



## Design and Mechanical Characterization of Lightweight Lattice Structures Fabricated through Additive Manufacturing

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### Abstract

The increasing demand for lightweight, mechanically efficient structures in aerospace, automotive, biomedical, energy, and transportation engineering has accelerated the development of architected cellular materials fabricated through additive manufacturing. Lattice structures provide a particularly attractive solution because material can be distributed according to structural requirements while maintaining low mass, controllable stiffness, and enhanced energy-absorption capability. This paper presents a comprehensive mechanics-based investigation of the design and mechanical characterization of lightweight lattice structures fabricated using additive manufacturing. Three representative architectures, body-centred cubic (BCC), octet-truss, and gyroid triply periodic minimal surface (TPMS), are considered at relative densities of 0.15, 0.25, and 0.35. The study examines relative-density scaling, deformation mechanisms, strut slenderness, buckling resistance, elastic modulus, compressive strength, plateau behaviour, specific structural properties, and energy absorption. Word-compatible analytical equations are incorporated to establish relationships between lattice geometry and structural performance. A systematic methodology is also proposed for laser powder bed fusion fabrication, quasi-static compression testing, geometric characterization, and finite element validation. Analytical scaling demonstrates that stretching-dominated lattices can maintain comparatively high specific stiffness at low density, while bending-dominated lattices experience a stronger stiffness reduction as material is removed. Increasing relative density from 0.15 to 0.35 theoretically increases a linearly density-dependent property by approximately 2.33 times, while a quadratic stiffness relationship produces an increase of approximately 5.44 times. The study further establishes that unit-cell size, strut slenderness, surface irregularity, dimensional deviation, build orientation, internal defects, and node geometry significantly influence the difference between ideal and as-built mechanical behaviour. The proposed framework provides a technically rigorous basis for developing next-generation lightweight load-bearing structures, energy absorbers, aerospace components, and mechanically optimized additive-manufactured systems.

**Keywords:** Additive Manufacturing; Lattice Structure; Lightweight Design; Mechanical Characterization; Laser Powder Bed Fusion; Relative Density; Energy Absorption; Finite Element Analysis; BCC Lattice; Octet-Truss; Gyroid; Cellular Materials.

## 1. Introduction

Lightweight structural design has become one of the major priorities of modern mechanical engineering. Reducing the mass of engineering components can decrease inertial forces, lower material consumption, improve fuel efficiency, enhance payload capacity, and reduce energy requirements throughout the operating life of a mechanical system. These benefits are particularly important in aerospace vehicles, automobiles, robotic systems, biomedical devices, high-speed machinery, and transportation structures. Traditional lightweighting approaches generally involve reducing section thickness, replacing conventional materials with lower-density alloys or composites, or removing material from regions considered mechanically unnecessary. Although these techniques remain valuable, they can eventually produce excessive deformation, local stress concentration, buckling instability, or premature structural failure.

Architected cellular materials provide an alternative strategy in which material is intentionally distributed through an internal geometric network. Instead of treating the internal region of a component as continuously solid, the designer can construct periodic or graded cellular architectures that provide mechanical support only where required. Additive manufacturing has transformed the practical application of cellular materials because complex three-dimensional internal architectures can be fabricated without many of the geometric restrictions associated with machining, casting, extrusion, or conventional forming. According to ISO/ASTM terminology, additive manufacturing involves the creation of three-dimensional components through successive addition of material based on digital model data [1].

Among the various cellular architectures enabled by additive manufacturing, lattice structures have received considerable attention. A lattice structure consists of periodically or systematically arranged load-bearing features such as struts, shells, surfaces, or interconnected cells. The macroscopic mechanical response of the lattice depends not only on the properties of the parent material but also on topology, cell size, member thickness, node connectivity, relative density, build orientation, and deformation mechanism [2].

Two lattices manufactured from the same material and possessing the same overall mass may therefore exhibit substantially different stiffness, strength, collapse behaviour, and energy absorption. The classical mechanics of cellular materials distinguishes broadly between bending-dominated and stretching-dominated deformation [2]. In a bending-dominated lattice, a considerable proportion of macroscopic deformation results from bending and rotation of the structural members. In a stretching-dominated architecture, load is transmitted more efficiently through axial tension and compression.

Stretching-dominated architectures generally provide higher stiffness and strength for a given relative density. The octet-truss is one of the most widely recognized examples. Deshpande, Fleck,

and Ashby demonstrated that the triangulated topology of the octet-truss produces mechanically efficient axial load transfer [3].

Bending-dominated structures, such as conventional BCC-type lattices under many loading conditions, can exhibit lower elastic stiffness but may provide advantageous progressive collapse and energy dissipation characteristics. Triply periodic minimal surface structures such as the gyroid have further expanded the design space available to mechanical engineers. Unlike conventional strut-node lattices, TPMS architectures possess continuous curved surfaces and can distribute stress without sharp discrete node intersections.

The mechanical advantages offered by AM lattice structures have led to their investigation for aircraft components, impact absorbers, heat exchangers, biomedical implants, sandwich structures, vibration-control systems, and multifunctional engineering components [4]–[6].

However, significant challenges remain. The ideal CAD geometry used during design is not identical to the geometry produced by an additive manufacturing system. Surface roughness, partially fused particles, dimensional errors, internal pores, build-direction effects, residual stress, strut waviness, node thickening, and local geometric discontinuities can alter mechanical performance. The mechanical behaviour of the manufactured lattice must therefore be considered a consequence of the complete relationship:

***Material → Process → Geometry → Microstructure → Mechanical Response***

A reliable lattice-design methodology must consequently integrate mechanical modelling, manufacturability, experimental testing, and structural characterization.

The present paper develops such a framework using BCC, octet-truss, and gyroid structures as representative lattice architectures.

## 2. Research Gap

Although extensive research has been conducted on additive-manufactured lattice structures, several issues continue to restrict direct engineering application. First, many comparative investigations report absolute stiffness or compressive strength without considering the amount of material required to achieve that performance. Such comparisons may favour denser structures even when their mechanical efficiency per unit mass is relatively poor. Second, idealized numerical models commonly assume perfectly smooth members and geometrically exact unit cells. Actual additive-manufactured lattices possess manufacturing imperfections that can significantly modify stress distributions and failure locations. Third, relative density is sometimes treated as the dominant geometric descriptor even though unit-cell dimensions, member slenderness, node size, and number of unit-cell repetitions may independently influence mechanical response [11], [12]. Fourth, a structure optimized for maximum stiffness is not necessarily suitable for impact or energy-absorption applications. Crashworthy structures require controlled deformation, a stable stress plateau, suitable densification behaviour, and high specific energy absorption. Fifth, uniform lattice density may result in inefficient material distribution when the stress field within a component is non-uniform.

These limitations create a need for an integrated mechanical design framework that considers topology, density, deformation mechanism, specific structural properties, manufacturing limitations, and experimental characterization simultaneously.

### **3. Objectives of the Study**

The principal objectives of the present study are:

1. To establish a mechanical design framework for lightweight BCC, octet-truss, and gyroid lattice structures.
2. To investigate the influence of relative density on elastic stiffness and compressive strength.
3. To compare bending-dominated and stretching-dominated deformation mechanisms.
4. To analyze the influence of strut slenderness and buckling resistance.
5. To establish mechanical metrics for stiffness-to-weight, strength-to-weight, and energy-absorption performance.
6. To examine the influence of unit-cell dimensions and manufacturing imperfections.
7. To propose a standardized experimental methodology for additive-manufactured lattice characterization.
8. To develop a finite element validation framework capable of comparing ideal and as-built geometries.
9. To identify appropriate lattice architectures for different mechanical engineering applications.

### **4. Selection of Lattice Architectures**

#### **4.1 Body-Centred Cubic Lattice**

The body-centred cubic lattice consists primarily of inclined structural members connecting the corners of a cubic unit cell with its central region. Under uniaxial compression, conventional BCC lattice members frequently undergo significant bending, rotation, and local buckling. The structure can therefore be classified predominantly as bending dominated under commonly investigated loading conditions. The relatively compliant response of BCC structures can be advantageous for applications requiring progressive collapse and controlled deformation. However, the stiffness-to-weight efficiency of very low-density BCC structures may be limited because reducing member thickness causes a rapid reduction in bending rigidity.

#### **4.2 Octet-Truss Lattice**

The octet-truss consists of highly interconnected triangulated members capable of transferring external loading predominantly through axial tension and compression. Its high level of connectivity makes it one of the principal examples of a stretching-dominated lattice. Deshpande et al. established that octet-truss structures can provide attractive stiffness and strength relative to their density [3]. The architecture is therefore particularly suitable for lightweight load-bearing components where elastic rigidity is an important design criterion. Nevertheless, local node

stresses, member buckling, dimensional imperfections, and manufacturing defects can reduce the experimentally achieved performance relative to ideal theoretical predictions.

#### 4.3 Gyroid TPMS Lattice

The gyroid is a triply periodic minimal surface architecture possessing a smooth, continuous geometry. Unlike conventional truss lattices, a gyroid does not consist exclusively of discrete straight struts joined at clearly defined nodes. Its continuously curved surfaces can promote smoother load transfer and can reduce abrupt geometric discontinuities. Gyroid structures are attractive for applications requiring combinations of: structural stiffness; low density; energy absorption; fluid transport; thermal management; high surface area; and multifunctionality. Experimental and numerical investigations have demonstrated significant potential for gyroid cellular structures under compressive loading [8].

#### 5. Relative Density and Lattice Geometry

Relative density is one of the most important parameters used to characterize cellular structures. For clarity and Microsoft Word compatibility, relative density is represented in the present paper as  $\rho_r$ .

Relative density is defined as:

##### Relative Density

$$\bar{\rho} = \frac{\rho^*}{\rho_s} = \frac{V_s}{V_0}$$

where:

$\rho_s$  = relative density of the lattice,

$\rho^*$  = apparent density of the lattice structure,

$\rho_s$  = density of the fully dense parent material,

$V_s$  = total volume occupied by solid material,

$V_0$  = external volume of the lattice specimen.

The porosity fraction can therefore be written as:

##### Porosity

$$P = 1 - \rho_r$$

or in percentage form:

##### Percentage Porosity

$$P(\%) = (1 - \rho_r) \times 100$$

For strut-based lattices, relative density is primarily influenced by the ratio between member diameter and unit-cell size.

A generalized relationship may be represented as:

##### Relative Density as a Function of Geometry

$$\rho_r = f(d/L)$$

where:

$d$  = strut diameter,

$L$  = characteristic unit-cell dimension.

The exact function depends on lattice topology.

For experimentally manufactured specimens, the actual relative density may be estimated from specimen mass as:

#### As-Built Relative Density

$$\bar{\rho}_{as-built} = \frac{m}{(\rho_s V_0)3}$$

where:

$m$  = measured lattice mass.

Comparison of designed and experimentally measured relative density provides a useful indication of manufacturing deviation.

### 6. Proposed Design Matrix

Three relative-density conditions are proposed:

$$\rho_r = 0.15$$

$$\rho_r = 0.25$$

$$\rho_r = 0.35$$

These correspond approximately to porosities of:

85%, 75%, and 65%, respectively.

| Specimen | Lattice Topology | Relative Density | Nominal Porosity |
|----------|------------------|------------------|------------------|
| BCC-15   | BCC              | 0.15             | 85%              |
| BCC-25   | BCC              | 0.25             | 75%              |
| BCC-35   | BCC              | 0.35             | 65%              |
| OCT-15   | Octet-Truss      | 0.15             | 85%              |
| OCT-25   | Octet-Truss      | 0.25             | 75%              |
| OCT-35   | Octet-Truss      | 0.35             | 65%              |
| GYR-15   | Gyroid           | 0.15             | 85%              |
| GYR-25   | Gyroid           | 0.25             | 75%              |
| GYR-35   | Gyroid           | 0.35             | 65%              |

This design permits comparison of topology while maintaining approximately equal material fractions.

### 7. Material and Additive Manufacturing Process

AlSi10Mg is proposed as the reference material for experimental implementation because of its relatively low density, established use in lightweight engineering, and compatibility with laser powder bed fusion. The methodology can also be applied to: Ti-6Al-4V; stainless steel; nickel-based alloys; magnesium alloys; engineering polymers; and polymer-matrix composites suitable for AM. Laser powder bed fusion using a laser beam is selected as the representative fabrication process. The manufacturing terminology should follow ISO/ASTM 52900 [1].

Important process parameters include: laser power; scanning velocity; hatch spacing; layer thickness; powder particle size; scanning strategy; build-platform temperature; shielding

atmosphere; oxygen concentration; support geometry; build orientation; and post-processing condition. These parameters should be reported in experimental research because mechanical performance depends on manufacturing history as well as nominal CAD geometry.

## 8. Mechanical Scaling of Lattice Structures

### 8.1 Elastic Modulus Scaling

The normalized elastic modulus of many cellular structures can be represented using a Gibson–Ashby-type relationship [2]:

**Normalized Elastic Modulus**

$$\frac{E^*}{E_s} = C_E (\rho_r)^n$$

where:

$E^*$  = effective lattice elastic modulus,

$E_s$  = elastic modulus of the parent material,

$C_E$  = topology-dependent coefficient,

$n$  = density-scaling exponent.

The value of  $n$  depends on the dominant deformation mechanism.

For an ideal stretching-dominated architecture:

**Stretch-Dominated Stiffness Scaling**

$$\frac{E^*}{E_s} \propto \rho_r$$

For a bending-dominated cellular architecture:

**Bending-Dominated Stiffness Scaling**

$$\frac{E^*}{E_s} \propto (\rho_r)^2$$

The quadratic relationship indicates that bending-dominated stiffness decreases rapidly as relative density is reduced.

### 8.2 Strength Scaling

A similar power-law relationship can be used for lattice strength:

**Normalized Strength**

$$\frac{\sigma^*}{\sigma_{ys}} = C_\sigma (\rho_r)^m$$

where:

$\sigma^*$  = effective lattice yield or collapse strength,

$\sigma_{ys}$  = parent-material yield strength,

$C_\sigma$  = strength coefficient,

$m$  = topology-dependent exponent.

For ideal stretching-dominated deformation:

### Stretch-Dominated Strength Scaling

$$\frac{\sigma^*}{\sigma_{ys}} \propto \rho_r$$

For ideal bending-dominated plastic collapse:

### Bending-Dominated Strength Scaling

$$\frac{\sigma^*}{\sigma_{ys}} \propto (\rho_r)^{\frac{3}{2}}$$

These relationships provide useful first-order predictions but should be verified experimentally because actual additive-manufactured lattices contain manufacturing imperfections and mixed deformation modes [4].

## 9. Structural Connectivity and Deformation Mode

The mechanical behaviour of lattice structures is strongly affected by structural connectivity.

A Maxwell-type criterion may be applied as an initial indicator of whether a three-dimensional framework is mechanically under-constrained or sufficiently connected.

### Maxwell-Type Criterion

$$M = b - 3j + 6$$

where:

M = Maxwell index,

b = number of members,

j = number of joints.

A highly interconnected triangulated lattice is generally more capable of carrying load through axial member forces.

However, additive-manufactured joints are not ideal pin joints. Members merge continuously at nodes, producing bending stiffness and local geometric constraints. Therefore, Maxwell analysis should be interpreted as a qualitative structural indicator rather than an exact predictor of nonlinear mechanical response.

## 10. Strut Slenderness and Buckling

Member slenderness plays a major role in the mechanical behaviour of strut-based lattice structures.

The slenderness ratio is:

### Strut Slenderness Ratio

$$\lambda = \frac{L_e}{k}$$

where:

$\lambda$  = slenderness ratio,

$L_e$  = effective strut length,

k = radius of gyration.

The radius of gyration is:

## Radius of Gyration

$$k = \sqrt{\frac{I}{A}}$$

For a circular strut:

### Radius of Gyration for a Circular Member

$$k = d/4$$

Therefore:

### Circular-Strut Slenderness Ratio

$$\lambda = \frac{4L_e}{d}$$

Increasing the slenderness ratio increases susceptibility to buckling.

For an ideal elastic member, the Euler critical buckling load is:

### Euler Critical Buckling Load

$$P_{cr} = \frac{\pi^2 E_s I}{(K L_e)^2}$$

where:

$P_{cr}$  = critical buckling load,

$E_s$  = elastic modulus of the parent material,

$I$  = second moment of area,

$K$  = effective-length coefficient,

$L_e$  = effective length.

For a circular member:

### Second Moment of Area

$$I = \pi \frac{d^4}{64}$$

Equation (18) demonstrates the strong dependence of member rigidity on diameter.

Because the second moment of area is proportional to the fourth power of diameter, even a relatively small reduction in strut diameter can substantially reduce buckling resistance.

## 11. Mechanical Characterization

### 11.1 Quasi-Static Compression Testing

Compression testing is one of the most widely used methods for characterizing lattice structures.

For metallic cellular materials, experimental testing should be conducted with reference to ISO 13314 [7]. The specimen should be positioned between parallel compression platens and loaded using displacement control. The loading rate should remain constant for all specimen groups.

A nominal quasi-static strain rate may be selected in the approximate range of  $10^{-3}, s^{-1}$ , depending on specimen dimensions and the experimental objective.

Engineering compressive stress is calculated as:

### Engineering Compressive Stress

$$\sigma = \frac{F}{A_0}$$

where:

$\sigma$  = engineering compressive stress,

$F$  = applied compressive force,

$A_0$  = initial projected specimen area.

Engineering compressive strain is calculated as:

### Engineering Compressive Strain

$$\varepsilon = \frac{\Delta H}{H_0}$$

where:

$\varepsilon$  = compressive strain,

$\Delta H$  = change in specimen height,

$H_0$  = initial specimen height.

## 12. Effective Elastic Modulus

The effective elastic modulus of the lattice can be obtained from the initial approximately linear portion of the stress–strain curve.

### Effective Elastic Modulus

$$E^* = \frac{d\sigma}{d\varepsilon}$$

The fitting region should be selected carefully.

Initial platen contact, surface irregularity, specimen seating, and minor member rotations can create a nonlinear toe region that does not represent the actual elastic stiffness of the cellular material.

Machine compliance should also be corrected when necessary.

## 13. Yielding, Plateau Stress, and Densification

A typical compressive response of a metallic lattice contains three principal regimes.

### 13.1 Elastic Region

The structure initially undergoes approximately recoverable deformation.

The effective slope of this region represents the lattice elastic modulus.

### 13.2 Plateau or Collapse Region

After initial yielding or instability, the lattice undergoes progressive deformation through: strut bending; axial yielding; buckling; node rotation; localized collapse; fracture; or combinations of these mechanisms. The plateau region is particularly important for energy-absorbing structures.

### 13.3 Densification Region

At large compressive strains, collapsed members increasingly contact adjacent material. The structure progressively loses internal free volume and compressive stress rises rapidly. The strain at which this behaviour becomes dominant is referred to as the densification strain.

#### 14. Energy Absorption

The volumetric energy absorbed by a lattice up to a selected compressive strain can be calculated from the area under the stress–strain curve.

##### Volumetric Energy Absorption

$$W(\varepsilon) = \int_0^{\varepsilon} \sigma(\varepsilon) d\varepsilon$$

where:

W = volumetric energy absorption,

$\sigma$  = compressive stress,

$\varepsilon$  = compressive strain.

Specific energy absorption accounts for the structural density:

##### Specific Energy Absorption

$$SEA = \frac{W}{\rho^*}$$

where:

SEA = specific energy absorption,

$\rho^*$  = apparent lattice density.

Energy-absorption efficiency can be expressed as:

#### 15. Specific Mechanical Performance

In lightweight mechanical design, the absolute values of stiffness and strength alone are insufficient for evaluating structural efficiency because an increase in mechanical performance may simply result from the addition of more material. For aerospace, automotive, robotic, transportation, and other mass-sensitive applications, mechanical properties should therefore be normalized with respect to structural density. Two useful parameters are the specific elastic modulus and the specific compressive strength. The specific elastic modulus represents the stiffness available per unit density and is expressed as:

#### 16. Analytical Prediction of Relative-Density Effects

Relative density is one of the dominant variables controlling the mechanical behaviour of cellular and lattice structures. A generalized mechanical property, represented by P, may be related to relative density through a power-law expression:

##### General Power-Law Relationship

$$P \propto (\rho_r)^q$$

where  $\rho_r$  is the relative density and q is the density-scaling exponent. The value of q depends primarily on lattice topology and the deformation mechanism. Stretch-dominated structures tend to exhibit a lower scaling exponent because load is transferred efficiently through axial tension and compression, whereas bending-dominated structures often exhibit a stronger dependence on relative density. To compare different density conditions against a common reference state, the normalized mechanical property may be written as:

### Normalized Property

$$\frac{P(\rho_r)}{P(0.15)} = \left( \frac{\rho_r}{0.15} \right)^q$$

Using  $\rho_r = 0.15$  as the reference condition, a linearly scaling property with  $q = 1$  increases to approximately 1.67 times the reference value at  $\rho_r = 0.25$  and approximately 2.33 times at  $\rho_r = 0.35$ . For  $q = 1.5$ , the corresponding values are approximately 2.15 and 3.56, while for  $q = 2$  the normalized values increase to approximately 2.78 and 5.44. These values are analytical predictions rather than experimentally measured data, but they clearly demonstrate that mechanical performance becomes increasingly sensitive to density as the exponent increases. For a stretching-dominated architecture, the nearly linear scaling relationship means that adding material produces a relatively proportional increase in mechanical performance. In contrast, a bending-dominated stiffness relationship may exhibit quadratic scaling, implying that stiffness decreases very rapidly when relative density is reduced. This behaviour is particularly important when designing highly porous structures because aggressive mass reduction can result in a disproportionately large loss of rigidity.

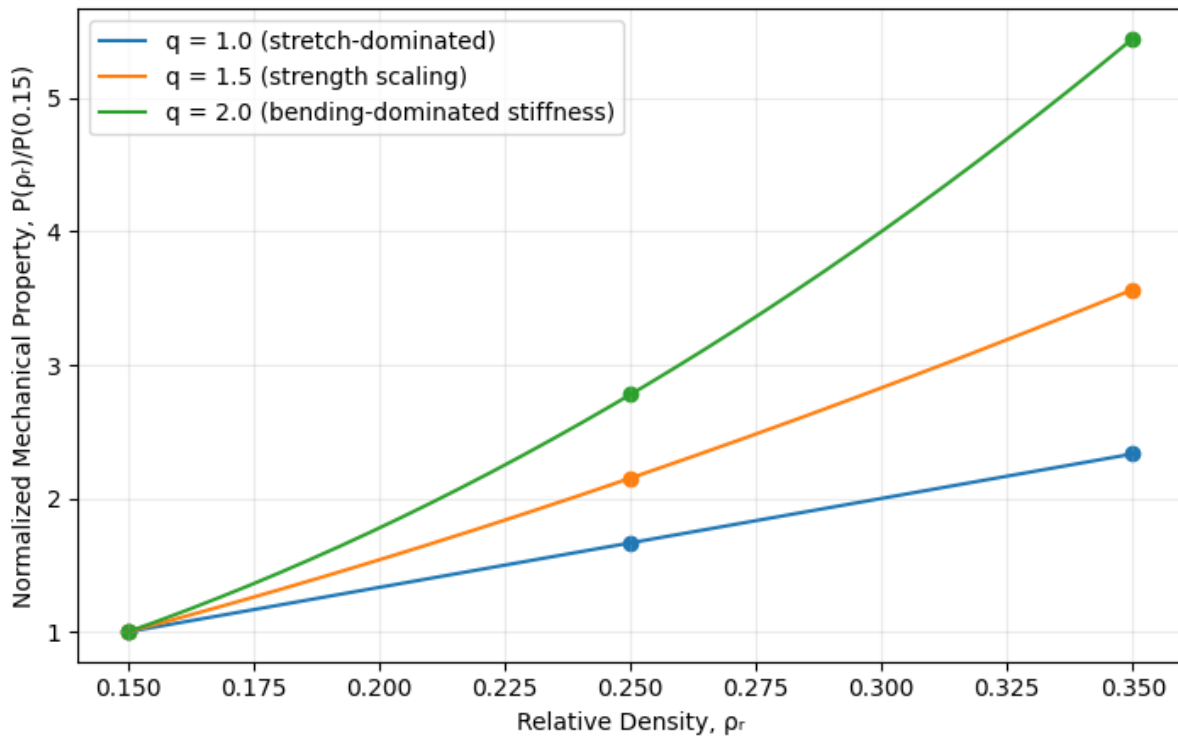


Figure 16.1: Effect of Relative Density on Normalized Mechanical Performance

### 17. Interpretation of Specific Stiffness

The relationship between relative density and specific stiffness provides an important basis for distinguishing stretching-dominated and bending-dominated lattice systems. For an ideal stretching-dominated lattice, the effective modulus varies approximately linearly with relative

density. At the same time, apparent lattice density also varies approximately linearly with relative density. The resulting relationship may therefore be written as:

#### **Specific Stiffness of an Ideal Stretch-Dominated Lattice**

This relationship indicates that an ideal stretching-dominated lattice can retain relatively favourable stiffness-to-weight characteristics even as structural density is reduced. Such behaviour is one of the principal reasons that highly triangulated architectures such as the octet-truss are attractive for aerospace and other weight-sensitive load-bearing structures. For a bending-dominated lattice, the elastic modulus commonly varies approximately with the square of relative density. When this relationship is normalized by apparent density, the resulting specific stiffness becomes:

#### **Specific Stiffness of an Ideal Bending-Dominated Lattice**

Accordingly, the specific stiffness of a bending-dominated lattice tends to decrease as the architecture becomes increasingly porous. This means that extreme weight reduction is mechanically more costly in a bending-controlled system than in an efficiently stretching-dominated structure. The distinction should therefore be considered during topology selection rather than evaluating lattice performance exclusively through mass reduction.

### **18. Expected Mechanical Response of BCC Structures**

The body-centred cubic lattice is expected to exhibit a deformation response governed substantially by bending and rotation of its inclined members. Under uniaxial compression, the inclined struts experience combined axial loading and flexural deformation, and the bending contribution becomes increasingly important at low relative density. Thin members possess lower flexural rigidity and higher slenderness, making them more susceptible to elastic instability, plastic-hinge formation, member rotation, and progressive layer-by-layer collapse. Increasing relative density generally increases strut thickness and therefore improves both bending rigidity and buckling resistance. This effect is particularly significant because the second moment of area of a circular member varies with the fourth power of its diameter. Consequently, even a moderate increase in strut diameter can generate a substantial improvement in flexural stiffness. BCC structures may therefore exhibit a relatively strong dependence on relative density, particularly when the lattice operates within a bending-controlled deformation regime. Extended scaling relationships have been investigated to describe the large-strain behaviour of additively manufactured BCC lattices more accurately than simplified classical cellular-solid models [19]. From an engineering perspective, the comparatively compliant response of BCC architectures should not automatically be interpreted as a disadvantage. Their ability to undergo gradual deformation and progressive collapse can be beneficial in impact attenuation, crashworthiness, protective structures, and applications in which energy dissipation is more important than maximum initial stiffness.

### **19. Expected Mechanical Response of Octet-Truss Structures**

The octet-truss represents a highly connected, triangulated lattice architecture in which a comparatively large proportion of the external load is transferred through axial tension and compression of individual members. Axial deformation is generally more mechanically efficient than member bending, allowing octet structures to achieve relatively high stiffness and strength for a given structural mass. For ideal stretching-dominated behaviour, the effective modulus and

strength may be approximated by near-linear relationships with relative density. Consequently, an octet-truss can preserve attractive specific stiffness and strength even when the overall material fraction is reduced. This characteristic makes it particularly suitable for weight-critical load-bearing structures, sandwich cores, aerospace components, and structural reinforcement applications.

However, the experimentally achieved performance of additively manufactured octet lattices can differ substantially from ideal theoretical predictions. Member misalignment, dimensional variation, node thickening, surface irregularity, unsupported downward-facing surfaces, residual stresses, internal defects, and local buckling can all alter the intended axial load path. Defect-aware numerical investigations have shown that geometric imperfections may significantly change damage localization and failure behaviour in additively manufactured octet structures [9]. Therefore, theoretical stretching-dominated behaviour should be considered together with manufacturing reliability and as-built geometric quality.

## **20. Expected Mechanical Response of Gyroid Structures**

The gyroid represents a fundamentally different class of architected cellular material because load transfer occurs through a smooth, continuously connected surface rather than through discrete straight struts joined at identifiable nodes. The continuous curvature of a gyroid can reduce abrupt geometric transitions and may provide a smoother distribution of stress than certain beam-based lattice systems. The mechanical behaviour of a gyroid depends on several interacting parameters, including relative density, wall thickness, cell size, loading orientation, surface curvature, parent-material properties, manufacturing accuracy, and whether the architecture is implemented as a sheet-based or skeletal structure. Experimental and finite element studies have shown that gyroid mechanical properties generally increase with relative density [8]. However, a single universal scaling exponent cannot be assumed for every gyroid configuration because the deformation mechanism changes with geometry and density. The gyroid is especially attractive for multifunctional mechanical systems. In addition to structural performance, its continuous internal pathways and high surface-area-to-volume ratio can support fluid transport, heat exchange, thermal management, acoustic control, and biomedical integration. Consequently, gyroid structures may provide advantages where mechanical and functional requirements must be satisfied simultaneously.

## **21. Effect of Unit-Cell Size**

Relative density alone is insufficient to describe the complete mechanical behaviour of a lattice structure. Two specimens may possess identical material, topology, external dimensions, and relative density while containing substantially different unit-cell dimensions. Their mechanical responses may nevertheless differ because changing cell size modifies member length, strut diameter, member slenderness, and number of repeating cells, boundary effects, node-to-member volume ratio, and the number of available load-transfer paths. Smaller unit cells can create a larger number of repeated structural elements within the same external specimen dimensions. This can change the degree to which local deformation is distributed and can reduce or increase boundary-dominated effects depending on the architecture. Cell size also affects manufacturing quality because smaller members can become increasingly sensitive to process resolution, powder

adhesion, dimensional variation, and incomplete fusion. Experimental studies have shown that unit-cell dimensions and arrangement affect the compressive behaviour of powder-bed-fusion lattice structures [11]. Similar cell-size-dependent mechanical behaviour has been reported for additively manufactured 316L diamond lattice structures [12]. A complete description of an experimental lattice should therefore report topology, relative density, and cell size, number of unit cells, material, build orientation, and manufacturing process. Reporting only relative density can make comparisons between studies incomplete or misleading.

## **22. Additive Manufacturing Imperfections**

### **22.1 Geometric Deviation**

The geometry represented by the digital CAD model should be regarded as the as-designed lattice, whereas the geometry produced by the additive manufacturing process represents the as-built lattice. These two geometries are rarely identical. Strut oversizing or undersizing, node thickening, irregular member cross-sections, local waviness, partially fused powder, unsupported-surface distortion, incomplete fusion, and local dimensional deviations can all occur during fabrication.

These deviations have direct mechanical consequences because even small geometric changes can alter local stiffness, load paths, buckling resistance, and stress concentration. The influence becomes increasingly severe as lattice members become smaller. A dimensional deviation that is negligible in a conventional solid component may represent a substantial percentage of the cross-sectional dimension of a thin lattice strut.

### **22.2 Surface Roughness**

Surface roughness is particularly important in additively manufactured cellular materials because the load-bearing members often possess small cross-sectional dimensions. Partially fused particles, layer-related irregularities, staircase effects, and local surface notches can increase stress concentration and may become preferential locations for fatigue-crack initiation. Investigations of additively manufactured NiTi lattice members have demonstrated that strut diameter and orientation can influence surface quality and local stress concentration [13]. For this reason, minimum lattice-member dimensions should not be determined solely from an ideal weight-optimization study. The selected geometry must remain within the dimensional and surface-quality capability of the chosen additive manufacturing process. A lattice that is theoretically optimal but cannot be produced reproducibly may possess lower real mechanical performance than a slightly heavier but more reliably manufacturable design.

## **23. Build Orientation and Mechanical Anisotropy**

Mechanical anisotropy in additive-manufactured lattices can arise from both the parent material and the cellular architecture. The material itself may exhibit direction-dependent mechanical behaviour because of variations in melt-pool morphology, grain orientation, thermal history, residual stress, porosity distribution, and interlayer structure. At the same time, the lattice introduces geometric anisotropy because its members are inclined at different angles relative to both the loading direction and the build direction. Printing orientation can affect dimensional accuracy, surface condition, unsupported-feature quality, microstructure, and defect distribution. Consequently, two nominally identical lattice specimens fabricated at different orientations may

exhibit different stiffness, strength, and failure behaviour. Constitutive investigations of additively manufactured lattice materials have emphasized the importance of printing-angle-dependent mechanical behaviour [10]. Experimental reports should therefore distinguish clearly between the loading direction relative to the lattice geometry and the orientation of the lattice relative to the additive-manufacturing build direction. Failure to report both conditions makes reproduction and comparison of mechanical results difficult.

#### **24. Finite Element Analysis**

Finite element analysis provides an effective framework for investigating the mechanical behaviour of lattice structures because it permits detailed examination of stress distribution, strain localization, member loading modes, buckling patterns, and progressive collapse. However, numerical modelling should complement rather than replace experimental characterization. A reliable computational study should progress from an idealized CAD-based model toward increasingly realistic representations of the as-built structure.

##### **24.1 Ideal Geometry Model**

The initial numerical model may employ the nominal CAD geometry to establish the fundamental relationship between topology and mechanical behaviour. Such a model can be used to predict effective elastic modulus, global deformation, local stress concentration, member bending, axial loading, initial instability, and topology-dependent load paths. The ideal model is valuable because it isolates the mechanical influence of geometry from manufacturing imperfections.

##### **24.2 Material Model**

The parent material should preferably be represented using properties obtained from specimens produced through the same or equivalent additive-manufacturing process. For the initial linear elastic regime, the uniaxial relationship may be written as:

##### **Hooke-Type Uniaxial Relationship**

$$\sigma = E_s \varepsilon$$

where  $E_s$  is the elastic modulus of the parent solid material. For simulations extending beyond the elastic regime, an elastic-plastic constitutive law should be incorporated using experimentally measured yield and hardening behaviour whenever possible. The use of bulk handbook values without considering the actual additive-manufactured microstructure can reduce model accuracy.

##### **24.3 Geometric Nonlinearity**

Large-deformation effects should be included when simulating compressive collapse because lattice members may undergo significant rotation, bending, buckling, contact, plastic deformation, and progressive densification. Linear finite element analysis may be adequate for estimating initial elastic stiffness but generally cannot reproduce the complete stress–strain response of a cellular structure subjected to large compressive strain.

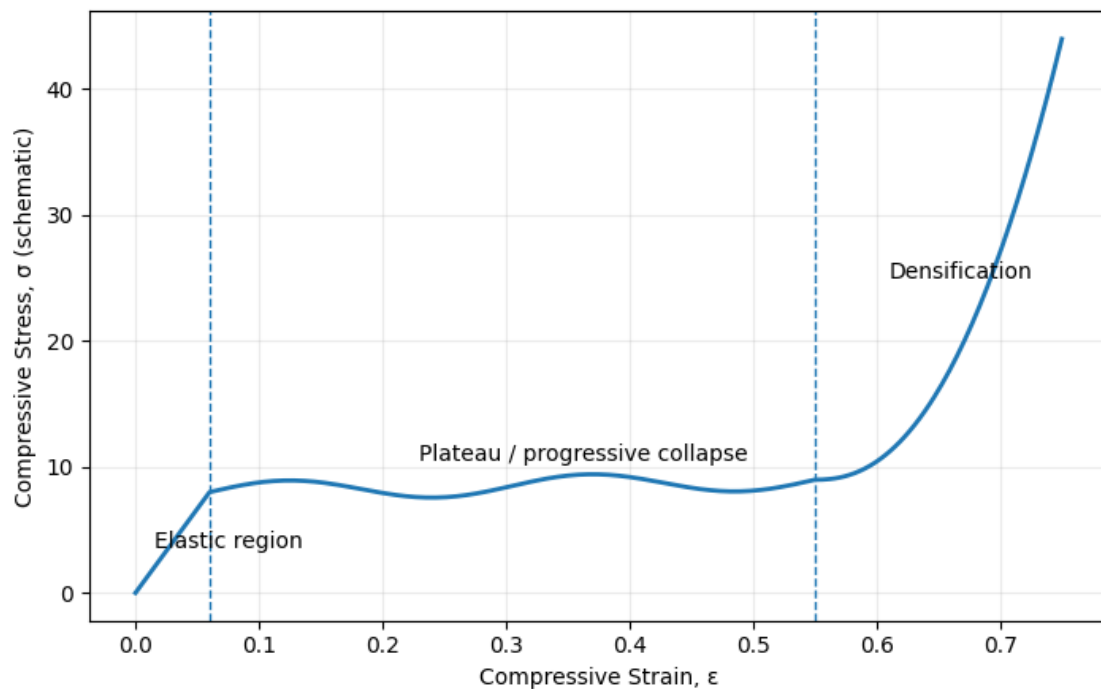
##### **24.4 Imperfection-Aware Modelling**

A higher-fidelity model can incorporate actual as-built geometry obtained from micro-computed tomography, optical scanning, or other high-resolution measurement techniques. Such models can capture variations in strut thickness, surface irregularity, local misalignment, and manufacturing defects that are absent from the ideal CAD geometry. Image-based modelling has been shown to

improve the understanding of damage development in additively manufactured lattices [9] and is increasingly being investigated for fatigue-life prediction [15].

## 25. Energy Absorption and Crashworthiness

For impact-protection and crashworthy structures, maximum stiffness is not necessarily the primary design objective. An effective energy absorber should develop a sufficiently high but controlled stress level, avoid an excessively large initial peak load, sustain progressive deformation, absorb substantial mechanical energy, delay densification, and maintain low structural mass.



**Figure 25.1: Idealized Compressive Stress–Strain Response of an Energy-Absorbing Lattice**

The characteristic compression response of a lattice generally consists of an initial elastic region, followed by a plateau or progressive-collapse region, and finally a densification region. The plateau region is particularly important for energy absorption because substantial deformation occurs while the stress remains comparatively stable. The energy absorbed up to a selected strain corresponds to the area beneath the stress–strain curve. Bending-dominated architectures can perform effectively in energy-absorption applications because sequential member bending, buckling, and progressive collapse can distribute deformation over a relatively large strain interval. Stretching-dominated architectures generally possess higher initial stiffness and strength but may exhibit more localized instability in certain configurations. Therefore, topology selection for crashworthiness should be based on the complete stress–strain response rather than maximum compressive strength alone.

The volumetric energy absorbed up to strain  $\epsilon$  may be expressed as:

$$W(\epsilon) = \int_0^\epsilon \sigma(\epsilon) d\epsilon$$

The specific energy absorption is then determined by normalizing the absorbed energy with respect to apparent lattice density:

$$SEA = \frac{W}{\rho} *$$

For lightweight crash absorbers, SEA is particularly useful because it distinguishes a structurally efficient energy absorber from one that achieves a high absorbed-energy value simply by containing more material.

## 26. Functionally Graded Lattice Structures

Uniform lattice structures maintain approximately the same relative density throughout the component. However, the stress field within an engineering structure is rarely uniform. Applying the same density to both highly loaded and lightly loaded regions can therefore produce inefficient material usage. Functionally graded lattices address this problem by allowing relative density, member thickness, cell dimensions, or topology to vary spatially. Higher-density cells may be positioned in regions subjected to greater mechanical demand, while lower-density cells may be used in regions carrying relatively small loads. Smooth density transitions can also reduce abrupt stiffness changes and may be designed to control the sequence of collapse during compression.

Recent reviews have highlighted the increasing importance of graded lattice architectures in additive manufacturing [16]. Experimental research on Ti-6Al-4V octet lattices has demonstrated that appropriate functional grading can improve compressive strength and energy-absorption capability [17]. Optimized density gradients have similarly been investigated as a method of tailoring structural stiffness while improving energy absorption [18]. The development of functionally graded structures represents an important transition from uniform cellular materials toward load-adaptive architected components in which material is positioned according to mechanical demand rather than geometric repetition alone.

## 27. Statistical Analysis for Experimental Validation

Experimental validation should include multiple specimens for every topology-density combination so that manufacturing variability can be quantified rather than relying on a single compression test. For a design containing three lattice topologies and three relative-density levels, a two-factor statistical framework can be used to evaluate the effects of topology, relative density, and their interaction. Mechanical responses suitable for statistical analysis include effective elastic modulus, compressive yield strength, plateau stress, densification strain, total absorbed energy, and specific energy absorption. Analysis of variance can determine whether the observed differences between specimen groups are statistically meaningful, while appropriate post-hoc comparisons can identify the specific lattice conditions responsible for those differences.

## 28. Discussion

The analysis demonstrates that lightweight lattice design should not be interpreted merely as the removal of material from a solid component. The mechanical efficiency of a lattice depends on how effectively the remaining material participates in carrying and redistributing load. Relative density determines the quantity of material available, while topology determines how that material is mechanically utilized. The analytical scaling results illustrate this principle clearly. When relative density increases from 0.15 to 0.35, a property governed by a linear scaling exponent increases by

approximately 2.33 times. For a bending-dominated stiffness relationship with an exponent of 2, the same density change produces an increase of approximately 5.44 times. Although the latter value appears larger, it demonstrates that bending-dominated stiffness is far more sensitive to changes in density. When material is removed, the stiffness of such a structure therefore decreases much more rapidly. Stretching-dominated lattices are consequently attractive for lightweight load-bearing systems because their triangulated geometry channels a greater proportion of external loading into axial deformation. The octet-truss illustrates this mechanical advantage. Nevertheless, the theoretical efficiency of a stretching-dominated geometry cannot be considered independently of the manufacturing process. Member misalignment, surface condition, node geometry, build orientation, and local defects can all reduce the performance of the as-built structure relative to the idealized design. The BCC lattice represents a different mechanical strategy. Its larger contribution from member bending produces lower initial stiffness but can promote progressive and controllable deformation. Such behaviour can be beneficial for crashworthiness and energy-absorption applications in which deformation stability is more important than maximum elastic rigidity.

The gyroid further expands the design space by replacing conventional discrete strut-node load paths with a continuous curved surface. This characteristic makes the gyroid particularly promising for multifunctional mechanical systems requiring structural performance together with thermal or fluidic functionality.

Manufacturing capability becomes increasingly important as relative density is reduced. Decreasing strut thickness lowers mass but simultaneously increases member slenderness and magnifies the relative influence of dimensional error. For example, a dimensional deviation of 0.1 mm represents a relatively small error in a thick structural member but can represent a substantial fraction of a sub-millimetre lattice strut. Very low-density designs may therefore become progressively more sensitive to manufacturing imperfections. The optimum theoretical lattice is consequently not always the optimum manufactured lattice. A more realistic engineering objective is to maximize reliable mechanical performance per unit mass while remaining within the dimensional, geometric, and material capability of the selected additive-manufacturing process. The use of specific modulus, specific strength, and specific energy absorption is particularly important in this context. Absolute stiffness and strength naturally increase when additional material is introduced, whereas lightweight engineering requires evaluation of the efficiency with which that material is used. Functionally graded design provides another important opportunity for increasing structural efficiency. A uniform lattice distributes the same amount of material throughout the component even when the internal stress field varies substantially. In contrast, a graded lattice can position material in proportion to local mechanical demand. The development of additive-manufactured lattice structures can therefore be viewed as a progression from uniform periodic lattices to density-optimized structures, functionally graded architectures, and finally defect-aware, application-specific optimized systems.

## **29. Practical Mechanical Engineering Design Guidelines**

### **29.1 High Stiffness-to-Weight Applications**

For structures in which stiffness-to-weight ratio is the dominant requirement, stretching-dominated architectures such as the octet-truss are generally preferable because their geometry promotes efficient axial load transfer. Highly triangulated cellular networks and topology-optimized axial load paths can similarly provide high specific stiffness. Node geometry should be carefully optimized to avoid excessive local mass and severe stress concentration, while minimum feature dimensions should remain compatible with the additive-manufacturing process.

### **29.2 High Energy-Absorption Applications**

For energy-absorbing systems, progressive collapse, a stable plateau stress, delayed densification, and high specific energy absorption should receive greater emphasis than maximum initial stiffness. Bending-dominated, hybrid, or functionally graded structures may offer significant advantages because they can distribute collapse over a large deformation interval and reduce abrupt force peaks.

### **29.3 Fatigue-Critical Components**

For fatigue-sensitive lattice components, ideal CAD-based finite element analysis is insufficient on its own. Surface condition, as-built geometry, dimensional variation, and local defects should be characterized because notches and geometric imperfections can become dominant sites for fatigue-crack initiation. Existing studies have demonstrated the importance of such defects in additively manufactured lattice fatigue behaviour [14], [15].

### **29.4 Very Low-Density Structures**

Very low-density lattice designs require careful assessment of minimum printable feature thickness, member slenderness, powder-removal capability, unsupported geometry, dimensional accuracy, buckling sensitivity, and inspection feasibility. Reducing relative density is useful only when the resulting architecture continues to satisfy stiffness, strength, stability, fatigue, and manufacturing requirements.

### **29.5 Large and Non-Uniformly Loaded Components**

For large components or structures subjected to strongly non-uniform loading, functionally graded lattices should be considered instead of a single uniform density. High-density regions can reinforce critical load paths, while lower-density regions can reduce unnecessary material consumption in lightly loaded zones. Such an approach provides a logical connection between cellular architecture and topology optimization.

## **30. Recommended Experimental Workflow**

A rigorous experimental investigation should begin with selection of the lattice topology and definition of the target relative density and unit-cell dimensions. The corresponding BCC, octet-truss, or gyroid geometries should then be generated in CAD and checked to confirm the required solid volume and relative density. Before fabrication, the design should be assessed for manufacturability, including minimum feature size, unsupported surfaces, build orientation, powder-removal pathways, and expected dimensional accuracy. The specimens should then be fabricated under controlled PBF-LB conditions, followed by appropriate powder removal, support

removal, heat treatment, and other post-processing procedures. Geometric characterization should include measurements of specimen mass, external dimensions, apparent density, strut dimensions, and surface condition. Micro-computed tomography or optical characterization can be used where available to identify internal defects and differences between as-designed and as-built geometry. Parent-material witness coupons should be mechanically characterized to provide realistic material input data for finite element analysis. Quasi-static compression testing can then be performed to obtain force-displacement data, which should subsequently be converted into engineering stress-strain curves. Effective modulus, yield or collapse strength, plateau stress, densification strain, energy absorption, and specific energy absorption should be extracted from the experimental response. Finite element models should then be validated against experimental behaviour, beginning with ideal geometry and progressing toward imperfection-aware modelling where appropriate. Statistical analysis should be used to quantify topology and density effects, after which multi-objective optimization can be performed to identify the architecture offering the most favourable balance between mechanical performance, structural mass, and manufacturing reliability.

### 31. Limitations

The numerical trends discussed in the present study are based primarily on mechanics-based analytical scaling and should not be interpreted as experimentally measured mechanical properties. Actual lattice behaviour depends on numerous factors, including alloy condition, additive-manufacturing system, processing parameters, thermal history, post-processing treatment, surface condition, build orientation, unit-cell size, dimensional accuracy, and the distribution of manufacturing defects. The coefficients  $C_E$  and  $C_\sigma$  and the scaling exponents'  $n$  and  $m$  should therefore be determined experimentally or through experimentally validated numerical modelling for each specific lattice-material-process combination. Classical scaling laws provide useful mechanical interpretation but should not be assumed to represent every lattice geometry accurately across the complete density range. The present analysis also focuses primarily on quasi-static compression. Under dynamic impact conditions, inertia, strain-rate sensitivity, collapse-wave propagation, and rate-dependent parent-material behaviour may alter the mechanical response. Similarly, static compressive strength cannot be used independently to predict fatigue performance because cyclic failure is strongly influenced by surface quality, local defects, stress concentration, and crack initiation.

### 32. Future Scope

Future research should integrate high-resolution geometric characterization with experimental mechanics and advanced computational modelling. Micro-CT-based reconstruction can provide a direct representation of the as-built geometry, allowing image-based finite element analysis to quantify the mechanical influence of surface irregularity, local dimensional variation, and internal defects. Such models may be particularly valuable for fatigue-crack initiation and life prediction. Dynamic impact testing should also be incorporated to evaluate the strain-rate-dependent behaviour of lattice structures intended for crashworthiness applications. Functionally graded TPMS systems

and hybrid architectures combining strut-based and surface-based cells provide further opportunities to balance stiffness, strength, deformation stability, thermal performance, and energy absorption. Topology optimization, machine-learning-assisted surrogate models, digital twins, uncertainty quantification, residual-stress modelling, multimaterial additive manufacturing, and process-aware design methods represent promising directions for future research. These approaches can reduce computational cost and allow a much larger design space to be explored. One of the most important developments will be defect-aware optimization. Conventional approaches often identify an optimum ideal geometry first and examine manufacturability afterward. A more reliable strategy is to incorporate minimum feature size, expected geometric deviation, surface condition, build-direction effects, and process variability directly into the optimization procedure. The long-term objective of additive lattice research should therefore not be limited to identifying the theoretically strongest or lightest cellular geometry. The more meaningful engineering objective is to design a lattice that is lightweight, mechanically efficient, damage tolerant, reproducible, inspectable, and manufacturable under realistic production conditions.

### 33. Conclusion

This study presented a comprehensive mechanical-engineering framework for the design and characterization of lightweight lattice structures fabricated through additive manufacturing. BCC, octet-truss, and gyroid architectures were considered as representative examples of bending-dominated, stretching-dominated, and continuous-surface cellular systems. Relative density was identified as a primary design parameter, but the analysis demonstrated that density alone cannot determine structural performance. Topology governs how efficiently the available material participates in load transfer. Stretching-dominated architectures provide favourable stiffness-to-weight characteristics because elastic stiffness can vary approximately linearly with relative density under ideal conditions. Bending-dominated structures exhibit a stronger density dependence and therefore experience a more significant reduction in stiffness when substantial material is removed. Increasing relative density from 0.15 to 0.35 produces a theoretical increase of approximately 2.33 times for a linearly scaling property and approximately 5.44 times for a quadratically scaling stiffness.

Strut slenderness and buckling resistance were shown to provide important links between unit-cell geometry and macroscopic mechanical response. Because member bending rigidity depends strongly on diameter, small dimensional variations can create substantial differences in local structural behaviour. Specific modulus, specific strength, and specific energy absorption were identified as essential performance indicators for lightweight engineering. The study also established that unit-cell size, cell count, build orientation, member inclination, surface roughness, geometric deviation, and internal defects must be considered during experimental interpretation.

A distinction must therefore be maintained between as-designed and as-built lattice behaviour. The octet-truss is particularly attractive for stiffness-critical applications, whereas BCC-type structures can provide advantages where controlled deformation is desirable. Gyroid architectures offer

significant potential for multifunctional applications requiring structural performance together with thermal, fluidic, or surface-related functionality. Functionally graded lattices represent an important route toward more efficient material placement and controlled collapse. The optimum lattice should therefore not be defined simply as the architecture with minimum density. A mechanically successful additive-manufactured lattice is one that delivers the required stiffness, strength, stability, energy absorption, durability, and manufacturability at the lowest practical mass. The integration of cellular-solid mechanics, additive-manufacturing constraints, experimental characterization, finite element modelling, and defect-aware optimization provides a strong foundation for the development of next-generation lightweight mechanical systems.

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