DEVELOPMENT LOGIC AND BUILDING BLOCK TESTING APPROACH FOR PRE-PREG LATTICE SATELLITE CENTRAL CYLINDER APPLICATIONS

Bart Smeets[(1)], Thijs Papenhuijzen[(1)], Leonid Pavlov[(1)], Menno Koot[(1)]

[(1)] ATG Innovation Ltd., Office 6 Level One, Liosbán Business Park, Tuam Road, Galway, Ireland
Email: leonid.pavlov@atg-europe.com

ABSTRACT

The lattice and grid-stiffened composite architecture has gained significant interest recently due to the advance of composite material performance and manufacturing method automation. Depending on its implementation the technology offers the promise of improving on the three most important aspects of spacecraft structures: cost, lead time and mass; while maintaining similar or improved component and system performance.

Despite the promise of efficiency improvement, the technology is yet to be flown on European launchers or spacecraft. The reason it has not happened so far is that the technology is rather complex, design and optimisation methods are not widely known or simply underdeveloped and the manufacturing and testing technologies are often at a level of maturity that requires significant further development. Due to the architecture's novelty and complexity, a development programme is never a straightforward task due to unsuitability of standard test methods and coupon geometries.

As part of an ESA Science Core Technology Programme (CTP) development, ATG Innovation Ltd. (subsidiary of ATG Europe) together with ÉireComposites Teo are working on further increasing the TRL of fibre-placed pre-preg lattice structures for spacecraft (specifically central cylinders). This should pave the way for their application on science and commercial missions by year 2020 already.

This paper elaborates on a comprehensive selection of tests and samples for the building block testing approach for this novel architecture and the logic behind this selection. Best cost and time saving practices were implemented in order to select the fastest and cheapest set of tests and test methods to increase the maturity of the architecture based on the current knowledge of the consortium in the field of lattice structures.

1. INTRODUCTION

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 (GS) 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 and proven as the leading technology in terms of structural performance and quality. Combined with the patented concepts and production method by ATG Europe, these advantages in terms of performance and quality are further enhanced by low cost and lead time of producing even the most complex shapes and parts. These cost and lead time performances are assured by the integration of all relevant structural features into a one-shot layup and curing process of the composite part. With further development and industrialization, the developed technology will significantly improve a wide range of products in the space domain: (small and large) launcher interstages, payload adapters and fairings, satellite central tubes, shear panels and stiff instrument benches, payload dispensers, etc.

Figure 1: Grid-stiffened technology demonstrator manufactured by ATG.

The current status of the developments internally funded by ATG are summarized in [1-4]. These efforts comprise development of the one-shot manufacturing methodology, development of dedicated analysis and optimisation tools, development, design and comprehensive testing of ‘pristine’ GS panels, load introduction zones for GS interstages, attachment areas for satellite central cylinders, all based on in-house developed analysis and optimisation approaches for the grid architecture. The performed developments allowed creating a manufacturing demonstrator (Fig. 1) which incorporated all of the to-date developed features into one part. The activities carried out by ATG place the developed grid technology at around TRL4.

The consortium of ATG Innovation and ÉireComposites Teo has recently started an ESA Science CTP development aimed at a further maturation of the grid and lattice structures technology with a focus on spacecraft central cylinders. This CTP development is regarded as one of the stepping stones between the current status of the technology and TRL 6 and is scheduled to complete in Q4 2018.

To facilitate the understanding of some of the test specimen layouts presented in later sections, the lattice structures terminology and nomenclature is shown in Fig. 2 and 3.

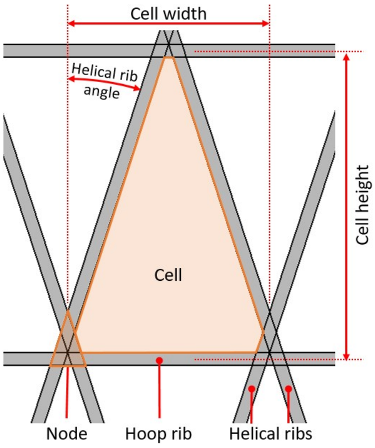


Figure 2: Lattice structures terminology.

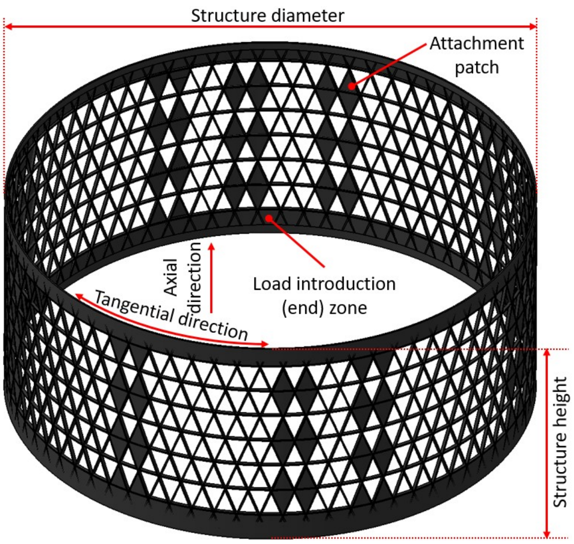


Figure 3: Lattice structures terminology.

The reader is invited to look into [1-4] as these introduce additional background information on lattice structures terminology, examples, development, testing and previous work performed by ATG.

2. DEVELOPMENT LOGIC AND BUILDING BLOCK APPROACH

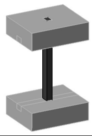
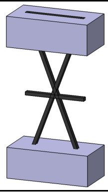
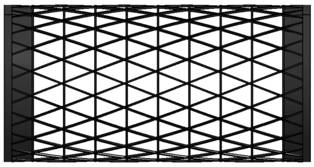
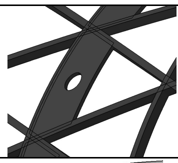
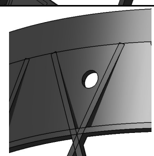
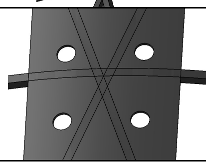
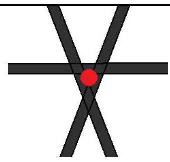
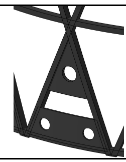
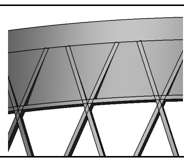
The “building-block” approach allows to develop structural architectures and components starting from ideas and culminating in full-scale structural testing at reduced level of development risk at every stage of the development. Every subsequent step of the building block approach features increasing sample complexity and cost. A lower number of samples needs to be tested compared to previous steps due to the confidence in analysis methods and structural behaviour that is gradually built over the course of the development. Every programme typically starts with:

1. Selecting the architecture, manufacturing method and material system, then moves to
2. Small samples to characterise the system behaviour and fine-tune the analysis method at a small scale,
3. Then larger structures are examined where multiple features are combined and tested together, buckling phenomena are assessed and analysis tools are further improved.
4. The development then culminates in testing of complex subcomponents or full scale components.

For an overview of the building block approach samples for lattice structures see [2].

Between the current development state and TRL 6, several topics are identified which are either necessary or desirable to be covered/researched. An overview is given in Tab. 1. This includes parts that will be covered during the CTP project, as well as parts that will be covered in subsequent development programmes. The provided list of test samples forms a comprehensive set of specimens that need to be designed, manufactured, tested and correlated in order to achieve TRL 6 – these form the bulk of the activities that are required on the front of mechanical performance testing. The activities on other fronts, i.e. NDI, quality assurance, etc. are not listed in this paper, but are already considered in the CTP project.

Table 1: Overview of the mechanical performance verification activities required in order to reach TRL 6.

Topic to cover		**Purpose and background information**	**Image**
Rib element tests	**	Determine knockdown factors for structural elements. Due to the manufacturing method, the fibres in the ribs are not always perfectly parallel, and can show some waviness. By testing a single rib these effects and the impact thereof can be quantified. In previous test campaigns weak areas were identified in the nodal region. The node element tests will be used to confirm the knockdown factor to use for these regions using the ultra-high modulus fibre pre-preg.	
Node element tests	**		
Cylindrical structures	**	Uncover and solve manufacturing difficulties and unforeseen effects of a cylindrical part compared to a flat part. The main additional complexity is the placement and fixation of tooling and outer mould as well as compensation for tool expansion and possible demoulding complications. Previously, tooling fixation was possible by gravity alone.	
Attachment patch on the outer diameter of a part	**	Uncover unforeseen effects in manufacturing, if any. All attachment parts made so far had the patch on one side of the panel, directly on the lower/inner mould. Patches on the outer mould side have not been manufactured yet.	
Attachment point in a panel end (load introduction) zone	**	Determine manufacturability and preferably also test to determine the behaviour and strength. With many attachment points in a satellite central cylinder, and regions of attachment points (e.g. for shear webs) extending all the way to the ends of the structure, it is unavoidable that some attachments end up in relatively unfavourable locations. Although conceptual evaluation and analyses show that this should be possible, it needs to be verified by test.	
Attachment point close to rib	**		
Attachment point on small radius cylinder		Determine manufacturability and effects of high curvature – useful for intermediate scale samples and for applications of smaller diameters	-
Attachment point in or at a rib or node		Determine possibility, and effect on main grid structure behaviour. Although ideally avoided in the design, an additional or repositioned attachment point can end up at a node or rib. In this case the base structure likely needs a local reinforcement to not compromise the overall strength (not shown in picture on the right).	
Multiple attachment patches in a single cell	**	Determine manufacturability. With a single piece of tooling in a cell adding multiple attachment points might result in unforeseen difficulties. In parts with many attachments (like seen in e.g. a central cylinder) this might become necessary.	
Attachment loads: out-of-plane load		Determine failure behaviour and prediction of previously untested load cases. Not all load directions and failure modes have been considered in previous test campaigns at ATG, so additional ones need evaluation.	-
Attachment loads: pull-out of patch from rib			-
Panel end-zone with open lattice structure	*	Evaluate behaviour and strength of end zones without a skin. Previous tests on end-zones have included a skin, and its omission might result in an unexpected change in behaviour.	
Full-size, full-complexity cylindrical structure	*	Combine all critical elements into a single component, demonstrating ability to make realistic SCT parts.	-

* Partially covered by foreseen CTP development

** Covered by foreseen CTP development

3. SELECTION OF SAMPLES FOR CTP

3.1 Sample Selection

The core of the CTP project for TRL maturation of lattice structures has been built around a subset of test samples described in Tab. 1. Within the timeframe and budget of the current CTP it is not possible to cover all the activities required to advance to TRL6, but a significant step can be made. Currently, four manufacturing and testing campaigns are foreseen:

1. Material coupon tests. This will feature a limited number of tests to determine reference data for e.g. compressive strength and shear strength of the material.
2. Structural element tests. For these tests a flat grid panel will be made, from which parts will be cut for node and rib element tests. These separate tests will be performed to give a lower-level insight into the behaviour of the grid elements, and find knockdown factors for the strength and stiffness in these elements, compared to the properties found in the coupon tests. Additionally this will serve as an input for prediction and correlation of the more complex tests.
3. Intermediate scale cylindrical sample, approximately 0.5 m diameter. This is primarily a manufacturing trial part and demonstrator. As such the complexity of this part will be high, with multiple attachment regions as well as attachment points in inconvenient locations. Additionally, options to manufacture and test a less complex sample with the same diameter are being explored.
4. A full-scale cylindrical sample, approximately 1.5 m diameter. The main purpose of this sample is to test the overall behaviour of a cylindrical open grid structure, in terms of both stiffness and strength. The complexity of this sample will be lower than the intermediate scale sample, but it will likely still include several more complex elements like laminates for attachment points, to see the effects on the overall behaviour. In order to limit the required amount of material, tooling and layup time, the sample is kept relatively short at 0.8 m.

As a material TenCate's RS-36/M55J prepreg is selected. The high-modulus M55J fibres are used because initial analyses and evaluations have shown that the design of lattice primary satellite structures is typically stiffness-driven, and less influenced by strength. The RS-36 resin, a modified epoxy, is selected for its low outgassing properties, and because the majority of lattice and grid-stiffened structures previously made by ATG used an epoxy resin. After communication with major parties in the field of spacecraft structures, it has been concluded that there is no specific reason for using cyanate ester resins in place of modified epoxies as long as the material outgassing properties are compliant with part requirements.

3.2 Sample Design Logic

Previous sections have introduced how the building block approach can deliver a well-founded, gradual increase of the TRL of pre-preg lattice structures. The next section goes into the logic behind the detailed design of the actual samples that make up the intermediate steps as described in Section 3.1. Two driving aspects are minimization of cost and risk. This section elaborates on how these two goals have guided decision-making in sample development.

As listed previously, there are four different test campaigns within the overall project. Out of those, the three most complex ones exhibit features that require moulds with a certain complexity, i.e. they cannot be simply cut out of a sheet of composite material, like the first one (the coupon test). The specifics of the manufacturing method developed by ATG for cylindrical grid structures feature a metallic mandrel defining the inner mould line, caul plates defining the outer mould line and expansion blocks placed inside the cells of the lattice and in between the inner and outer moulds. These expansion blocks are hard pieces of material with a high coefficient of thermal expansion that participate in the curing process by forming ribs, skins and patches of the lattice structure. The expansion blocks need to be produced individually and are currently the most labour intensive and often a costly part of the tooling preparation process.
Two major cost reduction measures are:

1. Strive to share as much tooling as possible between the various samples
2. Simplify tooling as much as possible. When feasible, use easily available materials

Logically, the expansion tooling design follows directly from the main dimensions of the grid pattern of the sample in question, and needs to be custom made for each grid design. Manufacturing the expansion tooling used for each of the samples is one of the greatest expenses in terms of manpower. For the final test article, almost 800 individual pieces of tooling are needed, in several different shapes, not yet taking into account a non-negligible scrap rate.
Rib height and width, as well as cell dimensions of the full scale test article are finely tuned to meet an externally specified set of structural requirements. The intermediate test stages however, only serve to raise TRLs sufficiently to be able to build the full scale test article. As such, their design is not necessarily driven by the specific load cases that apply to the final article.
The choice was made to have the critical dimensions of the intermediate samples be derived from those of the final test article, in such a way that the expansion tooling can be fully reused between the different samples (Fig. 4). In this way, the expansion tooling for these intermediate samples is essentially free, as there is no noticeable degradation of the tools in their first few uses.

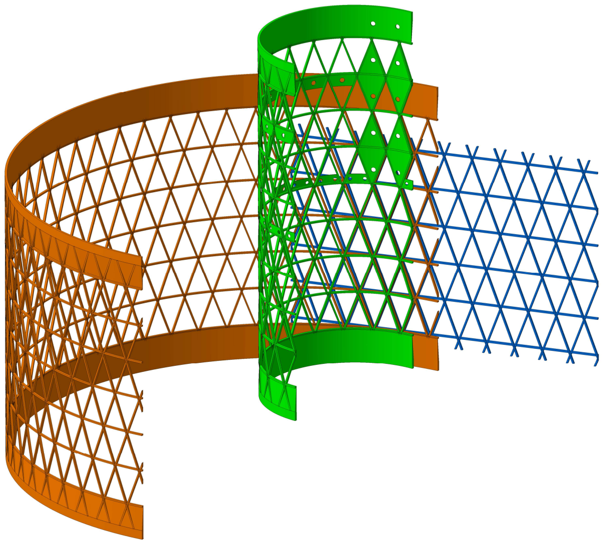


Figure 4: Overlay of the different test samples to be fabricated in the CTP development: blue – flat panel for rib and node tests, green – 0.5m diameter cylinder of high complexity, orange – simplified full scale lattice cylinder. All samples feature identical cell geometries for tooling reuse.

Another pre-full-scale sample selected for the CTP project technology maturation is a cylinder with a 0.5 m diameter (roughly scale 1:3 compared to the final article). However, instead of fully scaling the design of the final structure, the cell and rib size is kept identical. This is considered to provide a good balance between low complexity (and thus cost) on the one hand, and representativeness of the final article on the other hand. This last aspect is crucial, as it presents the first experience with manufacturing an actual fully cylindrical structure by ATG. The increase in cylinder diameter leads to a rapid increase in terms of build cost, so size should be kept small for cost minimisation. At the same time, choosing a diameter that is too small introduces significantly increased curvature which impacts the flexible expansion tooling (produced initially as flat parts), leading to dimensional inaccuracies through its thickness due to the curvature which the tooling needs to comply to during the curing cycle.
Apart from using expansion tooling that was already required for the full scale article, tooling cost for the last intermediate sample is further minimized by choosing the diameter such that the metal mould can be made out of a commercially available tube (20”) of which the outer diameter is subsequently precision-ground, to limit the amount of required tailored manufacturing steps.

In addition to material cost and representativeness, other factors are weighed in deciding on the size (diameter and overall height) of the intermediate-size cylinder. The overall scale plays a large role in determining the manufacturability. For example: increasing the cylinder height beyond a certain point makes it suddenly much more difficult to lay up individual helical rib plies for a single person. It can be difficult to get a good sense of scale from looking at a CAD model on a screen. At the same time, building a physical mock-up is a time consuming exercise. ATG combined the interactiveness of a physical dummy with the versatility of a parameterized CAD model by using a Virtual Reality (VR) environment (Fig. 5). Here, several differently sized cylinders and mandrels were implemented to perform simplified simulations of ply layup as well as to get a qualitative “feel” of what would be a: representative, manufacturable and appropriate sample size (as small as possible, but not too small)

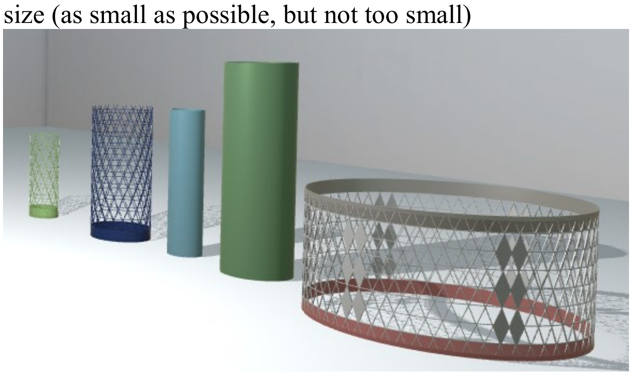


Figure 5: Implementation of various tube sizes and configurations in a VR “playground” for a “hands-on” suitability evaluation.

4. MANUAL VS. ROBOTIC MANUFACTURING

Laying up a grid-stiffened tube is a highly labour-intensive process. For example, the CTP final article includes over 6000 individual plies for the ribs alone. For this reason, future efforts will be aimed at developing an automated process for some or even most of the tasks involved in building composite lattice structures. To the extent that this can be achieved, it will greatly reduce overall cost. Typically, only a single rib width is used throughout a single structure. This built-in standardization lowers the bar for using automated layup, such as robotic tape placement. The end zones can then be produced by combining multiple tows side by side and the patches can be provided using pick and place techniques.
The overall manufacturing process has shown a reasonable tolerance for misplacement of plies and strips that does not exceed significantly beyond about a millimetre. With that in mind, the process of manually placing is a relatively (currently sufficiently) accurate one. However, tighter dimensional control, straighter fibres in the final ribs, and therefore higher quality products can likely be achieved when higher consistency is introduced for aspects like positioning and pretension of tows.
Increasing ply thickness can be another method of decreasing layup time, simply because of the resulting reduction of the total number plies. In the current development ply thickness has been increased significantly compared to the default ply thickness of the selected material: 0.194mm versus 0.073mm. This allows decreasing the layup time by a factor of ~3. The

test campaigns executed to date suggest that the specifics of lattice structures make it unnecessary to use low ply thickness for strength or load transfer reasons. The load introduction and attachment zone concepts are also robust enough to tolerate higher ply thicknesses without the need to overdesign them.
The increase in supplied ply thickness was possible thanks to Ten Cate's flexibility and support.
With the current state of development, the most feasible method for manufacturing grid-stiffened tubes is still a fully manual one. However all the developments are performed keeping automation in mind and ensuring that all the process, layup and positioning steps are entirely repeatable by a tow placement robotic head and industrial robots. Once automated manufacturing capabilities will become available, the process is thus directly transferrable to robotic means.

5. CONCLUSION

Lattice and grid-stiffened structures form a relatively novel architecture family that promises to improve the performance of certain space products while, at the same time, reducing cost and lead time of component manufacturing. There are, however, aspects related to the lattice architecture that require significant development before a widespread acceptance and implementation can be achieved. The maturity of the technology and the associated design and analysis approaches are the aspects that requires the most attention. From the different methods to manufacture lattice structures the continuous fibre pre-preg tow placement is the leading technology in terms of structural performance and quality. This paper elaborates on a sequential development logic following the so-called "building block" approach for lattice structures manufactured using a continuous fibre pre-preg tow placement process. The current status of ATG Innovation developments has been used as the starting point for the development approach. Cost saving and risk reduction practices are implemented in order to come up with a safe, cost-efficient and time-efficient development scenario. Part of this scenario is implemented in a first development programme under the ESA Science Core Technology Programme. Within this CTP, development samples of increasing complexity will be manufactured and tested starting from single rib elements to a full scale complex cylindrical test article. As an intermediate step a smaller cylindrical test article of high complexity will be manufactured to test a number of high-risk aspects and concepts before going to full scale. Upon completion of the final test of the CTP development the technology will be close to reaching a TRL 6 which is expected to happen in Q4 2018.

6. REFERENCES

1. Pavlov L., te Kloeze I., Smeets B. J. R., Simonian S. M. (2016), Development of mass and cost efficient grid-stiffened and lattice structures for space applications, *ECSSMET 2016*, Toulouse, France.

2. Smeets B. J. R., Pavlov L., Kassapoglou C. (2016), Development and testing of equipment attachment zones for lattice and grid-stiffened composite structures, *ECSSMET 2016*, Toulouse, France.

3. Pavlov L., Smeets B., Simonian S. M. (2016). Optimization of a Composite Lattice Satellite Central Cylinder Structure Using an Efficient Semi-automated Approach, *AIAA 2016-1497*, DOI: 10.2514/6.2016-1497.

4. Maes V. K., Pavlov L., Simonian S. M. (2016), An efficient semi-automated optimisation approach for (grid-stiffened) composite structures: Application to Ariane 6 Interstage, *Composite Structures*.