



Bioinspired functionally graded vorochiral metamaterials with enhanced energy absorption and dissipation

Hao Wang^{a,b,c}, Jian Jiang^{a,**}, Mohammed Rafiq Abdul Kadir^d, Sergei Bosiakov^e,
Hanxing Zhu^f, Yongtao Lyu^{a,b,c,g,*}

^a Department of Spinal Surgery, Central Hospital of Dalian University of Technology, Dalian University of Technology, Dalian, 116033, China

^b Department of Engineering Mechanics, School of Mechanics and Aerospace Engineering, Dalian University of Technology, No. 2 Linggong Road, Dalian, 116024, China

^c State Key Laboratory of Structural Analysis, Optimization and CAE Software for Industrial Equipment, Dalian University of Technology, Dalian, 116024, China

^d Department of Biomedical Engineering, Faculty of Engineering, Universiti Malaya, 50603, Kuala Lumpur, Malaysia

^e Faculty of Mechanics and Mathematics, Belarusian State University, Minsk, Belarus

^f School of Engineering, Cardiff University, Cardiff, UK

^g DUT-BSU Joint Institute, Dalian University of Technology, Dalian, 116024, China

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ABSTRACT

Designing bioinspired functionally graded metamaterials with tailored energy absorption (EA) and energy dissipation (ED) capacities through spatially regulating structural topology and local relative density distribution without increasing the overall material volume, remains a significant challenge. In this study, bioinspired functionally graded Vorochiral (BFG-VC) metamaterials were developed through the spatial modulation of chiral topologies, drawing inspiration from heterogeneous biological tissues. The EA capacity and deformation behavior of the BFG-VC metamaterial under quasi-static compression were systematically investigated. The finite element models developed in this work were validated using experimental testing, and dynamic rebound experiments were conducted to assess the ED capacity. The BFG-VC metamaterial exhibited up to a 78.85% improvement in EA compared to the conventional chiral metamaterial and demonstrated a tunable stress-deformation behavior enabled by BFG characteristics. The BFG-VC metamaterials displayed stress-strain responses with a well-defined, multi-step plateau characterized by an increased number of transitional stress fluctuations. Under low-velocity impact loading, the BFG-VC metamaterials outperformed the conventional chiral metamaterial in terms of ED. This superior synergistic static-dynamic performance demonstrates that the spatial modulation of Vorochiral architectures provides a highly effective design paradigm for advanced applications.

1. Introduction

Bioinspired functionally graded (BFG) structures have attracted considerable attention due to their excellent and tunable mechanical properties, including high specific stiffness and strength, light weight, and superior energy absorption (EA) and energy dissipation (ED) capabilities [1–3]. BFG structures draw inspiration from the evolutionary optimization of biological systems, in which material distributions are continuously adapted to enhance functionality and survivability under natural selection. In living organisms, tissues evolve optimized structural gradients that efficiently balance strength, stiffness and EA. These biological design principles provide valuable guidance for the development of novel

metamaterials with enhanced mechanical performance to meet demanding engineering requirements. As a result, BFG metamaterials have been widely applied in energy absorption and dissipation components for protective engineering [4–6], civil engineering [7,8], aerospace engineering [9–11], vehicle engineering [12,13], and marine engineering [14,15]. To date, most engineered BFG mechanical metamaterials are based on regular architectures or periodic unit cells [16–21], which differ fundamentally from the irregular and stochastic microstructures observed in biological tissues. Random BFG metamaterials, whose architectures more closely resemble natural biological structures, have the potential to achieve superior mechanical performance. To better understand the development and current state of this research field, evolution of representative

* Corresponding author. Department of Engineering Mechanics, Dalian University of Technology, No. 2 Linggong Road, Dalian, 116024, China.

** Corresponding author.

E-mail address: yongtaolu@dlut.edu.cn (Y. Lyu).

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energy-absorbing metamaterial designs is illustrated in Fig. 1. However, designing random BFG metamaterials with desired mechanical properties by spatially regulating structural topology and local relative density distribution without increasing the overall material volume, remains a significant challenge.

In recent years, a wide range of mechanical metamaterials has been developed for applications requiring effective EA. Among them, auxetic metamaterials exhibit exceptional EA performance owing to their counterintuitive deformation behavior, characterized by lateral contraction under compression and lateral expansion under tension [31–33]. Auxetic metamaterials can be broadly classified into re-entrant structures, chiral structures, rotating rigid structures, and perforated sheet structures, all of which exhibit negative Poisson's ratio characteristics [34–37]. Teng et al. [22] designed a simple three dimensional (3D) re-entrant auxetic metamaterial with enhanced EA performance, demonstrating both higher load-bearing capacity and superior EA. Zhou et al. [38] further developed a hollow re-entrant auxetic metamaterial by replacing solid struts with hollow ones, achieving up to 27.43% improvement in specific energy absorption (SEA). This design strategy was shown to be effective in enhancing the EA capacity of the structure [38]. Gupta et al. [39] investigated the in-plane mechanical performances of trichiral and anti-trichiral metamaterials, revealing that trichiral metamaterials exhibited superior EA performance at identical relative densities. Wang et al. [23] combined trichiral architectures with hexagonal honeycomb structures to form hexagonal trichiral metamaterials with enhanced EA and SEA capacities. Teng et al. [40] modified sandwich panels by introducing multiple rotating square units on the surface, demonstrating that appropriate surface cutting can significantly improve EA and SEA performance. He et al. [24] reported hexagonal perforated honeycomb metamaterials with substantial EA improvements under both vertical and horizontal impact loadings. Besides cellular metamaterials based on chiral and re-entrant architectures, origami-inspired metamaterials have recently attracted increasing attention due to their programmable

deformation, multi-stability, and EA capabilities [26,41,42]. Through carefully designed folding patterns and geometric parameters, origami-based metastructures can achieve tunable mechanical responses, such as controllable morphing behavior, enhanced ED, and improved EA. Recent advances in lightweight metamaterials have shown that geometric tailoring and bioinspired structural design provide effective ways for enhancing energy absorption and dissipation performance [25,43,44]. These studies further demonstrate that structural topology and deformation mechanisms provide important design variables for regulating EA beyond conventional unit cell optimization. Although these auxetic metamaterials demonstrate excellent EA capabilities, introducing functionally graded characteristics into such structures offers further opportunities to enhance EA performance.

Functionally graded metamaterials commonly inspired by natural biological system, generally exhibit superior EA performance compared to their uniform counterparts. By introducing functionally graded characteristics, the EA capacity of metamaterials can be significantly enhanced. Zhang et al. [6] investigated rotating structures with a layered gradient, and reported higher EA performance compared to non-graded designs. Zhao et al. [45] demonstrated that the EA of functionally graded triply periodic minimal surface (TPMS) structures was approximately 60% higher than that of uniform TPMS structures. Nian et al. [46] proposed a novel bio-inspired metamaterial by filling a circle tube with graded honeycomb structures; by employing a Kriging surrogate model coupled with a non-dominated sorting genetic algorithm, an optimal configuration was obtained, achieving an EA improvement of up to 89.73%. Zhang et al. [16] developed a BFG re-entrant anti-trichiral honeycomb by introducing two geometric parameters, namely, the cylindrical diameter and unit cell height, resulting in improved energy absorption efficiency (EAE). Liu et al. [18] presented an auxetic arc-curved honeycomb with a bioinspired layered gradient, achieving EA and SEA values that were 10.74 and 5.81 times higher than those of the non-graded structures, respectively. Daynes and Feih [27] proposed

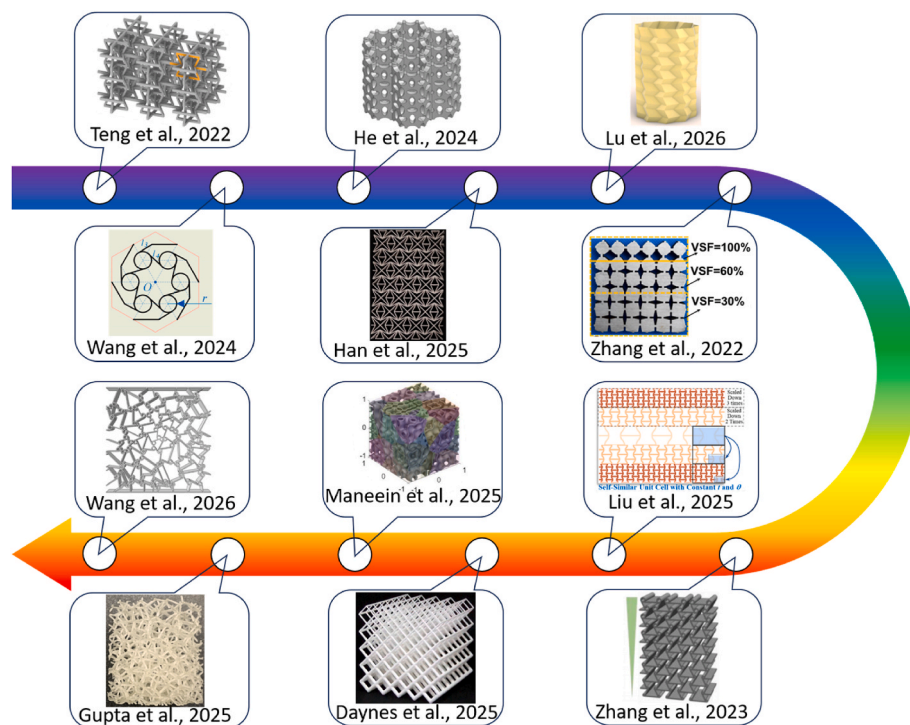


Fig. 1. Evolution of representative energy-absorbing metamaterial designs, including auxetic structures, re-entrant architectures, chiral metamaterials, bioinspired functionally graded structures, and random architectures figure adapted with permission from: Refs [22], Copyright 2022 Elsevier; [23], Copyright 2024 Elsevier; [24], International Journal of Mechanical Sciences, 2024 (CC BY 4.0); [25], Copyright 2025 Elsevier; [26], European Journal of Mechanics-A/Solids, 2026 (CC BY 4.0); [6], Copyright 2022 Elsevier; [16], Copyright 2023 Elsevier; [18], Copyright 2025 Elsevier; [27], International Journal of Mechanical Sciences, 2025 (CC BY 4.0); [28], Materials & Design, 2025 (CC BY 4.0); [29], Copyright 2025 Elsevier; [30], Copyright 2026 Elsevier.

a design strategy to enhance stiffness, strength, and EA in functionally graded lattice structures; by optimizing the distribution of strut thickness, the maximum EA was increased by 67.1%. Collectively, these studies demonstrate that programming functional gradients within conventional metamaterial architectures can significantly enhance EA performance. However, the most existing functionally graded metamaterials are still based on regular structures and periodic unit cells. To further improve EA performance, increasing attention has recently been directed toward random architectures, which more closely resemble the heterogeneous microstructures of biological tissues.

Random architectures possess heterogeneous topological features which closely resemble the structural characteristics of biological tissues and have demonstrated promising EA performance. While TPMS structures belong to the class of architectures based on periodic unit cells, Voronoi structures represent a typical category of random structures. Maneein et al. [28] proposed stochastic TPMS structures by introducing Voronoi-based randomness and demonstrated that the EA capacity increased with the number of random seed points. Spinodoid structures represent another class of surface-based random architectures [47–49]. Liu et al. [50] investigated the EA performance of Spinodoid, Primitive, Gyroid, and Octet structures, showing that Spinodoid structures exhibited the highest EA. Moreover, introducing gradient characteristics into Spinodoid structures further enhanced their EA performance, particularly at higher relative densities. These findings indicate that incorporating functional gradients into random architectures is an effective strategy for improving EA capacity. Additionally, both two dimensional (2D) and 3D functionally graded Voronoi structures have been developed by introducing gradient distributions [29,51], and these gradient designs have been shown to effectively enhance the EA performance of Voronoi-based architectures. Therefore, introducing bio-inspired functional gradient distribution characteristics into random structure is expected to further enhance their EA capacity. While spatial grading of random architectures provides an effective way for enhancing EA, ED remains comparatively less explored.

Despite the significant advancements in enhancing the EA capacities of mechanical metamaterials, a critical challenge remains regarding ED. Conventional lattice structures typically store the absorbed kinetic energy as recoverable internal strain energy during deformation. Without effective topological or material-driven dissipation mechanisms, such as internal friction, progressive buckling, or viscoelastic hysteresis, this stored energy is rapidly released upon unloading, leading to severe macroscopic elastic rebound. In practical engineering applications, such uncontrolled rebound behaviors can trigger catastrophic secondary impact damage to the protected objects. Therefore, achieving a synergistic coupling between EA and ED to fundamentally mitigate dynamic rebound effects has emerged as a paramount design objective.

In our previous work, a Vorochiral topology was developed by integrating Voronoi-based stochastic networks with chiral structural characteristics, providing an alternative to the periodically arranged topologies of conventional chiral metamaterials [30]. Through a parametric study of irregularity, wall thickness, and nodal circle radius, this Vorochiral metamaterial demonstrated excellent performance, including high stiffness and superior EA capabilities. Unlike conventional chiral structures with prescribed unit cells and regular connectivity, the Vorochiral topology exhibits spatially heterogeneous cell geometry and connectivity. The underlying deformation mechanisms remain associated with ligament bending and node rotation, whereas the stochastic topology changes their spatial distribution, load-transfer pathways and deformation localization. The resulting mechanical response was governed by the intrinsic stochastic chiral topology and its associated deformation characteristics. In contrast, the present study does not modify the fundamental Vorochiral topology itself. Instead, the BFG concept is introduced to spatially redistribute the local relative density along the loading direction. This strategy enables the local deformation and load-transfer sequence within the established Vorochiral architecture to be spatially regulated, providing an additional degree of freedom for tailoring its mechanical response.

In this paper, bioinspired functionally graded Vorochiral (BFG-VC) metamaterials were developed through the spatial modulation of chiral topologies, drawing inspiration from heterogeneous biological tissues. The EA capacity and deformation behavior of the proposed metamaterials under quasi-static compression were systematically investigated. Additionally, the finite element (FE) models developed in this study were validated through experimental testing, and the dynamic rebound experiments were conducted to assess the ED. The proposed BFG-VC metamaterials, exhibiting high synergistic energy absorption and dissipation performance, demonstrate promising potential for applications in aerospace, automotive, marine, and biomedical engineering.

2. Methods

2.1. Design strategy

The BFG-VC metamaterials were designed by incorporating bio-inspired gradient distribution concepts into Vorochiral metamaterials which are random chiral structures. In nature, many biological systems exhibit excellent mechanical performance as a result of spatial gradient distributions of heterogeneous tissue architectures. As illustrated in Fig. 2 (a)–(c), random tissues in wood stems, bamboo stems, and horse hooves exhibit a gradual increase in density from the interior toward the exterior [2]. This heterogeneous organization achieves a balance among lightweight characteristics, mechanical strength, and damage resistance in biological tissues by distributing material according to local mechanical requirements. For example, the denser outer regions provide enhanced load-bearing capability and impact protection, while the relatively compliant inner regions contribute to stress accommodation and weight reduction. Besides their randomness, these biological tissues also resemble chiral structures [16]. Therefore, the Vorochiral metamaterial proposed in our previous work [30] can also be regarded as a random biomimetic structure. The process of chiralization is shown in Fig. 2(d). Moreover, such gradient distributions are the outcome of long-term evolutionary optimization under natural selection. Inspired by these biological principles, two distinct gradient distribution strategies for BFG-VC metamaterials were also developed, as shown in Fig. 2(e). In the first configuration, the structure exhibited higher density in the top and bottom layers and lower density in the middle layer. In the second configuration, the density gradually increased from the top layer to the bottom layer. These gradient strategies were designed to enhance EA by tailoring local deformation and loading-transfer mechanisms along the structural height. The naming convention for proposed metamaterials is illustrated in Fig. 2(f) where “FG” denotes the “Functionally Graded”, and the numerical sequence represents the number of Voronoi seed points (i. e., nuclei) in the first, second, and third layers, respectively.

The Vorochiral metamaterials were proposed by introducing chirality into Voronoi tessellation structures. The Vorochiral diagrams were generated using MATLAB (v2023b, MathWorks Inc., Massachusetts, USA) based on randomly distributed seed points. First, irregularity degree of the Voronoi tessellation was defined. For a regular hexagonal honeycomb consisting of n cells distributed within a square area A_0 , the distance α_0 between any two adjacent nuclei is constant and can be expressed as:

$$\alpha_0 = \sqrt{\frac{2A_0}{n\sqrt{3}}} \quad (1)$$

For a random Voronoi tessellation with n cells within the same square area A_0 , the degree of irregularity Ir of the tessellation can be defined as:

$$Ir = 1 - \frac{\alpha}{\alpha_0}, \quad (2)$$

where α denotes the minimum distance between any two nuclei [52,53]. Second, nodal circles with identical radii were placed at the vertices of

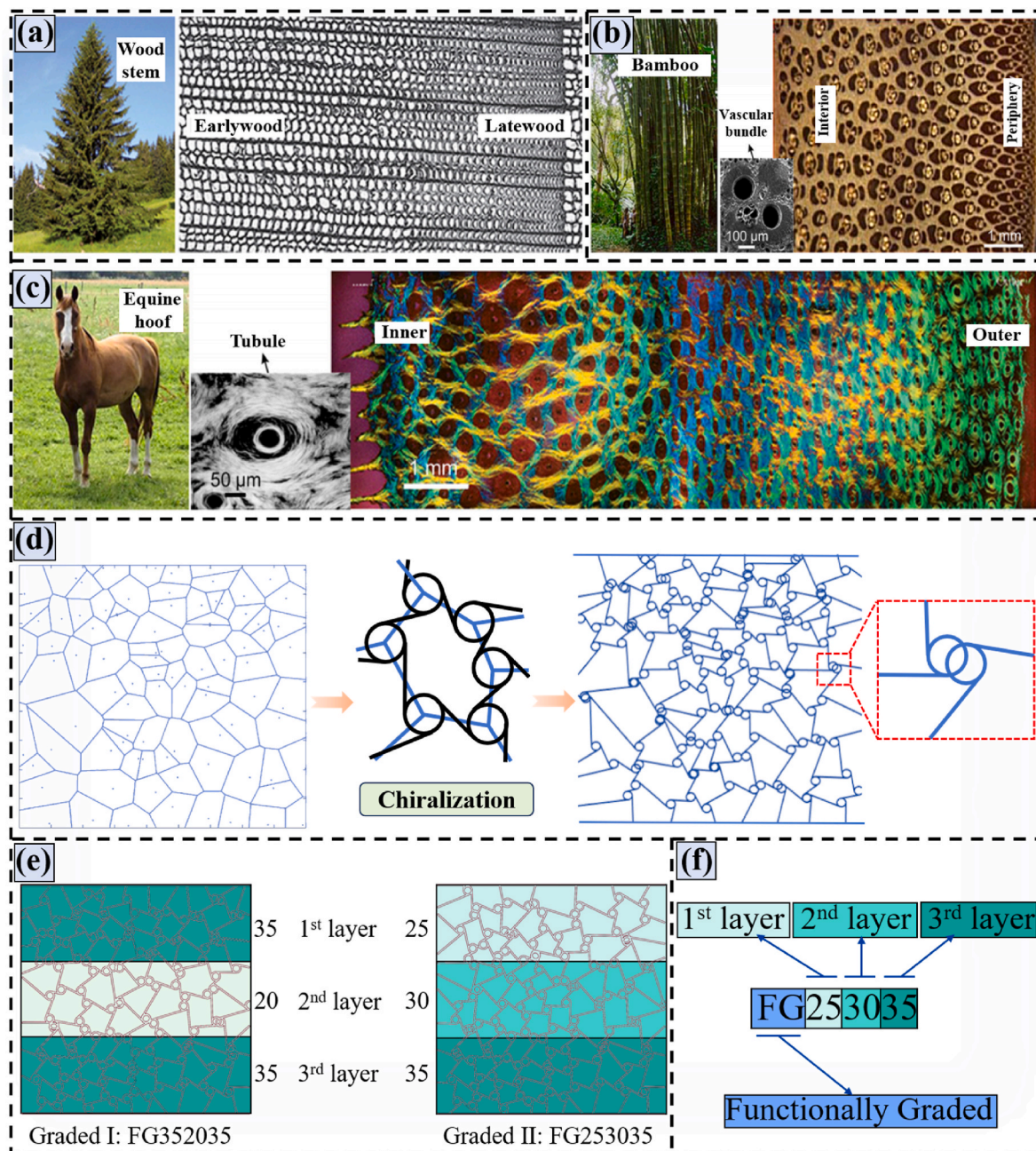


Fig. 2. Bioinspired gradient distribution strategies for BFG-VC metamaterials. (a) Gradual porosity variation in Norwegian spruce trunks from earlywood to latewood within growth rings. (b) Radial increase in the density of vascular bundles rich in cellulose fibers from the interior to the periphery of bamboo stems. (c) Increase in tubule density along the inner-to-outer direction across the wall thickness of a horse hoof figure adapted with permission from: Ref [2], Copyright 2017 Elsevier. (d) The formation process of Vorochiral metamaterial figure adapted with permission from: Ref [30], Copyright 2026 Elsevier. (e) Two bioinspired gradient distribution configurations of BFG-VC metamaterials. (f) Naming convention for the proposed functionally graded Vorochiral metamaterials.

the Voronoi tessellation, and tangentially attached ligaments were connected between adjacent nodal circles, as shown in Fig. 2(d). Chiral diagrams were generated by traversing each vertex using an adjacency matrix. If two adjacent circles intersected or were tangent, no ligaments were created between them to avoid geometric overlap. Two trichiral diagrams were merged into a tetrachiral diagram, as shown in the dashed red box in Fig. 2(d). Accordingly, the Vorochiral metamaterials can also be viewed as a combination of multiple types of chiral structures. The Vorochiral diagram was fully defined by assigning a radius R to the nodal circles. Last, given a wall thickness t and an out-of-plane thickness T , the geometry of Vorochiral metamaterial was constructed using SolidWorks (v2023, SolidWorks Inc., Massachusetts, USA), as shown in

Fig. 3(a) and (b). Notably, when the degree of irregularity was set to 0.0, the Vorochiral metamaterial degenerated into a conventional trichiral metamaterial, as illustrated in Fig. 3(a). In this study, the number of seed points n was set to 90, and the design domain A_0 was defined as a square area of $90 \times 90 \text{ mm}^2$. To emulate the gradient distribution observed in biological tissues, the square area was evenly divided into three layers, with different numbers of seed points assigned to each layer, as shown in Fig. 2(e).

Two gradient distribution strategies were considered. In the first configuration, the middle layer contained 20 seed points, while the top and bottom layers contained 35 seed points. In the second configuration, the number of seed points in the first, second, and third layers was set to

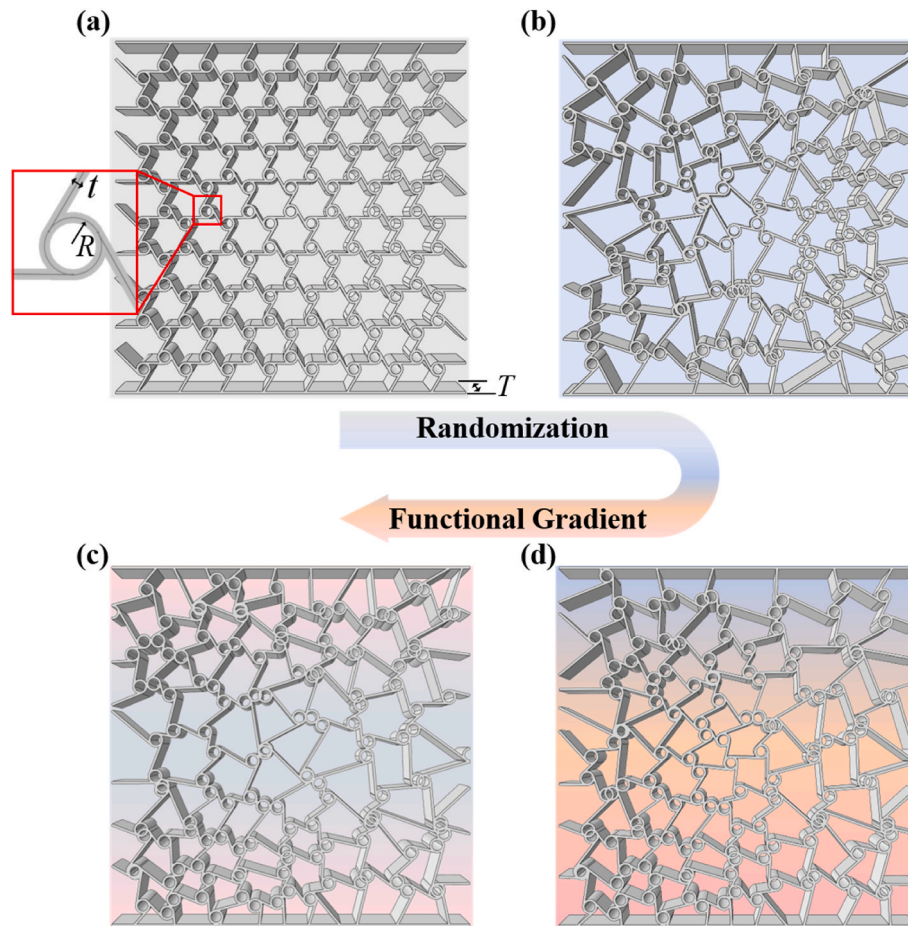


Fig. 3. Geometrical configurations of the chiral and Vorochiral-based metamaterials. (a) Conventional trichiral metamaterial. (b) Vorochiral metamaterial. (c) BFG-VC metamaterial FG352035. (d) BFG-VC metamaterial FG253035 figure adapted from Ref. [30].

25, 30, and 35, respectively. These two functionally graded Vorochiral metamaterials are illustrated in Fig. 2(e), 3(c) and 3(d). The selected gradient configurations were inspired by biological tissues, where denser outer regions and sparser inner regions are commonly observed to achieve a balance between load-bearing capability and lightweight characteristics. Therefore, this study focuses on bioinspired gradients with higher density at externally loaded regions. The two gradient configurations investigated in this study represent typical density redistribution strategies rather than an exhaustive exploration of all possible gradient designs. In this study, the spatial gradient was achieved by regulating the distribution density of Voronoi seed points in different regions. This approach controlled the local relative density of Vorochiral metamaterials while preserving their stochastic topology. The mechanical performance of the two BFG-VC metamaterials with gradient distributions was compared with that of a non-graded Vorochiral metamaterial. For consistency, the degree of irregularity for all Vorochiral-based structures was fixed at 0.4. Additionally, the performance of the conventional trichiral metamaterial was also evaluated for comparison. To ensure a fair assessment of EA performance, the relative density of all structures was maintained at 20%. Six structures of Vorochiral-based metamaterials were randomly generated to eliminate the contingency of the results. In the present study, the number of seed points was used as the primary design variable to regulate the spatial distribution of the Vorochiral topology. A larger number of seed points produces smaller Vorochiral cells and a denser local structural network, whereas a smaller number produces larger cells and a sparser topological distribution. Here, “density” refers to the spatial density of the structural topology rather than a prescribed layer-wise relative density. For each structural configuration, the wall thickness was adjusted

uniformly to ensure that the overall solid volume fraction was maintained at 20%. Therefore, the total material volume was kept consistent among different configurations, while different seed-point distributions generated distinct spatial topological gradients. The layer-wise solid fraction was not independently prescribed or used as a design variable in this study.

The Vorochiral metamaterials were generated using MATLAB code following the minimum-distance-constrained randomization procedure established in our previous work [30]. Candidate seed points were randomly generated within the prescribed design domain and accepted only when the minimum Euclidean distance from the previously accepted seed points satisfied $d_{\min} \geq \alpha$, where $\alpha = (1 - Ir)\alpha_0$, $Ir = 0.4$, and α_0 denotes the reference nearest-neighbor distance of the corresponding regular hexagonal tessellation. This process was repeated until the prescribed number of seed points was obtained in each layer. Six random realizations were generated for each Vorochiral-based configuration to account for the inherent stochastic variability. The complete set of geometrical configurations used in the present numerical analyses is provided in Supplementary Fig. S1.

2.2. Experimental tests and FE analysis for energy absorption

2.2.1. Fabrication of specimens

The dumbbell-shaped standard tensile specimens and the BFG-VC metamaterial specimens were fabricated using the fused deposition modeling (FDM) technique with a Bambu Lab P1S 3D printer (Shenzhen, China), as shown in Fig. 4(a) and 5(a). The STL files, generated using SolidWorks 2023, were imported into the Bambu Studio slicing software for toolpath preparation. A nozzle diameter of 0.4 mm was employed,

with a printing speed of 40.0 mm/s and a fixed layer height of 0.08 mm. Thermoplastic polyurethane (TPU) 95A HF, supplied by Bambu Lab, was selected as the base material for specimen fabrication.

All specimens were designed with the same overall relative density, while different gradient configurations were generated by spatially redistributing the structural topology and local relative density. Owing to the high dimensional accuracy of the employed FDM printing process, the deviations between the designed geometries and the fabricated specimens were small and considered negligible for the present comparative analysis. Consequently, the actual material usage among different configurations remained highly consistent, and the observed differences in energy absorption and dissipation mainly associated with the designed spatial distributions of topology and local relative density. Previous studies have demonstrated that FDM-based fabrication can provide acceptable geometric fidelity for lattice structures with appropriately selected feature sizes and printing parameters [54–56]. For example, dimensional deviations of FDM-printed lattice structures have been reported within 0.6%–1.8% compared with the designed geometries [55]. Therefore, the differences in mechanical responses among the investigated structures are mainly attributed to the designed topological and spatial density distribution rather than manufacturing inconsistencies.

All BFG-VC specimens were fabricated using the same printing orientation to ensure consistent manufacturing conditions. Since the proposed metamaterials are 2D structures, the structural plane was printed in the in-plane direction, while the deposited layers were stacked along the out-of-plane direction. Accordingly, the printing orientation was maintained for all specimens and was not considered as an independent variable in the present study. This controlled fabrication condition minimizes the influence of printing-orientation-related anisotropy on the comparative evaluation of different structural configurations. Nevertheless, the effects of varying build orientations on the mechanical response were not systematically investigated and warrant further study.

2.2.2. Material properties of TPU

The mechanical properties of the TPU were determined through uniaxial tensile tests. In accordance with the ASTM D638 international standard, dumbbell-shaped TPU specimens were designed and fabricated. The geometry and dimensions of the standard specimens are

shown in Fig. 4(a). Three specimens were tested using a universal testing machine (MTS Criterion 43.104) with a load capacity ranging from -10.0 kN to 10.0 kN and a maximum force indicator error of less than $\pm 1.0\%$. All tests were conducted at a constant testing speed of 10.0 mm/min, as illustrated in Fig. 4(b). During testing, force-displacement data were recorded and subsequently convert into nominal stress-strain curves. Based on the experimental results, a constitutive fitting was performed to describe the hyperelastic behavior of TPU material. Several hyperelastic constitutive models, including the Mooney-Rivlin, Polynomial, Neo-Hookean, Arruda-Boyce, Yeoh, and Ogden models, were evaluated against the average nominal stress-strain response. Among these, the second-order Polynomial model ($N = 2$) provided the best agreement with the experimental data. The individual nominal stress-strain curves obtained from the tensile tests are presented in Fig. 4(c). The fitted material parameters of the Polynomial ($N = 2$) model were subsequently implemented in Abaqus (v2021, Dassault SIMULIA, Rhode Island, USA) to define the TPU material properties for numerical simulations. The parameters are summarized in Table 1. The incompressibility assumption was introduced because TPU exhibits nearly incompressible behavior, and the volumetric deformation was neglected by setting $D_1 = D_2 = 0$ in the Polynomial hyperelastic model. Mullins effect mainly affects cyclic loading with repeated stress-softening, which was not involved in the present quasi-static compression simulations.

2.2.3. Setup of quasi-static compression tests

Quasi-static compression tests on the BFG-VC metamaterials were performed using the same universal testing machine at a constant crosshead speed of 2.0 mm/min, as shown in Fig. 5(b). Each specimen was compressed to a total displacement of 63.0 mm, corresponding to a nominal compressive strain of 0.7 , and the resulting force-displacement responses were recorded. To monitor the deformation process in real time, a high-resolution camera was directly positioned in front of the specimen throughout the test. A total of six specimens were tested, comprising three specimens for each of two gradient distribution configurations, as illustrated in Fig. 5(a). All specimens had an out-of-plane thickness of 15.0 mm to suppress buckling or global instability under quasi-static compressive loading. The relative density of all specimens was maintained at 20% to ensure a consistent basis for comparison.

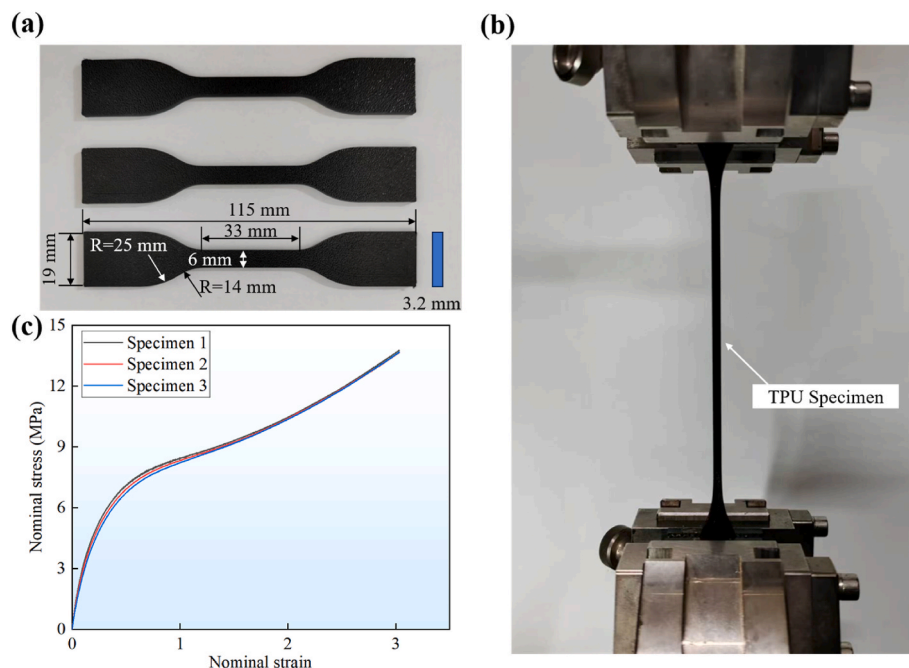


Fig. 4. (a) Three standard dumbbell-shaped TPU tensile specimens and their geometric dimensions. (b) Uniaxial tensile testing of a dumbbell-shaped TPU specimen. (c) Nominal stress-nominal strain curves of the TPU base material.

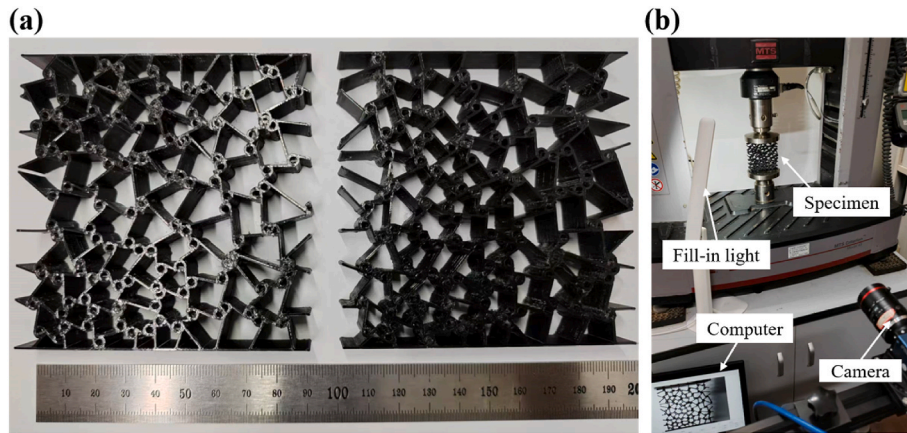


Fig. 5. 3D printed specimens and experimental testing platform. (a) 3D printed metamaterial specimens with two functionally graded distribution configurations. (b) Experimental testing platform used for quasi-static compression tests.

Table 1

Material parameters of TPU.

ρ (g/cm ³)	C_{10}	C_{01}	C_{20}	C_{02}	C_{11}	D_1	D_2
1.22	− 8.95	15.95	0.10	3.30	− 0.51	0.00	0.00

2.2.4. FE analysis

FE analysis was conducted using the commercial software Abaqus/Explicit 2021. The geometric models created in SolidWorks 2023 were imported into Abaqus, where the second-order Polynomial ($N = 2$) hyperelastic material model was assigned to simulate the mechanical behavior of the metamaterials. As illustrated in Fig. 6(a), two rigid plates were placed above and below the metamaterial to apply compressive loading. The metamaterial was discretized using eight-node reduced-integration hexahedral solid elements (C3D8R), while the rigid plates were modeled using quadrilateral rigid shell elements (R3D4). A mesh sensitivity analysis was performed to ensure mesh-independent results, and a mesh size of 0.36 mm was selected as it provided stable and converged responses. In the simulation, the bottom rigid plate was fully constrained, whereas the top rigid plate was prescribed a downward displacement of 63.0 mm to compress the structure. All nodes of the top and bottom plates were respectively coupled to reference points, through which the boundary conditions and loading were applied. Contact interactions between the rigid plates and the metamaterial were defined using the general contact algorithm in Abaqus/Explicit. The normal contact behavior was modeled using hard contact, while the tangential behavior was defined using the penalty friction formulation with a friction coefficient of 0.2. The kinetic energy remained much smaller than the internal energy throughout the compression process, confirming that the explicit simulation was conducted under quasi-static

conditions, as shown in Fig. 6(b). The contact status and contact force histories were also examined throughout the simulation, and no abnormal contact penetration or numerical instability was observed. The force-displacement response was obtained by extracting the reaction force and displacement at the reference point associated with the top plate. From this data, the corresponding stress-strain curve was calculated to evaluate the quasi-static mechanical behavior of all metamaterials.

2.2.5. Statistical analysis for quasi-static FE simulation

To evaluate the influence of topological randomness and functional grading on the EA performance, six independent random realizations were generated for each Vorochiral-based configuration. The EA results obtained from finite element simulations were statistically analyzed using one-way analysis of variance (ANOVA), followed by Tukey's honestly significant difference post hoc test for comparisons of non-graded Vorochiral metamaterials with two BFG-VC metamaterials. The normality and homogeneity of variance assumptions were verified before ANOVA. Statistical significance was determined at $p < 0.05$.

2.3. Experimental tests for energy dissipation

2.3.1. Setup of dynamic rebound tests

The metamaterial specimens used for rebound testing were also fabricated using the FDM technique, with printing conditions identical to those described in Section 2.2.1. Unlike the specimens prepared for quasi-static compression tests, all specimens were designed with an out-of-plane thickness of 90.0 mm to prevent buckling or global instability under impact loading, as shown in Fig. 7(a).

Dynamic rebound tests were conducted using a self-built experimental platform, as shown in Fig. 7(b). The platform consisted of a

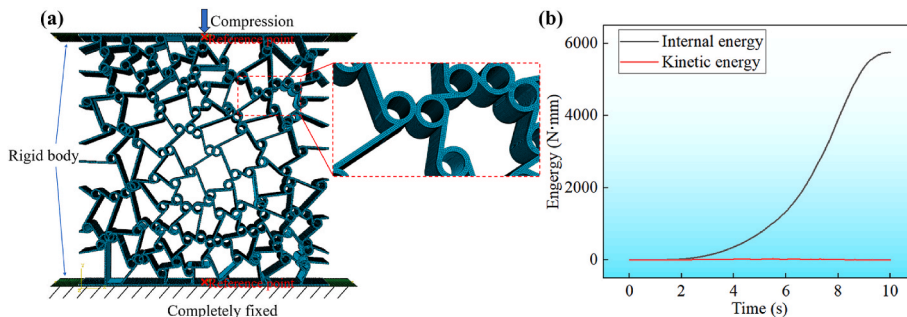


Fig. 6. (a) FE model of the BFG-VC metamaterials under quasi-static compression, showing the rigid loading plates, boundary conditions, and loading direction. (b) Evolution of internal energy and kinetic energy during quasi-static compression.

transparent acrylic tube and a retort stand equipped with a metal pole, a rigid base, and three adjustable clamps. The acrylic tube had an inner diameter of 60.0 mm and a wall thickness of 5.0 mm. One end of the tube was positioned in direct contact with the top surface of the test specimen, while a steel ball was released from the opposite end to undergo free fall.

Two clamps were used to firmly fix the acrylic tube, ensuring that it remained perpendicular to the ground throughout the tests. An additional clamp was employed to hold the steel ball prior to release, guaranteeing a zero initial velocity at the start of each experiment. Three steel balls with masses of 200 g, 300 g, and 500 g were used in this study. A measurement tape was attached along the tube to facilitate the measurement of rebound height. To capture the impact and rebound process, a high-resolution camera was positioned in front of the experimental setup.

At the beginning of each test, the lowest point of steel ball was located 500.0 mm above the top surface of the metamaterial specimen whose bottom plate was fully constrained to prevent parasitic energy loss. Based on free-fall kinematics, the impact velocity at first contact was calculated to be 3.13 m/s, corresponding to a low-velocity impact condition. During testing, the clamp holding the steel ball was gradually released, allowing the ball to fall vertically through the tube and impact at the center of the top surface of the specimen. Tests in which the steel ball contacted the tube wall during descent or initial rebound were discard. For each steel ball mass and each metamaterial configuration, ten repeated tests were performed. The rebound height of the steel ball was recorded from the high-speed camera footage and used for comparison of *ED* performance among the metamaterials.

2.3.2. Statistical analysis for dynamic rebound tests

Statistical analysis was performed to evaluate the variability and repeatability of the experimental measurements. For the dynamic rebound tests, each structural configuration was represented by one fabricated specimen, and ten repeated rebound measurements were conducted for each steel-ball mass. Therefore, the ten measurements were treated as repeated measurements on the same specimen rather than independent structural replicates. The rebound height and energy dissipation ratio (*EDR*) are presented as mean $\pm$ standard deviation (SD), and 95% confidence intervals (CI) were calculated to characterize the measurement variability under each impact condition.

2.4. Evaluation indicators of mechanical properties

The *EA* and *ED* capacities of the metamaterials was investigated in this study. Several commonly used indicators were employed to characterize *EA* performance [57], including *EA*, *SEA*, *EAE*, strain at the densification point (ε_d), and mean crushing load (*MCL*). Moreover, the *ED* performance can be assessed by energy dissipation ratio (*EDR*). The definitions of these indicators are given below:

Energy absorption, *EA*, represents the cumulative energy absorbed per unit volume of the structure, and is obtained by integrating the stress-strain curve up to the densification strain.

$$EA = \int_0^{\varepsilon_d} \sigma(\varepsilon) d\varepsilon. \quad (3)$$

Specific energy absorption, *SEA*, describes the energy absorbed per unit mass, and is calculated as:

$$SEA = \frac{EA}{\rho_m \rho_v}, \quad (4)$$

where ρ_m denotes the density of the base material, and ρ_v represents the relative density of the undeformed structure.

Energy absorption efficiency, *EAE*, is defined as the ratio of the energy absorbed by the structure to the product of instantaneous stress and corresponding strain, and can be expressed as:

$$EAE = \frac{\int_0^{\varepsilon_a} \sigma(\varepsilon) d\varepsilon}{\sigma_a \varepsilon_a}, \quad (5)$$

where ε_a is the instantaneous strain corresponding to the stress σ_a . The strain at the densification point ε_d is determined as the strain corresponding to the last local maximum of the *EAE* curve.

The mean crushing load, *MCL*, represents the average load sustained during compression up to densification and is defined as:

$$MCL = \frac{\int_0^d F d\delta}{d}, \quad (6)$$

where d denotes the displacement corresponding to the ε_d .

The energy dissipation ratio, *EDR*, is defined as the ratio of *ED* by initial gravitational potential energy E_0 . This is the most direct measure of energy dissipation efficiency of a structure, representing the proportion of total input energy that is dissipated by the structure.

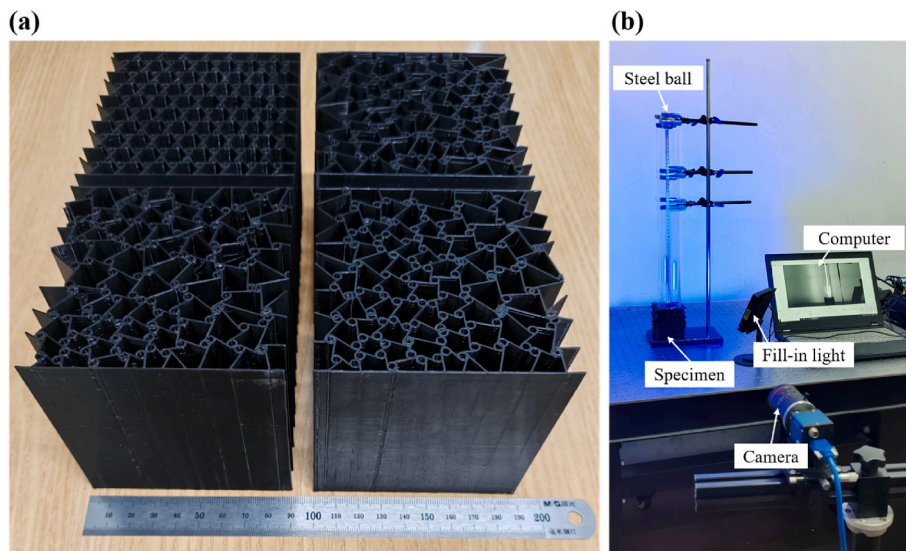


Fig. 7. Specimens and experimental platform for dynamic rebound tests. (a) Metamaterial specimens used for rebound testing: conventional trichiral metamaterial (upper left), Vorochiral metamaterial (upper right), BFG-VC metamaterial FG352035 (lower left), and BFG-VC metamaterial FG253035 (lower right). (b) Self-built low-velocity impact testing platform.

$$EDR = \frac{ED}{E_0} = \frac{Wh_0 - Wh_r}{Wh_0} = \frac{h_0 - h_r}{h_0} = 1 - \frac{h_r}{h_0}, \quad (7)$$

where W is the magnitude of the gravitational force (weight) acting on the steel ball, h_0 represents the initial height of steel ball, and h_r denotes the first rebound height.

3. Results and discussion

3.1. Experimental validation of FE model

The FE models were validated against the experimental results, by comparing both the stress-strain response and deformation behaviors of the BFG-VC metamaterials. As shown in Fig. 8(a) and (b), the stress-strain curves obtained from the FE simulations closely followed the overall trends of the experimental results for the BFG-VC metamaterials with different gradient distribution characteristics across three tested specimens. Minor discrepancies between the FE simulations and experimental results were observed, which can be primarily attributed to inevitable differences between the additively manufactured specimens and the idealized numerical models, including uncertainties in contact interactions, material parameters, and boundary conditions.

To quantitatively assess the agreement between the FE simulations and experimental results, the MCL and EA were compared. As summarized in Table 2 and Fig. 8(c)–8(f), the absolute deviations between FE results and the experimental results were within 9.05% for both gradient configurations, indicating good predictive accuracy of FE models. Furthermore, the deformation patterns of the BFG-VC metamaterials with different gradient distributions exhibited strong consistency between experimental observations and numerical simulation, as shown in Fig. 8(g). These results collectively demonstrated that the developed FE models were capable of reliably capturing both the mechanical response and deformation mechanisms of the metamaterials under quasi-static compression.

3.2. Quasi-static compression and energy absorption

The BFG-VC metamaterials exhibited significantly superior EA performance compared to Vorochiral metamaterials, in particular, substantially outperformed conventional trichiral metamaterial. To rigorously isolate the effect of gradient distribution on EA performance, key structural parameters of all metamaterials, including the degree of irregularity, the radius of nodal circles, and the relative density, were fixed at 0.4, 1.6 mm, and 20%, respectively. To account for the inherent randomness of Voronoi-based architectures and ensure reliability, six independent BFG-VC realizations were randomly generated for each gradient distribution configuration and evaluated for their EA capacities.

The EA values of Vorochiral, FG352035, and FG253035 were $13.51 \pm 2.27 \text{ kJ/m}^3$, $16.48 \pm 0.90 \text{ kJ/m}^3$, and $18.10 \pm 2.26 \text{ kJ/m}^3$, respectively, as shown in Table 3. Statistical analysis further confirmed significant differences among these configurations (one-way ANOVA, $p = 0.003$). Tukey's post hoc test indicated that both FG352035 and FG253035 exhibited significantly higher EA than the non-graded Vorochiral structure ($p < 0.05$), as shown in Table 3.

The BFG-VC metamaterials exhibited significantly higher EA and SEA compared to both conventional chiral and Vorochiral metamaterials, as summarized in Table 3 and Fig. 9(a). While Vorochiral metamaterials already demonstrated substantially improved EA relative to conventional trichiral metamaterials, the introduction of bioinspired functionally graded distributions led to a further and pronounced enhancement in EA . Specifically, the FG352035 and FG253035 configurations achieved improvements of 62.87% and 78.85%, respectively, in both EA and SEA compared to the conventional chiral metamaterial.

The enhanced EA and SEA performance of the BFG-VC metamaterials was primarily attributed to the incorporation of functionally graded distribution characteristics into the Vorochiral architectures. The strain at

the densification point ε_d is a critical indicator of EA , which is defined as the strain corresponding to the last local maximum of EAE , as shown in Fig. 10. The point marks the onset of densification, and the integral of the stress-strain curve up to ε_d represents the effective EA capacity of the structure.

As shown in Fig. 11(a), the uniform Vorochiral metamaterials exhibited a distinct multi-step plateau in their stress-strain response, reflecting a progressive cell collapse mechanism. In contrast, the BFG-VC metamaterials displayed stress-strain profiles with a well-defined, multi-step plateau characterized by an increased number of transitional stress fluctuations, as shown in Fig. 11(b) and (c). This specialized behavior stems from the layer-wise sequential triggering of distinct seed-point density domains, which governs a highly progressive deformation mode mediated by localized cell rotation. Consequently, the onset of densification was significantly delayed to a higher strain level for the BFG-VC metamaterials, thereby substantially expanding the effective plateau region and boosting the overall EA capacity.

In addition to ε_d , the MCL also plays a critical role in determining EA performance. As shown in Fig. 9(b) and (c), both the ε_d and MCL values of the BFG-VC metamaterials were markedly higher than those of the chiral and Vorochiral metamaterials, which collectively contributes to their superior EA capacity. A comprehensive comparison of the mechanical performance indicators is further provided by the radar diagram in Fig. 9(d), where a larger enclosed area corresponds to better overall performance. Although the enclosed area of Vorochiral metamaterial was obviously bigger than that of chiral metamaterial, the BFG-VC metamaterials clearly exhibited the larger enclosed areas, confirming their superior EA performance.

The EA capacity of Vorochiral metamaterials can be further enhanced by programming functionally graded distribution characteristics. The superior EA performance observed in the BFG-VC metamaterials, relative to both conventional chiral and non-graded Vorochiral metamaterials, was primarily attributed to the formation of a multi-step plateau with an increased number of stages in the stress-strain response. Structures exhibiting a greater number of plateau stages are known to process higher EA capacity, as widely reported in previous studies [58–62].

During compression, self-contact interactions within the structure significantly increased the local stress level, leading to the formation of successive local maxima in the EAE curve. The locations of these self-contact events are marked by red ovals in Fig. 11. Each additional self-contact interaction corresponded to the emergence of a new stress plateau stage in the stress-strain curve, thereby extending the effective EA process. By programming functionally graded distributions within the Vorochiral architecture, the number of such self-contact-induced plateau stages was increased, resulting in enhanced EA capacity for BFG-VC metamaterials.

Moreover, distinct deformation sequences and stress distributions were observed for the two gradient configurations. In the FG352035 structures, deformation initiated in the second layer and was subsequently followed by simultaneous deformation of the first and third layers. In contrast, the FG253035 structures exhibited a more orderly and progressive deformation mode, with deformation propagating sequentially from the first layer to the third layer, as shown in Fig. 8(e). A monotonic functional gradient distribution might have more potential in promoting progressive collapse and maximizing EA in Vorochiral metamaterials. Additionally, the incorporation of bioinspired functionally graded characteristics endowed the Vorochiral metamaterials with the capability to deliberately program stress distributions at low strain levels, as illustrated in Fig. 12. Through architectural design of relative density across different layers, the applied load was preferentially accommodated by the low-relative-density layer during the early stages of deformation. In contrast, the chiral and non-graded Vorochiral metamaterials exhibited a globally distributed stress field, indicating a more homogeneous engagement of the entire structure. The pronounced stress localization observed in the BFG-VC metamaterials highlighted the

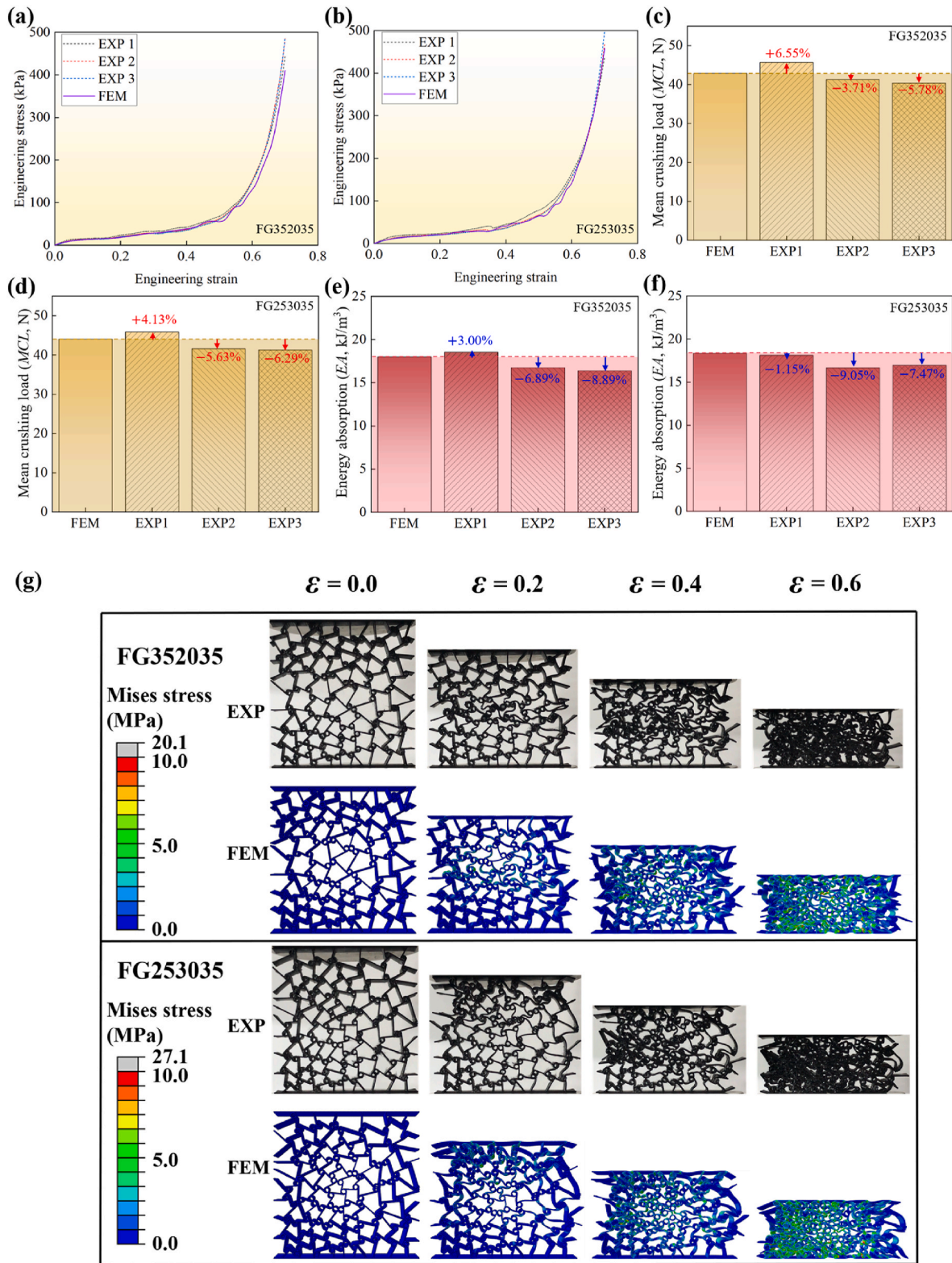


Fig. 8. Comparison between experimental tests and FEM. (a) Stress-strain curves of the BFG-VC metamaterial FG352035. (b) Stress-strain curves of the BFG-VC metamaterial FG253035. (c) Mean crushing loading (MCL) of the BFG-VC metamaterial FG352035. (d) MCL of the BFG-VC metamaterial FG253035. (e) Energy absorption (EA) of the BFG-VC metamaterial FG352035. (f) EA of the BFG-VC metamaterial FG253035. (g) Comparison of deformation behaviors of the two BFG-VC metamaterials.

effectiveness of the bioinspired functional gradient in guiding local deformation pathways and tailoring the overall mechanical response. Overall, the BFG-VC metamaterials demonstrated a tunable stress-

deformation behavior enabled by bioinspired functional gradient, rather than a uniformly distributed mechanical response inherent to conventional chiral architectures.

Table 2

Energy absorption (EA) and mean crushing load (MCL) of BFG-VC metamaterials obtained from three experimental tests and FEM.

Indicator	FG352035		FG253035	
	FEM	EXP	FEM	EXP
MCL (N)	42.88	42.46 ± 2.83	44.05	42.91 ± 2.57
EA (kJ/m ³)	17.99	17.22 ± 1.15	18.34	17.26 ± 0.77

Table 3

Energy absorption (EA) and specific energy absorption (SEA) of different metamaterials under quasi-static compression obtained from FE results.

Types	EA (kJ/m ³)	SEA (J/kg)	p-value
Chiral	10.12	41.48	
Vorochiral	13.51 ± 2.27 (+ 33.50%)	55.35 ± 9.30 (+ 33.50%)	
FG352035	16.48 ± 0.90 (+ 62.87%)	67.56 ± 3.70 (+ 62.87%)	0.043*
FG253035	18.10 ± 2.26 (+ 78.85%)	74.16 ± 9.28 (+ 78.85%)	0.002**

Note: “+” represents the enhancement compared to “chiral”, respectively. Values for Vorochiral, FG352035, and FG253035 represent mean ± SD calculated from six independent random numerical realizations. The conventional chiral metamaterial is a deterministic periodic reference model and is therefore reported as a single numerical value. Tukey's honestly significant difference post hoc test for comparisons of the non-graded Vorochiral metamaterials with two BFG-VC metamaterials. * $p < 0.05$, and ** $p < 0.01$.

The enhanced EA capability of the BFG-VC metamaterials originates from the synergistic effects of spatially regulated topology and gradient deformation behavior. Unlike the non-graded Vorochiral structure,

where deformation is relatively concentrated within several critical ligaments after initial instability, the gradient configurations promote a sequential collapse process from the compliant regions toward the denser regions. This layered deformation mode delays the occurrence of global densification and maintains a relatively stable load-bearing response over a broader strain range. Consequently, more structural regions participate in progressive deformation, leading to an increase in the area enclosed by the stress-strain curve and thus EA capacity was improved.

3.3. Low-velocity impact response and energy dissipation

The experimental results from dynamic rebound tests confirmed the superior ED performance of the Vorochiral-based metamaterials compared to the conventional chiral metamaterial. Low-velocity impact experiments were conducted using a free-falling steel ball on a self-built testing platform. In these experiments, the rebound height of the steel ball was adopted as a qualitative indicator of ED capacity, where a lower the initial rebound height corresponded to higher ED by the structure. It should be noted that the variability shown in the dynamic rebound results represents the repeatability of repeated impacts on the same fabricated specimen rather than variations among independent specimens.

As shown in Fig. 13(a), the steel ball may exhibit slight lateral deviation during rebound. However, the deviation angle was small, and its influence on the measured rebound height was considered negligible. As shown in Fig. 13(b), the BFG-VC metamaterials generally exhibited lower rebound heights than the conventional chiral metamaterial for all three steel-ball masses, indicating greater impact ED under the adopted testing conditions. For each structural configuration and impact mass,

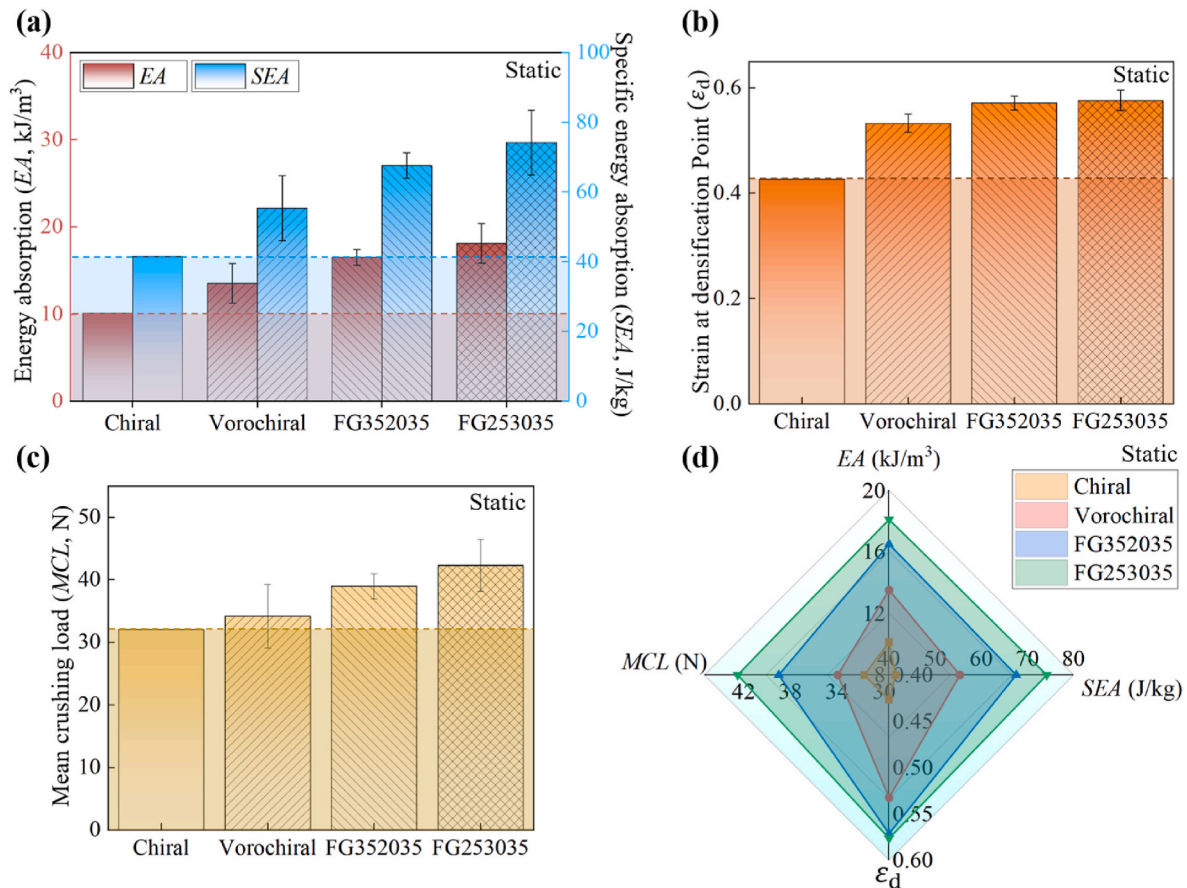


Fig. 9. Mechanical performance indicators of metamaterials with different configurations under quasi-static compression. (a) Energy absorption (EA) and specific energy absorption (SEA). (b) Strain at the densification point (ϵ_d). (c) Mean crushing load (MCL). The error bar for the chiral structure is zero because its geometry is deterministic. (d) Radar diagram summarizing the overall mechanical performance indicators.

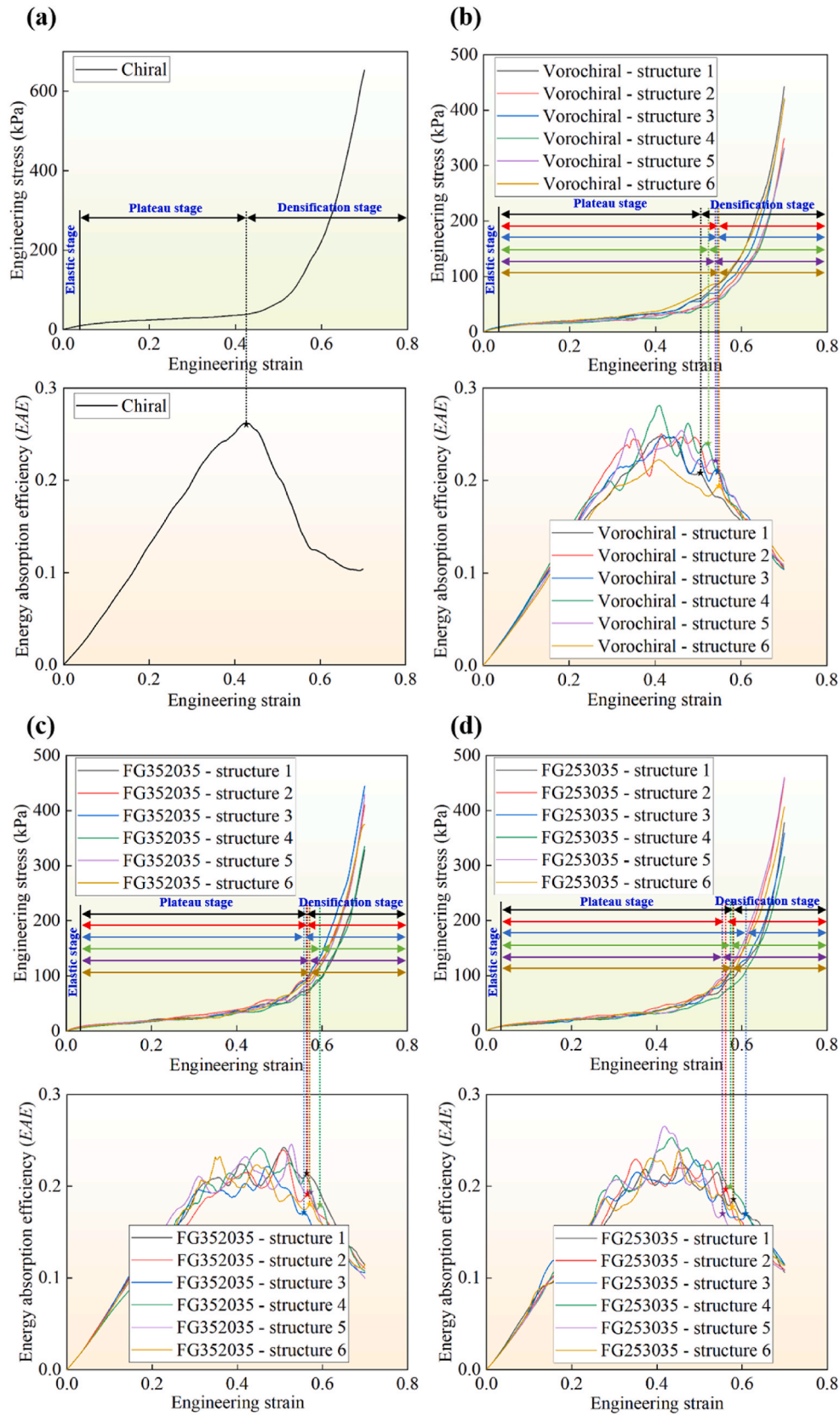


Fig. 10. Stress-strain curves and corresponding energy absorption efficiency (EAE) curves of different metamaterials under quasi-static compression. (a) Chiral metamaterial. (b) Vorochiral metamaterials. (c) BFG-VC metamaterial FG352035. (d) BFG-VC metamaterial FG253035. Colored stars symbols indicate the last local maximum values of the EAE curves, corresponding to the densification strain for each structure.

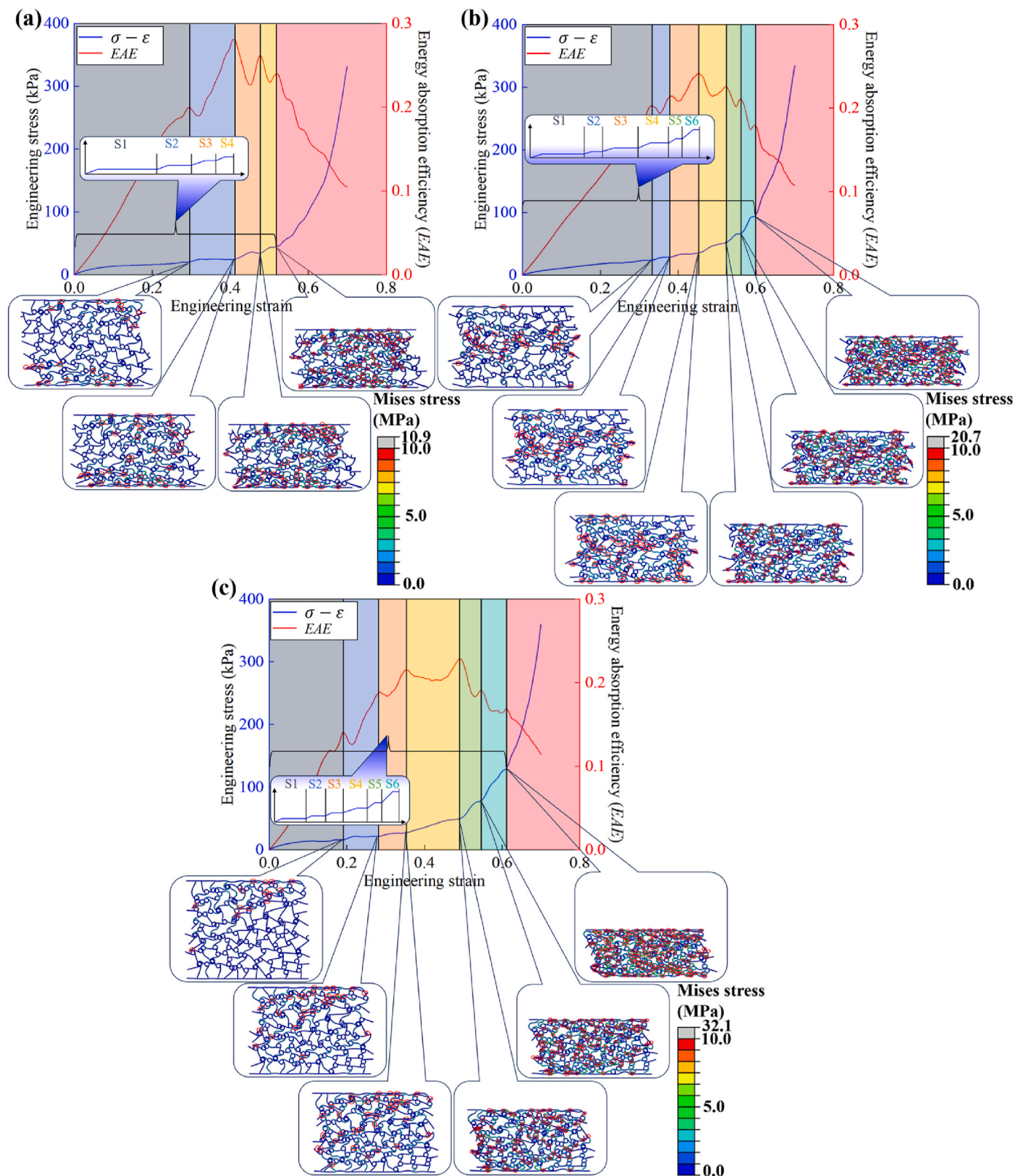


Fig. 11. Stress-strain curves, energy absorption efficiency (EAE) curves, and deformation modes with self-contact interactions of the Vorochiral metamaterial and BFG-VC metamaterials under quasi-static compression. (a) Vorochiral metamaterial (structure 4). (b) BFG-VC metamaterial FG352035 (structure 4). (c) BFG-VC metamaterial FG253035 (structure 3). Red ovals indicate the locations of successive self-contact interactions corresponding to the formation of individual stress plateau stages.

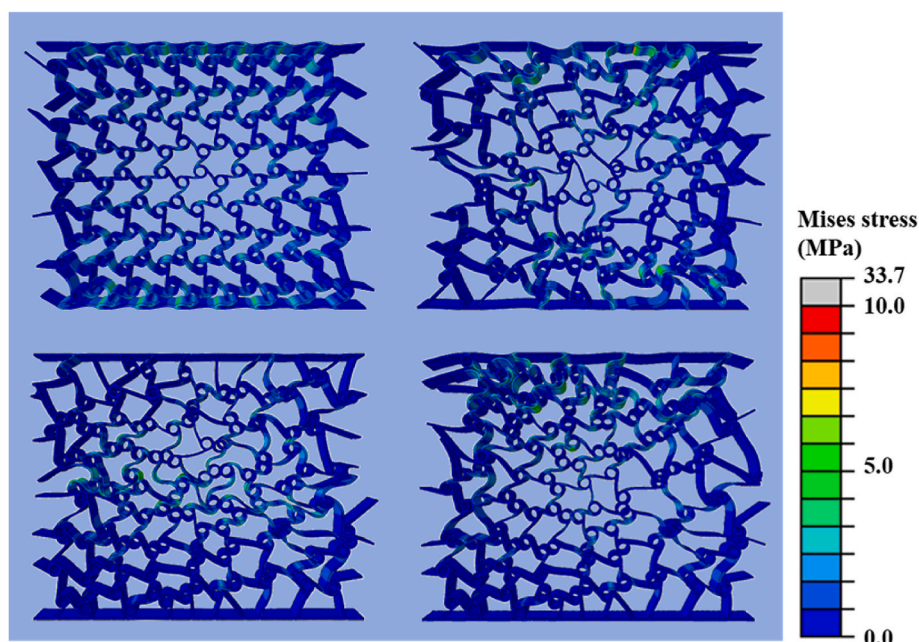


Fig. 12. Comparison of stress distribution among different metamaterials at a strain of 0.2: conventional trichiral metamaterial (upper left), Vorochiral metamaterial (upper right), BFG-VC metamaterial FG352035 (lower left), and BFG-VC metamaterial FG253035 (lower right).

the results were obtained from ten repeated rebound measurements on the same physical specimen and are presented as mean $\pm$ SD. The corresponding 95% CI of the mean EDR values are provided in [Supplementary Table S1](#). As summarized in [Table 4](#) and [Supplementary Table S1](#), the BFG-VC metamaterials exhibited higher EDR values than the conventional chiral and non-graded Vorochiral metamaterials across the tested impact conditions, demonstrating enhanced dynamic ED performance under the adopted rebound conditions. The EDR obtained from rebound-height measurements represents an effective ED metric, where minor energy losses from air resistance, lateral motion, and fixture compliance cannot be completely excluded. Since all specimens were tested under identical conditions, these factors are expected to have comparable effects on different configurations and thus have limited influence on the comparative evaluation. Future studies incorporating force-time or force-displacement measurements will enable a more detailed energy balance analysis.

These results demonstrate that BFG-VC metamaterials exhibit enhanced ED performance under the adopted rebound impact conditions. The improved EDR is attributed to the spatially regulated topology and progressive deformation characteristics of the gradient structures. It should be noted that the rebound tests were designed as a comparative evaluation of the dynamic ED behavior among different architectures rather than a comprehensive characterization of impact performance under various loading conditions. The measured EDR depends on the adopted impact velocity, specimen configuration, material properties, and testing setup. Therefore, the present results should be interpreted as demonstrating the relative advantages of the proposed gradient topology under the investigated impact conditions, rather than representing a universal impact response across different loading regimes.

The enhanced ED capability of BFG-VC metamaterials can be attributed to the synergistic effects of gradient topology and deformation regulation. Unlike uniform structures, the spatial gradient configuration introduces heterogeneous deformation characteristics within the metamaterial, enabling sequential activation of different regions during impact loading. The relatively sparser regions initially deform to absorb the impact energy, while the denser regions provide progressive resistance and prevent premature structural collapse. This progressive deformation process extends the deformation duration and promotes a more distributed ED pathway. Furthermore, the Vorochiral topology

contributes to ED through the coupled deformation mechanisms of ligament bending, node rotation, and structural interaction. During compression and rebound processes, the rotation and bending of ligaments induce repeated internal deformation, while possible self-contact between adjacent structural members further dissipates impact energy. Additionally, the gradient topology regulates the deformation sequence and local strain distribution, enabling more effective utilization of the intrinsic deformation capability of the TPU material without increasing material volume. Therefore, the enhanced ED capability of BFG-VC metamaterials is mainly attributed to the gradient-induced progressive deformation and optimized ED pathways.

Although functionally graded metamaterials have demonstrated great potential for tailoring mechanical responses through spatial variations in material composition or structural parameters, most existing designs rely on conventional periodic lattice architectures and primarily regulate mechanical behavior through soft-hard transitions. Such approaches may provide limited flexibility in controlling deformation pathways, because the underlying topology remains relatively uniform. In contrast, the proposed BFG-VC metamaterials integrate stochastic Vorochiral topology with functional gradient regulation, introducing an additional degree of freedom for mechanical performance optimization. By controlling the spatial distribution of Voronoi seed points, the local relative density can be tailored while preserving the intrinsic chiral deformation mechanism. This enables simultaneous regulation of load-transfer pathways, deformation localization, and progressive collapse behavior, which cannot be readily achieved by conventional functionally graded structures. Therefore, BFG-VC metamaterials provide a distinct design strategy beyond traditional soft-hard gradient architectures for achieving lightweight structures with enhanced EA and ED capability.

It should be noted that, for computational simplicity, the TPU material was modeled as a hyperelastic material in the present finite element analysis. In reality, TPU exhibits viscoelastic and rate-dependent behavior, particularly under dynamic loading. In our previous study using the same TPU material, tensile tests were performed under different low strain rates, and the corresponding stress-strain curves showed relatively small differences within the investigated range. This result indicates that the rate effect of TPU is limited under low-speed loading conditions, supporting the adoption of a hyperelastic

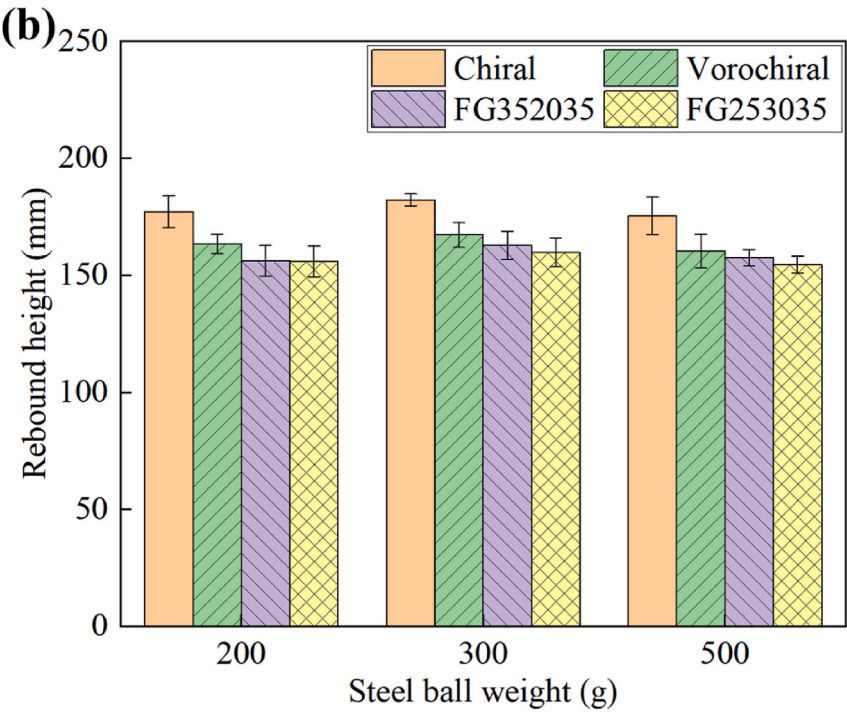
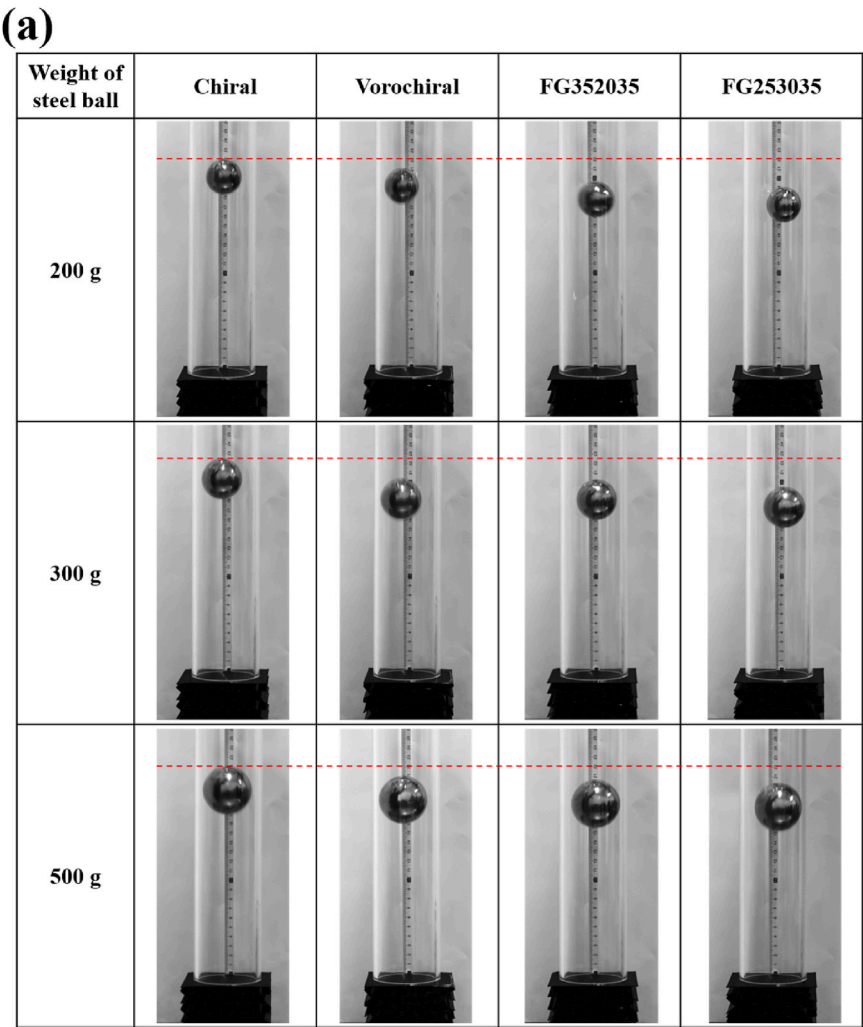


Fig. 13. Experimental evaluation of dynamic rebound tests. (a) Free-falling impact testing using steel balls. (b) Rebound heights of steel balls with different masses for various metamaterial configurations. Error bars represent standard deviations calculated from ten repeated rebound measurements on the same physical specimen.

Table 4

Energy dissipation ratio (EDR) of different metamaterials under impact loading.

Types	200 g steel ball	300 g steel ball	500 g steel ball
Chiral	64.56% ± 1.45%	63.56% ± 0.54%	64.94% ± 1.69%
Vorochiral	67.30% ± 0.87% (+ 4.24%)	66.56% ± 1.12% (+ 4.72%)	67.94% ± 1.55% (+ 4.62%)
FG352035	68.78% ± 1.42% (+ 6.54%)	67.44% ± 1.27% (+ 6.10%)	68.50% ± 0.74% (+ 5.48%)
FG253035	68.82% ± 1.38% (+ 6.60%)	68.06% ± 1.28% (+ 7.08%)	69.10% ± 0.78% (+ 6.41%)

Note: “+” represents the enhancement compared to “chiral”, respectively. Values are presented as mean ± SD based on ten repeated rebound tests conducted on the same physical specimen for each structural configuration and impact mass.

model calibrated from quasi-static data for the present simulations. However, the mechanical response of TPU may vary with increasing strain rate, and its behavior under impact loading may differ from that under quasi-static conditions. Therefore, the dynamic rebound results should be interpreted considering the intrinsic rate sensitivity of TPU. In the present study, the dynamic rebound tests were designed to compare the relative ED performance of different structural configurations rather than to characterize the intrinsic rate-dependent behavior of TPU. All specimens were fabricated using the same TPU material and tested under identical specimen dimensions, relative density, and rebound conditions, with the same testing procedure applied to each configuration. Therefore, the material-related rate-dependent effect was consistently involved in all structural comparisons. Nevertheless, local strain-rate histories may differ among different topologies due to their distinct deformation patterns. Accordingly, the present dynamic results represent a comparative evaluation under the adopted impact conditions, rather than a rate-independent characterization or a direct extrapolation to a broader range of loading rates.

A slight lateral deviation of the steel ball was occasionally observed during rebound. However, the rebound trajectory remained nearly vertical, and the influence of this deviation on the measured rebound height is expected to be negligible. Assuming that the actual rebound trajectory forms an angle θ with the vertical direction, the measured vertical height can be expressed as $h_r = h \cos \theta$, where h is the actual rebound height along the trajectory. The corresponding relative deviation in rebound-height measurement is therefore $1 - \cos \theta$. Even for a deviation angle of 5° , this deviation is only approximately 0.38%, indicating that a small lateral deviation has a negligible influence on the rebound-height measurement.

The specimens used for the dynamic rebound tests had a larger out-of-plane thickness compared with those used in the quasi-static compression tests. This modification was introduced to improve the out-of-plane stability of the specimens during impact loading and to ensure reliable contact between the steel ball and the specimen surface. Despite the difference in out-of-plane dimensions, the in-plane structural topology, gradient distribution strategy, relative density, and constituent TPU material were maintained identical for all configurations. Therefore, the rebound tests were designed to comparatively evaluate the relative ED performance induced by different structural architectures under the same impact conditions, rather than to directly compare the absolute mechanical responses obtained from quasi-static compression and impact tests.

Overall, the impact test results provided direct evidence that the programming BFG distributions within Vorochiral metamaterials effectively enhanced their ED capacity under impact loading.

3.4. Potential biomedical and engineering applications

Based on the superior mechanical performance demonstrated in this study, extensive application potential is envisioned for the proposed BFG-VC metamaterials across various scenarios, with particular emphasis on the field of biomedical engineering. Biological tissues generally exhibit heterogeneous architectures with spatially varying mechanical properties, enabling efficient load transfer and mechanical adaptation. Inspired by this principle, the BFG-VC metamaterials introduce spatial regulation of topology and local relative density to achieve controllable mechanical responses while maintaining lightweight characteristics. Such a gradient design strategy may provide potential opportunities for biomedical applications requiring locally tailored mechanical properties. For example, when combined with advanced additive manufacturing and patient-specific design approaches, BFG-VC architectures can offer a promising route for developing customized orthotic components, such as diabetic foot offloading insoles or midsoles, as shown in Fig. 14(a), where regional stiffness regulation and stress redistribution are critical [63]. Similarly, the heterogeneous porous characteristics of BFG-VC structures may provide inspiration for the design of bone scaffolds with spatially adjustable mechanical environments, as shown in Fig. 14(b). Nevertheless, further studies involving biological compatibility, cell response, and application-specific optimization are required before clinical translation. Beyond biomedical applications, BFG-VC structures also exhibit promising potential in aerospace, automotive, and marine engineering applications, where lightweight structures with controllable deformation and impact resistance are highly desirable. In aerospace systems, the proposed metamaterials could serve as lightweight energy-absorbing cores for sandwich panels, impact-resistant components, and protective structures, where spatially regulated mechanical properties may enable efficient load redistribution and damage mitigation, as shown in Fig. 14(c). In automotive engineering, BFG-VC architectures may provide new design opportunities for crashworthy components, such as crash boxes, bumper systems, and battery protection structures, by tailoring local stiffness and deformation sequences to achieve progressive EA while reducing structural weight, as shown in 14(d). Compared with conventional homogeneous lattice or cellular metamaterials, which generally exhibit relatively uniform mechanical responses, BFG-VC metamaterials introduce spatially tunable topology and local relative density variations, enabling customized deformation pathways and application-specific mechanical performance. Overall, it is anticipated that the development of next-generation customized, high-performance structural components will be significantly propelled by the integration of BFG design strategies with advanced 3D printing technologies.

3.5. Limitations of the study

Although the BFG-VC metamaterials demonstrated superior synergistic energy absorption and dissipation performance compared to conventional chiral metamaterial, several limitations of the present study should be acknowledged. First, although the two investigated gradient configurations (FG352035 and FG253035) represent typical density redistribution strategies, they do not cover the entire design space of possible gradient configurations. Other gradient patterns with different magnitudes, spatial directions, layer number and seed-point distribution strategies may further expand the design space of BFG-VC metamaterials. Future studies could systematically investigate the relationship between seed-point-controlled gradient characteristics and mechanical responses. Additionally, introducing gradients in other geometric parameters, such as wall thickness and nodal circle radius,

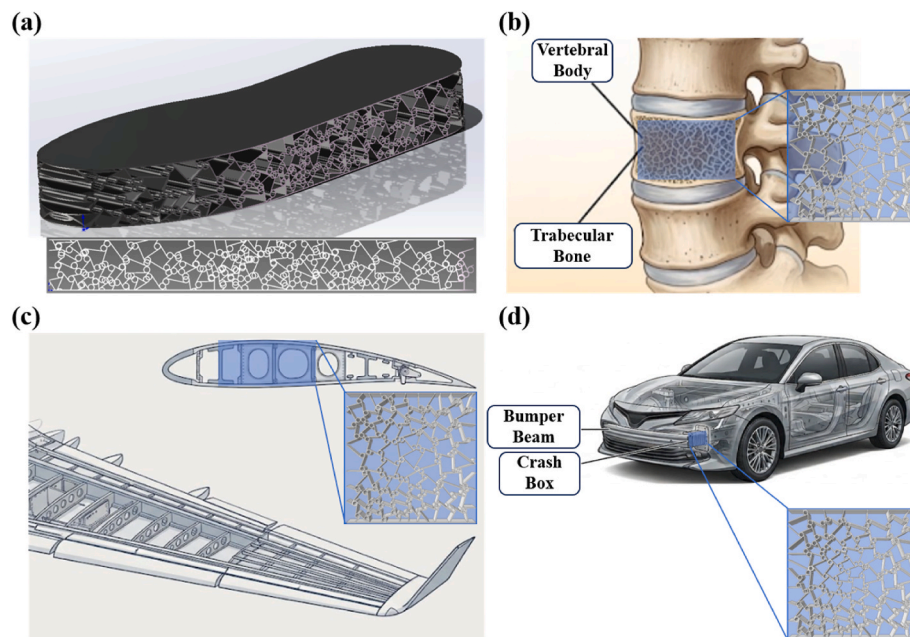


Fig. 14. Potential applications of bioinspired functionally graded Vorochiral metamaterials. (a) Customized diabetic foot insole or midsole for plantar pressure modulation. (b) Bone implant for bone defect repair. (c) Lightweight filling structure in aircraft wings for enhanced structural efficiency. (d) Energy-absorbing crash box for automotive crash protection.

represents another promising direction for further enhancing the *EA* and *ED* capacities of Vorochiral-based metamaterials. Second, although the BFG-VC metamaterials exhibited enhanced *ED* performance under low-velocity impact conditions, the effect of varying low-velocity impact speeds was not systematically investigated. A detailed parametric study on the relationship between impact velocity and *ED* capacity would provide deeper insight into the rate-dependent behavior of BFG-VC metamaterials. Third, previous studies have confirmed that FDM can provide acceptable dimensional accuracy for lattice structures. However, the fabricated relative density and local material distribution were not directly measured in the present study. Future work should further quantify the CAD-to-printing deviation through three-dimensional scanning, mass measurement, and microstructural characterization to establish a more rigorous relationship between designed and fabricated architectures. Finally, while the initial single-impact dynamic dissipation shows promising results for protective gear, comprehensive cyclic loading and fatigue tests (e.g., Mullins effect evaluation) are required in future work to fully validate their long-term durability for specific applications such as helmet liners and insoles.

4. Conclusions

In this paper, BFG-VC metamaterials were successfully developed by introducing nature-inspired distributions into chiral networks, unlocking the superior synergistic energy absorption and dissipation performance. The *EA* performance and deformation behaviors of the proposed metamaterials were systematically investigated under both quasi-static compression and impact loading conditions. FE models were developed and validated through experimental testing, and dynamic rebound experiments were conducted to assess the *ED*. The main conclusions can be summarized as follows.

- (1) The BFG-VC metamaterials exhibited significantly higher quasi-static *EA* capacity than both chiral and non-graded Vorochiral metamaterials. Specifically, the FG253035 configurations achieved improvements of 78.85%.
- (2) Compared with chiral and Vorochiral metamaterials, the BFG-VC metamaterials displayed an increased number of stress plateau,

which is attributed to more progressive deformation and more effective *EA*.

- (3) The BFG-VC metamaterials demonstrated a tunable stress-deformation behavior enabled by bioinspired functionally graded characteristics.
- (4) Under low-velocity impact loading, the BFG-VC metamaterials demonstrated superior *ED* capacities by dynamic rebound experiments.

Overall, the proposed BFG-VC metamaterial provides a distinct functional-gradient design strategy by integrating spatially tailored gradients with the heterogeneous and non-periodic Vorochiral topology. Unlike conventional functionally graded auxetic and chiral metamaterials that primarily rely on geometric or relative-density variations within periodic architectures, the present approach enables simultaneous regulation of structural topology and local relative density, offering an additional route for controlling deformation localization, *EA* and *ED*. Importantly, these performance enhancements are realized while maintaining a constant volume fraction, addressing a challenge in metamaterial design. Therefore, this superior synergistic static-dynamic performance demonstrates that the spatial modulation of Vorochiral architectures provides a highly effective design paradigm for advanced applications.

Data availability

The data supporting the numerical results in this study is available from the authors upon reasonable request.

Declaration of competing interest

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jmrt.2026.10.071>.

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