Simulating a triangular tube of a spacecraft solar array

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Abstract. The static analysis of anisogrid carbon-fiber triangular tubes is considered in the article. According to the minimum deformability, the optimum values of winding angles of the side ribs are determined. Buckling and stiffness analyses are included as well.

1. Introduction

The study and exploration of outer space require the constant development and improvement of spacecraft for various purposes. The creation of modern spacecraft involves the solution of diverse problems typical of space technology in general, such as ensuring the maximum mass of payload while minimizing the cost of its launch into orbit, as well as it assumes the presence of qualitatively new energy possibilities on board. One of the traditional sources of energy for spacecraft is solar arrays (figure 1).

Figure 1. Spacecraft solar array.

The increase of the requirements to the onboard systems of spacecraft leads to the need to design solar arrays with improved energy characteristics. One of the simplest and most obvious ways to increase the power of solar arrays is to increase the area of solar panels [1, 2]. Structurally, the spacecraft solar array consists of a panel [3, 4], electrical cables and mechanisms [5]. The solar panel consists of a frame with the solar cells mounted on it. The mechanisms ensure the installation of the solar array on the body of the spacecraft and the transfer of drop-down elements from the starting position to the working one with their subsequent fixation. The frame of the solar array is a frame of
carbon-fiber tubes, interconnected by metal fittings [6]. As a rule, carbon fiber tube frames have a ring-shaped cross section. To increase the coefficient of occupancy of the frame by solar cells, as well as to reduce the mass of the solar array, it is advisable to consider the tubes of the frame in the form of a thin-walled net structure of triangular cross section (figure 2).

Technologically, tubes are produced using the method of continuous winding of carbon-fiber composite on three longitudinal ribs of a sectoral section. As a result of the winding, side ribs of a rectangular cross-section, inclined at an angle $\phi$ to the profile generator, are obtained (figure 2, 3). In conjunction with the longitudinal ribs, they form the frame structure of mesh type. The laying angle of the side ribs varies. The characteristics of the material being used in the analysis are the following: $E_1=180$ GPa; $E_2=6.2$ GPa; $G=5$ GPa; $\mu_{12}=0.007$; $\mu_{21}=0.021$; $\rho=1500$ kg/m$^3$ [6].

![Longitudinal ribs and Side ribs](image1)

**Figure 2.** Triangular tube.

![Triangular tube section](image2)

**Figure 3.** Triangular tube section.

The strength, bearing capacity and rigidity of the frame depend on the mechanical properties of a composite, the macrogeometric parameters of the triangular section of the rods, the size of the side ribs and the angles of their laying. To determine the optimal combination of the entire set of design parameters, it is necessary to perform a numerical study on the influence of certain factors on the structural properties of the composite tube.

In this work, the value of the angle of inclination of the side ribs $\phi$ is determined (figure 2), at which the minimum deflection of the tube is ensured. At the same time, the bearing capacity (critical load) and stiffness (by the value of the frequency of the first natural oscillation) are evaluated.

2. **Choosing a finite element model**

To carry out a numerical experiment, it is necessary to develop a finite element model of a tube in which its design features would be adequately taken into account, and it would also be possible to promptly make changes to various design parameters with subsequent generation of the grid in automatic mode. This part of the work was carried out in the environment of the integrated package of finite-element programs COSMOS/M, whose basic module (GEOSTAR) provides a large set of tools for constructing geometric and finite-element models of objects. It sets all the necessary options for calculations of various types as well. At the first stage of modeling, the issue of the types of finite elements being used was resolved. Two options were considered as alternatives. In the first option, all the structural elements are simulated with the beam elements. This approach is based on the previous authors’ experience associated with the design of the spatial composite anisogride structures (antenna spokes, spacecraft adapters, etc.). The advantage of this option is associated with the high degree of reliability of girder finite elements, which allows varying the longitudinal dimensions of finite elements over wide limits and obtaining the high accuracy of the solution even in the case of using relatively coarse grids. The finite-element grid with large values of the average size of the beam
elements imposes lower requirements to the computational capabilities of a computer, since it provides a smaller (compared to a dense grid) order of the resolving system of equations. This circumstance significantly reduces the time of calculations. However, in a series of preliminary buckling analysis, the unreliability of the model with only beam elements was revealed. But this advantageous (in terms of solution speed) option had to be abandoned in favor of a hybrid mesh, in which finite elements of the thick-walled shell (SHELL4T) were used to model the longitudinal ribs of the structure. Here, for some values of the design parameters (in particular, for the large values of the winding angles of the side ribs), the forms of local buckling of the shell type in the elements of the longitudinal ribs that are not tracked in the first grid option (with only beam elements), turned out to be relevant. The use of a hybrid grid increases the computational cost of a computer; these computations must be made to obtain accurate results. It should be noted that the data of static analysis (on the function of deflections), obtained on the basis of the first option (only with beam elements), coincide with the results of the refined solution, made using a hybrid finite element model.

3. Creation of a calculation model
In the calculations, the main variable parameter is $\phi$ - the magnitude of the winding angles of the side ribs of the tubes (figure 2, 4).

Figure 4. Tube models with different winding angles of the side ribs $\phi = 15, 25, 35, 45, 55, 65 ^\circ$.

The creation strategy of finite element model consists of three stages:

- Formation of a geometric model of a typical tube sector (figure 5).
- Generation of a finite element mesh on the geometric primitives of the typical sector.
- Reproduction of a finite element mesh of a typical sector for the length of the entire tube.

It should be noted that the choice of this strategy is caused to the fact that in most cases (in particular, with large values of the winding angles of the side ribs, figure 2 and 4) it is impossible to build a full geometric model of the structure due to the restrictions on the number of standard geometric primitives in the package. The main geometric primitives (figure 5) are rectangular surfaces intended for modeling the longitudinal ribs of the tube with SHELL4T shell elements. At the same time, several longitudinal strips of such primitives should be distinguished to provide different thickness of the shell finite elements. The side ribs of the tube are modeled by BEAM3D girder finite elements, which will be located along the inclined lines of the side faces. Since the beam elements have a rectangular cross section, it is important to ensure their correct orientation. After triangulating the typical sector and
copying its elements along the length of the tube, we will form a complete finite element model of the structure (figure 6).

![Figure 5. Geometric primitives (lines and surfaces) of a typical segment.](image1)

![Figure 6. Finite element model (fragment) with a winding angle of the side ribs of 45°.](image2)

The calculation model is complemented by boundary conditions (connections) and loads (figure 7).

4. Numerical analysis

The result of the static analysis of the composite tube is the distribution of the parameters of the stress-strain state in the elements of the longitudinal and side ribs. In our case, the deformability is estimated by the magnitude of the deflection in the center of the tube (figure 7, 8). Table 1 presents the mass (m), deflection (Δ), critical load coefficient (k cr) and the first frequency (f 1) for triangular tube models with the length l=0.6 m, with different winding angles of the side ribs.

| φ (°) | m (g)  | Δ (mm) | k cr    | f 1 (Hz) |
|-------|--------|--------|---------|----------|
| 15    | 38,47  | 3,807  | 0,101 (-0,129) | 529      |
| 25    | 37,13  | 4,066  | 0,388 (-0,424) | 702      |
| 35    | 38,41  | 4,321  | 0,803 (-0,802) | 728,5    |
| 45    | 39,39  | 4,475  | 1,209 (-1,047) | 721      |
| 55    | 39,77  | 4,183  | 1,745 (-1,180) | 720      |
| 65    | 42,19  | 4,222  | 0,763 (-1,313) | 663,2    |

The calculation results indicate that the smallest deflection corresponds to the model with the smallest of the investigated angle of inclination of the side ribs (φ=15 °). This is consistent with the beam theory. The side ribs with the greatest slope (smallest φ) provide the greatest contribution to the value of longitudinal bending stiffness. As the winding angle φ increases, the central beam deflection increases as well, reaching a maximum at φ=45 °. However, the model with the deformation angle of winding of the side ribs (φ=15 °), which ensures the smallest deflection (regulated parameter), is the worst in stability. The critical load for it is 10 times less than the current one. At the same time, the ribs lose their stability locally within one typical sector (figure 9).
As the angle $\varphi$ of winding side ribs increases, the critical load increases as well. At the same time, the zone of local buckling increases (figure 10). The model with the angle $\varphi=55^\circ$ proves to be optimal in terms of stability, here the critical load is 74.5% higher than the current one. The zone of edges of the longitudinal ribs of the tube, where the thickness of the shell elements is equal to the thickness of the side ribs (figure 11), is weak in buckling.

With a larger angle of inclination of the side ribs ($\varphi=65^\circ$), the critical load drops sharply, due to more intense impact of the compressed side ribs on the thin edges of the longitudinal ribs.

With an asymmetrical structure of the tube, the carrying capacity should be assessed when changing the sign of the load. Table 1 presents a critical parameter for the case of changing the direction of the force. Its value, which is given in table 1 with a minus sign, also increases as the angle of winding of the side ribs increases, but for all models (except $\varphi=65^\circ$) its absolute value is less than in the original design model. The noted feature of the behavior of a tube of asymmetrical cross section must be taken into account in case of the impact of unstable direction.

In comparison, a similar analysis was carried out (according to the scheme in figure 7) on the deformability of the continuous composite tube of circular cross section, produced by the method of continuous winding of carbon-fiber composite ($\alpha$-angle of winding). The thickness (t), value of the deflection ($\Delta$) and mass (m) of round tubes with the length $l=0.6$ m and diameter $d=25$ mm for different angles of winding fiber are presented in table 2. For comparison, table 2 presents the difference on mass $\Delta m$ of the triangular and round tubes. The results obtained indicate that the round
tube with a winding angle $\alpha=+/45^\circ$ provides comparable central deflection with the wall thickness of 1.5 mm. In that case the mass of that tube (106 g) will be 2.5 times higher than the mass of the triangular tube.

| Table 2. The results of the calculation of a continuous composite round tube |
|------------------|--------|--------|-------|--------|
| $\alpha$, ($^\circ$) | t, (mm) | $\Delta$, (mm) | m, (g) | $\Delta m$ (%) |
| 45° | 1,5 | 4,138 | 106,0 | 165 |
| 35° | 0,95 | 4,113 | 67,11 | 68 |
| 25° | 0,65 | 4,128 | 45,92 | 15 |

If we increase the longitudinal stiffness of a round tube by reducing the winding angles, the mass of the tube will decrease. But, even in the best of the investigated options ($\alpha=25^\circ$, t=0,65 mm), the mass will be 15% higher than the mass of a triangular tube. At the same time, its bearing capacity ($k_c=1.26$) and rigidity ($f_1=484$ Hz) will be worse than these characteristics of a triangular tube ($k_c=1.745$; $f_1=720$ Hz).

Conclusions

The results of the presented study allow us to conclude about the advantage of using triangular anisogrid carbon fiber tubes instead of solid round tubes in the frames of solar arrays. The presence of an extensive list of variable design parameters, which in a complex way affect the deformability, rigidity and design ability, makes the task of determining the optimal combination of these parameters very laborious and requires a creative approach to its solution. Using the optimization calculation, the winding angles were determined to ensure the minimum deformability of the triangular tubes. The direction of the optimization search in the future may be to determine the parameters of the cross sections of the longitudinal ribs and the tube as a whole, the winding angles of the side ribs, as well as the use of the composite with improved mechanical properties. Exact recommendations can be made on the basis of the comprehensive study of the entire frame of the solar array, which uses tubes of different sections.

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