Uniaxial compression of bi-directionally graded lattice structures: Finite element modelling

C Rodrigo, S Xu, Y Durandet and D Ruan
Department of Mechanical and Product Design Engineering, Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, VIC 3122, Australia

E-mail: druan@swin.edu.au

Abstract. Lattice structures are widely used in various engineering applications due to their high weight-to-strength ratio and exceptional energy absorbing performance. The feasibility of using different base materials to fabricate these cellular structures with complex geometries has been significantly broadened with the development of additive manufacturing technology. In this paper, quasi-static mechanical properties and energy absorption capability of polyamide PA 2200 (nylon 12) lattice structures were investigated by using finite element analysis (FEA) in ANSYS/LS-DYNA. Three types of lattice structures composed of body-centred cubic (BCC) unit cells were studied, including uniform lattice structures, uni-directionally graded lattice structures and bi-directionally graded structures. Finite element simulations were consistent with experimental data reported in literature. The results showed that bi-directionally graded lattice structures exhibited superior crushing resistance and higher energy absorption capacity than uniform and uni-directionally graded lattice structures. It showed that density grading design of lattice structures had significant influence on the deformation patterns and therefore, energy absorption performance.

1 Introduction

In recent years, design and manufacturing of vehicle structures with lighter and safer structural elements have been driven by both environmentally friendly concerns and passenger safety requirements [1-3]. Lightweight vehicle structures are generally more environmental friendly because of reduced consumption of fuel and less emissions of greenhouse gases [2]. It is reported that a reduction of 57 kg mass from a vehicle is equivalent to an increase in its fuel economy by 0.09-0.21 km per litre [4]. Among many light-weighting technologies, the application of cellular materials plays an important role due to their exceptional properties such as high strength-to-weight ratio, improved energy absorption and heat transfer characteristics as compared with bulk materials. Therefore, cellular materials such as honeycombs, foams and lattice structures are increasingly utilised in the design of lightweight structures for automotive applications with enhanced crashworthiness and energy absorption properties [5].

Lattice structures are a form of periodically arranged cellular materials with repeated unit cells [6]. These structures are usually made of orderly interconnected struts, which can be easily tuned to manipulate the mechanical properties [7, 8]. In recent years, many studies have been conducted to enhance the mechanical performance of lattice structures for better energy absorption capacities, with the latest focus on employing functionally graded designs. Generally, functionally graded (FG) structures are defined as structures having at least one of its geometric or mechanical properties gradually varied over its volume, such as thickness, density, elastic modulus, energy absorption [1, 9,
Some other FG structures can be designed by altering materials [11], or even by transiting to hybrid materials [12]. A more popular method to achieve functional grading is to change the geometric parameters of the unit cell, such as cell size or strut diameter [1]. However, fabrication of these graded materials or structures using conventional manufacturing technologies is very challenging due to their varying microstructures, materials and geometric features [13].

The development of additive manufacturing (AM) technology has made it easier to fabricate open-cell, lattice or truss-like structures with complex geometries. A number of experimental, numerical, and theoretical investigations have been conducted to evaluate the mechanical properties of additively manufactured strut-based lattice structures consisting of different unit cells, including body-centred cubic (BCC) [14, 15], face-centred cubic (FCC) [9, 14], cubic [16], diamond [17, 18], octet [19-21] and Kagome [22]. However, limited studies have been conducted to focus on cellular structures with functionally graded features achieved by grading the strut diameters. Grunsven et al. [23] studied the progressive collapse of density graded Ti-6Al-4V diamond lattice structures fabricated using electron beam melting (EBM), revealing the great potential of using FG structures as dynamic load protection in biomedical applications. Maskery et al. [10] analysed strut-diameter graded BCC lattice structures of Al-Si-10Mg fabricated by selective laser melting (SLM). But the study was limited to experiments on structures with discontinuous strut-diameters between adjacent layers. Maskery et al. [24] also experimentally investigated the mechanical response of functionally graded polyamide PA 2200 (nylon 12) BCC and BCCZ lattice structures fabricated by selective laser sintering (SLS). The graded BCCZ structure was capable of absorbing around 114% more energy per unit volume as compared with non-graded structures, showing great potential to be used in energy absorption applications. Choy et. al. [16] studied the compressive properties of functionally graded Ti-6Al-4V lattices with cubic and honeycomb unit cells manufactured by SLM. Almost all the studied FG structures with different cell orientations showed higher plateau stress and specific energy absorption than uniform structures by up to 67% and 72%, respectively. Al-Saedi et al. [25] also utilised SLM technique to print AlSi12 F2BCC lattices with graded density achieved by positively grading the strut diameters along the loading direction. The study showed that the 45th shear band failure observed in uniform structure was completely absent in the FG structure which resulted in increased strengths. Recently, Bai et al. [26] investigated polyamide PA 2200 BCC lattice structures printed via SLS, in which the functional grading was achieved by varying both the strut diameters and the size of the unit cells. As compared with the diameter graded structures, size graded structures have shown high modulus and strength under small strains, due to highly stable connection between the lattice layers with same strut diameters.

However, density grading in most of these studies was linear and continuous throughout the structural layers and the strut diameters were gradually changed in a single direction. These designs resulted in weakened strength in the earlier stage of crush, due to the easy collapse of layers with the smallest strut diameter. In this study, finite element analyses were conducted to evaluate the deformation mechanisms and energy absorption capacity of novel functionally graded BCC lattice structures with bi-directional density grading. These bi-directionally graded structures are expected to have relatively high bending strength to weight ratio since the denser surface layers have higher strength than the uniform structures. This property makes bi-directionally graded structures a potential candidate in applications such as energy absorbers with enhanced crashworthiness in the case of side collision of vehicles when structural components are subjected to bending. The mechanical performance of FG structures was compared with that of the uniform and uni-directionally density graded structures with the same relative density. The finite element model was verified against the experimental work by Bai et al. [26] on PA 2200 BCC lattice structures fabricated by SLS. The main aim of this study is to reveal the influence of gradient design of lattice structures on their mechanical properties for the purpose of enhanced crashworthiness.
2 Finite element model

In this paper, commercial ANSYS/LS-DYNA was used to simulate the quasi-static compression of uniform and functionally graded lattice structures. LS-PrePost was employed for pre-processing and post-processing of the finite element models.

Three types of lattice cubes with identical overall relative density of 0.168 were studied, including a uniform structure and two graded structures as listed in table 1. For the graded structures, the diameters of the struts were gradually reduced in Z direction (loading direction), uni-directionally and bi-directionally. In uni-directional structure, the diameter of struts was reduced in one direction from one side to the other, whereas in the bi-directional structure, the diameter of strut was increased from the middle towards the two opposite directions. The cubic lattice samples had the dimension 30 mm × 30 mm × 30 mm, consisting of six BCC unit cells (5 mm for each layer). The BCC unit cell consisted of eight diagonal rods intersecting at the cell centre. For the uniform lattice structure, the strut/rod diameter of the unit cell was kept constant at 0.97 mm. In each layer of FG lattice structures, the relative density was varied by 35%. For uni-directionally graded lattices, the relative density of the six layers in loading direction were 0.070, 0.095, 0.128, 0.172, 0.233 and 0.314 from top to bottom. The corresponding strut diameters were 0.55 – 0.65 mm, 0.65 – 0.76 mm, 0.76 – 0.90 mm, 0.90 - 1.06 mm, 1.06 - 1.26 mm, and 1.26 - 1.51 mm, respectively. For the bi-directionally graded lattices, the two middle layers had the same relative densities of 0.121, which was increased to 0.163 in the adjacent layer and 0.221 in the top and bottom layers. The corresponding strut diameters were 0.74 – 0.87 mm, 0.87 – 1.03 mm, and 1.03 – 1.22 mm, respectively.

The geometric models of lattice cubes were designed in Solidworks and imported to LS-PrePost. In the model, lattice cubes were placed between a fixed (constrained in all degrees of freedom) lower rigid plate, and an upper rigid plate that was set to move downwards (constrained in all degrees of freedom except in translational Y direction) at a constant velocity to crush the sample, mimicking uniaxial compression test, as shown in figure 1. After testing the model for different velocities, the loading velocity was set to 1m/s as it reflected the quasi-static behaviour. The rigid plates were meshed by Belytschko-Tsay shell elements (ELFORM2) of 1.5 mm in size. The lattices were meshed with tetrahedron solid elements (ELFORM13) of 0.5 mm in size. This element size was determined based on a mesh convergence analysis when less than 5% difference in plateau force was observed for different meshing sizes ranging from 0.2 mm to 0.5 mm. Modified piecewise linear plasticity material model in ANSYS/LS-DYNA was employed and material properties of PA 2200 was used. The base material was defined as rate independent. The material constants used for PA 2200 were density \((\rho) = 955.8 \text{ kg/m}^3\), Young’s modulus \((E) = 1450 \text{ MPa}\) and Poisson’s ratio \((\nu) = 0.3\). Actual plastic stress-strain data calculated from the work by Bai et al. [26] was used for the plastic deformation, as listed in table 2 to obtain the post-yield behaviour of PA 2200. The upper and lower rigid plates were modelled using elastic material model having the material properties of steel with density \((\rho) = 7850 \text{ kg/m}^3\), Young’s Modulus \((E) = 210 \text{ GPa}\) and Poisson’s ratio \((\nu) = 0.33\).
Figure 1. A finite element model for uniaxial compression of a BCC uniform lattice structure.

Table 1. Geometry and density gradient of different lattice cubes.

| Type                      | Design                        | Stut diameter (mm) | Layer relative density |
|---------------------------|-------------------------------|--------------------|------------------------|
| BCC unit cell with uniform struts |                               |                    |                        |
| Uniform lattice cubes     |                               | 0.97               | 0.0281                 |
| Uni-directionally graded lattice cubes |                               | 0.55-0.65          | 0.070                  |
|                           |                               | 0.65-0.76          | 0.095                  |
|                           |                               | 0.76-0.90          | 0.128                  |
|                           |                               | 0.90-1.06          | 0.172                  |
|                           |                               | 1.06-1.26          | 0.233                  |
|                           |                               | 1.26-1.51          | 0.314                  |
| Bi-directionally graded lattice cubes | 1.22-1.03 | 0.221 |
|--------------------------------------|-----------|-------|
|                                      | 1.03-0.87 | 0.163 |
|                                      | 0.87-0.74 | 0.121 |
|                                      | 0.74-0.87 | 0.121 |
|                                      | 0.87-1.03 | 0.163 |
|                                      | 1.03-1.22 | 0.221 |

Table 2. True plastic stress-strain data of Nylon matrix material [26].

| Plastic strain (%) | 0   | 0.004 | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 |
|-------------------|-----|-------|------|------|------|------|------|------|
| Yield stress (MPa)| 23.3| 29.2  | 32.7 | 36.2 | 38.7 | 40.6 | 42.1 | 43.3 |

Figure 2. Comparison between the FEM results in this paper, the FEM and experimental results in [26] for a BCC uniform lattice crushing at a constant velocity of 1 m/s.

Automatic surface-to-nodes contacts with a friction coefficient of 0.35 were defined between the rigid plates and the lattice cube. All the other self-contacts were defined to have a friction coefficient of 0.1. Due to symmetry, a quarter model was used in the simulation with symmetrical boundary conditions defined on the two symmetrical planes, where degrees of freedom of the lateral displacements and rotations of nodes were constrained in each X and Z directions. The contact force between rigid plate and lattice sample was output. Other outputs included nodal displacements, energies, and von Mises stress and strain. The models were then solved using LS-DYNA solver in ANSYS. Once the simulation was completed, the results were analysed using LS-PrePost.
A finite element model of the same uniform lattice structures as the ones in literature [26] was verified by experimental data in [26]. Figure 2 compares the stress-strain curves obtained from the FEA in this paper, the FEA in [26] and the experimental results in [26]. It can be seen that the numerical results are in good agreement with the numerical and experimental results in [26]. The value of the plateau stress of the present FEM study was 2.4% smaller than the experimental value, which was acceptable. Based on the verified model, a series of finite element simulations were conducted to predict the mechanical response of uniform and FG lattice structures.

3 Results and discussions

3.1 Stress-strain curves
Significant difference in the stress-strain curves of the three types of lattice structures were observed, as shown in figure 3. The uni-directionally graded lattice had significantly lower strength than the other two types of structures and the bi-directionally graded lattice had the highest plateau stress of 1.06 MPa. The uniform BCC structures had a flat plateau region with an almost constant plateau stress of approximately 0.75 MPa, whereas both the uni-directionally and bi-directionally graded lattices had plateau regions with increasing stress. For the uni-directionally graded lattices, the stress dropped slightly after the onset of yield, followed by a step increasing in the sequence from 1 to 4 as illustrated in Figure 3. For bi-directionally graded lattice, the stress was lower than that of uniform structures before the strain of 0.3. It then surpassed the uniform structure and kept increasing. Unlike the uniform structure, which had a clear onset point of densification, both FG lattices had no clear turning point of densification. Uni-directionally graded structure had the largest densification strain of 0.84 while uniform structure and bi-directionally graded structure had similar densification strains of 0.64 and 0.67, respectively.

3.2 Deformation patterns
Figures 4, 5, and 6 display the deformation patterns of uniform, uni-directionally graded and bi-directionally graded lattice structures obtained from FEA at strains of 0, 0.2, 0.4, and 0.6, respectively. The uniform lattice structure showed uniform collapse pattern, as witnessed by a smooth and flat plateau region in the stress-strain curve. No uneven collapse was observed.

The uni-directionally graded lattice structure exhibited a typical progressive collapse, completely different from uniform lattice structures. Cells with the smallest density fully collapsed first, leading to a significantly low stress. Since the diameter of strut was continuously increasing from top to bottom as shown in figure 5, the progressive collapse continuously propagated to the denser part of the sample. In this case, the low-density cells had completely densified before the densification of high density cells started, leading to a stepwise increment of the plateau stress, as shown in figure 3. At the strain of approximately 0.6, as the progressive collapse propagated to layers with density close to or even higher than that of the uniform structures, the crushing stress surpassed that of the uniform structures accordingly. This unique collapse pattern led to extremely low initial plateau stress due to lowest relative density, and a smoothly transited densification. The deformation pattern and the stress-strain curve of the uni-directionally graded lattice structures are identical to those found in literature [24, 26].

Crushing of bi-directionally graded lattice structures initiated at the middle layers, where the density was the smallest, resulting in relatively lower stress. Subsequently, the collapse propagated to neighbouring higher density layers towards the bottom and top in a relatively uniform manner without fully densification, leading to continuously increasing stress. At the strain of approximately 0.3, the density of the remaining cells that were slightly deformed became larger than that of the uniform structures, and the stress also became increasingly higher. Since the deformation of cells was relatively uniform, the densification strain was similar to the uniform structures.
Figure 3. Stress-strain curves of lattice structures.

Figure 4. Collapse pattern of the uniform lattice structure at different strains 0, 0.2, 0.4 and 0.6 (v-m stands for von Mises).

Figure 5. Collapse pattern of the uni-directionally graded lattice structure at different strains 0, 0.2, 0.4 and 0.6 (v-m stands for von Mises).
3.3 Energy absorption capacity

The energy absorption capacity of these structures is expressed as the energy absorption per unit volume ($W_v$) as presented in equation (1), i.e., the area under the stress-strain curve up to the densification strain $\varepsilon_d$, which can be calculated by:

$$W_v = \int_0^{\varepsilon_d} \sigma(\varepsilon) d\varepsilon$$

where $\sigma$ and $\varepsilon$ are stress and strain, respectively. The total energy absorbed per unit volume up to densification was 0.47 MJ/m$^3$, 0.62 MJ/m$^3$, and 0.71 MJ/m$^3$ for the uniform, uni-directionally graded, and bi-directionally graded lattice structures, respectively.

Figure 7 compares the energy absorption per volume up to densification of the three types of lattice structures. The energy absorption capacity of the uniform lattice was almost linearly proportional to the strain, whereas it followed power relationships for both FG structures. The energy absorption capacity of uni-directionally graded lattice structure was found to be consistently the lowest in the comparable range. Bi-directionally graded structure had a lower energy absorption capacity than uniform structure up to 0.43 strain, but it surpassed uniform structure and increased sharply afterwards.
4 Conclusions

In this paper, different BCC lattice structures including one uniform and two FG lattice structures were designed and analysed by using finite element modelling. Finite element models for uniaxial compression of cubic samples were constructed and verified by experimental results from the published literature. The stress-strain curves, deformation patterns and energy absorption capacity of the lattice structures were analysed. The following conclusions were obtained:

1. The functionally graded designs affect the energy absorption capacity of lattice structures. Bi-directionally graded lattice structures had the highest plateau stress with the highest energy absorption capacity, while the uni-directionally graded lattice structures had the lowest plateau stress.

2. The collapse of FG lattice structures initiated from the cells with the lowest relative density. During compression, when the relative density of the remaining fully deformed or partially deformed cells surpassed the relative density of the uniform lattice structures, the crushing stress would also be greater.

3. In the earlier stage of crush, the energy absorption capacity of FG structures was lower than that of the uniform structures. However, in the final stage, their energy absorption capacity became larger as it was found to increase in a power relationship to the strain.

4. Overall, bi-directionally graded structures had the best mechanical performance and energy absorption capacity among the studied structures. Further optimisation of the structures and collapse mechanisms will be studied in the future.

References

[1] Xu F, Zhang X and Zhang H 2018 A review on functionally graded structures and materials for energy absorption Eng. Struct. 171 309-25
[2] Xiong F, Wang D, Zhang S, Cai K, Wang S and Lu F 2017 Lightweight optimization of the side structure of automobile body using combined grey relational and principal component analysis Struct. Multidiscip. O. 57 441-61
[3] Cui X, Zhang H, Wang S, Zhang L and Ko J 2011 Design of lightweight multi-material automotive bodies using new material performance indices of thin-walled beams for the material selection with crashworthiness consideration Mater. Des. 32 815-21
[4] Han H N and Clark J P 1995 Lifetime costing of the body-in-white: Steel vs. aluminum JOM 47 22-28
[5] Xu X, Zhang Y, Wang J, Jiang F and Wang C H 2018 Crashworthiness design of novel hierarchical hexagonal columns Compos. Struct. 194 36-48
[6] Gibson L J and Ashby M F 1999 Cellular solids: structure and properties (Cambridge University Press)
[7] Maconachie T, Leary M, Lozanovski B, Zhang X, Qian M, Farque O and Brandt M 2019 SLM lattice structures: Properties, performance, applications and challenges Mater. Des. 183 108137
[8] Xu S, Shen J, Zhou S, Huang X and Xie Y M 2016 Design of lattice structures with controlled anisotropy Mater. Des. 93 443-47
[9] Al-Saedi D S J and Masood S H 2018 Mechanical Performance of Functionally Graded Lattice Structures Made with Selective Laser Melting 3D Printing IOP Conf. Ser.: Mater. Sci. Eng. 433 012078
[10] Maskery I, Aboulkhair N T, Aremu A O, Tuck C J, Ashcroft I A, Wildman R D and Hague R J M 2016 A mechanical property evaluation of graded density Al-Si10-Mg lattice structures manufactured by selective laser melting Mat. Sci. Eng. A 670 264-74
[11] Miyamoto Y, Kaysser W A, Rabin B H, Kawasaki A and Ford R G 1999 Functionally graded materials: Design, processing and applications (United States: Kluwer Academic Publishers, Hingham, MA (US))
[12] Liu Z, Meyers M A, Zhang Z and Ritchie R O 2017 Functional gradients and heterogeneities in biological materials: Design principles, functions, and bioinspired applications Prog. Mater. Sci. 88 467-98

[13] Zhang C et al 2019 Additive manufacturing of functionally graded materials: A review Mat. Sci. Eng. A 764 138209

[14] Tancogne-Dejean T and Mohr D 2018 Stiffness and specific energy absorption of additively-manufactured metallic BCC metamaterials composed of tapered beams Int. J. Mech. Sci. 141 101-16

[15] Feng Q, Tang Q, Liu Z, Liu Y and Setchi R 2016 An investigation of the mechanical properties of metallic lattice structures fabricated using selective laser melting P. I. Mech. Eng. B-J Eng. 232 1719-30

[16] Choy S Y, Sun C N, Leong K F and Wei J 2017 Compressive properties of functionally graded lattice structures manufactured by selective laser melting Mater. Des. 131 112-20

[17] Xia Y, Feng C, Xiong Y, Luo Y and Li X 2019 Mechanical properties of porous titanium alloy scaffold fabricated using additive manufacturing technology Int. J. Appl. Electrom. 59 1087-95

[18] Zhong T, He K, Li H and Yang L 2019 Mechanical properties of lightweight 316L stainless steel lattice structures fabricated by selective laser melting Mater. Des. 181 108076

[19] Dong L 2019 Mechanical response of Ti–6Al–4V hierarchical architected metamaterials Acta Mater. 175 90-106

[20] Kang D, Park S, Son Y, Yeon S, Kim S H and Kim I 2019 Multi-lattice inner structures for high-strength and light-weight in metal selective laser melting process Mater. Des. 175 107786

[21] Ling C, Cernicchi A, Gilchrist M D and Cardiff P 2019 Mechanical behaviour of additively-manufactured polymeric octet-truss lattice structures under quasi-static and dynamic compressive loading Mater. Des. 162 106-18

[22] Liu Z, Chen H and Xing S 2020 Mechanical performances of metal-polymer sandwich structures with 3D-printed lattice cores subjected to bending load Arch. Civ. Mech. Eng. 20 89

[23] Van Grunsven W, Hernandez-Nava E, Reilly G, Goodall R 2014 Fabrication and Mechanical Characterisation of Titanium Lattices with Graded Porosity Metals 4 401-09

[24] Maskery I, Hussey A, Panesar A, Aremu A, Tuck C, Ashcroft I and Hague R 2016 An investigation into reinforced and functionally graded lattice structures J. Cell. Plast. 53 151-65

[25] Al-Saeidi D S J, Masood S H, Faizan-Ur-Rab M, Alomarah A and Ponnusamy P 2018 Mechanical properties and energy absorption capability of functionally graded F2BCC lattice fabricated by SLM Mater. Des. 144 32-44

[26] Bai L, Gong C, Chen X, Sun Y, Xin L, Pu H, Peng Y and Luo J 2020 Mechanical properties and energy absorption capabilities of functionally graded lattice structures: Experiments and simulations Int. J. Mech. Sci. 182 105735