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RESEARCH ARTICLE

Optimizing Lattice Structures for Tensile Performance: A Comparative Study of Six Geometries Using FDM 3D Printing

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ABSTRACT

In this study, six distinct infill designs Gyroid, Schwarz, Diamond, Lidinoid, SplitP, and Neovius were developed using ntopy engineering design software and fabricated with a Fused Deposition Modeling (FDM) printer to examine their tensile strength and weight characteristics. The analysis explored the relationship between structural geometry and mechanical performance, particularly tensile strength, while accounting for weight efficiency. Experimental results revealed significant differences in tensile behavior across the designs: Schwarz demonstrated the highest tensile strength (0.7 kN) and superior load-bearing capacity, while Lidinoid showed comparable strength but abrupt failure post-peak force. Neovius excelled in ductility with 7 mm elongation before failure, making it suitable for applications needing high deformation. Gyroid and Diamond offered a balanced performance with moderate strength and ductility, proving versatile for general use. SplitP exhibited unstable and erratic behavior, limiting its reliability for critical applications. These findings underscore the potential for optimizing lattice geometries for lightweight, high-performance applications using FDM, with Schwarz and Lidinoid suited for strength-centric uses, Neovius for flexibility, and Gyroid and Diamond for balanced mechanical needs.

Keywords: Lattice structures, FDM 3D printing, Tensile strength, nTop software, Lightweight design

1. Introduction

3D printing is a contemporary method for creating intricate designs of materials and components. Known by various terms such as additive manufacturing, fusion deposit molding, and fused filament fabrication, this technique primarily depends on filament as a crucial component in the production process. Filaments, which play a central role in 3D printing, are typically made from polymer-based materials and other composites. A wide range of filaments is used in 3D printers, including ABS (acrylonitrile butadiene styrene), PLA (poly(lactic) acid), PVA (polyvinyl alcohol), PTFE (polyethylene tetraphthalate), HIPS (high-impact polystyrene), and Nylon. Additionally, composite filaments such as Wood/PLA, Carbon/PLA, and Metal/PLA are also commonly employed [1–5].

Additive manufacturing has transformed how components are designed, offering the ability to create complex geometries and reduce weight. Conventional methods, such as casting and injection molding, are often limited by tool accessibility, material wastage, and challenges in producing intricate internal features like cooling channels. These methods typically require multiple parts to be manufactured separately and then assembled. In contrast, additive manufacturing allows for the integration of these features into a single structure, reducing production time and waste, while also enhancing sustainability [6].

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A key feature of additive manufacturing is the ability to produce lattice structures. These designs replace solid materials with a network of beams and nodes, significantly reducing weight without compromising strength. The material is placed only where it is structurally needed, ensuring a high strength-to-weight ratio. This makes lattice structures ideal for applications in aerospace and automotive industries, where reducing weight is critical for improving efficiency. For example, lattice components can be used in lightweight brackets and panels to reduce overall mass and improve fuel efficiency [7].

Additive manufacturing, particularly Fused Deposition Modeling, has enabled the fabrication of complex, lightweight lattice structures with tailored mechanical properties. Previous studies have explored the mechanical behavior of various lattice geometries, such as the compressive performance of microlattices made by laser powder bed fusion [8], and the importance of processing parameters for the mechanics of 3D-printed polymer lattices. However, a comprehensive comparison of the tensile properties of different lattice designs fabricated using FDM is lacking [9].

Lattice mechanics are highly dependent on the design configuration and printing process [9]. The choice of unit cell, strut diameter, and number of unit cells can significantly impact the compressive strength and fracture behavior of the structures [8]. Furthermore, inconsistencies in beam diameters and anisotropic deformation in 3D-printed lattices can lead to complex failure modes and strain rate dependencies [10].

This study aims to address the gap in the literature by investigating the tensile performance of six distinct lattice geometries fabricated using FDM 3D printing. The findings provide insights into optimizing lattice designs for high-strength, lightweight applications.

2. Experimental procedure

2.1. Materials and modelling

PLA filament from Eryone Standard PLA, manufactured in China, is utilized for producing the 3D samples. The process begins with designing the sample using modeling software, ensuring compliance with the dimensional specifications outlined in ASTM D638 standards. The design is then saved in STL (Stereo Lithographic) format. This STL file is subsequently uploaded to a 3D printing machine, the Bambu Lab A1, for fabrication [11].

Tensile test samples were designed using 3D modelling software and printed with a 3D Printer Bambu lab A1. Prior to initiating the printing process, the parameters are configured as follows: the print layer thickness is established at 0.2 mm, the filament diameter: 1.75 mm with +–0.03 mm tolerance and the melting temperature is set to 220 ˚C. The machine's bed temperature is adjusted to 65 ˚C. The material's fill density is designated as 100%, and the printing speed is (outer walls): 200 mm/sec and the (inner walls): 300 mm/sec, as in Table 1.

Table 1. Parameters of printer settings.

Item	Value
Filament	Eryone stander PLA
Filament diameter	1.75 mm with +–0.03 mm tolerance
Print speed (outer walls)	200 mm/s
Print speed (inner walls)	300 mm/s
Nozzle Temperature	220 ˚C
Bed Temperature	65 ˚C

An engineering design software known as **nTop** was employed to create six distinct infill patterns for each of the tensile test samples, as shown in Fig. 1. These infill designs were developed to explore variations in structural geometry and their impact on mechanical performance. After the designs were finalized, the samples were fabricated and subjected to precise measurements to determine their weight. Following this, tensile testing was conducted to evaluate their mechanical strength and deformation characteristics. The results from both weight and tensile tests were systematically compared to assess the influence of infill geometry on the balance between structural efficiency and mechanical performance. This comparative analysis provided valuable insights into optimizing infill patterns for specific applications.

The **Gyroid** sample has a minimal surface structure with smooth, continuous, and wavy surfaces that twist and curve through space without intersecting itself. Characterized by its lack of straight lines, it forms an open, porous design, providing strength while minimizing material usage. Its saddle-like curvature evenly distributes mechanical stress, making it both lightweight and strong. The Gyroid is highly symmetrical and periodic, meaning its pattern repeats uniformly in three dimensions, making it ideal for applications like 3D printing and engineering. Its complex yet organic appearance is also valued for architectural and aesthetic purposes, balancing functionality with visual appeal [12].

The **Schwarz** structure, specifically the Schwarz D minimal surface, is a periodic minimal surface characterized by its smooth, saddle-like curvature that extends through space without intersecting itself. It features a series of interwoven, web-like surfaces that create a highly symmetrical, repeating pattern. These surfaces divide space into multiple continuous,

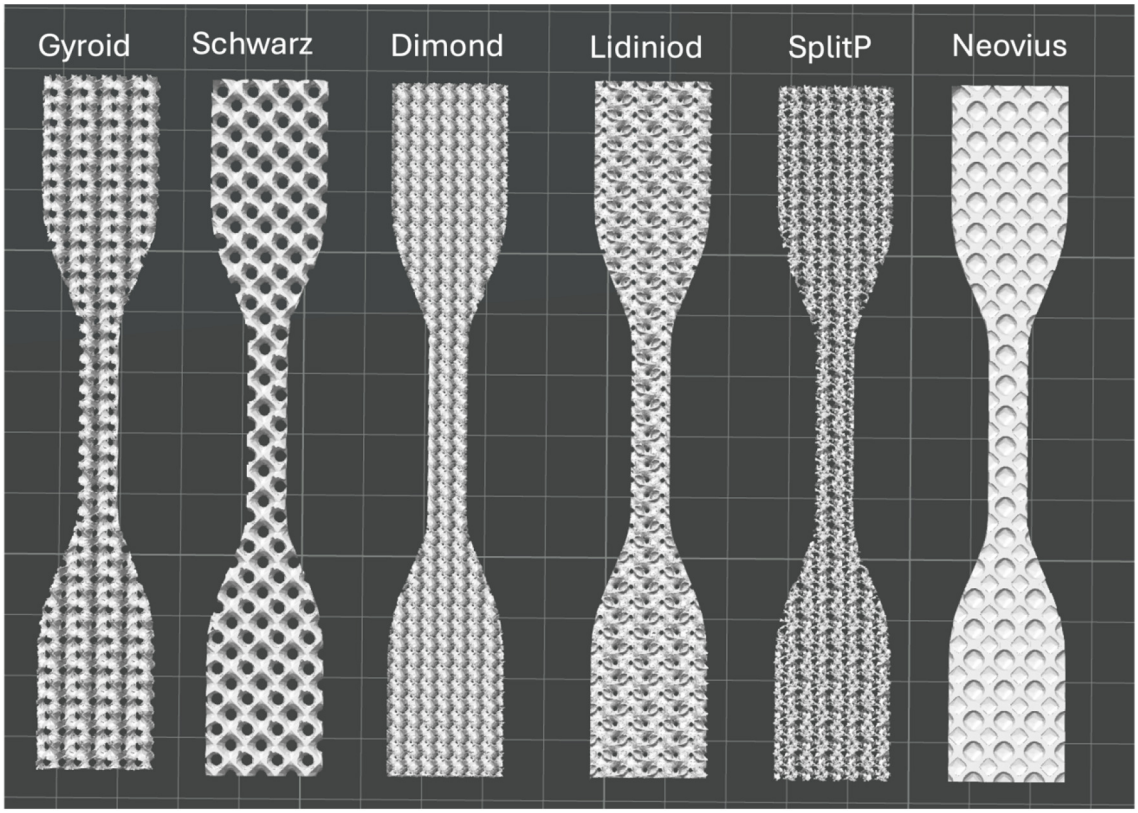

Fig. 1. The six infill patterns for each of the tensile test samples.

non-intersecting channels, making the Schwarz structure both lightweight and efficient at distributing mechanical stress. The design's open, porous nature allows for a high surface-area-to-volume ratio, making it ideal for applications requiring lightweight materials with strong structural integrity, such as 3D-printed lattices, filtration systems, or energy-absorbing structures. Its elegant and geometric form also gives it aesthetic value in architectural design [13].

The **Diamond** structure, also known as the Diamond minimal surface, is a highly symmetrical and repeating lattice geometry composed of smooth, curved surfaces that divide space into a complex network of interconnected voids. It gets its name from its resemblance to the crystal structure of diamond, with surfaces forming a continuous, triply periodic pattern. The Diamond structure has a balanced distribution of material and empty space, providing an efficient balance between strength and lightweight properties. Its open, porous design and three-dimensional periodicity make it ideal for applications in which both mechanical performance and material efficiency are crucial, such as 3D printing, filtration, and structural components. The geometric intricacy and natural symmetry of the Diamond structure also lend it aesthetic appeal in design and architecture [14].

The **Lidinoid** structure, a type of minimal surface, is characterized by its complex, interwoven network of smooth, continuously curved surfaces that extend throughout space without self-intersecting. This structure has a highly symmetrical and periodic design, with surfaces that form intricate, repeating patterns. The Lidinoid's geometry features open voids and channels, creating a lightweight, porous structure with a high surface-area-to-volume ratio. This makes it ideal for applications where material efficiency and strength are critical, such as in 3D printing, lightweight structural components, and energy-absorbing systems. Its organic, flowing form also gives it aesthetic appeal, making it suitable for use in architectural design and other creative applications [15].

The **SplitP** structure is a unique lattice geometry characterized by its open, interconnected surfaces that resemble twisted or branched pathways. The design features smooth, curved surfaces that divide space into complex, repeating units, creating a porous and lightweight structure. Unlike more traditional minimal surfaces, the SplitP has a distinctive branched pattern, offering a balance between material efficiency and structural integrity. Its intricate design allows for efficient stress distribution,

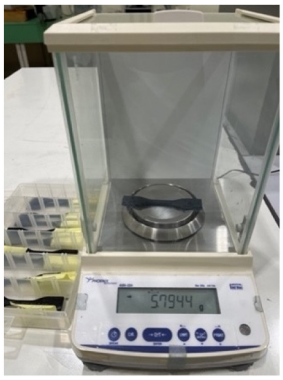

Fig. 2. Weighting setup.

making it suitable for applications requiring strength and reduced weight, such as in 3D printing, lightweight components, and energy-absorbing materials. The organic, flowing nature of the SplitP structure also lends itself to creative and architectural applications, where both function and aesthetics are important [15].

The **Neovius** structure is a minimal surface characterized by its highly symmetrical and interconnected network of smooth, curved surfaces that create a repeating, triply periodic pattern. It features large, open voids surrounded by thin, undulating walls, giving it a porous, lightweight appearance. The geometric arrangement forms a lattice with a balance of material and empty space, optimizing the structure for applications where both strength and low weight are essential, such as in 3D-printed components and energy-absorbing materials. The Neovius structure's intricate, organic design allows for efficient stress distribution while maintaining a high surface-area-to-volume ratio, making it ideal for use in engineering, architecture, and design where both function and aesthetic appeal are valued [16].

2.2. Weighting scale

The sample weights were measured using a precision electronic balance (±0.0001 g accuracy), calibrated according to ASTM E617-18 standards. Samples were weighed at room temperature. Each measurement was repeated three times to ensure consistency, and the average value was recorded for analysis, as seen in Fig. 2.

2.3. Tensile testing

Tensile tests were carried out using Gunt Hamburg WP310 universal testing machine in accordance with ASTM D638 standards shown in Fig. 3. Tests were conducted at a constant crosshead speed of 2 mm/min



Fig. 3. Tensile test setup.

until failure, with data on stress and strain recorded throughout. The specimen dimensions consist of a length of 75 mm, a width of 19 mm in the grip side area, a width of 6 mm in the gauge length side area, and a material thickness of 4 mm, as shown in Fig. 3.

3. Results and discussion

Lattice structures are intricate, repeating geometric frameworks that are used in various engineering and scientific applications, including tensile testing. These structures are designed to provide a combination of **lightweight properties** and **mechanical strength**, making them ideal for applications requiring high strength-to-weight ratios, such as aerospace, automotive, and biomedical devices [7].

Fig. 4 "Samples Weight" provides a detailed comparison of the weights of six distinct lattice design samples: Gyroid, Schwarz, Diamond, Lidinoid, SplitP, and Neovius. The x-axis labels each design, while the y-axis measures the corresponding weight in grams, with values ranging from 4.0 to 6.0 grams, offering insight into how different geometric structures influence the overall mass of the samples.

Starting with the Gyroid design, its weight is approximately 5.05 grams, positioning it as a mid-range weight among the samples. Similarly, the Diamond design weighs around 5.09 grams, indicating comparable material usage to the Gyroid, despite their differing internal geometries. The Schwarz design weighs approximately 5.1 grams, making it one of the heavier options among the three types in this range.

On the heavier end of the spectrum, both the Lidinoid and Neovius designs show significantly higher weights, each reaching approximately 5.8 grams. These designs likely feature more complex or dense internal structures, which contribute to their

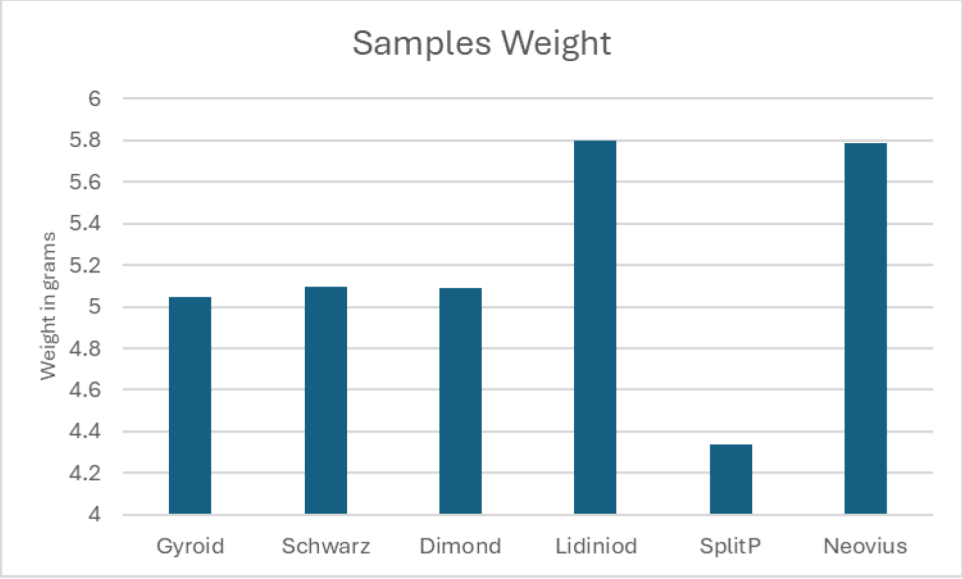

Fig. 4. Measured weight for various lattice structures.

increased weight. Lidinoid and Neovius stand out as the heaviest samples, potentially influencing their tensile performance due to their higher material content.

In stark contrast, the SplitP design is the lightest of all the samples, with a weight of around 4.4 grams. This substantial reduction in weight compared to the other designs suggests a more open or sparse internal structure, which may trade off weight savings for mechanical performance. The considerable difference in weight between SplitP and the other designs, particularly Lidinoid and Neovius, highlights the impact of structural design on material usage in additive manufacturing [15, 17, 18].

Fig. 4 reveals significant variations in the weight of the different lattice designs, with Lidinoid and Neovius being the heaviest, while SplitP is the lightest by a notable margin. These differences in weight can have implications for the strength-to-weight ratio and other mechanical properties of the samples, providing important insights for applications where both tensile strength and weight efficiency are key considerations. The detailed comparison of weight, volume, and density for the six lattice designs is summarised in Table 2.

$$p = m/V \tag{1}$$

Eq. (1) represents the mathematical relationship for density (p), where p denotes the density of an object, m represents the mass of the object, and V stands for its volume. In this formula, density is defined as the mass per unit volume of the PLA material. This

Table 2. Weight, volume and density data compares six different lattice designs.

#	infill	Sample weight in (g)	volume (cm^3)	Density (g/cm^3)
1	Gyroid	5.04420	52.65760	0.09579
2	Schwarz	5.09805	133.29600	0.03825
3	Diamond	5.08890	54.43840	0.09348
4	Lidinoid	5.79575	136.18300	0.04256
5	SplitP	4.33905	41.60020	0.10430
6	Neovius	5.78440	321.28900	0.01800

relationship indicates how much matter is packed into a given volume. The units for mass (m) are typically in grams, while the volume (V) is measured in cubic centimeters (cm^3), depending on the system of units being used. As a result, density (p) is often expressed in units such as grams per cubic centimeter (g/cm^3).

In practical terms, this equation helps to quantify how dense a substance is, meaning how tightly its particles are packed within a given space. Higher density implies more mass in a given volume, while lower density means less mass in the same amount of space. This equation is widely used in physics, material science, and engineering to analyze and compare the properties of different materials or substances.

The provided data compares six different lattice designs: Gyroid, Schwarz, Diamond, Lidinoid, SplitP, and Neovius, focusing on their weight, volume, and density. The Gyroid design weighs 5.04420 grams, with a volume of 52.65760 cm^3 and a density of 0.09579 g/cm^3, indicating a relatively dense structure that efficiently fills its volume. In comparison, Schwarz has a similar weight of 5.09805

grams but a much larger volume of 133.29600 cm^3, resulting in a lower density of 0.03825 g/cm^3. This suggests that Schwarz is more porous or open, despite its comparable weight.

Diamond, weighing 5.08890 grams with a volume of 54.43840 cm^3, has a density of 0.09348 g/cm^3, similar to Gyroid, implying a compact structure. On the other hand, Lidinoid has the highest weight of 5.79575 grams and a volume of 136.18300 cm^3, but its density of 0.04256 g/cm^3 is relatively low, signifying a more open internal geometry despite its heavier weight.

The SplitP design is the lightest, at 4.33905 grams, with a volume of 41.60020 cm^3 and a density of 0.10430 g/cm^3, making it the densest among the samples. This suggests a highly compact structure with significant material usage per unit volume, which could enhance its mechanical strength [18]. Finally, Neovius has a weight of 5.78440 grams and the largest volume of 321.28900 cm^3, yet it has the lowest density at 0.01800 g/cm^3, indicating a highly porous design with minimal material usage relative to its size.

Overall, the data highlights the significant variations in material distribution and internal structure among these designs. SplitP exhibits the most compact geometry, while Neovius has the most open and voluminous structure. Gyroid and Diamond have similar densities, which suggests they may perform similarly in terms of material efficiency and mechanical properties, while Schwarz and Lidinoid demonstrate lower densities due to their larger volumes and more open structures. These differences play a crucial role in determining the balance between strength, material efficiency, and weight for each design in additive manufacturing applications.

Fig. 5 "Density" provides a comparative analysis of the densities of six different lattice designs: Gyroid, Schwarz, Diamond, Lidinoid, SplitP, and Neovius. The x-axis represents the different designs, while the y-axis reflects the density in grams per cubic centimeter (g/cm^3), with values ranging from 0.01800 to 0.14000 g/cm^3. Each design is marked by a circle corresponding to its density, with the exact density value displayed inside the circle. The different colors represent the individual lattice structures.

Gyroid (denoted in blue) has a density of 0.09579 g/cm^3. This design shows a relatively high density compared to the others, indicating that it has a more compact internal structure that results in higher material usage for its volume.

Schwarz (denoted in orange) has a significantly lower density of 0.03825 g/cm^3, making it one of the least dense designs. This suggests a more open or porous geometry that reduces the amount of material needed to fill a given volume, potentially impacting its mechanical strength.

Diamond (denoted in green) presents a density of 0.09348 g/cm^3, which is similar to the Gyroid. This value suggests that the Diamond design has a dense internal lattice structure, which might provide good mechanical performance, similar to Gyroid.

Lidinoid (denoted in light blue) has a density of 0.04256 g/cm^3, positioning it as a mid-range design in terms of density. Its relatively moderate density indicates that it strikes a balance between material usage and internal structure.

SplitP (denoted in purple) has the highest density among the designs, measured at 0.10430 g/cm^3. This high density suggests that SplitP has a more closed or solid internal geometry, using more material per unit volume, which could lead to higher strength but also a heavier weight.

Neovius (denoted in light green) is the least dense design, with a value of 0.01800 g/cm^3. This exceptionally low density implies that Neovius has a highly porous or sparse internal structure, likely leading to the lowest material usage. However, such a low density might compromise the sample's mechanical performance due to reduced material support.

Fig. 5 reveals significant variations in the densities of the six designs, with SplitP being the most dense and Neovius being the least dense by a substantial margin. The Gyroid and Diamond designs exhibit similar densities, suggesting comparable material efficiencies, while Schwarz and Lidinoid fall into a mid-to-lower density range. The data clearly shows how different geometric structures influence the material distribution within the same volumetric space. These density variations are important for understanding the mechanical properties of each design, particularly in applications where weight-to-strength ratios and material efficiency are critical. For example, SplitP's high density may offer enhanced strength, but at the cost of additional material and weight, while Neovius might be advantageous in weight-sensitive applications, though potentially at the expense of strength.

Tensile testing using this specimen helps to characterize how a material behaves under a uniaxial load, providing valuable information for product design, quality control, and material selection.

Fig. 6 provides insight into the tensile performance of six lattice structures: Gyroid, Lidinoid, Diamond, Neovius, SplitP, and Schwarz, each exhibiting distinct force-displacement behaviors under tensile testing. The x-axis represents the displacement (ΔL) in millimeters, while the y-axis shows the force

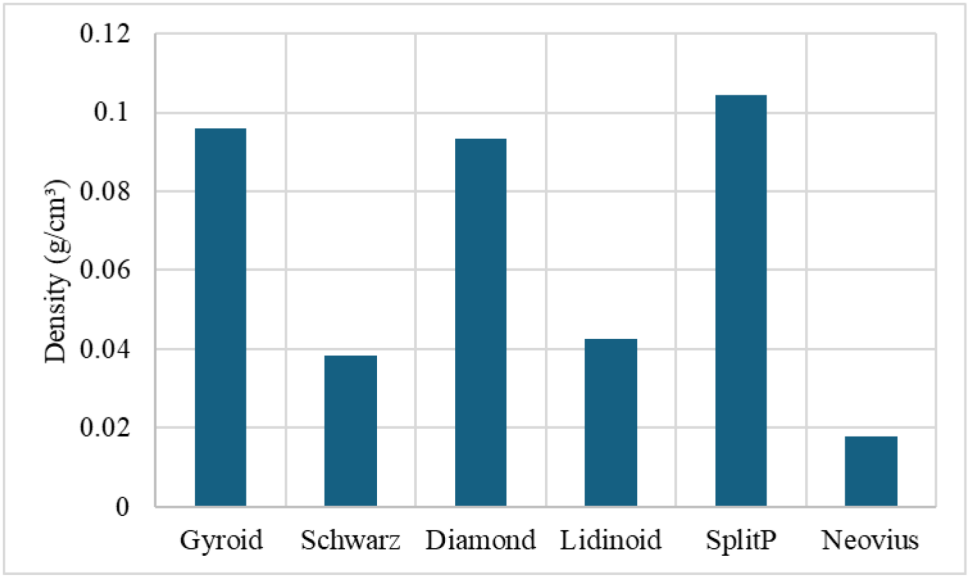

Fig. 5. Comparative density for various lattice structures.

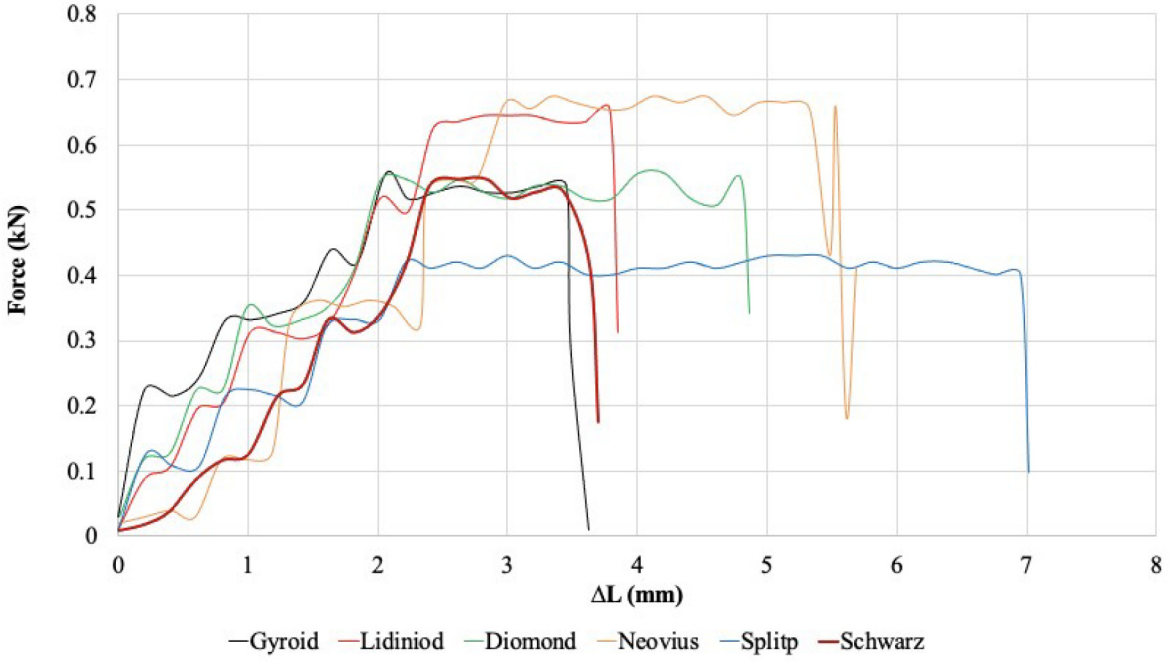

Fig. 6. Results of tensile testing of different structures.

in kilonewtons (kN). By analyzing each curve, we can draw conclusions regarding the mechanical properties such as tensile strength, ductility, and fracture behavior of each design.

The force-displacement behaviors of the tested structures reveal distinct mechanical characteristics under tensile loading. The Gyroid structure, represented by the black line, exhibits a smooth increase in force, peaking at approximately 0.5 kN around 3.5 mm displacement. It demonstrates a stable build-up of force without sudden drops until failure, offering moderate tensile strength and balanced ductility, though it fractures suddenly without gradual softening. The Lidinoid structure, shown by the red line, reaches a higher peak force of about 0.6 kN at 3.5 mm displacement. However, it experiences a sharp drop immediately after the peak, signaling catastrophic failure. While it has higher tensile strength than the Gyroid, its limited ductility results in abrupt fracturing with minimal elongation. The Diamond structure,

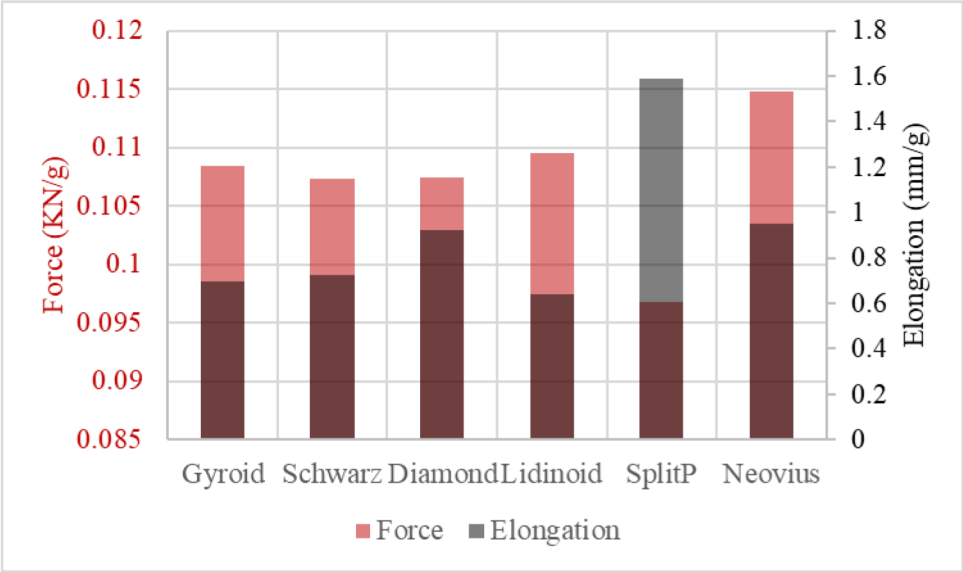

Fig. 7. Comparative analysis of the force-to-weight and elongation-to-weight ratios for various lattice structures.

represented by the green line, shows a rapid increase in force, peaking at around 0.5 kN at 4 mm displacement. Following the peak, minor fluctuations in force occur before it fails abruptly, indicating high strength and load-bearing capacity but less stability under tensile loading. It fractures without significant plastic deformation. In contrast, the Neovius structure, illustrated by the blue line, has a flatter force curve, peaking at just over 0.4 kN. It maintains a steady force response over a longer displacement range and fails at around 7 mm, demonstrating lower tensile strength but excellent ductility, making it highly flexible before ultimate failure. The SplitP structure, shown by the orange line, exhibits highly irregular force behavior with significant fluctuations. It peaks at about 0.5 kN but experiences multiple sudden drops before final failure. This erratic performance suggests inconsistent mechanical properties and localized failures, making it less reliable for load-bearing applications. Lastly, the Schwarz structure, also represented by the orange line, achieves the highest peak force of approximately 0.7 kN at 4 mm displacement. It shows a consistent increase in force before a sharp drop, demonstrating superior tensile strength but brittle behavior, failing abruptly under maximum load. Overall, the results highlight the diverse mechanical properties of these structures, emphasizing their potential applications based on specific strength, ductility, and stability requirements.

Fig. 7 compares the force-to-weight ratio and elongation-to-weight ratio of various structures. The results suggest that the structures can be categorized into three groups based on their force-to-weight ratio. The first group includes four structures (Gyroid, Schwarz, Diamond, and Lidinoid) which exhibit a force-to-weight ratio in the range of 0.107 to 0.11. This range places them in the medium level for force-to-weight ratio [19]. In terms of elongation-to-weight ratio, the Diamond structure stands out within the medium group, offering the highest elongation-to-weight ratio while maintaining an excellent force-to-weight ratio [19]. Conversely, the SplitP structure achieves a high elongation-to-weight ratio but has the lowest force-to-weight ratio. This makes it particularly suitable for applications requiring high elongation-to-weight ratio performance. On the other hand, the Neovius structure demonstrates exceptional performance in both force-to-weight and elongation-to-weight ratios, making it the best choice among the investigated structures for applications demanding balanced mechanical properties [16]. Overall, all the investigated structures can be integrated into a single mechanical body to enhance mechanical performance and manage failure mechanisms effectively.

4. Conclusion

From the tensile test results, several key conclusions can be drawn about the performance of these lattice structures:

1. The Schwarz structure exhibited the highest tensile strength, peaking at 0.7 kN, making it the top performer in load-bearing capacity. Lidinoid

closely followed in strength but failed abruptly upon reaching its peak force, indicating limited ductility.
2. Neovius demonstrated superior elongation, reaching 7 mm of displacement before failure. Despite having lower tensile strength, its high ductility makes it suitable for applications requiring significant deformation.
3. Gyroid and Diamond offered a good balance between tensile strength and elongation, with moderate load-bearing capacities. Gyroid exhibited a smoother, more stable response, while Diamond showed slight variability post-peak.
4. SplitP displayed erratic behavior under tensile loading, with sharp fluctuations in force. While it can withstand moderate loads, its instability and unpredictability limit its suitability for critical structural applications.
5. Neovius achieved the best balance of force-to-weight and elongation-to-weight ratios, making it the most adaptable choice for applications requiring a combination of mechanical performance and failure management.

In summary, the lattice structures display a wide range of mechanical properties, from the strong but brittle Schwarz to the highly ductile Neovius. For applications prioritizing tensile strength, Schwarz and Lidinoid are ideal. For those requiring significant elongation, Neovius is the best option. Gyroid and Diamond provide balanced properties, making them versatile for general use, while SplitP is best reserved for non-critical applications due to its unpredictable performance.

Conflict of interest

The authors declare no conflict of interest.

Author contribution

A. Alhuzaim: Conceptualisation, methodology, validation, formal analysis, investigation, writing original draft, supervision.

Talal T. Alshammari: Methodology, validation, formal analysis, writing review and editing, visualisation.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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