

Effects of Structural Parameters on Impact Performance of 3D Printed Double Arrowhead Negative Poisson's Ratio Structures

Ziqian Dong

*School of Mechanical Engineering, Hefei University of Technology, Hefei, China
1191925510@qq.com*

Abstract. Negative Poisson's ratio structures, characterized by their exceptional mechanical properties—including high stiffness, superior strength, and outstanding energy absorption capabilities—exhibit significant potential for widespread application across engineering domains. This study focuses on the design and systematic investigation of a double arrowhead honeycomb negative Poisson's ratio structure. Experimental specimens were fabricated using 3D printing technology, and finite element analysis (FEA) was employed to evaluate the effects of structural parameters on impact performance. The research primarily examines the influences of two key parameters: the half-longitudinal distance (l) and the angle (θ_1)—on the structure's energy absorption characteristics and impact response behavior. Findings reveal that increasing the half-longitudinal distance effectively mitigates local stress concentration and enhances the structure's impact resistance. Meanwhile, variations in the angle θ_1 exert a pronounced effect on the stress distribution and impact force response of the structure. By comparing FEA results with experimental data, the reliability of the finite element model was validated, thereby establishing a theoretical foundation for optimized structural design. This study provides a critical reference for the design and optimization of negative Poisson's ratio structures, holding particular engineering significance for applications in automotive and aerospace industries.

Keywords: 3D printing, double arrowhead honeycomb, negative Poisson's ratio, numerical simulation

1. Introduction

Negative Poisson's ratio (NPR) structures are a class of materials with remarkable mechanical properties, including exceptional fracture toughness, enhanced impact resistance, superior vibration damping characteristics, and high shear strength. These unique properties make NPR structures particularly valuable for use in impact-resistant applications, where durability and energy absorption are critical. As a result, NPR structures have found widespread utility across numerous engineering domains, ranging from packaging and biomedicine to sensors, automotive engineering, and aerospace technologies. Their ability to withstand and absorb impact forces effectively has made them indispensable in areas where the protection of delicate components from external shocks is

paramount, such as in automotive crash structures, protective equipment, and aerospace components [1-3].

Negative Poisson's ratio structures, distinguished by their exceptional fracture toughness, impact resistance, vibration damping properties, and high shear strength, render them highly suitable for application as impact-resistant component structures [1-3]. Consequently, these structures have found extensive utilization across diverse engineering domains, including packaging, biomedicine, sensors, automotive engineering, and aerospace [4].

Synthetic NPR materials can be fabricated in a variety of configurations, including the double arrowhead structure [5], chiral structure [6], and concave honeycomb structure [7]. Among these, the double arrowhead configuration stands out due to its superior mechanical performance, particularly in terms of its Young's modulus when compared to other structures at equivalent relative densities. This configuration also offers remarkable flexibility in design, enabling it to be tailored to meet specific performance requirements, making it a popular choice for research focused on energy absorption and impact resistance properties. For instance, Dadashi et al [8]. developed a hierarchically accreted double arrowhead lattice structure, which demonstrated significantly enhanced energy absorption capabilities compared to conventional materials. Additionally, Zeng et al. experimentally explored the energy absorption behavior of double arrowhead negative Poisson's ratio-filled tubes under transverse impact loading, further highlighting the structure's potential for energy dissipation under dynamic loading conditions [9]. Despite these advances, the intricate geometry of NPR materials presents substantial challenges in fabrication, especially when using conventional manufacturing techniques such as machining or casting, which often struggle to produce the complex geometries required for these structures [10].

Recent developments in 3D printing technology, however, have opened new avenues for the fabrication of NPR structures, providing a powerful tool for producing these complex geometries with high precision. Unlike traditional methods, 3D printing allows for the direct manufacturing of structures with intricate and optimized designs that would be difficult, if not impossible, to achieve using conventional machining processes. This technological advancement has significantly expanded the design space for NPR materials, enabling more efficient and cost-effective production of structures tailored for specific applications [11,12]. Moreover, the integration of finite element analysis (FEA) with 3D printing has further augmented the design process. FEA serves as a precise and efficient numerical tool for simulating the behavior of NPR structures under various loading conditions, offering valuable insights into their energy absorption characteristics and overall performance. By using FEA to evaluate the influence of different structural parameters, researchers can predict the mechanical response of NPR materials before physical prototypes are constructed, thereby saving both time and resources in the design optimization process [11,13].

However, while significant strides have been made in the design and simulation of NPR structures, the effects of parameter variations on the performance of double arrowhead NPR structures under quasi-static loading conditions remain insufficiently explored. The structural parameters, such as the half-longitudinal distance (l) and the angle of the arrowheads (θ), can significantly influence the mechanical performance of the structure, particularly in terms of its energy absorption and impact resistance. Therefore, there is a need for more systematic investigations into the relationships between these parameters and the structure's overall impact behavior.

This study aims to fill this gap by focusing on the design and optimization of double arrowhead NPR structures. The research begins with the fabrication of a solid prototype using 3D printing technology, followed by the establishment of a finite element analysis model. The reliability of the

finite element model is experimentally validated through impact testing, and the effects of key structural parameters on the energy absorption characteristics and impact response are thoroughly analyzed. By exploring the influence of these parameters, this work aims to identify optimal structural configurations that enhance the performance of double arrowhead NPR structures. The findings from this study will provide valuable insights for the future design and optimization of NPR structures, with significant implications for applications in industries such as automotive engineering, aerospace, and protective systems. Ultimately, this work seeks to offer a theoretical foundation for the development of high-performance, energy-absorbing materials with broad engineering applications.

2. Materials and methods

2.1. Materials

In this study, two thermoplastic resins were selected: polylactic acid (PLA) and thermoplastic polyurethane (TPU). PLA (4032D, Nature Works LLC, USA) was chosen for its good balance of strength and stiffness, with a density of 1.24 g/cm³ and a melt flow index (MFI) of 7.0 g/10 min at 210 °C under a 2.16 kg load. This makes PLA ideal for 3D printing due to its relatively low processing temperature and minimal warping. Thermoplastic polyurethane (TPU, Desmopan 5377A, Bayer, Germany), with a density of 1.14 g/cm³, was selected for its superior flexibility, impact resistance, and energy absorption capabilities. TPU's unique properties, such as high elasticity and wear resistance, make it particularly suitable for applications where dynamic loading and durability are crucial. These materials were chosen for their complementary mechanical properties and compatibility with 3D printing, enabling the precise fabrication of the designed double arrowhead negative Poisson's ratio structures.

2.2. Structure design and preparation

The geometric parameters of the double arrowhead negative Poisson's ratio structural unit cell are shown in Fig. 1(a), with the overall configuration of the model depicted in Fig. 1(b). The unit cell's geometry is defined by five primary parameters: the half-longitudinal distance (l), which refers to the length of the unit cell along its longitudinal axis; the angles θ_1 and θ_2 , which represent the two defining angles of the arrowhead structure; the wall thickness (t) of the unit cell, which plays a significant role in the structural integrity and load distribution; and the out-of-plane stretching height (d), which influences the overall vertical deformation and energy absorption capacity of the structure. These parameters collectively determine the mechanical response and energy dissipation characteristics of the structure. Additionally, the relative density of the structure, which is a measure of the material distribution within the unit cell, can be defined based on the specific configuration of these geometric parameters. The relative density of the structure can be defined as:

$$\rho_r = \frac{t \left(\sin \frac{\theta_1}{2} + \sin \frac{\theta_2}{2} \right)}{\frac{l}{2} \sin \left(\frac{\theta_2}{2} - \frac{\theta_1}{2} \right)} \quad (1)$$

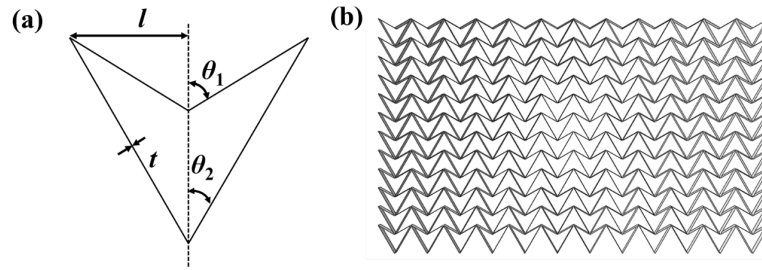


Figure 1. Configurations of double arrowhead negative Poisson's ratio structures

Printing was carried out using a fused deposition modeling (FDM) 3D printer equipped with a 0.4 mm diameter nozzle. The model was initially designed using SolidWorks software, which allowed for precise modeling of the double arrowhead negative Poisson's ratio structure. After the design phase, the model was imported into slicing software, where it was prepared for 3D printing. The print settings were carefully selected to ensure optimal print quality and material adhesion. Specifically, the print speed was set to 30 mm/s to balance efficient printing with accuracy. The extruder temperature was maintained at approximately 210 °C, a typical setting for polylactic acid (PLA), ensuring proper melting and extrusion of the material. The print platform was heated to 60 °C to prevent warping and ensure a stable base for the printed structure. After configuring these parameters, the model was sliced into individual layers, ready for printing.

2.3. Experiment

Axial low-rate impact tests were performed using a drop hammer testing machine (Shangtai Test Machine Co., Ltd., Jinan, China), specifically designed to simulate dynamic impact loading conditions. The specimen was carefully placed on the rigid base of a drop tower, ensuring that it remained stable and aligned during the testing procedure. A hammer, equipped with a rigid pad to ensure uniform impact, was raised to a predetermined height and then released to freely fall and impact the specimen. The impact energy was precisely maintained at 41.65 J, which was achieved by adjusting the height of the hammer's release. To generate the desired impact force, a counterweight of 6.8 kg was used, which produced an impact velocity of 3.5 m/s at the moment of contact. The parameters of impact energy and counterweight were rigorously controlled throughout the test to ensure consistent results and to accurately assess the specimen's response under low-rate impact loading conditions. These carefully controlled conditions allowed for a reliable evaluation of the structure's impact resistance and energy absorption performance.

2.4. Numerical simulation

Static compression analysis of the double arrowhead triangular structure was conducted using the finite element analysis software ABAQUS. The double arrowhead triangular structure was fabricated from polylactic acid (PLA), with material properties specified as follows: a density of 1.22 g/cm³, an elastic modulus of 413 MPa, and a Poisson's ratio of 0.3. Fixed constraints were applied to the lower boundary of the model, while a vertically downward displacement load was imposed on the upper boundary, as illustrated in Fig. 2.

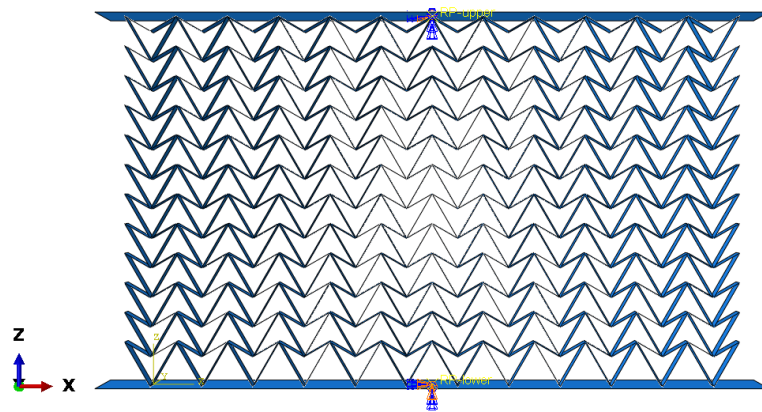


Figure 2. Finite element analysis model

3. Results and discussion

3.1. Model reliability validation

To verify the reliability of the Finite Element Model (FEM), the simulation results were compared with experimental data from impact tests. As shown in Fig. 3, the force-time curves from both the simulation and experiments follow a similar trend, with force values gradually increasing and fluctuating around similar peak values. This indicates that the FEM accurately captures the dynamic response of the structure under impact loading, confirming the model's reliability for practical applications.

The agreement between the simulation and experimental results validates the FEM's ability to predict the structure's impact behavior. This reliable model provides a solid foundation for further design optimization and parametric studies. Additionally, the successful validation demonstrates the effectiveness of the chosen material properties and modeling techniques, suggesting that the FEM can be confidently used for future studies and engineering applications involving impact-resistant structures.

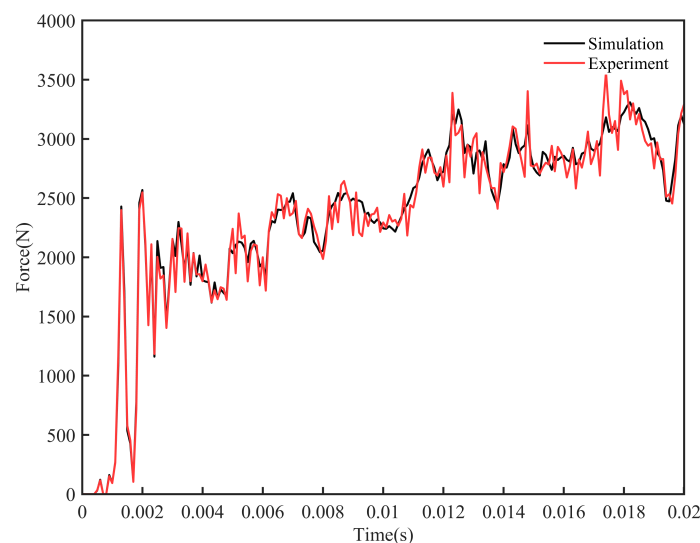


Figure 3. Reliability verification of finite element analysis model

3.2. Influence of structural parameters on impact properties

In this study, two key parameters of the double arrowhead negative Poisson's ratio structure were varied and analysed to investigate their effects on the impact performance of the structure. Specifically, the half-length distance l and the pinch angle θ_{11} in the structure were varied, respectively, and the impact response under different parameter combinations was evaluated by finite element simulations.

Fig. 4 demonstrates the effect of different half-length spacing l on the stress distribution and mechanical response of the double arrowhead negative Poisson's ratio structure under impact loading. From the stress cloud in the figure, it can be seen that with the change of half-length pitch, the stress distribution of the structure during the stressing process shows obvious differences. Specifically, when the half-length distance increases, the stress concentration region of the structure becomes more dispersed and the overall stress level decreases, indicating that a larger half-length distance can effectively mitigate the local stress concentration of the structure and enhance its load carrying capacity.

Meanwhile, the force-time curves presented in the figure (Fig. 4d) show the impact response at different half-length distances. In the figure, the structure exhibits more significant impact force fluctuations at half-length distance $l = 10$, while the magnitude of the impact force fluctuations gradually decreases as the half-length distance increases to $l = 12$ and $l = 14$, and the overall force value tends to be stable. This shows that the larger half-length distance helps to improve the energy absorption capacity of the structure, which makes the energy distribution more uniform during the impact process, and reduces the impact brought about by the impact.

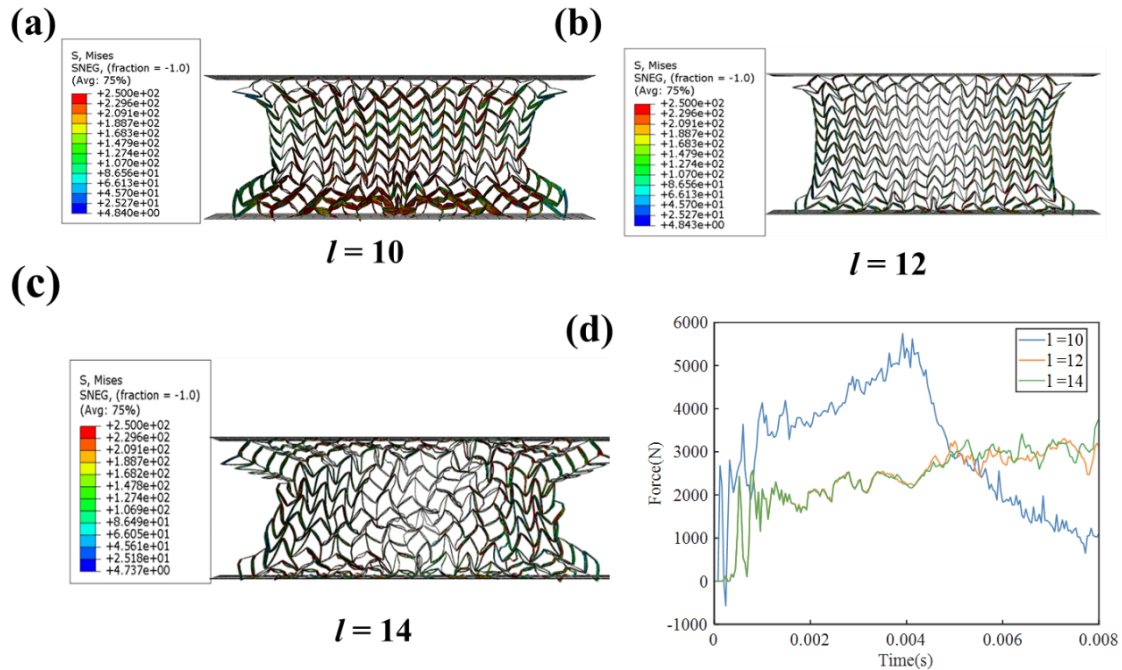


Figure 4. Shock response of double arrowhead honeycomb structures with different l

Fig. 5 demonstrates the effect of different θ_1 on the double arrowhead negative Poisson's ratio structure under impact loading. As can be seen from the stress cloud in the figure, the variation of the clamp angle has a significant effect on the stress distribution of the structure. At pinch angle $\theta_1 = 50^\circ$, the stress distribution of the structure is more uniform, while at pinch angle $\theta_1 = 60^\circ$, the stress

of the structure shows a more concentrated area, indicating that larger pinch angles increase the local stress of the structure, which may lead to the destruction of the structure or a decrease in the energy absorption capacity. In the force-time curves, the impact responses at angles $\theta_1=50^\circ$ and $\theta_1=60^\circ$ also show significant differences. At $\theta_1=50^\circ$, the force value of the structure rises rapidly after the impact, and the stability is better, and the force value tends to stabilise with time. At $\theta_1=60^\circ$, the impact response of the structure is slower, and the force value fluctuates more at the initial stage, and the final impact force grows more slowly.

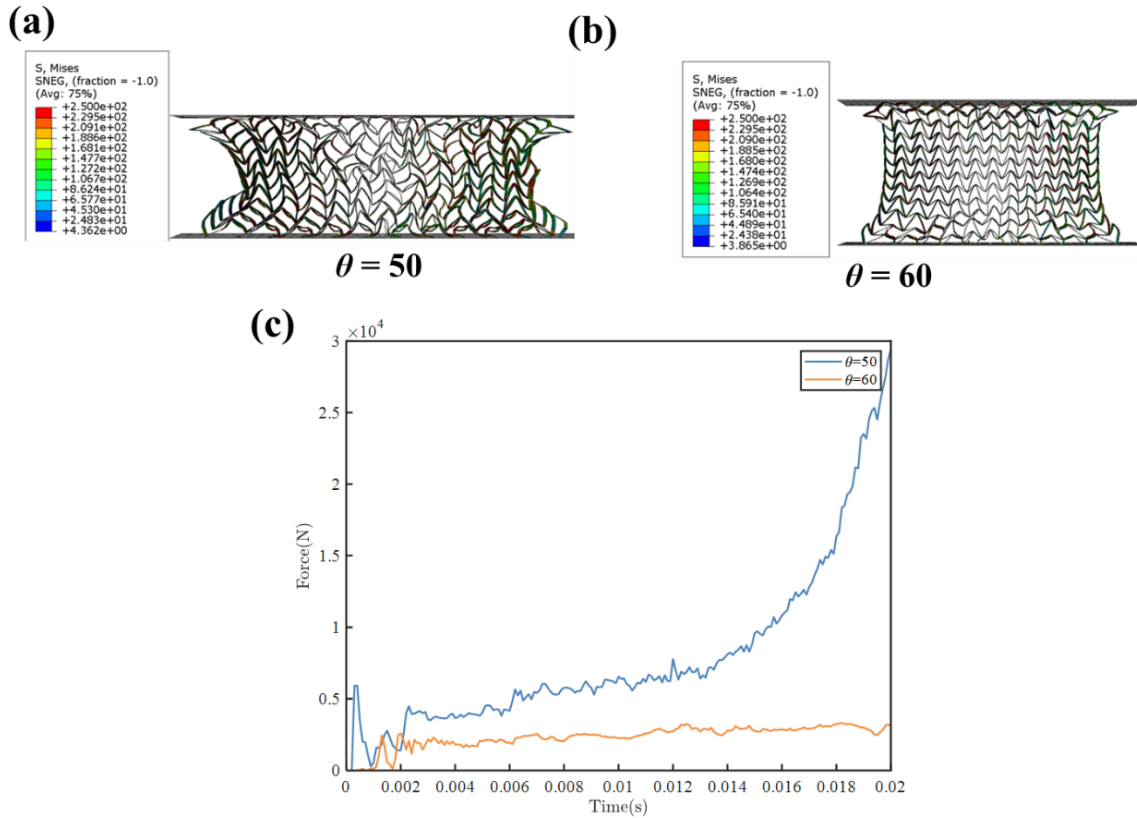


Figure 5. Shock response of double arrowhead honeycomb structures with different θ_1

4. Conclusion

In this work, a double arrowhead honeycomb negative Poisson's ratio structure was designed and fabricated via 3D printing technology, and its impact performance was systematically examined through finite element analysis. The validity of the FEA model was confirmed by direct comparison with experimental data, demonstrating its capability to precisely replicate the structure's dynamic response under actual impact conditions. This validation establishes a theoretical framework for subsequent structural optimization and performance enhancement. By systematically varying key structural parameters—the half-longitudinal distance (l) and pinch angle (θ_1)—the influences of these parameters on the structure's energy absorption characteristics and impact response were comprehensively investigated. The findings reveal that increasing the half-longitudinal distance effectively alleviates local stress concentration, enhances the structure's energy absorption capacity, and promotes a more uniform mechanical response under impact loading. Conversely, variations in the pinch angle exert a pronounced effect on stress distribution and impact dynamics, with a smaller pinch angle contributing to improved impact resistance. These results offer critical design guidelines

for high-efficiency energy-absorbing structures, particularly in aerospace and automotive engineering applications, underscoring their significant engineering value.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- [1] Song Y, Jiang S, Zhang B, Liu H, Liu F. In-plane impact performance of a gradient sinusoidal negative poisson-ratio honeycomb structure. *J Vib Eng Technol* 2025; 13: 202. <https://doi.org/10.1007/s42417-024-01686-5>.
- [2] Fang G, Yuan S, Meng S, Liang J. Graded negative poisson's ratio honeycomb structure design and application. *Jnl of Sandwich Structures & Materials* 2019; 21: 2527–47. <https://doi.org/10.1177/1099636218755555>.
- [3] Zhou Y, Jiang D, Wang L, Xiang P, Jia L-J. Cushioning performance of origami negative poisson's ratio honeycomb steel structure. *Thin-Walled Structures* 2024; 204: 112284. <https://doi.org/10.1016/j.tws.2024.112284>.
- [4] Gao Q, Ge C, Zhuang W, Wang L, Ma Z. Crashworthiness analysis of double-arrowed auxetic structure under axial impact loading. *Materials & Design* 2019; 161: 22–34. <https://doi.org/10.1016/j.matdes.2018.11.013>.
- [5] Xinting L, Wei L, Feiyan X, Yahui Y, Yangbo L. Low-velocity impact resistance of double arrowhead triangular structure with negative poisson's ratio. *Front Mater* 2025; 12. <https://doi.org/10.3389/fmats.2025.1435381>.
- [6] Fu M, Liu F, Hu L. A novel category of 3D chiral material with negative poisson's ratio. *Composites Science and Technology* 2018; 160: 111–8. <https://doi.org/10.1016/j.compscitech.2018.03.017>.
- [7] Xu H, Liu H-T, Li G-F. In-plane characteristics of a multi-arc re-entrant auxetic honeycomb with enhanced negative poisson's ratio effect and energy absorption. *European Journal of Mechanics - A/Solids* 2025; 109: 105473. <https://doi.org/10.1016/j.euromechsol.2024.105473>.
- [8] Dadashi A, Nedjad KH, Farrokhhabadi A, Ghannadpour SAM. Novel geometric functionally graded auxetic double arrowhead lattice structures design: Tailored unit cell angles for superior energy absorption. *Composites Part C: Open Access* 2025; 17: 100613. <https://doi.org/10.1016/j.jcomc.2025.100613>.
- [9] Zeng H, Ge C, Gao Q. Parametric analysis and optimization of tubes filled with double-arrowed negative poisson's ratio under transverse impact loadings. *Mechanics of Advanced Materials and Structures* 2023; 30: 4607–26. <https://doi.org/10.1080/15376494.2022.2101078>.
- [10] Liu B, Lou R, Liu X, Yao Y, Li H. Effect of printing path on compressive properties of 3D printed continuous fiber composite negative poisson's ratio structure. *Polymer Composites* 2023; 44: 6989–7001. <https://doi.org/10.1002/pc.27612>.
- [11] Li T, Chen Y, Hu X, Li Y, Wang L. Exploiting negative poisson's ratio to design 3D-printed composites with enhanced mechanical properties. *Materials & Design* 2018; 142: 247–58. <https://doi.org/10.1016/j.matdes.2018.01.034>.
- [12] Li W, Yang W, Li M, Zhang X, Zhang P, Zhao Y, et al. Energy absorption by 3D-printed mesh structures with a negative poisson's ratio. *Acta Metall Sin (Engl Lett)* 2024; 37: 205–12. <https://doi.org/10.1007/s40195-023-01640-6>.
- [13] Zhang M, Hu H, Kamrul H, Zhao S, Chang Y, Ho M, et al. Three-dimensional composites with nearly isotropic negative poisson's ratio by random inclusions: Experiments and finite element simulation. *Composites Science and Technology* 2022; 218: 109195. <https://doi.org/10.1016/j.compscitech.2021.109195>.