Original Research Article

A review of research on porous structure negative Poisson's ratio metamaterials

Abstract: Metamaterials with a porous structure possess a number of advantageous properties, including low mass, high specific strength, and a high energy absorption rate. When subjected to impact or compression, these materials exhibit excellent mechanical properties, which has led to their use in a variety of aerospace applications in recent years. In comparison with traditional porous materials, metamaterials possess mechanical and physical properties that traditional materials lack. This distinguishes them from traditional materials and provides new ideas for solving engineering problems. Starting from this deformation mechanism of concave contraction of such structures, this paper details the modeling of several types of porous negative Poisson's ratio superstructures, such as honeycomb, foam and tubular structures, and focuses on the mechanical properties of porous structures in terms of elasticity, impact resistance, and energy absorption when subjected to external forces. The paper commences with an exposition of the mechanism of negative Poisson's ratio effect of porous structure, accompanied by a discourse on the extant research status of several prevalent types of porous negative Poisson's ratio superstructures. Thereafter, the deformation mechanism of porous negative Poisson's ratio metamaterials under compressive load and impact is examined. conditions is introduced, and finally, the practical application of porous negative Poisson's ratio metamaterials in the fields of automobile industry, shipbuilding and other engineering fields are summarized, and the future of porous negative Poisson's ratio metamaterials is reviewed based on the existing research results. Finally, the practical applications of negative Poisson's ratio metamaterials with porous structure in engineering fields such as automobile industry and shipbuilding are summarized, and the future development trend and application prospects are prospected based on the existing research results.

Keywords: Porous structure; Negative Poisson's ratio; Energy absorption; Impact resistance

0 Introduction

Negative Poisson's ratio materials, as a kind of newly discovered metamaterials in recent years, refers to a class of materials with anomalous Poisson's ratio phenomenon. Most of the materials in the longitudinal direction will be subjected to longitudinal stretching, its transverse direction will be contracted, as shown in Fig. 1(a), and the negative Poisson's ratio materials will be subjected to longitudinal tension, its transverse direction will be swollen, as shown in Fig. 1(b). This unique mechanical property enables the negative Poisson's ratio metamaterials to exhibit higher toughness and energy absorption capacity when subjected to external forces[1]. Negative Poisson's ratio metamaterials with porous structure are high-performance materials developed in recent years. It is a kind of material with regular multi-cellular lattice structure in the internal arrangement, and the porous part of the lattice can be filled by air or other media, and the negative Poisson's ratio effect is realized by the internal rods in the process of stretching or compression deformation and the concave filling of the interstitial part. Because its internal structure is porous, it is more likely to shrink and absorb more energy when subjected to larger impacts.

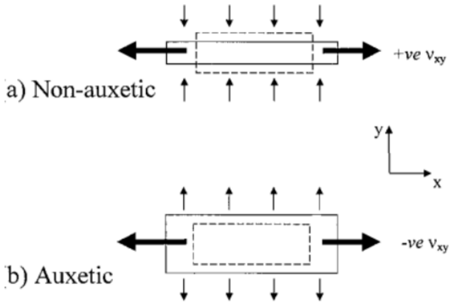


Fig. 1 Deformation of positive Poisson's ratio and negative Poisson's ratio materials under tensile loading[2]
(dotted line indicates before deformation, solid line indicates after deformation)
a) Positive Poisson's ratio material
b) Negative Poisson's ratio material

As the core of negative Poisson's ratio metamaterials, the negative Poisson's ratio cytosolic structure directly determines the overall performance. In recent years, a large number of artificial negative Poisson's ratio cellular structures have emerged on the basis of the abstraction and evolution of the microstructure of natural negative Poisson's ratio materials, which greatly enriches the variety of mechanical metamaterials. At the same time, the research on negative Poisson's ratio metamaterials with porous structure shows a trend of multidisciplinary cross-fertilization and gradually expands from mechanics to thermal and acoustic fields. In this regard, starting from the generation mechanism of negative Poisson's ratio effect, we focus on summarizing the research progress of negative Poisson's ratio cellular structure, combining with the specific application background, we introduce the application of negative Poisson's ratio metamaterials in many fields such as materials science, engineering and biomedicine, in order to expect more scholars to pay attention to and study negative Poisson's ratio metamaterials.

1 Negative Poisson's ratio mechanism for porous structured metamaterials

1.1 Elastic and shear moduli

The special properties of negative Poisson's ratio materials compared with the traditional positive Poisson's ratio materials are mainly in the elastic and shear moduli, indentation resistance, and energy absorption[3].

In homogeneous isotropic materials, elastic modulus and shear modulus are two important material parameters, for which only two of the three quantities, shear modulus G, modulus of elasticity E, and Poisson's ratio ν, are independent, and the following relationship exists between them:

$$G = \frac{3K(1-2\nu)}{2(1+\nu)}$$

$$E = 3K(1+2\nu)$$

where K is the bulk modulus (the reciprocal of the compressibility).As shown in Fig. 2, the shear resistance increases significantly as the Poisson's ratio goes from positive to negative.In conventional isotropic materials, the modulus of elasticity is at least twice the shear modulus. When the Poisson's ratio is negative, the two moduli become close; when ν = -0.5, the modulus of elasticity is equal to the shear modulus, i.e., the material becomes highly compressible but difficult to shear; and when the Poisson's ratio continues to decrease, the shear modulus exceeds the elastic modulus.

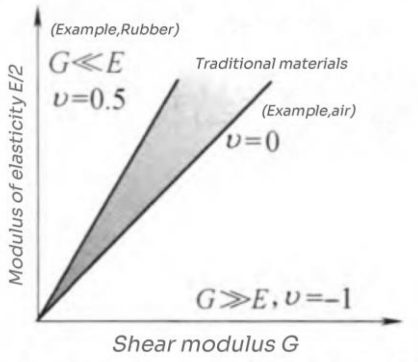


Fig. 2 Relationship between shear modulus G, modulus of elasticity E, and Poisson's ratio ν of the material[3]

The modulus of elasticity of a material is not always constant, but is also closely related to the density ratio and the rate of volume change of the material. In general, when the material is still in tension, the modulus of elasticity decreases with the increase of the volume compression ratio; when in compression, it increases with the increase of the volume compression ratio. In other words, under compression, negative Poisson's ratio metamaterials aggregate inwardly, increase in transient density, and exhibit higher strength externally. In view of the unique mechanical and physical properties of the porous structure, which is high-strength and lightweight, coupled with the possibility of optimizing the design of its internal structure, it has gradually attracted extensive attention and research from scholars at home and abroad.

1.2 Indentation resistance

The hardness of a material can be expressed as an expression for the relationship between the modulus of elasticity and the negative Poisson's ratio: $H = \left[E/2(1-\nu)^{2}\right]^{\gamma}$.According to the expression, it can be seen that the indentation resistance becomes more and more obvious with the increase of the absolute value of the negative Poisson's ratio, and when the Poisson's ratio ν tends to -1, the hardness of the material tends to infinity, that is, its indentation resistance tends to infinity. Compared with the positive Poisson's ratio material, the porous structure of the negative Poisson's ratio material in the impact load, the energy absorption rate is higher. As shown in Fig. 3, the material at the impact point of positive Poisson's ratio will diffuse to the surrounding, while the structural deformation of negative Poisson's ratio material is favorable to the centralized contraction in order to absorb more energy and thus improve its energy absorption effect. This special property makes the negative Poisson's ratio material with porous structure has a potential advantage in impact protection, when the positive Poisson's ratio material is impacted, the density of the material at the point of force will be reduced, which makes the material easier to be broken. Conversely, when a negative Poisson's ratio material is subjected to a localized impact load, the material around the point of stress accumulates near the point of stress. This results in an increase in the density of the material near the point of stress, which increases the strength at that point. As a result, negative Poisson's ratio materials have a greater resistance to indentation and are less likely to be shattered.

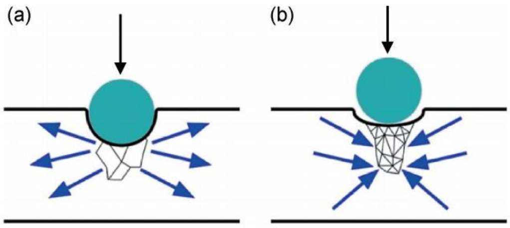


Fig. 3 Deformation pattern of a structure subjected to impact loading[4]
(a) Positive Poisson's ratio material (b) Negative Poisson's ratio material

Negative Poisson's ratio metamaterials exhibit excellent permeability tunability properties by virtue of their unique porous structure. Specifically, when negative Poisson's ratio metamaterials are stretched, their pores expand in the vertical dimension, leading to an increase in pore size in both the lateral and vertical directions. Thanks to the negative Poisson's ratio effect, this permeability tunability is not only applicable to macroscopic materials, but also to nanomaterials. The indentation resistance of porous negative Poisson's ratio metamaterials, such as dense lattice structure negative Poisson's ratio materials, fiber reinforced composites, etc., has been well proven by using the characteristic of pore size change with external force, and negative Poisson's ratio metamaterials have shown great potential in the field of filters and the manufacture of smart medical bandages.

1.3 Energy absorption

Negative Poisson's ratio lattice structure compared to traditional materials, in the energy absorption performance shows a unique superiority, this advantage is partly attributed to the porous characteristics of negative Poisson's ratio lattice material, the characteristics of the material in the impact can more easily achieve significant compression deformation[5]. Woodpeckers, for example, peck an average of 1.6 million times in their lifetime, and peck very fast, resulting in the inevitable head shock, but the woodpecker does not feel a headache. The reason for this is that the woodpecker's skull has a mesh multi-cellular structure, which can effectively absorb the vibration energy generated during the impact process[6].

1.4 Lightweight

Porous structure of the negative Poisson's ratio of most of the material for the loose structure, relative to the base material is more lightweight, and in the design of the aircraft wing, need to consider the wing in the high-speed, low-pressure and low-temperature environment of the strength of the toughness, while taking into account the weight of the aircraft itself as a whole, many of the current design of the wing are used in the design of this porous negative Poisson's ratio of the mesh structure as the inner core to achieve a higher strength and lightweight mass.

2 Progress in the study of porous negative Poisson's ratio cytostructures

The interior of a porous structure usually consists of periodic arrays of negative Poisson's ratio structural cytosolic elements, which can be assembled in different ways to form a three-dimensional negative Poisson's ratio structure. The rotation, inversion and arraying of 2D meshes are one of the common ways to map the 2D negative Poisson's ratio structure into 3D space, and the negative Poisson's ratio effect of the material can also be altered by adjusting the behavior of the negative Poisson's ratio structural cytosolic elements in terms of their shapes, sizes, and arrangements.

In daily life, natural porous structures are relatively common, such as honeycombs, plant stalks, bone tissues, etc. In the field of engineering, a wide variety of biomimetic porous materials have been prepared on the basis of the structural characteristics of natural porous, which has largely improved the application of this type of lightweight structures. Common porous structure can be divided into honeycomb, foam, dot matrix and tubular structure, honeycomb named after the natural world in the honeycomb, is a more typical bionic materials, mainly manifested in various types of polygonal structure in the same plane of the dense pavement and outside the face of the stretching and the formation of the front and rear panels will be added to the composition of the sandwich panel to enhance its mechanical properties in the practical application[7]. Among the larger sizes porous structures with negative Poisson's ratio properties were proposed in 1982 in the form of two-dimensional silicone rubber, and also aluminum honeycomb structures through the use of flexural deformation of rods. Foam structures are mostly formed by a matrix with internal closed or non-closed pores, and are characterized by high specific strength, high specific stiffness, and high energy absorption efficiency[8]. The dot matrix structure is a porous structure formed by the periodic arrangement of the same dot matrix cells[9], which will undergo plastic deformation inside the structure under the external load to absorb the impact energy, and the internal pores can also be filled with other substances to improve the performance of various aspects or to give the dot matrix structure of other special properties, to achieve the integration of structural functions. The cellular elements of porous structures, such as honeycombs, can often be extracted individually as energy-absorbing tubes, and tubular structures can also be expanded into various types of porous structures by means of geometrical topology.

2.1 Honeycomb structure

Honeycomb structure initially originated in bionics, because of its special pore space in the sound absorption and noise reduction advantages, with the continuous deepening of research in recent years, a variety of structures in the radial plane of the periodic arrangement of the composition of the honeycomb structure, also has a good energy-absorbing properties, which is also used as a sandwich structure of the core layer and is widely studied. The hollow form of metal honeycomb structure, combined with the concept of wave-absorbing can play a certain wave-absorbing stealth effect, such as the use of metal honeycomb made of electronic equipment shells, anti-electromagnetic radiation, electrostatic protection device. Honeycomb structure as a periodic porous structure, the solid part of the cross-sectional area is relatively small, the equivalent density is very low, and the wall plate is thin, from the overall point of view of the quality is very light, can be used as a kind of ideal damping cushioning material, in a variety of collision cushioning structure has a broad application prospect[10][11].

In the 1980s Gibson[12] have proposed negative Poisson's ratio concave hexagonal honeycomb structure (shown in Figure 4), this structure is subjected to stretching when the concave angle unfolds, at the same time, a certain relative bending of the folded rod occurs, which is the main reason for the structure to produce negative Poisson's ratio effect. Compared with other forms of negative Poisson's ratio structure, the deformation of the concave hexagonal open structure is relatively simple, there is no depression, and it is easy to control the overall rotation and other situations. Most of the traditional cushioning structures use positive hexagonal honeycomb, but when subjected to coplanar compression, it is prone to low platform stress, instability and other phenomena, which will lead to poor performance of the cushioning.

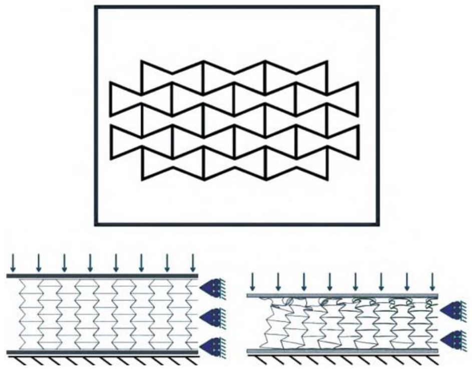


Fig. 4 Negative Poisson's ratio concave hexagonal honeycomb structure[12]

The mechanical properties of honeycomb structures are mainly characterized by their loading force-displacement curves, as shown in Fig. 5, which is the initial-displacement curve of a typical elastic-plastic honeycomb structure under anisotropic compressive loading. For the elastic deformation stage, the pore wall itself undergoes bending deformation at the initial stage of loading, and the load does not reach the flexural strength of the honeycomb structure before it exhibits the trend of increasing linearly with the increase of displacement, and the honeycomb structure absorbs the energy through elastic deformation at this stage, and the main elastic buckling occurs. Into the steady state plastic deformation stage thick, the load gradually tends to stabilize, this stage to axial regular plastic collapse deformation to absorb energy, which is the main stage of the honeycomb structure buffer energy absorption. With the gradual increase of deformation, the honeycomb is finally compacted and enters the dense stage, which is an important index for calculating the specific energy absorption of the cushioning device.

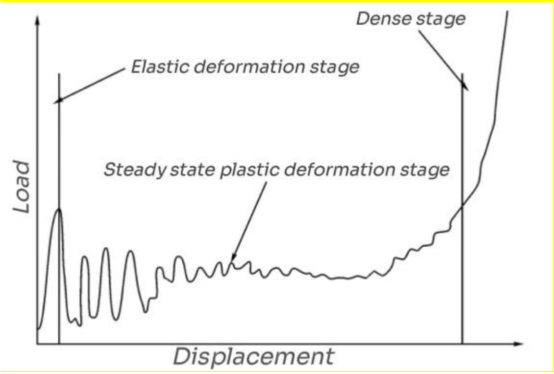


Fig. 5 Load-displacement curves of a typical elasto-plastic honeycomb structure under anisotropic compressive loading[13]

Compared with the general honeycomb, the negative Poisson's ratio honeycomb structure under unidirectional compression loading will go through the line elasticity stage, the stress plateau stage and the densification stage sequentially. Figure 6 shows the stress-strain curves of the positive and negative Poisson's ratio honeycomb structure under unidirectional compression. In the linear elasticity stage, both Poisson's ratio honeycomb structures increase with the increase of strain, and at the same time, with the aggravation of the extrusion deformation, the density also increases; to reach the stress plateau stage, the negative Poisson's ratio honeycomb structure has higher plateau stress, which means that the negative Poisson's ratio honeycomb structure in this stage can absorb more energy, so it has better energy absorption characteristics. This means that at this stage, the negative Poisson can absorb more energy than the honeycomb structure, so it has better energy absorption characteristics. This characteristic is attributed to the unique structure of the porous negative Poisson's ratio metamaterials, which can better resist deformation and damage when subjected to external forces, thus enhancing its energy absorption efficiency.

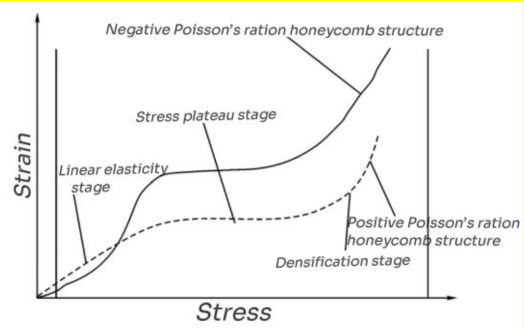


Fig. 6 Stress-strain curve of honeycomb structure[14]

Frost and Ashby[15] were the first to discover and present the effect of negative Poisson's ratio on cellular structural materials in 1982, which was an important discovery to advance the research on negative Poisson's ratio cellular structures.Dong[16] et al. investigated the change of negative Poisson's ratio effect during quasistatic compression of negative Poisson's ratio concave hexagonal cellular structures with different cellular wall thicknesses.Zied[17] et al. proposed a new type of concave angular cellular structure to enhance the in-plane stiffness and maintain the negative Poisson's ratio effect. Yaxin Guo[18] et al. concluded that the specific energy absorption of concave hexagonal honeycomb structure is higher than that of orthogonal and orthogonal honeycomb structures, and the energy absorption effect is optimal.Qi[19] and Liu[20] et al. also concluded that the negative Poisson's ratio concave hexagonal honeycomb has a better energy absorption capacity than that of the traditional hexagonal honeycomb by using the numerical simulation.Li[21] et al. proposed two types of concave hexagonal structures with negative Poisson's ratio, and investigated their energy absorption capacity, which showed that with the increase of compression velocity, the energy absorption capacity of concave hexagonal honeycomb can be improved. The results show that their energy absorption capacity increases as the compression rate increases.

2.2 Foam structure

A porous foam structure is a reticulated structure consisting of a certain number of pores, which may be interconnected or individually closed, bounded by pillars or flat plates. Most porous structures are anisotropic and they have higher out-of-plane stiffness than in-plane stiffness. By optimizing the structural topology of the cellular solids, adjustable negative Poisson's ratios from positive to negative can be obtained. With the advancement of composites technology, the incorporation and mixing of various reinforcing structures such as cladding tubes and various reinforcing particles have led to a significant improvement in the performance of foam structures[22].

In 1987 Lakes[23] first developed polyurethane foam materials with negative Poisson's ratio properties by utilizing the inner concave structure, he obtained negative Poisson's ratio materials with special microstructures by treating ordinary polymer foams and measured the Poisson's ratio value of -0.17, and since then two and three dimensional cellular structures with negative Poisson's ratio have been prepared[24][25], and all of these structures have demonstrated excellent mechanical properties such as High-pressure trace resistance, fracture toughness, and energy absorption.Brosten[26] et al. conducted a comprehensive study of the mechanical behavior of foam metals, including the relationship between their mechanical properties, preparation methods and a brief study of porosity and structure.Liu[27] et al. established an expression for the mechanical properties of porous foam metals with isotropic three-dimensional cytosol structure under multiaxial tensile loading, and derived the mechanical properties of the porous materials during multiaxial tensile damage. The lower relationship between principal stresses and pores in multiaxial tensile damage, and also obtained the strength criterion of the foam metal in this loading case.Chen[28] et al. prepared porous graphene oxide foam by freeze-drying method, and investigated the compressive mechanical properties of graphene oxide foam with different densities by means of uniaxial compression experiments and finite element simulations.Skibinski[29] et al. discussed the mechanical properties of open-cell porous materials, and utilized the computer to design the mechanical properties. The numerical design problem of the properties, the morphology of the foam was investigated using computed tomography post-processed images, and the structural parameters of LVT (Laguerre-Voronoi tessellations) were compared with those of the commercial material. Subsequently, finite element calculations were performed on both structures to verify the validity of the LVT design algorithm.Mizzi[30] et al. proposed a new class of mechanical metamaterials with a variety of star-shaped perforations, which have the potential to exhibit negative Poisson's ratio or zero Poisson's ratio properties. Through finite element modeling and experimental measurements on 3D printed prototypes, it is demonstrated that these star-shaped porous systems maintain their unusual mechanical properties at tensile strains exceeding 15%.Li[31] et al. successfully fabricated balsa-mimetic, multilayered, orthogonal, and radially-aligned porous plastics with balsa-mimetic, multilayered, orthogonal, and radially-aligned porous structures through a controlled controlled-monomer/water emulsion freezing process, followed by cryopolymerization and room-temperature thawing, which endowed the plastics with a complex porous structure and compositional distribution. The porous plastics with microstructures showed many excellent properties such as low density, high strength, negative Poisson's ratio, etc. Chen[32] et al. investigated the Poisson's ratio characteristics of microcellular foams under the conditions of intra-pore pressure and low porosity. The results showed that the Poisson's ratio of microcellular foams is a time-dependent parameter, and the overall Poisson's ratio may be negative due to the effect of intra-pore pressure, and the Poisson's ratio under uniaxial tension is different from the Poisson's ratio under uniaxial compression.

Thermoplastic foams (polyester-type urethane), thermoset foams (silicone rubber) and metallic foams (copper) with negative Poisson's ratio properties have since been reported in the literature[33]. It was concluded that the bending of the cell wall is the main deformation mechanism[34][35], as shown in Fig. 7, and similar to the honeycomb structure, the Poisson's ratio effect of foams is also realized by transforming the convex polyhedral cells of conventional foams into concave polyhedral cells.

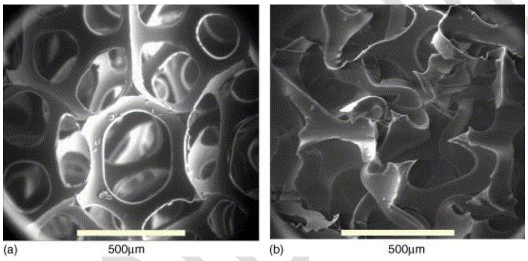


Fig. 7 Scanning electron micrographs of normal polymer foam (left) and negative Poisson's ratio polymer foam (right)[36]

2.3 Tubular structure

The traditional tubular structure is widely used for impact resistance and energy absorption due to its simple structure, easy processing and low cost. However, the traditional thin-walled tubular structure with simple geometrical cross-section configuration has more general characteristics in energy absorption, so a lot of research has been done on the improvement of tubular structure, and a series of new types of tubular structure have been gradually formed, which mainly include corrugated tubes, folded tubes, and grooved tubes, etc[37]. The corrugated tubes show water ripples in the axial direction. The pipe wall of corrugated pipe shows water ripples in the axial direction and is no longer smooth, with periodic changes in the pipe diameter, which greatly improves the deformation of the overall structure[38]; groove pipe has various microstructures set up on the pipe wall, which makes the deformation mode of the compression collapse can be controlled[39]; folded pipe absorbs a large amount of energy through its own layer by layer bending and folding deformation, which has a variety of cross-sectional forms and brings a variety of deformation modes and energy-absorbing characteristics. The folded tube absorbs a large amount of energy by folding and deforming itself in layers[40].

Thin-walled tubular structure can be regarded as a special kind of porous material, when it is subjected to impact load, it will absorb and dissipate energy through its own plastic deformation, its energy absorption efficiency is closely related to its own geometric configuration, the form of impact load and other factors, the compression and energy absorption characteristics of thin-walled tubular structure under impact load have also been studied a lot. Since the 1960s, foreign scholars have taken the lead in conducting systematic experiments and studies on the axial compression characteristics of thin-walled tubes.Alexander[41] conducted axial compression studies on thin-walled circular tubes with the simplest structure and proposed a theoretical model of axial buckling deformation with the formula of the average folding wavelength h. The study was based on a theoretical model of axial buckling deformation with the formula of the average folding wavelength h, which is the same as that of the average folding wavelength:

$$h = \frac{\pi\sqrt{Dt}}{2[3(1-\nu^2)]^{\frac{1}{4}}}$$

where D is the tube diameter, t is the wall thickness and ν is the Poisson's ratio. Subsequently, Johnson[42] and Singace[43] et al. carried out a more in-depth study on thin-walled circular tubes, further summarized their deformation modes, and revised the theoretical formula for the mean crush force.Grima[44] et al. designed a two-dimensional perforated plate material by randomly cutting the material with randomly distributed slits on the perforated plate, and succeeded in making a negative Poisson's ratio supersurface with a large negative Poisson's ratio effect. Ren[45] et al. coordinate transformed the above planar perforated plate structure and proposed a three-dimensional tubular structure, which has a more desirable negative Poisson's ratio effect.Hur[46] et al. effectively controlled the bending and torsional stiffness of the negative Poisson's ratio tubular structure by changing the geometrical parameters of the negative Poisson's ratio cytoskeleton.

3 Characterization of mechanical properties of porous structured mechanical metamaterials

Porous structured negative Poisson's ratio metamaterials, as a new type of material with special mechanical properties, have made great progress in recent years in the research of elastic properties, impact resistance and energy absorption. This material not only demonstrates unique mechanical properties in theory, but also shows a wide range of application potential in practical applications.

3.1 Elastic properties

In view of the extraordinary properties exhibited by negative Poisson's ratio metamaterials with porous structure, it is extremely important to analyze the mechanics of the structure under different loading conditions. In the study of small deformations in the online elastic range, scholars usually simplify the negative Poisson's ratio structure to a homogeneous plate. Through this simplification, researchers can characterize the elastic properties of the structure using three equivalent elastic parameters: equivalent elastic modulus, equivalent shear modulus, and equivalent Poisson's ratio.

In 1982, Gibson[47] was the first to propose a concave honeycomb structure with tensile expansion effect and the classical Gibson's formula for calculating its equivalent modulus of elasticity. However, this formula mainly focuses on the effect of bending moments in a small deformation framework, and the role of axial forces is neglected. Based on the three deformation mechanisms of bending, tension and articulation of hexagonal honeycomb structures, Evans[48] constructed a theoretical model of negative Poisson's ratio structures with respect to the equivalent elastic constants by analyzing the force constants. This theoretical framework is further extended to give the theoretical analytical solutions for a variety of honeycomb structures with respect to the equivalent elastic constants, and the results show that different deformation mechanisms can be utilized to control the relative magnitude of the force constants, thus realizing the regulation of the structural performance. Qiu Kepeng[49] et al. comprehensively considered the coupling effect of shear stress and axial stress, and derived the theoretical equations of the six-chiral structure about the equivalent elastic modulus based on the Euler beam and micropolar theory methods.Fu[50] et al. combined the concave hexagonal honeycomb structure with the rhombic structure, and designed a new type of negative Poisson's ratio honeycomb structure. They combined theoretical analysis and numerical simulation to systematically investigate the mechanical properties of this structure under static loading, and the final results showed that this novel structure has enhanced equivalent elastic modulus and critical flexural strength compared with the traditional concave honeycomb structure.

3.2 Impact resistance

Porous structure negative Poisson's ratio metamaterials show significant superiority in impact resistance. When traditional materials are subjected to impact, plastic deformation or fracture often occurs, resulting in poor energy absorption. While the negative Poisson's ratio material in the impact, its unique microstructure makes the material can be in the transverse direction of the expansion, thus effectively dispersing and absorbing the impact energy. This characteristic makes the porous structure of negative Poisson's ratio metamaterials in the impact load, can produce a larger transverse deformation, and then absorb more energy to improve the impact resistance of the structure.

Gao[51] et al. proposed a negative Poisson's ratio cylindrical structure collision box based on double V cells, which has higher energy absorption and stability under impact loading compared to thin-walled circular structures.Lee[52] et al. used a cylindrical tube with concave hexagon as the basic cell to improve the collision performance under low-speed impact conditions, and found that the specific energy absorption was higher than that of the conventional tubular structure and improved the low-speed. Zhang[53] et al. used the rotational method to design a new type of tubular structure, which has a negative Poisson's ratio effect in both the wall thickness and radial direction, and shows good stability under axial pressure. Zhang Xinchun[54] et al. investigated the effects of the cytosolic expansion angle and impact velocity of a hexagonal honeycomb structure with a concave face and found that the platform stress of the structure was proportional to the cytosolic expansion angle, and the energy absorbed by the structure increased with the increase in the impact velocity, while keeping the wall length and wall thickness constant. Cui Shitang[55] et al. investigated the effect of cell element expansion angle and impact velocity on the face deformation of honeycomb structures with internal concave hexagonal honeycomb structures, and found that the platform should decrease with the increase of cell element expansion angle and increase the platform stress and energy absorption with the increase of impact velocity, while keeping the relative density and wall length the same. Hou Xiuhui[56] et al. gave a new empirical formulation for solving the dynamic strength of multiconcave angular honeycomb structures based on the R-P-I model and numerical simulation methods, and found that the platform stresses of the concave hexagonal structure are proportional to the square of the impact velocity. The deformation modes can be classified into three categories by the impact speed: at low impact speed, the structure shows the phenomenon of instability; at medium impact speed, the deformation of the specimen shows the “V” shear deformation mode; at high impact speed, the deformation of the specimen shows the “I” and “V” type. When the specimen is impacted at high speed, the deformation of the specimen shows a mixed deformation mode combining “I” type and “V” type deformation. Qiao[57] et al. also analyzed the impact resistance of the double-arrow structure through finite element simulation, and derived the theoretical formulas of the structure with respect to the elastic modulus and yield stress, which provided an important theoretical basis for engineering applications.

3.3 Mechanical properties of energy

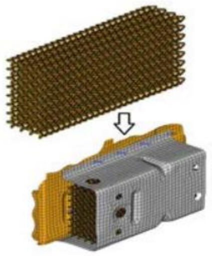
absorption

The energy absorption of porous structure negative Poisson's ratio metamaterials mainly originates from its unique microstructure and deformation mode, when subjected to external load, the concave fiber rods of the material will be straightened, resulting in transverse expansion in the thickness direction. This deformation mode not only improves the stability of the material, but also allows the material to absorb more energy during deformation. The porous structure itself also provides more energy-absorbing paths, allowing the material to disperse and absorb energy more efficiently upon impact.

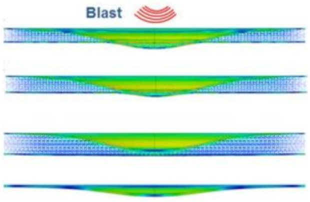
Bezazi and Scarpa[58] analyzed the energy absorption characteristics of conventional polyurethane foams and negative Poisson's ratio polyurethane foams in comparison by cyclic compression tests, and found that the energy dissipation rate of negative Poisson's ratio foams was 16 times higher than that of conventional foams. Yang Hang[59] et al. studied the spindle quasi-static energy absorption characteristics of stainless steel three-dimensional curved-wall double-arrow honeycomb structure, and the structure showed that the structure approximates an ideal elastic-plastic material under compression load, and the platform stress can reach 70%.Yuan[60] et al. found that the compression mechanical properties of thermoplastic polyurethane three-dimensional flexible flexure crystals were tested and found that the structure had a higher energy absorption efficiency under cyclic compression load, which is expected to be used in the Zhou[61] proposed the use of double-arrow honeycomb structure as the side door impact beam of automobiles, and through simulation analysis, it was found that this design can largely improve the crashworthiness of the vehicle.Gao[62] et al. designed a new type of energy-absorbing device by taking advantage of the impact mechanics of the double-arrow honeycomb structure, and explored the possibility of its application in automobile bumpers through finite elements.Qi[63] et al. designed a new type of energy-absorbing device for stainless steel inner concave honeycomb sandwich structure. conducted a vulgar impact and explosion test study for stainless steel concave honeycomb sandwich panels, and found that the explosion energy absorption characteristics of the concave honeycomb sandwich structure were 2.5 times higher than those of the solid panels, and the impact energy absorption characteristics were 19.1% higher than those of a conventional pair of honeycomb sandwich layers with comparable density.

4 Current status of engineering applications of porous structural mechanical metamaterials

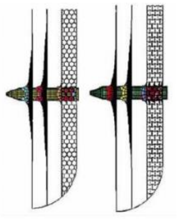
Porous structure negative Poisson's ratio metamaterials due to its excellent mechanical properties, such as shear resistance, impact resistance, fracture resistance, and energy absorption and vibration isolation, etc., in the case of impact, due to its unique deformation behavior, i.e., uniaxial compression occurs transversely contraction, uniaxial stretching occurs transversely expansion, it is able to effectively absorb and dispersed impact energy. In the field of automotive industry negative Poisson's ratio energy-absorbing structure has more engineering applications, Zhang Wei[64] prepared a double-arrow shaped three-dimensional negative Poisson's ratio energy-absorbing structure, and used it in the energy-absorbing device of the commercial vehicle body, after theoretical calculations and experimental results have shown that the new negative Poisson's ratio energy-absorbing box in the premise that does not affect the effect of the energy-absorbing, the overall weight is reduced by 44%.Zhou[65] et al. designed double-arrow three-dimensional negative Poisson's ratio energy-absorbing box structure. Poisson's ratio energy-absorbing box structure, through the comparison with the foam-filled energy-absorbing box and the traditional energy-absorbing box, it is found that the negative Poisson's ratio energy-absorbing box has a better energy absorption rate under the same conditions.Wang CY[66] et al. proposed a negative Poisson's ratio structure of the front bumper of the automobile, which is of low stiffness, and it can absorb more energy in the low-energy collision and has less damage to the calf bone of the person who was hit.Wang[67] et al. embedded three-dimensional negative Poisson's ratio structure in a square metal box to get the automotive energy-absorbing box, after the car is installed with a new type of energy-absorbing box in the frontal collision, the car structural deformation, energy-absorbing characteristics and personnel protection indexes of the collision safety performance has been significantly improved.Imbalzano[68][69] et al. put forward an automotive explosive protection armor plate structure, the armor plate adopts a negative Poisson's ratio core layer structure of the laminated plate is mounted on the underside of the military Land Cruiser, which has better protection against landmines and so on. The armor plate is installed on the bottom of military off-road vehicles with a negative Poisson's ratio core structure, which provides better protection against landmines and so on. In the explosion event, compared with the traditional protective armor, negative Poisson's ratio armor plate can effectively absorb the explosion impact energy, the ultimate energy absorption capacity of the armor plate has doubled, the maximum instantaneous velocity of the back has been reduced by about 70%, and the maximum plastic deformation has been reduced by about 30%, and the negative Poisson's ratio armor plate plays a relatively good role in protection enhancement. Yang Deqing[70] et al. proposed concave hexagonal honeycomb, star-shaped negative Poisson's ratio honeycomb of the ship's outboard armor-piercing protection structure, the numerical analysis results show that under the equal weight constraints, the macroscopic negative Poisson's ratio outboard protection structure of the impact resistance is better; macroscopic negative Poisson's ratio structure of the single-cell size of the outboard structure of the impact resistance of the performance of the large impact, the size of the single-cell size of the existence of the optimal solution. Jiang Kun[71] et al. proposed a macro-negative Poisson's ratio honeycomb structure based on the hull surface impact cover, numerical simulation results show that the impact velocity of the negative Poisson's ratio structure of the energy absorption has a certain effect, the greater the impact velocity, the greater the fluctuations in the internal energy of the structure.Luo[72] et al. numerical method to calculate the groove bulkhead, honeycomb sandwich bulkhead and negative Poisson's ratio structure bulkhead in the same equivalent explosion under the role of the response, the results showed that Concave negative Poisson's ratio due to the honeycomb structure pressure collapse failure, anti-explosive energy absorption ability to enhance; bulkheads and the hull shell version of the stress at the connection, reducing the probability of failure at the boundary under the action of the explosion load. In addition, the use of concave negative Poisson's ratio honeycomb sandwich structure to prepare a new type of impact vibration isolator[73][74], this vibration isolator without changing the weight of the premise has a good vibration isolation and impact resistance, which can ensure the stiffness, strength, vibration isolation and impact resistance performance design results.



(a) Automotive energy-absorbing boxes



(b) Explosion-proof armor for vehicles



(c) Ship's side armor

Fig. 8 Engineering application of negative Poisson's ratio protective structure

5 Summary and Prospects

The research of negative Poisson's ratio metamaterials with porous structure has made some progress, and the design idea of metamaterials has opened up a new road for the research and development of new materials, and has shown great potential value in various fields. The introduction of negative Poisson's ratio cytosolic structure into the design of metamaterials can not only produce many novel physical phenomena, but also make the design of metamaterials rational and evidence-based. Comprehensive analysis of the current research situation at home and abroad can be seen, at present reveals the deformation mechanism of the negative Poisson's ratio cytosolic structure of the study is becoming more and more mature, in the deformation mechanism under the guidance of the negative Poisson's ratio cytosolic structure of the types of increasingly rich; and based on the negative Poisson's ratio cytosolic structure of the design of metamaterials has also made great progress. However, in special applications, the materials need to have high stiffness and strength, good energy absorption ability, and wide Poisson's ratio range. For several types of classical models only a more systematic theory, simulation and experimental analysis, these biased theoretical analysis is less applicable in practical applications, other negative Poisson's ratio structure is not systematic analysis, more just stay in the simulation stage, for all types of negative Poisson's ratio structure of the application of the lack of specific practice. Therefore, there are still a lot of problems and challenges to be solved in the research process, based on this situation, the author finally puts forward several ideas for the development of negative Poisson's ratio metamaterials with porous structure in the future.

First, the combination of different negative Poisson's ratio structural designs should be explored, including the combination of different types and materials, and according to the loading conditions and application scenarios, a variety of design combinations should be selected to provide more theoretical models, which will provide possibilities for further understanding of the mechanical mechanism of the design and improving the mechanical properties of negative Poisson's ratio structures.

Secondly, while improving the mechanical properties of negative Poisson's ratio structures, the original deformation characteristics of negative Poisson's ratio structures should be ensured. For example, due to the change of the deformation mode, improving the stiffness of plastic negative Poisson's ratio structure by design may sacrifice the negative Poisson's ratio effect.

Thirdly, the manufacturing technology of the negative Poisson's ratio structure should be improved. At present, the negative Poisson's ratio structure cannot be put into practice, the main reason is still the lack of manufacturing technology or expensive manufacturing cost.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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