DEVELOPMENT OF FIBRE-PLACED PRE-PREG LATTICE STRUCTURES FOR SATELLITE CENTRAL CYLINDER APPLICATIONS

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ABSTRACT

As part of an ESA Core Technology Programme, ATG Innovation Ltd. (a subsidiary of ATG Europe) has furthered the development of uninterrupted pre-preg fibre-placed lattice structures, aiming to apply this technology to satellite central tubes (SCTs). This paper gives an overview of the progress achieved under the development program, which comprised three main steps. First, a flat lattice panel was manufactured, to be used for element level tests in support of the design and analysis of the larger structures. Secondly, an intermediate scale lattice cylinder of approximately 0.5 m diameter was manufactured, incorporating many complex features usually found in SCTs. Multiple local laminate patches for attachment points and a transition to a monolithic laminate were included in the cylinder, which served as a manufacturing trial and demonstrator. Finally, a 1.5 m diameter cylinder was manufactured and tested under satellite-representative global loads. This cylinder weighed less than 10 kg, and was easily capable of withstanding the 175 kN design compression load, ultimately failing at a line load of 184 kN/m, equivalent to an overall compression load of 870 kN.

1. INTRODUCTION

Composite lattice and grid-stiffened structures consist of sets of ribs forming a base grid, optionally complemented by a skin. When made from a fibre-reinforced composite material these structures typically have the fibres aligned with the rib direction, making optimal use of the directional stiffness and strength of the composite. This makes lattice and grid-stiffened structures highly efficient, and a promising technology for lightweight, high-performance structural components. Filament wound grid-stiffened launcher structures, with fibre volume fractions ~40%, have already been shown to achieve up to 60% mass saving compared to an aluminium baseline design [1]. Besides wet filament winding, various other manufacturing techniques can be used to manufacture composite lattice structures, including dry filament winding and infusion, and prepreg-based methods. The presented developments focus on structures made using pre-preg material. This manufacturing method offers several advantages, such as the higher obtainable fibre volume fraction of ~60%, resulting in a substantially higher specific stiffness and strength. Additionally this method allows local design features which are not possible with filament winding, e.g. local rib width and direction changes, and integrated local laminates in the cells of the grid.

The presented developments are funded by ESA under a core technology programme (CTP), and executed together with EireComposites, who are the selected manufacturing partner.

2. DEVELOPMENT APPROACH

Prior to the commencement of the CTP, development efforts had already been undertaken by ATG. On a smaller scale the individual building blocks of the structure were developed and tested [2,3], and overall optimisation studies were performed [4,5], bringing the technology readiness level (TRL) to around TRL4.

Building upon this heritage, the presented developments aimed to achieve TRL5, by manufacturing and testing a near full-scale (1.5 m diameter) lattice cylinder. With typical SCT diameters for science satellites of 1.65 m, this is considered practically full-scale. Several intermediate steps are taken as well, including multiple element level tests to characterise the behaviour of the structure at a lower level, and manufacturing of a smaller cylinder to test and demonstrate the manufacturability of full cylinders. The basic lattice parameters (cell size, rib dimensions and angles) are kept the same for all samples in order to facilitate correlation, and to allow the re-use of tooling.

3. FLAT PANEL AND ELEMENT TESTS

To support performance prediction and correlation efforts, multiple smaller element tests were performed, supported by material coupon tests:

- A single node loaded in compression
- A single node loaded in compression, after thermal cycling
- A single node loaded in 4-point bending
- A single rib loaded in compression

The nodes and ribs required for these tests were cut from a flat lattice panel, as shown in Figure 1, which also shows a finished test sample during testing.

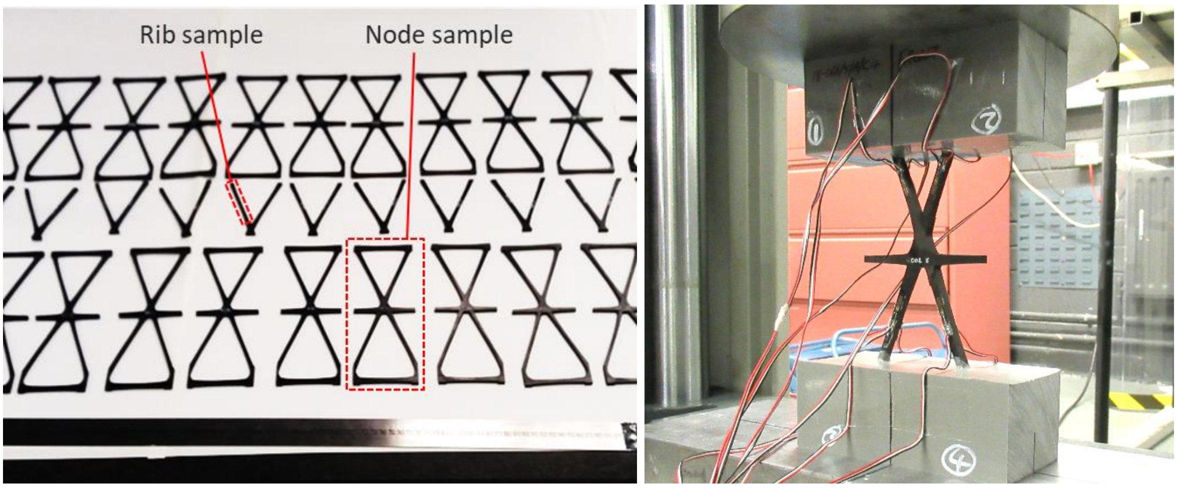

Figure 1: Left – Several samples cut from larger panel. Right – Node test sample during testing.

On this same panel, NDI trials using A-scan and C-scan were also performed, benchmarking these methods for later use on the cylinders. Microsectioning was performed on several parts of the panel to compare to the NDI findings.

Generally the test results were in line with initial expectations and FE predictions. Rib stiffness and strength were within 10% of UD coupon results, and average node compression strength was also within 10% of the predicted value. Thermal cycling did not have a noticeable effect on the node strength. The exception was the node strength in 4-point bending, which was noticeably higher than predicted, overshooting the predicted strength by at least 50%.

4. SUB-SCALE CYLINDER MANUFACTURING TRIALS

An intermediate scale lattice cylinder was made to trial the manufacturing of a complete cylinder, which presents additional difficulties not present in a flat panel.

4.1 Design

A high-complexity cylinder design was chosen for manufacturing, to not only show the manufacturability of a lattice cylinder, but to also show the feasibility of including local design features which are typically required for an actual SCT design. A diameter of approximately 0.5 m was chosen, to be sufficiently representative while keeping material cost and manufacturing effort at manageable levels. The design is shown in Figure 2.

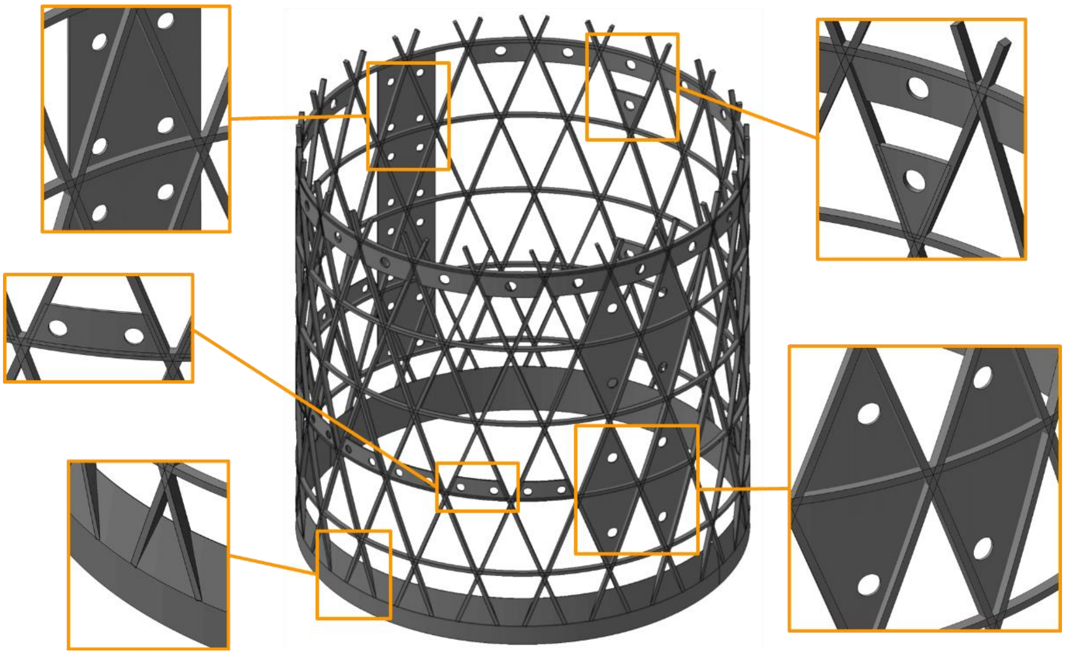

Figure 2: Design of the small cylinder, showing various design elements.

The cylinder contains a transition to a monolithic laminate at one end of the cylinder, which would facilitate joining of an end ring or direct joining to adjacent structures. Further, various configurations of local laminate 'patches' were introduced:

- Various patches in a single-cell, on both the inside and outside diameter, and of various thicknesses
- Cells containing multiple patches
- Patches covering multiple cells

These patches are typically used to provide attachment points, and can be used to provide attachment zones running along the circumference or length of the cylinder, as is typically required in satellite central cylinders for connections to shear webs and equipment decks.

4.2 Manufacturing

The structure was manufactured using the Toray Advanced Composites RS36 epoxy prepreg system, in unidirectional carbon fibre tape. To manufacture the cylinder, tows and plies of prepreg are laid up free-standing on a mandrel. For the alignment of the plies a paper template is used, which remains on the mandrel during the manufacturing process. After the layup is complete, flexible tooling is placed in the cells of the grid, and the layup is enclosed by metal edge dams and covered with metal caul plates. Figure 3 shows the finished layup and cured part.

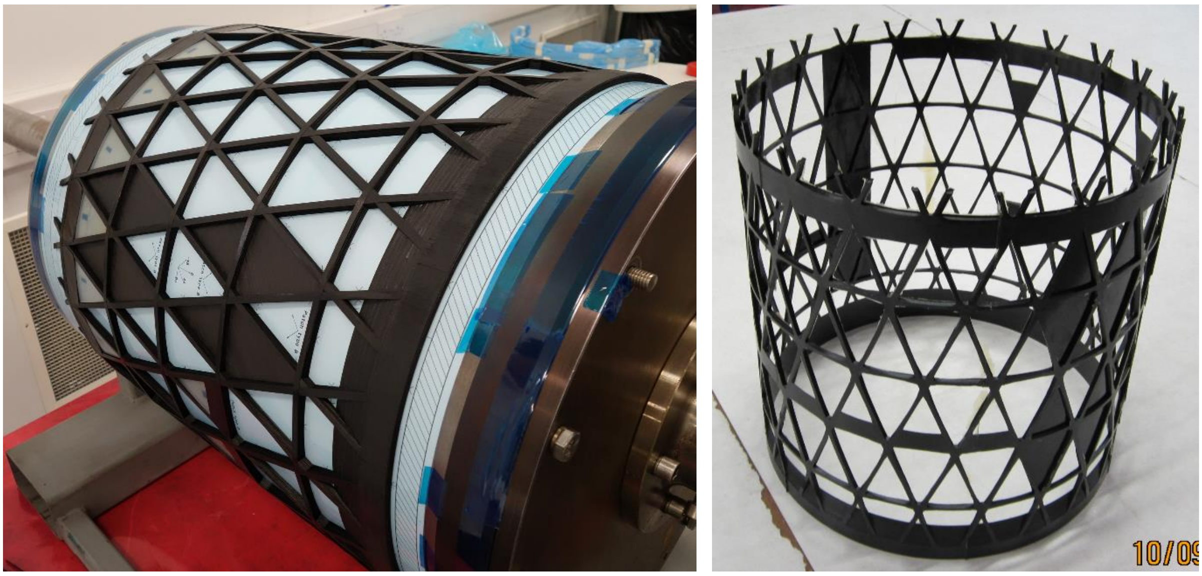

Figure 3: Left – Cylinder after layup, before tooling placement. Right – Cylinder as demoulded, before any trimming.

5. FULL-SCALE CYLINDER MANUFACTURING AND TESTING

Following the successful manufacturing of the small cylinder, the main cylindrical test article was manufactured and tested.

5.1 Design

In order to be able to use an already existing mandrel, the diameter of the cylinder was set at 1.5 m. A cylinder length of 0.8m ensures sufficient room for global strength and buckling behaviour to be present, while maintaining an easily manufactured size. Such cylinder lengths are also not unusual for science satellites. The grid cell and rib dimensions are the same as they were for the flat panel and the small cylinders, allowing the re-use of flexible tooling, and maximising the representativeness of the previous tests. The cylinder incorporates end laminates on both ends, a set of four patches to be used for local loading of the structure, and several other small patches for handling purposes. The cylinder is made using the same material as used for the previous cylinders and flat panel: Toray RS-36 prepreg with UD carbon fibre. The mass of the CFRP cylinder is less than 10 kg.

For mounting the cylinder in the test fixture, aluminium L-shaped fixtures are bonded to the end laminates, and subsequently also joined using close-fit shoulder bolts. Attachment points are provided in the 4 patches using bonded aluminium inserts. A load introduction bracket is then later bolted to these attachments for use during the test.

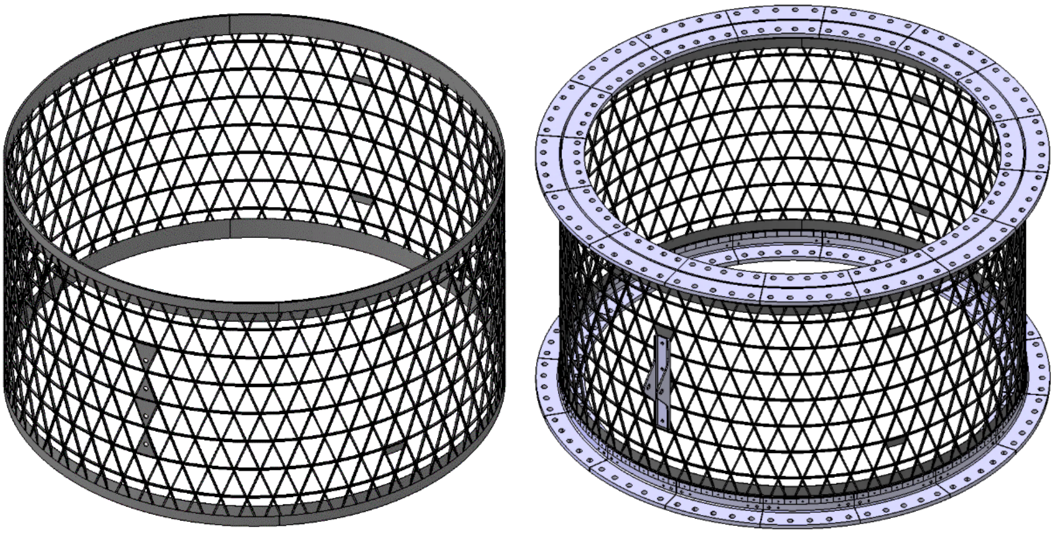

Figure 4: 1.5 m diameter test article design. Left – Composite part. Right – Assembled with metal fixtures.

5.2 Manufacturing

Manufacturing of the large cylinder used the same process as was used for the small cylinder, scaled up for the larger cylinder. A large part of the flexible tooling was re-used from the manufacturing of the other cylinders and panel, as can be seen in Figure 5. Figure 6 shows the cured composite cylinder, before drilling and assembly with the fixtures.

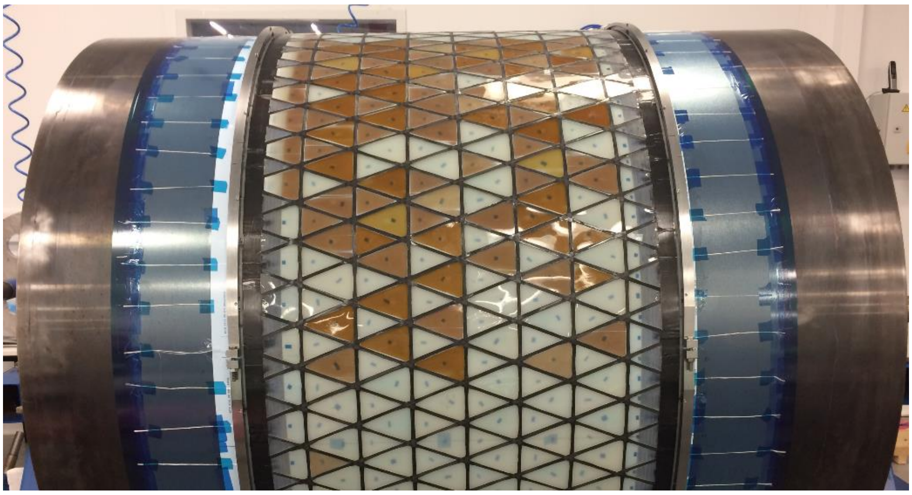

Figure 5: Large cylinder layup on the mandrel, before covering with caul plates. Re-used tooling clearly visible.

Figure 6: Large cylinder as manufactured, shown here with the small cylinder.

5.3 Testing

5.3.1 Setup

Testing was performed at National University of Ireland Galway, in conjunction with the Large Structures Research Group.

Two separate types of tests were performed on the cylinder. Local loading of the cylinder was applied using a small hydraulic cylinder connected to the load introduction bracket, applying an in-plane load at an offset from the cylinder. This test simulates loading through e.g. a shear web in a satellite. Global loading was performed using two large actuators, which introduce the load through a large I-beam and load diffusion structure into the cylinder. By controlling both actuators separately both pure compression and combined compression and bending could be introduced. The test setup is shown in Figure 7.

Figure 7: Test setup. Left - for local loading of the structure. Right – Overall setup.

5.3.2 Results

Following multiple low load level characterisation tests the design load cases were tested.

Local loading of the cylinder through the load introduction bracket was applied up to the design load level of 6650 N. No signs of failure were observed during or after this test. During the test the displacements in the lattice structure were captured using a Digital Image Correlation (DIC) system. The results showed a good correlation to the FE model results, as can be seen in Figure 8.

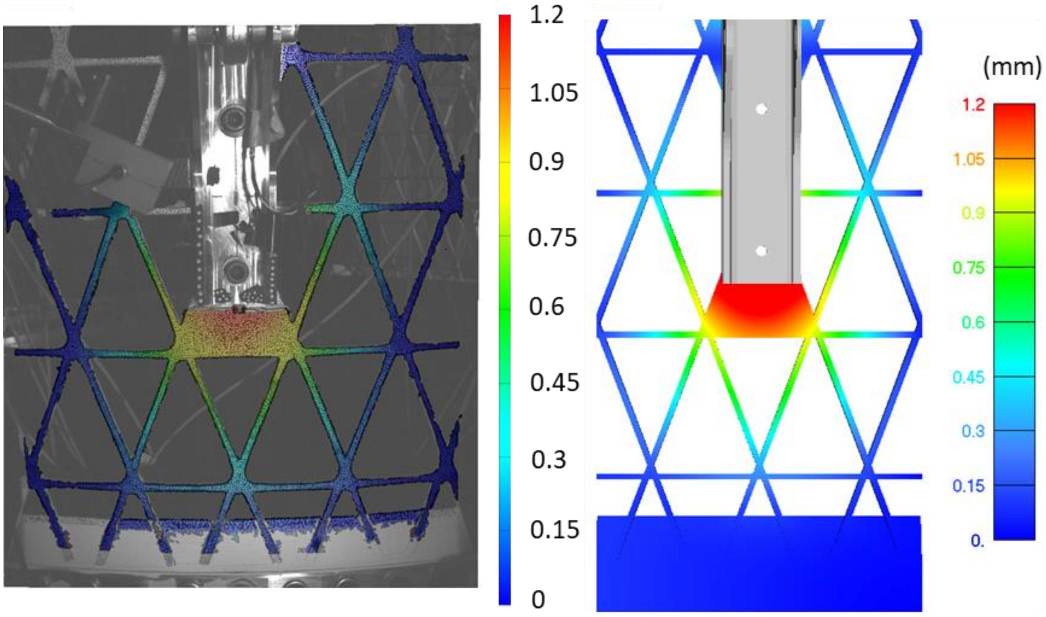

Figure 8: Displacements under side-loading. Left – Measured using DIC. Right – FE model.

The global compression load of 175 kN was then applied as pure compression load, and maintained for three minutes. No signs of failure were observed during or after this test.

Following the successful test of the design load cases, the cylinder was loaded to failure. This was done in combined compression and bending in order to be able to reach a high enough line load and to also direct failure towards one side of the cylinder. The cylinder failed at a line load of 184 kN/m, equivalent to an overall compression load of 870 kN, which is around 5 times the design load. At the failure load level, the FE model also indicated failure around the nodes where failure occurred in the test. Figure 9 shows a side-by-side comparison of the failure location and the FE model results. The successful test to failure and correlation of the FE models concluded the developments in the project.

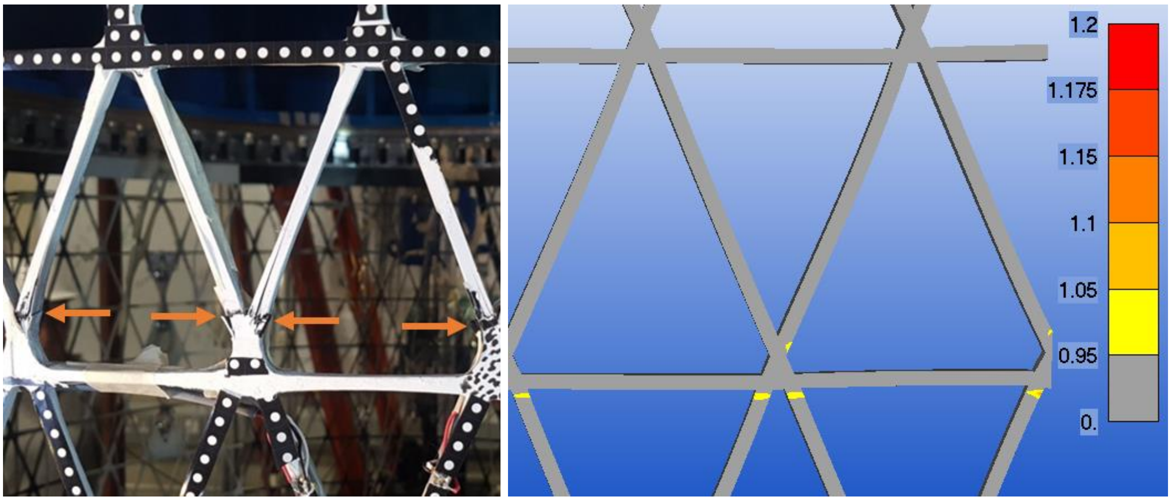

Figure 9: Left – Failure locations in the large cylinder. Right – Failure index in corresponding region of the FE model.

6. FUTURE DEVELOPMENTS

A follow-up ESA-funded CTP program aimed at advancing the lattice technology to TRL6 is currently in progress. This programme focuses on the interfaces between the cylinder and its surrounding structures, with specific emphasis on connections to a metallic end ring and different attachment types (brackets, tank struts, shear webs, etc.).

Furthermore, the automation of the layup process is a development which will offer many advantages. In collaboration with the University of Limerick, research on this topic is currently ongoing.

7. CONCLUSIONS

Through this successfully completed programme, the development of fibre-placed lattice structures have has been advanced significantly. A near full-scale cylinder was successfully manufactured and tested under satellite-representative loads, without failure. A subsequent test to failure showed significant margin on overall strength, and a good correlation to the established modelling method. The tests and developments performed cover what is typically required to reach TRL5.

Follow-up projects to advance the technology further to TRL6 are in progress. Development is on track to further the practical application of the technology in satellite structures.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

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