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High Transparency Inflatable Modules for Space Habitats

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ABSTRACT

In reaction to the prevalent space design paradigm, we would like to explore a combination of transparent polymer laminate membranes and high tensile strength webbing as the envelope of future transparent space habitats. Further study reveals fascinating possibilities in the use a tensegrity structures as the exo- or endo-skeleton for such envelopes.

In the following work we look at thin shell transparent structures as possible observation modules in space habitats or as the domed component for a colony on the moon or another planet. For such structures the internal pressure is not only a load but their shaping force as well, i.e. they are de-facto inflatables. We investigate their feasibility based on available technologies, such as lobed balloons. Other sources of technological transfer are ETFE (ethylene-tetrafluoroethylene copolymer) cushions, safety laminate foils, and hi-tech laminate sails design. We further develop the basic idea of using lobed transparent membranes in space habitats through several case studies. We would finally like to spur a discussion about design process as it relates to inflatable structures.

INTRODUCTION

The protracted acceptance of *Form follows function* liberated design in the last century from the dogma of stylistic formalism, while in a fascinating way, introducing a dogma of its own. Universally accepted by the rapidly multiplying design disciplines, it was often territorialized onto a familiar manifestation of *a* function and precluded invention, in much the same way the incessant tinkering with classic orders had stifled creativity before. Even areas of design, which would seemingly be immune to settled ideas, like automotive and aeronautic, paid at times homage to obsolete functional expressions. A familiar example are wheeled transportation vehicles. Despite an significant century long design evolution, they are still, according to a study by the MIT Media Lab, following the paradigm of “brick on wheels.” Similarly, the first designs of flying apparatuses could not rid themselves from the model of a man-bird, wielding functionally and substantially bird’s wings. The development of engine powered flight brought about vehicles with little resemblance to birds, usually made of aluminum alloys. Aerodynamically optimized, those are well suited to atmospheric flights in conditions of earth gravity. Because of the practical stratagem of space habitats to be preassembled on Earth and used as a stage in a space rocket, they by necessity followed the morphological principles that drove rocket design: in most case a cigar shaped aluminum body.

Alternative variants of this model have been scarce. With technological capacity and vision still associating rockets and space habitats, it is not difficult to see how the inferred function still controls form making in space architecture.

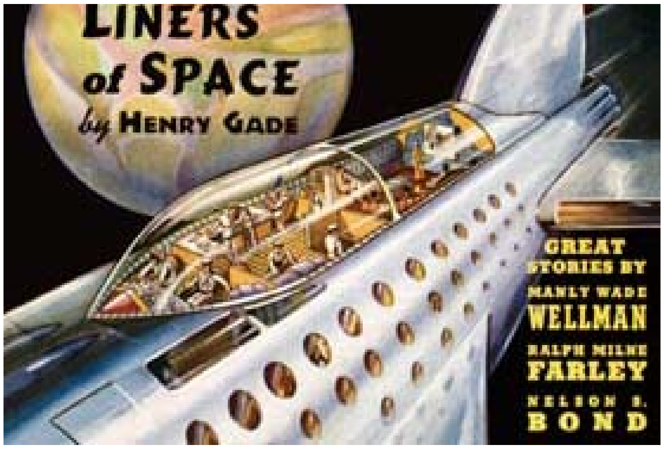


Figure 1 Space travel fiction

Old pictures from the pioneering years of space era show extensive glazing. But the reality is very different. Apertures of space habitats are sparing and look like the portholes of deep-sea submersibles. Such similarity has a structural reason – both underwater and space vehicles are pressurized vessels resisting external or internal pressure. Incorporating flat glazing in the walls of both the traditional rigid (aluminum alloy) or the newer expandable space habitats is difficult, bulky, and costly.

In comparison, the windows of large aquariums, withstanding pressure comparable to the internal pressure of a space station, have a mass comparable to a space station module. The fundamental cause of unsatisfactory mechanical properties of transparent materials is on atomic level. Moreover, often constructed flat for pragmatic reasons, the shape of such containers is far from the optimal for pressurized vessel walls.

The optimal shape for pressurized vessels is provided by the *Thin Shells Theory* [29]. Thin shells theory describes shells with no bending stiffness – membranes. The equilibrium shape of pressurized thin shells is always curved, and the stress in the shell is directly proportional to curvature radius. To keep optical distortion within an acceptable range, a curving transparent shell must be sufficiently thin. That led us to the idea of transparent membranes as the replacement of flat glazing.

Engineered membrane structures have a number of advantages for space applications, notably their low mass and compact volume when stowed for launch [1]. An increasing interest towards such structures as of late is boosted by some private initiatives for inflatable space habitats [2] and the proto development of space tourism [21].

A typical inflatable space module shell consists of a number of layers. Bladders form redundant air seals. The internal pressure is resisted by woven straps of fiber material, e.g. Kevlar™ or Vectran™, that form the structural restraint layer. Micrometeoroid, debris, and radiation shielding is incorporated into the outer layers [3 - 6].

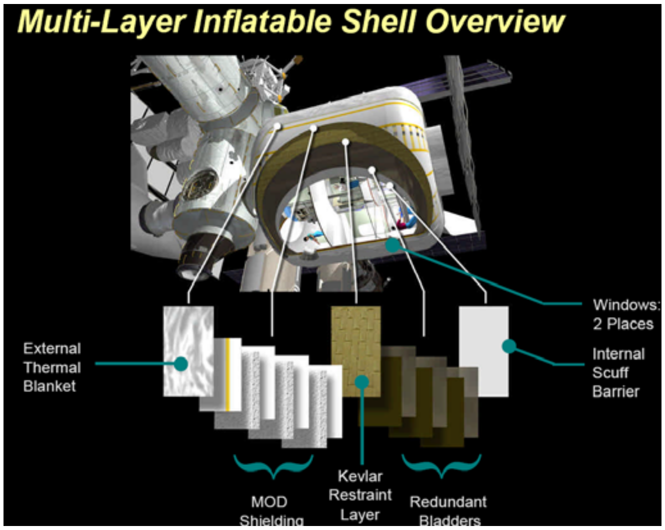


Figure 2 Section of the TransHab shell showing the various layers [NASA].

A structural scheme consisting of an airtight skin and webbing (tendons) made of high tensile strength fiber was utilized in another class of advanced inflatables – the lobed super-pressure balloons. Structural analysis of lobed structures was performed in a number of works connected to the NASA Ultra Long Duration Balloon Project. The deployment stability and patterning was successively improved [8,9,10].

The materials we refer to in our design proposal are described in their manufacturers' data sheets [11, 22] and in various papers on inflatable structures [16].

APPROACH

This work is essentially a series of proposals for constructing transparent envelopes for space and planetary environment. The proposed designs consist of airtight skin formed from transparent materials with a low elastic modulus and a large capacity for plastic elongation, and restraint tendons made from materials with a high elastic modulus.

One of our goals is to provide a feasibility study for the integration of transparent inflatable structures in space habitats. We have focused on a simple structural model demonstrating that a tendon restrained plastic film will maintain the pressure of artificial atmosphere in a space module. A number of issues arise during developing the work concerning material properties, space environment factors, deploying procedure etc. We will touch briefly on most of them but the scope of possible questions is too large to be covered within this discussion.

Our study is based on a simple model suggested in [15], on the proven technology of pumpkin balloon design (Fig.3), and structural analysis of membrane design in terrestrial architectural practice. A range of possible materials for the transparent membrane, which we will discuss later in this study, is provided by off-the-shelf commercial technology: polyester foil laminates. Sometimes called *safety laminates,* they are widely used in terrestrial architecture and automotive industry for securing and modifying the radiant properties of glazing. Our goal of incorporating expansive translucent walls enveloping observation decks in space habitats is illustrated through a couple of case studies. In these we introduce webbing patterns significantly different from the meridional tendons of a pumpkin shape.

Figure 3 Lobed inflatable – ULDB test model (Raven Industries, Inc.)

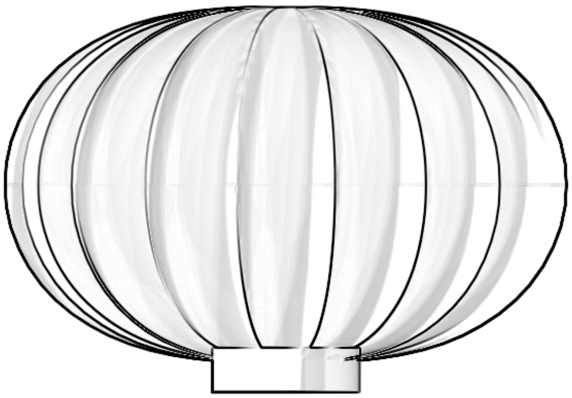


Figure 4 Elastica shape cupola

Our project aims to highlight the new potentials existing for architecture by the reprioritization of form-affecting forces on built structures. It explores the use and recombination of well known but less used structural principles, like tensegrity and pneumatics, and novel materials, to channel these forces along rarely used paths and arrive at a new architectural morphology.

SIMPLIFIED ANALYTICAL MODEL OF LOBED MEMBRANE

Membrane structures have negligible bending stiffness and can carry load only in tension. This fact has two consequences: 1. Equilibrium shape attained under uniform internal pressure is not arbitrary. It must be derived through a process of membrane formfinding. 2. Optimum structural efficiency is achieved by means of optimization of material properties utilization – pure tension, in contrast to bending in flat glazing, for instance.

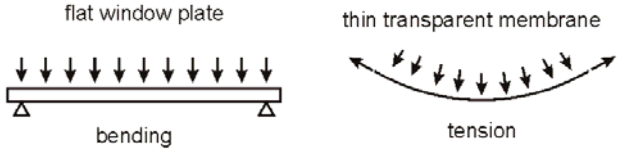


Figure 5 Flat plate and membrane under uniform normal load (pressure)

An alternative of formfinding from scratch is the design based on generic, already well analyzed, and proven in practice shapes. For our design we have chosen lobed inflatable structures, or in more general terms, tendon restraint pneumatic structures. In the following analysis we use the results of pumpkin balloon studies, as well as thin shell theory in general.

Placing a flaccid structure under a uniform normal load develops the elastica curve. [8] points out its analogy to the catenary shape, which is developed by placing a flaccid string under a constant gravity load. The related surface of revolution is known as *isotensoid*, or natural balloon shape.

Pumpkin balloons consist of meridional tendons that constrain a thin, highly curved plastic surface. The isotensoid is a spheroidal shape that carries stress only in one direction under uniform internal pressure. In this shape, the pressure loads are carried almost entirely by meridional stresses in the shell and the circumferential stresses in the film are very small.

A familiar approach in membrane theory is reducing the 3-D problem to an equivalent 2-D problem [13]. Considering locally the lobe as a cylindrical sector (Fig.7) we can estimate the stress in the membrane σ:

$$\sigma = \frac{RP}{t}, \qquad (1)$$

where R is the local radius, P is differential pressure, and t is the thickness of the membrane. Equation (1) is known as a boiler equation. In other words the membrane tension is directly proportional to the radius of curvature of the surface.

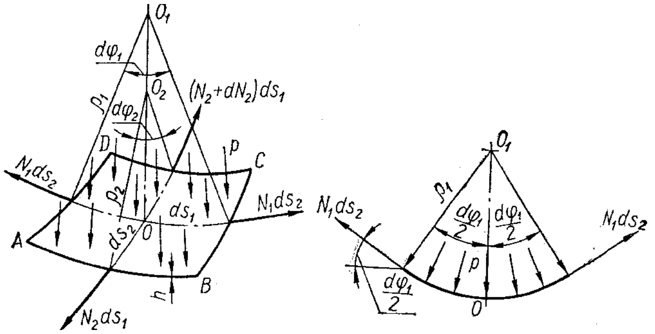
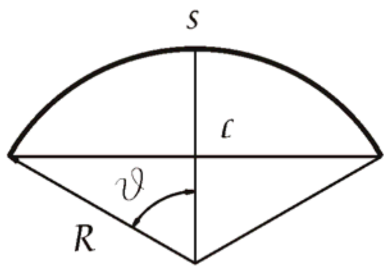


Figure 6 Transition from 3D to 2D model [13]

The principle behind the tendon restraint lobed structures is to use a lightweight film as a gas barrier and strong reinforcing tendons for pressure confinement. Roughly speaking, increasing the curvature by forming lobes has the effect of transferring most of the load to the tendons. Since materials with extremely high tensile strength are available in the form of filaments, such arrangement will have optimal structural efficiency.

The differential pressure in a typical terrestrial inflatable - ETFE cushions - is a few hundred Pascal. The internal pressure in a space habitat would be close to normal atmospheric pressure 70 – 100 kP. To decrease the membrane stresses that have to resist given pressure, it is necessary to proportionally decrease the radius of the surface curvature. Using lobed shapes as the inflated membrane reduces tension and allows the use of a thin membrane to maintain the desired low mass and high flexibility.



$$\sin\theta = \frac{c}{2R}$$

Figure 7 Lobe section and arch to chord ratio

A *cyclic symmetric lobed inflatable shape* is assembled from identical lobes. Each lobe is manufactured according to a specified cutting-pattern, called gore, and is initially flat. It attains its final sinclastic curved shape after visco-elastic deformation under pressurizing during inflation.

After the inflation, a lobe between tendons will have radius R, which is related to strain in the film, ε, by the equation [14]:

$$\arcsin\frac{c}{2R} = (1+\varepsilon)\frac{c}{2R} \quad (2)$$

where c is the chord of the lobe (see Fig. 7). We assume the length of *c* to be equal to the initial width of the gore pattern (Fig. 13). Let us look at the case when the lobe is formatted entirely by film stretching. Using the first *three* terms in the Maclaurin series for the inverse sine:

$$\arcsin x = x + \frac{1}{6}x^3 + \frac{3}{40}x^5, \text{where } x = \frac{c}{2R}$$

and solve it for the lobe radius, R. The expression for R is more complex than in [14] but produces a closer approximation even on large strain:

$$R = \frac{c}{2\sqrt{\dfrac{-1/6+\sqrt{1/36+0.3\varepsilon}}{0.15}}} \qquad (3)$$

By substituting for R in the boiler equation (1) and assuming P = const we derive the equation for stress in terms of strain

$$\sigma = \frac{Pc}{2t\sqrt{\dfrac{-1/6+\sqrt{1/36+0.3\varepsilon}}{0.15}}} \qquad (4)$$

Because stress/strain curve for polymer films is available as a diagram we can plot it together with graph of (4) and find solution for the equilibrium state as a crossing point of two graphs.

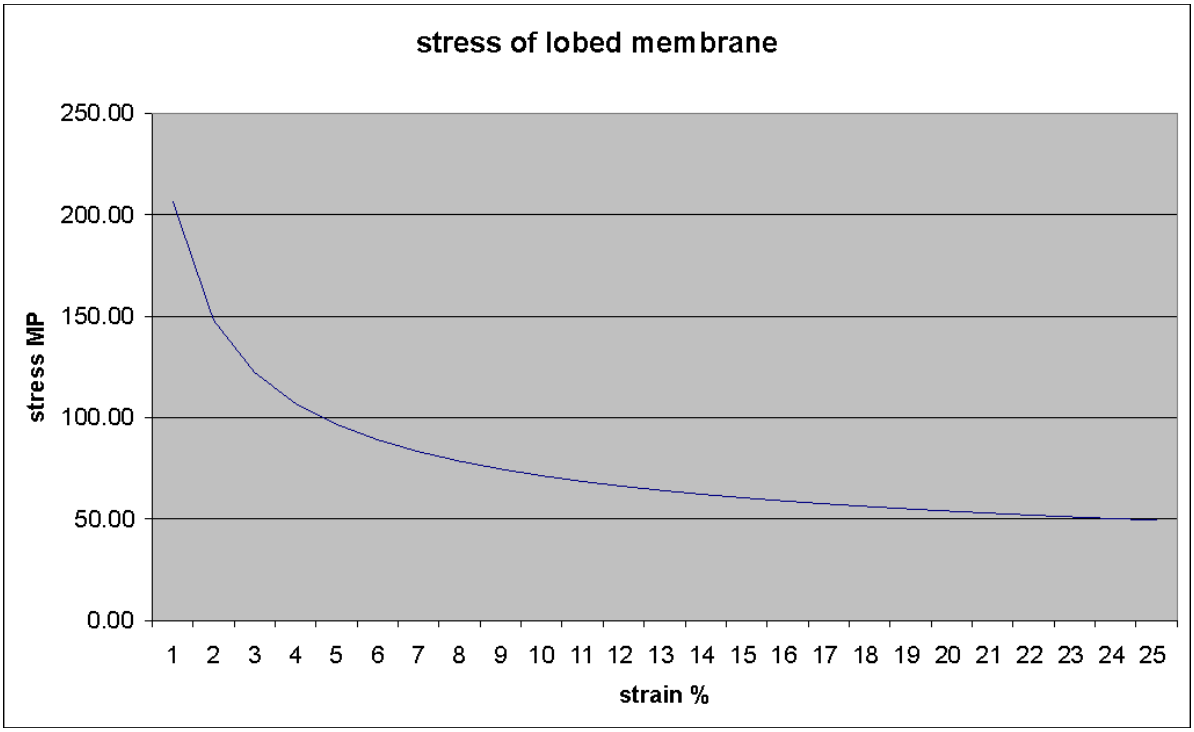


Figure 8 Stress/strain of lobed membrane: stress *decreases* with elongation because of decreasing lobe radius. The initial chord length *c* is 1 m, the membrane thickness is 1 mm.

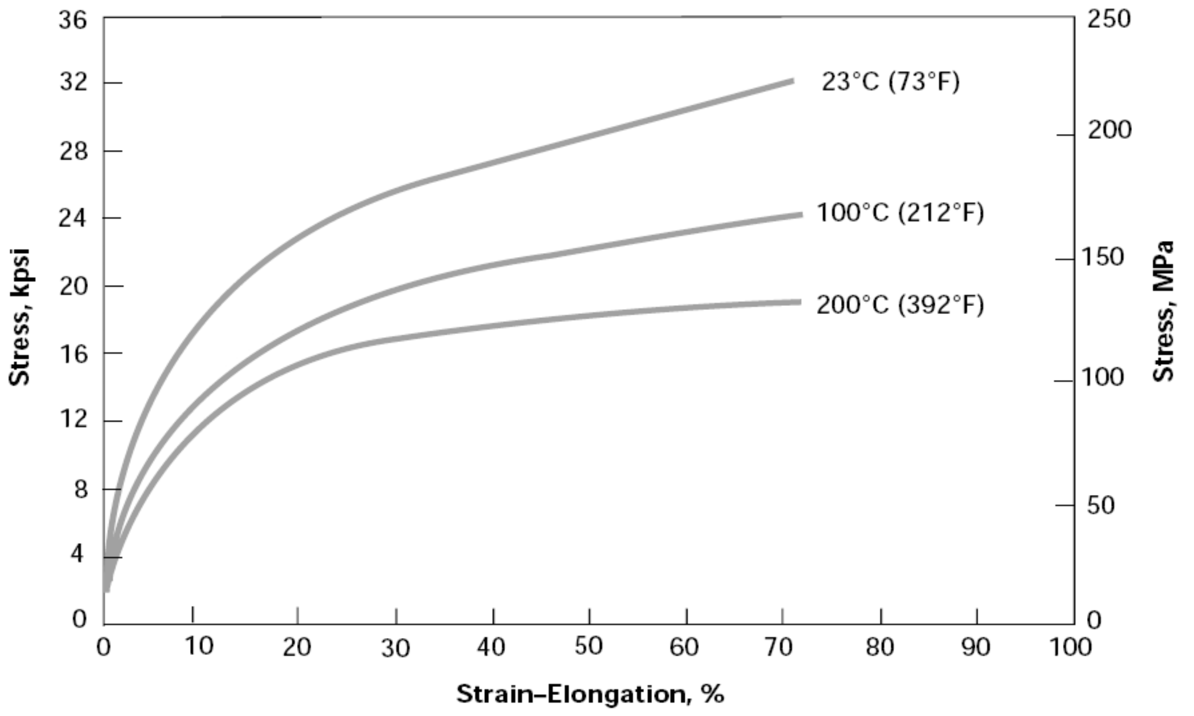


Figure 9 Strain/stress curve for typical polymer films. (DuPont®)

MATERIALS

This paper does not aim to introduce new materials and does not focus on extrapolation of material science achievements. Our emphasis is structural optimization. The material properties we use in our structural analysis are those of commercially available materials. The critical point of the proposed design is the ability of a few layers of plastic foil or laminate to protect the integrity of an inhabitable module from the harsh space environment. Here we will briefly discuss space environment factors concerning the used materials:

1. UV radiation
2. Thermal cycling
3. MMOD (MicroMeteoroid and Orbital Debris)
4. Radiation
5. Atomic oxygen

UV radiation is among the primary factors of space environment causing polymer degradation during its service life. Highly transparent membrane windows must provide protection from vacuum UV radiation according to crew habitation standards. The high technology security laminates provide ultra violet radiation control (transmittance reduction) of over 99% [17]. Vapor deposition thin film coating provides adequate UV attenuation. Special attention is needed for UV protection of tendon fibers to avoid degradation of its mechanical properties.

Heat transfer analysis of spacecrafts is very complex. Thermal transfer balance will strongly depend on mission environment – LEO, open space, Lunar or planetary surface. One specific problem of transparent cupola is the direct radiant energy transfer between the interior and open space. The cupola interior will lose radiant energy to the cold portions of the sky away from the sun and earth and will receive radiant energy from direct solar radiation; planetary albedo and planetary IR shine [19].

In conventional spacecrafts with controlled atmosphere, including inflatable ones, passive thermal control depends on the selection of materials with specific irradiative properties, in particular absorptivity/reflectivity ratio. In a high transparency module radiant transmittance control will play the same role. Adequate coating by vapor deposit thin films modifies the radiant transmittance of polymer membranes.

Defining emissivity ε as the ratio between the energy radiated by the real surface at temperature T and the blackbody emission at the same temperature:

$$\varepsilon = \frac{E_{real}}{\sigma T^4}$$

where Eb = Rate of Energy, W/m2 σ = 5.67X10-8W/m2K4 = Stefan-Boltzmann constant, T = Absolute temperature, W/m2. And if [30]

$$\alpha + \rho + \tau = 1$$

where α = Absorptivity, ρ = Reflectivity, τ = Transmissivity, then modifying transmissivity for short wavelength IR radiation will effect the radiative balance with the environment, decreasing solar thermal flux and preventing overheating.

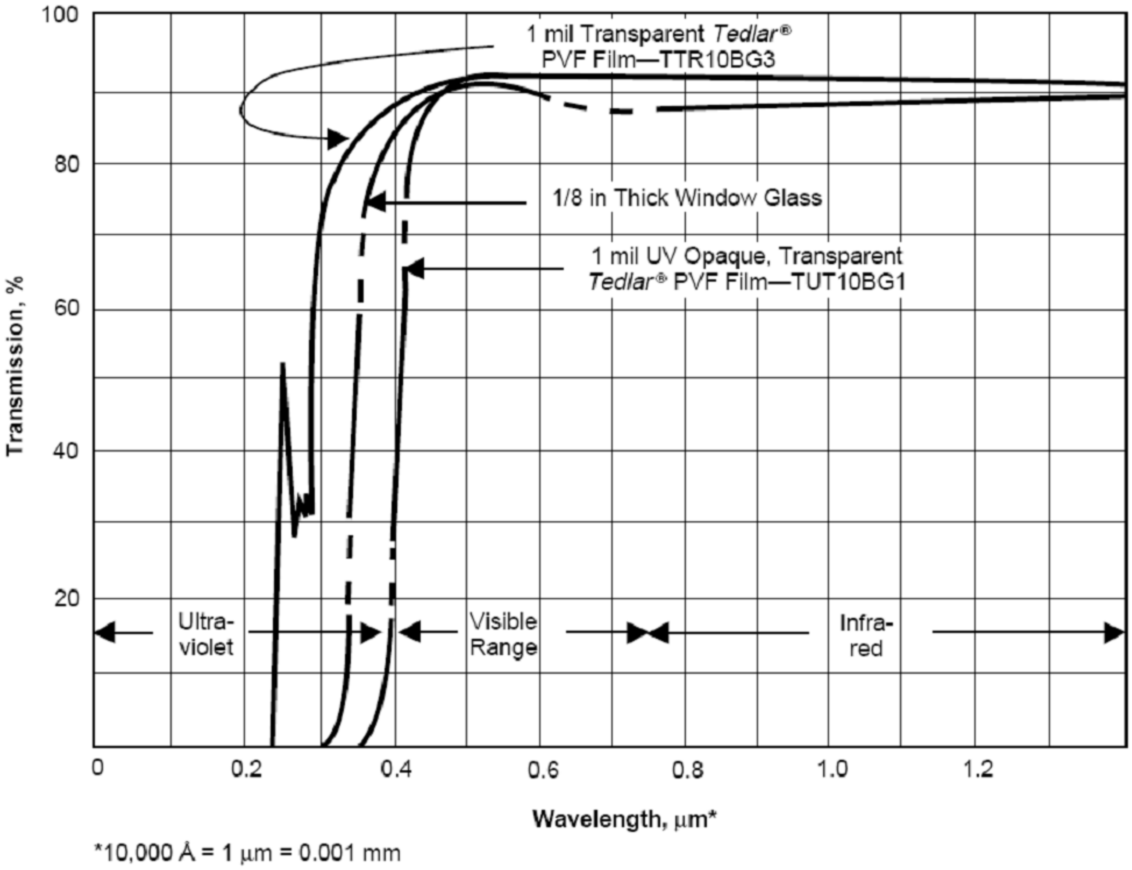


Figure 10 Spectral transmittance of uncoated and coated polymer film (DuPont® Technical Information Bulletin) [26].

Similar problem exists for any expansive glazing, even on earth. Overheating protection by means of selective filtering of incoming and outgoing IR radiation, combined with thermal shield and active thermal control, may be the possible solution for limiting the temperature within desired ranges. Selective wavelength filtering by a variety of vapor deposited thin films is a mature technique in commercial sun protective foil manufacturing. Conventional spacecraft windows made of fused silica also utilize thin films coating for modifying radiant transmittance.

Vacuum is the perfect thermal insulator. Multi-layer insulation of closely spaced layers of aluminized Mylar or Kapton™ is a part of the standard spacecraft thermal control. A multi-layer lobbed membrane will have similar characteristics when adequate thin film coating is applied. A special case is the environment on planets with significant atmosphere. On Mars for example, because of the atmosphere, there is convective heat transfer on the surface. In contrast to vacuum environment, additional thermal insulation will be needed for a Martian greenhouse.

MMOD MicroMeteoroid and Orbital Debris risk is a tough problem for thin shell structures. Nevertheless, polymer laminates are suggested for Multilayered Micrometeorite protection. According to [27] *"Empirical studies on MLI [Multilayered Insulation] have shown that it can provide the same impact protection as an aluminum bumper, but at 13 percent of the aluminum mass, per unit area."* The mechanism of absorbing high-speed projectiles includes the destruction of the first layer and absorbing the particles cloud by the next layers. We expect that a multi layer inflatable membrane will work in a similar way. To enhance MMOD protection we envision a retractable shield in our example described further. In terrestrial applications polyester laminates are used commercially for impact reinforcement of glazing [18].

Ionizing radiation in space consists predominantly of light charged nuclei. Materials containing light atoms, like hydrogen, are more effective protection against radiation. Therefore, polymers offer better protection than aluminum or fused silica. Metals become the source of secondary radiation when exposed to cosmic rays for an extended period. Protecting a crew against the effects of Galactic Cosmic Radiation involved the inclusion of hydrogen-rich materials, like polymers, and the exclusion of metallic materials from the habitat construction [32].

Atomic oxygen vulnerability of polymers is rare. In low earth orbit free oxygen erodes virtually all materials. Fluoropolymers, Polyimides and Mylar, in that order, have limited resistance to atomic oxygen.

TRANSPARENT MEMBRANE

Fluoropolymers. ETFE was chosen as the initial baseline. Our earlier research proved the feasibility of a pressurized membrane vessel made of several layers of commercial 200 micron ETFE foil widely used in architectural pneumatic cushions. Despite its relatively low tensile strength it may be attractive due to its flexibility and extreme capacity for plastic elongation, up to 800%. It is tolerant to space environment factors as most fluoropolymers. Some inherent opalescence, however may disturb the clarity of the view.

We considered different polymer films in the process of investigation. Further research and experimental studies will be needed to select the most adequate materials. We believe that multiple films laminates provide a more plausible research direction than a possible “lucky strike” discovery of a new material combining all the desired properties.

PVF (polyvinyl fluoride, Tedlar™) is routinely used in passenger aircrafts interior. We suggest it as the internal layer protecting the multiyear envelope from the inside and as a fire barrier.

Polyester Mylar is the first material used in a space inflatable – The *Echo* satellites in 1960. It is clear and has excellent optical properties. Mylar laminates have a better tear resistance, but also a limited flexibility.

Polyimide film can be laminated, metallized, formed or adhesive coated. Its high mechanical and thermal stability make it the preferred material for the majority of inflatable space structures. It also does not suffer from radiation damage. *Kapton*™ insulated wiring has been widely used in civil and military avionics, however it was later found to have very poor resistance to mechanical wear, mainly abrasion within cable harnesses due to aircraft movement.

As a fenestration material it has a significant disadvantage – poor transparency and a yellow-brown color.

Fluorinated polyimide films offer ‘the best of the two worlds’. LaRC™-CP1 and LaRC™-CP2 polyimides provide superior physical properties over a wide temperature range and in a number of harsh environments. These fluorinated polyimides may be dissolved readily in a number of solvents for use in various applications such as castings and coatings.

Table 1 Typical polyimide data

Physical and Thermal Properties of Kapton™(R) Type VN Film	
Ultimate Tensile MPa	231
Ultimate Elongation, %	82
Tear Strength-Propagating N	0.58
Tear Strength-Initial N	46.9
Folding Endurance (MIT),x10^3 cycles	5
Density, g/cc	1.42
Flammability , [standard]	94V-0

Table 2 CP1 Film Properties [25].

CP1 Film Properties (Space Qualified)	
Film Color (%T at 500nm/1 mil film)	Pale Yellow to Colorless
Film Density	1.434 g/cc
Glass Transition Temperature	263°C
Polymer Decomposition Temperature (TGA)	530°C
Refractive Index	1.58
UV Cut Off (0.2 mil film)	320 nm
Imide IR Bands	1780, 1725, and 745/cm
Specific Heat. Cp (at 25°C)	1.094 J/g°C
Tensile Strength	14.5 ksi
Tensile Modulus	315 ksi
Solar Absorptance. Full Spectrum (Uncoated Film)	0.072 (0.25 mil)
Solar Absorptance. Full Spectrum (Coated Film. Aluminum)	0.106 (0.25 mil)
IR Emittance. Hemispherical, 300K (Uncoated Film)	0.194 (0.25 mil)
IR Emittance. Hemispherical, 300K (Coated Film. Aluminum)	0.03

Competing polyimide materials have less UV resistance and are not as transparent as CP1 and CP2. CP1 and CP2 are superior for long-duration, space-based applications where *transparency* is needed for functionality. CP1 has been tested and is rated for a10 year life in GEO. It was developed by NASA and Produced under License to SRS Technologies. It has only one disadvantage, cost: $1750.00 per pound of unprocessed powder [24].

TENDONS

The structural efficiency of tendon restraint pressurized vessels is achieved by utilizing high tensile strength filamentary materials. Such arrangements date at least as far back as the Goddard fuel tank made out of soft aluminum and reinforced by piano-wire webbing, and the first hydrogen balloon of Charles costing gas bag and cable net. Prospective materials such as nanotubes are also highly anisotropic and can carry unidirectional load, lending themselves such a use.

Below is a brief summary of the features of the so called *super-fibers,* which can be used as tendon restraint material

Tendon fibers

PBO (Zylon)
Highest strength-to-weight ratio of any fiber Highest resistance to heat of among high modulus fibers (decomposes at 1200°F) Negligible creep Poor abrasion resistance Should be protected against degradation from light sources
ARAMID (Kevlar™, Twaron, Technora)
Excellent strength-to-weight ratio Excellent resistance to heat (chars at 800° F/427° C) Negligible creep Susceptible to axial compression fatigue Poor abrasion resistance
LCP (Vectran™)
Excellent strength-to-weight ratio Zero creep Excellent flex fatigue resistance Good abrasion resistance High resistance to heat (melting point of 626°F/330°C)

The UV stability of highly tensile fibers is unsatisfactory thus special measures to prevent degradation must be taken. Kevlar™ fibers in laminate sails lose up to 50% of their initial strength within 6 months exposed to terrestrial UV.

Of Special interest for space applications are carbon fibers because of their UV stability in combination with their excellent mechanical properties and moderate price.

Table 3 Mechanical properties of fibers used in restraint tendons [16]

TYPE OF FIBER	*TENSILE STRENGTH psi x10^6*	*ELONGA ATTION BREAK (%)*	*TENSILE MODULUS psi x10^6*
Kevlar™	22	2.4	850
Carbon	23	1.5	1480
Zylon	42	2.5	2000
Vectran™	23	3.3	525

EVALUATION

Here is a brief list of possible applications for the tendon restraint translucent/transparent membrane structures described so far:

- Attraction for a space hotel – orbital belvedere
- Greenhouses for space or planetary environments
- Observation cupola for space stations
- Large span transparent dome for planetary bases
- “Second skin” over planetary habitats

CASE STUDIES

ELASTICA SHAPE CUPOLA

This 16-leaf daisy is aimed to provide the ultimate panoramic view from an orbital space hotel. Minimal visual obstructions, combined with weightlessness, will create the perception of sky walking.

This project borrows its structural scheme from a lobed balloon. It consists of 16 sectors (lobes) spaced at 1 m along the equator. Assuming s/c ratio 1.2 (see Fig. 7), in equation (2) results in a value of 0.57 m for the lobe radius. The internal pressure is 100 kP. The corresponding stress may be obtained by referring to the diagrams on Fig. 8 and Fig. 9.

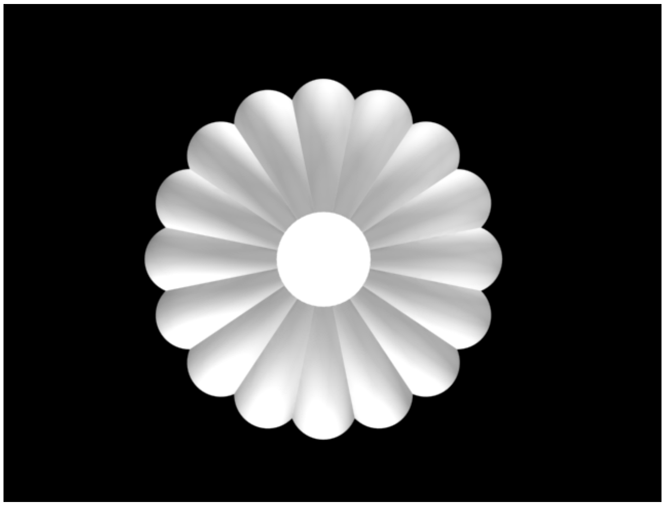


Figure 11 Elastica shaped cupola: plan.

The membrane material is polyester laminate in combination with fluoropolymer. Gores are sealed edge-to-edge. Sealing methods are well developed by inflatables manufacturers. Tendons use Kevlar™ – carbon unidirectional tapes welded on the gore seams. Similar tape is used in laminate sails design.

Assuming 20% elongation on equilibrium and membrane thickness of 1 mm, the stress will be 50 MP according to film data [12], if the lobe radius is 580 mm and the internal pressure is 100 kP. However, that implies a safety factor of 1. The safety factor must be at least 4.

Resolving the design as a multiyear membrane follows a common technique for producing architectural cushions.

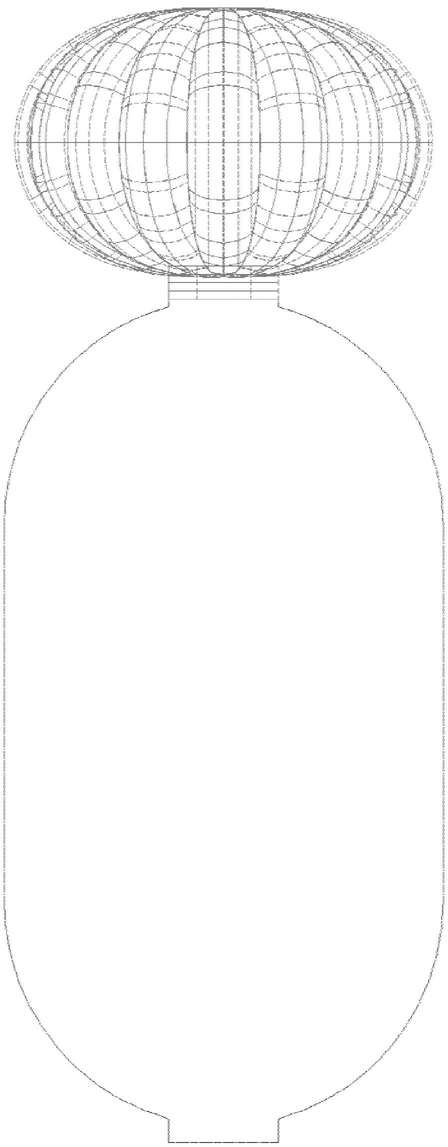


Figure 12 Elastica shaped cupola: schematic section.

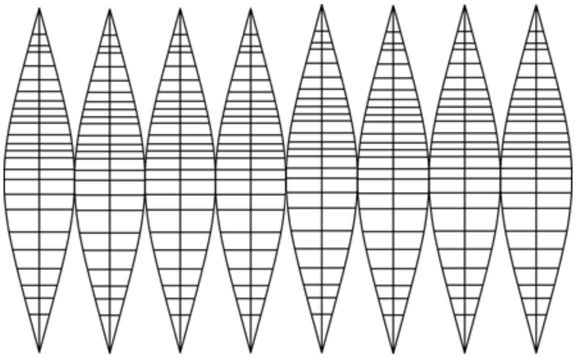


Figure 13 Gore patterning

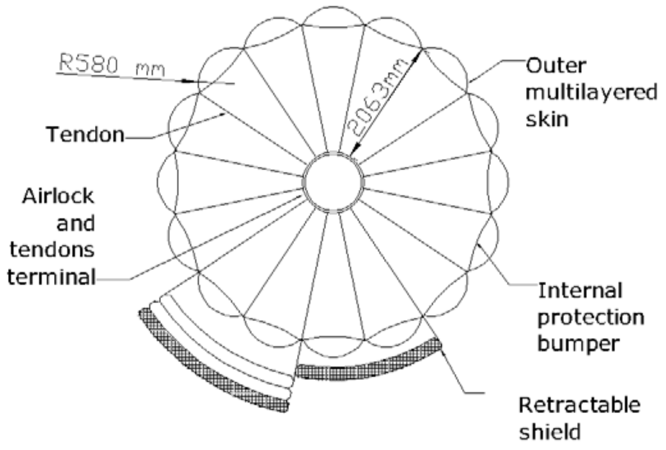


Figure 14 Equatorial section of elastica shape cupola

Spacing apart layers allows them to act as micrometeorite and debris shielding [5]. The safety factor is achieved both by additional layers and by the extended elongation capacity of ETFE film. The possibility for decreasing the curvature radius locally through expansion must be provided. In the proposed design every membrane layer is restrained by an independent set of tendons (Fig. 15).

Cascade pressure in the gaps between layers should be maintained to keep stresses equal for all layers.

Tendon stress may be estimated assuming uniform tension. The area of equatorial section is 23.3 m^2 at 100 kP pressure. 16 tendons must bear 2330 kN. At a safety factor of 5, the allowable stress will be 500 MP for Kevlar™/carbon fiber. The cross section of tendons will be 0.005 m^2. Each tendon is 6.6 m long. The entire mass of the webbing, including the terminals and the protection cover, is less than 100 kg (180 lb).

Polymer film mass estimation: the non-stretched membrane area is 83 m^2. Five layers of 1 mm each make 0.415 m^3. The average density of used polymers is ~1450 kg/m^3. Adding 5 % for seams results in 660 kg or 1455 lb for the polymer envelope. . Adding airlock, rigidizable MMOD and thermal shield, and some secondary structure, the mass of the module will not exceed 2 metric tons. The usable volume of the module is ~40 m^3 or 20 m^3/ton.

A thin membrane shell is vulnerable not only on the outside but from the inside. Any sharp object hurled at the plastic wall may damage it. In TansHab the multi layer bladder is protected from the inside by a scuff resistant layer and a fire barrier. The inner layer of PVF may be used for the same purpose in a multi-layer transparent envelope. While its contribution to carrying the pressure load will be negligible, some differential pressure will have to be applied to introduce enough prestress. Inverting the differential pressure will reverse the curvature of the inner layer forming a kind of a bumper between the interior and the primary structure membrane.

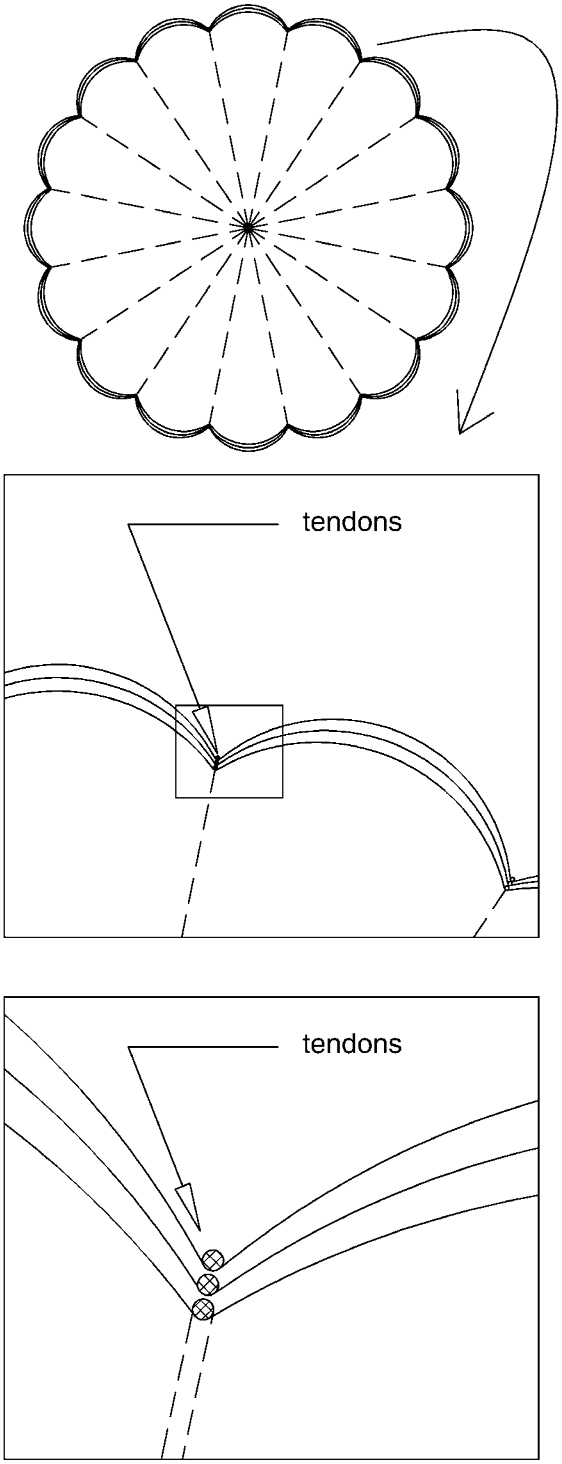


Figure 15 Multi layer lobed structure – only three layers are shown

A retractable shield arranged around the cupola will deliver additional protection. It will consist of TranHab style protective layers but instead of an open foam spacer it will include a foam rigidizable structure. Since the orbital debris threat and free oxygen erosion are not omni directional, a retractable shield will effect protection even when not fully deployed.

STRUCTURE: TENSEGRITY

So far we explored and attempted to define the use of transparency/translucency in space architecture through materials and their local behaviors and patterns. What are then the morphological possibilities as a whole for space structures enveloped by those materials?

The inflatable strand of space design morphology has traditionally resulted in bulbous shapes identifiable in standalone or clustered cupola. Those have captured and often monopolized the imagination of science and art visionaries and become a familiar image whenever the futuristic, or space architecture topic is brought up. For another approach to the tectonic challenges of space architecture we turn to a structural principle embodying pizzazz but limited applicability in terrestrial applications. Continuous tension – discontinuous compression (tensegrity) provides opportunities of hybridization with transparent tensile surface materials. It seems uniquely suitable to take advantage of the unique conditions of interplanetary environment. Conditions of lower gravity would help such structures distribute stress more efficiently due to the isolation of the forces of tension and compression. A major advantage is the manner in which a tensegrity is disassembled and stowed for transportation, and its speed of deployment upon arrival.

Another significant fact is the correlation between the tendons of a tensegrity and the tensile character of stresses in membranes albeit applied in a complex surface geometric systems, rather than a linear one. Thus it becomes possible to exchange locally groups of simple linear tendons with membrane surfaces to stunning effects. We are currently looking at a particular example described below.

Practically, inhabited space inflatables include some rigid elements i.e. they are hybrid structures. As exemplified by the TransHab concept, most of the designs incorporate a rigid central core comprising the airlocks, infrastructure and equipment. An expandable shell is arranged around the rigid core. Exploring the synergies between membrane and tensegrity design in space, we arrived at a tensegrity exo- or endo-skeleton for our modules.

GEODESIC WEBBING

Another development idea is to explore an alternative to the meridional/circumferential restraint webbing patterns. The webbing of lobed inflatables can also follow geodesic lines. The intended application of this approach is in the design of inflatable geodesic structures. If the patterning polygons are regular, the local curvature of the membrane becomes nearly spherical. In that case the pressure stress will be half as much as in the case of a locally cylindrical curvature. We plan a detailed investigation of a geodesic restrained inflatable structures in future works.

HOTEL AT THE END OF THE UNIVERSE

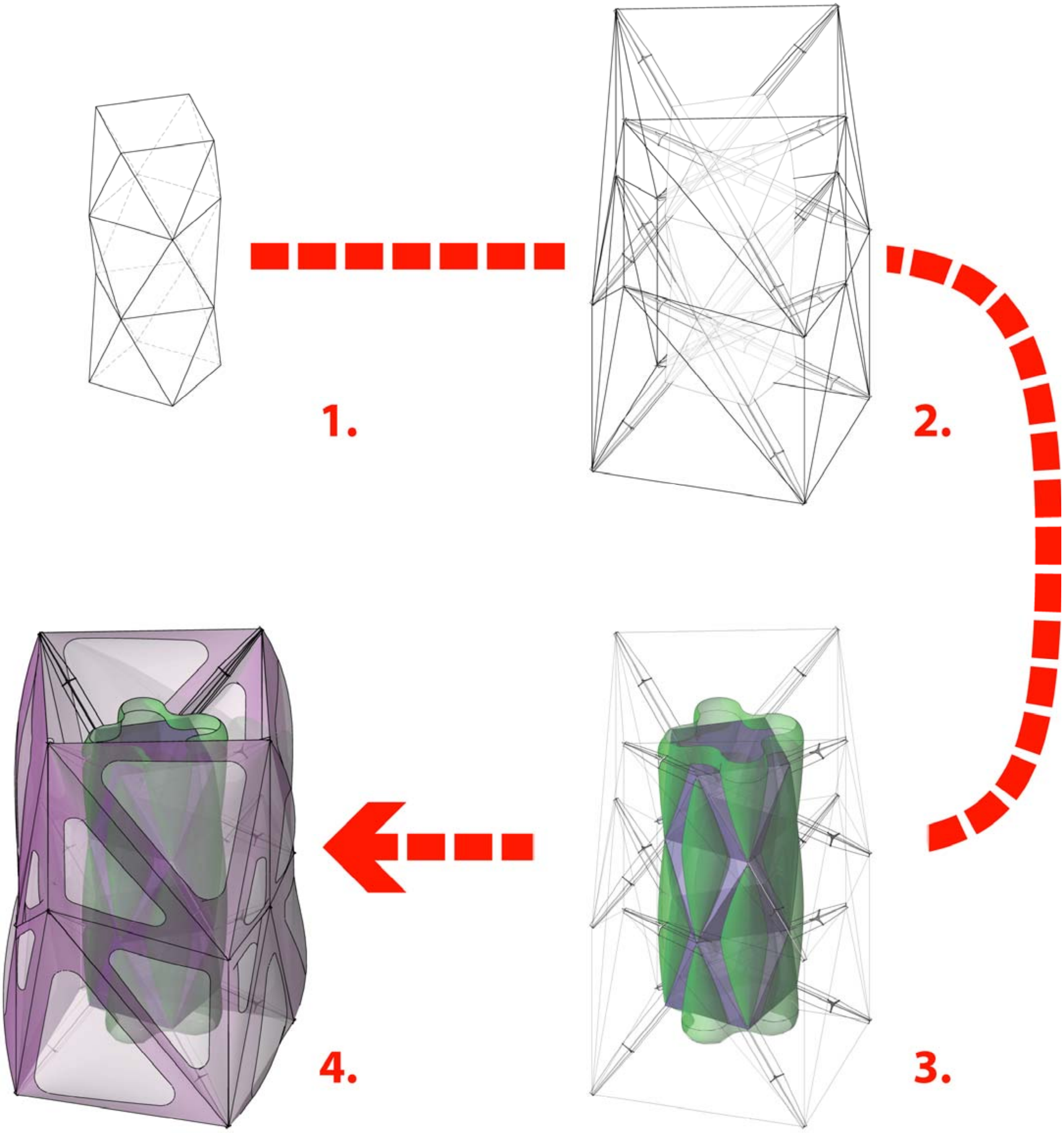


Figure 16 *Hotel at the End of the Universe*: morphogenetic sequence.

Our Hotel at the End of the Universe does not bend time like the related establishment from the book by Douglas Adams. To an extent, it does bend our time tested terrestrial understanding of structural principles, or at least helps broaden its scope.

Built on the tensegrity principle, all components of this design contribute synergetically to its structural stability. For the purpose of easier description, however, we can separate it into three subsystems.

The first one, a tension-compression skeleton, is a classical tensegrity structure made of stiff trussed compression struts and cable tendons. The trusses are arranged along the spatial diagonals of three latitudinaly layered square antiprisms with a=10m. The structure is kept in dynamic stability by cable rigging attached to the ends of the struts.

Secondly, the outer cable rigging serves as the support structure of an exterior membrane layer. Its make up recalls a windsurfing sail: the perimeter, made out of layered Nextel is less elastic and sturdier, hence it is opaque to translucent. The translucent middle portion is made out of several layers of fluorpolymer.

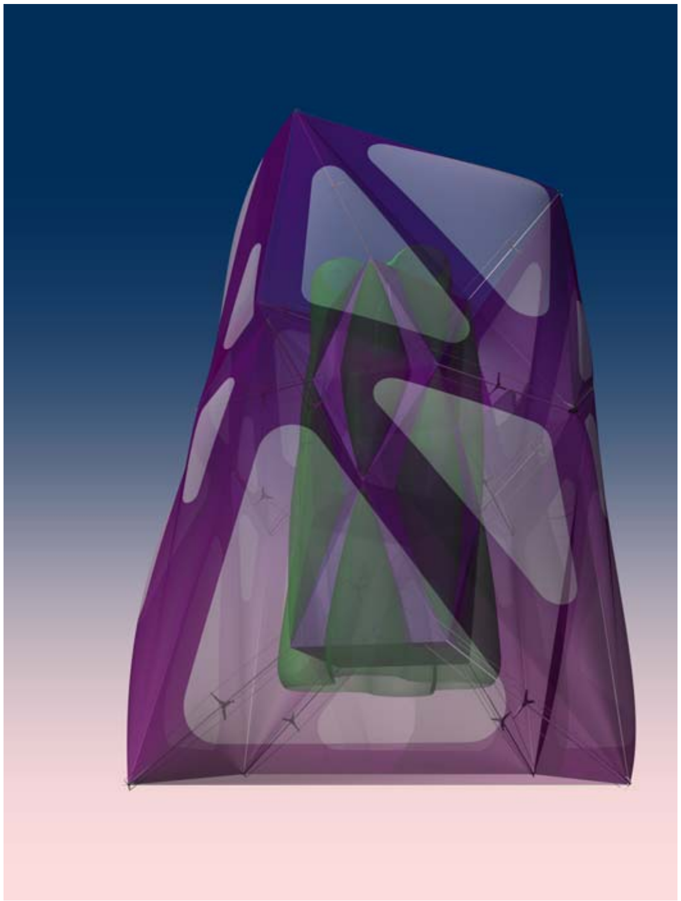


Figure 17 *Hotel at the End of the Universe* **– tensegrity antprism defines the space between the external protective layer and an inhabitable core.**

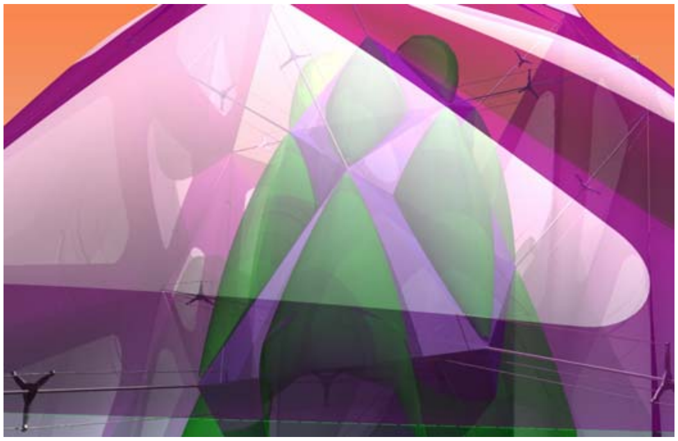


Figure 18 Hotel at the End of the Universe – detail

The morphogenetic nucleus, a polyhedral (antiprism) core, is outlined by an inner rigging belt, forming the third generative subsystem. It becomes the supporting outline for the inhabited internal envelope of the structure. It is constructed out of several layers of Vectran™ silicone composite which follows the outline of the antiprisms.

The envelope is further articulated by roughly conical “bays” made of translucent material, like laminated Mylar/CP1 membrane. This way the inhabited envelope takes advantage of both transparent and opaque perimeter areas creating greater variety in the surface treatment to allow more flexibility for a practical layout of the interior.

The hotel thus creates two envelopes with different pressurization. The exterior one (negligible low pressure) acts as the overall protection barrier to micrometeoric dust, UV radiation, etc. The interior one is the actual habitat where the needs of space tourists are taken care of.

As a structural principle, which transforms the gravity loads defining traditional built structures on Earth into tension and compression within a closed system, tensegrity has demonstrated its potential for use in space. We would like to draw attention to the great variety of forms, which would emanate from the blending and interaction between tensegrity and pneumatic construction methods. A curious impetus and conceptual justification for such a search comes from an unusual source: recent cytological theories uphold that mechanical behaviour in living cells is consistent with the tensegrity model. [25] Maybe we could export cellular structure to the level of cosmic habitats?

Following a basic principle of MMOD protection the design incorporates multilayered tensioned membranes as protective external envelope. That arrangement has two advantages: it eliminates the problems of gas leakage, and replaces the linear tension cables with stressed skin surfaces.

DISCUSSION

The governing force for terrestrial architecture is gravity. Weight is not only the main load, but the force upon which the structural integrity of a building usually depends on. For space architecture such a governing force is the internal pressure of the artificial atmosphere within the envelope. This is true even for structures on celestial bodies with low atmosphere and low gravity such as the Moon or Mars. The architectonic intuition of people living in the relatively strong gravitational field of the Earth is well trained to design structures to not only withstand but relay gravity to buried foundations. We have no such notation, we could say *gestalt*, concerning atmospheric pressure because only differential pressure may be perceived.

The above rationale have recently forced space designers to take a second look at pneumatics, long neglected out of a combination of misunderstandings and disastrous mishaps. Traditional pneumatic shapes, like spheres, cylinders, and regular spherical polyhedra lend themselves well to a generative force acting normal to their walls. Ironically for such a futuristic field, accumulated inertia kicked in once again and this traditionalism presented us with forms, which are often a combination of spherical, cylindrical and conical derivatives.

Since in a typical design process conceptual design goes before calculations, structural intuition lies at the heart of structural conceptions. We likely lack an inherent intuitive concept about the scale of forces shaping pneumatic structures. That may be the explanation for the scarce variety of inflatable structures, manifested in a set of generic shapes. The physical restriction on possible equilibrium shapes of pressurized thin walled shells can't be the sole reason for such a monotony.

Structural calculations usually verify or fine tune the shape already created by the designer. A remarkable exception to that scenario is the method of formfinding in membrane structures design – a well developed branch of terrestrial architecture [31]. In a heuristic process, physical models are used side by side with numerical algorithms in the conceptual design stage, and may be utilized to derive non-intuitive forms providing both architectural sense and structural efficiency.

CONCLUSIONS

From a structural point of view, it is possible to provide pressure confinement of normal artificial atmosphere at an adequate safety factor within highly transparent habitats made up of plastic film acting as gas barrier, and restraint net composed of high tensile strength tendons. Situating such tendon restraint structures in space or on planets with low-pressure atmosphere is possible, but a number of environmental problems still need be solved.

Figure 19 Carbon fiber tape reinforced laminate sails – visual metaphor of form follows *force* principle [UK- Halsey Tape-Drive® Sail Design]

A habitat shell made of a few translucent layers may look rather delicate to serve as a shelter, however we find no insurmountable obstacles for using this technique as an envelope of inflatable cupola or a space hotel.

Although several highly transparent film materials look promising in this context, the long-term behavior of most polymers is generally unknown. A highly charged issue is the micrometeoroid and orbital debris vulnerability of polymer film laminates. One possible solution lies in the use of external retractable shields. Recent projects witness the effective MMOD protection capacity of multilayered polymer films. Nevertheless extensive experimental studies are needed to verify that possibility.

Lobed pneumatics display extended possibilities for morphing generic pneumatic shapes. Non-trivial inflatable shapes can be derived by tailoring filament restraint webbing over a deformable bladder. The genesis of novel inflatable shapes will be greatly enhanced by combining simplified form/stress estimation, interactive formfinding software and the development of heuristic approaches to physical modeling.

The estimated cost for lobed structures designs is lower than the current expandable space habitats due to their enhanced structural efficiency and simplified design process.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

Antiprism:

***** An *antiprism* is a prismatoid whose bases are congruent and whose lateral faces are congruent triangles.[PlanetMath.org]
* An n-sided *antiprism* is a polyhedron composed of two parallel copies of some particular n-sided polygon, connected by an alternating band of triangles. [Wikipedia]
* An n-sided *antiprism* is a polyhedron composed of two parallel copies of some particular n-sided polygon, connected by an alternating band of triangles.[ScienceDaily]