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INTERNATIONAL ADVANCED RESEARCHES and ENGINEERING JOURNAL

Journal homepage: www.dergipark.org.tr/en/pub/iarej

e-ISSN: 2618-575X

International Open Access

Volume 08
Issue 02

August, 2024

Research Article

Experimental investigation on energy absorption capability of 3D-printed lattice structures: Effect of strut orientation

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ARTICLE INFO

Article history:
Received 28 March 2024
Accepted 10 July 2024
Published 20 August 2024

Keywords:
Axial loading
Crashworthiness
Lattice structure
3D printing

ABSTRACT

This experimental study aimed to investigate the effect of strut orientation in various lattice structures that were created using 3D printers on the energy absorption capabilities of the structures. The experiment involved producing three different lattice structures, namely a cube lattice with vertical and horizontal struts, an octet structure with horizontal and 45˚ angled struts, and a body-centered-cubic (BCC) lattice structure with horizontal, vertical, and 45˚ angled struts using the FDM method. Nylon filament mixed with chopped carbon fiber was utilized as filament, and each lattice structure was designed to contain three units in the x and y directions and one and three units in the z-direction. The study conducted axial crushing tests on single-layer and three-layer lattices to determine the energy absorption capabilities of the various lattice structures. The octet lattice demonstrated the highest energy absorption in both single-layer and three-layer samples, making it the most efficient sample. In single-layer lattice samples, the cube and octet structures absorbed 77% and 94% more energy than the BCC structure, which absorbed only 12.8 J. However, the cube structure demonstrated the lowest energy absorption in three-layer samples. This was attributed to the buckling behavior seen in the strut of the lattice structure under axial load. The octet structure had the highest specific energy absorption value in both layers, making it the most energy-efficient sample.

1. Introduction

The use of cellular structures in engineering applications has become increasingly popular due to their unique properties. However, the irregular and unpredictable shapes of such structures present a challenge in determining their mechanical properties. To overcome this obstacle, lattice structures made up of interconnected 3D cells have emerged as a viable alternative. These lattice structures offer consistent and adjustable mechanical properties, making them the preferred choice for constructing lightweight cellular structures in different sectors, such as aerospace, aviation and automotive. Moreover, the interconnected cells in these lattice structures can be repeated, allowing for easier fabrication and assembly. This has made lattice structures a go-to solution for engineering applications that require the use of cellular structures with predictable and adjustable mechanical properties while also being lightweight and easy to manufacture [1–10]. Lattice structures are three-dimensional structures composed of interconnected struts that form a repeating unit cell. These structures possess mechanical properties that are influenced by various factors, such as load type, material used, unit cell dimensions, topology, cell edge radius-to-length ratio, and density. The density of the structure influences its stiffness, strength, and energy absorption capabilities. The cell edge radius-to-length ratio plays a vital role in determining the mechanical properties of the structure. A higher radius-to-length ratio results in a structure that is more flexible and has a lower strength. On the other hand, a lower radius-to-length ratio results in a more rigid structure with a higher strength [11]. Lattice structures are ideal for applications that require high stiffness, energy absorption, and strength, such as aerospace, automotive, and biomedical industries. These structures provide a high strength-to-weight ratio, allowing them to withstand high loads while being lightweight. The introduction of additive manufacturing (AM) has revolutionized the production of lattice structures. This technique enables precise control of the geometry of cellular structures with intricate architecture at all scales, ranging from nano to macro. AM can be used to fabricate virtually any open-cell lattice architecture, including complex shapes and patterns. The design possibilities are endless, and the structures can be

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DOI: 10.35860/iarej.1460679

customized to meet specific requirements. Moreover, AM enables the production of structures with reduced material waste and increased productivity, making it a sustainable and cost-effective manufacturing process [12–18].

Mechanical analysis is a common approach to studying the mechanical properties of lattice structures. Experimental studies, as documented in sources [19–23], have been found to produce highly precise results. However, when dealing with more complex cellular geometries, numerical examination, as described in sources [24–28], is usually preferred due to the challenges associated with manufacturing such structures. Sun et al. [29] carried out an experimental and numerical investigation to examine the impact of relative density on the absorbed energy in lattice structures created using ABS material through the AM technique. The outcome of this research highlights a distinct association between the energy absorbed and relative density. The results indicate that an enhancement in relative density is directly proportional to an increase in energy absorption. A recent study has revealed a noteworthy finding related to the relationship between specific energy absorption and relative density. The research indicates that as the relative density increases, there is a steady rise in the specific energy absorption, implying a reliable and consistent bond between the two variables. This discovery can have significant implications for industries that rely on high-energy absorption materials, such as the automotive and aerospace sectors [30,31].

In their study, Wang et al. [32] explored the behavior of polyurethane 3D-printed lattice structures subjected to compression loads, specifically investigating the influence of lattice wall thickness on deformation force. Their findings offer valuable insights into optimizing lattice structures to enhance their capacity to withstand compression, thereby enhancing their applicability in real-world scenarios. The researchers observed a notable distinction in the behavior of lattice structures with variable wall thickness compared to those with fixed wall thickness. Specifically, they noted that as plastic deformation initiated, the force value increased for structures with variable wall thickness, while structures with fixed wall thickness maintained a constant force value throughout the process. This observation suggests that the material's response to deformation is influenced by the variability in wall thickness within the lattice structure. These findings carry significant implications for the design and manufacturing of products requiring specific levels of force resistance and structural integrity. By understanding how variations in lattice wall thickness affect deformation force, designers can tailor lattice structures to meet the desired performance requirements for various applications. Such insights pave the way for developing more robust and efficient lattice-based components and products across various industries.

The research study was focused on examining the orientation of struts in cube, octet, and body-centered-cubic (BCC) lattice structures with a relative density of 30%. The fused deposition modeling (FDM) method was used to manufacture the samples, and nylon filament with chopped carbon fiber was utilized as the printing material. The lattice structures had three units in each direction of x and y, while in the z-direction, they had either one or three units. The test speed was set as quasi-static, which means the test was conducted at a very low speed (2 mm/min), and the test results were examined to determine the energy absorption values of the samples. The absorbed energy values were evaluated by weighing the samples to obtain the specific energy absorption values. This research provides valuable insights into the strut orientation in lattice structures and highlights the potential of Additive Manufacturing (AM) in producing complex and efficient cellular structures. The findings of this study can be used to optimize the design of structures with improved energy absorption capabilities, which can be utilized in various applications such as automotive components, aerospace structures, and sports equipment.

2. Materials and Method

The current study involved the fabrication of various lattice samples using a nylon filament infused with chopped carbon fiber. The mechanical properties of this composite filament were rigorously quantified, yielding a Young’s modulus of 528 MPa and a yield strength of 22.6 MPa, as reported in reference [7]. The lattice structures were manufactured through the Fused Deposition Modeling (FDM) technique. This method was chosen for its precision and reliability in producing complex geometries. All lattice types were designed to maintain a consistent relative density of 30%, ensuring structural integrity and performance uniformity across the different samples.

Table 1 provides a comprehensive list of the printing parameters used during the 3D printing process. These parameters include but are not limited to, nozzle temperature, bed temperature, printing speed, layer height, and infill pattern. Such detailed documentation of the printing settings is crucial for reproducibility and for understanding the influence of these parameters on the mechanical properties of the final printed structures. Each unit cell of the lattice was meticulously designed with dimensions of 10 mm along the x, y, and z axes. For experimental purposes, the lattice structures were printed in arrays consisting of three units in the x-direction, three units in the y-direction, and either one or three units in the z-direction. This specific configuration was selected to explore the effects of varying structural height on the mechanical performance of the lattice. This detailed dimensional and configurational information is essential as it provides insights into the design considerations and scalability of the lattice structures. Understanding the geometric parameters is critical for correlating the observed mechanical properties with the structural design, thereby enabling the optimization of lattice structures for various engineering applications.

The selection of three lattice types — cube, octet, and body-centered cubic (BCC) — was based on their distinctive strut orientations. Figure 1 illustrates the 3D-printed unit lattices for each of these structures, providing a visual representation of their geometrical configurations. All lattice types were fabricated with struts having circular cross-sections, ensuring consistency in cross-sectional geometry. However, the orientation of the struts varies significantly among the different lattice types, which contributes to their unique mechanical properties and structural behavior. A detailed examination of Figure 1 reveals that the cube lattice is characterized by exclusively vertical (highlighted by a blue dashed box) and horizontal struts (highlighted by a red dashed box). This simple arrangement results in a straightforward, orthogonal lattice structure. In contrast, the octet lattice features a more complex arrangement with both horizontal struts and struts angled at 45 degrees (highlighted by a green dashed box). This configuration enhances the lattice's ability to distribute loads more evenly and efficiently. The BCC lattice, on the other hand, incorporates a combination of all the strut orientations found in the cube and octet lattices. This includes vertical, horizontal, and 45-degree angled struts, creating a more intricate and potentially more resilient structure. The diversity in strut orientation within the BCC lattice contributes to its superior mechanical properties, as it can better resist different types of mechanical stresses. The varied strut orientations among these lattice types are critical to understanding their mechanical behavior and performance. This selection allows for a comparative analysis of how different geometrical configurations impact the overall structural integrity and mechanical properties of the 3D-printed lattices.

Table 1. Printing parameters of nylon filament

Parameters	Specifications
Nozzle temperature (°C)	273
Layer thickness (mm)	0.1
Pattern	Solid
Density	100%

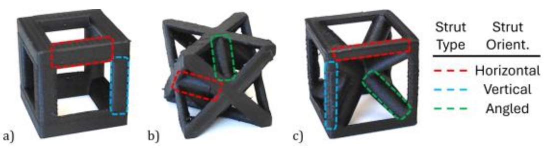

Figure 1. The unit lattice structures and the strut orientations of a) cube, b) octet, c) BCC

2.1 Crashworthiness Parameters

In order to discover the most efficient lattice type in terms of energy absorption, it was necessary to analyze the data collected from the experiments using specific crashworthiness parameters. To achieve this, the densification displacement needs to be specified to calculate the energy absorption values of the lattice samples. For this purpose, the crushing displacement efficiency parameter (η) defined in the literature [33,34] is used. The highest value of the calculated η represents the densification starting displacement value. The related equation of the crushing displacement efficiency parameter is given in Equation 1:

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

where the η, F and ε refer to the displacement efficiency, force and displacement values, respectively. The EA (energy absorption) value of the samples is determined through Equation 2, as shown below. It is worth noting that the displacement value considered as the final displacement was the one obtained at the highest value of the crushing displacement efficiency parameter.

$$EA = \int_0^{\varepsilon_D} F(\varepsilon) d\varepsilon \quad (2)$$

The computation of Specific Energy Absorption (SEA) is a crucial process that involves determining the amount of energy absorbed per unit mass. To derive the SEA value accurately, the following equation can be utilized, which takes into account the mass of the lattice structure. It is pertinent to note that, similar to EA, the calculation of SEA also extends up to the densification displacement. The m in Equation 3 refers to the total weight of the lattice sample and the ρ refers to the density of the bulk material.

$$SEA = \frac{EA}{m} = \frac{\int_0^{\varepsilon} F(\varepsilon) d\varepsilon}{\rho' \rho} \quad (3)$$

3. Results and Discussion

It is worth noting that all experiments were meticulously repeated thrice to ensure accuracy and consistency. A single curve with the average value was presented to minimize visual clutter in the graphs. The study began by examining the test results of single-layer lattice structures and then proceeded to investigate the test results of multi-layer lattice structures.

3.1. Single-layer lattice

The results of axial compression tests of various lattice structures, including cube, octet and BCC, are presented in Figure 5. The study investigates the force-displacement and compression efficiency-displacement curves of the samples and highlights their characteristics in the graphs. The force curve of all three lattice structures shows a similar behavior with a rapid increase at the beginning of the experiments, followed by a plateau region, and then a further increase. The plateau values are found to be approximately 6 kN, 5 kN and 2.5 kN for cube, octet and BCC lattice structures, respectively. The cube structure exhibits the highest plateau value, which can be attributed to the largest strut diameter in this structure. It is noteworthy that the octet structure, despite having the smallest strut diameter, shows a higher plateau value than the BCC structure.

The compressive force efficiencies were calculated to determine the energy values absorbed by the samples. The efficiency curves calculated with the expression given in Equation 1 highlight the displacement value corresponding to the highest value reached by the compressive force efficiency during the entire test period, which gives the value corresponding to the densification of the sample. Densification initial displacement values were calculated to be approximately 4.5 mm in cube and BCC lattice structures, and 5 mm in the octet structure. The energy values absorbed by the samples were calculated according to these displacement values (as the area under the force curves up to the initial values of densification).

The energy absorption values for the cube, octet, and body-centered cubic (BCC) lattice structures were measured to be 22.7 J, 24.8 J, and 12.8 J, respectively. This indicates that the cube and octet structures absorb 77% and 94% more energy compared to the BCC structure. Additionally, the octet structure absorbs 9% more energy than the cube structure. These observed differences in energy absorption are particularly noteworthy, considering that the cube lattice structure has the largest strut diameter among the three. The vertical orientation of the struts in the cube structure is likely the primary reason for the observed decrease in the force curve beyond a displacement of 3 mm. This behavior can be attributed to buckling occurring in the vertical struts of the cube lattice. If this buckling-induced decrease in force did not occur, the energy absorption value of the cube structure would likely be comparable to that of the octet structure. Therefore, the orientation and configuration of the struts play a significant role in the mechanical performance and energy absorption efficiency of lattice structures. These findings provide important insights into the relationship between strut geometry and mechanical behavior. The superior performance of the octet structure, despite its smaller strut diameter, suggests that optimizing strut orientation and preventing buckling can lead to significant improvements in energy absorption capabilities. This information is valuable for the further development and refinement of lattice structures for engineering applications that demand high energy absorption and mechanical stability.

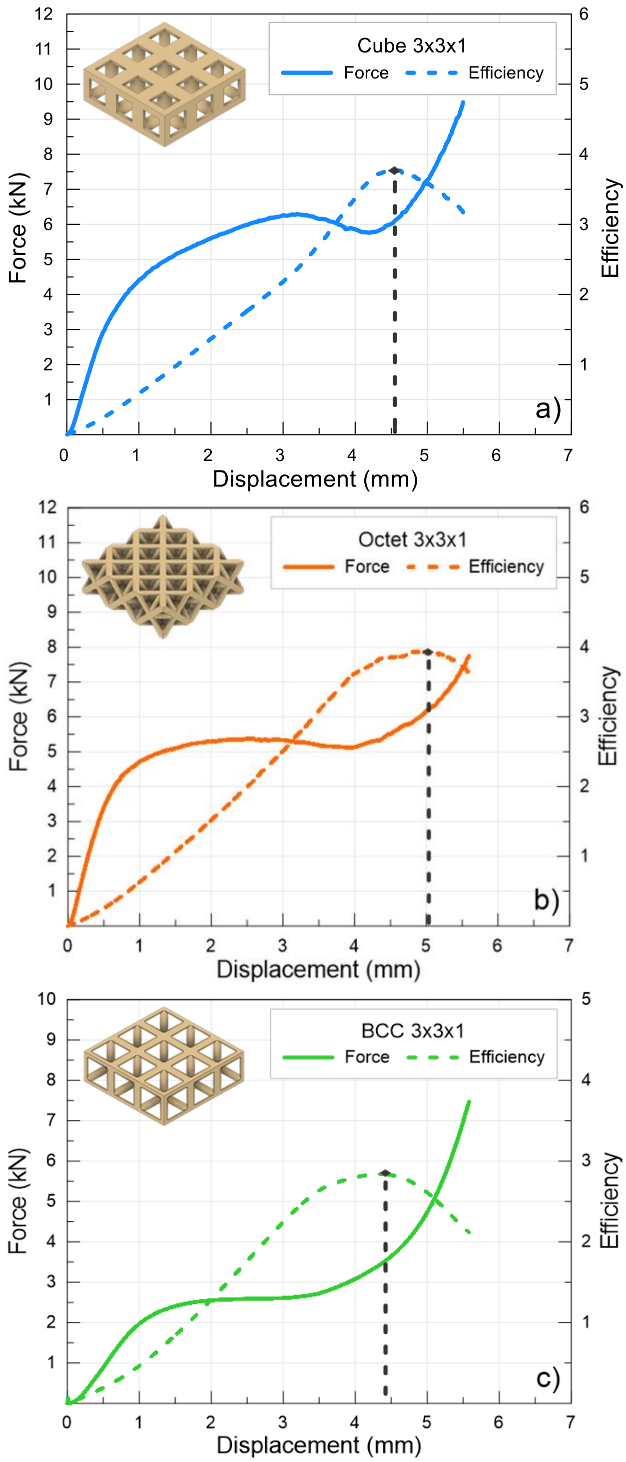

Figure 2. The force-displacement and efficiency-displacement curves of single-layer a) cube, b) octet, c) BCC lattice structures

3.2. Three-layer Lattice

The force-displacement curves of three-layer lattice structures under axial load are presented in Figure 3, along with the compressive force efficiencies shown with dashed lines of the same color as the force curves. Although the force values are similar for octet and BCC lattice structures, they have lower values. This happens because the struts that are forced between two rigid plates in single-layer lattices are forced to be crushed between a rigid plate and the lattice below in three-layer structures. Therefore, the decrease in plateau values is due to this reason. The sudden decrease in the force curve in the cube structure is another important issue. Due to the short vertical struts of the single-layer cube lattice, it was observed that a deformation in the form of barreling occurred in these structures instead of buckling. The struts of the three-layer cube structure are subjected to buckling between rigid plates under compressive force. It can be said that this buckling behavior is directly related to the decrease in the force value of the truss structure.

When examining the compressive force efficiency values of the samples, it is observed that the displacement values corresponding to densification are calculated as 11 mm, 15 mm, and 13 mm for the cube, octet, and BCC structures, respectively. The octet structure exhibits the highest displacement value, consistent with its behavior in single-layer structures. Although the single-layer samples show similar densification values, the lower displacement value of the cube lattice structure in the three-layer configuration can be attributed to the buckling behavior previously discussed. By calculating the absorbed energies of the cube, octet, and BCC lattice structures using the determined densification displacement values, it was found that the cube structure absorbed 26 J, the octet structure absorbed 34.7 J, and the BCC structure absorbed 27.3 J. In single-layer lattice structures, the cube structure absorbs 77% more energy than the BCC structure, though it remains at overall lower energy levels. Additionally, the octet structure absorbs 94% more energy than the BCC structure in a single layer, but this advantage decreases to 27% in the three-layer configuration. These findings highlight the critical influence of structural geometry and configuration on the energy absorption capabilities of lattice structures. The octet structure's superior performance in both single and three-layer configurations underscores its potential for applications requiring high energy absorption. In contrast, the cube structure's reduced efficiency in multi-layer setups due to buckling behavior suggests the need for design modifications to enhance its stability. These results provide valuable insights for the further research and development of optimized lattice structures for various engineering applications.

3.3. Crashworthiness

Table 2 displays the results of the axial crushing tests that were carried out on single and three-layer lattice structures. The tests were analyzed based on the energy absorption efficiency parameters explained in Section 2.1. It is seen that the samples had similar weights regardless of their geometry since the relative density was chosen at 30%. Choosing the same relative density for all lattices resulted in different strut diameters. The diameters of the lattices were measured as 2.05 mm, 0.87 mm, and 1.13 mm, respectively. The changes in strut diameters are mainly because of the varying strut numbers. Since the cube lattice has only four struts in a single unit, it has the highest strut diameter and vice versa.

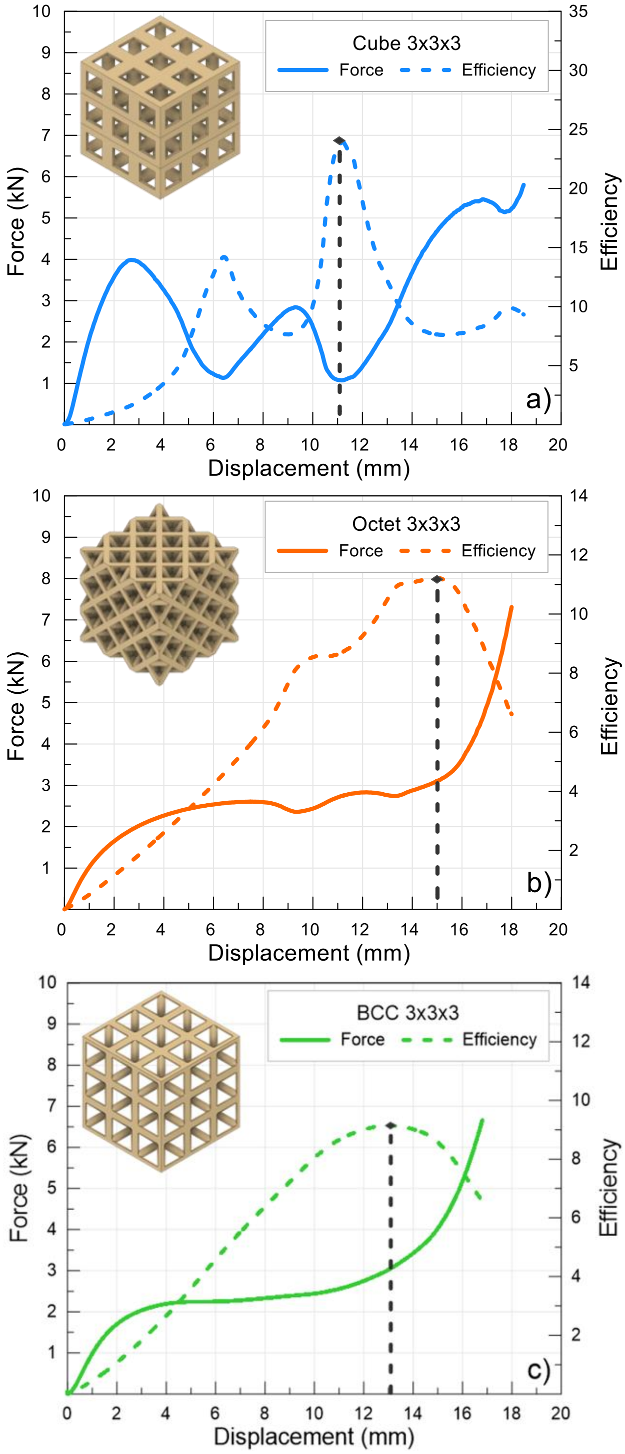

Figure 3. The force-displacement and efficiency-displacement curves of three-layer a) cube, b) octet, c) BCC lattice structures

The sample weights of the single-layer and three-layer structures were determined to be 3.8 grams and 9.8 grams, respectively. Analysis revealed that the octet structure exhibited the highest energy absorption values among the lattice types for both single-layer and three-layer configurations. However, the energy absorption values for the three-layer samples were lower than anticipated. This discrepancy is primarily attributed to the structural configuration of the three-layer lattices.

Table 2. Crashworthiness parameters of single-layer and three-layer lattices

Lattice type		Weight (g)	Densif. displ. (mm)	Energy absorbed (J)	SEA (J/g)
3x3x1	Cube	3.8	4.5	22.70	5.97
	Octet	3.8	5.0	24.80	6.53
	BCC	3.8	4.4	12.80	3.37
3x3x3	Cube	9.8	11	26.00	2.65
	Octet	9.8	15	34.70	3.54
	BCC	9.8	13	27.30	2.79

In these configurations, the struts were in contact with the rigid plate on only one side. In contrast, the struts in the single-layer lattices were compressed between two rigid plates, leading to more effective energy absorption. Moreover, it was observed that the cube lattice displayed buckling behavior in the three-layer configuration, a phenomenon that is not present in the single-layer structure. This indicates that the additional layers in the cube lattice introduced instability, resulting in buckling under compressive loads. These findings highlight the impact of layer configuration and boundary conditions on the mechanical performance of lattice structures. The difference in energy absorption and the occurrence of buckling provides valuable insights into the structural behavior of multi-layered lattices under load, informing future design and optimization of such structures for enhanced mechanical performance.

4. Conclusion

The effect of the strut orientation on the energy absorption capability of the lattice structures was experimentally investigated. Three different lattices of cube, octet, and BCC were chosen since the first two of them have vertical and angled struts, respectively, while the BCC has a combination of vertical and angled struts. The samples were manufactured using the FDM printing method. A nylon-based filament, that contains chopped carbon fiber, was chosen to print the samples. The lattice samples were printed at single and three-layer heights to observe the effect of the strut length on the deformation behavior of the samples.

The results of this study have shown that the orientation of the struts in 3D-printed lattice structures plays a critical role in their ability to absorb energy. It was seen that the 45° angled strut lattice resulted in the best in terms of the absorbed energy and the specific energy absorption parameters. The study found that vertical struts are prone to buckling when their length is increased, resulting in lower energy absorption. However, lattice structures that incorporate both vertical and angled struts, such as the three-layer BCC lattice, could demonstrate significantly higher energy absorption rates. Interestingly, the cube lattice with only vertical struts showed insufficient energy absorption due to buckling issues, as observed in both single and three-layer configurations. Therefore, it can be concluded that adding angled struts is a crucial factor in enhancing the energy absorption and crashworthiness of lattice structures. Also, the layer numbers of the lattices significantly affect the deformation behavior and energy absorption capability of the samples. Especially for the vertical struts, the increase in layer number increases the slenderness of the vertical struts, which causes buckling. These findings should be considered when designing 3D-printed lattice structures for applications in aerospace, automotive, and biomedical engineering.

Declaration

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The author also declared that this article is original and was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

Author Contributions

Muhammet Muaz Yalçın developed the methodology, performed the experiments, and wrote the manuscript.

Acknowledgment

The author would like to thank Prof. Dr. Mostafa ElSayed for his support for the 3D printing process of the samples.

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