DESIGN AND ADDITIVE MANUFACTURING OF HYBRID LATTICE STRUCTURES FOR ENGINEERING APPLICATIONS

1st Shaik UmarFarooq
Department of Mechanical Engineering GVR&S COLLEGE OF ENGINEERING AND TECHNOLOGY, GUNTUR, INDIA, shaik.umar944@gmail.com

2nd Dr. T.V.S.R.K. PRASAD
Department of Mechanical Engineering GVR&S COLLEGE OF ENGINEERING AND TECHNOLOGY GUNTUR, INDIA, prasad.tvsrk@gmail.com

***Abstract*—This research explores the development and eval- uation of hybrid lattice structures fabricated using Fused De- position Modeling (FDM) with ABS (Acrylonitrile Butadiene Styrene) material, emphasizing their potential in lightweight and high-performance structural applications. Three types of lattice geometries—triangular, simple cubic, and a hybrid configura- tion—were designed using Autodesk Fusion 360, incorporating structural enhancements aimed at optimizing mechanical in- tegrity and thermal performance. The fabricated samples were subjected to a comprehensive set of tests. Density measurements were conducted to assess material efficiency and potential weight reduction. Thermal conductivity was analyzed to determine the heat transfer capabilities, making the structures suitable for thermal management applications. Mechanical behavior under compressive loads was examined using the INSTRON 8801 universal testing machine at a controlled strain rate, providing insight into their load-bearing capacity. Additionally, optical microscopy was employed to analyze surface morphology and internal bonding quality, offering a deeper understanding of the FDM process's impact on structural fidelity. Complementing the experimental work, finite element simulations were performed in Fusion 360 to evaluate stress distribution under compression and validate the mechanical test results. The simulation outcomes closely matched the experimental data, reinforcing the accuracy and repeatability of the design and fabrication methodology. The study underscores the significant potential of hybrid lattice struc- tures manufactured through additive techniques for applications requiring tailored mechanical and thermal characteristics. It also sets the groundwork for future research focused on optimizing lattice topologies and developing multifunctional materials, po- sitioning these structures as promising candidates for advanced engineering applications.**

***Index Terms*—geometries—triangular, morphology, Fused De- position Modeling, mechanical integrity.**

I. INTRODUCTION

Additive manufacturing (AM), commonly known as 3D printing, has significantly transformed modern design and manufacturing processes by enabling the production of com- plex geometries with high precision and minimal material waste [1]. Among various AM techniques, Fused Deposition Modeling (FDM) is widely used due to its affordability and adaptability with thermoplastics like Acrylonitrile Bu- tadiene Styrene (ABS). One area that has seen consider- able advancement through AM is the development of lattice structures—porous, lightweight frameworks known for their exceptional mechanical performance and efficient material usage. These structures have found relevance in industries such as aerospace, automotive, and biomedical engineering, primarily because of their superior strength-to-weight ratios [2], energy absorption capabilities, and insulation properties. The fabrication process of a 3D printed object generally begins with creating a digital model using computer-aided design (CAD) software like Fusion 360, SolidWorks, or AutoCAD. This model is then converted into an STL file that describes the geometry using a triangulated surface mesh [3]. The STL file is further processed in slicing software such as Cura or PrusaSlicer, which generates G-code—a set of instructions that controls the printer's operations such as movement, tem- perature, and material deposition. The actual printing phase involves layer-by-layer construction of the object based on the G-code, followed by post-processing activities like removing support structures and improving surface quality [4]. In the context of engineering lightweight yet strong components, lattice structures offer an efficient solution by minimizing ma- terial usage without compromising structural integrity. Their ability to dissipate energy under compressive loads also makes them suitable for impact-resistant applications. However, while existing research has predominantly focused on uniform lattice geometries, there remains a need to explore hybrid lattice configurations that merge different patterns to enhance both mechanical and thermal performance [5]. The current study addresses this gap by designing and fabricating hybrid lattice models combining triangular, cubic, and zig-zag geometries using FDM and ABS material. These structures will be an- alyzed for their compressive strength, thermal conductivity,and density, with validation through experimental testing and simulation [6]. The aim is to gain insights into their feasibility for practical engineering applications and to contribute to the advancement of high-performance, additively manufactured lattice designs [7].

II. LITERATURE SURVEY

Lattice structures have gained significant attention in en- gineering applications due to their remarkable strength-to- weight ratios and adaptable architectural properties, making them suitable for lightweight structural solutions [8]. The foundational work by Gibson and Ashby laid the groundwork for understanding the mechanics of cellular solids, which has since served as a cornerstone in lattice structure design.

The advancement of additive manufacturing (AM) technologies has further enabled the creation of complex geometries, including triply periodic minimal surfaces (TPMS) and hybrid lattice systems, which offer enhanced structural performance. One of the key mechanical benefits of lattice structures lies in their capacity for energy absorption [9]. Studies have shown that hybrid lattices, combining configurations like BCC and FCC, can significantly improve energy dissipation. Re-entrant or auxetic lattices also contribute to superior impact resistance due to their negative Poisson's ratio. Additionally [10], geo- metric optimization in graded TPMS lattices has been proven to enhance energy absorption characteristics. The mechanical rigidity and load-bearing capacity of these structures are closely tied to their topology, with TPMS-based designs often outperforming conventional strut-based lattices in compression scenarios. However, anisotropy remains a challenge [11], particularly in Fused Deposition Modeling (FDM) processes, affecting overall structural integrity. Lattice configurations are also being employed in thermal management applications. Specific designs, such as gyroid lattices, have demonstrated substantial improvements in heat dissipation, while hybrid arrangements can successfully balance thermal performance with mechanical strength. Furthermore, the integration of polymer-ceramic compositions in lattice designs is being ex- plored for insulation purposes. Polymers like ABS are widely used in FDM due to their printability and cost-effectiveness, although enhancements such as carbon fiber reinforcement have shown to substantially increase stiffness [12]. Neverthe- less, there is a scarcity of comprehensive data on the thermal properties of these printed lattices. Computational tools have significantly accelerated the optimization of lattice designs. Techniques such as topology optimization, machine learning, and multiscale modeling are now being utilized to predict and refine mechanical behavior [13]. Meanwhile, innovations in additive manufacturing, including high-resolution printing and multi-material capabilities, have expanded design possibilities, and in-situ monitoring has improved quality control. Lattice structures are now being applied in aerospace, automotive, and biomedical fields, with demonstrated success in reducing component weight. Despite these advances [14], there remain gaps in the integration of thermal and mechanical optimization, limited validation of hybrid simulations, and the lack of standardized evaluation methods for FDM-printed lattices [15]. This study aims to bridge these gaps through the development and analysis of novel hybrid lattice structures.

III. Methodology

The design and development of the lattice structures were carried out using Autodesk Fusion 360 (student version), a comprehensive 3D modeling platform. Three different types of lattice geometries were created: a triangular structure, selected for its high energy absorption capability; a simple cubic design, chosen for its uniform load distribution; and a hybrid structure that integrates triangular, cubic, and zigzag elements to capitalize on the strengths of each configuration. During the modeling process, critical parameters such as cell size, strut diameter, and porosity were customized to ensure optimal performance during Fused Deposition Modeling (FDM) using Acrylonitrile Butadiene Styrene (ABS) filament. To enable a fair comparison across all designs, the external dimensions of each structure were standardized at 50 millimeters in height and 30 millimeters in diameter. Once the digital models were finalized, the physical prototypes were fabricated using a Flashforge Guider 2S FDM 3D printer. This printer was configured with suitable settings tailored for ABS material, ensuring consistent quality, dimensional accuracy, and surface finish. Following fabrication, Finite Element Analysis (FEA) was conducted to simulate the mechanical behavior of the lattice structures under compression. The simulations were performed in the static analysis module of Fusion 360, repli- cating the loading conditions observed during experimental testing. Forces corresponding to compressive strength values were applied, and boundary conditions were set by fixing the base of each model in all three translational directions (Ux, Uy, and Uz). A fine mesh with a size of 0.9 millime- ters was used, and triangular elements were employed to generate a detailed and accurate finite element model. This setup provided numerical insights that closely aligned with experimental observations, validating the structural behavior of the designs. The lattice structures varied in key design aspects: the triangular lattice used an 8 mm cell size with a 1.2 mm strut diameter and 72% porosity; the cubic lattice employed a 10×10×10 mm cell size with a 1.0 mm strut and 65% porosity and the hybrid model combined an 8 mm triangular and 10 mm cubic cell with graded strut diameters ranging from 1.0 to
1.5 mm and an overall porosity of 58%. These design choices reflect a strategic balance between mechanical performance and material efficiency.

IV. Results

The comparison between experimental and Finite Element Analysis (FEA) results revealed important insights into the compressive performance of various lattice structures. Among all the designs, the Hybrid Triangular-Simple Cubic Lattice exhibited the highest compressive strength of 43.18 MPa, which can be attributed to its optimized load-bearing ge- ometry and the presence of triangular reinforcements that efficiently resist shear deformation. On the other hand, the

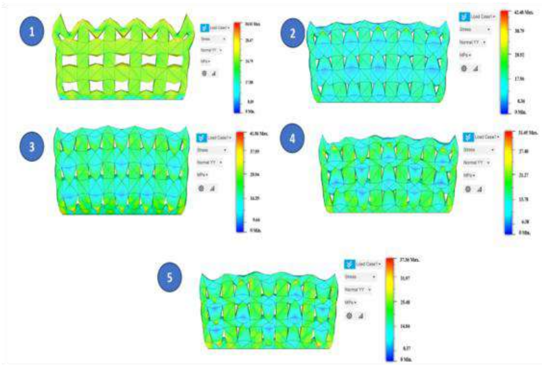


Fig. 1. Shows the results of FEA simulations of lattice structures

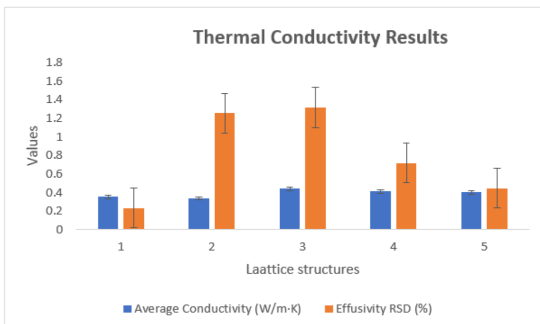


Fig. 2. Shows the results of the experimental ,FEA results and deviation

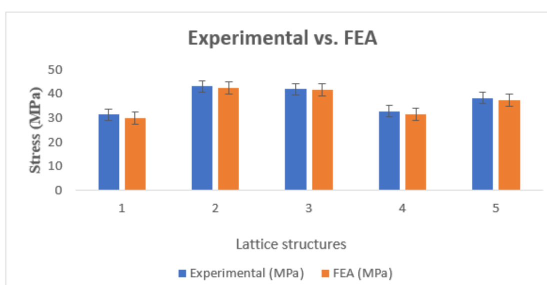


Fig. 3. Shows the difference between Experimental and FEA stress results

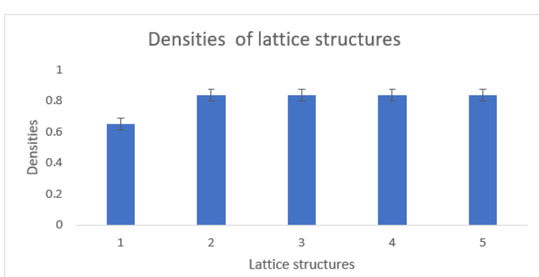
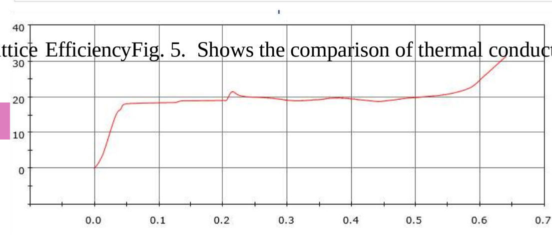


Fig. 4. Shows the Density and Lattice EfficiencyFig. 5. Shows the comparison of thermal conductivity and effusivity of lattice structures



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Name of the lattice structure	Experimental (MPa)	FEA (MPa)	Deviation (%)
Simple Cubic Lattice Structure	31.49	30.01	1.48
Hybrid Triangular-Simple Cubic Lattice Structure Chart Area	43.18	42.48	0.7
Inverted Hybrid Triangular-Simple Cubic Lattice Structure	41.95	41.56	0.39
Zig-Zag Hybrid Triangular-Simple Cubic Lattice Structure	32.82	31.45	1.37
Inverted Zig-Zag Hybrid Triangular-Simple Cubic Lattice Structure	38.23	37.36	0.87

Fig. 6. COMPRESSION TEST REPORT

Simple Cubic Lattice recorded the lowest compressive strength of 31.49 MPa due to its bending-dominated response and the concentration of stress at its orthogonal joints, making it structurally less efficient. Notably, the Inverted Hybrid configuration demonstrated excellent agreement between ex- perimental and simulated results, with only a 0.39% deviation, signifying high geometric stability and reliable predictability in performance. Slight discrepancies were observed in the Zig-Zag Hybrid design, where minor imperfections from the fabrication process led to a slightly higher variation of 1.37%. These observations reinforce the idea that combining multiple geometric features in hybrid designs enhances both energy absorption and structural resilience.

In terms of density and mechanical efficiency, the hybrid structures had a consistent material density of 0.836 grams per cubic centimeter and achieved compressive strengths ranging from 38.23 to 43.18 MPa. This was a marked improvement over the Simple Cubic Lattice, which had a lower density of 0.652 grams per cubic centimeter and correspondingly lower strength at 31.49 MPa. The strength increase of approximately

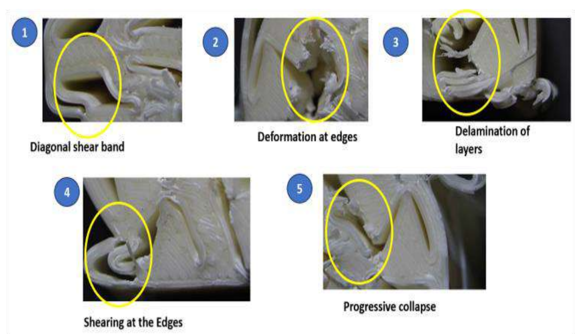

Fig. 7. Shows the deformation modes of the lattice structures

24 to 37 percent is directly linked to the higher density and lower porosity of the hybrid designs, which allow for more effective load distribution and less localized stress. Among these, the Hybrid Triangular-Simple Cubic Lattice demonstrated superior performance due to the synergy of increased density and the mechanical advantages of triangular reinforcement.

Thermal conductivity also varied significantly across the lattice types, influenced heavily by their internal geometries. The Inverted Hybrid design showed the highest conductivity at 0.4392 W/m·K, likely due to its streamlined internal pathways that facilitate heat flow. Conversely, the Hybrid Triangular- Simple Cubic Lattice offered the most thermal resistance, with a lower conductivity of 0.3370 W/m·K, indicating a more complex internal structure that impedes heat transfer. Addi- tional designs like the Zig-Zag Hybrid and Inverted Zig-Zag Hybrid fell in between, providing a balanced trade-off between structural strength and thermal management. Lastly, optical microscopy was used to closely examine deformation patterns and failure mechanisms post-compression. This microscopic analysis helped identify how each structure behaved under load, offering valuable insights into their mechanical reliability and the influence of design on failure modes.

V. Conclusion

This study confirms that hybrid lattice structures, produced using Fused Deposition Modeling (FDM) with ABS, offer notable improvements over traditional lattice geometries in both mechanical strength and thermal properties. Specifically, the Hybrid Triangular-Simple Cubic design delivered the high- est compressive strength of 43.18 MPa, demonstrating that integrating both stretch- and bending-dominated elements can enhance load-bearing capacity and energy absorption. The superior performance of these hybrid designs underscores the effectiveness of combining various unit cell geometries to achieve structural optimization. Finite Element Analysis (FEA) performed using Fusion 360 closely aligned with experimental results, showing deviations of less than 2% across all con- figurations. This strong correlation validates the simulation parameters and indicates that FEA can be a reliable tool for preliminary design and optimization, potentially reducing the need for extensive physical prototyping.

In terms of density, the findings indicate that increased material density contributes positively to compressive strength. Nevertheless, hybrid structures with the same or slightly higher densities consistently outperformed the simpler cubic lattice, suggesting that geometric design is equally, if not more, crucial than density alone. The orientation of struts, the configuration of nodes, and the combination of different unit cells significantly influence how stress is distributed and how the structure deforms under load. Thermal analysis further revealed that the complexity of internal geometry affects heat flow; structures like the Inverted Hybrid, with more direct pathways, demonstrated superior thermal conductivity, whereas those with intricate, maze-like geometries exhibited greater thermal resistance—an insight that can guide material design for thermal management purposes. Additionally, optical microscopy provided valuable understanding of the failure mechanisms, showing that fractures often initiate at structural discontinuities. Hybrid designs displayed more gradual and stable deformation, while the simple cubic design showed abrupt, localized failure. These results collectively highlight the potential of hybrid lattice structures for advanced appli- cations requiring mechanical resilience and tailored thermal behavior.

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