Deformation analysis of cylindrical lattice body of spacecraft in zone of high-pressure tank attachment

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Abstract. Finite element analysis of the strain-stress state in a load-bearing shell of the spacecraft body under longitudinal and lateral inertia loads was carried out. The shell is a composite anisogrid structure constituted by circumferential and helical ribs made of carbon fiber composite. A massive fuel storage tank is fixed inside the shell by means of a cable-stayed system. The shell structural behaviour in the zone of fuel tank installation was particularly addressed. A local reinforcement with additional circumferential ribs was shown to remarkably reduce the stress level and deflection in the tank attachment zone.

1. Introduction

Anisogrid lattice shells made of composite materials with superior specific strength and stiffness are widely used in rocket and space technology as they provide high weight efficiency and corresponding enhanced payload capabilities [1]. These structures are constituted by intersecting axial, circumferential and helical unidirectional composite ribs arranged in a repeating pattern that defines the membrane and bending stiffness. The lattice design concept provides a qualitative improvement in structural performance (particularly in buckling resistance) and design flexibility unachievable by continuous material counterparts. Although the principal manufacturing, design and analysis technologies for composite lattice structures are quite well developed [2-5], their mechanical behavior in each particular application still requires investigation.

Modern telecommunications satellites built on a modular design, such as those based on the Express platform, include a composite lattice cylinder as part of the service systems module. The shell is the primary load-bearing structure of the spacecraft body to which devices and mechanisms are attached. One of the main elements of the spacecraft propulsion system, a high pressure fuel storage tank, is fixed inside the shell structure by means of a cable-stayed system (figure 1). The tank is a metal-lined composite overwrapped pressure vessel made by filament winding [6-7]. The vessel designed to hold 300 l of xenon weighs about 440 kg at full load. During the launch phase of the mission, the spacecraft body experiences significant longitudinal and lateral overloads that are mandatory considered in design of the load-bearing shell structure. However, even if the overall (global) strength and stiffness requirements are met, the occurrence of local failure modes must be also evaluated especially in places where a stress gradient or/and massive equipment units are attached. Therefore, it is of considerable interest to analyze the structural behavior of the composite anisogrid
shell near the installation of fuel tank. The results of such analysis performed using finite element simulation are presented in this paper. A local reinforcement solution to decrease stress level and deflection of the shell wall is also addressed.

![Composite anisorgid cylindrical shell of spacecraft body with attached fuel tank.](image)

**Figure 1.** Composite anisorgid cylindrical shell of spacecraft body with attached fuel tank.

### 2. Finite element analysis

The lattice cylindrical shell under study with height $H = 3800$ mm and diameter $D = 1179$ mm consists of circumferential and helical ribs, and two end frames (figure 1). The helical ribs are oriented at $\varphi = \pm 14^\circ$ angle with respect to the shell axis. The circumferential ribs pass through the middle of segments between the intersection points of helical ribs. The number of pairs of helical ribs $N = 60$. Helical and circumferential ribs have a rectangular cross-section of $15 \times 6$ mm and $15 \times 2$ mm, respectively. The end frames made of B95 aluminium alloy have a rectangular cross-section of $22 \times 26$ mm. Inside the shell at a height of 2 m from the bottom, the fuel high-pressure tank with a mass of 440 kg is installed. The tank is attached to the shell at 20 points evenly spaced around the circumference. The mechanical properties of the materials used in calculation are shown in Table 1.

| Material          | Modulus of elasticity along the rib $E_1$ (GPa) | Shear modulus $G_{12}$ (GPa) | Shear modulus $G_{23}$ (GPa) | Poisson’s ratio $\mu_1$ | Density $\rho$ (kg/m$^3$) | Compressive strength along the rib $S_{1c}$ (MPa) | Tensile strength along the rib $S_{1t}$ (MPa) |
|-------------------|-----------------------------------------------|-------------------------------|-------------------------------|------------------------|--------------------------|-----------------------------------------------|-----------------------------------------------|
| Anisogrid lattice | 180                                           | 6.7                           | 2.3                           | 0.19                   | 1550                     | 480                                           | 800                                           |
| End frame         | 71                                            | 3.5                           | 2.3                           | 0.3                    | 2750                     |                                               |                                               |

Table 1. Properties of materials used in calculation.

Numerical analysis on deformation behavior of the anisogrid lattice cylindrical shell was carried out using a three-dimensional finite-element model constructed using MSC Nastran package [8]. The
shell structure is modelled with two-node BEAM type elements. The whole shell model is formed from FE model of repeating unit cell using operations of copying, rotating and transferring. The unit cell model (figure 2) consists of two fragments of helical ribs and a fragment of circumferential rib. The width \( b_c \) and height \( h_c \) of the unit cell are determined from the shell design parameters:

\[
b_c = \frac{\pi D}{N} \quad h_c = \frac{b_c}{2 \tan \varphi}
\]  

The finite element model is built up using an integrated macro code. Initially, a finite element model of the unit cell is created (figure 2). At this stage, the geometric parameters and elastic properties of ribs as well as the size of elements are specified. Then, using the copying procedure, a finite element model of a ring of interconnected unit cells is built. The ring elements are mirrored followed by successive copying of the obtained elements along the shell axis until the given shell height is achieved. The circumferential ribs at the shell ends are assigned the properties of aluminum frames. The bottom end of the shell is fixed from vertical and horizontal displacement. The spacecraft structure is subjected to longitudinal and lateral overloads of 11g and 3.5g, respectively.

The fuel tank is represented by a rigid element (RIGID type) with a concentrated mass element (MASS type) at the central node. The tank is connected to the shell wall using the beam elements that simulate a system of twenty uniformly tensioned cables. To evaluate the influence imposed by the cable-stayed system on deformation of the shell, a pretension \( P \) ranged from 500 to 2500 N with step of 250 N is set in these elements by means of the Bolt Preload tool. The cross-section and mechanical properties of the cable elements are selected so that the first natural vibration frequency of the tank structure matches the real value. It should be mentioned that the higher the pretention, the stiffer is the cable-stayed system. The rigid cable-stayed system is desirable as this improves the mechanical performance of the shell against the longitudinal acceleration.

3. Results and discussion
As expected, the maximum stress and deformation in the shell wall under applied loads occur in the zone of the installation of fuel tank and their magnitudes are governed by pretention in the cable-stayed system. There is a practically linear dependence of the minimum compressive stress (figures 3)
and maximum deflection, which is inward of the shell (figure 4) on the pretention force. Here, the attention is paid for the compressive stresses as their ratio to the ultimate value is much higher than that for the tensile stresses. The compressive stresses reach the compressive strength of the rib material when the cable pretention is equal or exceed 1750 N.

More crucial in terms of structural integrity is local bending of the shell wall in the installation zone as ribs buckling can occur at a stress level which is much less than the ultimate compressive strength [9-10]. The deformation pattern shown in figure 5 evidences a significant local deflection of the shell wall caused by the combined action of lateral load and cable-stayed system. This can result in local buckling failure and overall reduction in the load carrying capacity of the shell.

There are several ways to improve the local buckling resistance of lattice structures including the use of denser lattice configuration or local reinforcement. However, the former will inevitably lead to a significant increase in mass and corresponding reduction of the weight efficiency of the shell structure. To decrease the stress level and local bending in the shell, consider the reinforcement of the tank installation zone with additional circumferential ribs. Three variants of the ribs placements shown in figure 5 were examined. Note that the width of additional ribs which highlighted in red on figure 5 is not in scale. All the proposed options of local reinforcement can be easily implemented in the manufacturing process of the shell.
As follows from figures 3 and 4, the use of all variants of reinforcement resulted in reduction in both the compressive stresses and deflection in the tank installation zone. Regardless of the reinforcement scheme, the maximum stress does not exceed the material compressive strength for entire range of pretension values. Interestingly, the reinforcement according to variant 1 demonstrates practically the same dependence of the minimum compressive stress on the cable pretension as that according to variant 3 (figure 3), although in the former case only one pair of additional ribs are used.

The reinforcement variant 1 is preferable to variant 2 as it provides a greater reduction in the local bending of the shell wall. The most effective in terms of reducing the lateral deflections turned out to be the variant 3 of reinforcement. It is not surprising as this reinforcement scheme is in fact a combination of variant 1 and variant 2. The reinforcement solution allows to reduce the deflection of the shell wall by 27 % at \( P = 500 \) N and by 57 % at \( P = 2500 \) N in comparison with the initial unreinforced structure.

4. Conclusion
The composite anisogrid cylindrical shell of the spacecraft body with the fuel tank attached by means of cable-stayed system under longitudinal and lateral overloads was numerically analysed. The results revealed that there are the elevated stress level and large lateral deflection of the shell wall near the tank installation zone. The local reinforcement with additional circumferential ribs remarkably reduced the stress and deflection. This improved the strength and local buckling resistance of the shell structure. Different variants of such kind of reinforcement can be implemented in the manufacturing process of the shell. The presented approach can be applied in design of composite anisogrid structures used in the aviation and space applications.

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