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Anisogrid composite lattice structures – Development and aerospace applications ☆

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ABSTRACT

The paper is an overview of the recent Russian experience in development and applications of Anisogrid (Anisotropic Grid) composite lattice structures. Anisogrid structures have the form of cylindrical (in general, not circular) or conical shells and consist of a dense system of unidirectional composite helical, circumferential and axial ribs made by continuous filament winding [1,2].

High weight and cost efficiency of Anisogrid structures is provided by high specific (with respect to density) strength and stiffness of unidirectional ribs used as the basic load-carrying elements of the structure and by automatic winding process resulting in low-cost integral structures. Anisogrid structures proposed about 30 years ago are under serial production in Central Research Institute of Special Machinery (CRISM) which develops lattice interstages, payload attach fittings (adapters) and spacecraft structures for Russian space programs. By now, about 40 successful launches have been undertaken with Anisogrid composite lattice structures.

The paper provides the information about fabrication processes, design and analysis methods, mechanical properties of the basic structural elements and application of Anisogrid composite design concept to aerospace structures.

1. Introduction

Two basic structural concepts are widely used now for aerospace applications, i.e., stringer-stiffened and sandwich structures (Fig. 1a and b). These concepts are based on the idea of the load-carrying skin, whereas the ribs in stiffened structures and the core in sandwich structures provide high bending stiffness and resistance to buckling under compression and shear. It is important that in composite stiffened or sandwich structures, the skin and the ribs are not unidirectional and have a laminated structure consisting of unidirectional composite plies with various orientation angles. The efficient mechanical characteristics of such laminates are considerably lower than the corresponding properties of unidirectional composite materials. For example the modulus of a widely used quasi-isotopic (0/90/+45/−45) structure of the skin is about 54 GPa which makes only 41.5% of the longitudinal modulus of a unidirectional carbon–epoxy composite material (130 GPa) and is less than the modulus of aluminum alloys (70 GPa).

In addition to relatively low stiffness, the allowable strain of the laminated skin under tension is significantly reduced by the cracks which appear in the matrix of unidirectional carbon–epoxy plies if the transverse (across the fibers) strain exceeds (0.4–0.45)% [3]. Low temperature, moisture and cyclic loading result in the further reduction of the ultimate transverse strain, whereas the ultimate strain of carbon fibers is (1.5–1.8)%. This means that the fibers are underloaded in the laminated skin working under tension by the factor of about 4.

Under compression, the strength of a relatively thick laminated skin is dramatically reduced by delamination caused by transverse impact loading. As a result, the allowable strain is reduced up to (0.3–0.35)% which means that the fibers are underloaded by the factor of about 3.

And finally, the load-carrying laminated composite skin can be hardly joined with metal or composite adjacent structural elements. Typical for the load-carrying skin bolted joints cannot transfer high forces because of relatively low bearing strength of composite materials. For epoxy composites, the maximum allowable bearing stress does not exceed 160 MPa. Being loaded beyond this limit, composite material experiences residual strain associated with material microfracture in the vicinity of the bolt.

As a result, stringer composite structures (Fig. 1a), being used instead of aluminum aerospace structures, usually do not allow us to reduce significantly the structure weight. The same is true for the sandwich structures (Fig. 1b) whose load-carrying capacity is also governed by the skin.

In contrast to stringer and sandwich structures, strength and stiffness of lattice composite structures (Fig. 1c) are governed by the ribs that provide both membrane and bending stiffness of the structure. It is important that the ribs are made by continuous filament winding and have a unidirectional structure demonstrating

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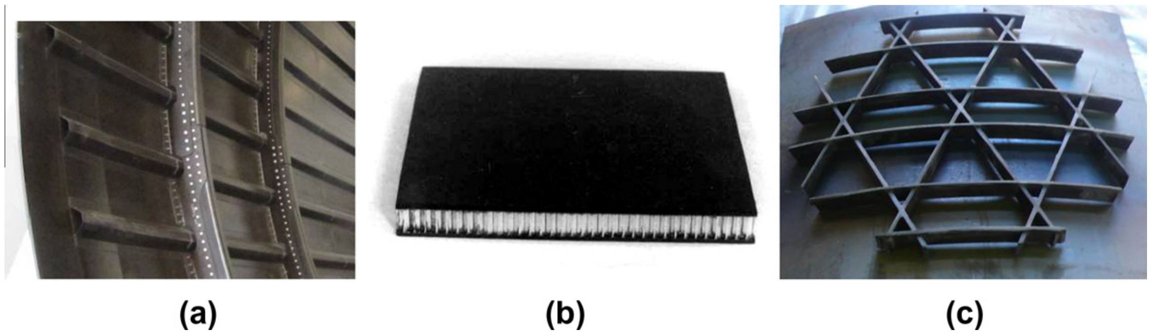

Fig. 1. Stringer (a), sandwich (b) and lattice (c) composite structures.

high specific (with respect to density) material strength and stiffness. The ribs of modern lattice structures fabricated in industrial conditions with carbon fibers of moderate modulus and strength which provide for traditional unidirectional epoxy composite material longitudinal modulus $E_1 = 140$ GPa, strength under tension $\overline{\sigma}_1^+ = 2100$ MPa, strength under compression $\overline{\sigma}_1^- = 1500$ MPa and material density $\rho = 1550$ kg/m^3 are characterized with modulus $E_r = 90$ GPa, strength under tension $\overline{\sigma}_r^+ = 1350$ MPa, strength under compression $\overline{\sigma}_r^- = 650$ MPa and density $\rho_r = 1450$ kg/m^3. The lower values of stiffness, strength and density of the ribs in comparison with the corresponding traditional unidirectional composite material ($E_r/E_1 = 0.6$, $\overline{\sigma}_r^+/\overline{\sigma}_r^- = 0.64$, $\overline{\sigma}_r^-/\overline{\sigma}_1^- = 0.43$, $\rho_r/\rho = 0.935$) are associated with the lower fiber volume fraction in the ribs. Because the structure thickness is the same at the points of ribs intersection and between these points, the fiber volume fraction being about 75% at the points of intersection reduces to about 40% between these points. Nevertheless, the rib modulus is about 30% higher whereas the rib density is 46.3% lower than the modulus and the density of aluminum alloys. For high-modulus fibers ($E_1 = 220$ GPa) the rib modulus can reach 185 GPa which is close to modulus of steel, whereas the density is 5.2 times lower. The foregoing properties of the ribs provide extremely high weight efficiency of composite lattice structures. To carry the load, lattice structures do not require the skin, but if the skin is necessary according to structural or operational conditions, it is also can be made by filament winding.

Being originally described by Vasiliev et al. [1,2], composite lattice structures have found recently wide study including design and optimization [4,5], fabrication [6], mechanical properties [7], local and general buckling [8–13], failure mechanisms [14,15] and applications [16].

2. Analysis and design

Lattice structures can be described with tradition equilibrium and geometric equations of the theory of composite shells [17]. Specific physical properties of a lattice structure are reflected in the constitutive equations which have the form

$$\begin{aligned} N_x &= B_{11}\varepsilon_x + B_{12}\varepsilon_y, \quad M_x = D_{11}k_x + D_{12}k_y \\ N_y &= B_{21}\varepsilon_x + B_{22}\varepsilon_y, \quad M_y = D_{21}k_x + D_{22}k_y \\ N_{xy} &= B_{33}\varepsilon_{xy} \quad M_{xy} = D_{33}k_{xy} \end{aligned} \tag{1}$$

Here, x and y are the meridional and the circumferential coordinates of the surface of revolution, N and M are the stress resultants and couples in the corresponding directions, ε and κ are the components of membrane and bending deformations. Eq. (1) include membrane (B) and bending (D) stiffness coefficients which for the system of rectangular ribs with height h (the shell thickness) and width δ are linked as follows

$$D_{mn} = \frac{h^2}{12}B_{mn} \tag{2}$$

where

$$B_{11} = B_\varphi \cos^4\varphi + B_x,\ B_{22} = B_\varphi \sin^4\varphi + B_y,\ B_{12} = B_{21} = B_{33} = B_\varphi \sin^2\varphi\cos^2\varphi \tag{3}$$

and

$$B_\varphi = 2E_\varphi h\overline{\delta}_\varphi,\ B_x = E_x h\overline{\delta}_x,\ B_y = E_y h\overline{\delta}_y \tag{4}$$

$$\overline{\delta}_\varphi = \frac{\delta_\varphi}{a_\varphi},\ \overline{\delta}_x = \frac{\delta_x}{a_x},\ \overline{\delta}_y = \frac{\delta_y}{a_y} \tag{5}$$

In Eqs. (3)–(5), subscript "φ" corresponds to helical ribs, subscripts "x" and "y" – to axial and circumferential ribs, respectively, a is the rib spacing (counted along the normal to the rib axes), E is the rib modulus (in general, different for helical, axial and circumferential ribs).

The foregoing equations can be used to construct the continuum models of lattice structures in which the ribs are smeared over the shell surface and discrete models in which the ribs are simulated with beam finite elements (Fig. 2).

Typical lattice structures have the form of cylindrical or conical shells consisting of helical and circumferential ribs. Such system of ribs demonstrates an additional advantage of lattice structures – relatively high resistance to buckling under axial compression. As known, experimental buckling loads for cylindrical shells are usually much lower than the theoretical values because of the shell shape imperfections which can be hardly measured and controlled. In contrast to stiffened shells, lattice structures demonstrate the shape stabilization under loading. Axial compression of helical ribs induces tension of circumferential ribs, and the shell cross sections become circular even if they have some initial imperfections. Thus, the experimental buckling load becomes close to the theoretical result, and no knock-down factors are used in design and analysis of lattice structures.

Design of cylindrical lattice structure under axial compression and bending can be performed using three basic approaches, i.e.,

- geometric programming method [18],
- method of minimization of the safety factors corresponding to the possible failure modes [3,19],
- numerical method [5].

The shell loaded with the axial compressive force F and the bending moment M is designed for the equivalent axial compressive force

$$P = F + \frac{4M}{D}$$