The concept of a large space construction cured directly in space orbit

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Abstract

The next step of space exploitation requires large construction in orbit. We need a sufficiently large volume of pressurized construction protecting the crew, passengers, space processing equipment, etc. However, the modern and planned space constructions – which are in a "ready-to-use" state, prepared on the ground and are launched by launch vehicles – are only the size of "one-car-garages". It limits our future in space and makes the space industry impossible. We have to be unlimited with space, in space. A large space construction (up to 7000 m^3) can be made using the chemical curing technology of a fibre-filled composite with a liquid polymer matrix applied directly in a free space environment. The fabric impregnated with a liquid matrix (prepreg) is prepared in terrestrial conditions and is shipped in a container to orbit. Then the prepreg is inflated and a chemical curing reaction is initiated. When the chemical curing reaction is completed, the durable solid construction can be fitted out with air, apparatus and life support systems. Our experimental studies of the curing reactions in free space simulator and in stratosphere flights showed that a strong composite could be cured directly in space. The curable large constructions can dramatically change space exploitation. New concepts of space stations, Moon bases, Mars bases, mining stations, interplanetary space ships, telecommunication stations, space observatories, space factories, antenna dishes, radiation shields and solar sail based on the curing in space technology are considered.

Keywords: space, composite, large space construction, space exploitation, curing

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1. Introduction, or why do we need a large-size space construction?

An era of space flight started in 1950th gave us a possibility to lose Earth's gravity and to step onto the Moon's surface. Since that time astronauts require a good physical shape for space flights and a risk remains despite modern technologies in rocket science. The crew must live in a small space module and has a limited volume for life-supporting systems, scientific devices and personal life on the board. The modern spaceships are not suitable for long term flights to Mars, Europa, other planets, asteroids and moons, where we dream to go. These

limitations, which were not important 70 years ago, are stopping us from moving forward now.
First spaceship Vostok was a 2.3 m diameter ball and could only fit one cosmonaut. The Mercury spaceship was a 1.88 m diameter cone and was 2.74 m in length. These spaceships were constructed with the minimal size and volume requirements. The prototype of these first spaceships was a cabin of aeroplane. The Apollo spaceship was bigger but only three astronauts occupied it. The Moon lander had a small cabin which was densely occupied by two astronauts. These first spaceships were designed with a goal to mark a human presence in space.
The ISS modules were larger but it took 10 years to build it and launch it into the Earth's orbit with multiple launch failures. The ISS did not have any autonomous life-support system providing air, water and food sufficient for the long term and needed permanent supplies from the ground. The ISS did not have the industrial capacity for the mass production of something in space. ISS did not have the massive radiation protection required for deep space flights. Such technology was not a proper way to explore our Solar system with a human crew.
We need the technology, which will allow us to create a large construction in space, which will be sufficient for a big crew, autonomous life permanent support system based on a large green house, sufficient radiation protection, enough storage volume for scientific equipment, fuel, air, water, spare tools and equipment and a rescue spaceship. This large construction must be durable enough for a long-term flight under the destructive influence of the cosmic radiation and temperature variations. This construction must be large enough to maintain industrial processes in space. This construction must be constructible in space or on a celestial body where it will be required for exploration.
Recent private and government projects and programs concludes that effective space exploration requires new construction and technological solutions which can significantly increase the size of space constructions. A deficit of energy on-board causes a necessity of larger solar panels, an increase of power consumption on board causes a necessity of large radiators, an increase of data transfer significance causes a necessity of large antennas, Moon and Mars bases as well as long distance space flight require large pressurised constructions. All these trends show a necessity for new technologies and materials for large space constructions.
In the space industry a large construction means a construction of a size more than the size of a launch vehicle transportation container. It means the construction cannot be placed in the transportation container of the existing space launch vehicle. Therefore, the construction must be extendable in orbit after launch. Two ways to extend the delivered space construction in orbit are:
- Delivering separate parts of the construction and joining these parts in orbit;
- Delivering the construction folded and deploying the construction in orbit.

The first way is used for module constructions like a space station. Such constructions are usually ready-to-use, have a high attachment accuracy and have a big mass. The assembly process of such constructions is difficult due to the extreme conditions of space such as vacuum, space irradiation and temperature variations. An involvement of an astronaut in the assembly process is not possible due to very limited movement in space suit. The ability of modern robots in the assembly process is very limited.

The second way includes a number of deployable constructions. They include deployable carcass constructions, umbrella-like constructions, different membrane constructions and inflatable constructions. The size of the constructions made of deployable elements is limited by the low stability of movable joints. The membrane constructions are only suitable for limited missions like a solar sail. Most inflatable constructions are promising. They can provide a high mechanical strength, practically have an unlimited size, they have a low mass, they have a low volume in their folded state while being transported and have a fast and easy deploying process. Therefore inflatable constructions are considered the most prospective type for future large space constructions.

2. Inflatable curable constructions

The inflatable constructions called Gossamer structures were proposed for space exploration a long time ago. The shell of a durable thin material is folded on Earth, delivered to orbit and inflated with internal pressure. These inflatable structures have been repeatedly tested in orbit since 1962. The first inflatable construction in space was the Echo satellite, a large thin ball of Mylar foil with an aluminium coating. Such a thin shell of a few microns thick survived more than year in orbit. The last test was done recently on the ISS when Bigelow's inflatable structure docked to the ISS was successfully unfolded. However, despite the long history of investigations and tests – including flight tests – the usage of the inflatable structures is very limited. The problem is a relatively low mechanical durability of the inflatable structure in comparison with rigid structures. The requirements for the pressurised volume with the sufficient stability and durability can be only satisfied with thicker walls (up to 0.6 m) for the construction. But it makes the construction heavy and the advantage of folding doesn't become great in comparison with the ready-to-use constructions. For example, the Bigelow module docked to ISS was not larger than the other ISS modules.

The walls of the inflatable construction after the orbital deployment must become strong. The rigidization technologies for inflatable wall materials have been tested and reviewed for space exploration such as a material with evaporable solvent, phase transition materials, foam-making materials and others. However, a stable material with sufficient strength can be cured by a chemical reaction such as some curable composite materials with a polymer matrix.

Composite materials based on a polymer matrix and fibres have been tested and used as strong construction material including making a pressurised volume for a human crew for a long time for environments including space. For example, carbon fibres impregnated with an epoxy resin composition is a well-known class of construction materials for space applications including rockets and satellite frames. The composite materials based on glass fibres with an epoxy resin composition are used for airplane frames like the Airbus 380. These materials have long lifetime in orbit and in deep space and have a good strength to mass ratio. The synthesis of these materials includes a stage of curing process, where a chemical reaction transfers the liquid resin composition into a rigid polymer matrix. Because of the curing reaction the soft prepreg (the fibres with a liquid or semi-liquid resin) becomes a rigid composite. We propose to use the same reaction in orbit.

The prepreg with the liquid resin is soft enough to be used for a shell for the inflatable structure. The prepreg with a long shelf life resin is prepared and folded on Earth, delivered to orbit in a compact container and is unfolded. Then the curing reaction is initiated and, after the reaction is complete, the prepreg is transformed into a rigid composite. Similar projects have been considered for other space constructions, but they have not been realized. It is because of the harsh conditions in free space for uncured liquid resin of the prepreg. The prepreg in orbit would be under a high vacuum, cosmic radiation and wide temperature variations. Several unknown physical-chemical processes can occur in the prepreg in these space conditions. The curing technology requires the understanding of these processes to predict the properties of the composite that is cured in space.

The first factor is the high vacuum. The pressure in a Low Earth Orbit (LEO) is much lower than the vapour pressure of all the liquid components of the uncured polymer matrix. It means that the liquid components of the uncured matrix evaporate into the high vacuum. As a result, the concentration of active components decreases, the stoichiometric ratio of active components breaks, the fibres to matrix ratio breaks and the composition cannot be cured. If the evaporation is fast enough, the resin composition will bubble and the final structure of the polymer matrix will be a foam. It significantly decreases the mechanical properties of the composite.

The second factor is cosmic radiation as a combination of both the different kinds of radiation from Sun and stars; and flux of the high energy charged and neutral particles. This cosmic radiation has a damaging effect on all materials including polymers. The active components of the uncured composition can be decomposed and deactivated. As the result, the composite will not be cured and/or significantly lose its mechanical strength.

Thirdly, the curing reaction is very sensitive to the temperature of the prepreg. The temperature of the space construction depends on orientation to the Sun and its surface reflection. The temperature variation of the prepreg makes the curing reaction unpredictable.

These factors make it impossible to transfer the ground technology of the composite materials directly into space. However, we have done a large number of experiments and theoretical investigations of the curing process in the prepregs under simulated space conditions – such as high vacuum, plasma and high energy ion beams and temperature variations – and showed that the curing of the prepreg could still be successful under such harsh conditions [1-13]. The flight tests on curing the prepregs in the stratosphere under cosmic radiation, high vacuum and temperature variations finally confirmed that the prepreg could be cured in a space environment. The mechanical properties of the composites cured in the stratosphere and in orbit are as strong as the composite cured under terrestrial conditions.

We propose a wall for the inflatable construction, which has a multilayer structure (Fig.1). Main structure layer is a prepreg. The three dimensional fabric of the prepreg can be made of organic, carbon or glass fibres depending on the space mission and requirements. The prepreg matrix can be thermo or UV curable resin. A selection of the resin depends on kind of space mission, required life-time of the prepreg and exploration conditions. The bottom layer is an inflation bag with a barrier layer to prevent atmosphere leaks through the wall. The inflation bag provides the inflation of the wall and holds the pressure in the construction.

In this article the main steps of this technology, its advantages and the new horizons of space exploration are considered.

3. Future missions using large space construction

The size of the inflatable construction delivered to space depends on the space vehicle capacity, thickness of the wall and weight of supporting structures such as inflating devices, docking port and engines for orientation. Due to the high mechanical strength of the wall after curing, the thickness of the wall could be significantly reduced. The cured construction should hold an atmospheric pressure, the walls of the construction can be optimised for the maximal size of the construction and mechanical strength of the construction. For example, a cylinder-shaped construction of 100 m in length, 10 m in diameter, with a wall thickness of 5 mm and a weight of 20 tons can be inflated and cured from the container with the prepreg delivered to LEO with existing space vehicles like the Proton, Ariane or Falcon. The internal volume of the unfolded and pressurised construction can be up to 7000 m^3 that is almost 10 times bigger than the total pressurised volume of ISS or more than 20 times bigger than the individual ISS modules. With the extra heavy vehicles designed by SpaceX the construction can be extended up to 500 m in length. Such a long structure can have a shape of a torus or a helix. The spaceship of such a shape and size can rotate for an artificial gravity during the space flight to avoid the problems of weightlessness for astronauts in long-term flights.

When the construction is pressurised, the spaceships with the crew can be docked and the crew can work in the construction without spacesuits to install the required systems and equipment.

Such a large construction can be used for many applications. For example, a scientific space station the size of the modern ISS can be created after one launch. An estimation of the cost for the station construction is about $1 billion – that is much less than cost of the modern ISS. Similar costs could be estimated for a Moon or Mars base of 7000 m^3 pressurised volume delivered by only one space vehicle.

The 7000 m^3 large size construction can be used for mass production in space, for example, growing unique crystals, producing highly pure materials or other industrial processes. The pressurised volume of the construction would be sufficient for the installation of large production equipment and increasing the scale of technological processes.

A space hotel of 7000 m^3 could suite about 100 tourists visiting the orbit. The price of a week's space tour with full service can potentially be about $50,000-$100,000.

A space observatory or space telecommunication station with a permanent crew for maintenance and upgrades in the orbit can be created and used. It means that small communication satellite launches would not be required every year and no more space waster would be created in Earth's orbit.

The constructions can be used for large greenhouses in orbit to provide a sufficient amount of food and to recover water and oxygen – as autonomous life support systems – for a long space journey to other planets. The large green houses can protect the crew against cosmic radiation in long-term flights. The toroid shell structure could be large enough to make a rotating station with an artificial gravity that will make the space flight less dangerous for humans.

The inflatable curable constructions can be used as frames for large antenna dishes hundreds of meters in diameter. Such dishes would provide a very high sensitivity that mobile telephones would not require local communication towers.

The inflatable curable constructions can be used as frames for large solar sails – a square kilometre in area. A satellite with such a solar sail would be faster than any chemical fuel engine.

Other space structures like a radiation shield for telescopes, pressurised constructions to repair satellites and space ships, large reflectors and others would be available. There would be no technology for space exploration which would not be affected with the new technology of large space constructions.

4. Following steps

A realisation of the large construction technology requires a development in existing technologies of composite materials and space constructions.

Firstly, the non-autoclave curing technology should be tested in space. The ground simulators of space environment should be redesigned for curing process simulations in real time. The simulator should provide a combination of critical space factors on the uncured prepreg such as high vacuum, atomic oxygen fluxes, electron beams, proton beams and temperature variations. The curing kinetics under these conditions should be measured in real time. The measurements of active component concentration, concentration of active groups, concentration of crosslinks and mechanical properties should be included in the simulator. The analysis of curing should be investigated under sun activity, atmospheric variations and flight regimes (orientation, altitude). As a result, the models of the curing process under space environment conditions should be developed and evaluated in stratospheric and orbital flights.

Secondly, the prepreg technology should be adjusted to the large structure with an internal bag. The non-autoclave and non-press technologies should be evaluated for the selected prepreg. The ground infrastructure of composites is developed for relatively small parts. The maximal size of the prepreg parts that can be found is up to 3 m. This limitation is connected with the requirement of uniformity of the polymer matrix in the cured composite. The liquid uncured resin is flowing in the prepreg under gravity influence. The curing process in space orbit does not have the flow due to microgravity and the uniformity of the liquid resin is not a problem. Therefore a winding of the whole structure could be done. The continuous stretched fibre through the whole structure at winding would provide a maximal mechanical strength of the composite. The winding machine with prepreg diameter of 10-20 m and length of 100 m and more is required.

The winding process should include an installation of the hermetic internal inflatable bag underneath of the prepreg. The hermetic bag should keep integrity during the winding, and the winding process should be quite gentle and accurate. The additional elements of the construction such as the docking block, windows, internal elements, barriers and fixing parts should be installed and winded together with the prepreg at this stage. Finally, the prepreg should be covered with an anti-sticking mesh. Not too dense mesh should be used to still provide free evaporation of low molecular components into space in orbit, no-sticking folding of the prepreg and to adjust reflectance coefficient of the sun irradiation to regulate the prepreg temperature during curing in orbit.

Thirdly, the prepared soft construction should be folded and kept in the transportation container under a low temperature and an inert atmosphere to exclude water adsorption, oxidation, dust attachment and uncontrolled reaction propagation. The folding and packing processes of the wet prepreg with embedded solid elements into the container should be developed. The container providing transportation conditions for the uncured prepreg should be adjustable to the space vehicle and should be designed. Some sophisticated engineering of the whole structure with all these elements is essential.

The launch conditions are not specific. The high acceleration during the launch is not critical due to the short time and the low viscosity of the resin. The container should be kept under a low temperature during the launch and orbit flight before it will be opened. The time in orbit before an opening the container should be minimised because of cosmic radiation could cause the crosslinking in the prepreg as a curing reaction. The radiation protection of the container can decrease the level of radiation and prolong lifetime of the prepreg in orbit if required.

Before opening of the container and deployment, the container should be heated up to the deployment temperature and should be stabilised so that all of the elements of the prepreg are heated and are soft enough for deployment. The temperature and heating time should be optimised for a minimal viscosity of the resin composition in the prepreg. The temperature should not to be high to prevent an unexpected reaction propagation.
After the temperature stabilises, the container should be opened and the inflation bag of the construction should be inflated. The inflation process should be optimised to provide a completely open construction and keep integrity of the structure. Depending on the temperature regime, the opening can be done on a shaded side, if the prepreg can be heated up high enough. This regime provides uniform temperature distribution on the shell surface. If the temperature cannot be high enough in comparison with the temperature decay during the inflating, the opening process is preferable on Sun side, when the Sun irradiation will heat up the prepreg during the inflating. In such case, the temperature will be not uniformly distributed over the shell surface and an optimisation of the rotation regime of the construction is essential to heat up all parts of the construction for smooth deployment. At the inflating stage the rotation should be fast enough to prevent a local overheat and an unexpected propagation of the curing reaction.

The optimisation of the flight regime in depends on the construction shape, curing rate of the resin composition and speed of which the inflation is required.

The curing reaction can be initiated by heating it up to the required temperature with embedded heaters or Sun irradiation. The selection of the heating method depends on the resin composition, shape of the construction and selection of the flight regime. A combination of two systems is also possible. Both curing systems have been tested in the simulated a free space environment and in a stratospheric flight. However, the difference of these two systems is significant and influences on the selection of the composition, flight regime and exploration conditions. The UV curing reaction is easier to manage and depends less on the unexpected heat spikes. However, the cosmic radiation initiates the curing reaction in UV curing system. Therefore the UV curing system prepreg cannot be stored in orbit flight for a long time. The deployment should be done in a shaded side to prevent an unexpected curing reaction of the partially deployed construction.
The thermal curing reaction is less sensitive to cosmic irradiation, however the reaction can be initiated when the temperature is higher than the threshold. The requirement of the stable prepreg before the flight makes this temperature relatively high. Usually, such compositions start to react at temperatures higher than 80C. This temperature can be achieved by irradiation from the Sun. The flight regime with complex motion of the construction can provide a uniform curing process over the construction. The temperature rise can be regulated by a reflective coefficient of the covering mesh at the top of the prepreg. Monitoring of the temperature distribution over the whole construction could be useful.

The verification of the curing is an important part of the composite material production. The curing reaction is sensitive to the temperature, cosmic radiation and fight regime. Ground technology includes always a verification of the completeness of the curing reaction with different methods. However, the verification of the curing reaction in the space construction during the orbital flight is complicated. The development of then resonance frequency analysis of the construction together with the simulation of the curing reaction based on flight data for the construction are essential for the verification. A robotic system with spectrometer movable on the construction surface could be useful for a local analysis of the curing reaction.

After the construction is cured and tested for that the curing reaction is completed, the construction can be pressurised up to an atmospheric pressure. Then the cargo and crew spaceships can be launched and docked to the construction. The crew without vacuum protecting spacesuits can come in and install the radiation protection systems and thermal protection systems. The individual thermal and radiation protection the crewmembers is required. An active phase of the installation can be done during the flight on the shaded side to minimise the radiation effect on the crew. The installation can be also optimised depending on the orientation to the Sun to minimise the radiation flux through the construction.

After installation of the protection systems, the construction is ready to install the necessary life-supporting systems, power system, electronic system, internal walls and structures, accept cargo ships with food, water, equipment for long space flights. After the installation of all systems the spaceship or space station will be ready for the desirable space mission.

6. Conclusions

The large space construction is required for following space exploration. The inflatable construction with chemically curable walls directly in free space environment opens a large number of possibilities in space exploration. The main achievement would be that we would be settled in space: we will build our habitats in orbits or other planets, not bring our "ships" from Earth. It would be next step in space exploration.

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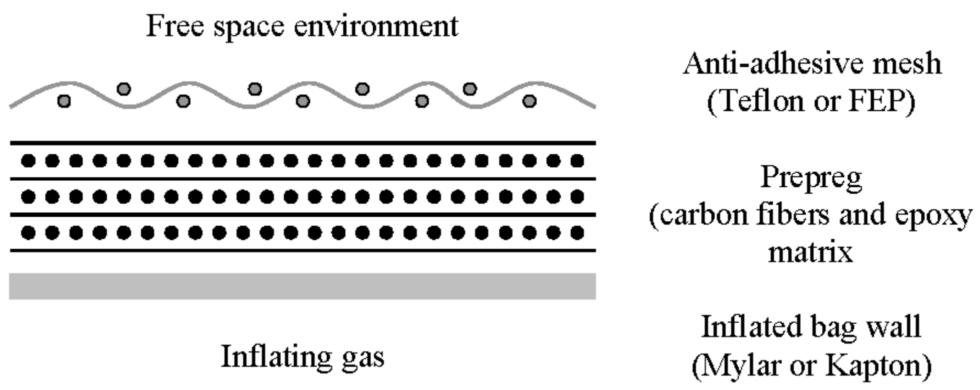

Fig. 1. Scheme of the curable wall of the large space construction. A rare top mesh provides free evaporation of low molecular components to prevent bubbling in the prepreg and sticking of the prepreg layers in the folded state. The multilayer 3D prepreg is to provide high strength of the construction after the curing. The inflating bag is for deployment of the construction in orbit.

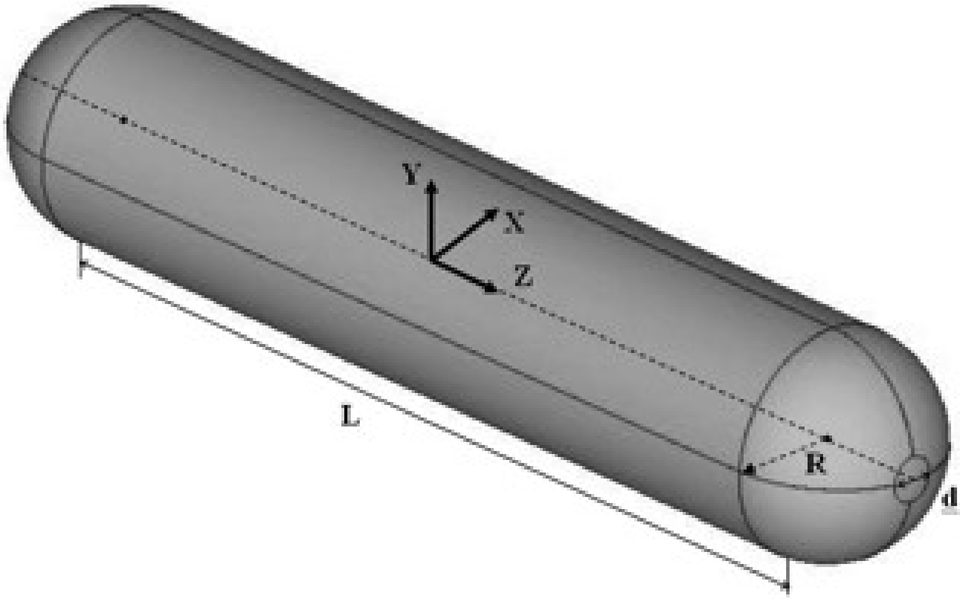

Fig. 2. Cylinder shape as an example of the inflatable curable space construction with a length (L) of 100 m, radius (R) of 10 m, internal pressurised volume of 7000 m^3. Mass is 20 tons. It can be delivered and unfolded on Earth orbit with one launch. Docking ports (d) are not shown.