Energy absorption characteristics of honeycomb materials with negative Poisson's ratio

Xiaonan Yan¹, Rong Wang²³, Yongxiong Chen², Yanhai Cheng¹ and Xiubing Liang²

¹School of Mechatronic Engineering, China University of Mining and Technology, Xuzhou 221116, China;
²National Innovation Institute of Defense Technology, Academy of Military Science PLA, Beijing 100071, China
³E-mail: wangrongerdos@126.com

Abstract. Using a combination of finite element numerical simulation and experimental verification, the honeycomb structure with different parameters of negative Poisson's ratio is compressed at a uniform speed. The influence of angle parameter θ, size parameter h and thickness parameter t on Poisson's ratio and energy absorption of the whole structure is studied, and the main factors influencing Poisson's ratio and energy absorption are discussed. The results show that the larger concave angle, the smaller size and the larger thickness of the honeycomb cell, the better energy absorption of the overall structure, and the angle is the parameter that has the greatest influence on the Poisson's ratio and energy absorption. Meanwhile, it is demonstrated that the honeycomb hybrid auxetic material has better energy absorption.

1. Introduction

Poisson’s ratio refers to the negative number of the ratio of transverse strain to longitudinal strain when a material is longitudinally tensioned or compressed, that is $\nu = -\varepsilon_y / \varepsilon_x$. It was first proposed by French scientist Simeon Denis Poisson (1787—1840). Classical elasticity theory proves that the Poisson's ratio of isotropic materials ranges from -1.0 to 0.5 [1]. Generally, the material will contract laterally when stretched, and expand laterally when compressed [2]. On the contrary, negative Poisson's ratio materials show the characteristics of both transverse and longitudinal contraction or expansion, as shown in Figure 1. Compared with positive Poisson's ratio materials, negative Poisson's ratio materials have some excellent properties, which are specifically manifested in light weight, high damping, energy absorption, elastic modulus and shear modulus [3-4]. It plays an important role in functional materials and is of great significance to the development of transportation, energy and power, military armor, aerospace, and building materials [5-8]. Among them, the hexagonal negative Poisson's ratio honeycomb structure is generally used in the design of marine vibration isolation bases [9]; the three-dimensional multi-cell structure is used in the design of the energy absorption box of the

*Beijing Science and Technology Project (Z191100002719009); National Key R&D Program of China (2018YFC1902400); Youth Program of National Natural Science Foundation of China (52005504).
automobile front longitudinal beam [10]; the concave honeycomb structure is used in the structural design of submarine power equipment compartments [11].

Figure 1. Deformation of positive and negative Poisson's ratio materials.

Due to the excellent mechanical properties of negative Poisson's ratio materials, researchers have conducted extensive research on negative Poisson's ratio metamaterials. In 1987, Lakes first obtained a negative Poisson's ratio foam material through heat treatment of polyurethane foam, and its Poisson's ratio was measured to be -0.7 [12]. Afterwards, researchers have successively proposed concave polygonal structures, rotating rigid body structures, chiral structures, etc., and the cell structure studied has gradually expanded from two-dimensional to three-dimensional [13-15]. At the same time, researchers began to study the cell array problem, and proposed the angle gradient and thickness gradient arrangement. The cell structure of different gradient arrangements is mechanically analyzed, and the advantages and disadvantages of various gradient arrangements are compared [16-17]. Since then, researchers have conducted in-depth studies on the static compression and dynamic impact of materials with negative Poisson's ratio, revealing the principle of force deformation of materials with negative Poisson's ratio [18-19].

The existing research results mainly focus on the design of cell structure, the gradient design of the overall structure, dynamic impact research, etc. These studies have made important contributions to the structural expansion and force analysis of negative Poisson's ratio materials, but the research on parameter optimization and energy absorption of cell structure has just begun. Among them, Chuong N et al. presented an approach for designing material micro-structures by using isogeometric analysis and parameterized level set method. By designing and optimizing two-dimensional and three-dimensional negative Poisson's ratio structures, the effectiveness of the topology optimization algorithm coupled with the reduced basis approach in designing metamaterials is proved [20]. Fábio A. O. F optimized the general helmet by comparing the performance of helmets with different parameters under double impact through numerical simulation. Finally, a helmet lining structure with superior overall performance and capable of withstandng multiple impacts is obtained [21]. These studies have made the material have better energy absorption and structural performance. But they have not studied the changes of Poisson's ratio and energy absorption under the change of geometric parameters, and the main parameters that affect energy absorption and Poisson's ratio.

As the core of negative Poisson's ratio metamaterials, the cell structure of negative Poisson's ratio directly determines the overall performance, so the optimization of cell structure parameters is very important. The honeycomb structure is widely used in structural applications due to its special strength. At the same time, considering the regularity of structural cells and the ease of production, this paper chooses the concave honeycomb structure as the research object. Through the combination of finite element numerical simulation and experiment, a concave honeycomb model with different parameters is established. In-depth study of the effect of the concave angle, thickness, and size of the cell geometric parameters on the Poisson's ratio value of the structure, and compare the energy absorption according to the compressive stress-strain curve. The research results show that the larger concave angle, the smaller size, and the larger thickness of the cell, the better energy absorption of the overall structure, and the angle is the parameter that has the greatest influence on the Poisson's ratio and
energy absorption. In addition, a metal-ceramic hybrid auxetic structure is proposed, and it is confirmed that the structure has better compression resistance, which provides a certain sense of guidance for the design and application of negative Poisson's ratio materials.

2. Models and methods

2.1. Specimen fabrication

Figure 2 shows the cell structure of the concave honeycomb. In the figure: \(h\) and \(l\) represent the length of the horizontal cell wall and the length of the inclined cell wall respectively, \(\theta\) is the concave angle, \(t\) is the thickness of the cell wall, and \(h/l=2\). When the concave honeycomb structure is longitudinally compressed, the diagonal ribs of the honeycomb unit will deform and gradually move from the diagonal direction to the horizontal direction, so that the material exhibits a negative Poisson's ratio effect. In fact, the main reason for the negative Poisson's ratio of the honeycomb material is the axial compression and hinged rotation, which causes the diagonal ribs to bend inward and cause the structure to contract both laterally and longitudinally.

Figure 3 shows the sample with a concave angle of \(-30^\circ\), printed by a flash-cast dreamer 3D printer with a precision of 0.1mm produced in Zhejiang. The printing parameters are shown in Table 1. The printing material is produced by Dake Intelligent and the hardness is 95A TPU material with a diameter of 1.75mm, 100% filling and printing is used at 200° to maximize the hardness. The printed model is arrayed with 3 cells in the high direction and 7 cells in the width direction, with a uniform depth of 20mm. When studying the influence of the concave angle on the structural performance, \(h=11.5mm\) and \(t=1mm\) are uniformly adopted, and the angle \(\theta\) is respectively \(30^\circ\), \(20^\circ\), \(10^\circ\), \(0^\circ\), \(-10^\circ\), \(-20^\circ\), \(-30^\circ\) seven types. A positive value represents a conventional honeycomb structure, and a negative value represents a concave honeycomb structure. All samples are printed by the same 3D printer to ensure the consistency of the printed sample quality.

Table 1. 3D printer printing parameters.

| Parameter name | Parameter index | printing speed/(mm’s\(^{-1}\)) | Printing thickness/ mm | Nozzle temperature/°C | Hot bed temperature/°C | Withdrawal speed/(mm’s\(^{-1}\)) |
|----------------|-----------------|----------------------|------------------------|-----------------------|------------------------|----------------------------------|
|                | 45              | 0.5                  | 220                    | 70                    | 80                     |

To study the compressive performance of materials, a universal testing machine is usually used to do a compression test to obtain a stress-strain curve. The area enclosed by the stress-strain curve and the coordinate axis represents the energy absorbed by the material [22]. The calculation method is calculated by formula (1):

\[
\omega = \int_0^{\varepsilon_0} \sigma d\varepsilon
\]

(1)

In the formula: \(\omega\) is the energy absorbed by the material; \(\sigma\) is the compressive stress; \(\varepsilon\) is the compressive strain; \(\varepsilon_0\) is the upper limit of the compressive strain.
2.2. Finite element modeling

In this paper, ABAQUS finite element simulation software is used for numerical simulation. The simulation diagram is shown in Figure 4. The middle of the model is a concave honeycomb structure, and the upper and lower sides are two rigid plates. The simulation uses ABAQUS's display dynamics analysis method to compress the structure slowly and uniformly.

The model material is TPU material, which is assumed to be an ideal elastoplastic model. The material parameters are measured by the tensile experiment, and the tensile stress-strain curve is shown in Figure 5. According to the tensile test, its material parameters are: Young's modulus $E = 207 \text{MPa}$, Poisson's ratio $\nu = 0.25$, yield stress $\sigma_y = 0.154 \text{MPa}$, and density $\rho = 1100 \text{kg/m}^3$. Both the compression end rigid body and the fixed end rigid body adopt discrete rigid bodies, and the upper and lower rigid bodies are bound to the structure. The upper rigid body is pressed down slowly at a uniform speed, and is restricted in the other directions. The compression end rigid body and the fixed end rigid body are both discrete rigid bodies, and the fixed end rigid body is completely fixed ($U_1 = U_2 = U_3 = U_{R1} = U_{R2} = U_{R3} = 0$), and the upper and lower rigid bodies are bound to the structure. The displacement curve of the upper rigid body is $y = 0.032t$, and it is restricted in the other directions. In order to prevent the materials from penetrating each other after compression [23], the whole structure adopts universal contact. The coefficient of contact friction is 0.2, and they are in hard contact with each other. In order to improve the quality of the mesh and the convergence of the analysis, the element shape is a hexahedron, and the meshing type is C3D8R. The average size of the unit is 1mm, and the structure is divided into 21200 units. The result of the structural grid division is shown in Figure 6. After compression deformation, the transverse strain $\varepsilon_{11}$ and the longitudinal strain $\varepsilon_{22}$ are obtained by measuring the deformation values of structure width AB and height CD, and then dividing the original length AB and CD. Finally, the Poisson's ratio of the compression model is obtained by Formula $\nu = -\varepsilon_{11}/\varepsilon_{22}$.

![Figure 4. Schematic diagram of compression simulation of honeycomb structure.](image)

![Figure 5. Stress-strain curve of TPU material.](image)
2.3. Experimental program

In this experiment, the MTS-20G microcomputer-controlled electronic universal testing machine is used, and the maximum test force is 20KN. In the experiment, the standard compression speed is 0.001% for compression, which is exactly the same as the compression speed in the simulation. The longitudinal stress and strain values are given by the computer during the compression process.

Figure 7 shows the test and simulation diagram of a sample with a concave angle of -30° and a compression of -10mm. It can be seen from the figure that the deformation of the structure in the experiment and simulation is similar. When the structure is compressed longitudinally, there is a concave phenomenon in the transverse direction, and the concave in the middle of the structure is the most obvious. Figure 8 shows the stress-strain curve of the specimens compression process with a concave angle of -30° and 30°. From the stress-strain curve, it can be seen that there is a certain error deviation between the test and the simulation, but the overall trend of the two curves is the same. The peak stress reached by compression is also very similar, indicating that the simulation data is accurate.
3. Results and discussion

3.1. Effect of angle parameter
After the experimental compression of 10mm, the seven-angle Poisson's ratio values are shown in Figure 9. It can be seen from the figure that the Poisson's ratio values are symmetrical, reaching the maximum and minimum values at 10° and -10°. The reason why the maximum value is reached at these two points is because the concave angle is small. During compression, the angle change is large, and the horizontal and vertical strain will also increase, so the Poisson's ratio reaches the maximum value. Figure 10 shows the stress-strain curves of seven angle experiments. It can be seen that the negative curve is significantly higher than the positive curve. The stress-strain curve of the concave honeycomb structure is significantly higher than that of the ordinary honeycomb structure, which means that the concave structure can absorb more energy, so the concave structure has an excellent energy absorption. Comparing the Poisson's ratio and energy absorption diagrams of the seven angles, it can be seen that as the angle becomes gradually concave, the value of Poisson's ratio first decreases and then increases. But at the same time the height of the stress-strain curve is rising, and the area enclosed is also larger. This shows that the greater concave angle, the greater energy absorbed by the structure. But it does not correspond to the smallest Poisson's ratio, indicating that the smaller the Poisson's ratio, the best energy absorption.

It can be seen from the stress-strain curve that the 0° and -10° structures have obvious softening phenomenon while the others are not obvious. The greater the absolute value of the angle, the less obvious the softening phenomenon. This is because the angle is small and the structure is not easy to deform during compression, so the stress value rises faster. However, when the structure deforms along the concave angle, the stress value will decrease and the softening phenomenon will occur. The structure with a large absolute value of angle is easy to be deformed along the concave angle during compression, so there is no softening phenomenon and the stress value rises gently. This also indicates that when the structure with small concave angle is subjected to angular compression, the anti-compression ability of the structure will decrease, which is far less than that of the structure with large concave angle.

![Figure 9. Poisson's ratio of seven angles.](image1)
![Figure 10. Stress-strain curves of seven angles.](image2)

3.2. Effect of size parameter
While studying the influence of angle parameters on the structure, it also demonstrated the correctness of the simulation. Therefore, four structures with cell length $h$ of 2mm, 4mm, 8mm and 16mm were selected for the simulation compression test. At this time $\theta$=-30°, $t$=1mm remains unchanged, the simulation result is shown in Figure 11. With the gradual increase of the cell length $h$, the Poisson's ratio is continuously reduced, and the peak stress is also reduced. The value of Poisson's ratio almost coincides with the value of stress, which shows that the value of Poisson's ratio and the peak stress are synchronized with the cell size. It can be seen from the figure that the stress value is the largest when
the cell length is 2\text{mm}, so it shows that the smaller cell size, the better energy absorption of the structure. But at this time the Poisson's ratio of the structure is the largest. At this time, it also shows that the smaller Poisson's ratio of the structure, the energy absorption is not the maximum.

3.3. Effect of thickness parameter
Four structures with thicknesses of 0.2\text{mm}, 0.3\text{mm}, 0.4\text{mm} and 0.5\text{mm} were selected for compression simulation, while $\theta$=-30°, $h$=8\text{mm} remained unchanged, and the simulation results are shown in Figure 12. It can be seen from the figure that as the cell thickness increases, the Poisson's ratio of the structure is increasing, and the stress value is also increasing. This conclusion is the same as that of Yang D U’s research. The value of Poisson's ratio and stress value also have the same trend as the simulation result of length, and both are synchronous and almost coincide. This shows that the greater thickness of the cell, the greater Poisson's ratio of the structure. Moreover, the stress value at this time is also large, and the energy absorption is also the best. This also shows that for a negative Poisson's ratio structure, it is not that the smaller Poisson's ratio, the better energy absorption.

4. Discussion and extension
Each parameter affects the performance of the overall structure, but the decision of which of the three parameters needs further discussion and analysis. Only knowing the decision parameters can easily change the parameters to improve the performance of the overall structure.

4.1. The main factors affecting Poisson's ratio
Figure 13 shows the influence of three parameters on Poisson's ratio. From the figure, it can be seen that it is the concave angle that determines the negative Poisson's ratio of the structure. Only when the concave angle is negative can there be negative Poisson's ratio. Secondly, it can be observed that the angle has the greatest influence on Poisson's ratio, which is much larger than the other two parameters and plays a leading role. Moreover, the Poisson's ratio has a linear relationship with the size $h$ and thickness $t$, but the angle is not. Although the 0° angle is closest to the zero degree line, the angles on both sides are symmetrically distributed. Moreover, the closer the negative concave angle is to 0°, the greater the Poisson's ratio, so it is not that the larger concave angle, the greater Poisson's ratio.
4.2. The main factors affecting energy absorption

Figure 14 is a graph of the influence of three parameters on energy absorption. It can be seen from the figure that thickness has the smallest influence on energy absorption, while angle and size have a relatively large influence on energy absorption. However, there are obvious differences between the two parameters. The size data is obviously lower than the angle data, which shows that the influence of the angle is much greater than the other two parameters. A slight modification of the angle can greatly improve the energy absorption of the overall structure. It can also be seen from the figure that when the upper value of the three parameters is taken, namely $\theta=-30^\circ$, $h=2\text{mm}$, and $t=0.5\text{mm}$, the energy absorption of the structure can reach the best.

4.3. Numerical simulation of concave honeycomb hybrid auxetic material

Ceramic materials have good mechanical properties such as low density, high strength and high hardness, and are good materials for impact resistance [24-25]. The metal-ceramic hybrid auxetic material formed by combining the metal honeycomb structure and the ceramic can not only exert the advantages of the high strength of the ceramic material, but also exert the concave characteristic of the honeycomb structure. The external metal concave structure can well wrap the broken ceramics, making the hybrid auxetic material an ideal material with light weight and high energy absorption.

Based on the above research conclusions, the energy absorption of negative Poisson's ratio honeycomb material, metal-ceramic hybrid auxetic material and metal solid material was compared through numerical simulation, and the best energy absorption material was finally obtained. The three simulated structural materials are shown in Figure 15. The metals of the three structural materials are all alumina materials, and the ceramic materials are SiC. The parameter setting in the simulation is the same as the above, with a slow and uniform pressure of 5mm.

(a) Honeycomb material    (b) Hybrid auxetic material    (c) Solid material

Figure 15. Three simulated structural materials.
The compression results of the three structural materials are shown in Figure 16. It can be seen that the three materials have undergone certain deformation. The concave phenomenon of honeycomb structure is obvious. In the hybrid auxetic material structure, the ceramic is broken and the outer metal is recessed. The solid structure is simply a compression deformation. Figure 17 shows the stress-strain curves of the three materials during compression. It can be clearly seen from the figure that the hybrid auxetic structure has the highest stress value, followed by the solid structure. By comparison, it can be found that the hybrid auxetic structure absorbs the most energy, which also shows that the hybrid auxetic structure has the best compressive performance. This is because the ceramic has high strength and the metal honeycomb structure can well wrap the broken ceramics, so the hybrid auxetic structure has the best mechanical performance.

![Figure 16. Compression results of three materials.](image1)

![Figure 17. Compression stress-strain curves of three materials.](image2)

5. Conclusions
In this paper, the different angle parameters $\theta$, size parameter $h$ and thickness parameter $t$ of the concave honeycomb structure are simulated and experimentally studied respectively. The effect of the three parameters on the overall structure is comparatively studied, and the main factors affecting energy absorption and Poisson's ratio are discussed. Get the following conclusions:

1. The larger concave angle of the concave honeycomb structure, the smaller size and the thicker thickness, the better energy absorption of the honeycomb structure. It can absorb more external pressure and improve the pressure and energy absorption of the material. In addition, it is also pointed out that no matter which parameter changes, it cannot be explained that the smaller the Poisson's ratio, the best energy absorption. There is no direct relationship between the two.

2. It explains why the energy absorption is the best under the three parameters discussed in the article. This is because the concave angle is large and it is not easy to compress and deform. The small size structure is dense and compressive, and the thickness of the structure is large, so the energy absorption is the best under these three parameters.

3. Through comparative studies, it is found that angle is the parameter that has the greatest influence on energy absorption and Poisson's ratio. Therefore, to change the performance of the overall structure, the adjustment of the angle should be considered first.

4. The honeycomb concave structure composited with ceramic has better compressive performance, because the ceramic has high strength and the honeycomb structure can well wrap the broken ceramics.

References
[1] Sokolnikoff IS 1983 Mathematical theory of elasticity Malabar:Krieger Publishing Company
[2] Yang D U, Lee S and Huang F Y 2003 Geometric effects on micropolar elastic honeycomb
structure with negative Poisson's ratio using the finite element method *Finite Elements in Analysis and Design* **39**(3) 187-205

[3] Grujicic M, Galgalikar R, Snipes J S, et al. 2013 Multi-physics modeling of the fabrication and dynamic performance of all-metal auxetic-hexagonal sandwich-structures **51** 113-130

[4] Tomasz S, Hubert J, Bogdan T M, et al. 2014 Computational analysis of sandwich - structured composites with an auxetic phase **251**(2) 354-366

[5] Hui W, Yuxuan Z, Wanqing L and Qinghua Q 2020 A novel two-dimensional mechanical metamaterial with negative Poisson’s ratio *Computational Materials Science* **171** 0927-0256

[6] Alderson A and Alderson K L 2007 Auxetic Materials *Proceedings of the Institution of Mechanical Engineers Part G Journal of Aerospace Engineering* **221**(4) 565-575

[7] Heo H, JU J and Kim D M 2013 Compliant Cellular Structures: Application to a Passive Morphing Airfoil *Composite Structures* **106**(12) 560-569

[8] Jacobs S, Coconnier C, DiMaio D, et al. 2012 Deployable auxetic shape memory alloy cellular antenna demonstrator: design, manufacturing and modal testing **21**(7)

[9] Binghong W, Xiangwen Z and Deqing Y 2018 Analysis of real ship application of negative Poisson's ratio metamaterial vibration isolation base *Ship Engineering* **40**(02) 56-62

[10] Xing Y, Ye Y, Wei Z and Wenbin H 2017 Optimal design of automobile energy-absorbing box based on three-dimensional multi-cell structure *Journal of Dalian University of Technology* **57**(04) 331-336

[11] Lifu X and Deqing Y 2019 Analysis of submarine vibration and sound radiation performance of metamaterials with negative Poisson's ratio *Journal of Vibration Engineering* **32**(06) 956-965

[12] Lakes R 1987 Foam structures with a negative Poisson’s ratio *Science* **235**(4792) 1038-1040

[13] Miller W, Hook P B, Smith C W, Wang X and Evans K E 2009 The manufacture and characterisation of a novel, low modulus, negative Poisson’s ratio composite *Compos. Sci. Technol.* **69**(5) 651-655

[14] Babae S, Shim J, Weaver J C, Chen E R, Patel N and Bertoldi K 2013 3D Soft metamaterials with negative Poisson’s ratio *Adv. Mater.* **25**(36) 5044-5049

[15] Jingjun Y, Yan X and Xu P 2018 Research progress of negative Poisson's ratio metamaterials *Chinese Journal of Mechanical Engineering* **54**(13) 1-14

[16] Shufrin I, Pasternak E and Dyskin A V 2015 Negative Poisson’s ratio in hollow sphere materials *Int. J. Solids Struct.* **54** 192-214

[17] Guansheng Y and Zhaoan Y 2017 Analysis of impact dynamics performance of gradient negative Poisson's ratio honeycomb material *Journal of Dynamics and Control* **15**(01) 52-58

[18] Huilong H, Xinchun Z and Peng W 2019 Dynamic response and energy absorption characteristics of honeycomb materials with negative Poisson’s ratio *Explosion and Shock* **39**(01) 47-57

[19] Milton G W 2013 Complete characterization of the macroscopic deformations of periodic unimode metamaterials of rigid bars and pivots *Mech.Phys.Solids.* **61**(7) 1543-1560

[20] Chuong N, Xiaoying Z, Ludovic C, et al. 2020 Three-dimensional topology optimization of auxetic metamaterial using isogeometric analysis and model order reduction **371**

[21] Fábio A. O. F, Ricardo J. Alves de S, Mariusz P, et al. 2019 Helmet Design Based on the Optimization of Biocomposite Energy-Absorbing Liners under Multi-Impact Loading **9**(4)

[22] Gibson L J and Ashby M F 1997 Cellular solids: Structure and properties *2nd ed. Cambridge:Cambridge University Press* 87-148

[23] Xiaolin D 2016 In-plane impact dynamics analysis of a honeycomb structure with a layered ladder variable negative Poisson's ratio *Machine Design and Manufacturing* **(04)** 219-223

[24] Kaufmann C, Cronin D, Worswick M, et al. 2001 Influence of Material Properties on the Ballistic Performance of Ceramics for Personal Body Armour **10**(1)

[25] Ullah I, Brandt M and Feih S 2016 Failure and energy absorption characteristics of advanced 3D truss core structures **92** 937-948