Study on negative Poisson's ratio structure with low porosity

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Abstract. Most two-dimensional negative Poisson's ratio structures are highly porous, resulting in insufficient structural bearing capacity and only for small strain conditions. In this paper, the simulation method is used to prove that the low porosity and negative Poisson's ratio structure with concave hexagon has "incremental" behavior, and then the correctness of the simulation model is verified by experiments based on digital image technology (DIC). In addition, the effect of unit cell parameters on the negative Poisson's ratio at the same porosity is studied. The results show that at the same porosity, the length of the unit cell has the greatest influence on the Poisson's ratio, and the longer the unit cell, the smaller the Poisson's ratio; at different porosity, the larger the porosity, the larger the Poisson's ratio.

1. Introduction

“Supermaterials” is a new type of material that emerged in the 21st century. It refers to artificial composite structures or materials that have extraordinary physical properties not found in natural materials, such as negative refractive index (left-handed materials), negative Poisson's ratio controllable structures, negative thermal expansion coefficient material, etc. Science listed it as one of the ten important scientific advances in the first 10 years of this century, which triggered major changes in the fields of defense industry, new energy technology, micro-processing technology and so on. The negative Poisson's ratio structure has been successfully applied in sensors, biomedicine, aviation industry and many other fields due to its unique auxetic properties and outstanding mechanical and mechanical properties (stronger shear resistance, fracture toughness, vibration damping properties, and higher hardness values and crack propagation resistance) [1-2]. Since Lakes proposed a negative Poisson's ratio structure [3], it has been proved that two-dimensional periodic geometry and structures can achieve negative Poisson's ratio.

The Poisson's ratio is controlled by an ingenious design of the unit cell structure. The common cell types include concave structures, chiral microstructures, rotating units, origami structures, etc [4-8]. These common negative Poisson's ratio structures are generally porous structures with high porosity, high compression ratio and low stiffness. They are not suitable for stress-bearing materials and cannot meet the requirements of low porosity requirements. For example, in gas turbines, there are many perforated surfaces in the combustion chamber, turbine section, bypass piping, and exhaust nozzles, all of which can benefit from auxetic behavior, but the target value of porosity is typically 2%-10% [9]. Therefore, the negative Poisson's ratio structure with low porosity has also been developed.

Typically Taylor M used topological techniques to optimize the aspect ratio of elliptical holes to achieve a Poisson's ratio close to -1 at very low porosity (2%-5%) [9]; Grima J N, etc., realized the design of zero Poisson's ratio controllable structure by combining positive and negative Poisson’s ratio cells [10]. Shan S used the nonlinear finite element method to analyze the relationship between...
material Poisson's ratio and unit cell geometry [11]. Giorgio C et al. proposed a two-dimensional porous solid design with omni-directional negative Poisson's ratio. The effects of geometric parameters on the negative Poisson's ratio were studied by numerical simulation and experimental test methods [12]. Luca F et al. demonstrated that the tensile behavior of the structure can be adjusted by changing the geometry of the pores in the low porosity metal negative Poisson's ratio structure [13]. The above literature gives the effect of the negative Poisson's ratio and the structural parameters on the negative Poisson's ratio of the material with different structural parameters, but does not consider the effect of porosity on the bulging characteristics of the structure.

In view of the high porosity of negative Poisson's ratio structure and the effect of porosity on the negative Poisson's ratio structure, this paper mainly studies the low porosity and negative Poisson's ratio structure composed of the concave hexagonal unit cell structure, and analyses the influence of the cell structural parameters on the auxetic effect under different porosity.

2. Modeling and experimental verification of two-dimensional negative Poisson ratio structure

2.1. Deformation Characteristics of Negative Poisson Ratio Structures

Poisson's ratio is defined as the ratio of the vertical strain of the force to the directional strain of the force during uniaxial stretching. Negative Poisson's ratio structure appears to expand laterally when subjected to tension; on the contrary, shrinkage occurs under pressure, as shown in figure 1 [14].

![Figure 1. Dilatancy and compression diagram (a) positive Poisson's ratio (b) negative Poisson's ratio](image)

2.2. Modeling of two-dimensional negative Poisson's ratio structure

The unit cell structure herein selects a concave hexagon, as shown in figure 2. In a 2D rectangular metal sheet, a square array of low porosity, mutually orthogonal concave hexagonal voids is designed.

![Figure 2. Diagram of a concave hexagon](image)

ANSYS simulation analysis software provides two methods of modeling and analysis, interactive and programming. Using interactive finite element analysis, it is easy to use and intuitive to operate, but it is inconvenient to modify the model. This paper modifies the model parameters more, so the parametric design language APDL is used to build the solid model. Then meshing is performed to obtain a finite element analysis model. The applied experimental load is approximated by fixing at one edge and specifying a static displacement at the opposite edge. Based on the simulation results, the local strain average is used to calculate the effective Poisson's ratio.

The rectangular plate size is 240 mm × 40 mm, and the dimension of the concave hexagon is 20 mm, b is 1.4 mm, c is 0.6 mm, and the porosity is 5%. The simulation sets the left end of the rectangular plate completely fixed, and the right end exerts a pulling force. The results of the rectangular plate strain distribution are shown in figure 3. From the strain distribution diagrams in the
x and y directions, the ratio of the y-direction strain 0.041 to the x-direction strain 0.093 is calculated, and the Poisson's ratio of the structure is calculated to be -0.44, which proves that the structure is a negative Poisson's ratio structure.

![Strain distribution result chart](image)

**Figure 3.** Strain distribution result chart (a) y-direction (b) x-direction

### 2.3. Experimental verification

In order to verify the bulging characteristics of the designed structure, the design experiment uses digital image correlation technology (DIC) [9] and binocular stereo vision technology to achieve the three-dimensional coordinates of the surface of the object during the deformation process by tracking the speckle image on the surface of the object. Displacement and strain measurement, portable, fast, high precision, easy to operate and so on.

For ease of processing and cost savings, five samples were made from brass using laser cutting techniques, as shown in figure 4. A total of 5 bulging experiments were performed to facilitate repeatability and consistency verification.

![Sample map](image)

**Figure 4.** Sample map

#### 2.3.1 Design of experimental scheme

The test system is mainly composed of a computer, industrial high-speed cameras, clamping heads, a universal tensile testing machine, etc., as shown in figure 5. Before the test, the sample needs to be covered with a white matt paint, the contrast is added, and then the mark is sprayed with a black matt paint. The dot density is 3-6 pixels, and the treated sample is shown in figure 6. Through computer control, the universal testing machine applies tension at a speed of 0.24mm/min, and the left and right industrial cameras simultaneously capture photos of the sample at 2 frames per second. In this experiment, five sets of repetitive tests were carried out, and the experimental results were compared with the simulation results to illustrate the correctness of the above simulation analysis model.

![Test device diagram](image)

**Figure 5.** Test device diagram

![Sprayed sample](image)

**Figure 6.** Sprayed sample

#### 2.3.2 Experimental result

The unit areas that are jointly focused by two industrial cameras are selected for analysis, as shown in figure 7. The upper and lower 24 points and left and right 24 points are selected respectively to obtain the three-dimensional coordinates and stress-strain data. The difference of y-values between the upper and lower points is the y-direction displacement deformation of the
analysis region, and the difference of x-values between the left and right points is the x-direction displacement deformation of the analysis region.

![Figure 7. Test device diagram](image)

According to the data analysis, the results are shown in Table 1. From the results of Table 1, the Poisson's ratio of the structure is a negative value, indicating that it has an auxetic effect. The maximum error of the five sets of experimental Poisson's ratio is 6.5%, indicating that the five groups of experiments have good repeatability. And comparing the experimental and simulation results, the experimental and simulation values differ by 4.5%, and good consistency is obtained, which shows the correctness of the simulation model.

| Sample | 1 | 2 | 3 | 4 | 5 | Simulation |
|--------|---|---|---|---|---|------------|
| Poisson's ratio | -0.44 | -0.44 | -0.43 | -0.44 | -0.46 | -0.44 |

### 3. Structural parameter optimization of two-dimensional negative Poisson's ratio

This paper mainly analyzes the influence of three structural parameters a, b, c on the Poisson's ratio under the respective porosity $\mu$. The low porosity ranges from 2% to 10%, so the porosity of 5%, 6%, 8% and 10% is selected for analysis. Under the same porosity, the parameter a ranges from 16 to 30, the parameter c ranges from 0.2 to 1, and the parameter b depends on the porosity. A small analysis unit is taken from Figure 7 in the dotted line box, as shown in Figure 8. Porosity is defined as the percentage of the pore volume in the structure to the total volume of the structure in its natural state, and the formula (1) is obtained. Then, by converting to the formula (2), the value of b can be obtained.

![Figure 8. Analysis unit diagram](image)

$$ \mu = \frac{(b + a) \times \frac{a}{2} \times \frac{1}{2} \times 2}{10 \times 10} $$

$$ b = \frac{\mu \times 10 \times 10}{2a} - c $$

At the same porosity, the effects of parameters a and b, a and c, b and c on the Poisson's ratio are analyzed, as shown in Figure 9. The results show that under the same porosity, the parameter a value has a greater influence on the Poisson's ratio than the b value. The parameter a value has a greater influence on the Poisson's ratio than the b value. The parameter b value has a greater influence on the Poisson's ratio than the c value. The unit cell a value has the greatest influence on the negative Poisson's ratio, the b value is second, and the c value has the least effect.
Based on the above analysis results, the influence of the b-to-c ratio on the Poisson's ratio is analyzed when the value of a is constant at the porosity. It can be seen from figure 10 that when the value of a is constant, as the ratio of b to c changes, the negative Poisson's ratio shows a decreasing trend but the difference is not large. And as the value of a decreases, the effect of the ratio of b to c on the Poisson's ratio is smaller.

In addition, the effect of the ratio of b to a on the Poisson's ratio is also analyzed when the c value is constant at the porosity. As can be seen from figure 11, when the value of c is constant, as the ratio of b to a increases, the negative Poisson's ratio increases, that is, the thinner the concave hexagon, the more obvious the negative Poisson's ratio effect.

In general, the unit cell parameter a value has the greatest influence on the Poisson's ratio. The larger the value of the parameter a, the smaller the Poisson's ratio, that is, the more obvious the negative Poisson's ratio effect. Moreover, the smaller the ratio of the parameters b to a, the more obvious the negative Poisson's ratio effect.

4. Conclusion

In this paper, a two-dimensional negative Poisson's ratio structure with low porosity is adopted, and the DIC method is used to carry out experiments to verify the correctness of the simulation model. Through APDL parameterized language modeling, the simulation analysis is carried out. By adjusting the parameter structure change of the concave hexagon, the Poisson's ratio can be effectively adjusted.
The work of this paper provides guidance for the simple design of negative Poisson's ratio structure, but as a basis for future research on structural symmetry and pore shape optimization, more research on different topologies will be carried out.

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