The in-plane dynamic crushing of quadrilateral chiral honeycomb coatings

Li Jun-Jie¹, Wu Yue¹, Wang Shi-Peng¹, Tao Meng¹

¹School of Mechanical Engineering, Guizhou University, Guiyang 550025, China
¹Corresponding author: Tao Meng, Email: tomm_in@163.com

Abstract. For the anti-impact performance of hyperelastic coatings covered on the ship hull, the in-plane dynamic crushing behaviors of quadrilateral chiral honeycomb coatings (including chiral and anti-chiral) were numerically studied by explicit dynamic finite element simulations. The deformation mode, energy absorption and supporting reaction force under different impact speeds have been analyzed. The results show that: (1) If the impact speed is low, the chiral honeycomb coatings display the rotational deformation; (2) With the increase of impact speed, the deformation at the top of coating is remarkable; (3) The response of energy absorption and supporting reaction force corresponds to the macroscopic deformation mode of chiral honeycomb coatings.

Keywords: chiral honeycomb; hyperelastic rubber claddings; deformation characteristic; reaction force

1. Introduction

The coatings which are made of hyperelastic materials such as rubber are usually covered on the ship hull, of which the aim is to block the impact wave or isolate the sound propagation. In order to improve the performance of sound insulation and impact resistance, some hyperelastic-viscoelastic coatings which are designed to include different kinds of holes or embedded scatterers have already been launched, especially some designed coatings which have the negative Poisson’s ratio property attract more and more attentions.

As to now, lots of theoretical, numerical and experimental analyses of dynamic response about hyperelastic-viscoelastic coatings have been carried out [1-10]. Compared with the traditional coatings, the rotating deformation and the concave deformation, which belong to the chiral honeycomb structure with negative Poisson's ratio property, result in the better performance on the impact resistance and shear resistance. Lots of achievements are focused on the in-plane dynamics of porous honeycomb structures such as chiral honeycomb, but most of them are concentrated on thin-walled structures using ideal elastic-plastic materials to be the matrix. It has been confirmed that the chiral honeycomb...
coating which is made of hyperelastic materials can eliminate acoustic radiation effectively [4], also have the potential of impact resistance.

Taking the quadrilateral chiral and the quadrilateral anti-chiral honeycomb coatings as examples, the deformation mode, the energy absorption and the supporting reaction response of honeycomb coatings under the condition of in-plane impact are studied in the next sections, which is aimed to give the relationship between the macroscopic mechanical properties or the anti-impact performance with the geometric topology of the chiral structure.

2. Finite element model

Figure 1 shows the structural parameters of the quadrilateral chiral and the quadrilateral anti-chiral honeycomb cells, where \( r \), \( t \), and \( l \) are the outer radius of annulus, the thickness of ligament, and the center distance between two adjacent annulus respectively. First, a set of parameters including \( r = 3.4 \) mm, \( t = 2 \) mm, \( l = 9 \) mm is used to shape the quadrilateral chiral honeycomb cell (C1) and the quadrilateral anti-chiral honeycomb cell (AC). Since the cross-sectional area of anti-chiral honeycomb cell is usually smaller than that of chiral honeycomb cell because of different arrangements, a new quadrilateral chiral honeycomb cell (C2) of which the cross-sectional area is the same as the anti-chiral honeycomb cell is also shaped.

![Figure 1. Schematic diagrams of quadrilateral chiral and anti-chiral honeycomb cells](image)

The relative density of the honeycomb coating which contains quadrilateral chiral holes can be given as follows:

\[
\bar{\rho} = \frac{\rho^*}{\rho_s} = \sum_{i=1}^{n} \frac{l_i}{L_1L_2}
\]  

(1)

Where the density of the honeycomb coating is \( \rho^* \), the density of matrix is \( \rho_s \), the ligament length and the corresponding thickness of the \( i \)th cell are \( l_i \) and \( t_i \), and the overall length and height are \( L_1 \) and \( L_2 \) respectively.

According to Equation (1), some parameters of different honeycomb coatings are shown in Table 1.

| Coating                     | \( r / \text{mm} \) | \( t / \text{mm} \) | \( l / \text{mm} \) | \( L_1 / \text{mm} \) | \( L_2 / \text{mm} \) | \( \bar{\rho} \) |
|----------------------------|---------------------|---------------------|---------------------|---------------------|---------------------|------------------|
| Chiral honeycomb (C1)      | 3.5                 | 2.0                 | 9.00                | 103.5              | 62.5                | 0.539            |
| Chiral honeycomb (C2)      | 3.5                 | 2.0                 | 7.48                | 92.0               | 56.0                | 0.599            |
| Anti-chiral honeycomb (AC) | 3.5                 | 2.0                 | 9.00                | 92.0               | 56.0                | 0.663            |
The dynamics software ABAQUS is used to analyze the impact response of honeycomb coatings which contain chiral or anti-chiral holes numerically. Figure 2 shows the two-dimensional model in the software. The rigid plate is meshed by the two-dimensional element of rigid joint, and the honeycomb coating is meshed by the stress element of reduced integral plane. In order to confirm the convergence of stress and strain at the corner of cell and other large deformation regions, the size of grid is assumed to be 0.5mm. The relationship between the rigid plate and the honeycomb coating at their interface is described by a face-to-face contact algorithm. To prevent contact penetration of the matrix during compression deformation, self-contact is adopted inside the honeycomb coating. Compared to the ship hull, the stiffness of honeycomb coating is usually much lower, so the bottom of honeycomb coating is set to be fixed if the impact wave is normally incident (or along the y direction), which is the same as the boundary conditions given by Zhang [6]. But, the left and the right boundary conditions should be symmetric in order to describe the horizontal periodicity of honeycomb coating according to Xiao [3]. The effective anti-impact performance of honeycomb coating requires that the coating should not be completely densified when compressed, so the nominal strain $\varepsilon = 0.6$ is taken as the nominal amount of compression in the y direction.

Figure 3 shows some nominal stress-strain data of rubber measured by the uniaxial, the biaxial and the plane experiments [11]. The constitutive model Ogden_N2 which can accurately describe the nonlinear relationship between stress and strain in the large strain interval, is used to fit the material parameters as follows: $\mu_1=0.375810163\text{MPa}$, $\lambda_1=1.88384694\text{MPa}$, $\mu_2=0.001140191\text{MPa}$, $\lambda_2=-2.86492799\text{MPa}$, $D=0$, and the density of rubber is $1500\text{kg/m}^3$.

Figure 2. Diagram of honeycomb coating under in-plane impact.  
Figure 3. Tested data of rubber material

3. Dynamic responses of chiral honeycomb coatings

Figure 4 shows the typical deformation mode of the quadrilateral chiral honeycomb coating (C1) under different impact velocities. Under the quasi-static velocity 1m/s, the compression stress wave is gradually transferred from the top to the bottom of coating, and the weak deformation of cells can be observed. After the compression stress wave reaches the bottom of coating, the wave will be reflected from the bottom to the top reversely. Thus, the stress wave is transmitted up and down through the annulus and the ligament of cells, and all circular holes are gradually compressed into elliptical holes. Correspondingly, the ligaments of cells are rotated when the circular holes are under compressed deformation.
With the impact velocity increased to 5 m/s, the circular hole appears a layered buckling deformation from the top to the bottom, but it is not compacted. During the compressed process, the ligaments and the annuli of cells are rotated obviously. Moreover, with the impact velocity increased higher to 10 m/s, the inertia effect is significant, so the circular hole wall at the top of coating is crushed instantaneously. With the downward compression, the walls of circular holes are crushed layer by layer, and the response at the bottom is obviously delayed compared to that at the top of honeycomb coating.

![Image](a) v=1 m/s  
(b) v=5 m/s  
(c) v=10 m/s

**Figure 4.** Deformation mode of chiral honeycomb coating (C1) under different impact velocities

Figure 5 shows the typical deformation mode of the quadrilateral anti-chiral honeycomb coating (AC) under different impact velocities. Under the quasi-static velocity 1 m/s, the compressive stress wave is transmitted layer by layer from the top to the bottom, and the cell is little deformed. With further compression, the longitudinal and the transverse cell walls come into contact.

With the impact velocity increased to 5 m/s, the upper circular holes appear buckling deformation firstly, and the circular holes present torsional deformation according to the clockwise and the counterclockwise directions alternately, which is due to the arrangement of anti-chiral honeycomb coating. Furthermore, with the impact velocity increased higher to 10 m/s, it is similar to the chiral honeycomb coating that the top of coating is significantly deformed, which is consistent with the I-shaped compaction collapsed of the chiral honeycomb coating under high-speed impact.

![Image](S, Mises (Avg: 75%))  
(S, Mises (Avg: 75%))  
(S, Mises (Avg: 75%))
4. Energy absorption of chiral honeycomb coatings

The kinetic energy and the structural deformation energy resulting from the compressive motion of chiral honeycomb coating are the most important energy absorption forms. The energy absorption rate (SEA) is an important parameter to estimate the energy absorption capacity of multicellular structures [12]:

\[ E_n = \frac{W_i}{\bar{\rho} \rho S} \]  

(2)

Where \( W_i \) is the absorbed energy per unit volume, \( \bar{\rho} \) is the relative density of coating, and \( \rho S \) is the matrix density.

According to Equation (2), Figure 6 shows the energy absorption rate (SEA) of three different chiral honeycomb coatings under different impact velocities. The energy absorption capacity of coating becomes better with the increase of impact velocity, especially before the whole coating is shifted into compaction stage. In addition, the anti-chiral honeycomb coating (AC) exhibited much stronger energy absorption capacity than the chiral honeycomb coating (C1) under the assumption of same cell parameters, and also than the chiral honeycomb coating (C2) under the assumption of same volume.

5. Supporting reaction force of chiral honeycomb coatings

Figure 7 shows the relationship between the supporting reaction force and the compressive nominal strain of three different chiral honeycomb coatings under different impact velocities. In the quasi-static process (\( v = 1 \text{m/s} \)), the overall trend of supporting reaction force curves of three different coatings becomes higher with the increasing of nominal strain. The honeycomb hole wall appears linear elastic bending under the low impact velocity, and the linear relationship between the reacting force and strain can be approximately obtained. After that, the hole walls are buckled and collapsed, and contacted to each other. As a result, the overall stiffness of chiral honeycomb coating increases, and also the supporting reaction force increases obviously. The collapsed process of honeycomb coating layer by layer during the crashing compression causes the curve of supporting reaction force to oscillate.

When the impact velocity is \( v = 5 \text{m/s} \), the supporting reaction force of three different coatings is increased from zero when the nominal strain reaches around 0.2, and the increasing rate is faster than that under quasi-static condition. Then, the value of supporting reaction force reaches the first peak,
which is caused by the compressive stress wave transmitted from the top to the bottom of coating. Next, the honeycomb hole walls is collapsed layer by layer and the supporting reaction force decreases a little. After the compression goes to the compaction stage, the supporting reaction force reaches the second peak value, which is higher than the first peak value and the ascending rate is faster. Moreover, the peak value of supporting reaction force of the coating (AC) is the highest in the three different coatings in the whole process.

When the impact velocity is \( v = 10 \text{m/s} \), the supporting reaction force of three coatings is almost equal to zero in the early stage of impact response, and the bottom is not subjected to stress before the compression wave transmitted to the bottom of coating. When the strain reaches to 0.35 approximately, the reacting force is ascended rapidly. The ascending rate of reacting force of coating (AC) is faster than that of C1 and C2, and reaches the higher peak when the strain is smaller. This is directly related to the distribution of quadrilateral chiral cells: the cells of coating (AC) are distributed more closely than that of C1 under the assumption of same geometric parameters, or the relative density of coating (AC) is greater than that of C2 under assumption of same volume. In the compaction stage, the supporting reaction force curves of three coatings all oscillate up and down. Totally speaking, the response of supporting reaction force of chiral honeycomb coating varies greatly with the change of impact velocity, and there is a corresponding relationship between the response of supporting reaction force and the deformation process of coating.

![Figure 6](image1.png)

**Figure 6.** SEA of three chiral honeycomb coatings under different impact velocities

![Figure 7](image2.png)

**Figure 7.** Reacting force of three chiral honeycomb coatings under different impact velocities

6. **Conclusions**

Based on the two-dimensional dynamic compression model, the in-plane impact dynamics responses of the quadrilateral chiral and the quadrilateral anti-chiral honeycomb coatings have been numerically analyzed. It is found that:

1. Impact velocity affects the deformation modes of chiral honeycomb coatings. Under a lower velocity, the rotation of honeycomb cell and the ligaments twining with each other is the prominent deformation. With the increase of impact velocity, the deformation of the coating top is much significant.
(2) The performance of energy absorption by the coating becomes better with the increase of impact velocity or strain. Under the same impact velocity, the energy absorption of anti-chiral honeycomb coating is the highest.

(3) The response of supporting reaction force is related to the macroscopic deformation of coating. Under a lower impact velocity, the deformation is uniform, and the supporting reaction force is raised with the increase of strain. If the impact velocity increases, the supporting reaction force is greatly affected by compression stress and the coating deformation. The effective stiffness of quadrilateral chiral honeycomb coating is less than that of anti-chiral honeycomb coating, which results in the smaller supporting reaction force under the same nominal strain.

7. References

[1] Ruan D, Lu G, Wang B, et al. In-plane dynamic crushing of honeycombs—a finite element study J 2003 International Journal of Impact Engineering, 28:161-182.

[2] Liu X N, Huang G L, Hu G k. Chiral effect in plane isotropic micropolar elasticity and its application to chiral lattices J 2012 Journal of the Mechanics & Physics of Solids 60 1907-1921

[3] Alderson A, Alderson K L, Attard D, et al. Elastic constants of 3-, 4- and 6-connected chiral and anti-chiral honeycombs subject to uniaxial in-plane loading J 2010 Composites Science & Technology, 70:1042-1048.

[4] Lorato A, Innocenti P, Scarpa F, et al. The transverse elastic properties of chiral honeycombs J. 2010 Composites Science & Technology, 70:1057-1063.

[5] Reis F D, Ganghoffer J F. Equivalent mechanical properties of auxetic lattices from discrete Homogenization J. 2012, Computational Materials Science, 51:314-321.

[6] Zhang X C, Liu Y, Li N. The In-plane dynamic crushing of honeycombs with negative Poisson’s effects J 2012 Explosion and Shock Waves 32 475-482

[7] Xiao F, Chen Y, Sun J Y, et al. Dynamic crush behavior and performance of layered honeycomb hyperelastic rubber claddings J 2013 Journal of Vibration and Shock 32 13-20

[8] Gao Q, Wang L, Zhou Z, et al. Theoretical, numerical and experimental analysis of three-dimensional double-V honeycomb J 2018 Materials & Design 139 380-391

[9] Zou T, Zhou L, Mechanical property analysis and experimental demonstration of zero Poisson’s ratio mixed cruciform honeycomb J 2017 Materials Research Express 4 4 045702

[10] Lim, Teik-Cheng. A 3D auxetic material based on intersecting double arrowheads J 2016 physica status solidi (b) 253 1252-1260

[11] ZHUANG Zhuo, ZHANG Fan, CEN Song, et al. The nonlinear finite element analysis and example of ABAQUS M. 2005. Beijing: Science Press

[12] Kooistra G W, Deshpande V S, Wadley H N G. Compressive behavior of age hardenable tetrahedral lattice truss structures made from aluminium J. 2004 Acta Materialia, 52:4229-4237.

8. Acknowledgements

This work was supported by the National Natural Science Foundation of China (Nos. 51765008, 51365007), the High-level Innovative Talents Project of Guizhou Province (No. 20164033), and the Science and Technology Project of Guizhou Province (No. 20175781).