CRUSHING BEHAVIOUR OF CARBON FIBRE LATTICE STRUCTURES

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Keywords: Carbon fibers, Lattice cores, Sandwich structures, Mechanical properties, Resin infusion

ABSTRACT

Composite lattice truss core sandwich structures have been focus of investigation in recent years. In this paper, a recently-developed manufacturing method is presented to manufacture carbon fibre reinforced composites (CFRC) lattice truss sandwich panels using a combination of lost mould method and vacuum assisted resin infusion process (VARTM) technology in one manufacturing operation ensuring core and facesheets are connected integrally. Here, a fiber stitching operation was performed through a series of holes drilled into a salt slab (lost mould) ensuring that there are no fibre discontinuities in entire lattice structure. The dry fibre assembly was subjected to VARTM process to infuse resin into the vacuum system and allowed to cure. Following this method, columnar and pyramidal based topologically modified lattices were manufactured with different fiber volume fractions and relative densities. Quasi-static compression tests were conducted on the composite lattice specimens and their strength and failure modes were observed. The tests results showed that the columnar lattices offer specific strengths in the range of 41.5 – 109 MPa for a fixed fiber volume fraction of 0.14. The values were higher when fiber volume fraction in the columnar lattice members was increased to 0.37, there being in range of that 89.7 – 132.1 MPa. However, pyramidal lattices have shown that at a fiber volume fraction of 0.44, the structures exhibit comparable specific strength properties to those of the columnar lattices. The failure modes in the columnar lattices were buckling of the rods, crushing and fracture. Similar failure modes were observed in the pyramidal lattices, although the failure mode transitioned from buckling to splitting and fracture as the relative densities was increased. This manufacturing method offers significant potential for fabricating more complex lattice truss cores, providing the fiber are aligned in the direction of the trusses to give efficient strength capability.

1 INTRODUCTION

The use of sandwich structures has grown phenomenally in engineering applications in recent years provided by their efficient properties to weight ratio. Sandwich structures consist of two facesheets separated by a lightweight core, where the core plays a crucial part in the overall performance of the sandwich structure. Cores in sandwich structures range from stochastic foams, honeycomb, eggbox, corrugated to lattice truss cores. Lattice truss structures have a high nodal connectivity that deform by the stretching of the constituent cell members. They have been shown to exhibit superior mechanical properties to closed cell foams made from same material with a similar density and thereby, initial attention was given to metallic lattice core structures.

Recently, composite cellular structures with lattice truss topologies have been shown as a promising alternative to metallic materials. Therefore, lattice materials present a promise for filling gaps in the material property chart. Many fabrication approaches have been developed to produce composite lattice core sandwich structures. For example, Finnegan produced composite pyramidal lattice core by a water-jet cutting process and a snap fitting method [1]. Thereafter, many technologies have emerged to manufacture composites lattice cores with different topologies for sandwich structures, such as hot press molding method [2,3], thermal expansion molding method [4,5], intertwining [6], interlocked method [7], electrical discharge machining [8] and stitching technology [9-11]. Although all these manufacturing methods for composites lattice cores are innovative, they generally involve complicated tooling approaches and high production costs.

In the present study, a recently-developed method to fabricate composite lattice core sandwich panels is presented. The lattice truss cores and the face sheets (or skins) are manufactured in one process without secondary bonding. Inevitably, this will avoid the weak interface between the core and skins. This approach uses a lost mould concept to fabricate the lattice core sandwich structures. The lost mould replicates the shape of the lattice truss in which the continuous carbon fiber tow incorporated in this core construction. This method efficiently uses the material whereby fibers are aligned along the truss direction and thus the design fully exploits the intrinsic strength of fiber reinforced composites. This process results in a stitched structure that is impregnated with a thermosetting resin using the vacuum assisted resin infusion process. The research explores the use of this technique to manufacture composite lattices and the resultant structures undergoes compression tests.

2 SANDWICH PANEL FABRICATION

Here, the sandwich structure is fabricated in one manufacturing process without a secondary bonding. The one manufacturing process eliminates the weak interface between the core and facesheets, a common problem with sandwich structures. This technique, is based on stitching fibers into a salt slab that acts as a lost mould and through the dry fabric (facesheets) placed on the top and bottom of the salt slab. Through repeated regular stitching of the fiber from one side to the other through the thickness of the salt slab, a truss-like cellular core is produced. The salt slab which was machined to the desired core height containing the features of the truss core construction by means of drilling holes into it. In this work, the salt slab was machined with dimension of 300 x 200 x 37 mm in the length, width and thickness directions, respectively.

The sandwich face sheets were made from 8 layers of woven fabric preform (2/2 Twill 3k fabric). The top and bottom face sheets of the sandwich panels were interconnected with dry carbon fiber tow (12k filaments) to form a dry assembly of the sandwich panel. The detailed fabrication process for composite lattice core sandwich structures using this method is described as follows. Firstly, the holes were drilled into the salt slab according to desired lattice truss core configuration. The size of drilled holes was 2, 3, and 4 mm. Then, four layers of woven fabric were overlaid to form the facesheets on the top and bottom surfaces of the salt slab and were kept in place using masking tape.

Prior to fiber stitching, the filaments in the carbon fiber tow were held in place by dipping one end of the dry fiber tow in distilled water, and then pulled through a small hole in a rubber membrane to squeeze out the excess water [10]. By doing this, fiber damage during sewing as the tow contacts the surfaces of the holes was minimized and eventually reduces the lint formation on the surface of the tow. Following this, the end of the wetted fiber was tied to a thread and fixed to the end of a needle for stitching. A continuous carbon fiber tow was manually stitched from one side to another side of the salt slab in the through thickness direction. The process was repeated until the truss configuration was complete. Interestingly, the same fiber tow was used to stitch all of the holes in a unit cell lattice truss, thereby ensuring that there were no fiber discontinuities in the entire structure. After stitching, the assembly was heated up to 60°C for 1 hour in an oven to remove any moisture. Then, the stitched dry assembly was covered with an additional four woven fabric layers. Finally, the sample was resin infused by VARTM and cured at room temperature under vacuum pressure for 24 hours.

It is also worth noting that a constant fiber volume fraction was ensured by altering the number of fiber tows during stitching to produce three distinct sizes of composite struts. The carbon fibre tow had a designation of 12k, consisting of 12,000 filaments. The volume fraction of fibers was estimated from the cross-sectional area of the filaments in the tow and the cross-sectional area of the struts as follows;

$$V_f = \frac{1200 \quad {}_f^{\,2}}{d^2} \tag{1}$$

where d_f and d denote the filament diameter and the diameter of the struts.

2.1 Core design

In the present work, we present a simple core topology that consists of a vertical truss (columnar) core lattice sandwich structure. A unit cell of the columnar truss core is based on four by four vertical members and a representative unit cell is sketched in Figure 1 (a). The height, t = 39mm, width, w = 60 mm, and length, b = 60, including strut diameter, d of 2mm, 3mm and 4mm. The centreline distance between struts is 15 mm. The relative density of the lattice core depends on the geometrical properties of the struts and the unit cell of the structures. Thus, the relative density, $\tilde{\rho}$, of the core structures is determined by 1) the volume occupied by the strut members in a unit cell of the core divided by the unit cell volume and/or 2) the ratio of core density (ρ_c) to that of the solid parent material (ρ_s) from which it is manufactured. The relative density, $\tilde{\rho}$, of the columnar truss core is given by:

$$\tilde{\rho} = \frac{\rho_c}{\rho_s} = \frac{4\pi d^2}{bw} \tag{2}$$

Following this, a pyramidal lattice truss core was designed and manufactured using the lost-mold fabrication method. The unit cell of a pyramidal truss core is shown in Figure 2 (b) and it can be shown that the relative density of the core is given by:

$$\bar{\rho} = \frac{\pi d^2}{\sin\omega\left(\sqrt{2}l\cos\omega + 2b\cos\omega\right)^2} \tag{3}$$

where, the symbols l = *52.3 mm* and $\omega = 45°$ denote the strut length and the inclined angle of the truss, respectively. The pyramidal core height is 37 mm and inclined strut centre distance, b is 10 mm.

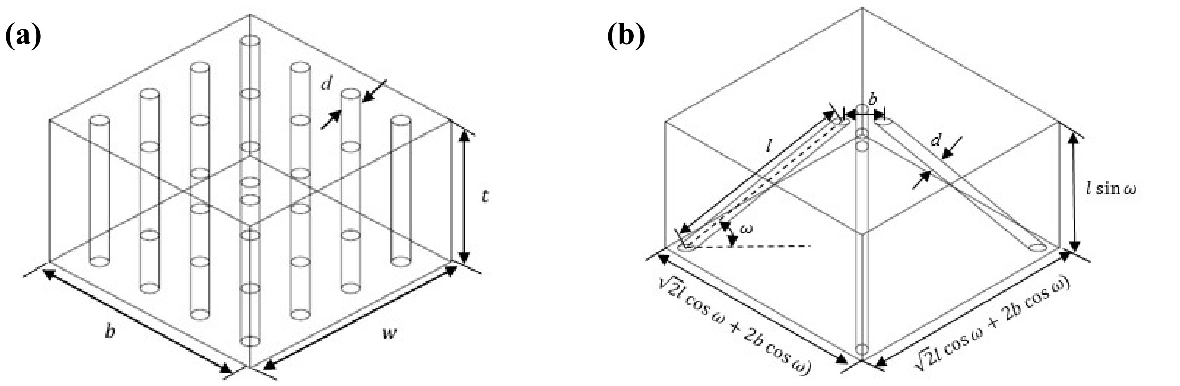

Figure 1: Schematic of the unit cell lattice truss core sandwich structures. (a) columnar and (b) pyramidal

The work was further extended to design more complex lattices based on pyramidal topology by including more struts into the open pyramidal core structure. This resulted in the design of a modified pyramidal truss core lattices, referred to as of type-1, -2 and -3. A type-1 (T-1) core structures have a central vertical strut through the apex of the pyramidal core. A type-2 (T-2) core structure were designed to include another four inclined struts in a pyramidal topology reflecting from the base of the unit cell, and, type-3 (T-3) contained an additional vertical column through the apex of the type-2 core design. These three types of core design were explored to fully investigate the feasibility of the lost mould (LM) method. Figure 2 shows the specimens that were manufactured using the method described above.

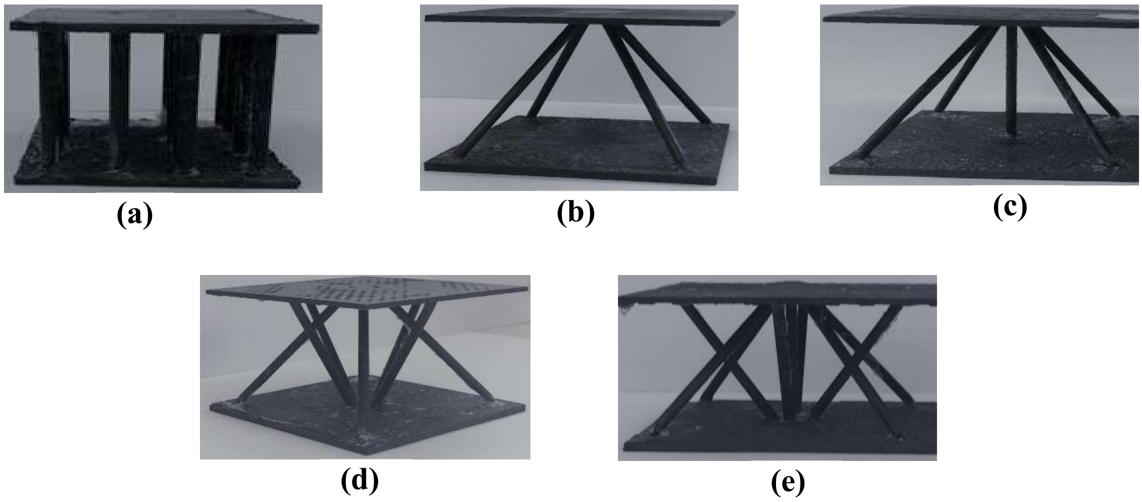

Figure 2: The images of the unit cell of lattice truss sandwich specimens. (a) columnar, (b) pyramidal (c) modified pyramidal -Type 1, (d) Type-2, and (e) Type-3

3 EXPERIMENTAL PROCEDURE

The primary aim of this research study was to investigate the crushing response of lattices manufactured by a lost-mould method. However, the mechanical properties of the composite lattice core sandwich structures depends on the mechanical properties of the parent material and the geometry of the lattice core. Prior to testing, a similar fabrication method was used to produce a range of single straight rods with varying diameter and fiber volume fraction to their corresponding lattice core sandwich structures to satisfy the boundary conditions of the rods. Initially, the columnar sandwich structures were simply produced with rods having a lower fiber volume content of approximately 14% and increased to 37% in order to study the influence of volume fraction on the properties of struts. Pyramidal lattice core rods were manufactured with a slightly higher fiber volume content, estimated to be close to 44 %.

The compressive tests on the columns were performed according to ASTM D695-15 on a universal testing machine at a constant displacement rate of 1 mm/min. Five samples were tested for each test condition to take account of the variability in the test measurements. The manufactured rods and a schematic diagram of test specimen are shown in Figure 3. The stress-strain responses for the various rod diameters (2mm, 3mm and 4mm) and varying fiber volume fractions (0.14, 0.28, 0.37, 0.44 and 0.59) were measured. Images of the specimen deformation were also taken using a digital camera during the tests to reveal the failure modes.

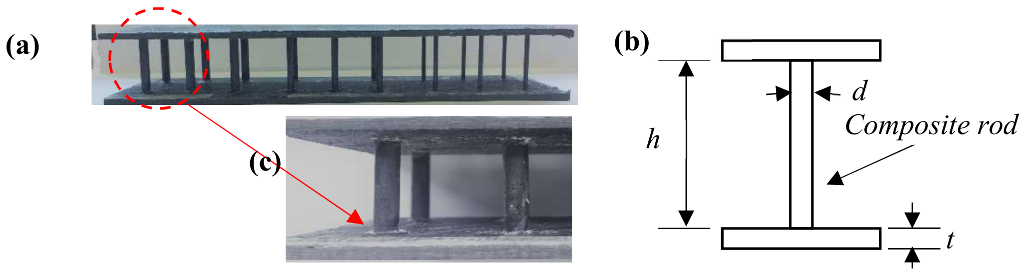

Figure 3: (a) Photograph of individual columns or rods and (b) the dimension of the specimen, the length h = 25 mm and facesheet thickness t = 2 mm., (c) Connection between the skin and core via fiber stitching.

To quantify the performance of the lattices, through-thickness compression tests on the composite lattice cores sandwich structures were performed at a displacement rate of 0.5 mm/min at room temperature between two steel compression platens. The columnar cores were constructed in arrays of four by four to form a unit cell and the square specimen was cut into dimensions of 60 x 60 mm with a core height of 39 mm. The pyramidal and modified-pyramidal (T-1) truss core sandwich structures were cut into 1x1 and 2x1 unit cells that were produced using 2mm, 3mm and 4mm diameter rods. The dimension of the specimens was 75 mm×75 mm in the width and length directions, with 37 mm core thickness. Finally, the unit cells of the more complex lattice core structures referred to as of type T-2 and T-3 were manufactured using 3mm rod diameters. A universal testing machine (INSTRON) was used for the compression tests, and tests were performed according to the ASTM C365 standard to determine the out-of-plane compressive strength and to investigate the failure mechanisms under this loading condition.

4 RESULTS AND DISCUSSION

4.1 Column compression tests

The compression performance of the rods was investigated for different slenderness ratios (*d/l*), defined as the ratio of the diameter to the rod length and were studied for various fiber volume fractions. The length of the rod was fixed at 25 mm. Tests shown that compressive responses are linear up to initial failure, where micro-buckling occurs and is followed by continuous cracking and splitting incurred in the region of initial failure until the rod fracture at one end of the column, where the stress drops abruptly. Figure 5 shows the variation of compressive strength with fiber volume content. It was noticeable that the compressive stress also increases rapidly as the fiber volume fraction in the composite rod increases. Figure 6 shows the failure modes for the rods with different diameters. The tests show that the failure mode of rods transitioned from buckling mode to fracture when the diameter of rod increased from 2mm to 4mm. However, failure modes were observed to be crushing with no sign of buckling mode when higher fiber volume fraction used.

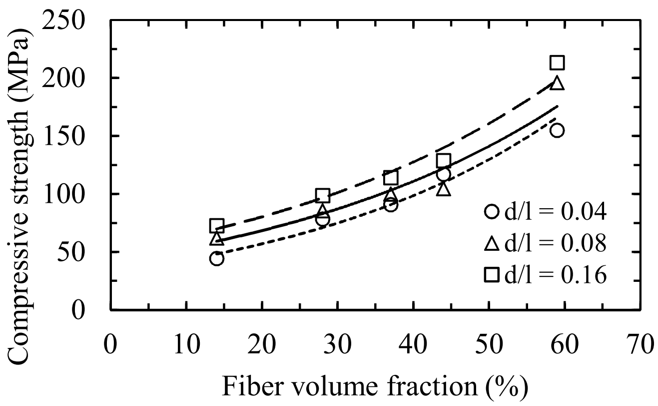

Figure 5: Compressive strength versus fiber volume fraction for the composite rods

Figure 6: Typical failure modes in the carbon fiber composite rods based on three different diameters

4.2 Compression behaviour of columnar lattice structures

The columnar lattice truss was fabricated in three different diameters, 2mm, 3mm and 4mm, resulting in relative densities of 2.3%, 4.9% and 8.4%, respectively. Figure 7 shows the representative compressive stress-strain responses of these structures based on two different fiber volume fractions. The stress is calculated by taking force divided by the planar area of the columnar truss rather than the diameter of the rods which resulted in lower stresses than the individual column tests. Following an initial linear response, the peak compressive stress occurs at the point where failure of the truss members occurred. Subsequently, the strength decreases as the crosshead displacement increases and there are fluctuations in the stress-strain curves associated with a series of failure events in the truss members. The failure modes changes as the the diameter of truss members increased.

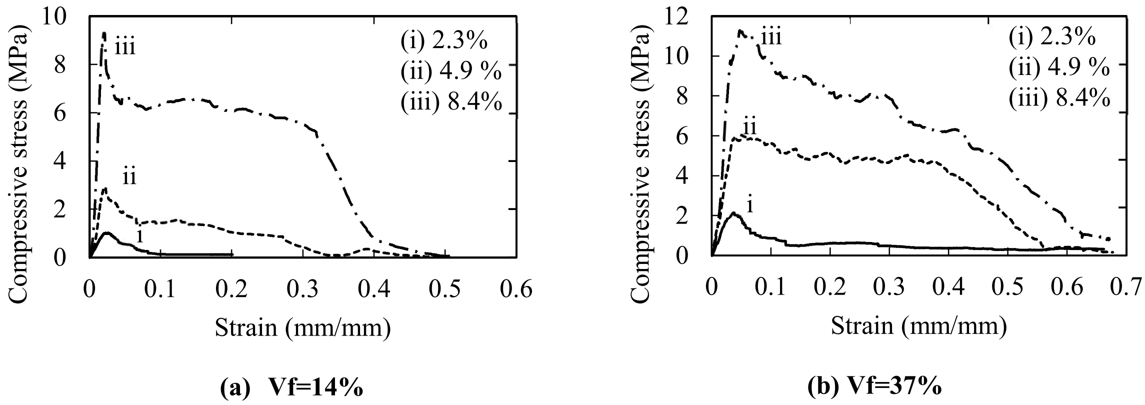

Figure 7: Stress versus strain of columnar lattices with two different fiber volume contents.

Columnar lattices with 2mm diameter rods tends to fail dominantly by buckling and following fracture in the middle rod members at a lower strain. Similar failure was observed in the 2mm diameter samples when the fiber volume fraction of the rod members was increased from 0.14 to 0.37. As the rod diameter increased to 3mm, the failure mode in the rod members with a lower fiber volume fraction failed by buckling and splitting closer to the joints. In contrast, at higher fiber volume fractions in the 3mm rod members, failure mode predominantly occurred by the crushing of the rod members at the joints from one end to another, although, some members were observed to fail by a splitting mode. The failure mode associated with the 4mm diameter rod members was crushing of rods at the joints and followed by fracture of the columns. The failure modes observed during the compression tests on columnar lattices are shown in Figure 8.

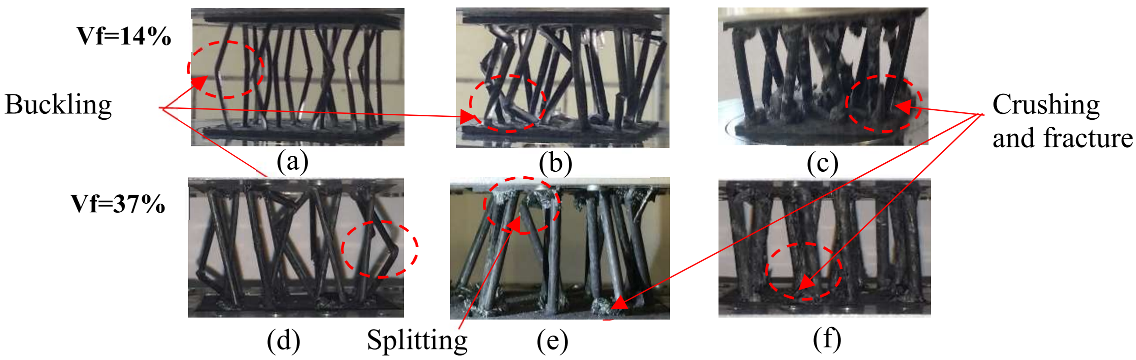

Figure 8: Photographs of columnar lattice structures with failure modes. (a) d = 2mm and vf = 14%, (b) d = 3mm and vf = 14%, (c) d = 4mm and vf = 14%, (d) d = 2mm and vf = 37%, (a) d = 3mm and vf = 15%, (a) d = 4mm and vf = 37%,

It is worth noting that for columnar lattices having slenderness ratios of 0.04 and 0.08, the peak compressive stress is almost doubled as the fiber volume content is increased. However, for the structures having larger slenderness ratio, the peak compressive stress is only increased by 20% although the fiber volume content increased by almost 150%. Figure 9 shows the specific compression properties, defined as the ratio of the compression properties with respect to the relative density of the columnar lattices. It is found that increasing the slenderness ratio increases the specific strength, however the increase depends on the transition in failure modes. For example, at a lower fiber volume fraction, the specific strength and modulus increased linearly as the failure mode changed from buckling to fracture. With increasing fiber volume fraction, there was steady increase in specific strength as the slenderness ratio increased from 0.04 to 0.08, however the specific modulus decreased when the failure changed from buckling to crushing of the rods. As the slenderness increased from 0.08 to 0.16, the specific strength and modulus increased slightly when a similar mode of failure (fracture) occurred in both.

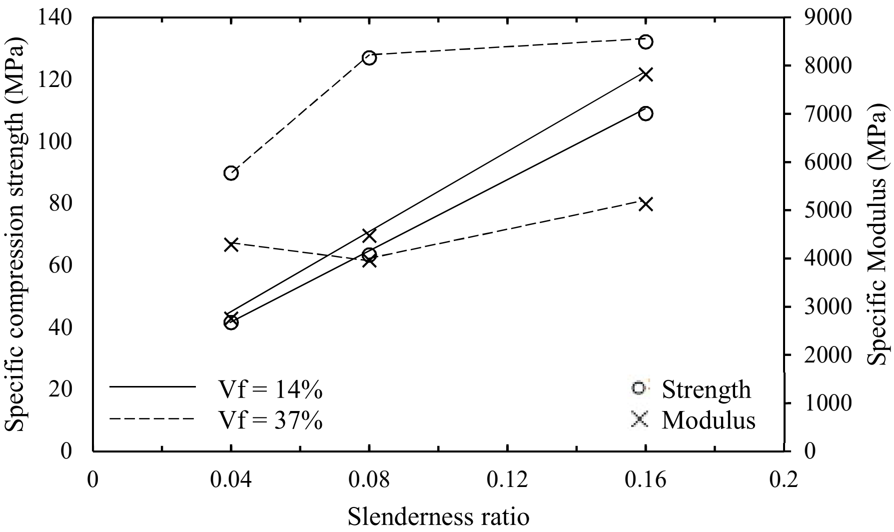

Figure 9: Specific compression properties as a function of slenderness ratio.

4.3 Compression behavior of pyramidal based lattice structures

Figure 10 shows compression stress-strain curves for the pyramidal and modified-pyramidal (T-1) truss cores for three relative densities at a fiber volume fraction of 0.44. The initial compressive responses are all linear before the maximum stress is reached and the elastic region measured at strain less than 0.015 mm/mm. Thereafter, the load dropped slightly and subsequent failure in truss members leads to stress dropping rapidly as the test continues. The peak strength for both structures increases with increasing relative density. The peak strength increased about 100% following the addition of a central column to the pyramidal lattice based on 2 mm rod diameter, however the increases is only 50% for the 3mm and 4mm rod diameters. Table 1 shows the variation of the strength properties with relative density for both types of pyramidal core lattice.

The compressive responses of samples based on two unit cells of these structures also exhibit similar behaviour, however with a slightly lower strength than expected. This may due to the misalignment of the rod members during the manufacturing process which may have led to failure of truss members and thus reduces the strength. It was found that the strength reduces by about 13%, 9% and 2% for the pyramidal structures and by 35%, 16% and 19% for the modified pyramidal (T-1) structures with increasing relative density.

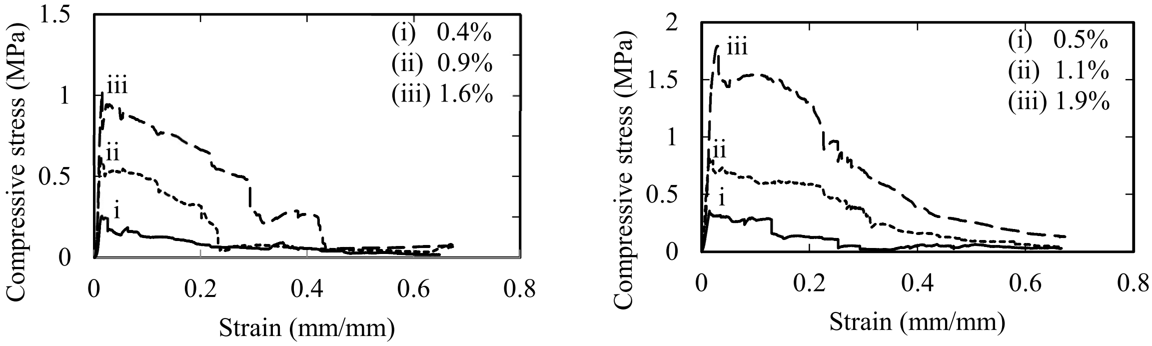

Figure 10: Compressive stress-strain responses of the pyramidal and modified-pyramidal (T-1) lattices at a different relative density.

Pyramidal			Modified Pyramidal - Type1		
Relative density (%)	Maximum strength (MPa)	Specific strength (MPa)	Relative density (%)	Maximum strength (MPa)	Specific strength (MPa)
0.4	0.21	52.5	0.5	0.44	93.62
0.9	0.60	65.93	1.1	0.91	85.05
1.6	1.07	66.46	1.9	1.69	89.42

Table 1. Summary of the strength properties of the pyramidal and modified pyramidal lattice based on a unit cell.

In the final part of this study, the investigation was extended to study the potential offered by the lost-mold technique for manufacturing more complex all-composite pyramidal based structures that are difficult to manufacture using other methods. Table 2 lists the experimental data obtained for 3 mm rod diameter where a unit cell of these structures was tested in compression. The more complex structures offer an increased strength compared to initial pyramidal based lattices.

Modified Pyramidal	Relative density (%)	Maximum strength (MPa)	Specific strength (MPa)
Type-2	1.68	1.15	68.5
Type 3	1.83	1.68	91.8

Table 2. Summary of the measured strength properties of the complex modified pyramidal lattice core sandwich structures.

5 CONCLUSIONS

A recently-developed method to manufacture CFRP composite lattices has been presented in this paper. In this method, the lattice core is integrally stitched to the facesheets with unidirectional carbon fiber tows and the panel is fabricated in a one manufacturing process using vacuum assisted resin infusion technology. Under static compression, the force-displacement responses were measured for the all carbon composite lattice truss core based on columnar and pyramidal configuration. The columnar lattices offered specific strengths in the range of 41.5 – 109 MPa when the fiber volume fraction is 0.15 and the values are higher (89.7 – 132.1 MPa) when fiber volume fraction in the columnar lattice members is increased to 0.37. However, pyramidal lattices have showen that at a fiber volume fraction of 0.44, the structures exhibit comparable specific strength properties to those of columnar lattices. The failure modes in the columnar lattices were buckling, crushing and rod fracture. Similar failure modes were observed in the pyramidal lattices whereas the failure mode transitioned from buckling to splitting and fracture as the relative density was increased. This manufacturing method has enormous potential in fabricating more complex lattice truss core provided the fibers are aligned in the direction of the trusses, thereby exploiting their intrinsic strength efficiently.

ACKNOWLEDGEMENTS

The author is grateful to the Malaysian Education Ministry and University Tun Hussein Onn Malaysia for offering research scholarship.

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