Proceedings of the Eighteenth International Conference on
Civil, Structural and Environmental Engineering Computing
Edited by: P. Iványi, J. Kruis and B.H.V. Topping
Civil-Comp Conferences, Volume 10, Paper 3.3
Civil-Comp Press, Edinburgh, United Kingdom, 2025
ISSN: 2753-3239, doi: 10.4203/ccc.10.3.3

Topology Optimization of Gyroid-Based Mechanical Metamaterials Using Artificial Intelligence

P. Lacki, A. Derlatka, W. Lacki and K. Lachs

Czestochowa University of Technology,
Poland

Abstract

This study presents a comprehensive approach for the topology optimization of gyroid-based mechanical metamaterials, aiming to develop intelligent, adaptive materials that respond effectively to mechanical loads. Experimental validation was performed by fabricating 3D-printed samples using carbon fibre-reinforced nylon via fused deposition modelling (FDM) technology. Key mechanical properties, including Young's modulus and Poisson's ratio, were determined to benchmark the performance of the metamaterials. A parametric numerical model was developed using the finite element method (FEM) and rigorously validated against experimental data. A substantial dataset capturing the mechanical behaviour under varied loading conditions was generated. This dataset served as the basis for training an artificial neural network (ANN), which facilitated rapid evaluation of design variations. To navigate the complex, the trained ANN was integrated with a genetic algorithm (GA) for topology optimization. The GA iteratively explored candidate solutions through selection, mutation, and recombination processes, specifically targeting parameters such as porosity, wall thickness, and effective density. The combination of ANN and GA provided an efficient framework for the intelligent design and optimization of gyroid-based mechanical metamaterials with tuneable properties. A significant contribution of this work is the demonstration of an integrated experimental–numerical–AI workflow for the intelligent design and topology optimization of mechanical metamaterials.

Keywords: gyroid, mechanical metamaterials, topology optimization, finite element method, artificial neural network, adaptive materials.

1 Introduction

A gyroid is a geometric structure belonging to the class of minimal three-dimensional surfaces, i.e. those that locally minimize their surface area. A characteristic feature of gyroid is the lack of straight lines or flat surfaces, the gyroid is a very curved, fluid structure. This structure has no planes of symmetry, even though it is periodic. It also has no intersection points despite its complexity, the surface of gyroid does not intersect itself. The gyroid as a minimal surface can be described by the function:

$$f(x, y, z) = \sin(x)\cos(y) + \sin(y)\cos(z) + \sin(z)\cos(x) \qquad (1)$$

Gyroid structures are lightweight and durable, so they are often used as structural or shock-absorbing elements. Cell structures are increasingly produced by additive manufacturing processes, especially 3D printing which produces objects based on layer-by-layer deposition. Authors of paper [1] emphasized that a freedom in design and an ability to print complex structures with minimum waste are the main benefits of 3D printing. Like presented in [2, 3], the most used printers for making polymer composites are the fused deposition modelling (FDM) printers.

As shown in [1, 2, 4], 3D printing is used in numerous industries such as electronics, aviation, construction and even medicine. In the automotive industry, mainly materials and structures with a shape memory and a high energy absorption are appreciated [5–7]. The auxetic structures show a negative response of the Poisson coefficient deserve special attention. This means that, with a tensile load applied in the longitudinal direction, the auxetic structure also extends in the transverse direction, which was proved in [6]. On the other hand, works [7–9] show that under an applied compressive load, auxetics compact and contract perpendicular to the direction of the load. Due to this mechanism, auxetic materials exhibit an excellent impact resistance, a fracture toughness and a vibration transmission. As it results from the works [6–11], the re-entrant honeycomb is the most popular among the various auxetic discovered structures. This is due, inter alia, to the fact that, under bending conditions, the re-entrant honeycomb structures show a global failure mode due to the relatively homogeneous stress distribution, which was proved in the studies conducted by the authors of the works [10, 11].

The studies published in [12] should be noted. Seven variants of 3D printed cores in a sandwich beam subjected to a three-point bending test were analysed. Although, the loading force was applied parallel to the analysed core cross-sections. It was emphasized in the conclusions that the greatest load was transferred by the re-entrant honeycomb sandwich beam. On the other hand, a triply periodic minimal surfaces (TPMS) structure known as Gyroid was found to be the toughest and most resistant to damage. Additionally, the Gyroid core achieved the highest strength, modulus, and stiffness-to-weight ratio.

Triply periodic minimal surfaces (TPMS) are a set of different highly interrelated mathematical topologies. TPMS is a minimal area that is invariant under a rank-3 lattice of translations. In publication [13] it was emphasized that the gyroid is characterized by a similar moment of inertia with respect to the three axes of the

Cartesian coordinate system. Therefore, the results of the numerical calculations presented in [13] showed that the gyroid structures under hydrostatic pressure react in an equilibrium with respect to each of the axes. In the experimental studies on compression of Gyroid structure samples, the similar results were obtained [14]. It was found that the Gyroid structures deform uniformly within the elastic region. Moreover, Gyroid structures with high relative densities deform more uniformly also beyond the elastic region. Similar conclusions were obtained during the quasi-static compression of the Gyroid structure made with the selective laser melting of 316L stainless steel, which was presented in paper [15].

In paper [16], the compressive load capacity of periodic and stochastic Gyroids was analysed. Both the periodic and stochastic cellular materials were found to exhibit collective deformation without shear band formation. Both computational and experimental results also showed that the periodic Gyroid TPMS network exhibits better mechanical properties as a function of relative density compared to the stochastic counterpart. The research of the authors of the publication [17] proved that the annealing at 100°C and 130°C of Gyroid structures made of PA12 material produced by the FDM method did not affect the carried compressive load. The annealing did not affect the flexibility to a large extent, but the differences were a few percent within the measurement errors.

2 Methods

To comprehensively investigate the mechanical behavior and optimize the performance of gyroid-based metamaterials, a multi-stage methodology was adopted, combining experimental testing, numerical modeling, and advanced data-driven optimization techniques.

The study began with the fabrication of physical samples using additive manufacturing, specifically utilizing carbon fiber-reinforced nylon to produce lightweight, mechanically robust gyroid structures. These samples were subjected to experimental mechanical tests to determine key properties such as Young’s modulus, Poisson’s ratio, and deformation behavior under controlled loading conditions. The results served both as a validation benchmark and a source of training data. 3D prints of cubic samples were prepared using Creality Ender 5 Plus 3D printer in FDM technology. The PA12+CF15 material from which the gyroids are made is characterized by 120 MPa tensile strength at break and 7 GPa flexural modulus. Wall thickness was limited by printer nozzle diameter, on the market the most common variant was 0,4 mm. According to filament datasheet nozzle temperature was set to 255℃ and printer heated bed temperature was set to 100℃. The rest of printing settings e.g. printing speed, extrusion speed, print cooling, retraction speed was set as default during G-code generation. During the printing process, the 3D printer was placed under the heat shield. As shown in Figure 1, three variants of gyroid samples were fabricated with an equal 3D printing process for the experimental purposes: a cell size 25^3 mm^3 (25mm x 25mm x 25mm), cell size 10^3 mm^3 (10mm x 10mm x 10mm) and cell size 5^3 mm^3 (5mm x 5mm x 5mm). The gyroid cells comprised a total sample size of 50 mm x 50 mm x 50 mm.

Experimental determination of key mechanical properties such as Young's modulus and Poisson's ratio for printed samples is essential. Gyroid structures do not have a single, constant Young's modulus or Poisson's ratio – these values depend on base material, gyroid geometry (e.g. thickness, porosity, orientation), loading method and structure scale (macro/micro/nano). To determine Young's modulus *E* and Poisson's ratio *ν* for such a structure, the following methodology was used:

1. Gyroid structures (50×50×50 mm^3) were designed and printed.
2. Samples were subjected to compression testing in a testing machine (Zwick Roell Z50).
3. The force (*F*) and elongation (*ΔL*) of the sample and its initial dimensions were measured.

The Young's modulus was calculated using the formula:

$$E = \frac{\sigma}{\varepsilon} = \frac{F \cdot L_o}{A \cdot \Delta L} \tag{2}$$

where: *A* – cross-sectional area of the sample,
L_o – original length of the sample,
ΔL – change in length under load.

The Poisson's ratio was calculated using the following formula:

$$\nu = \frac{\varepsilon_{transverse}}{\varepsilon_{longitudinal}} \tag{3}$$

An analytical approximation for foams and porous structures, which is also applicable to gyroids, based on the Gibson-Ashby model [18]. The model provides power-law relationships:

$$E_{eff} = E_s \cdot C \cdot \left(\frac{\rho_{eff}}{\rho_s}\right)^n \tag{4}$$

E_{eff} – The static modulus of the gyroid structure.
E_s – The static modulus of the gyroid structure's bulk material.
C – Gibson-Ashby constant, the value of which is dependent on the unit cell topology and geometry and is derived from experimental results. Geometry-dependent constant typically C = 0.1–1 for gyroids.
ρ_{eff} – Density of the gyroid structure.
ρ_s – Density of the gyroid structure's bulk material.
n – Exponent (~1.5–2 for open structures).

The Gibson–Ashby model enables analytical prediction of the mechanical performance of gyroid-based metamaterials by linking structural density with stiffness and strength. Although it simplifies complex geometries, it provides a powerful baseline for designing and optimizing lightweight, porous gyroid structures in engineering and biomedical applications.

A FEM parametric 3D model of the gyroid structure was built using ADINA software. FEM analysis was performed to simulate the mechanical behaviour of the structure under compression. The FEM simulation results were then compared with experimental data to calibrate and verify the numerical model. Figure 1 shows the numerical models of the analysed structures with their dimensions.

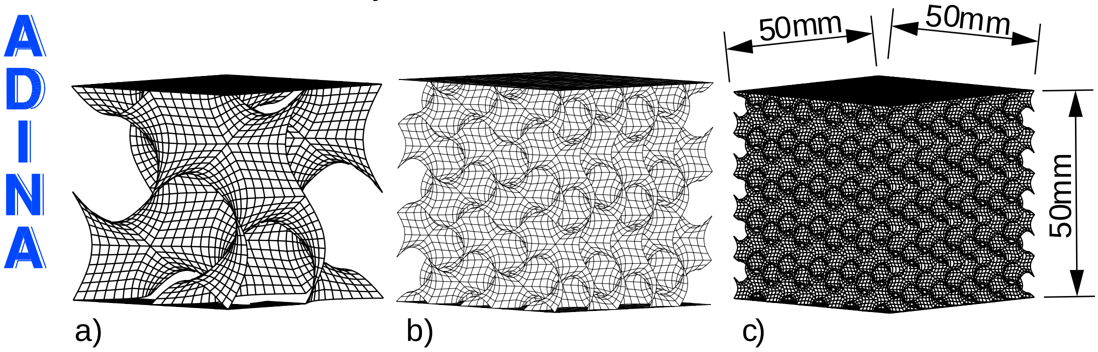

Figure 1. Numerical FEM models of the analysed structures; a) cell size 25^3mm^3, b) cell size 10^3mm^3, c) cell size 5^3mm^3.

FEM was used to simulate the gyroid structures with various geometric configurations (e.g., wall thickness, porosity). A parametric model was created and validated against experimental data obtained from 3D-printed samples. A large dataset of input parameters (e.g., structural density, geometry) and corresponding FEM-computed Young's modulus values was generated. Then, this dataset was used to train the ANN, which learns the relationships between design variables and mechanical response. The prepared dataset generated using FEM was normalized and structured for machine learning. The accuracy of ANN predictions was assessed by comparing them with the validation set. The schematic process is shown in Figure 2.

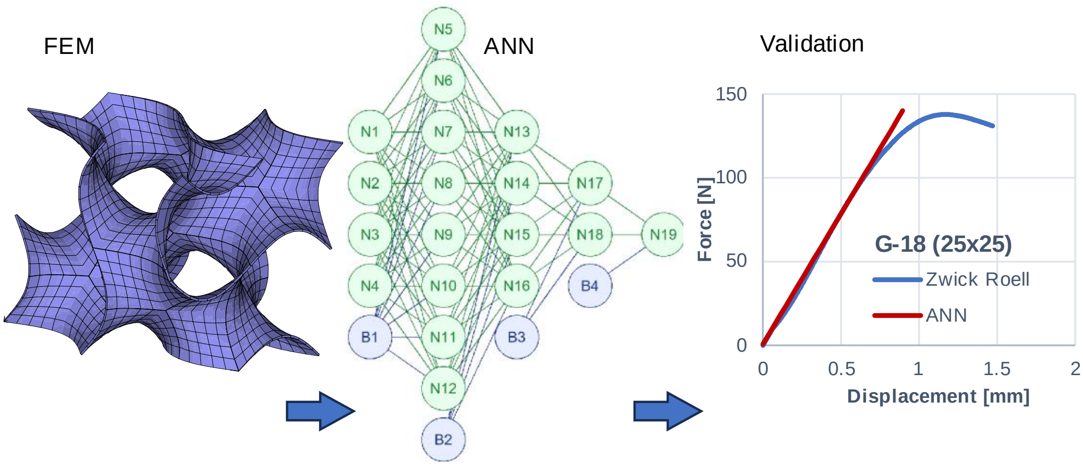

Figure 2. Flowchart for predicting Young's modulus of gyroids.

The ANN, once trained and validated, can rapidly predict Young's modulus for new design configurations, eliminating the need for time-consuming simulations or tests. Once trained, the ANN serves as a fast surrogate model, capable of predicting material behaviour without re-running expensive simulations.

Genetic algorithms were then used as the optimization engine. GA explores the design space, developing a population of candidate solutions through selection, crossover, and mutation. Instead of using FEM at each iteration, ANN rapidly evaluates the performance of each design, significantly reducing computational cost.

3 Results

The comprehensive results obtained from each phase of the study, providing a detailed account of the methods, findings, and interpretations that underpin the development and optimization of gyroid-based mechanical metamaterials were presented. Figure 3a) – Figure 5a) show physical samples of gyroid structures that were fabricated using additive manufacturing techniques from carbon fibre reinforced nylon. These specimens were subjected to standardized mechanical testing to determine fundamental material properties, such as Young's modulus, Poisson's ratio, and compressive strength. The experiments provided not only essential validation data for numerical modelling but also essential information on the actual behaviour of the structures under load, including aspects such as deformation modes, anisotropy, and failure mechanisms.

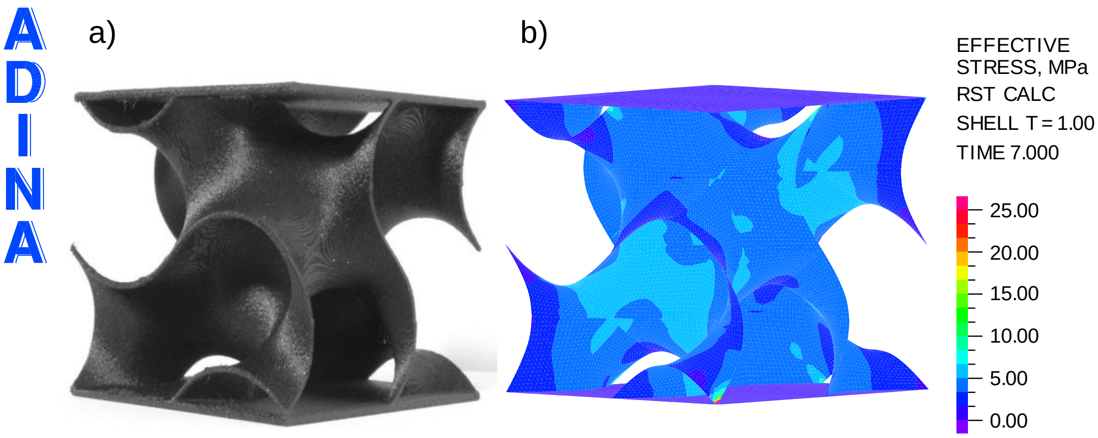

Figure 3. Gyroid sample with a cell size of 25^3mm; a) 3D printed model, b) FEM numerical model; effective stresses, MPa.

Following the experimental phase, the study advances to the FEM simulations, where a detailed parametric model of the gyroid structure was developed. Figure 3b) – Figure 5b) present the results of FEM numerical calculations for three gyroid cell sizes and a wall thickness of 0.4 mm. The FEM model was used to simulate the mechanical response across a huge range of geometric configurations and material properties. These simulations enabled the generation of a large, high-resolution dataset, capturing the influence of key design parameters, such as porosity, wall thickness, and unit cell size, on mechanical performance metrics. The FEM results were benchmarked against the experimental data to ensure model fidelity and predictive accuracy. In the case of gyroid, the way the structure resists deformation can follow two basic modes: bending-dominated or compression/tension-dominated. In bending-dominated structures, loads are mainly resisted by the bending of the structural component (walls or struts). This mode is common in lightweight structures with thin walls or low relative density, and while it provides flexibility and energy absorption, it generally offers lower stiffness and strength. The dominant deformation mechanism in standard gyroid structures is typically bending, which contributes to their characteristic mechanical efficiency at low to moderate densities.

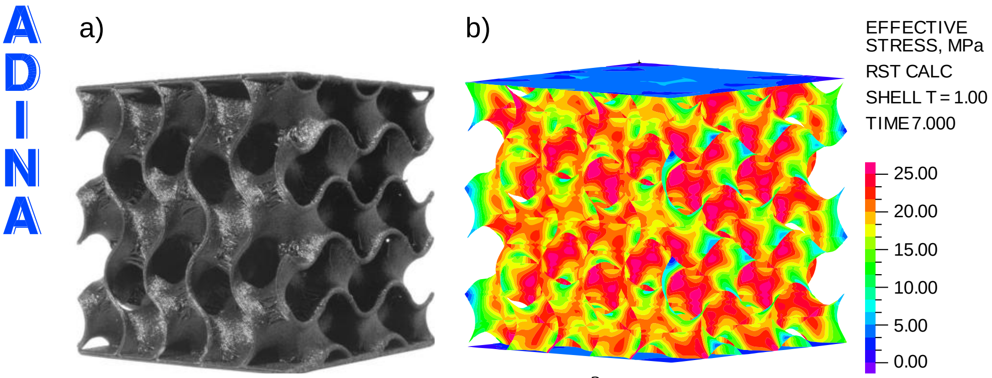

Figure 4. Gyroid sample with a cell size of 10^3mm; a) 3D printed model, b) FEM numerical model; effective stresses, MPa.

However, as wall thickness increases or relative density rises, the mechanical behaviour transitions toward a stretching- or tension-dominated regime, resulting in enhanced stiffness and load-bearing capacity. As the wall thickness increases or the relative density (i.e., the ratio of solid material to total volume) rises, the structural component become more strength. This causes the material to shift its deformation mode: instead of bending, the walls start to resist loads through stretching or compression, which are more efficient mechanical responses. This compression/tension-dominated behaviour significantly improves the material's ability to carry load, resulting in:

- Higher stiffness (greater resistance to deformation under a given force),
- Greater strength (higher maximum load before failure),
- Improved buckling under compressive or tensile forces.

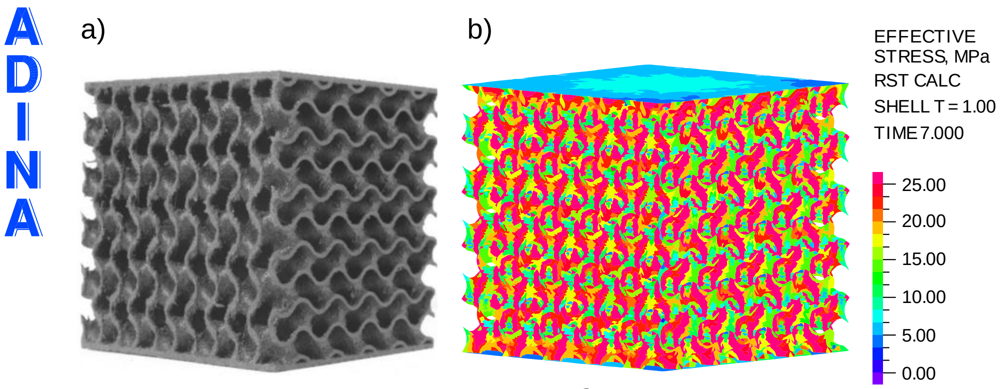

Figure 5. Gyroid sample with a cell size of 5^3mm; a) 3D printed model, b) FEM numerical model; effective stresses, MPa.

This transition is supported by simulation data (FEM results showing changes in stress distribution and displacement fields) and experimental observations, where denser gyroid structures shows less localized bending and more uniform load transfer through stretching. Due to their inherent geometric symmetry, gyroids offer nearly isotropic mechanical properties, meaning their stiffness and strength are relatively uniform in all directions. However, these properties can be selectively tuned by modifying parameters such as the orientation, relative density, or unit cell geometry, enabling the design of anisotropic structures with customized mechanical responses for specific loading scenarios.

The training and validation results of the ANN trained on the FEM simulation dataset revealed the complex relationships between structural design parameters and mechanical responses. Key performance metrics such as prediction accuracy, training loss, and generalization ability, along with validation against FEM and experimental data, demonstrated the effectiveness of the ANN as a fast surrogate model, capable of replacing computationally expensive simulations in optimization problems.

Figure 6 shows the results of the topology optimization process, where the trained ANN is coupled with a genetic algorithm (GA) to explore and identify optimal gyroid configurations. The GA uses the ANN to evaluate the mechanical performance of thousands of individuals designs efficiently, enabling rapid convergence toward solutions that meet predefined criteria such as maximum stiffness-to-weight ratio, targeted compliance, or custom mechanical gradients.

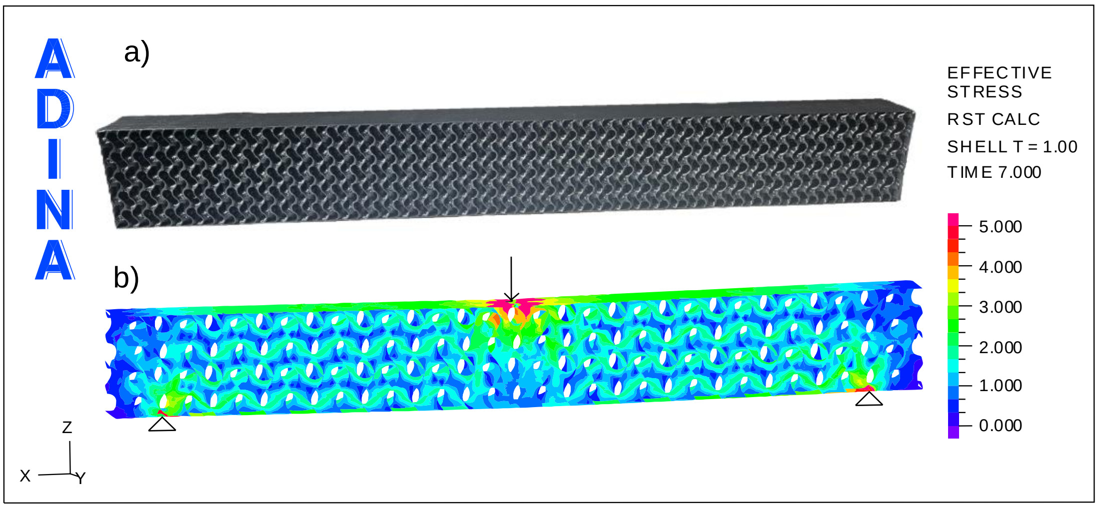

Figure 6. Results of the topology optimization process; a) 3D printed beam model, b) FEM numerical model; effective stresses, MPa

As the conducted analyses showed, gyroid walls can buckle, particularly under compressive loading, but whether they do depend on several geometric and material factors. When the walls of the gyroid are thin relative to their height or unsupported length, they behave like slender plates or shells. Under compression, these thin-walled elements are prone to local buckling before the bulk of the structure yields. If the structure is made with a low-modulus material (e.g., soft polymers), even a relatively dense gyroid may buckle if it lacks sufficient wall rigidity.

Although gyroids are generally isotropic, asymmetric loading or off-axis compression can induce localized instability, especially at transition zones between cells. Additive manufacturing (AM) processes like SLA or FDM can introduce surface roughness, residual stress, or thickness variations, which act as imperfections and reduce the critical buckling load.

4 Conclusions and Contributions

This study has demonstrated, through both experimental investigations and FEM simulations, that gyroid-based structures exhibit an exceptionally high stiffness-to-weight ratio, making them well-suited for applications where lightweight yet mechanically robust materials are required.

The mechanical performance of gyroid structures, including Young's modulus and compressive strength, was found to scale predictably with relative density, in accordance with the Gibson–Ashby power-law model.

It was shown that the Poisson's ratio of gyroid structures can be geometrically tuneable, generally remaining in the positive range of 0.2 to 0.35 for structures fabricated from polymer-based materials..

Future work will focus on the accurate characterization and prediction of buckling behaviour in gyroid structures. This includes employing FEM to simulate critical buckling loads and eigenmodes, and exploring the role of post-processing techniques to enhance structural uniformity and improved buckling resistance.

References

[1] T. D. Ngo, A. Kashani, G. Imbalzano, K. T. Nguyen, D. Hui, "Additive manufacturing (3D printing): A review of materials, methods, applications and challenges", Composites Part B: Engineering, 143, 172–196, 2018. doi: 10.1016/j.compositesb.2018.02.012

[2] X. Wang, M. Jiang, Z. Zhou, J. Gou, D. Hui, "3D printing of polymer matrix composites: A review and prospective", Composites Part B: Engineering, 110, 442–458, 2017. doi: 10.1016/j.compositesb.2016.11.034

[3] P. Lacki, A. Derlatka, M. Kwapisz, A. Idziak-Jabłońska, "An experimental and numerical evaluation of the mechanical properties of 3D prints made by Fused Filament Fabrication", Zeszyty Naukowe Politechniki Częstochowskiej, 29, 79–84, 2023. doi: 10.17512/znb.2023.1.12

[4] S. Limmahakhun, A. Oloyede, K. Sitthiseripratip, Y. Xiao, C. Yan, "3D-printed cellular structures for bone biomimetic implants", Additive Manufacturing, 15, 93–101, 2017. doi: 10.1016/j.addma.2017.03.010

[5] M. Kuczma, "Shape memory materials and structures: Modelling and computational challenges" in *Advances in Mechanics: Theoretical, Computational and Interdisciplinary Issues*, M. Kleiber, T. Burczyński, K. Wilde, J. Gorski, K. Winkelmann, and Ł. Smakosz, Eds.: CRC Press, 2016, 35–38

[6] V. A. Lvov, F. S. Senatov, A. M. Korsunsky, A. I. Salimon, "Design and mechanical properties of 3D-printed auxetic honeycomb structure", Materials

Today Communications, 24, 101173, 2020. doi: 10.1016/j.mtcomm.2020.101173
[7] C. Zeng, L. Liu, W. Bian, J. Leng, Y. Liu, "Compression behavior and energy absorption of 3D printed continuous fiber reinforced composite honeycomb structures with shape memory effects", Additive Manufacturing, 38, 101842, 2021. doi: 10.1016/j.addma.2021.101842
[8] H. Niknam, A. H. Akbarzadeh, "Graded lattice structures: Simultaneous enhancement in stiffness and energy absorption", Materials & Design, 196, 109129, 2020. doi: 10.1016/j.matdes.2020.109129
[9] R. Johnston, Z. Kazancı, "Analysis of additively manufactured (3D printed) dual-material auxetic structures under compression", Additive Manufacturing, 38, 101783, 2021. doi: 10.1016/j.addma.2020.101783
[10] T. Li, L. Wang, "Bending behavior of sandwich composite structures with tunable 3D-printed core materials", Composite Structures, 175, 46–57, 2017. doi: 10.1016/j.compstruct.2017.05.001
[11] S. Hou, T. Li, Z. Jia, L. Wang, "Mechanical properties of sandwich composites with 3d-printed auxetic and non-auxetic lattice cores under low velocity impact", Materials & Design, 160, 1305–1321, 2018. doi: 10.1016/j.matdes.2018.11.002
[12] A. W. Alshaer, D. J. Harland, "An investigation of the strength and stiffness of weight-saving sandwich beams with CFRP face sheets and seven 3D printed cores", Composite Structures, 257, 113391, 2021. doi: 10.1016/j.compstruct.2020.113391
[13] A. S. Dalaq, D. W. Abueidda, R. K. Abu Al-Rub, I. M. Jasiuk, "Finite element prediction of effective elastic properties of interpenetrating phase composites with architectured 3D sheet reinforcements", International Journal of Solids and Structures, 83, 169–182, 2016. doi: 10.1016/j.ijsolstr.2016.01.011
[14] D. W. Abueidda, M. Elhebeary, C.-S. Shiang, S. Pang, R. K. Abu Al-Rub, I. M. Jasiuk, "Mechanical properties of 3D printed polymeric Gyroid cellular structures: Experimental and finite element study", Materials & Design, 165, 107597, 2019. doi: 10.1016/j.matdes.2019.107597
[15] X. Li, L. Xiao, W. Song, "Compressive behavior of selective laser melting printed Gyroid structures under dynamic loading", Additive Manufacturing, 46, 102054, 2021. doi: 10.1016/j.addma.2021.102054
[16] O. Al-Ketan, D.-W. Lee, R. K. Abu Al-Rub, "Mechanical properties of additively-manufactured sheet-based gyroidal stochastic cellular materials", Additive Manufacturing, 48, 102418, 2021. doi: 10.1016/j.addma.2021.102418
[17] M. Ali, R. K. Sari, U. Sajjad, M. Sultan, H. M. Ali, "Effect of annealing on microstructures and mechanical properties of PA-12 lattice structures proceeded by multi jet fusion technology", Additive Manufacturing, 47, 102285, 2021. doi: 10.1016/j.addma.2021.102285
[18] G. Ashby, M. B. Casale, "Empirical dissociations between rule-based and similarity-based categorization", Behav Brain Sci, 28, 1, 15–16, 2005. doi: 10.1017/S0140525X05230017