Light Weight Lattice Truss Structures

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The aim of this project was to investigate the influence of topology and geometry on the specific strength of light weight lattice truss structures; the ultimate goal being to determine which design provides a better relative strength to relative density. This project was driven by a desire to bridge current research and fine which topologies and geometries performed better under compressive and shear loads. Due the numerous independent variables present in the analysis without specific design criteria it is hard to categorically state which topology and geometry is the best under compressive and/or shear loads. However, we are able to provide a design decision making tool was produced and future research on this topic have been identified.

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I. INTRODUCTION

This report will cover the steps taken during the research of topological and geometrical effects on the strength of lightweight lattice structures. The content of this report is a summary of a joint research project conducted in conjunction with Captain Benjamin Bruce.

A. Motivation

During an extensive literature survey of lightweight lattice truss structures it was identified that designs analysed focused primarily on functionality rather than finding the best solution. The driving factor that limited research was the complexity and cost to manufacture lightweight lattice truss structures of varying designs and configurations. There has been limited research conducted into optimization of structures and determination of the best performing topology or geometry.

B. Aim

The aim of this project was to investigate the influence of topology and geometry on the specific strength of lightweight lattice truss structures; the ultimate goal being to determine which design provides a better relative strength to relative density.

II. MANUFACTURE

In order to confirm the results from FEA models, a method for manufacturing complex geometries was required. This project presented several manufacturing problems; the first being the production of complex geometries with high accuracy and repeatability. The second is that the samples produced need to consist of multiple cells in order to reduce the influence of localised imperfections. Minimising defects in the sample should lower the uncertainty in experimental results. A process such as this could be done by hand through the manufacture and bonding of individual members to produce a large sample. However, the time it would take to produce a single model in this way would restrict the analysis to that single sample; limiting any examination of additional configurations and designs. As traditional machining techniques were out of the question due to the complex nature of the geometries to be analysed, more innovative techniques were investigated. Several manufacturing methods were looked at as possible means to produce samples for testing. The constraints in terms of this project were that the manufacturing process needed to be able to produce a large number of samples, relatively rapidly and at a very low cost.

C. Fused Deposition Modeling

Fused deposition modelling is a form of rapid prototyping sometimes referred to as 3D printing. It involves the automatic construction of physical objects by building up layers of melted material, usually a type of plastic. A printer head melts the plastic and deposits the resulting paste as directed by 3D model data. The paste solidifies via heat conduction, producing a hard material base onto which the next layer is applied. To produce hollow and
overhanging shapes this process requires the placement of additional material to support the structure during construction. In most cases, a wax-like material is used as it is easily dissolved in a bath after printing (Gebhardt, 2003).

The School of Physical, Environmental and Mathematical Sciences (PEMS) workshop operates a Dimension uPrint Plus FDM machine that is capable of producing complex three dimensional lattice structures quickly and cheaply. The cost of manufacture is approximately AU$0.65 per cm³ of lattice structure, with a small additional cost for support material. After printing some test samples to assess the capability of the machine; it was determined that 1mm thickness was the absolute minimum feature that could accurately be produced. However, 2mm x 2mm square trusses were able to be produced accurately with limited small defects. Figure 1 is a sample produced by the printer; each truss element is 2mm x 2mm square with the whole structure measuring 59mm x 59mm x 44mm. The time required to produce four samples of approximately the same size and complexity was around 18 hours.

Fused deposition modeling requires a three dimensional model of the final product to be produced, which ties in quite well with our project as a three dimensional model is also needed in order to conduct FEA of our designs. Exportation of this model is relatively simple compared to the design and manufacture of extrusion tooling and/or punch and die sets.

### D. Photo Curable Polymers

Photo curable polymers are the basis of another form of rapid-prototyping involving the jetting of thin layers of photopolymer material which is then cured by an ultra-violet light prior to the placement of the next layer. One of the main benefits with this method is that fully cured models are produced which can be handled and used immediately without any post-curing.

This method shares many of the advantages of FDM; however the School of Engineering and Information Technology (SEIT) recently purchased and are now operating a Objet30 Desktop 3D printer. This printer is able to produce samples meeting the requirements and was made available to this project as a priority. It was also requested by the school that this printer be used, as investigation of the as-printed material properties was of significant interest to them. In addition, three dimensional models produced in CATIA can be exported straight to the printer; thus reducing the need for access to the workshop or the production of tooling to produce the lattice structures. A limitation imposed by the printer is the build area of 300mm x 200mm x 150mm; however this is not likely to be an issue for the purpose of this investigation.

Since this project was primarily focused on the comparison of different geometries, a manufacturing method that can rapidly produce samples for testing to confirm simulations was required. The desired turnaround time for each configuration needed be in the order of days from the initial concept to final testing in the laboratory. Photo curable polymer based printing in the form of the Objet30 will provide the relatively short production and testing process desired; allowing the generation and analysis of more initial design concepts. For these reasons a decision was made to utilise the Objet30 Desktop printer to produce our test samples.

The material property data of the Objet Fullcure720 used by the Objet30 is listed in Table 1. It was uncertain if these values held true for the as-printed material and therefore testing was conducted to establish the compressive, tensile and shear strength of the material.

**Table 1. Objet Fullcure720 Material Data (Objet, 2010)**

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Material</th>
<th>Units</th>
<th>Imperial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength</td>
<td>MPa</td>
<td>50.65</td>
<td>psi</td>
<td>7250/450</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>%</td>
<td>15.25</td>
<td>%</td>
<td>15.25</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>MPa</td>
<td>2000-3000</td>
<td>psi</td>
<td>290,000-435,000</td>
</tr>
<tr>
<td>Flexural Strength</td>
<td>MPa</td>
<td>40-110</td>
<td>psi</td>
<td>600,000-1600</td>
</tr>
<tr>
<td>Flexural Modulus</td>
<td>MPa</td>
<td>270-3200</td>
<td>psi</td>
<td>390,000-480,000</td>
</tr>
<tr>
<td>Hot, °C</td>
<td>°C</td>
<td>42-59</td>
<td>°F</td>
<td>113-122</td>
</tr>
<tr>
<td>Iod Titrated Impact</td>
<td>g/in</td>
<td>20.30</td>
<td>lb/in</td>
<td>0.375-0.562</td>
</tr>
<tr>
<td>Water Absorption</td>
<td>%</td>
<td>1.52.2</td>
<td>%</td>
<td>1.52.2</td>
</tr>
<tr>
<td>E</td>
<td>%</td>
<td>48.60</td>
<td>%</td>
<td>118.122</td>
</tr>
<tr>
<td>Shore Hardness</td>
<td>Shore D</td>
<td>82.68</td>
<td>Shore D</td>
<td>82.88</td>
</tr>
<tr>
<td>Rockwell Hardness</td>
<td>Shore D</td>
<td>73.76</td>
<td>Shore D</td>
<td>73.76</td>
</tr>
<tr>
<td>Polymeric density</td>
<td>g/cm³</td>
<td>1.18-1.19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ash content</td>
<td>%</td>
<td>0.01-0.02</td>
<td>%</td>
<td>0.01-0.02</td>
</tr>
</tbody>
</table>
III. MATERIAL TESTING

Limited information is available on the material properties of the printed product. To overcome this shortfall in data, material property testing was conducted. Samples were produced and tested in the as printed state; there was no surface finishing done to any of the samples. In addition, the samples went through the same process as the final test structures. This meant that all of the samples were post treated in a 2 percent solution of sodium hydroxide for a period of between 30 and 60 minutes and the rinsed in water and air dried.

All material property testing was carried out as closely in accordance with the applicable standards as possible. The applicable standards are; ASTM D628 - 10, Standard test method for tensile properties of plastic, ASTM D695 - 10, Standard test method for Compressive properties of plastic and ASTM D5379/D5379M – 05, Standard shear test method for shear properties of composite materials by the v-notched beam method. These standards detail the steps required to accurately determine the tensile, compressive and shear properties of plastics and composites. Despite both the tensile and compressive test methods being limited to plastics with a yield strength of up to 40MPa (ASTM, 2010), it was decided that for the purposes of this project this approach would still generate acceptable results.

E. Compressive Strength

It was proposed that two sets of samples be produced; the first set printed with the layers perpendicular to the applied load, the second with the layers printed parallel to the applied load. This would determine if the orientation of the layers had any significant effect on the compressive strength of the material. This was unable to be achieved due to material consumption restrictions; instead five compressive samples were printed with a diameter of 15mm and a height of 30mm. This minimised material usage while still achieving the 2:1 ratio required. Images of the samples before testing are available at Figure 2.

The testing was conducted using the T20K Tensile Testing Machine with a 20kN load cell and LE05 Laser Extensometer. A displacement was applied to each sample at a rate of 0.5mm per minute until a total displacement of 5mm was reached; with load and displacement values recorded throughout the test. The results are available in Figure 3.

As can be seen in Figure 3 the results were relatively consistent across the five samples tested. The shape of the curve was as expected, with an initial region of linear increase up until the commencement of yielding, prior to reaching a peak stress, before a continued region of yielding as the sample is compressed. The gradient of the initial linear portion of the curve yields the elastic modulus of the material. The value specific to each sample is displayed in the figure; a mean value was taken, combining the results across the sample set to give an $E = 2.38 \text{ GPa}$ with a $\sigma_{\text{standard dev}} = 0.31 \text{ GPa}$.

F. Tensile Strength

For the tensile testing two sets of specimens were produced with the layers parallel to the applied load and another set with the layers perpendicular to the applied load. This was done as it was decided that layer orientation was likely have the greatest affect on this property. Each sample set consisted of 6 samples, five at a thickness of 3mm and one at 2mm, to facilitate a minor investigation into the effect of thickness on tensile strength. Images of the samples before are available in Figure 4.

The testing was conducted using the T20K Tensile Testing Machine with a 5kN load cell and LE05 Laser Extensometer. A displacement was applied to
samples exhibited a nonlinear relationship. In order to estimate the elastic modulus of the material a line of best fit was used. As can be seen in Figure 5 the elastic modulus for the 3 mm samples were relatively consistent; while the peak stresses vary considerably. The mean elastic modulus of the 3 mm samples is $E_{\text{transverse}} = 1.57 \text{ GPa}$, with $\sigma_{\text{standard dev}} = 0.044 \text{ GPa}$.

Figure 6 show similar overall trends in the longitudinal samples; but a definitive peak stress was reached followed by an extended region of plastic deformation. This can be attributed to a significant reduction in stress concentrations due to the orientation of the layers. The samples elongated significantly before failure; with some samples stretched up 30 percent. The mean elastic modulus of the 3 mm samples is $E_{\text{longitudinal}} = 1.76 \text{ GPa}$, with $\sigma_{\text{standard dev}} = 0.11 \text{ GPa}$.

The change in elastic modulus from the 3 mm samples to the 2 mm sample was consistent in both longitudinal and transverse cases. There was also a noticeable reduction in elastic modulus between the two orientations. It is hypothesised that the variation in elastic modulus is most likely a result of a skin effect, as at a lower thickness the defects account for a larger percentage of the cross-sectional area. Investigation into this phenomenon could be conducted by way of testing samples at a range of thicknesses; in addition to exploring methods of surface defect removal.

In terms of the types of fracture observed throughout the tensile testing, the transverse layered samples all exhibited clean brittle fracture along the layers. In the case of the longitudinal samples, a combination of clean brittle and shattering fractures were observed. Whilst this could be considered unusual behaviour for a polymer; sense can be made of it by taking into account the large number of defects resulting from the manufacturing method.

G. Shear Strength

Five samples, with a thickness of 3mm were produced in accordance with the standard. As financial constraints limited the testing of alternate layer orientations the layers were printed parallel to the applied load as this was deemed most likely yield more conservative results. Images of the samples before and after the test are available in Figure 7. The testing was conducted using the T20K Tensile Testing Machine with a 5kN load cell and LE05 Laser Extensometer. Each of the five samples was positioned within the Iosipescu test device each sample at a rate of 0.5mm per minute until failure; with load and displacement values recorded throughout the test.

The results are available in Figure 5 and Figure 6. As can be seen in Figure 5 and Figure 6 all of the 3mm transverse samples exhibit the same stress strain relationship; however there points of failure vary considerably. These failures are likely to be caused by stress concentrations in the test samples. The 2mm transverse sample exhibited a similar trend to the 3 mm samples but the gradient of the stress strain curve was significantly lower.

The stress strain curve for all of the transverse tensile
and a displacement applied at 0.5mm per minute until failure. The results generated by the first two samples were completely erroneous due to mistakes made during the initial testing procedure; this left three data sets from which to determine the material properties. The results are available in Figure 8. The stress displacement curves exhibited consistent trends across the three samples. A mean value was taken, combining the results across the sample set to give $\tau_{\text{peak}} = 30.5 \, \text{MPa}$, with $\sigma_{\text{standard dev}} = 2.19 \, \text{MPa}$. Modes of failure among the shear samples were consistent and best described as shattering; with a primary fracture observed along a line at 45 degrees to the applied displacement.

**H. FEA Model**

The material property testing was conducted in order to facilitate the accurate prediction of lattice structure performance in compression and shear. As can be seen, significant variations in elastic modulus exist between the compression and tension tests. ANSYS does not support the use of such properties; therefore the decision was made to assume the most conservative elastic modulus for use in the model. The elastic modulus implemented in the FEA model was $E = 1.57 \, \text{GPa}$.

**I. MODELLING**

**I. General Outline**

ANSYS was used as the primary analysis program throughout the project as it allowed the scripting of various complex truss structure designs and configurations for multiple simulations. The lattice structures were modeled in ANSYS as it allowed the construction and analysis of a variety of configurations quickly using a macro. This also enabled the sequential simulation of assorted configurations, meaning large portions of data could be gathered promptly and with little need for manual manipulation. The results from the simulations were then easily fed into MATLAB for plotting and further analysis. By reducing the work required to produce the complex lattice structures the amount of configurations could be significantly increased, thus allowing for a more in depth comparison of geometries and topologies. In essence the model works by applying a 1N test load in either compression or shear, to all key points in the uppermost plane of the structure. An Euler buckling analysis is then conducted to determine the critical buckling load of each member; this can be likened to a buckling safety factor. The chosen beam element then provides the outputs that facilitate plane stress analysis to determine the safety factor relative to the yielding of the structure. Also conducted during the simulation is a stiffness and relative density calculation, along with a Von Mises stress estimate. All results are then outputted to a space delimited file for further processing and analysis in MATLAB.

**J. Beam 189**

The truss lattice structures were constructed using key points joined by line sections, which were then meshed using the BEAM189 element. BEAM189 is a quadratic three-node element in three dimensions with six degrees of freedom occurring at each node; enabling translation and rotation in the x, y, and z directions (ANSYS, 2010). This element was selected as it allowed for the definition of the beam cross-sectional shape, meaning the three dimensional properties of the trusses could be represented by a one dimensional line. It is suitable for analysing
beam structures consisting of slender to moderately thick trusses and incorporating theory which includes stress and stiffness terms as well as shear-deformation effects. Importantly, this beam element also allows the use of eigenvalue buckling analysis as well as providing direct and bending stress outputs. The beam geometry is defined in Figure 9 (ANSYS, 2010).

At each node BEAM189 outputs the direct stress along the member (the x-direction in the beam local coordinate system) as well as the bending stresses in each of the four sides of the square profile. This enables the calculation of the principal stresses (ANSYS, 2010).

**K. Boundary Conditions**

In order to conduct a static analysis of the structure, boundary conditions sufficient to prevent free body motion needed to be applied. This was achieved via the constraint of specific key points. The bottommost key points were constrained in all Cartesian directions; while the uppermost key points remained unconstrained during the application of shear loads, but had their displacement restricted in the x and y directions for compressive load application.

**L. Structure Size**

The size of the structure in terms of number of unit cells was an important consideration in the development of the model as it influenced both the accuracy of results and computational work required to achieve them. Unfortunately the relationship between the two is inversely proportional, with increased structure size providing more data and hence better results; while a smaller structures lead to much quicker run times. A study was conducted in order for a reasonable compromise to be reached; simulations were run over a series of structure sizes at multiple base lengths. The study was restricted to a size of 11x11 cells due to a limitation of allocated hard drive space at the time of simulation. The results become quite consistent at sizes greater than around 8x8 cells, as reliable results could be achieved with reasonable use of available hard drive allocation, this size was selected for implementation throughout the project.

**M. Linear Buckling Analysis**

ANSYS linear buckling method performs an eigenvalue buckling analysis which predicts the theoretical buckling strength of an ideal linear elastic structure. This technique was selected as the initial buckling analysis prior to experimental testing due to its simplicity and speed. As this method corresponds to a classical Euler buckling analysis, results were expected to be less than conservative due to imperfections and nonlinearities in the material; however they were deemed sufficient for the purposes of this project (ANSYS, 2010).

The linear buckling results provided ANSYS were compared to the theoretical buckling analysis based on Equation 1. The study investigated the effect of line divisions and the buckling load on a single column. The column was set up with one end fixed and the loaded end free ($K = 2$).

$$P_{crit} = \frac{\pi^2 EI}{(KL)^2}$$  \hspace{1cm} (1)

The difference between a single line division and theoretical result is only 1.4 percent; however this difference is reduced considerably as the number of line divisions is increased. This trend continues until around five line division at which point the disparity becomes constant. The decision was made to use six line divisions throughout the FEA.

In order to conduct a linear buckling analysis in ANSYS a uniform load must be applied. This caused significant problems when simulating multi-layered structures as the inversion of pyramids leaves
Unsupported overhanging members at edge regions. The application of forces to such members resulted in very high stress concentrations leading to erroneous data that was not indicative of topology performance. The application of a displacement rather than a load easily negates this issue; however a uniform load is essential for the buckling analysis operation. The solution to this dilemma came in the form of a layer study; the results of which removed the need to model multi-layered structures at all, by way of proving a relationship between them and single layer structures of the same design.

N. Safety Factor

The elemental results produced by ANSYS allowed a plane stress analysis to be conducted; this was used to approximate the load conditions that would cause yielding. Due to the anisotropic nature of the material the safety factor calculations needed to take into account both tensile and compressive loads as well as shear stresses. The safety factor was calculated at five positions at each node using the following allowable stresses extracted from material test data:

\[
\sigma_{c, \text{allowable}} = 60 \text{ (MPa)} \\
\sigma_{r, \text{allowable}} = 20 \text{ (MPa)} \\
\tau_{\text{allowable}} = 30 \text{ (MPa)}
\]

The minimum safety factor was selected in order to determine the maximum allowable applied load for each structure.

O. Relative Density

In order to remove the influence of material from the final results; the relative density was used to compare different geometries and topologies. This value was calculated by determining the volume of the lattice and dividing it by the volume of an imaginary box enclosing the entire structure, as per Equation 27.

\[
\rho_s = \frac{V_{\text{lattice}}}{V_{\text{box}}} \quad (2)
\]

P. Von Mises Stress

Since the material used to produce the model was anisotropic a Von Mises stress analysis could not be used to predict yield failure. However, as a point of interest and for potential application with isotropic materials the Von Mises stress was calculated using elemental data; this data is outputted for convenient analysis as opposed to the averaged nodal results calculated by ANSYS. These results are not displayed within this report as they are not relevant.

IV. RESULTS

Q. Cross-sectional Area

A study was conducted in order to analyse the effect of cross-sectional area on the yield and buckling failure of a single layered structure. For a constant height and varying cellular base length, the simulation was run for two different topologies at cross-sectional areas of 1mm x 1mm, 2mm x 2mm, and 4mm x 4mm. The results of this investigation are available in Figure 10.

Figure 10 displays a clear correlation between the cross sectional area and the maximum allowable stress, this relationship is obvious in both the square and triangular based pyramid structures. As the cross sectional area is increased the critical buckling and yielding loads of the structure increase; buckling proportional to cross-sectional area squared and yielding directly relative to that area.
These Equations 3 and 4 were used to predict the behavior of designs with 2mm x 2mm and 4mm x 4mm square cross-sections based on the results of the 1mm x 1mm cross-section designs, these results are also plotted in Figure 10. As can be seen, the predicted results are quite consistent with the simulations; meaning computational resources could be saved as simulations at 1mm x 1mm cross sections could be extrapolated out provide data for the same designs at any cross-sectional area.

\[ P_{\text{crit,yielding}} = \sigma A \]  
\[ P_{\text{crit,buckling}} = C_1 l = C_1 A^2 \left( \text{where } C_1 = \frac{x^2E}{12(1-\nu^2)} \right) \]

R. Number of Layers

To simplify the complexity of simulated data collection and analysis, a study was conducted with the aim of proving that a relationship existed between the resultant stresses in multi-layered structures and those of single layer structures. A uniform strain was applied to the top layer of the square based pyramid topology for one, two, four and eight layer structures; and the reactive forces and resultant stresses calculated. The results of this investigation are displayed in Table 2 and Figure 11 shows an image describing the stress distribution through the eight layer structure.

As can be seen Figure 11 the stress is distributed evenly throughout the layers with the maximum stress occurring in the pyramidal truss members. The results in Table 2 show that for the same applied strain the stress in a structure is independent of the number of layers. It was important to note that the reaction forces due to the applied strain were uniform for multiple layers; this implies that resultant buckling stresses also behave independent of the number of layers. These findings meant that results of an analysis conducted on a single layer structure could be manipulated to provide the same data for structures of multiple layers. This greatly reduced the complexity of the analysis by removing all issues surrounding the application of boundary conditions to overhanging members in multi-layer designs. It also simplifies the design considerations inherent in the application of these structures as it enables the stacking of specifically designed layers to achieve required dimensions without compromising strength or stiffness.

S. Compression Modeling

A compressive load of 1N was applied to the uppermost key points of each structure over varying base lengths and series of heights. The data collected was initially collated and displayed in a separate plot for each design topology. An example is shown in Figure 12; these results are specific
to the hexagonal-based prism with diamond bracing.

As can be seen in Figure 12 buckling is the dominant failure method for all heights across the variance in base length; this was the case for all topologies in compression. This plot is for designs with a cross-sectional area of 1mm x 1mm; so this relationship is specific to such a cross-section. As previously mentioned, these results can be scaled to provide data for designs of varying cross-sectional areas. When the scaling factor difference of the two curves is considered it is clear that the dominant failure mechanism would change through manipulation of this variable. This means that a while a cross-over point between buckling and yielding failure is not observed in these plots, the existence and location of such a transition is influenced by member cross-sectional area.

In order to facilitate a comparison between the topologies an arbitrary height of 40mm was selected and the results of each design plotted together on the same graph. This plot is displayed in Figure 13.

As can be seen in Figure 13 the hexagonal prism with diamond bracing performs best across the range of relative densities. The results also show that the prism with diamond bracing design performs best within each base-shape. This makes sense as use of the diamond bracing effectively shortens the length of each member of the cell.

**T. Shear Modeling**

A shear force of 1N was applied to the uppermost key points of each structure over varying base lengths and series of heights. As the designs were anisotropic, shear forces applied in different directions were likely yield different results; in the case of the designs investigated only two directions were required in order to account for this. The data collected was initially collated and displayed in a separate plot for each design topology. Examples are shown in Figure 14 and Figure 15; these results are specific to the hexagonal-based prism with diamond cross bracing.

As can be seen in Figure 14 and
Figure 15 the failure mechanism is much less clear cut than it is with compression. Buckling dominates at lower relative densities prior to transitioning to an extended region of yielding dominant failure. As mentioned earlier, changes in cross-sectional area will influence the point at which this transition occurs; however due to the relative closeness of the yielding and buckling curves this manipulation would have much less of an effect on the max applicable stress than would be the case with compressive loading. In order to facilitate a comparison between the topologies an arbitrary height of 40mm was selected and the results of each design plotted together on the same graphs. These plots are displayed in Figure 16 through Figure 19.

As can be seen in Figure 16 and Figure 17 an increase in relative density produces a significant increase in max applied load. This relationship holds true for all designs analysed. It can also be seen that different designs perform better at different relative densities with no single design performing best across the densities investigated.

As can be seen in Figure 17 and Figure 18 beyond a certain point, increasing the relative density of a structure does not yield an increase in the max applied load. A notable difference between the shear and the compression investigations is that the performance of the designs is not consistent between yielding and buckling. The relative performance of the topologies changes dependent upon the failure mechanism considered; this was not the case in the compressive modeling results.

U. Experimental Testing

In order to confirm the modeled results experimental testing was conducted. Due to constraints on time and resources only compressive testing was undertaken. The topologies assessed as the best performing under compressive load were selected and two samples produced. The samples were printed at an arbitrary height of 40mm and at base lengths appropriate to achieve equal relative densities between the square and hexagonal prism designs, both with diamond bracing. An image
of these samples is displayed in Figure 20.

The FEA model constrains the top nodes of the structure in the X and Y directions during the compression simulation. So as to best achieve this in the experiment the samples were bonded to 2mm thick aluminum plates top and bottom using a two-part epoxy. Figure 21 and Figure 22 display images of the samples ready to be tested.

The square based prism sample in Figure 21 was tested in the JJ Loyd using a cross over compression rig at a constant displacement rate of 0.5 mm/min. This test was not entirely successful as it was soon realised that the compression rig did not apply the displacement evenly across the top face of the sample. This meant that the structure was not uniformly stressed resulting in buckling failure along one edge of the sample. The results of the sample are available in Figure 23 and Figure 24. The relative density of the square based prism was determined to be 0.061.

As can be seen in Figure 23 and Figure 24 the curves demonstrate an increasing reactive force with increased displacement; however as the displacement was not uniformly distributed over the sample an edge failed via buckling causing the test rig to widen on the face registering displacement. This caused the looping back of the load displacement curve observed in Figure 23 and Figure 24, when this was observed the sample was unloaded at the same rate till a zero force was recorded. The strange unloading curves can likely be attributed to the misalignment of the faces on the cross over rig. Images of the buckling failure of the square based sample are displayed in Figure 25.

The peak stresses observed in tests 1 and 2 were 0.2189 MPa and 0.1767 MPa respectively. The FEA model predicted failure at 0.5569 MPa. In this case, the discrepancy between the predicted value and that of the experimental results is more likely due to inaccuracies in the setup of the test rather than the ANSYS model. The uneven application of the displacement caused stress concentrations not even close to representative of the uniform boundary conditions applied in the simulation and as such comparison would not be a fair examination of the model.
the first test, the hexagon based prism sample in Figure 22 was tested in the ELE Digital TRITEST machine under direct compression at a constant displacement rate of 0.25 mm/min. The reactive force and displacement were recorded with post processing done in MATLAB. The results from the experiment can be seen in Figure 26. The relative density of the hexagonal based prism was determined to be 0.067.

As can be seen in Figure 26 there are several distinct regions in the curve; the initial part of the curve up to the 0.3mm displacement, is most likely caused by the bedding in of the test setup. From that point onwards a linear region is observed with the load increasing directly proportional to the applied displacement. A final roll over point is observed just prior to failure, with a peak load of 4.289 kN and a peak stress of 0.565 MPa. The FEA model predicted failure at 0.76 MPa.

The variance in the predicted and actual strength of the hexagonal sample is most likely attributed to the material used to produce the sample. It was observed in the material properties testing that the elastic modulus was likely affected by member cross sectional area, as seen in Figure 5 and Figure 6; whilst this phenomenon was observed in tensile testing only, it is reasonable to assume a similar effect would be observed on thin members under compressive load. As the material property testing was conducted on samples of cross-sectional area significantly larger than that of the members of the experimental test samples, it is likely that the material properties used in the FEA do not closely apply to the experiment. The elastic modulus is directly proportional to member buckling performance and as such any variance in this regard would cause considerable discrepancy between the predicted and experimental results. Figure 27, Figure 28 and Figure 29 show images of the hexagonal based sample at different points throughout the test.

As can be seen in Figure 28 the initial signs of buckling were quite obvious at the edge of the sample as the displacement increased. Figure 29 shows the sample at the point of failure, members at the centre were the first to collapse; the subsequent propagation of failure through the structure followed almost immediately.

V. DISCUSSION

The problem considered at the outset of this project consisted of such a vast array of variables; it was difficult to conceive any form of direct comparison between them for the purpose of design or analysis. The task at hand was decidedly difficult as the lack of any design criteria meant that the project was unable to focus on any particular component of possible design configurations. As the majority of the variables considered have an independent effect on design performance it was impossible to prioritise any one and systematically optimise the rest relative to it. The number independent variables were eventually reduced through extensive research, investigation and analysis to a point where an acceptable level of comparison was achieved by way of the ANSYS model described in this report.

It enables a user armed with design criteria to make informed decisions regarding the performance of designs based on how topology and geometry affect the end product. Different variables can be systematically eliminated, enabling the focus of a study to shift to whichever argument deemed
A notable shortcoming of the model is the overestimation of relative density values. The relative density of the square and hexagonal samples was determined to be 0.061 and 0.067 respectively. The FEA model predicted a relative density of 0.11 for both configurations. The variance in the predicted and actual relative density is wholly contributed to the overestimation of material used at member joints. Although the density is considerably lower than the predicted value the configuration of members within the structure remains unchanged between the FEA and the experimental sample, this variance in density should not affect the performance of the experimental sample. In essence all this discrepancy did was to complicate comparison between the predicted results and those of the experimental tests.

The experimental results did not completely correlate with those predicted; however if the extenuating circumstances mentioned above are all taken into account, the model can still be considered a good tool for the direct comparison of structural topologies and geometries.

VI. CONCLUSIONS

This project investigated the influence of topology and geometry on the specific strength of light weight lattice truss structures. The determination of which design provides a better relative strength to relative density proved problematic due to the extensive number of dependencies involved; however a tool for good comparison of topology and geometry of light weight lattice truss structures was produced. Further research topics were identified during the course of this project however resources did not allow us to investigate them.

VII. RECOMMENDATIONS

The following points are recommendations for future research to enhance the work completed during this research project:

- Investigate the effect of cross sectional area on as-printed material properties of samples produced by the Objet30.
- Enhance 1D FEA by conducting a 3D FEA on better performing designs identified in this project.
- Investigate methods to improve performance of the as-printed material, some potential techniques and methods are as follows:
  - Electrodeless nickel plating of lattice structure;
  - Surface coating, or
  - Material additives (carbon nano-tube technology)

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Figure 29. Buckling failure occurs at the centre of the structure and propagates outwards

IX. REFERENCES


