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Comparison of Mechanical Properties of 3D-printed PLA+ Lattice Infills at Different Build Orientation

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ABSTRACT
Additive manufacturing (AM) can ensure the fabrication of complex structures as well as replace conventional parts for extensive modification and cheaper alternatives. Although the mechanical behaviors of different lattice structures have been studied extensively, the corresponding mechanical performances of integrated-manufactured structures with complex infills should be systematically investigated as the usage of 3D-printed parts replacing metals for strength applications can be seen more than ever. The main objective of this study was to investigate how printing factors like infill lattice structure and printing orientation affects the mechanical characteristics of printed samples. Samples were produced via an FDM 3D printer with similar conditions for each case. Kelvin and Octet lattice structures were compared on both horizontal and vertical printed orientations. The test was conducted on a specific geometry, 60mm cubic infill area with top and bottom wall and open sides. The comparison was done based on strength-to-weight characteristics of the samples with fixed weights for all cases. Compression tests using a universal testing machine (UTM) were done on the printed samples. The results of this study demonstrate that infill lattice structure and orientation significantly affect the compression strength of the PLA+ printed samples. The result shows that the lattice structure with unit cell of Octet lattice can withstand higher loads before failure, and the Kelvin lattice structure shows more ductile properties. It can also be seen that the horizontal printing orientation results in superior mechanical properties subjected to top loads than vertical orientation of printing. The research findings are helpful in understanding greater mechanical and physical characteristics that would undoubtedly assist designers and manufacturers worldwide as the FDM 3D printer becomes increasingly crucial in manufacturing engineering parts.

Keywords: 3D Printing, Lattice Structure, Compression Strength, Energy Absorption

1. Introduction

3D printing technology has gained significant attention in various fields due to its versatility and potential applications. One area of interest is the use of PLA for FDM 3D printing. PLA, or polylactic acid, is a commonly used material in 3D printing due to its biodegradability and ease of use. Jiang et al. [1] conducted a preliminary study on 3D printing for rock mechanics and found that FDM 3D printing with PLA is unsuitable for direct rock simulation. However, Prashantha et al. [2] explored the multifunctional properties of 3D printed PLA/graphene nanocomposites using FDM technology, showcasing the nanocomposite's mechanical, electrical, and electromagnetic induction shielding properties. Furthermore, Hua et al. [3] demonstrated the 3D printing of shape-changing composites using PLA and MWCNTs for constructing flexible photothermal-responsive actuators. This highlights the potential of PLA-based materials in creating functional and responsive structures. Tümer et al. [4] provided a comprehensive review of extrusion-based 3D printing applications of PLA composites, emphasizing the various fields where novel PLA composites can be utilized with FDM technology.

Nguyen et al. [5] introduced a method for generating lattice structures for additive manufacturing, allowing for the creation of conformal and non-conformal lattice structure models. Li et al. [6] designed a novel three-dimensional cellular structure with a negative Poisson's ratio by alternating cuboid surface indents on vertical ribs. Habib et al. [7] focused on fabricating polymeric lattice structures for optimum energy absorption using Multi Jet Fusion Technology. Guo et al. [8] worked on designing and characterising 3D AuxHex lattice structures. Wang et al. [9] explored the mechanical behaviors of 3D-printed lightweight concrete structures with hollow sections. Khosravani et al. [10] studied the structural performance of 3D-printed composites under various loads and environmental conditions. Guo et al. [11] investigated the thermal performance of a 3D-printed lattice-structure heat sink packaging phase change material. Yuze et al. [12] analyzed the energy absorption characteristics of functionally graded polymer-based lattice structures filled with aluminum tubes under transverse impact loading. Libonati et al. [13] focused on 3D-printed architected materials inspired by cubic Bravais lattices. The design choice of using Kelvin cell and Octet lattice structure came with consideration of strength, lightweight design, energy absorption, and thermal performance—key factors for engineering-grade 3D-printed components. Despite the complexity, nearly isotropic properties make these two lattices exceptionally good in strength scenarios [14, 15].

The recent surge in studies on additive manufacturing of various standard and custom lattice designs is impressive; however, further research is needed to explore the impact of printing orientation on the mechanical properties of additively manufactured Kelvin and octet lattice structures. In this study,

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the compressive mechanical properties are characterized to decipher the effect of lattice structures and the orientation.

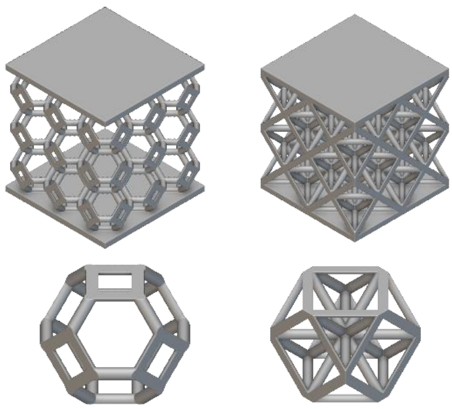
2. Methodology

2.1 Model Design

In this study, a Kelvin Cell lattice and an Octet lattice was selected with standard unit cell dimensions and modeled in between two 2.25mm thick plates. Both structures have an overall dimension of 42mm × 42mm × 46.2mm and the weight of both structures is 19.5g. Other dimensions are stated below in Table 1.

Table 1 Dimensions of Lattice Structures

Unit Cell	Parameter	Dimensions (mm)
Kelvin Cell	Unit Cell Size	14 × 14 × 14
	Orientation	UVW
	Rotation	0
	Lattice Thickness	2.002
	Unit Cell count	3
Octet	Unit Cell Size	21 × 21 × 21
	Orientation	UVW
	Rotation	0
	Lattice Thickness	2.1
	Unit Cell count	2



(a) (b)

Fig.1 Isotropic view of the lattice test geometry and their unit cell: (a) Kelvin Cell and (b) Octet.

2.2 Materials and Fabrication

PLA+ is improved and upgraded based on ordinary PLA (Polylactic Acid). The PLA plus filament of 1.75 mm diameter was used. Being based on PLA material, the toughness and layer adherence of the print are improved. With good strength, rigidity, toughness balance, and strong impact resistance, the physical and mechanical properties of PLA+ filament are illustrated in Table 2.

Table 2 Material Properties of PLA+

Property	Value.
Density (g/cm3)	1.23
Tensile Strength (MPa)	63
Flexural Strength (MPa)	74
Flexural Modulus (MPa)	1973
Elongation at break (%)	20
Young's Modulus (GPa)	3.1

The PLA+ samples were fabricated using Creality CR-10 Smart 3D Printer. The printer has a 0.4-mm nozzle diameter. The fixed parameters used in this work are presented in Table 3. The infill density of 100% was used as the structure is prepared to test the lattice performance.

Table 3 Fixed parameters used in FDM 3D printing

Parameter	Value.
Material	1.23
Filament Diameter	175 mm
Printing temperature	215℃
Layer height	0.2 mm
Nozzle diameter	0.4 mm
Printing precision	±0.1mm
Printing platform	Carborundum Glass

2.3 Experimental Procedure

A compression test of 3D printed structures was performed using a universal testing machine (UTM). The testing procedure has been done with a constant speed of 4mm/min. For each of the four distinguished cases, two specimens were tested.

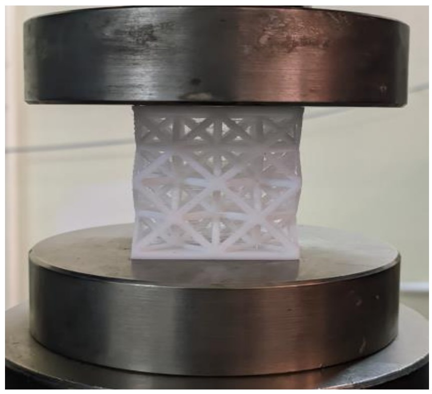


Fig.2 Compression test on UTM

A displacement limit of 25mm was considered for the test purpose based on the overall height and the densification characteristics of the specimens. Figure 2 depicts the compression test setup at the initial position for the Octet lattice structure.

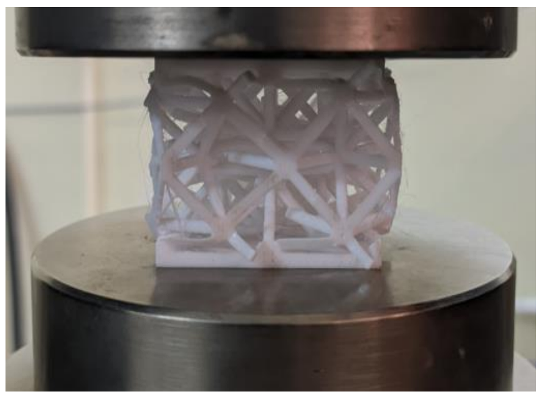


Fig.3 Breakage after elastic limit

In Figure 3, the breaking or cracking after the elastic limit is shown. This figure indicates the maximum strength after the elastic limit. Based on the lattice structure, variation in cracking behaviour was noticed during the testing.

Figure 4 illustrates the fully compressed state of the specimen within the limit after 25mm of displacement. The materials were in a compact condition without any inter-cell air gap, and densification was started; consequently, the force gradually increased from the position.

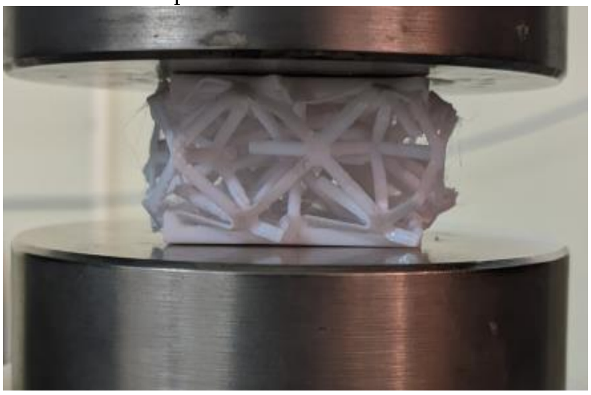


Fig.4 Fully compressed within the limit.

3. Results and Discussion

A total of four individual cases were considered for two different lattice cell structures and two printing orientations. These are K-V (Kelvin cell, vertical orientation), K-H (Kelvin cell, horizontal orientation), O-V (Octet cell, vertical orientation), and O-H (Octet cell, horizontal orientation).

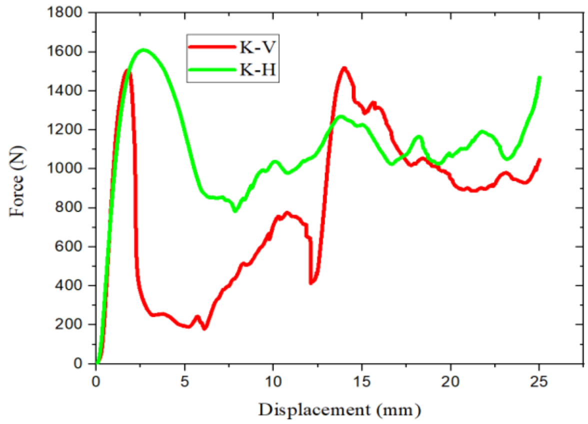


Fig.6 Force vs displacement curve of Kelvin Unit Cell

Figure 6 indicates the force vs displacement curve for Kelvin lattice structures where the force has a much higher increasing rate in the elastic limit compared to the displacement. The curve shows a sharp downward trend after the first breakage point passing the elastic limit. The reason for this declination is the breakage of a few lattice struts within the whole structure. When further force is applied, the force again starts to increase. After some time, it again decreased. Finally, after a certain portion, much densification happened. The force tends to increase exponentially.

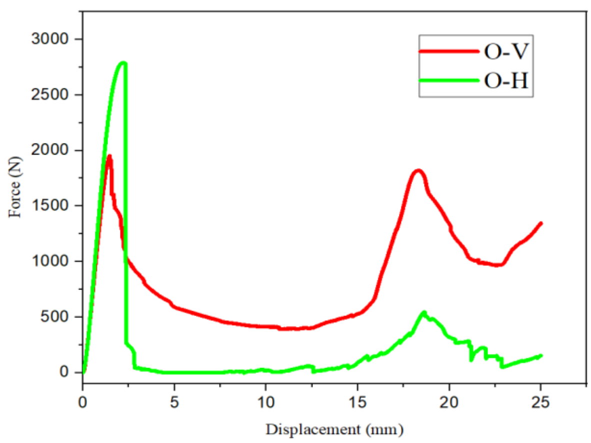


Fig.7 Force vs displacement curve of Octet Unit Cell

The same behaviour is noticed in Figure 7, where the Octet lattice structure characteristics are shown. The difference between the two structures lies in the force requirements. Octet structure has a higher amount of force requirements within the elastic limit, mainly due to its superior structural integrity of the unit cell.

In Figure 8, energy absorption is shown, which is calculated from the force vs. displacement curve by deducing the area under the curve to 25mm of displacement. This area represents the work done on the material during the compression test, which correlates to the energy absorbed by the material. The K-H structure has the highest energy absorption, while the O-H structure has the lowest, even though they share the same printing orientation. This difference is likely due to the design and behavior of the two lattice structures.

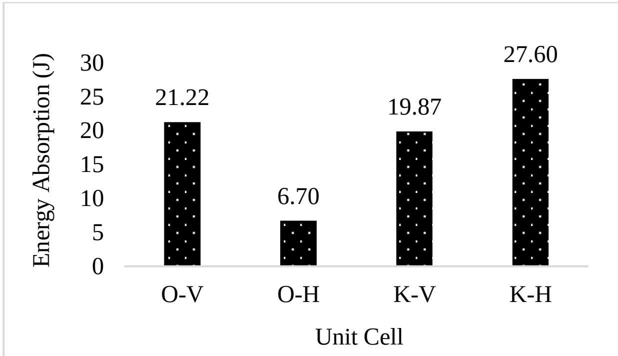


Fig.8 Bar Chart of Energy Absorption

The Kelvin cell has a more uniform and balanced structure, which helps it distribute stress evenly and absorb more energy when compressed horizontally. On the other hand, the Octet cell, while strong in vertical orientation, may face stress build-up and bending issues in the horizontal orientation due to its design. This makes it absorb less energy compared to the Kelvin cell.

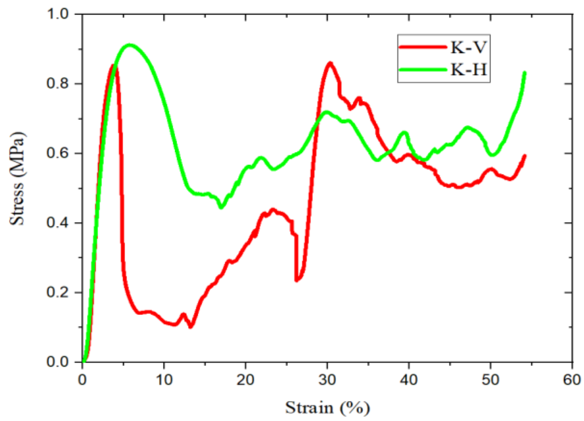


Fig.9 Stress vs Strain curve of Kelvin Structure

Though O-H shows the maximum force, after the elastic limit, it falls downward very rapidly and remains lower, not like the K-H structure. Thus, if performance within the elastic limit is considered, then O-H shows better results. However, if total energy absorption is considered, then K-H will have a higher overall performance.

The stress vs strain curve in Figure 9 follows the same trend as force-displacement. K-H structure has much maximum stress than K-V. If it is considered Octet structure, in Figure 10, O-H has more stress than O-V.

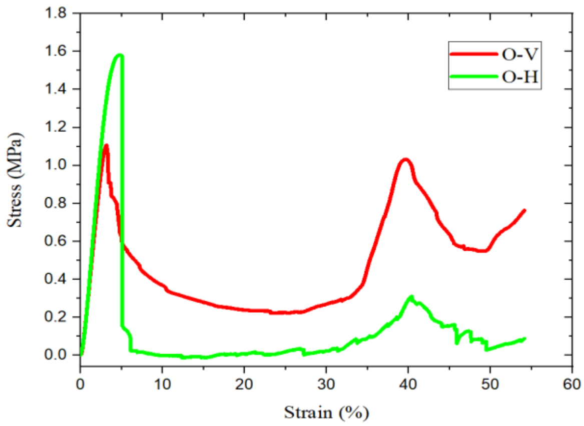


Fig.10 Stress vs Strain curve of Octet Structure

With the help of the compressive modulus, O-H structure has the maximum value among the four structures, so this structure is the most brittle structure among them. On the other hand, K-H shows ductility, as shown in Figure 11. It shows a trend where vertical structure shows more brittle characteristics than horizontal.

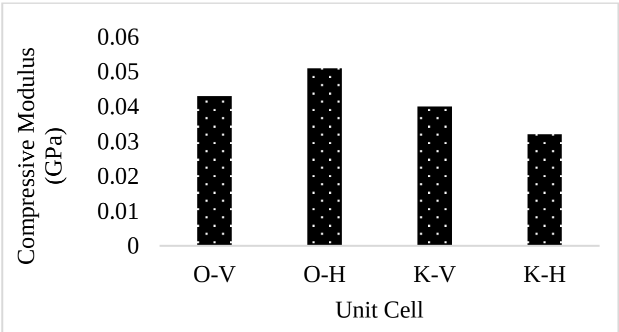


Fig.11 Compressive modulus of Unit cells

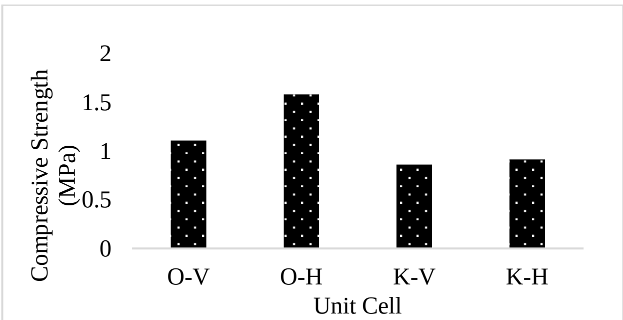


Fig.12 Compressive Strengths of Unit cells

With the help of the compressive strength at Figure 12 and the compressive modulus, it can be said that O-H structure nature like hard material, it has the maximum strength as well as maximum modulus-H acts like a ductile material among them.

4. Conclusion

In the study, compression test specimens were produced through FDM additive manufacturing method with PLA+ filament in accordance with the standard procedures. The direct effects of lattice structure variation and orientation of the 3D printing were investigated. The mechanical properties of the Kelvin lattice and Octet lattice structures in both horizontal and vertical orientations were compared. According to the findings from the experimental results, it has been observed that the orientation of unit cells (horizontal vs vertical) significantly affects their mechanical behavior, with horizontal structures generally being more ductile and energy-absorbent. Kelvin structure has the highest energy absorption among the samples but Octet lattice structure exhibits the highest compressive strength and modulus. Both Kelvin and Octet structures follow a similar force vs displacement trend, but Octet structures sustain higher maximum forces after the elastic limit. Thus, the choice of unit cell and orientation should depend on the specific application requirements, balancing energy absorption, strength, and material ductility.

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References

[1] C. Jiang and G.-F. Zhao, “A Preliminary Study of 3D Printing on Rock Mechanics,” *Rock Mech. Rock Eng.*, vol. 48, no. 3, pp. 1041–1050, May 2015.

[2] K. Prashantha and F. Roger, “Multifunctional properties of 3D printed poly(lactic acid)/graphene nanocomposites by fused deposition modeling,” *J. Macromol. Sci. Part A*, vol. 54, no. 1, pp. 24–29, Jan. 2017.

[3] D. Hua *et al.*, “3D printing of shape changing composites for constructing flexible paper-based photothermal bilayer actuators,” *J. Mater. Chem. C*, vol. 6, no. 8, pp. 2123–2131, Feb. 2018.

[4] E. H. Tümer and H. Y. Erbil, “Extrusion-Based 3D Printing Applications of PLA Composites: A Review,” *Coatings*, vol. 11, no. 4, Art. no. 4, Apr. 2021.

[5] D. S. Nguyen and F. Vignat, “A method to generate lattice structure for Additive Manufacturing,” in *2016 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, Dec. 2016, pp. 966–970.

[6] D. Li, J. Ma, L. Dong, and R. S. Lakes, “Three-Dimensional Stiff Cellular Structures With Negative Poisson’s Ratio,” *Phys. Status Solidi B*, vol. 254, no. 12, p. 1600785, 2017.

[7] F. N. Habib, P. Iovenitti, S. H. Masood, and M. Nikzad, “Fabrication of polymeric lattice structures for optimum energy absorption using Multi Jet Fusion technology,” *Mater. Des.*, vol. 155, pp. 86–98, Oct. 2018.

[8] Y. Guo *et al.*, “Thermal performance of a 3D printed lattice-structure heat sink packaging phase change material,” *Chin. J. Aeronaut.*, vol. 34, no. 5, pp. 373–385, May 2021.

[9] L. Wang, H. Jiang, Z. Li, and G. Ma, “Mechanical behaviors of 3D printed lightweight concrete structure with hollow section,” *Arch. Civ. Mech. Eng.*, vol. 20, no. 1, p. 16, Feb. 2020.

[10] M. R. Khosravani, A. Zolfagharian, M. Jennings, and T. Reinicke, “Structural performance of 3D-printed composites under various loads and environmental conditions,” *Polym. Test.*, vol. 91, p. 106770, Nov. 2020.

[11] M.-F. Guo, H. Yang, and L. Ma, “Design and characterization of 3D AuxHex lattice structures,” *Int. J. Mech. Sci.*, vol. 181, p. 105700, Sep. 2020.

[12] Y. Nian, S. Wan, P. Zhou, X. Wang, R. Santiago, and M. Li, “Energy absorption characteristics of functionally graded polymer-based lattice structures filled aluminum tubes under transverse impact loading,” *Mater. Des.*, vol. 209, p. 110011, Nov. 2021.

[13] F. Libonati, S. Graziosi, F. Ballo, M. Mognato, and G. Sala, “3D-Printed Architected Materials Inspired by Cubic Bravais Lattices,” *ACS Biomater. Sci. Eng.*, vol. 9, no. 7, pp. 3935–3944, Jul. 2023.

[14] Li, P., Yang, F., Bian, Y. et al. Design of lattice materials with isotropic stiffness through combination of two complementary cubic lattice configurations. Acta Mech 234, 1843–1856 (2023).

[15] Sun, Q., Zhi, G., Zhou, S. et al. Compressive Mechanical and Heat Conduction Properties of AlSi10Mg Gradient Metamaterials Fabricated via Laser Powder Bed Fusion. Chin. J. Mech. Eng. 37, 123 (2024)