Investigation of the Energy Absorption Characteristics and Negative Poisson's Ratio Effect of an Improved Star-Shaped Honeycomb

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Abstract: An improved star-shaped honeycomb (ISSH) is a kind of honeycomb structure with excellent performance. The main objective of this study was to provide some ideas for the optimization of the ISSH structure in ships. As a result, 2D-ISSH specimens were fabricated using 3D printing technology, and a quasistatic compression test was carried out to investigate the deformation mode and mechanical properties. The experimental results showed that the 2D-ISSH structure exhibited “V”-shaped and “-”-shaped deformation patterns with a double-platform stress stage. To further utilize the excellent performance of the structure and obtain a better negative Poisson’s ratio effect and broader application, based on the properties of the 2D-ISSH specimen, a 3D-ISSH structure was proposed and a finite element simulation was carried out. The simulation results of the 3D-ISSH structure showed different deformation patterns, including “X”-shaped and “-”-shaped patterns. According to the deformation mechanism of typical cells, the stress formula for the 3D-ISSH double platform was derived, and the theoretical results agreed well with the numerical results. The effects of the structural design, materials, and dimensions on the mechanical properties, such as the energy absorption and negative Poisson’s ratio, of the ISSH and similar structures were explored. The combined performance of various honeycombs was evaluated from multiple perspectives.

Keywords: 3D star-shaped honeycomb; platform stress; stress–strain curve; specific energy absorption; negative Poisson’s ratio

1. Introduction

Ships are inevitably exposed to the threat of various shocks, explosions, vibrations, and other intense loads in their normal operating environment. Therefore, the excellent performance of anti-explosion and anti-impact structures is the developmental direction of naval research. The existing design idea of the traditional protection structure is to alternate the arrangement of empty and liquid compartments [1]. Traditional protection design optimization ideas often rely on increasing the weight of the structure to improve the protection performance of the structure. However, a limited number of studies have focused on the design of lightweight protective structures. How to design lightweight protective structures is a popular research topic nowadays.

Lightweight porous structures have attracted much attention owing to their excellent mechanical properties, such as their light weight and high strength, and multifunctional properties, such as their vibration damping and energy absorption. A variety of porous structures have been developed, including dot-matrix, honeycomb, grid, and corrugated structures. Ullah et al. [2] investigated the energy absorption properties of face-centered...
cubic (FCC), body-centered cubic (BCC), face–body-centered cubic (FCC + BCC), and 3D-Kagome structures under compression and shear loading conditions. Zhang et al. [3] proposed an energy-absorbing enhancement design method for cardio-cubic dot structures. Kooistra et al. [4] proposed a new, multilevel corrugated sandwich structure with ten times the strength of a single-stage corrugated plate of the same mass. Pasqualino et al. [5] conducted simulation calculations and tests on the uniaxial compression of honeycomb sandwich panels in order to promote the integration of aluminum honeycomb sandwich structures into the structural design of ships. Due to their excellent performance, porous structures are used as advanced protective structures in marine fields.

Poisson’s ratio is a typical structural characteristic. Generally, the macroscopic Poisson’s ratio of a porous structure is positive. However, negative Poisson’s ratio honeycombs have a negative Poisson’s ratio effect that is not found in common porous structures, which gives them many excellent mechanical properties, such as relatively high load-carrying capacities [6,7], high shear modulus [8], high fracture toughness [9], excellent impact resistance [10,11] and superior specific energy absorption performance [12,13]. Under impact loading, the negative Poisson’s ratio honeycomb allows for more material to accumulate near the point of force to absorb more impact energy than other structures, which gives it great application prospects in the field of impact protection. In recent years, many scholars have performed studies on negative Poisson’s ratio honeycombs. Many distinctive negative Poisson’s ratio structures have been designed, such as concave structures, rotating polygonal structures, chiral structures, lamellar pleated structures, perforated plate structures, and interlocking polygonal structures [14]. Among these structures, the concave structure has been highly developed over the years, and various structural forms with excellent performance have been designed. Gibson et al. [15] proposed a 2D concave hexagonal honeycomb structure in 1982, which was the first negative Poisson’s ratio honeycomb structure that was designed. In 1985, Almgren [16] designed a concave hexagonal honeycomb structure and derived the analytical equations for its Young’s modulus and Poisson’s ratio, which amounted to $-1$. Larsen et al. [17] pioneered the design of negative Poisson’s ratio structures using topology optimization methods and proposed an arrow-shaped honeycomb negative Poisson’s ratio material, which was found to have a Poisson’s ratio reaching $-0.8$, according to the theoretical analysis. Theocaris et al. [18] proposed a star-shaped negative Poisson’s ratio honeycomb structure, which was widely recognized as a deformation of the traditional concave structure.

Although the traditional honeycomb has excellent performance, it is still incapable of facing certain complex and intense work scenarios. Thus, many scholars have designed various improved honeycombs by introducing other configurations based on traditional honeycombs. Wang et al. [19] combined a double-arrow structure with a conventional star structure to propose a novel tensile-expansive honeycomb, and investigated its in-plane elastic properties and energy absorption characteristics. Wei et al. [20–22] introduced triangles into the traditional star-shaped honeycomb and proposed a novel star–triangle honeycomb, and its deformation behavior at different velocities was investigated. The negative Poisson’s ratio effect of the star–triangle honeycomb under pressure in two directions was analyzed using a simulation, and a theoretical model was established to predict its Young’s modulus and Poisson’s ratio more accurately. The star–triangle honeycomb was also extended to three dimensions, and its deformation mode was investigated by combining experiment and simulation, and the effect of the gradient design on the deformation and energy absorption of the structure was analyzed. Hu et al. [23] constructed an improved star-shaped honeycomb structure by introducing arrow-shaped and square-shaped structures, and by performing finite element simulation calculations. The testing results showed that the specific energy absorption of the improved star-shaped honeycomb is better than that of the star-shaped honeycomb, and the deformation is more stable under low-speed loading. Yang et al. [24] designed a new 3D star structure with a negative Poisson’s ratio based on the traditional 2D star structure with a negative Poisson’s ratio, and explored the effects of impact velocity and design angle on the dynamic deformation.
mode and mechanical response of the star model. Li et al. [25] designed a crossed star honeycomb by evolving the horizontal and vertical walls of a conventional star honeycomb into crossed sloping walls and explored the effects of the inclination angle on Poisson’s ratio, Young’s modulus, and the energy absorption. Hu et al. [26] printed models using 316 L steel and performed material tensile testing and honeycomb compression testing. They investigated the compressive mechanical properties of anti-tetrachiral honeycomb materials with different thickness ratios of the ligament to the cylindrical. They found a variety of deformation modes and obtained critical values for the transformation of the anti-tetrachiral honeycomb deformation modes. Wang et al. [27] printed models using 316 L steel and performed honeycomb compression testing, and also investigated the effect of nodal configuration on the mechanical properties of hexachiral honeycombs.

However, most studies focus on 2D negative Poisson’s ratio materials; only a limited number of studies have focused on the 3D negative Poisson’s ratio structure. Moreover, these studies are mainly limited to numerical simulations and lack detailed experimental studies and validation. To obtain a better negative Poisson’s ratio and energy absorption performance, further playing with the role of structural design and broadening the application scenarios for the structure are needed. Here, an improved star-shaped honeycomb structure is designed, and its deformation pattern and mechanical properties are analyzed using a combination of experiments and finite element simulations. Moreover, there is a discussion of the structure used in this paper and similar structures to evaluate the performance advantages and disadvantages of the honeycomb from multiple perspectives. The main research of this paper is as follows: quasistatic compression tests of the 2D-ISSH are conducted in Section 2 to reveal its deformation pattern and mechanical properties. In Section 3, the validity of the finite element simulation calculation method is verified and finite element simulation calculations are carried out on the 3D-ISSH to reveal its deformation patterns and mechanical properties. In Section 4, the theoretical derivation of the double-platform stresses of the 3D-ISSH under quasistatic compression is presented; the effects of the structural design, materials, and dimensions on the mechanical properties, such as the energy absorption and negative Poisson’s ratio, of the ISSH and similar structures are explored. And the combined performance of the various honeycombs is evaluated from multiple perspectives. The main conclusions of this paper are presented in Section 5.

2. An Improved Star-Shaped Honeycomb

2.1. Model Design, Preparation, and Testing

Based on the traditional star-shaped honeycomb, an improved star-shaped honeycomb structure (ISSH) was constructed by introducing arrow-shaped and rectangular structures, using arrow-shaped structures instead of the horizontal walls of the star-shaped honeycomb, and bringing the thin-walled rectangles into contact with the four concave angles. The configuration and geometric parameters of the cell are shown in Figure 1. The main geometric parameters are shown in Table 1. The honeycomb had seven and eight cells along the x and y directions, with lengths of 99.61 mm and 80 mm, respectively. To prevent instability during compression, the length of the honeycomb was extended along the outwards direction of the face by 80 mm. A quasistatic compression test was carried out using a material testing system (MTS), as shown in Figure 2.

Table 1. Geometric and material parameters of the 2D-ISSH.

<table>
<thead>
<tr>
<th></th>
<th>H (mm)</th>
<th>α (°)</th>
<th>t (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D-ISSH</td>
<td>10</td>
<td>30</td>
<td>0.25</td>
</tr>
<tr>
<td>Materials Density (kg/m³)</td>
<td>Young’s modulus (GPa)</td>
<td>Poisson’s ratio</td>
<td>Yield strength (MPa)</td>
</tr>
<tr>
<td>316 L steel</td>
<td>7980</td>
<td>205</td>
<td>0.3</td>
</tr>
</tbody>
</table>
The tested honeycomb sample was fabricated using a selective laser melting molding process, with monolithic printing and no welding splicing; 316 L steel was selected as the base material. The 316 L steel material parameters are shown in Table 1. During the fabrication process, a high-powered laser was used to completely melt the metal powder layer-by-layer until the samples were completed. In addition, to eliminate some defects in the material structure and to fully utilize the performance potential of the material, the honeycomb was heat-treated.

2.2. Deformation Mode

As shown in Figure 3, the main deformation mode of the 2D-ISSH specimen under quasistatic compression is the rotational deformation of the tilted wall of the cell around the plastic hinge. The rotation of the tilted wall leads to the contraction of the cells, which induces a negative Poisson’s ratio effect. Below a compression strain of 0.02, the honeycomb mainly undergoes elastic deformation, and an overall contraction is observed. As compression proceeds, the honeycomb enters the plastic phase, and the lower part of the honeycomb is first deformed. Due to the presence of the intermediate rectangle, the cells cannot be compressed directly, and the walls of the cells fit diagonally, resulting in an inverted “V”-shaped region of localized deformation. Subsequently, the deformed cells gradually spread upwards, and a “V”-shaped localized deformation region appears on the impact side. At this stage, the rectangular structure in the middle of the cells is compressed into a hollow bamboo shape. Moreover, part of the inclined wall becomes horizontal, and

![Figure 1. Design of the 2D-ISSH.](image1)

![Figure 2. Quasistatic compression test set. (a) 2D-ISSH test model. (b) Quasistatic compression test.](image2)
the honeycomb produces a significant contraction. As the specimen is further compressed, the arrow-shaped structures on both sides of the cells deform, and the horizontal walls of the honeycomb overlap, showing a “-”-shaped dense region. Subsequently, the middle region of the cytosol collapses and comes into close contact with the upper and lower cytosolic walls, at which point the honeycomb densifies.

Figure 3. Deformation patterns for quasistatic compression tests of the 2D-ISSH specimen.
2.3. Mechanical Properties

The stress–strain curve of the 2D-ISSH specimen under quasistatic compression is shown in Figure 4, which can be divided into elastic, first plateau, transition, second plateau, and densification stages. After the elastic phase, due to the yielding of the walls of the star-shaped cells, the first plateau stage appears with a “V”-shaped deformation pattern. This deformation pattern flattens the stress curve, avoids peak stresses, and improves the honeycomb’s impact resistance performance. Subsequently, the star-shaped cell wall deforms to a horizontal degree, and the arrow-shaped structure yields and deforms. With the gradual increase in the yielded cell wall, the stress–strain curve reaches the transition stage, and the stress gradually increases. In this state, the honeycomb exhibits a “—”-shaped deformation pattern. This deformation pattern prevents the honeycomb from experiencing a sudden increase in stress prior to densification. As the number of yielding cell walls stabilizes, the second plateau stage appears. Subsequently, the cells are gradually compacted, the “—”-shaped regions gradually overlap, and the whole honeycomb is pressed into a square shape to achieve densification.

![Stress-strain curve of the 2D-ISSH specimen.](image)

**Figure 4.** Stress–strain curve of the 2D-ISSH specimen.

3. An Improved Star-Shaped Honeycomb

3.1. Method Validation and Structural Design

Based on the improved star-shaped honeycomb structure, a 3D improved star-shaped honeycomb structure was obtained by cross-combining two 2D-ISSHs. The width of the cross-cells was b. As a result of the structural crossover, the tilted wall above the cell became shorter (from L1 to L2), and the angle between the tilted wall and the horizontal became larger (from α to θ). The other parameters remained the same as in the 2D-ISSH. The geometric configuration and the geometric parameters of the cells are shown in Figure 5a, and the main geometric parameters are shown in Table 2. The finite element model was built based on Abaqus (2022) software, as shown in Figure 5b. Two plates were arranged at the top and bottom of the honeycomb, which were set as discrete rigid bodies. Fixed constraints were added to the lower plate and the upper plate was impacted downwards at a constant velocity. General contact with a friction coefficient of 0.2 occurred between the honeycomb itself and the upper and lower plates. The honeycomb took 7, 8, and 7 cells along the x, y, and z directions, with lengths of 99.61 mm, 80 mm, and 99.61 mm, respectively. The whole...
structure was modeled with S4R shell elements. When the cell size is reduced, equivalent stresses tend to converge and, considering accuracy and computational efficiency, this paper chose 0.5mm mesh for the finite element calculation, and a total of 310,464 meshes were generated. The base material was 316L steel. The material properties are shown in Table 1.

To verify the accuracy and reliability of the simulation method, finite element simulation calculations were carried out on the two-dimensional honeycomb test, and the test and simulation results were compared. As shown in Figure 6, the deformation patterns of the two structures were consistent, and the stress value under the same strain was increasingly consistent, indicating the accuracy of the finite element simulation method.

Table 2. Geometric parameters of the 3D-ISSH.

<table>
<thead>
<tr>
<th></th>
<th>H (mm)</th>
<th>α (°)</th>
<th>t (mm)</th>
<th>b (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D-ISSH</td>
<td>10</td>
<td>30</td>
<td>0.25</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 5. Geometric and finite element models for the 3D-ISSH. (a) Design of the 3D-ISSH. (b) Finite element model of the honeycomb structure.
3.2. Deformation Mode

The deformation pattern of the 3D-ISSH specimen is shown in Figure 7. The 3D-ISSH shrinks simultaneously in the x and z directions. Before a compression strain of 0.02, the honeycomb undergoes mainly elastic deformation and the whole structure shrinks. After the elastic stage, the middle region of the 3D-ISSH shrinks first. Due to the presence of the middle rectangle, the cells cannot be compressed directly and the cell walls rotate with compression. When the strain reaches 0.13, an “X”-shaped region of localized deformation appears in the honeycomb. At this time, the degrees of deformation of the cells in the left and right regions of the “X”-shape are large, and the degrees of deformation of the cells in the upper and lower regions are small. When the specimen is compressed further, the upper and lower portions of the honeycomb shrink. When the strain reaches 0.4, the upper and lower regions of the “X”-shaped cytosol undergo large degrees of deformation, the middle rectangle of the cell is compressed into a hollow bamboo shape, and part of the inclined wall is pressed to the horizontal. When the strain is 0.5, the arrow-shaped structure around the cells deforms, and the horizontal walls of the honeycomb overlap, showing a “-”-shaped dense region. Subsequently, the middle rectangle of the cells collapses and is in close contact with the upper and lower cell walls, and the “-”-shaped regions gradually overlap; at this time, the honeycomb is densified. The 3D-ISSH top-view observation resembles the cross-assembly of plate parts, and a phenomenon similar to the yielding of plates occurs under pressure, resulting in the bending and rotation of some of the surrounding cells.
3.3. Mechanical Properties

As shown in Figure 8, the stress–strain curve of the 3D-ISSH specimen under quasistatic compression is similar to that of the 2D-ISSH specimen, and both can be divided into elastic, first plateau, transition, second plateau, and densification stages. After the elastic stage, due to the yielding of the walls of the star-shaped cells, the first plateau stage appears, where the main deformation pattern of the honeycomb is “X” shaped. This deformation pattern flattens the stress curve, avoids peak stresses, and improves the honeycomb’s impact resistance performance. Subsequently, the wall of the star-shaped cell is
deformed to a horizontal degree, and the arrow-shaped structure around the cell yields and deforms. With the gradual increase in the yielding cell wall, the stress–strain curve reaches the transition stage. At this moment the stress gradually increases, and the honeycomb shows a “-”-shaped deformation pattern. This deformation pattern prevents the honeycomb from experiencing a sudden increase in stress prior to densification. As the number of yielding cytosolic walls stabilizes, the second plateau region appears. Subsequently, the cells gradually collapse, and the “-”-shaped regions gradually overlap. In this stage, the whole honeycomb is densified.

4. Discussion

4.1. Theoretical Deduction

Platform stress is an important indicator of structural energy absorption. Based on the law of conservation of energy and plastic hinge theory, the stress equations for the quasistatic platform of the 3D-ISSH specimen are derived, and the predicted results are utilized for comparison with the simulation results.

The typical cell morphologies at the start and end stages of the first plateau are shown in Figure 9a,b. Due to the symmetry of the model, the inclined wall AB is rotated around points A and B until it reaches the horizontal direction. Similarly, the inclined wall BC is rotated around B and C until it comes into contact with CD. The thin square wall in the center also rotates around points A and C due to contraction. The 24 plastic hinges appearing in this plane of the cell at this stage are highlighted by red circles in Figure 9a, where the angle of rotation of the inclined wall AB is $\Delta \phi$, the angle of rotation of the inclined wall BC is $\Delta \phi$, and the angle of rotation of the square thin-walled plastic hinge is $\Delta \delta$. It is assumed that the angle of rotation of each plastic hinge in a thin square wall is the same, and that the length of each inclined wall is constant, with due consideration for the wall thickness of the cell. The plastic hinge angle is calculated as follows:

$$\Delta \phi = \theta$$

(1)

$$\Delta \phi = \alpha$$

(2)
Figure 9. Deformation stages of the typical cells of 3D-ISSH under quasistatic compression. (a) Initial form. (b) Middle form. (c) Densified form.
The work conducted by the external force on the honeycomb is equal to the energy dissipated by the plastic hinges on the sloping and thin square walls of the honeycomb. Based on the conservation of energy, the following equations can be obtained:

\[ W_p = \sigma_{p1} s_0^2 \Delta y \]  

\[ \Delta y = H_0 - H_1 = H - \frac{H \sin \alpha}{\cos \alpha} - 2t \]  

where \( s_0 \) is the initial transverse length of the cell, \( \sigma_{p1} \) is the stress at the first platform of the honeycomb, \( \Delta y \) is the relative displacement in the compression direction, \( H_0 \) is the initial height of the cell, and \( H_1 \) is the height of the cell at the end of the first platform stage.

The total energy dissipation from the initial phase to the intermediate phase consists of two parts: the inclined-wall plastic hinges, \( E_1 \), and the square thin-wall plastic hinges, \( E_2 \), and can be expressed as follows:

\[ E_1 = 16M_1 \Delta \phi \]  

\[ E_2 = 16M_1 \Delta \delta = 16M_1 \arcsin \left( \frac{\Delta x}{L - 2t} \right) \]  

The plastic ultimate bending moment, \( M_1 \), of a rectangular section beam is as follows:

\[ M_1 = \sigma_0 bt^2 / 4 \]  

\[ \sigma_0 = \sqrt{\frac{\sigma_y \sigma_u}{1 + n}} \]  

where \( n \) is the strain intensification index of the material. \( \Delta x \) is the transverse shrinkage displacement:

\[ \Delta x = S_0 - S_1 = H \left( 2 - \tan \alpha - \frac{1}{\cos \alpha} \right) \]  

According to the conservation of energy, we obtain the following equation:

\[ W_p = E_1 + E_2 \]  

In summary, the first plateau stress for the 3D-ISSH specimen under quasistatic compression can be expressed as follows:

\[ \sigma_{p1} = \frac{16M_1 \Delta \phi + 16M_1 \Delta \phi + 16M_1 \Delta \delta}{S_0^2 \Delta y} = \frac{4\sigma_0 bt^2 \left[ \theta + \alpha + \arcsin \left( \frac{\Delta x}{H(1 - \tan \alpha) - 2t} \right) \right]}{\left[ H(1 - \tan \alpha) - 2t \right]^2} \]  

When the inclined wall is adhered to the arrow-shaped long edge, as shown in the middle form of Figure 9b, the stresses start to increase and the second plateau stage is initiated. In the second platform stage, the inclined wall BC is rotated around points B and C, and the arrow-shaped long side CD is rotated around points C and D. The two fit together and rotate at the same angle. The arrow-shaped short side DE is rotated around points D and E. The number of plastic hinges in a thin square wall increases from 8 to 12 in a single plane. The 28 plastic hinges appearing in this plane of the cytosol at this stage are highlighted by the red circles in Figure 9b,c.

The starting height of the cytosol at the second platform stage and the height at the time of densification are as follows:

\[ H_1 = H \tan \alpha + 2t \]
The initial cytosolic transverse length is as follows:

\[ H_2 = 11t \]  (13)

The plastic hinge rotation angle of the tilted wall BC of the cell and the arrow-shaped long edge CD is as follows:

\[ \Delta \phi' = \alpha - \arcsin(H_2/2L_1) \]  (15)

The angle of rotation of the plastic hinge of the short edge of the arrowhead shape of the cell is as follows:

\[ \Delta \phi'' = \frac{\pi}{2} - \alpha - \arcsin(H_2/2L_1) \]  (16)

The thin wall AF in the square is rotated around points A and F, and CF is rotated around points C and F. It is easy to know that the angle of rotation of the plastic hinge at point F is \( \pi/2 \), according to the characteristics of squares, and the sum of the angles of rotation of the plastic hinges in the 1/4 square structure is \( \pi \).

The second platform stress is still obtained from the law of the conservation of energy, which is expressed as follows:

\[
\sigma_{p2} = \frac{16M_2\Delta \varphi' + 16M_1\Delta \varphi' + 16M_1\Delta \delta'}{S_1^2(H_1 - H_2)} = \sigma_ybt^2\left[\frac{14\pi}{3} - 12\arcsin\left(\frac{11t \cos \alpha}{H}\right)\right]\left(\frac{H}{\cos \alpha}\right)^2(H \tan \alpha - 9t)
\]  (17)

where \( M_2 \) is the plastic ultimate bending moment of the overlapping inclined wall, and \( M_2 = 2M_1 \).

A comparison of the theoretical and simulation results for the platform stress is shown in Table 3. The theoretical analysis results of the platform stress in the two segments are in good agreement with the numerical simulation results. During the second platform stage, the honeycomb is compressed to the late stage, where the cells have a certain degree of rotation. Affected by the boundary effect, the degree of rotation from the center to the surroundings is gradually intensified. Due to the rotation from the absorption of part of the energy, the stress produces a tendency to enhance the stress, and the stress begins to exceed the theoretical value.

### Table 3. Comparison of theoretical and simulation results for platform stress.

<table>
<thead>
<tr>
<th></th>
<th>First Platform Stress, MPa (Average Value)</th>
<th>Second Platform Stress, MPa (Average Value)</th>
<th>Second Platform Stress, MPa (Starting Value)</th>
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<tbody>
<tr>
<td>Simulation</td>
<td>0.45</td>
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<td>1.18</td>
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<tr>
<td>Theory</td>
<td>0.46</td>
<td>1.19</td>
<td>1.19</td>
</tr>
</tbody>
</table>

#### 4.2. Specific Energy Absorption

The specific energy absorption values of the 2D-ISSH and 3D-ISSH specimens under quasistatic compression are shown in Figure 10. When the compression strain is less than 0.6, the deformation mode is similar for the 2D-ISSH and 3D-ISSH structures. Thus, the trend of stress is basically the same, inducing an equivalent specific energy absorption value. At a later stage, as the 3D-ISSH cytosol rotates, additional energy absorption occurs and the specific energy absorption values of the 3D-ISSH structure are larger than those of the 2D-ISSH structure. Relative to the 2D-ISSH, the specific energy absorption value of the 3D-ISSH is increased by 5.02%.
The cells rotate after the 3D honeycomb is compressed, increasing the energy absorption.

### 4.3. Elasticity and Deformation

To explore the relationship between the structural design and energy absorption in depth, and to analyze the effects of the structural materials on the specific energy absorption, other honeycombs are introduced. Figure 10 shows the specific absorption energy of the 2D-ISSH, 3D-ISSH, star-shaped honeycomb (SSH), star–arrowhead honeycomb (SAH), double arrowhead honeycomb (DAH), 2D star–triangular honeycomb (2D-STH), and 3D star–triangular honeycomb (3D-STH) at densification. It can be observed that the SAH adds an arrow-shaped structure to the SSH and replaces the straight wall in it, and the deformation of the arrow-shaped structure increases the number of plastic hinges that absorb additional energy; therefore, the specific energy absorption is improved by 21.11% compared to that of the SSH. The specific absorption energy of the SAH is still lower than that of the DAH because the number of plastic hinges in the star-shaped structure is less than that in the arrow-shaped structure. The SSH and SAH are made of aluminum, which is weaker. However, for the 2D-STH and 2D-ISSH, the material is 316 L steel, which is relatively strong; thus, each plastic hinge can absorb more energy. The specific energy absorption levels of the SSH and SAH are significantly weaker than those of the 2D-STH and 2D-ISSH. When both the 2D-STH and 2D-ISSH are expanded to three dimensions, the specific energy absorption is increased, which is mainly attributed to the fact that some of the cells rotate after the 3D honeycomb is compressed, increasing the energy absorption level. The 3D-ISSH has a 5.02% improvement in specific energy absorption over the 2D-ISSH.

**Figure 10.** Comparison of the SEA of the existing configurations at densification [19,22].

The transverse contraction displacement of the honeycomb during compression can be obtained by arranging the measurement points uniformly on the left and right sides of the honeycomb model, and the transverse strain of the honeycomb can be obtained by dividing the average value by the original length of the honeycomb. Figure 11 illustrates Poisson’s ratio–strain curves of the 2D-ISSH, 3D-ISSH, SSH, SAH, DAH, 2D-STH, and 3D-STH structures. The negative Poisson’s ratio effect is most pronounced in the early stage of DAH due to the special deformation trajectory of the arrow-shaped structure. But...
the advantages and disadvantages of a structure cannot be evaluated from one angle of negative Poisson’s ratio alone; they have to be analyzed from multiple factors. According to the use scenarios of the honeycomb structures, in addition to the negative Poisson’s ratio effect and the specific energy absorption mentioned above, the load-carrying capacity and regularity during deformation should be considered as important evaluation criteria.

Figure 11. Comparison of the Poisson’s ratio–strain curve between existing configurations [19,22].

The carrying capacity of a honeycomb structure is evaluated by $E^*$. The greater the value of $E^*$ is, the greater the carrying capacity of the honeycomb.

$$E^* = \frac{E_1}{E_s \rho} \quad \text{(18)}$$

where $E_1$ is Young’s modulus of the honeycomb structure, $E_s$ is Young’s modulus of the substrate, and $\rho$ is the relative density of the honeycomb structure.

Deformation regularity is evaluated using the maximum deviation of unidirectional horizontal strains (MDUHS) [25]. The smaller the value of MDUHS is, the more regular the overall deformation of the honeycomb. MDUHS can be expressed as follows:

$$MDUHS = \max \left\{ \frac{\max \{|X_{Li}| - \min \{|X_{Li}| \} \}}{L}, \frac{\max \{|X_{Ri}| - \min \{|X_{Ri}| \} \}}{L} \right\} \quad \text{(19)}$$

where $|X_{Li}|$ and $|X_{Ri}|$ are the displacements in the x-direction on the left and right sides of the honeycomb, and $L$ is the original horizontal width of the honeycomb. The overall deformation regularity of the honeycomb is evaluated by taking the MDUHS of each honeycomb strain as 0.4–0.5 when the cells are fully deformed. To visualize the results of the representation, $1/MDUHS$ is used as the rubric. In addition, to visualize the combined performance of each honeycomb, the maximum Poisson’s ratio, $E^*$, and $1/MDUHS$ are used to plot the radargrams in Figure 12.
Figure 11. Comparison of the Poisson’s ratio–strain curve between existing configurations [19,22].

Figure 12. Comprehensive evaluation mapping the existing honeycomb structures [19,22].

As shown in Figure 12, due to the arrow-shaped structure being more stable compared to that of a straight wall, an increase in regularity during deformation, but a decrease in the negative Poisson’s ratio performance and load-carrying capacity are observed in the SAH structure relative to the SSH structure. The negative Poisson’s ratio effect is most pronounced for DAH due to the special deformation trajectory of the arrow-shaped structure. However, because of this, DAH’s load-carrying capacity and deformation regularity are poor. Compared to the SSH and SAH structures, the 2D-STH structure designs the triangular structure on the left and right sides of the cell, with improved negative Poisson’s ratio performance, load-carrying capacity, and deformation regularity. Moreover, the 2D-ISSH in this paper uses an arrow-shaped structure to replace the horizontal wall and adds a rectangular structure in the center of the star, which significantly improves the overall performance of the honeycomb, especially in terms of load-carrying capacity and deformation regularity. The most obvious change in the expansion of the 2D honeycomb to a 3D honeycomb is the improvement in the negative Poisson’s ratio performance, which is attributed to the biaxial contraction property. The Poisson’s ratio value of the 3D-ISSH is close to twice that of the 2D-ISSH. However, due to the rotation of some of the 3D honeycomb cells, the regularity of the 3D honeycomb deformation decreases.

5. Conclusions

In this paper, a 3D-ISSH was first designed based on a 2D-ISSH, and a comprehensive study of the 2D-ISSH and 3D-ISSH structures was carried out through a combination of experiments and numerical simulations under quasistatic compression loading conditions. There was also a discussion of similar structures, which explored the effects of structural materials on the energy absorption and negative Poisson’s ratio properties. For the deformation process of a typical cell in a 3D-ISSH structure, the platform stress formula was derived. The following conclusions can be drawn from this study:

(1) In the quasistatic compression process, the 2D-ISSH and 3D-ISSH presented different deformation patterns. The lower part of the 2D-ISSH was first deformed, showing a “V” shape, and this deformation was gradually transferred to the upper part of the honeycomb during the compression process. The 3D-ISSH deformation first occurred in the middle position and then developed simultaneously up and down in an “X”-
shape. At the end of the first plateau region, both honeycombs showed a “-”-shape deformation pattern. As the specimen was further compressed, the “-” shapes gradually overlapped and the honeycombs were crushed. The two honeycombs exhibited similar stress stages during deformation, and both had double platforms (the 2D-ISSH double platform stress averages were, respectively, 2.54MPa and 8.18MPa; the 3D-ISSH double platform stress averages were, respectively, 0.45MPa and 1.33MPa).

(2) According to the deformation mechanisms of typical cells, the theoretical formula for the 3D-ISSH dual-platform stress was derived based on the law of energy conservation and the plastic hinge theory, validating the accuracy of the numerical model.

(3) After comparing multiple types of honeycomb structures, it was found that the ordinary star-shaped honeycomb could increase the plastic hinge during deformation by introducing certain structures, such as an arrow-shaped structure, which could increase the specific energy absorption of the structure. The expansion of the 2D honeycomb to a 3D honeycomb not only lightened the structure but also improved the specific energy absorption, which was mainly attributed to the fact that some of the cells rotated during the deformation of the three-dimensional honeycomb, absorbing additional energy. The 3D-ISSH has a 5.02% improvement in specific energy absorption over the 2D-ISSH.

(4) After considering the above honeycombs in multiple dimensions, it was found that, for star-shaped honeycombs, the replacement of the original straight wall with certain structures, such as arrows and triangles, could reduce the occurrence of instability and improve the regularity of the honeycomb during deformation. In addition, the adding of an arrow-shaped structure and a center rectangle in the 2D-ISSH greatly improved the loading capacity and the regularity of deformation. When the 2D honeycomb was expanded to 3D, the negative Poisson’s ratio effect was greatly enhanced due to the biaxial shrinkage property. The Poisson’s ratio value of the 3D-ISSH is close to twice that of the 2D-ISSH.

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