NOVEL LATTICE STRUCTURES BASED ON CONTINUOUS FIBERS: FABRICATION AND MECHANICAL PROPERTIES

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Abstract
Composite sandwich structures containing high-performance core materials based on composite lattice structures have been manufactured using a lost-mold technique. The structures were prepared by drilling holes at specific locations through a dissolvable mold block. Long carbon fiber strands were then inserted into each of the holes, ensuring that one continuous tow extended through all of the elements within a given core structure. Well-defined lattice structures based on what are termed BCC, BCCz, FCC and F_2BCC, Pyramid and Octet designs were produced. Following infusion with epoxy resin, using the VARTM manufacturing procedure, individual specimens were removed from the blocks in preparation for subsequent compression testing. The specific compression strengths were found superior to those of more traditional core materials. A number of failure mechanisms were also highlighted, including strut buckling, fracture at the strut-skin joints and debonding of reinforcing members at the central nodes. Finally, it is believed that the properties of these lattices can be further increased using higher fiber volume fractions.

1. Introduction

Currently, there is a strong interest in developing lightweight, high-performance structures for enhanced aerospace design. Traditionally, many lightweight aircraft components have been based on sandwich structures, consisting of composite skins bonded to honeycomb or foam cores. More recently, there has been a growing interest in the use of foldcore structures and lightweight lattice architectures for use in aerospace design. The unique and attractive properties offered by cellular materials based on lattice truss topologies have, in recent years, been investigated by a number of authors [1-5]. One particular area of interest relates to those structures whose members deform in stretching-dominated, rather than bending-dominated response modes. Previous work has shown that such lattices exhibit stiffness and strength properties that scale linearly with density, ρ. This is in contrast to polymer and metal foams whose strength and stiffness properties scale as $\rho^{3/2}$ and ρ^{2} respectively. Queheillalt and Wadley [1] investigated the compressive properties of pyramidal lattice truss structures with hollow sections and compared their response to an equivalent solid truss structure. They showed that the compression strength of the hollow sections was approximately double that of a solid pyramidal lattice of similar density. Deshpande [3] investigated the properties of the stretching-dominated octet-truss lattice structures that were manufactured by stacking layers of pre-fabricated triangulated layers and tetrahedral cores together. The authors concluded that octet-truss type structures offer significant potential for use in lightweight design. In a subsequent study, Wang [4] investigated the performance of panels based on a 3D Kagomé core structure. The authors produced truss panels in which the members were manufactured from a copper alloy using an investment-casting process. Unfortunately, following testing, many of the samples highlighted the presence of localised porosity associated with the casting process.

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To date almost all lattice structures have been manufactured from either metallic materials or plastic. However, in a novel study, Finnegan and co-workers [5] investigated the compressive properties of carbon fibre-based truss structures. Composite-based lattice structures offer enormous potential given that they potentially offer extremely high values of strength at a low density.

The aim of the work outlined in this paper is to investigate the mechanical properties of a range of lattice structures based on a continuous carbon fiber reinforced epoxy composites produced using a lost mold technique. The strength and energy-absorbing characteristics of these structures are then investigated experimentally and the data compared to the FE predictions.

2. Experimental Procedure

Several, all-composite lattice designs, were considered in this study, these being the BCC, BCCz, FCC F_2BCC and Pyramidal and Octet designs. The lattices were prepared using a lost-mold procedure that has previously been used to manufacture a range of vertical truss cores for energy-absorbing applications [6]. Here, 4 mm diameter holes were drilled into wax blocks with a thickness of 38 mm. The non-vertical holes were introduced by placing the wax blocks on an inclined wooden support. Following the drilling procedure, carbon fiber tows were inserted through the holes with the aid of a large steel needle. The fiber volume fraction within a unit cell can be varied by using increasing numbers of fiber tows during the threading process. It is worth noting that values of V_f up to approximately 50% can readily be achieved using this technique [6].

Once the threading procedure was complete, the wax blocks were vacuum-bagged and infused with an epoxy resin, Prime™ 20LV (Gurit Ltd.), using the VARTM technique. A distribution medium, Gurit Knitflow40®, was placed on the upper skins to ensure the effective flow of resin from top to bottom skins through the holes in lattice block. The stack was placed on a glass table in order to follow the resin flow process during manufacture. The sandwich panel was infused with resin under vacuum and then allowed to cure at room temperature for 12 hours. Once cured, the panels were removed from the bagging material and then post-cured for 7 hours at 65 ^oC. Finally, the wax mold was removed by placing the panels in an oven heated to 120 ^oC for four hours. Figure 1 shows several lattice design manufactured using this technique.

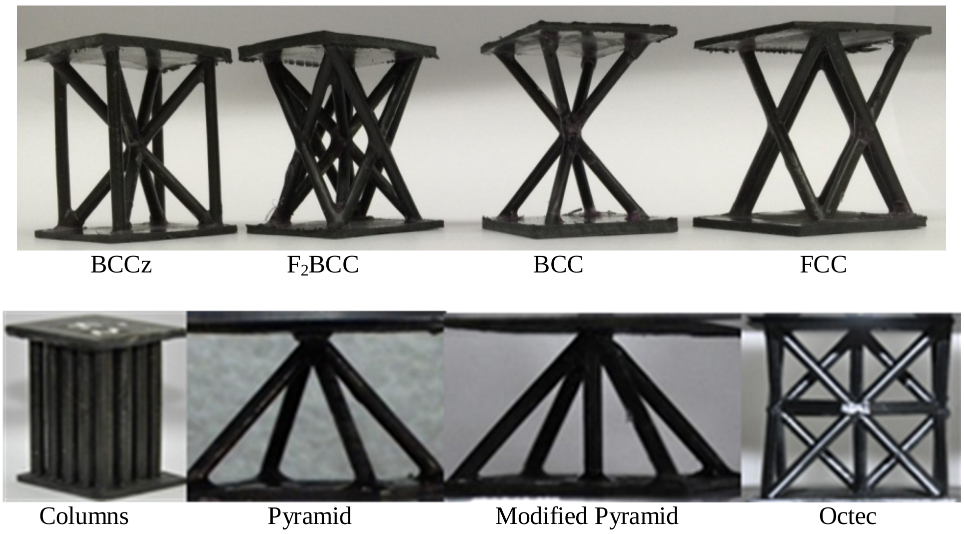

Figure 1. Photographs of the lattice structures following manufacture.

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The quasi-static properties of the lattice structures were evaluated by loading the specimens in an Instron 1425 at a crosshead displacement rate of 2 mm/min. Typically, four repeat tests were conducted on each lattice structure. Following testing, the specimens were photographed and examined under a low power microscope.

3. Numerical Modeling

A series of finite element analyses were performed in order to predict the response of the lattice cores under conditions of compression loading. Here, finite element models were created using the Timoshenko beam element, BEAM188 element in the ANSYS FE package and the predictions compared with analytical solutions and the experimental results. The BEAM188 element is a three-dimensional beam element defined by two nodal points. The struts are assumed to be rigid-jointed at the nodes. Hashin's damage model was considered in the analysis. The model includes four damage initiation mechanisms that are determined according to the following criteria:

Fiber tension ($\sigma_{11} > 0$)

$$F_f^T = \left(\frac{\sigma_{11}}{X^T}\right)^2 + \frac{{\sigma_{12}}^2 + {\sigma_{13}}^2}{(S^L)^2} \tag{1}$$

Fiber compression ($\sigma_{11} \leq 0$)

$$F_f^C = \left(\frac{\sigma_{11}}{X^C}\right)^2 \tag{2}$$

Matrix tension ($\sigma_{22} > 0$)

$$F_m^T = \left(\frac{\sigma_{22}}{Y^T}\right)^2 + \left(\frac{\sigma_{12}}{S^L}\right)^2 \tag{3}$$

Matrix compression ($\sigma_{22} \leq 0$)

$$F_m^C = \frac{\sigma_{22}}{Y^C}\left[\left(\frac{Y^C}{2S^T}\right)^2 - 1\right] + \left(\frac{\sigma_{22}}{2S^T}\right)^2 + \left(\frac{\sigma_{12}}{2S^L}\right)^2 \tag{4}$$

Where, X^T and $X^C$are the longitudinal tensile and compressive strengths. Y^T and $Y^C$are the transverse tensile and compressive strength. S^L and S^T are the in-plane (axial) and out -of-plane shear strengths respectively.

4. Results and Discussion

Figure 1 shows photographs of all lattice structures following the lost-mold manufacturing procedure. An examination of the photographs indicates that the lattices are generally of a high quality, with there no evidence of any signicant defects on the surfaces of the samples. The struts all appear to be well anchored to the skins and the central nodes, where several struts meet, appear to be clearly defined. An examination of polished cross-sections removed from the individual struts indicated that the fibers were fully impregnated by the resin, with there being little or no evidence of voids or porosity [6]. Only four lattice designs are investigated in this study.

Figure 2 shows the stress-strain traces following tests on the selected four lattice structures, from where it is clear that there is a reasonably high level of repeatability, particularly in the early stages of the test. All traces exhibit an initial linear region prior to reaching a maximum at stress values. The stress then drops steadily as the lattices begin to fail. The stress reaches a minimum before increasing rapidly to values that can, in certain cases, exceed the initial strength of the structure. This second peak is associated with loading the lower pyramid in the BCC lattice (Figurer 2a), once the crosshead has reached roughly the mid-point of the lattice structure, as shown in the photographs presented in Figure 2a. This second loading regime then continues until the lowermost nodes begin to fail, at which point the entire structure collapses. Clearly, there is some scatter in the behavior of the lattices during this second phase of loading, with one structure resisting a stress of over 3.2 MPa and another just 0.75 MPa. The lower value is associated with nodal failures occurring in the upper and lower pyramids

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during the initial loading cycle. Clearly, when the crosshead reaches the height of the lower pyramid, its properties are already significantly degraded. In the final part of the test, the stress increases very rapidly as the lattice is crushed between the two steel plattens of the test machine.

Figure 2b shows the stress-strain curves for the BCCz structure, where it is clear that the inclusion of four vertical struts greatly enhances the compression strength of the lattice. Here, the initial stress increases linearly to values exceeding 7.5 MPa, before dropping steadily as the vertical struts and the angled struts fail at the skin-core interface, as observed previously. With continued loading, the stress in some samples begins to increase to values observed previously in the BCC structure, as in this case, the upper pyramid is loaded and ultimately fails, Figure 2b.

Figure 2c present the stress-strain traces and associated photographs for the FCC structure, where the initial stress increases to values of up to 7 MPa, i.e. similar to those observed in the BCCz lattice. The stress then drops sharply as the struts fail in a global buckling mode, with some mid-nodes failing due to the fact that the fibers are not intertwined at these locations. The secondary peak is associated with the crosshead loading the lower triangular structures on the four walls of the unit cell.

Finally, the F_2BCC structures, shown in Figure 2d, offer the highest compression strengths of the four lattices considered in this study. Here, the initial part of the stress-strain trace increases to a peak value of up to 13 MPa before dropping as the struts in the four walls fail in a global buckling with mid-nodes failing. Following this, some of the joints at the skin-core interface begin to fail. The second peak in the traces is associated with loading both the lower pyramid as well as the triangular structures on the vertical faces of the cell. The fact that the maximum stress recorded during this part of the test is greater than that recorded on the other samples, is due to the fact that more sub-structures are loaded during this part of the compression process.

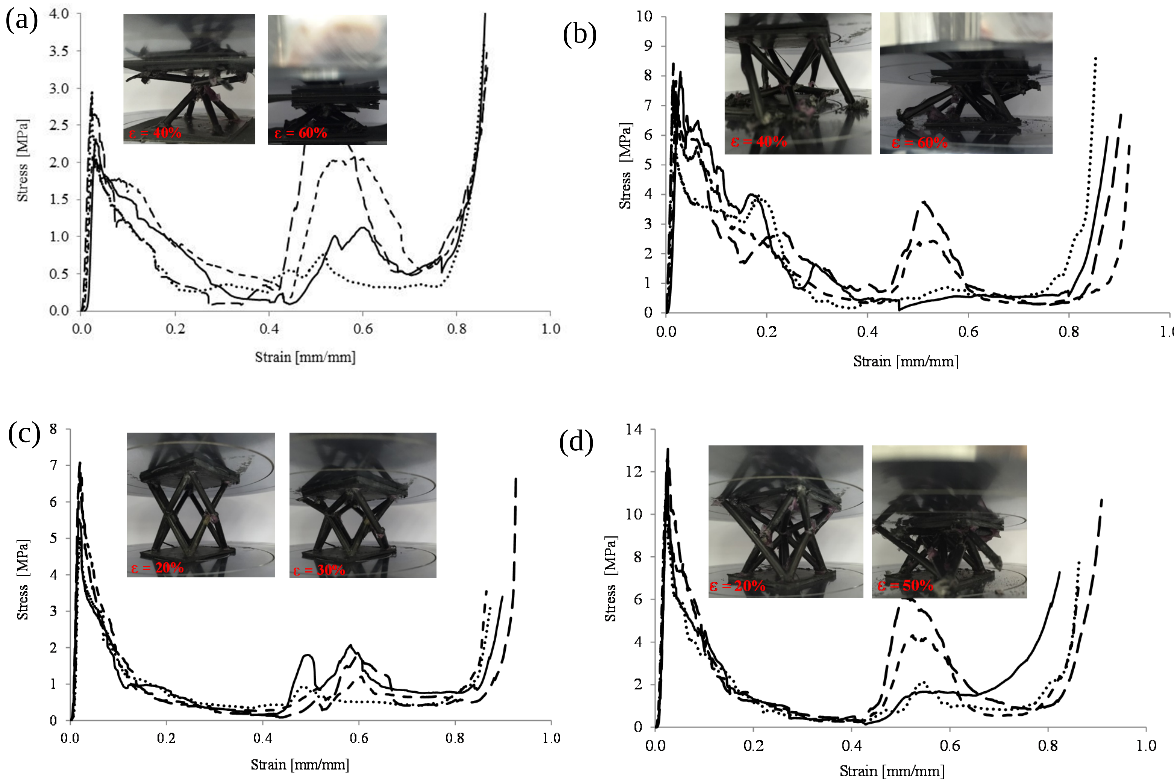

Figure 2. Stress-strain traces and photographs showing the deformation modes with increasing strain for the lattice structure (a) BCC, (b) BCCz, (c) FCC, and (d) F_2BCC.

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4.1. Mechanical Properties of the Lattices

Figure 3a compares the experimentally-determined values of the compression strength of the four lattices with the FE model. It is evident that the F_2BCC structure offers the highest strength of the four designs considered in this study, with the average value being 12 MPa. The BCCz structure, with its four vertical members offers the second highest strength, with values averaging 8 MPa. In contrast, the BCC lattice offers a relatively low resistance to compressive loading, with the properties averaging just over 2.5 MPa. An examination of the figure indicates that the finite element models over-estimate the measured values of compression strength. The disparity between the measured and predicted values are likely to be associated with the presence of micro-level defects in the lattices and fiber distortion in the nodal regions. It is interesting to note, however, that the models correctly rank the four lattices in terms of their maximum strength.

Given that the relative densities of the four lattices differ greatly, a more appropriate comparison can be made by dividing the specific compression strengths from the measured strengths by their respective density. The resulting values, shown in Figure 3b, indicate that when normalized with respect to relative density, the overall differences between the lattices are reduced. Here, the BCCz offers the highest specific properties, with the BCC continuing to offer the lowest values. The values for the BCCz and F_2BCC structures compare favorably with published data on a range of core materials. For example, crosslinked PVC foams typically offer values between 11 and 30 kNm/kg [7], aluminum honeycomb structures based on two densities of an A3003 alloy have been shown to exhibit values between 46 and 55 kNm/kg [8] and a Nomex honeycomb, with a density of 48 kg/m^3, has been shown to offer a value of approximately 29 kNm/kg [9].

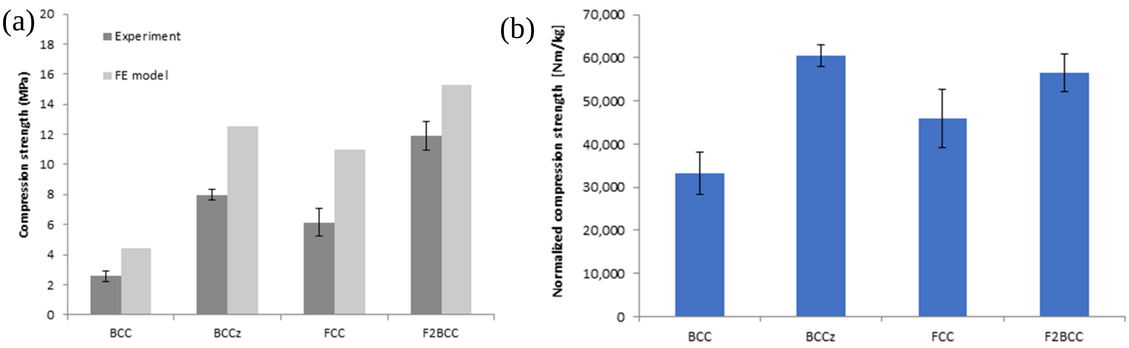

Figure 3. Comparison of the compression strengths of the four lattice structures and (b) comparison of the specific compression strengths (experimental data) of the lattices.

4.2. Energy Absorption

The specific energy absorption values of the lattice structures were characerised by dividing the area under the load-displacement trace by the mass of the lattice structure (excluding the skins). Figure 4 summarises the resulting values of SEA for the structures tested in this study. The BCCz structure offers the highest specific energy absorption characteristics of the four lattices, with values averaging 80 kJ/kg. This is an encouraging value, suggesting that these particular structures are effective energy-absorbing systems. The energy-absorbing capability of the F_2BCC is slightly lower than that assocciated with its BCCz counterpart, with the average value being approximately 75 kJ/kg. The BCC structure offers the lowest values of SEA, with the average being just over 43 kJ/kg.

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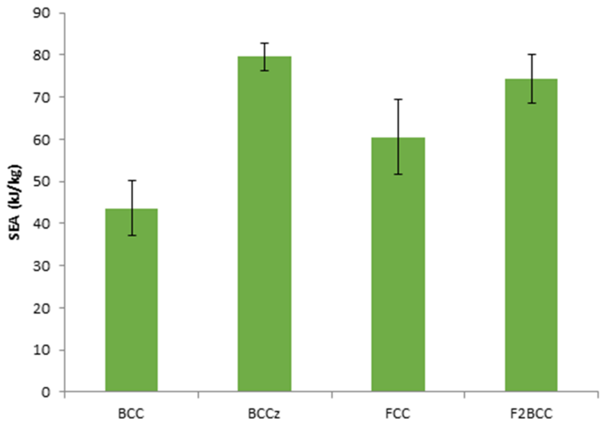

Figure 4. Summary of the specific energy absorption values of the four lattice structures.

5. Conclusions

A lost mold manufacturing technique combined with the VARTM technique has been used to produce a range of lattice structures based on a carbon fiber reinforced epoxy composite. The mechanical properties of the four lattices were predicted using the finite element method. The F_2BCC and BCCz structures offered the highest values of compression strength when normalized by density, whereas the BCC system offered the lowest values. When normalized by their density, several structures offered mechanical properties that compete favorably with those exhibited by more traditional core materials. The experimentally-determined compression strengths were lower than the values predicted by the finite element method, due to differences in the assumed boundary conditions at the ends of the struts. It has been shown that composite-based lattice structures offer attractive values of specific energy absorption, with values exceeding 75 kJ/kg for both the BCCz and the F_2BCC structures. It is likely that these values can be increased significantly by employing higher values of fiber volume fraction during the manufacturing process, suggesting that these structures could be attractive candidates for use in energy-absorbing structures.

6. Acknowledgements

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