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Axial deformability of the composite lattice cylindrical shell under compressive loading: Application to a load-carrying spacecraft tubular body

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ABSTRACT

Analysis of axial deformability of filament-wound composite anisogrid lattice tubular body of the spacecraft subjected to compressive loading is presented in the paper. The axial compressive load is applied to the lattice cylinder through the rigid ring attached to its end. The lattice structure is modelled using a continuum model of the orthotropic cylindrical shell. Based on this model, an analytical formula providing the value of the axial deformation of the rigid ring and assessment of the shell's axial stiffness is derived. This formula is verified by the finite-element analysis and employed to investigate the effects of the length, number of helical ribs and their angle of orientation on the axial deformability of the lattice cylinder. Using these results the full size physical prototype of the spacecraft body was designed, manufactured and tested. The axial displacement predicted by the analytical formula is correlated well with that measured in the experiment. Thus, the analytical formula proposed in this work can be utilised by design engineers in the efficient design analyses of similar composite lattice structural components.

1. Introduction

In recent years, composite lattice cylindrical shells are widely used in the designs of load-carrying spacecraft tubular bodies [1,2]. In such designs, the box-like structure assembled of sandwich panels is attached to the lattice cylinder as shown in Fig. 1. Various instruments, antennas, and solar batteries are accommodated on the panels of the box. The fuel tank and engine can be placed inside the cylinder. The design of such a structure requires strength, stiffness, buckling, and dynamic analyses to be performed. These analyses can be performed using either continuum or discrete analytical models. In the former, ribs can be smeared over the shell surface when modelled and the lattice layer can be simulated with a continuous layer having some effective (apparent) stiffness. Stress and strain analysis of such a structure is normally based on the equations of the theory of orthotropic cylindrical shells. Continuum models of composite lattice shells and their applications are discussed in the monographs published by Vasiliev [3], Vasiliev and Morozov [4], and articles published by Totaro and Gurdal [5], Buragohain and Velmurugan [6], Paschero and Hyer [7], Totaro [8–9], and Zheng et al. [10].

Discrete models of the lattice shells are usually composed of a large number of finite elements and their use involves a substantial computational effort. Results of finite-element analyses of composite lattice shells were reported by Hou and Gramoll [11], Zhang et al. [12], Frulloni et al. [13], Fan et al. [14], Morozov et al. [15], and Buragohain and Velmurugan [16]. Applications of both, continuum and discrete models can be found in the papers published by Lopatin et al. [17,18].

The composite lattice spacecraft body is subjected to substantial axial compressive loadings during the launch and injection into orbit phases. Analysis of its axial deformability is an important part of the design process. In this analysis, the lattice cylinder is modelled as a cantilever cylindrical shell at the free end of which a compressive load is applied. The load is determined by the product of the mass of spacecraft and the maximum axial g-force. The displacement of the loaded edge of the shell is a measure of axial stiffness of the lattice spacecraft body [19]. For design purposes, it is desirable to have an analytical model that enables a reliable assessment of the deformability and, hence, the axial stiffness of the lattice shell without involving time and resources consuming finite-element computations. An analytical solution to this problem based on the continuum model of the lattice structure is presented

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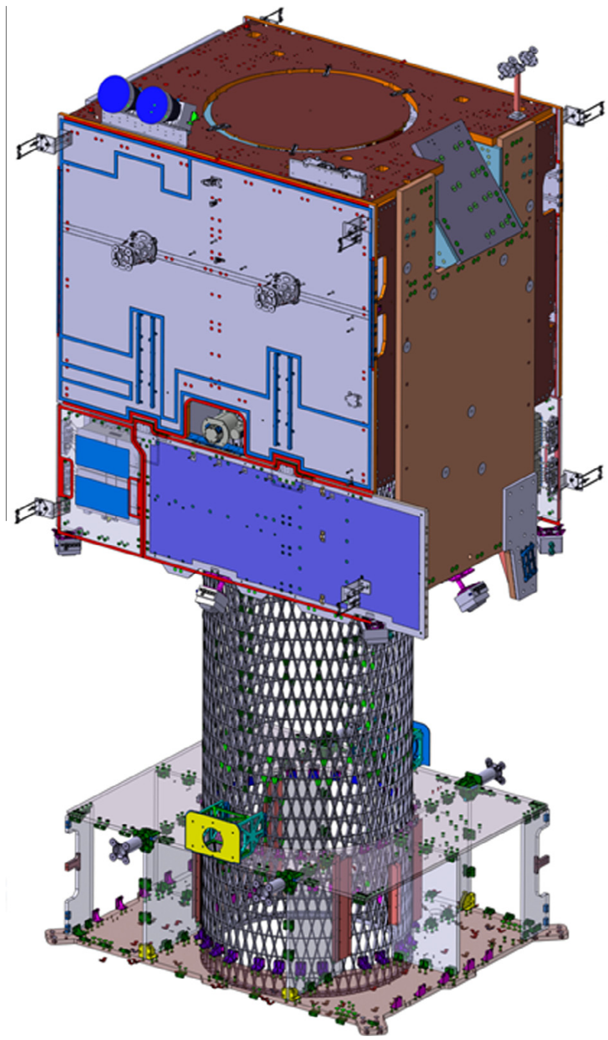

Fig. 1. Load-carrying lattice tubular body of the spacecraft (Courtesy of ISS-Reshetnev Company).

in this article. The lattice cylinder is modelled as an orthotropic cylindrical shell with the rigid ring attached to its free end. The box-like structure of the spacecraft is attached to this ring as shown in Fig.1. The analytical formula has been derived to calculate the axial displacement of the ring and assess the stiffness of the lattice structure. This formula has been verified by the finite-element analysis and employed to investigate the effects of the length, number of helical ribs and their angle of orientation on the axial deformability of the lattice cylinder. Using these results the full size prototype of the composite spacecraft body was designed, manufactured and tested. The axial displacement predicted by the analytical formula is correlated well with that measured in the physical test.

2. Governing equations

Consider a cantilever anisogrid lattice cylindrical shell of radius R and length l with the rigid disk attached to its free end. The shell is loaded by compressive axial load, N uniformly distributed over the ring circumference as shown in Fig. 2. The shell structure is made of a dense and regular system of helical and circumferential (hoop) composite ribs formed by filament winding. Employing a continuum approach, the lattice shell is replaced with a continuum structure with effective orthotropic stiffness parameters. The middle surface of the shell is referred to the curvilinear coordinate frame α, β, and γ (see Fig. 3) which is formed by the longitudinal and hoop axes α and β, respectively, and the coordinate γ is measured along the outer normal to the middle surface.

The stress–strain state of the shell under consideration is axisymmetric and can be modelled using the equilibrium equations [4]

$$\frac{dN_\alpha}{d\alpha} = 0 \tag{1}$$

$$\frac{d^2M_\alpha}{d\alpha^2} + N_\alpha\frac{d^2w}{d\alpha^2} - \frac{N_\beta}{R} = 0 \tag{2}$$

constitutive equations

$$N_\alpha = B_{11}\varepsilon_\alpha + B_{12}\varepsilon_\beta \tag{3}$$

$$N_\beta = B_{21}\varepsilon_\alpha + B_{22}\varepsilon_\beta \tag{4}$$

$$M_\alpha = D_{11}\kappa_\alpha \tag{5}$$

and strain–displacement relationships

$$\varepsilon_\alpha = \frac{du}{d\alpha} \tag{6}$$

$$\varepsilon_\beta = \frac{w}{R} \tag{7}$$

$$\kappa_\alpha = -\frac{d^2w}{d\alpha^2} \tag{8}$$

in which N_α and N_β are the membrane stress resultants; M_α is the stress resultant couple; ε_α and ε_β in-plane normal membrane strains; κ_α change in curvature; u and w in-plane axial displacement and deflection; $B_{11}, B_{12}, B_{22}, (B_{21} = B_{12})$ and D_{11} are the averaged membrane and bending stiffnesses of the shell wall, respectively as per the continuum model of the lattice shell presented in [3,4]. Note that the equation of equilibrium, Eq. (2) is nonlinear and allows for the change in the meridian curvature of the

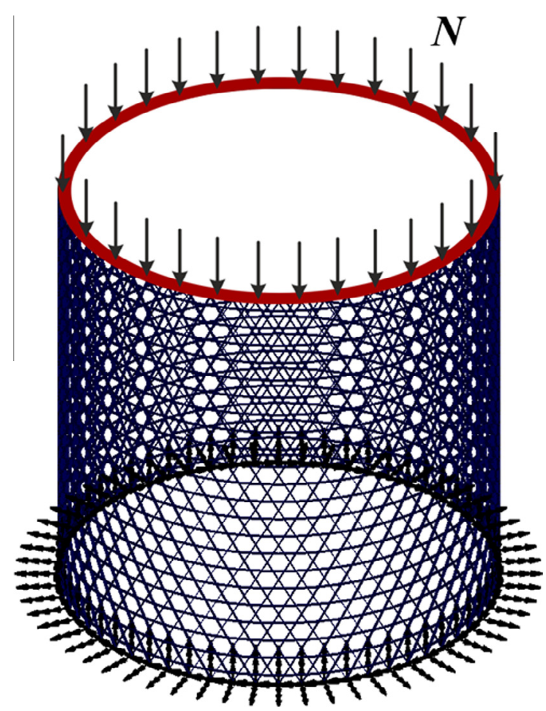

Fig. 2. Compressed lattice cylindrical shell.