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Numerical Simulation of Crushing and Energy Absorption of Graded Hierarchical Honeycomb

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Abstract. Hierarchical structures are widely observed in nature, and they have been considered to have excellent mechanical properties. In this paper, a novel hierarchical honeycomb with graded design is proposed to improve impact resistance. Two parameters are selected to determine the design of hierarchy and gradient respectively. A series of nonlinear finite element models are developed in Abaqus to systematically explore the crashworthiness. In in-plane crushing, the deformation mode of honeycomb is studied, and the specific energy absorption (SEA) is mainly discussed in out-of-plane crushing. Compared with the traditional honeycomb, the energy absorption characteristics can be increased by up to 81.4% in the simulation.

Keywords. Honeycomb, energy absorption, hierarchical, graded, impact

1. Introduction

Honeycomb metal sandwich structure with high specific strength, high specific stiffness and high energy absorption performance, has a wide range of potential applications in the field of engineering structure lightweight and impact protection. And the core plays a decisive role in the overall performance.

Much theoretical and experimental work has been carried out on the honeycomb [1-4]. In structural geometry design, Ruan et al. [5] studied the in-plane dynamic behavior of hexagonal aluminum honeycombs, and deformation modes in the X direction change significantly with different values of cell wall thickness and impact velocity. The in-plane uniaxial collapse response of a second order hierarchical honeycomb was investigated, and the failure modes and collapse stresses were obtained [6]. Zhang et al. [7] studied both in-plane and out-of-plane crushing of triangular vertex-based hierarchical honeycomb, and the energy absorption efficiency is increased by more than 100% in two in-plane direction.

In addition to the geometric design of the structure, the gradient distribution of the material can also greatly improve the performance of the honeycomb. Simon et al. [8] investigated the energy absorption of hyperplastic honeycombs with 4 density grading methodologies in quasistatic, cyclic and high strain-rate impact. The in-plane gradient

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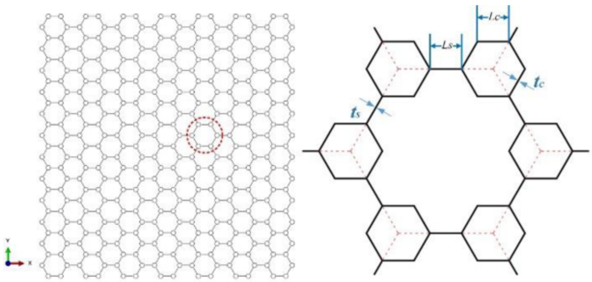
was introduced by changing the thickness of each cell wall of honeycomb unit cell along its side length in [9]. Zhang et al. [10] researched the in-plane double shock deformation mode in density graded honeycombs by tests and numerical simulation.

2. Geometric Design and Finite Element Model

2.1. Geometric Design

The traditional honeycomb structure consists of regular hexagonal cells arranged in sequence, and in this paper the traditional hexagon honeycomb is reconstituted with graded hierarchical design. A micro-hexagon cell is used to replace each three-sided intersection point of the traditional honeycomb. The center of the micro-hexagon cell coincides with the original three-sided intersection point. Meanwhile, the gradient is introduced by changing the thickness of the micro-hexagon cell and the remain hexagonal cell segment, as shown in Fig. 1.



(a) Top view (b) Single cell design

Figure 1. Geometric design of graded hierarchical honeycomb.

Two parameters *k* and *p* are defined to describe the graded hierarchical honeycomb. *k* is the ratio of the lengths of the micro-hexagon cell to the original hexagonal cell. *p* is the ratio of the thicknesses of the micro-hexagon cell to the remain hexagonal cell segment:

$$L_c / L_0 = k \tag{1}$$

$$t_c / t_s = p \tag{2}$$

where L_c denotes the length of the micro-hexagon cell, t_c denotes the thicknesses of the micro-hexagon cell, t_s denotes the thicknesses of remain hexagonal cell segment. The value range of k is [0, 0.5]. When k=0, it is the traditional honeycomb. When k=0.5, all traditional hexagon cells are replaced by micro-hexagon cells, and there are no remain hexagonal cell segments. Theoretically, the value of p is all positive values. In this paper, considering the actual situation, the wall thickness should not be too large or too small, so 8 fixed values are selected. The relative density of the graded hierarchical honeycomb should remain the same as that of the traditional honeycomb to keep the mass of the new cell equal to that of the traditional cell. Because the position of the center point of the hexagonal cell does not change, it means that the nominal volume does not change, and the graded hierarchical honeycomb changes the wall thickness so that the mass is consistent, and the relative density is consistent. The wall thickness after the graded and hierarchical is calculated as follows:

$$t_s = \frac{t_0}{1-2k+4kp} \tag{3}$$

In this paper, the honeycomb have 12 rows and 13 columns. The traditional honeycomb cells have a side length of 10 mm and an initial wall thickness of 0.2 mm, The geometric dimensions of each configuration are shown in Table 1.

Table 1. The geometric parameters of the examples.

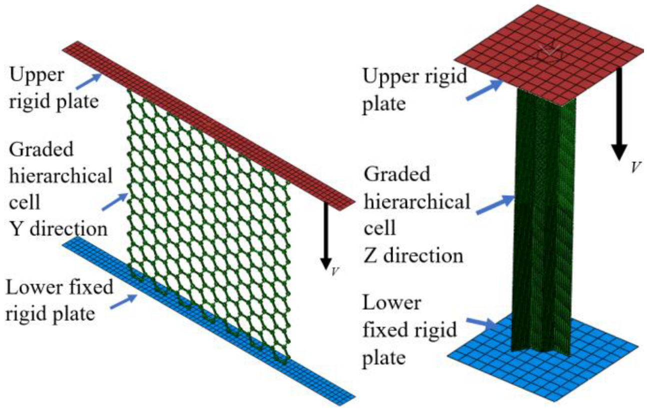
k	L_c/mm	p	t_c/mm	t_s/mm
0.1	1	0.5	0.1000	0.2000
		0.8	0.1429	0.1786
		1.0	0.1667	0.1667
		1.5	0.2143	0.1429
		2.0	0.2500	0.1250
		2.5	0.2778	0.1111
		3.0	0.3000	0.1000
		4.0	0.3333	0.0833
0.2	2	0.5	0.1000	0.2000
		0.8	0.1290	0.1613
		1.0	0.1429	0.1429
		1.5	0.1667	0.1111
		2.0	0.1818	0.0909
		2.5	0.1923	0.0769
		3.0	0.2000	0.0667
		4.0	0.2105	0.0526
1/3	10/3	0.5	0.1000	0.2000
		0.8	0.1143	0.1429
		1.0	0.1200	0.1200
		1.5	0.1286	0.0857
		2.0	0.1333	0.0667
		2.5	0.1364	0.0545
		3.0	0.1385	0.0462
		4.0	0.1412	0.0353
0.4	4	0.5	0.1000	0.2000
		0.8	0.1081	0.1351
		1.0	0.1111	0.1111
		1.5	0.1154	0.0769
		2.0	0.1176	0.0588
		2.5	0.1190	0.0476
		3.0	0.1200	0.0400
		4.0	0.1212	0.0303
0	0	1.0	0	0.2
0.5	10	1.0	0.1	0

2.2. Finite Element Model

Honeycomb is a typical anisotropic material with two in-plane directions X and Y and one out-of-plane direction Z. The compression behavior of honeycomb is a highly nonlinear problem. If the actual model is used for numerical simulation, it will consume a lot of time, and there is a problem of calculation convergence. In view of the characteristics of in-plane and out-of-plane impact, different simplified models are adopted in the research.

In the simplified model of in-plane compression, in order to reduce the calculation amount of numerical simulation, the thickness of honeycomb in the Z direction is set as 2mm, which represents a typical section in the actual honeycomb. The material model uses the ideal elastoplastic model, the material is aluminum alloy, and the material parameters are Young's modulus E=68.2GPa, yield strength σ=350MPa, Poisson's ratio μ=0.3. The density is 2700kg/m3. Fig. 2 shows the finite element model of Y and Z direction compression. Both the upper and lower plates are set as rigid bodies, wherein the lower plates are fixed and the upper plates are assigned a velocity v=1 m/s in the Y direction to compress the honeycomb. In the compression numerical simulation at the X direction, the model is similar to the situation in the Y direction. The left and right pressure plates are set on both sides of the honeycomb, wherein the right plate is fixed and the left plate is assigned a velocity v=1 m/s in the X direction.

In the simplified model of out-of-plane compression, the widely accepted Y-type single cell is used for calculation, and the height of single cell is uniformly 50 mm. It should be noted that after the introduction of micro-hexagon cell, the corresponding Y-type single cell needs to be modified accordingly. When the micro-hexagon cell is small, it does not play a dominant role in buckling deformation. In this case, the modified Y-type single cell should contain a complete micro-hexagon cell and half of the three remain hexagonal cell segments, and the X-symmetric boundary conditions are applied to the three remain cell segments. With the continuous increase of k value, the micro-hexagon cell gradually occupies the dominant position of deformation, and the remain hexagonal cell segments becomes shorter and shorter. In this case, X-type single cell should be used to calculate it. In this paper, X-type single cell is used for the configuration of k=0.33 and k=0.4. The modified X-type cell consists of four half-length micro-hexagon cell walls and a complete remain hexagonal cell segment. In this case, symmetric boundary conditions in the X-direction are applied to the four micro-hexagon cell walls, as shown in Fig. 3



(a) In-plane compression model (b) Out-of-plane compression mode

Figure 2. Finite element model.

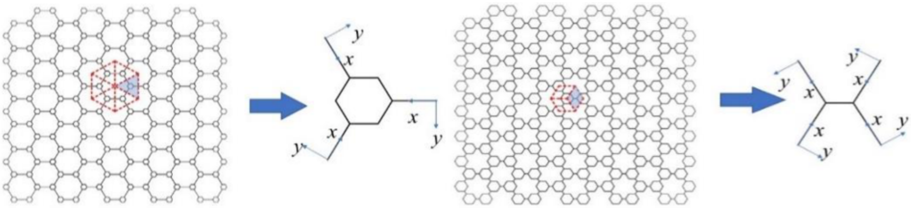


Figure 3. Boundary conditions in out-of-plane crushing.

3. In-plane Crushing

3.1. Deformation Mode at X Direction

Define the compression ratio along the crushing direction as γ :

$$\gamma=\omega/\omega_0 \tag{4}$$

where ω and ω_0 respectively represent the compression displacement and initial height of the honeycomb along the crushing direction.

Fig. 4 shows the deformation mode of graded hierarchical honeycomb compression in X direction with different length ratio *k* at uniform wall thickness. For the traditional honeycomb and the novel honeycomb with *k*=0.1 and *k*=0.2, as shown in Fig.4 (a) and (b), I-shape compression band appears locally at the beginning of crushing. With the continuous crushing, the compression band accumulates continuously until the core is dense. However, in the compression process, the I-shape compression band of the traditional honeycomb is denser, and the compression band is the loosest when *k*=0.2. With the increase of *k*, the compression deformation mode gradually changes from the local compression band to the whole compression. When *k*=0.3, the honeycomb first starts to compress from a certain area, but the compression band is not dense, presenting a semi-compressed state. Then the remaining uncompressed part is rapidly semi-compressed, and the honeycomb presents a negative Poisson's ratio on the whole. After semi-compression, the core continues to compress with the upper plate, and the whole is gradually compressed and dense. When *k*=0.4 and 0.5, the honeycomb is basically in the overall compression deformation mode, and there is no obvious local compression band.

3.2. Deformation Mode at Y Direction

Fig. 5 shows the deformation mode of graded hierarchical honeycomb compression in Y direction with different length ratio k at uniform wall thickness. When the traditional honeycomb begins to compress and deform, as shown in Fig. 5(a), it first deforms in the direction of 45° on both sides, and the compression band presents an X-shape. With increasing compression, the compression band is continuously piled up until compaction. In Fig. 6(b) and (c), the compression deformation pattern is similar to that of traditional honeycomb. This is because the micro-hexagon cell is too small compared with the single cell when the side length ratio *k* is small, and the cell wall of micro-hexagon cell is less prone to deformation than that of remain hexagonal cell segment under the same compression. Therefore, it shows that the wall of remain hexagonal cell segment is crushed first, and then the micro-hexagon cell is crushed. In Fig. 5(d), there is no obvious compression band and it is in a transitional state. With the increasing of k, as shown in

Fig. 5(e), the deformation mode changes, and the micro-hexagon cell and remain hexagonal cell segment are buckling simultaneously. With the increase of compression distance, a large number of micro-hexagon cells begin to crush, and the honeycomb shows negative Poisson's ratio as a whole. When all the three-sided intersection point of the traditional honeycomb is completely replaced by the micro-hexagon cell, as shown in Fig. 5(f), the structure tends to be consistent, showing the overall buckling deformation.

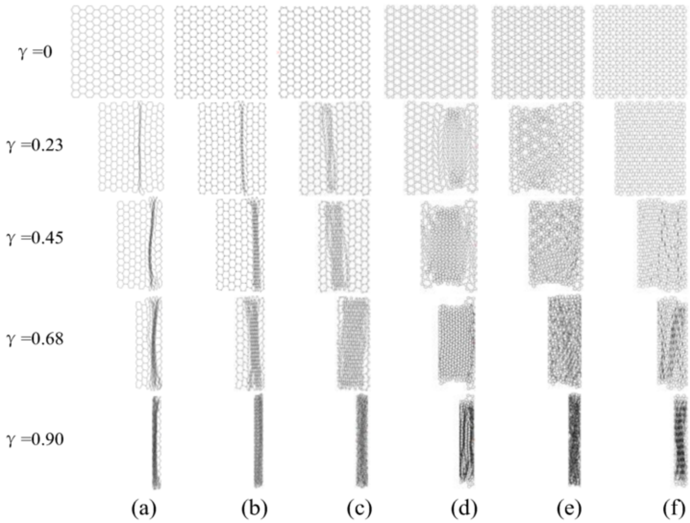


Figure 4. Deformation mode in X direction with different k at p=1.
(a) k=0, (b) k=0.1, (c) k=0.2, (d) k=0.33, (e) k=0,4 (f) k=0.5.

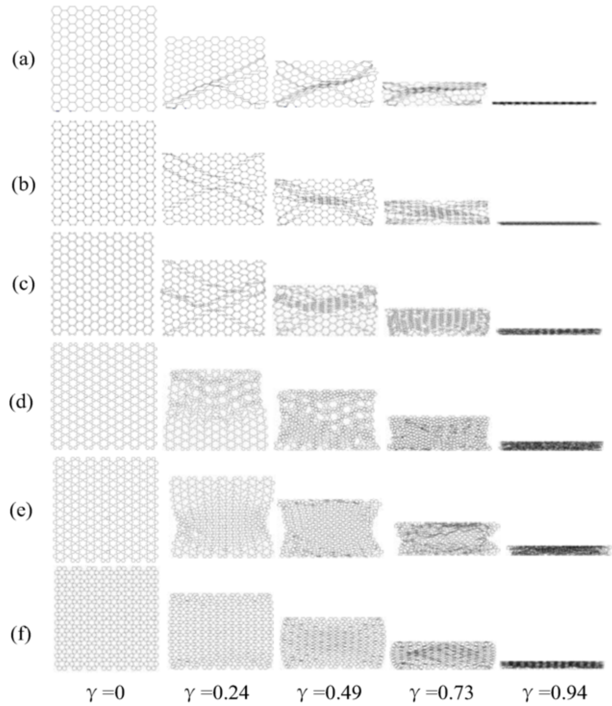


Figure 5. Deformation mode in Y direction with of different k at p=1.
(a) k=0, (b) k=0.1, (c) k=0.2, (d) k=0.33, (e) k=0,4 (f) k=0.5.

In the same geometric configuration, that is, when k is constant, the different wall thickness ratio p has little influence and will not change the deformation mode.

4. Out-of-Plane Crushing

4.1. Deformation Mode

All the out-of-plane compression single cells crushed layer by layer, as shown in Fig. 6. With the increase of k, the number of complete folding units decreases first and then increases, and the change of folding wave side length is opposite. When k=0.1, the number of complete folding units is at least 5, and when k=0.4 and 0.5, the number of complete folding units is at most 10. In each configuration, within the range of the studied wall thickness ratio p, it does not affect the number of folding units, and the geometric shape plays a leading role in the deformation mode.

4.2. Energy Absorption

Although the single cells with different geometric configurations have the same height, the compression amount into the compaction stage is different due to the difference of the folding wave side length. In this paper, 70% of the total height, namely the crushing amount of 35mm, is taken as the comparison reference point. As shown in Fig. 3, the mass of the X-type single cell is two-thirds that of the Y-type single cell. Therefore, specific energy absorption is used to describe the plastic energy absorption efficiency of the single cell, and it is defined as

$$SEA = \frac{EA}{m} \tag{5}$$

where EA and m denote the total energy absorbed and mass of the single cell respectively.

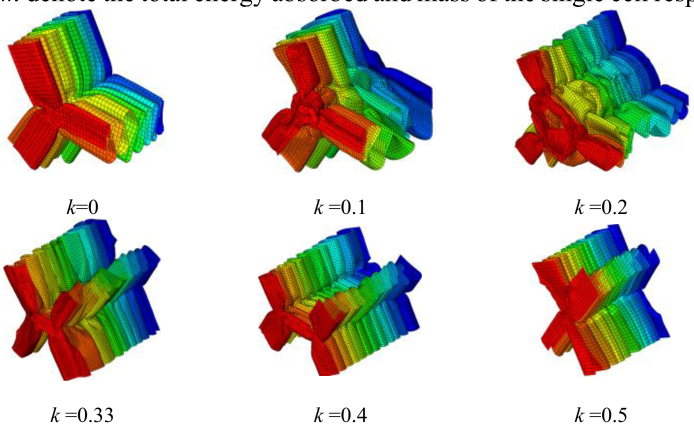


Figure 6. Deformation mode of single cell in out-of-palne crushing.

As shown in Fig. 7, k=0 and k=0.5 correspond to the two limit cases of geometric configuration, and their wall thickness ratio p can only be 1. The line in the figure is for the convenience of comparison. The SEA is 12.7 J/g when the traditional honeycomb cell is completely replaced by micro-hexagon cell, and it is 38.3% lower than that of 20.6 J/g. When p=0.5, the mass of the single cell is concentrated on the remain hexagonal cell segments. The SEA of each geometric configuration is very close, and there is little difference between it and the traditional honeycomb cell. With the increase of p, the mass gradually concentrated to the micro-hexagon cell, and the SEA of the cells with different k shows a great difference. When the micro-hexagon cell is small, i.e., k=0.1 and 0.2, the SEA of the two kinds of cells increases with the increase of p, but the difference between the two cells is very small. When p=4, the maximum SEA of the two cells is obtained, which increased by 76.7% and 81.4% compared with the traditional cell respectively. When k=0.3, the side length of the micro-hexagon cell is the same as that of the remain hexagonal cell segment, and the SEA increases first and then decreases with the increase of p. The SEA reaches the peak value when p=1, which is basically the same with that of the traditional honeycomb cell, and it has the lowest SEA at 16.5 J/g when p=4, which is 80.1% of the traditional cell. When k=0.4, the SEA decreased with the increase of p until it stabilized at the level of the total micro-hexagon cell at 12.8 J/g, which is 62.1% of the traditional cell.

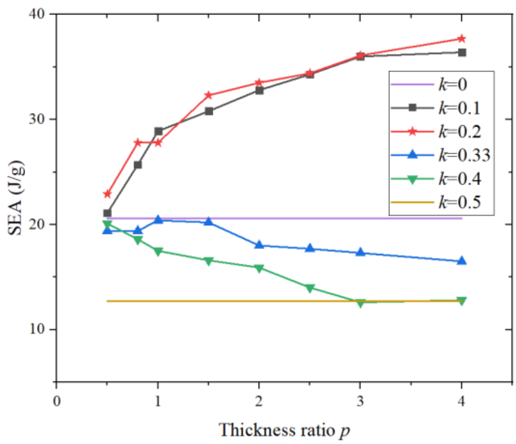


Figure 7. SEA for out-of-plane crushing.

5. Conclusions

In this paper, the deformation mode of graded hierarchical honeycomb and the energy absorption efficiency at out-of-plane crushing are researched. The main conclusions can be summarized as:

(1) For out-of-plane crushing, the honeycomb shows local deformation at the beginning of crushing when $k \leq 0.2$. I-shape compression band appears in the X direction crushing, and X-shape compression band appears in the Y direction crushing. The honeycomb shows a whole deformation mode when $k \geq 0.33$, and it shows negative Poisson's ratio at both k=0.33 and k=0.4. The different wall thickness ratio p can not change the deformation mode.

(2) For in-plane crushing, Y-type and X-type single cells are selected for simplified model. All single cells crush layer by layer. Parameters k and p both have important effects on the SEA of the cell. With the increase of p, SEA shows an overall rising trend when $k \leq 0.2$ and an overall decreasing trend when $k \geq 0.33$. The SEA of the graded

hierarchical cell is improved up to 81.4% and 76.7% when *k*=0.2 and 0.1 at *p*=4 compared with that of the traditional honeycomb cell.

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