The 11th International Congress
Motor Vehicles & Motors 2026
Kragujevac, Serbia
October 8th - 9th, 2026

Motor Vehicles & Motors

MVM2026-059
https://doi.org/10.24874/CMVM2026.059
Technical paper

Dušan Milojević[1]
Nikola Kotorčević[2]
Đorđe Damljanović[3]
Nikola Živčević[4]
Dušan Arsić[5]
Fatima Živić[6]

EFFECTS OF UNIT CELL GEOMETRY AND STRUT THICKNESS ON THE COMPRESSIVE BEHAVIOR OF 3D-PRINTED MECHANICAL METAMATERIALS

ABSTRACT: This study analyzes the compressive behavior of 3D-printed mechanical metamaterials with three unit-cell geometries and three nominal strut thicknesses. Nine specimens made of polylactic acid (PLA) were fabricated using fused deposition modeling (FDM). The specimens had approximate dimensions of 21 × 21 × 21 mm and consisted of regularly arranged 3 × 3 × 3 unit cells. Honeycomb, elliptic, and triangular geometries were investigated, with nominal strut thicknesses of 0.7, 1.0, and 1.4 mm for each geometry. The maximum recorded forces and fracture behavior were analyzed. Complete failure occurred in three specimens, whereas the remaining six did not fail completely within the testing machine's load limit of 500 N. The observed fracture was predominantly brittle, with cracks initiating at strut junctions, corresponding to the expected stress-concentration zones.

KEYWORDS: mechanical metamaterials, FDM 3D printing, lattice structures, honeycomb unit cell, elliptic unit cell, triangular unit cell

[1] *Dušan Milojević, University of Kragujevac, Faculty of Engineering, Sestre Janjic 6, 34000 Kragujevac, Serbia, dusanmilojevic@uni.kg.ac.rs , https://orcid.org/0009-0005-0113-3918*
[2] *Nikola Kotorčević, University of Kragujevac, Faculty of Engineering, Sestre Janjic 6, 34000 Kragujevac, Serbia, kotorcevic@kg.ac.rs, https://orcid.org/0000-0002-5664-9832*
[3] *Đorđe Damljanović, University of Kragujevac, Faculty of Engineering, Sestre Janjic 6, 34000 Kragujevac, Serbia, djordjedamljanovic12@gmail.com*
[4] *Nikola Živčević, University of Kragujevac, Faculty of Engineering, Sestre Janjic 6, 34000 Kragujevac, Serbia, nikolazivcevic1994@gmail.com*
[5] *Dušan Arsić, University of Kragujevac, Faculty of Engineering, Sestre Janjic 6, 34000 Kragujevac, Serbia, dusan.arsic@fink.rs, https://orcid.org/0000-0003-0326-0898*
[6] *Fatima Živić, University of Kragujevac, Faculty of Engineering, Sestre Janjic 6, 34000 Kragujevac, Serbia, zivic@kg.ac.rs, https://orcid.org/0000-0003-2509-187X*

UTICAJ GEOMETRIJE JEDINIČNE ĆELIJE I DEBLJINE NOSEĆIH GREDICA NA PONAŠANJE PRI PRITISKU 3D-ŠTAMPANIH MEHANIČKIH METAMATERIJALA

REZIME: Cilj rada je analiza ponašanja pri pritisku 3D štampanih mehaničkih metamaterijala sa tri geometrije jedinične ćelije i tri nominalne debljine nosećih gredica. FDM postupkom izrađeno je devet PLA uzoraka približnih dimenzija 21 × 21 × 21 mm, sa pravilno raspoređenim jediničnim ćelijama u konfiguraciji 3 × 3 × 3. Ispitane su heksagonalna, eliptična i trouglasta geometrija, sa debljinama nosećih gredica od 0,7, 1,0 i 1,4 mm za svaku geometriju. Analizirane su maksimalne zabeležene sile i ponašanje uzoraka pri lomu. Potpuni lom nastao je kod tri uzorka, dok kod preostalih šest nije zabeležen u raspoloživom opsegu opterećenja do 500 N. Uočeni lom bio je pretežno krt, sa nastankom prslina na spojevima nosećih gredica, odnosno u očekivanim zonama koncentracije napona.

KLJUČNE REČI: mehanički metamaterijali, FDM 3D štampa, rešetkaste strukture, heksagonalna jedinična ćelija, eliptična jedinična ćelija, trouglasta jedinična ćelija

INTRODUCTION

Mechanical metamaterials are engineered materials whose effective mechanical properties are determined not only by the constituent material but also by their internal architecture, particularly the unit-cell geometry (Jiao, P. et al. 2023). The geometry and arrangement of unit cells significantly affect the mechanical performance of lattice structures, including their compressive response, load-bearing capacity, and energy absorption (Qin, D. et al. 2022). FDM-printed lattice structures have been investigated for automotive crash absorbers, where cell size and strut diameter can be tailored to improve energy absorption and achieve a smoother force–displacement response (Boursier Niutta, C. et al. 2022). Owing to their low weight, high energy-absorption capacity, and favorable stiffness-to-weight ratio, lattice structures are promising for lightweight energy-absorbing applications, particularly in the automotive sector (Wu, B. et al. 2023; Saleh, M. et al. 2022). Studies of FDM-printed structures have also demonstrated that the selected infill pattern affects compressive force, deformation, and dimensional accuracy (Zisopol, D. G. et al. 2023). Therefore, this study aims to compare the compressive behavior of three unit-cell geometries—honeycomb, elliptic, and triangular—fabricated from polylactic acid (PLA) using FDM, with nominal strut thicknesses of 0.7, 1.0, and 1.4 mm.

MATERIALS AND METHODS

The specimens were fabricated from PLA filament using a Bambu Lab X1E 3D printer, with 100% infill of the struts and a layer height of 0.16 mm. A total of nine specimens, with approximate dimensions of 21 × 21 × 21 mm and a 3 × 3 × 3 unit-cell arrangement, were produced. Three unit-cell geometries—honeycomb, elliptic, and triangular—were investigated, with nominal strut thicknesses of 0.7, 1.0, and 1.4 mm for each geometry, as shown in Figure 1.

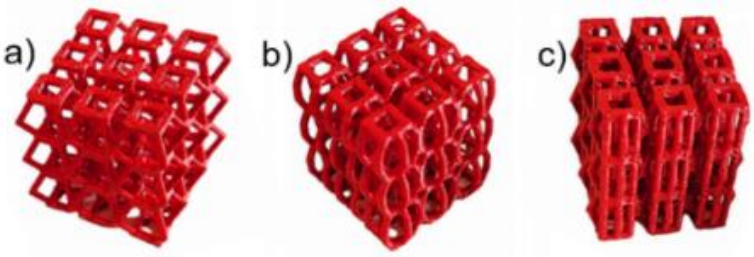


Figure 1 Actual 3D-printed unit-cell geometries: (a) honeycomb, (b) elliptic, and (c) triangular.

Compression tests were performed using an Ametek Brookfield CT3 texture analyzer (Middleboro, MA, USA), following the general procedure of ASTM D695 (D20 Committee, 2026). The specimens were loaded in the negative Z-direction at a constant displacement rate of 0.02 mm/s. Testing was terminated when complete failure occurred or when the machine load limit of 500 N was reached. Force–displacement data were recorded, and the fracture zones were examined by optical microscopy at 40× magnification.

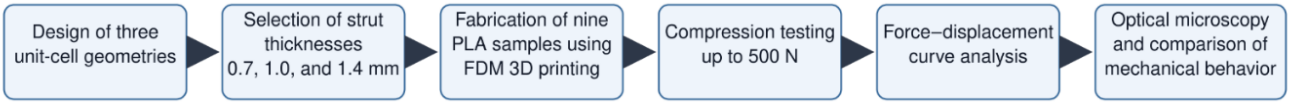


Figure 2 Flowchart of the main steps of the experimental procedure, from specimen design and 3D printing to compression testing and analysis of the results.

RESULTS AND DISCUSSION

Three specimens failed completely; the other six reached the 500 N machine limit without complete failure. Figure 3 shows the maximum recorded forces. At 0.7 mm, honeycomb, elliptic, and triangular specimens reached 131, 369, and ≥500 N, respectively. Honeycomb reached 294 N at 1.0 mm and 500 N at 1.4 mm; elliptic specimens at 1.0 and 1.4 mm and all triangular specimens reached 500 N. Thus, their actual maximum forces and the precise effect of strut thickness could not be determined.

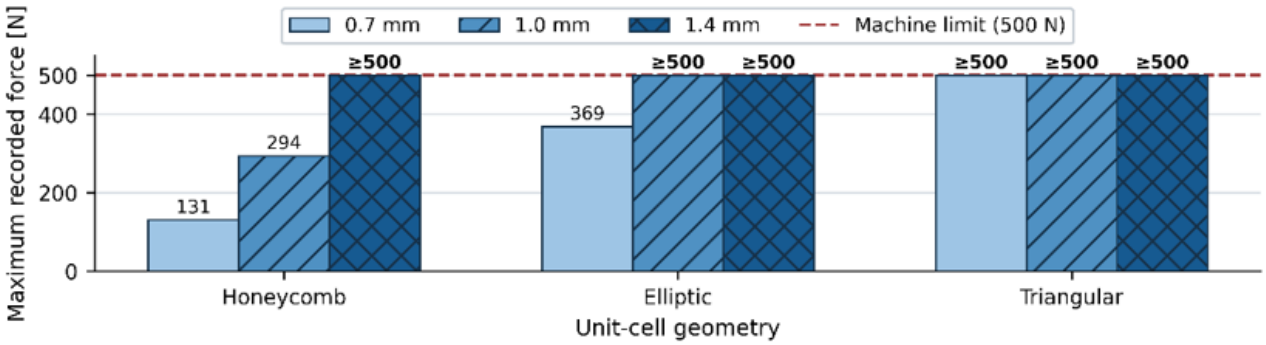


Figure 3 Maximum recorded forces for the investigated 3D-printed mechanical metamaterials. Values marked as ≥500 N indicate that the specimens reached the load limit of the testing machine

In the present tests, the honeycomb geometry showed the greatest susceptibility to fracture. Previous studies have shown that unit-cell geometry affects the compressive response and energy-absorption behavior of 3D-printed metamaterials (Jayswal, A. et al. 2025). In the present tests, brittle fracture was observed, with cracks initiating at strut junctions, which represent local stress-concentration zones. The observed brittle fracture and crack initiation at highly stressed regions are consistent with published research (Xiong, S. Et al. 2026). Layer delamination was also observed. Manufacturing defects in honeycomb cell walls may additionally influence the mechanical response (Rahaman, K. M. et al. 2018).

CONCLUSIONS

- Unit-cell geometry and nominal strut thickness influenced the recorded compressive behavior of the investigated 3D-printed mechanical metamaterials.
- At 0.7 mm, the maximum recorded forces were 131 N for the honeycomb, 369 N for the elliptic, and at least 500 N for the triangular geometry.
- For the honeycomb geometry, the maximum recorded force increased from 131 N to 294 N and then to at least 500 N as the strut thickness increased from 0.7 to 1.4 mm.
- The honeycomb specimen at 1.4 mm, the elliptic specimens at 1.0 and 1.4 mm, and all triangular specimens reached the 500 N machine limit. Therefore, their actual maximum compressive forces and the precise effect of strut thickness could not be determined.
- Complete failure occurred in three of the nine specimens. Fracture was predominantly brittle, with cracks initiating at strut junctions, while layer delamination was also observed.
- Replicate testing of stronger specimens on a higher-capacity machine is needed to assess repeatability, actual load capacity, and the effects of manufacturing imperfections.

ACKNOWLEDGMENTS

This research was supported by the A-SIDE project within the EIT Higher Education Initiative, coordinated by EIT RawMaterials and funded by the European Union. Additional support was provided by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia under project No. 451-03-34/2026-03/200107.

REFERENCES

Boursier Niutta, C., Ciardiello, R., & Tridello, A. (2022). Experimental and numerical investigation of a lattice structure for energy absorption: application to the design of an automotive crash absorber. *Polymers*, 14(6), 116. https://doi.org/10.3390/polym14061116

D20 Committee. (2026). Standard test method for compressive properties of rigid plastics. https://doi.org/10.1520/D0695-23

Jayswal, A., Angelopoulou, P. P., Rohewal, S. S., Kearney, L. T., Gupta, S., Bowland, C. C., Toomey, M. D., & Amit, K. (2025). High compressive energy absorption and shape recovery behavior of additively manufactured textile-inspired cylindrical braided metamaterials. *Additive Manufacturing*, 110, 104925. https://doi.org/10.1016/j.addma.2025.104925

Jiao, P., Mueller, J., Raney, J. R., Zheng, X., & Alavi, A. H. (2023). Mechanical metamaterials and beyond. *Nature Communications*, 14(1), 6004. https://doi.org/10.1038/s41467-023-41679-8

Qin, D., Sang, L., Zhang, Z., Lai, S., & Zhao, Y. (2022). Compression Performance and Deformation Behavior of 3D-Printed PLA-Based Lattice Structures. *Polymers*, 14(5), 1062. https://doi.org/10.3390/polym14051062

Rahman, K. M., Hu, Z., & Letcher, T. (2018). In-plane stiffness of additively manufactured hierarchical honeycomb metamaterials with defects. *Journal of Manufacturing Science and Engineering*, 140(1), 011007. https://doi.org/10.1115/1.4038205

Saleh, M., Anwar, S., Al-Ahmari, A. M., & Alfaify, A. (2022). Compression performance and failure analysis of 3d-printed carbon fiber/PLA composite TPMS lattice structures. *Polymers*, 14(21), 4595. https://doi.org/10.3390/polym14214595

Wu, B., Chen, Q., Liu, F., Chen, M., Lu, Y., Jiang, D., & Yi, Y. (2023). Study on dynamic mechanics of node-enhanced graded lattice structure and application optimization in automobile energy absorbing box. *Materials*, 16(21), 6893. https://doi.org/10.3390/ma16216893

Xiong, S., Liu, X., He, L., Huang, J., Yang, L., Liu, X. W., Yan, C., & Shi, Y. (2026). State-of-the-art advances in crack propagation control of lattice metamaterials: A review," *Review of Materials Research*, 2(1), 100153. https://doi.org/10.1016/j.revmat.2026.100153

Zisopol, D. G., Minescu, M., Iacob, D. V. (2023). A Study on the evaluation of the compression behavior of PLA lattice structures manufactured by FDM. *Engineering, Technology & Applied Science Research*, 13(5), 11801–11806. https://doi.org/10.48084/etasr.6262