UDK 62-112.5:52-334.2
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
Mater. Tehnol.

3D-PRINTED POLYLACTIC ACID REINFORCED CARBON FIBER IN BULK AND TRIPLY PERIODIC MINIMAL SURFACE (TPMS) LATTICE STRUCTURES: A MECHANICAL PROPERTIES COMPARATIVE STUDY

TRIDIMENZIONALNA TISKANA STRUKTURA IZ POLILAKTATNE KISLINE OJAČANE Z OGLJIKOVIMI VLAKNI V TRDNI OBLIKI IN TROJNO PERIODIČNI MINIMALNI MREŽNI STRUKTURI; PRIMERJALNA ŠTUDIJA ANALIZE MEHANSKIH LASTNOSTI

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Prejem rokopisa – received: 2025-09-24; sprejem za objavo – accepted for publication: 2026-02-19

doi:10.17222/mit.2025.1571

Focusing on lightweight design while maintaining mechanical integrity at the highest levels has made triply periodic minimal surface (TPMS) lattice structures one of the promising structural concepts.[1] Therefore, this study investigates the mechanical performance of polylactic acid (PLA) reinforced with 15 *w*/% carbon fiber (CF) in both bulk and TPMS lattice. Bulk PLA/CF (15 *w*/%) exhibited a 58.2 % increase in the tensile modulus over neat PLA, though stiffness decreased with the temperature due to matrix softening. Compression tests showed that the gyroid lattice structure achieved higher compressive strength (19.02 MPa) with stable energy absorption, while the honeycomb structure had greater stiffness (691.53 MPa) but lower strength (17.73 MPa). Finite element simulations confirmed these trends, highlighting stress localization in the honeycomb and a uniform stress distribution in the gyroid. Overall, gyroid lattices are preferable for energy absorption applications, whereas honeycomb structures are more suitable for stiffness-critical lightweight designs.

Keywords: fused filament fabrication, polymer composites, triply periodic minimal surface, compression test, mechanical properties

Avtorji v tem članku opisujejo razvoj nove obetavne trdne kompozitne strukture v obliki mreže s trikrat periodičnimi minimalnimi površinami (TPMS; angl.: gyroid) izdelane na osnovi lahkih materialov, ki ohranja svojo mehansko integriteto na najvišji ravni. V pričujoči študiji so avtorji raziskovali mehanske lastnosti polilaktatne kisline (PLA), ojačane s 15 mas. % ogljikovih vlaken (CF), tako v trdnem stanju kot v mreži TPMS. Trdni kompozit PLA/CF s 15 mas. % CF je imel 58,2-odstotno povečanje nateznega modula v primerjavi s čistim PLA, čeprav se je njegova togost zmanjševala s temperaturo zaradi mehčanja matrice. Tlačni preizkusi so pokazali, da je imel giroid večjo tlačno trdnost (19,02 MPa) s stabilno absorpcijo energije, medtem ko je imel material v obliki satovja večjo togost (691,53 MPa), vendar nižjo tlačno trdnost (17,73 MPa). Simulacije s pomočjo metode končnih elementov so potrdile te trende in poudarile lokalizacijo napetosti v satovju in enakomerno porazdelitev napetosti v giroidu. Na splošno so mreže giroidov bolj primerne za aplikacije absorpcije energije, medtem ko so strukture v obliki satovja bolj primerne za lahke zasnove, pri katerih je togost kritična.

Ključne besede: izdelava taljenih filamentov, polimerni kompoziti, trojno periodična minimalna površina, tlačnii preizkus, mehanske lastnosti

1 INTRODUCTION

Additive manufacturing (AM), particularly fused filament fabrication (FFF), enables the fabrication of complex lattice structures that combine low density with tunable mechanical performance.[1] Such materials are increasingly used in aerospace, biomedical, and protective applications, where weight reduction and mechanical efficiency are critical.[1] Among various lattice designs, triply periodic minimal surface (TPMS) such as the gyroid, and strut-based topologies such as the honeycomb, have attracted significant attention due to their distinct deformation behaviors and stress distribution characteristics. The gyroid lattice features a continuous, smooth surface without sharp edges, which facilitates uniform stress distribution and gradual failure under compressive loading. This geometry promotes progressive collapse, leading to improved energy absorption compared to strut-based designs. Conversely, the honeycomb lattice, consisting of well-defined cell walls and nodes, exhibits a high stiffness-to-weight ratio and efficient load transfer along its struts.[2] However, its geometry often results in localized stress concentrations and brittle-like collapse, especially under high compressive loads.

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Apart from design geometry, materials also contribute to the mechanical performance of a printed part. Studies on polymeric composites indicated that an addition of filler can enhance the tensile strength by 10–15 %.[3,4] A study on polyamide-12 highlighted that a filler was used to absorb and distribute the load evenly, hence increasing the mechanical performance.[5] However, the strength tends to plummet as the filler addition increases, causing the filler to be poorly bound by the polymer. Studies also reveal that apart from the material itself, there are also other factors that significantly contribute to the performance of a printed lattice structure, including wall thickness.[1,6] A thicker wall thickness, up to a maximum of 0.5 mm, shows improved elastic modulus and structural integrity compared to a thinner wall thickness of 0.1 mm. Studies reveal that a thicker wall allows the face and core panels to remain intact, with a reduced risk of microfractures arising from poor bonding between the filler and the matrix.[7,8]

Experimental and simulation studies demonstrated these differences quantitatively. For example, under compressive loading, gyroid structures often exhibit lower peak stresses but sustain deformation more uniformly, while honeycomb structures display higher maximum stress but localized failure. Simulation results indicate that the gyroid structure experienced a maximum equivalent von Mises stress of 23.405 MPa with a minimum of 0.048 MPa, whereas the honeycomb structure reached a slightly higher maximum stress of 23.504 MPa with a minimum of 0.497 MPa.[9,10] These results suggest that although both topologies sustain comparable peak stresses, the honeycomb exhibits sharper stress gradients, corresponding to localized deformation and potential premature collapse. Experimental compression tests further validate these observations. The stress–strain response of gyroid lattices typically reveals smoother curves with extended plateau regions, reflecting gradual energy absorption. In contrast, honeycomb structures show more abrupt stress drops following peak load, indicative of brittle failure modes.

The correlation between experimental data and finite element simulations highlights the role of geometry in governing deformation behavior: gyroid structures distribute stresses more evenly across the lattice, while honeycombs concentrate stresses within struts and nodes. The current study highlights the importance of defining a structural design that exhibits excellent mechanical properties through the use of polymer composite materials.[1,11] This enables broader applications and allows researchers to explore 4D printing applications with a minimal risk of failure.[12,13] This comparative study of gyroid and honeycomb lattices, integrating both experimental and simulation results, provides critical insights into their structural performance. The findings provide mechanical evidence supporting the use of gyroid structures in advanced applications such as energy-absorbing components and adaptive or 4D-printed structures. This study underlines the potential of gyroid structures in applications requiring enhanced energy absorption and resilience, whereas honeycomb structures remain favorable where stiffness and load-bearing capacity are prioritized. Samples were prepared using in-house fabricated polylactic acid reinforced with carbon fiber (PLA/CF) and printed in the form of lattice structures (gyroid and honeycomb) prior to compression testing. The experimental data were then validated using ANSYS simulations.

2 MATERIAL AND METHODS

2.1 Sample preparation

The filament was prepared using PolyLite PLA/CF by Polymaker supplied by Pebblereka Sdn. Bhd. The filament used had a density of 1.29 g/cm^3 and melt index of 9.2 g/10 min. The melting temperature of the filament was 162.4 °C, and it had a diameter of 1.75 mm. Before the printing process, the filament was dried for a minimum of 5 hr before being printed by Ultimaker S3, corresponding to fused filament fabrication (FFF). The printing parameters were set to a nozzle temperature of 220 °C, a bed temperature of 60 °C, a layer height of 0.2 mm, a printing speed of 50 mm/s and an infill density of 100 %.

2.2 Structural design and fabrication

The filament was printed as the TPMS gyroid and honeycomb lattice structures designed on the basis of CAD models. The TPMS structures were generated using the mathematical model defined with Equation (1):

$$\Phi_G = \sin x \cos y + \sin y \cos z + \sin z \cos x = c \qquad (1)$$

where $x = 2\pi x/L_x$, $y = 2\pi y/L_y$ and $z = 2\pi z/L_z$.

This model represents normalized spatial coordinates scaled by the unit cell dimensions L_x, L_y and L_z along x, y and z axes, respectively, ensuring the interconnected ligament-based morphology is preserved.[14,15] The TPMS structure was analyzed using ANSYS software (student version), which employs the level-set method to approximate TPMS geometry. The design parameters were set as 5 mm unit cell and 19 % relative density.[16,17]

The finalized computer-aided design (CAD) models of the compression test specimens, highlighting the TPMS lattice structures, are illustrated in **Figures 1a** and **1b**. The compression test was conducted in accordance with ASTM D695 as indicated in **Figure 2**, with the detailed parameters summarized in **Table 1**. The printed TPMS structures prepared for the compression test conducted on a universal testing machine 30 kN, model Instron 3355, are shown in **Figures 1c** and **1d**. In comparison, the bulk structure samples were performed based on the ASTM D638 (Type I) standard geometry. This design choice localized stress concentration within the lattice region during tensile loading while maintaining standardized grip sections to prevent premature fail-

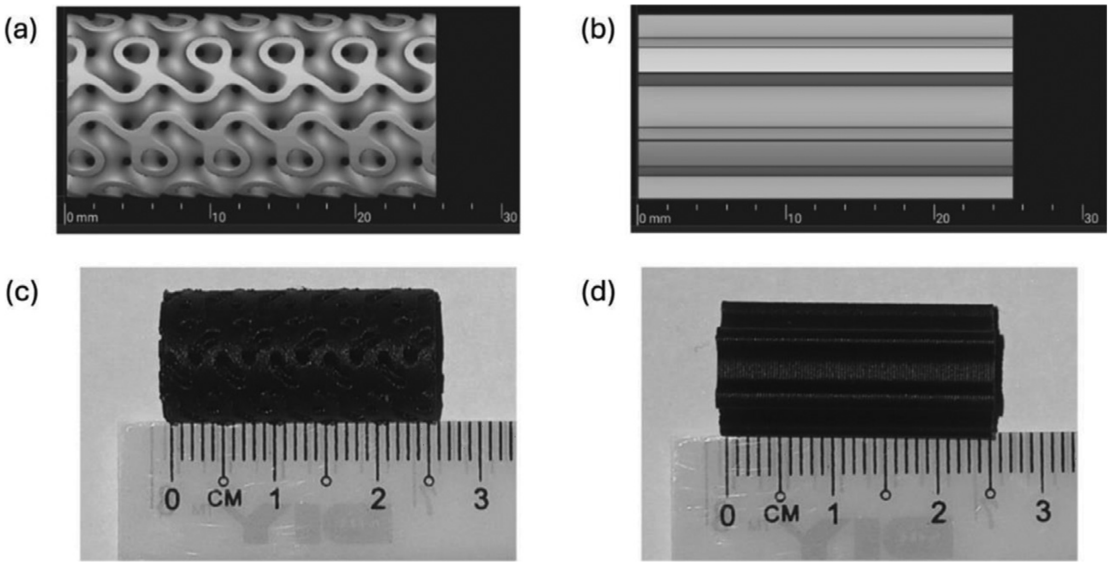

Figure 1: CAD models of: a) gyroid and b) honeycomb structures; fabricated samples of c) gyroid and d) honeycomb structures. The compression sample geometries were identical and conformed to ASTM D695.

ure at clamping interfaces.[18,19] The tensile test parameters included a strain rate of 6.6×10^{-3} s^{-1} (crosshead speed of 5 mm/min) for the bulk structure. To obtain comprehensive data for the bulk PLA/CF samples, tests were performed at different temperatures, specifically (30, 55 and 80) °C.

Table 1: Compression test parameters for TPMS structure

Parameters	Values
Load cell	20 kN
Displacement rate	3 mm/min
Strain limit	40 %
Test repetitions	3

2.3 Finite element analysis

The simulation compression test was carried out using the parameters summarized in **Table 2**. An explicit dynamic analysis was selected instead of a static structural approach to capture large deformations extending into the plasticity region.[20] The material properties were defined using isotropic elasticity in the elastic regime and multilinear isotropic hardening in the plastic regime.[21] Although FDM-fabricated components exhibit anisotropic material behavior, isotropic material properties were adopted in this study to ensure a consistent basis for comparing the deformation mechanisms of different lattice topologies under identical loading conditions. These material data were obtained from tensile tests on

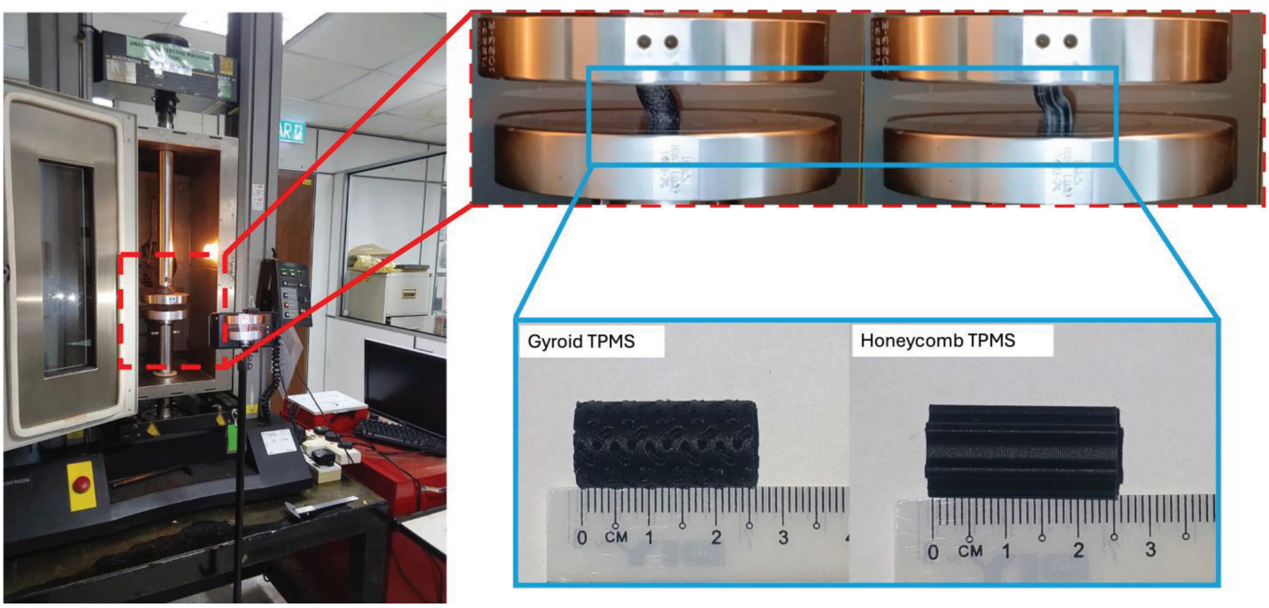

Figure 2: Compression test setups for both bulk and TPMS lattice structure samples

bulk structures conducted in accordance with the ASTM D638 standard, which provided the elastic modulus, yield strength, and stress–strain curve.[20] The compressed sample was modeled as PLA/CF material, while the top and bottom plates were assigned as steel. A mesh size of 0.5 mm was applied to ensure computational accuracy. For boundary conditions, the bottom plate was fixed while the top plate applied a downward displacement onto the sample, replicating the experimental compression setup.[22] In addition, the friction coefficient between all components was set to 0.2, consistent with the values reported in a previous study.[23] The simulation setup for the compression test is shown in **Figure 3**. In this study, the TPMS gyroid and honeycomb lattices were not generated using the built-in ANSYS library. Instead, the lattice geometry was independently defined using mathematical formulations, and the curvature formulations from Equation (1) are therefore necessary to describe the lattice generation process.[24,25]

Table 2: Simulation compression test parameters

Parameters	Details
Analysis type	Explicit dynamic
Material properties	Isotropic elasticity & multi-linear isotropic hardening
Mesh size	0.5 mm

3 RESULTS AND DISCUSSION

3.1 Tensile strength test for bulk PLA/CF composites

The tensile test results indicate a significant enhancement in the tensile strength and elastic modulus of the PLA/CF samples compared to pure PLA. At room temperature, the average elastic modulus was 3216.06 MPa, representing a 58.2 % increase over pure PLA (2032.95 MPa). This improvement aligns with the findings reporting that carbon fiber (CF) additions elevate the PLA tensile strength to ≈56 MPa due to efficient load distribution by carbon fibers within a polymer matrix[26]. As these data were intended for use in the simulation analysis, the experiments were performed across a wider temperature range. At elevated temperatures (80 °C), the tensile modulus of PLA/CF decreased to 128.73 MPa compared to 3216.06 MPa at 30 °C. This reduction stems from the PLA matrix softening near its glass transition temperature (≈60 °C), diminishing the matrix's ability to transfer stress to fibers.[26] In addition, there is a 30 % tensile strength decline in PLA/CF at 80 °C due to polymer matrix thermal degradation. The data from the bulk analysis were used for the simulation analysis of the compression test.

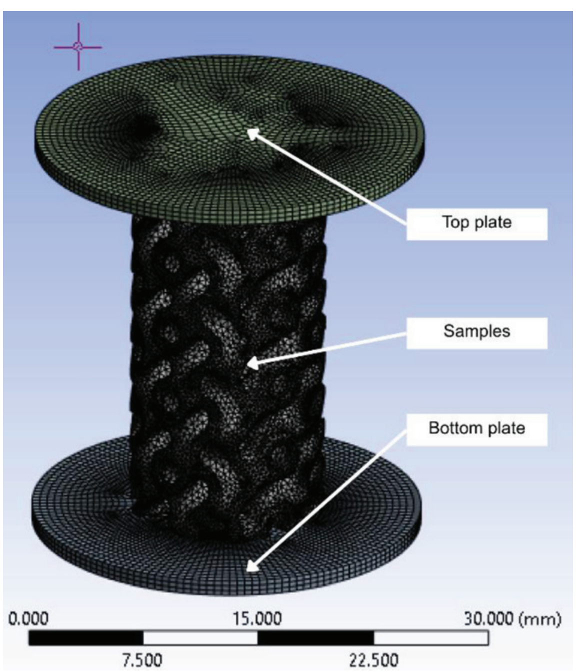

Figure 3: Simulation compression test setup

Table 3: Analysis of the tensile strength of bulk PLA/CF samples

Analysis	Materials	30 °C	55 °C	80 °C
Tensile modulus (MPa)	PLA/CF	3216.064	17.24	128.77
	PLA	2032.95	453.22	1.88
Tensile strength (MPa)	PLA/CF	25.85 ± 0.19	2.57 ± 0.11	5.07 ± 0.04

3.2 Compression testing of TPMS structures

The TPMS gyroid and honeycomb lattice structures are presented in the form of stress–strain curves in **Figure 4**. The gyriod lattice structure experienced a higher compression strength of 19 MPa, compared to the honeycomb value that was 17 MPa. Both structures exhibit the typical three regions of cellular material deformation: an initial linear elastic region, a plateau region, and a densification region. In the elastic region (up to ≈5 % strain), both structures display a steep linear slope, indi-

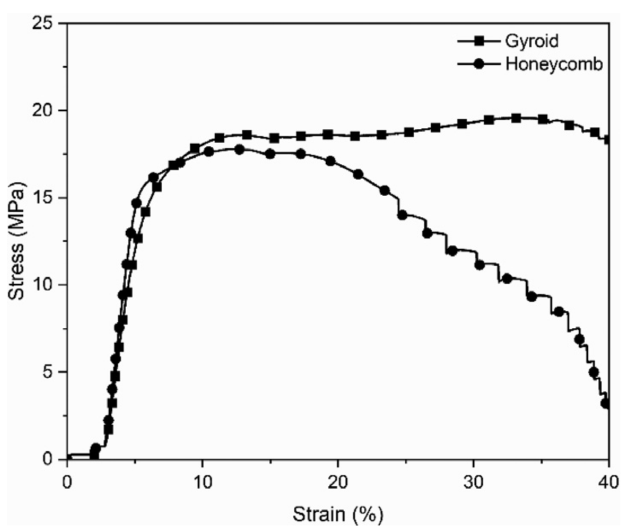

Figure 4: Stress-strain curves under compression testing

cating elastic deformation of the struts. Beyond this, the plateau region is observed, where stress remains relatively stable with increasing strain due to the progressive buckling and collapse of the lattice walls. The gyroid structure demonstrates a higher plateau stress (≈18–20 MPa) and maintains structural stability up to ≈35 % strain, reflecting its continuous and interconnected geometry that allows for better load distribution.[27] In contrast, the honeycomb structure reaches a similar initial peak stress but shows a gradual stress drop beyond ≈15 % strain, suggesting localized failure and weaker post-yield stability.[28] In the densification region (>30 % strain), the gyroid maintains higher residual strength, whereas the honeycomb experiences a marked reduction in stress. Overall, the gyroid structure exhibits superior compressive performance and energy absorption capability compared to the honeycomb design.[28] Compared to the bulk PLA/CF structure, the data obtained for both TPMS lattice structures are slightly lower (≈24 %). This indicates that the lattice structure exhibited good tensile strength properties even when the density structure was lower (≈50 %).

The comparative mechanical properties of gyroid and honeycomb lattice structures under uniaxial compression are presented in **Figure 5**. As shown in **Figure 5a**, the honeycomb structure demonstrates a higher elastic modulus (691.53 MPa) relative to the gyroid (562.24 MPa), indicating superior stiffness. This behavior can be attributed to the anisotropic, strut-dominated architecture of the honeycomb, which efficiently transfers applied loads along the cell walls oriented parallel to the loading axis.[28] The alignment of load-bearing members minimizes bending deformation, thereby enhancing the stiffness response. In contrast, the gyroid structure, which is classified as a triply periodic minimal surface (TPMS), relies on curved, continuous surfaces for load distribution. While this topology improves isotropy and stability, the bending-dominated nature of the gyroid geometry reduces its effective tensile modulus.

Conversely, the compressive strength results, shown in **Figure 5b**, indicate that the gyroid (19.02 MPa) outperforms the honeycomb structure (17.73 MPa). The continuous three-dimensional network of the gyroid provides more uniform stress redistribution and delays localized instabilities, such as wall buckling, which commonly govern failure in honeycomb structures.[1,29] This three-dimensional connectivity allows for progressive collapse and greater energy absorption before catastrophic failure occurs. The honeycomb, by contrast, tends to fail through localized buckling or fracture along preferential planes, resulting in a comparatively lower strength. The distinct deformation mechanisms observed indicate that the TPMS lattice structure plays a dominant role in dictating the macroscopic performance of additively manufactured structures.

Figures 6a–b illustrate the deformation behavior of the gyroid and honeycomb lattice structures during uniaxial compression at 0 % and 40 % strain. At the initial state (0 % strain), both structures maintain their designed geometrical integrity with no visible damage or deforma-

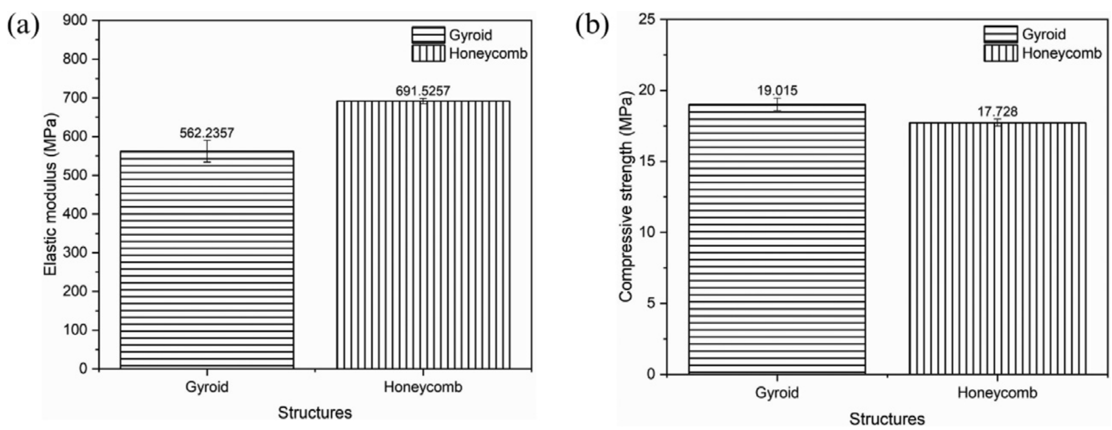

Figure 5: Mechanical properties under compression testing: a) elastic modulus and b) compressive strength

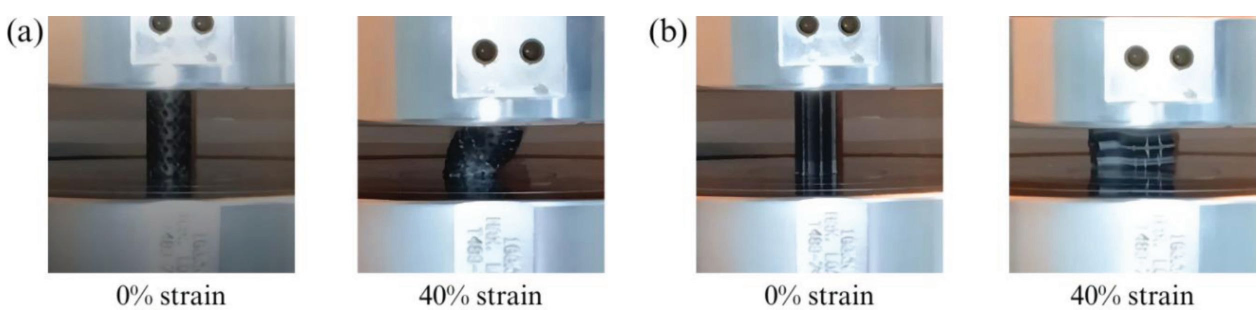

Figure 6: Deformation behavior under compression testing of: a) gyroid and b) honeycomb structures

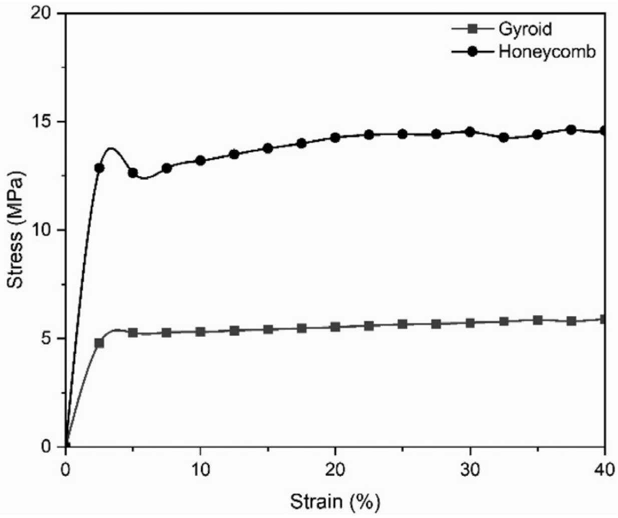

Figure 7: Compressive stress-strain curves obtained through simulation testing

tion. However, their responses under large strain differ significantly due to the differences in structural topology. As shown in **Figure 6a**, the gyroid structure undergoes pronounced bending and progressive distortion of its curved surfaces at 40 % strain. The deformation is more homogeneous across the structure, without abrupt localized collapse. This behavior is consistent with the bending-dominated nature of gyroid geometries, where stresses are redistributed across continuous, curved load paths. Such deformation mode enhances energy absorption and provides improved resistance to catastrophic failure, in line with its superior compressive strength reported earlier.[29]

In contrast, **Figure 6b** shows the deformation of the honeycomb structure at 40 % strain. The cell walls collapse in a more localized and brittle manner, characterized by the buckling of vertical struts and the formation of shear bands. The anisotropic, strut-based architecture of the honeycomb promotes directional instability, leading to concentrated failure zones under compressive loading. While the honeycomb initially exhibits higher stiffness, its failure mechanism is less progressive compared to the gyroid, which explains its lower compressive strength.[9,29] Also, these observations highlight the influence of deformation mechanisms on the macroscopic mechanical response. The gyroid demonstrates a more ductile-like, energy-dissipative failure mode, whereas the honeycomb exhibits a brittle-like, localized collapse.[30]

3.3 Finite element analysis

Figure 7 shows the compressive stress–strain responses of gyroid and honeycomb structures obtained via simulation analysis. The honeycomb exhibits a steep initial rise to ≈13 MPa, followed by a slight drop due to localized buckling and then gradual hardening up to ≈15 MPa at 40 % strain. This strut-dominated deformation reflects its higher stiffness and tensile modulus.[31] In contrast, the gyroid displays a lower stress plateau of ≈5–6 MPa with stable, progressive deformation, indicating a bending-dominated mechanism. While the honeycomb provides higher load-bearing capacity, the gyroid offers smoother stress distribution and controlled collapse, making it more suitable for energy absorption applications.[10]

The elastic modulus and compressive strength of gyroid and honeycomb structures are shown in **Figures 8a–b**. The honeycomb shows a significantly higher elastic modulus (512.97 MPa) compared to the gyroid (191.98 MPa), reflecting its strut-dominated geometry that provides greater stiffness along the loading direction. Similarly, the honeycomb achieves higher compressive strength (14.74 MPa) than the gyroid (6.04 MPa), indicating better load-bearing capacity. The gyroid lower values are attributed to its bending-dominated architecture, where curved surfaces deform progressively under load.

The difference in the behavior observed for the honeycomb structure between the experimental (**Figure 4**) compression test and FE simulation (**Figure 7**) is mainly attributed to manufacturing-induced imperfections and failure mechanisms that are not fully captured in the numerical model. In the experimental samples, factors such

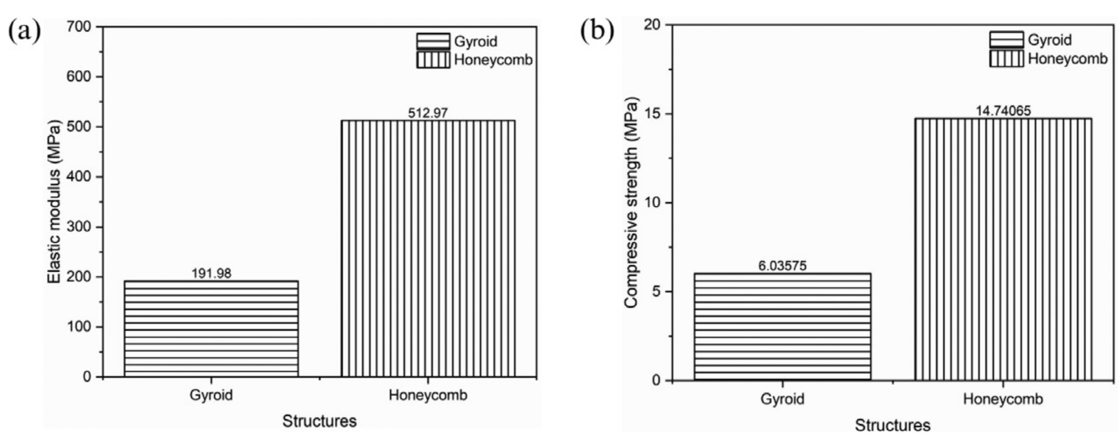

Figure 8: Mechanical properties under simulation testing: a) elastic modulus and b) compressive strength

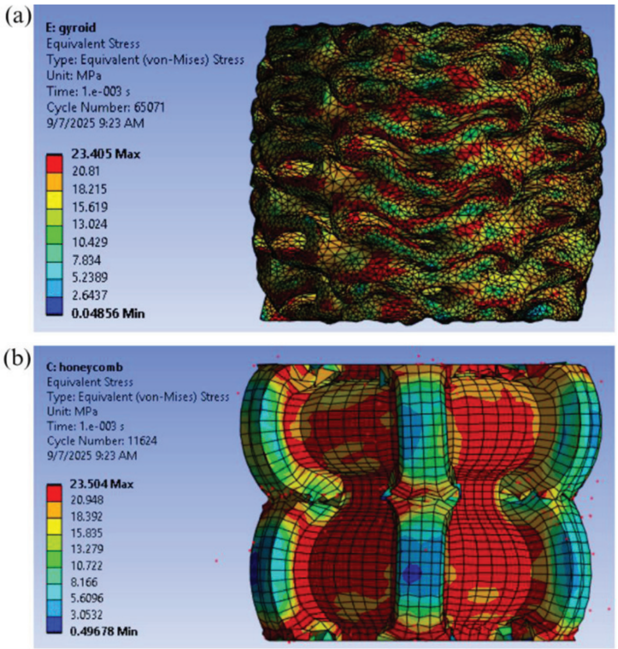

Figure 9: Von Mises stress under simulation testing for: a) gyroid and b) honeycomb structures

as layer-wise anisotropy, interlayer bonding defects, local geometric irregularities, and early buckling or wall collapse significantly influence the compressive response of the honeycomb structure. This observation is supported by prior studies, in which the gyroid lattice exhibits earlier deformation due to its bending-dominated, curvature-based load transfer, whereas the honeycomb structure maintains higher initial stiffness owing to its stretching-dominated straight cell walls.[32,33] In contrast, the FE simulation assumes ideal geometry, perfect material continuity, and uniform load distribution, which result in a more stable and idealized deformation behavior. These effects are more pronounced in honeycomb structures due to their straight cell walls and load-bearing orientation, making them more sensitive to imperfections compared to gyroid structures.

Figures 9a–b present the von Mises stress distribution of gyroid and honeycomb structures under compression. For the gyroid (**Figure 9a**), stresses are more uniformly distributed across the continuous curved surfaces, with a maximum value of 23.4 MPa. This indicates that the gyroid efficiently redistributes load, delaying localized failure and promoting progressive deformation.[34] In contrast, the honeycomb (**Figure 9b**) shows stress concentration along the vertical struts and junctions, also peaking at ≈23.5 MPa. Such localized accumulation explains its tendency toward premature buckling and brittle collapse, as observed experimentally. The simulation results confirm that the gyroid provides superior stress homogenization, while the honeycomb offers higher directional stiffness but is more prone to instability under load.[10]

4 CONCLUSIONS

This study investigated the mechanical performance of bulk and lattice-structured PLA reinforced with 15 *w*/% carbon fiber (PLA/CF) fabricated via fused filament fabrication. The study concludes as follows:

Bulk PLA/CF (15 *w*/%) showed a 58.2 % increase in the tensile modulus compared to neat PLA. The tensile modulus decreased with increasing temperature due to PLA matrix softening near its glass transition.

The TPMS gyroid lattice structure exhibited higher compressive strength (19.02 MPa) and stable energy absorption when compared to the honeycomb lattice structure. The honeycomb lattice structure recorded higher elastic modulus (691.53 MPa) but lower compressive strength (17.73 MPa).

Finite element simulations agreed with the experiments in which the honeycomb lattice structure is stiffer, but stress is concentrated at strut junctions, leading to localized buckling. Meanwhile, the gyroid lattice structure indicated a more uniform stress distribution, promoting progressive collapse.

Design analysis clearly shows that the gyroid TPMS lattice structure is suitable for energy absorption and controlled deformation compared to the honeycomb lattice structure, which is better for lightweight stiffness-critical structures.

Abbreviations

Additive manufacturing	AM
Carbon fiber	CF
Finite element analysis	FEA
Fused filament fabrication	FFF
Polylactic acid	PLA
Polylactic acid-reinforced carbon fiber	PLA/CF
Triply periodic minimal surface	TPMS

Conflict of interests

Nabilah Afiqah binti Mohd Radzuan reports that financial support was provided by Dana Padanan Kolaborasi: Geran Pembiayaan Sepadan (DPK-GPS), grant number DPK-GPS-JORDAN-2024-005. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The author acknowledges the financial support provided by Dana Padanan Kolaborasi: Geran Pembiayaan Sepadan (DPK-GPS), grant number DPK-GPS-JORDAN-2024-005, which enabled the successful completion of this research. Additional support was provided by the Faculty of Engineering and Built Environment &