PERIÓDICO TCHÊ QUÍMICA
ARTIGO ORIGINAL

DEFINIÇÃO DE DEFORMAÇÕES NA ESTRUTURA COMPOSTA DE GRADE SOB A AÇÃO DE CARGAS COMPRESSIVAS

DETERMINATION OF DEFORMATION IN MESH COMPOSITE STRUCTURE UNDER THE ACTION OF COMPRESSIVE LOADS

ОПРЕДЕЛЕНИЕ ДЕФОРМАЦИИ В СЕТЧАТОЙ КОМПОЗИТНОЙ КОНСТРУКЦИИ ПРИ ДЕЙСТВИИ СЖИМАЮЩИХ НАГРУЗОК

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RESUMO

Uma das tecnologias inovadoras importantes é a criação de estruturas de grande porte que funcionam por um longo período no espaço e atendem a restrições rigorosas das características gerais de massa. Entre essas estruturas, em primeiro lugar, está a seção de treliças de suporte de carga. Este artigo apresenta os resultados de estudos experimentais de compressão das seções de treliças de suporte de carga na estrutura de grada. Recentemente, os invólucros cilíndricos de grade compostos são usados como carcaças de naves espaciais. O invólucro de grade é uma estrutura de suporte à qual os instrumentos e mecanismos da espaçonave estão conectados. A seção de treliça de suporte é feita do material compósito de polímero da estrutura de grade usando fibras de carbono. O objetivo dos testes é confirmar a possibilidade de criar uma estrutura de grade leve usando um material compósito de polímero reforçado com fibra de carbono. Para atingir esse objetivo, os autores definiram as seguintes tarefas: escolher o preenchimento de carbono de materiais compósitos de polímeros (MCP); escolher os ligantes de MCP, determinar o grau de reforço de fibra de carbono; escolher o número e trajetórias de orientação das nervuras em espiral, o número de nervuras anulares e o tamanho das nervuras individuais. Para teste, foi desenvolvida a "Instalação para teste da treliça de suporte". Como resultado da pesquisa, são obtidos os indicadores calculados para garantir a capacidade de carga e a rigidez sob a aplicação de carga compressiva axial. Simultaneamente com a determinação da capacidade de carga, as características de deformação da estrutura são determinadas duas vezes para confirmar sua repetibilidade, bem como a natureza linear da dependência de deformações axiais e radiais como resultado da carga aplicada.

Palavras-chave: *tetronamotka, fibra de carbono, treliça de suporte, nave espacial, lançador de foguetes.*

ABSTRACT

One of the significant innovative technologies is the creation of large-sized structures that work for a long time in space and meet stringent restrictions on overall mass characteristics. Among these structures, in the first place, is the section of bearing truss (BT). This article presents the results of experimental studies of sectors of load-bearing trusses of mesh design for compression. Recently, composite mesh cylindrical shells are used as spacecraft housings. The mesh shell is a supporting structure to which the instruments and mechanisms of the spacecraft are attached. The truss section is made of cross-linked polymer composite material with carbon fibers. The objective of the tests is to confirm the possibility of creating a lightweight mesh construction using a carbon fiber reinforced polymer composite material. To achieve this goal, the authors were assigned the following tasks: selection of carbon filler of polymer composite materials (PCM); selection of PCM binder; determination of the degree of carbon fiber reinforcement; choice of the number and orientation paths of spiral ribs, number of ring ribs and the sizes of individual ribs. As a result of the research, the calculated indicators for ensuring the bearing capacity and stiffness under the application of axial compressive load were obtained. At the same time, with the determination of bearing capacity, the deformation characteristics of the structure were twice determined in order to confirm their repeatability, as well as linear nature of the dependence of axial and radial deformations as a result of the applied load.

Keywords: *tetra-winder, carbon fiber, bearing truss, spacecraft, rocket launcher.*

АННОТАЦИЯ

Одной из важных инновационных технологий является создание крупногабаритных конструкций, длительное время работающих в условиях космического пространства и отвечающих жестким ограничениям по габаритно-массовым характеристикам. К числу таких конструкций, в первую очередь, относится секция несущих ферм (НФ). В данной статье приведены результаты экспериментальных исследований секций несущих ферм сетчатой конструкции на сжатие. В последнее время композитные сетчатые цилиндрические оболочки находят применение в качестве корпусов космических аппаратов. Сетчатая оболочка является несущей конструкцией, к которой присоединяются приборы и механизмы космического аппарата. Секция несущей фермы изготовлена из полимерного композиционного материала сетчатой конструкции с использованием углеродных волокон. Целью испытаний является подтверждение возможности создания облегчённой сетчатой конструкции с использованием полимерного композиционного материала, армированного углеродным волокном. Для достижения поставленной цели перед авторами были поставлены такие задачи: выбор углеродного наполнителя полимерных композиционных материалов (ПКМ); выбор связующего ПКМ, определение степени армирования углепластика; выбор количества и траекторий ориентации спиральных ребер, количества кольцевых ребер и размеров индивидуальных ребер. Для проведения испытаний была разработана «Установка для испытаний несущей фермы». В результате исследований получены расчетные показатели по обеспечению несущей способности и жесткости в условиях приложения осевой сжимающей нагрузки. Одновременно с определением несущей способности дважды определяются деформационные характеристики конструкции с целью подтверждения их повторяемости, а также линейного характера зависимости осевых и радиальных деформаций в результате действия приложенной нагрузки.

Ключевые слова: *тетронамотка, углеродное волокно, несущая ферма, космический аппарат, ракетный носитель.*

1. INTRODUCTION:

One of the essential innovative technologies is the creation of large-sized structures that work for a long time in space and meet stringent restrictions on overall mass characteristics. Among these structures, in the first place, is the section of bearing truss (BT). For the production of a section truss of structural carbon fiber, the technology of tetra-winding can be effectively used, which allows one to obtain cylindrical compartments that withstand intense compressive loads. This design has high bending stiffness and compressive strength in combination with reduced weight (Berezovskii *et al*., 2015; Babaytsev *et al*., 2017a; Varsavas and Kaynak, 2018).

To increase rigidity, BT design provides reinforcing axial stringers (longitudinal ribs) in four planes along four ribs, as well as ending flanges made in a single technological winding cycle together with mesh shell. These problems were considered in detail in (Antufev *et al*., 2019a; Antufev *et al*., 2019d; Antufev *et al*., 2019c; Bodryshev *et al*., 2019; Zhavoronok *et al*., 2019; Rabinskiy and Tushavina, 2019; Dmitriev *et al*., 2011).

The section of bearing truss (BT) is one of the structures that have been operating for a long time in outer space conditions and meet stringent restrictions on overall mass characteristics. Power elements of the design of spacecraft stages, interstage compartments, propulsion systems, space tug support frames, spacecraft, and space platforms are traditionally made in the form of frame-tubular shells from various alloys (aluminum, titanium), as well as stainless steel (Babaytsev *et al*., 2017a; Babaytsev *et al*., 2017b; Antufev *et al*., 2019a; Antufev *et al*., 2019b; Babaytsev and Zotov, 2019; Sevryukova *et al*., 2012). In recent years, both in foreign and domestic practice, non-metallic composite materials reinforced with glass, organic, or carbon fibers have become increasingly used to reduce the mass characteristics of structures for space constructions (Berezovskii *et al.*, 2015; Kyanishbayev *et al.*, 2016; Suprun *et al.*, 2018; Babaytsev *et al.*, 2017a; Babaytsev *et al.*, 2017b; Koshoridze *et al.*, 2017; Babaytsev and Zotov, 2019; Babaytsev *et al.*, 2019). Some examples are the following:

- mesh shells of transition compartments made of organoplastic having unidirectional reinforcement with the technology of continuous winding of the thread on forming tooling;

- conical adapters and cylindrical power truss of spacecraft and space platforms in the form of wire-mesh shells made of carbon fiber reinforced with high-strength carbon fiber.

As practice demonstrates, the use of composites provides a more than twofold decrease in the characteristics of the load-bearing elements of power frames and trusses in comparison with metal structures with the same levels of bearing capacity, rigidity, and stability of shells. Production capabilities make it possible to create large enough products with a diameter of more than 2 meters and a length of more than 6 meters with the appropriate refinement of the process and technological equipment (Golushko and Semisalov, 2015; Pintossi *et al.*, 2019).

2. MATERIALS AND METHODS:

As applied to the section of bearing truss (BT) of spacecraft, the smallest weight characteristics can be realized using PCM reinforced with both aramid and carbon fibers, however, taking into account rather high levels of radiation exposure, requirements for a long-term stay of the product in open space and higher stiffness characteristics, preference ought to be given to carbon fiber structures (Umbetov *et al.*, 2016; Mustafin, 2006).

Polymer composite materials are understood as multicomponent materials consisting of a plastic base (matrix), which is reinforced with fillers that have high strength and rigidity. The properties of the new material quantitatively and qualitatively differ from the properties of each of its components. By changing the composition of the matrix and the filler, their ratio, the orientation of the filler, a wide range of materials with the desired set of properties is obtained. The use of polymer composite materials can reduce the mass of the structure while maintaining or improving its mechanical features.

The use of PCMs based on glass, polymer, carbon, and ceramic fibers is currently directly related to progress in rocket science, aviation, automotive, shipbuilding, mechanical engineering, construction (Tokiwa *et al.*, 2009; Farhadinia, 2014). The properties of PCMs depend on the choice of the initial components and their ratio, the interaction between them, the method and technological conditions for manufacturing the product (pressure, temperature, time), additional processing of the product, and a number of other factors. The determining factor in creating a PCM is the interaction and mutual influence of components at the fiber-matrix interface (binder). The higher the required properties of the PCM created for structural use, the more complex the set of requirements must be maintained when choosing the source components (Gattringer *et al.*, 2019; Mishra *et al.*, 2019; Hao *et al.*, 2019). The final characteristics of carbon-epoxy composites are strongly influenced by the chemical structure of the epoxy resin, its properties, and curing conditions. Improving the adhesive characteristics is achieved by creating a covalent chemical bond at the interface as a result of surface treatment of the fibers and modification of the composition of the binder (Alosime, 2019; Kumar, 2019). The mesh structure consists of two symmetrical systems of spiral ribs and a system of ring ribs. Spiral ribs are located at angles to the generatrix of the cylinder. The annular ribs pass through the midpoints of the segments of the spiral ribs located between the points of their intersection.

In this case, the most relevant development objectives are:

- selection of carbon filler of PCM (fiber) that meets the optimal set of requirements for physic-mechanical characteristics and provides the possibility of its application in continuous winding technologies (except for breaks at a tension of the thread and kinks both in the manufacture of elements of large curvature and in the movement of thread (wisp) in the layout and saturation systems of the binder;

- selection of PCM binder that provides uniform impregnation of carbon tow and sufficient adhesion to the formed unidirectional matrix;

- determination of the degree of carbon fiber reinforcement, which is responsible for compressive strength of unidirectional PCM (in the direction of calculations and carbon tow) at least 0.5 GPa and tensile strength at least 0. 9 GPa;

- to optimize the rigidity and strength of PCM while minimizing the mass of the mesh shell – choice of the number and orientation paths of spiral ribs, number of ring ribs and the sizes of individual ribs (width, height – for the implementation of automated manufacturing in a single technological cycle – it is advisable to keep the ribs dimensions constant over the entire mesh surface).

To test the BT at this stage of the study, the axial compressive force was adopted as the main load acting on the shell: the calculated value of which corresponds to the bearing capacity of 14 tf. Total dimensions of the BT section are – diameter 1200 mm, length 3800 mm. To increase rigidity, the design provides reinforcing axial stringers (longitudinal ribs) in four planes of four ribs, as well as end flanges (Skvortsov *et al*., 2012; Tkachev *et al*., 2018; Baymuratov *et al*., 2018).

The mesh elements have the following geometric dimensions:

- rib height – 15 mm,
- the thickness of the spiral ribs is 3 mm,
- the thickness of the annular ribs – 3 mm,
- the thickness of the longitudinal ribs – 4.2 mm
- the angle of orientation of the spiral ribs relative to the generatrix – 29 degrees.

BT has two end frames. The frames intersecting the ribs of the mesh structure are made of carbon fiber. Based on the accepted structural parameters and geometric dimensions, the design of the BT section was done. A general view of BT is presented in Figure 1.

To test the design of BT for mechanical strength (axial compression), "Installation for testing the load-bearing truss" was developed and manufactured. The test bench layout is displayed in Figure 2. The structure of the stand includes base floor plate 1; lower mounting plate with a restrictive ring to prevent radial displacement of the model from the axis and its alignment 2; the upper base and mounting plate with a restrictive ring to prevent radial displacement of the model from the axis and its alignment 3; power exciter (manual hydraulic jack) 4; force meter (strain gauge force sensor) 5; set of centering sleeves 6; technological support for mounting 7; string type displacement sensors, potentiometric – 8 (four vertical through 900 (Dat1-Dat4) and one horizontal in diameter (Dat5). Sensors Dat1 and Dat2 are nearby, as are Dat3, Dat 4.

The model was loaded according to the step diagram with a step of ~ 20 kN and exposure at each step of ~ 100 seconds to the total compressive force of ~ 138 kN (14 tf). Continuously recorded magnitude of the deformation of BT in the axial and radial directions and accompanied by visual monitoring of the state of the structure. At the maximum value of the applied compressive force with a hold time of 10 minutes.

3. RESULTS AND DISCUSSION:

Two tests of the BT section with the identical loading mode were carried out. The second test was carried out in order to confirm the absence of the phenomenon of micro-tears and cracks caused by the cyclic regime of load changes. The reduction in length and increase in diameter in cross-section in the middle of the height of the truss model is shown in Figure 2 and Tables 1, 2.

The design of the transition compartment constitutes the core system that remains unchanged after exposure to loads. The farm is manufactured by continuously winding a tow with a binder based on phenolic resins. Production of transition compartments started involving carbon composite materials to reduce mass characteristics while maintaining the strength and rigidity of the structures. The use of such materials provides a more than twofold decrease in mass characteristics compared to metal structures while maintaining the rigidity and strength of structural elements.

Figure 3 and Figure 4 present the first readings of recording devices during a time period. The stepwise nature of loading can be seen. During the initial period of time, a linear increase in readings of the string displacement sensors is observed at practically constant load. This mode corresponds to the movement of the plate 7 up to its contact with the counter plane of the end flange and the formation of the snug fit of both plates of the stand to the corresponding flanges of the model. At some point in time, the force sensor begins to register an increase in corresponding value, and at the same time, the nature of the sensor's readings changes to a gentler one. Based on the tests, was obtained a dependency on indications of sensors (external load) on time. (Figure 3). Figure 4 presents a compression diagram (the dependence of truss movements and an increase in diameter depending on the applied forces).

4. CONCLUSIONS:

1. Through the measurement range, the model of the BT section retained its integrity and stability, and there were no violations of continuity

of the polymer composite material, cracks, or delamination.

2. The nature of the deformation of the BT prototype when applying axial force is close to linear, which indicates the absence of irreversible fracture processes in the polymer composite material and development of only elastic stresses without accumulation of damage. The elastic nature of displacements is also confirmed by the similarity of displacement curves in the load-unloading modes of the model (there are no residual deformations within the measurement accuracy).

3. The relative value of axial strain was ~ 0.1%. There was good convergence of the measurement results with the strength calculation data, and the errors did not exceed 6%.

4. The registered small levels of structural displacements under the action of compressive load and their satisfactory reproducibility, including at significant forces of 14 tf, lets us consider the possibility of modernizing the design scheme of the model of BT section to provide an additional reduction in its mass.

Particularly, it is advisable to optimize the size and number of axial ribs (stringers). Likewise, in further work, it is advisable to clarify the possible variation in properties of the polymer composite material implemented in the design of the model using the suggested manufacturing technology.

BT tests have demonstrated that at a given axial load of 14 tf, the product retains its bearing capacity and stability at the levels of relative deformations of no more than 0.1%, which corresponds to the results of strength calculations for given properties of the material. Deformations of the product are noticed in the elastic region without significant changes. The deformation characteristics of the model remain stable and vary linearly depending on the applied load.

5. ACKNOWLEDGMENTS:

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Figure 1. *Image of the mesh structure*

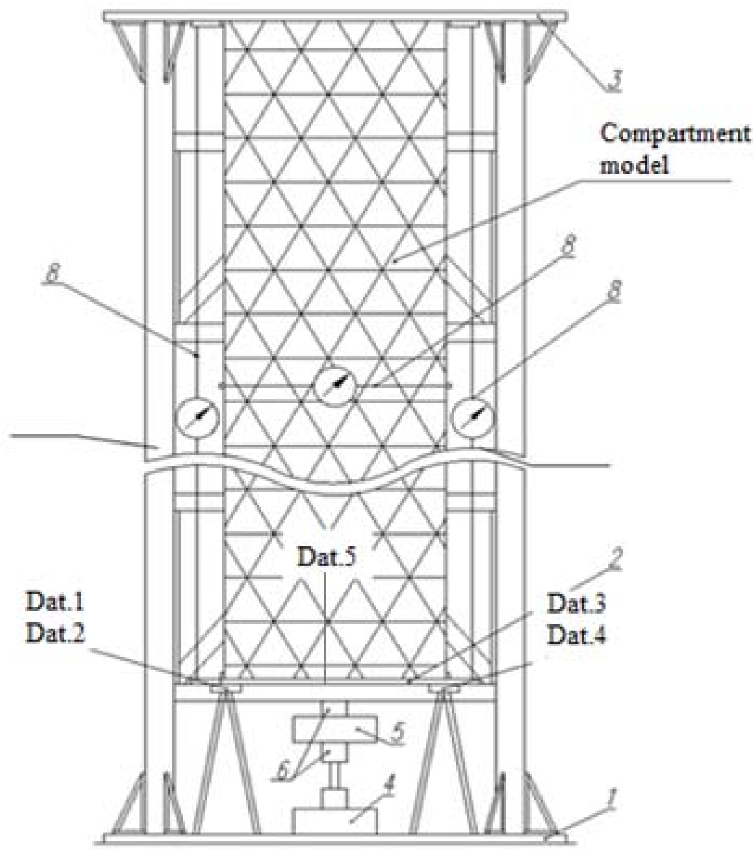

Figure 2. *Scheme of the test stand*

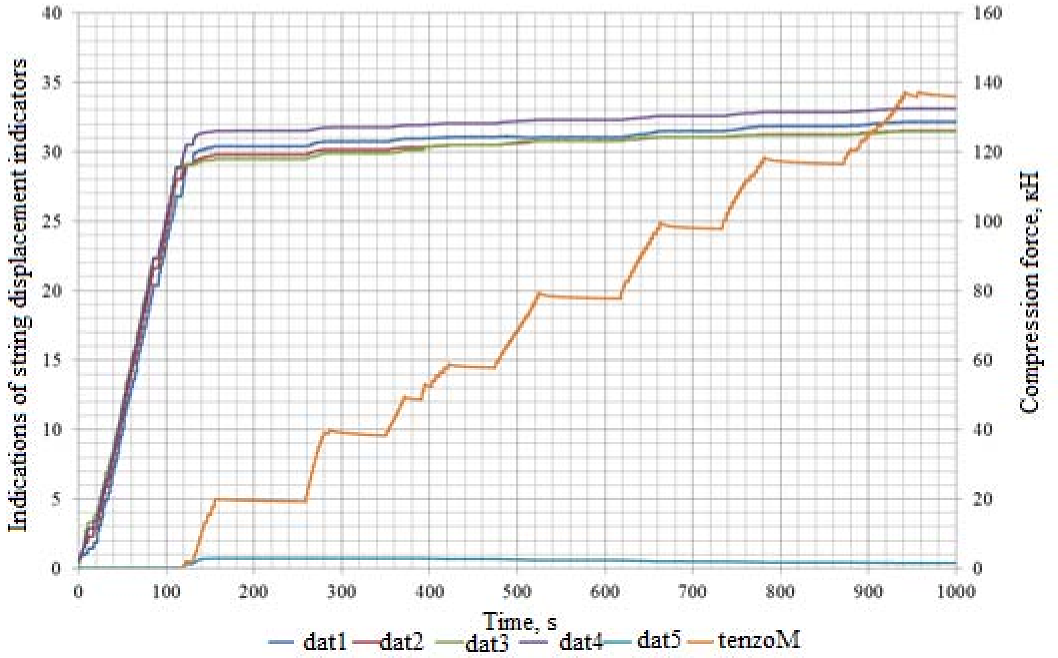

Figure 3. *The dependence of displacements and compressive forces on time*

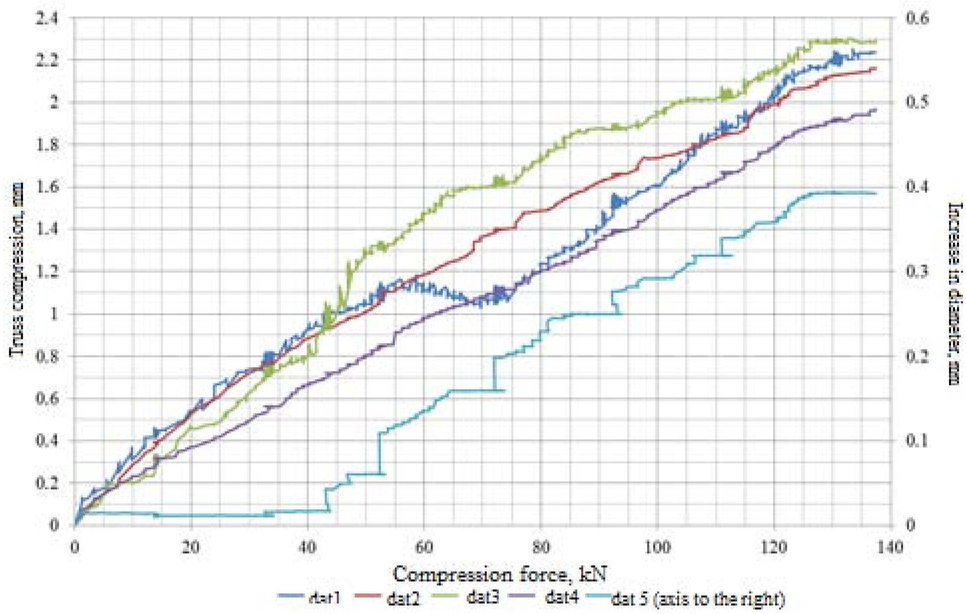

Figure 4. *The compression Chart*

Table 1. *Average values of deformation characteristics. Test 1*

Compressive load, kN	Truss compression * Δl, mm	Diameter increase ΔD, mm
20	0.45	0.00
40	0.80	0.00
60	1.20	0.15
80	1.45	0.23
100	1.52	0.30
120	2.00	0.35
138	2.10	0.39

Table 2. *Average values of deformation characteristics. Test 2*

Compressive load, kN	Truss compression * Δl, mm	Diameter increase ΔD, mm
20	0.45	0.00
40	0.80	0.00
60	1.05	0.10
80	1.35	0.20
200	1.70	0.23
120	2.0	0.30
138	2.20	0.32