DEVELOPMENT OF A SATELLITE CENTRAL CYLINDER USING UNINTERRUPTED PRE-PREG FIBRE-PLACED LATTICE STRUCTURES

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KEYWORDS

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ABSTRACT

ATG Innovation Ltd. has developed an innovative and highly optimised process for manufacturing lattice grid structures with uninterrupted fibres in a true one-shot process. The lattice grid accommodates load introduction zones and attachment points in a seamless, one-piece structure. This offers structural, weight and cost advantages for Satellite Central Tubes (SCTs). SCTs have been identified as an area for improvement and optimisation under the ESA Cosmic Vision Plan. The lattice grid development programme described in this work is aimed at addressing this area. The development involved three separate campaigns: (1) material characterisation and element level tests to establish baseline values for analysis models; (2) manufacture of a small-scale cylinder to overcome manufacturing challenges; and (3) the knowledge gained from the first two campaigns was used to manufacture and test an SCT sized cylinder. The development campaign culminated in the successful test of the lattice cylinder under global and local loads.

1. INTRODUCTION

The recent growth in the space sector has led to an increased demand for lightweight structures which can be manufactured simply and without costly processes. Exotic technologies, like the use of advanced composite materials, offer attractive improvements in performance by reducing mass, thus leading to expanded mission capabilities. However, such advancements often come at the price of complex, time-consuming, and costly manufacturing processes, which negate some of the performance advantages.

One promising technology is that of the lattice grid, which uses a series of overlapping ribs to create a pattern of repeating cells. By altering the geometric characteristics of the lattice grid, it is possible to efficiently tailor the structure to accommodate mission-specific load conditions, while keeping material use (and thus cost and mass) at a minimum. In addition, using uninterrupted fibres for the entire length of the rib further improves the structural efficiency and reliability of the end product. These characteristics make the technology particularly attractive for the aerospace sector. However, manufacturing such an architecture is complex, and requires careful development to produce a reliable process that is also low cost.

ATG Innovation and ATG Europe have developed a highly optimised lattice architecture – an uninterrupted lattice grid with directly integrated interface zones – which can be manufactured in a true one-shot process [1-5]. The load introduction interface zones integrated into the grid are particularly suited for use on Satellite Central Tubes (SCTs), which must be capable of withstanding high local and global loads in a lightweight structure while maintaining global rigidity. Utilising the uninterrupted lattice grid architecture can therefore lead to mass savings over existing technologies, while the one-shot process can make the technology viable from a cost point of view. [1].

Previous developments for the lattice grid have focused on the manufacturing methods as well as interface joint concepts suitable for SCTs [1,2,5]. Earlier work identified the logical next steps of the development campaign: a building-block approach to design, manufacture and test a full-scale lattice cylinder [6]. Initial quality assurance and NDI process definition and execution were also identified. This paper describes the technical progress in meeting that development plan, which proceeded as follows. Firstly, flat test specimens (including coupon and element level) were designed and tested to provide strength and stiffness data for use in analysis models. Secondly, an intermediate scale, full complexity cylinder was designed and manufactured to identify challenges when transitioning to cylindrical geometries. Knowledge gained from these two activities were applied to the design and manufacture of a full-scale cylinder for static testing. The cylinder was representative of an SCT in size and global configuration, and was designed to withstand representative design loads.

To verify the manufacturing, analysis, and quality processes, the full-scale cylinder was tested under local and global loads. The global tests included several pure compression tests up to design limit loads, followed by a combined compression and bending to failure. The global tests are described in this work, while the local attachment tests are described in a related work [7]. The full-scale lattice cylinder weighed 9.82kg and withstood a design compression load of 170kN for 3 minutes, before being tested to failure at a 184kN/m compressive line load. The loads achieved during testing, along with a successful correlation campaign, verified the manufacturing and analysis methods developed, and demonstrated the viability of the technology for use in SCTs.

2. DEVELOPMENT PATH

The development path followed a traditional building block approach, involving coupon, element, and finally component level tests (see Table 1).

Further details behind the logic of the development path can be found in [6]. Each stage of the manufacturing and test campaign involved inspections and checks for quality assurance and ensure repeatability of the processes. Finite element analysis models were updated in parallel to breadboard testing to improve correlation and predictions. Each stage of the development process, including goals and outcomes, is described in further detail in the subsequent sections.

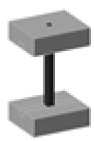
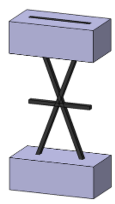
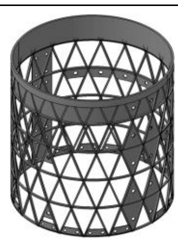
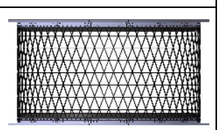
2.1. Grid geometry, materials, and manufacturing

The grid parameters (helical angle, cell spacing, and rib dimensions) are normally driven by loading requirements, and subsequently dictate the design of silicone expansion blocks and other tooling used during manufacture. Manufacturing silicone tooling is labour intensive, and therefore the decision was made to fix the grid geometry across all the manufactured specimens (flat and cylindrical). Consequently, the grid geometry parameters were set following preliminary analysis of the full-scale cylinder under static test conditions. The element tests and cylindrical demonstrator then used this grid geometry, allowing for the re-use of tooling and silicone blocks.

The material used was Toray's RS-36/M55J prepreg. The high-modulus M55J fibres were used because initial analyses and evaluations showed that the design of lattice primary satellite structures is typically stiffness-driven, and less influenced by strength. The RS-36 resin, a modified epoxy, was selected for its glass transition temperature and 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 was concluded that there is no specific reason for using cyanate ester resins in place of modified epoxies once the material outgassing properties are compliant with part requirements.

The manufacturing of all parts was performed at Éirecomposites in Galway, Ireland. Manual lay-ups using ATG Europe's patented lattice grid processes were used throughout this development. The manufacturing sequence involves manually laying up specimens and installing the lattice grid tooling ahead of bagging and autoclave curing using a modified cure cycle. The interface zone laminate and patches for local attachments were directly integrated during the lay-up process. Once removed from the autoclave, the cylindrical parts did not need further post-processing to achieve the final component shape. The flat panels were cut to create specimens for coupon and element tests, while the cylindrical specimens only required light cleaning of flash from the cure.

Table 1: Manufacturing and testing activities undertaken.

Activity	**Purpose**	**Specimen geometry**
Material characterisation tests.	Determine mechanical properties.	Standard characterisation tests.
Rib element tests.	Verify FE modelling and analysis methods, and knockdown factors for structural elements.	
Node element tests		
Small scale cylindrical structure manufacturing demonstrator	Uncover and solve challenges associated with cylindrical geometries	
Large cylinder	Static test of global and local loads	

2.2. Finite Element Analysis

Finite Element (FE) models were used to predict and subsequently correlate the stiffness and strength behaviour of the breadboard element tests as well as the static test of the full-scale cylinder.

The methods have been developed through previous development campaigns to capture the structural behaviour of the uninterrupted lattice grid. The models were created and analysed using FEMAP with NX Nastran, and used solid elements for the breadboard specimens, and both shell and solid elements for the full-scale cylinder (for global and detailed analysis).

2.3. Flat Panel Specimens

The purpose of the flat panel specimens was to provide strength and stiffness data for the material, as well as knock-down factors associated with the lattice grid manufacturing process. These values would later be applied to the performance predictions analysis of the large-scale cylinder for static tests (see section 2.6).

2.3.1.Material characterisation

Coupon level tests were conducted for material characterisation, which included uni-directional and quasi-isotropic coupons tested in compression, tension, flexural and shear configurations. Fibre volume and glass transition temperature assessments were also made. Mechanical properties obtained from these tests were used in FE models of the rib and node regions, along with heritage knock-down factors (deduced in previous campaigns). Correlation activities would then determine if these values accurately predicted lattice structure behaviours.

2.3.2. Elemental breadboard tests

Elemental tests were conducted on the lattice grid, with a focus on isolating the rib and the node. These elements were chosen due to the differences in the processes during lay-up and cure between these regions and regular monolithic laminates, for which data was obtained in the material characterisation tests. Preliminary analysis of a full-scale cylinder identified compression and flexural tests as being a priority, and so these test configurations were chosen.

The compression tests loaded a section of the lattice, with a single node, in pure compression. The test specimen geometry is shown in Figure 1, with the lattice section encapsulated in potting at the top and bottom. The potting was used for load introduction, and so the top and bottom surfaces were CNC machined flat and parallel to apply pure compression via a standard universal tester.

A total of 19 specimens were tested to failure, of which 6 specimens were thermal-vacuum cycled (+70°C to -40°C).

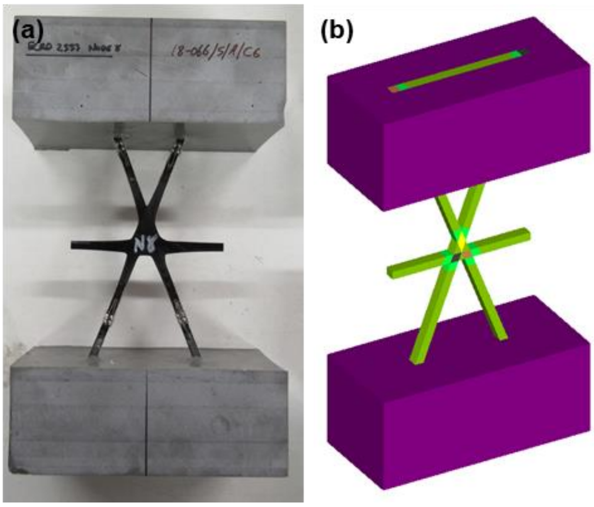


Figure 1: Elemental level node compression tests.

Overall, the results showed minimal differences between the as-formed node specimens and the thermally cycled specimens, with results giving an average failure initiation load of 15.49kN and 15.71kN respectively. FE analysis predicted local failure at a load of 14.8kN. The strains in the helical rib at this load are shown in Figure 2. This indicates that the knock-down factors applied provide a good (and in some cases a conservative) correlation with experimental measurements.

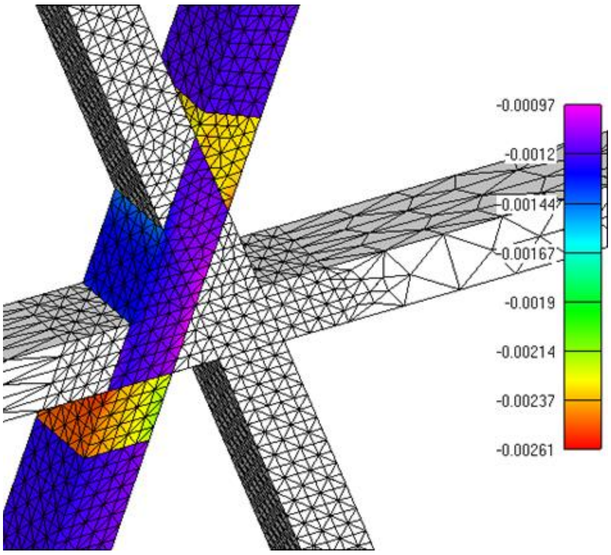


Figure 2: FE Strains along a helical rib at 14.8kN.

Flexural tests involved subjecting a lattice section to 4-point bending, resulting in a bending moment being introduced over the node region of the specimen (see Figure 3). A total of 6 specimens were tested to failure. Three of the specimens failed at the loading location, and not in the desired node region. Nonetheless, the failure loads for all specimens fell within a range of 1030N and 1160N, with an average of 1118N.

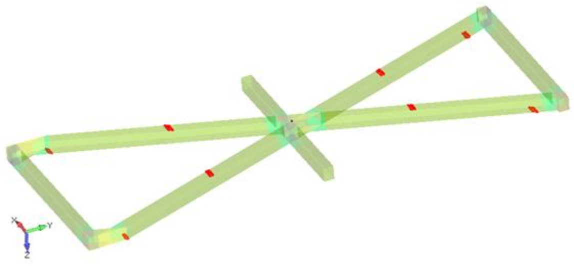


Figure 3: Flexural test specimen, showing 4-pt bend locations (in red).

The experimental failure results were significantly higher than those predicted. FE models predicted that the failure strain would be reached at 660N (as shown in Figure 4). This indicates that the knock down factors applied are overly conservative under this loading regime. Contributing to this conservatism is the final micro-structural configuration of the material near the node region, which is not entirely accounted for in models. Due to the conservative nature of the knock-down factor in this instance, along with the fact that good correlation was seen in the compressive cases, it was decided to maintain the knock down factors applied for the analysis of the full-scale cylinder.

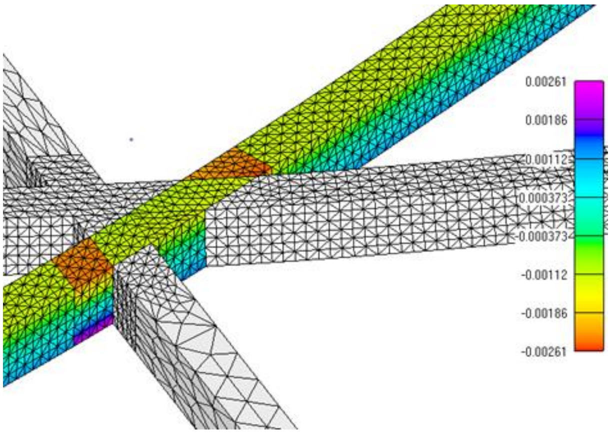


Figure 4: FE strains along a helical rib at 660N.

NDI checks were also performed on the flat specimens to assess the consolidation achieved using the lattice grid specific cure cycle used. These checks included A-scans and C-scans. Key areas of interest were also micro-sectioned to compare against NDI results. No issues with respect to quality were uncovered.

2.4. Small scale cylindrical demonstrator

With mechanical test data obtained, the next step focused on maintaining the quality observed in flat panels when transitioning to cylindrical sections. To do this, two identical small-scale cylinders were manufactured, with multiple load introduction configurations being incorporated. At the bottom, a blended monolithic laminate region was introduced to provide a potential interface and load path to adjacent structure. For local loads, various combinations of full- and partial-patches, on the inner- and outer-diameter of the cylinder, and of different thicknesses, were included. These configurations were chosen to accommodate an extensive range of potential interface load magnitudes and locations, as could be required for an SCT.

The first cylinder was manufactured using methods adapted from the flat panel manufacturing process. This cylinder, along with some key features, is shown in Figure 5. Following cure, it was found that the methods were largely suitable as is, with only a few areas of the tooling requiring modification to improve quality of the produced part. These modifications were incorporated into the manufacture of the second cylinder.

Figure 5: Small cylindrical lattice grid demonstrator, featuring multiple load introduction configurations.

NDI checks on the cylinders were limited to A-scan as the C-scan equipment available was not suitable for a cylindrical part. A thorough assessment was performed, which confirmed that the programme could progress to the building and testing a third, full-scale cylinder with no further modification to the manufacturing methods.

2.5. Full scale cylindrical demonstrator

2.5.1.Design

Successful completion of the second small-scale cylinder allowed for the final phase of the development work – the design, manufacture and test of a full-scale cylinder. The design of the cylinder was based on test load requirements, which specified a 175kN global compression load, as well as a 6.5kN local load applied at a small offset from the cylinder surface. This resulted in a cylinder with the following characteristics:

- Upper and lower laminate load introduction regions
- 4 full-cell patches for a local load attachment
- Cylinder diameter = 1.499 m
- Cylinder height = 0.8 m
- Cylinder mass = 9.8 kg

The designed cylinder can be seen in Figure 6. Segmented aluminium feet were added to the upper and lower circumferences to introduce loads into the cylinder during the global tests. The local load bracket was not attached for these tests.

2.5.2.Manufacture and inspection

The manufacturing was performed at Éirecomposites' premises in Galway, Ireland. The manufacturing procedure encompassed lessons learned from the flat panel and small cylinder manufacturing campaigns. Following cure, close inspection showed no issues during the cycle. The cylindricity tolerance of the full-scale cylinder was measured using a Faro arm and found to be 0.62mm over its length of 0.8m.

2.5.3.Finite element analysis for test predictions

A global model was prepared and analysed using the same general methods that were used for the breadboard campaign. The model used shell elements to model the ribs and the laminate region, with a section of solid elements being used to analyse the region where failure was expected in the ultimate test. As is common practice with the analysis of SCTs, an RBE2 element connecting the lower circumference of the cylinder to a central node was created, with the central node constrained in all degrees of freedom. Similarly, a top node and RBE was used to apply loads (consistent with the load introduction in the static test). The finite element model configuration is shown in Figure 7.

2.6. Static tests of full-scale cylindrical demonstrator

2.6.1.Overview

The global tests involved compression tests to reach the design limit load, followed by a combined compression and bending test to failure. The test sequence is given below:

- 3 tests to 40% Design Load of 175kN
- 3 tests to 50% Design Load
- 1 test to 70% Design Load (pre shear web test characterisation)
- *Shear web tests completed*
- 1 test to 70% Design Load (post shear web test characterisation)
- 1 test to 85% Design Load
- 1 test to 100% Design Load (including 3 minute dwell time)
- 1 test to 100% Design Load
- 1 test to failure (combined compression and bending).

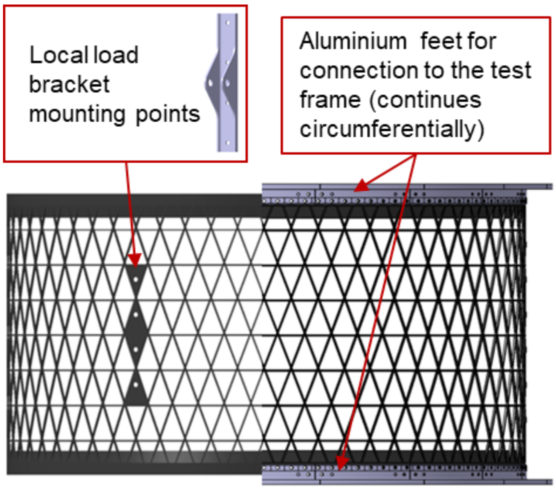


Figure 6: Design of the large-scale cylinder for static tests

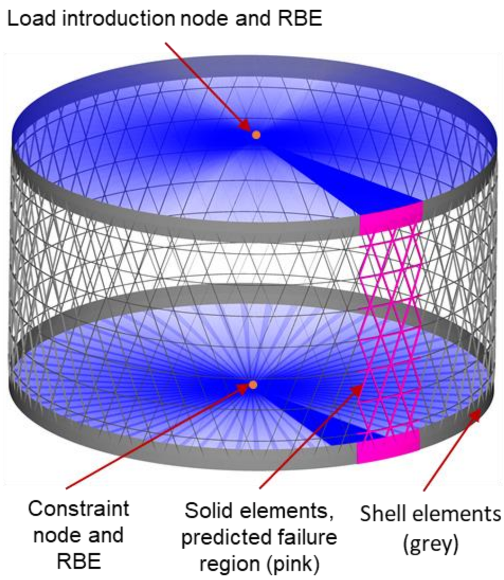


Figure 7: FE model of the large-scale cylinder used for the analysis of the static test.

Note that the local load test (shear web test) is described in a related work [7], and so is not explored further here.

2.6.2. Test set-up and instrumentation

The testing took place in the heavy structures laboratory in the National University of Ireland, Galway. The laboratory contains a 10m x 6m reinforced floor suitable for large scale static tests. The test design is as per Figure 8, with the test article sitting in between two load diffusion structures. The upper load diffusion structure was attached to two large steel I-Beam sections, which were used to introduce loads from two Zwick calibrated hydraulic actuators placed at either end of the beams. This configuration allowed for global compression and bending loads to be introduced as required. The cylinder installed in the test frame is shown in Figure 8.

The cylinder was heavily instrumented, with 90 strain gauges being used to monitor the strains at ribs and patch regions, both on the inner- and outer-diameters. The gauge locations were chosen to monitor global behaviour, as well as the local load-introduction region and expected failure region. In addition, 13 LVDTs were positioned around the test article and the test frame, while a GOM ARAMIS Digital Image Correlation (DIC) system was used for non-contact, full-field, 3D deformation measurement of the test cylinder. The DIC measurement area can be seen as the white painted portion of the cylinder in Figure 9.

2.6.3. Test execution and results

The initial compression tests (up to 70% design load) were performed to remove slacks in the test structure by comparing loading and unloading force-displacement curves. In addition, these tests provided early stiffness data to verify that the test article was behaving as expected.

Following succesful completion of the local load tests, the 70% design load test case was repeated. The loading and unloading curves were compared to the previous 70% test case, and were found to be indentical, indicating that no damage had occurred during the local test. This cleared the way for progressing the test to 100% design load including a hold for 3 minutes. The load graph for this test is given in Figure 10, and shows that the load was succesfully maintained during the 3 minute dwell.

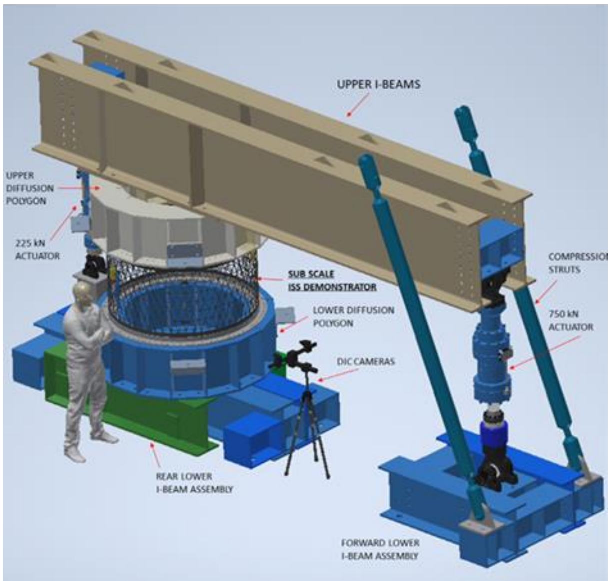


Figure 8: Static test frame used for global tests

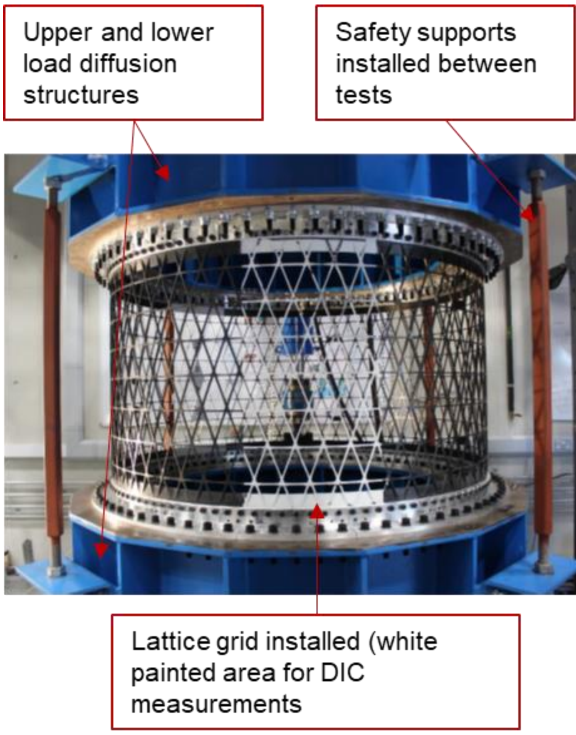


Figure 9: Test article installed in the test frame.

Examining actuator displacement data indicates that no appreciable change in displacement was applied during this period, indicating that no damage occurred. Likewise, comparing the loading and unloading stiffnesses showed no sign of

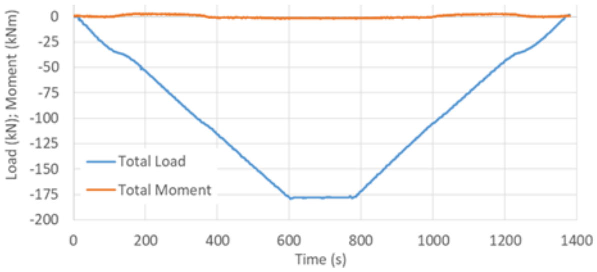


Figure 10: Applied load and moment during the 100% design limit load test

damage. This data indicated that the objective of withstanding the design limit load for 3 minutes with no damage was met.

Experimental measurements during the 100% test case were compared against FE predictions. Figure 11 shows strain gauge measurements for relevant strain gauges. It can be seen that the majority of readings lie within the +-20% band when compared to predictions. This was encouraging, but the band range was wider than expected. Investigating further, a number of the outliers related to low-level strain gauge readings below 150 microstrain, which are susceptible to wide percentage deviations. In addition, careful analysis indicated that the test frame alignment was not optimal, leading to some undesired load conditions being introduced which altered the strain distributions.

A comparison of the predicted and measured displacements was also performed. Some compliance from the test frame fixtures was noted in both LVDT and DIC measurements, which were not accounted for in FE models. An example of this can be seen in the DIC measured displacements shown in Figure 12, where the bottom edge of the cylinder shows higher displacements when compared against FE predictions. These are a result of compliance in the lower feet connecting the cylinder to the test frame, which is not captured in FE models. It must be noted as well that the nature of the lattice grid, with thin ribs and open cell spaces, makes obtaining clean strain or displacement data challenging. Therefore, the measured DIC values are indicative only. Nonetheless, the displacements behaved as expected once the test frame compliance was accounted for.

The final test conducted was a test to failure to verify strength predictions of finite element models, which incorporated lessons learnt from element level testing. The strength of the cylinder was such that the loads required to break it in pure compression were excessive. Therefore, a combination of compression and bending moment were applied to increase the line-load in a section of the cylinder until failure was reached. This was achieved by adding an unbalanced load through the two actuators. The cylinder failed at a peak compressive line load of 184kN/m. Achieving this in pure compression would result in an approximate failure load of 870kN.

Upon examination, multiple nodes and ribs were found to have failed. This was most likely due to rapid load re-distribution following the failure of a single element, resulting in a number of areas failing in rapid succession. The failure region was correctly predicted in FE analysis; however, the exact failure locations were offset slightly from those predicted due to unaccounted influences of the test frame altering the load distribution.

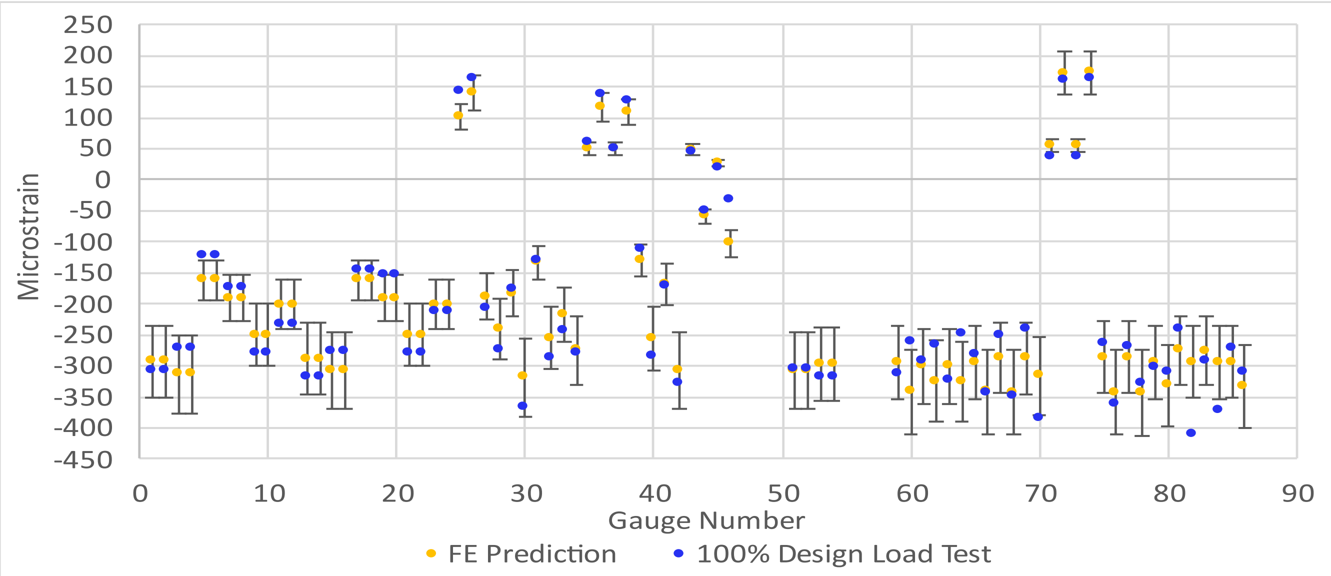


Figure 11: Strain gauge measurements during 100% Design Load Test (±20% error bands on FE Predicted values). Note: X axis refers to strain gauge identifier only, and not the position around the cylinder

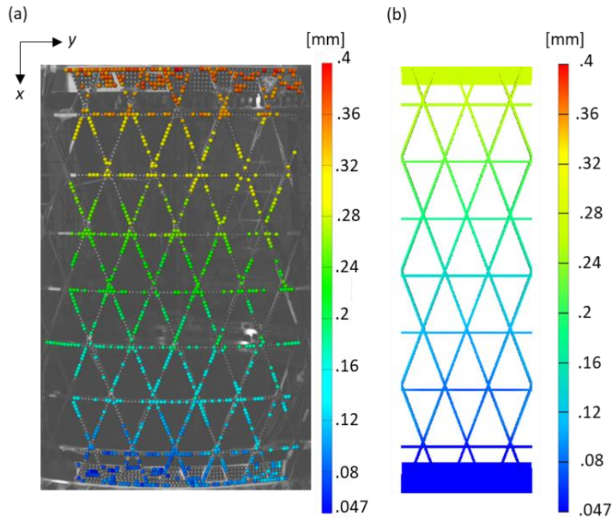


Figure 12: Contour plots of displacement for a section of the cylinder in the 100% Design Load case: (a) measured from DIC; (b) predicted by FE. Note: Positive x values denote axial compression.

2.7. Conclusions and follow-on development.

The development campaign has successfully advanced the lattice grid technology for SCTs. The development followed an incremental building-block approach, combining manufacturing, testing and analysis to verify the suitability of the manufacturing and analysis methods. Knock-down factors which were applied for analysis of flat breadboard specimens, showed good correlation for compression tests, and conservatism during flexural tests. This was determined to be due to the microstructure of the material at the node regions, and so were maintained as-is for use in design and analysis. Increasing the manufacturing complexity of lattice grids from flat specimens to cylindrical components showed minimal changes to the process being required to maintain quality. The know-how gained in manufacturing and analysis methods was verified through the successful design, manufacture, and static testing of a full-scale cylinder. Compression tests to design limit loads showed good correlation against FE predicted strain gauge readings (with 69 of 78 strain gauges lying with +-20% of predictions), and deformations. The cylinder was subsequently tested to failure, which occurred at a local line load of 184kN/m. Finite element models predicted local failure index of values of 0.95 and higher in the failure region, at that load.

With the confidence in the global behaviour of the cylinder, future development work will focus on further development and characterisation of the local load interface zones. Multiple interface zone configurations will be tested using the same building block approach employed in this project to verify and modify (as needed) analysis methods. Interface specimens will be tested to failure under SCT representative in-plane, out-of-plane, and bending loads. Conclusion of that development will demonstrate the viability of using lattice grid technology to meet all the requirements of SCTs in a lightweight and cost-effective package.

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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. (2019). An efficient semi-automated optimisation approach for (grid-stiffened) composite structures: Application to Ariane 6 Interstage. *Composite Structures*. 209,1042-1049.
5. Pavlov, L., Te Kloeze, I., Smeets, B.J.R., Simonian, S.M. (2017). WO2017099585A1: Composite Grid Structure Patent.

6. Smeets, B., Papenhuijzen, T., Pavlov, L., Koot, M. (2018). Development logic and building block approach for pre-preg lattice satellite central cylinder applications. *ECSSMET 2018*, Noordwijk, Netherlands.
7. Telford, R., Murray, B.R., Smeets, B.J.R., Matthews, K., Fagan, E.M., Flanagan, M. (2021). Testing local attachments of cylindrical lattice spacecraft structures. *ECSSMET 2021,* Bremen, Germany.