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Research and defence application progress of negative poisson's ratio materials

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Abstract: *In contrast to traditional materials, materials and structures with negative Poisson's ratio (NPR) transverse shrinkage (expansion) occurs under uniaxial pressure (tension). This characteristic makes NPR materials have many excellent advantages. Shear capacity and indentation resistance of NPR materials are introduced in this paper. According to these two characteristics, the paper also introduces the defence application of NPR materials.*

Keywords: *NPR materials; defence application; auxetic*

1. Introduction

Common materials contract when they are stretched and expand when they are compressed. But NPR materials do the opposite: when stretched lengthwise, they expand laterally. It is generally believed that the first recorded fact of engineering mechanics for materials with a NPR was in a book published in 1944, in which Love described a material with a NPR[1]. The next reference to NPR material was made by Gibson in 1982[2], who realized the negative compressibility of the bending deformation of the ribs in the form of two-dimensional silicone rubber or aluminum honeycomb. Five years later, Lakes reported for the first time in Science that a synthetic NPR material with a special concave structure was obtained by placing the polyurethane foam in an aluminum mold and compressing, heating, cooling and relaxing it. Since then, many man-made NPR materials have been exploited rapidly.

NPR material has some special properties, which are embodied in elastic modulus and shear modulus. At present, the applications of NPR materials have involved many fields such as shock absorbers[3] and sound isolators[4]. In this paper, the characteristics and classification of negative Poisson ratio metamaterials, the research progress of negative Poisson ratio metamaterials and the application progress of negative Poisson ratio metamaterials are introduced.

2. Mechanical properties of NPR material

When the material is compressed in a certain direction, it tends to expand perpendicular to the stress direction, which is Poisson effect. Poisson's ratio is a physical quantity for quantitative evaluation of Poisson's effect. If the material is stretched, it usually tends to shrink laterally in the tensile direction[5]. For example, when the rubber band is stretched, it will obviously become thinner, which is a common phenomenon (as shown in Figure 1a). In contrast, the NPR material would expand when it is compressed, or shrink when it is expanded.

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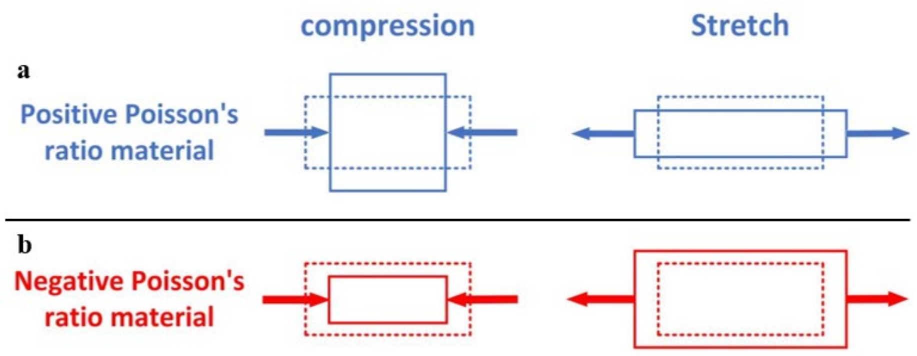

Figure 1: Deformation of positive and NPR materials

$$\upsilon = -\frac{d\varepsilon_{trans}}{d\varepsilon_{axial}} = -\frac{d\varepsilon_y}{d\varepsilon_x} = -\frac{d\varepsilon_z}{d\varepsilon_x} \tag{1}$$

Where, υ represents Poisson's ratio, ε_{trans} represents transverse strain (tension is negative and compression is positive), and ε_{axial} represents axial deformation (tension is positive and compression is negative).

For most materials, their Poisson's ratio value is a constant greater than 0 and less than 0.5. The Poisson's ratio of completely incompressible material with elastic deformation under small strain is just 0.5. When most metals and rigid polymers are used within their design limits (before yield), their Poisson's ratios' value is about 0.3, and the post yield deformation increases to 0.5, while the post yield deformation mainly occurs on a constant volume. It is generally believed that the Poisson's ratio of rubber is close to 0.5 and that of gas is 0.

Through the analysis of the equation, it can be seen that less Poisson's ratio will lead to the increase of shear modulus, so the material has better shear resistance.

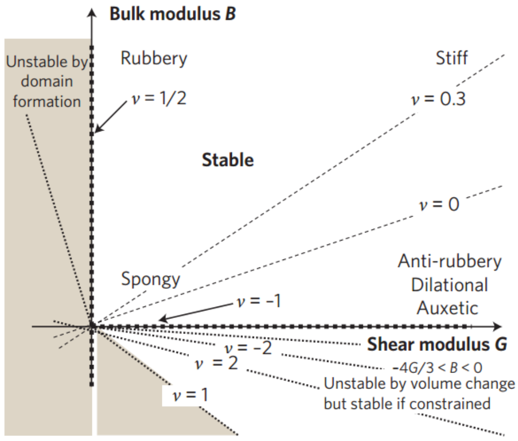

Figure 2: Relationship between bulk modulus K and shear modulus G of isotropic solid materials[6]

In Figure 2, the horizontal axis represents the shear modulus and the vertical axis represents the bulk modulus. The dotted line in the figure represents Poisson's ratio. For stable unconstrained solids, the shear modulus must be positive. This means that the value of Poisson's ratio is between - 1 and 0.5, which is the numerical range of the Poisson's ratio of isotropic solids. This relationship leads to the shear modulus tending to infinity at the extreme negative value of Poisson's ratio.

Under the same conditions, NPR materials are more resistant to shear force than "conventional" materials. The classical elastic theory of three-dimensional isotropic solid shows that the elastic behaviour of the object can be described by two of the four constants: E, G, K and υ are Young's modulus, shear modulus, bulk modulus and Poisson's ratio respectively. In three-dimensional materials, the relationship between these constants is given by equations 2 and 3:

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

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$$G = \frac{E}{2(1+\nu)} \tag{3}$$

When the conventional material is subjected to local compression, in order to compensate for this local pressure, the material expands in the direction perpendicular to the applied load, as shown in Figure 3 (a); however, when indentation occurs in isotropic NPR materials, local shrinkage is observed[6]. Under the indenter, the local density of the material becomes higher, as shown in Figure 3 (b), forming a dense material region with higher indentation resistance. In this way, compared with traditional materials, NPR materials have better indentation resistance[7].

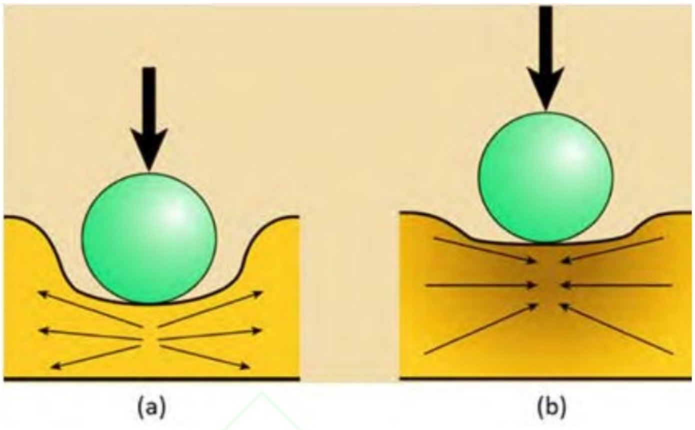

Figure 3: Collapse response of materials with positive / negative Poisson's ratio[2]

According to the elastic theory, we can prove the relationship between indentation resistance and hardness. The indentation resistance is related to the hardness (H), Poisson's ratio and elastic modulus of the material itself. The relationship is:

$$H \propto \left[\frac{E}{(1-\nu^2)}\right]^{\gamma} \tag{4}$$

The upper limit of Poisson's ratio of two-dimensional isotropic system is 1. Therefore, the material with positive Poisson's ratio can also have infinite hardness value. NPR materials have better fracture resistance than "traditional" materials [9]. Their crack growth rate is also very low, and more energy is required to expand them compared with "traditional" materials [4]. Therefore, these materials have brittle fracture resistance.[8]

3. Defence applications of NPR materials

Since NPR is expected to help improve toughness, elasticity and shear strength, as well as vibration related acoustic properties, auxiliary materials may be better than traditional materials. Explore these unusual features. These materials were supported by Boeing and NASA.

Because of the mechanical characteristics of NPR structure, researchers carried out the study on its compression performance, three-point bending performance and high-speed impact performance. A large number of comparative experiments and simulation calculations [9]have been done to illustrate the advantages of NPR structure in defence. Adidas futures team made a new sports helmet with NPR

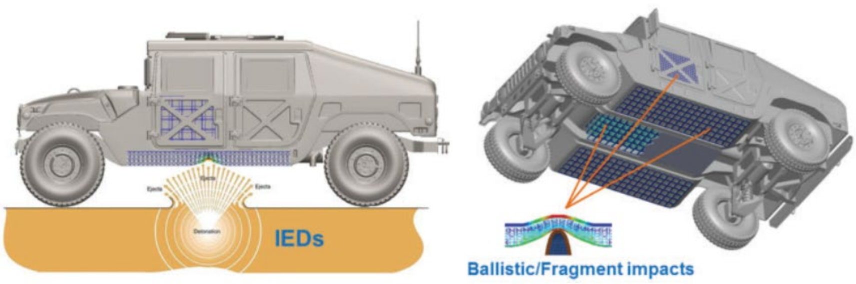

Figure 4: NPR material is used for vehicle explosion-proof bottom plate[10]

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Imbalzano et al. recommended the use of sandwich plates with NPR lattice cores between metal surfaces for local impact applications, as shown in Figure 4. They also numerically simulated the sandwich plate with NPR lattice core, and used the J-C constitutive model in the process of calculation and analysis. The main structural parameters affecting the NPR properties of the material are analyzed. In terms of deformation and plastic energy dissipation, the calculated results are compared with those of veneers with equivalent area, equivalent mass and equivalent material. By simplifying the model, the calculation time can be significantly shortened, in which the shell element is used for mosaic and the beam element is used for NPR core. When the projectile impact velocity reaches 200m / s, it is found that NPR composite plate can absorb similar amount of energy through plastic deformation, and the maximum post displacement is reduced by 56% due to the increase of local density of NPR core in the impacted part and the influence of subsequent plastic deformation.

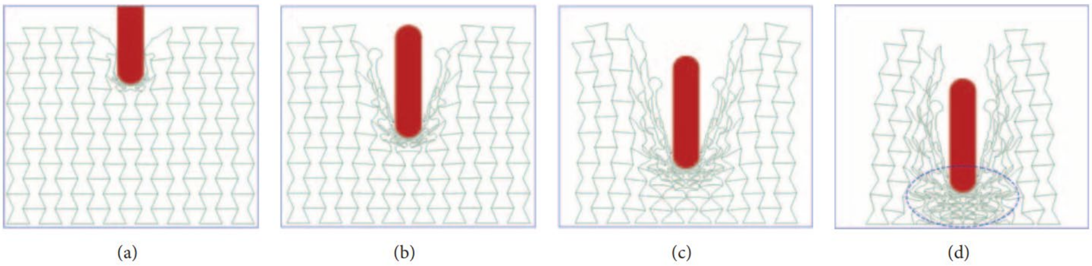

Figure 5: Penetration results of NPR material [11]

Yang et al. Proposed a novel auxetic sandwich panel. The perforation resistance of high speed projectile impacted by high-speed projectile was numerically analysed and compared with the same size and weight of aluminium foam sandwich panels. It has been found that the ballistic resistance of auxetic sandwich panel is much better than that of aluminium foam sandwich panels due to the NPR effect and the material concentration in the impact area. The results show that the ballistic limit and energy absorption characteristics of the whole sandwich plate can be affected by adjusting the structural parameters of the NPR materials, as shown in Figure 5.

4. Conclusions

NPR materials are a promising new field in the field of national defense. This paper discusses some unique physical properties of auxetic materials and various methods to realize these properties. The key to the use of auxetic materials in future applications is their successful synthesis and development. Although there are a large number of papers on the theory of auxiliary materials, there are few reports on the scale application of NPR materials. With the development of advanced manufacturing technology, more and more materials with NPR have been developed. It is believed that the large-scale application of NPR materials in the field of protection will not be far away.

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