DESIGN, ANALYSIS, AND MANUFACTURING OF A GRID-STIFFENED CFRP INTERSTAGE FOR A COMMERCIAL LAUNCHER

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KEYWORDS

Grid-stiffened, lattice structure, interstage, launcher structure, CFRP, composite, fibre-placement.

ABSTRACT

The paper presents the design, analysis, and manufacture of a CFRP lattice grid-stiffened launcher interstage structure which was completed for a commercial end user. This project followed a new space design-production approach encompassing the design finalisation, material procurement, tooling design and fabrication, final part production, and the delivery of two components to the end user in 10 months. An overview of the design methodology employed is provided which focused on allowing flexibility for evolving design requirements up to manufacturing commencement through the integration of strategic design decisions and optimisation techniques, which did not impact the design of the tooling required for production. Several new manufacturing techniques were also successfully trialled for handling and demoulding the components during production, with laser tracker measurements showing conformance to design tolerance requirements. The cylinders are currently awaiting integration and qualification testing, with successful testing leading to incorporation in future launch activities.

1. INTRODUCTION

Grid-stiffened and lattice composite structures have seen increased interest in space applications due to their excellent structural performance and inherently lower mass in comparison to traditional sandwich and monolithic designs [1-4]. These structures can be made using wet winding, dry winding and infusion processes, but the use of pre-preg materials offers additional benefits such as higher specific performance (due to the higher fibre volume contents possible) and the use of COTS materials which aids in the flexibility of the manufacturing process (in terms of supply chain availability).

Lattice structures are a design methodology which uses a repeating grid pattern of intersecting stiffeners (or ribs) which combine to create a lightweight optimised design which is tailored to an applied loading configuration (whether that be compression or bending focused). In cases where the grid is wrapped with a skin, the architecture is typically referred to as a grid-stiffened structure. ATG Europe has developed [4-9] and patented [10] a cost-efficient manufacturing methodology for continuous pre-preg fibre placed grid-stiffened and lattice structures that allows for the manufacturing of high quality, complex, integrated grid-stiffened composite products in a true one-shot process. In addition, the design and manufacturing methods employed by ATG Europe with this technology allow for the production of a low-cost component on a reduced manufacturing timeline with the flexibility of the design playing a major role in adapting to changing design requirements right up to the start of manufacturing.

The current work outlines the entire development process for the production of two interstage components, from initial design concepts to part delivery. This process was achieved in a 10-month period with multiple design changes implemented throughout the project's lifetime (at the request of the end user), showing the flexibility of the technology. The current work builds on a FLPP study [11] which assessed two different interstage components on an exploratory level at a preparatory stage in the parts development process. Since that study, the loads have more than doubled and the configuration has changed drastically, necessitating a full re-design of the grid-stiffened structure. However, based on the positive response to this initial design study and the manufacturing flexibility of the grid-stiffened technology, additional funding was secured to fabricate and test a grid-stiffened version of the component with an aim towards inclusion as a future flight article.

2. PROJECT OUTLINE

2.1. Schedule

This project spanned a highly compressed timeline of 10 months, thus the planning around this project and the times at which different portions of the work had to be completed were stringently controlled. In addition, the requirements for the component were not finalised at the start of the project. Overall configuration, cylinder height, the supported equipment, and global as well as local loads were changed multiple times throughout the development. This resulted in ongoing component design and analysis performed up to closely before manufacturing start. As a result several activities, including material procurement and tooling fabrication, had to begin well before the design was finalised. The overall project timeline, as achieved, is shown in the Gantt chart of Fig. 1 giving an overview of the project as a whole.

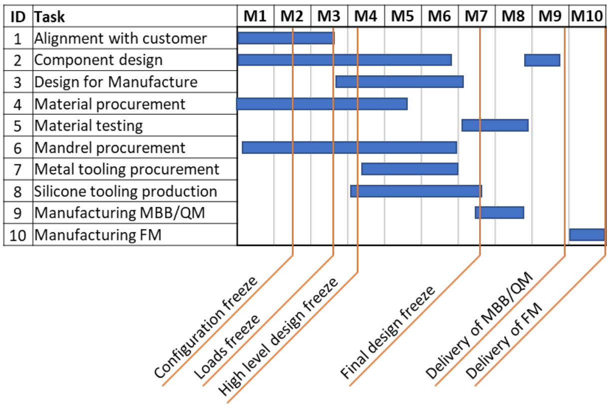

Figure 1: Overview of the achieved project schedule, key milestones highlighted.

The schedule itself will be discussed in more detail in terms of the individual tasks which constituted each work package and the constraints surrounding those specific pieces of work in the following stages of this paper. The main focus of the project originally was to produce two interstage components:

1. Manufacturing Breadboard (MBB)
2. Qualification model (QM)

The MBB was included in the project due to the scale of the component and the possibility of unforeseen issues related to manufacturing a part of this size with the grid-stiffened technology for the first time. The goal of the MBB was to trial and refine the manufacturing processes, and to assess the achievable quality, before manufacturing of the QM. In reality, the MBB was so successful and the resulting part of such quality that it was later decided that it will be used as the QM as well. The second component, originally intended to be the QM, was then promoted to a flight model (FM).

3. DESIGN

3.1. Component Overview

The design of the grid-stiffened structures was based on preliminary requirements provided by the commercial launch company with updates given throughout the project's lifetime. The component was part of the 1st stage of the launch vehicle and consisted of a cylinder section of over 2 m diameter, and several metres in length. The top and bottom interfaces consisted of a prescribed pattern of fasteners which at the top connect to a separation ring and separation system, while the bottom is connected to the propellant tank. The cylinder section supports the upper stages and payload. Relevant loads are mostly global compression, shear, and bending. Factors of safety of 1.25 for strength and 2.0 for buckling have been incorporated into the design.

3.2. Grid-Stiffened Design

An overview of the structure design is shown in Fig. 2.

Figure 2: Image of the grid-stiffened interstage component along with an outline of the structure's main constituents.

The main load-bearing components are the composite ribs, with a thin skin to close the outer surface. At the top and bottom ends of the cylinder monolithic laminates are included, which provided the integration points between the lattice and the rest of the launch vehicle structure.

The part was made with a T700S carbon fibre-based unidirectional prepreg. This material was chosen from an array of options as it provided the desired balance between design performance and mass reduction, based on a cost benefit analysis of the mass savings provided by the grid-stiffened structure.

3.3. Design Decisions

Due to the short project timeline several design parameters had to be fixed before the design was finalised, to allow the tooling affected by those parameters to be manufactured or procured.

The first parameter to be fixed was the inner diameter, since this controlled the diameter of the mandrel, an item with significant lead time. Fixing this diameter early but leaving the outer diameter free still allowed for the retention of most of the design freedom.

More limiting was the selection of rib's height, amount, and direction. These decisions determine the design of the silicone tooling that forms the ribs as the part cures in the autoclave. With significant time associated with the manufacturing of this tooling, the rib parameters had to be selected even before the loads specification was considered final.

With grid-stiffened structures a certain degree of flexibility in performance can be incorporated by variation of the skin layup alone. While there is not a single grid design that is optimal for all load levels, varying the skin layup does allow a grid design to give good performance as well at load levels around the level for which it is the optimum.

Simply taking grid parameters from the best design for the specified load level as baseline however is not the best approach, since the flexibility with the skin layup could be heavily biased towards either higher or lower loads. Hence a larger part of the design space had to be explored. In order to select the best set of grid parameters design curves outlining performance versus weight had to be created for suitable grid designs. To achieve this multiple finite element analyses were run (in Nastran) for grid designs with various skin layups, determining the load level at which these designs would either experience material failure or buckling. For a single grid design the results are shown in Fig. 3.

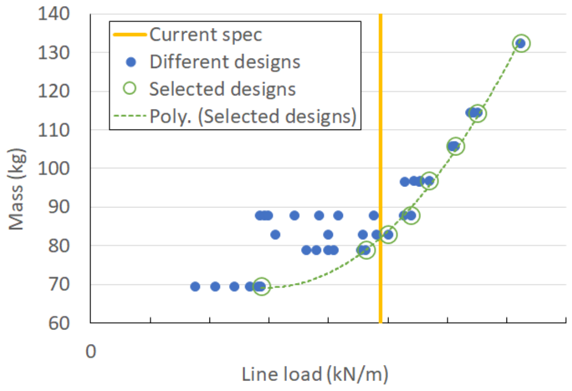

Figure 3: Determining the design curve for a constant rib layout with varying skin layup.

In Fig. 3, the blue dots each represent a different analysed skin layup, with green circles indicating the designs that were considered best for a certain skin thickness. A design curve can then be interpolated through the selected designs using a polynomial best fit.

Performing such a study for multiple different grid designs and combining the design curves yields an overview as pictured in Fig. 4.

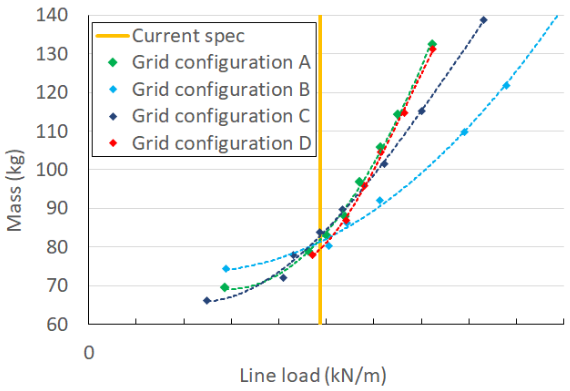

Figure 4: Design curves for different rib configurations.

It can clearly be seen that some grid designs perform better at higher load levels, while some others offer larger weight reductions as loads are decreased. Expectations of which direction the load levels were likely to change therefore played an important role in the selection of the grid layout. Following discussions with the customer to understand the level of conservatism in the specification, and expectations of how the load levels would develop, a design was chosen that would offer decent mass reduction at lower load levels but was still able to take higher loads should that be necessary. At the specified load level this meant accepting a mass penalty of several kg, in order to gain more flexibility on load levels.

Following load level changes after the grid design was fixed, the final selected design for the first cylinder weighed in at 87.5 kg, with the breakdown of structural masses given in Tab. 1.

Table 1: Structural mass overview for the grid-stiffened cylinder

Components	Value (kg)
Ribs	32.0
Laminate	10.5
Skin	45.0
Total Mass	87.5

4. MANUFACTURING

4.1. Long Lead Items

The first piece of tooling ordered was the mandrel. With the grid-stiffened cylinder having a constant and fixed inner diameter, the mandrel diameter could be fixed early in the project timeline. However, a configuration change at launcher level resulted in changes to the length of the interstage. As a result, the manufacturing of the mandrel had to be paused, and the half-finished mandrel had to be extended in length in order to accommodate the longer interstages. In the end, the mandrel was manufactured with additional margin on the length, anticipating further design changes. The mandrel is pictured in Fig. 5.

Figure 5: Metallic mandrel for part layup.

The design of the other metallic tooling parts were adjusted as well to allow for any foreseeable design changes to the interstage.

The engine and gearbox for rotating the mandrel were ordered, but experienced significant delays and so did not arrive on time. In order to still be able to rotate the mandrel a temporary solution was found, using an electrically driven rubber wheel pressed against the outer surface of the mandrel.

4.2. Preproduction

4.2.1. Autoclave Ramp Trials

One of the main concerns for production of the part was the significant tooling mass of the large mandrel, and how it would affect achievable heat-up rates. To achieve the best results, relatively high heat-up rates must be achieved when curing the grid-stiffened structure. Hand calculations based on system specific parameters were undertaken beforehand to assess the likelihood of these issues, but trials had to be undertaken with the actual mandrel and autoclave to arrive at a realistically achievable cure cycle. Fine-tuning of the target ramp rates, allowable temperature spread on the part, and duration and tolerance of the intermediate-temperature dwell resulted in a cure cycle expected to give good results. The autoclave data showed good conformance to the desired profile, giving confidence in the ability to achieve the required ramp rates while curing the cylinder. Fig. 6 shows thermocouple (TC) data from one of the trial runs. The data shows that there is some lag in the temperature of the mandrel, but it generally follows the target profile quite closely.

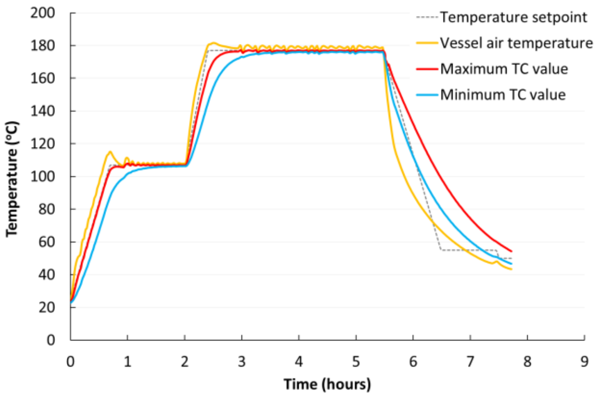

Figure 6: Thermal cure cycle for the component following max and min thermocouples versus internal air temperature.

In the final cure cycle trials a small lattice panel was cured in the autoclave along with the mandrel, and inspected to investigate the achieved quality. Good microstructural quality was observed.

4.2.2. Design Finalisation

Once the previously mentioned components were in place, the final design of the part was solidified such that ply books, layup templates and all associated manufacturing documentation could be provided to the manufacturing partner so that production could begin. This included the cutting of the laminate and skin plies using an automated cutting machine in preparation for the start of production, as well as generating all the required work instructions.

4.3. Production

Manufacturing of the cylinders was performed together with a manufacturing partner, Airborne Aerospace, an experienced company for designing, manufacturing and industrialising composites for aerospace and space hardware.

In addition to the previously mentioned long lead items, Airborne have designed and procured or manufactured the additional ground support equipment. This included the mandrel support trolleys, product support trolleys, and tooling for demoulding and mandrel manipulation.

4.3.1. Layup

Layup was done in accordance with established ATG manufacturing methods. This included all layering steps as well as the integration of all laminate sections in the lattice grid such that a single cure cycle could be used, to result in a net-shape part. An image of the layup procedure in progress is shown in Fig. 7. Once the layup of the lattice grid was complete, silicone tooling was placed between the ribs, and final post-layup inspections were undertaken.

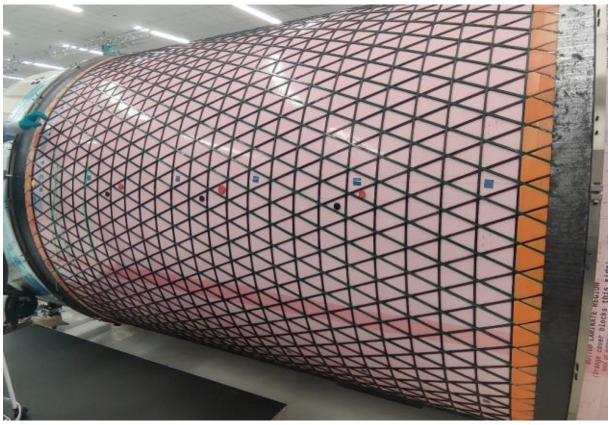

Figure 7: Image of layup in progress.

4.3.2. Debulking

Once the part was laid up, debulking of the lattice gird was undertaken. This involved wrapping the layup in release film and using the caul plates and vacuum bag pressure to compress the ribs to the desired height. Once complete, the vacuum bag was removed along with the caul plates and release film, so that the skin could be applied in the final layup procedure. Once in place, the caul plates were installed again, as shown in Fig. 8, and the part was bagged for curing as per normal composite manufacturing methods.

Figure 8: Caul plate installation after skin layup.

4.3.3. Curing

The curing of the cylinder involved transport of the mandrel from the cleanroom towards the autoclave and running the predefined cure cycle which was mapped with the previously mentioned autoclave trials in Section 4.2.1. The additional composite material and silicone tooling provides only a relatively small incremental difference in the energy needed to heat the component and so the production run followed the cure cycle trial results closely.

4.3.4. Demoulding

Demoulding of the part took some additional considerations due to the sheer size of the part and mandrel, when realising the part must slide off the mandrel in one operation. The combined length exceeded the working height of the available lifting mechanisms (for vertical removal) and so a horizontal removal was used. The use of a steel mandrel helped with demoulding as the tool expands during the autoclave cycle and the part solidifies at this expanded dimension. Once cooled, the mandrel returns to its room temperature dimensions and facilitates a small clearance between the cured part and the mandrel. For horizontal demoulding, the support on one side of the mandrel was moved to the far end of an elongated shaft. This gave enough room to push the part off the mandrel, as shown in Fig. 9, before changing the support of the mandrel again to allow the part to be removed entirely.

Figure 9: Image of the demoulding process with the extended shaft and part removed from the mandrel.

Following separation from the mandrel the silicone tooling was removed to yield the net-shape composite structure.

5. INSPECTION AND MEASUREMENTS

5.1. Initial Part Quality Assessment

Figure 10: Demoulded component.

The initial assessments of the part once demoulded included a visual inspection of the internal and external surfaces of the part. No clear defects or deviations to the part design were found and consolidation of the skin and ribs looked as desired, as shown in Fig. 10 and Fig. 11.

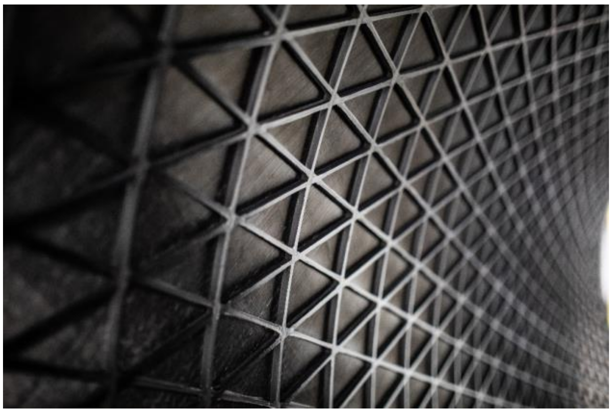

Figure 11: Image showcasing part quality on the internal surface post demoulding.

5.2. Dimensional Accuracy

The dimensional accuracy of the part was most important on the inner diameter of the laminate regions, where the main interfaces are located. A laser tracker measurement of the cylinder diameter in this region was taken to assess the conformance of the design to the specified dimensional tolerances. However, as the structure flexes under its own self weight when resting in a horizontal position, this creates a non-uniform surface profile which is out-of-round. Since this is easily pushed back into round when integrating the interstage in the launcher this is not problematic. However, it does have an influence on the measured diameter, which might indicate an out of tolerance part as a result. While a diameter is specified, the parameter of interest is actually the circumference. Thus, the laser tracker data was processed to calculate the circumference, and equivalent diameter. This showed that the part was still within tolerance of the customer interface ring, but on the low side of the tolerance band for the cylinder itself.

5.3. Follow On-Improvements

Further to the assessments on the diameter tolerance conformance, the subsequent manufacturing of the second cylinder included some improvements to allow for better part production and further optimisation. First, an additional paper shim was added below the layup in the upper laminate region. This had the benefit of slightly increasing the diameter of the component, to be closer to the middle point of the tolerance band. Laser tracker measurements confirmed that the manufactured part showed even closer conformance to design tolerances in this region, with the measured diameter having a less than 0.1 mm deviation from the target diameter.

5.4. Mass measurement

The masses of both cylinders were measured after demoulding and clean-up of the parts. The measured masses deviated from the expected mass by 0.4% and 0.2% respectively, well within acceptance limits.

6. CONCLUSIONS

For this project, a grid-stiffened composite interstage structure was designed, analysed, optimised, and manufactured in a 10-month project timeline, including procurement and manufacturing of all tooling, materials, and ground support equipment. This project has shown the versatility of the grid-stiffened architecture to adapt to changing requirements and tight timelines, with the achieved project schedule providing a baseline for future work in the area of rapid grid-stiffened component development.

7. ACKNOWLEDGEMENTS

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