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A novel 3D-printed unit cell with the compression-torsion coupling effect and negative Poisson's ratio

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Abstract

Metamaterials have received extensive research interests since they can be artificially designed to achieve unprecedented material properties beyond what we can obtain from the nature. As such, it is widely acknowledged that metamaterials have great potential application perspectives in many areas, e.g., mechanical engineering, civil engineering, aerospace, biomedical engineering, etc. Recently, mechanical metamaterials that are designed based on multi-functional properties or behaviours have received much attention due to the increasing demands of new materials with superior properties. Inspired by the grasshopper's leg, this paper proposes a novel unit cell where 3D 'zig-zag' rods are introduced to connect the circular planar elements. The mechanical behaviours of this novel unit cell under axial compression are studied both experimentally and numerically. In particular, the effect of different geometric parameters of the 3D 'zig-zag' rod on both compression-torsion coupling (CTC) and negative Poisson's ratio (NPR) are studied for this novel unit cell. Compared with previous designs, the novel unit cell proposed in this work can improve the design flexibility, achieve large NPR, strong CTC, and high load-carrying capacity, simultaneously. Finally, this work can provide some references for designing novel metamaterials with multiple deformation mechanisms.

Keywords: Compression-torsion coupling, Negative Poisson's ratio, Metamaterials, 3D-printing

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1. Introduction

The artificially-designed mechanical metamaterials have attracted great research interests due to their ability to achieve unusual properties, such as negative stiffness [1], tension-torsion coupling (i.e., compression-torsion coupling) [2], negative Poisson's ratio (NPR) [3], negative compressibility [4], and negative thermal expansion [5], etc. These metamaterials have been applied in many areas, for example auxetic metamaterials with NPR have been widely applied for impact shields, energy absorbers, sensors, cardiovascular stents [6–9], and aircraft morphing structures [10]. The negative compressibility metamaterial has an application in extremely sensitive pressure detectors [11], the metamaterial with compression-torsion coupling (CTC) provides a great opportunity for mechanical cloaking [12, 13], displacement-rotation conversion [14–16], energy absorbers [17, 18], and vibration isolation [19], etc. With the development of advanced 3D/4D-printing technologies, a large variety of metamaterials with distinct mechanical or physical properties, e.g., programmable stiffness [20], controllable anisotropy [21], and intelligence [22, 23], have been developed thrivingly, which will meet the increasing demands from various industrial sectors, e.g., mechanical engineering, civil engineering, aerospace, and biomedical engineering [24–26].

Mechanical or deformation mechanisms, e.g., Poisson's ratio effect, elastic instability, compression-torsion coupling, etc., provide extensive means for designing metamaterials to achieve desired and unprecedented properties. Yao et al. [27] demonstrated, both theoretically and experimentally, a transition between anticlastic and synclastic bending curvatures for 2D lattices with star-shaped unit cells when bent in one direction, which breaks away from the usual understanding. Nevertheless, this deformation mechanism enables an independent design of in-plane and bending Poisson's ratios for lattice structures, which may benefit many engineering applications, e.g., shape shifting. Guo et al. [28] studied the auxetic metamaterials reinforced by origami graphene, which can effectively manipulate elastic waves. Bhullar et al. [29] demonstrated that the metamaterial structure made of rotating squares with circular holes that possess enhanced mechanical properties through tailored NPR can be well applied in the stents because of its unique deformation mechanism and lightweight properties. In recent years, the metamaterials with coupling deformation mechanism, such as compression-twisting, bending-twisting, and tension-twisting coupling, have received much attention due to its applications in morphing blades [30].

Chiral structures, as a class of NPR metamaterials, usually are used to drive and design special deformation mechanisms, e.g., the CTC effect. Fig. 1 illustrated some typical metamaterials that are driven by the CTC effect. Frenzel et al. [2] first discovered the unique tension-twist coupling effect and applied it to design 3D chiral metamaterials. Ebrahimi et al. [31] proposed a type of 3D anti-chiral metamaterials, in which oblique

load-bearing ligaments are used to link the topology circular elements, resulting in the CTC effect and a large range of NPRs. Duan et al. [32] introduced a new type of 3D chiral lattices with the CTC effect and developed a homogenization method to study the relationship between the elastic constant and geometry parameters. Zheng et al. [33] investigated the size effect of 3D anti-chiral structure metamaterials with tension-torsion coupling, both experimentally and numerically. Farrell et al. [34] proposed an auxetic structure with the extension-twisting coupling and developed an analytical model to characterize its non-linear twist-deformation relationship. Lemkalli et al. [35] analyzed the twisting behavior of a new chiral metamaterial theoretically and numerically and demonstrated its substantially superior twisting behavior. For the 3D unit cell proposed by Ebrahimi et al. [31], Yang et al. [36] derived its stiffness matrix and studied its CTC effect. The research works in [2], [33], [35], [37] demonstrated that the CTC effect will be gradually diminished with the increase of the cell number, which means that the twisting effect is unscalable in such designs. To achieve a scalable twisting effect, Xu et al. [38] developed a general design rule and analyzed the relationship between microscale geometry and twisting effect using the screw theory. Chen et al. [39] proposed a 3D metamaterial with compression-twist coupling effect and explored the relation between compression-twist coupling effect and geometric parameters detailedly.

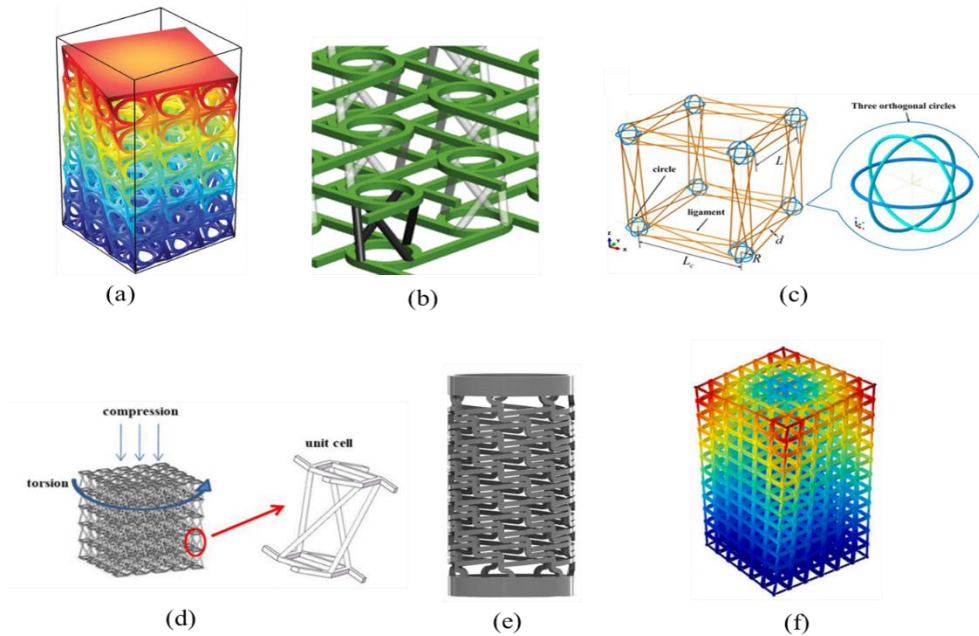


Fig. 1. Different metamaterials with CTC effect: (a) 3D chiral mechanical metamaterials [2], (b) 3D anti-chiral structure [31], (c) 3D chiral lattice [32], (d) 3D anti-chiral structure with square loops [33], (e) a rolled cylindrical shell [34], and (f) the structure consisted of cubic unit cell with perforated edges [35].

Up to now, many innovative design strategies of metamaterials have been proposed, including the unique

node design [31], hierarchical design [40], re-entrant design [41], chiral design [42], programmable design [43], bio-inspired design [44], origami design [45], and kirigami design [46], etc. Based on the principles of differential stiffness and self-contacting hard stops, Farzaneh et al. [47] introduced a new concept to design metamaterials with desired Poisson's ratios. In most of previous works, only single deformation mechanism, e.g., NPR [41, 47] or CTC [2, 35], was applied to design the metamaterials. However, applying multiple deformation mechanisms to design metamaterials is also attractive, as it provides much more design options to achieve unprecedented properties and behaviours [48]. 3D metamaterials with multiple deformation mechanisms, such as CTC effect and NPR, have been designed [49, 50]. Tang et al. [51] developed a theoretical model to guide the design of Young's modulus and Poisson's ratio of 2D chiral and anti-chiral structures by tuning the tension-torsion coupling effect. Cui et al. [52] designed and fabricated a 3D unit cell with multiple deformation mechanisms (CTC effect and NPR). Duan et al. [53] developed a new method to design the desirable positive and negative Poisson's ratio material utilizing the tension-twist coupling effect.

In this paper, a novel unit cell with 3D 'zig-zag' rods inspired by the grasshopper's leg is proposed and designed. This novel unit cell presents both CTC effect and NPR due to the 3D 'zig-zag' rods. Firstly, the novel unit cells with different geometric parameters are fabricated by 3D printing. Both experimental testing and finite element analysis (FEA) are carried out to study the deformation mechanisms of those different unit cells. Moreover, the effects of different geometric parameters on the deformation mechanism and load carrying capacity are investigated systematically. The results show that the ability of tuning the NPR of this proposed novel unit cell is improved obviously compared with the traditional unit cell with the CTC effect [31, 33]. In addition, the load carrying capacity of this unit cell is also enhanced.

2. Methodologies

2.1 Proposed geometry of novel unit cell

Studies in the field of biomechanics have shown that the zig-zag shape of grasshopper's leg has distinct advantages in movement, structure, and material. Following good mechanical properties of grasshopper's leg have been reported: (1) The flexible hind leg of grasshopper is the key to control the elevation and speed of jump due to its strong contraction and good jumping ability [54, 55]; (2) The grasshopper's leg acts as a natural shock absorber, dissipating the impact force generated during jumping or landing [56]; (3) The grasshopper's leg can reduce energy loss and convert the stored energy to kinetic energy when jumping [57]. Inspired by the above advantages of the zig-zag shape of the grasshopper's leg, in particular the energy dissipation mechanism and the strong contraction, the 3D unit cell with 'zig-zag' rods is proposed to obtain the compression-torsion

coupling (CTC) and negative Poisson's ratio (NPR), simultaneously, for meta-structures. Fig. 2 describes the FEA model of this 3D unit cell. As shown in Fig. 2(a), this FEA model is composed of top and bottom circular loops and four evenly distributed rods around the loops. Inspired by the three joints of grasshopper's leg, each rod is designed in a 3D 'zig-zag' form which is determined by three non-colinear key nodes. Fig. 2(b) presents the sketch of top view for this unit cell, it is seen that the top, middle, and bottom key nodes of the four 3D 'zig-zag' rods are concyclic, respectively. The parameter λ is the radius angle between the bottom and middle nodes for each 3D 'zig-zag' rod. r_1 and R are the radii of the circle consisted of four middle nodes, and the circular loops, respectively.

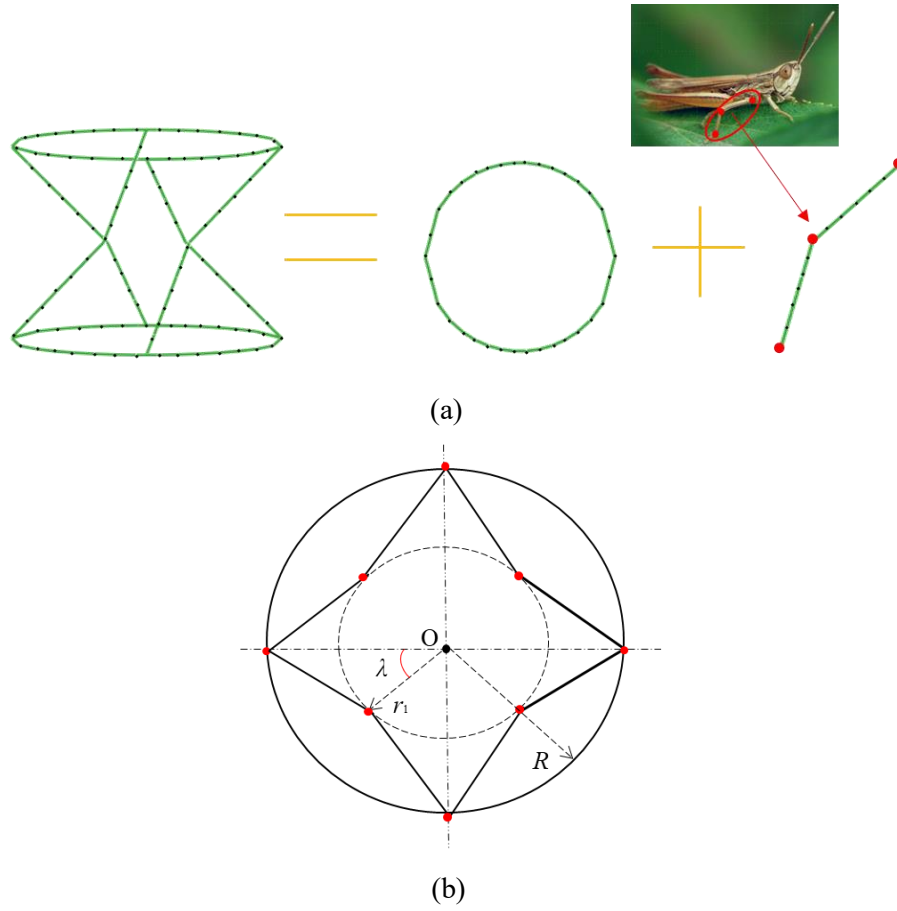


Fig. 2. The novel unit cell: (a) FEA model, and (b) sketch of top view.

The experimental models of this novel unit cell and the traditional unit cell without the 'zig-zag' rods design are shown in Figs. 3(a) and 3(b), respectively. The red points located at the centre line of the solid rods as shown in Fig. 3(a) are the corresponding nodes of the FEA structure in Fig. 2(b). The parameters H and d are the thicknesses of the unit cell and circular loop, respectively. r_0 is the radius of the rod. The width of circular loop is t , $t = 2r_0$. With the same size, Fig. 3(b) presents the side and top views of traditional unit cell

without the ‘zig-zag’ rods design. As it was studied in references [31] and [58], its CTC effect and NPR can be tuned by the oblique angle φ of the inclined rod.

To obtain a better understanding of the coupling relation between CTC effect and NPR of the novel unit cell with 3D ‘zig-zag’ rods, the twist deformation under uniaxial compression is derived. It is assumed that the four 3D ‘zig-zag’ rods have the same deformation mechanism and rotation direction, and the two circular loops are rigid. In fact, Fu et al. [58] had illustrated that the base material of loops had a negligible influence on the results for the traditional unit cell.

Taking one ‘zig-zag’ rod as an example, the theoretical model of the unit cell is presented in Fig. 4. In Fig. 4(a), the broken lines EBA and EB_1A_1 denote the 3D ‘zig-zag’ rods before compression and after compression, respectively. The reference lines EA and EA_1 denote the corresponding straight rods before compression and after compression, respectively. l_1 , l_2 , and l are the lengths of the ‘zig-zag’ rods and straight rods. ψ is the angle between the two parts of the ‘zig-zag’ rod, and α is rotation angle of the node A. Under a small compression displacement h , the motion track $\overline{AA_1}$ of the top node A is expressed as

$$\overline{AA_1} = \sqrt{(R\alpha)^2 + h^2}. \quad (1)$$

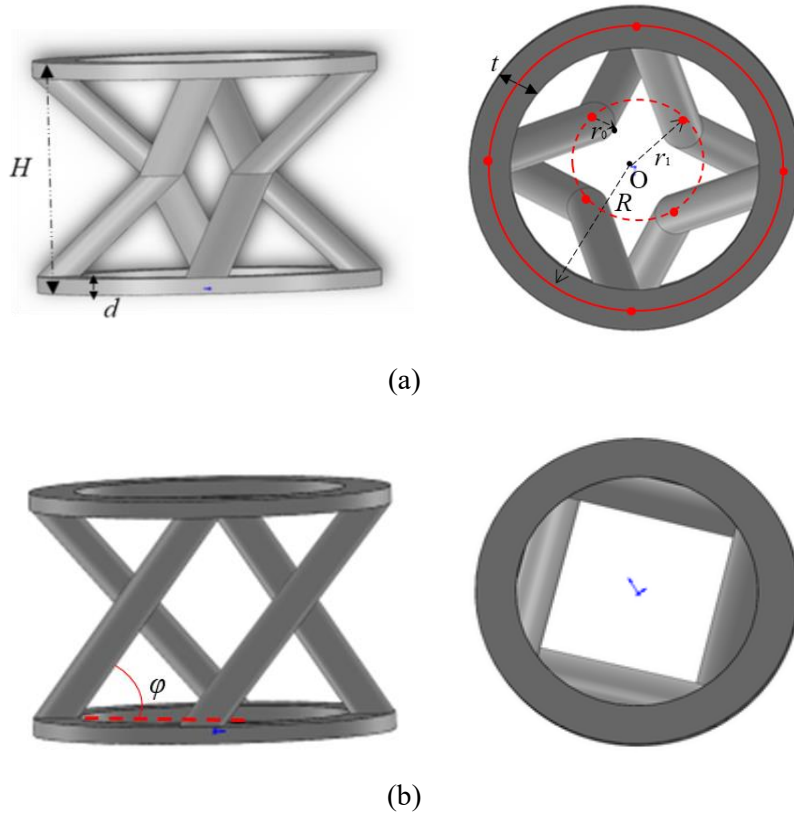


Fig. 3. Experimental models of unit cells under side and top views: (a) novel unit cell, and (b) traditional unit cell.

From the geometry of the unit cell as illustrated in Fig. 4(a), the formula for $\overline{AA_1}$ can be further simplified and expressed as [59],

$$\overline{AA_1} = l\alpha . \quad (2)$$

In $\triangle AEB$, the cosine law is applied between the angle ψ and three edges AB, AE, and BE,

$$\overline{AE} = l = \sqrt{l_1^2 + l_2^2 - 2l_1l_2 \cos(\psi)} . \quad (3)$$

From Eqs. (1) - (3), the relationship between the rotation angle α and the compression displacement h is expressed as

$$\alpha = h / \sqrt{l_1^2 + l_2^2 - 2l_1l_2 \cos(\psi) - R^2} . \quad (4)$$

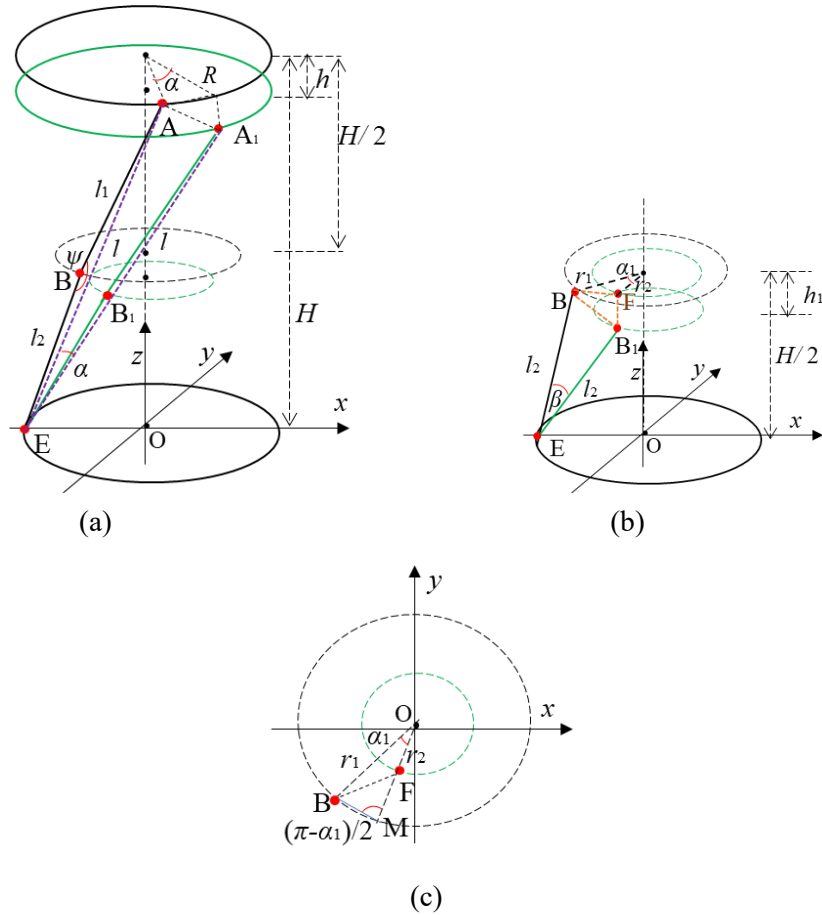


Fig. 4. Deformation sketches of the 3D zig-zag rod: (a) side view for global rod, (b) side view for the bottom part of the rod, and (c) top view for the middle key node B.

Fig. 4(b) shows the deformation of bottom part for the 3D ‘zig-zag’ rod. α_1 represents the rotation angle of middle node B of the ‘zig-zag’ rod, which is proportional to the rotation angle α of the node A. h_1 means the vertical displacement of middle node B, which is proportional to the vertical displacement h of the node

A. β is the angle between the lines BE and B₁E. r_2 is the radius of the circle consisted by middle four nodes of a deformed unit cell. Therefore, the shrinkage rate b for the unit cell is defined as

$$b = -(r_2 - r_1)/r_1. \quad (5)$$

Moreover, $r_2 < r_1$ indicates that this is a NPR structure, and the Poisson's ratio is defined as

$$\nu_{rz} = \frac{b}{-h/H}. \quad (6)$$

Similarly, the motion track $\overline{BB_1}$ can be written as

$$\overline{BB_1} = \sqrt{h_1^2 + \overline{BF}^2}, \quad (7)$$

which also can be expressed as

$$\overline{BB_1} = l_2 \beta. \quad (8)$$

From the geometry illustrated in Fig. 4(c), the length of BF is given by

$$\overline{BF} = \sqrt{(r_1 \alpha_1)^2 + (r_1 - r_2)^2 - 2r_1 \alpha_1 (r_1 - r_2) \cos\left(\frac{\pi - \alpha_1}{2}\right)}. \quad (9)$$

Using Eqs. (5), (7) - (9) and applying the relation $\sin\left(\frac{\alpha_1}{2}\right) \approx \frac{\alpha_1}{2}$, the following expression is derived as,

$$\alpha_1 = \sqrt{(\beta^2 l_2^2 - h_1^2)/(r_1^2 (1-b)) - b^2/(1-b)}. \quad (10)$$

The rotation angle α of node A and the shrinkage rate b of node B denote the rotation angle and the shrinkage rate of the unit cell, respectively. Eqs. (4) and (10) reveal that the coupled relationships between the rotation angle and compression displacement, rotation angle and shrinkage rate for the novel unit cell, respectively. Compared with the traditional unit cell, this proposed unit cell can be designed flexibly due to that the space angle ψ for the 3D 'zig-zag' rod can be tuned by changing relevant geometry parameters.

2.2 FEA

The FEA is carried out in ABAQUS to analyze the deformation of this proposed novel unit cell under a given compression. The 'B31' elements are used to mesh the FEA model for all the circular loops and rods in this unit cell, and the mesh sizes are set to be small enough to achieve the convergence. The profile of 'zig-zag' rods is circular, whereas the cross-section of the top and bottom circular loops is rectangular. The bottom circular loop is fixed, while the top is being applied a given displacement h along z direction at its centre point. The material parameters are $E = 663$ MPa and $\nu = 0.3$. Finally, the displacements and distances of the key nodes can be obtained by the static analysis step with a consideration of geometric nonlinearity.

Fig. 5 shows the deformation of node A for this novel 3D unit cell through top view. The lines AG and GA_1 are the displacements U_A and V_A of node A along x direction and y direction, respectively. Applying the law of cosines in $\triangle AOA_1$, the rotation angle of the unit cell α is expressed as

$$\alpha = \arccos\left[1 - (U_A^2 + V_A^2) / 2R^2\right]. \quad (11)$$

The shrinkage rate and Poisson's ratio are obtained using Eqs. (5) and (6).

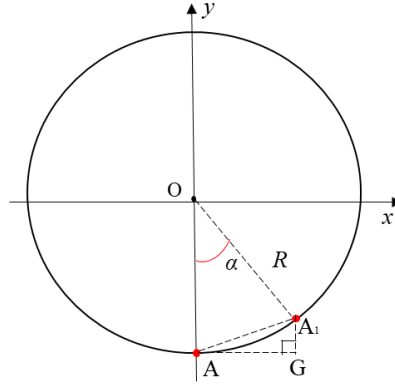


Fig. 5. Deformation of key node A for top view.

2.3 Experiment

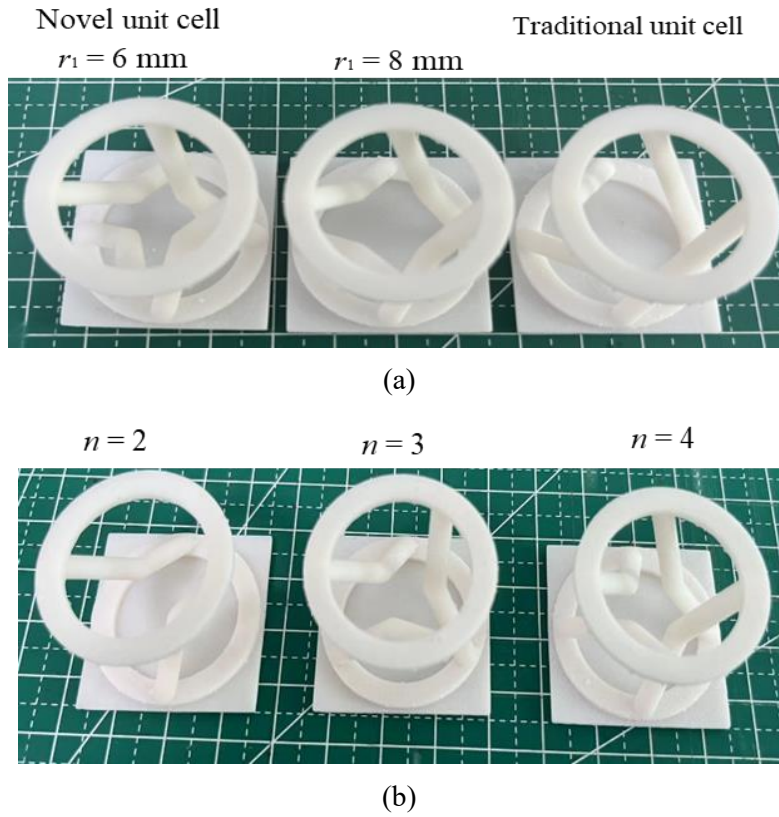
Table 1 Geometry parameters of the novel unit cells under different cases.

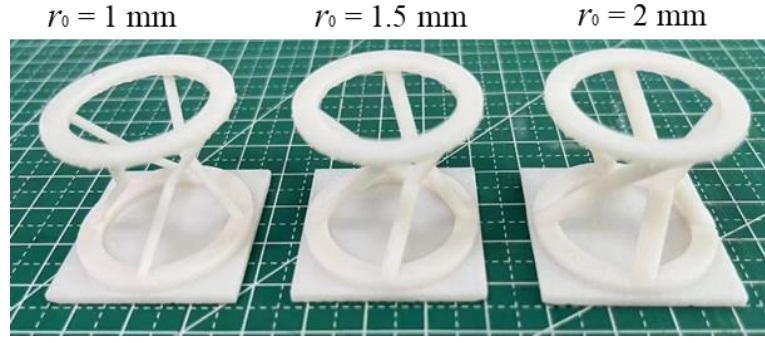
Parameters	Case I	Case II	Cases III	Case IV	Case V	Case VI
r_1 (mm)	variable	6	6	6	6	6
n	4	variable	4	4	4	4
r_0 (mm)	2	2	variable	2	2	2
R (mm)	14	14	14	variable	14	14
H (mm)	21.5	21.5	21.5	21.5	variable	21.5
λ	$\pi / 4$	$\pi / 4$	$\pi / 4$	$\pi / 4$	$\pi / 4$	variable
d (mm)	1.5	1.5	1.5	1.5	1.5	1.5

Firstly, the proposed novel 3D unit cells are fabricated by the AUTOCERA-R ceramic 3D printer machine (Beijing Ten Dimensions Technology Co., Ltd.) with the materials of polylactic acid (PLA) water washable resin. Subsequently, the deformation and load carrying capacity of different unit cells are measured by the quasi-static compression test method with the electronic universal testing machine (Shimadzu AGS-X). Finally,

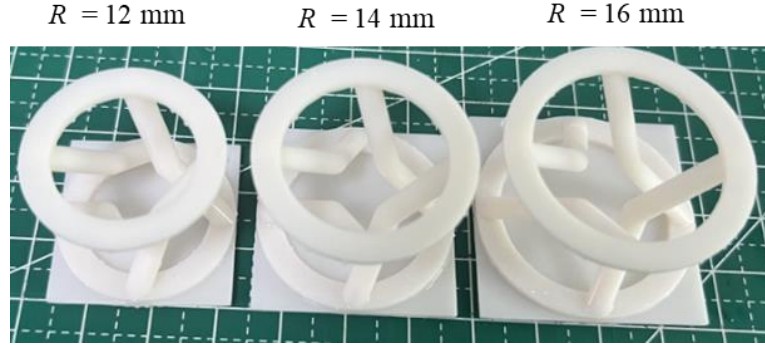
the experimental results validated the Poisson's ratio ν_{rz} , and CTC effect represented by the rotation angle α . Note, the experimental results for the traditional unit cell are obtained with the electronic universal testing machine and Digital Image Correlation (DIC, VIC-3D). However, the manual measurement is added for the novel unit cell with the ruler and rigid thread due to that the displacements of 3D 'zig-zag' rod can't be measured by DIC accurately.

In this work, six different geometry parameters are considered to explore the influence factors of the deformation for the novel unit cell. All the geometric parameters of the six cases are presented in Table 1. Fig. 6 displays different types of 3D printed unit cells for these six cases. Fig. 6(a) presents the traditional unit cell and novel unit cells with different values of r_1 (case I), and Figs. 6(b) ~ 6(f) show the novel unit cells with different geometry parameters for cases II – VI, respectively. Specifically, Figs. 6(b) ~ 6(f) are the novel unit cells with different rod numbers (case II), different rod radii r_0 (case III), different radii R of centre circle for two circular loops (case IV), different thicknesses H (case V), and different radius angle λ between the bottom and middle nodes (case VI), respectively. To eliminate the effect of torque on the boundary during the compression process, a top face is added in the experimental model of unit cell.

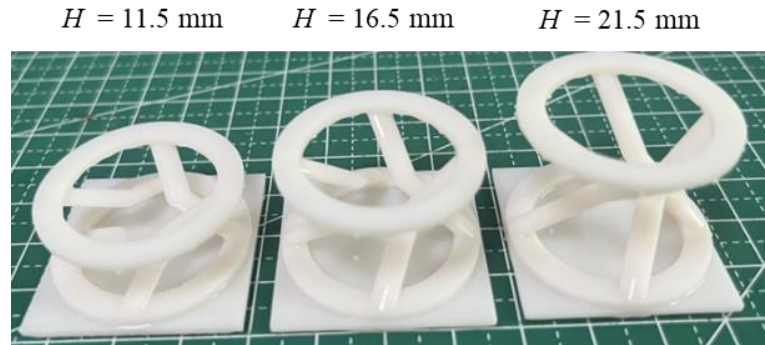




(c)



(d)



(e)



(f)

Fig. 6. 3D printed unit cells: (a) traditional and novel unit cells (case I), (b) case II, (c) case III, (d) case IV, (e) case V, and (f) case VI.

Fig. 7 demonstrates the experimental procedures. Fig. 7(a) shows the experimental process for the

uniaxial compression testing of a 3D unit cell, from which the deformation mechanism is observed and the load-displacement curve of the unit cell during the compression process is determined. The flat punch is coated with lubricants to reduce the effect from friction. The flat punch is loaded at a constant rate of 1 mm/min under the control of the displacement sensor until the unit cell fails. Fig. 7(b) presents the experiment layout for DIC test. The spherical indenter coated with lubricants is selected and then is loaded at a constant rate of 1 mm/min under the control of the displacement sensor until the unit cell descends by 5mm. The force sensor with a range of 500 N is selected in both compression test and DIC test. After obtaining the displacements data from experiments, the shrinkage rate, Poisson's ratio, and rotation angle are computed from Eqs. (5), (6), and (11). It is noted that the rotation angle of the specimen is influenced greatly by the torque from the contact area between the indenter and specimen. To diminish the effect of torque, spherical indenter is applied when measuring the rotation angle. However, to prevent the specimen from being penetrated by the spherical indenter, the flat punch is used for obtaining the load-displacement curve.

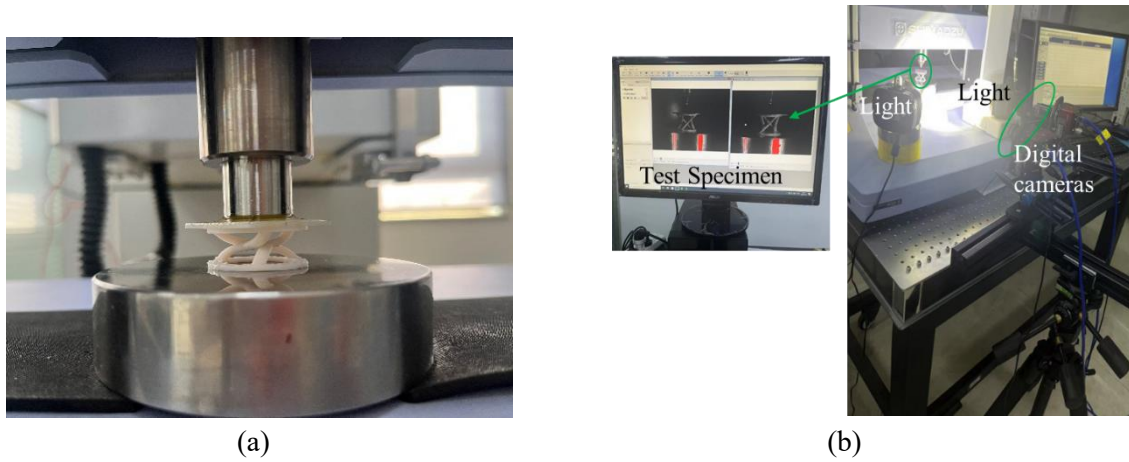


Fig. 7. Procedures of experiment: (a) experiment process for uniaxial compression test, and (b) experiment layout for DIC test.

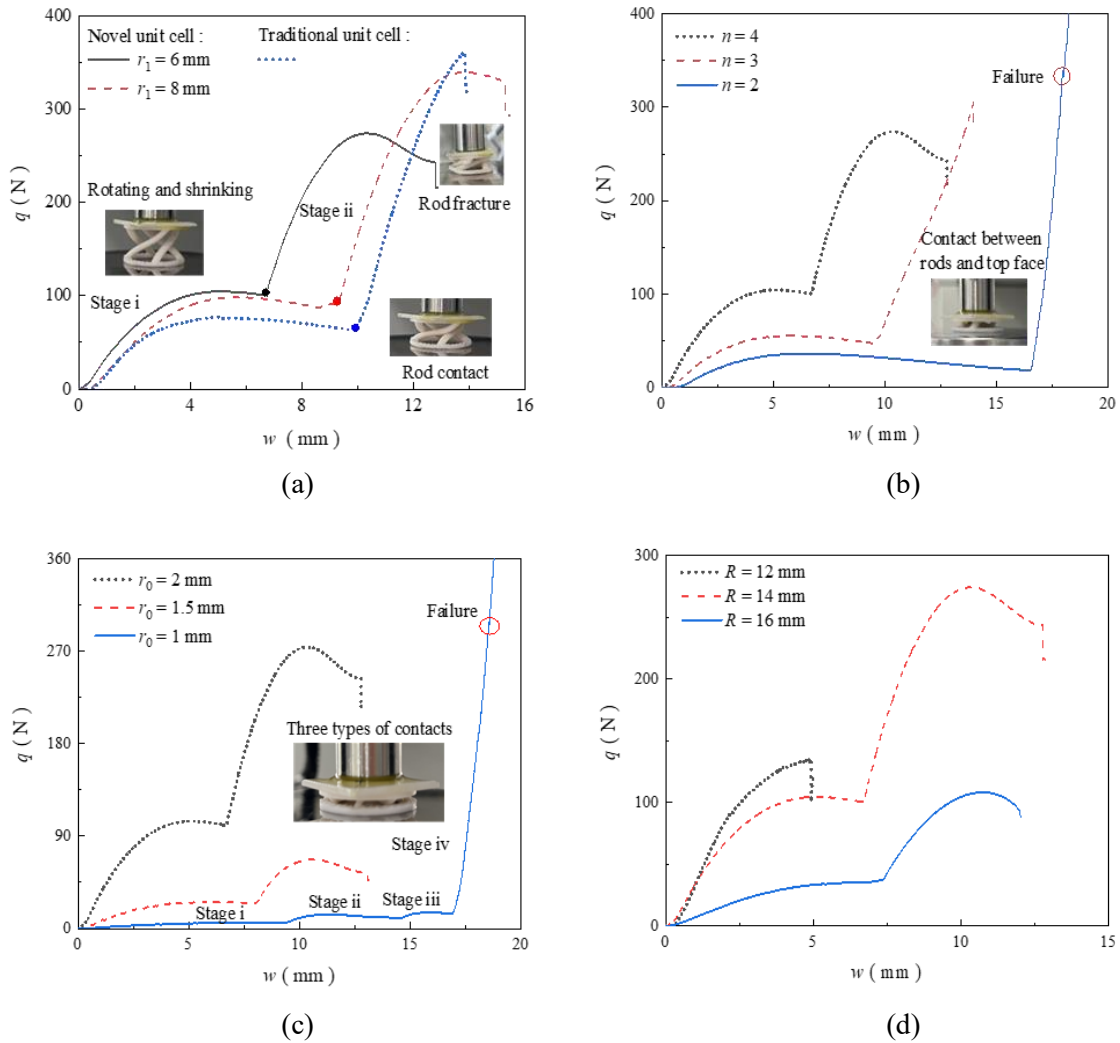
3. Results and discussion

In this paper, a novel 3D unit cell with both CTC and NPR is designed and fabricated. The effects of geometric parameters on the deformation for the unit cell are investigated through FEA and experimental test. It is found that the design parameters determining the space angle of ‘zig-zag’ rods play a crucial role to the deformation and load carrying capacity of this proposed novel 3D unit cell.

3.1 Deformation mechanism

In this section, a quasi-static uniaxial compression test is carried out to reveal the deformation mechanism of the novel unit cell. Fig. 8 illustrates the load-displacement curves of different unit cells presented in Fig. 6.

Fig. 8(a) compares the load carrying capacity between the novel and traditional unit cells. During the compression process, these two types of the unit cells exhibit similar deformation mechanism, which can be divided into two stages i and ii, respectively. The unit cell first experiences rotating and shrinking under the axial displacement load in stage i (i.e., shows CTC effect and NPR), then, stops rotating, shrinking, and only descends in stage ii due to rods contact. Finally, two types of unit cells fail due to the rod fracture. Both the unit cells undergo the similar elastic and buckling in stage i. In stage ii, significant increase of the load is due to that the rods contact can provide additional load carrying capacity for the unit cells. The load carrying capacity of the novel unit cell is larger than that of the traditional unit cell in stage i due to the increased buckling resistance of ‘zig-zag’ rods. The transition point between these two deformation stages emerges at $w = 10$ mm for the traditional unit cell, at $w = 9$ mm for the novel unit cell with $r_1 = 8$ mm, at $w = 7$ mm for novel



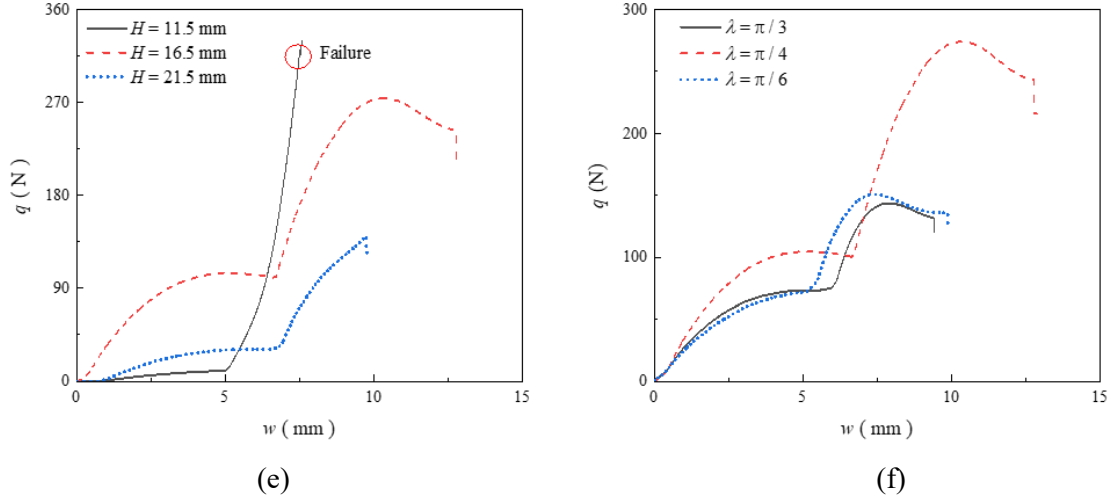


Fig. 8. Load-displacement curves of the unit cells presented in Fig. 6: (a) case I, (b) case II, (c) case III, (d) case IV, (e) case V, and (f) case VI.

unit cell with $r_1 = 6$ mm. The reason for the earlier emergence of the transition point for the novel unit cell with smaller r_1 is because that the space between its rods is decreased, and its shrinking ability is improved. These results also illustrated that the shrinkage rate and load carrying capacity increased with the decrease of r_1 for the novel unit cell.

Fig. 8(b) presents the load-displacement curves of novel unit cells with different numbers of rods n (case II). Similarly, the deformations of these unit cells with $n = 2$, $n = 3$, and $n = 4$ are divided into two stages. All unit cells rotate and shrink in stage i, and then only descend in stage ii. In stage ii, the unit cell with $n = 2$ shows the contact between rods and top face while the unit cells with $n = 3$ and $n = 4$ exhibit the rods contact. The load carrying capacity of the unit cell increases with an increasing rod number since the rods serve as the primary components for bearing forces. The reason for the earliest contact of rods occurring at $n = 4$ is that the space between its rods is the smallest. The failure of all the unit cells is due to the rod fracture.

As shown in Fig. 8(c), the changes of rod radius r_0 (case III) have a great effect on the load-displacement curves of the unit cells. The load carrying capacity of the unit cell decreases with the decrease of rod radius r_0 . The rods contact for the unit cell with larger r_0 occurs earliest due to the small space between its rods. For the $r_0 = 1$ mm, the stage iii means that the contact between rods and top face occurs, and stage iv denotes that the contact between rods and substrate occurs. In other words, there are three types of contacts for the unit cell with $r_0 = 1$ mm in stage iv.

Fig. 8(d) presents the load-displacement curves for novel unit cells with different centre radii R of the two circular loops (case IV). It was observed that the load carrying capacity of the unit cell increases as the R value

decreases. The rod fracture appears at $w = 5\text{mm}$ for the unit cell with $R = 12\text{ mm}$, because of it has a very strong CTC effect. In other words, the rotation angle for $R = 12\text{ mm}$ is largest under the same w , and its strongest rod buckling leads to the rod fracture firstly.

Fig. 8(e) shows the load-displacement curves of novel unit cells with different thicknesses of unit cell H (case V). The thickness is also a significant factor influencing the load carrying capacity, furthermore, its impact is not monotonous. With the increase of the thickness, the load carrying capacity of the unit cell increases and then decreases.

Fig. 8(f) presents the load-displacement curves of novel unit cells with different radius angles λ (case VI). It was found that the load carrying capacity of the unit cell is largest when $\lambda = \pi / 4$. When $\lambda = \pi / 4$, it signifies that the lengths and spatial configuration of the two segments in the 3D ‘zig-zag’ rod are same with each other, resulting in the highest stability of 3D ‘zig-zag’ rod.

According to Fig. 8, all cases have obvious influences on the load-displacement curves of the unit cells because all these geometric parameters can change the spatial configuration of 3D ‘zig-zag’ rods directly or indirectly. Therefore, the 3D ‘zig-zag’ rods can be designed flexibly by tuning these related parameters.

3.2 Experimental validation

Fig. 9 shows the comparison of rotation angle, shrinkage rate, and Poisson’s ratio for the novel and traditional unit cells by FEA and experiment. To ensure the same displacement along the z -direction that is applied to top circular loop, the displacement-controlled loading is set as 4.6 mm in FEA, and that value is set as 5 mm in experiment due to the added plate. The results obtained by FEA and experiment for the novel unit cell are in good agreement. Compared with the traditional unit cell, the mechanical properties for novel unit cell are well improved. Specifically, the range of Poisson’s ratio broadens while maintaining an increasing rotation angle.

3.3 Influence factors for deformation

To explore the deformation mechanism of the unit cell, six influence factors are considered. The FEA results have been validated by experimental results, as presented in Section 3.2. This section only presents FEA results. Since the CTC effect and shrinking of the novel unit cell mainly occurs in stage i, the effects of different factors on stage i are discussed as in the followings.

Fig. 10 illustrates the impact of case I on the deformation of the unit cell. With the decrease of r_1 , both rotation angle and shrinkage rate exhibit an upward trend, and the NPR becomes remarkably pronounced,

reaching a value as -4.2 . A higher shrinkage rate corresponds to a stronger NPR. Additionally, the influence of r_1 on the shrinkage rate and Poisson's ratio is more significant than that on the rotation angle. This suggests that r_1 can substantially adjust the NPR while simultaneously increasing the rotation angle.

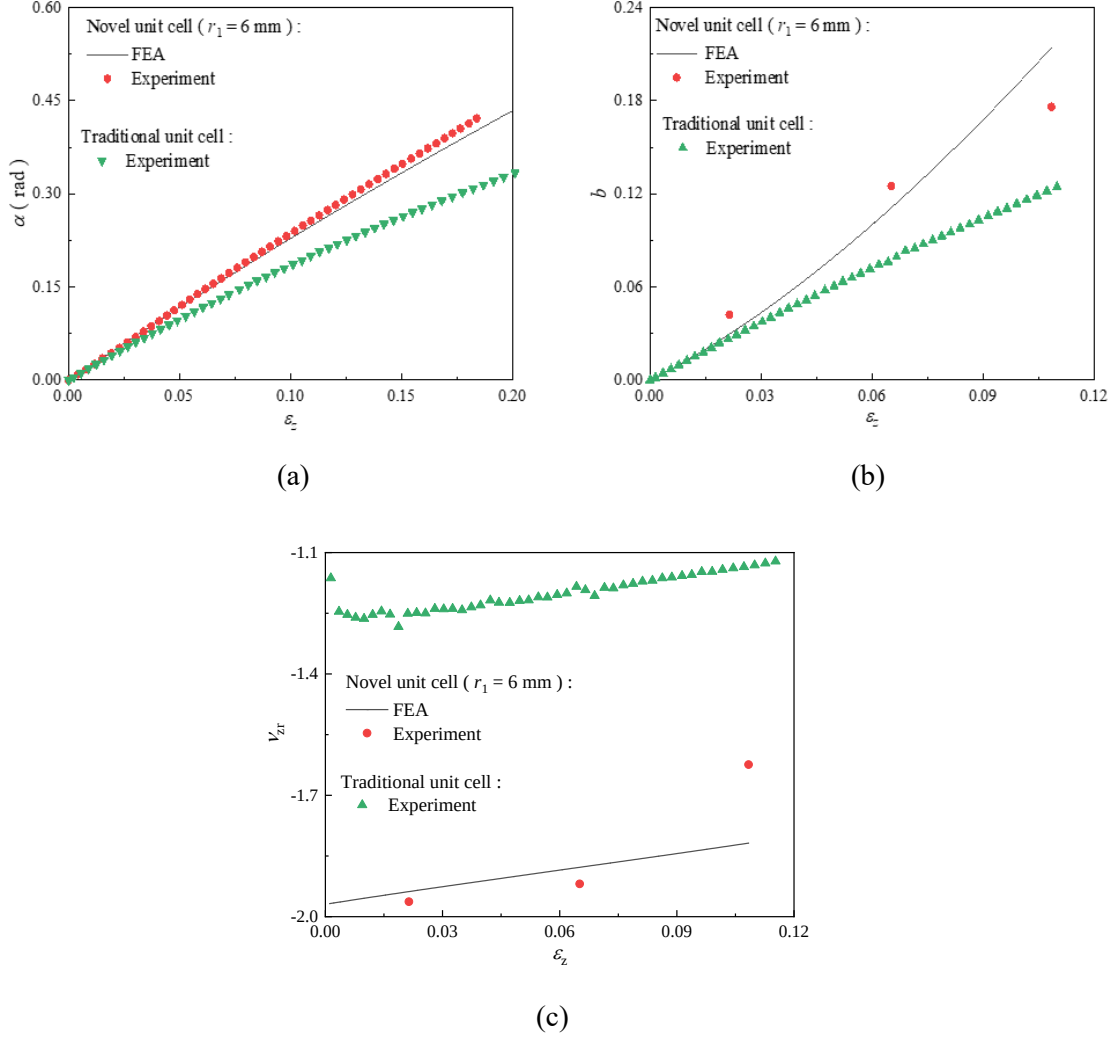
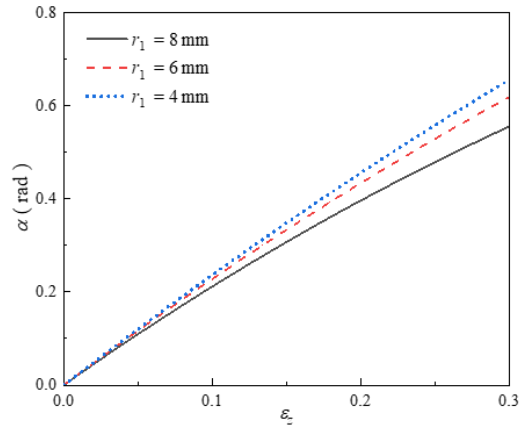


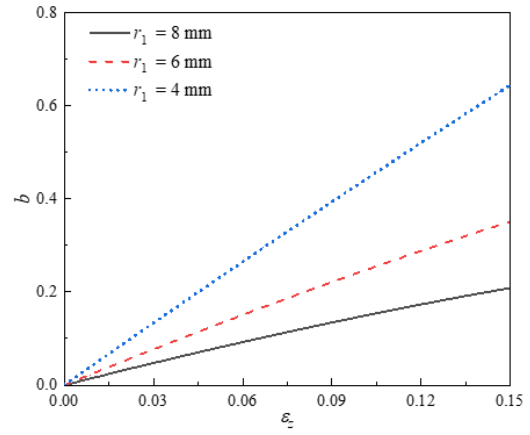
Fig. 9. Comparison of the novel and traditional unit cells by FEA and experimental results: (a) rotation angle, (b) shrinkage rate, and (c) Poisson's ratio.

Fig. 11 depicts the influence of rod number (case II) on the rotation angle, shrinkage rate and Poisson's ratio of the unit cell. It was observed that the rotation angle, shrinkage rate, and Poisson's ratio remain constant with an increase in the number of rods for this proposed novel unit cell. This implies that the number of 'zig-zag' rods has an insignificant effect on the deformation mechanism.

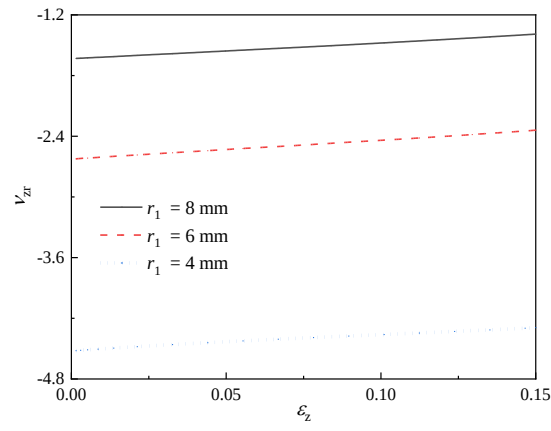
Fig. 12 illustrates the variations in deformation with the normal strain ϵ_z for the unit cell under case III. The rod's radius has a minor effect on the rotation angle and Poisson's ratio. Consequently, the radius of rods can only slightly tune the Poisson's ratio and rotation deformation.



(a)

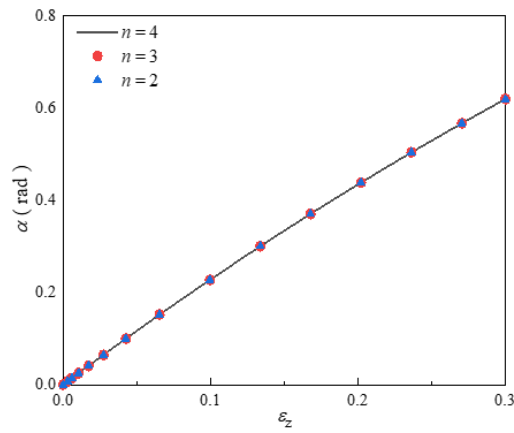


(b)

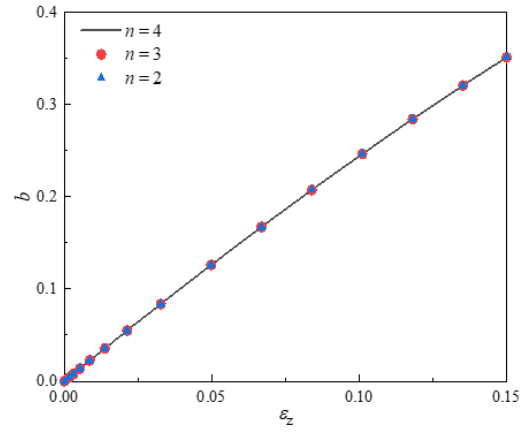


(c)

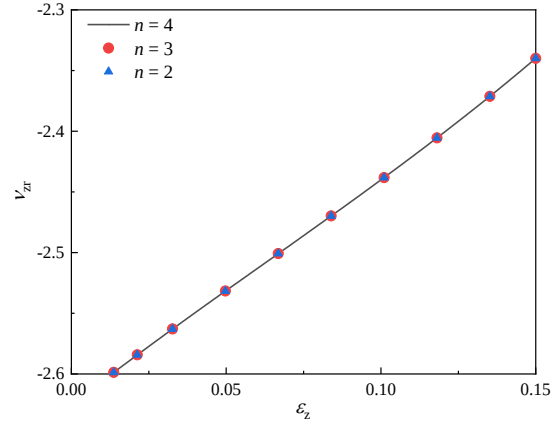
Fig. 10. Effect of case I on the deformation for the unit cell: (a) rotation angle, (b) shrinkage rate, and (c) Poisson's ratio.



(a)

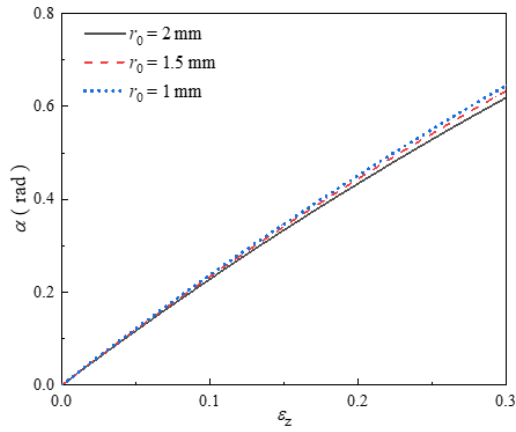


(b)

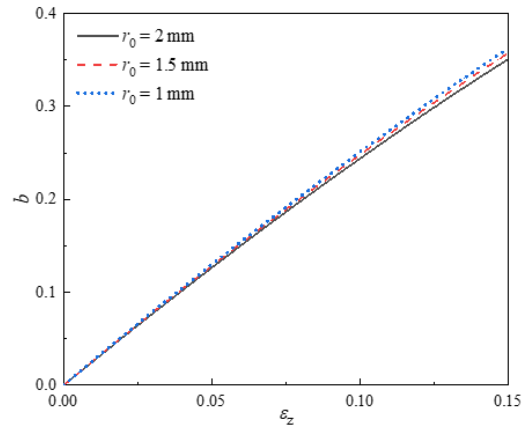


(c)

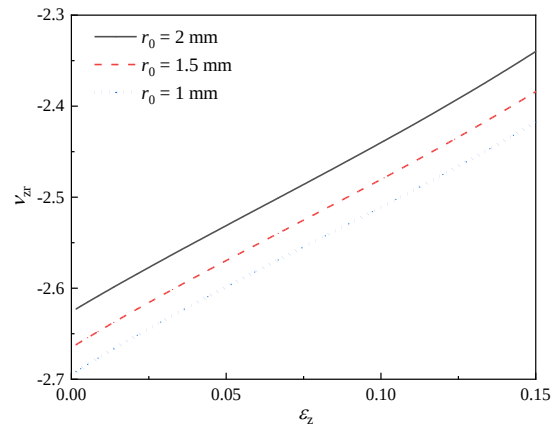
Fig. 11. Influence of case II on the deformation for the unit cell: (a) rotation angle, (b) shrinkage rate, and (c) Poisson's ratio.



(a)



(b)



(c)

Fig. 12. Variations of the deformation of the unit cell with the normal strain under case III: (a) rotation angle, (b) shrinkage rate, and (c) Poisson's ratio.

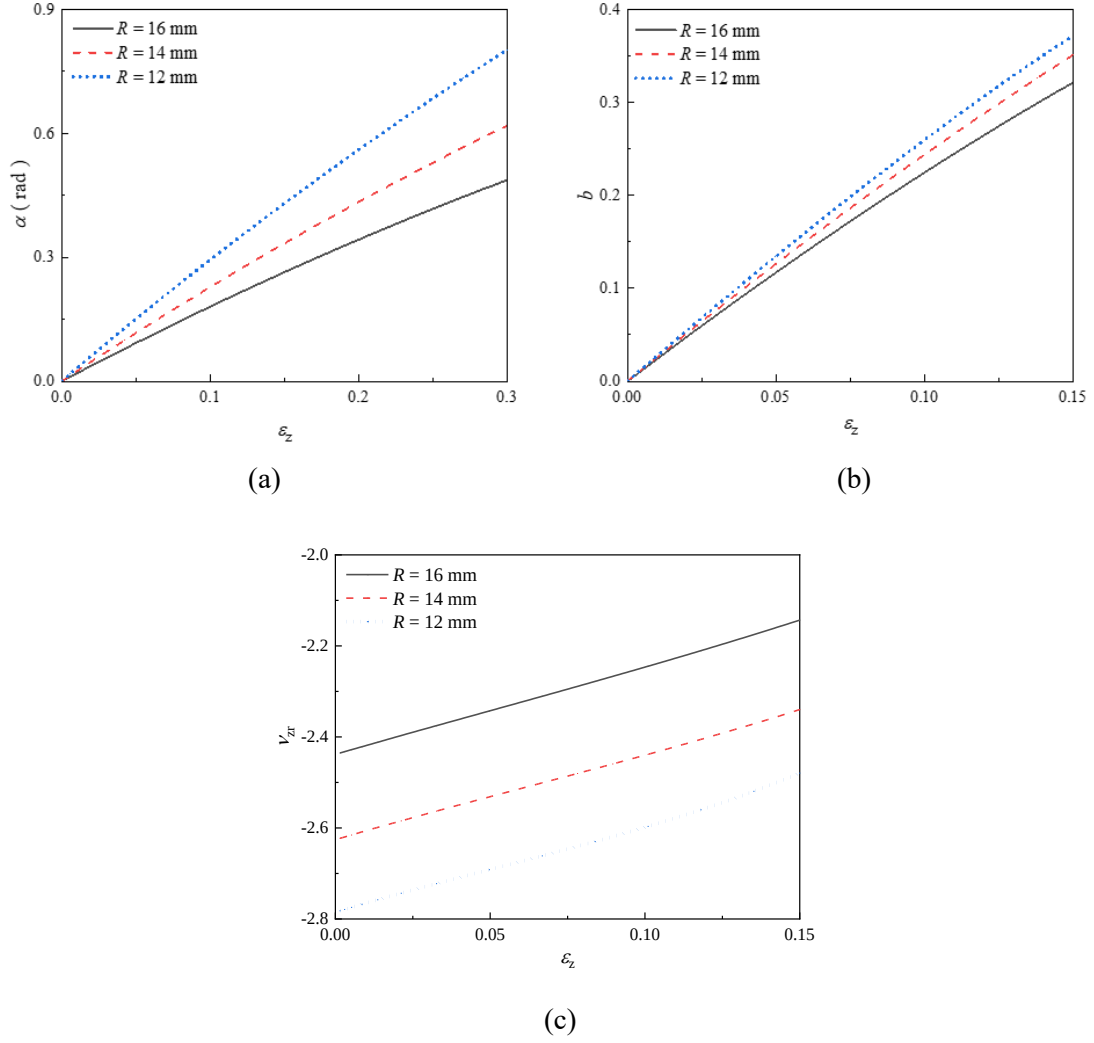


Fig. 13. Deformation curves under case IV for the unit cell: (a) rotation angle, (b) shrinkage rate, and (c) Poisson's ratio.

The deformation curves of the unit cell for case IV are presented in Fig. 13. It is seen that the rotation angle significantly increases with a decrease of R . Simultaneously, the NPR became strong as R decreases, indicating that the shrinkage rate increases with the reduction of R . Fig. 13 demonstrates that the parameter R can effectively tune the rotation angle over a wide range, while maintaining a consistent upward trend for the NPR.

Fig. 14 illustrates the variation of the deformation with the normal strain under case V. It was observed that the thickness of unit cell strongly influenced the rotation angle, shrinkage rate, and NPR. Under the same strain, a large thickness leads to a large α , b , and NPR, indicating that the unit cell with a larger H may result in a stronger CTC effect and greater shrinking ability. Therefore, it can be concluded that the parameter H can effectively adjust the rotation angle and NPR over a wide range.

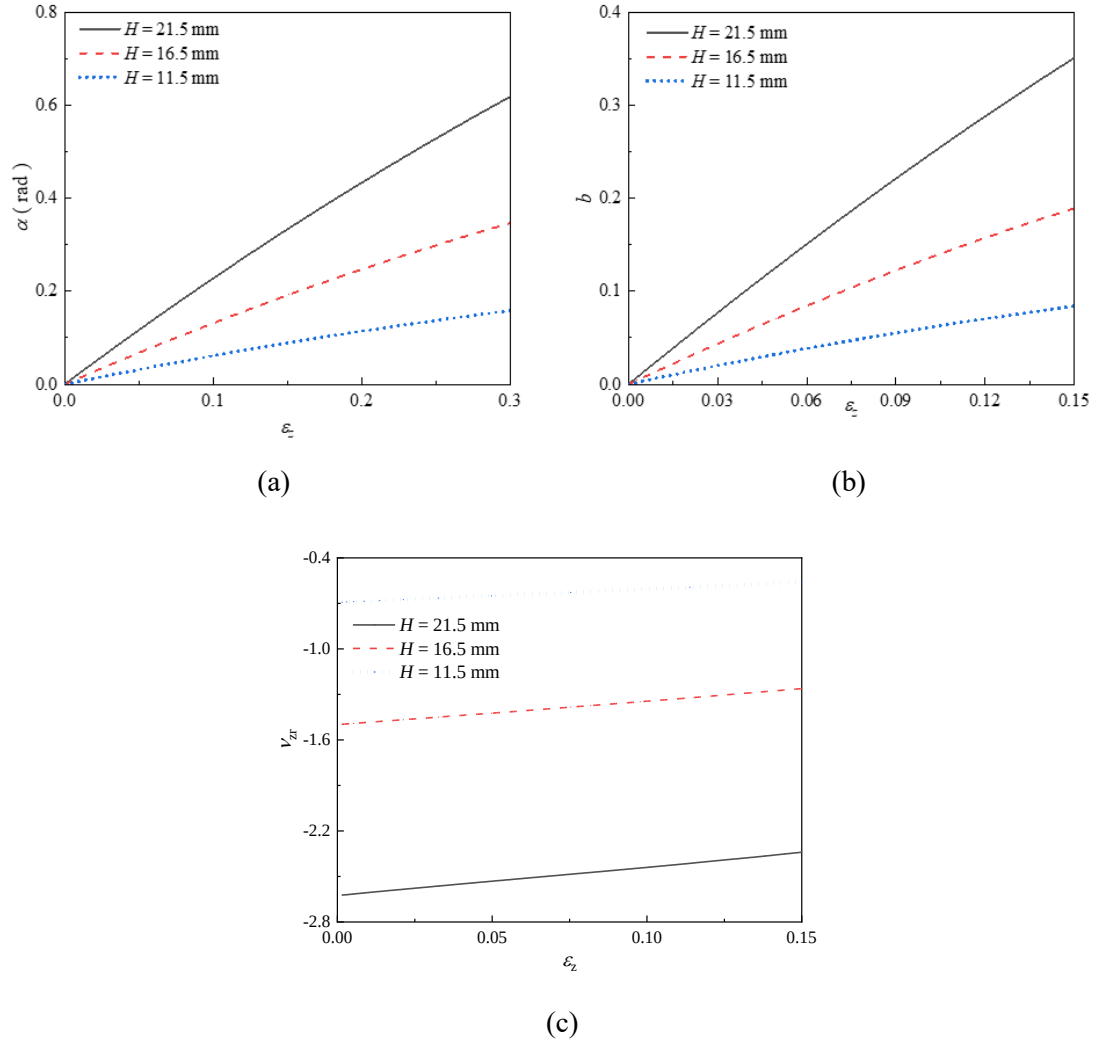
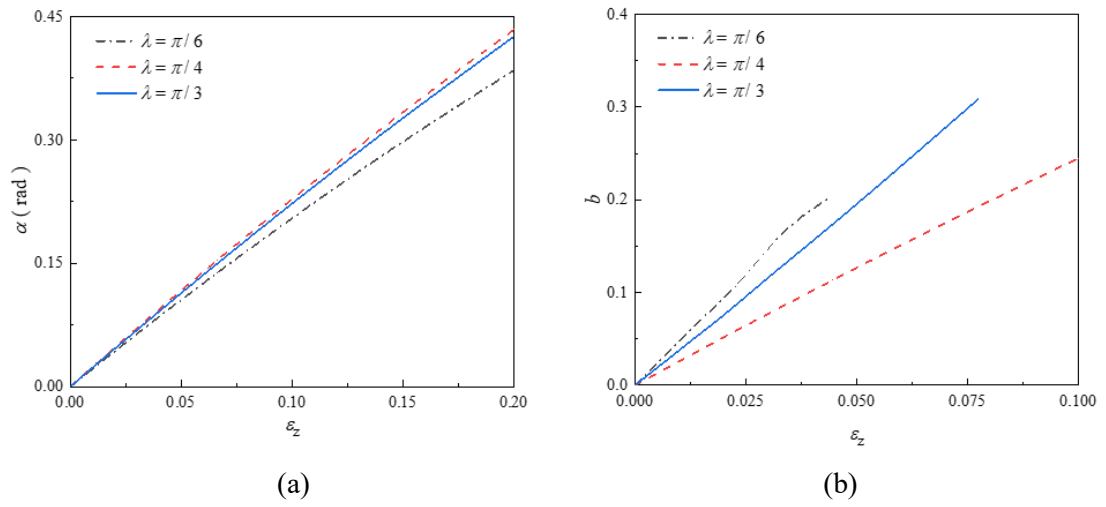
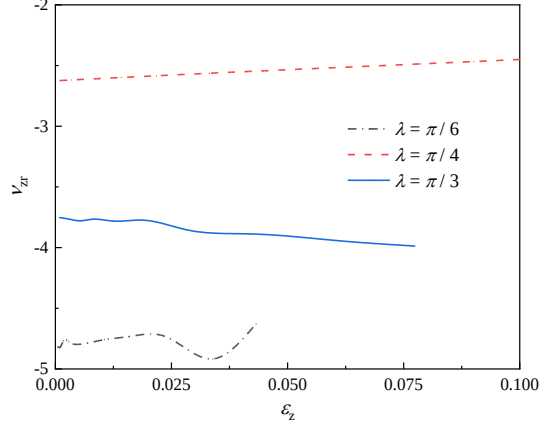


Fig. 14. Variations of the deformation for the unit cell under case V: (a) rotation angle, (b) shrinkage rate, and (c) Poisson's ratio.





(c)

Fig. 15. Influence of case VI on the deformation for the unit cell: (a) rotation angle, (b) shrinkage rate, and (c) Poisson's ratio.

Fig. 15 illustrates the influence of case VI on the deformation of the unit cell. The illustration clearly shows that the CTC effect of the unit cell reaches its maximum strength when $\lambda = \pi / 4$ while the NPR is at its weakest but exhibits the most stability. The NPR of the unit cell with $\lambda = \pi / 6$ is strongest, but it fluctuates due to structure instability. Among the six influence factors, λ is the only factor that exhibits an opposite effect on the CTC effect and NPR.

4. Conclusions

With a 3D ‘zig-zag’ rod design concept, we design, analyze, and fabricate a novel unit cell with CTC effect and NPR in this work. Compared with traditional unit cells, this proposed novel 3D unit cell has an improved design flexibility, load carrying capacity, CTC effect and shrinkage rate. Moreover, the range of NPR is much larger than that of the traditional unit cell. The deformation mechanism and its influence factors for the novel unit cell are thoroughly analyzed through FEA and experimental testing. Six cases with different geometry parameters for the novel unit cell are fabricated for the investigations. While all six cases have noticeable impacts on load carrying capacity, only cases I, and IV – VI significantly affect the deformation mechanism of the novel unit cell. Following conclusions are arrived in this research:

- (1) The primary load-carrying capacity of the unit cell is provided by the 3D ‘zig-zag’ rod. This load carrying capacity can be improved by increasing the values of n and r_0 , or by decreasing the values of R and r_1 .
- (2) The NPR of the unit cell is mainly influenced by the parameters r_1 and λ , while the CTC effect is determined by the r_1 , H , and R .

- (3) The parameter R has the capacity to tune the rotation angle over a wide range and has a slight influence on NPR.
- (4) Adjusting parameter H allows for achieving a wide range of NPR and CTC effects simultaneously.
- (5) The parameter λ exhibits an opposite effect on the CTC effect and NPR, whereas other parameters have similar influences to the CTC effect and NPR.

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References

- [1] Tan XJ, Wang LC, Zhu SW, Chen S, Wang B, Kadi M. A general strategy for performance enhancement of negative stiffness mechanical metamaterials. *Eur J Mech A-Solids* 2022; 96: 104702. <https://doi.org/10.1016/j.euromechsol.2022.104702>.
- [2] Frenzel T, Kadic M, Wegener M. Three-dimensional mechanical metamaterials with a twist. *Science* 2017; 358: 1072–1074. <https://doi.org/10.1126/science.aao4640>.
- [3] Cabras L, Brun M. A class of auxetic three-dimensional lattices. *J Mech Phys Solids* 2015; 91: 56–72. <https://doi.org/10.1016/j.jmps.2016.02.010>.
- [4] Yao Y, Ni Y, He LH. Rutile-mimic 3D metamaterials with simultaneously negative Poisson's ratio and negative compressibility. *Mater Des* 2021; 200: 109440. <https://doi.org/10.1016/j.matdes.2020.109440>.
- [5] Miller W, Smith CW, Mackenzie DS, Evans KE. Negative thermal expansion: a review. *J Mater Sci* 2009; 44: 5441–5451. <https://doi.org/10.1007/s10853-009-3692-4>.
- [6] Cong PH, Long PT, Nhat NV, Duc ND. Geometrically nonlinear dynamic response of eccentrically stiffened circular cylindrical shells with negative Poisson's ratio in auxetic honeycombs core layer. *Int J Mech Sci* 2019; 152: 443–453. <https://doi.org/10.1016/j.ijmecsci.2018.12.052>.
- [7] Zhang SL, Lai YC, He X, Liu RY, Zi YL, Wang ZL. Auxetic foam-based contact-mode triboelectric nanogenerator with highly sensitive self-powered strain sensing capabilities to monitor human body movement. *Adv Funct Mater* 2017; 27: 1606695. <https://doi.org/10.1002/adfm.201606695>.
- [8] Winczewski S, Rybicki J. Negative Poisson's ratio from pentagons: A new auxetic structure combining three different auxetic mechanisms. *Comp Mater Sci* 2022; 201: 110914. <https://doi.org/10.1016/j.commatsci.2021.110914>.
- [9] Jiang H, Ziegler H, Zhang ZN, Zhang H, Le Barbenchon L, Atre S, Chen YY. 3D printed tubular lattice

- metamaterials for mechanically robust stents. *Compos Pt B-Eng* 2022; 236: 109809. <https://doi.org/10.1016/j.compositesb.2022.109809>.
- [10] Airoidi A, Bettini P, Panichelli P, Sala G. Chiral topologies for composite morphing structures – part II: novel configurations and technological processes. *Phys Status Solidi B-Basic Solid State Phys* 2015; 252: 1446–1454. <https://doi.org/10.1002/pssb.201584263>.
- [11] Baughman RH, Stafström S, Cui C, Dantas SO. Materials with negative compressibilities in one or more dimensions. *Science* 1998; 279: 1522–1524. <https://doi.org/10.1126/science.279.5356.1522>.
- [12] Xu X, Wang C, Shou W, Du ZL, Chen YY, Li BC, Matusik W, Hussein N, Huang GL. Physical realization of elastic cloaking with a polar material. *Phys Rev Lett* 2020; 124: 114301. <https://doi.org/10.1103/physrevlett.124.114301>.
- [13] Wang LW, Boddapati J, Liu K, Zhu P, Daraio C, Chen W. Mechanical cloak via data-driven aperiodic metamaterial design. *Proc Natl Acad Sci* 2022; 119: e2122185119. <https://doi.org/10.1073/pnas.2122185119>.
- [14] Wang YJ, Lai CL, Cao HY, Jiang RY. Metastructure with torsion-compression coupling behaviors: Additive-manufacturing, experimental and numerical investigations. *Compos Struct* 2023; 322: 117418. <https://doi.org/10.1016/j.compstruct.2023.117418>.
- [15] Wang YB, Liu HT, Zhang DQ. Compression-torsion conversion behavior of a cylindrical mechanical metamaterial bases on askew re-entrant cells. *Mater Lett* 2021; 303: 130572. <https://doi.org/10.1016/j.matlet.2021.130572>.
- [16] Wang YB, Liu HT, Zhang ZY. Rotation spring: rotation symmetric compression-torsion conversion structure with high space utilization. *Compos Struct* 2020; 245: 112341. <https://doi.org/10.1016/j.compstruct.2020.112341>.
- [17] Huang JL, Yang N. Composite compression-twist structures made by additive manufacturing for energetic absorption with controllable inner friction. *Compos Struct* 2023; 303: 116349. <https://doi.org/10.1016/j.compostruct.2022.116349>.
- [18] Design and testing of a DNA-like torsional structure for energy absorption. *Mater Des* 2023; 226: 111642. <https://doi.org/10.1016/j.matdes.2023.111642>.
- [19] Liu XB, Zhang K, Shi HZ, Hong F, Liu H. Origami-inspired metamaterial with compression-twist coupling effect for low-frequency vibration isolation. *Mech Syst Signal Proc* 2024; 208: 111076. <https://doi.org/10.1016/j.ymssp.2023.111076>.
- [20] Yang C, Boorugu M, Dopp A, Ren J, Martin R, Han D, Choi W, Lee H. 4D printing reconfigurable

- deployable and mechanically tunable metamaterials. *Mater Horizons* 2019; 6: 1244–1250. <https://doi.org/10.1039/c9mh00302a>.
- [21] Kim Y, Yuk H, Zhao RK, Chester SA, Zhao XH. Printing ferromagnetic domains for untethered fast-transforming soft materials. *Nature* 2018; 558: 274–279. <https://doi.org/10.1038/s41586-018-0185-0>.
- [22] van Manen T, Janbaz S, Zadpoor AA. Programming 2D/3D shape shifting with hobbyist 3D printers. *Mater Horizons* 2017; 4: 1064–1069. <https://doi.org/10.1039/c7mh00269f>.
- [23] Zhao W, Li N, Liu X, Liu LW, Yue CB, Zeng CJ, Liu YJ, Leng JS. 4D printed shape memory metamaterials with sensing capability derived from the origami concept. *Nano Energy* 2023; 115: 108697. <https://doi.org/10.1016/j.nanoen.2023.108697>.
- [24] Zhou XL, Ren LQ, Song ZY, Li GW, Zhang JF, Li BQ, Wu Q, Li WX, Ren L, Liu QP. Advances in 3D/4D printing of mechanical metamaterials: From manufacturing to applications. *Compos Pt B-Eng* 2023; 254: 110585. <https://doi.org/10.1016/j.compositesb.2023.110585>.
- [25] van Manen T, Janbaz S, Jansen KMB, Zadpoor AA. 4D printing of reconfigurable metamaterials and devices. *Commun Mater* 2021; 2: 56. <https://doi.org/10.1038/s43246-021-00165-8>.
- [26] Sinha P, Mukhopadhyay T. Programmable multi-physical mechanics of mechanical metamaterials. *Mater Sci Eng R-Rep* 2023; 155: 100745. <https://doi.org/10.1016/j.mser.2023.100745>.
- [27] Yao Y, Ni Y, He LH. Unexpected bending behavior of architected 2D lattice materials. *Sci Adv* 2023; 9: eadg3499. <https://doi.org/10.1126/sciadv.adg3499>.
- [28] Guo LT, Zhao SY, Guo YQ, Yang J, Kitipornchai S. Bandgaps in functionally graded phononic crystals containing graphene origami-enabled metamaterials. *Int J Mech Sci* 2023; 240: 107956. <https://doi.org/10.1016/j.ijmecsci.2022.107956>.
- [29] Bhullar SK, Hewage ATM, Alderson A, Alderson K, Jun MBG. Influence of negative Poisson's ratio on stent applications. *Adv Mater* 2013; 2: 42–47. <https://doi.org/10.11648/j.am.20130203.14>.
- [30] Gu HY, Taghipour J, Shaw AD, Amoozgar M, Zhang JY, Wang C, Friswell MI. Tailored twist morphing achieved using graded bend-twist metamaterials. *Compos Struct* 2022; 300: 116151. <https://doi.org/10.1016/j.compstruct.2022.116151>.
- [31] Ebrahimi H, Mousanezhad D, Nayeb-Hashemi H, Norato J, Vaziri A. 3D cellular metamaterials with planar anti-chiral topology. *Mater Des* 2018; 145: 226–231. <https://doi.org/10.1016/j.matdes.2018.02.052>.
- [32] Duan SY, Wen WB, Fang DN. A predictive micropolar continuum model for a novel three-dimensional chiral lattice with size effect and tension-twist coupling behavior. *J Mech Phys Solids* 2018; 121: 23–46. <https://doi.org/10.1016/j.jmps.2018.07.016>.

- [33] Zheng BB, Zhong RC, Chen X, Fu MH, Hu LL. A novel metamaterial with tension-torsion coupling effect. *Mater Des* 2019; 171: 107700. <https://doi.org/10.1016/j.matdes.2019.107700>.
- [34] Farrell DT, McGinn C, Bennett GJ. Extension twist deformation response of an auxetic cylindrical structure inspired by deformed cell ligaments. *Compos Struct* 2020; 238: 111901. <https://doi.org/10.1016/j.compstruct.2020.111901>.
- [35] Lemkalli B, Kadic M, Badri YE, Guenneau S, Bouzid A, Achaoui Y. Mapping of elastic properties of twisting metamaterials onto micropolar continuum using static calculations. *Int J Mech Sci* 2023; 254: 108411. <https://doi.org/10.1016/j.ijmecsci.2023.108411>.
- [36] Yang CQ, Yang KJ, Tian YP, Fu MH, Hu LL. Theoretical analysis on the stiffness of compression-torsion coupling metamaterials. *Extreme Mech Lett* 2021; 46: 101336. <https://doi.org/10.1016/j.eml.2021.101336>.
- [37] Zhong RC, Fu MH, Chen X, Zheng BB, Hu LL. A novel three-dimensional mechanical metamaterial with compression-torsion properties. *Compos Struct* 2019; 226: 111232. <https://doi.org/10.1016/j.compstruct.2019.111232>.
- [38] Xu WY, Wang LW, Zhao L, Zhu P. General assembly rules for metamaterials with scalable twist effects. *Int J Mech Sci* 2023; 259: 108579. <https://doi.org/10.1016/j.ijmecsci.2023.108579>.
- [39] Chen X, He TW, Hu YD, Feng ML. A 3D dislocated re-entrant structure with compression-twist coupling effect. *Smart Mater Struct* 2023; 32: 055009. <https://doi.org/10.1088/1361-665X/acc621>.
- [40] Gao M, He DY, Guo XY, Wu HR, Tan Z, Wu X, Shao W, Wang GH. Design, preparation and characterization of a 3D hierarchical auxetic lattice structure produced by selective laser melting. *Structures* 2022; 44: 1219–31. <https://doi.org/10.1016/j.istruc.2022.08.050>.
- [41] Zhang XY, Ren X, Zhang Y, Xie YM. A novel auxetic metamaterial with enhanced mechanical properties and tunable auxeticity. *Thin-Walled Struct* 2022; 174: 109162. <https://doi.org/10.1016/j.tws.2022.109162>.
- [42] Zhang XG, Ren X, Jiang W, Zhang XY, Luo C, Zhang Y, Xie YM. A novel auxetic chiral lattice composite: Experimental and numerical study. *Compos Struct* 2022; 282: 115043. <https://doi.org/10.1016/j.compstruct.2021.115043>.
- [43] Chen Y, Ye WJ, Xu RZ, Sun Y, Feng J, Sareh P. A programmable auxetic metamaterial with tunable crystal symmetry. *Int J Mech Sci* 2023; 249: 108249. <https://doi.org/10.1016/j.ijmecsci.2023.108249>.
- [44] Wang X, Qin RX, Zhang X, Chen BZ. Quasi-static and dynamic behavior of additively manufactured metamaterial structures with layered-hybrid topologies. *Thin-Walled Struct* 2023; 183: 110434. <https://doi.org/10.1016/j.tws.2022.110434>.

- [45] Han HS, Sorokin V, Tang LH, Cao DQ. Origami-based tunable mechanical memory metamaterial for vibration attenuation. *Mech Syst Signal Proc* 2023; 188: 110033. <https://doi.org/10.1016/j.ymssp.2022.110033>.
- [46] Sun Y, Ye WJ, Chen Y, Fan WY, Feng J, Sareh P. Geometric design classification of kirigami-inspired metastructures and metamaterials. *Structures* 2021; 33: 3633–43. <https://doi.org/10.1016/j.istruc.2021.06.072>.
- [47] Farzaneh A, Pawar N, Portela CM, Hopkins JB. Sequential metamaterials with alternating Poisson's ratios. *Nat Commun* 2022; 13: 1041. <https://doi.org/10.1038/s41467-022-28696-9>.
- [48] Wu WW, Hu WX, Qian G, Liao HT, Xu XY, Berto F. Mechanical design and multifunctional applications of chiral mechanical metamaterials: a review. *Mater Des* 2019; 180: 107950. <https://doi.org/10.1016/J.MATDES.2019.107950>.
- [49] Zhang TP, Huang ZX, Li Y, Xu ZS, Zhou ZW, Chen ZY. Compressive mechanical behaviors of PPR and NPR chiral compression–twist coupling lattice structures under quasi-static and dynamic loads. *Thin-Walled Struct* 2023; 182: 110234. <https://doi.org/10.1016/j.tws.2022.110234>.
- [50] Hao J, Han D, Zhang XG, Teng XC, Xu HH, Jiang W, Lang JP, Ni XH, Luo YM, Li HR, Ren X. A novel compression-torsion coupling metamaterial with tunable Poisson's ratio. *Constr Build Mater* 2023; 395: 132276. <https://doi.org/10.1016/j.conbuildmat.2023.132276>.
- [51] Tang HH, Zhang CL, Li L, Mei CS, Ling L, Hu YJ. Contribution of tension–torsion coupling effect on elastic properties of chiral and anti-chiral structures. *Thin-Walled Struct* 2023; 182: 110199. <https://doi.org/10.1016/j.tws.2022.110199>.
- [52] Cui JP, Zhang LC, Gain AK. A novel auxetic unit cell for 3D metamaterials of designated negative Poisson's ratio. *Int J Mech Sci* 2023; 260: 108614. <https://doi.org/10.1016/j.ijmecsci.2023.108614>.
- [53] Duan SY, Xi L, Wen WB, Fang DN. A novel design method for 3D positive and negative Poisson's ratio material based on tension-twist coupling effects. *Compos Struct* 2020; 236: 111899. <https://doi.org/10.1016/j.compstruct.2020.111899>.
- [54] Sutton GP, Burrows M. The mechanics of elevation control in locust jumping. *J Comp Physiol A* 2008; 194: 557–563. <https://doi.org/10.1007/s00359-008-0329-z>.
- [55] Li CC, Gorb SN, Rajabi H. Biomechanical strategies to reach a compromise between stiffness and flexibility in hind femora of desert locusts. *Acta Biomater* 2021; 134: 490–498. <https://doi.org/10.1016/j.actbio.2021.07.030>.
- [56] Bayley TG, Sutton GP, Burrows M. A buckling region in locust hindlegs contains resilin and absorbs

- energy when jumping or kicking goes wrong. *J Exp Biol* 2012; 215: 1151–1161. <https://doi.org/10.1242/jeb.068080>.
- [57] Bennet-Clark HC. The energetics of the jump of the locust *Schistocerca gregaria*. *J Exp Biol* 1975; 63: 53–83. <https://doi.org/10.1242/jeb.63.1.53>.
- [58] Fu MH, Liu FM, Hu LL. A novel category of 3D chiral material with negative Poisson's ratio. *Compos Sci Technol* 2018; 160: 111–118. <https://doi.org/10.1016/j.compscitech.2018.03.017>.
- [59] Li H, Yao HL, Cao YB, Jia RY, Dou JX. Chiral metamaterial-inerter nonlinear energy sink for torsional vibration suppression of the rotor system. *Mech Syst Signal Proc* 2023; 200: 110640. <https://doi.org/10.1016/j.ymssp.2023.110640>.