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Space Architecture
Advanced Material Habitat Structures

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Abstract

The International Space Station has been humanity's Low Earth Orbit (LEO) laboratory and home for human space exploration for more than 20 years. A new chapter is currently being developed through commercial space efforts to design, engineer, and build space stations that can support a future LEO ecosystem. Advanced composite material structures can pave the way for a new generation of space stations that are stronger, lighter, less expensive, and offer a range of design possibilities. This study includes the development of graphene-reinforced composites, advanced manufacturing, and architectural design considerations for habitat architecture. The composite materials and methods developed can be used in station-type facilities as large pressure vessels and shielding structures for habitation. The results of the study are intended to provide considerations and a process for implementation in the future design of space architecture. The study provides recommendations for practical applications in other industries and will support the future manufacturing and testing of ongoing research.

Keywords: (Carbon Fiber, Space Architecture, Graphene, Structures, Manufacturing)

Acronyms/Abbreviations

TRL	Technology Readiness Level
LEO	Low Earth Orbit
AE	Architecture and Engineering
ISS	International Space Station
MMOD	Micrometeoroid and Orbital Debris

1. Introduction

The International Space Station (ISS) has served as a Low Earth Orbit (LEO) laboratory and home for human space exploration for more than 20 years. A new chapter in exploration is currently being developed through commercial space efforts to design, engineer, and build space stations that can support a growing ecosystem into the future. This research proposes new material technologies that can be used in the design of space habitat architecture and play a critical role in commercial space station development. The research looks into the possible applications for multi-functional structures. The goal is to investigate the potential for advanced material structures using graphene-reinforced composites. The team builds on capabilities and experience including space architecture, material science, aerospace engineering, and manufacturing. Advanced composite materials can pave the way for a new generation of space structures and other products. The research and development team believes that the material technologies being investigated combined with advanced manufacturing, and engineering is needed to spur new ideas for future space habitat architecture and other industry innovations.

The research is focused on applying the material and manufacturing technology to the design and development of large habitat structures and environmental protection systems. Using graphene-reinforced multi-axial composites, the research has identified the potential to improve the performance, cost, and functionality of structures for space and/or other destinations.

Conventional space structures utilize solid aluminum pressure shells articulated with reinforcement iso-grids. For example, the European Space Agency Columbus module was built by Thales Alenia out of aluminum 2219. The pressure vessel shell has a thickness of 4.8mm and 3.8mm at the end cones. The pressure vessel is only one of several layers that make up the habitat architecture and additional layers are also very important to the overall function and performance. The micrometeoroid and debris protection system is called the Whipple shield and is made of aluminum 6061-T6 for the primary barrier and, Kevlar / Nextel panels for the secondary barrier. The thermal protection includes a Multi-Layer Insulation composed of Aluminised Kapton multi-layer system and an insulation blanket. The internal secondary structure is also made up of several types of aluminum including 7475, 7075, 5056, 2024, 7075, and 7050 [1]. Each system and layer serves a very specific and important role in making sure that the space habitat is safe, reliable, and can meet the performance standards of human-occupied spacecraft. The design of the structure and environmental protection will be essential to ensuring that the habitat will function as intended.

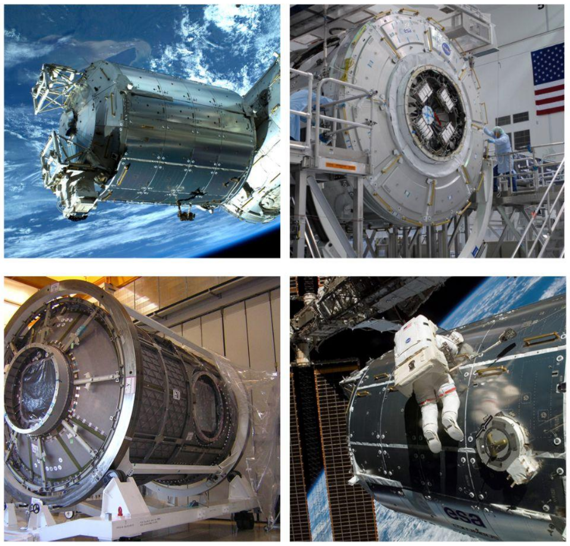

Fig. 1. International Space Station - Metallic Structure Pressure Vessels

Our goal is to investigate the adoption of advanced graphene-reinforced composites for each of the systems described to develop uniquely integrated habitat architecture. By identifying potential applications for the graphene-reinforced composites and other advanced 2d materials in the different assemblies and layers we can improve the design across functions such as MMOD, Therma, Structure, and Architecture. The potential applications will rely on a number of factors such as structural constraints, interfaces, complexity, and manufacturability.

Currently, there is a wide range of aerospace, automotive, and energy applications for advanced composites. Some of the key drivers behind the use of composites in other industries are due to their advantages in design flexibility, vibration damping, fatigue resistance, corrosion resistance, low mass, and high tensile strength. In the space sector, composites have been used for transportation systems such as rocket bodies, fairings, pressure vessels, and other applications. In 2007 the NASA Engineering & Safety Center (NESC) [2] evaluated a composite crew module as an alternative to the baseline Orion concept.

Fig. 2. NASA's NESC Composite Crew Module - Interior

This study investigated the feasibility of developing a primary structure for the crew module made from carbon fiber composites and other materials. The goal was to quantify the technical characteristics required to manufacture, test, and validate a Composite Crew Module (CCM) Pressure Vessel. The design was called the split clamshell, made from two major pieces, the top and lower sections of the pressure shell. The two pieces were then spliced together after the integration of additional structural and reinforcement elements. There were a number of lessons learned from this exercise that if applied today could lead to much more effective pressure vessel designs when combined with multi-axial 3d woven fibers, 2d materials, and advanced manufacturing.

Fig. 3. NASA's NESC Composite Crew Module - Exterior

2. Challenges

Some of the key challenges in designing a space structure and environmental protection system include shielding from radiation, maintaining a pressurized environment, damage tolerance from micrometeoroids and space debris, and extreme temperature variations. The three main sources of charged particle radiation naturally occurring in space are galactic cosmic rays, solar proton events, and trapped radiation belts. For example, on the ISS, the effects of AO and UV can overshadow any effects of particulate radiation on most materials. Depending on the polymer, particulate radiation can result in cross-linking or chain scission, similar to damage by UV, resulting in embrittlement [3].

Extreme temperature variations experienced in space affect the level of thermal cycling extremes depending on the absorptance and thermal emittance properties of a material. When a material is facing the sun, it is exposed to high temperatures and when it facing away from the sun it is exposed to low temperatures. The temperature differences can range from -120 °C to +120 °C. The ISS experiences about sixteen thermal cycles per day as it orbits the Earth and this repeated change in extreme temperatures damage most materials over time (peeling, deformation, cracking, fatigue, etc.).

Micrometeoroid and orbital debris impact can affect all systems in space, traveling up to 60 km/2. As a space structure orbits the Earth, the side of the habitat and its materials facing the direction of travel is most likely to experience impact with higher velocities. As more waste and materials are added to the space environment, the hazard of debris impact will continue to increase. Space debris can also be separated into two categories, larger trackable objects, and smaller untrackable ones, which continue to increase in quantity with decommissioning of spacecraft and waste in space.

By combining graphene and other two-dimensional materials, together with lightweight fiber-reinforced composites, it will be easier to mitigate many of the negative effects that exposure to the space environment produces on habitats and other structures. In this early technology development activity, we have looked into the potential benefits of integrating these materials into habitat design. As part of this, the team is placing an emphasis on manufacturing a primary structure (with minimum joints) by leveraging advanced materials and bespoke advanced robotics. The advantages of manufacturing fewer parts rather than assembling many parts, include minimizing failure points at the joints, developing multi-functional structures, and optimizing the distribution and use of materials. For this purpose a combination of advanced materials, including Graphene (one of the best-known heat conductors), MXene, and aerogel, have been studied at the specimen-level, to assess the vibration damping properties, heat dissipation, and radiation shielding properties. The plan is to take the selected structural material candidates and use them to manufacture a scaled model of a single structure. The models will then undergo rigorous testing in order to validate a wide range of criteria. These criteria will include structure, performance, and architecture. By conducting physical tests, we can identify unique opportunities to improve the overall design.

3. Material and Manufacturing Methods

The materials selected for this research were carbon fiber, graphene, aerogel, and MXene. Carbon fiber composites can be up to 40% lighter compared to aluminum structures and will be used as the primary material for the pressure vessel. Graphene is one of the best heat conductors and in this project, graphene is used to dissipate heat from the hot side to the cold side of the environmental protection system. As an ultra-light material, Aerogel is one of the best insulators to protect polymer composites from thermal degradation. MXene is a single layer of transition metal carbides, nitrides, or carbonitrides, and in this project, the authors are exploring the use of Mxene for its radiation shielding properties as part of the environmental protection system.

One of the major challenges that had to be overcome in this project was the coating of nanomaterials on carbon fiber preform. Mixing graphene with the resin system and infusion poses the problem of filtration of graphene by multifilament carbon fiber. Spraying graphene nanoplatelets on the surface of the pre-form cannot coat graphene at the intersection of fibers due to filtration. To overcome the filtration challenge we chose to coat graphene on the fiber prior to pre-forming.

The first step in the manufacturing process is to coat graphene and other 2D materials onto carbon fiber. This coated fiber is then converted into a preform using the novel carbon fiber manufacturing or pre-forming process that can incorporate off-axis fibers as well through thickness fibers with tow steering capabilities [4]. Finally, the carbon fiber composites enhanced with 2D materials can be manufactured and then assembled into the final structure.

3D woven fabric made using the conventional weave machine, i.e. looms with jacquard mounting have the limited capability of fiber direction. The new robot as seen in Fig.4 under development can place fibers in any orientation as well as through thickness binders. The added benefit of the new manufacturing system is the capability to place additional fibers to stiffness certain sections of the preform based on the mechanical performance requirements.

Fig.4. New robot to manufacture multiaxial 3D preform

The novelty of this advanced manufacturing process is in the integration of advanced materials like graphene and the capability of the robot to create complex fiber architecture based on the structural and mass performance requirements.

5. Testing and results

The presence of through-thickness fibers or Z-fibre reinforcement can prevent crack propagation and delamination, providing enhanced fracture toughness and micrometeoroid impact damage tolerance properties. Traditional 3D woven composites have low in-plane mechanical properties as well as weak in off-axis direction. However, in this study, this was overcome by adding fibers in the off-axis as well as through thickness fibers with reduced crimp, and this will help maintain the in-plane properties [4].

To study the effect of multiaxial or 3D fabric with off-axis and through-thickness binders, two sets of samples were developed and tested for mechanical properties.

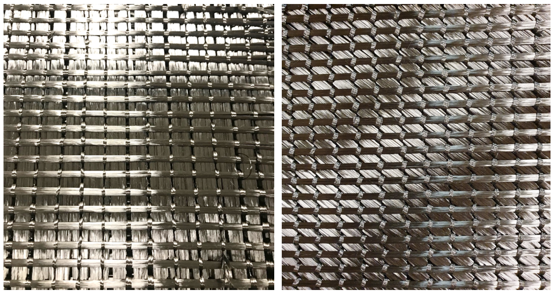

Fig.5. Sample A *Sample B*

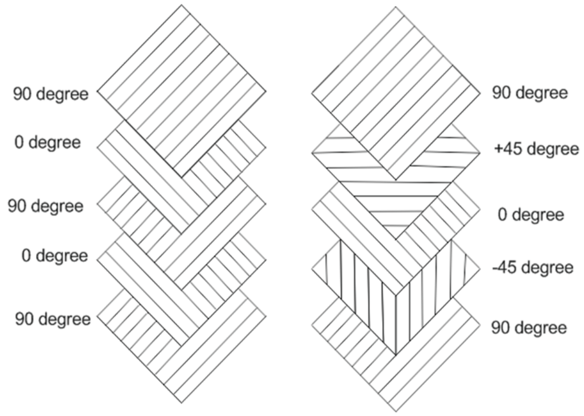

Fig.6. Samples A and B fiber direction

Sample A is a traditional 3D woven fabric with fibers in 0^0 and 90^0 directions with 5 layers, and Sample B is the new multiaxial 3D woven structure with fibers in 0^0, 90^0, $+45^{0,}$ and -45^0 directions with 5 layers. The images and the fiber orientation of Samples A and B are shown in Fig. 5 and 6.

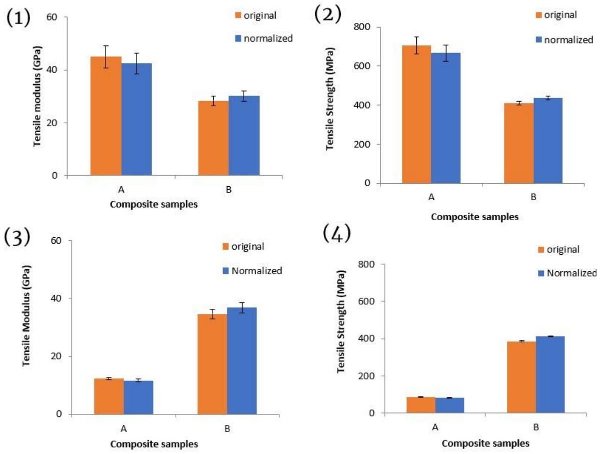

Fig. 7. Tensile strength and modulus in 0^0 and 45^0 directions

Tensile test of both the samples was conducted in 0^0 and 45^0 directions. The results are shown in Fig. 7. The two left (1) and right (2) bar chart shows the tensile modulus and strength in 0^0 direction. It can be seen from the graph that the traditional 3D woven composite or sample A is slightly stronger compared to the multiaxial composites or sample B. The key difference can be seen in the bottom two graph, showing tensile modulus (3) and strength (4) in the off-axis direction or 45^0. The multiaxial preform composite developed in this work is significantly stronger than traditional composites. Traditional composites are weak due to the lack of continuous fiber. The data shows the multiaxial composite retained its strength in both directions.

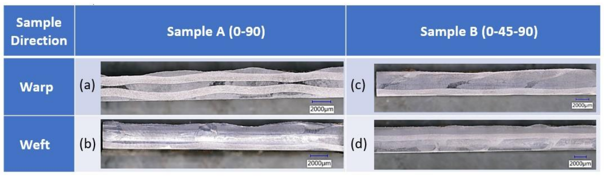

Fig.8. Cross section images of composites

One of the drawbacks of traditional 3D woven composites is the loss in the in-plane mechanical properties and this is due to the presence of crimp imparted by the through-thickness fibers. In Fig.8 the sample A crimp can be seen, and in sample B the multiaxial 3D structure, there is almost no crimp, thereby retaining the inplane properties while enhancing the out-of-plane properties.

The future potential of this technology can build ultra-thick composites with through-thickness fibers. The authors developed up to 75mm thick multiaxial 3D structures as seen in Fig.9 and are in the process of developing 300mm thick composite preform.

Fig.9. 75mm thick multiaxial 3D preform

The technology was further developed to incorporate additional fibers to varying the stiffness and strength as required. This can be seen in below Fig. 10. Further test is underway to study the effect of radiation shielding [5] and thermal management of the 2D materials.

Fig. 10. Mutiaxial 3D preform and composite with reduced joints or variable stiffness

6. Applications

Composites enhanced with graphene and other materials are cable of reducing the weight of any conventional metal structure used in space including space habitats, as well as the cost of building and maintaining these structures. The novel composite structural material developed in this early research work can also reduce the weight and improve structural performance compared to traditional composites that use enhanced carbon fiber.

The material system the authors have developed will have several applications in other industries as well. These industries include the transportation, energy, aerospace, and medical sectors in addition to space. One such unique future opportunity can be in the development of rapidly deployable structures for human settlements in pursuit of science and exploration in the Arctic or Antarctic, where temperatures reach as low as -94^{0}C [6] and mass is a major factor.

This material system is also applicable to both aerospace and automotive structures where weight reduction and impact damage-tolerant composites can have a positive impact, helping bring improvements across multiple functions.

7. Space Architecture Considerations

There are numerous opportunities to apply graphene-enhanced composites and other 2d materials to the development of Space Architecture. These materials can be applied to the pressure vessel and environmental protection systems in the design of habitats at the material production and system assembly level. A significant part of Space Station Architecture relies on designing for a limited volume and mass, transportation launch and vibration loads, and resolving complex interfaces between different elements. The transportation systems place a significant limit on the mass and volume for any given payload but more considerably on habitat designs due to their higher volumetric requirements. Although challenging, transportation limits can be overcome by designing with a combination of lightweight materials, geometries, and assembly strategies. As previously mentioned, the CCM used a clamshell approach, where two elements needed to be spliced together after they were structurally reinforced. This approach takes advantage of unique levels of integration, geometry, and assembly.

The design of any space structure has to consider the loads of transportation exerted on all of the systems and components. The habitat structure and systems will need to survive launch loads of about 5g axial / 1g lateral loads.

Our baseline concept will consider various parameters such as volume, structure, mass, systems integration, and architecture. This means, taking the advantage of the materials we have developed and making them an essential part of the design process. With a deeper understanding of the performance properties and challenges associated with manufacturing, our team will be able to establish a uniquely integrated design process. This approach to design is an essential part of material technology development due to the number of interdependencies that arise from unique design decisions. The composite architecture will offer the benefit of achieving complex forms that affect the entire habitat design. Our approach will constrain the architecture to both architectural and material manufacturing limitations with an emphasis on the structural elements.

Currently, the preliminary design includes three primary segments that are assembled together along reinforced sections. The geometry will be simplified in order to achieve a more continuous composite structure. The top and bottom segments articulate the ends with accelerated curvature to minimize the stresses and achieve a tangential relationship with the connecting segment. The mid-segment, also the largest segment, is derived from a tapered shape that is the widest at the midsection. This allows for a continuous overwrap structure that maximizes the use of the mandrel manufacturing method. Wherever penetrations exist, either at the end or mid segments, reinforcement is articulated to support the weakest zones. This provides the design with an optimal distribution and use of material.

The habitat penetrations will be made by machining the openings from the structural shell using precision robotics described previously. These openings will need to be carefully designed and manufactured in order to fit additional elements that interface with these areas such as window frames, reinforcement, docking ports, and other elements. Each penetration will need to be sealed using a proprietary detail and reinforcement method. The graphene-reinforced composites also help maintain seals due to their high impermeability properties [7].

An advantage of composites is that we can achieve unique geometries based on the requirements and constraints of any habitation system. This provides a wider range of design possibilities that make use of complex shapes while maintaining a level of manufacturability and performance that cannot be achieved using conventional materials. When conventional materials have been utilized the types of geometries are limited to cylindrical, spherical, or cone-type shapes. We propose to adopt a mandrel system which is also a rotating tool together with filament winding. The continuous fiber layer can be placed directly on a mold that is pre-manufactured with the desired geometry. This technique has been used in the manufacturing of panels and entire segments of airplane fuselage [8].

In our design, a segment of the habitat architecture will be selected based on complexity and interfaces using the manufacturing methods studied. The demonstration model will provide a roadmap to extend further development toward a structurally integrated habitat. The design and manufacturing of the molds will also need to consider the scale, geometry, reusability, and quality to ensure that the habitat prototype can be used for the intended review and testing purposes in the future. The mold will enable us to optimize the time, utility, joint complexity, and fabrication process.

Preliminary Design and Manufacturing Process:

- Develop the scale, geometry, and elements of the habitat.
- Develop the tool/mold for each segment that will be joined together after each has been manufactured.
- Each joint will need to have a lapping detail where the shells are joined together.
- Design the number, shape, and size of the cutouts in the pressure vessel. These areas will be reinforced.
- Identify where metal inserts and fittings at connection points are required. Keep in mind that thermal expansion will need to be minimized.
- Identify where a honeycomb sandwich core will be required if necessary.
- Develop the reinforcement structure that will be installed prior to the segments being joined.
- Develop the details and connections for the environmental protection system which is a multi-layer assembly. This will require reinforcement zones for the mechanical fastening of the outer system.

8. Conclusions

The study is intended to provide a valuable roadmap and process for the implementation of advanced composites in the future design of a habitat structure. The strategies developed at this stage are meant to provide opportunities for practical applications that will require further prototyping and testing. The team and partnership will demonstrate a process for using advanced lightweight material structures and resolving the various challenges associated with designing a habitable structure that can support various mission activities, from scientific to industrial. This can only be achieved through a cross-sector partnership that aligns with achieving sustainable commercial space human habitation.

Acknowledgments

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