ORIGINAL ARTICLE

Assessing the Design and Compressive Performance of Material Extruded Lattice Structures

Jayme D. Rossiter,¹ Andrew A. Johnson,¹ and Guy A. Bingham²

Abstract

With additive manufacturing increasingly being embraced in the area of sports technology, focus has shifted toward cellular structures for impact protection. Periodic lattice structures can be tailored for a specific response by modifying the geometry of individual cells, with the structure capable of being modified to conform around a given body. However, the effect of modifying specific design characteristics within a lattice and the inter-relationships between them are not well understood. This study examines five geometric design variables: cell width, strut cross-sectional area (CSA), strut shape, cell orientation, and joint filleting, and their effect on the compressive behavior of a lattice structure. Truncated octahedron lattices were manufactured using nylon through the process of material extrusion and tested under compression at a constant strain rate of 1.0 s^{-1} . Design of experiments was utilized to analyze the results by implementing a $2^{(5-1)}$ factorial design. Results indicated that the strut CSA, cell width, and interaction between the two design characteristics had the largest effects on the plateau stress of the lattice and its energy capacity.

Keywords: additive manufacturing, cellular structures, design of experiments, energy absorption, protective equipment

Introduction

PROTECTIVE EQUIPMENT IN sport is used to reduce the risk of incurring injury while competing, with many of these items focused on reducing the impact forces and loading rates experienced by the wearer during blunt force trauma.^{1–4} Cellular materials such as foams are commonly used for these applications as their cellular nature produces a three-stage loading response.⁵ The plateau regime of this response has a long strain range with a near-constant stress value, known as the plateau stress, which has a significantly higher energy absorption capacity compared with a homogeneous sample of the same base material at a similar stress level.⁶ The energy absorption capacity is indicative of the impact energy that a cellular material can absorb, while plateau stress relates to the level of force that is transferred to the wearer during the impact.⁷

While foams are effective at offering protection from impact, disadvantages of their use with respect to protective clothing include:

- poor thermal regulation^{8,9}
- excessive weight/bulk^{10,11}
- restricted movement¹¹

With increasing utilization of additive manufacturing (AM), attention has been paid to its potential application to personal protective equipment.^{12–15} Interest has also grown in the areas of additively manufactured cellular structures (AMCSs) and bespoke sports equipment,^{13,16} in particular the area of AM-based running shoe midsoles. Brands such as Adidas,¹⁷ New Balance,¹⁸ and Under Armour¹⁹ have already released limited runs of AM-based running shoes, with Nike likely to follow having signed a partnership agreement with HP in 2016.²⁰

One significant advantage that AMCSs offer over traditional foaming techniques is the increased level of control that is achievable through the use of AM technologies with respect to the size and shape of pores.^{21,22} Foams exhibit random variation due to the nature of their manufacturing processes.²³ While it is possible to recreate this level of variation through AM using a stochastic model,^{21,24,25} it is resource intensive when compared with generation a uniform cell structure such as a periodic lattice.²⁶ While a regular lattice offers the advantage of uniform stiffness throughout its structure, manufacturing these through AM offers design freedom on a cell-by-cell basis with the possibility of realizing:

¹School of Design and Creative Arts, Loughborough University, Loughborough, United Kingdom.

²School of Design, De Montfort University, Leicester, United Kingdom.

FIG. 1. Lattice specimen dimensions featuring pore detailing.

- functionally graded stiffness through a lattice structure²⁷
- tailored lattices to specific performance requirements^{14,28}
- personalized fit through the use of 3D scanning²⁹
- optimization of the structure to reduce weight³⁰

These applications can predominantly be achieved by editing specific design variables in each cell such as strut cross-sectional area (CSA), strut shape, and the level of filleting placed at each strut joint. When examining individual cells, the design variables of the complete periodic lattice, such as the cell size and orientation, must also be examined to fully understand any interaction effects that may exist between the two.

The aim of this study was to identify the key design variables that had a significant effect on the energy capacity of lattice structures manufactured by material extrusion (MEX) and the plateau stress of their response.

Materials and Methods

Specimen manufacture

The truncated octahedron has previously been identified as a suitable candidate for the manufacture of AM lattice

scaffolds in tissue engineering.^{31,32} As this polyhedron is also the best single-cell solution to Kelvin's minimal surface conjecture,³³ the truncated octahedron was used as the base unit for all specimens used within this study.

The size of the test specimens was based on the ASTM D3574-11 Standard Test Methods for Flexible Cellular Materials,³⁴ which recommended that specimen dimensions should measure 50×50×25 mm, as depicted in Figure 1.

Specimens were modeled using SolidWorks® 2015 and exported as .stl files for slicing in Cura 2.3.1 using the settings as outlined in Table 1. As these lattice structures were self-supporting, no additional support structures were required during their build.

Test specimens were manufactured on Ultimaker 2+ (Ultimaker, Geldermalsen) MEX printers using a 0.4 mm diameter nozzle and printed using Ultimaker Nylon (Ultimaker). Specimens were printed with their z-axis, as shown in Figure 1, perpendicular to the build plate and tested in the same orientation to minimize delamination, which can occur at the interlayer boundary.^{35,36}

A total set of 48 specimens were manufactured across three Ultimaker 2+ printers and had print times varying between 3 and 8 h per specimen depending on their specific design configuration. To account for possible interprinter variability, the specimens were split into 3 blocks to represent each of the 3 printers being used, with each block containing a full run of 16 variations, thus allowing the manufacturing phase to be screened for interprinter variation. The print order for each printer was randomized to negate the effect of environmental factors during manufacture.

TABLE 1. PRINTER SETTINGS IN CURA 2.3.1

Setting	Level
Nozzle temperature	250°C
Bed temperature	60°C
Layer	0.1 mm
Infill	100%
Retraction	Enabled
Z-hop	Disabled
Print speed	25 mm/s
Outer wall speed	15 mm/s
Travel speed	100 mm/s
Print acceleration	1000 mm/s ²
Travel acceleration	1000 mm/s ²
Fan speed	40%
Support	Disabled
Skirt	Enabled
Skirt line count	4
Skirt distance	0.4 mm

TABLE 2. LEVELS FOR FACTORIAL ANALYSIS FOR EACH DESIGN VARIABLE

Design variable	Low	High
Cell width (mm)	12	16
Strut area (mm ²)	2	4
Fillet %	10	90
Cell orientation	Ribbon	Transverse
Strut shape	Circular	Triangular

FIG. 2. Examples featuring low (10%) and high (90%) levels of filleting.

Design of experiments

Five design variables were identified as having the potential to affect the energy capacity of lattice structures, therefore a design of experiments methodology was used for this study. These identified five design variables included:

- strut CSA
- strut cross-sectional shape
- filleting between joints
- cell width
- cell orientation

Within this study, a $2^{(5-1)}$ fractional design was chosen and implemented using Minitab 17 (Minitab, Pennsylvania) and involved a run of 16 variations with two levels. Three replications of each specimen were tested as stipulated by ASTM D3574-11 Standard Test Methods for Flexible Cellular Materials.³⁴

A half-fractional model was used, which enabled all of the main effects and two-way interactions between each of the variables to be analyzed and is not sensitive to interactions involving more than two factors. Higher order interac-

tion effects are less common and tend to have significantly smaller effect sizes and, as such, their exclusion halves the total number of variations to be manufactured. It is also common practice to undertake a screening study before using a higher level design to minimize the total number of runs required.³⁷

When selecting levels for a factorial analysis, it was important that the differences between the levels were significantly different to evoke a response for each factor while staying within the bounds of the system being examined. It is important to note that within a screening study, the relative range between the chosen levels across factors is not relevant, as demonstrated in prior literature.^{38,39} In the case of this study, the aim when selecting the levels, as displayed in Table 2, was to maximize the difference between the high and low levels while avoiding level combinations that were incompatible for manufacture using MEX.

The lower level for strut CSA was set at 2 mm^2 as this was the smallest cross section that the triangular strut could be maintained on when specimens were printed on the Ultimaker 2+. Sixteen millimeters was chosen as the upper level for cell width as this was the largest cell size that could fit within a 25-mm-thick specimen with multiple layers of intact cells at 1.5 layers. The lower levels for both cell width and strut CSA were selected so that a pore still formed in the square face of the truncated octahedron. The combination of a 12-mm cell width, 4-mm^2 strut CSA, and a triangular cross section produced a viable pore measuring 0.36 mm in diameter, as previously detailed within Figure 1.

The level of filleting was expressed as a percentage (%) of the straight edge length of each pore in which a fillet was applied. A clear comparison of the effect of applying the low level 10% and high level 90% fillet settings is shown in Figure 2.

Levels of 10% and 90% were selected to prevent excessive stress concentrations occurring at either the vertices if, for example, a 0% condition had been set or the strut midpoint if a 100% value had been set.

Two lattice orientations were used in this study, which are based on similar orientations used by Bates *et al.* while investigating honeycomb structures.⁷ These were the ribbon and transverse orientations and are shown in Figure 3.

A complete list of the specimen variations used within this study is listed in Table 3.

FIG. 3. Example specimens featuring ribbon (left) and transverse (right)-orientated cell configurations.

TABLE 3. CELL VARIATIONS USED FOR DESIGN OF THE EXPERIMENT

Specimen	Cell width (mm)	Strut CSA (mm ²)	Fillet %	Orientation	Strut shape
TO01	12	2	10	Ribbon	Circular
TO02	16	2	10	Ribbon	Triangular
TO03	12	4	10	Ribbon	Triangular
TO04	16	4	10	Ribbon	Circular
TO05	12	2	90	Ribbon	Triangular
TO06	16	2	90	Ribbon	Circular
TO07	12	4	90	Ribbon	Circular
TO08	16	4	90	Ribbon	Triangular
TO09	12	2	10	Transverse	Triangular
TO10	16	2	10	Transverse	Circular
TO11	12	4	10	Transverse	Circular
TO12	16	4	10	Transverse	Triangular
TO13	12	2	90	Transverse	Circular
TO14	16	2	90	Transverse	Triangular
TO15	12	4	90	Transverse	Triangular
TO16	16	4	90	Transverse	Circular

CSA, cross-sectional area.

Apparatus

All compression tests were performed using an Instron 3366 Dual Column Universal Testing System (Instron, Norwood) installed with a 10 kN load cell, with data captured using Instron's Bluehill 3 (Instron) software package. The compression protocol used was based on ASTM D3574-11³⁴ with specimens tested in the same orientation as their manufacture, as shown in Figure 4.

A strain rate of 1.0 s⁻¹ was used, and tests were terminated when the sample entered its densification phase, as indicated by a sharp increase in loading rate. Raw data were processed using MATLAB R2016a (MathWorks, Natick) to calculate the plateau stress and total energy capacity for each specimen and subsequently exported to Minitab 17 for statistical analysis.

Calculation

To calculate the energy capacity of the plateau regime, the onset strain of densification, which refers to the point on the

FIG. 4. Apparatus setup.

TABLE 4. ANALYSIS OF VARIANCE

	DF	Adj SS	Adj MS	F	p
Plateau stress					
Model	17	13.54	0.796	105.83	0
Error	30	0.226	0.00753	—	—
Total	47	13.766	—	—	—
Energy capacity					
Model	17	3.570	0.211	99.53	0
Error	30	0.064	0.002	—	—
Total	47	3.643	—	—	—

Adj SS, adjusted sum of squares; Adj MS, adjusted mean squared.

stress-strain response that represents the border between the plateau and densification regimes, must be found.⁵ The onset strain of densification marks the end of the plateau regime and is calculated by plotting the energy absorption efficiency against strain where energy absorption efficiency is given by Equation (1).⁴⁰

Energy absorption efficiency

$$\eta = \frac{1}{\sigma(\varepsilon)} \int_0^{\varepsilon} \sigma(\varepsilon) d\varepsilon \quad (1)$$

where η =energy absorption efficiency, σ =stress, and ε =strain.

The onset of densification is identified by peak efficiency or the last peak of the plateau within the efficiency plot.⁴¹

Energy capacity of the plateau regime within the stress-strain response is given by Equation (2).⁵

Energy capacity

$$W_d = \int_{\varepsilon_y}^{\varepsilon_d} \sigma(\varepsilon) d\varepsilon \quad (2)$$

where W_d =energy absorbed by the plateau, ε_d =strain at onset of densification, and ε_y =yield strain.

TABLE 5. MEANS AND STANDARD DEVIATIONS FOR EACH SPECIMEN VARIATION

	Plateau stress (MPa)		Energy capacity (MJ)	
	Mean	SD	Mean	SD
TO01	0.279	0.070	0.154	0.049
TO02	0.068	0.005	0.040	0.008
TO03	1.339	0.076	0.713	0.052
TO04	0.522	0.026	0.310	0.023
TO05	0.342	0.086	0.195	0.050
TO06	0.135	0.036	0.078	0.020
TO07	2.012	0.219	1.069	0.109
TO08	0.507	0.058	0.274	0.057
TO09	0.130	0.024	0.071	0.017
TO10	0.092	0.003	0.057	0.002
TO11	0.861	0.175	0.355	0.066
TO12	0.270	0.009	0.155	0.005
TO13	0.368	0.040	0.176	0.016
TO14	0.060	0.009	0.035	0.007
TO15	1.165	0.137	0.551	0.073
TO16	0.446	0.014	0.249	0.006

SD, standard deviation.

FIG. 5. Main effect plots for factorial design.

The plateau stress is given by Equation (3).⁴²
Plateau stress

$$\sigma_{pl} = \frac{\int_{\varepsilon_y}^{\varepsilon_d} \sigma(\varepsilon) d\varepsilon}{\varepsilon_d - \varepsilon_y} \quad (3)$$

where σ_{pl} = plateau stress and ε_y = yield strain.

Results

Results of the analysis of variance are displayed in Table 4. Mean results and standard deviations with respect to the 16 design variations for each output are given in Table 5.

The factorial plots given in Figure 5 show that the direction and magnitude of the main effects were similar for both plateau stress and energy capacity across all five design characteristics.

The cell width and strut CSA appear to display larger main effects than the other factors examined. This is confirmed by the larger effect sizes demonstrated by both of these factors within Tables 6 and 7.

Using Pareto charts, these effects were placed in rank order based on their effect size, as shown in Figure 6.

A technique known as backward elimination was implemented to reduce the model complexity. This involved iteratively removing the least significant variable from the analysis until only significant variables remain where significance to the 95% confidence interval is indicated by the

red dashed line in Figure 6.⁴³ The results following backward elimination are displayed in Figure 7.

Three interaction effects were removed from the analysis for both plateau stress and energy capacity, specifically these were as follows:

- cell width $\times$ strut shape (BE)
- strut CSA $\times$ strut shape (AE)
- % fillet $\times$ orientation (CD)

TABLE 6. REGRESSION COEFFICIENTS FOR PLATEAU STRESS

Term	Effect	Coef.	T	p
Constant		-2.882	42.90	0.00
Cell width (A)	-0.545	0.174	-21.95	0.00
Strut CSA (B)	0.706	1.546	28.20	0.00
% Fillet (C)	0.184	0.010	7.36	0.00
Orientation (D)	-0.226	-0.305	-9.03	0.00
Strut shape (E)	0.104	0.035	4.16	0.00
Cell width $\times$ strut CSA	-0.359	-0.090	-14.32	0.00
Cell width $\times$ % fillet	-0.135	-0.001	-5.39	0.00
Cell width $\times$ orientation	0.136	0.040	5.41	0.00
Cell width $\times$ strut shape	-0.031	-0.008	-1.26	0.22
Strut CSA $\times$ % fillet	0.100	0.001	4.00	0.00
Strut CSA $\times$ orientation	-0.183	-0.096	-7.30	0.00
Strut CSA $\times$ strut shape	0.036	0.018	1.44	0.16
% Fillet $\times$ orientation	-0.013	-0.0002	-0.51	0.61
% Fillet $\times$ strut shape	0.118	0.059	4.70	0.00
Orientation $\times$ strut shape	-0.069	-0.034	-2.74	0.01

Coef., coefficient.

TABLE 7. REGRESSION COEFFICIENTS FOR ENERGY CAPACITY

Term	Effect	Coef.	T	p
Constant		-1.367	42.2	0.00
Cell width (A)	-0.261	0.082	-19.63	0.00
Strut CSA (B)	0.359	0.719	27.03	0.00
% Fillet (C)	0.096	0.006	7.27	0.00
Orientation (D)	-0.148	-0.024	-11.12	0.00
Strut shape (E)	0.052	0.038	3.91	0.00
Cell width $\times$ strut CSA	-0.164	-0.041	-12.36	0.00
Cell width $\times$ % fillet	-0.078	-0.0005	-5.88	0.00
Cell width $\times$ orientation	0.097	0.024	7.27	0.00
Cell width $\times$ strut shape	-0.004	-0.001	-0.33	0.75
Strut CSA $\times$ % fillet	0.056	0.001	4.22	0.00
Strut CSA $\times$ orientation	-0.116	-0.058	-8.73	0.00
Strut CSA $\times$ strut shape	0.021	0.010	1.56	0.13
% Fillet $\times$ orientation	-0.003	-0.0002	-0.22	0.825
% Fillet $\times$ strut shape	0.077	0.001	5.82	0.00
Orientation $\times$ strut shape	-0.045	-0.023	-3.42	0.00

With nonsignificant factors now dropped from the analysis, the resulting regression models are given by Equations (4) and (5).

Reduced model for plateau stress:

$$\begin{aligned} \text{Plateau stress} = & -2.882 + 0.174 \times A + 1.546 \times B + 0.010 \times C - 0.313 \times D + 0.022 \times E - 0.090 \\ & \times A \times B - 0.001 \times A \times C + 0.034 \times A \times D + 0.001 \times B \times C - 0.092 \times B \times D \\ & + 0.001 \times C \times E - 0.034 \times D \times E \end{aligned} \quad (4)$$

Reduced model for energy capacity:

$$\begin{aligned} \text{Energy capacity} = & -1.367 + 0.082 \times A + 0.719 \times B + 0.006 \times C - 0.223 \times D - 0.038 \times E - 0.041 \\ & \times A \times B - 0.0005 \times A \times C + 0.024 \times A \times D + 0.0007 \times B \times C - 0.058 \times B \times D \\ & + 0.001 \times C \times E - 0.023 \times D \times E \end{aligned} \quad (5)$$

The R^2 values for the plateau stress model were calculated at 94.92%, while the energy capacity model value was 98.24%, therefore indicating that these models fit very well to

the data collected. The predicted R^2 for the plateau stress model was 91.9%, while 96.87% was calculated for the energy capacity model. Given that the predicted R^2 values for both models are close to the R^2 , this indicated that the models are not overfitted.

The block analysis of interprinter variation yielded p -values of $p=0.26$ for plateau stress and $p=0.37$ for energy capacity, which indicate that there was no significant difference between the printers used for manufacturing the test specimens.

Discussion

Strut shape had the smallest effect of all the main effects, with circular struts demonstrating larger values for both energy capacity and plateau stress. In addition, circular struts also have no edges, which enabled the manufacture of specimens with smaller cross sections. However, Brennan-Craddock²⁶ noted that using triangular struts significantly reduces .stl file size and, as a result, is far less computationally expensive. Where computation power is not a limiting factor, circular struts are suggested for future investigations.

Fillet percentage showed the weakest effect with both outputs of the three continuous variables. The positive correlation for energy capacity supports previous research by

FIG. 6. Pareto charts of effect sizes prereduction. Note that the dashed line indicates significance of the 95% confidence interval.

FIG. 7. Pareto charts of effect sizes for the reduced model.

Cell orientation had a significant main effect, with the ribbon orientation producing higher values for both plateau stress and energy capacity. This is in support of previous research by Bates *et al.*⁷ when using honeycomb structures. It also demonstrated interactions with cell width, CSA, and strut shape, with the ribbon orientation displaying a larger interaction for both outputs. Given that cells in the ribbon orientation also have a smaller cell height, they are useful for applications where specimen thickness is to be minimized. It is therefore recommended that the ribbon orientation should be adopted for future research in the area of AM-based protective clothing.

Cell width had the second largest effect size with a negative correlation for both outputs. Cell width also displayed strong interaction effects with strut CSA and a slightly weaker interaction effect with both cell orientation and fillet %, both of which were effective at smaller cell widths. It is therefore suggested that cell width should be minimized where possible, within the constraints of the AM process being utilized.

Strut CSA had the largest effect, showing a strong positive correlation for both outputs. Strut CSA also displayed a negative interaction effect with cell width, while the main effect cell width displayed a strong negative correlation and the second largest effect size for both outputs.

Energy capacity is an important property for impact protection as it illustrates how much kinetic energy a lattice structure can absorb. Plateau stress is also important as it relates to the pressure transmitted to the wearer. Both a smaller cell width and larger strut CSA increase energy capacity and plateau stress. Fujikawa *et al.* found that a peak pressure of 1.46 MPa carries a 10% probability of a minor soft tissue injury from human–robot interactions⁴⁵; however, further research is needed on soft tissue injury thresholds specific to sport.

For applications that require the tailoring of lattice properties at a local level, each cell may need to be tuned individually. Of the design variables examined within this study, strut CSA is the most appropriate for this application. However, its strong interaction effect with cell width must also be considered in applications where cell size is not constant, such as within a conformal lattice structure. While this study focused on specimens manufactured solely using MEX, the

factors analyzed are related to unit cell geometry and thus are not AM process specific—further investigation is, however, required to verify this.

The half-fractional model used within this study was not sensitive to curvature in the response between the three continuous variables and plateau stress or energy capacity. Use of Equations (4) and (5) is therefore cautioned until a higher resolution study is performed on these variables.

Conclusions

In this study, the effects of five geometric design characteristics within additively manufactured, truncated, octahedron lattice structures were examined in relation to their compressive response. In summary:

- All variables tested were found to have significant main effects.
- Strut CSA was shown to have the largest effect on the performance of lattices and was suggested as the most suitable design characteristic to adjust for a cell-by-cell tailored response.
- Cell width also exhibited a strong main effect and a strong interaction effect with strut CSA for both outputs. This should be considered in applications such as conformal structures where the cell size may vary in the lattice.
- Lattice orientation had a significant main effect for both outputs, and it is recommended that a ribbon orientation should be adopted in applications where there are limits on lattice thickness.
- Results of this study suggest that for future work relating to all protective applications, the truncated octahedron lattice shows potential for generation of a tailored response and conformal structures.

A wide range of opportunities exist for further investigation with a view to advance the domain of AM-based protective structures, including, but not exclusive to, the development of functionally graded and conformal lattices; consideration of alternative periodic structures such as the rhomboid, dodecahedron, triply minimal surfaces and auxetic structures; the use of digital test methods such as finite element analysis; higher definition additive manufacture processes; and materials such as laser sintering.

Author Disclosure Statement

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Address correspondence to:

Jayme D. Rossiter
 School of Design and Creative Arts
 Loughborough University
 LE11 3TU Loughborough
 United Kingdom

E-mail: j.d.rossiter@lboro.ac.uk