COMPRESSIVE STRENGTH EVALUATION OF 3D PRINTING INFILL PATTERNS DESIGNED WITH STRUT LATTICES

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ABSTRACT: Lattice structures have emerged as an effective strategy in additive manufacturing to achieve lightweight components with tailored mechanical performance. This study investigates the compressive behaviour of three strut-based lattice configurations—Body-Centered Cubic (BCC), Diamond, and Face-Centered Cubic (FCC)—fabricated using Fused Deposition Modelling (FDM) with Polylactic Acid (PLA). The lattice geometries were modelled in SolidWorks, produced under consistent printing parameters, and evaluated through both Finite Element Analysis (FEA) and experimental compression testing in accordance with ASTM D695. FEA was performed using ANSYS to assess deformation, stress distribution, and strain under a 20,000 N compressive load, while physical testing validated these predictions and identified failure mechanisms. The results show that the FCC lattice provided the highest experimental compressive strength due to its reduced air gaps and improved structural continuity, followed by the Diamond structure with balanced strength and ductility. The BCC lattice demonstrated the lowest strength but exhibited significant deformation capacity suitable for energy-absorbing applications. Discrepancies between simulation and experiment were attributed to FDM-related imperfections such as strut inaccuracies and thermal shrinkage. Overall, the findings highlight the critical influence of lattice topology on mechanical performance and provide guidance for optimizing lightweight structures in additive manufacturing applications.

KEYWORDS: *Additive Manufacturing; Lattice Structures; FDM; PLA; Compressive Strength*

1.0 INTRODUCTION

Additive 3D printing, as an additive manufacturing process, utilizes digital blueprints to create three-dimensional objects by adding material layer by layer, contrasting with subtractive methods that remove material from a solid block. Its core advantage lies in the ability to produce complex geometries and structures, often unattainable with traditional manufacturing techniques. Various 3D printing methods, including digital light processing (DLP), stereolithography (SLA), selective laser sintering (SLS), and fused deposition modeling (FDM), enable the production of objects with differing levels of complexity and precision by employing diverse materials and technologies [1]. This versatility has made 3D printing an indispensable tool for rapid prototyping, especially for intricate designs, while significantly shortening product development cycles [2].

This study focuses on FDM, a widely used desktop 3D printing method for creating plastic objects. FDM printers deposit polymer components through multiple extrusion nozzles, often requiring structural support during the printing process [3]. The success of the printing process heavily depends on the filament type, as it determines the extrusion quality and final product performance. Lattice structures, often used as internal supports, serve as lightweight and robust alternatives to solid infills. These structures reduce model weight and improve mechanical properties by replacing solid interiors with hollow designs [4].

Lattice structures, categorized into planar-based, strut-based, and surface-based types, offer flexibility in design and application. Their geometric configurations—comprising repeating patterns of struts or beams—provide strength while minimizing weight. Among the most common designs are strut lattices, planar lattices, and triply periodic minimal surface (TPMS) lattices, each with specific benefits. Strut lattices, formed by interconnecting beams, are commonly used in consumer goods, medical implants, and aerospace applications due to their strength and adaptability. Planar lattices, made up of flat, two-dimensional layers, are widely employed in trusses, honeycombs, and simple lattice structures. TPMS lattices, defined by trigonometric formulas, are prominent in medical and industrial applications due to their customizable shapes and sizes [5]. Research has explored the mechanical properties of various infill patterns, such as line, concentric, and honeycomb designs, highlighting the superior robustness of hexagonal geometries over rectilinear ones [6]. Advanced software like SolidWorks and ANSYS enables the design and simulation of lattice structures, providing unprecedented opportunities for engineering applications. These tools facilitate the creation and optimization of intricate structures tailored to specific mechanical requirements, thereby transforming the manufacturing of complex and functional components.

The focus of this study is on the compressive strength evaluation of three distinct lattice designs: body-centered cubic (BCC), diamond, and face-centered cubic (FCC). Lattice structures, known for their ability to enhance mechanical properties and reduce weight, have been extensively studied across various 3D printing methods, including SLA, SLS, and FDM. While planar lattice patterns are sufficient for many applications, strut-based lattice structures offer enhanced load-bearing capacity and structural resilience. However, there is a relative lack of studies focusing on strut-based designs within FDM-based 3D printing [7].

This gap in research underscores the need to investigate the structural performance of strut-based lattices under compressive loads. The study aims to bridge this gap by analyzing and comparing the compressive strength of BCC, diamond, and FCC lattice structures, with a particular emphasis on FDM applications. By focusing on these parameters, the research seeks to contribute valuable insights into the structural optimization of lattice designs for additive manufacturing.

2.0 RELATED STUDY

Lattice structures have become an essential design strategy in 3D printing, enabling the creation of lightweight yet robust components. These structures, formed by repeating unit cells, offer significant advantages in impact absorption and customization for specific applications. Depending on their mechanical responses, lattice structures can be categorized as stretch-dominated, which provides high stiffness and strength, or bending-dominated, which allows for greater compliance and load reduction [8]. The ability to tailor the geometric parameters of lattice structures, such as cell topology and strut dimensions, has led to innovative applications in engineering and architecture, including trusses, frames, and scaffolding [9]. Among the common lattice designs, body-centered cubic (BCC), face-centered cubic (FCC), and Diamond configurations stand out for their unique mechanical and aesthetic properties [10]. Other characterization of lattice structures is done by [11], as shown in Figure 1.

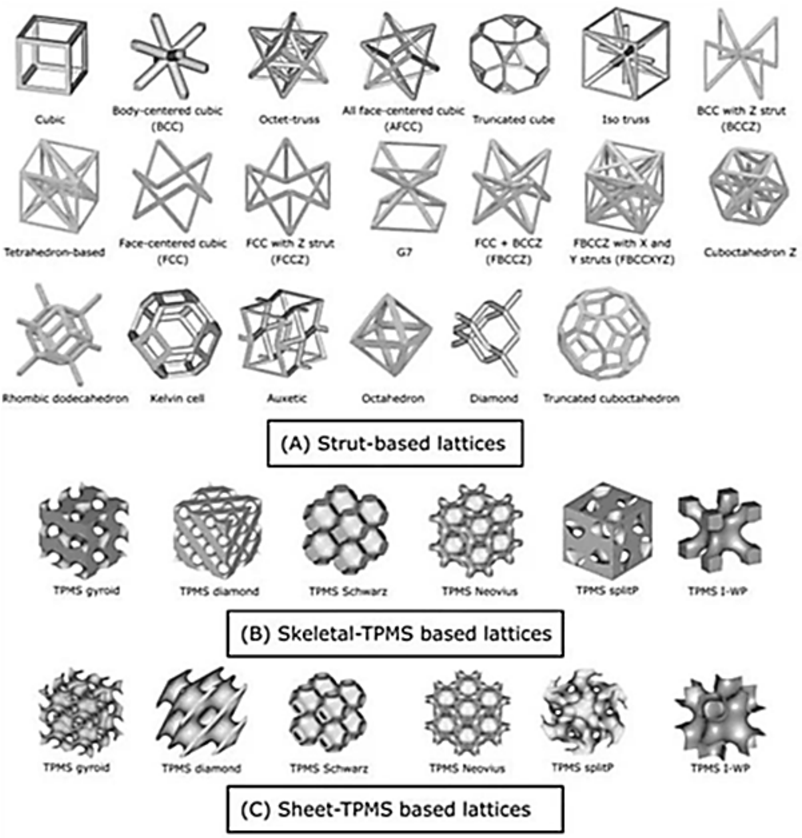


Figure 1: Classifications of lattices

The BCC lattice is particularly well-suited for applications requiring energy absorption and flexibility. Its isotropic nature and compatibility with selective laser melting (SLM) make it a preferred infill pattern in additive manufacturing. Studies highlight its moderate compressive strength and potential for enhancement through graded strut designs, which improve impact resistance and energy absorption capabilities [12]. Research has also demonstrated that BCC lattices can outperform traditional materials like aluminum honeycombs in impact performance, further establishing their relevance in structural applications [13, 14].

The Diamond lattice, inspired by the crystalline structure of natural diamonds, excels in stiffness and stability while maintaining a low density. Its symmetrical arrangement of struts ensures uniform load distribution, making it ideal for aerospace, automotive, and biomedical applications where weight reduction is critical [15]. The Diamond structure's high porosity, combined with its ability to be manufactured without additional supports, simplifies the production process and enhances its mechanical performance [16].

In contrast, the FCC lattice is distinguished by its combination of high compressive strength and ductility. This structure is particularly effective in additive manufacturing, where its properties enhance the mechanical behavior of metals and alloys [17]. Studies have shown that FCC structures are well-suited for biomedical implants and structural components, providing a balance between strength and flexibility [18]. Its design minimizes stress concentrations and facilitates energy absorption, further broadening its applications.

The production of these lattice structures often employs Fused Deposition Modeling (FDM), a widely used 3D printing technique. FDM operates by depositing thermoplastic materials layer by layer to build complex designs. Its affordability and versatility, especially in using biodegradable materials like Polylactic Acid (PLA), have contributed to its popularity [19]. PLA, derived from renewable resources, offers advantages such as high tensile strength, stiffness, and environmental friendliness. Compared to Acrylonitrile Butadiene Styrene (ABS), PLA is easier to process and less toxic, making it ideal for applications in automotive, electronics, and packaging [20, 21]. Studies have demonstrated that PLA's mechanical properties can be enhanced through additives, such as copper particles, to meet specific performance requirements [22].

To optimize the design and performance of 3D-printed structures, computational tools like Finite Element Analysis (FEA) play a critical role. FEA enables the evaluation of mechanical properties, such as stress and strain distribution, under various loading conditions. It has been extensively used to simulate the performance of different lattice infill patterns and refine design parameters for specific applications [23]. Using software like ANSYS, researchers have demonstrated the utility of FEA in identifying failure sites and ensuring structural integrity, thereby improving the performance of additively manufactured components [24, 25]. Compression testing further complements these analyses by providing experimental validation of mechanical properties. Studies on PLA have revealed that factors such as infill patterns, material composition, and process parameters significantly affect compressive strength [26]. Enhanced strength has been observed with denser infill patterns and the incorporation of material additives, demonstrating the potential for tailoring PLA's properties to specific design and functional needs. These advancements underscore the importance of integrating computational and experimental approaches to maximize the capabilities of lattice structures in additive manufacturing.

3.0 RESEARCH METHODOLOGY

3.1 Design of Infill Patterns

Lattice structures, comprising repeated cellular units, offer lightweight and porous alternatives to solid designs, suitable for various applications [27]. Three primary lattice types were studied: Body-Centered Cubic (BCC), Face-Centered Cubic (FCC), and Diamond structures (Figure 2). Key design parameters, such as cell size and relative density, were defined for these structures using SolidWorks and optimized for 3D printing through horizontal orientations to reduce support requirements [28].

(a) (b) (c)

Figure 2: Unit cell for (a) Body-centered Cubic (BCC); (b) Face-centered Cubic (FCC); (c) Diamond lattice structures

Polylactic Acid (PLA), a biodegradable material adhering to ASTM D695 standards, was employed. The designs were prepared in SolidWorks, saved in .stl format, and imported to Ultimaker Cura for slicing. Printing parameters, including layer height (0.2 mm), printing temperature (205°C), and speed (50 mm/s), were standardized for all specimens (Table 1).

Table 1: Printing parameters

Material	PLA
Specimen Size	27648 mm^3
Layer height	0.2 mm
Printing temperature	205°C
Build plate temperature	60°C
Printing speed	50 mm

3.2 Fabrication Using FDM

Fused Deposition Modeling (FDM) ensured structural integrity while balancing speed and material efficiency. SolidWorks was utilized to design the infill patterns, and Ultimaker Cura set the printing parameters. Layer height and printing temperature significantly influenced print quality. Figure 3 depicts the FDM process schematic.

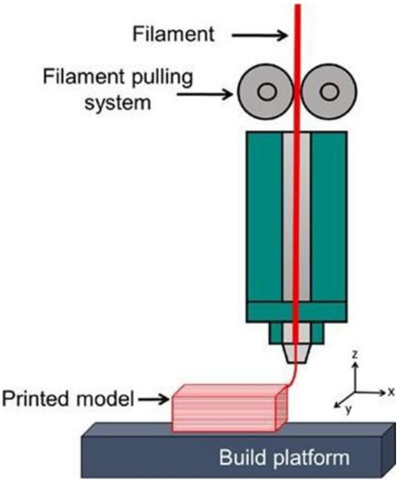
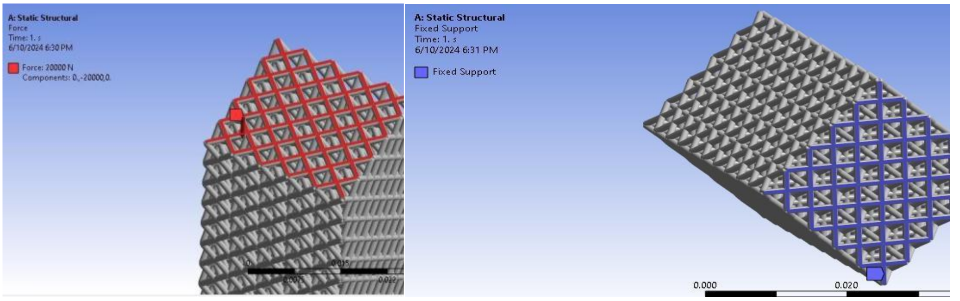


Figure 3: Schematic representation of the FDM process

3.3 FEA by ANSYS

Using ANSYS, lattice designs were analyzed to evaluate mechanical performance under compression. PLA properties were included, and meshing was applied. A downward force of 20,000 N was applied to the top surface, with fixed support at the bottom (Figure 4). The simulation assessed total deformation, equivalent stress, and safety factors.



(a) (b)

Figure 4: Boundary conditions applied in ANSYS; (a) force and (b) fixed support

3.4 Compressive Test

Compressive tests, following ASTM D695, evaluated material behavior under force. Tests measured parameters like compressive strength and modulus of elasticity, revealing vital properties for practical applications [29]. Specimens adhered to DIN 50134 and EN ISO 604 standards (Figure 5). The setup involved a UTM machine with a 20,000 N capacity.

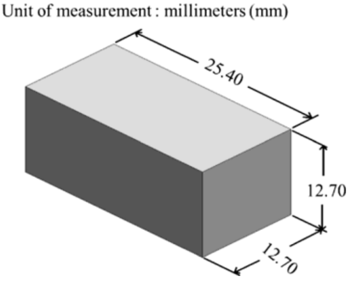


Figure 5: Specimen size according to ASTM D695

Specimens were consistently positioned and measured using precision tools. Variables such as extension rate (2 mm/min) and maximum load influenced outcomes (Table 2). Tests revealed variations in compressive strength among lattice configurations, offering insights for optimizing structural designs.

Table 2: Compressive test parameters

Parameters	Values
Extension rate	2 mm/min
Maximum reachable load	20000 N
Maximum reachable extension	10 mm

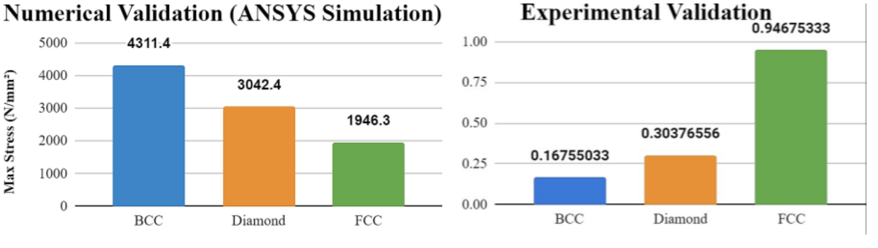
4.0 RESULTS AND DISCUSSION

4.1 Finite Element Analysis (FEA)

FEA was employed to analyze lattice structures for total deformation, maximum stress, and strain using ANSYS Workbench. Simulated results were compared to experimental findings to assess consistency. Variations were attributed to thermal shrinkage, defects, and inconsistent strut diameters, which led to differences between simulation and experimental results [30]. The numerical validation showed BCC had the highest compressive strength in simulations, while FCC structures exhibited the highest experimental compressive strength (Table 3). Figure 6 demonstrates discrepancies between FEA and experimental results.

Table 3: Numerical validation for compressive strength

Sample	Max Force (N)	Max Displacement (mm)	Max Stress (N/mm2)	Max Strain (%)
BCC	20000	16.186	4311.4	1.77
Diamond	20000	29.964	3042.4	1.30
FCC	20000	13.635	1946.3	0.82



(a) (b)

Figure 6: (a) Numerical validation and (b) Experimental validation

4.2 Compression Test

Twenty-seven specimens of three lattice types—BCC, Diamond, and FCC—were subjected to compression tests. Results provided insights into mechanical properties, including stress, strain, and deformation characteristics. The average compressive strength and other metrics for each structure are summarized in Tables 4, with FCC demonstrating the highest compressive strength and BCC the lowest.

Table 4: Numerical validation for compressive strength

Sample	Max Force (N)	Max Displacement (mm)	Max Stress (N/mm2)	Max Strain (%)	Break Force (N)
BCC	20000	16.186	4311.4	1.77	
Diamond	20000	29.964	3042.4	1.30	
FCC	20000	13.635	1946.3	0.82	

BCC structures showed high ductility and moderate compressive strength. They exhibited significant deformation before failure, making them suitable for impact-resistant applications. However, large air gaps between unit cells were identified as a factor for structural weaknesses [14].

Diamond structures displayed balanced properties, with moderate strength and ductility. They failed through continuous shearing at a 45° angle, indicating controlled deformation behavior.

FCC structures had the highest compressive strength and moderate deformation resistance, attributed to narrow air gaps and enhanced ductility. Their design made them resistant to failure under high stress but prone to dislocation [31]. Figure 7 depicts the compressive strength trends for all structures.

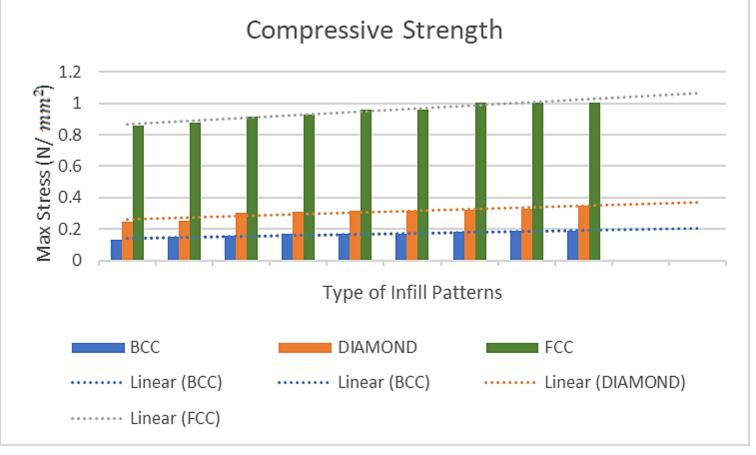


Figure 7: Compressive strength graph for BCC, Diamond and FCC

4.3 Printing Process Observations

Errors in FDM printing influenced specimen accuracy, including inconsistent strut thickness and material deposition defects. FCC structures showed better resilience to such errors due to their design, while BCC structures were more susceptible due to larger air gaps and joint weaknesses. Diamond structures offered a balance between these extremes, providing moderate resilience and structural integrity [32].

4.4 Comparative Evaluation

The study highlights the influence of lattice design on compressive strength. BCC is suitable for energy-absorbing applications but limited by lower compressive strength. Next, Diamond shows balanced performance, ideal for applications requiring moderate strength and ductility. Finally, FCC has superior compressive strength and stress resistance, recommended for high-stress environments.

5.0 CONCLUSION

This research examines the design, fabrication, analysis, and comparative evaluation of the compressive strength of proposed 3D-printed lattice infill patterns. Using the fused deposition modeling (FDM) method with polylactic acid (PLA) as the material, three distinct lattice designs—Body-Centered Cubic (BCC), Diamond, and Face-Centered Cubic (FCC)—were fabricated and tested. The compressive testing involved applying a maximum load of 20,000 N and compressing each specimen to a 10 mm maximum extension. Among the three patterns, the FCC structure exhibited the highest compressive strength at 0.946 N/mm^2, followed by the Diamond structure with moderate strength at 0.303 N/mm^2, and the BCC structure with the lowest compressive strength at 0.167 N/mm^2. To further understand these results, Finite Element Analysis (FEA) simulations were conducted and compared with experimental data. Due to the absence of imperfections in the simulated models, the FEA results consistently demonstrated higher compressive strengths than the experimental outcomes. The study also revealed a significant relationship between the lattice printing patterns and the weight of the samples, emphasizing the critical impact of design on compressive strength.

These findings underscore the potential for optimizing lattice infill structures in additive manufacturing to enhance mechanical performance and material efficiency.

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AUTHOR CONTRIBUTIONS

N.F.M. Azizi: Writing-Original Draft, Methodology, Data curation; H. Hasib: Validation, Writing-Reviewing and Editing, Supervision; S.H. Yahaya: Validation, Writing-Reviewing and Editing; A.E.W. Rennie: Validation, Writing-Reviewing and Editing. All authors approved the final version of the manuscript.

CONFLICTS OF INTEREST

The manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agree with its submission and declare no conflict of interest on the manuscript.

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