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Design and manufacturing of an isogrid structure in composite material: Numerical and experimental results

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ABSTRACT

Isogrid structures are constituted by a thin skin reinforced with a lattice structure. Such structures are adopted in aeronautical industry since they present both structural resistance and lightness. These structures were initially made of aluminium and were obtained by milling process. Nowadays, composite materials are used in order to improve the lightness peculiarities of such structures. The aim of this research work was to design an isogrid cylinder, made of composite material, fit to withstand a defined axial load. The design was carried out in two step: in the former, the Vasiliev theory was used to define the rib dimension of the lattice structure, while in the latter both material and thickness of the skin were determined by FEM. Then, the manufacturing process was designed, paying particular attention to the mould design and to the curing process. In fact, the curing tools and the thermal cycle strongly affect the quality of the produced part. Finally, the designed part was produced and tested to assess the quality of the manufacturing process and the correspondence to the design requirements.

1. Introduction

Nowadays the most advanced engineering applications require the use of both advanced materials and design techniques. For example, in the transport industry, fuel consumption and emissions can be reduced introducing very light parts that, however, must also be strong and withstand very high loads. An optimal solution to these problems consists in the adoption of composite materials for the construction of isogrid structures. The former present high resistance associated with the lightness, while the latter are often used for aerospace and aeronautical structures, as they provide excellent performances for thin-walled components subjected to buckling failure. These structures are constituted by a thin cylindrical or conical wall and by an internal structure, consisting of circumferential and helical ribs that intersect each other in points called nodes. A distinctive parameter of isogrid structures is the γ angle that the helical ribs form with the longitudinal axis; the final product is a very lightweight structure, which presents high mechanical performances.

The isogrid structures have represented for many years now a reality in the design of aircraft and space structures [1,2]. In aeronautic industry, large-scale lattice cylinders have been used for fuselage structures, inter-stage structures and payload adapters [3]. Examples of the use of such structures can be space station Skylab Orbital Workshop module or carriers of the family “Delta”. Aeronautical large aircraft manufacturers such as Boeing have used such structures. Such structures are in fact designed to ensure the structural integrity of thin-walled components subjected to buckling failure modes caused by compression loads or high G loads. Moreover, isogrid structures allow a considerable saving of mass [4,5].

Among the manufacture steps of polymer-matrix composite component, the most critical is the cure one. In fact, some defects may arise, such as low degree of cure, resin degradation and residual stress and deformation. The thermal conductivity of the resin is so low that the heat reaching the core could be not sufficient to cure the matrix, giving rise to low mechanical properties of the component [6]. On the other hand, the heat developed from curing reaction could accumulate, provoking resin deterioration [7]. Moreover, the increase of the temperature in the inner layers speeds up the cure, therefore the trend of the cure degree between the core and the external surface is different. This phenomenon lets internal stresses arise since resin undergoes chemical shrinkage during cure, so the cure degree along the thickness of components must be uniform to reduce curing stresses. However, residual stresses also rise during the cooling phase (more than 50%) and are caused by CTE mismatch of fibre, matrix and mould material.

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In fact, further stresses can arise during the cure due to differential strains between the part and the tool on which it is manufactured, since aluminium or steel tools have a much higher CTE than composite parts: they tend to stretch the parts during cooling, letting small shear stresses arise at the tool interface and causing tension in the part [8,9].

Finally, it must be remembered that the resin viscosity diminishes and the matrix flows away during the cure process. Therefore, defects can arise, such as porosity, irregular fibres content and voids, that negatively affect the material mechanical strength, so to wisely design the mould is very important to assure the right degree of compaction.

The aim of this research was to design an isogrid structure that meets fixed resistance requirements, containing as much as possible the weight. The forming technology, the necessary equipment and the process parameters were also determined, because they strongly affect the quality of the produced parts. In particular, the mould shape had to be carefully designed since the part presented a complex geometry, due to the presence of ribs. In fact, a common defect that usually occurs is a bad compaction of the ribs, which involves porosity and low mechanical strength. The extraction of the part from the mould, after the cure process, must be guaranteed, therefore the mould shape must be wisely defined. Furthermore, a good compaction and a high level of surface uniformity must be ensured for the skin. The thermal cycle for cure process must be defined in order to avoid the typical manufacturing defects, such as residual stress and resin degradation due to exothermic peak. Finally, some parts were manufactured and experimental tests were carried out in order to assess the reliability of product/process design. At first, tests to value the degree of compaction and the degree of cure were effected on samples, then a test regarding the strength of the whole structure was carried out.

2. Isogrid structure design

The structure to be designed is constituted by a cylindrical skin reinforced with ribs, whose section dimensions has been designed according to the Vasiliev method [1], whose schematization is shown in Fig. 1. Then, the numerical FEM design was used to choose the materials for the skin and to optimise the skin thickness.

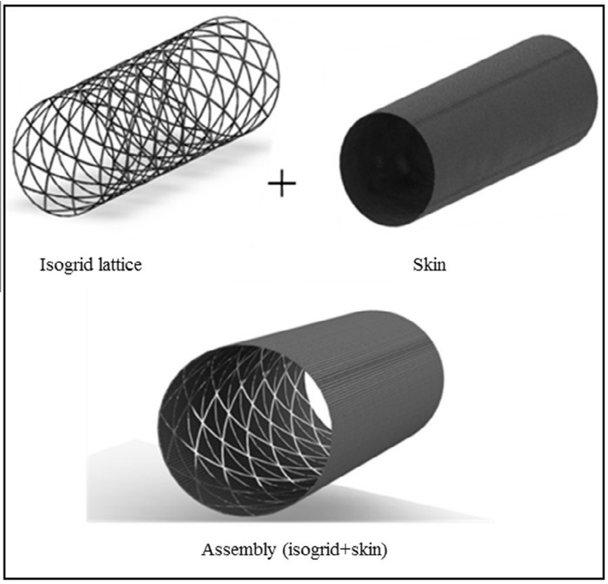

Fig. 1. Skin + isogrid reinforced structure.

2.1. The Vasiliev model

The characteristic values, concurring in the Vasiliev model, of an isogrid element are the curvature radius R and the height L, with the following quantities and size characteristics:

- $\pm\varphi = 30°$: the angle of the helical rib with the longitudinal axis of the structure.
- a_c, a_h: the normal distance between the circumferential rib (c) and the helical ones (h), with $a_c = a_h = a$, as will be shown later on.
- b_c, b_h: thickness of the circumferential rib (c) and the helical ones (h), with $b_c = b_h = b$.
- H_c, H_b: height of the circumferential rib (c) and the helical ones (h), with $H_c = H_b = H$.
- d: distance between the helical rib in the direction normal to the longitudinal axis of the structure.

The Vasiliev model executes the design by calculating only two variables: H and b. The minimisation of the mass is obtained by expressing the equations in terms of safety factors, each of which must be greater than one to avoid the failure and instability of the structure.

2.1.1. Generality

Initially the radius R, the height L and the applied compressive load P must be fixed. Then the material to be used is chosen, namely:

- Young's modulus E_h of helical rib.
- Young's modulus E_c of the circumferential rib.
- Density ρ_h of helical rib.
- Density ρ_c of the circumferential rib.
- The ultimate stress σ_u.

The equation that describes the buckling of an isogrid structure is:

$$\begin{aligned}&\tfrac{\pi}{n_0 P}\bar{\delta}H^2\sqrt{\tfrac{3}{2}}\sqrt{E_h E_c} = 1\\&\bar{\delta} = \tfrac{b}{a}\end{aligned} \tag{1}$$

where n_0 is the safety factor associated with the global buckling. As regards the applied stress, it can be defined that:

$$\frac{3\pi}{2n_s P}D\sigma_u H\bar{\delta} = 1 \tag{2}$$

where n_s is the safety factor associated to the stress acting on the structure.

The minimisation of the mass of the structure M is obtained with $n_s = 1$, therefore

$$M_{opt} = (2\rho_h + \rho_c)\frac{2LP}{3\sigma_u} \tag{3}$$

The equation that describes the local buckling in the plane tangent to the point isogrid element is expressed as:

$$\frac{3k\pi^3}{32n_l P}E_h D H\bar{\delta}^3 = 1 \tag{4}$$

where n_l is the relative safety factor and k is the coefficient of buckling, which is assumed equal to 4.

It is so found as follows:

$$H_{opt} = \sqrt{\frac{2}{3}}\frac{n_0 P}{\pi\sqrt{E_h E_c}}\frac{1}{(H\bar{\delta})_{opt}} = \sqrt{\frac{3}{2}}\frac{D\sigma_u n_0}{\sqrt{E_h E_c}} \tag{5}$$