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Preliminary Mass Validation of Adapting Payload Fairing Geometries as Pressurized Modules for Various LEO Applications

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This paper presents a continuation of previous research that outlined a design methodology of adapting launch vehicle payload fairing geometries into pressurized single or multi-element space stations. The initial research focused on investigating possibilities to employ the fairings of diverse launch systems used for delivering satellites to Geostationary Orbit (GTO) and Low-Earth Orbit (LEO), as pressurized habitats. The guiding principle behind the proposal is the utilization of fairings' composite material carbon fiber reinforced polymer with aluminum honeycomb core (CFRP-Al/HC) as the primary structure of a habitat. This material is designed to have great "strength to weight ratio", provide large usable volume, to maintain internal temperatures between 50° - 120°F, and withstand extreme environmental ascent conditions. This paper focuses on the methods used in composite materials for space structures and applying these concepts to the proposal of payload fairings as the main acreage panels of a pressurized habitat.

Nomenclature

LEO = Low-Earth Orbit
GTO = Geostationary Orbit
ISS = International Space Station
CLD = Commercial LEO Destinations project
HEO = NASA Human Exploration and Operations
PFSS = Payload Fairing Space Station
CFRP-Al/HC = Carbon fiber reinforced polymer sandwich with aluminum honeycomb core
CTE = Composite Technology for Exploration project
FEM = Finite Element Model
SW = SolidWorks 3D CAD Design Software
MTH = Mars Transit Habitat
PAF = Payload Attached Fitting
CG = Center of Gravity
ECLSS = Environmental Control and Life Support System
IDA = International Docking Adapter
TRL = Technology Readiness Level

I. Introduction

Surpassing the previous year's record of 103 launches to orbit, in 2020 alone there were 112 successful orbital missions.[1] Looking to generate returns on investments, launch companies are optimizing and increasing their capabilities to reach Low-Earth Orbit (LEO) and Geostationary Orbit (GTO). This industrial growth is largely dedicated to satellite and large constellation deployments as well as resupply missions to the International Space Station (ISS). But even though aerospace companies and international space agencies are increasing their launch vehicles' payload capabilities, cargo and crew transportation services, the number of new pressurized space stations has not increased in decades.

With the Commercial LEO Destinations (CLD) project[2], the NASA Human Exploration and Operations (HEO) Mission Directorate is looking to sponsor the development of a more robust private LEO economy and award contracts to the generation of new private space stations. In looking to maintain continuous US human presence in orbit by transitioning capabilities from the ISS to future platforms, the agency is addressing the space industry demand for in-

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space production, private astronaut missions, crew accommodations, commercial use payloads, human research, physical and biological research, and research and development of applications. With the need of economic expansion in LEO, the purpose of the CLD is to simulate private industry development of free-flying orbital destinations capabilities and concepts.[2]

Understanding the growth of the satellite industry along with the need of new concepts for LEO free-flying destinations, as stated in the CLD objectives, this paper looks to expand on a concept that merges both fields. As a precedent, SpaceX has proven that solving objectives in both human exploration and satellite deployment markets with the same launch vehicles can have highly effective outcomes. With its Falcon 9 vehicle, SpaceX has taken a lead in the commercial satellite deployment market while at the same time efficiently providing crew and cargo capabilities to the ISS.[1] Instead of having to develop three completely separate launch vehicles for their satellite deployment capabilities, crew transportation and cargo transportation to the ISS, utilizing the common Falcon 9 architecture for the different mission helped in reducing development time and overall costs.

If the rest of the launch vehicle industry where to transition its preexisting satellite deployment infrastructure to space exploration capabilities, just as SpaceX has done with Falcon 9, the LEO economy can widely benefit. This paper looks to advance on proving a design methodology of converting payload fairing geometries into pressurized LEO habitats, or PFSS (Payload Fairing Space Station).[3] Expanding on the proposal presented at ICES 2019, *Payload Fairing Geometries as Space Stations with "Flexible Plug and Play" Rack System*[3], this paper focuses on presenting a preliminary mass study to validate that current satellite-intended vehicles could be utilized for habitat deployment.

Commonly flown vehicles such as SpaceX's Falcon 9 and Arianespace's Ariane 5 utilize CFRP-AI/HC (carbon fiber reinforced polymer with aluminum honeycomb core) as their payload faring's main material.[4,5] Functioning as important materials that effectively reduce overall structural weight, research is being conducted into composites like carbon fiber reinforced polymers with honeycomb core as the main external shell of lighter space exploration habitats. This paper looks to combine composite habitat manufacturing precedents and research and adapt it to the main proposal of PFSS without changing the external aerodynamic shape of the vehicle. This proposal is not the reuse of fairings, but a methodology of using the preexisting infrastructure of fabricating launch vehicle fairings, redesigned for pressurized habitats.

In Reference 3, Table 1 was constructed to provide initial proof that if previous space station modules and current ISS modules where to be launched using today's capabilities, they could in theory reach LEO. The paper separated launch vehicles into three different categories: Type A, Type B, and Type C, where the first type considers mostly already launched vehicles purposed for mainly commercial satellites, resupply and crew delivery missions to ISS maintaining a <31t range. Given that these smaller capacity vehicles amount for most of today's 100+ launches to orbit, the methodology of PFSS will focus on the Type A Ariane 5 fairing geometry as validation.

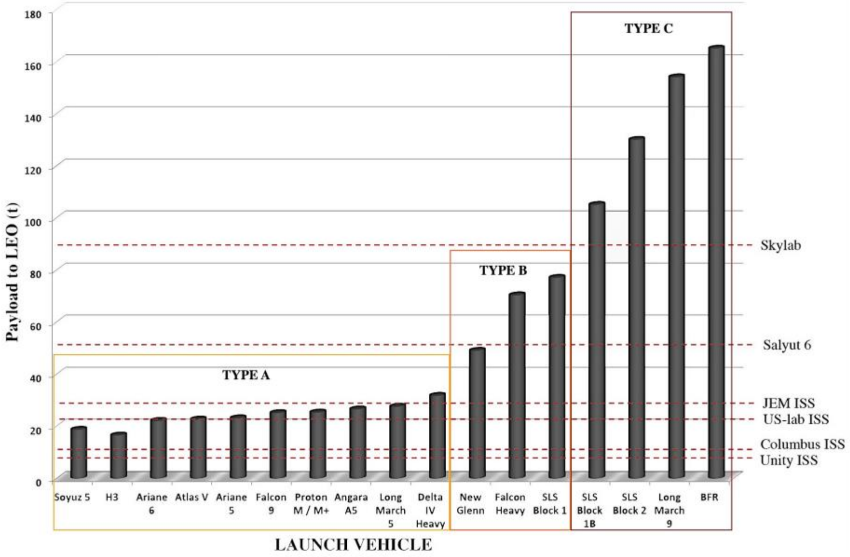


Table 1. Launch Vehicle Capabilities[3]

It is key to note that in order for payloads like satellites to reach their intended orbit, fairings are jettisoned once in orbit for shedding weight purposes. Designing this part of the launch vehicle to stay together by not releasing the fairing halves, would equate to a one-to-one mass penalty. In order to provide preliminary mass validation for having fairings as part of the pressurized structure, the mass of the main structural components of the habitat need to be defined and kept under the launch vehicle's maximum capability. As in the previous ICES 2019 paper, this proposal utilizes Arianespace Ariane 5 payload fairing geometry and its 20,000kg maximum capacity to LEO[3,4]. In order to approach this problem, it is important to ask the questions: what is the minimal weight, systems and volume necessary to have a single element space station deployed in one launch? And can these systems be adapted to fairing geometries whilst still maintaining their total mass under the launch vehicle capability? If so, then a preliminary ratio be generated between a vehicle launch capacity to the weight of having its fairing as pressurized habitat.

A. Vision

Provide methodology to diverse launch vehicle manufacturers for designing their fairing geometries as pressurized habitat structures.

B. Mission

Provide preliminary mass validation to the proposal that launch vehicles intended for deploying satellites can be redesigned as pressure vessels and reach LEO. Understanding the mass, application and physical properties of the composite habitat structures can allow for a preliminary design approach to using TRL-9 payload fairings as the habitat's main acreage panels.

C. Goals and Objectives

This proposal looks to adapt current manufacturing methods used for composite habitat concepts and other aerospace applications as a conceptual validation. The research into composite materials was defined by two main references: the NASA Langley study *Application of Composite Materials to Reduce Mass of Internal and Exploration Habitat Structures*[6] and the Composite Technology for Exploration (CTE)[7] project. From these two composite research proposals, key elements were abstracted to the PFSS concept.

Following the design proposed in Reference 3 and along with the abstracted elements of Chapter II a Finite Element Model (FEM) is proposed in Chapter III. This FEM will be used for future stress analysis studies and to serve as a baseline for simulations of the structure in different the physical environments. Chapter III also defines the general architecture of the PFSS, following mass reducing techniques with the total number of necessary acreage panels and joints required in the assembly process. The FEM provides figures for the preliminary mass calculation of the materials conducted in SolidWorks CAD Software (SW) for the Type A Ariane 5 Fairing Geometry.[8] Defining these preliminary values and figures for the Ariane 5 vehicle will generate a scalable ratio of launch vehicle capability to LEO to the weight of having its fairing as a pressure vessel in future work. The structure of this preliminary weight study proposal is defined in figure 1.

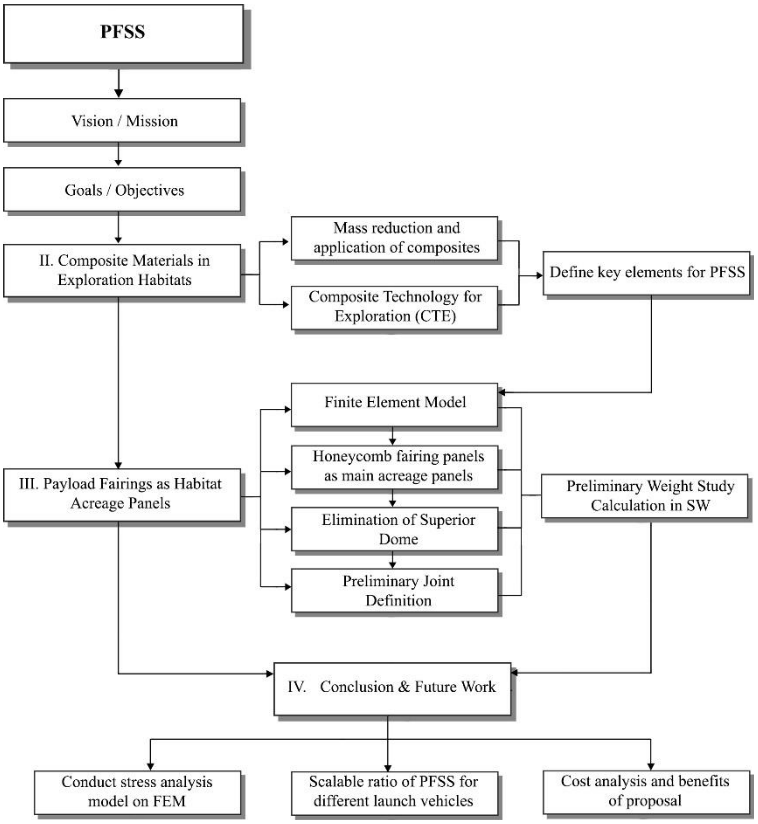


Figure 1. Paper Structure

II. Composite Materials in Exploration Habitats

The launch vehicle capability is one of the main constraints in space missions, so producing optimal designs with materials that reduce weight while maintain their physical capabilities is key to development and affordability. In the past decades, we can find a growth in the number of systems and aerospace applications that utilize composite materials.[6,7] Even though many composites are still in the certification phase for human-rated habitats, resolving inherited requirements and facing challenges in manufacturing large scaled sealed structures, their strength-weight ratio and mass saving benefits are still moving these proposals forward. NASA Langley studies like *Application of Composite Materials to Reduce Mass of Internal and Exploration Habitat Structures*[6] presented at ICES 2019, provides important research into the considerations of composites habitats in comparison to traditional metallic structures. Given that Langley study targeted >20% mass savings, provided valuable footnotes and followed the NASA Strategic Roadmaps TA 12.1.1, TA 112.2.1, this paper adapts many of the same strategies to the PFSS proposal.

A. Application of composite materials to reduce mass of internal and external exploration habitat structures[6]

The study presented in ICES 2019 defines that the designs of composites have faced challenges in certification, damage tolerance, inherited requirements, lack of early consideration of joints, and challenges in the manufacturing of large scaled sealed structures.

The human-rated certification challenge is the main hurdle to composite habitat, but following the NASA roadmaps, these concepts will eventually become constant in the industry. Understanding the knowledge gaps in these technologies, the study generated quantitative mass and structural data to different materials and provided research into joint consideration. These variables were defined in a conceptual MTH (Mars Transit Habitat) composite design. The paper provided a trade study on the structural composite concepts: stiffened panel (TRL 9), composite facesheets sandwich with a lightweight core (TRL 9), most recent generation of stitched composites PRESEUS (TRL 6), and 3-D fabric preforms (TRL 3). The study also defined the main habitat structural features and associated design requirements: acreage structure, domes, secondary structure, hatch interface panels hatches/docking mechanisms, and internal system support structure (Figure 2).[6]

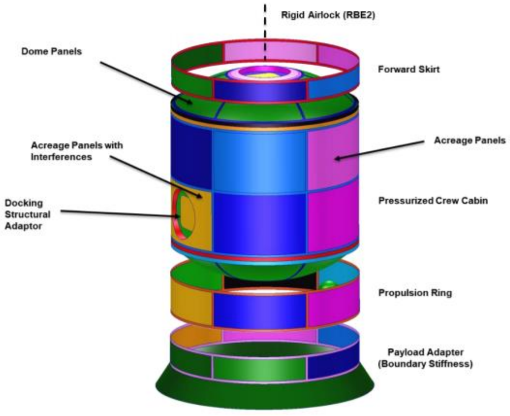


Figure 2. MTH Finite Element Model[6,7]

This study concluded that the most mass-efficient structural composite for the main acreage panels was the facesheets sandwich with a lightweight core. Given that the payload fairings material in Ariane 5 and Falcon 9 is composite facesheets sandwich with aluminum honeycomb core,[4,5] these conclusions provide a validation to the PFSS proposal on the main halves as the acreage panels of the habitat. Also, given that one of the main challenges of composite designs is the manufacturing of large scaled structures, utilizing the flight proven CFRP-AI/HC payload fairings provides a direct application answer.

On Chapter III, the paper's PFSS proposal takes this baseline architectural composition of parts and follows the redesign distribution to the geometry of payload fairing presented in Ref 1. This allows for the definition of an analogous finite element to be developed in SW and in turn, provide a preliminary mass definition.

B. Development of composite sandwich bonded longitudinal joints for space launch structures[7, 9]

While utilizing composites in the different structures provide weight savings, the full savings are realized by providing composite bonded joints. In defining PFSS main acreage panels and dome panels in Chapter III, the definition of the joint technology will follow the Composite Technology for Exploration (CTE) project.[7,9]

The CTE demonstrated approaches to design analysis and testing of acreage panel joints and circumferential joints for SLS-like structures. In studying these bonds in a SLS Payload Attach Fitting (PAF), it was concluded that for longitudinal acreage sandwich panels, utilizing a double lap joint-configuration was most effective. For the circumferential joints, the joint that connects domes to side acreage panels, a 3-D woven fabric and pi-preform was used to create a y-joint.[9] As concluded in Ref. 2, the CTE project demonstrated excellent manufacturing and damage tolerance for the double lap joint. Even though this project provided initial load variables to using composite joints in large launch vehicle structures, further analysis tools would have to be created for internal pressurized volume variables.

Taking the main joint design principles and fabrication principles from the CTE Point Design, these ideas will be provided on the two main payload fairings longitudinal sections and as well as in the connection of the inferior dome and superior bulkhead. The longitudinal and circumferential joints mentioned will be adapted to the PFSS proposal in Chapter III.

III. Design of Payload Fairings as Habitat Acreage Panels

One of the initial goals of the study is to maintain the mass of the structure under the Type A Ariane 5 launch vehicle max capability of 20,000kg to LEO and to account for a one-to-one mass penalty of not releasing the fairing halves[5,10]. Following the research conclusions of composites in Chapter II and through the geometric design techniques expanded in this Chapter and in Ref 3., there was initial optimization the number of parts and joints to the maintain positive preliminary mass validation of the structure. The distribution of systems id defined by the assembly sequence, which as defined in Ref 1, respond to both launch and ascent center of gravity CG variables and on-orbit deployment sequence (Figure 3).[3]

The Finite Element Model (Section A) was modelled in SolidWorks 3D CAD Design Software (SW). This allowed the preliminary mass figures to be calculated with specific measurement tools in the software.[8] The PFSS Finite Element model defined the figures: honeycomb acreage panels, superior and inferior International Docking Adapters (IDA), beam rough estimate, and pressurized volume atmosphere calculation. These figures together provided a total weight of 4489.84kg and a 1 to 1 mass penalty to the launch vehicle capacity, by the maintaining fairing halves, of 2023.11kg.

Other systems that are necessary for a functioning habitat will be weighted in posterior studies of this concept. Following Ref 1., these systems include those such as power & attitude control systems, ECLSS & H_2O, logistic and hygiene spaces, and external solar arrays, radiators, Xe tanks and thrusters. The initial numbers provided in this preliminary SW study to structural variables provide an initial validation figure, that can in turn provide a ratio to other launch vehicle fairing structures.

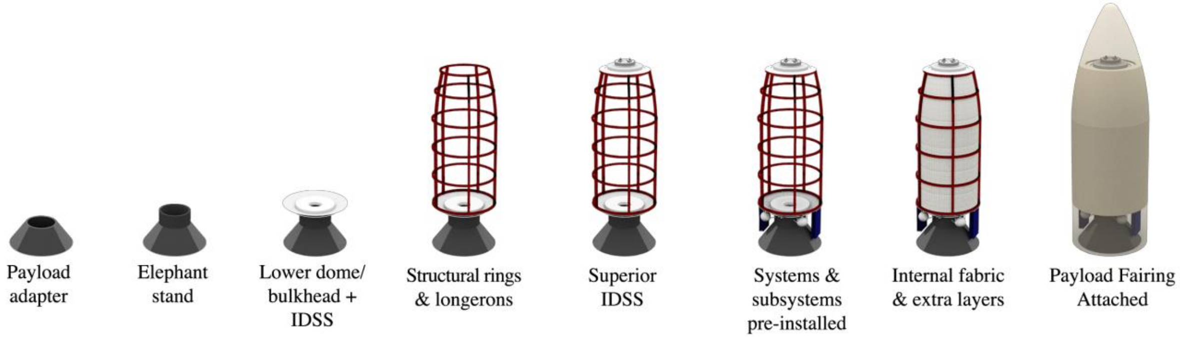


Figure 3. PFSS Assembly Sequence[3]

A. PFSS Finite Element Model

Ref. 3 states *"complying with redundancy and risk mitigation requirements, the aerospace industry has been applying a "structure inside structure" strategy to habitat design with the sizing of habitat modules and structures to fit internal dimensions of payload fairings. This paper investigates the idea of removing the internal module structure to decrease overall weight and facilitate more pressurized volume for diverse missions."* Replacing the conventional internal shell with a composite acreage panels, just as in the composite MTH proposal, can initially reduce the mass of the structure, while providing extra usable volume. The fairing weight and size figures were provided in the *Ariane 5 User's Manual*.[5]The complete fairings halves are weighed at 2675kg, and with a SW calculated surface area of 263.04m^2, the Unit wt. for was 10.17kg/m^2 for the side acreage panels 1 and 2. As depicted in the methodology of Ref 1., the fairing cap and lower fairing halves will be jettisoned to the remove the extra weight of 781.36kg, this in turn defined the main acreage panel sizes. Along with the FEM defining initial weight figures in SW, the CAD model of PFSS will be used for further stress analysis studies. This will also to serve as a baseline for simulations of the structure in different the physical environments such as ascent and in-orbit vacuum conditions.

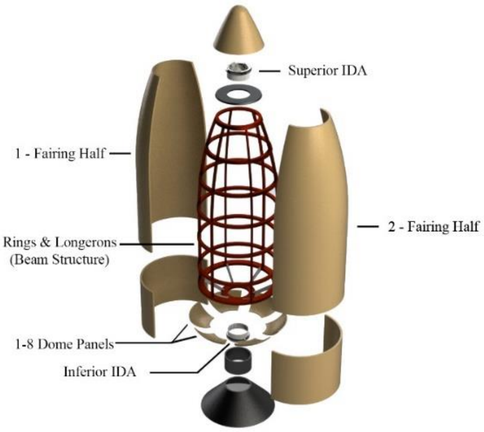


Figure 4. PFSS Finite Element Model

B. Honeycomb fairing panels as habitat main acreage panels

The MTH finite element model (Figure 2) defines a total of 12 acreage panels, that all have to be fabricated separately and the joined together. Added to this, the concept has 16 panels that compose the superior and inferior dome structures. The classic idea of having an external shell of multiple acreage panels is restructure by the PFSS design. Having to provide and manufacture 12 different curved composite panels and then join them, as expanded in Chapter II.B., requires long manufacturing time and extra added weight. By its design distribution, PFSS would optimize the manufacturing development time by just having 2 large acreage panels (Figure 5).

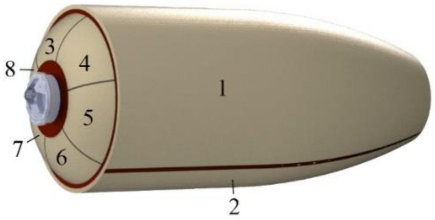
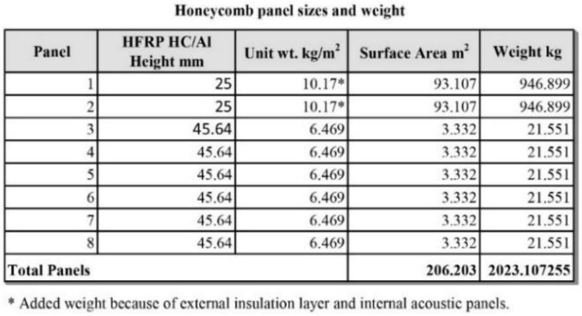


Figure 5. Honeycomb Panels

Along with this optimization factor, these fairings already have an industry established manufacturability, allowing for testing and certification time to be shortened. Along with the optimization of the side acreage panels, Section C expands on how the superior dome can be eliminated by the inherent geometrical aspects of a fairing shape, allowing for 8 panels instead of the compared 16 of the MTH. The bottom dome composite panels, were defined by referencing the study conducted by NASA Langley[6].

The main acreage panels were modelled in SW, allowing for a preliminary weight calculation. Table 2 provides the initial calculation to the Ariane 5 PFSS concept. With 2023.11kg, the structure panels account for just 10% of the capacity to LEO of the Ariane 5.



Honeycomb panel sizes and weight

Panel	HFRP HC/Al Height mm	Unit wt. kg/m^2	Surface Area m^2	Weight kg
1	25	10.17*	93.107	946.899
2	25	10.17*	93.107	946.899
3	45.64	6.469	3.332	21.551
4	45.64	6.469	3.332	21.551
5	45.64	6.469	3.332	21.551
6	45.64	6.469	3.332	21.551
7	45.64	6.469	3.332	21.551
8	45.64	6.469	3.332	21.551
Total Panels			**206.203**	**2023.107255**

* Added weight because of external insulation layer and internal acoustic panels.

Table 2. Honeycomb Panel Sizes and Weight

C. Elimination of Superior Dome

Figure 6 illustrates how all fairings can be geometrically abstracted as a series of circles (cylinder) that decrease in diameter, as they get closer to the top. For aerodynamic purposes, above the cylinder, the shape becomes an ogive or paraboloid. Given that all shrouds maintain these relative geometries, as you reach the top of the structure, eventually you will all have a 3.5 m diameter. This diameter is of importance because it can support a complete superior International Docking Adapter (IDA) with a Bulkhead. The loads of this 526kg structure[11] would be distributed along the longerons, to not add weight to the fairings.

This principle of having a superior docking port at the top of the fairing structure can be validated with the SpaceX Dragon vehicles. One of the main physical reasons SpaceX has achieved commonality between its Falcon 9 vehicle and Cargo Dragon and Crew Dragon vehicles external shape, is because these transit vehicles follow the top geometry of a fairing. Applying these principles to the PFSS allows for optimal double Egress/Ingress.

As stated in Section B, this inherent geometrical aspect of the fairing would eliminate the need for a superior dome structure composed of beams, curved longerons, and the outside acreage panels. Just as in the case of the side acreage panels, optimizing the count of panels to be manufactured equates to lower manufacturing and assembly time with the joints.

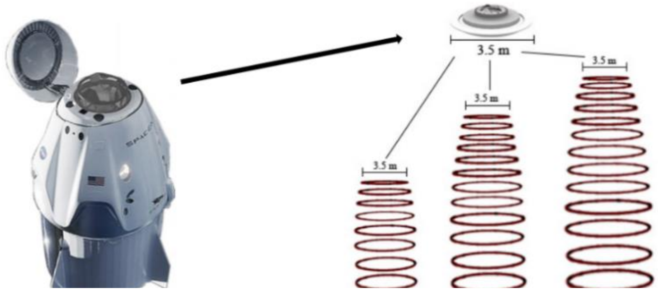


Figure 6. SpaceX Dragon Superior IDA Concept Reference

D. Preliminary Joint Definition

The referenced MTH design accounts for a total of 12 longitudinal double lap joint-configuration for its side acreage panels and 5 circumferential joints of its curved panels.[7] Joints account for an extra mass loads and assembly processes that are still being studied in composite habitat proposals. Understanding this weight aspect, the PFSS design of less acreage panels provides in turn a reduced number of joints: 2 longitudinal and 3 circumferential. Having a reduced number of joints allows inherently improves the potential risks to the habitat, given that less systems on the external shell of the habitat, the less probable is for one to fail.

For ideas in specific manufacturing processes for longitudinal and circumferential joints of sandwich composite acreage panels, the studies of *Composite Technology for Exploration (CTE)*[9] project and *Adhesively bonded joints in composite materials: an overview*[12] serve as initial guides. Further studies of PFSS will provide more exact design and weight figures when applying these figures to the adaptable methodology.

E. Preliminary Mass Figures

The weight of the CFRP-Al/HC acreage panels, along with the other preliminary mass figures: beams, the superior and inferior IDA[11,] and pressurized atmosphere and volume were defined in a *Multi-body Parts* design in SW. By defining global variables to the different systems of the adaptable fairing geometry, allows for optimality generating surface area, mass, density and volume figures to different materials. In Table 2, we found how the weight variables were defined for the honey acreage panels and now Figure 7 provides the atmospheric weight (14.7 psi) to a Ariane 5 PFSS volume of 237.78m^3.

Ref. 6 provides a sizing of the composite MTH FEM following a HyperSizer Composite Mass Analysis process were the masses for primary and secondary structures are defined. In this analysis, the composite beams were 57% of the mass of the acreage panels.[6] Following this ratio, the Ariane 5 PFSS concept utilizes this figure for a rough estimate sizing of its own beams and longerons.

```
Mass properties of Volume Calc
     Configuration: Default
     Coordinate system: -- default --

Density = 1.10 kilograms per cubic meter

Mass = 261.56 kilograms

Volume = 237.78 cubic meters

Surface area = 225.51 square meters

Center of mass: ( meters )
        X = 0.00
        Y = 8.66
        Z = 0.00
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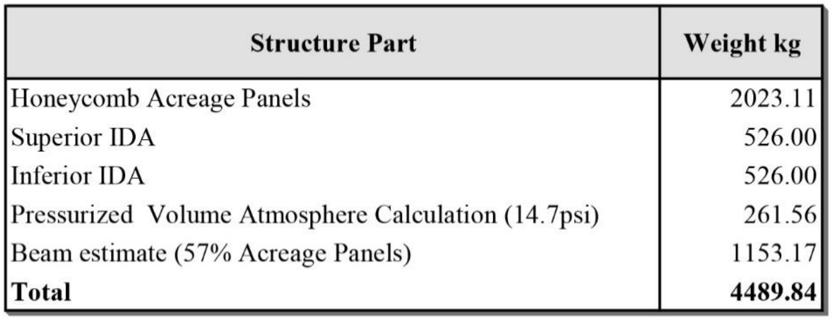
Figure 7. SW Air calculation of Ariane 5 PFSS

With the FEM providing the distribution and size of the honeycomb acreage panels (2023.11kg), the location of a superior and inferior IDA (526kg/ea.), a rough structural beam estimate and the calculation of the atmospheric weight for the Ariane 5 PFSS (1153.17kg), a preliminary mass calculation was conducted in SW for the composite external structure of the habitat.



Structure Part	Weight kg
Honeycomb Acreage Panels	2023.11
Superior IDA	526.00
Inferior IDA	526.00
Pressurized Volume Atmosphere Calculation (14.7psi)	261.56
Beam estimate (57% Acreage Panels)	1153.17
Total	**4489.84**

Table 3. Preliminary Mass Calculation in SW

IV. Conclusion

In subtracting the calculated mass 4489.84kg of the finite model figures, the Type A launch vehicle would still have 15,510.16kg to dispose to the other necessary systems (Chapter 3) of the habitat. These other habitat variables will be studied and weighed as part of the next steps in the PFSS proposal.

One of the important objectives of this ongoing research is to define what is the minimum capability of a launch vehicle necessary to get to orbit as a PFSS and provide a scalable ratio to other launch vehicle fairing architectures. From the preliminary mass figures, we can provide the requirement that a vehicle must have at least 4.5t capacity to LEO. In next studies, weighing the minimum systems necessary for a functioning LEO single element space station, will define what requirements and characteristics are necessary for a launch vehicle to qualify as a PFSS. A ratio of mass savings (kg/m^3) will be developed and compared to conventional launch vehicle with an internal aluminum habitat concept.

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