Three-dimensional meta-architecture with programmable mechanical properties

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ABSTRACT
Artificial metamaterials have attracted widespread attention of research communities due to their anomalous physical properties compared to those of conventional materials. In this study, we designed a three-dimensional (3D) lightweight meta-architecture consisting of 6-connected anti-chiral honeycombs. The mechanical properties (e.g., Young’s modulus, compression strength, and Poisson’s ratio) of the proposed meta-architecture could be programmed by adjusting a series of geometric parameters, as shown through numerical simulations. Moreover, an optically sensitive polymer-based 3D meta-architecture with 6-connected anti-chiral features was constructed by the stereolithography method. Owing to the regulation of the negative Poisson’s ratio, 3D meta-architecture achieved a greater ductility under compression than those of traditional truss structures while retaining a relatively high strength and low density. Compression experiments validated the excellent tunability of the mechanical properties of the proposed 3D 6-connected anti-chiral structure. The results suggest the promising applications of this structure in lightweight aircraft, vibration isolation, and mechanical sensors.

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1. Introduction

Metamaterials, as specifically designed artificial materials, have attracted widespread attention because of their anomalous physical properties generated by the rational design of the structure compared to those of conventional materials [1]. In general, metamaterials are composites that have a desired combination of properties that cannot be obtained by combining the properties of their constituents. At present, there are several typical artificial metamaterials that are used in different engineering applications, including mechanical [2,3], acoustic [4–6], magnetic [7,8], thermal [9–11], and optical [12] applications. Mechanical metamaterials have demonstrated many extraordinary properties, such as negative elastic moduli, negative Poisson’s ratios (NPRs), and negative effective mass densities [13]. Among these, NPR metamaterials exhibit programmable properties through the regulation of the deformation behavior at multiple scales, including low densities, high toughness, and large ductility. These play an important role in the development of new-generation engineering materials, such as smart sensors [14,15], aerospace components [16], optical components [17], biomedical materials [18–20], and building materials [21].

The Poisson’s ratio reflects the transverse elastic deformation of materials under vertical compression. With positive values of the shear modulus \( G = E/(2(1 + \nu)) \) and volume modulus \( K = E/(3(1 - 2\nu)) \), classical elasticity theory predicts that the Poisson’s ratios of isotropic materials range from −1.0 to 0.5 [22]. In the 1980s, simple mechanical and thermodynamic models were investigated, which predicted negative Poisson’s ratio behaviors [23–26]. After foams with negative Poisson’s ratios were developed by Lakes [27], it was found that materials and structures with negative Poisson’s ratios exist in nature, such as in bovine nipple skin [28], some rocks and minerals [29,30], and cubic metals [31,32]. With the rapid progress of production technology, more NPR materials have been successfully manufactured, and different properties of the NPR metamaterials have been studied [33–35]. Currently, there are mainly two kinds of artificial NPR materials: ordered and disordered. The disordered NPR materials are mainly foam-like materials, such as polymer foams [36,37] and metal foams [38–40]. Many ordered NPR materials are produced by artificial design based on certain physical principles. Based on the different deformation mechanisms, ordered NPR structures normally include reentrant, rigid rotating, and chiral structures.

The concept of chirality in material structures was first reported by Lakes in 1991 [41], which refers to the asymmetry of the mirror image of the structure with itself. A structure with chiral features is composed of a central node and connected ligaments along the tangential direction. Basically, the origin of chirality is the loss of long-range ordering features in periodic structures. Local deformation changes result in multiscale regulation under compression. A chiral structure, as a novel meta-architecture, normally possesses excellent mechanical properties. Based on the number of tangential connected ligaments, the two-dimensional (2D) chiral materials include 3-, 4-, and 6-connected forms. Of these, a 4-connected anti-chiral material has demonstrated significant NPR effects [42]. The mechanical properties of the structure can be adjusted separately without influencing the Poisson’s ratio characteristics [43]. By making use of the unique mechanical features of chiral elements, various types of 2D and three-dimensional (3D) chiral mechanical metamaterials have
been designed and proposed for industrial applications [44]. However, there are still unexplored fields needing further investigation with the extending of 3D anti-chiral material [45–50].

In this study, we designed a novel 3D 6-connected anti-chiral meta-architecture with a center stiffness beyond those of 2D 4-connected anti-chiral honeycombs. The mechanical properties and deformation mechanism of the meta-architecture were comparatively investigated by theoretical calculations, finite element method simulations, and experiments, which demonstrated the material’s enhanced NPR effects in three directions. The Poisson’s ratio ranged from −0.23 to −0.83. Attributed to the more accessible geometric parameters for structural design in multiple dimensions, the proposed 3D 6-connected anti-chiral structure effectively enhanced the toughness and ductility without weakening the NPR performance, which offers a new approach for designing multifunctional metamaterials with low densities and programmable mechanical properties.

2. Methods

2.1. Structure design

Based on the rules of designing 3D chiral units proposed by Huang et al. [51], many researchers have studied the idiosyncratic physical properties and potential applications of 3D anti-chiral auxetic metamaterials [52–54]. In this study, we designed a novel 3D anti-chiral meta-architecture based on 2D 4-connected anti-chiral honeycombs. The specific details for the structural evolution from 2D to 3D are described as follows. First, a typical 2D 4-connected anti-chiral honeycomb was designed, as shown in Figure 1(a), in which the yellow elements are the central nodes and the gray elements are connected ligaments. Four critical geometric parameters were selected, 2r, L, tc, and tp, which denote the length of the central node, the distance between the centers of the two adjacent central nodes, the wall thickness of the central node, and the wall thickness of the connected ligaments, respectively. Second, a 2D 4-connected anti-chiral structure was rotated about the x- and y-axes, as shown in Figure 1(b). Third, as shown in Figures 1(c) and (d), the 2D 4-connected anti-chiral honeycombs were extended and assembled on the x-y, y-z, and x-z planes. Finally, a 3D 6-connected anti-chiral meta-architecture was successfully obtained, as shown in Figure 1(e), with the projections on the three planes being consistent with the 2D 4-connected anti-chiral honeycomb. After extension from a 2D to a 3D structure, the 3D anti-chiral meta-architecture was periodically constructed by the 6-connected basic units, as illustrated in Figure 1(f). This meta-architecture not only had the chiral structure of the minimum unit but also exhibited the long-range ordering of the basic unit.

2.2. Theoretical modeling

Prall et al. [55] studied the mechanical properties of 2D 4-connected anti-chiral chiral honeycombs. In previous theoretical research on the mechanical properties of 3D anti-chiral meta-architectures, many researchers assumed that the central nodes (or circles) were perfectly rigid body, and only the bending deformation of the ligament was considered [43,52]. When the material of the central nodes (or circles) is soft or the slenderness is large,
this assumption is not accurate enough. In this study, the deformation of all components in the structure was considered. We primarily assume that the strains applied on the 3D 6-connected anti-chiral meta-architecture are small. Figure 2 displays the schematic illustration of basic unit deformation in the 3D 6-connected anti-chiral meta-architecture on the x-y plane projection. Under vertical compression, the central node of the proposed structure only rotates and then drives the connected ligaments to bend. When the central node rotates by a small angle $\xi$, the distance between the two adjacent central nodes is

$$L' = L - 2r \cos \xi$$  \hspace{1cm} (1)$$

where $\xi = \frac{\pi}{2} - \phi$. Under a small strain, $\xi$ tends to 90°, and thus,

$$dL' = 2r \sin \xi d\xi = 2r\phi$$  \hspace{1cm} (2)$$

The basic unit of the 3D 6-connected anti-chiral meta-architecture is isotropic in three directions. Under a compression load in the y-direction, the x- and z-directions have the same deformation, with the strain described as follows:

$$\varepsilon_i = \frac{dL'}{L'} = \frac{2r\phi}{L}, (i = x, y, z)$$  \hspace{1cm} (3)$$

Theoretically, the Poisson’s ratio in the i-j plane approximately equals −1 under a small deformation:

**Figure 1.** The evolution illustration of 3D meta-architecture. (a) Typical 2D 4-connected anti-chiral structure and critical geometric parameters. (b) – (d) Structure evolution from 2D to 3D, including rotation, translation and assembly. (e) The 3D 6-connected anti-chiral structure. (f) Basic anti-chiral unit used for construction of 3D meta-architecture.
\[ v_{ij} = \frac{\varepsilon_{ij}}{\varepsilon_{ii}} = -1 \]  

The in-plane elastic modulus of the basic unit of the 3D 6-connected anti-chiral structure was obtained by the energy method. The elastic energy caused by the bending of a connecting ligament is

\[ W = 2 \int_{2r+L_{eff}/2}^{0} \frac{M^2}{2EI} dl = 2 \left( \int_{2r}^{0} \frac{M^2}{2E_{lc}} dl + \int_{0}^{2r+L_{eff}/2} \frac{M^2}{2E_{il}} dl \right) = 2 \left( \frac{M^2 r}{E_{lc}} + \frac{M^2 L_{eff}}{4E_{il}} \right) \]

where \( L_{eff} \) is the length of the connecting ligament, \( E_c \) and \( E_l \) are the elastic moduli of the materials of the central node and the connecting ligament, respectively, and \( I_c \) and \( I_l \) are the moments of inertia of the central node and connecting ligament, respectively. \( L_{eff}, I_c, \) and \( I_l \) are defined as follows:

\[ L_{eff} = L - 2r, \quad I_c = \frac{t_c^4}{12}, \quad I_l = \frac{t_l^4}{12} \]

The rotation angle generated by the bending of a connecting ligament and the central node is

\[ \varphi = \int_{0}^{2r+L_{eff}/2} \frac{MdI}{EI} = \frac{2Mr}{E_{lc}} + \frac{ML_{eff}}{2E_{il}} \]

The elastic energy stored in a connecting ligament and the central node is

Figure 2. Schematic illustration of the compression deformation in the plane projection of a basic unit of the 3D 6-connected anti-chiral meta-architecture.
\[
W = 4 \left( \frac{2r}{E_{cl}} + \frac{L_{eff}}{2E_{li}} \right) \left( \frac{2E_{li}E_{cl}l_{i} \phi}{2E_{li}r + E_{cl}L_{eff}} \right)^2
\]

\[
= \frac{32E_{cl}(E_{li})^2 r \phi^2}{(2E_{li}r + E_{cl}L_{eff})^2} + \frac{8E_{li}(E_{cl})^2 L_{eff} \phi^2}{(2E_{li}r + E_{cl}L_{eff})^2}
\]

Equation (8)

Note that \( W_c = \frac{8E_{cl}(E_{li})^2 r \phi^2}{(2E_{li}r + E_{cl}L_{eff})^2} \) and \( W_l = \frac{8E_{li}(E_{cl})^2 L_{eff} \phi^2}{(2E_{li}r + E_{cl}L_{eff})^2} \) are the elastic energies stored in a central node and the connecting ligament, respectively.

For a basic unit, the strain energy caused by the strain in direction \( i \) is equal to the elastic energy caused by the connecting ligament bending and the central node rotation in the basic unit:

\[
\frac{1}{2} E_i \varepsilon_i^2 = \frac{\sum (W_c + W_l)}{V}
\]

where \( V = (2L)^3 = 8L^3 \) is the volume of the basic unit, and \( E_i \) is the elastic modulus of the basic unit in direction \( i \). Substituting Equations (3) and (5) into Equation (9) yields the following expression for \( E_i \):

\[
E_i = \frac{48E_{cl}(E_{li})^2}{rL(2E_{li}r + E_{cl}L_{eff})^2} + \frac{12E_{li}(E_{cl})^2}{r^2L(2E_{li}r + E_{cl}L_{eff})^2}
\]

Equation (10) shows that the in-plane elastic modulus of the 3D 6-connected anti-chiral meta-architecture is governed by a series of geometric and physical parameters \((r/L, E_c, E_p, l_c, \text{and } l_i)\). \( l_c \) and \( l_i \) can be adjusted simply by varying \( t_c \) and \( t_p \), respectively. By changing these parameters, the mechanical properties of the proposed material can be programmed accordingly.

2.3. Numerical simulations

Numerical simulations were conducted using the finite element commercial software of ANSYS R19.0. The finite element analysis of the 3D 6-connected anti-chiral structure was implemented with the BEAM188 element as the basic element, which is based on Timoshenko beam theory. The mesh size of the finite element model was 0.2 mm. The primary parameters were set as \( L = 4 \) mm and \( t_c = 0.5 \) mm. The materials of both the central node and the connecting ligaments were consistent with the light-cured resin used to fabricate the experimental samples of the 3D meta-architecture. The density, Young’s modulus, and Poisson’s ratio for the light-cured resin were 1.2 g/cm\(^3\), 100 MPa, and 0.3, respectively.

We established a series of finite element models with the bottom boundary fixed. A negative displacement in the \( y \)-direction \( \Delta_y \) was applied to the model. The total displacements of the structure in the \( x \)- and \( y \)-directions are denoted as \( L_x \) and \( L_y \), respectively. A negative displacement \( \Delta_y \) was applied to the effective area of the top
surface, which is denoted as $A_{\text{eff}}$. The resultant force of the constrained boundary of the structure in the $y$-direction is denoted as $F_y$. Then, strain in the $y$-direction and the equivalent elastic modulus of the 3D 6-connected anti-chiral meta-architecture in the $x$-$y$ plane are defined respectively as follows:

$$
\varepsilon_y = \frac{\Delta_y}{L_y} \\
E_y = \frac{F_y}{A_{\text{eff}}\varepsilon_y}
$$

Corresponding to a negative displacement $\Delta_y$ in the $y$-direction, the displacement on one side in the $x$-direction is denoted as $\Delta_x$, and the engineering Poisson’s ratio is defined as follows:

$$
\nu_{xy} = \frac{\varepsilon_x}{\varepsilon_y} = \frac{2\Delta_x L_y}{\Delta_y L_x}
$$

### 3. Results and discussion

The mechanical properties of the 3D 6-connected anti-chiral meta-architecture were systematically investigated by combined analysis at multiple scales using theoretical calculations, numerical simulations, and experiments. Equation (10) reveals that the mechanical properties of our proposal 3D meta-architecture could be regulated through the optimization of a geometric quantity ($r/L$) and the material properties ($E_c, E_p, \nu_c$, and $I_l$). One type of tunable materials are multi-phase composite material having no voids within their internal structure and yet exhibiting the NPR behavior. Recently, many researchers have investigated multi-phase materials with negative Poisson’s ratios [56–58]. Beyond the basic unit, macroscale structure models containing more units in three directions were established for different $r/L$ values (0.1, 0.15, 0.2, 0.25, 0.3, and 0.35) with $t_v/t_c = 1$ and $E_t/E_c = 1$ and for different $t_v/t_c$ values (0.6, 0.8, 1.0, 1.2, 1.4, and 1.6) with $r/L = 0.25$ and $E_t/E_c = 1$. The meta-architecture samples with related structural parameters were controllably constructed via the stereolithography method from optical sensitive resin.

The mechanical properties of our proposed 3D meta-architecture were validated by comparison with the related traditional frame structure. As shown in Figure 3, the 3D meta-architecture exhibited completely different stress–strain behaviors than the traditional frame structure, with much more ductile performances under compression deformation. In contrast, the traditional frame structure underwent typical brittle deformation without an apparent yield stage. In the initial stage of compression, the frame structure had a high strength compared with the anti-chiral structure but failed rapidly owing to the local instability of elements. When the traditional frame structure was compressed, the vertical ligaments were subjected to only a uniform compressive load. Owing to the high slenderness, local instability of the vertical ligaments occurred easily. The comparison showed that the 3D meta-architecture exhibited multi-stage features of compressive deformation, with a larger ductility. Specifically, with the increase in $r/L$, the distance between elements before contact gradually decreased, the transition stress for the local buckling stage increased to over 0.5 MPa, and the maximum compressibility was around
60%. When \( r/L \) was small, the connecting ligaments were longer and had greater flexibility. Owing to the high slenderness, the connecting ligaments could easily lose stability with a shorter elastic stage. When \( r/L \) was larger than 0.2, the contribution of the center node to the entire stiffness increased with a significant enhancement of the stability and moment of inertia of the basic unit.

In detail, the multiscale deformation mechanism of the 3D meta-architecture was further investigated by finite element simulations with \( r/L = 0.25 \) as an example. The strain–stress curves from the experiments overlapped with those in Figure 3. The structural evolution also exhibited a multi-step behavior during compressive deformation rather than the one-step process of the traditional frame (Figure 4). Fundamentally, the difference between them originated from the different loading transfer processes and overall distributions. As shown in Figure 4(a), the vertically aligned elements individually bore compression loads. In contrast, all the elements, including the center node and the connecting ligaments, of the 3D meta-architecture bore the load, which also demonstrated the better deformation capacities with more freedom around the stiffness centers. The multi-step deformation behaviors are directly shown in Figures 4(b)–(d). The first stage (referred to as the linear elastic stage) mainly resulted from the bending of the connecting ligaments initially due to a small deflection. The second stage (referred to as the nonlinear elastic stage) showed large deflection bending of the connecting ligaments and the derived small-level rotation of the central node. The third stage (referred to as the bucking stage) was caused by the instability of the structural members under large deformation, corresponding to a slight drop or stress plateau of the

![Figure 3. Stress–strain curves of the 3D 6-connected anti-chiral meta-architecture with \( t_l/t_c = 1 \) and \( E_l/E_c = 1 \): (a)–(f) \( r/L = 0.1, 0.15, 0.2, 0.25, 0.3, \) and 0.35, respectively.](image-url)
stress–strain curve. After that, the structure evolved to the solidification stage, with a compaction deformation due to the contact and extrusion of the elements. The related stress sharply increased as the structure became dense.

To understand the influences of the geometric parameters on the mechanical properties, both the Poisson’s ratio and Young’s modulus were systematically investigated. As shown in Figure 5 (a), the experimental deformation of the 3D meta-architecture was coincident with the finite element simulation results in Figure 4, including the macroscopic configuration, element bending mode, and center node rotation. In contrast to the traditional frame in Figure 4(a), the 3D 6-connected anti-chiral meta-architecture shrank in the two directions perpendicular to the compression direction because the connecting ligament bending caused rotation of the center node. This indicated the significant NPR effect. The middle regions of the samples exhibited significant deformation. Owing to the new deformation form, the NPR effect of our proposed 3D meta-architecture was immediately

![Finite element simulation results under compression deformation: (a) traditional frame structure at 10% strain and (b)–(d) structural evolution from the entire structure to the elements at 5%, 10%, and 20% strains, respectively.](image)
triggered if compression loading was applied. The Poisson’s ratio values tended to be stable at a compression strain of around 10%, which was selected as the key point to extract the transverse strain and calculate the Poisson’s ratio.

Figures 5 (b) and (c) show the results of the relative elastic modulus of the 3D 6-connected anti-chiral structure with different r/L and t/t_c values. The relative elastic modulus values of the material obtained by theoretical calculations, finite element simulations, and experiments exhibited the same variation trend, with reasonable differences. With the decrease in r/L, the length of the central node decreased and the length of the connecting ligaments increased. This resulted in a decrease in the relative elastic modulus because the weakening of the center stiffness led to ligament instability and center rotation. In comparison, with the increase in t/t_c, the relative elastic modulus increased. The reason was the stiffness of the connecting ligament increased with a cubic power law, which limited the rotation of the central node and the deformation of the connecting ligament.

Figure 5. (a) Optical images of printed samples during compressive experiment. Comparison of relative elastic moduli with different (b) r/L and (c) t/t_c values. Comparison of Poisson’s ratios with different (d) r/L and (e) t/t_c values.
Figures 5 (d) and (e) show the results of the Poisson’s ratio of the 3D 6-connected anti-chiral structure obtained by the finite element simulations and experiments. The bending deformation of the connecting ligaments caused the central node to rotate inward, which determined the NPR performance of 3D meta-architecture. Remarkably, the results clearly indicated that upon increasing $r/L$ and $t_l/t_c$, the NPR effect was restrained, and the NPR increased from $-0.82$ to $-0.23$. This was mainly because the connecting ligaments played a leading role in the emergence of the NPR effect. Increases in both $r/L$ and $t_l/t_c$ led to the shorter and tougher connecting ligaments, and the stiffness between the connecting ligaments and the center node became similar to the rotation of the central node when the connecting ligament deformation was restrained.

To further optimize the mechanical properties of the 3D meta-architecture via the rational selection of the geometric parameters, we conducted orthogonal numerical simulations with the coupling influence of different $r/L$ and $t_l/t_c$ values. The mappings were used to determine the relative elastic modulus and the Poisson’s ratio of the structure at a 10% compressive strain. As shown in Figure 6(a), the contour plot indicated that the relative elastic modulus was negatively dependent on $r/L$ but positively dependent on $t_l/t_c$. The optimal point of the maximum modulus was at a minimum $r/L$ of 0.1 and a maximum $t_l/t_c$ of 1.6. In contrast, Figure 6(b) shows that the smaller $r/L$ and $t_l/t_c$ values resulted in a more significant NPR effect, with NPR values as low as $-0.83$. The 3D meta-architecture had a large tunable range from $-0.83$ to $-0.23$ depending on the rational selection of the geometric parameters. In addition, there was an exception for the Poisson’s ratio regulation with $r/L < 0.175$, the impact of $t_l/t_c$ became small, and the regulation was mainly dominated by $r/L$ in the range from 0.1 to 0.175. The high designability of the 3D meta-architecture to meet different needs in practical applications was therefore validated.

Figure 6. Three-dimensional contour plots of the (a) relative elastic modulus and (b) Poisson’s ratio of the 3D 6-connected anti-chiral meta-architecture for various $r/L$ and $t_l/t_c$ values.
4. Conclusion

In this article, we presented a 3D 6-connected anti-chiral meta-architecture that consisted of six connecting ligaments and a center cubic node. The minimum unit possessed a typical chiral feature, while the basic unit had repeatability with its mirror image. A theoretical model of the modulus for the basic unit as a center stiff structure was established based on an energy method, which gives the critical parameters programming the mechanical properties depending on \( r/L \) and \( t/t_c \). Through theoretical calculations, finite element simulations, and experiments, the systematic investigation of the mechanical properties validated the greater negative Poisson’s ratio effect, higher toughness, and larger ductility of our proposed 3D anti-chiral meta-architecture than those of the traditional frame structure. The negative Poisson’s ratio had a broad tunable range from \(-0.83\) to \(-0.23\) based on the optimization of the geometric parameters. The compression curve and finite element simulations revealed the structural evolution mechanism with multi-step deformation features during compression, including connecting ligament bending and center node rotation. The proposed meta-architecture therefore shows potential for application in lightweight aircraft, vibration isolation, and mechanical sensors.

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