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An Evaluation of Composite Primary Structure for Habitat Modules

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Abstract

Boeing studied the use of composite structures in deep space habitats. Compared to metallic modules, composite structures offer increased strength and stiffness with reduced mass. The study evaluated the design considerations and the mass benefits of an all composite primary structure. The composite module design included a continuous pressure shell, composite longerons, and circumferential ring frames. The composite material selected was a high strength carbon fiber and epoxy slit tape prepreg. The manufacturing involved automated fiber placement and utilizing existing facilities and autoclaves. Analysis showed a 33% reduction in primary structure mass and an overall net reduction of nearly 1900 kg compared to metallic modules. The composite module demonstrated improved mass efficiency and opens new possibilities for mission performance in deep space exploration.

Keywords: Composite, Structure, Habitat (maximum 6 keywords)

1. Introduction

Composite structure in space applications has demonstrated the material's benefits of increased strength and stiffness while decreasing mass when compared to aerospace metals. Habitat mass becomes increasing important to mission efficiency as human exploration moves further from Earth. A habitation module's primary structure is traditionally the heaviest subsystem, so any percent reduction in mass has a significant impact to the vehicle's overall mass and performance. Boeing has experience designing, manufacturing, and flying composite structures for aviation and space applications and is studying how best to incorporate composite structures into human deep space habitats while maintaining the high level of assured safety required for human spaceflight.

Boeing performed an evaluation of the mass benefits of incorporating an all composite material primary structure design into the habitation module and compared it against a baseline metallic module. The same Design Reference Mission, Ground Rules and Assumptions, internal volume, vehicle diameter, loading, interfaces and boundary conditions were applied to both modules. To gain the full benefits of the composite system, the design was modified from the metallic baseline to take advantage of composite's strengths, such as a continuous layup of structure from dome to dome as opposed to the metal configuration requiring multiple segments and welded joints. Other subsystem impacts of a composite primary structure were evaluated and briefly discussed in this paper. At the module level, including all subsystems, a substantial reduction in mass demonstrated the benefits of a composite habitat.

2. Composite Design

It is envisioned that the primary structure of the Habitat module will be an all composite structure design. The structure includes a continuous pressure shell. Composite longerons and composite circumferential ring frames will be integrated to increase the buckling strength of the long module cylinder and to withstand launch loads. The composite longerons and frames will be either co-cured or secondary bonded to the cylinder of the composite module. The longerons and frames provide hard structure for mounting secondary clips and brackets to support external outfitting (MM/OD shields, Insulation, external equipment, etc.) and internal outfitting (crew quarters, waste and hygience compartments, interal equipment, etc.) Other methods to provide secondary structure support include the use of composite click-bonds and locally bonded composite pad-ups as structure hard points. Access to the inside of the Habitat will be via polar opening at both ends of the module. The access openings will be locally thickened and will have standard interface to the docking mechanism. Similar structural interface can be provided for radial docking port if required. One of the concerns with composite pressure shell is the leaking thru the wall of the pressure shell if there is no liner on the IML to act as leak barrier. Because the leaking or permeation is caused by microcrack networks developed in the resin if the resin is excessively strained under loads, the wall of the pressure shell is sized so that the wall strain is kept below the strain levels that cause microcracks in the resin. Additionally, a carbon fiber and epoxy system is selected that minimizes the risk of permeation (see Section 4.1).

Fig. **1** below shows the composite module's primary structure design.

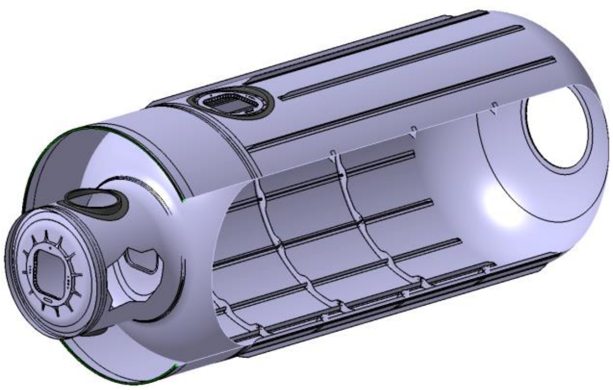

Fig. 1. Composite Habitat Design

3. Configuration

The first application of the composite habitat module was studied for a Mars Transit Habitat (MTH). This module would be self-sufficient for long duration deep space missions, with a separate propulsion module. The Design Reference Mission is a 1200 day round trip to Mars with four crew and all the logistics and supplies needed (no resupply assumed). Large portions of the module are utilized for logistics storage. A Safe Haven and Airlock Compartment (SHAC) on the aft end provides a separate pressurized volume that can be used for contingency spacewalk or provide a safe haven that is separate from the main habitat volume. The aft end Skirt extends down and interfaces with the launch vehicle via the Payload Attach Fitting (PAF). Body mounted radiators and deployable solar arrays are mounted on the exterior. The module features two axial and one radial docking ports.

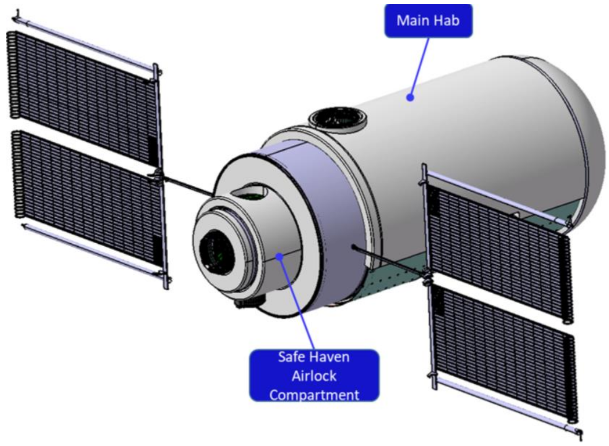

Fig. 2. Mars Transit Habitat Configuration

This configuration with a long cylindrical section has a large portion of the structure as acreage areas, or locations without significant geometry changes or interfaces. The composite material reaps the most benefit in large acreage areas, making this an excellent fit for the use of light weight composites.

4. Materials

4.1 Material Selection

Selecting the optimal material for a deep space habitat involves quantifying benefits and risks. Metal has been used successfully in similar applications and therefore offers a low risk solution. However, trade studies indicate that significant mass savings are possible by implementing composite structure. There is a common perception that certification of composite structure for this application will be challenging, primarily because prior habitable space structures have all been metal. However, composite structures have proven to provide a safe habitable volume for Boeing's 787 Dreamliner commercial aircraft fuselage (also a pressurized composite structure) and companies such as Sierra Space are pursuing implementation of their all-composite Dream Chaser for human space flight to low earth orbit, beginning with a cargo resupply vehicle.

The baseline composite material that Boeing has selected for the current deep space habitat study is Toray's T1100G/3960 slit tape prepreg. This is an aerospace grade carbon/epoxy prepreg with the highest strength, yet still high strain-to-failure, commercially available carbon fiber and well controlled material manufacturing processes. A publicly available database of material properties and specifications is currently in development by NCAMP. This public availability of data and specifications provides the benefit that the information can be shared with NASA and industry partners without complicated non-disclosure and proprietary usage agreements. The layup process is controlled by employing automated fiber placement (AFP), which uses a robotic head with spools of slit tape prepreg to lay the composite onto a rotating tool (see

Fig 3). AFP is an efficient layup process which minimizes the potential for operator error and can be done similarly to how the 787 airliner composite fuselage is built.

4.2 Material Allowables

Allowables for the material were taken from the Toray's database. An open hole tension (OHT) allowables was selected for sizing the structure because the pressure shell is a tension driven structure. The habitat design is using 0.25-inch open hole strength allowables given that test data and allowables are more readily available for this standard size hole.

4.3 Damage Tolerance Approach

Since the primary acreage loads are tensile, the structural thickness is driven by the open hole tension (OHT) strength allowable. For reference, the OHT strength allowable is less than 60% of the pristine un-notched tension allowable. Eventually, in acreage areas where there are no fastener holes, the OHT strength allowable will be replaced by a "damage tolerant" strength allowable defined based on the residual strength of the structure with the worst-case flaw that could realistically occur. In an effort to quantify and bound this worst-case flaw, a preliminary damage threat assessment was conducted which considered a wide range of threats and the potential of each threat to damage the composite structure

Ground rules and assumptions for this assessment included:

1) All external composite structure is protected by MMOD shielding and/or insulation
2) Vehicle is protected inside of a fairing during launch
3) Rotating components of high energy equipment are self-contained within the unit's housing

The following are examples of the types of threats that were considered:

1) Manufacturing discrepancies found during inspection that are below the defect acceptance threshold
2) Ground handling damage during acceptance/qualification
3) Inadvertent bump/kick during ground operations or in space environment
4) Crew induced equipment impact
5) Robotic arm impact
6) MMOD impact including surface ejecta
7) Degradation due to radiation (ultraviolet and/or ionizing)
8) Handling of habitat including offloading from launch vehicle and positioning on surface

The list is not exhaustive and is intended to cover multiple different threat environments ranging from deep space transit to a surface habitat.

A Damage Threat Assessment was performed and the residual threats that cannot be fully mitigated were brought forward and incorporated into a planned test matrix. These include both hypervelocity impacts and lower energy impacts. The pressure structure would be impacted at the associated energy levels and then undergo permeation testing while under bi-axial loading. It is believed that permeation will be the more limited failure mode, happening before a structural failure occurs.

5. Manufacturability

As previously mentioned, the body of the Habitat module is a continuous composite shell. The Automatic Fiber Placement (AFP) process will be used to lay up the Habitat shell. The habitat module is similar in size to composite tanks Boeing designed, manufactured, and tested under NASA Composite Cryogenic Technologies and Demonstration (CCTD) program and DARPA eXperimental Space Plane (XSP) programs (4.3m to 5.5m.) The layup mandrel is made up of multiple segments that can be disassembled and removed after the module shell had been cured. Fabrication of longerons and frames will be either hand layup, drape forming, punch forming or by ply-by-ply fiber placement. These components will then be either co-cured or by secondary bonding to the Habitat shell. If secondary bonding is employed, then a layer of film adhesive is used at the bond interface. This capability already exists with the Boeing Company and would not necessitaty huge capital expenditures as the large autoclave, AFP robot, and other facility releated equipment already exist.

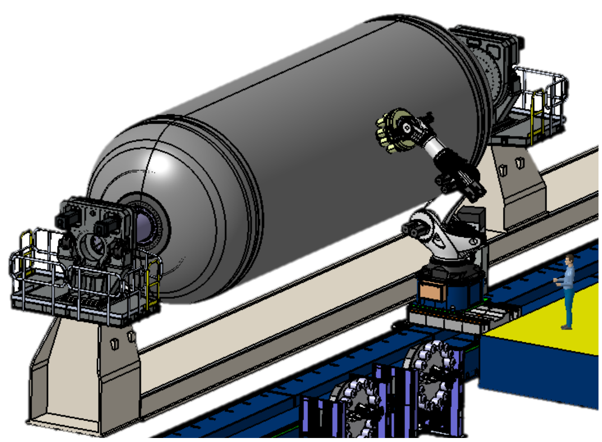

Fig 3. Composite Habitat Manufacturing

6. Composite Analysis

For the composite module, a FEM model was created, stress/strain was extracted, and margins of safety were generated based on the composite material allowables.

The primary loading events are from launch, on-orbit pressure, NASA Docking System (NDS) interface loads, and the fully outfitted module's Trans Mars Injection (TMI) burn. Other loading scenarios such as thermal loads, crew loads, or other propulsive burns were determined to not be the critical load cases for the primary structure and were not included.

Launch load factors were enveloped from both the SLS and the SpaceX Starship to ensure that either launch vehicle (or a similar class vehicle) could be used. The Maximum Design Pressure (MDP) was set to 15.2 psi and applied to the pressure shell. NDS interface loads were applied to all of the ports (2 axial, 1 radial). An envelope of the International Docking System Standards cases 1-3 was used and the in-plane shear and moments were clocked every 30°. The final case considered was the TMI burn case with the vehicle fully outfitted with all necessary equipment and logistics for the 1100 day mission. A 0.3 g load was applied to the fully outfitted module.

The boundary conditions for the Transit Habitat vary between the launch and on-orbit configuration. During launch, the module is constrained at the aft end where the module would interface to the delivery bus (which then attaches to the launch vehicle). On-orbit, the module is constrained at the forward NDS interface representing the Transit Habitat docked to the Gateway. Additionally, when representing free-flying or NDS interface loads applied to the forward NDS an inertial relief condition was applied.

Factors of Safety (FS) were applied to the load cases within the sizing analysis. Per NASA-STD-5001B the factors of safety for metallic, inflatable softgoods, and composites were set to the following in Table 1.

Table 1. Factors of Safety

Hardware	Load Case	FS_{ult}
Composite	All	1.4
Habitable Module	Internal Pressure Only	2

A FEM model, shown in Fig. 4, was developed utilizing 2D elements of the thin laminate that includes the pressure shell and internal and external longerons.

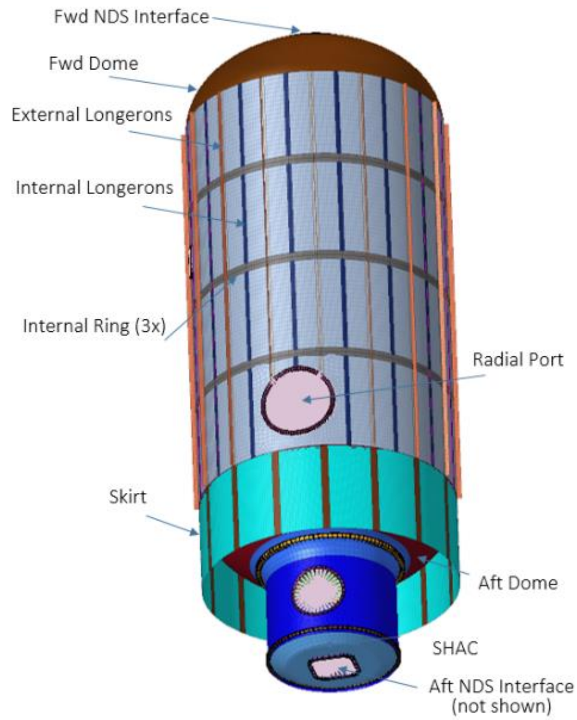

Fig. 4. FEM Model of Composite Module

Getting the total mass of the model is important for running the inertial loads during launch and for the inertial relief conditions on-orbit. The non-structural mass was applied to the model to reach the full launch mass (run with the cases that cover launch loads) and the full Mars outfitted mass target (run for the TMI burn case). Mass was applied as a lump (or point) mass for large mass items with a known location in the vehicle. The remaining mass was smeared over the pressure shell via non-structural mass.

The laminate thickness (number of plies) was sized based on the FEM stress/strain results to ensure the predicted stress/strain remained within the material allowables after including the Factors of Safety. Buckling modal frequency checks were also performed and ensured the final design provided adequate stiffness to support launch requirements.

7. Comparison of Material Systems

Boeing completed a trade study of multiple primary structure material systems and configurations for a Mars Transit Habitat to determine the minimum mass configuration [1]. Four configurations were traded over a multi-phased approach. The four configurations are: 1) 5.5 m diameter metallic module, 2) 7.0 m diameter metallic module, 7.6 m diameter inflatable module with metallic pressureized base, and 4) 5.5 m diameter composite module, see Fig 5. Each configuration was designed to the same Design Reference Mission and Ground Rules and Assumptions (GR&A). A constant volume constraint was also imposed so that each configuration had equal overall volume to aid in direct comparisons. Each module configuration and structure was optimized for it's material system.

The first phase of the comparison involved developing the first three configurations and downselecting. The 5.5 m diameter metallic module was the downselected module and it was further refined. Then a composite system was introduced to the trade space and compared directly to the refined 5.5 m metallic module. In order to have a direct comparison of the benefits and challenges of a composite primary structure versus metallic, the Composite Habitat design cycle used the preferred 5.5 m diameter configuration. As much as possible, the design of the 5.5m metallic TH is carried forward for the design with the same GR&As, Con Ops, design constraints, etc. Subsystems and specialty engineering disciplines that are impacted by the incorporation of the composite primary structure are assessed and the impacts were reported and incorporated into the Master Equipment List (MEL).

The results from the comparison study between the 5.5 m diameter metallic and the 5.5 m diameter composite showed that the introduction of composite primary structure impacted other subsystems such as secondary structure, Micrometeroid Orbital Debris (MMOD), Power, and Thermal Control System (TCS). The subsystems with a mass impact are shown below in Fig 6.

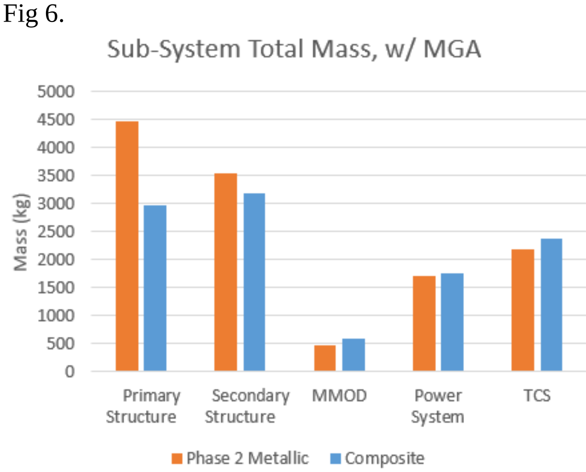

Fig 6. Subsystem Comparison of Composite vs Metallic

The composite design results in a 33% reduction of primary structure mass and an overall net reduction of nearly 1900 kg. This mass efficient structure is just 14% of the total vehicle dry mass, a significant improvement over traditional space habitats.

The secondary structure was able to reduce mass over the metallic module by incorporating detailed external outfitting attachments that bond to the Skirt or other equipment mounting directly to the internal and external longerons. For the MMOD subsystem, metallic modules have well knownd and tested hyper-velocity impact failure modes while the composite material needed to be conservative on ballistic limits for a composite panel due to limited data or literature on the matter and unknowns in the failure criteria.

Power system mass increased for the composite configuration driven by the composite's lack of electrical conductivity requiring a Current Return Network. The Thermal Control System mass also increased for the composite system due to the lack of thermal conductivity precluding traditional patch heaters on the shell to maintain temperatures above due point. The solution was a ventilation based design to keep the shell above the dew point. This increased the mass, but also allowed for a reduction in total power consumption.

In the comparison between all four traded configurations, the composite module stands out as the lowest mass configuration, coming in well below the mass target. Both metallic modules have similar total mass while the inflatable option was the heaviest at the overall module level. Fig 7 shows the comparison of total module mass. The error bands shown represent the mass threats and opportinuties associated with each configuration.

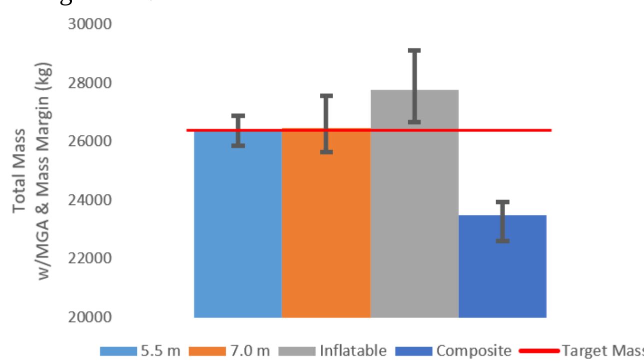

Fig 7. Total Mass Comparison of 5.5m/7m Metallic, Inflatable, and Composite Modules

8. Results and Conclusion

The unique and proven composite material capabilitues of The Boeing Company enables the design of a continuous dome to dome Automated Fiber Placement (AFP) layout that results in a very mass efficient structure. Manufacturing can be performed using existing manufacturing facilities, robotic equipment and autoclaves. This eliminates the need for major structural joints along the pressure shell which add complexity and mass. Since a composite habitat has not flown in space before, Boeing is continuing to mature composite habitat designs, has developed a certification path [2], and is conducting testing to increase the Technology Readiness Level. Composite habitats open new opportunities for higher mission performance by reducing total mass or reallocating mass the saved mass to other subsystems that further the mission objectives.

Acknowledgements

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References

[1] AIAA ASCEND paper

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Fig. 5. Four Configurations Traded