FEA and Quasi-static Test on Energy Absorption Characteristic of Space Orthogonal Concave Honeycomb Structure with Negative Poisson's Ratio

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Abstract. As a representative of metamaterials, negative Poisson's ratio (NPR) material possesses special mechanical properties such as expansion, negative compression ratio and so forth. As a result, it is widely used in the fields of vehicles, aerospace, et al. In this paper, a novel space orthogonal concave honeycomb structure (OC) is designed based on traditional concave honeycomb structure (CHS). In order to explore the influence rule of OC structure on the deformation and energy absorption capacity of crash box under low-speed collision, mechanical analysis and parameter research on OC structure are conducted through quasi-static compression test and numerical simulation. The results suggest that the finite element results of OC structure fit well with the experimental results, and the FEM is highly credible. In addition, the novel OC sandwich structure can effectively enhance the deformation capacity and improve the energy absorption performance of the crash box. When the wall thickness $t$ of OC structure is 1mm and angle $\varphi$ is 50°, the deformation and energy absorption capacity of the crash box increased by 25.6% and 19.3% respectively.

1. Introduction
Due to its special deformation behavior and great energy absorption performance, NPR structure is widely used in military industry, aerospace, mechanical engineering and many other areas\cite{1}. In 2018, X Zhang\cite{2} investigated the dynamics performance of the CHS with NPR effect. The study found that the impact of the structure’s performance depends on the cell expansion angle. With the absolute value of divergence angle increasing, the impact stress of platform rose as well. Additionally, the improvement of impact velocity was of great significance to the energy absorption ability. W Zhang\cite{3} et al. studied the mechanical properties of a new multi-cell structure with concave triangle and NPR. Through experiments and simulation, it was shown that this new type of NPR multi-cell structure plays an important role in the light weight application of car body. P Zhang\cite{4} et al. built four sandwich structures according to Miura origami structures. By studying the quasi-static mechanical behavior and dynamic response of these structures, they found that these structures could be used as programmable materials to meet specific engineering requirements. Finally, it was concluded that the larger the angle between the initial z axe and y axe is, the smaller the NPR is. Z Chen\cite{5} designed a novel concave annular honeycomb structure (RCH) with NPR effect based on the concave hexagonal honeycomb (CHH). And they studied the RCH under in-plane impact deformation behavior by explicit dynamic FEM. The result indicated that under the same impact velocity, RCH could reduce the peak stress of CHH. Nejc Novak\cite{6} et al. systematically studied the quasi-static and high-strain rate
response behaviors of chiral structures. The result suggested that the platform stress of chiral structure increases exponentially with the increasement of impact velocity.

With the further development of metamaterials research, NPR structures are constantly replacing traditional structures to improve the energy absorption of some crash-proof structures. Among them, the NPR structures are extensively used in crash boxes. In 2017, X Yang [7] et al. filled a new type of arrow NPR structure into the crash box, and optimized the structure with the optimal Latin hypercube sampling and ABAQUS software. The result showed that this crash box can meet the requirements of lightweight under the condition of complying with Research Council for Automobile Repairs (RCAR) standard. C Wang[8] designed a novel type of crash box with NPR sandwich core by imitating human tibia. And optimized the structure based on AMGA and NSGA-II. The result of optimization concluded that the crash box can make the vehicles more stable during the collision. Q Gao[9] et al. designed a bidirectional arrow NPR structure and analyzed the influence of slenderness ratio, angle and thickness on collision performance. The result indicated that the parameters of long inclined beam of bidirectional arrow structure have more influence than those of short inclined beam under impact load. A Ciampaglia[10] et al. studied the dynamic response of the NPR crash boxes made of Carbon Fibre Reinforced Plastics under axial impact through LS-DYNA software. The result showed that the higher the inclination angle of the top inclined plane is, the smaller the peak value of collision force will be.

The research results above conclude that the NPR structure can improve the anti-collision and energy absorption performances of the traditional crash box. However, the structures in these studies are slightly complex and are not easy to manufacture and test. Based on this, a novel NPR orthogonal concave honeycomb structure is designed, which is filled into the crash box. In this paper, the influence of the NPR structure on the energy absorption of hollow box is investigated through quasi-static compression test and numerical simulation. In addition, the cellular parameters of the structure are studied as well.

2. Finite Element Model

The height $h$, maximum width $a$, initial wall thickness $t$ and initial angle $\varphi$ of cell structure used in this study are 48mm, 55mm, 1mm, and 60° severally. Firstly, the Cell Space Crossover Method (CSCM) is adopted to redesign the inner CHS. In this method, two CHS with the same configuration are spatially crossed to form the OC. The design process is shown in Figure 1(a). Next then, in conformity with the Chinese standard of GB 17354-1998, the length, width and height of the crash box are 55×55×96mm respectively, and the wall thickness is 1mm. Finally, OC sandwich structure is filled into the crash box and assembled into a neoteric OC crash box (OCCB). The design process is shown in Figure 1(b).

![Modeling processes of the cellular structure](image1)

(a) Modeling processes of the cellular structure

![Modeling processes of the crash box](image2)

(b) Modeling processes of the crash box

Figure 1. Modeling processes of the structure

(a) Static loading method

(b) Mesh generation

Figure 2. Finite element model of OCCB

It is assumed that a car with a mass of 1000kg take on a driving speed of 4.17m/s and a collision time of 0.1s under low-speed collision. Depending on the theorem of momentum: $Ft = m\nu$, the
impact force during the collision can be calculated as 50kN. Therefore, in the static simulation, a uniformly distributed load \( F = 50 \text{kN} \) is applied on the upper surface of OCCB, and a fixed constraint is used on the lower surface, as shown in Figure 2(a). During the processing, OC sandwich structure should be welded into the inner wall of the crash box. Hence, the contact relationship between OC sandwich and the crash box is set as the tied relationship. The elements mesh method adopts the default partition mode of ANSYS, the minimum size is set to 1mm, and the growth rate is 1.2, as shown in Figure 2(b). In low-speed collisions, the crash box is generally plastic deformed to irreversibly absorb the kinetic energy into internal energy. As a result, cold rolled steel (CRS) is selected as the material of crash box in this paper, and its mechanical parameters are shown in Tab.1

| Material | \( \rho \) [Kg\( \cdot\)m\(^{-3}\)] | \( E \) [GPa] | \( \sigma_s \) [MPa] | \( E_t \) [GPa] | \( \mu \) |
|----------|----------------|----------|----------------|-----------|--------|
| CRS      | 7850           | 200      | 250            | 1.45      | 0.30   |

3. Numerical Analysis

3.1. Model Comparison

The aim of the static simulation on OCCB and hollow crash box (HCB) is to explore the influence rule of OC on energy absorption. The computational maps of the structure are shown in Figure 3.

In Figure 3(a), it is found that the displacement at the upper section of OCCB is 0.13849mm, while the displacement at that of HCB is merely 0.12577mm. The maximum displacement of OCCB occurs on OC sandwich structure. So it can be considered that the NPR effect of OC structure increases the deformation of crash box. As shown in Figure 3(b), stress distribution of OCCB is more uniform than that of HCB. The filling of OC sandwich structure is conducive to the uniform stress distribution of the structure and the improvement of the ultimate bearing capacity of the structure. During the low-speed impact, the crash box transforms the work done by the impact force into internal energy stored in the solid by deforming. Therefore, in order to better compare the energy absorption effect of the two structures, strain energy is introduced to measure the energy absorption performance. The greater the strain energy of the structure produces, the better the energy absorption capacity of the structure possesses. The strain energy \( W \) formula is

\[
W = \int_0^{\varepsilon_f} \sigma \cdot \varepsilon \, dV
\]

where \( \sigma \) is applied stress, \( \varepsilon \) is structural strain.

It can be obtained by calculation that the strain energy of OCCB structure is 3408.7mJ, while that of HCB structure is 2887.1mJ. The strain energy of OCCB structure is 521.6mJ more than that of HCB structure. Hence, this phenomenon shows that OC structure can improve the energy absorption performance of the crash box by 18.1%. It also proves that the NPR structure takes on excellent deformation and energy absorption capacity.

3.2. Parameter Research

In order to explain the deformation phenomenon of the structure in Figure 3, the static load model
established in this paper is as follows: assuming that the cell of the structure is subject to uniformly distributed load \( F \) and the cell base is under fixed constraints \( u(x, y, z) = 0 \), the deformation diagram of the structure under load is shown in Figure 4. In the figure, the solid line represents the shape of the cell structure before stress, and the dotted line represents the shape after stress. Since the structural wall is regarded as a rigid body before and after impact, no change in length and only changes in bending and angle occur. And the structural top angle changes from the original \( \varphi \) to \( \varphi_1 \), the height of the structure is changed from \( h \) to \( h_1 \), other conditions remain still. As OC is an axisymmetric structure, only a quarter part of the structure is taken for analysis. The structural nodes are named node 1, 2 and 3.

![Figure 4](image.png)  
**Figure 4.** The deformation of the OC under load

![Figure 5](image.png)  
**Figure 5.** The behavior of joints of the OC

Before compression, the force system is in equilibrium and the energy inside the structure is stable. The balance of the structure is broke under the load and the force changes begin to appear. The direction and magnitude of each force on the node are named as shown in Figure 5. According to the equilibrium conditions of the forces, the equilibrium equations of each node can be established.

1) Stress on node 1

\[
\begin{align*}
 f_{1x} &= f_1 \cos \varphi_1 \\
 f_{1y} &= f_1 \sin \varphi_1
\end{align*}
\]

2) Stress on node 2

\[
\begin{align*}
 f_1 &= f_2 \\
 f_2 \sin \varphi_1 &= N_2 \sin \varphi_1 \\
 k_2 &= f_2 \cos \varphi_1 + N_2 \cos \varphi_1 \\
 M_{21} &= k_2 \cdot \frac{h_1}{2}
\end{align*}
\]

3) Stress on node 3

\[
\begin{align*}
 f_3 &= N_2 \\
 f_{3x}' &= f_{3x}' + f_3 \cos \varphi_1 \\
 f_{3y}' &= f_{3y}' + f_3 \sin \varphi_1 \\
 M_{23} &= k_2 \cdot \frac{h_1}{2}
\end{align*}
\]

where \( F' \) is the external force on the structure, \( f_{1x} \) is the component of the force along the x direction, \( f_{1y} \) is the component of the force along the y direction, \( f_i \) is the axial force along the rod direction of
the node, $k_2$ is the resultant force on node 2, $M_{2i}$ is the bending moment of node 2 on the node $i$.

It can be seen from the above equations that the deformation of OC is mainly affected by the included angle $\varphi$. In addition, the structure is assumed to be a bar while the wall thickness is ignored in the force analysis in this paper. However, in practice the thickness of the structure is also one of the crucial factors affecting the energy absorption performance. Therefore, the parameters $t, \varphi$ of OC are explored in this paper to further optimize its energy absorption performance. The cell length, width and height of OC structure, and the thin-wall thickness of the crash box remain unchanged, the geometric parameters affecting OC structure are listed in Table 2. The range of the value $t$ is 0.8mm~1.6mm, and the step length is 0.2mm. The value $\varphi$ range is 50°~70° and the step length is 5°.

**Table 2.** Geometric parameters of OC

| Group | $t$(mm) | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 |
|-------|---------|---|---|---|---|---|---|---|---|---|---|
|       |         | 0.8 | 1.0 | 1.2 | 1.4 | 1.6 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| $\varphi$(°) | 60 | 60 | 60 | 60 | 60 | 50 | 55 | 60 | 65 | 70 |

4. Results and Discussion

4.1. The Effect of Wall Thickness $t$ on Structure

It can be seen from Figure 6(a) that the curves of maximum stress and maximum displacement are divided into two stages bounded by $t=1$mm. In the first stage, the maximum stress value of the structure presents a downward trend, while the maximum displacement value presents an upward trend. When thickness $t$ is 1mm, the maximum stress value reaches the minimum value of 260.02MPa, and the maximum displacement reaches the peak value of 0.1558mm. In the second stage, the maximum stress value rises slowly while the maximum displacement value drops sharply. In the first stage, the thickness is of vital influence on the ultimate bearing capacity of the structure. When thickness $t$ is 0.8mm, the maximum stress value of the structure has exceeded the ultimate strength and the structure becomes unstable. In the second stage, the stiffness and strength of the structure are enhanced with the thickness increasing, which limits the deformation of the structure and improves the stability.

According to the equation 1, the strain energy of each structure is calculated, as shown in Figure 6(b). The strain energy is divided into two stages as well in the bar chart. Thickness $t=1$mm is a turning point. When thickness $t$ is less than or equal to 1mm, the strain energy increases gradually, while when the thickness $t$ is more than 1mm, the strain energy decreases piece by piece. The maximum strain energy at the turning point is 3408.7mJ. Compared with the HCB structure, when $t$ is 1mm, the energy absorption capacity of the crash box is improved by 18.1%. As a consequence, the structure possesses superior deformation capacity and energy absorption performance at $t=1$mm.

(a) The maximum displacement and mises stress

(b) The effect of thickness $t$ on strain energy

**Figure 6.** The result of the effect of cell thickness $t$ on structure
4.2. The Effect of Angle $\phi$ on Structure

Under the premise that the wall thickness $t$ of all structures is set as 1mm, the research results of the included angle $\phi$ are summarized in Figure 7(a) and (b). As the value $\phi$ gradually decreases, the maximum stress value first decreases and then increases, while the maximum displacement value generally decreases and rises when $\phi$ is 55°~60°. The maximum stress value is 379.45MPa and occurs at $\phi=50^\circ$, while the minimum stress value is 260.02MPa and occurs at $\phi=60^\circ$. The maximum displacement is 0.1575mm and occurs at $\phi=50^\circ$. Depending on equations 6, 7 and 11, it is not difficult to understand that the smaller the value $\phi$ is, the larger the deformation of the structure produces. This also indicates that the NPR effect of the structure becomes more obvious with the decrease of the value $\phi$. On the other hand, the stiffness of the structure is enhanced with the growth of the value $\phi$ while the deformation of the structure is limited.

According to the equation 1, the strain energy of each structure can also be calculated. When $\phi$ is 50°, the maximum deformation energy is 3443.9mJ. And then, when $\phi$ are equal to 60° and 55°, the deformation energy is severally 3408.7mJ and 3045.1mJ. When $\phi$ are equal to 65° and 70°, the lowest strain energy are 3352.5mJ and 3302.0mJ respectively. Through the analysis of the maximum stress value, maximum displacement value and deformation energy, it can be found that when $\phi$ is 50°, the structure has been locally damaged, while it produces the largest displacement, absorbs the most internal energy. The energy absorption capacity of HCB is effectively improved by 19.3%. In the other four structures without failure, the deformation and energy absorption capacity are optimal when $\phi$ is 60°.

![Graph](image1)

(a) The maximum displacement and mises stress

![Graph](image2)

(b) The effect of angle $\phi$ on strain energy

**Figure 7.** The results of the effect of angle $\phi$ on structure

5. Quasi-static Compression Test on OC Structure

5.1. Test Method

To further explore the deformation behavior of OC, the quasi-static compression test is carried out in conformity with the Chinese standard of GBT7314-2005, and the testing machine adopts the universal tester CMT5205 of SANS company. The specimen is made of CRS DC01. Firstly, the specimen is placed in the bottom platform center. And then it is compressed by rigid upper platform which loading speed is 5 mm/min, the axial compression displacement is 50% of the specimen height. The compression test is shown in Figure 8. Through the pressure sensor, force-displacement curve is measured. At the same time, the deformation of the specimen at different displacement model is recorded by camera.
5.2. Verification of FEM

To verify the credibility of finite element simulation, the FEM is compared with the experimental model. Figure 9 shows the structure displacement diagram under quasi-static loading and finite element simulation.

![Figure 9. The comparison of the test and finite element model](image)

As can be seen from the deformation diagram of specimens in Figure 9, with the increase of displacement, the thin-walls on four sides of OC structure continuously shrank inward, showing an obvious NPR effect. When axial compression $\Delta h$ is 5mm, the adjacent thin-wall critical contact of OC is observed. After 10mm, the adjacent thin walls squeeze each other, and the upper part is bent. The bending degree increases steadily. When axial compression reaches its peak, the largest deformation occurs at the sharp angle of the sidewall. In the FEM, when $\Delta h$ is 5mm, the structure begins to contact; After 10mm, the structural wall undergoes the same extrusion deformation. Compared with each other, it can be found that their deformation process is basically similar. To further study the rationality of the model, the force-displacement curves of the two are fitted, as shown in Figure 10 and 11. In figures, the variation trend of the FEM and the test curve are nearly the same, with good fitting between the displacement values of 0–2mm, 5–7.5mm and 20–25mm. The average error bar is 313.0, and the maximum error bar is 1223.0. On the whole, the FEM has high credibility.

![Figure 10. The curves of Force-Displacement](image)

![Figure 11. The error bars of Exp and FEM](image)
6. Conclusion
In this paper, a novel OC with concave interior is designed, which possesses good NPR effect and can generate large deformation to absorb energy. Additionally, the influence rule of OC on the energy absorption performance of HCB is investigated. Moreover, the cellular parameters of OC are studied. Through finite element simulation and theoretical analysis, the following conclusions are obtained:

(1) Compared with HCB, OC can make the structural stress evenly distributed, which can effectively enhance the deformation and energy absorption capacity.

(2) With the increase of $t$, the stiffness and strength of OCCB are enhanced while its deformation is limited. When $t$ is 1mm, the structure possesses the best energy absorption effect.

(3) With the $\varphi$ of OC decreasing, the NPR value of the structure drops continuously. When $\varphi$ is 50°, the structure is damaged. However, its energy absorption effect is the best, which can absorb 3443.9mJ of energy. Compared with HCB, the energy absorption capacity is improved by 19.3%. When $\varphi$ is 60°, the structure is still in the plastic stage, and the energy absorption of HCB can be increased by 18.1%.

(4) Through comparison of quasi-static compression test and finite element simulation, the results show that the deformation history and force-displacement curve of FEM are in good agreement with the test results. The average error bar is 313.0. Thus, the rationality of FEM is verified.

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