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Local buckling modelling of anisogrid lattice structures with hexagonal cells: An experimental verification

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ABSTRACT

Following the analytical modelling, the first experimental verification of the local buckling failure mode of anisogrid lattice structures with the system of hexagonal cells is here discussed. Such verification is based on a test-article extracted from the composite cylindrical prototype that was designed and manufactured at CIRA for a lightweight launch vehicle interstage. Therefore, the test-article consists of a curved anisogrid lattice panel (without skin) including multiple hexagonal cells (but with a limited cell periodicity) and subjected to an axial compressive load. Complementary mechanical tests on specimens of helical ribs extracted from the same prototype are conducted in order to evaluate the effective flexural stiffness (and strength) properties which are relevant in the bending mechanism. Finite-element models simulating the lattice cylindrical shell and the panel are constructed in order to corroborate the analytical buckling prediction. Finally, the axial compressive test on the panel demonstrates the buckling mode under investigation and the complete correspondence with theoretical and numerical evaluations.

1. Introduction

The local buckling mode involving the lateral deflection of hoop and helical ribs represents a peculiar failure mechanism of lattice structures (without skin) subjected to axial compressive load. Indeed, by progressively reducing the rib thickness, aiming at minimum mass configurations, the lattice structure turns out to be increasingly exposed to local and global buckling mechanisms, which usually manifest before the occurrence of material failure. This situation is clearly depicted by the original analytical approach [1,2] and by the alternative numerical method for preliminary design [3]. In any case, the global (axisymmetric) buckling of the shell and the local (lateral) buckling of helical ribs are demonstrated to be the first limiting failure mechanisms in correspondence of minimum mass solutions, whereas material failure of carbon fibre helical ribs are still characterised by margins of safety. Nevertheless, in the framework of preliminary design, the local buckling failure mode is based on an approximate evaluation of the end condition of the single helical rib which is supposed to collapse.

The successive formulations developed by Totaro [4,5] for the system of triangular and hexagonal isogrid and anisogrid lattice cells, respectively, have demonstrated with more details such buckling modes as functions of the cell geometry and the stiffness of intersecting hoop and helical ribs, moreover suggesting the existence of an additional design variable in comparison to the classical analytical approach.

In particular, the formulation for the system of hexagonal cells has shown that the critical local buckling load can theoretically change by nearly an order of magnitude, even though the upper bound of the possible range is accompanied with rather unrealistic design parameters in view of optimised structures. Such formulation has been preliminarily verified in the light of corresponding finite-element models, demonstrating a very good correspondence for the given examples. Nevertheless, an experimental verification of this buckling mode has not been undertaken yet.

It is worthwhile to mention that, besides the wide set of Russian products and operative structures, which are far beyond the status of prototyping [2], manufacturing experiences and experimental validations concerning anisogrid lattice structures are not so common to find in the open literature, especially for applications which are close to the full-scale.

In fact, a brief review of the recent literature includes two works by Kim on a composite stiffened cylindrical shell in one case [6], and on a similar stiffened panel in the other one [7]. Both structures were conceived with a typical isogrid pattern (equilateral triangular cells) integrated with an outer skin, and manufactured in form of carbon fibre prepreg tows and unidirectional tapes. These structures were tested with axial compression, resulting in primary failures in correspondence of some helical ribs caused by local buckling (despite the supporting skin), and secondary consequent failures caused by pocket buckling of the skin. Overall, a good damage tolerant behaviour was exhibited from the structures in both cases.

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About 10 years later, Fan et al. [8] conceived a stiffened cylindrical structure with dimensions similar to the earlier application but with a rather dense system of hexagonal cells and a double skin (a sandwich structure with a Kagome lattice core). Except for a limited weight increase, the mechanical test demonstrated rather improved stiffness and strength performances in comparison to the referenced example. The reason of such success was attributed to the constraint exerted by the double skin against the rib buckling failure mechanism.

Before this work, sandwich panels were also manufactured using an interlocked Kagome lattice core and tested under various loading conditions [9], including axial compression. The double solid skin played a prominent structural role in comparison to the lattice core.

An important application of composite grid-stiffened shell structure of significant dimensions is referred in [10] for the development of the Minotaur payload fairing. In this case, the structural configuration was realised with a lattice isogrid pattern (triangular cells) with the stiffeners oriented along the meridians of the shell instead of the hoop direction. Structural optimisation resulted in a thin skin whose main role was just to stabilize the ribs against buckling. In fact, upon disbonding of the skin–rib interface, ribs were no longer laterally supported against buckling and failed.

Such examples address the structural behaviour of composite isogrid lattice shells or panels integrated with a single outer skin or a double skin (sandwich). From the design point of view, all the cited works testify the importance of the rib buckling control, as one of the primary failure modes, which is contrasted using a more or less cooperative integrated skin. For this reason, the possibility to predict with sufficient accuracy the local buckling failure mode of lattice structures without the skin is essential to efficiently address possible design or manufacturing improvements (including the possibility to increase the buckling strength just acting on the system of ribs). At this proposal, there is a lack of experimental information concerning the structural behaviour of anisogrid lattice structures without the skin. An example of such applications can be found in [11] where a small cylindrical lattice shell (radius about 0.15 m) was initially manufactured by filament winding in form of carbon fibre prepreg tows. Nevertheless, the outcome of the axial compressive test was not so satisfying at that time, showing a premature failure of the shell attributed to a poor strength of the ribs. An alternative version of the same cylinder (but again with an outer thin hoop skin) was then produced using the wet filament winding process. The overall manufacturing approach and the outcome of the mechanical test appeared to be more convincing than the foregoing version.

In more recent years, thanks to a project funded by the Italian Space Agency (ASI), an anisogrid cylindrical prototype was designed, manufactured and tested as composite interstage prototype for a typical space launcher. This prototype experimentally demonstrated the weight saving of 40% in comparison to the aluminium counterpart and benchmark, under the same stiffness and strength requirements. The main design steps, the manufacturing approach, and the outcome of mechanical tests are outlined in [12].

Thus, taking advantage of the availability of such prototype, a curved lattice panel was then selected and extracted as a representative test-article for the purpose of the current work. For the same reason, additional mechanical tests were conducted on specimens of helical ribs extracted from the same prototype in order to input the proper stiffness data in the analytical and finite-element models. Finally, the outcome of the axial compressive test of the lattice panel is shown and compared with theoretical and numerical evaluations.

2. Flexural properties of ribs

Flexural properties of ribs are particularly significant for the proper design of anisogrid lattice structures without the skin, in which the bending mechanisms are rather emphasised, and thus able to determine the possible occurrence of local buckling failure modes for the system of periodic cells.

The distinction between flexural and longitudinal mechanical properties of ribs is normally neglected in the open literature for composite anisogrid structures, in which the recurring stiffness property is related to the longitudinal compressive modulus of helical ribs. Indeed, experimental data of the flexural stiffness and strength of composite ribs are not available elsewhere, and are moreover lacking for the non-traditional manufacturing process adopted for the prototype. Thus, in order to provide effective flexural properties, a minimum set of four-point bending tests are conducted on specimens of helical ribs extracted from the same prototype (Fig. 1). For this reason, such specimens feature the natural curvature and twist related to the helical trajectory as a function of the radius of the shell and the specific helical angle adopted. In this case, however, the twist and curvature are rather small and are rapidly recovered during the first part of the bending test.

The adopted standard for the four-point bending test is ASTM D790 [13], in conjunction with the support span $L = 66$ mm, the load span of one-third of the support span, the central extensometer, and the cross-head velocity equal to 1.0 mm/min (Fig. 2). According to this procedure, the modulus of elasticity in bending, which hereafter is denoted as E_f, is calculated as follows:

$$E_f = 0.21\frac{L^3 m}{Hb_h^3} \tag{1}$$

in which m denotes the slope of the load–deflection curve in correspondence of the linear portion, H is the rib thickness, and b_h is the rib width.

For the flexural strength of the rib, $\overline{\sigma}_f$, we have:

$$\overline{\sigma}_f = \frac{P_{\max}L}{Hb_h^2} \tag{2}$$

in which $P_{\max}$ is the maximum load in the load–deflection curve.

The load–deflection curves of five specimens are reported in Fig. 3. According to Eqs. (1) and (2) the mean value of the flexural modulus of helical ribs is $E_f = 57$ GPa, and the flexural strength is $\overline{\sigma}_f = 830$ MPa. We remark that such values turn out to be about 20% lower and 65% higher, respectively, than the corresponding longitudinal mechanical properties. This fact confirms the significance of the four-point bending test, particularly for the stiffness property which directly affects the buckling mode under study.

Fig. 1. Specimens of helical ribs.