Study on dynamic compression behavior and energy absorption characteristics of three negative Poisson's ratio materials under different velocities

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Abstract: This paper uses finite element analysis to study the impact dynamics of three negative Poisson's ratio materials. Different Poisson's ratio generation mechanisms, deformation modes, and dynamic response characteristics of three materials at different impact speeds are discussed. The unique necking phenomenon, the deformation mode diagram, dynamic response curve, and energy absorption curve are obtained after processing. The results of numerical simulations have deepened our understanding of negative Poisson's ratio honeycomb materials, and have guiding significance for us to explore new high-performance honeycomb materials later.

1. Introduction

The development of modern technology has more and more special requirements for materials, and materials with normal physical and mechanical properties can no longer meet specific requirements. Because of its unique physical and mechanical properties, negative Poisson's ratio materials have advantages that other materials cannot match. Therefore, research on negative Poisson's ratio materials has become a hot issue [1]. Negative Poisson's ratio materials can improve the mechanical properties of materials, including shear modulus, fracture toughness, thermal shock, strength, and indentation resistance [2]. It has a wide range of application prospects, which can be directly used in some special fields. It can also improve other properties of the material and even produce other new materials. For example, the expansion properties of negative Poisson's ratio materials can be used in some new types of fasteners [3], and studies have also been conducted in vibration isolation bases [4]. In the biological field, there are 3D printed PLA negative Poisson's ratio vascular stents experimental studies. These studies have shown that the unique mechanical properties of negative Poisson's ratio materials can effectively control the intravascular restenosis of vascular stents [5]. Negative Poisson's ratio material is not only of great significance in daily necessities, but also has great potential application value in some important areas of the country, such as aviation, defense, and electronics.

Negative Poisson's ratio material, as a new type of porous material, must be based on in-depth study of its physical and mechanical properties to achieve its wide application. Existing research work has mainly focused on discovering new negative poisson's ratio topologies, predicting their quasi-static mechanical properties and explaining the negative Poisson's ratio deformation mechanism [6]. In practice, negative Poisson's ratio materials are generally used as shock absorption and energy absorbing materials to withstand external shocks. The inertia in the process cannot be ignored, and negative Poisson's ratio materials have large differences in bearing mechanical response and static
load response, so it still needs to be further studied. Therefore, it is particularly urgent and necessary to study the dynamic mechanical properties of negative Poisson's ratio honeycomb materials under impact load.

This paper uses numerical simulation method and simulation with finite element analysis software to study the deformation mode and energy absorption characteristics of materials at different impact speeds, so as to determine the deformation mode and energy absorption performance of each material at different impact speeds, deepen our understanding of negative Poisson's ratio materials, and lay the foundation for the subsequent study of dynamic impact behavior of three-dimensional conditions of bulging materials.

2. Material model

2.1 Model’s establishment

Figure 1. Geometrical parameters of 3 honeycomb units with negative Poisson’s ratio.

The two main mechanisms for negative Poisson's ratio materials to produce negative Poisson's ratio characteristics are concave and rotating. Among them, the representative structures are concave honeycomb and anti-chiral structure. Based on the traditional research on traditional two-dimensional honeycomb materials, this paper designs two kinds of two-dimensional anti-chiral materials for research: Model A is a general two-dimensional backchiral material. Model B is based on the original two-dimensional anti-chiral materials, and the cavity is changed to a circular shape to change the deformation law of the cavity. Model C combines a two-dimensional anti-chiral structure with a concave honeycomb structure. Figure 1 shows the schematic diagram of the 3 models and the specific dimensions.

2.2 Material parameters

Table 1 implies the specific material parameters of aluminum alloy.

| E/GPa | E_s/GPa | σ_y/MPa | μ | ρ/kg·m⁻³ | D/s⁻¹ | P |
|-------|---------|---------|---|-----------|-------|---|
| 68.97 | 200     | 276     | 0.33 | 2700      | 6500  | 4 |

2.3 Method

Figure 2. Diagrammatic sketch for honeycomb under in-plane impact

Figure 2 shows the schematic of the in-plane impact loading of a negative Poisson's ratio honeycomb material. The model is placed between the upper and lower impact rigid plates. During the analysis, the lower rigid plate is fixed. The upper rigid plate impacts the experimental model downward at a
constant speed. The impact speed is selected from 1m/s, 5m/s, and 10m/s, 50m/s. In the calculation process, the out-of-plane displacement of all nodes of the entire model is limited to ensure the state of plane strain [6].

3. Simulation results and discussion

3.1 Deformation mode analysis

In the case of in-plane impact compression, the localization of the deformation and the enhances of stress of the honeycomb material are the typical characteristics of its impact response. The research by Ruan D showed that when the hexagonal honeycomb is dynamically crushed, the deformation mode shows a "V" shape collapse zone at low speed impact, and the "I" shape collapse zone appears under the high speed impact [7].

3.1.1 Dynamic response of three models under low speed shock

Figures 3 to 6 show the macro modes of deformation of 3 honeycombs under a velocity of 1m/s, where $\varepsilon$ is the nominal compressive strain of the honeycomb, that is, the ratio of the compression displacement of the honeycomb top surface to the initial height of the model.

At the beginning of compression, the deformation of the material is mainly concentrated on the impact end and the support end, and the degree of deformation gradually weakens from the upper and lower sides to the middle, and shows the unique "necking" phenomenon of negative Poisson's ratio material; The internal deformation is first reflected as the support rods’ bending makes cells rotation and causes the distance between each other to decrease continuously. The middle part of the model is first tightened together and pillars wrapped around cells. The deformation mode is reflected by the compression deformation of the hole wall. The deformation band is further expanded and the model is gradually crushed.

The analysis of three models’ deformation modes is as follows: Under the combined effect of cell rotation and concaving deformation, a multi-layer deformation band appears in Model A. The deformation band concentrated at the impact end, and the contour shape of the deformation band
becomes clearer as compression continues. It shows an “S” shape, and the deformation zone squeezes the undeformed part. Eventually, the whole tends to be dense; Model B’s cells are mainly subjected to rotational deformation in the early stage, and the extrusion deformation is not obvious. Deformation extends from the left and right sides to the middle and the square outlines touch each other. Eventually, they deform each other. Under the combined action of the anti-chiral structure and the concave honeycomb structure, model C first exhibits a “necking” phenomenon, and continues to compress, forming multiple squeeze layers at the impact end and support end. The two ends also show a concentrated deformation zone, which gradually expands from both ends to the middle, forming an O-shaped deformation zone and eventually tends to be dense.

Figures 6 to 8 shows the macro deformation of 3 models when the impact speed of the rigid plate is increased to 5 m/s.

![Figure 6. Deformation modes of model a under the impact velocity of 5 m/s](image)

![Figure 7. Deformation modes of model b under the impact velocity of 5 m/s](image)

![Figure 8. Deformation modes of model c under the impact velocity of 5 m/s](image)

At the beginning of compression, the deformation is mainly concentrated at the impact end. At the impact end, the cells near the left and right sides are under tension, and the cells near the center are under compression. The in-plane dynamics of the test piece shows a certain properties of a soft core material [2]. Units near the impact end exhibit different levels of collapse deformation and units in the middle shrinks in the horizontal direction, thus exhibiting a unique Poisson's ratio effect unique to pultruded materials. A "V" shaped collapse zone appears. The deformation of the support end is generally not as obvious as that at 1m/s, and the degree of deformation of the support end is B> A> C. As the compression continues, after the cells near the impact end collapse, an elastic precursor wave and highly plastic waves is generated inside the honeycomb [8]. Due to the interaction of incident and reflected waves at the support end, a local deformation band is formed near the support end face. At this speed, a more obvious "V" shape deformation is shown. On the same horizontal deformation surface, the left and right cells are under tension, and the middle cells are under compression. When the deformation rate $\varepsilon = 0.25$, the degree of deformation is B> A> C, because the model B is mainly subjected to the cell rotation caused by the bending of the support rods around the cell, and the model A is the rotation and indentation caused by the bending of the support rod. When model C is impacted, it appears as rotation caused by the bending of the connecting rod and concave deformation of the concave honeycomb cell, which is the same as B. Obviously, model C has better energy absorption
characteristics. When $\varepsilon = 0.40$, almost all the cells of model B are in close contact, and the subsequent deformations are transformed into concave deformations of the cells, which tend to be dense; the local deformation zones of models A and C continue to develop from top to bottom, from both sides to the middle and the degree of deformation $A > C$; when $\varepsilon = 0.70$, model A shows multiple squeeze layers, model B is compacted, and model C deforms more uniformly.

Further increasing the impact velocity ($V = 10\text{ m/s}$), the material exhibits an inertial effect: as the impact velocity increases, the deformation mode of the cell is transformed from elastic buckling to plastic deformation. The local deformation band is getting closer to the impact end, and gradually develops towards the support end. The necking phenomenon near the impact end is more obvious, and the deformation near the support end obviously lags behind the impact end and the degree of the degrees of deformation weakens. Figures 9 to 11 show deformation patterns of 3 models at the velocity of $10\text{ m/s}$.

![Figure 9. Deformation modes of model A under the impact velocity of 10m/s](image)

![Figure 10. Deformation modes of model B under the impact velocity of 10m/s](image)

![Figure 11. Deformation modes of model C under the impact velocity of 10m/s](image)

When the rigid plate and the model began to contact, local deformation only occurred near the impact end, and the deformation was different from the above two cases. The deformation near the impact end is mainly caused by the collapse of the hole wall, and accompanied by a small amount of bending deformation of the pillar. The deformation is concentrated at the impact end and develops toward the support end. The necking phenomenon near the impact end is weaker than the above two low-speed cases. As compression progresses, the deformation also continues to expand from the impact end to the support end. When the deformation rate $\varepsilon = 0.25$, the deformation layer of Model B is narrow and the crushing phenomenon is the most obvious. The deformation layer of model A is the widest, and rotation and indentation coexist. Model C has the narrowest deformation layer. Rotation and indentation coexist, and the energy absorption effect is better. When the deformation rate $\varepsilon = 0.40$, the degree of crushing behavior of the impact end is $B > C > A$, the deformation range is $B > A > C$, and the support end deformation degree is $B > A > C$. When the deformation rate $\varepsilon = 0.70$, model B is...
compacted. Model A shows several squeeze layers and model C’s squeeze layer is mainly concentrated at the impact end, and has a downward trend.

As a whole, the above three deformation trends under different impact speeds have common points: After each model is subjected to an impact load, it is compressed and deformed in the direction of the load, and the free edges' sinking appears in the direction perpendicular to the impact load which shows obvious characteristic negative Poisson's ratio.

With the further increase of the impact velocity \( V = 50 \text{ m/s} \), the inertia effect becomes more and more obvious. The deformation manifests as the alternating collapse of cells and pillars, and the cells are collapsed one by one. Similar to the previous three cases, the local deformation is obviously concentrated at the impact end. Under high-speed impact, the cell limits on the same horizontal section are almost the same. The deformation is mainly concentrated at the impact end, which is manifested by the collapse and accumulation of surrounding pillars and cells. The necking phenomenon is almost not seen near the impact end. The deformation of the support end is not obvious, which is similar to the compression form of other structural forms of honeycomb materials [8-9]. A negative Poisson's ratio phenomenon occurs in the later stage of compression. Figures 12-14 show the specific deformation modes.

3.2 Platform stress and energy absorption characteristics

3.2.1 Force analysis of three model platforms (impact ends) at the same speed

Figure 15 shows the nominal stress-strain diagrams of the impact platform of three different models under four different velocity impacts.
As a whole, the peak stress at the impact end increases as the impact speed increases, and as the impact speed increases, the amplitude of the "platform section" on the stress-strain curve also increases. At low and medium speeds, the curve shows two oblique lines and one platform segment, and only one platform segment under high-speed impact. The specific explanation is as follows: The two oblique lines are the buckling deformation of the material during compression, which is related to the characteristics of the material itself. Related, the platform segment is where the negative Poisson structure plays a role, and it is the characteristics of this platform stress that makes it a better energy absorption capacity when used as a structural protection material [10].

The analysis of the three models shows that the average stress is B> A> C, indicating that model B has the strongest cushioning and shock absorbing ability. Model A is the second, while model C is the worst.

3.2.2 Platform stress and energy absorption characteristics of each model

After analysis, it is known that at 1 m/s, 10 m/s, and 50m/s, the nominal stress B> A> C, and at 5 m/s, B> C> A, indicating that the model's nominal stress may be related to the magnitude of the impact velocity. Then, it is proposed to guess whether the energy absorption characteristic of the model is also related to the impact velocity.

In the energy absorption process, in addition to the cell rotation caused by the bending of the support rod, there is also a plastic deformation of the cell wall. The bending of the support rod deforms the cells of the entire honeycomb model in a coordinated manner, so that the energy absorption effect of each cell can be fully exerted. The difference in this degree of bending is also related to the deformation of different cell structures, and the mechanism’s explanation is more complicated to explain. Cell contact is the cell's compression deformation. The shape and position of the support rod
after bending are different. Therefore, the internal structure affects the honeycomb model deformation mode, and the influence of energy absorption characteristics is more complicated. It is a new idea for the energy absorption design of porous materials to increase the energy absorption capacity of cellular materials by increasing the ratio of the cell’s rotational kinetic energy and cell extrusion deformation in energy absorption.

The energy is absorbed by honeycomb material when it is compressed to a certain strain, that is, the energy under the nominal stress-strain curve until the compression strain is [11]:

\[ W = \int_{0}^{\varepsilon_d} \sigma d\varepsilon \]  

(1)

Where \( \varepsilon_d \) is the maximum strain before compaction, and \( \sigma \) is the stress that changes with the compression behavior. Based on formula (1), the energy absorption properties of the three honeycomb materials are compared, and Figure 16 gives the relationship between the energy absorbed by the honeycomb material and the nominal strain at different impact speeds.

Figure 16. Energy absorption of 3 honeycombs under different velocities

It can be seen from the pictures that for each model, the energy absorption characteristics are 50 m/s > 10 m/s > 5 m/s > 1 m/s, and the energy absorption characteristics at high speed impact are better than those at low speed. And when the speed impact is 50 m/s, the energy absorption characteristic is B > A > C. When the impact speed is 10 m/s, the energy absorption characteristic is B > C > A. When the impact speed is 5 m/s, the energy absorption characteristic is B > C > A. When the impact speed is 1 m/s, the energy absorption characteristic is B > A > C. Then came to the conclusion: for each model, its energy absorption characteristics are related to the impact speed, the greater the impact speed, the better its energy absorption characteristics, and vice versa.

This is the result of the increase in the strength of the honeycomb material with the increase of the impact speed. The reason can be attributed to the effect of inertial effect. The increase of the impact
speed increases the height and length of the load platform. At the same time, the honeycomb rotates rapidly, deforms and presses. It will cause the proportion of kinetic energy in energy absorption to increase significantly, and the honeycomb will show a stronger energy absorption capacity.

4. Conclusions
This paper studies the dynamic mechanical properties and energy absorption characteristics of three different Poisson's ratio honeycomb structures in vertical plane impact. The numerical results show that the deformation mode and energy absorption characteristics of negative Poisson's ratio honeycomb in-plane impact depend on the impact speed and internal structure.

1) When impacted at a low speed, the three models are firstly represented as a "quasi-static" mode macroscopically. Firstly, they show the unique "necking" phenomenon of negative Poisson's ratio materials. Secondly, then irregular crush zones appear until the model is completely crush.

2) When impacting at low to medium speeds, a "necking" phenomenon appears at the impact end. The support end deforms to varying degrees, and the three models have different degrees of deformation;

3) When impacting at high speed, the deformation is mainly concentrated at the impact end, and the cells at the impact end collapse one by one and gradually pass to the support end. The "necking" phenomenon is not obvious;

4) At low to medium speed impacts, the negative Poisson's ratio effect mainly occurs at the early stage of the crushing process. At high speed impacts, the negative Poisson's ratio effect mainly occurs at the later stage of the impact process;

5) At the same impact speed, different models show different stresses on the impact end and different energy absorption characteristics at different compression stages;

6) As the impact speed increases, the energy absorption characteristics of the model also increase, and the energy absorption characteristics of different models are different.

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