

Study on the Static and Dynamic Performance of Concave Triangular Honeycomb Sandwich Panels

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Abstract: Negative Poisson's ratio (NPR) material perform well in shear resistance, impact resistance, and fracture resistance. In this study, a novel honeycomb sandwich panel is introduced, named Concave Triangular Honeycomb Sandwich Panel (CTHSP), which employs a concave triangle structure with NPR effect as the core layer. The study on the static and dynamic performance of CTHSPs are conducted through numerical simulation. Specifically, the influence of main geometric parameters (single cell size a , core layer thickness t , face-plate core layer thickness ratio h/H , concave angle α) on the bending stiffness, buckling critical load and natural frequency of CTHSPs are studied. Moreover, a new index of specific stiffness is introduced to evaluate the advantages of lightweight and high strength of the sandwich panels. The above research can provide a basis for the selection of CTHSPs in practical application.

Keywords: Concave Triangle, Honeycomb Sandwich Panel, Negative Poisson's Ratio, Buckling Analysis, Free Vibration

1. Introduction

Lakes [1] first obtained a NPR material with special microstructure in 1987, and proved in 1988 [2] that NPR material can reduce the stress concentration coefficient. Since then, many scholars have carried out research on NPR materials. In 1989, Rozvany [3] et al proved that composite materials with specific microstructure characteristics can present NPR. Wan.H [4] et al. studied the influence of geometric parameters of holes on Poisson's ratio, and pointed out that the size of strain was one of the factors affecting Poisson's ratio. The earliest honeycomb NPR material was the chimeric inverted hexagon designed by Gibson and Asbby in 1982 [5-9]. In subsequent studies, different shapes of honeycomb NPR materials were designed. A. Javadi et al. [10] designed some honeycomb structures with NPR characteristics, such as chiral honeycomb, star honeycomb, arrow honeycomb and re-entered hexagonal honeycomb. Gibson et al. [11] designed periodic NPR honeycomb materials with concave hexagonal honeycomb structure, and derived polygonal concave structure, chiral structure and origami structure. Masters and Evans [12] designed a theoretical model to predict the stretch modulus, shear modulus and Poisson's ratio of reentering hexagonal honeycomb. Liu [13] et al. studied the fragmentation mode and energy absorption performance of reentry hexagonal honeycomb by finite element method. Zhang Xinchun et al. [14] studied the in-plane impact characteristics of honeycomb materials with NPR effect, and found that the greater the absolute value of cell expansion Angle was, the higher the plateau stress of honeycomb materials at the impact end was.

Many scholars have proved that NPR materials have excellent mechanical properties, such as extremely high stiffness [15], strong impact resistance [16] and fracture resistance [17-19], which can reduce the stress concentration coefficient [2], control deformation and vibration, and thus improve the stability and durability of the structure. Due to its excellent mechanical properties, NPR materials have been widely used in many fields, such as aerospace. NPR honeycomb structure can be used to make aircraft tail fins [20] and engine blades [21] due to its excellent in-plane carrying capacity. In the medical field, NPR materials are often used to make medical devices such as pulse detectors [22] due to their good torsion-resistance. In the field of ships, negative Poisson ratio materials are mainly used as protective structures such as hull base vibration isolation [23] due to their good stiffness and vibration isolation performance. In the field of civil engineering, NPR materials have also been widely used, because they can reduce the stress concentration coefficient

and other excellent properties, and are often used to produce layered composite panels and beams, which can be smoothed by cold metal forming process [24].

As a lightweight and high-strength material, honeycomb sandwich panels have good energy absorption capacity and exhibit good damping effect under collision and impact loading. Honeycomb sandwich panels have received extensive attention due to their superior material properties, and Wang A J and McDowell [25] studied the compressive strength and stiffness of metal sandwich panels under planar compression. Chi Y [26] et al. studied the mechanical properties of aluminum honeycomb-core circular sandwich plates under air impact load, and concluded that the densations of the core materials can be delayed and the backplane deflection can be reduced by increasing the thickness of the core materials. Wang H [27] et al. used experimental and simulation methods to study the response of sandwich panels with different core materials under medium-speed impact, and analyzed the influence of core materials on the impact response of sandwich panels. Zhang Dahai [28] et al. found that the metal plate honeycomb aluminum sandwich plate has good impact resistance and good energy absorption capacity, and pointed out that the core layer plays an important role in the process of energy absorption.

In recent years, honeycomb sandwich panels have been widely used due to their excellent mechanical properties and are relatively common due to their easy molding. The Navy has applied honeycomb panels to the bulkhead protection structure [29]. In addition, the use of honeycomb sandwich board well meets the requirements of structural quality limitation in aerospace. Many aircraft shell, floor, tail and other structures are made of honeycomb sandwich board. For example, the area of honeycomb sandwich board used in F-111 fighter aircraft accounts for more than 90% of the overall aircraft contour area. The amount of honeycomb sandwich structure on Boeing 747 passenger aircraft is up to 4000m² [30]. In the field of construction, honeycomb sandwich panels are used as structural members of houses or shopping malls because of their excellent bearing capacity; In the field of bridge, honeycomb sandwich plate can be applied to bridge pier anti-collision device or bridge guardrail because of its good performance in impact resistance and vibration absorption.

The core layer of traditional honeycomb sandwich mainly adopts non-negative Poisson's ratio structure such as regular hexagon, triangle, square and diamond. However, with the development of NPR material, many scholars have found that the NPR material as the core layer has better mechanical properties. Qi et al. [31] studied the impact and closed explosion response of reentering hexagonal honeycomb sandwich. It is pointed out that this composite material has more outstanding force limiting and anti-explosion performance compared with the traditional honeycomb sandwich board. Ren X et al. [32] proved that the negative Poisson ratio honeycomb sandwich board has more advantages in energy dissipation and energy absorption than the traditional hexagonal honeycomb core honeycomb sandwich board. However, at present, there are still few studies on the NPR structure honeycomb sandwich board. In this paper, the concave triangular honeycomb with NPR effect is innovatively introduced into the sandwich board, so that it has the excellent performance of both sandwich board and NPR material, hoping to provide a new solution for various engineering and scientific and technological applications. In this paper, the parameters of CTHSPs were analyzed, and the effects of several main geometric parameters (single cell size a , core thickness t , panel core thickness ratio h/H , and concave Angle α) on the buckling stiffness, critical load and natural frequency of honeycomb sandwich panels were studied.

2. Research Content

As shown in Fig. 1, the research object of this paper, the concave triangular honeycomb sandwich board is obtained by the single cell array in the x and y directions, and the single cell is composed of the upper and lower face-plates and the middle honeycomb core layer. For honeycomb sandwich panels, when the shearing action is mainly borne by the core layer, the bending load is mainly borne by the face-plate. Therefore, the face-plate of CTHSP is selected as low carbon steel

material with high strength (density $\rho = 7850 \text{ kg/m}^3$, elastic modulus $E=210 \text{ GPa}$, Poisson ratio $\mu = 0.3$). When the core layer is selected with low strength aluminum alloy material ($\rho = 2700 \text{ kg/m}^3$, $E=70 \text{ GPa}$, $\mu = 0.33$).

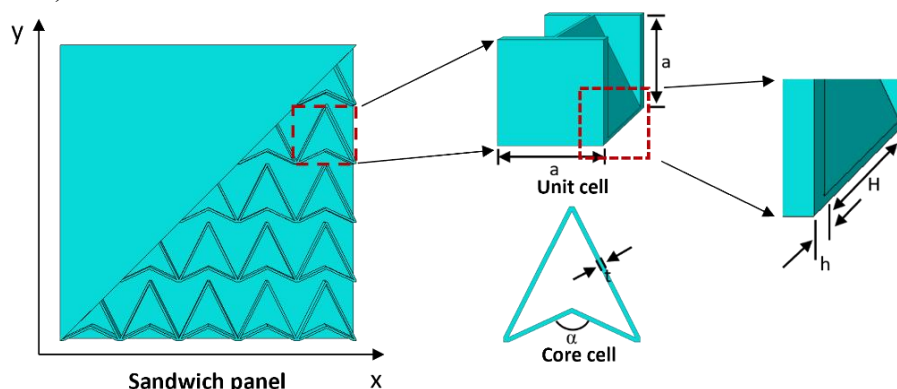


Fig. 1 Single Cell Parameter

As shown in Fig. 1, the single cell side length a , the height ratio r ($r=h/H$) between the face-plate and the core layer, the concave Angle of the inner concave triangle of the core layer α , and the thickness t of the core wall are the most important geometric parameters of the inner concave triangle honeycomb sandwich panel. This study plans to study the relationship between the above parameters and the static and dynamic performance of the sandwich plate. The geometric parameters of the standard cell are set as $a=30 \text{ mm}$, $r=0.125$, $\alpha = 25^\circ$, $t=1 \text{ mm}$, while the parameters of other cells are changed on the basis of the standard cell. The specific changes of parameters are shown in Table 1.

Table 1 Parameter changes of concave triangular honeycomb sandwich plate

	$a \text{ (mm)}$	r	$\alpha \text{ (}^\circ\text{)}$	$t \text{ (mm)}$
a	10	0.125	25	1.4
	20			
	30			
	40			
r	30	0.086	25	1.4
		0.095		
		0.158		
		0.194		
α	30	0.125	15	1.4
			20	
			30	
			35	
t	30	0.125	25	0.6
				0.8
				1.2
				1.4

2.1 Three-point Bending Analysis

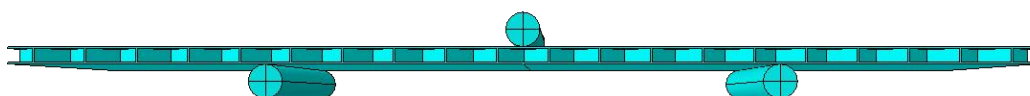


Fig. 2 Schematic diagram of three-point bending loading

Sandwich panels are widely used as flexural members in practical engineering, so it is of great significance to study the flexural behavior of CTHSPs under different parameters. As shown in Fig. 2, this paper uses the finite element software ABAQUS to simulate the three-point bending loading of the concave triangular honeycomb sandwich plate, which is commonly used and simple in

scientific research. The distance between the bottom support and the edge of the sandwich plate on the left and right sides is 150 mm. Based on the principle of control variables, the macroscopic size of the concave triangular honeycomb sandwich board is $600 \text{ mm} \times 300 \text{ mm} \times 10 \text{ mm}$ during the three-point bending analysis. The force-displacement curves of different sandwich plates subjected to bending load are obtained. Prior to the numerical simulations, the mesh convergence analysis has been completed to ensure that the FE models in Section 2.1 three-point bending analysis, Section 2.2 buckling analysis, and Section 2.3 free vibration analysis meet the computational accuracy requirements. For the three-point bending analysis in this section, the grid element type is C3D10, the number of grids is 26130, and the number of nodes is 113336.

2.2 Buckling Analysis

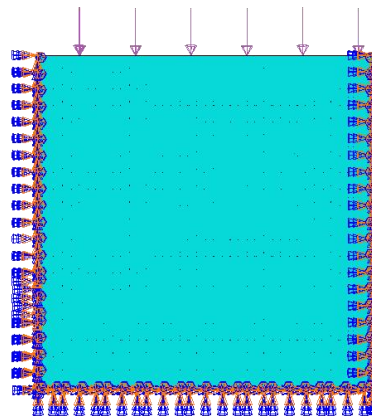


Fig. 3 Plate boundary conditions under buckling analysis

Under the action of in-plane load, the sandwich plate may easily enter the buckling state and then fail, so it is necessary to study the influence law of different geometric parameters on the buckling capacity of concave triangular honeycomb sandwich plate. For the convenience of analysis, the macroscopic size of the uniform concave triangular honeycomb sandwich plate is $600 \text{ mm} \times 600 \text{ mm} \times 10 \text{ mm}$ during buckling analysis and free vibration analysis. The boundary constraints of the plate during the buckling analysis are shown in Fig. 3. The three sides of the concave triangular honeycomb sandwich plate are completely fixed, and uniformly distributed surface loads are applied to the remaining free sides, so that the first eight orders of buckling critical loads and deformation cloud maps corresponding to different sandwich plates are obtained. In buckling analysis, the grid element type is C3D10, the number of grids is 71270, and the number of nodes is 123490.

2.3 Vibration Analysis

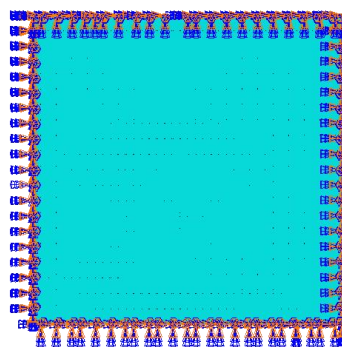


Fig. 4 Plate boundary conditions under free vibration analysis

The free vibration frequency of components is a very important dynamic performance. Considering that the sandwich plate may be subjected to dynamic loads, the variation law of the natural frequency of the concave triangular honeycomb sandwich plate under different geometric parameters is studied. In the free vibration analysis, the four edges of the sandwich are fixed, and

the first eight order natural frequency values and deformation cloud maps of the sandwich under different parameters are obtained. In the free vibration analysis, the grid element type is C3D10, the number of grids is 71270, and the number of nodes is 123490.

3. Results and Analysis

3.1 Three-point Bending Analysis

The force-displacement curves of CTHSPs with different cell sizes (a) under three-point bending load are shown in FIG. 5(a), and the slope of the force-displacement curves can be used as an index to reflect the bending performance of the panels. With the increase of cell size, the bending stiffness of the plate decreases gradually. The increase of cell size means the decrease of the total number of cells. Under the condition that other geometric parameters remain unchanged, the increase of the total volume of core hollowed-out (honeycomb) will inevitably lead to the weakening of the mechanical properties of CTHSPs, that is, the bending performance of the panels will be reduced accordingly. Although the smaller the cell size is, the greater the bending stiffness of the sandwich plate is, the amount of material also increases. Considering the economic factors in the practical engineering application of the sandwich plate, this paper introduces the specific stiffness k/ρ^* (the slope of the force displacement curve of the bending stiffness k , ρ^* is the equivalent density of the plate) as a comprehensive performance index. As shown in FIG. 5(b), the specific stiffness of the panels increases with the increase of the panel size. Therefore, in the practical application of CTHSPs, if the bending stiffness of the sandwich panels is not very high, the sandwich panels with larger element size should be selected as far as possible.

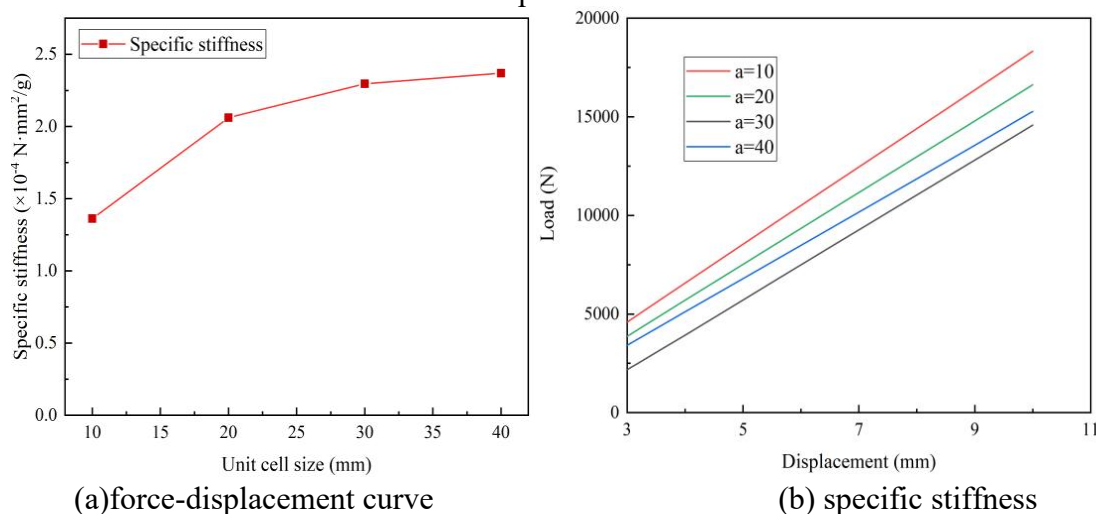


Fig. 5 Three-point bending analysis for different element sizes

Force-displacement curves of CTHSPs with different core thickness (t) under three-point bending load are shown in FIG. 6(a). It can be found that with the increase of the thickness of the core layer, the bending stiffness of the panel increases, and this change also makes the panel tend to be solid. Due to the reduction of the hollow (honeycomb) volume, the mechanical properties will inevitably be enhanced, that is, the bending performance of the panel will be improved accordingly. However, except for the plate with a core thickness of 1.4 mm, the bending stiffness of the other four plates does not change significantly. The specific stiffness changes are shown in FIG. 6(b). When $t < 0.8$ mm, the specific stiffness of the concave triangular honeycomb sandwich plate increases with the increase of the core thickness t , while when $0.8 \text{ mm} < t < 1.2$ mm, the specific stiffness of the plate decreases with the increase of t , and when $t > 1.2$ mm, the specific stiffness of the plate increases with the increase of t . Therefore, in the engineering application, if there is no high requirement for bending rigidity, the core thickness of 0.8 mm or so can be selected to improve the cost-effectiveness.

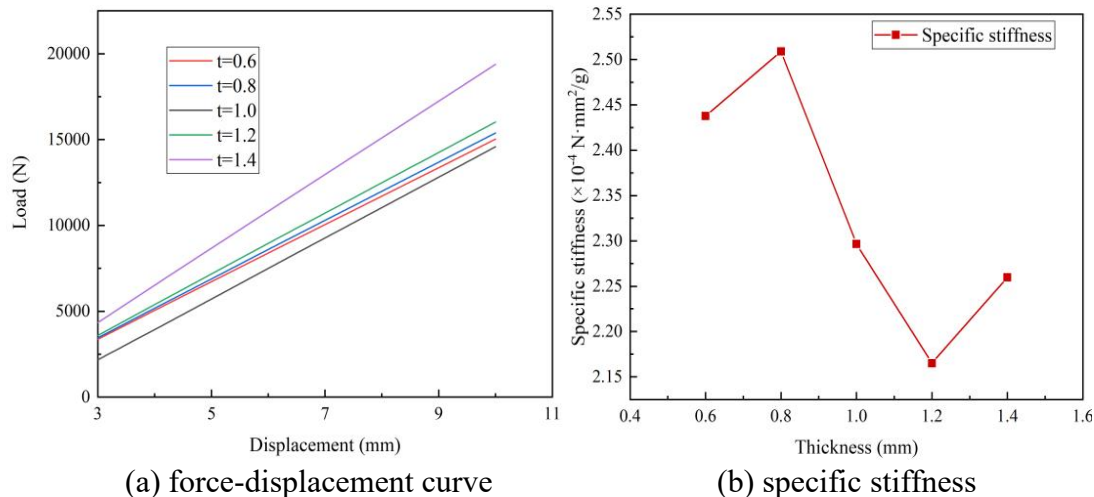


Fig. 6 Three-point bending analysis under different core thickness

While keeping the total height of the sandwich board unchanged, the height ratio of the face-plate to the core layer is changed, so as to obtain the force-displacement curves of the concave triangular honeycomb sandwich board with different height ratios (r) under three-point bending load, as shown in FIG. 7(a). With the increase of the height ratio of the face-plate to the core layer, the bending stiffness of the panel increases. This is because the face-plate is far away from the central axis than the core layer, so the bending moment provided by the face-plate accounts for the main part of the bending rigidity of the plate, and the face-plate material has stronger bending performance than the core material. Therefore, the greater the height ratio of the face-plate core layer is, the greater the height of the face-plate is, the greater the bending moment can be provided, and the higher the bending rigidity of the panel is. The specific stiffness of CTHSPs with different height ratios (r) is shown in FIG. 7(b). When $r < 0.095$, the specific stiffness of the panels decreases with the increase of r ; when $0.095 < r < 0.125$, the specific stiffness of the panels increases with the increase of r ; when $r > 0.125$, The specific stiffness of the plate decreases with the increase of r . Therefore, on the premise that the panels can meet the load-bearing performance requirements, it is recommended to choose CTHSPs with $r = 0.125$ or so to obtain a better cost-effectiveness. It is not recommended to choose the plate with small r , because the poor bending performance is difficult to meet the load-bearing requirements, and it does not have a good cost-effectiveness.

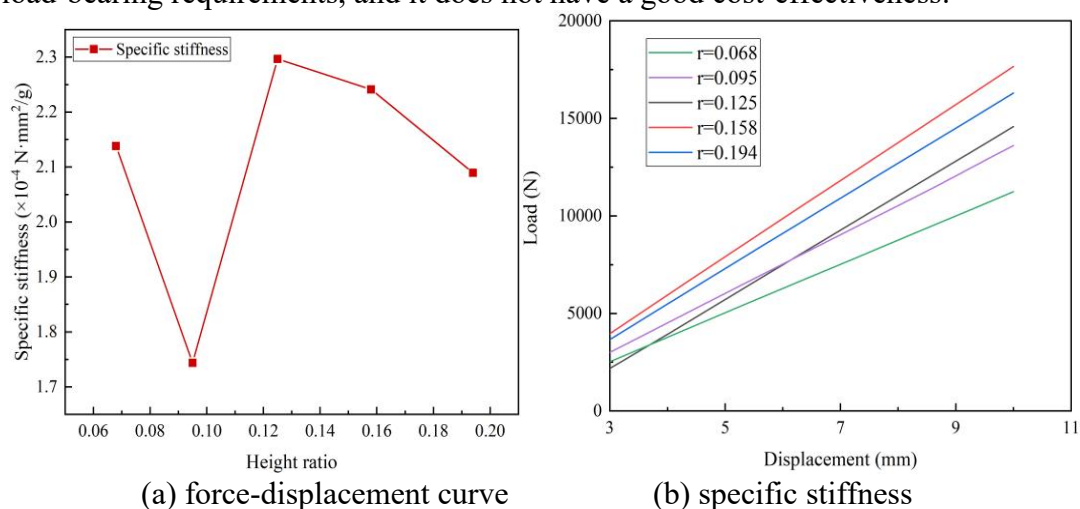
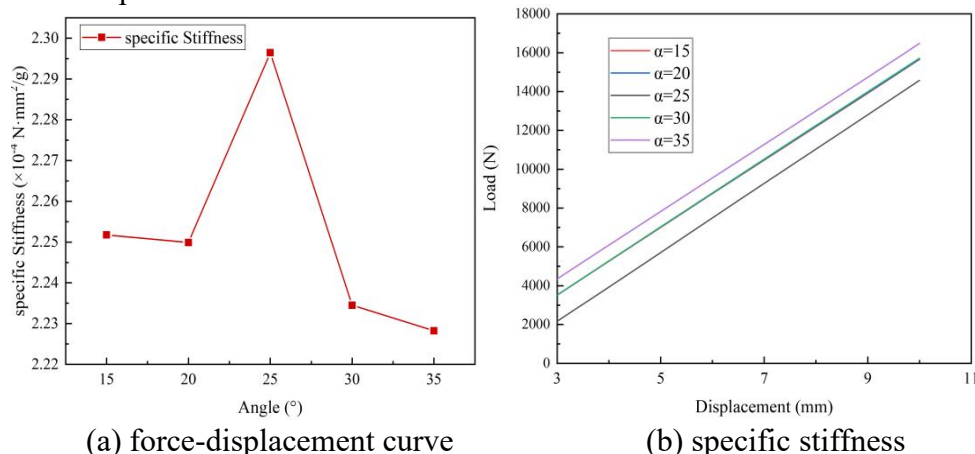


Fig. 7 Three-point bending analysis under different panel core layer height ratios

Force-displacement curves of CTHSPs with different concave angles (α) under three-point bending load are shown in FIG. 8(a). It can be found that with the increase of the concave Angle, the bending stiffness of the panels slightly decreases, but there is no significant change, indicating

that the concave Angle has little influence on the overall bending performance of the panels. The specific stiffness of the plate is shown in FIG. 8(b). The specific stiffness of the plate with an indented Angle of 25° is the highest. Therefore, it is recommended to choose the plate with an indented Angle of about 25° in the practical application of the indented triangular honeycomb sandwich plate to improve the cost-effectiveness.



(a) force-displacement curve (b) specific stiffness
Fig. 8 Analysis of three-point bending under different concave angles

3.2 Buckling analysis

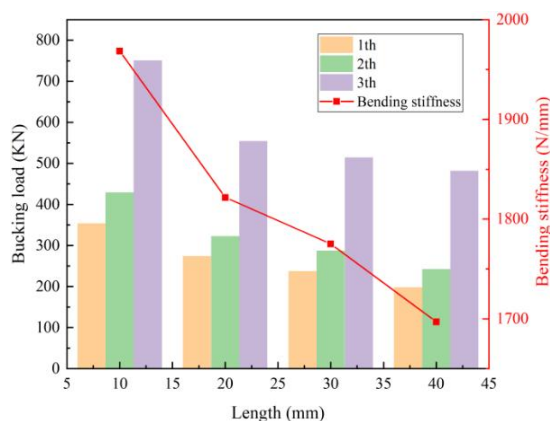


Fig. 9 Buckling analysis under different cell sizes

The buckling critical loads and deformation cloud maps of CTHSPs are obtained through buckling. The variation of the critical buckling load with the single cell size is shown in FIG. 9. With the increase of a , the critical buckling load of the concave triangular honeycomb sandwich plate decreases accordingly. The buckling critical load of the plate is related to the flexural rigidity. The smaller the cell size is, the greater the flexural rigidity of the plate is, and the less likely the out-of-plane instability is to occur when the plate is subjected to in-plane load, that is, the greater the corresponding buckling critical load is. Therefore, when the plate is used to bear in-plane load in practical application, the concave triangular honeycomb sandwich plate with small cell size should be selected as much as possible.

The variation of buckling critical load with core thickness is shown in FIG. 10. With the increase of core thickness (t), the critical buckling load of the concave triangular honeycomb sandwich increases accordingly. The buckling critical load of the plate is related to the bending stiffness. The larger the thickness of the core layer is, the greater the bending stiffness of the plate is, the less prone to out-of-plane instability is, and the greater the buckling critical load is. In the practical application of plates, the plates with large core thickness should be selected as much as possible as far as cost allow.

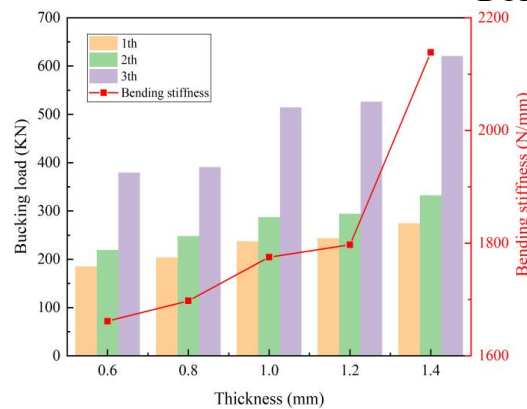


Fig. 10 Buckling analysis under different core thickness

While keeping the total height of the sandwich board unchanged, the height ratio of the face-plate to the core layer is changed to obtain the critical buckling load of the concave triangular honeycomb sandwich board with different height ratio (r), as shown in FIG. 11. With the increase of the height ratio of face-plate core, the buckling critical load of the concave triangular honeycomb sandwich plate increases, and the flexural performance related to the buckling critical load also increases, and the out-of-plane instability is less likely to occur under the in-plane load. Therefore, when the plate is used to bear in-plane load in practical application, the concave triangular honeycomb sandwich plate with large core thickness should be selected as far as possible.

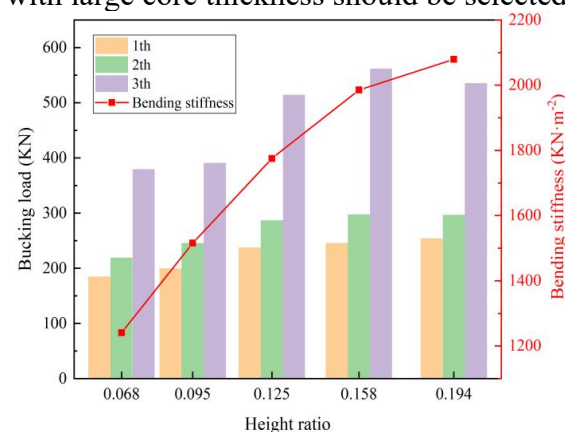


Fig. 11 Buckling analysis under different height ratio of core layer of panel

The variation of buckling critical load with the Angle of incavity is shown in Fig. 12. The buckling critical load of the concave triangular honeycomb sandwich plate satisfies the positive correlation with the bending stiffness, which is consistent with the objective mechanical law, and they all reach the peak when the concave Angle is 25° . Therefore, when the plate is used to bear in-plane load, the plate with an indented Angle of about 25° should be selected.

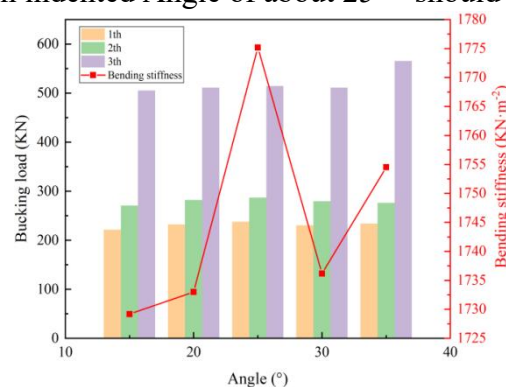


Fig. 12 Buckling analysis under different concave angles

Fig. 13 shows the first five order buckling deformation cloud map of the concave triangular honeycomb sandwich plate. For the sandwich plates with different parameters, the deformation cloud map is similar, the first to third order has one wave peak in the x direction, the fourth to fifth order has two wave peaks in the x direction, in addition to the third order has one wave peak in the y direction, the rest of the fourth order has only half of the wave peak in the y direction. It can be found that when the number of wave peaks in the x and y directions of the cloud map does not change, the deformation region gradually extends to the interior of the plate with the increase of the order, such as the second order compared with the first order, and the fifth order compared with the fourth order. Of course, the deformation of the plate is also related to the boundary constraints of the sandwich plate. The above law is only applicable to the case when the three boundaries are completely fixed and the uniform load is applied to only one free edge.

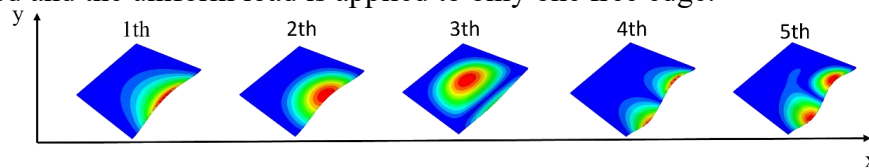


Fig. 13 Deformation cloud maps under flexural analysis

3.3 Free Vibration Analysis

The natural frequencies of CTHSPs are obtained by free vibration analysis. Fig. 14(a) shows the change rule of the natural frequency of the sandwich plate with the single cell size. The natural frequency of the sandwich plate increases with the increase of the single cell size. The natural frequency is positively related to the flexural stiffness of the sandwich and negatively related to the sandwich mass (equivalent density as a proxy for mass). Fig. 14(b) shows the variation law of the bending stiffness and equivalent density of sandwich panels with the single cell size. It can be found that with the increase of the single cell size, the bending stiffness and equivalent density of the panels decrease, which indicates that for CTHSPs with different single cell size, the quality of sandwich panels plays a major role in influencing the natural frequency.

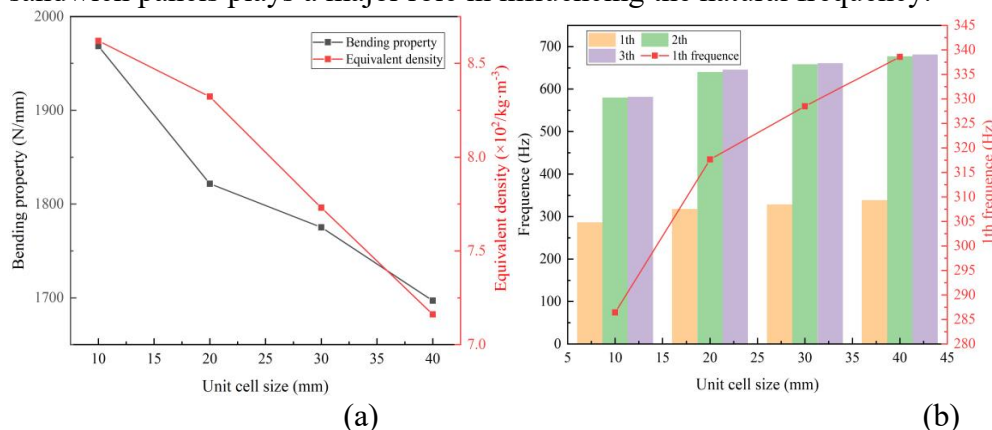


Fig. 14 Free vibration analysis under different core thickness

Fig. 15(a) shows the variation law of the natural frequency of the sandwich plate with the thickness of the core layer. When $t < 1.2$ mm, the natural frequency of the sandwich plate decreases with the increase of the core layer thickness, but when $t > 1.2$ mm, the natural frequency increases with the increase of the core layer thickness. Fig. 15(b) shows the change law of flexural stiffness and equivalent density of sandwich plate with the thickness of core layer. It can be found that as the thickness of core layer increases, the flexural stiffness and equivalent density of plate increase. This indicates that when $t < 1.2$ mm, the quality of sandwich plate plays a major role in influencing the natural frequency, while the flexural stiffness plays a minor role because the increase is less than the equivalent density. However, after $t > 1.2$ mm, the increase of flexural stiffness is significantly

greater than the increase of equivalent density, so the importance of the influence of sandwich plate mass and flexural stiffness on natural frequency is reversed.

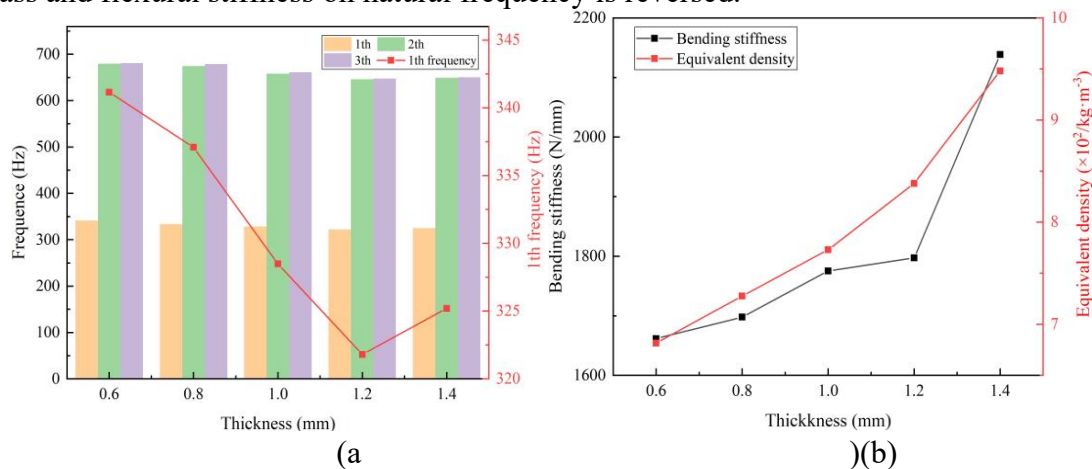


Fig. 15 Free vibration analysis under different core thickness

Fig. 16(a) shows the variation law of natural frequency of sandwich panel with the height ratio of the face-plate to the core layer. When $r < 0.125$, the natural frequency of plate increases with the increase of r , but when $r > 0.125$, the natural frequency of plate decreases with the increase of the r . Fig. 16(b) shows the change law of flexural rigidity and equivalent density of sandwich plate with the height ratio of core layer of face-plate. It can be found that with the increase of r , the flexural rigidity and equivalent density of plate will increase, which indicates that the flexural rigidity plays a major role in affecting the natural frequency when $r < 0.125$. However, when $r > 0.125$, the influence of sandwich plate mass and flexural stiffness on the natural frequency is reversed.

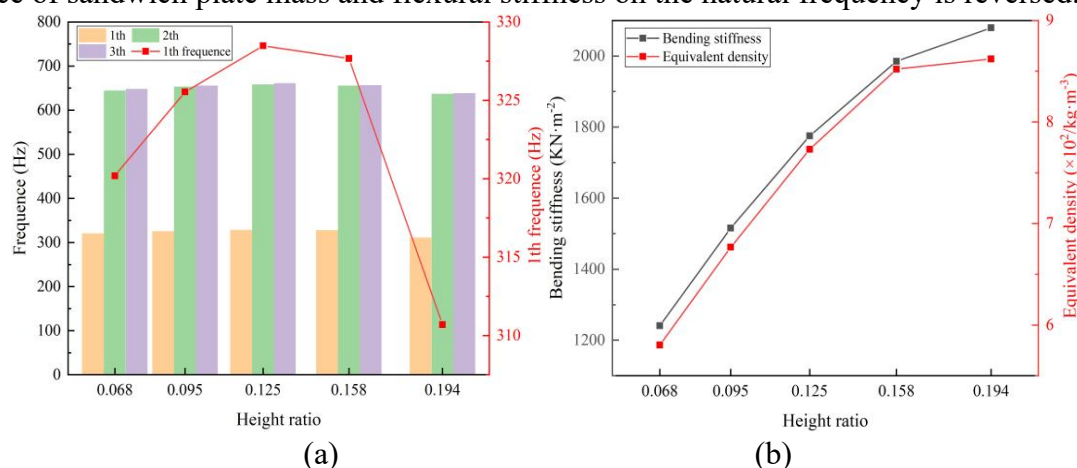


Fig. 16 Free vibration analysis under different panel core layer height ratios

Fig. 17(a) shows the variation of the natural frequency of the sandwich plate with the Angle of the incavity. It can be seen from Fig. 17(a) that the natural frequency of the plate decreases with the increase of the concave Angle. The bending stiffness and equivalent density of sandwich plate with the increase of the concave Angle are shown in Fig. 17(b). It can be found that with the increase of the concave Angle, the equivalent density of sandwich plate increases. When $\alpha < 25^\circ$, the bending stiffness increases with the increase of the concave Angle; when $25^\circ < \alpha < 30^\circ$, the bending stiffness decreases with the increase of the concave Angle; The bending stiffness increases with the increase of the concave Angle, so when $\alpha < 25^\circ$ or $\alpha > 30^\circ$, the mass of the sandwich plate has the main influence on the natural frequency.

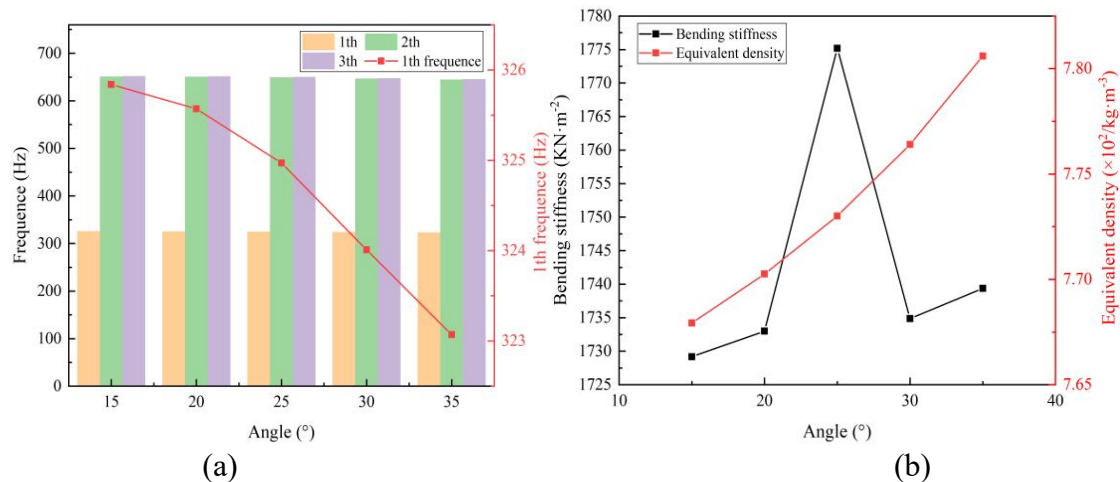


Fig. 17 Analysis of free vibration under different concave angles

Fig. 18 shows the first six order vibration deformation cloud diagram of the concave triangular honeycomb sandwich plate. For the sandwich panels with different parameters, the deformation cloud map is similar, and the deformation at each step is close to the center of the panel. The first order has only one waveform in the x and y directions; The second order has one waveform in the x direction and two waveforms in the y direction; The third order has two waveforms in the x direction and one waveform in the y direction; The fourth and fifth orders have two waveforms in the x and y directions, so there are four waveforms, and the center is symmetric; The sixth order panel has a large deformation in the center, with two small waveforms around it, and they are symmetric left and right.

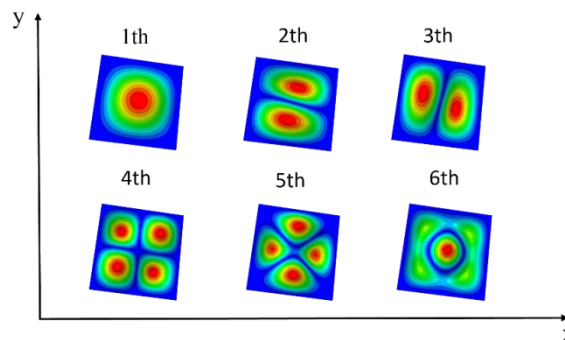


Fig. 18 Deformation curve of standard panel in free vibration analysis

4. Conclusion

This paper mainly studies the static and dynamic properties of CTHSPs. Specifically, the effects of four geometric parameters (a , t , r , α) on the bending stiffness, critical load and natural frequency of the panels are studied. This study lays a foundation for the study of the complex mechanical properties of the concave triangle, and also provides a reference for the selection of the concave triangle honeycomb sandwich plate in practical application. The main conclusions of this paper are as follows:

(1) Through the numerical simulation of three-point bending loading, the influence law of the main geometrical parameters on the flexural performance of the concave triangular honeycomb sandwich plate is obtained. The results show that when a is smaller and t and r are larger, the bending performance of the concave triangular honeycomb sandwich plate is stronger, while the influence of parameter α on the bending performance is not obvious.

(2) This paper proposes a comprehensive index to measure the economic performance of sandwich panels, that is, specific stiffness. The study found that:

With the increase of a , the specific stiffness increases gradually. With the increase of t , the specific stiffness first increases, then decreases and then increases. With the increase of r and α , the

specific stiffness first decreases, then increases and then decreases. It is worth noting that the change rules of specific stiffness and bending stiffness are not completely consistent. Within the scope of this study, the sandwich plate with $t=0.8$ mm, $r=0.125$ and $\alpha=25^\circ$ has the largest specific stiffness, that is, the bending performance of the unit mass material has reached the maximum.

(3)The buckling critical load of concave triangular honeycomb sandwich plate under specific boundary conditions is studied. When a is smaller and t and r are larger, the critical buckling load of the sandwich plate is larger. In addition, the buckling critical load first increases, then decreases and then increases with the increase of α , reaching a maximum value when $\alpha=25^\circ$. The buckling critical load of sandwich plates is positively related to the flexural performance.

(4)For CTHSPs, the larger a is, the smaller α is, and the greater the natural frequency of the panel is. In addition, with the increase of t , the natural frequency first decreases and then increases, reaching a peak at $t=1.2$ mm. With the increase of r , the natural frequency first increases and then decreases, reaching a peak at $r=0.125$. The variation of the above natural frequency depends on the variation of the sandwich board mass and stiffness.

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