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DESIGN AND ANALYSIS OF OCTET LATTICE STRUCTURES USING ADDITIVE MANUFACTURING TECHNIQUES

[1]Gopal G, [2]Dr.S.Somasundram
[1]PG Scholar, [2]Professor
[12] Department of Mechanical Engineering
[12]National Institute of Technical Teachers Training and Research, Chennai, India

Abstract: The growing need for lightweight and high-performance materials in loads through the axial forces in the struts instead of the bending of members in the engineering field has led to increased research on metamaterial-based lattice structures. These structures derive their mechanical properties primarily from their geometry, not the base material. The octet truss structure is of interest among different lattice topologies due to its stretch-dominated behaviour and efficient load transfer. However, loads through the axial forces in the struts, instead of the bending of members, limit the energy absorption capacity and adaptability of traditional octet lattices to application-specific requirements. The research is aimed at designing, analysing and manufacturing a novel three-dimensional lattice structure based on the octet truss design. The base unit cell is obtained from two directional re-entrant octahedral honeycombs, which show better deformation behaviour and energy absorption characteristics than the conventional octet geometries. From this two-dimensional unit cell, three hybrid unit cell configurations are developed by introducing square, diamond, and hexagonal support elements in the third direction. The unit cell models are designed in SolidWorks and assembled in three orthogonal directions to form the complete three-dimensional lattice structures. Finite element analysis (Ansys) is used to study the stress distribution and deformation behaviour of each configuration under compressive loading. To validate the simulation results, physical prototypes are manufactured in nylon PA12 by selective laser sintering (SLS), a powder-bed fusion additive manufacturing process that is well suited to produce complex, self-supporting lattice geometries without the need for support structures. Prototypes are compression tested to assess stiffness, strength, and energy absorption capability. The results show that the base lattice geometry and the different support configurations have a significant influence on the structural performance. All designs have advantages in respect of load distribution, stiffness and deformation behaviour. Among the three configurations, the hexagonal support design showed the highest elastic modulus, stress response, and energy absorption efficiency, followed by the diamond design, while the square design showed the lowest mechanical response. To summarise, our results underline the importance of the unit cell architecture for tuning the mechanical response and demonstrate that SLS is a feasible and reproducible fabrication process to produce complex, high-fidelity lattice structures with reproducible mechanical response.

Index Terms : Octet Truss, Lattice, Re-entrant Honeycomb, Unit Cell Design, Energy Absorption, Finite Element Analysis, and Selective Laser Sintering (SLS).

I.INTRODUCTION

Lightweight structures with high mechanical strength and energy absorption capabilities are increasingly required in modern engineering applications. However, conventional solid materials often fail to meet these requirements efficiently, particularly in applications that demand weight reduction and performance optimisation. Thus, lattices are attracting a lot of interest due to their unique geometrical configurations and superior mechanical behaviour. These structures are formed from interconnected struts in periodic or non-periodic patterns that allow them to achieve high strength to weight ratios while maintaining structural integrity.

The octet truss lattice is a type of lattice geometry that is known to be stretch dominated. The stretch-dominated lattices transfer loads through the axial forces in the struts instead of through the bending of members in the bending-dominated structures. This results in increased stiffness and load-carrying capacity, making the octet lattice very suitable for advanced engineering applications. The inherent efficiency of this structure has led to its increasing use in the fields of aerospace, automotive and biomedical engineering.

Additive manufacturing technologies are evolving rapidly, making lattice structures more feasible. Selective Laser Sintering (SLS) can produce complex internal geometries that are difficult to manufacture using traditional manufacturing methods. This progress has allowed scientists and engineers to explore and use lattice-based metamaterials for practical applications. However, these developments still require an understanding of the mechanical behaviour of such structures under various loading conditions.

The motivation of this work is to achieve a deeper understanding of the mechanical behaviour of lattice structures, trying to bridge the gap between theoretical analysis and practical implementation. Numerical simulation tools can be useful for gaining insight into structural behaviour, but they often rely on idealised assumptions that may not be representative of real-world conditions. Material anisotropy, manufacturing imperfections and the limitations of the fabrication process can have a significant impact on the performance of fabricated structures.

In addition, the geometry and material properties of the lattice structures are relevant to their mechanical behaviour. Differences in lattice configuration can result in substantial differences in stress distribution, deformation behaviour, and energy absorption characteristics. Therefore, a systematic study is needed to assess and compare different lattice designs under controlled loading conditions. The motivation of this study is two-fold: to identify the efficient lattice configuration and to establish a reliable framework for future experimental validation through additive manufacturing.

II. LITERATURE REVIEW

Lattice structures are periodic frameworks in three dimensions, with their mechanical response dominated by the geometric topology and the relative density rather than the properties of the base material [1, 2]. This feature allows tailored performance for lightweight engineering applications [16]. Based on how they transfer loads, lattice structures are divided into two types: stretch-dominated (like the octet truss), which handle loads through straight strut forces and are very stiff and strong, and bending-dominated, which bend and can absorb more energy during collapse.

Two limitations of traditional single-topology lattices are the limited tunability of properties and the local stress concentration at the nodes, which can lead to premature failure [14]. Auxetic lattices (negative Poisson's ratio) can overcome some of the limitations in properties, improving shear resistance and fracture toughness, but the geometric complexity limits the manufacturability, especially in 3D [5, 8]. To overcome these limitations, hybrid, gradient and hierarchical design approaches have been proposed [9, 11, 12]. Hybrid lattices mix different shapes of the unit cell to achieve a balance between stiffness and energy absorption. Gradient lattices introduce spatial variations in the strut diameter, cell size or density to enhance the stress distribution and energy absorption [11, 12]. Hierarchical lattices have multiscale features inspired by natural materials such as bone and wood to enable progressive and damage-tolerant failure [15, 16].

Among lattice geometries, the octet truss is especially well studied for its stretch-dominated, near-isotropic behaviour and high stiffness-to-weight ratio [2, 3], with Deshpande et al. [2] establishing the analytical linear scaling of stiffness and strength with relative density. But octet trusses have problems concerning energy absorption and nodal stress concentration [6, 14]. This leads to the development of strategies to modify it, such as hybridisation with geometries that can compensate for their deficiencies [9, 13], functional grading (e.g., TPMS metamaterials) [11], and node reinforcement with larger cross-sections or spherical junctions [8, 14].

Additive manufacturing has been essential in realising these complex architectures [6, 7]. Fused deposition modelling (FDM) and selective laser sintering (SLS) are widely used due to cost-effectiveness and material compatibility, though process parameters (layer thickness, infill, build orientation) strongly affect mechanical fidelity, and FDM parts in particular show anisotropy and inter-layer bonding defects [6, 7, 10].

Mechanical characterisation is typically performed via quasi-static compression testing, capturing the characteristic elastic, plateau, and densification regimes of the stress–strain curve, with energy absorption quantified as the area under the curve up to densification [1, 17]. The hybrid and gradient designs exhibit consistently more stable, longer plateau regions and higher specific energy absorption than the uniform topologies [9, 11, 12].

The literature collectively suggests that hybridisation and gradient strategies, coupled with the high stiffness provided by the octet truss and supported by AM fabrication, are a promising route towards lattices with lower stress concentrations and better energy absorption [3, 4, 9, 10, 11, 13]. Based on this foundation, the present study numerically evaluates several modified octet-truss-inspired lattice arrangements in ANSYS, followed by SLS fabrication and compression testing to validate the optimal design.

III.DESIGN METHODOLOGY

3.1 Concept Design

The modified 3D metamaterial lattice was produced via a hierarchical design method, starting from a base unit cell to a full truss-based lattice. The base geometry is a bidirectional re-entrant octahedral honeycomb with the inward-sloping struts allowing controlled progressive deformation under compression, which enhances energy absorption and structural resilience. The bi-directional layout enables efficient load transfer and deformation in multiple planes, making it a suitable basis for further geometrical modification.

The third spatial direction of the re-entrant base was introduced with different support geometries to develop three variants of hybrid unit cells, namely Design A (square), Design B (diamond), and Design C (hexagonal). Every modification changes the inner architecture and thus the stiffness, deformation behaviour, and load distribution of the resulting lattice.

3.2 Design considerations and choice of hybrid support geometries

We selected the square, diamond, and hexagonal geometries because they cover a broad spectrum of load-transfer mechanisms and deformation behaviours reported in the literature, enabling a systematic evaluation of the topology-driven mechanical response. Lattices are generally either stretch-dominated (axial load transfer, high stiffness) or bending-dominated (progressive flexural deformation, greater energy absorption) [1, 2]; the three support geometries were selected to span this range relative to a common base cell.

3.2.1 Square support: This topology mainly transmits load through axial compression with orthogonal struts and thus exhibits a stretch-dominated response with high stiffness and load-bearing ability [2]. This topology is the reference point for high stiffness in the design spectrum.

3.2.2 Diamond support: The struts are arranged diagonally, which gives rise to multiple load paths, resulting in more uniform stress redistribution and almost isotropic behaviour. It is reported that diamond and TPMS type geometries have better energy absorption through progressive deformation and efficient material distribution [9, 10]. Diagonally connected lattices have higher specific strength and stiffness than cubic configurations [11]. This geometry is an intermediate between the axial (square) and the multi-directional (hexagonal) extremes.

3.3.3 Hexagonal support: Distribution of load in many directions This topology is almost isotropic and has high shear resistance due to the multiple axs of symmetry. Hexagonal lattices have been shown to provide improved stiffness, energy absorption and isotropy over traditional geometries [12] and are advantageous for complex, multidirectional loading. It is integrated with the re-entrant base and is intended to offer a balanced combination of stiffness, energy absorption and deformation stability.

The three shapes were selected for specific reasons to provide an obvious comparison between them: square (which is strong and stiff), diamond (which is better at load handling and absorbs more energy), and hexagonal (which performs well in many directions and under complex loads). The finding is consistent with previous results, where hybrid lattices that combine multiple topologies significantly improve energy absorption and deformation stability [13, 14]. In the present study, each support geometry was systematically combined with a common re-entrant octahedral base so as to identify the best compromise between stiffness, strength and energy absorption under quasi-static compressive load.

C. Octet Truss Lattice Design

Unit cell	Strut type 3D Lattice Struture	Top view

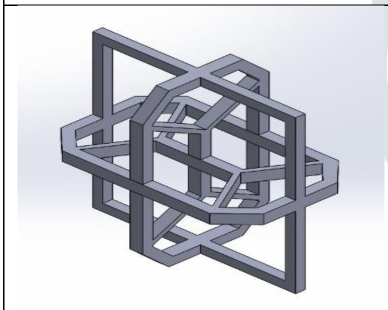
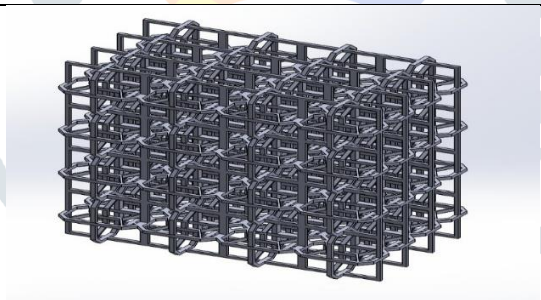
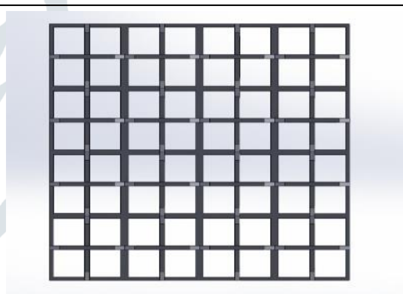

		

Fig 3.1 Design A - Square support		

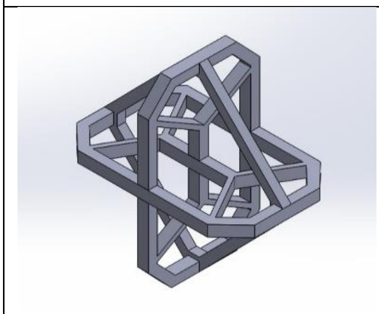
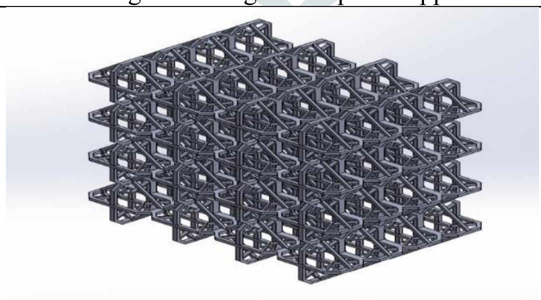
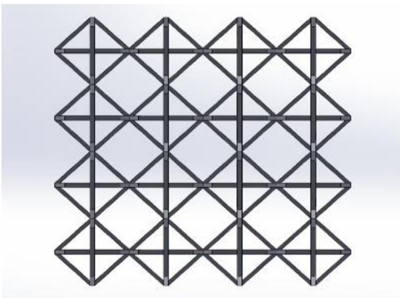

		

Fig 3.2 Design B - Diamond support		

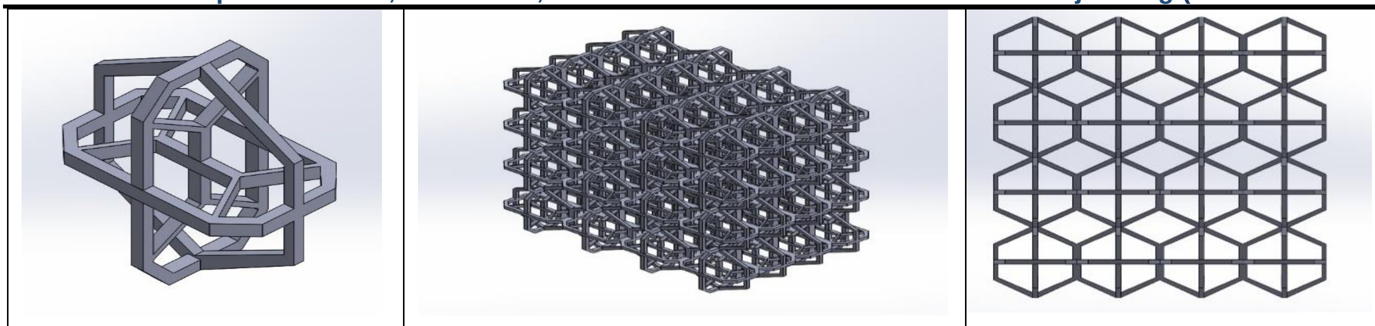


Fig 3.3 Design C - Hexagonal support

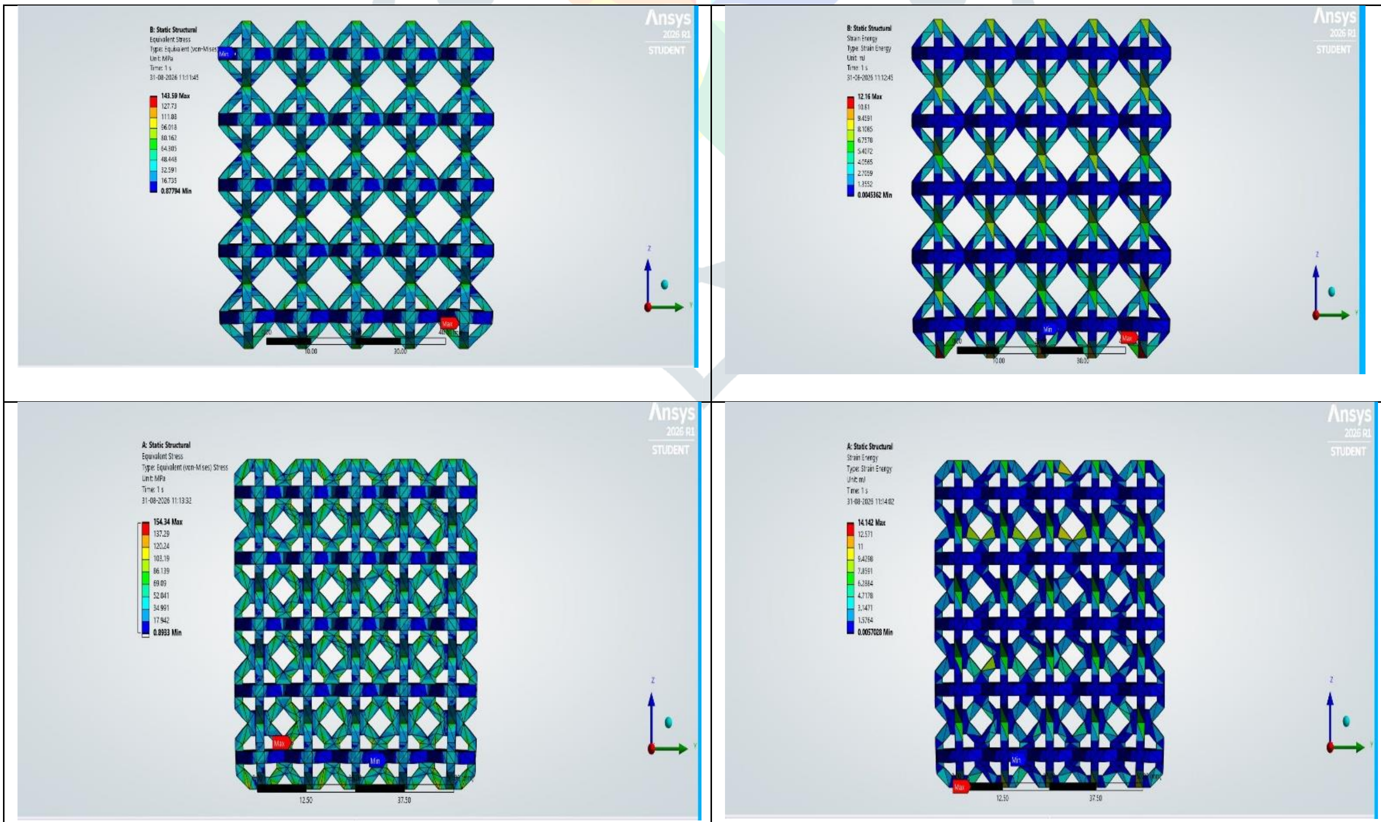
IV.THEORETICAL ANALYSIS RESULTS

Finite-element (ANSYS) simulations at the final load step (t = 1 s) compared three re-entrant octahedral hybrid lattice designs — Square (A), Diamond (B), and Hexagonal (C) — under identical applied compressive displacement.

Table 4.1 Theoretical Analysis Results

Criterion	Design A (Square)	Design B (Diamond)	Design C (Hexagonal)
Avg stress (MPa)	8.0373	7.426	7.9167
Total strain energy (J)	3488	1913.1	2335.8
Stiffness / utilisation	Highest	Lowest	Medium
Failure mode	Stiffness-driven nodal overload	Localised low-stress fracture	Progressive, base-initiated

All metrics follow the consistent order B < C < A, in agreement with $U = \frac{1}{2}K\delta^2$: at fixed displacement δ, higher stored strain energy implies higher effective stiffness K and correspondingly higher stress. Design A's orthogonal, stretch-dominated framework thus proves stiffest and most heavily stressed; Design B's diagonal, sp^3-like diamond geometry distributes load most efficiently and remains most compliant; Design C's hexagonal, multi-path framework is intermediate on every criterion.



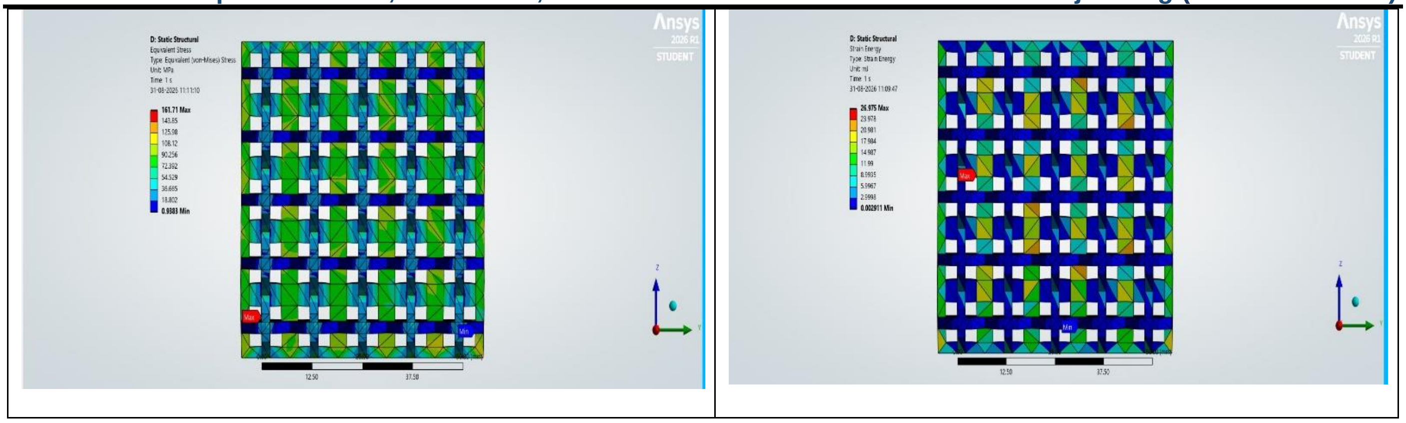


Fig 4.1 Theoretical analysis using ANSYS 2026

4.1 Failure Analysis

Peak stresses in all designs (7.4–8.03 MPa) mark the most probable yield-initiation sites for the base material (Plastic PA12), under linear-elastic assumptions. Design A concentrates stress at re-entrant/square nodal junctions, with high average stress implying rapid, stiffness-driven nodal overload and abrupt fracture. Design B shows the lowest peak and average stress, localised at isolated diagonal-strut junctions, giving a highly contained failure with delayed propagation. Design C shows peak stress converging at the fixed base, consistent with progressive, layer-by-layer failure as successive unit cells yield a more gradual response than Design A.

4.2 Discussion

Stress intensity and distribution scale together across all three geometries (no design combines high peak with low average stress). Stiffness/energy-absorption ranking: A (3488 J) > C (2355 J) > B (1913 J). Design A's superior energy storage is only practically usable if node reinforcement (fillets, spherical inserts, thickened junctions) raises its yield margin, since it also carries the highest peak stress.

4.3 Recommendations

Design B (Diamond Hybrid) — preferred where minimising failure risk (lowest peak/average stress) is the primary driver.

Design A (Square Hybrid) — preferred for stiffness- and energy-absorption-critical applications, pending node reinforcement.

Design C (Hexagonal Hybrid) — balanced choice offering a gradual, distributed failure mode.

Experimental validation via SLS-printed specimens (unit cell ≈10–12 mm, 5×5×5 array, ~80×60×60 mm) under quasi-static compression is proposed to confirm these numerical trends.

V. FABRICATION OF LATTICES

5.1 Fabrication of Lattice Specimens by Selective Laser Sintering

Physical specimens of the three modified octet-truss hybrid designs (Design A – square, B – diamond, and C – hexagonal) were fabricated by Selective Laser Sintering (SLS) using Nylon PA12 to experimentally validate the ANSYS 2025 numerical results. SLS was selected over extrusion-based methods (e.g., FDM) because the powder-bed process is inherently support-free, allowing faithful reproduction of the re-entrant octahedral hybrid unit cells, which contain internal undercuts, inclined strut intersections, and fine nodal features unachievable without risking damage during support removal.

Material properties (PA12, SLS): tensile strength (X–Y) ≈ 48 MPa, elongation at break ≈ 18% (ISO 527); flexural modulus ≈ 1,700 MPa (ISO 178); sintered density ≈ 1.00 g/cm³. PA12 was chosen over PA11, TPU, and PEEK for its superior stiffness–processability balance (flexural modulus ~1,700 MPa vs. ~1,400 MPa for PA11), wide sintering window for dimensional stability of fine strut features, and extensive published mechanical data enabling direct benchmarking against the literature.

Design-for-SLS considerations: Strut diameters were held at a minimum of 1.2 mm (above the 1.0–1.5 mm self-supporting threshold for nylon powders) to ensure sintering continuity; nodal junctions, being larger in cross-section, were not subject to this constraint. The open-strut architecture permits free powder egress during depowdering, though inter-cell opening geometry differs across the three support types (square, diamond, hexagonal) and was checked via simulated powder-flow pathways prior to fabrication. Standard SLS tolerances (±0.25 mm, layer height 0.06–0.12 mm) were assumed, with strut diameter, unit-cell edge length, and overall dimensions flagged for post-fabrication verification. Characteristic SLS surface roughness (Ra ≈ 11 μm) was judged negligible for quasi-static compression testing, since deformation and failure are governed primarily by strut geometry and material volume rather than surface texture.

Specimen preparation: STL files were checked and repaired for mesh defects (non-manifold edges, inverted normals, gaps), particularly at strut–node junctions, before slicing. All three designs were built simultaneously, horizontally oriented, with ≥5 mm inter-part spacing, to ensure identical thermal history and powder age across specimens. Post-processing comprised the following: (1) compressed-air depowdering, with focus on nodal regions prone to powder entrapment; (2) light glass-bead blasting for surface uniformity; (3) dimensional verification via digital callipers (overall dimensions) and optical microscopy at five locations per specimen (strut diameter); and (4) conditioning at 23°C / 50% RH for ≥48 h per ISO 1110 to eliminate moisture as a test variable.

Quality considerations: SLS-processed PA12 exhibits inherent porosity (~7.95% total), which reduces effective load-bearing cross-section and introduces internal stress concentrations, lowering apparent mechanical properties relative to bulk material. This effect was controlled by holding process parameters (laser power, chamber temperature) constant across all three builds and using measured (rather than nominal) strut geometry in subsequent analytical calculations, since these parameters are known to jointly govern the achieved strength of SLS PA12 parts.

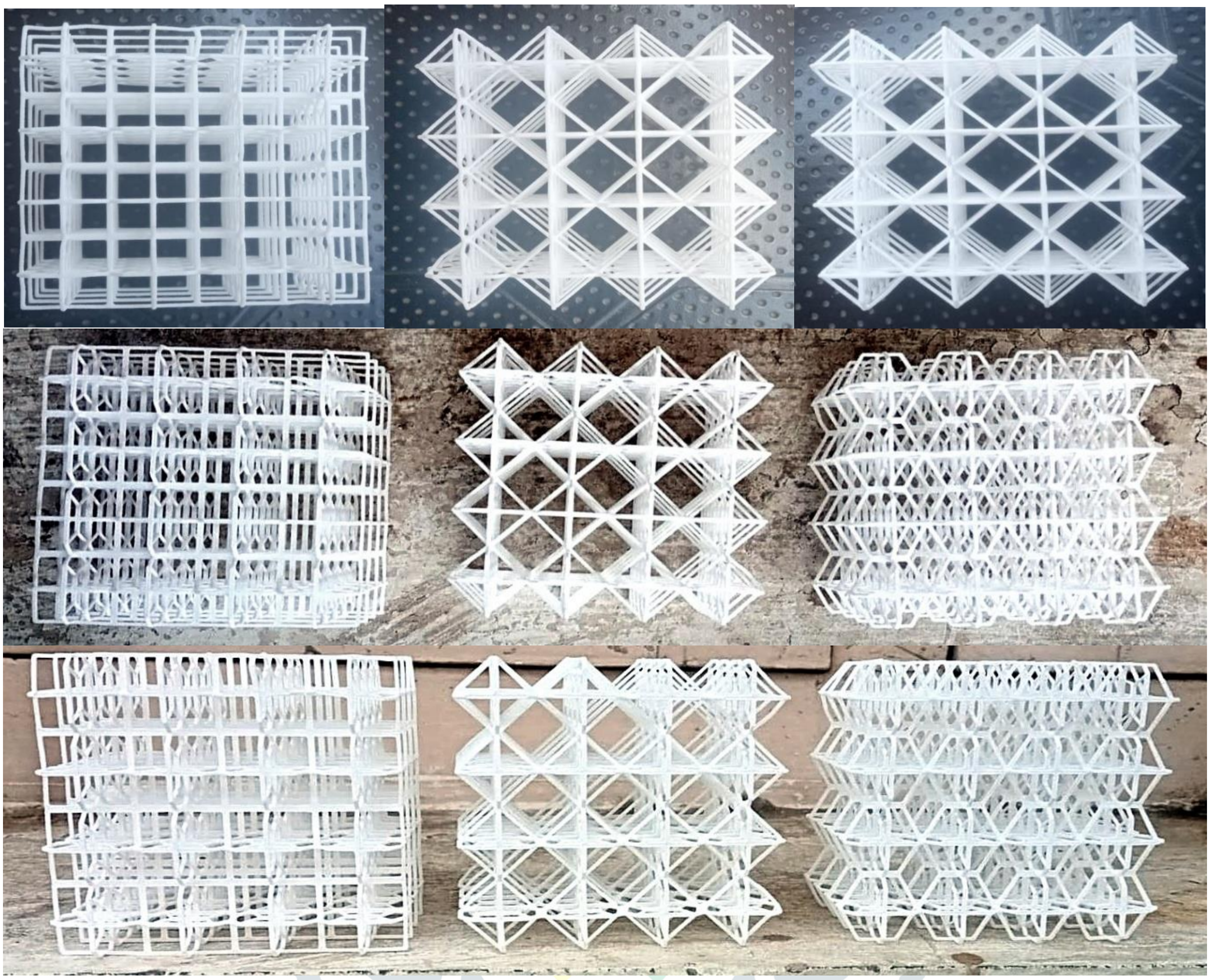


Fig 5.1 3D Printed Lattice Designs Using SLS Nylon P12 Material

VI. MECHANICAL COMPRESSION TESTING

A comparative experimental study showed that the mechanical behaviour and the energy absorption capacity under compression loading were significantly different for the lattice support topologies Square, Hexagonal and Diamond. Among the three configurations, the square topology shows the best overall performance and is the preferred design for further development and application.

The behaviour of energy absorption also supported the square topology. The stress-strain integration results showed that the strain energy density was highest (2.353 MJ/m^3) in the square design, then 1.978 MJ/m^3 in the diamond design, and finally 1.604 MJ/m^3 in the hexagonal design. The total strain energy absorption for each case was calculated on the basis of the volume of the specimen utilized in the analysis and was found to be approximately 626.82 J for the square structure, 526.95 J for the diamond structure and 427.21 J for the hexagonal structure. The square configuration also demonstrated the highest specific energy absorption of 5.964 J/g, which was efficient in energy absorption at a comparable relative density of approximately 6.01%, while still maintaining a lightweight structure.

Moreover, the square topology demonstrates a more favourable and progressive collapse mechanism in terms of deformation response. Its plateau region underwent relatively higher stress levels with a gentler deformation response, implying better structural stability and less vulnerability to sudden localized failure. This controlled collapse behaviour is especially useful for lightweight structures in impact mitigation and energy-absorption applications.

In general, the experimental results show that the square lattice topology provides the best compromise in terms of stiffness, load bearing capacity, strain energy absorption and specific energy absorption of the three topologies investigated. The square support structure is therefore chosen as the best final design for future prototyping, detailed numerical analysis and application-level validation in lightweight energy-absorbing structural systems.

Table 6.1 Compression Test Results

Criterion	Design A (Square)	Design B (Diamond)	Design C (Hexagonal)
stress (MPa)	6.86	6.76	6.51
Total strain energy (J)	626.82	526.95	427.21
Strain energy density(MJ/m³)	2.3529	1.978	1.6036

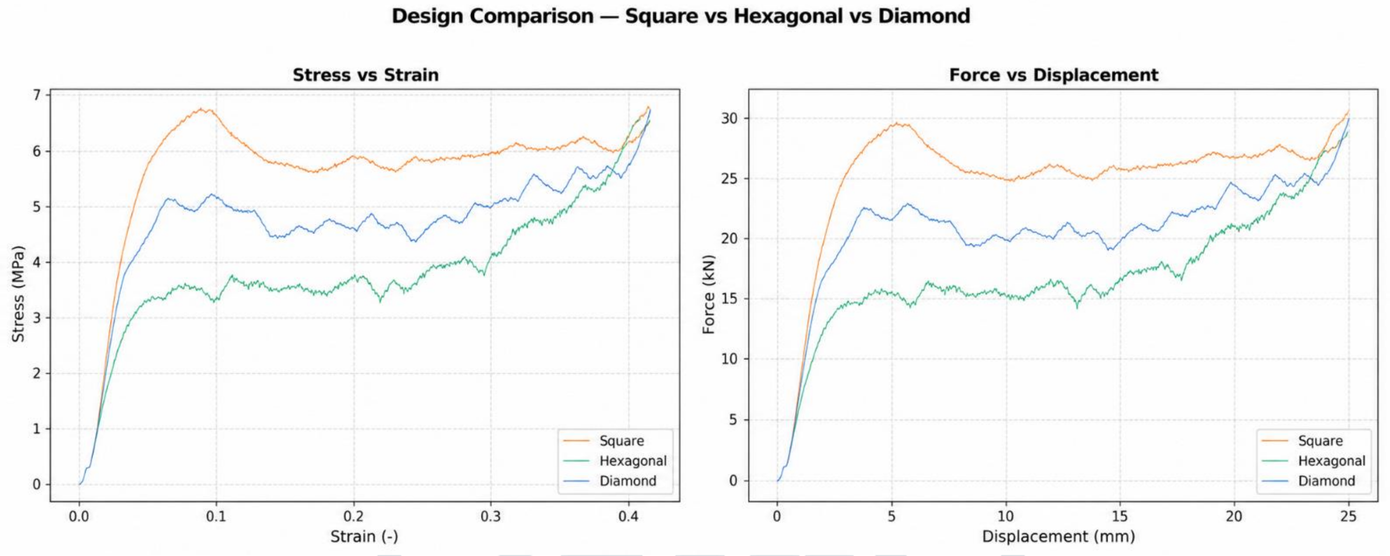


Fig 6.1 Stress vs Strain & Force vs Displacement Graph

6.1 Comparison Between Theoretical and Experimental Results and Final Conclusion

Theoretical analysis and experimental compression tests were performed to evaluate the mechanical performance of the three lattice topologies, namely square, diamond and hexagonal. Comparison of the two approaches reveals both coherent trends and marked differences caused by idealized assumptions in the theoretical model and the actual deformation behavior during physical testing.

The theoretical analysis showed the square topology had the best overall mechanical performance with the average stress of 8.0373 MPa and the total strain energy of 3488 J. The hexagonal topology had an intermediate performance with an average stress of 7.9167 MPa and strain energy of 2335.8 J. The diamond topology had the lowest values with an average stress of 7.426 MPa and a total strain energy of 1913.1 J. The theoretical results ranked the design in order of load bearing capacity and total energy absorption as Square>Hexagonal>Diamond. The predicted failure characteristics also differed, with stiffness-driven nodal overload for the square design, progressive base-initiated collapse for the hexagonal design, and localized low-stress fracture for the diamond design.

The experimental results showed a partially different performance trend. Based on the measured stress–strain response, the experimentally determined strain energy density was highest for the square topology (2.353 MJ/m³), followed by the diamond topology (1.978 MJ/m³) and the hexagonal topology (1.604 MJ/m³). The corresponding total strain energy values were 626.82 J, 526.95 J, and 427.21 J, respectively. Therefore, the order of energy absorption experimentally was Hexagonal > Diamond > Square. This confirms that the square topology has the best energy absorption capability and remains the best design in both theoretical and experimental investigations.

The differences in the relative ranking of the diamond and hexagonal structures are due to several factors related to real experimental conditions. Theoretical analysis is mostly based on idealized geometry, material properties, boundary conditions, and uniform distribution of load. In contrast, the experimental response is affected by the manufacturing imperfections, dimensional variations, material inhomogeneity, interlayer bonding, stress concentrations, friction between the specimen and the loading platens, and localized buckling or fracture. These factors can affect the collapse mechanism and the actual energy absorption behaviour of lattice structures significantly.

Both theory and experiment agree that the square topology is the most mechanically efficient arrangement. There are quantitative differences between the two methods. The theoretical model predicted that the square structure would have the highest average stress and maximum total strain energy, which is also proved by the experimental results, with the highest strain energy density and total energy absorption. Thus, the agreement in the overall choice of the best-performing topology provides confidence in the design assessment.

VII.FINAL CONCLUSION

The combined theoretical and experimental investigation indicates that the square lattice topology provides the best overall mechanical performance among the three considered designs. It has the highest load capacity, stiffness, and energy absorption capacity under the investigated loading conditions. Despite the inconsistency between the theoretical and experimental findings in terms of the absolute magnitude of the strain energy and the relative performances of the diamond and hexagonal configurations, the consistent superiority of the square topology validates the suitability of this as the final design for further development.

Although the diamond topology displays a lower mechanical performance, the hexagonal topology can still be advantageous in case of a controlled and progressive collapse behaviour. Therefore, the square lattice structure is proposed as the most suitable topology for further prototyping, numerical validation, and application in lightweight load bearing and energy-absorbing structural systems. Future work should focus on optimizing the nodal regions of the square design to reduce stress concentrations and enhance optimizing the nodal regions of the square design to reduce stress concentrations and improve the nodal regions of the square design to reduce stress concentrations and improve the stability of its deformation and failure behaviour under practical loading conditions.

VIII. ACKNOWLEDGMENT

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