# Finite Element Analysis of the Size Effect of Vertebral Implant with Honeycomb Sandwich Structure

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**Research**

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# Abstract

**Background:** Because of osteoporosis, traffic accidents, falling from high places and other reasons, the vertebral body could be compressed injury, even collapse. Vertebral implant can be used for clinical treatment. Because of the advantages of honeycomb sandwich structure, such as low cost, less material, light weight, high strength, and good cushioning performance, honeycomb sandwich structure was used as the basic structure of vertebral implant.

**Methods:** In this paper, we applied the orthogonal experiment method to analyze the size effect of honeycomb sandwich structure by finite element method. Based on the minimum requirements of three indexes of peak stress, axial displacement, and anterior-posterior displacement, the optimal structure size was determined. Further, through local optimization of the overall structure of the implant, we designed better honeycomb sandwich structure vertebral implant.

**Results:** The optimal structure size combination is determined as the face sheets thickness 1mm, wall thickness 0.49mm, cell side length 1mm, height 6mm. Than through local optimization, the peak stress is further reduced, the overall stress distribution is uniform, and the deformation is reduced. The optimized peak stress decreases to 1.041MPa, the axial deformation is 0.111%, and the anterior-posterior deformation is 0.014%. The honeycomb sandwich structure vertebral implant with stable structure and good mechanical performance was designed.

**Conclusions:** The research result provides a method for the optimal design of vertebral body implant structures, as well as provides a new idea and biomechanical basis for clinical treatment after vertebral body injury.


# Background

In recent years, the frequent occurrence of diseases, natural disasters, traffic and the aging of the population, obesity, lack of exercise and other external factors have led to a growing number of clinical bone tissue damage, and clinical demand for bone defect repair is growing [1]. The bone has a strong ability to self-repair when the injury is minor. However, for bone defects beyond the critical size, implants are needed to repair bone defects, including autogenous and allogeneic or artificial bone grafts [2]. Autologous bone graft has a better adaptability for bone grafting. However, because of limited donor bone graft and the incidence rate of allograft or immune rejection, it is impossible to widely applied [3]. Researchers have been turned their attention to artificial bone repair materials [4–5].

Generally, artificial bone repair materials must have good compatibility with surrounding cell tissue to promote the repair ang healing of the defect site. In addition, implants must also have good mechanical properties to withstand the load during the bone defect repair process and to provide a stable and complete structure [1, 5]. However, these artificial bone materials are only limited to the critical-sized defects of nonbearing bones due to their poor mechanical properties [5, 6]. Many methods can be used to improve the mechanical properties of the implant, for example, by compounding other materials while optimizing the structure of the implant. According to the structural characteristics and excellent mechanical properties of the honeycomb, a porous CS/nHA scaffold with 3D printing was manufactured by Hongxia Zhao [7]. The scaffold with high porosity were found to improve compressive strength (1.62 ± 0.22 MPa) and Young’s modulus (110 ± 22 MPa), which was similar to that of cancellous bone. According to the osteogenic capacity and mechanical properties including excellent strength and toughness of nature bone, using HA / collagen composite nanofibers, a kind of bone scaffold with bionic multilayer hierarchical structure and similar to natural bone components was constructed by Tierong [8]. The compressive strength of the multi-stage hierarchical bone structure scaffold was 3 MPa.

Porous scaffold with honeycomb structure, which exhibits excellent mechanical properties, has great application potential in tissue engineering [9]. And honeycomb sandwich is a structure that consists of two relatively thin face sheets bonded to a relatively thick lightweight honeycomb core [10]. The face sheets primarily carry tensile and compressive loads which have high stiffness and strength, the core have sufficient shear strength to withstand transverse shear stresses and also thick to provide high shear stiffness to resist buckling of the panel [11].The structures are broadly used in automotive, aerospace and transportation and many other fields, because of their high strength, high bending stiffness/weight ratio, light weight and so on [12]. This kind of implant structure with good mechanical properties is also needed in the field of clinical bone implantation It can not only fill bone defects, restore the geometric size of original bone tissue, but also meet the biomechanical requirements of the bone tissue.

The vertebra is an important part of the human body's system, which has the functions of supporting the trunk, protecting the internal organs and performing exercise. And it is also a place that is relatively easy to be injured. Trauma, incorrect posture, etc. will cause vertebral injuries [13]. Bone cement is usually used in clinical treatment to repair the defect [14], but it is impossible to predict whether the biomechanical properties of the vertebral body meet the requirements before the operation.

Honeycomb structures with different geometric sizes have different mechanical properties, so optimizing the geometric parameters of the structure is an important means to improve its mechanical properties [10–12]. In this paper, the size effect of the honeycomb sandwich structure was analyzed using the finite element analysis software ABAQUS and orthogonal test method. According to the minimum requirements of three indexes of peak stress, axial displacement, and anterior-posterior (AP) displacement of the structure, the optimal structure size was determined. In addition, through the local optimization of the structure, a honeycomb sandwich structure vertebral implant with stable structure and good mechanical performance was designed.

# Results

The orthogonal experimental results of 9 different combinations of structural geometric parameters were shown in Table 1. The size effect of honeycomb sandwich structure on three indexes of peak stress, axial displacement, and AP displacement could be obtained.

Table 1
Result of the orthogonal experiment

| No. | Factors | | | | Results | | |
|---|---|---|---|---|---|---|---|
| | A | B | C | D | peak stress (MPa) | axial displacement (mm) | AP displacement (mm) |
| 1 | 1 | 1 | 1 | 1 | 1.354 | 0.0150 | 0.0017 |
| 2 | 1 | 2 | 2 | 2 | 3.407 | 0.0418 | 0.0071 |
| 3 | 1 | 3 | 3 | 3 | 6.692 | 0.1065 | 0.0177 |
| 4 | 2 | 1 | 2 | 3 | 3.511 | 0.0443 | 0.0072 |
| 5 | 2 | 2 | 3 | 1 | 5.979 | 0.0833 | 0.0191 |
| 6 | 2 | 3 | 1 | 2 | 1.160 | 0.0209 | 0.0023 |
| 7 | 3 | 1 | 3 | 2 | 6.165 | 0.0827 | 0.0198 |
| 8 | 3 | 2 | 1 | 3 | 1.243 | 0.0213 | 0.0018 |
| 9 | 3 | 3 | 2 | 1 | 2.881 | 0.0285 | 0.0049 |

Taking the peak stress, axial displacement and AP displacement of the structure as indexes, the average value of the experimental results at each level was calculated, which was recorded as K. The optimal level of each factor was judged according to the value of K, and the optimal level of each factor was taken as the structural combination parameter. The difference between the maximum value and the minimum value of K was calculated respectively, which was recorded as the range R. According to the size of R, the order of the influence of each factor on the index was judged [15]. The range analysis of orthogonal experiment results was shown in Table 2. The size effect of honeycomb sandwich structure was analyzed. According to the minimum requirements of each indicator, the optimal structural combination parameters were selected.

Table 2
Range analysis of the orthogonal experiment

| | **peak stress (MPa)** | | | | **axial displacement (mm)** | | | | **AP displacement (mm)** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | A | B | C | D | A | B | C | D |
| K1 | 3.818 | 3.677 | 1.253 | 3.405 | 0.0544 | 0.0473 | 0.0190 | 0.0422 | 0.0088 | 0.0095 | 0.0019 | 0.0085 |
| K2 | 3.551 | 3.544 | 3.267 | 3.578 | 0.0628 | 0.0488 | 0.0382 | 0.0484 | 0.0095 | 0.0093 | 0.0064 | 0.0097 |
| K3 | 3.343 | 3.579 | 6.279 | 3.816 | 0.0441 | 0.0519 | 0.0908 | 0.0573 | 0.0088 | 0.0082 | 0.0188 | 0.0088 |
| R | 0.475 | 0.134 | 5.026 | 0.411 | 0.0186 | 0.0046 | 0.0717 | 0.0151 | 0.0006 | 0.0012 | 0.0169 | 0.0011 |

It could be seen from Table 2 that for the peak stress index, the K3 value of the factor A was less than other values, which indicates that when the factor A was at level3, the peak stress was lower than other levels; similarly, the K2 value of the factor B was close to K3, less than other value; for the factor C and D, the K1 value was the minimum, so the level 1 was taken as the optimal level. Considering the peak stress, the optimal geometric parameters combination of the honeycomb sandwich structure was A3 B2/3 C1 D1. For the range R, it could be seen that RC > RA > RD > RB, that was, the factors affecting the peak stress from the primary to the secondary order: were the cell side length, face sheets thickness, honeycomb height, and honeycomb wall thickness.

Similarly, for the axial displacement index, the optimal geometric parameters combination was A3 B1/2 C1 D1. For the range R, it could be seen that RC > RA > RD > RB, that was, the factors affecting the axial displacement index from the primary to the secondary order were cell side length, face sheets thickness, honeycomb height, and honeycomb wall thickness. For the AP displacement index, the optimal geometric parameters combination was A1/3 B3 C1 D1. For the range R, it could be seen that RC > RB > RD > RA, that was, the factors affecting the AP displacement index from the primary to the secondary order were cell side length, honeycomb wall thickness, honeycomb height, and face sheets thickness.

Based on the above analysis, for three indexes of peak stress, axial displacement, and anterior-posterior (AP) displacement, the optimal value the factor A, C, and D were all A3 C1 D1, but the optimal level of the factor B was inconsistent. Therefore, when the other three factors were selected as the optimal level combination, the single-factor five-level test analysis of factor B was conducted. The results were shown in Table 3.

Table 3
Single factor five level test results of bee wall thickness

| **factor B** | **Indexes** | | |
|---|---|---|---|
| | **peak stress (MPa)** | **Axial displacement (mm)** | **AP displacement (mm)** |
| 0.28 | 1.246 | 0.0143 | 0.0015 |
| 0.385 | 1.260 | 0.0138 | 0.0017 |
| 0.49 | 1.141 | 0.0135 | 0.0018 |
| 0.595 | 1.246 | 0.0133 | 0.0020 |
| 0.7 | 1.238 | 0.0131 | 0.0022 |

It could be seen from Table 3 that when the other three factors were the optimal combination, the peak stress reached the minimum as the bee wall thickness was 0.49 mm. With the increase of honeycomb wall thickness, the axial displacement values decreased, and the AP displacement values increased. Considering the three indexes, the wall thickness of 0.49 mm was selected as the optimal value. Through the above analysis, it could be concluded that the optimal parameter combination of honeycomb sandwich structure was A3 B2 C1 D1. The optimal combination of structural geometric parameters of honeycomb sandwich structure was determined as follows: face sheets thickness, honeycomb wall thickness, cell side length and honeycomb height were 1 mm, 0.49 mm, 1 mm and 6 mm respectively. The stress distribution diagram of honeycomb sandwich structure under compression was shown in Fig. 1. The peak stress was 1.141 MPa, and calculate the deformation according to the formula 1. The axial deformation was 0.168%, and the AP deformation was 0.025%.

$$deformation(\%) = \frac{deformation\ displacement}{total\ length} \times 100\%$$

Further, the honeycomb sandwich structure was locally optimized, and the structure of the surrounding edge area lacking support was supplemented. After loading the same load, the stress distribution diagram was shown in Fig. 2.

It could be found from Fig. 2 that after local optimization of the honeycomb sandwich structure, the internal stress distribution was uniform, the maximum peak stress was 1.041 MPa, which was lower than before the structure. It indicated that the peak stress of the structure was reduced through local optimization. The peak position occurred on the edge of the lower face sheet. And the overall axial deformation was 0.111%, and the AP deformation was 0.014%, which were both less than that before the optimization, it showed that the deformation degree of the honeycomb sandwich structure decreased after local optimization. The large deformation and stress concentration can be effectively avoided through local optimization, and the safety of the implant is ensured. Finally, the honeycomb sandwich structure vertebral implant with stable structure and high mechanical performance is designed.

## Discussions

Due to the geometric complexity of the honeycomb structure, the geometric structure can be simplified to clarify the relationship between the equivalent elastic parameters and geometric parameters, and then equivalent elastic parameters are used to describe the mechanical properties of the honeycomb structure [16]. Commonly used geometric parameters are honeycomb wall thickness $t$, cell side length $l$, and honeycomb height $h$. The size effect of the honeycomb structure is divided into in-plane size effect and out-of-plane size effect. The in-plane size effect refers to the influence of the changes of cellular in-plane size on the mechanical properties of the sandwich structure, such as the honeycomb wall thickness and the cell side length, etc. The out-of-plane size effect refers to the effect of changes of the honeycomb height direction size on the mechanical properties of the sandwich structure.

# Influence of the ratio of wall thickness to cell side length on mechanical indexes

According to the Gibson [17] formula and the formula of equivalent elastic modulus of the honeycomb material was re-deduced by Fu Minghui [18] it could be seen that for regular hexagonal honeycomb structure, each equivalent elasticity parameter was only related to the ratio of wall thickness to cell side length of honeycomb. When the face sheets thickness and the height were the optimal geometric parameters, the influence of the ratio of wall thickness to cell side length ($t/l$) on the mechanical properties of honeycomb sandwich structure was analyzed in Table 4.

Table 4
The influence of *t/l* on mechanical indexes

| *t/l* | indexes | | |
|---|---|---|---|
| | peak stress (MPa) | axial displacement (mm) | AP displacement (mm) |
| 0.163 | 5.576 | 0.0710 | 0.0162 |
| 0.245 | 2.908 | 0.0301 | 0.0053 |
| 0.28 | 1.246 | 0.0143 | 0.0015 |
| 0.49 | 1.141 | 0.0135 | 0.0018 |
| 0.7 | 1.232 | 0.0131 | 0.0022 |

It could be seen from Table 4 that with the increase of the ratio of wall thickness to cell side length (*t/l*), the peak stress first decreased and then increased, the axial displacement values decreased; and the AP displacement values first decreased and then increased slowly. The results showed that the mechanical properties of the honeycomb sandwich structure had obvious in-plane size effect. Considering comprehensively, *t/l* of 0.49 was the optimal value, which was consistent with the optimal geometric parameter combination obtained above.

# Influence of ratio of cell side length to height on mechanical indexes

Ma Lianhua et al. [19] have proved that the equivalent elastic parameters of honeycomb sandwich structure are not only related to the structural parameters of the cell, but also to the sandwich height. The experimental results of Pan et al. [20] and M.K. Khan et al. [21] showed that the influence of the honeycomb height on the shear modulus and strength of honeycomb sandwich was significant. When the face sheets thickness and the honeycomb wall thickness were optimal geometric parameters, the influence of the ratio of the cell side length to the height (*l/h*) on the mechanical properties of the honeycomb sandwich structure, was analyzed in Table 5.

Table 5
The influence of *l/h* on mechanical indexes

| *l/h* | indexs | | |
|---|---|---|---|
| | peak stress (MPa) | axial displacement (mm) | AP displacement (mm) |
| 0.083 | 1.243 | 0.0213 | 0.0018 |
| 0.111 | 1.237 | 0.0174 | 0.0018 |
| 0.167 | 1.141 | 0.0135 | 0.0018 |
| 0.333 | 2.908 | 0.0301 | 0.0053 |
| 0.5 | 5.576 | 0.0710 | 0.0162 |

It could be seen from Table 5 that the increase of *l/h*, the peak stress and the axial displacement values first decreased and then increased; and the AP displacement values increased. The results showed that the mechanical properties of honeycomb sandwich structure had obvious out-of-plane size effect. Considering comprehensively, the ratio of cell side length to height (*l/h*) of 0.167 was a better value, which was consistent with the optimal geometric parameter combination obtained above.

By analyzing the influence of the ratio of honeycomb wall thickness to cell side length, cell side length to height on the mechanical properties of the structure, it is helpful to determine the range of geometric parameters in the design of honeycomb sandwich structure implants.

## Conclusions

In this paper, the honeycomb sandwich structure is used as the basic structure of the vertebral implant, using orthogonal test method, the finite element analysis is performed on the size effect of the honeycomb sandwich structure. Based on the minimum requirements of the peak stress, axial displacement, and AP displacement, the optimal geometric parameters are determined, Through the local optimization of implant structure, the honeycomb sandwich vertebral implant with stable structure and good mechanical properties was designed.

1. According to the range analysis of orthogonal test, the factors that affect the peak stress index from primary to secondary order are the cell side length, face sheets thickness, honeycomb height, and honeycomb wall thickness. The factors that affect the axial displacement index from primary to secondary order are the cell side length, sheets thickness, honeycomb height, and wall thickness. The factors that affect the AP displacement index from primary to secondary order are cell side length, wall thickness, honeycomb height, and sheets thickness.
2. Through the analysis of the ratio of the honeycomb wall thickness to the cell side length ($t/l$) and the cell side length to the height ($l/h$), it is found that the mechanical properties of the honeycomb structure have obvious in-plane and out-of-plane size effects. When $t/l$ is 0.49 and $l/h$ is 0.167, the three mechanical indexes are better.
3. According to the comprehensive minimum requirements of the three mechanical indexes of the peak stress, axial displacement, and AP displacement, the optimal geometric parameter combination is determined as the face sheets thickness 1mm, wall thickness 0.49mm, cell side length 1mm, height 6mm. According to this size combination, honeycomb sandwich structure with good mechanical properties is designed. And the peak stress is 1.141MPa, the axial deformation is 0.168%, and the AP deformation is 0.025%.
4. In addition, through local optimization of the structure, the peak stress is further reduced, the overall stress distribution is uniform, and the deformation is reduced. The optimized peak stress decreases to 1.041MPa, the axial deformation is 0.111%, and the AP deformation is 0.014%.

## Methods

The geometric model of 5 × 3 honeycomb sandwich was established using the software SolidWorks. The model was composed of upper and lower face sheets and honeycomb core, as shown in Fig. 3. According to the anatomical size of the lumbar vertebrae and the size of the posterior surgical incision, the orthogonal test was designed with four-factor three-level. Four factors and three level were set as face sheets thickness (factor A), values were 0.8 mm, 0.9 mm, 1 mm; honeycomb wall thickness (factor B), values were 0.28 mm, 0.49 mm, 0.70 mm; Cell side length (factor C), values were 1 mm, 2 mm, 3 mm; honeycomb height (factor D), values were 6 mm, 9 mm, 12 mm.

A three-dimensional finite element model of honeycomb sandwich structure implant was establish using the finite element software ABAQUS. The element type was tetrahedral element C3D10, and the element size of the whole model was 0.25 mm in model. The implant material property was assumed as an isotropic linear elastic material, and the mechanical parameters of the material were the same as cancellous bone. The Elastic modulus was 291 MPa, the Poisson's ratio was 0.25, and the Density was $0.17e^{-09}$ tone/$mm^3$ [22]. The bottom panel of the honeycomb sandwich structure was fixed and constrained, and the load on the upper panel was applied to simulate the load on the upper surface of the L4 lumbar spine when standing on two feet, that is, the upper body weight of the of the human body is 400 N, which the axial compression condition of the honeycomb sandwich structure implant was simulated.

Four-factor three-level orthogonal test was designed to simulate 9 different combinations of structural geometric parameters by finite element method, three indexes of peak stress, axial displacement, and anterior-posterior displacement (AP displacement) of each parameter combination were recorded. The optimal geometric parameters are determined.

The stress distribution diagram (Fig. 1) of honeycomb sandwich structure has been obtained above. It could be found that the peak stress was concentrated at the edge of honeycomb sandwich structure without support. Because the implant design needs to meet the function of supporting the vertebral body and restoring the original height of the vertebral body, the deformation of the implant after loading should be as small as possible. In order to avoid large deformation and reduce stress concentration as far as possible, the honeycomb sandwich structure was locally optimized, and the structure of the surrounding edge area lacking support was supplemented (Fig. 4). The honeycomb sandwich structure vertebral implant with stable structure and high mechanical performance was designed.

(a) the whole structure (b) honeycomb core

# Abbreviations

AP displacement: Anterior-posterior displacement.

# Declarations


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### Authors'contributions

All authors read and approved the final manuscript.


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### Availability of data and materials

Not applicable.

### Ethics approval and consent to participate

Not applicable.

### Consent for publication

Not applicable.

### Competing interests

The authors declare that they have no competing interests.

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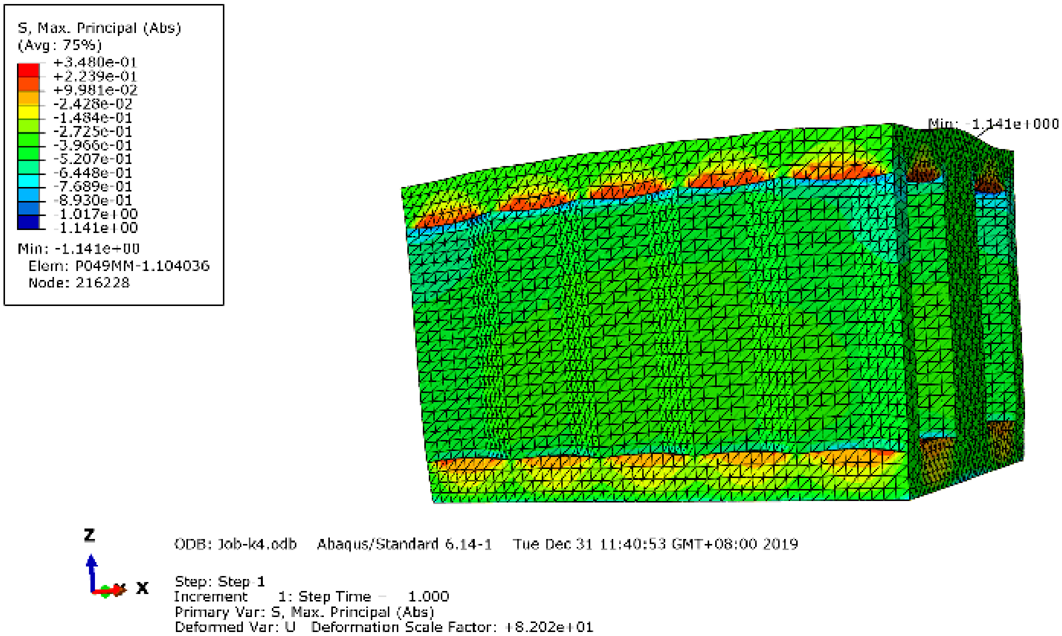
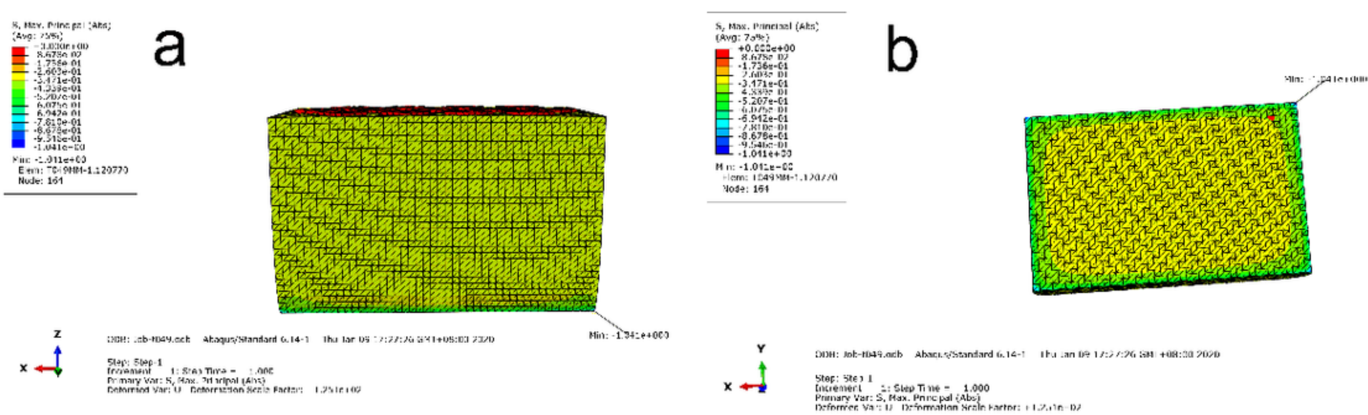
# Figures




## Figure 1

Stress distribution diagram of honeycomb sandwich structure




## Figure 2

Stress distribution diagram of honeycomb sandwich structure with local optimization (a) stress distribution of structure (b) stress distribution of lower face sheet

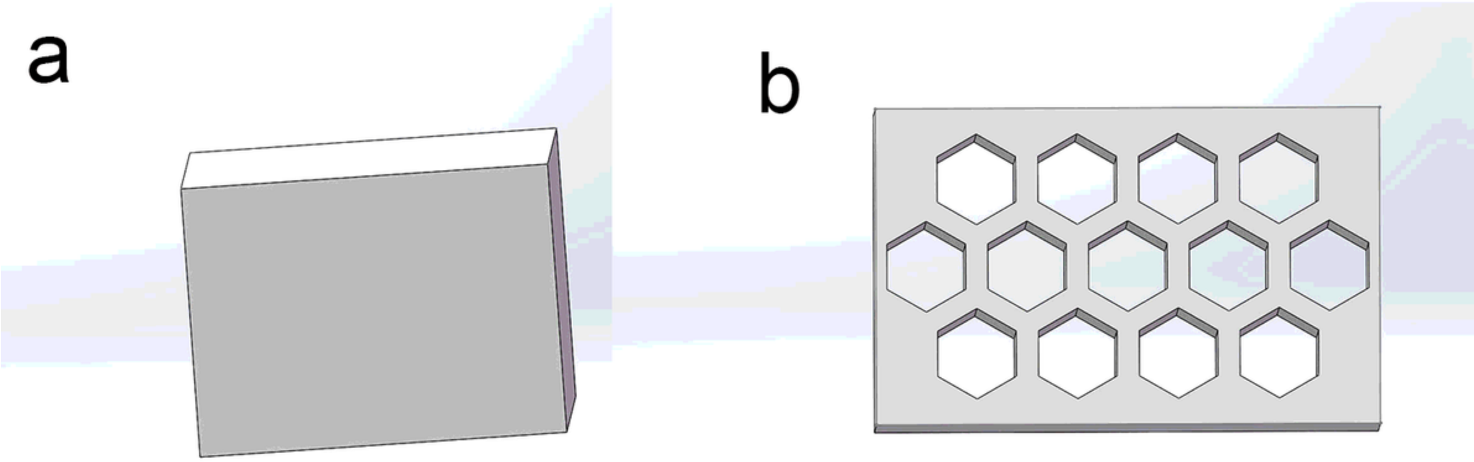



**Figure 3**

The model of honeycomb sandwich structure. (a) honeycomb sandwich (b) honeycomb core

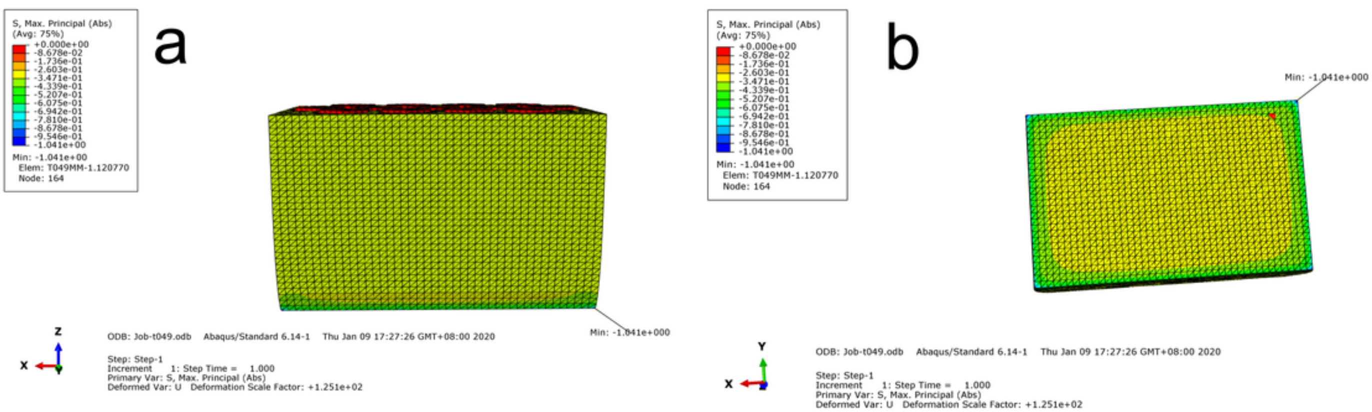



**Figure 4**

The model of honeycomb sandwich structure with local optimization (a) the whole structure (b) honeycomb core