Compression property of hierarchical pyramid lattice

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Abstract. Hierarchical lattice structures have excellent mechanical and multi-functional properties. A novel hierarchical pyramid lattice structure was designed and the mechanical behaviours were studied using a finite element method. In order to reflect the advantages of hierarchical pyramid lattice structure, the compression simulation of the traditional pyramid lattice structure with the same relative density was also carried out. The results showed that the designed hierarchical pyramid lattice structure increased the buckling resistance, reduced the stress concentration at the joint of panel and core, and increased the energy absorption performance and specific strength. The designed hierarchical pyramid lattice structure contributes to the expansion of hierarchical lattice structure.

1. Introduction
Lattice structure has been widely studied due to its lightweight, high specific strength and multi-functional properties. As one of the typical lattice structures, the pyramid lattice structure has been extensive investigated by scholars for its compression [1,2], shear [3], three-point bending [4], high-speed impact [5], underwater impact [6]. These studies showed that the pyramid lattices had outstanding mechanical and multi-functional properties.

Hierarchical lattice structure has stronger energy absorption and specific strength. For the hierarchical lattice structure, scholars are interested in the hierarchical honeycomb structure, i.e., 2-D hierarchical lattice structures. Cote et al. [7] studied the compression failure modes and mechanical properties of hierarchical square honeycomb structures; Liu et al. [8] introduced flatwise compression property of hierarchical thermoplastic composite square lattice, and the results showed that the energy absorption was greatly improved; Fan et al. [9] had carried on the detailed numerical analysis to the energy absorption of hierarchical square lattice structures; Zheng et al. [10] has studied the energy absorption mechanisms of hierarchical woven lattice composite and a plastic model had been suggested; Feng et al. [11] studied compressive and shear properties of carbon fiber composite square honeycombs with optimized high-modulus hierarchical phases. However, there were few researches on the hierarchical pyramid lattice structure.
In this paper, we designed a hierarchical pyramid lattice structure based on square honeycomb lattice structure. According to the ABAQUS /Explicit, the compression behaviours were compared between the hierarchical pyramid lattices and the traditional pyramid with the same relative density.

2. Materials and methods

2.1. Hierarchical pyramid lattice structure
Hierarchical pyramid lattice structure has two order lattice structure: square lattice structure is the first order lattice structure; pyramid lattice structure is the second order structure. Figure 1 shows the geometry: the geometry of the unit cell of square lattice is defined by its thickness of panel, \( t_f \), core height, \( t_c \), the wall thickness, \( t_{cw} \), and inner length \( L_0 \) of square honeycomb; the geometry of the unit cell of pyramid lattice is defined by its length, \( L \), thickness, \( T \), Width, \( T_W \), and angle, \( \beta \).

![Figure 1. Geometry of (a) square lattice and (b) traditional pyramid lattice](image1)

The relative density of the cores of square lattice structure and pyramid lattice structure can be obtained from equations (1) and equations (2) respectively.

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

\[
\rho_2 = \frac{2TT_W}{\sin \beta (T/\sin \beta + T_W/2 + L \cos \beta)^2}
\]

The designed hierarchical lattice structure is shown in Figure 2.

![Figure 2. Hierarchical pyramid lattice structure core](image2)
According to equation (1) and equation (2), the relative density of hierarchical lattice structure can be given by equation (3).

\[
\rho_3 = \frac{2T(2t_f + t_r \rho_3)}{\sin \beta \left( \frac{T}{\sin \beta} + \frac{2t_f + t_r}{2} + L \cos \beta \right)^2}
\]

In order to analyze the compression performance of hierarchical pyramid lattice structure, we set up a traditional pyramid lattice structure with the same relative density, which was realized by changing the value of \(T\). 4mm and 2.15mm are the thickness values of hierarchical lattice structure and traditional lattice structure, respectively. Table 1 shows the specific dimensions of two lattice structures: 1* represents hierarchical lattice structure; 2* represents traditional lattice structure.

| Lattice structure | \(L\) (mm) | \(\beta\) (°) | \(T_w\) (mm) | \(T\) (mm) | \(t_r\) (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

SOMOS-8000 photosensitive resin was adopted, which was produced by DuPont company (DSM) [12]. Its density is 1.16g/cm\(^3\), Poisson's ratio is 0.41, and modulus of elasticity is 1400MPa, and table 2 shows the true plastic stress and strain.

| Number | Yield Stress (MPa) | Plastic Strain | Number | Yield Stress (MPa) | Plastic Strain | Number | Yield Stress (MPa) | Plastic Strain |
|--------|--------------------|----------------|--------|--------------------|----------------|--------|--------------------|----------------|
| 1      | 1                  | 0.00           | 7      | 31                 | 0.03           | 13     | 57.5               | 0.06           |
| 2      | 8                  | 0.01           | 8      | 34                 | 0.035          | 14     | 66                 | 0.065          |
| 3      | 14                 | 0.015          | 9      | 39.5               | 0.04           | 15     | 67                 | 0.07           |
| 4      | 20                 | 0.018          | 10     | 42.5               | 0.045          | 16     | 68.3               | 0.075          |
| 5      | 22.5               | 0.02           | 11     | 49.6               | 0.05           | 17     | 70                 | 0.08           |
| 6      | 26                 | 0.025          | 12     | 54                 | 0.055          | 18     | 72                 | 0.1            |

2.3. Simulation model

ABAQUS/Explicit was used to predict the mechanical properties of the hierarchical pyramid lattice structure under quasi-static flatwise compression. Figure 3 shows the 3*3 cores simulation model.
In the model, we designed two homogenized panels with the same thickness of 2.5mm, and these were tied with core together, respectively. Besides, the discrete rigid shell lunar was designed to simulate the pressure plate, and it was modelled with 4-node 3-D bilinear rigid quadrilateral elements(R3D4). Panels and cores were modelled with 8-node linear brick, reduced integration, hourglass control elements(C3D8R). The hierarchical pyramid lattice structure consisted of approximately 57132 C3D8R elements and 1600 R3D4 elements. At the same time, the number of C3D8R elements and R3D4 elements for traditional pyramid lattice were 46875, 1600 respectively. Besides, surface-to-surface contact (Explicit) was adopted between rigid shell planar and panel surface, and the friction coefficient was 0.36. Finally, reference point of rigid was moved down 5 mm, and another panel surface was fixed.

3. Results and discussion

3.1. Deformation process

According to the output results, the upper and lower panels have almost no deformation due to their large thickness, and the deformation of 3*3 core is consistent with that of single core. Thus, the deformation of a single core will be used to illustrate the deformation of the whole structures. Figure 4 illustrates the deformation process of hierarchical pyramid lattice structure core, in which the rest of the simulation model is hidden. In order to explain the deformation process conveniently, we use D to express the displacement value of rigid body.
When D is 0-0.25 mm, the stress distribution of the core is uniform, and there is almost no stress concentration; when D is 0.25-2.75mm, with the increase of displacement, the core of pyramid appeared obvious elastic deformation, and the stress concentration occurs in the local area of the panel of square honeycomb lattice; when D is 2.75-5mm, The value of local maximum stress, s, is kept at 72 MPa, the pyramid core appears obvious buckling, the local stress concentration area increases rapidly, and the core of square honeycomb structure occurs wrinkling.

Figure 5 shows the compression simulation results of 3*3 traditional pyramid lattice structure with the same relative density, and other parts of the simulation model are hidden. Compared with Figure 4 (c) and Figure 5, it can be seen that the core of the traditional lattice structure has significant buckling, and the hierarchical lattice structure has markedly reduced the buckling.

3.2. **Connection strength at the joint of panel and core**

The simulation results show that the stress concentration of traditional pyramid lattice not only appears at the joint of panel and core, but also in the middle part of core; however, the stress concentration of hierarchical lattice structure occurs in the area of square honeycomb panel rather than the connection between core and panel. This shows that the hierarchical lattice structure improves the connection strength between the panel and the core.

3.3. **Specific strength and energy absorption properties**

Figure 6 shows the stress-strain curves of two lattice structures.
According to figure 6, the maximum compression strength of layered hierarchical structure is greater than that of traditional pyramid lattice, which indicates that hierarchical lattice structure has higher specific strength. According to the simple mechanical knowledge, the area surrounded by the stress-strain curve is the absorbed energy. We can see clearly that the stress-strain curve of hierarchical lattice structure includes a larger area, which indicates that it has a stronger energy absorption characteristic.

4. Conclusions
Based on the finite element method of ABAQUS/Explicit, the compression performance of hierarchical pyramid lattice structure was studied. According to the simulated results, the hierarchical lattice structure reduced the stress concentration at the junction of face sheets and cores, and increased the energy absorption performance and specific strength. What’s more, the deformation process of hierarchical lattice structure was clarified.

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