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# COMPARATIVE ANALYSIS BETWEEN THE MECHANICAL BEHAVIOUR OF GRADIENT AND UNIFORM LATTICE STRUCTURES USING FINITE ELEMENT ANALYSIS

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**Abstract**

The objective of this paper is to study the mechanical characteristic of gradient lattice structures. Lattice structures can be found in the automotive, aircraft, biomedical and aerospace industries due to their high strength-to-weight ratio properties. Gradient lattice structure, also known as the functionally graded structure is a complex design of metallic lattice structure that can be manufactured using additive manufacturing. However, despite the manufacturability of complex forms offered by additive manufacturing, the mechanical characteristics and design of these structures are yet to be fully understood. A study was conducted to study the mechanical behaviours of gradient lattice structures. The method consists of uniaxial compression tests using finite element analysis to identify the translational displacements. Two case studies of gradient and uniform lattice structure containing the same design space were conducted. From the simulation results, in comparison to uniform lattice structures, it was observed that gradient lattice structures have different mechanical behaviours and deformation. In the same design space, the gradient lattice structure which has a lower mass value than uniform cubic lattice structure showed lower displacement values for both cases compared to uniform lattice structure. In conclusion, the results demonstrate that gradient cubic lattices in a trapezium-shaped design space are better than a uniform lattice structure when overcoming stresses and displacements. This finding is significant in the design methods of more efficient lightweight parts in the future.

Keywords: Additive manufacturing, Finite element analysis, Gradient lattice structure, Mechanical behaviour, Translational displacement.

## 1. Introduction

Cellular structures were introduced 30 decades ago. Earlier researchers in this field, L. J. Gibson [1] stated that lattice structures consist of a combination of connected trusses, as shown in Fig. 1. Cellular solids' unique hollow and periodic geometry provides a high strength-to-weight ratio which increases the chances of the formation of architectured materials [2]. This property of cellular structures makes it popular in the automotive [3], aerospace [4], aircraft [5] and biomedical field [6]-[10]. Figure 1 shows one unit cell repeated in XYZ direction forming a larger cubic lattice structure made of small unit cells (5 x 5 x 5 unit cell).

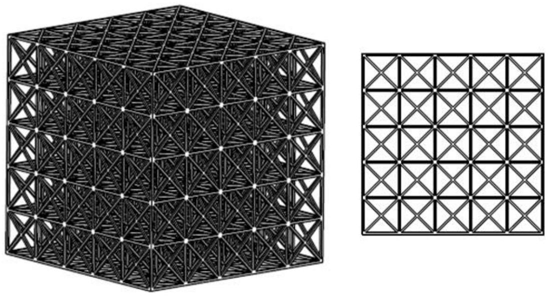
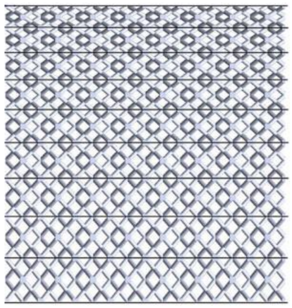


**Fig. 1. Isometric view and front view of the lattice structure.**

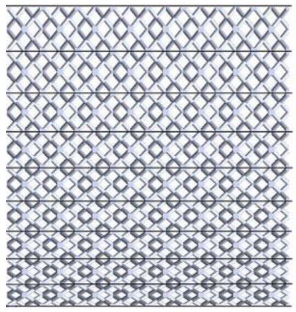
However, a uniform lattice structure provides limitations such as no control in density and porosity along the volume [11], and lack of control over localisation change in stiffness. Besides, the capability of additive manufacturing advance technology enlarges the geometrical freedom of lattice structure by offering a layer based building process [12]. Hence, gradient lattice structure (GLS), or also known as the functionally graded structure was introduced. Physical properties of the inner structure change over the volume resulting in the change of its density. Gradient characteristics can be formed by changing the cell size [13], cell grading [14], and strut thickness [15-17]. This has been discussed by a great number of authors in literature.

Maskery et al. (2016) [18] developed an Al-Si10-Mg body-centered cubic (BCC) graded lattice structures manufactured via selective laser melting technology. The density of the structure changes gradually throughout the layers of the structure by varying the cell diameter. They reported that the graded density structure showed novel deformation behaviour when it collapses sequentially layer-by-layer from low densification layer to high densification layer (top to bottom layer). Choy et al. (2017) [17] varied struts diameter for cubic and hexagon in two different orientations resulting in the increase of density from the top to the bottom layer. They reported that the deformation behaviour between uniform and graded lattice structure are not the same especially when the first maximum values of compressive strength for uniform lattice structures (both orientations) were higher than graded lattice structures. Xiao and Song [13] varied the size of the unit cell for rhombic dodecahedron lattice structure with step-wise and continuous gradient designs. They performed static compressive analysis for positive and negative gradient lattice (as shown in Fig. 2). Alsaedi et al. [15] (2018) results reported to have a good agreement as Maskery et al. and Choy et al. Their F2BCC graded lattice structure collapse in sequence and have higher first maximum compressive strength compared to uniform lattice structure in both experimental and numerical results. In addition, Alsaedi et al. also proved that functionally graded lattice structure can provide better energy absorption.

Moreover, a series of recent studies have shown that lattice structures are suitable for energy absorption parts. Tancogne-Dejean [19] showed that specific energy absorption increases depending on the relative density. The theory was proven by Kohnen et al. [20] where F2BCC,Z lattice structure shows the same performance under compression with an energy absorption function. Hollow lattice truss reinforced honeycomb (honeytubes) proposed by Yin et al. [21] were found to be superior in crushing protection and absorption.



**a) Positive gradient**



**b) Negative gradient**

**Fig. 2. Step-wise rhombic dodecahedron gradient lattice structure with two types of progressivity a) positive gradient and b) negative gradient [13].**

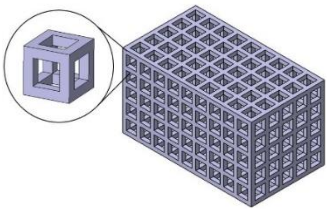
GLS can lead to different mechanical behaviours compared to uniform lattice structures. However, even though the existence of lattice structures has been known for several years, the design of gradient lattice structure is yet to be explored by researchers. The capability of gradient lattice structure in withstanding uniaxial stress compares to uniform lattice structure is not yet studied. Further research is needed to analyse the design of gradient lattice structures [22]. The main purpose of this paper is to determine the advantages of gradient lattice structures compared to uniform lattice structures through the investigation of their mechanical properties, especially in displacement and energy absorption. Gradient lattice structures are expected have lower displacement values and higher energy absorption compared to uniform lattice structure when quasi-static stress is applied.

## 2. Methods

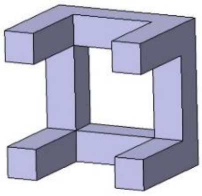
This section presents the methodology in modelling uniform and gradient lattice structures and finite element analysis of the models to obtain the translational displacements.

### Modelling and analyzing uniform and gradient lattice structure

The lattice structure is formed by repeating a simple cubic unit cell in x and y-axis directions. Figure 3 shows an example of a cubic lattice structure designed in CAD software where each elementary structure is constructed using 12 solid square cross-section trusses.



**a) A simple cubic unit cell made of 12 trusses**



**b) Cross section of the unit cell**

**Fig. 3. Simple cubic unit cells forming a uniform lattice structure.**

The lattice structure samples were designed and analysed using CAD software CATIA V5R15 using the Generative Structural Analysis tool. It is suitable for linear static analysis and has the same interface as the design environment. From the flowchart in Fig. 4, the first step is to develop the cubic lattice structures. Two cases were form named case 1 and case 2 respectively, where the topology is a simple cubic unit cell with a trapezium design space. Each case has uniform and gradient lattice with the same size and mass and difference in the total number of unit cells inside the structure. The size of the elementary unit cell is 5 x 5 x 3.33 mm in case 1, and 3 x 5 x 3.33 mm in case 2. And the size is unchanged throughout the volume for uniform lattice structure. As for GLS, The struts' lengths were varied layer-by-layer by a constant multiplication of 0.85. A formula used in forming gradient structure was presented by Azman [23] as shown in Eq. (1) where the lengths in the Z-direction changes gradually by the multiplication of 0.85. As shown in Figs. 5(b) and 5(d), the lengths in the Z-direction for gradient lattice structures in both cases were 5, 4.25, 3.61, 3.07, 2.61 and 1.46 mm.

$$Z = z^* \text{ (maths formula or constant dimension)} \quad (1)$$

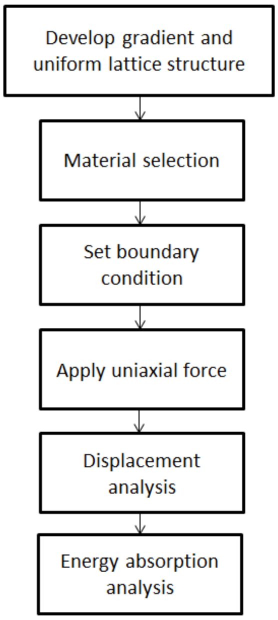


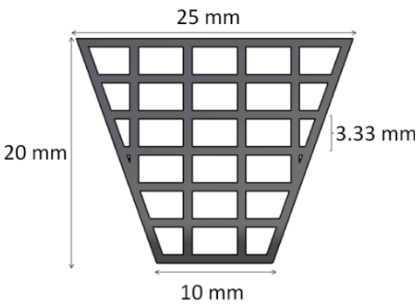
**Fig. 4. Flowchart of GLS development methodology.**

The design volume for each lattice structure was fixed to 25 x 25 x 20 mm and then cut to a trapezium shape to obtain a gradual decrease of the sectional areas of the part (as shown in Fig. 5). The dimensions of the models were based on the standard specifications of SLM and EBM additive manufacturing machines, which are 200 x 200 x 200 mm design volume, minimum layer thickness of 0.05 mm minimum feature size of 0.1 mm, hence ensuring manufacturability of the lattice structures chosen in this work. The lower the sectional area, the higher the stress applied. Hence, we proposed denser layers at the lower of the part and less dense layers at the higher area of the part for the gradient lattice structures. While the size of the strut 0.8 mm diameter remains unchanged. The mass of each lattice structure was adjusted to be similar for a suitable comparison. As shown in Table 1, the uniform lattice structures for both cases have 2.17% and 2.59 % more mass than gradient lattice structures.

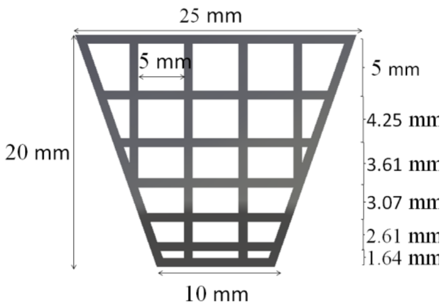
**Table 1. Physical properties of the final product of lattice structures.**

| Properties | Case 1 | | | Case 2 | | |
|---|---|---|---|---|---|---|
| | Uniform lattice | Gradient lattice | Difference (%) | Uniform lattice | Gradient lattice | Difference (%) |
| Mass (g) | 10.35 | 10.13 | 2.17 | 11.62 | 11.33 | 2.59 |
| Volume ($\times 10^{-6}$) ($m^3$) | 2.32 | 2.27 | 2.2 | 2.60 | 2.54 | 2.6 |
| Area ($m^2$) | 0.007 | 0.007 | 0 | 0.009 | 0.009 | 0 |

**Case 1**

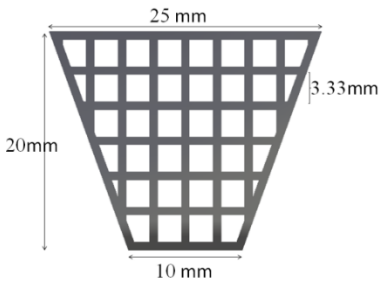



**a) Uniform lattice structure**

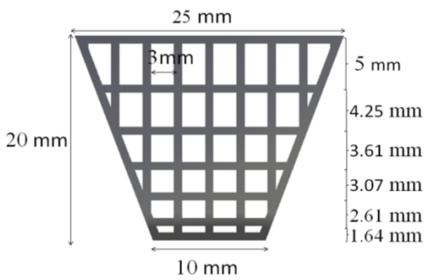



**b) Gradient lattice structure**

**Case 2**




**c) Uniform lattice structure**




**d) Gradient lattice structure**

**Fig. 5. Dimensions of a) uniform and b) gradient lattice structure in case 1 and c) uniform and d) gradient lattice structure in case 2.**

After the models were fully created, the material is selected. In this case, titanium (Ti-6Al-4V) is selected as the material because it is weight saving compared to steel and its biocompatibility property. Ti-6Al-4V are commonly used in additive manufacturing parts in the aerospace and biomedical industry and can be manufactured using SLM and electron beam melting (EBM) machines. The mechanical properties of Ti-6Al-4V are 120 GPa for its modulus of elasticity and 950 MPa yield strength. Next, set the boundary condition of the structure. Figure 6 shows the position of the clamp and uniform force applied for compression and shear tests of the quasi-static analysis. A clamp was fixed at the bottom part while the distributed force of 1000 N on the surface of the top part of the structure was applied. A force of 1000 N was chosen to remain in the elastic region of the lattice structure. Octree tetrahedron mesh was applied with a size of 0.27 mm which is three times smaller than the strut size [23]. Approximately 770000 elements and 130000 nodes were generated and the mesh convergence has been verified (Fig. 7). The FEA was conducted and the displacement for each layer for all the lattice structures was analysed and compared.

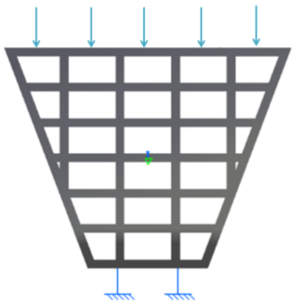


**Fig. 6. Load and clamping position for uniaxial compression test.**

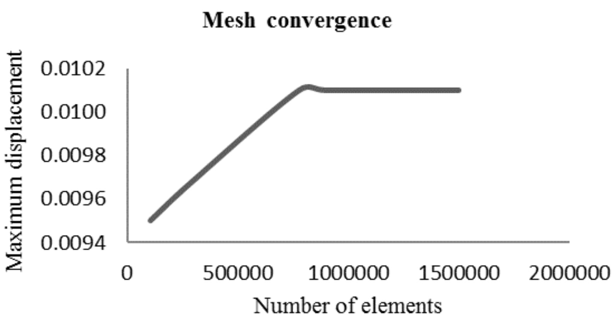



**Fig. 7. Mesh convergence test of maximum displacement value with the number of elements.**

## 3. Results and discussion

This section presents the displacement and shear analyses of uniform and gradient lattice structures for case 1 and case 2.

### 3.1. Displacement analysis

The displacement analysis is divided into two parts. The first part is the maximum displacement value and the second part is the displacements at a specific location for each layer of all the lattice structures. One centre point for six layers of the structure is picked as shown in Fig. 8 and the displacements were compared for both structures.

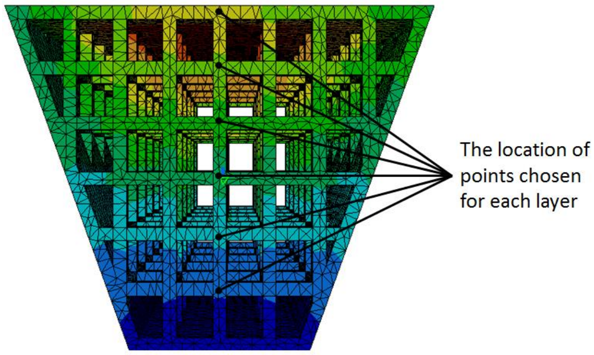



**Fig. 8. The points are chosen to compare the displacement value for uniform and lattice structure.**

#### 3.1.1. Case 1

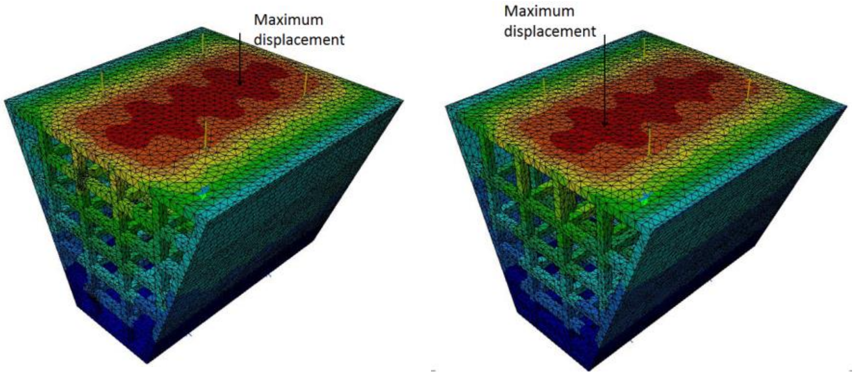
The translational displacement magnitude of the FEA model after the stress analysis was conducted is presented in Fig. 7. The uniform lattice structure was observed to have a lower maximum displacement compared to the gradient lattice structure as shown in Table 2. Lower displacement values in uniform lattice structure indicate a higher compressive strength. The same case was observed by Choy et al. [17] where the initial maximum compressive strengths of all functionally graded material samples were smaller than for uniform strut samples. The failure started from the lowest density and gradually increased for the functionally graded material structures. While for uniform lattice structures, the deformation started randomly in the struts. The maximum displacements were located on the top part of the first layer which is red and yellow in colour, as shown in Fig. 9.

**Table 2. The maximum displacement values and their positions for case 1.**

| Case number | Type of lattice structure | Coordinate | | | Maximum displacement (mm) |
|---|---|---|---|---|---|
| | | *x* | *y* | *z* | |
| **Case 1** | Uniform | -17.4 | 22.5 | 20.4 | 0.00916 |
| | Gradient | -17.4 | 22.5 | 21.2 | 0.00923 |

Even though the maximum translational displacement for uniform lattice structure is lower, a comparison of displacement at a specific point is a novel behaviour. Table 3 shows the displacement magnitudes at each layer in case 1. The gradient lattice structure compared uniform lattice structure has a lower displacement value on the first layer with 12.1 % and increases throughout the layer and can reach as high as 59 % on the sixth layer. Relative density for uniform lattice structures which is unchanged across the volume differs to gradient lattice structures, where the relative density increases gradually from the top to the bottom layer. Based on Table

3 from layer 1 to layer 6, as the density of the layers increases, the displacement decreases and less deformation occurs during the compression process which cause the percentage difference value to increase from 12.1% to 59 %.




**a) Uniform lattice structure** **b) Gradient lattice structure**

**Fig. 9. FEA displacement analysis result for case 1.**

**Table 3. Displacement magnitudes at each layer in case 1.**

| Layer | Uniform lattice structure | | | | Gradient lattice structure | | | | Difference (%) |
|---|---|---|---|---|---|---|---|---|---|
| | Coordinates of layer | | | Displacement of layer (mm) | Coordinates of layer | | | Displacement of layer (mm) | |
| | *x* | *y* | *z* | | *x* | *y* | *z* | | |
| **1** | 0.4 | 22.6 | 20.0 | 0.0066 | 0.4 | 22.5 | 20.4 | 0.0058 | 12.1 |
| **2** | 0.4 | 22.6 | 16.7 | 0.0051 | 0.4 | 22.4 | 16.2 | 0.0043 | 15.7 |
| **3** | 0.4 | 22.5 | 13.4 | 0.0040 | 0.4 | 22.3 | 11.9 | 0.0030 | 11.1 |
| **4** | 0.4 | 22.5 | 10.0 | 0.0031 | 0.4 | 22.5 | 8.3 | 0.0019 | 38.7 |
| **5** | 0.4 | 22.5 | 6.7 | 0.0020 | 0.4 | 22.3 | 5.2 | 0.0010 | 50 |
| **6** | 0.4 | 22.5 | 3.3 | 0.0010 | 0.4 | 22.5 | 2.6 | 0.00041 | 59 |

### 3.1.2. Case 2

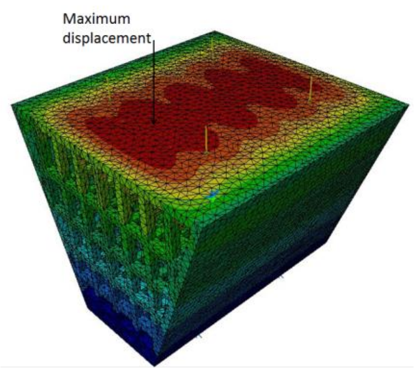
The smaller size of unit cells in case 2 causing more unit cells needed to fill in the same design space (25×25×20 mm) as in case 1. Therefore, the high amount of unit cells in case 2 resulting in a higher relative density as well. Hence, the trend for displacement analysis observed in case 2 is the same as in case 1 with lower values. Table 4 shows the difference in maximum displacement values for both structures.

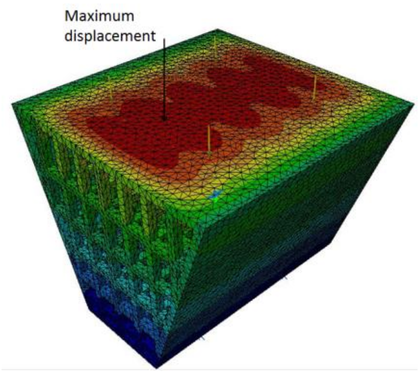
The translational displacement of gradient lattice structure is 8.8 % to 55.9 % lower than the uniform lattice structure. The smaller the height of the elementary structure, the higher the force it can withstand. The density of the lattice structures in case 2 is higher than in case 1. Table 5 shows that the displacement of each layer is lower compared to the value in Table 3, this is due to the higher relative density in case 2.

**Table 4. The maximum displacement values and their positions for case 2.**

| Case number | Coordinate |
|---|---|

| | Type of lattice structure | *x* | *y* | *z* | Maximum displacement (mm) |
|---|---|---|---|---|---|
| **Case 1** | Uniform | -7.4 | 13.8 | 20.4 | 0.00568 |
| | Gradient | -7.4 | 14.3 | 20.4 | 0.00569 |




**a) Uniform lattice structure** **b) Gradient lattice structure**

**Fig. 9. FEA displacement analysis result for case 2.**

**Table 5. Displacement magnitudes at each layer in case 2.**

| **Layer** | **Uniform lattice structure** | | | | **Gradient lattice structure** | | | | **Diff-erence (%)** |
|---|---|---|---|---|---|---|---|---|---|
| | **Coordinates of layer** | | | **Displace-ment of layer (mm)** | **Coordinates of layer** | | | **Displace-ment of layer (mm)** | |
| | ***x*** | ***y*** | ***z*** | | ***x*** | ***y*** | ***z*** | | |
| **1** | 0.4 | 14.9 | 20.1 | 0.0034 | 0.4 | 15.2 | 20.4 | 0.0032 | 8.8 |
| **2** | 0.4 | 15.0 | 16.7 | 0.0032 | 0.4 | 15.0 | 16.9 | 0.0028 | 12.5 |
| **3** | 0.4 | 15.0 | 13.4 | 0.0025 | 0.4 | 15.0 | 13.4 | 0.0019 | 24 |
| **4** | 0.4 | 15.0 | 10.0 | 0.0019 | 0.4 | 15.0 | 9.8 | 0.0013 | 31.6 |
| **5** | 0.4 | 15.0 | 6.6 | 0.0013 | 0.4 | 15.0 | 6.6 | 0.00073 | 43.8 |
| **6** | 0.4 | 15.0 | 3.4 | 0.00068 | 0.4 | 15.0 | 3.4 | 0.00030 | 55.9 |

Gradient lattice structures have less deformation compared to uniform lattice structures when subjected to a uniaxial compression force and that smaller the height of the unit cells, the higher the density, hence causing it to have less deformation, as demonstrated from the results in case 1 and 2. Further investigations need to be performed by manufacturing the lattice CAD models using SLM and perform experimental tests on the models to find a more accurate result. Considering results from past studies [17], experimental and simulation results can differ to each other mainly because of manufacturing error such as porosities and coarse surface roughness.

To validate the results, a comparison was made to other results in the literature. The FEA results in this work and the FEA results in the literature shows good agreement [23]. For the same relative density of 0.19, the relative Young's modulus obtained from the FEA on the uniform lattice structure in this work is 0.08, while the result obtained from the literature based on the equation: $y = 0.9337x^{1.4034}$ is

0.09. The findings are directly in line with previous findings. In addition, the FEA results obtained by Azman [23] have been compared and validated to other methods in the literature and shows good correlation for FEA, analytical and experimental results [24].

## 3.2. Energy absorption

Since the compression analysis for this paper happened at the elastic region, the energy absorption analysis is limited to elastic region only (Fig. 11) and is compared to other researchers. However, the deformation pattern of Alsaedi et al. [15] and Maskery et al. [25] analyses is similar to the analysis in this work in the initial deformation. Maskery et al. explains that linear elastic behaviour occurs at low strain and changes when entering the plastic region. The behaviour of uniform and graded lattice structure at the plastic region is completely different where the collapse occurs layer-by-layer in graded lattice structures which supports the hypothesis that gradient lattice structures are better when overcoming stresses [15]. This novel behaviour resulting in higher cumulative energy absorption by gradient lattice structure reported by Alsaedi. Alsaedi et al. [15] reported that the determination of energy absorption is by integrating the area under the compressive stress-strain curves. The deformation in the FEA model in case 1 and case 2 needs further investigation in the analysis as well as experimentation to get a clearer image about energy absorption behaviour comparison between uniform and gradient lattice structures in the plastic region.

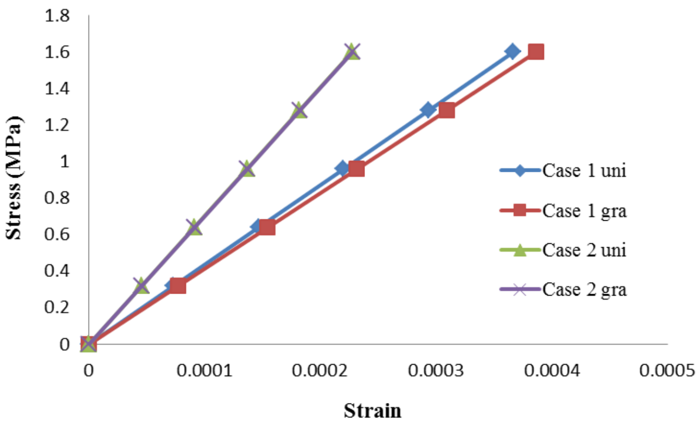



**Fig. 11 Stress-strain graph (elastic region) of case 1 and case 2 lattice structures**

The lattice structure models developed are suitable for the biomedical application. The progressivity of the gradient lattice structure produces scaffold patterns that carry almost similar property as human bones and can provide a structure for new bone tissues to grow into. Previous literature has been published by Han et al. for producing new methodologies to design and manufacture bone implant scaffold structures by varying the strut diameters of the lattice structures [6]. In addition, van Grunsven et al. reported that the layer-by-layer deformation behaviour is suitable for surgical implants and become protection against dynamic loads [26]. Similarly, the models presented in this paper have the possibility of producing a better lightweight bone implant structure in the future. The cell variation and strut thickness progression of the gradient lattice structure can be optimized to match the stiffness of the surrounding bone. It may be possible to create a strain gradient on the bone, which can accelerate growth.

## 4. Conclusions

Gradient lattice structures in case 2 are observed to have lower translational deformation than gradient lattice structure in case 1. In conclusion, this study shows that gradient lattice structures have better performance in the quasi-static analysis since it has gradual higher density compared to uniform lattice structures; hence it has a lower magnitude of displacements layer-by-layer. The FEA performed can be applied in investigating the mechanical characteristics of lattice structures. Hence, gradient lattice structures are better when overcoming stresses than uniform lattice structures. This finding will contribute to the design of more efficient lightweight parts in the future in the automotive, biomedical and aerospace industries. Future work will be conducted in biomedical field especially in bone implant applications.

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### Nomenclatures

| | |
|---|---|
| *Z* | New strut length in Z-direction |
| *z* | Old strut length in Z-direction |

**Abbreviations**

| | |
|---|---|
| BCC | Body-centered cubic |
| CAD | Computer-aided design |
| EBM | Electron-beam melting |
| FEA | Finite element analysis |
| F2BCC | Combination of two face-centered cubic and body-centered cubic |
| F2BCC,Z | F2BCC with the addition of z strut in every unit cell |
| GLS | Gradient lattice structure |
| SLM | Selective laser melting |
| Ti-6Al-4V | Titanium alloy |

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