A LOW COST AND VERY LIGHTWEIGHT SMALL LAUNCHER INTERSTAGE, USING PRE-PREG COMPOSITE GRID-STIFFENED TECHNOLOGY

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KEYWORDS

Grid-stiffened, lattice, CFRP, interstage, small launcher, design, low cost

ABSTRACT

ATG Europe has developed and patented a grid-stiffened and lattice technology using high performance pre-preg composite materials, including the manufacturing process and efficient attachment methods. While previous design studies concerned large launcher and satellite applications, recent developments in the small launcher industry are pushing towards new targets keeping a low mass while minimising cost and lead time.

The paper presents a design study applying ATG technology to a small launch vehicle's interstage structure, considering typical industrial requirements. The study aims to achieve a very low mass and superb structural performance, while considering manufacturability, cost and commercial potential. This is achieved through iterations of mechanical design and finite-element analysis, manufacturability evaluation, cost assessments and a comparison between the found solution and a conventional structural configuration.

It is found that for small launcher structures the grid-stiffened architecture can offer a solution with a significantly lower mass while remaining a very cost-competitive option.

1. INTRODUCTION

Grid-stiffened and lattice composite structures have been the subject of multiple recent studies due to the promise of excellent structural performance and low mass. These structures can be made using various manufacturing methods, including but not limited to wet winding, dry winding and infusion, and pre-preg-based methods. Of the multiple manufacturing methods, the method using pre-preg composites offers the highest specific performance, due to the high fibre volume fraction and good microstructural quality.

Composite lattice structures are a family of structural architectures that are normally fabricated using a continuous fibre composite material. These structures are defined by a lattice pattern (grid) of intersecting stiffeners often called ribs. The ribs are most often fabricated using unidirectional carbon fibres, aligning the fibres with the rib direction. Where the ribs intersect, nodes are formed. In the case that this grid is supporting a shell structure (skin), the architecture is typically referred to as a grid-stiffened structure; structures with only ribs (no skin) are referred to as lattice. Further popular reference terms are isogrid or anisogrid depending on the configuration. In most cases ribs run in two to four directions forming a regular pattern.

ATG Europe has developed and patented a cost-efficient manufacturing methodology for continuous pre-preg fibre placed grid-stiffened and lattice structures that allows manufacturing of high quality, complex integrated grid-stiffened composite products in a true one-shot process. Among the different methods to manufacture grid structures, the continuous fibre pre-preg tow placement is recognized as the leading technology in terms of structural performance and quality. These advantages are combined with the patented attachment concepts which offer improved weight-saving capabilities with increased functionality, as the structural configuration can be altered to accommodate different design loads making the technology incredibly versatile. Besides, the one-shot integrated layup and curing method developed by ATG Europe generates a low cost and lead time of producing even the most complex shapes and parts. The developed technology improves a wide range of products in the space domain such as (small and large) launcher interstages as presented in this document, as well as payload adapters and fairings, satellite central tubes, shear panels, and stiff instrument benches, payload dispensers, etc.

Previous developments were performed by ATG in the field of both lattice (grid without a skin), progressing towards TRL 6, and grid-stiffened structures (skin supported by a grid), progressing towards Technology Readiness level (TRL) 5. The first developments internally funded by ATG are summarized in [1-4]. These efforts comprise the development of the one-shot manufacturing methodology, building complex features into the structure (such as end-panel laminate transition and the laminate patches for in-panel attachments), as well as the development of dedicated analysis and optimisation frameworks. Several types of element-level breadboards were successfully designed, analysed, manufactured, tested, and correlated to the finite element (FE) models. The tests were focusing on far-field grid-stiffened structures, laminate transitions, and in-panel attachment points. An example of grid-stiffened panel including several attachment features is presented in Fig. 1.

Figure 1: Grid-stiffened conical panel demonstrator

As required for TRL 5, the performance of a (close to full scale) lattice structure similar to a satellite central tube, manufactured with ATG's technology, has been successfully tested under global and local qualification level loads in an environment relevant for its application. Furthermore, grid-stiffened structures have also been developed for a grid-stiffened inter-tank structure based on A6 ULPM ITS requirements. This included sample testing and material characterisation, while trial panels were manufactured and scaled-down demonstrators were analysed, manufactured, and tested. These activities have shown the viability of lattice and grid-stiffened structures in future space applications. The current Future Launchers Preparatory Programme (FLPP) design study builds on this work by focusing on two small launcher interstages and assesses the viability of incorporating grid stiffened structures in their designs to reduce mass and cost, further expanding the applicability of this technology. The design, analysis, and performance of such structures, including manufacturing aspects and cost comparisons, are presented in this paper. To facilitate the understanding of some of the design layout presented in later sections, the lattice structures terminology and nomenclature is shown in Fig. 2 and Fig. 3.

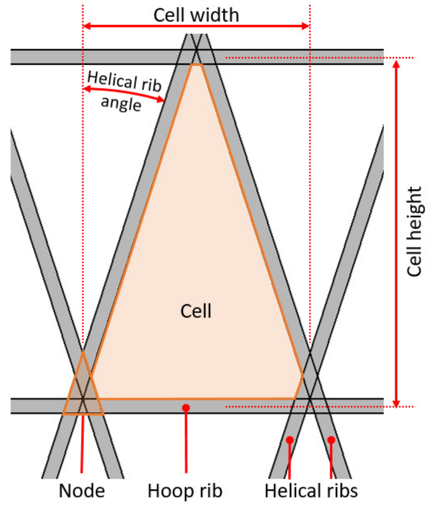

Figure 2: Lattice structures terminology

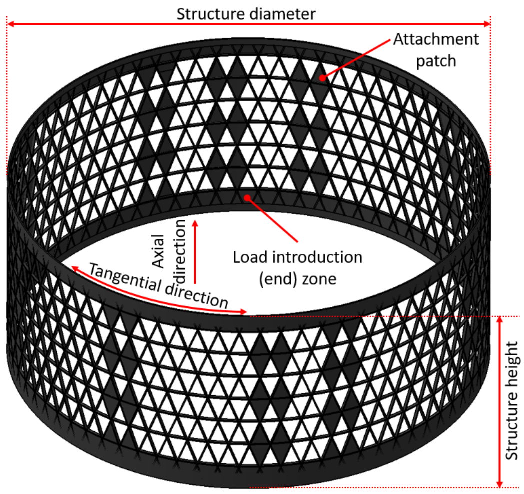

Figure 3: Lattice structures terminology

2. DESIGN

The design of the grid-stiffened structures is based on preliminary requirements provided by an industrial small launcher company. A long, a first stage interstage and a shorter, second stage interstage are the objects of this study. Both top and bottom interfaces are a prescribed pattern of bolts or rivets connecting to the adjacent separation rings (top) and propellant tanks (bottom). The top interface includes several cutouts for the release mechanism, while the bottom interface needs to account for the gap between the tank and the cylinder, together with the tank radial motion when filled and pressurised. These loads go through the fasteners attached to the lower interface. On its inside, the 1st stage interstage supports high-pressure tanks of a given mass. Both interstages are loaded with axial acceleration, lateral

acceleration, overall compression loads, and overall bending moments. Load factors as well as factors of safety of 1.25 for strength and 2.0 for buckling are considered, the margins of safety then being calculated using the failure index and the first eigenvalue of the FE analyses. Given the preliminary nature of the study, the thermal flux during flight is not considered.
The design approach for the two parts is to arrive at an optimal balance between low mass and cost. This is especially true for the first stage interstage, where a kilogram of mass reduction is worth less than it is for the second stage. The overall approach taken is to use a parametrised Computer Aided Design (CAD) model to generate possible designs, for each of which performance is assessed using a strength and a buckling analysis. Both interstages are designed for minimum mass, then branching off to optimise for a low total cost by modifying the materials, end-zones dimensions, skin thicknesses and layups, ribs angle, ribs number, and ribs dimensions. The cost minimisation typically results in an increase in mass which in turn adds to the material cost, so a balance is to be found for each part.

2.1. Long interstage

The long cylinder design is shown in Fig. 4Figure 4, where the different regions are presented. The cylinder is reinforced locally to accommodate tank attachments, with a thicker layup in the patch regions and in the reinforced skin regions. A closer view of the lower load introduction region is presented in Fig. 5. The lower region contains a thinner section towards the lower end of the interstage. The interface to the propellant tank is located in the section indicated as the 'bottom laminate region'. The design is such that the inner diameter of the cylinder is constant throughout the length.

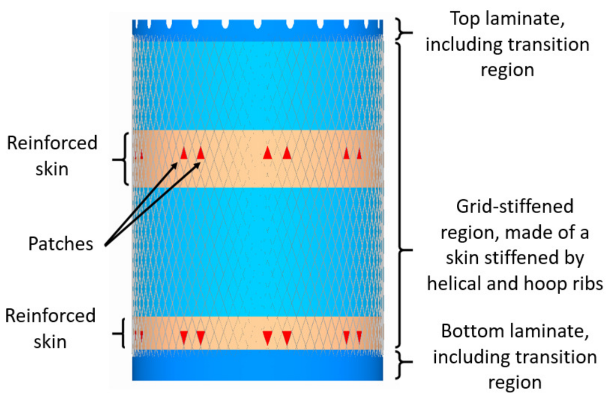

Figure 4: Long interstage design, cut view from inside

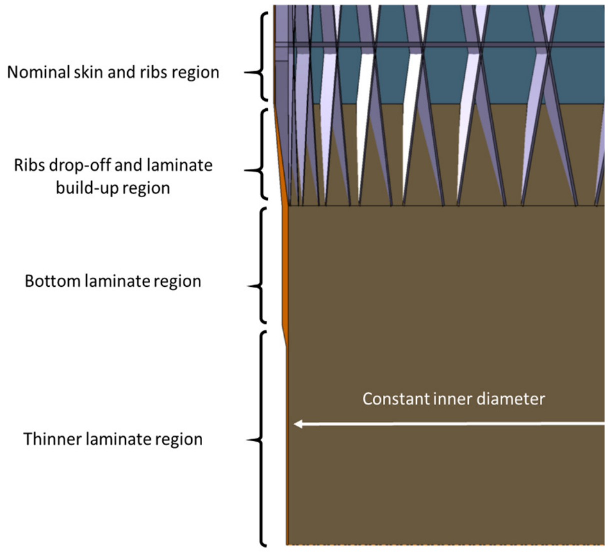

Figure 5: Architecture of the lower laminate region

Two different designs are optimised. One mass-optimised design is using M40J fibres, and one cost-optimised design, somewhat heavier, is using noticeably cheaper T700 fibres. Given the position of the interstage on the launcher, the second solution using a prepreg material with T700 fibres is selected, generating a mass increase of 18% and a manufacturing cost saving of 24% compared to the mass-optimised solution. The cost-optimised design has mass of 63kg while the baseline monolithic Carbon Fibre Reinforced Plastic (CFRP) interstage design has mass of 120kg, which represents a mass saving of 48%. The mass distribution of this solution is given in Tab. 1.

Table 1: Overview of the mass distribution for the long interstage design

Components	Percentage of total mass
Ribs	40
Laminate	15
Skin	41
Skin reinforcements + patches	4

2.2. Short interstage

The short cylinder design is shown in Fig. 6, where the different regions are presented. The lower laminate region has a layout similar to Fig. 5.

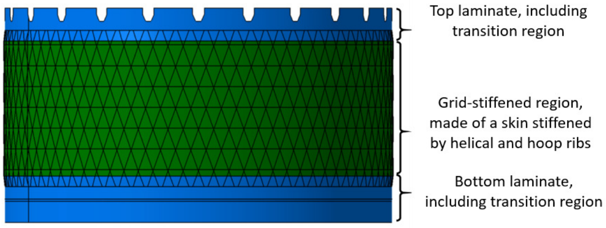

Figure 6: Short interstage design, cut view from inside

Due to the position of the short interstage on the launcher, the benefits of mass minimisation are increased relative to the long interstage. The manufacturing cost savings achievable with a cost-minimisation exercise are outweighed by the additional mission costs associated with launching a heavier mass to a higher altitude. Therefore, while both cost and mass optimisations were performed, it was found that both converged to the same result. The final solution has a mass of 21kg using a prepreg system with M40J fibres, generating a mass saving of 48% compared to the baseline 40kg monolithic CFRP design. The mass distribution of the grid-stiffened solution is given in Tab. 2.

Table 2: Overview of the mass distribution for the short interstage design

Components	Percentage of total mass
Ribs	18
Laminate	48
Skin	34

3. ANALYSIS SETUP

Two types of analyses are conducted on the possible designs for both the first and second interstage. First, shell elements are used on the overall designs to simulate the behaviour of the whole cylinder and to perform the parametric optimisation. Second, detailed analyses using solid elements are used to assess the local behaviour of the lower laminate region where the shell model's ability to predict the strength behaviour is known to be limited. Likewise, a detailed solid analysis of the critical patch region of the selected first stage interstage design is performed. A-basis material values are considered.
The global analyses were performed in order to evaluate strength and buckling eigenvalues under the selected loads. The entire composite cylinders were modelled using shell elements. The overall model of the long interstage design is shown in Fig. 7, while the short interstage is shown in Fig. 8, with colours representing different regions of the design.

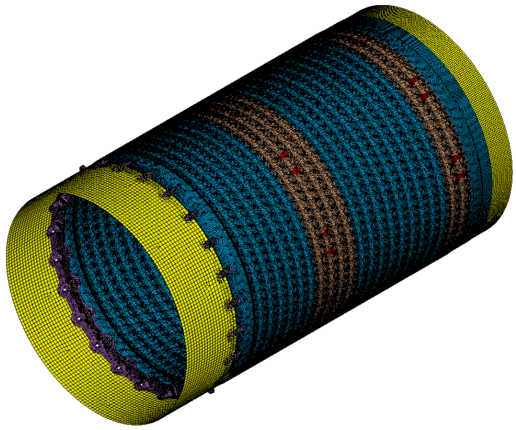

Figure 7: Overall model of the first stage interstage model, including adjacent structures

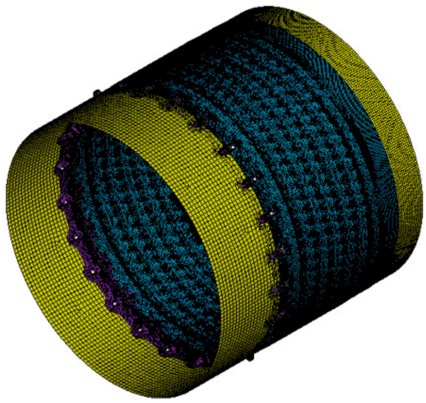

Figure 8: Overall model of the second stage interstage, including adjacent structures

The elements were assigned 2D orthotropic material properties. The tanks of the long interstage are represented by RBE3 elements and a load is applied to their centre nodes, as shown in Fig. 9. The boundary conditions are applied using the adjacent parts geometries and properties provided upon by the prospective customer. The top of the interstages are connected to separation rings, followed by a dummy cylinder representing the stiffness of the adjacent part. The bottom of the cylinder is connected to the propellant tank interface, through sets of rigid beams elements. In order to represent the gap closing magnitude between those parts, the beams are given the necessary Coefficient of Thermal Expansion (CTE) in order to shrink during a thermal step included in the analyses. The bottom of the tank interface is fixed, while the overall compression and bending loads are introduced through an RBE2 element connected to the top of the dummy cylinder, as shown in Fig. 10.

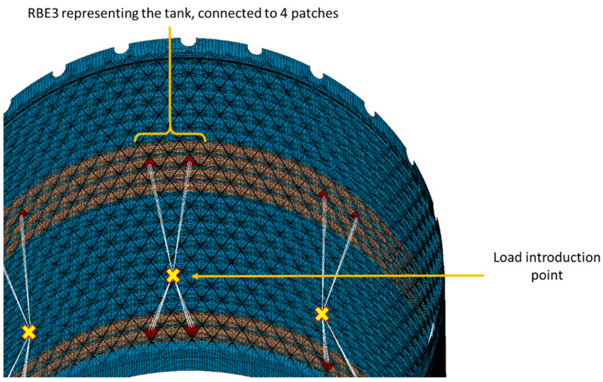

Figure 9: Location of the RBE3s representing the tanks

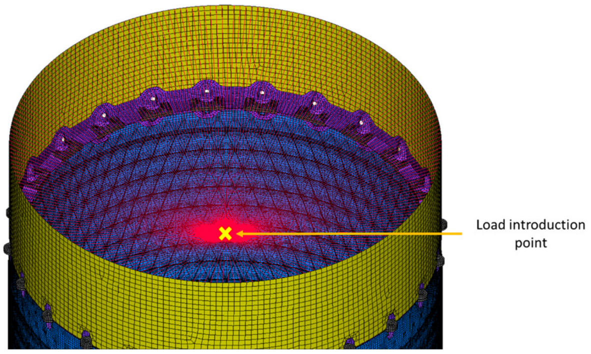

Figure 10: RBE2 element and load introduction point at the top of the composite cylinders

A detailed analysis of the lower laminate region is setup for both designs to obtain a refined strength prediction in that critical area. It focuses on the transition between the ribs and the bottom laminate of the cylinder, using solid elements assigned with 3D anisotropic material. An overview of the model is represented in Fig. 11. A vertical line load is calculated based on the overall bending and compression loads and is introduced at the top of the model. A constraint is applied as well to fix all degrees of freedom except from vertical translation. The bottom boundary condition is applied with a fixed portion of the tank interface, connected to the laminate via a beam and two RBE2 elements, as shown in Fig. 12. This configuration allows to simulate the fitting constraints. A symmetry constraint is applied on the sides of the cylinder and tank interface.

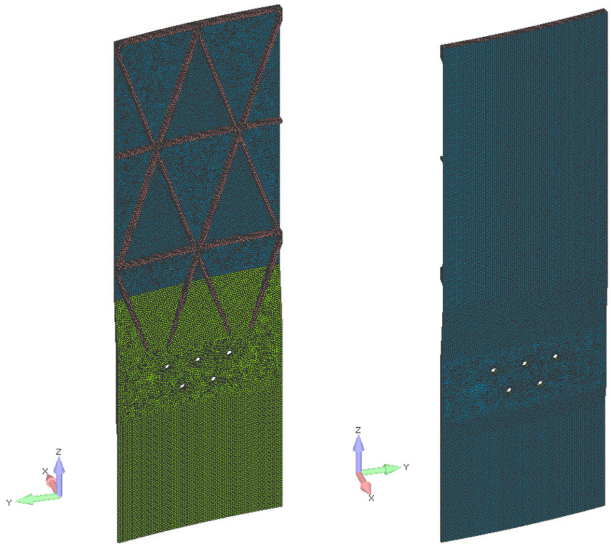

Figure 11: Detailed model of the end laminate for the long interstage design. Blue: skin plies, orange: ribs, green: laminate plies

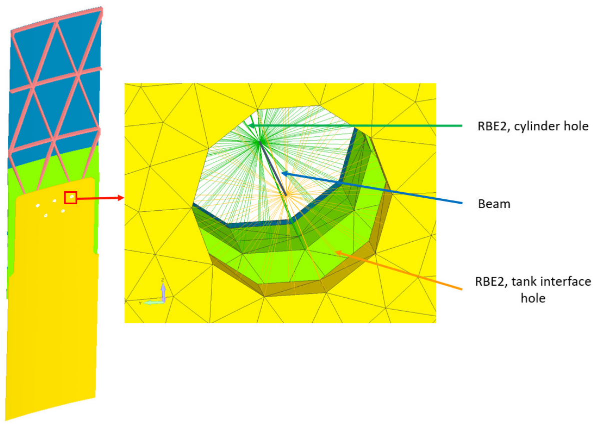

Figure 12: RBE2 and beam elements connecting the tank interface to the bottom end laminate detailed model

In addition, the prediction of the strength behaviour around the patch regions is not captured properly with a shell model, which leads to high local strain peaks. Therefore, detailed analysis of the patches was conducted for the long interstage. The analysis focuses on the two patches which show the highest failure indices in the shell model. Using the shell global models, the immediate region surrounding these patches is replaced by solid elements assigned with 3D anisotropic material properties. An overview is represented in Fig. 13.

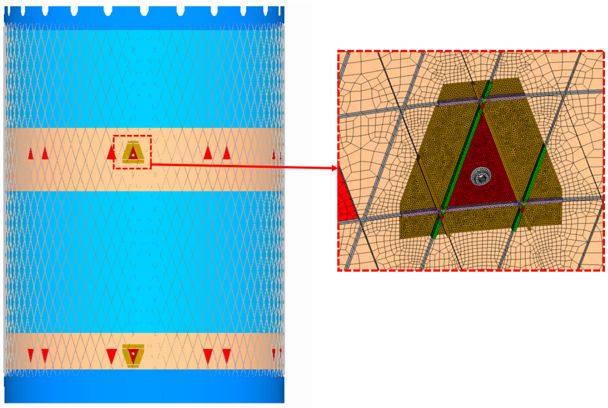

Figure 13: Detailed model for the tank patch analysis of the long interstage model

4. ANALYSIS RESULTS

For both interstages, margins of safety (MoSs) can be defined in Eq. 1 and Eq. 2, using the maximum Failure Index (FI) and the EigenValue (EV) over the model, the strength factor of safety equal to 1.25, and the factor of safety (FoSb) equal to 2.0.

$$MoS_{strength} = {}^{1}/_{FI * FoSu} - 1 \tag{1}$$

$$MoS_{buckling} = {}^{EV}/_{FoSb} - 1 \tag{2}$$

4.1. Long interstage

The performance of the mass-minimised first stage interstage are summarised in Tab. 3, including the resulting margins of safety. The buckling eigenvalue and failure index are both satisfactory and provide some additional margin with respect to the target performance. The modelling accuracy in the laminate bolted zone is however insufficient for the global model to obtain a reliable strength value, therefore the bottom load introduction zone is excluded from the result. Performance indication in this zone instead relies on the detailed model for a better assessment. While the strength analysis on the tank attachment point detail indicates a comfortable margin of safety, on the end laminate detail the margin is slightly negative for the transverse tension failure mode. However, given that materials in a laminate benefit from a higher in-situ transverse strength than the unidirectional coupon tests indicate, this result is not considered problematic. A slight increase in the local laminate thickness can as well allow increasing the margin.

Table 3: Performance of the first stage interstage models

Model	Parameter	Value	MoS
Global model	Max. FI	0.31	1.58
	Location of the max. FI	Rib next to node, at bottom patch	
	First buckling eigenvalue	2.19	0.10
	Buckling mode	Local skin buckling next to the bottom region	
End laminate detail	Max. FI	0.90	-0.11
	Location of the max. failure index	Bolt hole at the lower interface	
Tank patch detail	Max. FI	0.44	0.82
	Location of the max. failure index	Rib next to node, at top patch	

The buckling mode obtained with the global shell model is shown in Fig. 14. Fig. 15 and Fig. 16 present the failure indices obtained for the two detailed analyses.

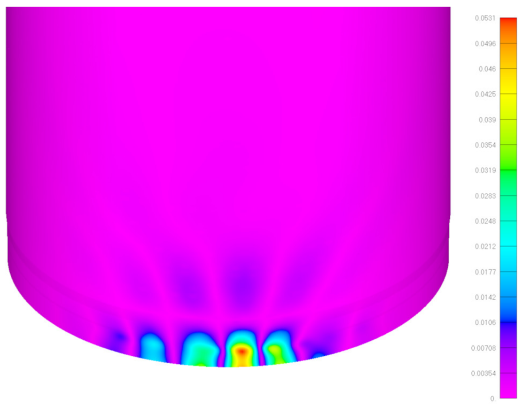

Figure 14: Buckling mode -showing total displacement- for the long interstage global model

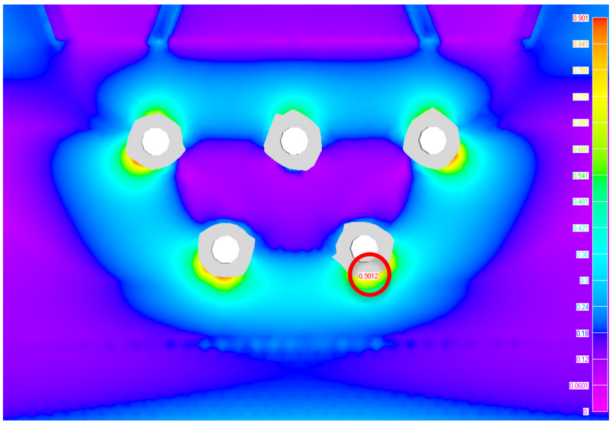

Figure 15: Maximum failure index in the end laminate detailed model (excluding unrealistic results) for the long interstage

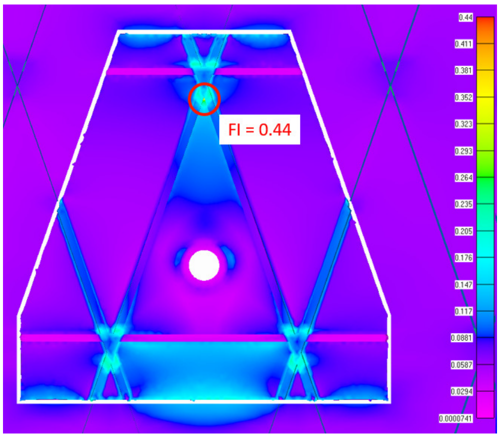

Figure 16: Maximum failure index in the solid tank patch detailed model for the long interstage

4.2. Short interstage

The performance of the second interstage is summarised in Tab. 4. As with the long interstage, the peak failure index and the buckling eigenvalue both show positive margins in the global model. Additionally, the end laminate detailed analysis confirms a positive strength margin. Since the location of the peak failure index in the global model's lower laminate interface is not captured accurately by the modelling strategy, the failure index of this zone is left out.

Table 4: Performance of the second stage interstage models

Model	Parameter	Value	MoS
Global model	Max. FI	0.32	1.5
	Location of the max. FI	Rib next to node, at bottom patch	
	First buckling eigenvalue	2.23	0.115
	Buckling mode	Local skin buckling	
End laminate detail	Max. FI	0.63	0.27
	Location of the max. FI	Bolt hole at the lower interface	

The buckling mode of the long interstage is shown in Fig. 17, and Fig. 18 presents the failure indices obtained for the detailed analysis.

Figure 17: Buckling mode -showing total displacement- for the short interstage global model

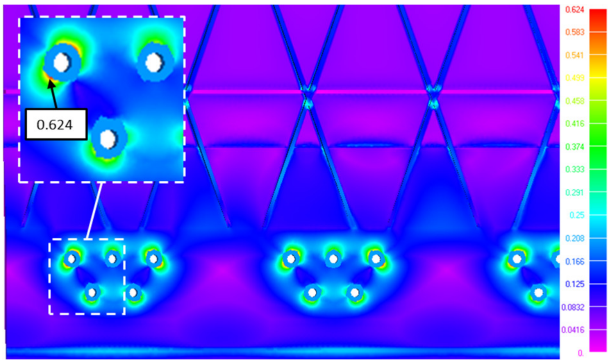

Figure 18: Maximum failure index in the solid tank patch detailed model for the short interstage

5. MANUFACTURING PLAN

A manufacturing and integration plan is proposed, detailing the manufacturing of both lattice interstages and the final assembly/machining steps before shipment to the customer. This plan is developed to be as cost-effective as possible in the current development context, therefore involving hand lay-up of the parts. This strategy was estimated as the most economical solution for small production series and for the relatively low complexity of the parts. First, manufacturing preparation of the parts consists of inspection checks, moulds preparation, and documentation. Layup and cure cycle are then composed of a manual prepreg layup followed by the remaining tooling placement, bagging procedure, and autoclave curing. A first inspection is performed before demoulding, while the assembly step is composed of a full inspection and tolerance check, followed by machining, drilling, insert bonding and final inspection.

Automated manufacturing is an alternative considered in the future, replacing the manual grid layup steps with an automated fibre placement robotic system. The benefits of such semi-automation lie in the uninterrupted service provided, the speed, the accuracy, and the repeatability of the process, which would therefore be suitable for steady commercial production. Machining and drilling can as well benefit from an automated process, through the resulting ease of operations and repeatability. It would however require significant investments, and the added benefit of this system would increase proportionally with the complexity and number of cut-outs. Another benefit of automation is to allow tracking and inspection of operations, while a software could be developed to automatically detect problems. Defect tracing would therefore be improved, in a case where the complexity and number of parts would compensate for the high initial investment.

6. COST ESTIMATION

The topic of cost estimation and comparison is one where significant time investment is required in order to reach an objective conclusion. Due to such time constraints, only one comparison was made in the reported work, where the grid-stiffened solution is compared to the baseline. In this particular case, the baseline solution - a monolithic cylinder design - is one which is difficult to compete against because it represents the simplest possible approach to fabricate an interstage structure. Nevertheless, the differences in pricing between a monolithic and a grid solution are not overwhelming. Upon a detailed cost comparison of the two solutions (monolithic and grid), for this specific design case the following conclusion has been drawn:

- The recurring cost of the pair of grid cylinders fabricated manually is 39% higher than that of a monolithic pair of cylinders (fabricated using an automated method).
- The recurring cost of the pair of grid cylinders fabricated in an automated way is 27% higher than that of a monolithic pair of cylinders (fabricated using an automated method).

These results correspond to a set of grid-stiffened components that offer a 48% decrease in mass, which is advantageous for high performance applications. Actionable insight is therefore provided here on the topic of comparison of price versus mass saving. Knowing how much every kilogram is “worth”, one can make an educated guess whether it is interesting to further look into the use of lattice or grid structures for their particular application.

There is a range of numbers used to define the value of each kilogram of mass delivered to orbit by a launcher. These numbers typically range from 3,300€/kg - 16,500€/kg at the time of writing, depending on the launcher specifics. With this in mind, a mass saving of 19kg on an upper stage structure could be “worth” between 63,000€ and 313,000€ per item. This range of numbers and the actual pricing of the grid-stiffened cylinders offered by ATG makes the grid solution an extremely attractive proposition for a wide array of applications from both the performance and cost perspectives.

A few additional remarks have to be carefully considered if one were to attempt drawing any conclusions from the information above:

- The data reported is highly subject to the specific load case considered, structural shape and other design requirements. The reported conclusions are not directly transferrable to any other application or product.
- The data reported is highly sensible to the factory cost rates and the hourly rates of the employees doing the work. Because the amount of labour involved in fabricating the baseline and the grid-stiffened structures is unequal, the cost comparison will also differ per country, under the influence of typical wage differences.

The data reported assumes the usage of certain materials. If other materials are used, the conclusions could change significantly.

7. CONCLUSION

The current study covered various aspects of the development of grid-stiffened structures for small launcher commercial applications, including design, analysis, manufacturing planning, and cost estimations for a first and second stage interstages. The result of the structural optimisation indicated a promising mass versus cost trade-off for the two designs compared to a baseline CFRP monolithic design, leading to a 48% mass reduction in both cases, which constitutes a significant advantage over competition given the cost of operating such products at higher masses. To obtain such a result, detailed designs were defined, optimising towards structural performance while considering both mass and cost aspects. In particular, the first stage interstage cost-optimisation strategy is preferred over mass-optimised strategy, as it provides a worthwhile cost advantage given the position on the launcher, as well as satisfactory structural performances. It was found that the designs selected for the first and second stage have a sufficient margin in buckling eigenvalue and global strength. The second stage design local analyses revealed a satisfactory margin in strength as well. The first stage design shows an acceptably small negative strength MoS given the failure mode, which could easily be compensated for by the addition of few plies of material in the bottom laminate region. In addition, a plan for hand lay-up manufacturing has been developed, including the potential benefits of introducing semi-automatisation in the future of the process.

Overall, this study confirms the potential of the technology for the targeted application and its commercial advantage compared to existing competitive designs. The preliminary results contribute as well to the product maturity towards TRL5.

ATG is currently working on a follow-on step of grid structures maturation. This involves fabrication and full-scale testing of a grid-stiffened interstage by Q2 2022.

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