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Morphology of Polyhedral Space Habitat Modules

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Abstract

The form and function of semi-permanent space habitats has not much changed in the past fifty years. Large space habitat projects remain logistically daunting and unpalatably expensive, especially for a questionable return on investment.

This paper explores the particularities of various polyhedrons for use in a new kind of space habitat typology. The goals of exploring polyhedral modules are to mitigate many of the hitherto unrecognized drawbacks and limitations of the extant cylindrical habitat typology, implement a flexible system for creating large-volume habitats, and provide a relatively low-risk testbed for large habitat construction in orbit. As noted in this paper, the rhombic dodecahedron stands out as a superior shape in comparison to other comparable shapes when structure, economy, and other geometric considerations are taken together in aggregate.

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1. INTRODUCTION

Since the beginning of the semi-permanent space habitat industry, the architecture has followed a general pattern. The habitats have all been fully assembled, able to fit inside the fairings/cargo holds of the transit vehicles of their time, and static within their boundaries (that is to say they do not move or transform). The size and shape of these habitats have been limited by the transit capability available and the placement of apertures have been limited by where and whether they are included in the final design.

This document aims to provide a way forward for the eventual construction of large-volume habitats without the decades-long, protracted construction projects implied by more ambitious space habitat concepts such as the O'Neill cylinder, Stanford torus (Johnson and Holbrow 1977), and even Kalpana One (Globus, et al. 2007). This somewhat more modest approach would provide an economical testbed for space-based construction projects. To achieve these goals, this document investigates which polyhedral shapes offer the most advantages and the fewest drawbacks. This document also explores topics adjacent to polyhedral habitat engineering such as deployment, radiation protection, engineering, and architectural considerations.

2. DEFINITION OF TERMS

dihedral angle

the angle formed by the intersection of two planes

plesiohedron

a space-filling polyhedron that can fill three-dimensional space with copies of itself with no overlap or gaps

space habitat

an environment in space capable of sustaining prolonged human habitation

galactic cosmic radiation (GCR)

radiation comprised of high-energy protons and atomic nuclei originating from outside the solar system which move through space at nearly the speed of light

solar particle event (SPE)

occurs when particles (mostly protons) emitted by the Sun become accelerated either close to the Sun during a flare or in interplanetary space by coronal mass ejection shocks

3. MORPHOLOGY

3.1 OVERVIEW

Not all polyhedrons are equal in their suitability to space habitat design. This section covers the topics of structure, economy, and plesiohedrons to determine which shapes may be worth pursuing in initial concepts for polyhedral space habitats. The shapes that will be compared in this paper are the tetrahedron, cube, octahedron, dodecahedron, rhombic dodecahedron, and icosahedron. Each of these shapes are polyhedrons with homogenous faces and dihedral angles.

3.2 **STRUCTURE**

The forces acting on an internally pressurized structure in the vacuum of space are entirely different from those same structures on Earth. In a vacuum, all force vectors are centrifugal as the internal air pushes outward on all sides of the volume. This in turn means that all forces are reconciled as tensile forces acting tangentially to the surface of the volume. This is convenient from a structural standpoint as tensile forces can be carried through much smaller profiles of material than compressive forces. Stiffness and stability are not as essential in microgravity (in contrast to terrestrial structures). These forces can even be carried through low-strength bulk shielding material by way of slender, high tensile strength material such as titanium in the form of embedded cables or mesh.

When pressurized internally, a polyhedron will carry tensile forces along its faces and joints. Depending on the construction, the joints are the most likely location of pressurization-related failures. The forces are also the most concentrated at the joints, acting on a smaller cross-sectional area. The relationship between the maximum tensile forces along the faces and the maximum stress at the joints is not fixed, but rather dependent on the convex dihedral angles of the shape, where *0° < angle < 180°*. At acute angles there are greater stresses on the joints due to the force vectors of the adjacent faces being more opposed to each other. This additional opposing force on the joints beyond that of the tension carried by the faces contributes nothing to the strength of the structure[1]. At more obtuse angles, forces at the joints asymptotically approach the tensile force carried through the faces. This relationship gives us a *joint stress factor* for the angles of a polyhedron (see Figure 1), where joint stress equals face tension when the dihedral angle is 180° and joint stress is maximized when the dihedral angle approaches 0°.

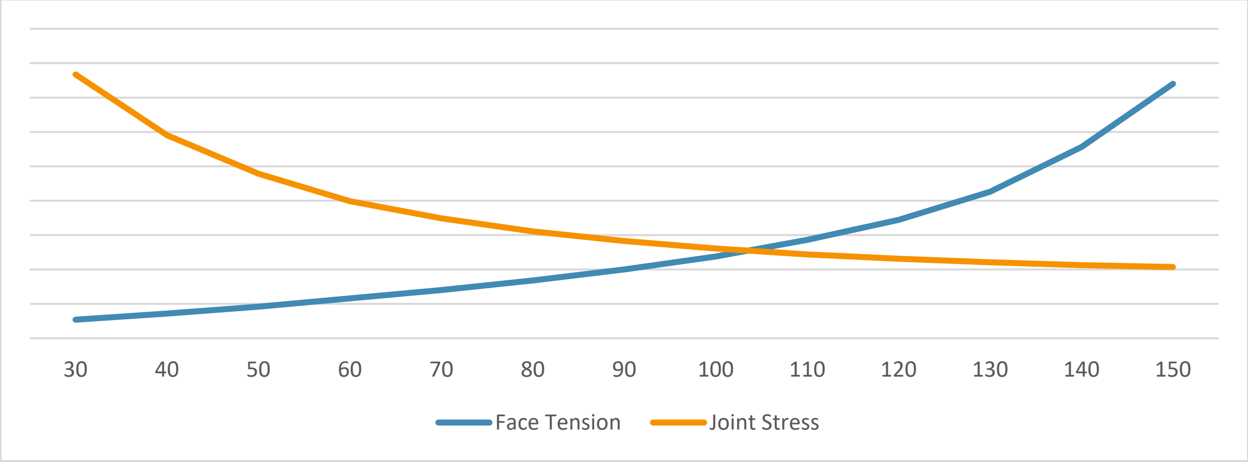

Figure 1: Relationship between maximum face tension and joint stress as a function of dihedral angle (relationship only, no comparative units are implied).

[1] There is a non-structural opportunity for these opposing forces to be utilized for benefit in a compressive gasket application. The tensile forces could be transformed into strong compressive forces on the gaskets at the joints. See Figure 12.

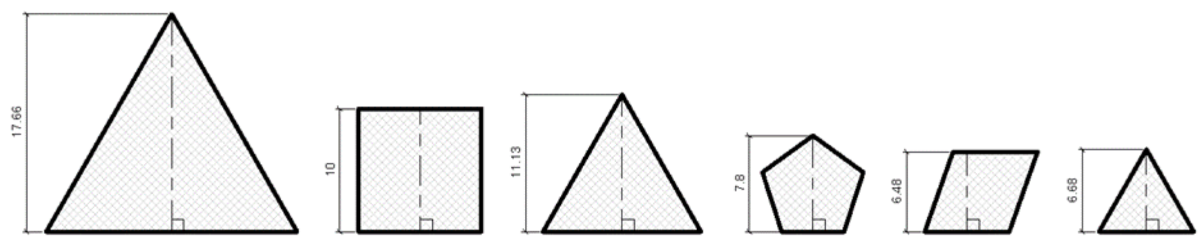

Figure 2: Face sizes for polyhedrons with equal volume (1,000 cubic units). From left to right: tetrahedron, cube, octahedron, dodecahedron, rhombic dodecahedron, and icosahedron.

While the dihedral angle informs the relationship between the face tension and the joint stress, it cannot alone describe the actual forces on the faces and the joints. For example, though a tetrahedron and an icosahedron share the same shape for their faces (an equilateral triangle), for a given volume the area of a face of the tetrahedron will be vastly greater (7x) than that of the icosahedron. This inequality of face size leads to a difference of forces at their joints, with the larger face corresponding to a greater force as more force from internal pressure builds up before reaching the joints. The maximum tension at the edge of the face can be estimated using the maximum length along a face perpendicular to a joint[2] (see Figure 2).

It is these two aspects (dihedral angle and face geometry) that determine the maximum stress at the joints for a given internal pressure of an evenly pressurized polyhedron. The maximum stress can be

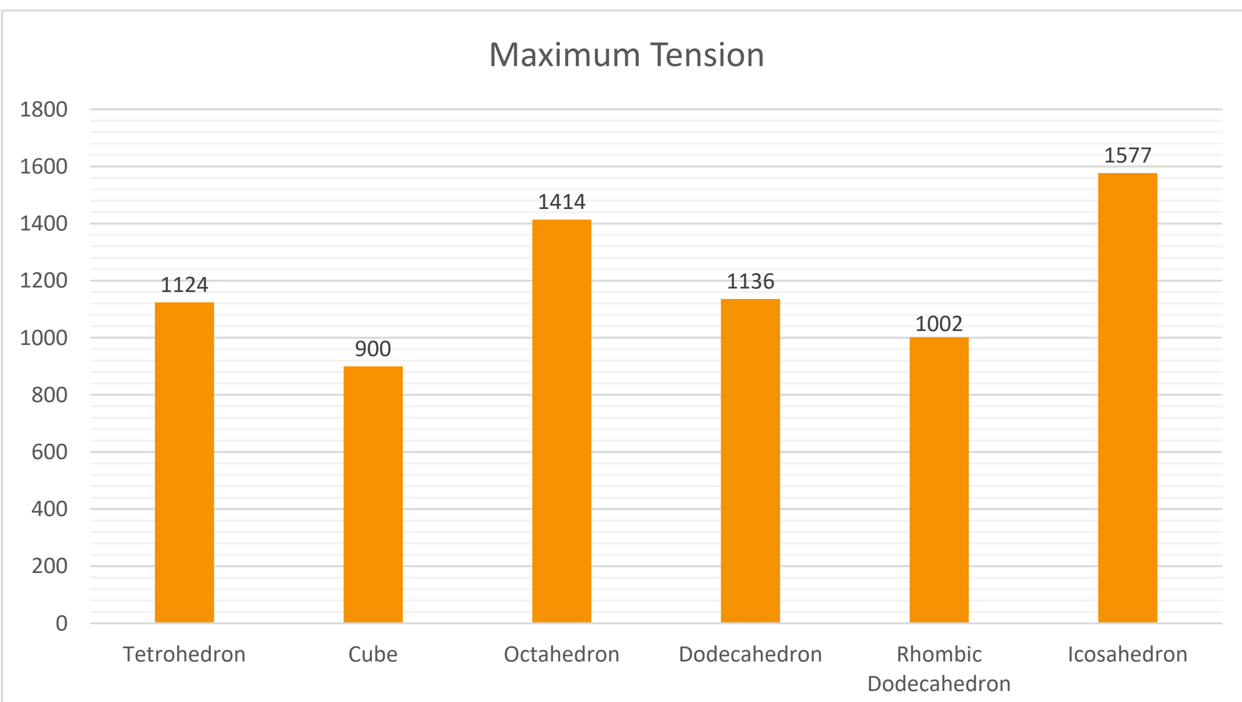

Figure 3: Max tension along faces of geometries.

[2] This is of course a rough estimate given by the span of the face and a constant, equally distributed pressure. Structural simulations would need to be conducted for more accurate figures.

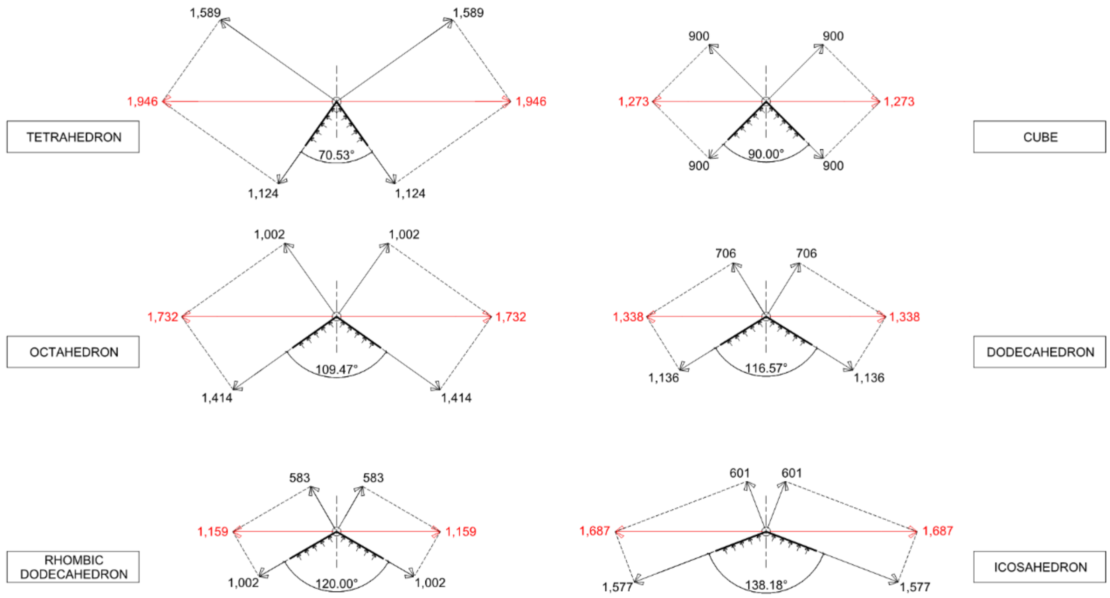

Figure 4: Comparative dihedral angles, face tensions, and joint forces (red) for various polyhedral figures under internal pressure.

estimated using the product of the maximum tension at the edge of the faces (dependent on the shape of the polyhedron, see Figure 3) and the joint stress factor of the dihedral angles. Figure 4 illustrates the outward force caused by the internal pressure (upper), the tension along the faces (lower), and the joint stress (red) for various shapes.

3.3 Economy

The economics of space habitats, as with many things, can be viewed through the lenses of minimizing cost and maximizing value. When considering these principles as they relate to the shape of a polyhedron, the main considerations are the volume to surface area ratio, the variety of faces, and the stowed volume to deployed volume ratio.

3.3.1 Volume to Surface Area Ratio

A polyhedral habitat module would be comprised of multiple structural faces, the minimum number of which being four (a tetrahedron) while the maximum number is limited only be practicality. Given that the shielding of a habitat should typically be of even thickness on the exterior of the habitat, the shielding mass of a habitat can be ascertained as a function of the surface area of the habitable volume. Since mass is costly to send into orbit, surface area should be minimized as much as practical. For a given volume, the relative surface areas for various polyhedrons are given in Figure 5. The shapes with the lowest surface area (cost) to volume (value) are those with the greatest number of faces (those most resembling a sphere). While keeping surface area low is worthwhile, it is important to note that there are diminishing returns to adding more faces if the only reason for doing so is to lower the surface area. For example, the more faces there are, the more potential points of failure and construction complications there may be.

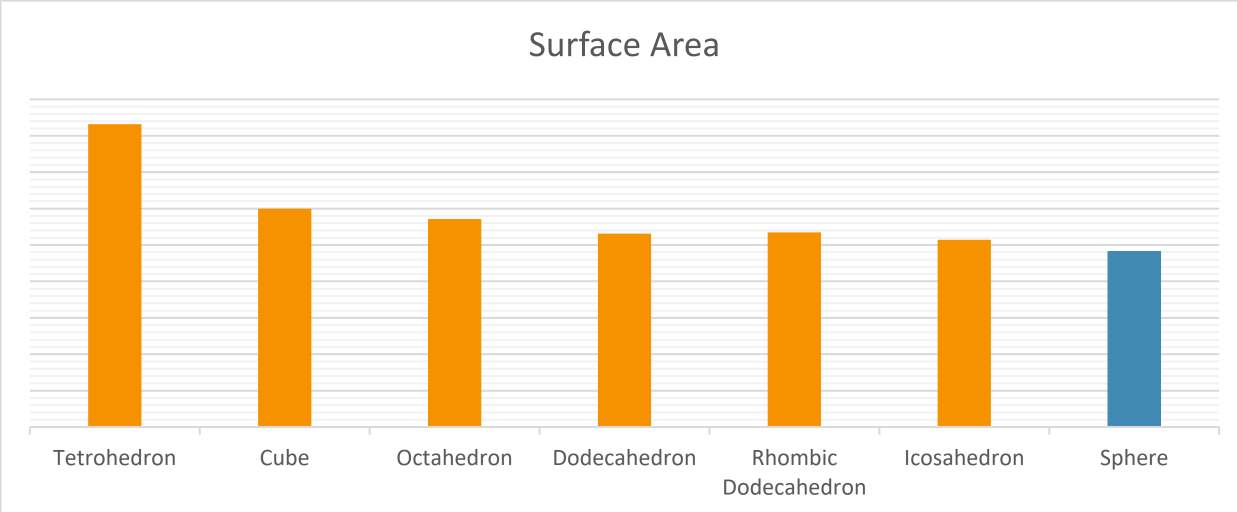

Figure 5: Relative surface areas for a given volume.

3.3.2 Variety of Faces

Each unique type of face panel in a polyhedral habitat module needs to be designed and engineered. Once this process has been completed the module can be duplicated indefinitely. The more types of panels (size and shape) are required, the more time and resources need to be spent on structural simulations and engineering. In addition, these panels may require different components from one another, they are not interchangeable with each other, and their structural interactions are more complex as the panel sizes and dihedral angles would be different from one another. Such differences mean that one panel type would have less structural capacity than the other(s), allowing either a weak point at worst or a structural inefficiency at best. In this respect, the most economical shape would be one with a single face type, such as is the case with the platonic solids and other many other shapes. This would increase efficiency, predictability, and interchangeability.

3.3.3 Stowed Volume to Deployed Volume Ratio

The faces of a habitat of appreciable size must be packed flat together inside a rocket fairing. Many polyhedrons may not be space efficient to stow in a cylindrical fairing due to the size and shape of their constituent faces. For example, the large size of a tetrahedron's faces makes for an inefficient component to stow as the maximum face dimensions limit the maximum deployed volume. These maximum face dimensions can be either the circumscribed diameter of the faces or the short width of the faces; the circumscribed diameter applies to faces whose axes are oriented parallel to the axis of the rocket fairing,

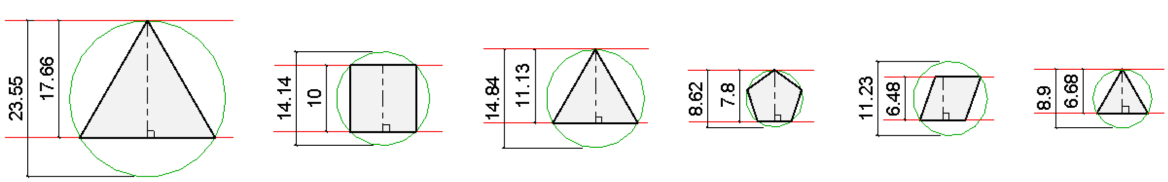

Figure 6: Representative face areas for polyhedrons of 1000 cubic unit volume (from left to right: tetrahedron, cube, octahedron, dodecahedron, rhombic dodecahedron, icosahedron). The circumscription is shown in green and the minimum width is shown in red.

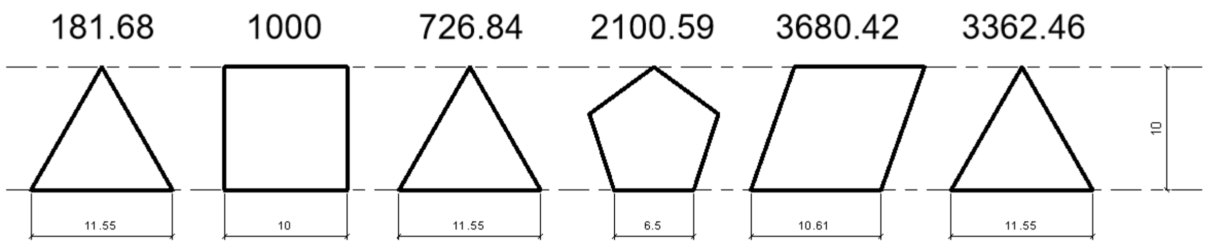

Figure 7: Representative deployed volume for polyhedrons with faces fitting into a fixed fairing diameter of 10 units when oriented perpendicular to the axis of the fairing (from left to right: tetrahedron, cube, octahedron, dodecahedron, rhombic dodecahedron, icosahedron).

while the short width applies to faces whose axes are oriented perpendicular to the axis of the rocket fairing. The circumscribed diameter and minimum width for various polyhedrons are shown in Figure 6. Intuitively, the minimum required fairing diameter decreases as the number of faces increases. There is an exception with the rhombic dodecahedron however, as the minimum width of the rhombic dodecahedron is less than that of the icosahedron. The relationship between fairing diameter and volume can be reversed to calculate the maximum deployed volume of polyhedrons for a given fairing diameter (see Figure 7). Comparatively, the rhombic dodecahedron provides the largest deployed volume for a given fairing diameter.

3.4 **PLESIOHEDRONS**

A plesiohedron is a class of three-dimensional solid shape which has the following attribute: three-dimensional space can be filled using only copies of the shape, having no overlaps and leaving no gaps. Simple examples of plesiohedrons include the cube (or any other rectangular prism), the hexagonal prism, the truncated octahedron, and the rhombic dodecahedron. In the context of space habitats, plesiohedrons offer several advantages over other polyhedrons including their ability to form contiguous structures, increase total effective shielding, and enclose contiguous volumes.

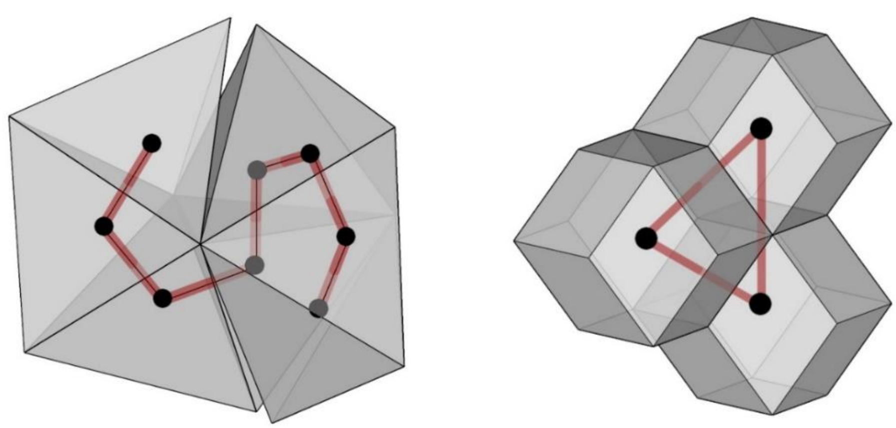

Figure 8: Comparison between connected tetrahedrons (left) and rhombic dodecahedrons (right). The grouping of tetrahedrons cannot create a looping pathway, while the rhombic dodecahedron creates a looping pathway with only three modules.

3.4.1 Contiguous Structures

One property of a plesiohedral lattice is that each face of any one module can abut a mirror image of another module. This attribute permits multiple pathways throughout a module complex. This stands in contrast to non-plesiohedrons, as even if they were connected to other copies of themselves, they could not have such a face congruency throughout the complex. For example, multiple tetrahedrons can be connected, but no looping pathways could be formed, as no face of any module would be coplanar to the face of another module (see Figure 8). The uniform congruency of plesiohedrons also allows complex-wide structural rigidity.

3.5.1 Module Configuration as Increased Shielding

Since the modules proposed here each have their own exterior shielding, the total effective shielding for each module becomes greater once the modules conglomerate as more shielding is effectively added to each of the modules. This added shielding applies to each module regardless of its position, as even modules on the exterior of a configuration will see shielding benefits in at least the direction of its nearest neighbor. Figure 9 illustrates this concept (abstracted in 2-dimensions) for GCR and SPE for a configuration of modules surrounding a single core module. As more modules are added, greater protection factors will be achieved for all modules.

3.5.2 Increased Volume

The opportunity to increase the occupiable volume of habitats does not stop at the individual module level. Plesiohedrons afford the opportunity to partition space contiguously. Many modules can be connected to form a shell of contiguous modules surrounding a hollow volume. The interior of this volume can be made air-tight and subsequently pressurized, effectively creating an even larger habitable

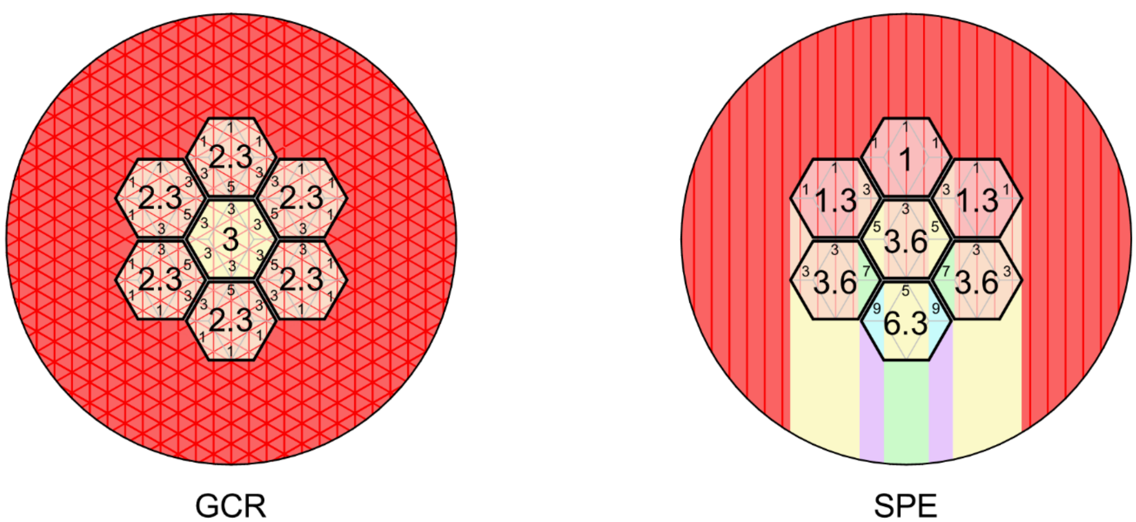

Figure 9: A cross-section of the same rhombic dodecahedron configuration for each of GCR and SPE. The small numbers indicate the effective number of shields against the radiation, while the large numbers indicate the aggregate protection for each module as the sum of its barriers. (Note: if the orientation of the vessel is not static relative to the sun, the average aggregate SPE protection of the exterior modules would be averaged over time to a value of 2.85).

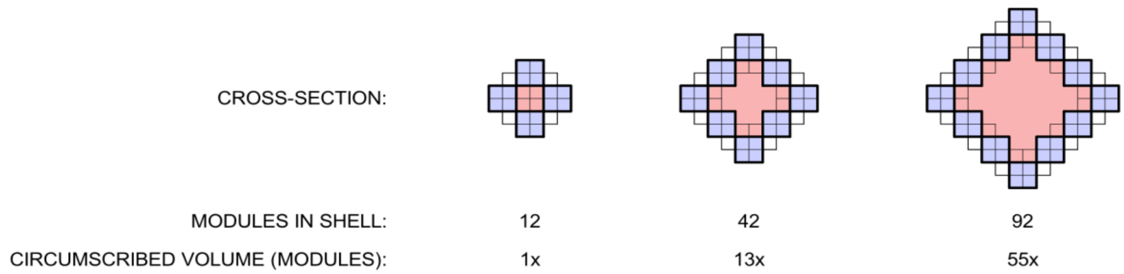

Figure 10: Shells of rhombic dodecahedron modules with open interior volumes. Cross section through module shown in blue. Open interior volume shown in red.

volume (see Figure 10). This method allows for large contiguous volumes to be constructed gradually in lieu of long construction projects requiring many thousands of hours of EVAs and remote robot arm control. Such interior spaces can be thought of as free habitat space requiring only the investment of enough modules to surround an appreciable volume.

4. Engineering

4.1 Overview

Polyhedral space habitats present many unique engineering challenges. This section addresses those of the deployment of the module (including challenges related to construction and pressurization) as well as modular inserts to the panel faces.

4.2 Deployment

One of the advantages afforded by fixed modules is that they require no complicated deployment once docked or berthed. Moving components are always going to carry more risk of failure than their stationary counterparts. Each additional dynamic system compounds this risk. Beyond proving functionality during testing, the secondary goal of designing a deployment system should be to minimize the risk of failure. Generally speaking, there is a relationship between the number of dependencies a system has and the risk of failure for that system. For example, a widget that is purely mechanical with relatively few components has a lesser risk for failure than a similar widget that has many components, relies on electricity to function, and is controlled by a cloud computer system. To minimize risk, a good solution to habitat deployment should have fewer dependencies than a conventional (read: overdesigned) solution. Ideally, the solution should rely on physics to achieve the goal passively, guiding a high-potential-energy state (stowed components) to a low-potential-energy state (deployed habitat).

In the case of a polyhedral habitat, deployment may come in multiple stages depending on the systems used. These stages may include:

1. Orienting the faces into the correct positions
2. Connecting the faces together structurally
3. Engaging an airtight seal against the vacuum of space

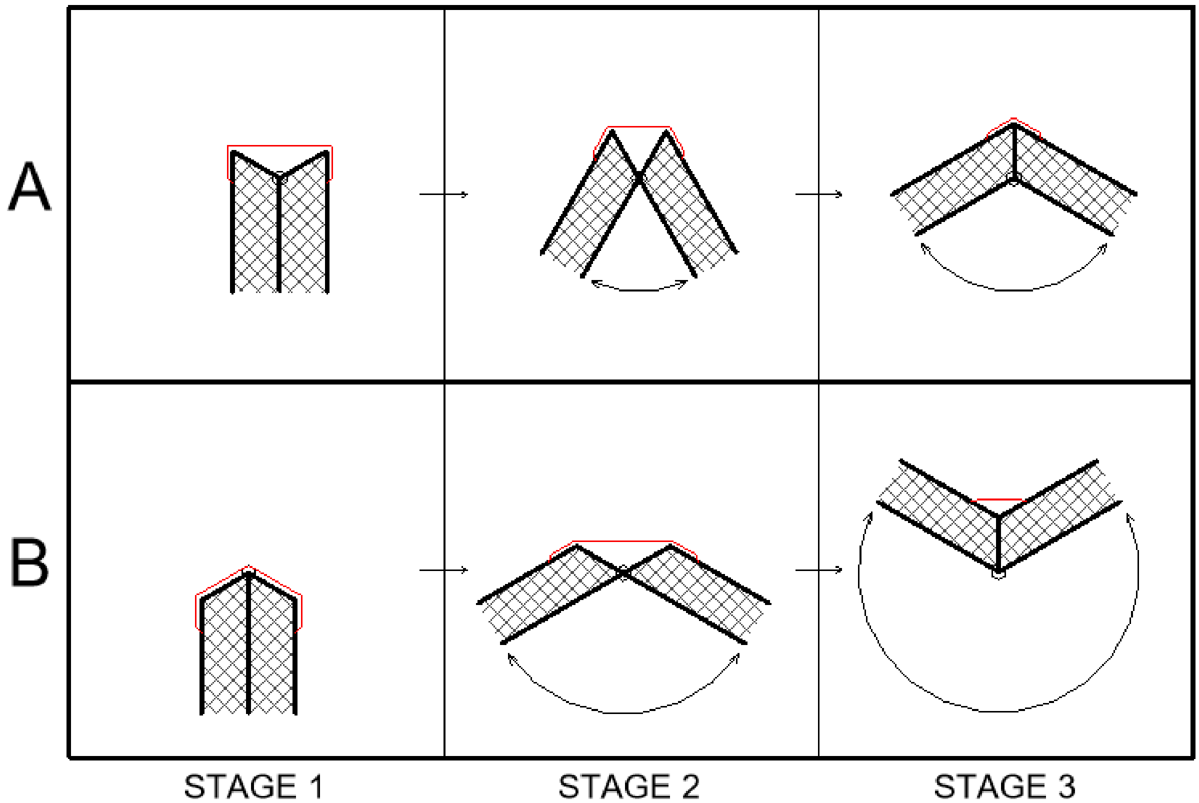

Figure 11: The unfolding of two flat-packed panel pairs (A & B), each oriented opposite each other. A tensile element is shown in red.

4.2.1 Orienting the Faces

In contrast to terrestrial construction where gravity and friction prevent small forces from acting on massive objects, microgravity allows small forces to overcome inertia over time. This is the same principle that allows photons to push objects in space; given enough time photons can appreciably move even massive asteroids[3]. This principle provides an opportunity. The flat-packed panels can be joined to each other under tension using elements analogous to elastic cords or springs. When deployed, each panel could slowly swing out, one at a time, due to the tensile elements (see Figure 11). These tensile elements can then be in static equilibrium when the panels are in the appropriate position relative to each other. When connected in this way the panels of a polyhedral module can each in turn unfold into their appropriate position. Once the panels are structurally connected, these tensile elements can be removed.

[3] This is in fact one of the predominant strategies for neutralizing asteroids on a collision course for Earth. An asteroid can be intercepted and painted white. The light from the sun would push on the asteroid over the course of months/years and its course would be directed away from Earth.

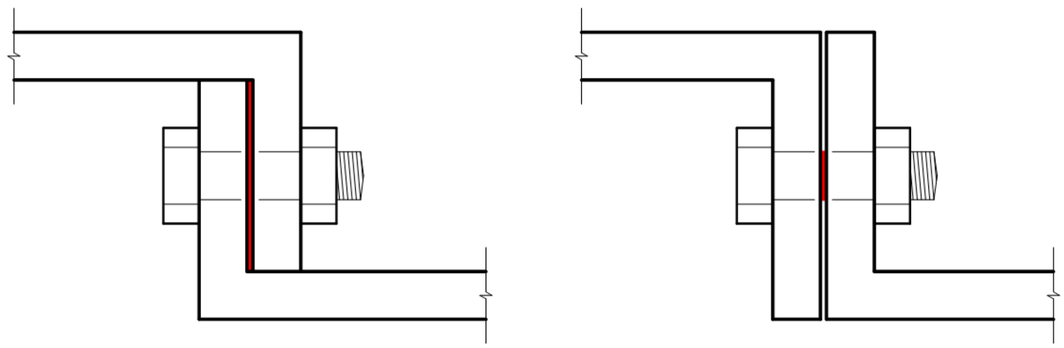

Figure 12: Two configurations of opposing brackets showing tension forces being resisted by the bracket (left) and tension forces being resisted by the fastener (right). The profile of resistance is shown in red.

A feature that would aid this system greatly would be a modest electromagnet system located at the edges of the panels. The electromagnets could activate when the gaskets are about to meet so that the gaskets have a greater likelihood of seating correctly. An example of such a system would be a scaled-down version of the TESSERAE magnetic connection system conceived of at MIT Media Lab (Ekblaw and Paradiso 2019). The use of electromagnets would also be useful when it comes time for a panel to be removed, replaced, or relocated. At that time, the structural connection could be disengaged, and the electromagnets can be pulsed to repel the detached face from the rest of the module. Integral thrusters in the panel can then control the orientation and repositioning of the panel.

4.2.2 Connecting the Faces

The closest analogue in common practice for connecting masses together in microgravity is that of the International Docking System Standard (IDSS) (International Space Station Multilateral Control Board 2016). This procedure uses twelve opposing hook mechanisms to tie two vessels together structurally. When applied to connecting panels together however, the active system of docking may not be practical for a semi-permanent connection.

It may be more advantageous to employ exterior and/or interior structural brackets. This system of structural connection can be robust enough to ensure a strong connection while maintaining the flexibility required for infrequent disassembly and reassembly without the use of several actuators. As opposed to brackets with fasteners that oppose the outward force of the pressurized interior, it may also be advantageous to employ a bracket mechanism which uses the outward force to secure the panels. This way, the brackets themselves can be the primary carriers of the tension forces instead of the smaller cross-sectional area of the fasteners, see Figure 12.

4.2.3 Engaging an Airtight Seal

It may be a small part of the overall engineering design, but a robust airtight seal may be one of the most difficult challenges for a polyhedral space habitat to overcome. Space habitats do however have an advantage over terrestrial habitats with respect to predictability: the direction of air migration is constant. The pressurized interior is always pushing outwards against the vacuum, and this is a static condition that

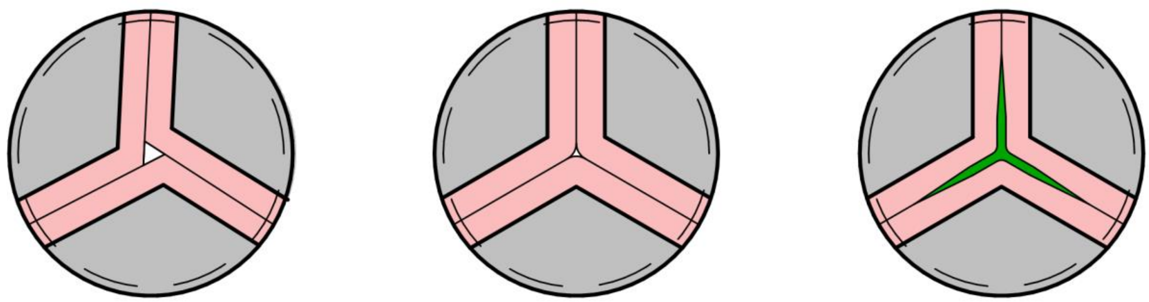

Figure 13: From left to right: misalignment of panels/gaskets, large gasket bevel, gasket bridge (green). Gaskets shown in red.

does not change with time of day, season, or weather, as is the case with terrestrial habitats. This may allow a more simplified system compared to terrestrial ones. For example, the constant outward pressure can aid in the system that engages a strong, airtight seal.

Broadly speaking, there are (3) types of ways to make a joint between two air barrios airtight:

1. Fusion (ex: welding, melting, etc.)
2. Mechanical (ex: reusable gasket systems)
3. Single-Use Physical Barriers (ex: spray foam, tape, etc.)

Fusion of materials is a destructive process that is difficult (and imperfect) to reverse. This is not ideal for habitats that need to be able to disconnect and reconnect potentially multiple times in their lifetime. There is a similar argument to be made for Single-Use Physical Barriers in that, when deconstructed, require moderate refurbishment to prepare the surfaces for a replacement system of air barriers. In addition, when the air barrier is broken the entire contiguous system of air barrier may need to be replaced. This creates waste and requires labor. This leaves the reusable gasket systems.

Gaskets used in human spaceflight thus far have been employed in a continuous, circular application (for hard dock connections). Used in this way, there are no breaks in the continuity of the gasket seal. When applied to polyhedral space habitats, while a traditional gasket system could function perfectly well between two linear edges, the system becomes more complicated at the vertices as the connection of three or more gasket systems at a point may allow air to escape through an opening if the gaskets at the vertex are not precisely aligned or if the bevel of the gaskets is large enough, however this may be mitigated with the application of a gasket bridge which could preserve the continuity of the gasket edges (see Figure 13), however this would likely require additional human intervention to employ.

There is no common use of air-tight gaskets for {3}/{4} face vertices, and any prospective system for use in space would have to be robust enough to work the first time with minimal intervention for several vertices at once. This challenge may be solved with further advances in material science, but more research in the field must be conducted.

4.2.4 Modular Panel Inserts

In conventional space habitat construction, locations for docking modules, windows, structure, etc., are determined during the design/engineering phase and their placement does not change over the lifetime of the project. The options for aperture locations in polyhedral habitats are more numerous than

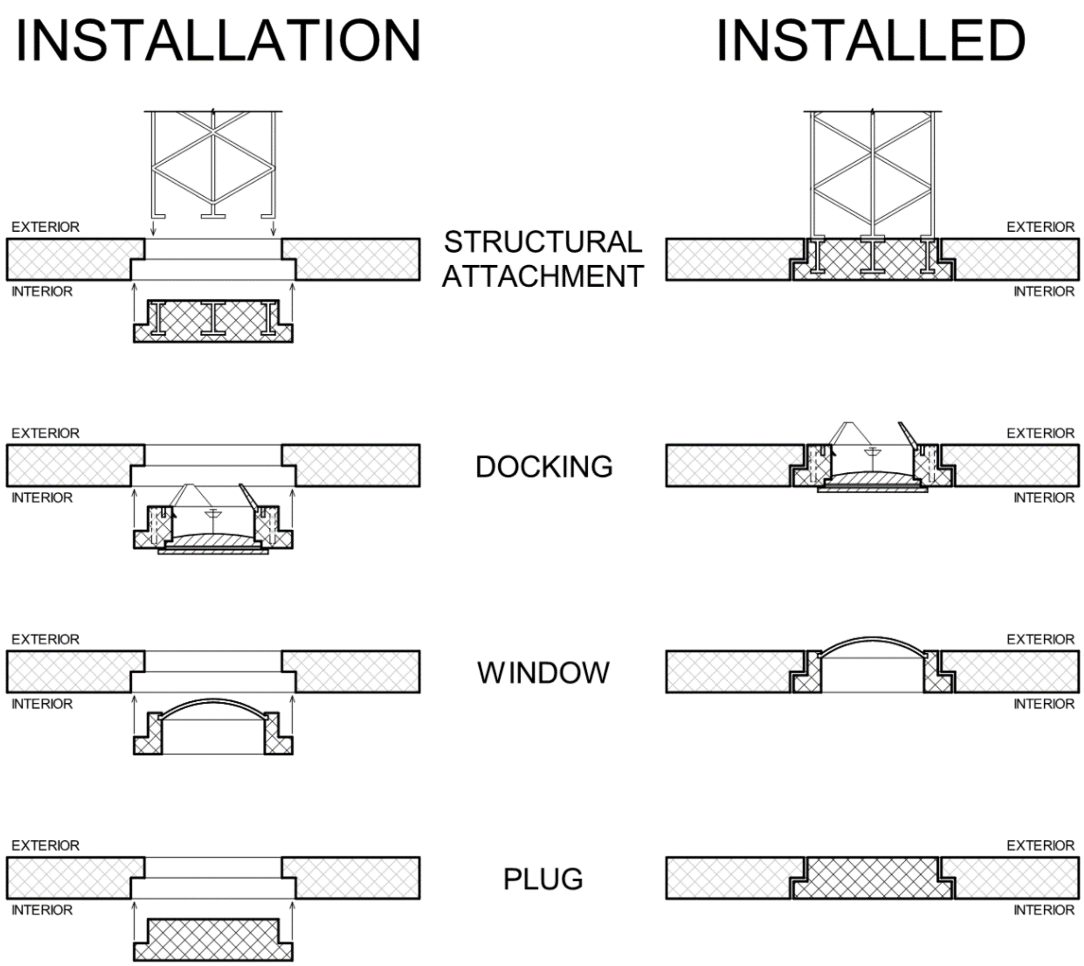

Figure 14: Potential types of panel insert modules. Installation and replacement of the inserts occurs on the inside face.

those of simple cylindrical habitats. This means that each of the flat faces can potentially be a location for an aperture of some kind, which would greatly increase flexibility for the future of the habitat. Locating an aperture on each of the several faces is both unnecessary and uneconomical, however. This elucidates a conflict between the desire for more aperture locations and the reluctance to include too many. There is however a solution that can achieve both goals.

If each of the faces were to have an aperture in their bulk structure/shielding, then this aperture can be fitted with varying types of inserts, each having their own purpose. Such types of inserts might include a docking module, a window module, a structural attachment module, or even a plug module (see Figure 14). These inserts could be removed, replaced, and swapped from one face to another. Each of the panels would be held in place against a sturdy, gasketed lip in the panel face by alignment bolts and the internal pressure.

5. CONCLUSION

The result of this exploration has been the overwhelming indication that for prospective polyhedral space habitat modules the rhombic dodecahedron stands out as the shape with the most advantageous qualities:

1. It is a polyhedron having only one type of face that repeats across the entire structure, increasing flexibility and decreasing engineering and manufacturing costs.
2. It is a plesiohedron, which has the ability to connect each module to each other module efficiently, increase the effective shielding level for interior modules, and enclose contiguous volumes of space.
3. The expected face tension is relatively low compared to other common shapes.
4. It has the lowest joint stress compared to other common shapes, increasing structural efficiency.
5. The volume to surface area ratio is high compared to other shapes, increasing value.
6. Its faces have the smallest minimum width compared to other common shapes, allowing a larger deployed volume for a rocket fairing of a given size.

As described in this document, such a polyhedral space habitat would benefit from the following qualities:

1. Composite structural system independent of the bulk shielding material
2. Passive deployment system
3. Compression-strengthened gasket system
4. Modular panel inserts

Suggested future work:

- Determine the most ideal module size based on current and future lifting capacity.
- Determine the best shielding strategy.

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