of interest to deliver larger payloads. The focus of this paper is to investigate the feasibility and advantages of an alternative concept for use on the entry vehicle backshell that explores beyond just the use of alternative materials. Current backshell structural designs consist of an array of HSS panels which are bolted around their perimeter to a frame structure as can be observed in Fig. 2a. The TPS consists of many ceramic tiles bonded to the outer surface of each HSS panels. The large number of tiles is due to manufacturing constraints, where tile size is limited due to cracking that occurs on larger tiles during cool-down in the manufacturing process. The tiles used on the Orion backshell are visible in Fig. 2b. Though the materials have been upgraded over the years since Apollo, for both the TPS and HSS, where more advanced carbon fiber reinforced plastic (CFRP) composite facesheets are in use today in lieu of metallic facesheets used in the past for the honeycomb structure, the overall approach to backshell design, i.e., ceramic tile TPS bonded to underlying HSS, has not changed.



a) Image of Orion backshell panels, credit: Lockheed Martin



b) Image of Orion backshell tiles, credit: NASA

Fig. 2 Orion backshell design attributes.

The current study was motivated by recent advances in additive manufacturing techniques which allow for highly tailored structural components. The desire to employ an additive manufacturing approach, which has the potential for significant improvements in manufacturing structural components with mass savings led to this preliminary investigation of a cellular type structure to replace the HSS structure. This cellular structure approach will need to employ a metallic material system which will still require external TPS to maintain structural temperatures below maximum material use temperatures. However, due to the shortcoming associated with TPS tiles being bonded to the underlying structure, which are susceptible to fracture and have issues related to the integrity of bond lines, in addition to the significant manufacturing and assembly costs in bonding a myriad of tiles to the structure, an alternative approach was explored. Thus the use of advanced thermal blanket insulation as the outer TPS in conjunction with the cellular structure was considered herein as a possible alternative to the use of tiles for potential additional mass savings.

Overall, this paper introduces the preliminary development of a novel concept for a backshell design. An overview of cellular structures is provided in the next section, followed by introducing the approach for initiating development of the cellular backshell concept. The structural analysis models created and results are then presented. Finally, preliminary development of blanket TPS for use with the cellular structure is introduced followed by concluding remarks for the overall effort.

II. Cellular Structures Overview

The ability to digitally automate the production of cellular structures with minimal flaws is currently being pursued by many industries. Recent advancements in additive manufacturing have enabled digitally-guided production of structural components, particularly cellular structures that are specifically tailored to meet the loading requirements of the structure without having excess structural mass in regions where mass can be readily eliminated with three-dimensional (3-D) digital printing capability. Cellular structures offer many benefits compared to traditional HSS structures. They eliminate the need for bonding facesheets to the honeycomb core material, where manufacturing flaws lead to stress concentrations and disbonding that can cause premature structural failure [7].

There is a myriad of cell shapes that can be considered for cellular structures. Depending on the cell shape, they can either offer an exceptional stiffness to mass ratio, such as the case with a stretch-dominated structure, or be effective at absorbing energy in compression, as with a bending-dominated structure [8]. The mechanical properties of the overall structure can be tailored to fit the needed application by changing one or more properties of the cell. By changing the density of the cell, including changing the ratio of strut thickness to the strut length, the desired elasticity is obtained. Changing the material of the cell can also change the macroscopic properties. The behavior of a cellular structure can be defined by the following equation:

$$\frac{E^*}{E} \approx k\left(\frac{\rho^*}{\rho}\right)^a \quad (1)$$

where E^* is the macroscopic stiffness of the cell, E is the material stiffness, ρ^* is the macroscopic density, and ρ is the material density. The variable k is dependent on the direction of the applied load, and a is dependent on the lattice shape [9]. Equation 1 shows that the elasticity of a given cellular shape is proportional to the density of the cell. The geometry of the cell can also be changed or struts could also be added or removed from the cell to obtain a different macroscopic response from the structure.

III. Cellular Backshell Concept Development

A building block approach was adopted for the development of a novel cellular backshell structure. Current manufacturing limitations necessitated the need to fabricate the baseline backshell with an array of panels that are bolted around their perimeter to a frame structure. Alternatively, there is significant potential for mass savings using a cellular structure, where the entire backshell can be additively manufactured as a monocoque unit. A monocoque cellular unit can reduce mass by eliminating the need for the frame structure and the large number of bolts connecting each panel to the frame. However, for this initial consideration of a cellular backshell concept, the study was limited to a single backshell panel from a generic Orion-like 5-m diameter capsule. Limiting the analysis to the geometry associated with just one backshell panel allowed for a quick comparison to be made between a cellular and baseline backshell panel with a more manageable sized model. Additionally, the methodology/attributes for developing a cellular structure could be initially interrogated with this simple, relatively small model, and then later used to develop an entire cellular backshell structure for optimal performance.

Both the baseline backshell panel and the cellular backshell panel concepts were structurally evaluated for comparison using the global panel dimensions displayed in Fig. 3, which is a 120° arc segment of a generic conical

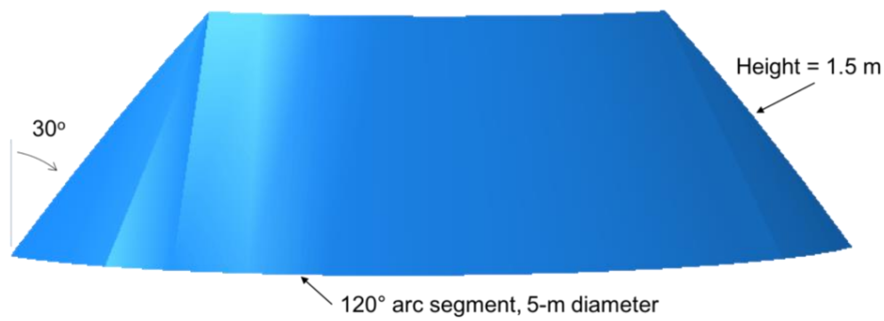


Fig. 3 Panel dimensions, for both baseline and cellular models, from 5-m diameter conical backshell.

backshell from a 5-m diameter capsule with a 30° cone angle. The panel height modeled is 1.5 m. The baseline model attributes were consistent with the traditional design approach and included a HSS, where ceramic tiles would be bonded to the outer surface for the TPS. The HSS consisted of composite laminate facesheets and a metallic honeycomb core. For simplicity, the conceptualized cellular backshell structure consists of a truss-like structure with repeating rows of one cell shape forming the entire structure, as shown in Fig. 4. The cellular structure could be additively manufactured as a single piece or in panel sections that are later welded together. Alternatively, each individual cell could be manufactured as a separate piece and then the cells could be fastened together to form the backshell structure. The latter option may allow for potential in-space assembly in the future. The cellular concept could also readily be scaled up, to potentially consider a 10-m diameter capsule. At this scale, there could be even more significant mass savings and efficiency for an additively manufactured cellular backshell.

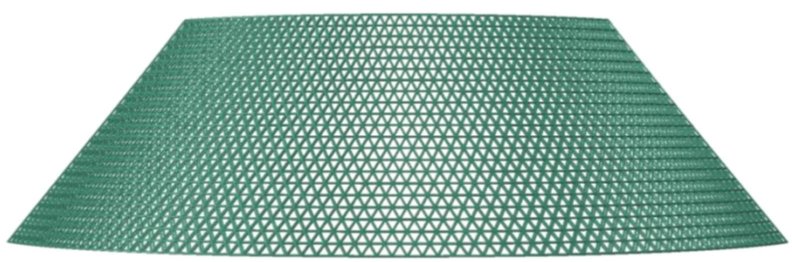


Fig. 4 Cellular backshell panel structural concept.

The primary cell shape evaluated in this study was a bending-dominated configuration as shown in Fig. 5. The cell was composed of a simple isosceles triangle on each surface with three internal (through the thickness of the panel) struts connecting the two triangles. A characteristic length, L_c, defines the in-plane size of the cell in the circumferential direction of the cone. Since the cells were forming a conical structure with the radius of the structure decreasing with an increase in height, Fig. 4, the height of the cell was set so that for *n* number of cells on the bottom layer, the next layer contains *n-1* cells. Due to the geometry of the cone and the cells connecting at the vertices, the cells decrease slightly with each layer in the height direction. The thickness of the cell in the radial direction was kept equal to the thickness of the baseline backshell. The geometry and connectivity of the cell in Fig. 5 defines the cell as bending-dominated.

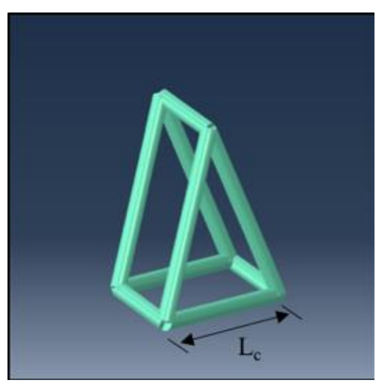


Fig. 5 Bending-dominated cell configuration.

An alternative stretch-dominated cell design shown in Fig. 6 was also evaluated in order to compare the structural response with that of the cell shape in Fig. 5. This cell configuration shown in Fig. 6 contains two stretch-dominated pyramid structures connected at a single node.

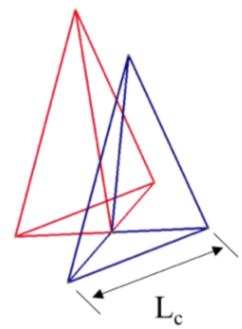


Fig. 6 Stretch-dominated cell configuration.

IV. Structural Analysis Models and Results

Abaqus[ϒ] analysis software [10] was used to create the finite element models (FEM) of the backshell panel and perform structural analyses on a baseline model and cellular structure models. The global panel dimensions given in Fig. 3 were used for all models. For this initial study, the models were subject to a 138 kPa pressure load on the outer surface of the conical section panel. A clamped boundary condition around the outer perimeter of the panel was modeled as the assumed simple representation of the panels being bolted to the frame structure. A factor of safety (FS) of 1.5 was chosen where the margin of safety (MS), was calculated using the following equation:

$$MS = \frac{\sigma_{all}}{FS * \sigma_{FEM}} - 1 \quad (2)$$

where allowable stress, σ_{all}, is a material strength property and σ_{FEM} is the maximum principle stress predicted in the FEM. Linear static structural analyses were performed. Although buckling analysis should be performed in future work, since the panels were loaded in a bending mode, the effort initiated with just linear static analyses.

The baseline HSS model utilized all two-dimensional (2-D), linear quadrilateral shell elements. A total of 902 elements were contained in the model. A more refined mesh was considered with approximately twice the number of elements, where results revealed that the mesh shown in Fig. 7 was sufficient to achieve a converged solution. The shell element composite properties modeled represented a metallic honeycomb sandwich construction with composite laminate facesheets. The composite laminate material had B-Basis design allowables reported on by the Advanced General Aviation Transport Experiments (AGATE). The composite ply material is designated Newport Carbon Plain Weave Fabric 3K70P/NB32[ϒ] [11]. The honeycomb core material utilized was 5052 aluminum from Hexcel[ϒ] [12]. Honeycomb properties for a cell size of 4.8 mm with density of 140 kg/m^3 were selected for this model as a mid-range option using engineering judgement based on the overall panel size and configuration. However a sizing study would be warranted for a higher fidelity trade study. Preliminary analysis resulted in the need for 6-ply composite facesheets with a stacking orientation of [60,0,-60,60,0,-60] to achieve all positive MS values for the baseline model with a 2.5-cm thick honeycomb core. For the 6-ply composite facesheet model, a total of 13 plies were defined, where layer 1 to 6 represented the composite plies of the inner surface facesheet of the conical panel, a single layer 7 represented the honeycomb core, and layers 8 to 13 represented the last six composite facesheet plies on the outer surface of the conical panel. The MS values for ply layer 12 in the baseline model, which contained the lowest MS values, is shown in Fig. 7. The majority of the ply layer has a MS between 0.142 and 1.417. The average MS value throughout the entire structure was 2.75.

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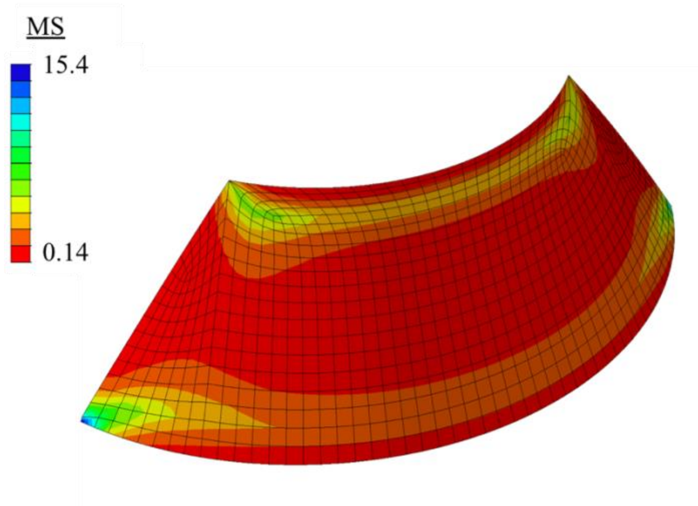

Fig. 7 MS values predicted in the baseline model.

The displacements predicted are displayed in Fig. 8. The maximum displacement was 0.96 cm which occurred in two locations symmetric about a plane in the height direction of the panel. The overall mass of this baseline HSS panel was predicted to be 42 kg.

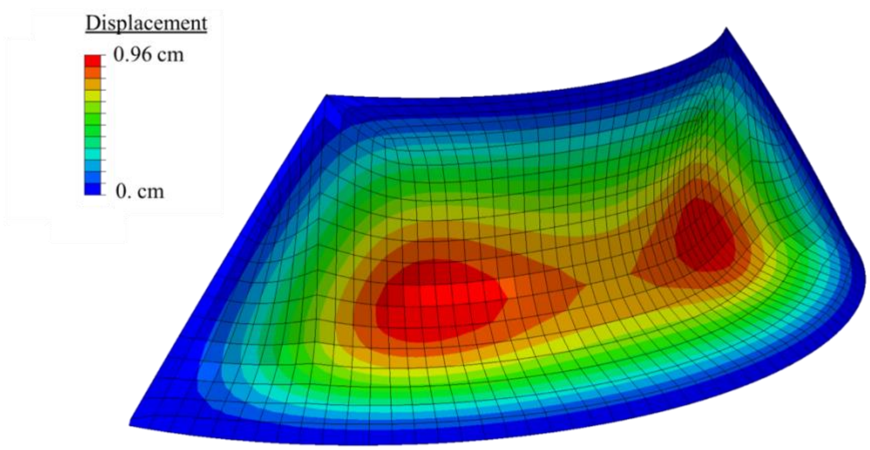

Fig. 8 Displacement magnitudes predicted in the baseline model.

The bending-dominated cellular structure was modelled in Abaqus using one-dimensional (1-D) beam elements for the cellular unit shown in Fig. 5. The FEM for this concept is displayed in Fig. 4 for the model with L_c = 7.6 cm, and with the 1-D elements visualized as three-dimensional objects. This FEM contained a total of 76388 1-D beam elements. A more refined mesh was not evaluated for the cellular model but should be in future work. In order to simply apply a distributed pressure load to the outer surface of the beam structure, 2-D shell elements with a Young's Modulus two orders of magnitude less than that of the cellular material was placed on the outer surface of the cellular structure using tie connections. Material properties for aluminum 2024 were utilized for the cellular structure models, representing a metal that could be used in an additive manufacturing process. The thickness of the cell normal to the cone surface was kept equal to the 2.5-cm honeycomb core thickness in the baseline backshell model. Several values for the radius of the beams and the in-plane characteristic length, L_c, were evaluated in this initial study, and the values for the radius and L_c were kept uniform in each model analyzed. For each value of L_c considered here, the strut radius was varied to find the minimum radius needed to achieve all positive MS values predicted for the model. The MS values predicted for the model with a beam radius of 0.59 cm and L_c = 7.6 cm are displayed in Fig. 9. Interestingly,

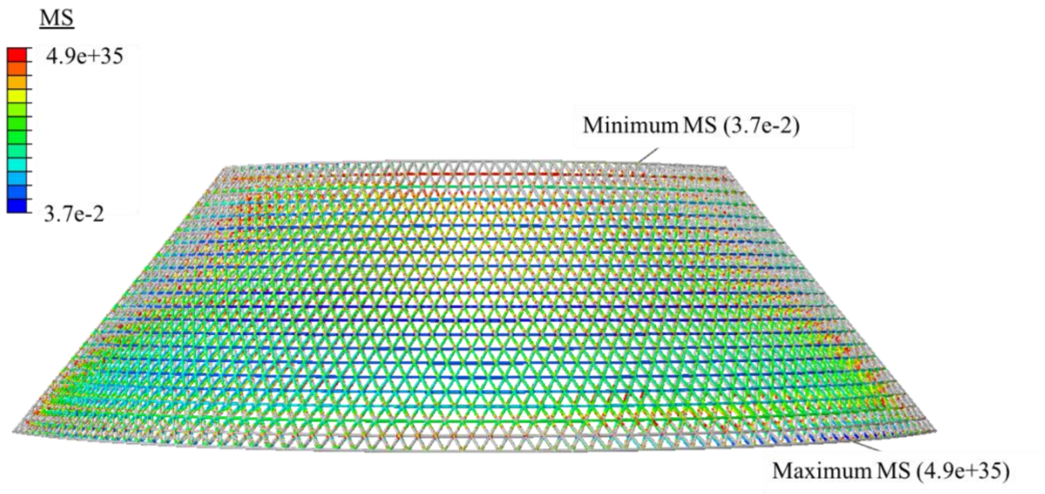

Fig. 9 MS values predicted in the bending-dominated cellular model.

the MS values for this cellular design exhibited extremely large variations, ranging from the minimum of MS = 0.04 to a maximum of MS = 4.9 x 10^{35}. This result indicates that optimization could be readily achieved with a tailored design as opposed to using uniform cell attributes employed herein. However, a full backshell model should be developed prior to pursing a high fidelity tailored cellular design. The displacements predicted for this model are displayed in Fig. 10. A maximum displacement of 0.5 cm was predicted with a displacement distribution very similar

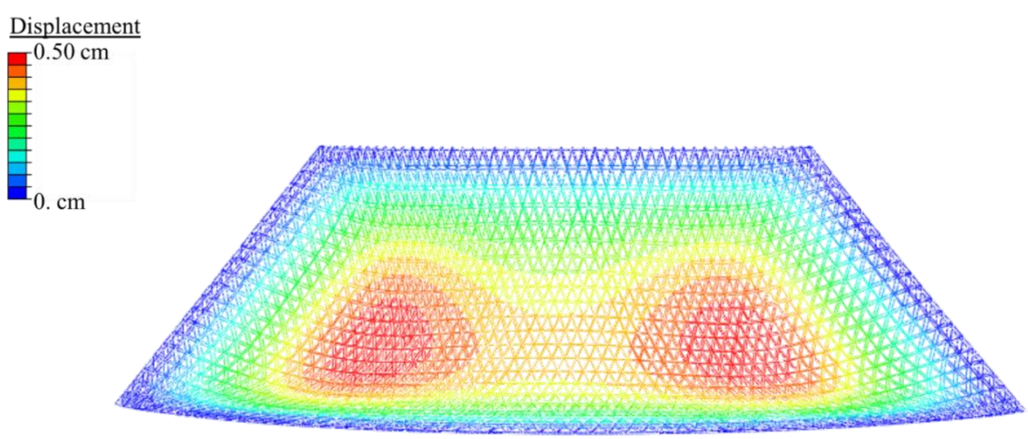

Fig. 10 Displacement magnitudes predicted in the bending-dominated cellular model.

to the baseline model. However, the maximum displacement for this cellular model was approximately 50% lower than the maximum displacement of the baseline. The resulting beam radius to achieve all positive MS in the model, along with the predicted mass and displacement results, for the varying values of L_c considered in the analyses, are provided in Table 1. As would be expected, these results show that as the value of L_c decreases so does the minimum beam radius needed to achieve positive MS. The results also show that as Lc decreases, the mass increases up to a value of L_c = 5 cm, then decreases for the lower value of L_c = 2.5 cm, where a beam radius of only 0.36 cm was needed to achieve all positive MS values. For these preliminary analyses, the predicted mass of the cellular structures were approximately 4 times greater than the mass of 42 kg predicted for the baseline model. However, some important observations can be made about the potential to decrease the mass of the cellular structure. One observation was related to the fact that for shorter L_c there were more beams in the radial direction, and these beams were lightly loaded. In essence, they are needed to generate space between the beams that are in-plane to the conical section and provide bending stiffness, similar to the concept of honeycomb core. Consequently, smaller radius beams than needed for the conical in-plane beams could be used. This tailoring of the cell beams would provide ample opportunity for a more optimized structure. Additionally, the mass of the baseline model did not include the significant amount of mass that would be associated with all the bolts and the frame structure needed for assembling the HSS panels on the backshell. Consequently, the comparison of baseline panel mass to the cellular structural mass is not appropriate at this preliminary analysis stage. However, comparison of behavior between the baseline and cellular model was of interest to justify the consideration of a cellular structure, and most importantly the evaluation of the variation of mass verses the parameters varied in the model was critical towards future use in optimizing a cellular concept.

Table 1. Results for Bending-Dominated Cellular Structure Model

L_c [cm]	Beam Radius [cm]	Mass [kg]	Maximum Displacement [cm]
10.2	0.64	157	0.55
7.6	0.59	179	0.39
5	0.53	231	0.44
2.5	0.36	219	0.4

For comparison, the stretch-dominated cell shape in Fig. 6 was analyzed for a characteristic length, L_c, of 7.7 cm with the same material and boundary conditions used for the bending-dominated cellular structural model. The minimum strut radius of 0.48 cm was determined to achieve a positive MS throughout the panel. Although the minimum strut radius was less than that of the minimum strut radius in the bending-dominated cellular structure with the same L_c, the calculated mass of the stretch-dominated structure was approximately 189 kg, higher than that of the bending-dominated structure at 179 kg. A similar pattern for the MS compared to that of the bending-dominated cellular structure is shown in Fig. 11. The stretch-dominated structure had a maximum displacement of 0.56 cm as

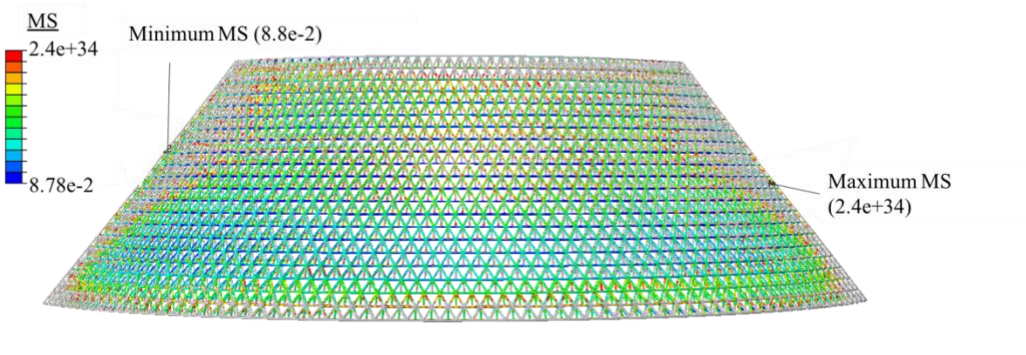

Fig. 11 MS values predicted in the stretch-dominated cellular model.

shown in Fig. 12, slightly greater than that of the bending-dominated structural model. Consequently, a bending-dominated type cell would be the preferred cell type for the backshell structure where the structural response was that of a bending mode of deformation.

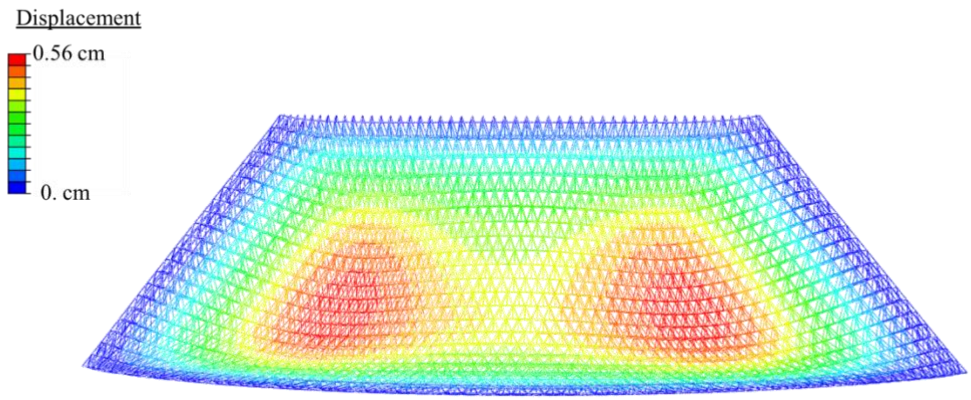

Fig. 12 Displacement magnitudes predicted in the stretch-dominated cellular model.

V. Thermal Protection System Development for the Cellular Backshell Concept

The baseline concept represents the traditional backshell design where the TPS consists of ceramic tiles that are bonded to underlying HSS. This approach for TPS could also be applied here to the cellular structure concept. However, since ceramic tiles are susceptible to fracture and have issues related to the integrity of bond lines, there was the desire here to find an alternative system to avoid these shortcomings, and thus to potentially produce a more reliable design. With recent advances in lightweight thermal blanket technology, the possibility of utilizing these blankets on the outer surface of the cellular structure was explored to evaluate the potential for this approach for the TPS on the backshell of a planetary entry capsule with an underlying cellular structure. This blanket insulation approach was similar to advanced flexible reusable surface insulation (AFRSI) used on the leeward side of the Space Shuttle Orbiter [13].

Sizing of the thermal blanket was conducted considering the thermal loading conditions developed for a 4.5-m diameter capsule entering the Mars atmosphere [2]. The general 1-D thermal analysis model is illustrated in Fig. 13. A heat transfer code, High temperature fibrous Insulation thermal analysis software (HTFITAS), developed at NASA Langley Research Center was utilized to perform the transient thermal analysis [14]. A heat flux profile with a peak value of 30 W/cm^2 for 35 seconds at 3.65 kPa in carbon dioxide was applied as a simple approximation of the peak heating condition on the outer surface of the backshell. Materials that were considered for the TPS layers included Nextel 440 [ϒ] [15] and silicon-carbide (SiC) fabric for the outer layer, alumina paper insulation (APA) and Q-Fiber[‡] insulation for the blanket insulation, and Nextel 440 and Kapton[§ϒ] [16] for the inner layer. Note the Q-Fiber was also used for insulation in AFRSI. A 0.25-cm thick layer of aluminum was used to represent the structural layer and the peak temperature for the aluminum was limited to T_{max} = 30ºC. An adiabatic boundary condition was applied at the inner surface.

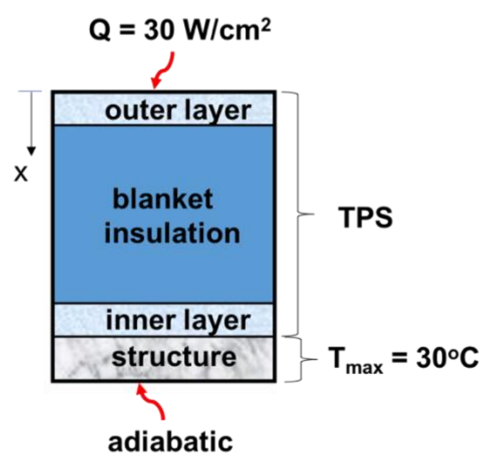

Fig. 13 1-D thermal model components for cellular TPS concept.

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‡ Johns Manville Corporation. This is not an endorsement by NASA.

Protection from micrometeoroid and orbital debris (MMOD) is an issue that needs to be considered for an entry capsule backshell that is exposed on the outer surface of the vehicle during space travel [17]. The sizing of the Orion backshell tiles was driven by MMOD requirements [4]. The approach being considered here provides additional protection against MMOD by adding a layer or more of Kevlar within the insulation layer. Long-term operational temperature for Kevlar is limited to about 177ºC, and this needs to be considered in applying the Kevlar within the TPS design. To determine the best location to position Kevlar layers in the insulation, the insulation was modeled as four separate layers so that potential locations of Kevlar layers could be evaluated based on the thermal conditions within the insulation, as illustrated in Fig. 14. The reason that an additional layer of insulation was desired after the Kevlar layer lies in dynamics of hypersonic MMOD. The motivation was that the Kevlar layer would be able to break up MMOD debris, minimizing the damage from an impact. The greater the distance the internal structure is from the Kevlar layer, the lower the terminal velocity of the debris before impacting the structure. Also, there may be a desire to consider several Kevlar layers and/or SiC-fabric layers to provide sufficient thermal protection after an MMOD impact that causes TPS damage. Additionally, there was a desire for a rigid outermost layer for MMOD protection and to maintain the aerodynamic shape of the backshell. This rigid layer may be realized utilizing a rigid coating on the outer surface. However for this initial evaluation, Kevlar layers and the rigid outer coating layer were not included in the thermal sizing analysis model. However, the potential viable location of the first Kevlar layer was determined based on the temperature results between insulation layers.

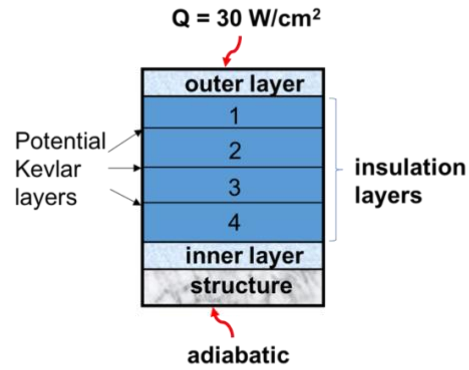

Fig. 14 Thermal model considering Kevlar layers for MMOD protection.

Thermal analyses were performed for a few sets of stacking sequences evaluating the TPS material layers described previously and for a couple TPS layer thickness values. A viable thermal sizing result is illustrated in Fig. 15 where a peak outer mold line temperature of 723ºC was predicted. This stacking sequence initiated with a 0.1-cm thick outer layer of SiC fabric, followed by Q-Fiber insulation with a total thickness of 1.05 cm, then a 0.05-cm thick layer of Nextel 440. After thermal sizing was complete, the determination was made that a Kevlar layer could be located within the Q-Fiber insulation at 0.8 cm below the outer layer, as illustrated in Fig. 15, without exceeding the 177ºC temperature limit for the use of Kevlar. Not including the Kevlar layer thickness, the overall thickness of this TPS is 1.2 cm.

Due to a lack of material properties to perform MMOD analysis for this TPS concept, a test using a hypervelocity test laboratory would be recommended to assess this TPS concept and further optimize the design for MMOD protection attributes.

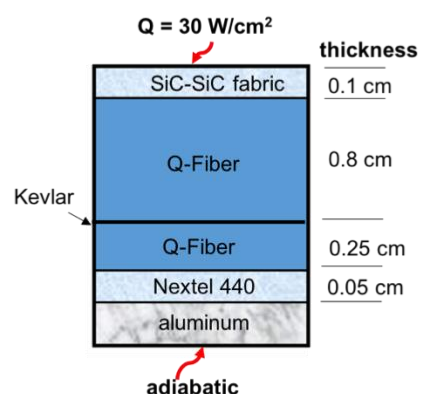

Fig. 15 Thermal sizing results.

VI. Concluding Remarks

The development of a cellular structural concept with an advanced thermal protection system has been initiated for the backshell of a planetary entry capsule. The motivation for this work was to evaluate the possibility of employing a cellular type structural concept on the backshell to yield improvements in the structural performance and thus justify employing an advanced concept on future mission vehicles. With recent advancements in additive manufacturing techniques, the possibility of efficiently fabricating a cellular structure has become realistic with potential for significant improvements. Also, advancements in thermal blanket technology motivated an initial examination of whether they could be utilized as an alternate to traditional ceramic tile TPS concepts with improved performance for the backshell.

A building block approach was followed in this developmental effort. The initial structural study presented here was limited to a single panel from a backshell to obtain a simple model for initial evaluation. A comparison was made to a traditional backshell design. Results showed similar behavior in the structural deformation observed. Although the mass results predicted for the cellular concepts were higher in this study when just the panel mass was considered, considering the additional mass associated with the large number of bolts and the frame structure used with baseline construction, and considering that a monocoque cellular structure could be constructed without bolts and a frame, a full backshell structure model would need to be considered to make a valid comparison. Also, importantly, the cellular model was not yet tailored. The use of additive manufacturing would efficiently allow extreme tailoring where each beam and cell size could vary as needed to achieve an optimally efficient, lightweight design. Future work with tailoring the concept based on local and global load requirements should lead to significantly lower mass cellular designs. Additionally, future research to consider larger, 10-m diameter capsules, to enable future missions with larger payloads should consider cellular concepts. At this level, the use of the cellular approach could lead to significant mass savings along with other benefits through simplifying the fabrication and assembly of the structure.

Development of a thermal protection system based on utilizing thermal blankets on the outer surface of the cellular structure was also initiated. The feasibility of this approach will require testing to determine the behavior of the concept under impact loading to meet MMOD requirements for future space exploration.

VII. Acknowledgements

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