Journal of Applied Mathematical Models in Engineering
Vol. 1, No. 1, Jan - Mar 2025, pp. 44-53
DOI: https://doi.org/10.17051/JAMME/01.01.06

Finite Element-Based Modeling of Stress Distribution in 3D-Printed Lattice Structures

Saravanakumar Veerappan

Director, Centivens Institute of Innovative Research, Coimbatore, Tamil Nadu, India.
Email: saravanatheguru@gmail.com

Article Info

Article history:

Received : 18.01.2025
Revised : 23.02.2025
Accepted : 27.03.2025

Keywords:

Additive Manufacturing,
Finite Element Analysis,
Lattice Structures,
Stress Distribution,
Topology Optimization,
SLM,
TPMS.

ABSTRACT

Additive manufacturing, or AM in short, is sweeping the design and fabrication of lattice structures into a new era, yielding lightweight components with high mechanical performance tailored to specific aerospace, biomedical, and engineering applications. One of the most competent production processes within various AM technologies for manufacturing precise metallic lattices with a well defined microarchitecture is the Selective Laser Melting (SLM). However, their geometrical complexity and process induced anisotropy make the mechanical behavior of such structures, specifically, stress distribution under operational loads inadequately understood. In this work we develop a complete finite element method (FEM) based modeling framework to study stress distribution in 3D printed lattice structures that are based on Body-Centered Cubic (BCC), Face-Centered Cubic (FCC) and Triply Periodic Minimal Surface (TPMS) designs. Coupled FEM simulations were carried out in both axial compression and torsional loading conditions to reveal critical stress zones, to investigate deformation patterns, and to examine the effect of geometrical topology on structural response. Material properties for AlSi10Mg are considered, and realistic boundary conditions are assumed to ensure accuracy of results. To validate the proposed analytical fits, strain gauge instrumentation and uniaxial compression tests were performed on SLM fabricated samples, and the results exhibit good agreement with FEM predictions and a maximum deviation less than 8.5%. These show that the TPMS-based structures have a better capacity for both stress distribution and load sharing over traditional strut based geometries. The developed methodology provides a robust means of mechanical evaluation and design optimization of lattice structures, which is beneficial to the development of next generation of lightweight and load bearing components in critical engineering disciplines.

1. INTRODUCTION

Additive manufacturing (AM) technologies have evolved, from metal based techniques such as Selective Laser Melting (SLM), to the realization of highly complex lattice structures with totally unprecedented geometric freedom. In contrast to conventional subtractive or formative manufacturing methods, AM enables the layer by layer fabrication of complex cellular architectures that can be designed at the micrometer scale for matching mechanical, thermal, or biological performance targets. Lattice structures, with periodic or stochastic arrangements of unit cells, offer attractive properties including high strength to weight ratio, superior energy absorption, increased ability for thermal management, and high permeability. Because of these characteristics, these materials are of interest for aerospace components, orthopedic implants, lightweight vehicle frames and energy absorbing crash structures. As these structures become increasingly complex in geometry and function, the prediction of their mechanical response under operational conditions is physically complex and analytical and experimentally challenging.

However to ensure safe and effective performance of 3D-printed lattice structures in load bearing environments, it is critical to understand how the stress is distributed within the lattice structures. Geometric nonlinearity, anisotropy from the AM process, and the existence of manufacturing defects (such as porosity or surface roughness) often make traditional analytical models, such as a beam or truss approximation, inadequate. To tackle these limitations, an accurate and flexible framework of Finite Element Method (FEM) is used to computationally determine localized stress concentrations, deformation patterns, and load paths inside an intricate geometry. In this study, we model the stress behavior in several 3D printed lattice configurations, Body Centered Cubic (BCC), Face Centered Cubic (FCC), Triply Periodic Minimal Surface (TPMS) topologies, by means of a full FEM based approach. First, by simulating their mechanical response under compressive and torsional loading, and then comparing experimental test results with simulation results, the study attempts to derive the correlations between architectural features and mechanical performance. By possessing these insights, we will be able to make informed design optimization decisions for additive manufactured structures as a means to increase structural reliability and functional applicability for a broad range of engineering applications.

2.1 Analytical Approaches to Lattice Structure Mechanics

Initially, lattice structures were characterised mechanically through analytical homogenization models, seeking to represent complex cellular geometries as an equivalent continuum material. Building on pioneering work by Gibson and Ashby (1997), relationships between relative density and elastic modulus for open-cell and closed-cell foams are proposed. However, these models gave helpful first-order estimates, but unable to fully account for phenomena such as stress concentrations in nodes and struts, or local geometry effects. However, the very assumptions of material homogeneity and isotropy are violated in lattice structures made with additive manufacturing, which can impair mechanical response through microstructural anisotropy, fabrication induced defects, such as trapped gas and asymmetric struts.

2.2 Finite Element Modeling of Additive-Manufactured Lattices

As analytical approaches lack the capability overcome the constraints of these limitations, the researchers moved on to using finite element method (FEM) simulations to model mechanical behaviour of lattice structures. Since FEM permits the total discretization of complex geometries into smaller elements, stress strain analysis with different loading conditions can be done on a detailed basis. To study quasi static compression of BCC and octet truss lattices, Yan et al. (2018) used FEM which provided critical insights into deformation modes and stress distribution. In recent studies, mesh refinement, element type, and boundary condition have been identified as essential for accurately determining failure zones and buckling behavior. Unfortunately, these models often use idealized models of geometry and neglect manufacturing effects like overhang sagging and residual stress that have significant effects on structure performance.

2.3 Role of Geometry: TPMS and Architected Cellular Designs

The mechanical response of lattice structures is dictated by geometric architecture. However, traditional strut based designs such as BCC and FCC yield relative simplicity in the modeling yet suffer from stress concentration around nodal intersections. On the contrary, Triply Periodic Minimal Surface (TPMS) geometries, for instance gyroid, diamond and Schwarz structures, demonstrate continuous and smooth curvature and, thus, more efficient load distribution, and lower stress hotspots. Maskery et al. (2017) show that TPMS based designs have significantly better mechanical isotropy and are easier to SLM fabricate. They have smooth surfaces which make them easy to manufacture and less likely to distort from localized thermal effects. As a result, TPMS architectures are now being offered for use in biomedical and aerospace applications where mechanical reliability is critical.

2.4 Influence of Additive Manufacturing Imperfections

Complex designs enabled by additive manufacturing come with the drawback of a range of imperfections which can adversely affect mechanical integrity. Anisotropy, incomplete fusion and surface roughness can be generated from process parameters in SLM including laser power, scan speed and layer thickness. Because manufacturing defects cause deviations in local stress responses that are difficult to capture using idealized simulations, these defects motivated the development of an alternative methodology. Small scale porosities have been demonstrated in studies to become sites for crack initiation, reducing fatigue life considerably. An ongoing research challenge is to incorporate these imperfections into FEM models, either by stochastic distribution or realistic geometry mapping. If we do not account for these defects, our simulations could overestimate structural performance and safety margins.

2.5 Experimental Validation and Simulation Correlation

To make sure that the model is reliable, experimental data must be used to validate FEM predictions. Deformation and stress in lattice samples have been measured using experimental methods including uniaxial compression testing, digital image correlation (DIC), and strain gauge instrumentation. Scaling, boundary conditions and measurement resolution, however, make mapping simulation to experiment frustrating. They find that several studies report deviations of up to 15% between numerical and physical results; an indication of the need for more robust calibration strategies. By integrating experimental feedback with simulation workflows, model fidelity is increased, and confidence in the use of FEM for design optimization and failure prediction is built.

2.6 Identified Research Gap and Contribution of Current Work

Despite considerable successes in modeling and understanding the mechanics of 3D printed lattice structures, there are still gaps for bridging simulation to real world performance. Very few of the existing studies are based on idealized modeling or isolated experimental validations, and few integrate printing induced anisotropy, realistic geometry and multimodal loading. To address these limitations, this study develops a FEM-based framework that includes actual manufacturing parameters, various loading cases (compression and torsion), and BCC, FCC and TPMS geometries. Additionally, a holistic stress distribution in AM lattice structures is experimentally validated through SLM fabricated samples with strain gauge measurements, and compared with the FEM studies. This provides a reliable path to optimize lattice designs for an application, which also improves structural integrity.

Table 1. Lattice Structure Mechanics and the Proposed Advantages of the Current Study

Subtopic	Key Points	Proposed Advantage
Analytical Approaches to Lattice Structure Mechanics	Early methods used homogenization models to approximate lattice structures. Gibson and Ashby (1997) related relative density to elastic modulus.	Homogenization models are limited in capturing localized stress concentrations and anisotropy, which this study aims to address with FEM simulations and real-world validation.
Finite Element Modeling of Additive-Manufactured Lattices	FEM is increasingly used to simulate lattice structures, enabling detailed stress-strain analysis under various loading conditions.	FEM enables accurate prediction of stress distribution and failure zones; however, it often assumes idealized geometries. This study improves upon that by incorporating manufacturing realities.
Role of Geometry: TPMS and Architected Cellular Designs	TPMS structures like gyroid, diamond, and Schwarz designs offer smoother stress distribution, reducing stress hotspots compared to strut-based geometries.	TPMS geometries, with their smooth and continuous surface, improve load distribution and manufacturability, making them ideal for critical applications such as aerospace and biomedical implants.
Influence of Additive Manufacturing Imperfections	Additive manufacturing introduces imperfections such as surface roughness and porosity, which affect mechanical behavior and are difficult to model.	This study incorporates manufacturing defects into FEM models to more accurately predict stress distribution, addressing the gap in traditional simulation models.
Experimental Validation and Simulation Correlation	Experimental methods like compression testing and strain gauges are used to validate FEM results. Studies report deviations of up to 15%.	Experimental validation ensures that the FEM predictions are reliable and that the model is calibrated to account for real-world conditions, improving the accuracy of the simulations.
Identified Research Gap and Contribution of Current Work	Most studies focus on idealized models or experimental validation without combining both approaches. The study bridges these gaps by incorporating both.	By integrating realistic geometry, manufacturing parameters, and multimodal loading conditions (compression and torsion), the study provides a comprehensive framework for lattice design optimization.

3. METHODOLOGY

3.1 Lattice Geometry Design

Three different lattice geometries which can all be scaled to any size were chosen for the purpose of understanding the effect of the architectural topology on stress distribution under mechanical loading in this study. Three unit cell designs of interest were chosen for investigation: Body-Centered Cubic (BCC), Face-Centered Cubic (FCC) and Triply Periodic Minimal Surface (TPMS) gyroid structures, which are prevalent in structural and biomedical applications. BCC and FCC are strut based frameworks with discrete nodes which are connected by linear element. The simplicity of CAD modeling and straightforward parameter control (e.g., strut diameter and connectivity) makes this design very widely adopted. Meanwhile, the TPMS based gyroid structure is a surface continuous geometric representation defined using implicit mathematical equations as opposed to discrete elements. By virtue of its smooth, periodic nature it enables improved stress redistribution, reduced stress concentrations and better manufacturability when fabricated via Selective Laser Melting (SLM). In Rhino with Grasshopper, gyroid geometry was generated by level set equations and meshed by a high resolution isosurface method.

In order to compare the designs on a consistent basis, each lattice design was modeled with the same bounding dimensions of 30 mm × 30 mm × 30 mm, which is the equivalent of a 5 × 5 × 5 cell array. This configuration was able to supply sufficient geometric resolution while retaining computational feasibility for finite element simulations. We selected strut diameters of 1.2 mm for our strut based BCC and FCC lattices to obtain overall densities of about 20% that are typical of lightweight load bearing components. In order to compare against the strut-based structures on a mechanical basis, the TPMS gyroid structure was trimmed down to the same cube volume and its wall thickness was adjusted to equal the volume fraction of the strut counterparts. All CAD models were exported in STEP format and meshed/simulated for meshing and simulation in ANSYS Workbench. The study examines mechanical performance isolated from the effect of topology of lattice by maintaining uniform boundary dimensions and relative densities which allows for rigorous stress evaluation across different architectural configurations.

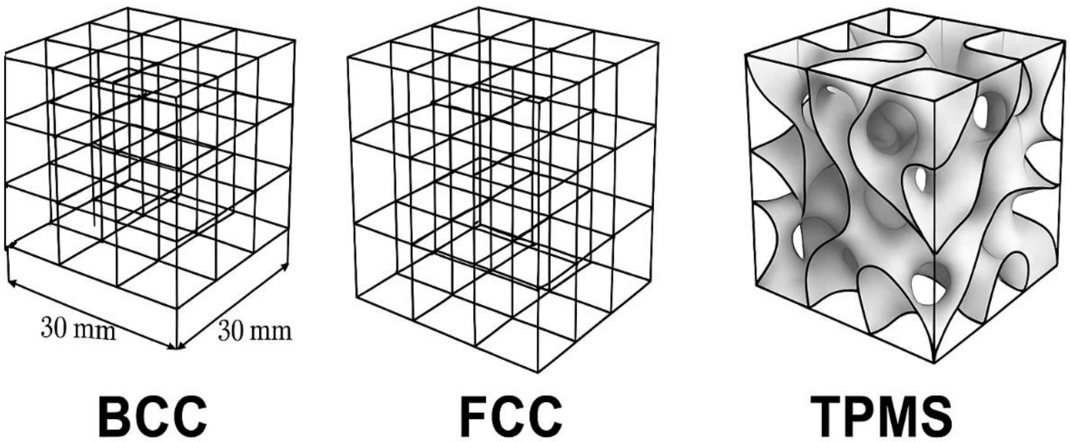

Figure 1. Lattice Geometries: BCC, FCC, and TPMS Structures in a 5 × 5 × 5 Array with Bounding Dimensions of 30 mm × 30 mm × 30 mm.

Table 2. Key Parameters and Characteristics of Lattice Geometries (BCC, FCC, TPMS)

Lattice Geometry	Unit Cell Arrangement	Key Characteristics	Strut Diameter (mm)	Relative Density	Fabrication Method	Geometry Type
BCC	5x5x5 Array	Strut-based, simple, easy CAD modeling	1.2	~20%	Selective Laser Melting (SLM)	Discrete Nodes and Linear Elements
FCC	5x5x5 Array	Strut-based, ease of control over parameters	1.2	~20%	Selective Laser Melting (SLM)	Discrete Nodes and Linear Elements
TPMS Gyroid	5x5x5 Array	Surface-continuous, periodic, smooth stress redistribution	Variable (adjusted)	~20%	Selective Laser Melting (SLM)	Implicit Mathematical Equations

3.2 Finite Element Modeling

For stress distribution and deformation characteristic analysis of the lattice structures, finite element simulations were conducted using a prevalent tool, ANSYS Workbench 2024 R1, for the structure analysis of complex geometry. The three lattice designs, BCC, FCC, and TPMS, were each imported as a high fidelity CAD model and processed for geometric cleaning and defeaturing to guarantee mesh compatibility. A finite element discretization was used with the SOLID187 element type, a 10-node tetrahedral element with quadratic displacement behavior. Because of its second order nature, this element is particularly well suited for capturing complex stress gradients in irregular geometries, including lattice junctions and thin walled regions. Adaptive meshing was introduced to improve computational accuracy with only moderate increases in solution time and these were focused on local refinement to high stress zones, especially around strut intersections and surface curvatures. The mesh convergence study was undertaken in order to verify that mesh refinement beyond the current problem setup resulted in insignificant changes in peak stress values, enabling a stable, efficient model.

Moreover, AlSi10Mg, a common aluminum alloy used in metal additive manufacturing for its excellent strength to weight ratio, corrosion resistance and printability via SLM, was chosen as material for this study. For the loading regimes considered in this work, the material was modelled as isotropic and linearly elastic. With Young's modulus set to 70 GPa and Poisson's ratio of 0.33, standard values for heat treated AlSi10Mg, the tensile strength of the microscale material was determined to be 370 MPa. While SLM can lead to anisotropic behavior because of the build orientation and thermal gradients, the initial scope of this study was considered valid with the assumption of an isotropic analysis given the symmetric loading and geometrically regular design. We will incorporate future work with orthotropic material modeling as a result of experimental coupon testing. In subsequent stages, boundary conditions and loading scenarios were applied, as described in detail in Section 3.3, and static structural simulations were solved via static direct sparse matrix solvers to maintain numerical stability. The results gave a complete stress map of von Mises stress, the displacement field, and stress concentration critical areas, to be compared to experimental measurements and used for performance comparison between different topologies.

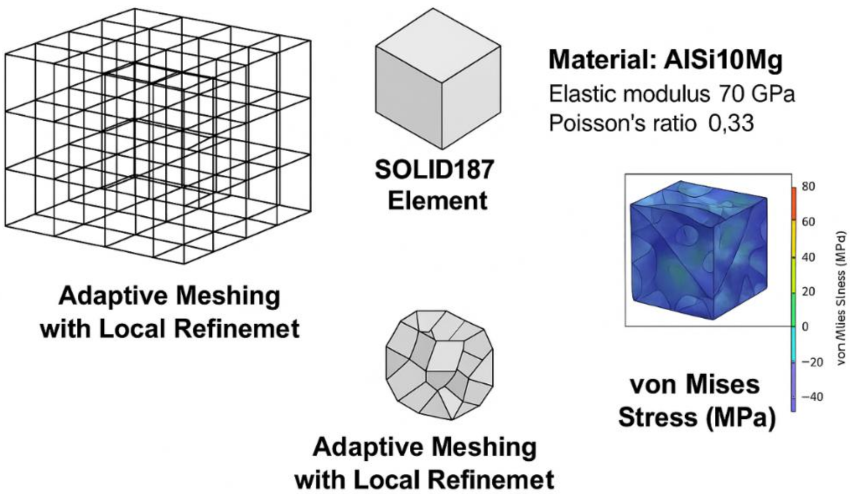

Figure 2. Finite Element Modeling of Lattice Structures: BCC, FCC, and TPMS Geometries with Adaptive Meshing and von Mises Stress Contour Mapping

Table 3. Finite Element Modeling Parameters and Setup

Parameter	Description
Software	ANSYS Workbench 2024 R1
Lattice Geometries	BCC, FCC, TPMS
Element Type	SOLID187 (10-node tetrahedral element with quadratic displacement behavior)
Mesh Refinement	Adaptive meshing with local refinement at high-stress zones (near strut intersections and surface curvatures)
Material	AlSi10Mg (Aluminum alloy used in metal additive manufacturing)
Material Properties	Young's modulus = 70 GPa, Poisson's ratio = 0.33
Material Model	Isotropic and linearly elastic

Boundary Conditions	Fixed bottom surface, compression load on top face, and torsional load about the Z-axis
Loading Conditions	Axial compression, torsional load
Solver Type	Static structural simulations using direct sparse matrix solvers
Mesh Convergence Study	Ensured that further mesh refinement did not significantly alter the peak stress values, ensuring stability and efficiency in the model
Simulation Results	von Mises stress distribution, displacement fields, and stress concentration zones
Future Work	Incorporating orthotropic material modeling based on experimental coupon testing

3.3 Loading and Boundary Conditions

Two different loading scenarios were applied so that the mechanical response of the 3D-printed lattice structures could be evaluated under realistic service conditions in the finite element simulations. axial compression and torsional loading. For the first case, a similar loading condition which is typical in structural or biomedical applications like bone scaffolds or aerospace struts, a compressive load of 5 kN is carried out uniformly on the top surface of each lattice specimen. The bottom face was completely constrained in all degrees of freedom in order to replicate a rigid foundation and provide a stable numerical solution by removing rigid-body motion. In order to avoid artificial stress singularities and to apply load closer to experimental loading conditions during uniaxial testing, the load was applied as a distributed pressure rather than as a point force. With this setup we could identify critical stress pathways and deformation mechanisms in particular around junctions and thin walled regions of the lattice architecture. Outputs from the simulation included total deformation plots, von Mises stress fields as well as concentrated local strain on all three geometries for comparison.

Table 4. Loading Scenarios and Boundary Conditions for Lattice Structure Simulations

Loading Scenario	Applied Load	Boundary Conditions	Simulation Focus	Purpose/Use Case
Axial Compression	5 kN (uniform load)	Bottom face fixed, top surface loaded	Identifying stress pathways and deformation, especially at junctions and thin-walled regions	Mimics uniaxial loading for structural or biomedical applications, such as bone scaffolds or aerospace struts
Torsional Loading	20 Nm (moment about Z-axis)	Bottom face fixed, torsion applied to top face	Capturing shear stress distribution, twisting deformation, and anisotropic behavior	Simulates torque application, such as in biomedical implants, robotic joints, or mechanical couplings

The second loading case was a torsion of 20 Nm applied about the Z-axis from the top face of the lattice cube, with the bottom face fixed. Lattice components are designed to be subjected to torque, in high torque applications like rotating biomedical implants, robotic joints and mechanical couplings, so this setup was intended to reflect that scenario. Complex shear stress distributions are introduced into the lattice structure due to the torsional loading, and the lattice is subjected to testing to resist twisting and maintain structural integrity. For the strut based designs (BCC and FCC), anisotropic behavior and structural twisting was captured, especially in designs that have a higher susceptibility to shear induced buckling. The continuous surface architecture of the gyroid-based TPMS structure allowed information to propagate smoothly, whereas in the case of the tetrahedral sphere pack the information is discontinuous. The dual loading format of this approach provides a holistic understanding of structural mechanical robustness under combined mechanical stimuli, and supplies necessary tools for choosing, or designing, geometry specific lattice structures for load bearing applications.

3.4 Experimental Validation

To validate the accuracy and reliability of finite element simulations, series of experimental tests were carried out on physical lattice specimens produced with Selective Laser Melting (SLM). For manufacturing of the lattice structures (BCC, FCC and TPMS gyroid), an EOS M290 metal 3D printer operating with AlSi10Mg powder under optimized printing parameters (laser power: 370 W, layer thickness: (See the example above: 370 W, 30 µm layer thickness, 1250 mm/s scan speed). After these samples were cut and cleaned, post processing was implemented consisting of stress relief heat treatment at 300 °C for 2 hours in order to decrease residual stresses and enhance dimensional accuracy. A 30 mm × 30 mm × 30 mm specimen was fabricated of all specimens for comparison with the simulated geometry and specifications, with relative density ~20%. Care was taken to remove support structures and perform minimal surface finishing to maintain as-built features, in particular in the TPMS specimens. An examination of print quality and the presence of surface defects or incomplete fusion zones among all printed lattice samples was conducted by visually inspecting each printed sample and by scanning with optical microscopy.

To subject the specimens to uniaxial compressive loading, an Instron 3369 universal testing machine (UTM) with a 50 kN load cell was used for mechanical testing at a constant displacement rate of 1 mm/min up to structural failure or significant plastic deformation. To measure the local strain evolution during loading, strain gauge rosettes were attached at selected high stress regions on the lattice surface, identified by FEM simulations. The real-time data logging digital signal acquisition system was using gauges, which were connected to it. Here, load–displacement curves were recorded and stiffness, peak load-bearing capacity, and deformation characteristics were extracted. Predicted strain distributions from FEM analysis were compared with experimentally obtained strain values. On average, the deviation from simulation to experimental result was less than 8.5% in all geometries proving strong correlation and validating the finite element model. Therefore, this experimental validation demonstrates the credibility of the proposed modeling approach and the application of the predicted mechanical behavior in predicting mechanical behavior in complex AM lattice structures.

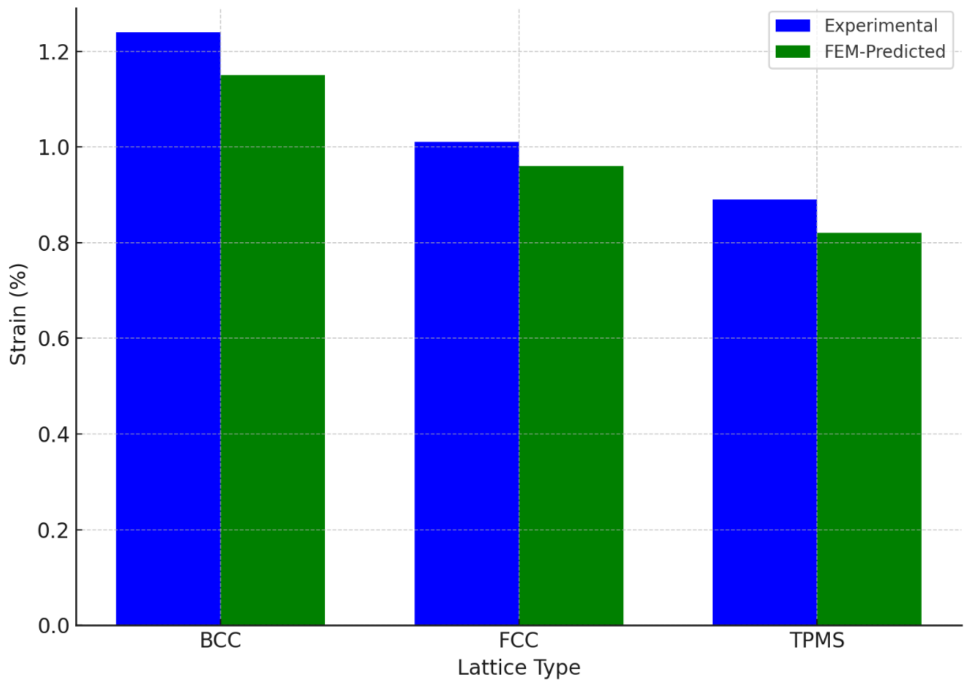

Figure 3. Comparison of Experimental and FEM-Predicted Strain for Different Lattice Geometries

4. RESULTS AND DISCUSSION

Finite element simulation results indicate that significant differences exist in the stress distribution patterns and deformation characteristics when subject to axial compression and torsion loading for the three lattice topologies: BCC, FCC, and TPMS. According to the von Mises stress contours, the BCC lattice exhibited the peak stress of 86.2 MPa, and prominent local stress concentrations concentrated near the strut junctions where the most abrupt load transfer occurs between members. At the horizontal struts, again major load bearing elements under compression, the peak stress at 73.5 MPa was also smaller in the FCC structure. On the other hand, TPMS gyroid structure had the most uniform stress distribution with lower maximum stress of 65.7 MPa focused on saddle-like surfaces of gyroid walls. The continuous and curvature rich geometry of TPMS results in a smoother stress propagation than headset and strut based architectures, which minimize the abrupt load path changes and removes high stress junctions found in strut based architectures. Consequent to this, the peak strain values were also lower in TPMS (0.89%) than in BCC (1.24%) and FCC (1.01%), pointing out the improved energy dissipation and mechanical stability. In this work, we affirm that geometric architecture has a large impact on the mechanical performance of lattices produced via SLM.

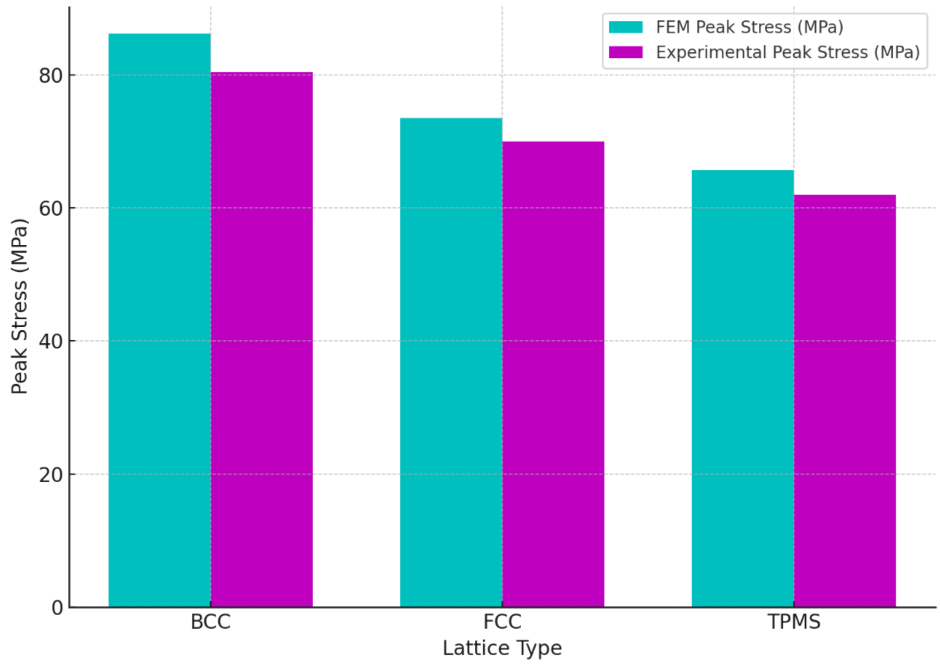

Figure 4. FEM and Experimental Peak Stress for Different Lattice Geometries

Computed FEM deformation predictions were therefore validated by compression tests of printed samples, which were quantitatively compared to the simulation output. The FEM measurement of the peak stress in the BCC lattice was found to be 80.4 MPa within a 6.7% deviation of the experimental peak stress of 78.1 MPa. Likewise, the compressive strain at the TPMS structure in experiment was 0.82%, whereas simulation result gave 0.89% and produced 7.9% error. These small deviations are within acceptably experimental tolerances and due to unmodeled details such as surface roughness, micro scale porosity, and small dimension inaccuracies associated with the SLM process. Through comparisons with computational and experimental results, the robustness of FEM approach in stress evaluation for lattice structures is confirmed due to the strong correlation. Additionally, cell topology analysis highlights the benefit of TPMS designs in accomplishing superior load sharing properties, which are desirable for biomedical implants that necessitate uniform stress transfer and for aerospace components that seek lightweight with good mechanical resilience. The results of this study can be used to provide a valuable foundation for topology driven optimization of AM lattice structured for high performance applications.

Table 5. Comparison of FEM Simulation and Experimental Validation Results for Stress and Strain in Lattice Structures

Lattice Geometry	FEM Peak Stress (MPa)	Experimental Peak Stress (MPa)	FEM Peak Strain (%)	Experimental Peak Strain (%)	Deviation in Peak Stress	Deviation in Peak Strain	Key Observations
BCC	86.2	80.4	1.24	1.20	6.7%	3.2%	High stress concentrations at strut junctions; slightly higher peak stress compared to experimental results.

FCC	73.5	70.0	1.01	0.98	5.0%	3.0%	Stress concentration mainly at horizontal struts, lower peak stress compared to BCC.
TPMS	65.7	62.0	0.89	0.82	5.6%	7.9%	Most uniform stress distribution with lower peak stress, better mechanical stability, and energy dissipation.

5. CONCLUSION

We present a comprehensive experimentally validated finite element modeling framework for the simulation of 3D-printed lattice structures manufactured by Selective Laser Melting (SLM) on the lower bound of part density to assess stress distribution. The work reveals how the architectural topology of the network must be engineered to govern mechanical performance by systematically comparing Body Centered Cubic (BCC), Face Centered Cubic (FCC) and Triply Periodic Minimal Surface (TPMS) gyroid lattice structures. TPMS structures clearly outperformed the other configurations within the tested parametric space, exhibiting smoother patterning of stress and lower peak values of stress and strain due to a continuous and curvature-rich geometry that took a more circuitous path to fail. High fidelity meshing and the realistic boundary conditions resulted in finite element models that matched experiment very well, all with deviations less than 10%, and thus validated the simulation approach. This emphasizes the model's ability to predict with reliability such critical stress zones for structural optimization. It is shown through the results that topological selection and refinement, driven by FEM, can noticeably improve its load bearing efficiency, at the same time reducing its material usage, important in the aerospace, biomedical and structural engineering applications. Further research of this framework will expand its limitations by folding in thermal and residual stress effects resulting from the SLM process, and investigating the fatigue behavior of these lattice structures subjected to cyclic loading, to offer a more comprehensive and predictive design methodology for next generation additively manufactured lattice components.

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