

Compressive Properties of Additively Manufactured Functionally Graded Kagome Lattice Structure

Rinoj Gautam and Sridhar Idapalapati *

Singapore Centre for 3D Printing, School of Mechanical and Aerospace Engineering,
Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore; rinoj001@ntu.edu.sg

* Correspondence: msridhar@ntu.edu.sg; Tel.: +65-6790-4784

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Abstract: Cellular lattice structures have important applications in aerospace, automobile and defense industries due to their high specific strength, modulus and energy absorption. Additive manufacturing provides the design freedom to fabricate complex cellular structures. This study investigates the compressive properties and deformation behavior of a Ti-6Al-4V unit Kagome structure fabricated by selective laser melting. Further, the mechanical performance of multi-unit and multi-layer Kagome structure of acrylonitrile butadiene styrene (ABS) ABS-M30™ manufactured by fused deposition modeling is explored. The effect of a number of layers of Kagome structure on the compressive properties is investigated. This paper also explores the mechanical properties of functionally graded and uniform density Kagome structure. The stiffness of the structure decreased with the increase in the number of layers whereas no change in peak load was observed. The functionally graded Kagome structure provided 35% more energy absorption than the uniform density structure.

Keywords: additive manufacturing; cellular lattice; Kagome; SLM; FDM; functionally graded; energy absorption

1. Introduction

Cellular lattice structures have major applications in the aerospace, automobile and defense industries due to their high specific strength, stiffness and energy absorption capacity. The mechanical performance of the lattice structures depends on the architecture and the parent material. Conventional manufacturing methods of open lattice structures include investment casting, deformation forming and wire woven textile [1]. The effectiveness of producing complex design is limited in conventional methods. Additive manufacturing (AM) is a new state of art which provides design freedom in the fabrication of the lattice structures. With various AM processes, these structures can be fabricated with a wide range of materials and various polymers for ferrous and non-ferrous metal alloys.

The performance and deformation behavior of the various cellular structures under different loading conditions has been investigated. The stretch dominated structures have higher compressive peak strength and modulus than the bending dominated structures [2]. Octet truss structure is a stretch dominated structure with favorable properties over metallic foams, which can be considered as an alternative in the lightweight design. 3D Kagome structure is another near stretch dominated structure which is formed by the combination of two tetrahedral structures vertically inverted with each other and offset by 60° as shown in Figure 1 [3]. It has higher compressive strength and effective moduli than other competitive structures, tetrahedral and pyramidal [4,5]. A Kagome structure exhibited more resistance to plastic buckling under the compression and shear than other lattices structures. A wire woven Kagome structure showed higher compressive strength and better energy absorption characteristics to aluminum foams and egg box structures [6]. Ti-6Al-4V Kagome structures fabricated by selective laser melting showed better compressive and shear strength to conventional honeycomb

structures [7]. They displayed similar effective moduli and energy absorption capacity to the honeycomb structures [8]. A strut-reinforced Kagome structure displayed better compressive strength and effective moduli but lower failure strain and energy absorption when compared to Kagome [9].

Functionally graded materials have a gradual change in the composition or the morphology over the volume, which results in a gradual change in its mechanical or functional properties over the thickness [10,11]. They can be graded either compositionally or geometrically. With additive manufacturing, functionally gradient structures can be obtained by using two approaches. One approach can be the manipulation of various process parameters to get variation in the density of the parts. The density variation with this approach has no control over the internal architecture of the parts [12]. The second approach is to design the lattice structures with the variation in the density using the CAD modeling at the design stage and fabricate the whole structure with the same process parameters. Many investigations focused on the mechanical properties of graded density foam structures, honeycomb and open lattice structures. Maskery et al. investigated the deformation and compressive properties of selective laser sintering (SLS) fabricated polyamide (PA 2200) BCC (body centered cubic) and BCCZ (BCC with vertical column) structures with uniform and graded density [13]. The graded density structure exhibited higher energy absorption prior to the densification. Their research on the aluminum BCC structures fabricated by selective laser melting (SLM) revealed the progressive collapse failure in the graded density structures [14]. Choy et al. explored the mechanical properties of functionally graded cubic and honeycomb lattice made of Ti-6Al-4V fabricated by SLM [12]. The graded structures exhibited progressive layer collapse starting with the least dense layer whereas abrupt shear failure was observed in the uniform density structures.

In this study, initially, the compressive properties of a unit Kagome structure fabricated by selective laser melting are investigated. The ultimate goal of this study is to explore the deformation and compressive properties of uniform and graded density Kagome structure. It is difficult to fabricate multilayer Kagome structure with intact face sheets using selective laser melting without any support material. Thus, to understand the deformation behavior of the graded and uniform density of multi-layer structures, the multi-unit specimens were fabricated using fused deposition modeling. The effect of the number of layers on the compressive load and stiffness of a multi-layer Kagome structure was investigated. Further, the deformation behavior and compressive properties of graded structure were explored and compared with that of a uniform density. For the same weight, the graded structure on the load application can absorb more energy than the uniform density one.

2. Materials and Methods

2.1. Design and Fabrication

The unit Kagome structure is geometrically fully defined by the height of the core (h), the inclination of the strut with the horizontal plane (θ) and the diameter of the struts (d) as shown in Figure 1. In our study, the unit Kagome structures were designed with a core height of 11.5 mm, the inclination angle of 54.74° ($\theta = \tan^{-1} \sqrt{2}$) and 1.12 mm strut diameter along with two face sheets of 2 mm thickness for SLM printing. The FDM cannot fabricate the structure with a low diameter, thus the Kagome structure was designed with a 13 mm core height, 2.62 mm strut diameter and 3 mm face sheets thickness.

A Kagome structure with 3×3 units was designed to study the compressive properties of a multi-unit Kagome structure. The arrangement of the unit structures in the multi-unit Kagome is illustrated in Figure 2 through the front, side and isometric views. To study the effect of the number of layers on the compressive performance of the Kagome structure, the specimens were designed to have one to three layers. The 2 mm thick face sheets were used at the interfaces between the layers. Single layer specimens have 3×3 units of Kagome whereas two layered specimens have 4×4 units in the bottom layer and 3×3 units on the top layer. The specimens with three layers have 3×3 units on the top layer, 4×4 units in the intermediate layer and 5×5 units on the bottom layer. It was designed with these increasing numbers of the units so that the load applied on the top layer Kagome struts can

be transmitted all the way to the bottom layer, as shown in the side view of Figure 3. The design with an equal number of units in each layer, some struts near the boundary would have been redundant in supporting the applied load [6].

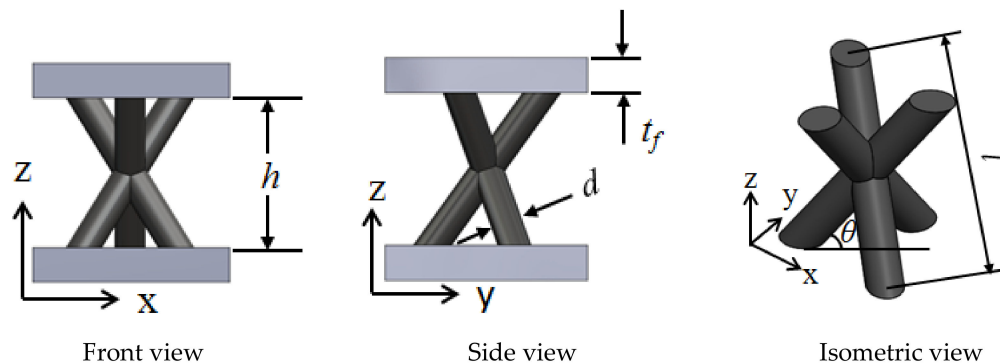


Figure 1. Front, side and isometric views of Kagome unit structure.

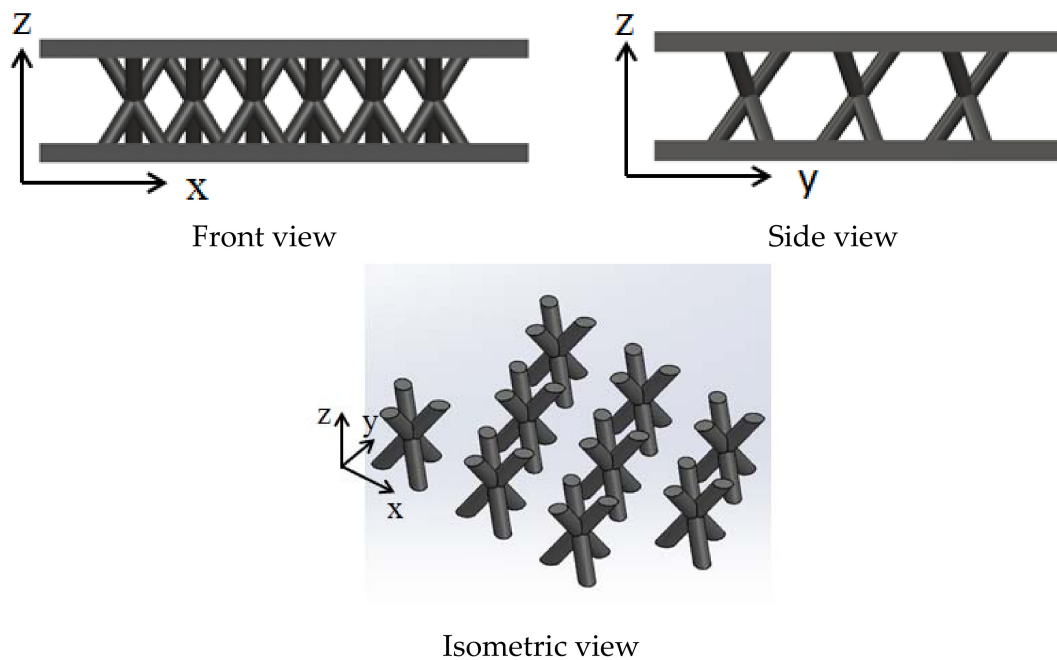


Figure 2. Front, side and isometric views of Kagome structure with 3×3 units.

The graded structure also has three layers with the same number of Kagome units as in a normal three layered structures. The relative density of the uniform diameter Kagome truss with the given core height of 13 mm and diameter of 2.62 mm is 9%. To compare the mechanical performance of uniform and graded density lattice structures on an equal mass basis, the graded structure with relative densities of 6.36%, 8.9% and 11.83% at the top, intermediate and the bottom layer, respectively was designed. The average relative density of these three layers is 9% which is equal to the relative density of uniform density structures. The corresponding diameter in the graded density Kagome structures is 2.2 mm, 2.6 mm and 3.0 mm at the top, intermediate and bottom layers respectively. The design of the uniform density structure and graded density structure is shown in Figure 3.

The unit Kagome structures were fabricated by SLM 250HL (SLM Solutions®) with Ti-6Al-4V powder. The machine specific Grade 23 Ti alloy powder was supplied by SLM Solutions and obtained through gas atomization with spherical particle of size range 20 to 63 μm . The SLM build parameters include the laser power of 175 W, layer thickness of 30 μm , scan speed of 710 mm/s, hatch spacing of

120 μm and line scan strategy. The printing was carried out in an argon environment with less than 0.05% oxygen to prevent oxidation during the process.

In view of the limited SLM machine time availability, we analyzed the multi-unit layer structural behavior through fused deposition modeling (FDM) on a Stratasys® F370 using ABS-M30™ material. The manufacturer claims that ABS-M30™ material is 25%–70% stronger than standard ABS and is used for manufacturing tools and production parts. The support material was dissolved in using the detergent (Ecoworks™ cleaning agent) water. The printed model parts were treated chemically with 90% by vol. acetone for three minutes to reduce the surface roughness [15]. To measure the diameter of the struts in Kagome structures, individual struts oriented in the same angles as in whole structures were fabricated keeping the same processing conditions.

2.2. Mechanical Testing

Compression testing of all Kagome structures was carried out on Instron® universal testing machine (Instron 5969, Instron, Norwood, MA, USA) equipped with 50 kN load cell. The compressive load was applied at the rate of 0.5 mm/min for Ti-6Al-4V unit Kagome structure whereas 0.2 mm/min for ABS Kagome structures. A digital camera (Nikon® D7200, Nikon, Tokyo, Japan) was used to record the test and frames were extracted to illustrate the deformation at different stages of the compression.

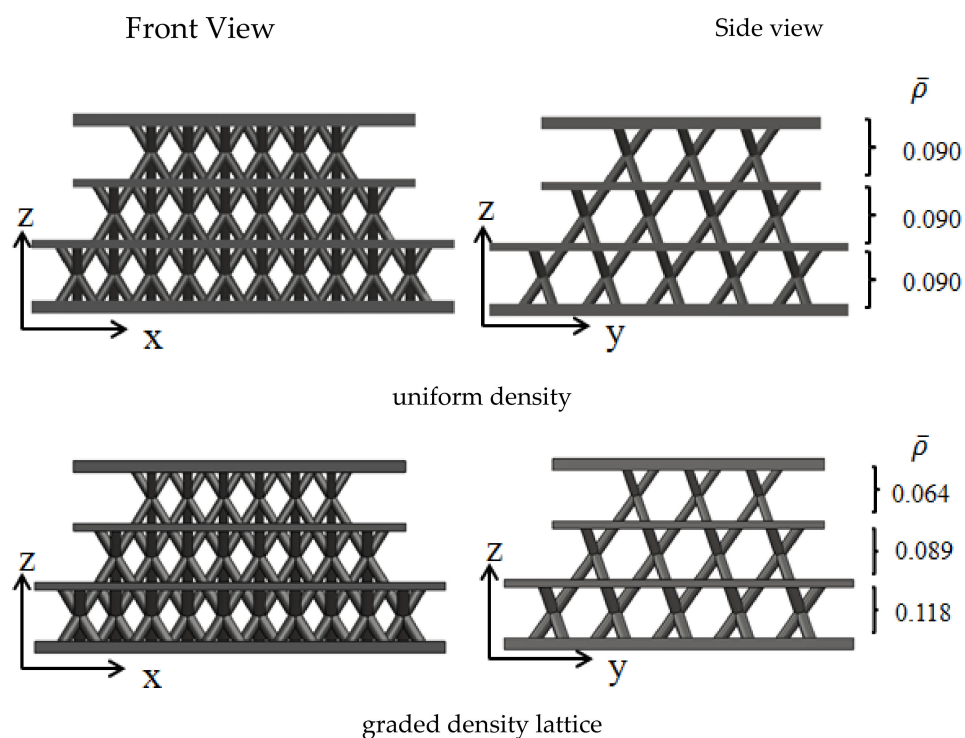


Figure 3. CAD model of uniform and graded density Kagome lattice structures.

3. Results and Discussion

The mechanical properties of the cellular lattice structures depend on the relative density and architecture. The effective modulus and peak strength of the stretch dominated lattice structure linearly depend on the relative density of the structure and can be predicted by the following formula [1,8]:

$$E_{eff} = \bar{\rho} E \sin^4 \theta, \quad (1)$$

$$\sigma_{cr,yielding} = \bar{\rho} \sigma_y \sin^2 \theta, \quad (2)$$

where E is Young's modulus, σ_y is the yield strength of the parent material, $\bar{\rho}$ is the relative density of the cellular structure and θ is the slant inclination angle (the angle made by the inclined struts with the face sheet).

The relative density of the cellular structure is the ratio of the cellular structure to that of the solid from which it is made. It is also the volume fraction of the unit cell occupied by the material. The relative density of the Kagome structure can be obtained by:

$$\bar{\rho} = \frac{V_l}{V_{eff}} = \frac{3\pi d^2 l}{4A_{eff} h} \quad (3)$$

where $A_{eff} = \frac{\sqrt{3}}{2}l^2$ is the area supported by a unit cell, l is the length of the truss, h is the height of the core and d is the diameter of the struts. Equation (2) predicts the compressive strength of the lattice structure which fails after the yield of the material. For the low relative densities structure, the failure is controlled by elastic buckling rather than the plastic yield. In this condition, the σ_y is replaced by the elastic buckling strength of the strut member.

3.1. Compression Properties of Unit Kagome Structure Fabricated by Selective Laser Melting

The diameter of the struts was obtained through the optical microscope by focusing on the edge of the struts of the Kagome structure. The average diameter of the printed struts in Kagome structure was 1.255 ± 0.028 mm which was 11% higher than the modeled diameter of 1.12 mm. The increase in the diameter is due to the attachment of the partially melted powder with the struts. The other reason for this increase could be the bigger width of the melt pool than the laser spot size.

Table 1 lists the experimental and predicted properties of the Kagome structure fabricated by SLM. For the analytical solution, the value of 110 GPa and 1028 MPa were used for Young's Modulus (E) and yield strength (σ_y) of Ti-6Al-4V respectively, which were taken from Ullah et. al [6]. The experimental measurements of the effective modulus of Kagome structure differed by around 30% from the analytical solution (Equation (1)). The discrepancies of the result might be caused by the measurement of the diameter of the struts. The attachments of semi-molten satellite particles on the struts have contributed to the increase of diameter, thus increasing the relative density but without a positive contribution in the mechanical properties. The measured experimental peak strength was higher than the analytical solution (Equation (2)). The analytical yield solution assumes the ideal elastic-plastic yielding without considering the plastic hardening, thus representing the equivalent yield stress rather than peak stress.

Table 1. Compressive properties of Kagome structures fabricated by selective laser melting.

Properties	Predicted	Experimental
Average Effective Modulus (MPa)	1293.11	909.70 $\pm$ 6.18
Average Peak Strength (MPa)	18.12	20.01 $\pm$ 0.63

Figure 4 shows the deformation behavior of Ti-6Al-4V unit Kagome structure under uniaxial compression. The initial linear slope of the graph indicates the elastic deformation of the structure until it reached the yielding. With strain hardening, the structure supported increased stress to reach peak strength. Further compression caused the bending of the struts, resulting in a decrease in the stress. Cracks appeared on the surface of the struts with further bending. With further compression, the structure failed with the opening of the initial cracks.

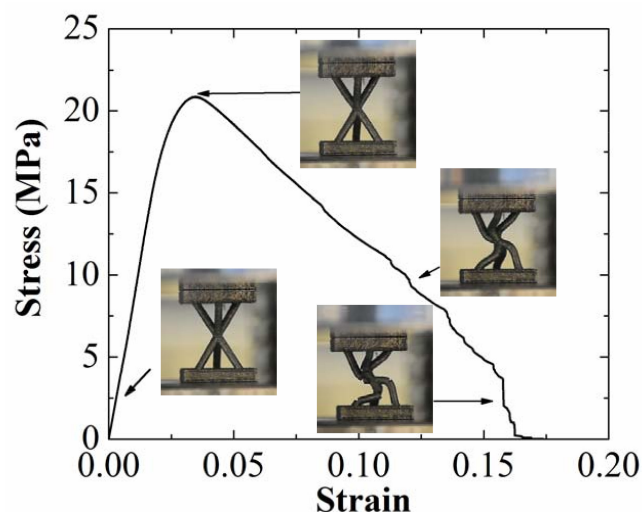


Figure 4. Compressive stress-strain curve of Ti-6Al-4V unit Kagome structure with the video frames at various compression stages.

3.2. Compression Properties of Kagome Structure Fabricated by Fused Deposition Modeling

Dimensional accuracy of the samples was accessed by measuring the strut diameters printed in the same orientation as they were in the whole structures through the use of digital micrometer and are listed in Table 2. The average diameter of the fabricated struts was smaller than the designed diameter. In the FDM process, the variation of diameter is inevitable and is more prominent when printed in angles due to the staircase effect [16]. It was found that the difference in the diameter of the modeled and fabricated struts reduced with the increase in the diameter.

Table 2. Variation in the fabricated and designed diameter of the struts.

Designed Strut Diameter (mm)	Measured Strut Diameter (mm)	Difference (%)
2.20	1.914 ± 0.042	13.00
2.60	2.445 ± 0.013	5.96
2.62	2.506 ± 0.027	4.35
3.00	2.883 ± 0.034	3.90

The bulk compression properties of the printed material were obtained by uniaxial compression testing on ABS-M30™ samples (standard samples for material properties) using a Shimadzu® Universal Testing Machine with 50 kN load cell under displacement control at a rate of 1.3 mm/min. The samples were printed in the direction of the struts in Kagome structures and their average compressive properties are listed in Table 3.

Table 3. Bulk compression properties of the FDM printed ABS-M30™ as per the orientation of the struts in Kagome structures.

Young's Modulus (MPa)	2% Offset Yield Strength (MPa)
1498.53 ± 102.67	28.51 ± 0.39

Table 4 lists the predicted as well as the experimental measurement of the compressive properties of single layer Kagome structure (3×3 units). The experimental measurement of elastic modulus of the Kagome structure agreed well with the predicted results given by Equation (1). But the

experimental measurement of the peak strength was around 33% higher than the analytically predicted result (Equation (2)). The reason is the same as that mentioned in Section 3.1. The analytical yield solution assumes the ideal elastic-plastic yielding without considering the plastic hardening. This resulted in the lower analytical solution for the peak strength.

Table 4. Compressive properties of Kagome structures fabricated by fused deposition modeling.

Properties	Predicted	Experimental
Average Effective modulus (MPa)	55.17	54.49 ± 1.78
Average Peak strength (MPa)	1.58	2.11 ± 0.05

3.2.1. Deformation of Multi-Unit Kagome Structure

Figure 5 shows the compressive stress-strain curve of a single layer Kagome structure and the corresponding images at different strains. Initially, it exhibited the linear elastic region followed by the plastic deformation to reach the peak strength as in a metal structure. The load carrying capacity decreased gradually with further compression. The struts failed near the joints to the face sheets at 13% strain as shown in image 2. The decrease in the load is continuous as all the struts did not fail simultaneously. While some units failed at the beginning, other units still supported the load, leading to the continuous decrease in the strength. With further compression, all the struts failed to provide low stress. The struts failed near one end of the face sheet, whereas the other side of the Kagome structure was still intact (image 3). After further displacement, the central part started to touch the face sheet and again the stress started to increase due to the strength of the other half of the intact Kagome and again reached the second peak strength. The load started to decrease again with the failure of the second half of the Kagome (image 4).

Figure 6 shows the force-displacement curve for the Kagome structures with a different number of layers. As the number of units in the top layer of the double layer, as well as triple layer structure, was the same as 3×3 single layer structure, only the first peak load was compared. The measured average peak loads were 4.18 kN, 4.31 kN and 3.99 kN for a single layer, double layer and triple layer respectively, indicating no significant effect of a number of layers. But the stiffness decreased with the increase in the number of layers as measured from the initial slope of the force-displacement curves in Figure 6. The double layer and triple layer structure also displayed a similar failure as described in the single layer, from near the joints to the face sheet of the top layer. As the area of the top layer is low (with 3×3 units) in a multi-layered structure, hence top layer struts experienced higher stress. Thus, the top layer failed first. After reaching the peak load, the load decreased gradually due to the gradual failure of the struts at the top layer.

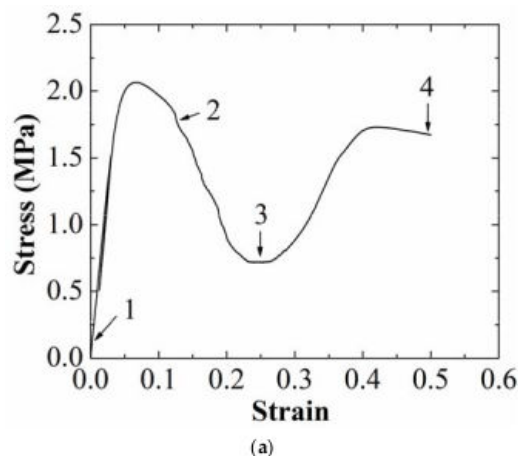


Figure 5. Cont.

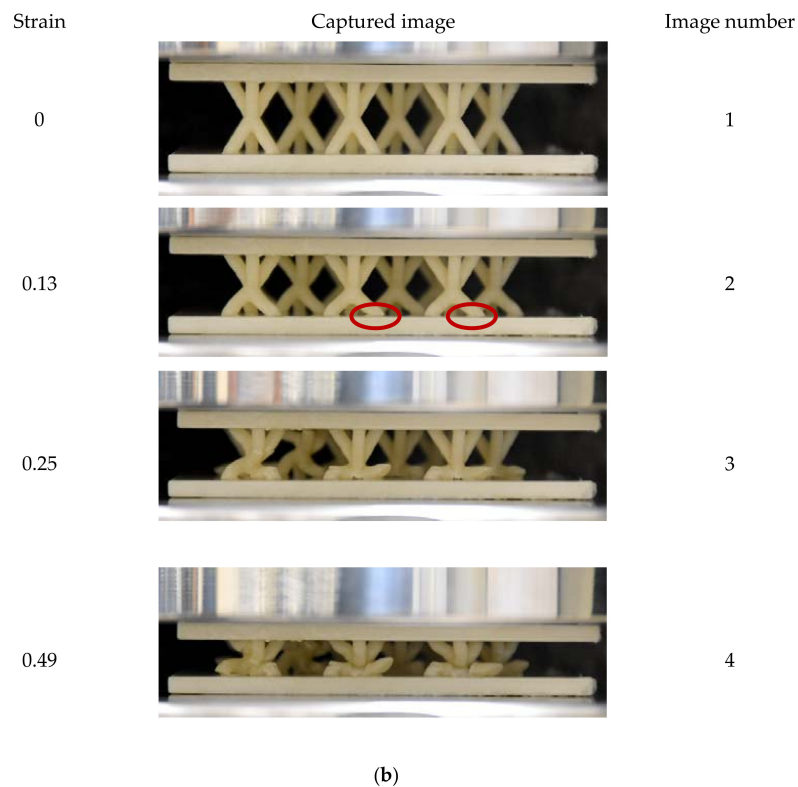


Figure 5. Compressive stress-strain graph of Kagome Structure and (b) images at different strain during compression.

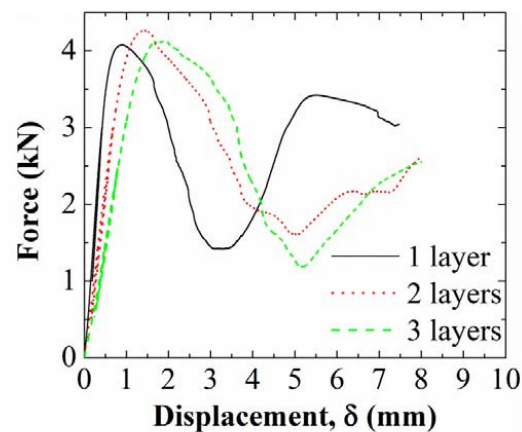


Figure 6. Force-displacement curves of Kagome structure with a different number of layers.

3.2.2. Uniform Density and Graded Density Kagome Structure

Compression tests were carried out on the uniform as well as graded samples with three layers. The top layer has 3×3 units; the middle layer has 4×4 units, and the bottom layer has 5×5 units of Kagome structures. As there were different numbers of Kagome unit in different layers (resulting in a different area for each layer), the compression behavior of uniform and graded density lattice were analyzed through the force-displacement curve. Figure 7 shows the force-displacement curves of both uniform and graded density Kagome structures with the number 1–5, which indicates the positions where images of Figures 8 and 9 were captured. Both the structures exhibited linear behavior in the initial stage of the compression followed by non-linear deformation to reach the peak load. The load decreased with further compression. The first maximum compressive load of the graded density samples was smaller than for the uniform density samples as graded samples failed from the

lowest core density and gradually increased with an increase in core density. The second peak load for both structures was the same as the middle layer core density (0.09) was equal.

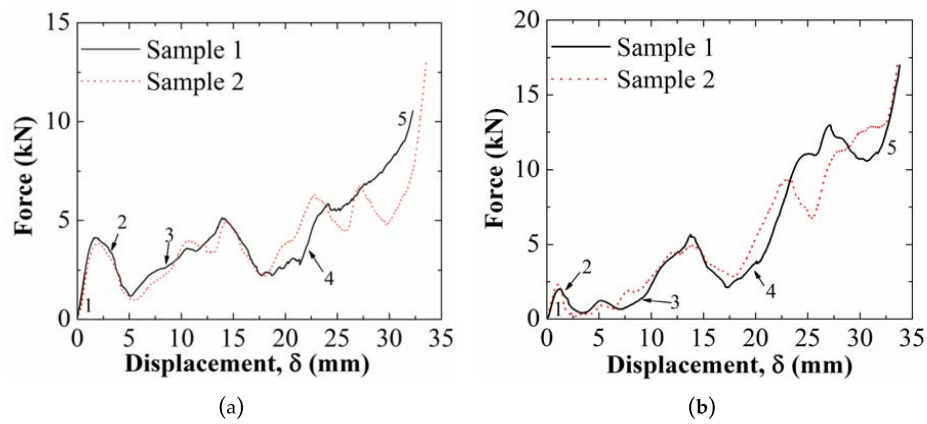


Figure 7. Load-displacement curves for (a) uniform and (b) graded density Kagome structures.

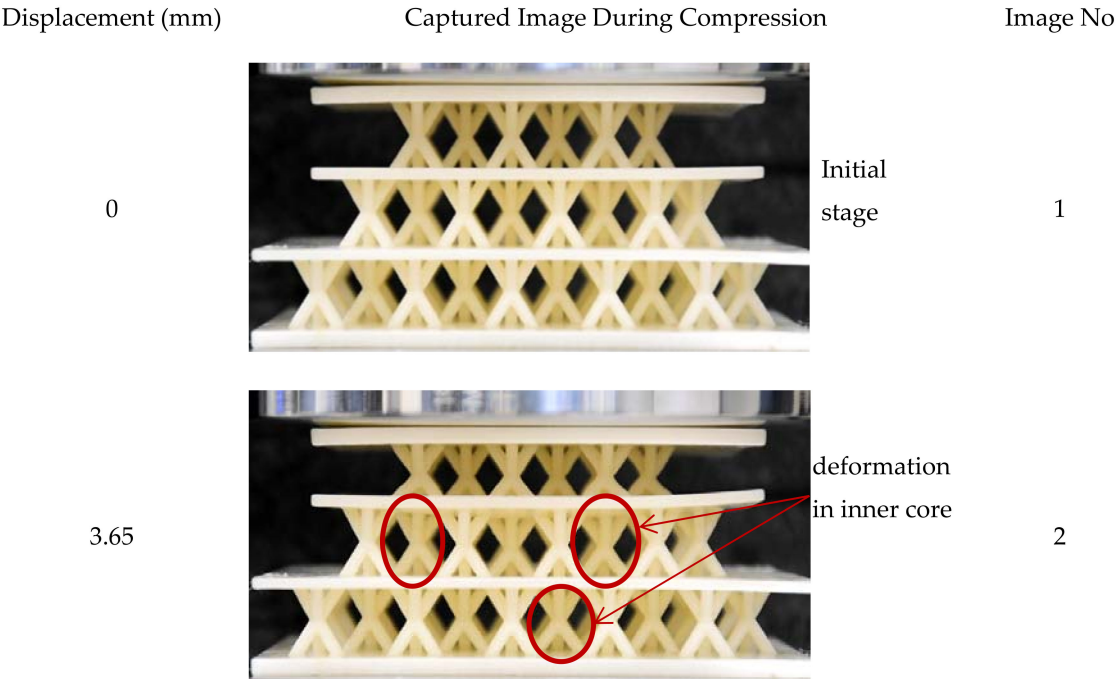


Figure 8. Cont.

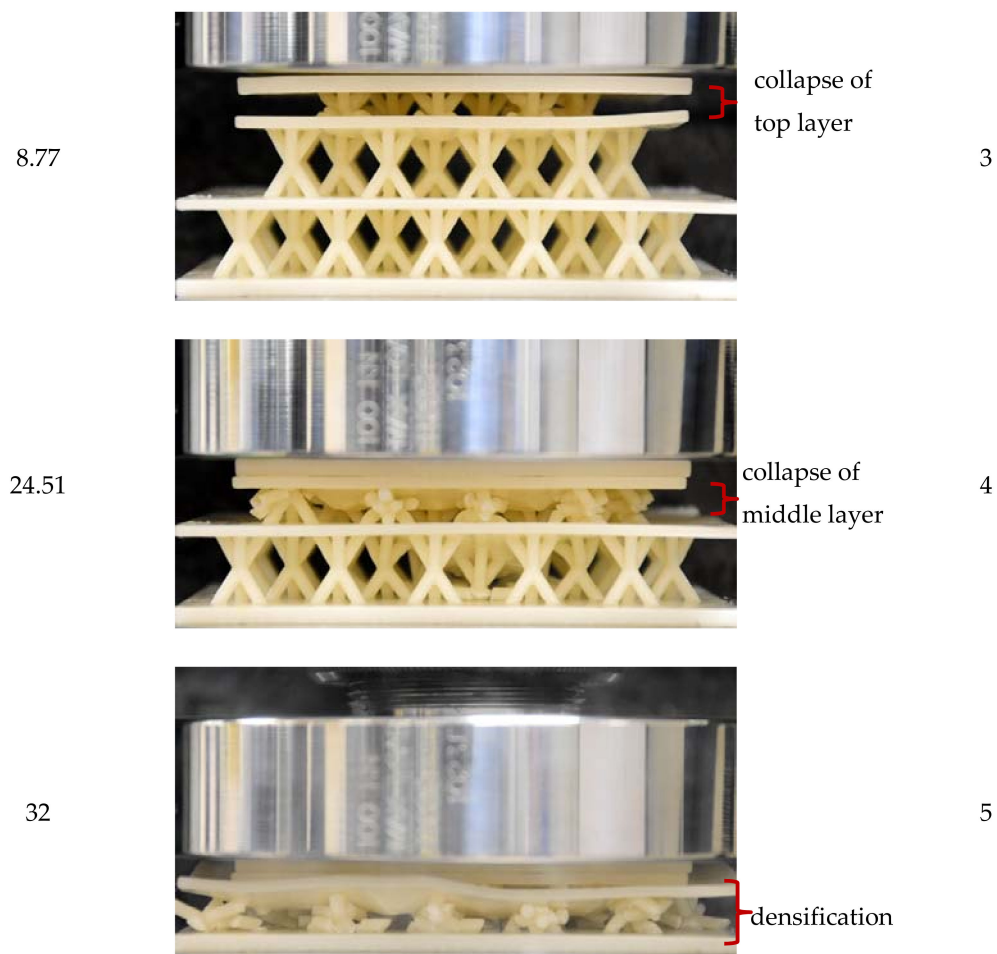


Figure 8. Deformation of a uniform density Kagome at different displacement during the compression test.

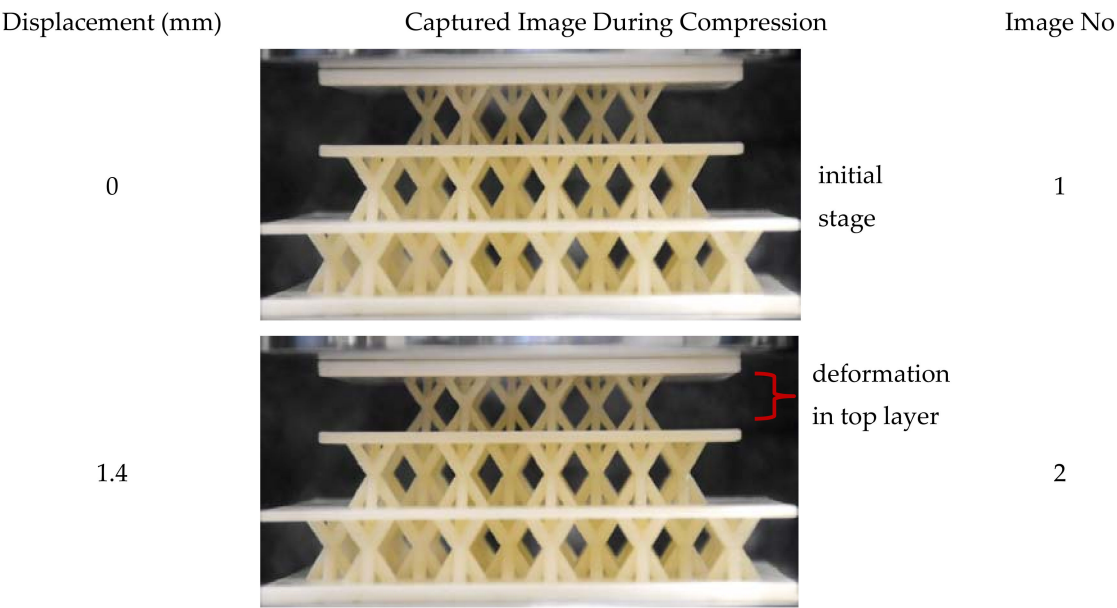


Figure 9. *Cont.*

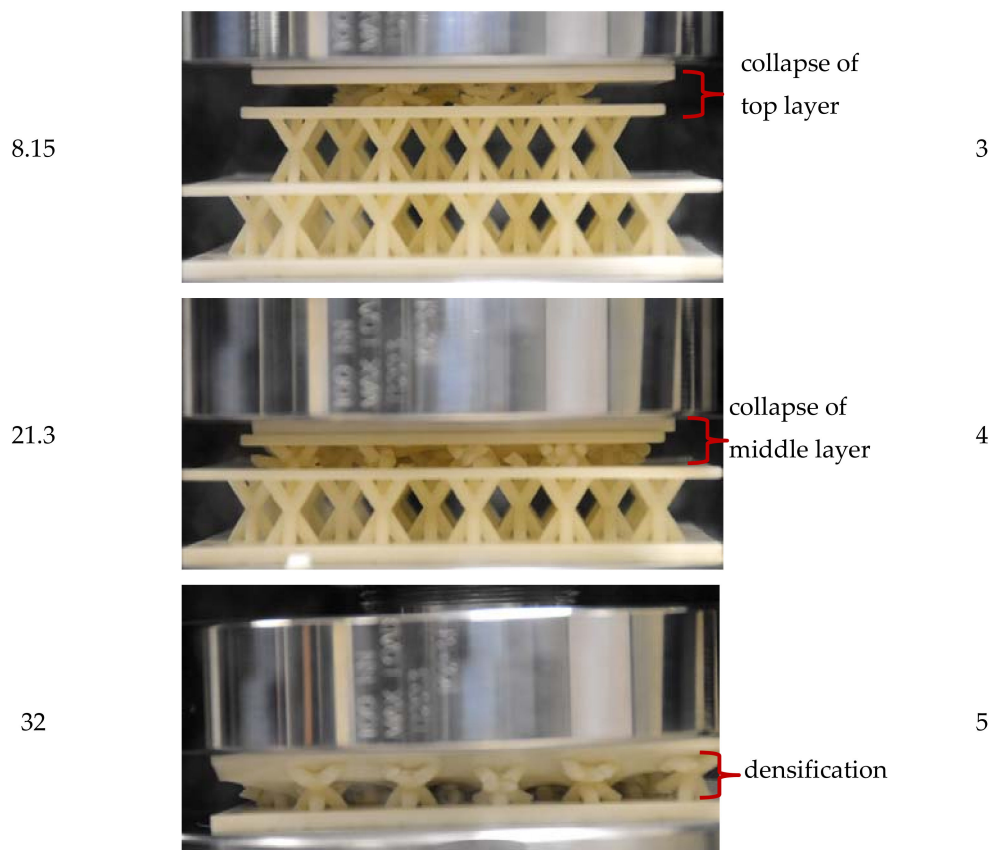


Figure 9. Deformation of a graded density Kagome sample at different displacement during the compression test.

Figure 8 shows the deformation pattern in a uniform density Kagome structure at different displacement levels (as numbered in the force-displacement curve). In uniform density structures, the displacement of the interface sheets along with the inner core (especially area beneath 3×3 core) can be observed in the early stages of the deformation. With further loading, the bending of the core can be noticed on the top layer along with the deformation in the inner core of the middle and bottom layers (image 2). The deformation is localized at the central units of Kagome, without any predominant deformation in the outer units of middle and bottom layers. As the outer units supported the face sheet, the deformation prominently occurred in the units of top layer, leading to the failure. The failure of the top units was resembled in the force-displacement curve in Figure 7a as the lowest load of 1 kN after the first peak load. With the contact of failed struts of the top layer with face sheets, the load again increased. With further compression, the middle layer core supported the load to reach the second peak load of 5 kN. The drop in the load in the graph again resembled the collapse of the second layer. With the contribution of the bottom layer, the load again increased to reach the third peak. Further loading caused the densification of the Kagome structures, which increased the load significantly from 31.5 mm onwards with a small increase in displacement. The onset of the densification is regarded as a displacement of densification. Images 3, 4 and 5 of Figure 8 show the uniform density Kagome structure after the collapse of each layer.

In graded density lattices, the load-displacement curve started with smaller peaks corresponding to the lowest density core in the top layer. The subsequent peaks were increasingly higher with greater load resistance due to higher core density. After reaching the first peak load of 2.16 kN, the top layer of Kagome with a relative density of 6.36% started to deform without any change in other layers. Subsequently, the core of the top layer failed with the fracture near the joints to face sheet. The significant reduction in load after reaching the peak was due to the collapse of the top layer core.

The second and third peaks were due to the load resisted by the middle and bottom cores and the subsequent reduction in the loads were due to the collapse of these layers, respectively. The images of graded density Kagome under compression loading at different displacement stages are shown in Figure 9. Images 3, 4 and 5 show the graded density Kagome after the collapse of each layer.

Table 5. Average compressive properties of uniform and graded density Kagome structure.

Specimens	First Peak Load (kN)	Displacement at Densification, δ (mm)	Total Energy Absorbed to Densification (J)
Uniform density	3.99 ± 0.14	31.55 ± 0.05	121.24 ± 1.02
Graded density	2.16 ± 0.16	32.26 ± 0.26	164.25 ± 0.09

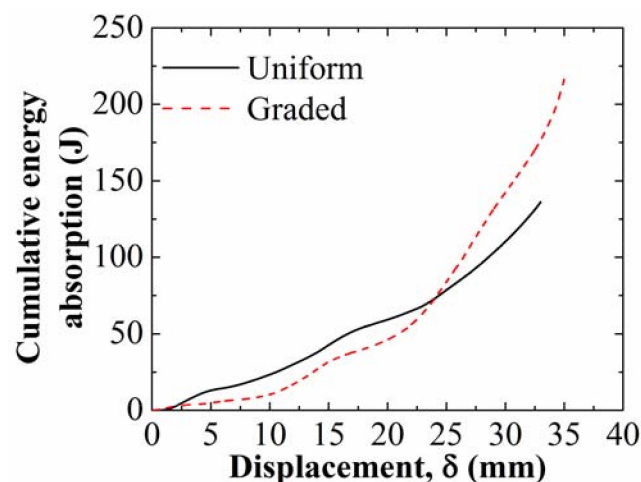


Figure 10. Cumulative energy absorption versus displacement curves for uniform density and graded density Kagome lattice structure.

The cumulative energy absorption of the lattice structures under compression was calculated by numerically integrating the load-displacement curves and is shown in Figure 10. It was found that the graded density structures absorbed less energy than uniform density structures with low deformation. With further displacement beyond 24 mm, the graded density structures had more energy absorption than uniform density structures. The total energy absorbed is calculated to the densification displacement of the curve and are presented in Table 5. For the samples with an average relative density of 9%, the total energy absorption to densification increased by 35% when graded density design was incorporated instead of the uniform density lattice structure.

The change in design form uniform density to graded density among different layers of Kagome structures have resulted in an increase in the energy absorption capacity of fused deposition modeled samples. This design aspect of FDM printed samples can be utilized in metal printing as well so that the change in the design would give a better energy absorption capacity for the same relative density.

Due to the time constraint on the usage of SLM Machine and requirement of the huge amount of metal powder, the multilayer samples were fabricated with ABS plastic material using FDM. Most of the struts failed near the joints to the face sheets. It would be interesting to see how the multilayer metal samples (both graded as well as uniform density) would behave under the compression for energy management application under static and impact loading conditions. Also, the multi-layered structures can be filled with polymeric foam and their response under shock type loadings can be studied.

4. Conclusions

In this paper, initially, the uniaxial compression properties of the Ti-6Al-4V unit Kagome structure fabricated by selective laser melting were investigated. The unit Kagome structure under compression

exhibited the almost linear elastic behavior to the peak-load before which the trusses start to yield, followed by peak-load, after which there is a gradual collapse. The analytical solutions for the compressive strength and modulus agreed with the experimental measurements.

Secondly, the deformation behavior of multi-unit Kagome structure fabricated by fused deposition modeling was explored experimentally under uniaxial compression. The effect of the number of layers in the compressive performance Kagome structure was studied. Within experimental scatter, the single layer and multi-layer structures have shown similar initial failure loads but also a decrease in the stiffness with the increase in a number of layers. The compressive properties, as well as the deformation behavior of the uniform and graded density structures for the same weight, were compared: there is a 35% increase in the energy absorption of the graded structure.

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References

- Wadley, H.N. Multifunctional periodic cellular metals. *Philos. Trans. A Math. Phys. Eng. Sci.* **2006**, *364*, 31–68. [[CrossRef](#)] [[PubMed](#)]
- Deshpande, V.S.; Ashby, M.F.; Fleck, N.A. Foam topology: Bending versus stretching dominated architectures. *Acta Mater.* **2001**, *49*, 1035–1040. [[CrossRef](#)]
- Moon, S.K.; Tan, Y.E.; Hwang, J.; Yoon, Y.-J. Application of 3D printing technology for designing light-weight unmanned aerial vehicle wing structures. *Int. J. Precis. Eng. Manuf. Green Technol.* **2014**, *1*, 223–228. [[CrossRef](#)]
- Hyun, S.; Karlsson, A.M.; Torquato, S.; Evans, A.G. Simulated properties of Kagome and tetragonal truss core panels. *Int. J. Solids Struct.* **2003**, *40*, 6989–6998. [[CrossRef](#)]
- Wang, J.; Evans, A.G.; Dharmasena, K.; Wadley, H.N.G. On the performance of truss panels with Kagome cores. *Int. J. Solids Struct.* **2003**, *40*, 6981–6988. [[CrossRef](#)]
- Lee, B.-K.; Kang, K.-J. A parametric study on compressive characteristics of wire-woven bulk Kagome truss cores. *Compos. Struct.* **2010**, *92*, 445–453. [[CrossRef](#)]
- Ullah, I.; Elambasseril, J.; Brandt, M.; Feih, S. Performance of bio-inspired Kagome truss core structures under compression and shear loading. *Compos. Struct.* **2014**, *118*, 294–302. [[CrossRef](#)]
- Ullah, I.; Brandt, M.; Feih, S. Failure and energy absorption characteristics of advanced 3D truss core structures. *Mater. Des.* **2016**, *92*, 937–948. [[CrossRef](#)]
- Gautam, R.; Idapalapati, S. Performance of strut-reinforced Kagome truss core structure under compression fabricated by selective laser melting. *Mater. Des.* **2019**, *164*, 107541. [[CrossRef](#)]
- Qian, X.; Dutta, D. Design of heterogeneous turbine blade. *Comput. Aided Des.* **2003**, *35*, 319–329. [[CrossRef](#)]
- Ocylok, S.; Weisheit, A.; Kelbassa, I. Functionally graded multi-layers by laser cladding for increased wear and corrosion protection. *Phys. Procedia* **2010**, *5*, 359–367. [[CrossRef](#)]
- Choy, S.Y.; Sun, C.-N.; Leong, K.F.; Wei, J. Compressive properties of functionally graded lattice structures manufactured by selective laser melting. *Mater. Des.* **2017**, *131*, 112–120. [[CrossRef](#)]
- Maskery, I.; Hussey, A.; Panesar, A.; Aremu, A.; Tuck, C.; Ashcroft, I.; Hague, R. An investigation into reinforced and functionally graded lattice structures. *J. Cell. Plast.* **2017**, *53*, 151–165. [[CrossRef](#)]

14. Maskery, I.; Aboulkhair, N.; Aremu, A.; Tuck, C.; Ashcroft, I.; Wildman, R.D.; Hague, R.J. A mechanical property evaluation of graded density Al-Si10-Mg lattice structures manufactured by selective laser melting. *Mater. Sci. Eng. A* **2016**, *670*, 264–274. [[CrossRef](#)]
15. Gautam, R.; Idapalapati, S.; Feih, S. Printing and characterisation of Kagome lattice structures by fused deposition modelling. *Mater. Des.* **2018**, *137*, 266–275. [[CrossRef](#)]
16. Ravari, M.R.K.; Kadkhodaei, M.; Badrossamay, M.; Rezaei, R. Numerical investigation on mechanical properties of cellular lattice structures fabricated by fused deposition modeling. *Int. J. Mech. Sci.* **2014**, *88*, 154–161. [[CrossRef](#)]



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