INTERSTAGE 2-3 OF VEGA C LAUNCHER: COMPOSITE GRID STRUCTURE TECHNOLOGY

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Abstract

The Interstage 2/3 is the structure that interfaces the Z40 second stage with the Z9 third stage of the new VEGA-C launch vehicle. The design concept developed for this structure is a “composite GRID architecture” which consists in a regular and rather dense system of interlaced hoop and helical unidirectional ribs completed with a thin outer skin with a secondary structural role.
Interlaced ribs determine a fiber volumetric fraction that, except for the nodal regions, is usually lower than standard applications in composite material. Despite this, the typical mechanical properties are sufficient to design highly efficient solutions for heavily-loaded structures.
The developed manufacturing process is based on the automated parallel winding of dry carbon fiber tows followed by liquid resin infusion under vacuum bag. The combination of a suitable design method and manufacturing process turns out to be very appealing to produce lightweight and low cost composite grid structures for space applications.
This paper shows the general aspects inherent to the technology development and the design definition of the new VEGA C Interstage 2-3.

1. INTRODUCTION

The Grid technology in composite material based on Filament Winding is probably the most efficient design and manufacturing solution to address heavily-loaded axisymmetric shell structures [1-2]. Other automated deposition techniques based on Fiber Placement are being developed, as per [3].
In the last years, CIRA has developed methods to optimize the Grid technology by winding in terms of design and manufacturing with the aim to: identify the proper structural configuration, enhance the mechanical properties and the overall quality of the process, reduce the cost. This know-how has been successfully applied for the structural model of the Vega I/S 2-3 in the framework of a project funded by the Italian Space Agency [4]. Starting from this background, CIRA and Avio have proposed the GRID concept for the “Development and qualification of the Interstage 2/3 of the VEGA C launcher” winning the dedicated ITT of the European Space Agency.

2. I/S 2-3 PRELIMINARY DESIGN APPROACH

The I/S 2-3 is a conical shell structure that must fulfil the following main functions:
- To transmit the thrust from the second stage SRM to the launcher third stage;

- To provide a certain overall stiffness;
- To house and protect equipment and components;
- To guarantee the separation of the second stage

The conical grid structure has been designed in order to guarantee this overall capability with minimum mass and cost. In principle, this design concept appears quite peculiar in view of the mass minimization and the general design constraints (strength, buckling, stiffness). Indeed, there are several configurations for a grid structure that are identified by the number of hoop and helical ribs, and by three continuous variables H, b_c, b_h that represent the radial thickness and the width of hoop and helical ribs, respectively (Figure 1). The spacings between hoop and helical ribs are denoted with a_c and a_h, in the same figure. The angle φ between the helical rib and the local meridian of the shell is the fundamental design variable. We remark that, in contrast to cylindrical grid structures, since the path of helical ribs needs to be coincident, in any case, with the geodesic trajectories of the shell (in order to provide a stable trajectory during the continuous deposition of fibers by filament winding) the helical angle and the spacing are not constant along the meridian of the cone. In particular, in correspondence to the large radius of the shell (lower section), the helical angle is minimum and vice versa in correspondence to the small radius of the shell (upper section).
The identification of the minimum mass configuration in terms of the number of hoop and helical ribs and corresponding cross-sections has been undertaken with the aid of an optimization procedure similar to the approach proposed in [5]. The objective function of this procedure is given by the mass of the conical grid structure (without the skin) with design constraints that are analytically formulated based on the intact structure (i.e., no interfaces or any kind of discontinuity). These constraints correspond to the main failure mechanisms that can be experienced by the structure under the action of compressive/bending loads, namely, global buckling modes of the shell, lateral buckling modes of ribs, and material failure of helical ribs. Further design constraints involve the axial and the bending global stiffness requirements of the shell that have been analytically addressed according to the recently formulated models [6].

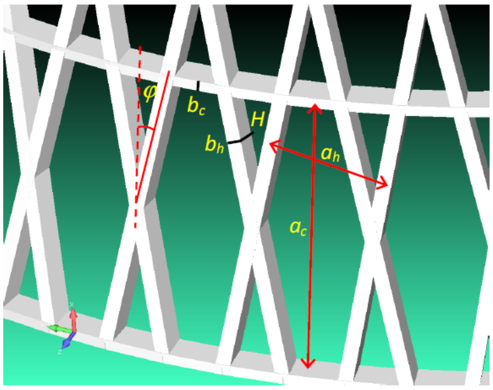

Figure 1. Typical design parameters of a grid structure.

An example of optimization loop is represented in Figure 2: for a fixed number of hoop ribs all the possible grid configurations are explored changing the number of helical rib as a parameter. The optimization routine finds the minimum mass for each configuration acting on the three continuous variables. The final configuration is presumably selected in correspondence to the absolute minimum, unless other considerations (e.g., manufacturing constraints or an excessively dense or coarse system of ribs) suggest to deviate from this “obvious” choice. As already anticipated, the helical angle increases from the lower to the upper section. However, given the small angle of the cone, this deviation is in any case included within few degrees.

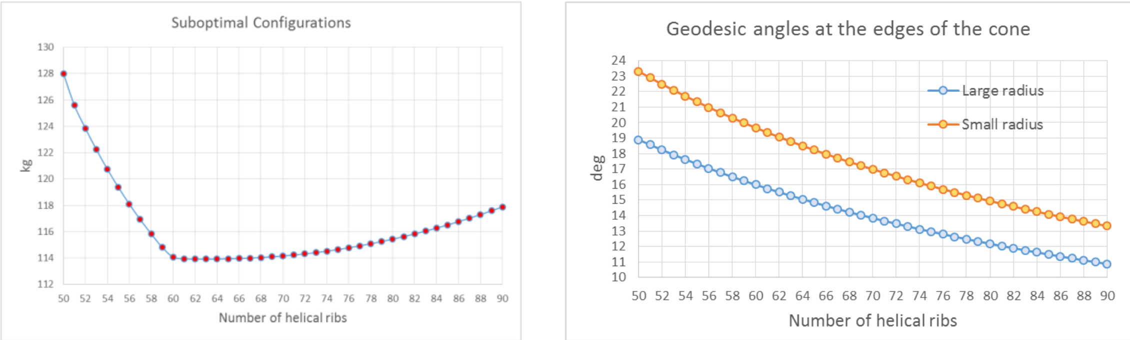

Figure 2. Example of an optimization loop (left), helical angles at the edges (right)

After the identification of the optimal grid configuration, several minor design loops were conducted with the aid of additional routines. The objective of these loops was to facilitate the concurrent design and integration of the aluminium flanges (connection and separation flanges) according to the specific pattern of the grid structure. This was done verifying the effect of small modifications of the basic geometry of the conical shell (the small and large radius, the height and even the angle of the cons) in the range of few millimetres or few tenths of degree. After each modification of the geometry a successive step with CAD tools was necessary in order to construct the fully 3D model of the grid structure and check the proper integration with the flanges. Then, all the necessary steps to complete the design were undertaken.

Finally, with a mass evaluated at 165 Kg, the grid structure can sustain a compression load close to 430 tons. The grid structure layout (Figure 3) is composed of:

- 60+60 helical ribs (helical angle between 16° and 20°);
- 10 hoop ribs;
- 4 CFRP interlaced "end rings" which allow the connection between the structure and the metallic flanges of the interstage.

The Forward and Aft access door openings are cut out by direct trimming of the ribs. Connections between the metallic flanges and the CFRP end rings are made of close fit shear bolts. Internal equipment items, separation spring supports, access door frames and closure panels are connected to the composite structure through metallic inserts positioned directly on the helical ribs before the winding of the skin.

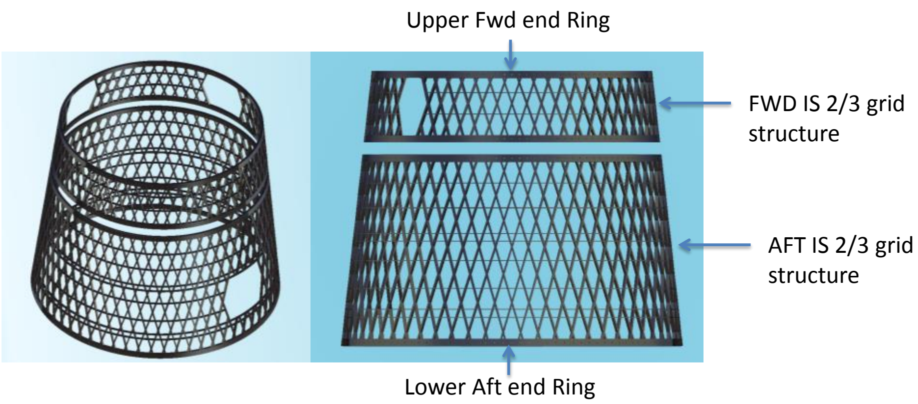

Figure 3. I/S 2-3 grid structure layout

3. MANUFACTURING APPROACH

The manufacturing process is based on the robotic/filament winding of dry tows in a rubber carpet with grooves corresponding to the grid architecture to be realized. Then the process is completed with resin infusion under vacuum bag. The dry winding process with respect to the wet winding eliminates the exposure to solvents and volatiles of the resin, avoids pot life problems, and limits the entrapping of air bubbles. At the same time, the fiber volumetric fraction and the basic mechanical properties are very similar to the wet winding process.

The main phases of the manufacturing process of the Interstage 2-3 are:

- Preparation and assembly of rubber carpet on the mandrel
- Winding of the grid structure (including end rings)
- Winding of the outer skin
- Resin infusion at RT under vacuum bag and cure in autoclave

The *rubber carpet* is realized by casting in a metallic mould and reproduces the geometrical parameters and trajectories of hoop and helical ribs. The rubber tool, with its thermal expansion during the cure cycle, appears useful to consolidate the ribs and to locally increase the fiber volumetric fraction, squeezing out voids and compacting the rib-skin interface. The use of rubber carpet is similar to the original American or Russian process, but an improvement has been conceived, that is, the adoption of a double carpet made of a massive (and reusable) part, and a light part that gives the surface finishing to the ribs. This is useful to facilitate the extraction of the carpet itself in case of grid structures with skin.

Regarding the *winding of the grid structure*, the deposition strategy is patented [7] and is based on a “parallel winding” of hoop and helical ribs. This means that the system of interlaced hoop and helical ribs is layered down in the grooves by means of a parallel scheme, as represented in Figure 4. A multiple spool, with a number of separate eyes equal to the number of hoop ribs, all fixed in the right positions along the axis of rotation, supplies fibers to the rotating mandrel, while an extra eye moves along the mandrel to wind helical ribs. This logic scheme allows us to have a really continuous process, providing a complete interlaced dry preform, without the necessity to cut tows for each layer in the hoop ribs, nor to introduce dummy helical ribs in order to pass from a hoop to another one.

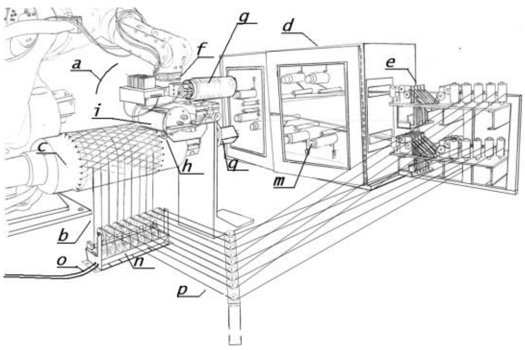

Figure 4. Patented technique to interlace the grid structure ribs (helixes) and hoop

Also the CFRP end rings are interlaced with the helical ribs, and ensure the integration of continuous reinforcing “black rings” made of biaxial fabric, in order to allow the connection between the CFRP grid structure and the metallic flanges of the interstage.
Once the grid structure is complete, the metallic insert are positioned and the outer skin is wound with the same dry tows that are used for the ribs. It is particularly thin and has a secondary structural role.

At the end of the winding, the overall dry preform (made of grid with the interlaced end rings and external skin) is co-infused at room temperature and co-cured in autoclave.

4. MATERIAL TRADE-OFF

Most of the initial activities were aimed at the proper selection of all the materials needed, considering the nature of the manufacturing process to be implemented for the interstage, and starting from the preliminary design of the grid structure. The materials to be selected were:

- Carbon tow for the ribs,
- Carbon tape for the end rings,
- Resin for the composite matrix.

Selection of the optimum system was based on material characterization. To that end, five types of specimens were manufactured and tested:

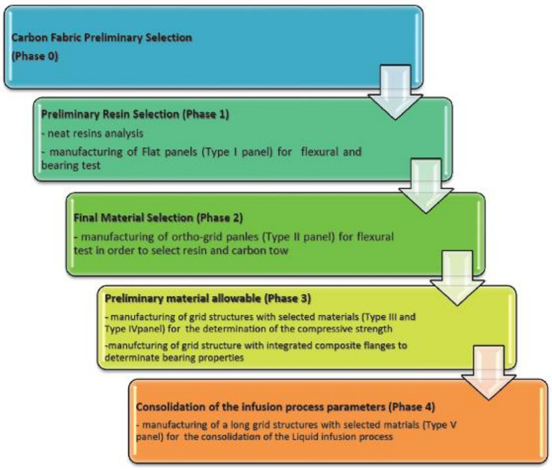

Figure 5. Material trade-off sequence

4.1. Type I specimens

The type I specimens are flat panels designed for a quick preliminary resin requirements verification, using a plain weave fabric and eight different resin systems. The resins were pre-selected based on information from their datasheets and chemical-physical analysis. The preliminary resin selection was driven by the following requirements:

- ➢ Exclusion of products containing: Carcinogenic, Mutagenic, Reprotoxic (CMR) components and substance of Very High Concern (SVHC)
- ➢ Product injectable at room temperature
- ➢ Minimum pot-life of four hours at injection temperature
- ➢ Viscosity at injection temperature lower than 400 mPa*s
- ➢ Glass transition temperature higher than 120°C
- ➢ Onset cure temperature at least 40°C above the injection temperature
- ➢ Heat produced during curing lower than 450J/g
- ➢ No separation of volatiles during the infusion under vacuum or during curing

4.2. Type II specimens

The type II specimens are simple ortho-grid panels made with interlaced dry tows and infused under vacuum bag. They have been manufactured with two different pre-selected tow fibers (intermediate modulus) and with resin systems compliant with the requirements reported in the previous section.

Figure 6. Type II panels

Ribs with several combinations of resin system and tow fibers have been extracted from the ortho-grid panels and tested in terms of flexural strength. At the end of this phase, one fiber tow was selected and one baseline resin system plus one back-up solution were identified.

4.3. Type III specimens

The type III large grid panels (Figure 7) were manufactured with the selected tow fiber and the two resin systems identified in the previous step (baseline and back-up solution). These panels have the same cross sections of ribs resulting from the preliminary design and are referred to the upper section of the interstage. The samples extracted from these panels were constituted of two hoop ribs and two helical ribs which form a triangular unit (named clepsydra). These samples were tested in compression to compare the resin systems performance.

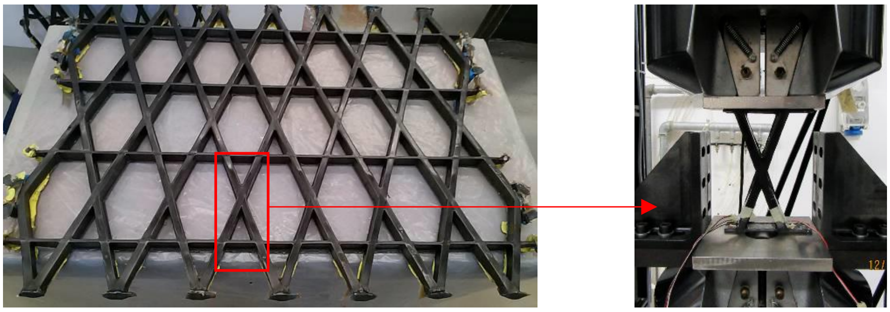

Figure 7. Type III panels and Clepsydra sub-components testing

4.4. Type IV specimens

The type IV panels are similar to type III, but include interlaced carbon tape to obtain the integrated end rings (Figure 8). Several carbon tape materials were tested. Samples trimmed from these panels in the form of triangular units allowed us to verify the bearing capabilities of the end rings.

Figure 8. Type IV panels and end ring sub-components testing

4.5. Type V specimens

After the selection of the baseline materials, the next step was to verify the capability of the liquid infusion process to guarantee good material quality on an entire sector. The type V panels represent a sector of 18° of the I/S 2-3 grid structure encompassing the full height of the structure. Their design is identical to the flight hardware, including metallic inserts. The aim of these panels was to verify several aspects:

- The infusion process set-up at full scale,
- The quality of the interface between the metallic inserts and the ribs,
- The quality of the interface between the skin and the ribs,
- The possibility of NDI techniques to assess the material quality at full scale level.

Results from type V manufacturing and inspection show high material quality in the ribs and end-rings along the whole panel height. No significant voids are identified.

Figure 9. Type V panels and X-ray photograph

5. I/S 2-3 FEM ANALYSYS

Experimental results obtained from clepsydras and from additional elements not mentioned here have allowed us to fully characterize stiffness and strength properties of ribs. These properties have been adopted in FE analysis models. With the aid of FEM simulations some typical failures in the ribs have been identified (Figure 10).
Moreover, a global non-linear three-dimensional FEM was implemented with the aim to identify the minimum static margin of safety and the buckling strength of the structure. A minimum static margin of safety of 61% is obtained with a non linear simulation. The minimum margin of safety is in the area closest to the Aft and Forward access doors (Figure 11).
A non-linear buckling analysis including perturbation analysis was run showing good capability of the structure to sustain, with no instability, twice the ultimate in-service compression load. Moreover, the

perturbation analysis demonstrates very low structure sensitivity to geometrical deviations with respect to the nominal shape. With a geometry perturbation equal to 5% of the rib thickness, the maximum knock-down factor is 16.4% with respect to the nominal eigenvalue and 6.1% with respect to the nominal non-linear buckling failure.

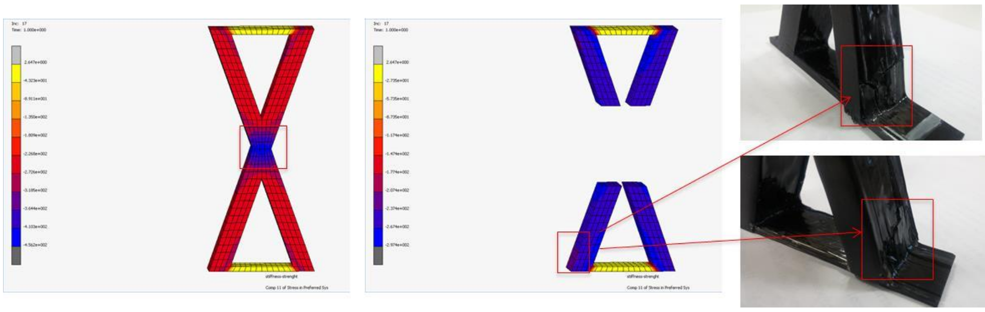

Figure 10. Comparison between FEM simulation and experimental results

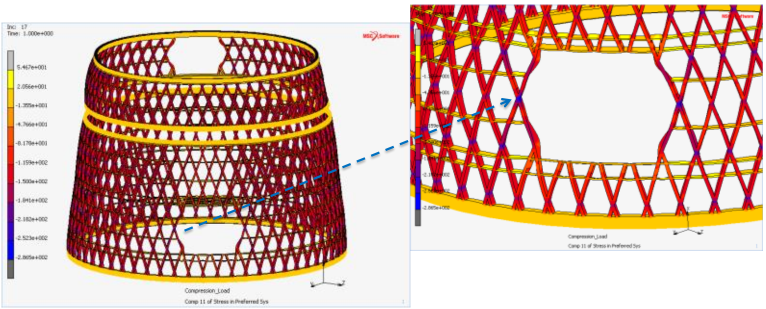

Figure 11. Static strength

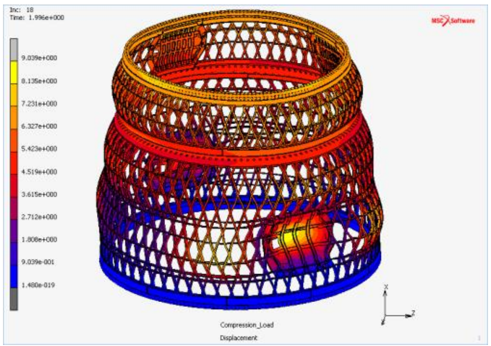

Figure 12. Non-linear buckling analysis

6. I/S 2-3 DEVELOPMENT ACTIVITIES COMPLETION

The development of the I/S 2-3 grid structure has a very tight schedule. The starting TRL was 5, thus a great effort was made to concentrate the activities on achieving adequate TRL in less than two years. Up to now, the following results have been achieved:

- Material trade off completed,
- Liquid infusion validated at full scale level,

- PDR completed successfully,
- I/S 2-3 structure fully defined,
- All manufacturing tools designed, manufactured and delivered.

Currently the manufacturing of the first full scale model (I/S 2-3 TM0) is on going. Completion of the TM0 grid structure manufacturing is foreseen by June.

Figure 13. Winding of the grid structure of I/S 2-3 TM0

TM0 will be tested under flight limit loads in two step:

- Static test to flight limit loads x 1.25 in simple configuration (grid structure + aft and forward flanges)
- Static test to flight limit loads x 1.1 in full configuration (with the addition of the separation flanges and access doors)

Then following models will then be manufactured and tested:

- DM0/QM0: testing up to structure collapse are foreseen before September 2018
- QM1: end of 2018

FM1 DRB: March 2019

7. CONCLUSIONS

The current work presents the general aspect inherent to the development of the Interstage 2-3 of the new VEGA C launcher, characterized by an innovative composite grid architecture adopted in Europe for the first time.
The developed manufacturing process is based on an automated parallel winding of dry carbon fiber tows followed by liquid resin infusion under vacuum bag.
The material selection and the determination of the material allowable values have been fruitfully supported by an intense experimental activities, characterized by the manufacturing and testing of sub-elements with increasing complexity and representative of the designed grid structure.
FEM simulations in the rib area and global non-linear 3-D FEM have been performed in order to clearly identify the failure stress, the minimum static margin of safety and the buckling strength of the structure, respectively.
The combination of proper design methods and manufacturing process turns out to be very efficient to produce lightweight and low cost composite grid structures for space applications.
Currently the manufacturing of the first full scale technological model is on going and it will be tested under flight limit loads in several configuration by July.
The qualification model is foreseen by the end of 2018, while the Flight model by March 2019.

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