Designing with Technical Textiles on Mars: Material Properties and sustainable-by-design Principles for Enhancing Efficient Construction in Extreme Environments

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Abstract. The flexibility and adaptability provided by technical textiles make them suitable for the aerospace field.
Specific requirements for space structures such as resilience, payload constraints, and economic costs can be tackled through a smart use of the newest technologies in material sciences. The future of space exploration has in store the building of human settlements beyond Earth; therefore, it is crucial to improve and perfect the technologies we use to go to space and sustain human life there.
For this reason, this paper focuses on studying textiles applied to a Martian habitat named E.L.L.E., an Extreme Livable Lightweight Environment, by proposing a new combination of materials for an inflatable system that allows to decrease the total weight of at least 30% than current space modules.
Experimenting with technical textiles in space will enable a deeper understanding of these technologies to encourage their application in extreme environments on Earth for a sustainable architecture.

Keywords: Technical Textiles, Inflatable, Lightweight, Extreme Environments.

Introduction

Technical textiles and membranes can be employed within the aerospace field and their area of application is rather wide. The necessity of using these materials rises from the possibility to obtain lightweight structures which can withstand fatigue and stress and reduce fuel consumption for launches to space.

This kind of materials are suitable for the construction of various products, such as space suits, aircraft, or gossamer structures, which represent that category of ultra-lightweight structures which also includes inflatables.
Compared to traditional materials, technical textiles provide several advantages and help better manage certain critical points of the aerospace field, such as fuel consumption, economic costs, and habitability.
Studying technical textiles in extreme environments such as Mars allows to perfect these technologies due to the many challenges that such an environment poses, therefore bringing benefits to different fields of application that can also involve terrestrial contexts.

1 Technical Textiles in the Aerospace Field

1.1 Gossamer Spacecrafts

The term "gossamer spacecraft" identifies a category of ultra-lightweight space structures which represent an example of the use of technical textiles and membranes in the aerospace field. Examples belonging to this category are space antennas, solar panels, inflatable structures, and solar shields [1]. The materials used for this kind of structures are usually thin and have a low level of stiffness. This type of technology allows to obtain both tensioned-planar and inflatable-curved conformations.
Gossamer spacecrafts will be more and more present in the context of space explorations, since their use facilitates the construction of larger and more efficient structures, thus improving the quality of exploration itself. Indeed, using a lower amount of resources would guarantee both a sustainable approach to space exploration and the possibility to widen the horizons and constraints of traditional space constructions [2].

Space Antennas. Space antennas can be considered part of the gossamer structures category. An example of this is brought by NASA and the Department of Defense of the United States who worked on the design of an inflatable antenna, called IAE - Inflatable Antenna Experiment. This is the first experiment of this genre and proved to be successful. The IAE was launched into orbit onboard a Space Shuttle in 1996, it inflated as expected and thus demonstrated that it was possible to have inflatable structures in space. The antenna consisted of a reflecting parabolic structure with a 14-meters diameter with a transparent cap and a toroidal structure guaranteed the support of the reflector. The structure had a total size of 14 by 28 meters once deployed, while during the launch phase it had been packaged in a much smaller volume [3].

Solar Panels. In order to support space exploration, it is necessary to design systems for energy production. Solar panels are particularly efficient and useful to generate the required energy to sustain the artificial probes sent to space. As research in the aerospace field progresses energy requirements increase too. The inflatable technology

appears to be applicable to different types of structures, among which there are solar panels.
In 1993 a company named L'Garde, Inc. developed a project for an inflatable solar panel for DARPA (Defense Advanced Research Projects Agency) and Philips Laboratory. This structure was designed to be launched into orbit while packaged; upon arrival it deployed and stiffened.
LISA-T is another example of inflatable solar panel, its name is an acronym for Lightweight Integrated Solar Array and Transceiver. Its purpose is the increment of energy production to power satellites while using a lightweight structure [4].

Inflatable Structures. The inflatable technology could represent the starting point to implement and improve orbital habitats and to start building on other planets.
Future planetary settlements could be configured as clusters of inflatable shelters, which would be packed up before launch and deployed once they arrive at destination. These characteristics allow to obtain larger constructions, therefore providing habitats with more livable spaces if compared to current human space habitats, such as the International Space Station (ISS).
The TransHab (see Fig. 1) is an inflatable habitat designed in 1997 by a team of architects and engineers from the Johnson Space Center, headed by Doctor William Schneider.

Fig. 1. View of the TransHab [5].

It is a hybrid space structure made of a rigid central core to which an inflatable outer shell is attached. It was the first project of an inflatable habitable module, and it was subjected to various tests, all brilliantly passed [5]. This project was later bought and

further developed by the private space company Bigelow Aerospace. As a result, BEAM – Bigelow Expandable Activity Module was built and launched it into orbit, where it was connected to the ISS Tranquility Node [6].
Inflatable technologies also turn out to be useful for rovers, which could benefit from having inflatable wheels, therefore facilitating exploration by overcoming obstacles more easily and being faster and more efficient. An example of these inflatable rovers is Tumbleweed, invented by Jack Jones of NASA's Jet Propulsion Laboratory. It was designed to explore Mars and would take advantage of the planet's winds to move faster and explore a wider area [7].

Solar Shields. Solar shields are important to avoid overheating of space structures. An example is the James Webb Space Telescope, initially called the Next Generation Space Telescope, which was launched into orbit on December 25th, 2021, and is equipped with a main mirror with a 6.5 meters diameter and a solar shield made with a five-layer structure of Kapton®. Each layer has a lower temperature than the previous one, this keeps the telescope at low temperatures which allows the observation of more distant points in the universe [8].

2 Traditional Space Habitats Technologies

2.1 Traditional Materials

There are several examples of space habitats that were built since the space exploration era began. One of the first of this kind is the Lunar Module (LM) which was created for the Apollo program in the 1960s, with the aim of bringing the first humans to the Moon. The LM ascent stage had an aluminum structural part, covered with layers of several materials whose purpose was to guarantee protection from heat and micrometeoroids. Above the aluminum skin there was a package of 25 layers of aluminized polyimide foil in Mylar® or H-film, each foil was covered with a very thin layer of aluminum on one side. These layers were then crimped to increase their thermal insulation capacity and the most exposed portions had additional layers of H-film or a sandwich layer made of two thin sheets of nickel, spaced out by a mesh made of Inconel®. The descent stage was also composed of a structure covered by a thermal and micrometeoroid shield similar to that of the ascent module. Here a Teflon® coated titanium shield was added, in order to protect against possible explosions during the ascent operation of the upper stage [9].
Skylab was the first station built by the United States, it was launched into orbit on April 14th, 1973, and remained operational until 1979. Its thermal protection device consisted of an internal layer of aluminum, covered with a Mylar® sheet which was attached to an outwards-facing layer of nylon with an adhesive [10].
Mir was launched in 1986 and was operational until 2001. The materials used for this space station included chemically milled 2 mm thick aluminum sheets welded to a 4 mm thick mesh. There also was a thermal blanket made of 25 layers of aluminized

Mylar® coated with layers of materials with properties similar to those of Kevlar® [11].
The International Space Station is the first station to be built thanks to international cooperation between NASA, ESA, the Russian Federation (Roscosmos) and Japan (JAXA). It became operational in 1998 and hosted its first human mission in 2000. The external casing of the ISS modules is made with a type of light aluminum, above which there is a layer up to 10 cm thick that is composed of materials such as Kevlar® and ceramic fabrics, such as Nextel™, to guarantee protection from micrometeoroids and external temperatures [12].
The analysis of the materials used in past missions shows that aluminum has always been the most used element when building structures for space, since it is a light-weight metal. For this reason, space habitats are rigid and have several constraints in terms of volume, weight, and habitability.

2.2 Launch Vehicles and Payload Constraints

The current space scene has different stakeholders involved with launches of cargo and astronauts into space, such as NASA (National Aeronautics and Space Administration), ESA (European Space Agency), and CNSA (China Nation Space Administration). In these last few years, private space companies started emerging and infiltrating into a field that has always been led by government space agencies. Two examples of this are SpaceX, founded by Elon Musk in 2002, and Blue Origin, founded by Jeff Bezos in 2000. Therefore, collaboration between private and government space agencies has become crucial for the development of this field and to widen the horizons of space exploration. This cooperation brings novelties to launch systems since it is now customary for private space agencies to provide vehicles for government space missions. Falcon 9 (see Fig. 2) is an orbital reusable two-stage rocket developed by SpaceX and used by NASA to transport astronauts to the ISS. It is a 50 meters rocket with a payload capability to low Earth orbit (LEO) of 22.8 tons [13].

Fig. 2. Falcon 9 rocket with Dragon capsule [https://www.nasa.gov/image-feature/falcon-9-rocket-with-dragon-spacecraft-vertical-at-launch-complex-39a].

Another SpaceX developed vehicle is Starship, which is a Super Heavy Rocket, that will be used to go to orbit, the Moon, or Mars. It can transport up to 100-150 tons of payload, therefore it will be especially useful for longer travels that require more cargo [14].
NASA's SLS (Space Launch System) is a super heavy lift launch vehicle that will be used to go beyond Earth's orbit [15]. The SLS Block 1 was employed to send Artemis 1 to the orbit of the Moon, therefore marking the first launch that combined SLS and the Orion capsule; this has a payload capability of 27 tons, while the other SLS Blocks go up to 46 tons in terms of cargo capacities [16].
Europe uses other types of space vehicles to send astronauts and cargo into space. ESA currently operates Ariane 5 and Vega-C from Europe's spaceport in French Guiana. Vega-C can transport 2.3 tons to orbit, while Ariane 6 has a payload capability of 21 tons [17].

3 E.L.L.E. an Extreme Livable Lightweight Environment

3.1 E.L.L.E.'s Technology

E.L.L.E. (see Fig. 3) is an inflatable module designed to accommodate six astronauts for 600 days on Mars.

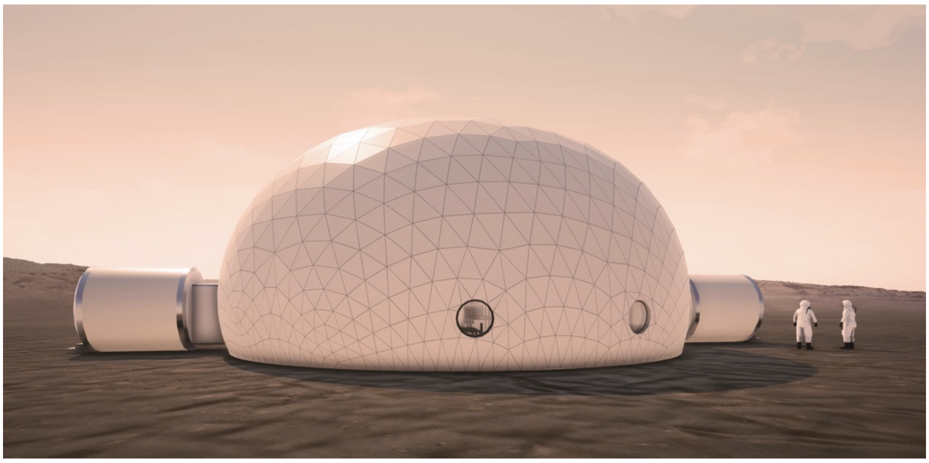

Fig. 3. External view of E.L.L.E.

Designing a project on Mars means that several challenges must be addressed: Mars has no magnetic field, a thin atmosphere mainly made of carbon dioxide, a reduced surface pressure, and low temperatures [18]. It is necessary to design a structure that can protect the internal environment against these external hazards, consequently a deep analysis on the material selection is required.
The inflatable membrane comprises different layers joined together using adhesives, with redundancy being a crucial consideration during its development [19]. The

pneumatic system should be made of multiple layers to grant redundancy and protection against external hazards. A new combination of materials is proposed, each chosen based on prior research and technical properties [1]. The layers of the shell have specific functions, with the inner layer consisting of Nomex® to protect against fire, punctures, and other hazards, while also providing sound insulation and protection for the bladder layer. Nomex® is produced by DuPont and it is a flame-resistant meta-aramid synthetic fiber [20].
The bladder layer is composed of nylon laminate and ethylene vinyl alcohol and offers gas impermeability, flexibility, durability, and resistance to high temperatures. The strategy used to connect the bladder to the inner layer is an ultrasonic welding [1-19].
The restraint layer consists of MadFlex, which has vibration damping properties, is five times stronger than structural steel and has a flexible and a rigid side. This material was developed in 2015 by an Italian start-up called CoRe [21].
The protective layer protects against micrometeoroids and debris and is made of Vectran™ and Duocel®Foam, a foamy material that attenuates impacts. Vectran™ is a multifilament fiber obtained from a liquid crystal polymer manufactured by Kuraray. It provides qualities of resistance against heat, cut, and abrasion, it is an elastic material which is five times stronger than steel, therefore making it suitable for space applications [1-22].
The outer layer provides thermal insulation and radiation protection using Kapton® and Cermex. Kapton® is produced by DuPont and is a polyimide film, it provides a certain level of protection against radiation and Cermex has thermal insulation properties, to shield the internal environment from the low temperatures of Mars [23].
However, an adequate protection against galactic cosmic rays and solar flares can be achieved by adding an additional thick layer made of a high-density material, such as Martian regolith, this would reduce radiation absorption in long-term missions [18].

3.2 Mass of the Inflatable System

E.L.L.E. will be transported to Mars using Starship by SpaceX, which has a payload capability of over 100 tons. During transportation, the inflatable module will be deflated and packed.
The mass of the module can be easily determined because the project was entirely developed using Grasshopper3D, which is an algorithmic modeling software that allows for an easy and automatic calculation of the volume of the habitat.
As previously stated in paragraph 3.1 the inflatable shell is composed of Nomex®, nylon laminate, ethylene vinyl alcohol, Madflex, Duocel®Foam, Vectran™, Cermex, and Kapton®, each with a unique density and thickness.
In order to calculate the total mass of the system it is necessary to identify the density of each of the materials that constitute the external shell (Table 1).

Table 1. Thickness and density of the materials of E.L.L.E.'s shell.

Material	Thickness	Density
Nomex®	0.5 cm	1.37 g/cc
Nylon laminate	7 cm	1.15 g/cc
Ethylene vinyl alcohol	0.005 cm	1.14 g/cc
Madflex	0.5 cm	0.16 g/cc
Duocel®Foam	7 cm	1.4 g/cc
Vectran™	0.05 cm	1.4 g/cc
Cemex	5 cm	0.0961 g/cc
Kapton®	0.445 cm	1.42 g/cc

The next step consists in combining the densities of the different layers, to find the value of the density of the shell. Each density is converted into a percentile that describes the contribution of each material to the layers of the shell, these values are then multiplied by the densities. Table 2 shows the results of these calculations.

Table 2. Percentile values of the materials.

Material	Percentile values	d x percentile
Nomex®	0.0244	33.41 kg/m^3
Nylon laminate	0.3415	392.68 kg/m^3
Ethylene vinyl alcohol	0.0002	0.28 kg/m^3
Madflex	0.0244	3.90 kg/m^3
Duocel®Foam	0.3415	478.05 kg/m^3
Vectran™	0.0024	3.41 kg/m^3
Cemex	0.2439	23.44 kg/m^3
Kapton®	0.0217	30.82 kg/m^3

By adding up the percentile values multiplied by the densities we obtain the density of the shell which equals to 966.00 kg/m^3. A module with a radius of 7.5 meters leads to a volume of 96.89 m^3, therefore the total mass of the system equals to 93,596.21 kg (≈ 94 tons).

If the same structure was made of aluminum as if it was constructed with traditional technologies and materials, there would be some differences in terms of total mass of the system. Aluminum has an approximate density of 2,710.00 kg/m^3 [24], so if we consider the same volume of the shell and this density value the resulting mass is 262,571.90 kg (≈ 263 tons).

This means that the payload capacity of Starship is respected when considering E.L.L.E.'s technology. Compared to traditional methods there is a decrement of approximately 64% of the mass, thus complying with the premises of the research.

3.3 Terrestrial Applications

The use of lightweight materials brings several advantages to the aerospace field, by ensuring a more sustainable way to build and manage space structures. However, the advancements that such research produces are not limited to the aerospace field, rather they can be extended to terrestrial environments.
Inflatables are particularly suitable for situations that require high levels of protection against external hazards or immediacy in construction, such as terrestrial extreme environments, like polar regions or oceans, or temporary emergency shelters. Therefore, E.L.L.E.'s technology could be repurposed, thus transferring its advantages to benefit other situations.

Conclusions

The purpose of the research consisted in demonstrating that technical textiles and membranes can be applied to a space architecture project to reduce the weight of the transportable cargo during a space mission to another planet.
E.L.L.E. was developed as a space architecture project that proposes an inflatable technology with a novel combination of materials that can fulfill the premises of the research. This study demonstrated that the obtained decrease in mass is equal to 64%, therefore exceeding initial expectations. This result shows that it is crucial to invest in lightweight materials within the aerospace field, since such technologies facilitate sustainable projects by decreasing the economic costs and the resources needed to travel to space.
Additionally, using an inflatable technology such as the one developed for E.L.L.E. allows to obtain larger livable volumes for the crew, therefore providing higher levels of comfort and habitability of space structure. This will improve the astronauts' lifestyles, which is particularly important point to consider for the longer missions to the Moon and Mars that will be seen during the next decades.

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