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ЧИСЛЕННОЕ И ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ РАСКРЫВАЮЩЕЙСЯ КОСМИЧЕСКОЙ КОНСТРУКЦИИ НА ОСНОВЕ ТОНКОСТЕННЫХ КОМПОЗИТНЫХ ПРОФИЛЕЙ

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Потребности спутниковой радиосвязи и дистанционного зондирования Земли приводят к появлению раскрывающихся космических рефлекторов с увеличивающейся апертурой, что приводит к ужесточению требований к снижению их массы и объема в транспортном положении и повышению коэффициента укладки. Современные ферменные рефлекторы обладают приведенными характеристиками, однако им свойственен и ряд недостатков, а именно: большая сложность изготовления и юстировки, наличие большого числа подвижных частей и малая первая собственная частота колебаний. Предложен вариант раскрывающейся космической конструкции, на базе которого в перспективе возможно построение ферменного рефлектора с более высокими жесткостью и надежностью раскрытия. Предлагаемая конструкция представляет собой пространственную ферму, образованную тонкостенными композитными стержнями, профиль которых при приложении определенных нагрузок способен уплощаться, обеспечивая тем самым возможность их складывания. Изготовление рефлектора только из углепластика за счет его высокой удельной прочности, жесткости и малого коэффициента термического расширения в перспективе позволит обеспечить повышенную частоту первого тона колебаний и размеростабильность конструкции в широком температурном диапазоне. В предлагаемой конструкции отсутствуют металлические детали, что позволяет дополнительно снизить массу и избежать проблемы стыка “металл–композит”.

***Ключевые слова*:** крупногабаритные космические конструкции, раскрывающийся космический рефлектор, композитный материал, тонкостенные конструкции, конечно-элементное моделирование.

NUMERICAL AND EXPERIMENTAL ANALYSIS OF DEPLOYABLE THIN-WALLED ALL-COMPOSITE SPACE CONSTRUCTION

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Advanced deployable space reflectors are widely used for radio-communication and Earth remote sensing. The increase of reflector aperture imposes increasingly strict requirements on its mass, storage volume and stowage ratios. Among other types of deployable reflectors, space truss reflector can be marked as low weight, low storage volume and high stowage ratio solution. However, reflectors of this type have several drawbacks, like high manufacturing and adjustment complexity, large amount of movable parts and low magnitudes of first eigenfrequencies. In current paper, the new deployable space construction design possibly appropriate for reflector is proposed that possesses all the advantages of space truss reflectors while reducing structural complexity and price, rising low eigenfrequencies and guaranteeing needed *deployed shape. The proposed design is a space truss made of foldable composite rods with thin-walled collapsible cross-section. The design structural integrity allows the manufacturing of reflector as a single part made of carbon fiber reinforced plastics with high specific strength and stiffness as well as low thermal expansion, thus providing necessary rigidity and stability of the structure in wide temperature range. All-composite design will additionally reduce the mass and will allow to avoid composite-metal joining issues.*

Keywords: large space structures, deployable space reflector, composite materials, thin-walled structures, finite element modeling.

1. Introduction Rising demands on space radio-communication and Earth remote sensing satellites require the enlargement of aperture of onboard antenna. At the same time, the lift capabilities of launch vehicles are limiting significantly the payload mass and size, that's why conventional and advanced large space antennae structures are designed as deployable.

Large deployable antennae structures could be subdivided into different types [1]: rigid petals with hinges forming the continuous reflecting surface (RadioAstron, TRW Sunflower); textile reflecting surface held by deployable support structure (ISS Reshetnev Loutch, Astromesh), inflatable reflector and/or support system (Model-2, NASA IAE), hybrid concepts and other (shape memory support structures, springback structures and so on). The choice of antenna type for given spacecraft is based on the required reflector aperture and operating wavelength. Typical root mean square (RMS) of reflecting surface is higher for rigid type antenna and lower for inflatable ones, contrariwise, stowage coefficient, the ratio of characteristic dimension in deployed to transport position, is rising from rigid to inflatable reflectors. The intermediate characteristics of RMS and stowage coefficients of textile reflecting surface and truss support antennae structures allows them to fill the gap between rigid and inflatable reflectors. However, reflectors of this type usually consist of large amount of mechanically jointed parts having their own freeplays and dimension tolerances, resulting in high manufacturing and adjustment complexity.

Historically, composite materials with high specific stiffness and strength properties are widely used in large space structures, providing excellent performance characteristics along with significant weight savings, but the field of their application is significantly limited due to, among others, low reliability of composite joints. Therefore, most advanced truss support structures are made of composite parts jointed together with metallic ones. This solution partially eliminates the benefits of composite material structure by increasing overall weight, decreasing lowest eigenfrequency magnitude and introducing technological problems with metal-composite joints.

Meanwhile, deployable structures based on furlable or bi-stable thin-walled beams are studied [2]. Most of these structures are used as antenna blade or straight support booms and masts. Structures of this type are packed by flattening the beam's cross section and further rolling it on the

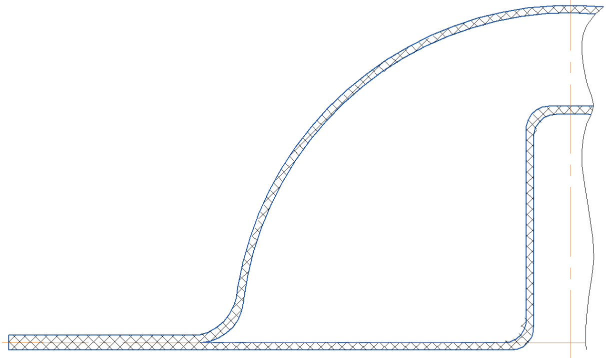


Fig 1. Typical cross-section of proposed bi-stable beam

spool. The deployment, controllable or not, is performed by unreeling the beam from the spool. Another utilization of bi-stable structures is a tape-spring based hinges, one or several thin metallic curved strips connecting two hinged parts [3].

2. Design and experiments. The deployable space construction design possibly appropriate for reflector is presented in this paper. Such design allows retaining the advantages of space truss reflector while reducing its complexity and price. The proposed solution is a space truss, formed by bi-stable beams with closed cross-section, which can be flatten by pressing the beam with compression forces in cross-section symmetry plane. Rigidness of flattened beam reduces significantly, leading to the formation of so called “dynamic” hinge in structure. Structure with such a set of “dynamic” hinges can be folded just like the one with mechanical hinges. The cross-section of bi-stable beam is schematically shown in Fig. 1, typical space truss elements are shown in Fig. 2.

The bottom surface of observed cross-section was made flat in order to couple it with textile reflector and could be made curved to fit the required geometrical form.

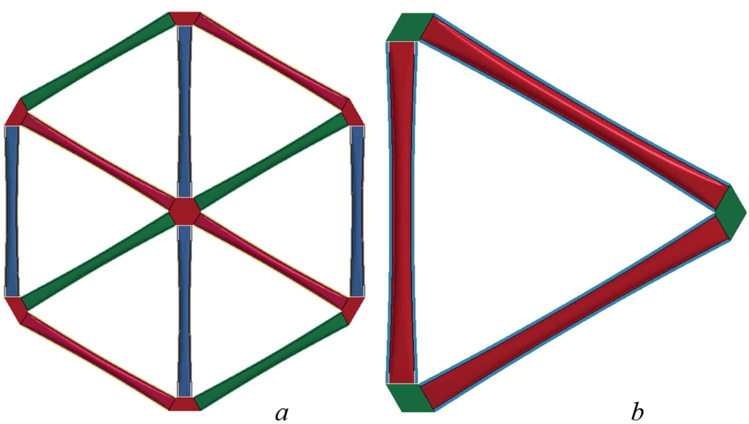
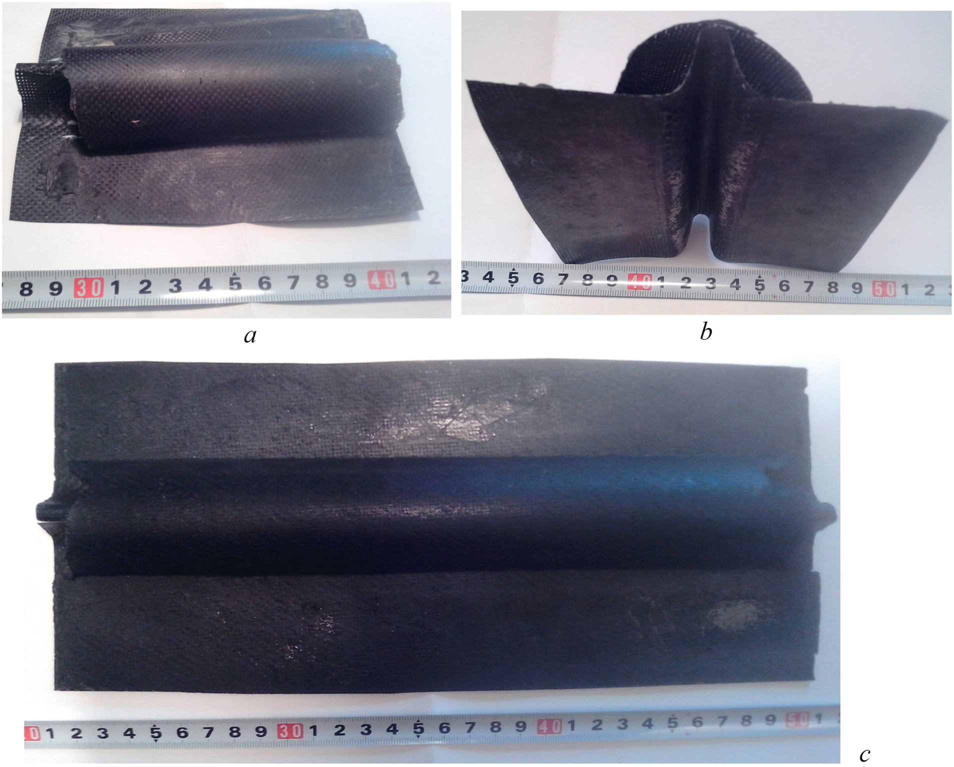


Fig 2. Typical triangle and hexagonal space truss elements formed of bi-stable beams



a *b* *c*

Fig 3. Bi-stable CFRP test beams

Basic principles of current design were tested by fabricating two test bi-stable beams made of CFRP, short and long, with the same cross-section as shown in Fig. 3.

The dimensions of test samples were 155 mm × 110 mm × 24 mm and 298 mm × 125 mm × 24 mm for short and long version respectively. Cross-section of each beam was formed with semicircular upper mold with 24 mm radius and lower one with 8 mm wide fold and 20 mm height. The thickness of the walls was 0.2 mm. Comfiber carbon plain 80 g/m^2 fabric and Axon EPOLAM 2017 resin was used for the fabrication of test samples with vacuum infusion process. The choice of 80 g/m^2 fabric is due to the fact, that the use of 100 or 200 g/m^2 fabric for the test samples, while allowing it to keep shape perfectly, introduces excessive rigidity, which leads to cracking or failure during flattening. The use of fabric with density less than 80 g/m^2 leads to an excessive decrease of stiffness and inability to hold shape. The choice of the resin was due to the similar reasons.

The next step of experimental validation was the folding testing. The sample was slowly flattened and rolled on the round bobbin. The folded and fixed test article is shown in Fig. 4.

During folding tests, the phenomenon was observed, referred further as self-locking of bi-stable composite beam. Simply flat surface supported long test specimen, loaded with concentrated force in its geometrical center, changed its form from initial stable to deformed, self-locked one, as shown in Fig. 5.

3. Analysis. Stowage and deployment analysis of the proposed design was fulfilled with using LS-DYNA nonlinear code. The triangle unit with proposed bi-stable composite beams components was analyzed as a typical building block of real space trusses. The specimen observed is shown in Fig. 2.

Fig. 4. Folded short test sample

Numerical analysis of unit was separated into two stages. First was stowage analysis, when the final form of the truss was deformed with concentrated forces to the folded state with the accumulation of potential energy. Second stage was the deployment analysis, when the folded truss was deployed to final state by releasing the potential energy.

During the first stage of the analysis, the specimen was constrained by restricting out-of-plane translational motion in the corners of the structure. Concentrated tension forces were applied at geometrical centers of the beams to flatten its cross-sections. Folding of the beams was then caused by the concentrated forces, applied at the same points, but directed normally to final state of the truss.

The second stage of the analysis began with the fixing the model in stowed state and damping its oscillations, caused by the sudden application of constrain. The deployment analysis was then started, when the most of the kinetic energy of the specimen was dissipated and the constrains were released. There were no constrains at the time of deployment applied. 4-noded shell finite elements were used for numerical modelling on both stages of the analysis. Material properties used are listed in Table.

Fig. 5. Long test specimen in self-locked state

Mechanical properties of composite material

Property	Value
Young's modulus, $E_1 = E_2$ (GPa)	63
Shear modulus, G_{12} (GPa)	4.5
Poisson's ratio, υ_{12}	0.1
Density, kg/m^3	1500

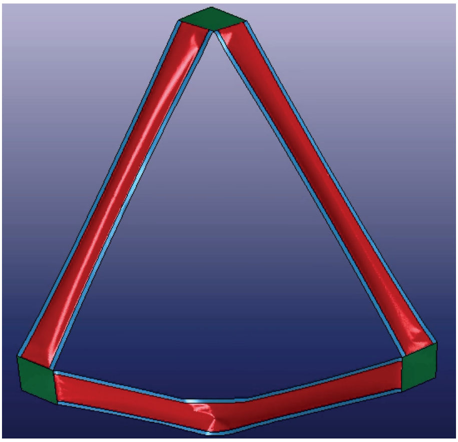


Fig. 6. Self-locking effect in numerical analysis of triangle test sample

Verification of the numerical model was made by the analysis of deployment of triangle unit. The result have shown real-scale stresses in deployment process and have confirmed the presence of self-locking phenomenon in numerical analysis (Fig. 6).

Thus, the basic principles of space all-composite bi-stable beam truss are validated by technological and numerical experiments. The developed mathematical model is applicable for further detailed investigation of similar type structures.

4. Conclusions. Further investigations plan consist of following steps:

- Numerical analysis of folding/deployment, dimensional stability and eigenfrequencies analysis of hexagonal unit;
- Manufacturing of hexagonal unit, folding/deployment testing and eigenfrequencies measurement;
- Numerical analysis of folding/deployment, dimensional stability and eigenfrequencies analysis of real size space truss ;
- Manufacturing of real size space truss, folding/deployment testing and eigenfrequencies measurement.

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