From sea sponge to space: Compressive characterisation of a novel lattice structure for aerospace application

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Abstract
Composite shell structures have increasingly been applied within the space sector due to the high material specific strength and stiffness, however their high cost and susceptibility to imperfections increases the cost of spacecraft components. Meanwhile, nature has many examples of lattice structures achieving high compression performance with efficient use of material. The use of a bio-inspired lattice structure was applied within a rocket payload fairing adapter to investigate the performance of natural lattice structures with high performance engineering materials. Non-linear finite element analysis was combined with mechanical testing to test the performance of a sea-sponge lattice against a conventional lattice shell. This was analysed to investigate material and mass savings possible.

Introduction
Glass sea sponge lattice structures have emerged as a bio-inspired solution for enhancing compression structures in various engineering applications [1]. Drawing inspiration from the complex skeletal systems of the Euplectella aspergillum, this project has optimised this structure to design novel lattice configurations for aerospace applications (Fig.1). This bio-inspired lattice structure mimics the unique architecture of glass sponges [6,7,8], incorporating vertically, horizontally, and diagonally oriented struts (Fig.1.b,c,d), to achieve superior strength and flexural resistance, while optimising strength-to-weight ratio, making the structures lightweight yet robust [2]. These lattice structures exhibit anisotropic compression behaviour, allowing them to withstand loads in different directions; enhancing their versatility and performance in applications that require high strength and durability under compressive loads. Through topological optimisation, novel lattice designs are created to enhance mechanical properties and anisotropic compression behaviour, showcasing their potential for high-performance applications requiring superior strength and structural efficiency [3].

Design and modelling
The modelled structure was a payload coupling fairing for use in a sub scale rocket, with the design objective to minimise mass and required composite material. The two-driving load-cases were axial compression and transverse shear, with the bio-inspired lattice requiring modification to take greater shear load. This led to the design of a thin shell baseline truncated cone using a biaxial laminate structure, which was compared to the bio-inspired lattice design comprised of thin tapes and pultruded rods emulating the sea-sponge lattice (Fig.1). As both truncated cones had skins significantly smaller than the radius, elastic stability was the driving form of failure. To investigate this, finite element analysis (FEA) combining linear eigenvalue analysis with non-linear Riks arc length analysis was conducted to investigate negative eigen-values (Fig 2.b). NASA standard knockdown factors derived through empirical imperfection and buckling analysis were applied for the shell cone [4]. No knockdown factors were applied to the lattice structure due to the highly discretised nature of the lattice acting as an initial imperfection [5]. This assumption would be analysed through post-manufacture laser scans of the structure being inputted back into the analysis to capture the full extent of manufacturing features in the structure. These would be subsequently compared against experimental compression tests to further compare the extent of validity of both initial and post-manufactured FEA models.

Experimental testing
To verify the computational models, both thin shell baseline truncated cone and lattice cone structures were manufactured using low temperature out-of-autoclave carbon fibre prepreg and over-braided pultruded rods. To apply realistic boundary conditions, the rotational degrees of freedom at top of the cone are left unconstrained. Compressive loads will be applied with full field strain analysis and deformations captured through stereoscopic digital image correlation (stereo-DIC) (Fig.2a). Strain gauges were also applied to verify DIC measurements in the

most critical regions of the lattice cone. As from the FEA, elastic stability will be a driving failure mode, and it is expected defects within manufacturing will cause premature failure. These were captured through three-dimensional laser scanning before reapplication into FEA models. The performance of the realistic geometry will be compared against the compression testing results and applied further transverse shear loading. This comparison of real and perfect structures will also provide evidence for post manufacture non-destructive testing to provide certification and validation for composite lattice structures. Repetition of experiments with improved manufacturing methods and materials will be carried out to provide greater certainty regarding the effect of defects on the lattice structure. This, combined with transverse shear testing of the truncate cone, provide robust analysis and design parameters for composite lattice structures for spacecraft applications.

Figures

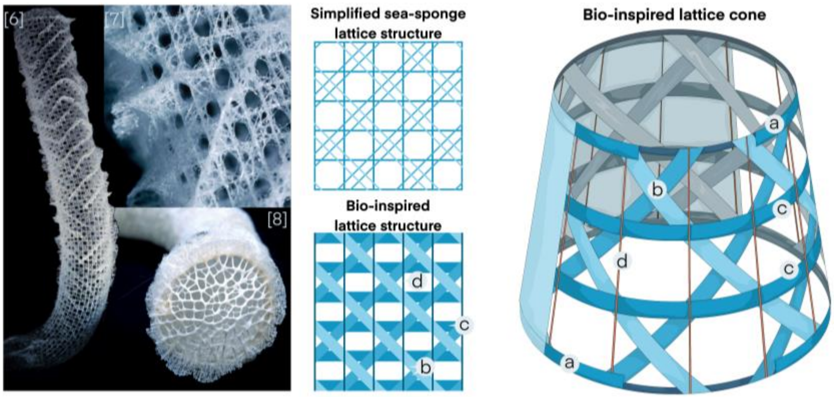

Figure 1. Euplectella aspergillum, simplified lattice and bio-inspired lattice. Images: [6, 7, 8]. a. Top and bottom horizontal 12 mm-width unidirectional (UD) tape. b. Diagonal 12 mm-width UD tape lattice structure. c. Horizontal 12 mm-width UD tape. d. Carbon fibre over-braided pultruded rods. e. Top and bottom horizontal 12 mm-width UD tape (2nd layer).

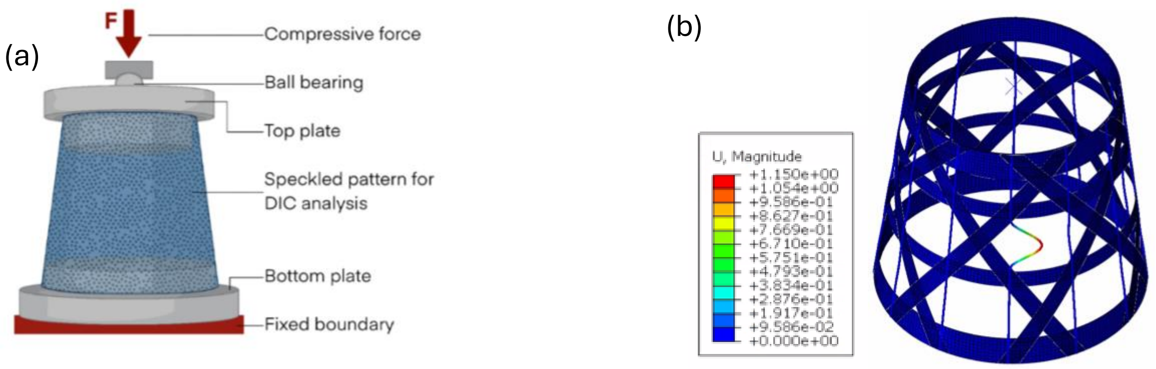

Figure 2. a. Figure 2. a. Experimental DIC compression test, b. FEA and buckling/stability graph

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