A sizing method for cylindrical grid-stiffened structures in composite material

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Abstract

In this work the structural behaviour of the so-called grid-stiffened structures is studied by means of finite element analysis; the focal target is to verify their applicability in the design of a low cost and low weight aircraft fuselages, to fabricate in composite material using the Filament Winding technology.

A grid-stiffened structure is characterized by beam elements (ribs) and shell elements (skin); the ribs constitute the main reinforcements and individuate the type of grid structure.

Starting from a set of requirements, a lattice structure is sized, that is a grid-stiffened structure with ribs only and without a skin (inner and/or outer). The characteristics of the isotropic material used for the ribs are derived from the properties of a common high-strength graphite/epoxy composite material.

The variables to optimise are: number of helical ribs, number of circumferential ribs, winding angle of the helical ribs with respect to the longitudinal axis, rib height, circumferential rib thickness, helical rib thickness, distance between the helical ribs, distance between the circumferential ribs.

The design criteria are no-strength failure and no-buckling failure at ultimate load for the beam elements of the ribs. The best lattice structure has all the margins of safety (MS) as positive and the minimum mass. In particular, the margins to check are: beam tension MS, beam compression MS and global buckling MS.

Finally, a scaling method for a lattice structure is also developed in order to apply the right loads on a scaled structure for the experimental tests. All the analyses are performed with a general-purpose finite element software (MSC/Nastran).

Keywords: grid-stiffened structure, lattice structure, circumferential rib, helical rib, winding angle, scale factor, scaling method, critical multiplier.
1 Introduction

The classical structural configuration used for aeronautical fuselages is a stiffened shell commonly referred to as semi-monocoque construction, in which the skin is divided in very thin panels that carry the shear from the applied external transverse and torsional forces. In this configuration, longitudinal elements (stringers) provide great concentrated areas able to carry great axial loads induced by the bending moment.

In figure 1 a typical section of a fuselage in reinforced shell is represented: it is possible to see the longitudinal stingers that reduce the dimensions of the skin panels.

To increase the critical shear load of the skin panels, the longitudinal dimensions of the panels are limited by means of transversal elements (ring frames) which have the same task of the ribs in a wing structure. Some of these elements are extremely thin because the loads on them are very low.

But the ring frames have also the task to introduce the loads, in this case they are referred as main frames. The main frames are more consistent than an ordinary ring frame: their cross section must be able to absorb axial and shear forces and bending moment; generally, the torsional load is low.

For the fabrication of a fuselage in classic configuration metallic materials, in particular aluminium alloys, are usually used; in this paper grid structures in composite material only are considered.

In a grid fuselage the longitudinal stringers are substituted with helical ribs. The transversal stiffeners (ring frames) are only named in a different way that is circumferential ribs. The skin is thinner than that one of a metallic fuselage.

Grid-stiffened structures are largely used in the space field (for the structure of space launch vehicles, shock absorbers for payload, interstage rings and so on).

![Figure 1: Classical fuselage.](image)

![Figure 2: Grid-stiffened fuselage [2].](image)
This structural concept was considered for the fabrication of the fuselage shell of the Beechcraft Starship 2000 [1,2]. The reasons for which it was discarded in favour of the sandwich are not well known.

2 Design requirements on the full-scale structure

For the sizing of a full-scale fuselage barrel in grid structure it is necessary to fix a set of design requirements in terms of geometry and loads.

A cylindrical barrel of a fuselage of a reference aircraft aimed at the passengers transportation (max 10) is considered. In table 1, the fundamental geometrical characteristics of the aircraft are listed.

Table 1: Aircraft Geometry.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>15 m</td>
</tr>
<tr>
<td>Height</td>
<td>2.5 m</td>
</tr>
<tr>
<td>Wing Span</td>
<td>15 m</td>
</tr>
<tr>
<td>Wing Area</td>
<td>30 m²</td>
</tr>
</tbody>
</table>

The aircraft is non-pressurized, high wing, JAR 23 and has a maximum take-off weight of 40000 N. The barrel considered in this study can be seen like the fuselage section between the aft main frame and the tail plane of the aircraft.

The cylinder has a length \( L = 3400 \text{ mm} \), the cross section shape is circular with an outer diameter \( D = 1700 \text{ mm} \), so the aerodynamic fineness results \( L/D = 2.0 \).

The aircraft reference system has the \( x\)-axis oriented from forward to backward, the \( y\)-axis toward the pilot right side and the \( z\)-axis from bottom to up. The origin is fixed in the intersection point between the \( x \) axis and the aft main frame cross section.

For the class of the considered aircraft and for the considered fuselage section the dimensioning load condition is a horizontal tail manoeuvring according to \( JAR \ 23.423 \) paragraph [3]. The aerodynamic load on the horizontal tail and the inertial loads in the barrel bays determine a bending moment with an almost linear trend along the cylinder axis.

![Figure 3: Barrel scheme.](image-url)
The effective bending moment is compared with the equivalent one produced by a vertical force of 22500 N applied at a distance of 5900 mm from the aft main frame. In the design this force will be considered to reproduce the bending moment so that the design will result conservative because the equivalent bending moment is slightly higher than the effective one. It is variable from a maximum of 132750 N*m on the aft main frame cross section to a minimum of 56250 N*m on the free cross section (the values are relative to ultimate loads).

Figure 4: Bending moment diagram.

3 Sizing of the full-scale structure

In this work, a grid-stiffened structure with ribs only and without a skin (inner and/or outer) is sized (lattice structure).

Tri-directional grid structures are used: the reinforcements run along three different directions (0, ϕ, -ϕ with respect to the longitudinal axis). The ribs are made out of all 0° plies and in the numerical models an isotropic material is used for them. The properties of this material are derived from those ones of IM7/977-2, a common high-strength graphite/epoxy composite material produced by ICI Fiberite.

Table 2: Rib material properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>126000 MPa</td>
</tr>
<tr>
<td>G</td>
<td>48460 MPa</td>
</tr>
<tr>
<td>ρ</td>
<td>1580 kg/m³</td>
</tr>
<tr>
<td>ν</td>
<td>0.3</td>
</tr>
<tr>
<td>Ftu</td>
<td>770 MPa</td>
</tr>
<tr>
<td>Fcu</td>
<td>504 MPa</td>
</tr>
<tr>
<td>Fsu</td>
<td>28 MPa</td>
</tr>
</tbody>
</table>

The allowable values of the material are knocked down to take in account the effects of moisture absorption and impact damages. According to previous experiences on the composite materials, the applied knock down factors are 50-60%, then the design will be quite conservative.
The parameters of a lattice structure are [4,5]:

- Rib height \((H)\);
- Helical Rib Thickness \((\delta_h)\);
- Circumferential Rib Thickness \((\delta_c)\);
- Distance between two successive helical ribs \((a_h)\);
- Distance between two successive circumferential ribs \((a_c)\);
- Winding angle \((\phi)\) of the helical rib respect to the longitudinal axis.

![Figure 5: Parameters of a lattice structure [5].](image)

The last three parameters are linked from a simple geometrical relationship:

\[ a_h = 2 \ a_c \sin (\phi) \]

The structure is designed according to two fundamental criteria:

1) no-strength failure
2) no-buckling failure

at ultimate load.

For the analysis, a general-purpose finite element software is used (MSC/Nastran); in the models, standard finite elements are used (beam and shell elements); the beam element used for the ribs has a zero offset.

The generic finite element model is clamped on the aft main frame and loaded from a negative vertical force in the node at a distance of 5900 mm from the aft main frame. A rigid finite element (RBE2) connects this node to the nodes on the last circumferential rib [6].

Since the parameters of a lattice structure are numerous, it is necessary to begin fixing the value for some of them so to reduce the number of finite element models to analyse. In particular, rib cross section dimensions are fixed:

- **thickness** \( \delta_h = \delta_c = 12.0 \text{ mm} \)
- **height** \( H = 12.0 \text{ mm} \)

In other words, rib cross section is a square with a side of 12.0 mm and between 80 and 90 lay-ups are needed to fill the 1.2 cm deep slots by stacking each tape fiber on top of each other until it was filled to the top.

For the finite element analysis, twenty-five models have been prepared with the hoop ribs number variable from 5 to 9 with a unitary step and the helical ribs number variable from 16 to 32 with a step of 4.

All the models with the relative loads have been developed by means of an automatic mesh generation procedure in Matlab.
In the figure 6, structural mass diagram is presented as function of the helical rib angle. Helical rib angle is linked to helical ribs number: the curves are parametric in circumferential ribs number.

![Figure 6: Structural mass diagram.](image)

### 3.1 Global buckling analysis

Critical multiplier as function of the helical rib angle is presented in the figure 7. The critical multiplier represents the value for which the applied load must be multiplied to obtain the critical load for the considered load condition. In other words, if the critical load is indicated with $P_{cri}$, the critical multiplier with $\mu$ and the applied load with $P_{app}$, it is verified that:

$$P_{cri} = \mu \cdot P_{app}$$

Moreover the margin of safety is:

$$MS = \frac{P_{cri}}{P_{app}} - 1 = \lambda - 1$$

The structure results unbuckled if the critical multiplier is greater than 1.0 or equivalently if the global buckling MS is greater than 0.0.

The first structure for which the critical multiplier is greater than 1.0 ($1.03$) is characterized by 28 helical ribs, 6 circumferential ribs, a helical rib angle of $15.7^\circ$ and a mass of 30.1 kg.

Between all lattice structures with a critical multiplier greater than 1.0, the best one from a global buckling point of view has 7 circumferential ribs and 24 helical ribs, a critical multiplier of $1.14$, a winding angle of $21.4^\circ$ and a mass of 28.7 kg.

For this structure $a_c=566.7 \text{ mm}$ and $a_h=417.2 \text{ mm}$.

The first global buckling mode is characterized by buckle waves along the cylinder axis.

In a second run, fixing $n_h$ and $n_c$, the dimensions of the cross section of the ribs are changed around the previous values. For the best lattice structure $\delta_h = 10.0 \text{ mm}$, $\delta_c = 9.0 \text{ mm}$, $H = 13.0 \text{ mm}$, critical multiplier = 1.04 and mass = 25.2 kg.
3.2 Static analysis

After the global buckling analysis, the results of the static analysis on the best lattice structure selected in the previous paragraph are examined; in particular, the margins of safety on the beams are checked. The static deformation on the x-z plane of this structure is represented in figure 9.

For the considered constraint and load condition, the maximum vertical displacement is obtained on the free cross section (8.75 mm).

The stress along the helical beams decreases from the clamped cross section to the free cross section following the bending moment trend; the maximum value is 109.7 N/mm², the minimum value is -109.7 N/mm². Starting from these values it is possible to calculate the minimum tension and compression margins of safety (6.02 and 3.59 respectively). So the minimum margin of safety for the structure is the global buckling MS (0.04).
These results confirm one of the conclusions reached by the professor Vasiliev during his works with this type of structure. The lattice stiffened structures haven’t strength problems, the global buckling regulates the behaviour of these structures [7]. Another of the buckling failure modes specific for the lattice structures is the local buckling of the ribs between the nodes [8]. This mode is observable, from a numerical point of view, if an intermediate node is placed between the nodes of the triangle side. In this case, to preserve the right stiffness of the structure a skin must be introduced.

4 Scaling of lattice structures

The scaling problem of lattice structures is tackled and resolved in terms of geometry as well as of applied loads. The presented scaling method can be extended also to a conical-trunk structure, eventually with a non circular cross section (elliptical for example).

The fundamental hypothesis is that all the linear dimensions of the small structure are scaled of the same scale factor ($\lambda$) respect to the correspondent linear dimensions of the full structure.

If $\lambda=4$ the best scaled lattice structure has the following geometrical characteristics:

Table 3:  Scaled structure dimensions.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>L</td>
<td>850 mm</td>
</tr>
<tr>
<td>D</td>
<td>425 mm</td>
</tr>
<tr>
<td>H</td>
<td>3.25 mm</td>
</tr>
<tr>
<td>$\delta_c$</td>
<td>2.25 mm</td>
</tr>
<tr>
<td>$\delta_h$</td>
<td>2.50 mm</td>
</tr>
<tr>
<td>$\phi$</td>
<td>21.4°</td>
</tr>
<tr>
<td>$a_L$</td>
<td>141.7 mm</td>
</tr>
<tr>
<td>$a_h$</td>
<td>104.3 mm</td>
</tr>
</tbody>
</table>
The scale factor for areas (cylinder cross section area, rib cross section area) is \( \lambda^2 \), for volumes and masses is \( \lambda^3 \). The mass of the scaled structure is 0.39 kg. At this point the scale factors for the loads must be individuated.

If the previous vertical force is used on the scaled structure, the critical multiplier became 0.065, that is scaled of \( \lambda^2 = 16 \) respect to that one of the full structure. So as the global buckling analysis is linear, if on the vertical force a scale factor \( \lambda^2 = 16 \) is applied \( (F_z = 1406.3 \text{ N}) \) and this force is applied at a distance of 1475.0 mm from the aft main frame, the same value for the critical multiplier is obtained.

The maximum vertical deflection for the scaled structure became 2.19 mm.

If on the structure a moment acts, the critical multiplier results scaled of \( \lambda^3 = 64 \).

So, if the scale factor for the lengths is \( \lambda \), the scale factor for the forces (axial and/or shear) must be \( \lambda^2 \), while the scale factor for the moments (bending and/or torque) must be \( \lambda^3 \).

![BENDING MOMENT ON THE Scaled STRUCTURE](image)

**Figure 10:** Bending moment on the scaled structure.

If on the full structure forces and moments are applied at the same time, it is sufficient to apply the correct factor to the forces and moments to obtain the same critical multiplier for the two structures.

In this way, the internal stresses read in the scaled structure are equal to those ones read in the full structure, because a stress is a force on an area and the scale factors for forces and areas are coincident.

In figure 10 the bending moment on the scaled structure is presented; it is variable from a maximum of 2074 N*m to a minimum of 879 N*m.

## 5 Conclusions

This work has proposed a first sizing of a fuselage barrel with the structural concept named grid structure, initially developed in the Central Research Institute of Special Machine Building (CRISM), the leading Russian Composite Center.
From a numerical point of view, structural design effort on the full structure is completely equivalent to that one on the scaled structure.

In this work it has been chosen to dimension the full scale structure. Applying the right scale factors, the results obtained on the scaled structure are equal.

The fabrication of structures in reduced scale allows:
1. a strong reduction of the costs because lower quantities of material are used;
2. reduction of the problems linked to the volumes of 1:1 scale prototypes, linked essentially to autoclave and test machine dimensions.
3. to do some experimental tests to individuate the real structural behaviour of a so complex structure characterised by several parameters to optimise.

The testing phase become determinant also because the characteristic parameters of a grid-stiffened structure locally tend to undergo a remarkable reduction (until 20% for Young Modulus and 60% for the compression strength) essentially because of the intersections between the helical and circumferential ribs and of the non-uniform distribution of the fibres. Moreover, the fibre volume fraction isn’t equal to the expected value and then the numerous segments of the ribs have different length.

At the end of the testing phase, an intense phase of numerical-experimental correlation is necessary to validate the numerical models.

In future works, the lattice structures with a composite laminate skin will be sized: the lay-up of the skin will be another variable to optimise.

References