Research on the application potential of lattice materials based on the cell configuration

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Abstract. Lattice materials are recognized as the most potential functional material, with remarkable periodic and modular characteristics. The 3D models and mechanical models of ECC, BCC, GBCC and BCC$_{xy}$ cells are established. The mechanical properties of different cell configurations under static and dynamic loads are studied by finite element simulation. The results show that the straight-rod dominant cells such as the ECC and GBCC cells have higher equivalent stiffness, and the lattice material composed of that will be provided with better bearing performance. The inclined-rod dominant cells such as the BCC and BCC$_{xy}$ cells have greater strain energy, and the lattice material composed of that will be provided with better buffer and energy absorption. By studying the mechanical properties of different cells, it provides a reference for cells selection and optimization of lattice materials to meet different engineering application requirements.

1. Introduction

In recent years, with the increasing maturity of additive manufacturing technology, the development of lattice material technology has been promoted significantly [1]. Lattice materials are of great application value in the structural lightweight, with the advantages of the lightweight, high porosity, low relative density, high specific stiffness and specific strength [2]. In addition, the lattice structure also has multi-functional potentials such as anti-vibration, anti-impact, heat transfer and heat dissipation, sound absorption and noise reduction, zero/negative thermal expansion and so on [3]. Lattice materials have become a new functional material and have good application prospects in many fields such as aerospace, mechanical engineering, medicine and so on [4].

Scholars at home and abroad have carried out a lot of research on lattice materials. Gibson and Wang [5] studied the mechanical properties of honeycomb structures using simple beam theory. Liu [6] used the finite element analysis method to analyze the mechanical properties of the lattice structure with equal relative density. Stephen [7] and Martin [8] studied the stiffness and strength properties of lattice structural materials through experiments and discussed the effects of different rod sizes on the mechanical strength of lattice materials. Xin [9] and Wang [10] optimized the topology of continuum geometry and realized the modeling of the variable density lattice structure. Sing [11] and Liu [12] explored the design and manufacture of gradient honeycomb lattice materials with different densities according to the one-dimensional shock wave theory. It was found that the variable density lattice structure showed an obvious impact energy absorption advantage.

However, the existing research work mainly depends on a large number of simulations and experiments. Moreover, the research work on a single cell is still rare. Therefore, this paper studies from the perspective of cell configuration. The 3D model and mechanical model of four kinds of lattice cells...
are established, and the influence of cells on material mechanical properties is studied by finite element simulation. Through the research, the application potential of lattice cells is studied, and the equivalent stiffness theories and energy absorption laws of cells are explored.

2. Mechanics model of lattice cells

2.1. Cells model

Lattice materials consist of cells one by one, which have significant periodic and modular characteristics. Two common lattice materials are shown in figure 1. As shown in figure 1 (a), the honeycomb material is composed of hexagonal cells. As shown in figure 1 (b), the GBCC lattice material is composed of GBCC cells. The macro mechanical properties of lattice materials are determined by the micro topological configuration of cells. The mechanical properties of lattice materials can be predicted by the mechanical properties of cells.

![Figure 1. Two common lattice materials.](image)

Four cell models are shown in figure 2, including edge cubic cell (ECC), body-centered cell (BCC), body-centered cubic cell (GBCC) and half body-centered cell (BCCxy). The ECC cell is composed of straight rods, the BCC cell is composed of inclined rods, the GBCC and BCCxy cells are composed of straight rods and inclined rods. The cell size is defined by the cell side \( a \) and the rod section dimension \( t \). The straight rod adopts a square section and the inclined rod adopts a regular hexahedron.

![Figure 2. Four cell models.](image)

The weight reduction ratio of materials is 70%, then the relative density is 0.3. The cell side length \( a \) is selected, \( a=10\text{mm} \). The cell rods size \( t \) is calculated as shown in Table 1.

![Table 1.](image)
2.2. Mechanical model of cells

The mechanical properties of lattice cells are mainly determined by the connection mode and size of rods in the cells. It is found that almost all lattice cells are connected by straight and inclined rods according to certain rules. The deformation of lattice cells under stress is the result of the coupling of the deformation of straight and inclined rods in the cell.

The mechanical model of the cells rod is established, as shown in figure 3. Figure 3(a) shows the compression deformation of the straight rod, figure 3(b) shows the bending deformation of the inclined rod, and figure 3(c) shows the stress of the inclined rod.

![Figure 3. The mechanical model of rod.](image)

The deformation of straight rod and inclined rod are as follows:

\[
\begin{align*}
\Delta l &= \frac{Fl}{EA}, \\
\Delta h &= \left[\frac{Fl}{EA} + \frac{F \cos \theta t_2}{3EI \sin \theta}\right]^{1/2}.
\end{align*}
\]

(1)

Where, \(E\) is the elastic modulus, \(A\) is the cross-sectional area of the rod, and \(I\) is the moment of inertia of the rod. It can be seen that the bending deformation of the inclined part is obviously greater than the compression deformation of the straight rod.

According to Hooke’s law, the relationship between the equivalent stiffness of straight bar and inclined bar is as follows:

\[k_{\Delta l} > k_{\Delta h}\]

(2)

Under the same load, the smaller the deformation, the greater the equivalent stiffness. It can be seen that the equivalent stiffness of the straight bar is greater than that of the inclined bar.

According to energy conversation law, the work of the external force is equal to the strain energy of the rods. The strain energies of four kinds of cells are calculated as follows:

\[
\begin{align*}
U_{BCC} &= \frac{F^2}{Et_1} \left[1 + \frac{512t_4^4}{75t_2^4}\right]^{1/2}, \\
U_{GBCC} &= \frac{F^2}{Et_1} \left[c_1 + c_2 \left(1 + \frac{512t_4^4}{75t_2^4}\right)^{1/2}\right], \\
U_{BBCC} &= \frac{F^2}{Et_1} \left[1 + \frac{512t_4^4}{75t_2^4}\right]^{1/2}, \\
U_{BCCy} &= \frac{F^2}{Et_1} \left[1 + \frac{512t_4^4}{75t_2^4}\right]^{1/2}.
\end{align*}
\]

(3)

Where, \(c_1\) and \(c_2\) are dimensionless coefficients, \(t_1, t_2, t_3\) and \(t_4\) are sectional dimensions of rods.
According to the theoretical analysis, the straight-bars dominant cells have greater dynamic stiffness, and the inclined-rod dominant cells have greater energy absorption capacity. Therefore, the lattice materials composed of straight-rod dominant cells such as ECC and GBCC cells have better bearing performance. The lattice materials composed of inclined-rod dominant cells such as BCC and BCC\textsubscript{xy} have better buffer and energy absorption potential.

3. Simulation and discussion

The 3D models of lattice cells are established by the Creo software. The lattice cells are simulated under static and dynamic load in the popular ANSYS Workbench 18 software.

3.1. Stress nephogram of cells

Under static load and dynamic load, the simulated stress nephogram of four lattice cells is shown in figure 4. It can be seen from figure 4 that the stress distribution law of the four lattice cells under impact load is consistent with that under static load. It is found that the stress of straight rod dominant cells such as ECC and GBCC cells are mainly concentrated on the rod along the force action direction, and the stress of inclined rod dominant cells such as BCC and BCC\textsubscript{xy} cells are mainly concentrated at the intersection of inclined rods. Therefore, the cell microstructure can be optimized and the mechanical properties of the cell can be improved by increasing the size of the intersection area of the straight rod and the inclined rod to smooth the material transition.

3.2. Analysis of static simulation results

Under static load, the deformation curves of cells are shown in figure 5 (a). During the compression process, the compression deformation of the four kinds of cells increases gradually with the increase of time. The maximum deformation of the four cells is as follows: \( u_{\text{ECC}} = 9.88 \times 10^{-7} \text{ mm} \), \( u_{\text{BCC}} = 1.92 \times 10^{-6} \text{ mm} \), \( u_{\text{GBCC}} = 1.27 \times 10^{-6} \text{ mm} \), and \( u_{\text{BCC}_{xy}} = 2.96 \times 10^{-6} \text{ mm} \). Among the four kinds of cells, the deformation peak of the ECC cell is the smallest, and that of the BCC\textsubscript{xy} cell is the largest. Compared with the BCC\textsubscript{xy} cell, the maximum deformation of the ECC cell is reduced by 66.6%.

The stress curve is shown in figure 5 (b). The maximum stresses of four cells are as follows: \( \sigma_{\text{ECC}} = 12.01 \text{ MPa} \), \( \sigma_{\text{BCC}} = 36.72 \text{ MPa} \), \( \sigma_{\text{GBCC}} = 16.63 \text{ MPa} \), and \( \sigma_{\text{BCC}_{xy}} = 67.37 \text{ MPa} \). Among the four kinds of cells, the stress of ECC cell is the smallest and that of the BCC\textsubscript{xy} cell is the largest. Compared with the BCC\textsubscript{xy} cells, the maximum stress of the ECC cells decreased by 82.1%.

The static simulation results show that compared with the inclined-rod dominant cells such as BCC and BCC\textsubscript{xy} cells, the straight-rod dominant cells such as the ECC and GBCC cells have greater equivalent stiffness and better bearing performance. Moreover, among the four cells, the ECC cell has the best bearing performance.
3.3. Analysis of dynamic simulation results

The parameter curves in the impact process are shown in figure 6. As can be seen from figure 6, the impact time of four kinds of cells is as follows: $\Delta t_{\text{ECC}}=0.00003$ s, $\Delta t_{\text{BCC}}=0.000065$ s, $\Delta t_{\text{GBCC}}=0.000035$ s, $\Delta t_{\text{BCC}_{xy}}=0.00005$ s. Among the four kinds of cells, BCC cells have the longest impact time and ECC cells have the shortest impact time. Compared with ECC cells, the impact time of BCC cells was prolonged by 116.6%.

The stress curve is shown in figure 6 (a). During impact, the maximum stresses of the four cells are as follows: $\sigma_{\text{ECC}}=202.46$ MPa, $\sigma_{\text{BCC}}=517.09$ MPa, $\sigma_{\text{GBCC}}=222.52$ MPa, $\sigma_{\text{BCC}_{xy}}=223.70$ MPa. Among the four kinds of cells, the stress peak of the ECC cell is the smallest and that of the BCC cell is the largest. Compared with BCC cells, the maximum stress of the ECC cells was reduced by 60.8%.

The strain energy curve is shown in figure 6 (b). In the process of impact, the strain energy peaks of the four cells are as follows: $U_{\text{ECC}}=3.93$ mJ, $U_{\text{BCC}}=26.16$ mJ, $U_{\text{GBCC}}=4.31$ mJ, $U_{\text{BCC}_{xy}}=6.04$ mJ. Among the four kinds of cells, ECC cells have the smallest strain energy and BCC cells have the largest strain energy. Compared with ECC cells, the peak strain energy of BCC$_{xy}$ cells increased by 565.6%, and that of BCC cells increased by 53.6%.

The impact simulation results show that the straight-rod dominant cells such as ECC and GBCC cells have greater dynamic stiffness and better bearing performance. The inclined-rod dominant cells such as BCC and BCC$_{xy}$ cells have longer buffer time and greater energy absorption and have better buffer energy absorption potential. Moreover, among the four kinds of cells, the BCC cell has the longest buffer time and the largest energy absorption.

![Figure 5. The parameter curves under static load.](image)

![Figure 6. The parameter curves under impact load.](image)
4. Conclusions
In this paper, the 3D models of lattice cells are established by the Creo software. The static and dynamic simulation of lattice cells is carried out in the popular ANSYS Workbench software. The simulation results are consistent with the theoretical analysis. The conclusions are as follows:

(1) According to the rod connection and deformation of cells, the cells can be divided into the straight-rod dominant type (ECC and GBCC) and the inclined-rod dominant type (BCC and BCC$_{xy}$). The stress of the straight-rod dominant cells is mainly concentrated on the rod along the force action direction, and the stress of the inclined-rod dominant cells is mainly concentrated on the intersection of rods.

(2) The straight-rod dominant cells such as the ECC and GBCC cells have greater equivalent stiffness. The lattice materials have better bearing performance. Among the four kinds of cells, ECC cells have the best bearing performance.

(3) The inclined-rod dominant cells such as the BCC and BCC$_{xy}$ cells have longer buffer time and greater energy absorption. The lattice materials have better buffer energy absorption potential. Among the four kinds of cells, BCC cells have the best buffer performance.

This study can provide support for cell selection and optimization design of functional lattice materials to meet different engineering application requirements.

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