Compression property of hierarchical pyramid lattice

Liu Tao¹, Zhu Guodong¹, Yang Na¹²³⁴*, Wang Jianfeng¹

¹ School of Automotive Engineering, Harbin Institute of Technology, Weihai 264209, P.R. China
² CATARC（Tianjin）Automotive Engineering Research Institute, Tianjin, Tianjin, 300300, P.R. China
³ Automotive Engineering Research Institute, China Automotive Technology & Research Center, Tianjin 300300, P.R. China
⁴ School of Mechanical Engineering, Tianjin University, Tianjin 300072, P.R. China

*Corresponding author’s e-mail: ynhelen@126.com

Abstract. Hierarchical design can not only effectively improve the mechanical properties of lattice structure, but also enhance the multi-functional design ability of lattice structure. Based on pyramid lattice structure, a novel hierarchical pyramid lattice structure was designed to enhance the energy absorption property. The finite element method (FEM) was carried out to explore mechanical behaviors of the hierarchical pyramidal lattice structure. The simulation results showed that the new lattice structure can improve the bearing capacity of the structure, and has a good specific energy absorption capacity. In addition, it can effectively reduce the stress concentration and improve the strength of the structure.

1. Introduction

Due to its excellent mechanical properties and absorption capacity, lattice structure has been paid more and more attention. The two-dimensional lattice structures have strong energy absorption performance and normal bearing capacity of the panel [1,2], and the three-dimensional lattice structure has a larger design space, its structure forms are diverse, and its core is hollow through, which is convenient for filling to achieve multi-functional design [3,4]. Researchers have extensively studied the mechanical properties of different materials, preparation processes, and environments. These studies showed that the pyramid lattices had outstanding mechanical and multi-functional properties.

Hierarchical design can effectively improve the weight efficiency of the structure, so that the structure can bear more loads with smaller mass, which is in line with lightweight design. Wu et al. [5] introduced the pyramidal-pyramidal topological configuration for hierarchical sandwich structures and developed three-dimensional (3D) failure mechanism maps. Their results showed that the pyramidal-pyramidal hierarchical configuration can improve the load-bearing capacity and core buckling resistance of the sandwich structures at low density. Fan et al. had carried out a detailed numerical analysis of the energy absorption of hierarchical lattice structures, such as hierarchical square lattices [6], isogrid structures [7], and hierarchical isogrid stiffened cylinders [8], reporting that these structures have higher specific energy absorption (SEA) than the multi-layered sandwich panels [9,10].

In order to further improve the mechanical properties and energy absorption efficiency of pyramid lattice structure, we design a hierarchical pyramid lattice structure with quadrilateral honeycomb structure as the first-order structure. In order to obtain its mechanical properties, the flat compression properties of the composite were studied by finite element ABAQUS.
2. Materials and methods

2.1. Hierarchical design

The square honeycomb structure is shown in the Fig. 1(a), and the pyramid lattice structure is shown in the Fig.1(b). The ribs in the pyramid lattice structure are transformed from solid to quadrilateral honeycomb structure, forming a hierarchical pyramid lattice structure, which is shown in the Fig.2. As shown in Fig.1, the dimension parameters of the model are marked: at the square honeycomb, $t_f$ stands for thickness of panel, $t_c$ stands for core height, $t_{cw}$ stands for the wall thickness, and $L_0$ stands for inner length; at the pyramid lattice $L$ stands for length, $T$ stands for thickness, $T_W$ stands for Width, and $\beta$ stands for angle.

![Figure 1](image1.png)

**Figure 1.** Geometry of (a) square lattice and (b) traditional pyramid lattice

![Figure 2](image2.png)

**Figure 2.** Hierarchical pyramid lattice structure core

In order to deduce the relative density of the hierarchical pyramid lattice structure, the relative density of the quadrilateral honeycomb structure $\rho_1$ and the traditional pyramid lattice structure $\rho_2$ is derived, which can be expressed by Formula (1) and (2) respectively.

\[
\rho_1 = 1 - \frac{L_0^2}{(L_0 + t_{cw})^2} \tag{1}
\]

\[
\rho_2 = \frac{2TT_w}{\sin \beta (T/W + T_W/2 + L \cos \beta)^2} \tag{2}
\]
Therefore, the relative density of the new designed lattice structure $\rho_3$ can be obtained by multiplying the relative density $\rho_1$ and $\rho_2$, which can be expressed as

$$\rho_3 = \frac{2T(2t_f + t_c \rho_1)}{\sin \beta \left( \frac{T}{\sin \beta} + \frac{2t_f + t_c}{2} + L \cos \beta \right)^2} \tag{3}$$

As shown in Table 1, the size parameters of traditional pyramid lattice structure and hierarchical lattice structure with the same relative density are shown. It can be seen from Table 1 that the thickness of ribs in the two lattice structures is different. The rib thickness of 1* is 4, which represents the new lattice structure designed, the second thickness is 2.15, which represents the traditional pyramid lattice structure.

| Lattice structure | L (mm) | $\beta$ (°) | $T_w$ (mm) | $T$ (mm) | $t_f$ (mm) | $t_c$ (mm) | $t_{cw}$ (mm) | $L_0$ (mm) | Relative density |
|-------------------|--------|-------------|------------|----------|------------|------------|--------------|-----------|----------------|
| 1*                | 30     | 45          | 4          | 0.5      | 4          | 1          | 2            |           | 0.04248        |
| 2*                | 30     | 45          | 5          | 2.15     |            |            |              |           | 0.04227        |

2.2. Material

The material used in this paper is nylon PA12. Its elastic parameters are shown in Table 2 and its plastic parameters are shown in Table 3.

| PA12       | Density | Poisson's ratio | Elasticity modulus | Yield strength |
|------------|---------|-----------------|--------------------|---------------|
| Value      | 1.06g/cm³ | 0.35            | 573.3MPa           | 59.5MPa       |

| Number | Yield stress (MPa) | Plastic strain | Number | Yield stress (MPa) | Plastic strain |
|--------|--------------------|----------------|--------|--------------------|----------------|
| 1      | 59.5               | 0              | 16     | 70.57              | 0.075          |
| 2      | 60.90              | 0.005          | 17     | 70.80              | 0.080          |
| 3      | 62.15              | 0.010          | 18     | 71.03              | 0.085          |
| 4      | 63.29              | 0.015          | 19     | 71.15              | 0.090          |
| 5      | 64.30              | 0.020          | 20     | 71.28              | 0.095          |
| 6      | 65.25              | 0.025          | 21     | 71.41              | 0.100          |
| 7      | 66.10              | 0.030          | 22     | 71.49              | 0.105          |
| 8      | 66.85              | 0.035          | 23     | 71.55              | 0.110          |
| 9      | 67.56              | 0.040          | 24     | 71.61              | 0.115          |
| 10     | 68.16              | 0.045          | 25     | 71.64              | 0.120          |
| 11     | 68.70              | 0.050          | 26     | 71.67              | 0.125          |
| 12     | 69.18              | 0.055          | 27     | 71.72              | 0.130          |
| 13     | 69.60              | 0.060          | 28     | 71.80              | 0.135          |
| 14     | 69.97              | 0.065          | 29     | 71.93              | 0.140          |
| 15     | 70.28              | 0.070          | 30     | 72                 | 0.145          |
2.3. Simulation model

Using the finite element software ABAQUS, the flat compression performance of two lattice structures with the same relative density was studied. As shown in Fig.3, each lattice structure has 3 * 3 cores.

![Figure 3](image-url)

Generally speaking, the lattice structure is composed of core and upper and lower panels. Therefore, this paper added a panel with upper and lower 2.5mm, and set binding relationship between core and panel. In addition, the compression plane of lattice structure was simulated by setting a rigid plane with larger area than the upper panel, and the R3D4 grid was used to divide it. Because the panel and core of lattice structure are solid materials, C3D8R grid is used to divide them. For the hierarchical pyramid lattice structure, there are 58000 C3D8R grids and 1700 R3D4 grids. Relatively, for the traditional pyramid lattice structure, there are 47000 C3D8R grids and 1700 R3D4 grids. What is more, the normal friction was set between the rigid plane and the upper panel, and the friction coefficient was set to 0.3. The last but not least, the loading mode was that the lower panel was fixed and the rigid plane moved downward by 5mm.

3. Results and discussion

3.1. Deformation process

In the process of flat pressing, the deformation of the core is mainly lattice structure, and the upper and lower panels of the core are basically not deformed, and because the core is formed periodically, the deformation mode of the whole core is the same as that of the single core. Therefore, in order to better deform the core, the rigid plane is hidden from the upper and lower panels, and the core only shows one deformation. As shown in Fig.4, the deformation process of a single core with compression displacement is designed for the layered pyramid lattice structure. In Fig.4, the compression displacement of the rigid plane is represented by D.

![Figure 4](image-url)
When D is 0-0.25 mm, the deformation of the whole structure is very small and there is no buckling, which indicates that the structure is in the elastic stage; when D is 0.25-2.75mm, a small area of stress concentration appears at the edge of the first-order structure panel, and the structure transforms from elastic deformation to plastic deformation; when D is 2.75-5mm, the obvious buckling of the structure indicates that plastic deformation has been invented. In addition, a large area of stress concentration occurs in the first-order structural panel.

As shown in Fig.5, the final deformation diagram of the traditional pyramid lattice structure is shown. In order to better show the deformation mode, its rigid plane and upper and lower panels are hidden. It can be seen from Fig.5 that the buckling mode of traditional pyramid lattice structure is more obvious when the same displacement is compressed.

3.2. Stress concentration

Compared with Fig.4 (c) and Fig.5, it can be seen that the stress concentration of the hierarchical lattice structure appears at the panel of the first-order structure, and the stress concentration is not obvious at the joint between the core and the panel. For the traditional pyramid lattice structure, the stress concentration not only appears in the middle of the rib, but also appears at the connection between the panel and the core.
3.3. Specific strength

The quasi-static compressive stress-strain curves are shown in Fig.6.

![Stress-Strain Curve](image)

Figure 6. The quasi-static compressive stress-strain curves

From the above figure, the maximum stress of the new layered lattice structure is 29.4% larger than that of the traditional pyramid lattice structure, which indicates that the layered design is willing to effectively improve the specific strength of the structure. According to the principle of mechanics, the area surrounded by the stress-strain curve is the energy absorbed per unit volume of the structure. It can be seen from the above figure that the new structure has greater absorption capacity.

4. Conclusions

In this paper, a novel hierarchical pyramidal lattice structure with excellent mechanical properties was designed, and its compression mechanical properties were investigated through FEM. The simulation resulted showed that the new lattice structure can improve the bearing capacity of the structure, and has a good specific energy absorption capacity. In addition, it can effectively reduce the stress concentration and improve the strength of the structure.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (51905121), and the Project (HIT.NSRIF.2019082) supported by Natural Scientific Research Innovation Foundation in Harbin Institute of Technology.

References

[1] Vital P, Francucci G, Rapp H and Stcchi A 2018 Compos Struct 194 188-98
[2] Anne K, Kumar D and Williams K 2018 Int J Impact Eng 117 13-31
[3] Yungwirth C J, Radford D D, Aronson M, and Wadley H N G 2008 Compos B Eng 39 556-69
[4] Li X D and Wu L Z 2016 J. Reinf. Plast. Compos. 35 1260-74
[5] Wu Q Q, Ashkan V, Mohamad EA and Ranajay G 2019 J Mech Phys Solids 125 112-44
[6] Luo Y H and Fan H L 2018 Thin Wall Struct 124 88-97
[7] Li M, Lai C L, Zheng Q, Han B, Wu H and Fan H L 2019 Mater Des 168 107664
[8] Wu H, Lai C L, Sun F F, Li M 2018 Acta Astronaut 145 268-74
[9] Zheng J, Zhao L and Fan H L 2012 Compos B Eng 43 1516-22
[10] Fan H L, Qu Z X, Xia Z C and Sun F F 2014 Mater Des 58 363-7