An Egg-Box Sandwich Structure Static Behavior

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Abstract. There is a significant theoretical and applied value to study sandwich structures mechanical behavior in the anti-collision device due to their excellent physical and mechanical performance. A new egg-box sandwich structure device was designed. Next, the important factors (cell half-height $h$, cell thickness $t_o$ and cell width $b$) affecting the deformation capability and energy absorption performance of the structure were explored by the finite element method in this paper. The findings show that cell geometric parameters have a remarkable effect on structural deformation capability and energy-absorption performance. In addition, the structural displacement rises significantly with the size of cell half-height $h$ increasing. Besides, the more quickly the cell thickness $t_o$ rises, the more obviously the displacement and the stress of the structure decrease. Also, with the size of cell width $b$ gradually enlarging, the displacement and the stress increase at first and then decrease. When cell width $b$ is 50mm, the structure has extraordinary deformability and energy-absorption characteristics. Thus, the study of the parameters of the egg-box sandwich structure can provide some effective inspirations for the design of vehicle anti-collision device.

1. Introduction

Sandwich structure found widespread application in many fields such as impact science, vibration, and machinery manufacturing due to its characteristics of light weight, high specific strength, large deformation and high energy absorption efficiency. In 2013, it was found that using the thickness and the stiffness of the damping layer as parameters would help improve the damping performance [1]. In 2017, it is proposed that when the polyurea elastomer is used as a sandwich, the anti-knock performance of the steel sheet can be improved [2]. In 2019, a simplified experiment was carried out with two different structures and suggested that the design form of cell size could affect the magnitude of the impact force [3]. In addition, the shear performance at the sandwich cell of a multi-layer corrugated structure was better than that of a traditional PP honeycomb structure [4]. Also, Kevlar fiber and Zylon fiber were mixed into the sandwich structure, which effectively changed the impact resistance [5].

The egg-box sandwich structure, as a large deformation and energy-absorbing superstructure, was widely used as an anti-collision device in vehicle engineering fields [6]. In 2002, it was proved that the energy absorption of egg-box material was comparable to that of metallic foams [7]. However, it was suggested that the egg-box material had a similar energy absorption capacity to that of hexagonal honeycombs and was superior to that of metal foams in the same year [8]. In 2006, Scaling laws were determined for the stiffness and strength as a function of relative density of the egg-box material [9]. The optimal material and draping condition were proposed for a composite egg-box panel [10]. Moreover, egg-box structure and fiber reinforced composite materials were used in bridge protection...
structure, which could increase energy absorption in 2018 [11]. There was a law identified that local splitting damage at cell joining regions and crushing of the cell of the egg-box structure was proven as the primary failure mechanism in the sandwich panels [12].

Currently, the scholars have explored widely the geometric forms, structural parameters, and many applications of the sandwich structure and the egg-box structure, but their research on the cell parameters are relatively simple. Based on the research of scholars at home and abroad, a new egg-box sandwich structure was proposed, in this paper. The influence of the geometric parameters (cell half-height \( h \), cell thickness \( t_0 \) and cell width \( b \)) of the egg-box sandwich on the structural performance was studied by static compression experiments.

2. Finite Element Analysis

2.1. Structural Geometric Model

Based on the geometric characteristics of the egg-box structure, a new egg-box cell structure is proposed, in Figure 1(a).

\[
f(x) = h \cos \left( \frac{2\pi}{b} x + \varphi \right)
\]

where \( f(x) \) is defined as the egg-box curve contour function.

The starting point of the function curve is determined by the cell initial phase position \( \varphi \). The cell initial phase positions \( \varphi \) of the cell structure studied in this paper satisfies \( \varphi = 0 \), in order to ensure the high symmetry of the cell structure. Figure 1(b) is a single-layer sandwich arrayed from the cells, whose side length is \( L = 250 \text{mm} \) and specific dimensions are listed in Table 1.

| Group                | \( E1^a \) | \( E2^b \) | \( E3^c \) |
|----------------------|-----------|-----------|-----------|
| Cell half-height \( h \) | 4 6 8 10 12 14 10 10 10 10 10 10 10 10 10 10 10 | 50 50 50 50 50 50 25 35.7 41.7 50 62.5 50 50 50 50 50 | 1.1 1.1 1.1 1.1 1.1 1.1 1.0 1.0 1.0 1.0 1.0 0.1 1.2 1.4 1.6 |
| Cell width \( b \)    | 50 50 50 50 50 50 25 35.7 41.7 50 62.5 50 50 50 50 50 | 1.1 1.1 1.1 1.1 1.1 1.1 1.0 1.0 1.0 1.0 1.0 0.1 1.2 1.4 1.6 |
| Cell thickness \( t_0 \) | 0 0 0 0 0 0 1.0 1.0 1.0 1.0 1.0 0.8 0.8 0.8 0.8 |

\(^a\)E1 is the group of studying cell half-height \( h \).
\(^b\)E2 is the group of studying cell width \( b \).
\(^c\)E3 is the group of studying cell thickness \( t_0 \).
In this paper, the egg-box structure as a core is assembled to two force plates whose sizes are $300mm \times 180mm \times 20mm$, in Figure 2(a).

![Figure 2](image)

(a). The arrangement of egg-box sandwich  
(b). Mesh and loads  

Figure 2. Finite element model of egg-box sandwich.

2.2. Finite Element Analysis Model

Finite element simulations are conducted by the Ansys static structural module in this work. The temperature is set to 22 °C during the trial to make the simulation result closer to the actual situation. Besides, all materials are made of aluminum alloy, whose parameters are listed in Table 2.

| Density $\rho$ (kg/m$^3$) | Elastic Modulus $E$ (MPa) | Poisson's Ratio $\mu$ | Compression Yield Strength $\sigma_s$ (MPa) |
|---------------------------|---------------------------|-----------------------|---------------------------------------------|
| 2770                      | 710                       | 0.33                  | 280                                         |

The plasticity and large deformation condition of the structure are considered in simulation, because of the good plasticity for the aluminum alloy. The model is meshed with the default elements in Ansys. The loads, constraints and mesh method are shown in Figure 2(b). To simulate the compression trial, the bottom surface of the egg-box sandwich structure bottom plate is completely fixed, and a uniform pressure $p$ is applied to the top plate surface. There is a linear relationship between load $Q$ and time as follows:

$$Q = \begin{cases} pt, & 0 \leq t < 1 \\ -pt + 2p, & 1 \leq t < 2 \end{cases}$$

3. Results and Discussion

3.1. The Results of the Cell Half-height

To investigate the influence of the cell half-height $h$ on the mechanical behavior of the structure, the models of the egg-box sandwich structure, based on different cell half-height $h$, are established, whose sizes are listed in Table 1. Moreover, the same constraints and loads methods are adopted to explore the effects of different cell half-height $h$ on the mechanical behavior of the egg-box sandwich structure.

The relationship between the different cell half-height $h$ and the displacement under the same experimental conditions shows an upward tendency in Figure 3. At the same time, the influence of cell half-height $h$ on the maximum mises stress is plotted in Figure 4. It is noted obviously that the displacement and the stress value increase by a large margin with the cell half-height $h$ rising. When the cell half-height $h$ of the egg-box structure equals 10mm, the deformation and the stress reach the
maximum value. However, the displacement and the stress value of the structure decrease relatively, when the cell half-height $h$ is greater than 10mm.

Figure 5 is the force diagram of the egg-box cell with different cell half-height, where one edge of the cell is completely fixed. When the cell is subjected to vertical force $F$, the region around the point $O$ will produce the displacement because of suffering from the moment $M$ generated by the force $F$, where the moment $M$ can be defined by $M = Fh_x$. Therefore, the larger the size of the cell half-height $h$ is, the greater the moment $M$ at the point $O$ of the structure is, which makes the structure more likely occur the large deformation.

Accordingly, increasing the cell half-height $h$ of the egg-box sandwich structure can effectively enhance the deformation ability and energy absorption characteristics of the structure. When the cell half-height $h$ equals 10mm, the deformation performance and energy absorption capacity of the structure reach the maximum. It is a good choice that the cell half-height $h$ adopts 10mm in the design of structure, which can augment the mechanical properties.

### 3.2. The Results of the Cell Thickness

The cell thickness $t_0$ affecting the structural rigidity is closely connected with the mechanical behavior of the structure, which possesses an important significance on the study of the structure. The E3 are established to study the influence of different cell thickness $t_0$ on the displacement and stress of the structure, whose sizes are listed in Table 1. The constraints and loads methods are the same as above (Figure 2 (b)).

The relationship between the cell thickness $t_0$ and the displacement presents a downward tendency, which is shown in Figure 6. Moreover, the maximum mises stress gradually decline with the cell
thickness \( t_0 \) rising in Figure 7. The structural rigidity of the egg-box sandwich positively correlates with the cell thickness \( t_0 \), resulting in the reduction of structural elasticity and plasticity with the cell thickness \( t_0 \) increasing. Therefore, the sandwich is not easy to produce large deformation in this situation, which makes the displacement and the stress decline conspicuously. However, if the size of cell thickness \( t_0 \) is so small, the structural ultimate capacity will be greatly reduced, which causes compression failure of the sandwich. Therefore, the proper cell thickness \( t_0 \) should be considered in the design of engineering.

3.3. The Results of the Cell Width

The cell width \( b \) affects the egg-box curve contour function (Eq. 1) and the geometric characteristics of the structure. In this paper, the egg-box sandwich geometry models of the different sizes of the cell width \( b \) are established to analyze parameters. At the same time, the constraints and loading methods are guaranteed to adopt the same as above (Figure 2 (b)).

Figure 8 shows the law between the displacement and the cell width \( b \) under compression simulation. The changes about the maximum mises stress possess the same trend in Figure 9. The deformation of the structure increases at first and then decline with the cell width \( b \) increasing. It is because when the cell width \( b \) size of the structure is small, the number of the cell is so large in the same height of structure, which lead directly to enlarge structural stiffness, decline the plasticity and make the sandwich not deformable. Therefore, the number of cells in the sandwich decrease with the
increase of cell width $b$, and the stiffness of the structure gradually decreases so that the structure tends to deform greatly. When the cell width $b$ reaches about 50mm, the deformation appears the maximum value, but the deformation capacity of the structure decreases sharply beyond this value.

It is found that the cell width $b$ of the egg-box structure has a palpable effect on the deformation performance and energy absorption characteristics of the structure. As the cell width $b$ of the structure rises, the deformation of the structure increases first and then decreases. Therefore, when the cell width $b$ of the egg-box structure equals 50mm, it is a proper value in the design of structure to guarantee the great performance of the egg-box sandwich structure.

4. Conclusions
In this paper, the mechanical performance of a new egg-box sandwich structure is investigated by finite element simulation experiments. The structural geometric parameters (cell half-height $h$, cell thickness $t_0$ and cell width $b$) of the egg-box sandwich structure are studied, and the effects on the structural deformation performance and energy absorption characteristics are explored. The conclusions are as follows:
(1) Structural cell geometric parameters have a palpable effect on structural deformation capacity and energy absorption performance.
(2) The structure deformation rapidly augments with the size of cell half-height $h$ increasing. When the size of the cell half-height $h$ is 10mm, structure possess an excellent mechanical property.
(3) With the increase of cell thickness $t_0$, the displacement and stress of the structure decrease obviously. The size of the cell thickness $t_0$ is 0.8mm, which makes structure not be damaged by the load.
(4) The displacement and stress increase at first and then decrease with the increase of cell width $b$. When the cell width $b$ is 50mm, the structure has excellent deformability and energy absorption characteristics.

5. References
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