



Bending Response of Integrated Multilayer Corrugated Sandwich Panels

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Abstract

In this study, integrated multilayer core corrugated sandwich panels with different shapes of corrugated cores (triangular, trapezoidal, and rectangular) and the different number of core layers were fabricated using 3D printing technology, and the mechanical behavior of such multilayer core corrugated sandwich panels under quasi-static three-point bending was investigated using experiments and numerical simulations. The effects of core shape and number of core layers on the bending deformation process, damage mode, load carrying capacity, and bending energy dissipation capacity of multilayer core sandwich panels are discussed. It is found that the increase of the number of core layers significantly improves the bearing capacity, deformation capacity and energy consumption capacity of the corrugated sandwich. Parametric design of multilayer triangular core corrugated sandwich panels was also carried out by finite element software ABAQUS. It is found that through the combined design of different core shapes, a new type of multi-layer core corrugated sandwich plate with better bending bearing capacity, energy consumption capacity and deformation capacity than the single-core multi-layer core corrugated sandwich plate can be obtained, such as J-S-S, S-J-S, S-S-S-J corrugated sandwich plate with better bearing capacity and deformation performance than S-S-S.

Keywords Multi-layer core corrugated sandwich panel · Three-point bending · 3D printing · Core shape · Number of core layers

1 Introduction

Sandwich structures are widely used in various industries due to their good bending properties, and their lighter mass [1]. Meanwhile, different materials such as foam, Nomex, aluminum alloys, wood, laminated composites, and polymers have been used for the fabrication

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of sandwich structures [1–5], and with the abundance of materials, 3D printing technology has started to be increasingly used for the fabrication and study of a wide variety of sandwich structures [6–10]. Corrugated sandwich panels consist of a corrugated core and upper and lower panels, which have a higher resistance to bending load bearing capacity than the common foam, honeycomb, and lattice core sandwich panels [11]. Corrugated cores possess different shapes, and the common triangular [12], trapezoidal [13], and rectangular cores [14] are widely used because of their simple structure, ease of fabrication, and mass production. In previous studies, the bending properties of corrugated sandwich structures have been extensively studied, and Xia et al. investigated the mechanical response of aluminum corrugated sandwich panels with various core shapes, such as triangular and trapezoidal, under the action of longitudinal three-point bending, and parametrically studied the effects of corrugated core web thickness, length, and corrugation angle on the bending mechanical properties of corrugated sandwich panels, and optimized the design for trapezoidal core corrugated sandwich panels [15]. Atar et al. investigated and compared the bending stiffness and shear stiffness of corrugated sandwich panels including triangular, trapezoidal, and rectangular cores with a single core, and found that triangular and rectangular corrugated sandwich panels have the highest and lowest load carrying capacity, respectively, and the angle of the corrugated core web has a significant effect on the transverse shear stiffness of corrugated sandwich panels [16]. Rubino et al. experimentally investigated the longitudinal bending of sandwich panels with Y-frames and corrugated cores and found that the corrugated sandwich panels with these two core shapes have similar bending mechanical responses under the same boundary conditions [14]. However, for studies related to multilayer corrugated core sandwich panels, Kilicaslan et al. investigated the impact response of multilayer aluminum corrugated core sandwich panels under the action of various tips such as spherical and conical by experiments and simulations. The effects of different impact pin types and corrugated layer orientations on structural deformation and energy absorption were discussed [17]. Hou et al. investigated multilayer corrugated sandwich panels with a different number of layers under quasi-static compressive loading and obtained the failure mechanism and energy absorption capacity of multilayer corrugated sandwich panels with a different number of layers [18]. Cao et al. investigated multilayer corrugated sandwich panels under out-of-plane compression and impact loading and found that the structure has a significant sensitivity to impact rate and this sensitivity can be reproduced by numerical simulation [19]. It can be seen that the studies on multilayer corrugated sandwich panels have mainly focused on the mechanical properties of the structure under quasi-static compression and impact loading, while there are few studies on the mechanical properties of multilayer corrugated sandwich panels under bending loading. Farrokhabadi et al. investigated the mechanical behavior of a new three-layer corrugated core composite sandwich panel under quasi-static three-point bending and discussed the bending damage mechanism of three-layer core corrugated sandwich panels with three core shapes including triangular, trapezoidal, and rectangular [20], but did not investigate the bending behavior of conventional multi-layer core corrugated sandwich panels or discuss the effect of a different number of core layers on the bending performance of the structure.

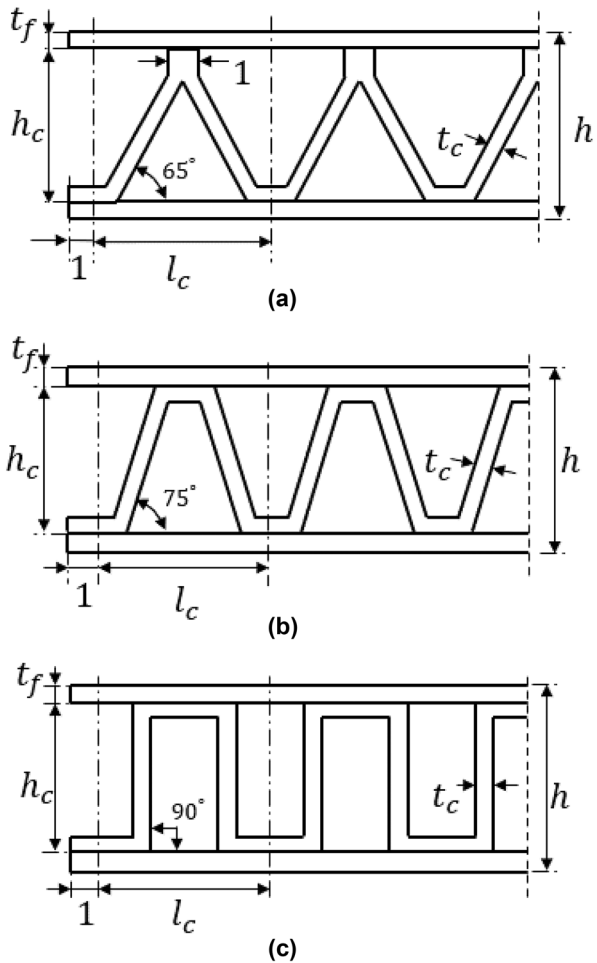
As a multilayer core corrugated sandwich structure with good engineering application prospects, it is often subjected to bending loads in engineering applications. The triangular, trapezoidal and rectangular core corrugated sandwich panels are widely used as corrugated sandwich panels at present. In order to further grasp its mechanical characteristics under bending load, in this study, three types of integrated multi-layer corrugated sandwich panels with core material shapes were manufactured by 3D printing technology, and the tests were carried out under transverse bending load. The number of core layers and core shape were

studied by parameters, and the effects on the deformation and failure mode, peak load and energy absorption of corrugated sandwich panels under transverse bending were also studied. Both peak force and specific energy absorption vary with geometric parameters. At the same time, considering the characteristics of different core shapes, the structure of multi-layer triangular core corrugated sandwich panel was optimized by core shape combination design.

2 Structural Design and Manufacturing

In this paper, three geometric configurations of corrugated sandwich panels with triangular (Fig. 1a), trapezoidal (Fig. 1b), and rectangular (Fig. 1c) cores were designed. For each configuration of corrugated sandwich panels, three types of corrugated sandwich panels with single-layer core, double-layer core, and triple-layer core were designed respectively, totaling nine corrugated sandwich panels (Fig. 2). In order to better study the effect of corrugated core layer and number of layers on the bending mechanical properties of

Fig. 1 Schematic diagram of geometric parameters of corrugated cell of core layer



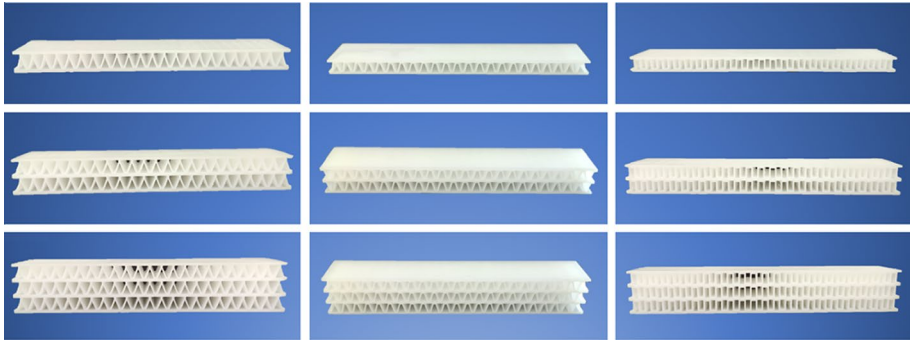


Fig. 2 Sandwich plate samples manufactured with different corrugated core shapes and number of corrugated core layers

corrugated sandwich panels, the overall dimensions of corrugated sandwich panels with different core shapes were controlled. The overall dimensions of all corrugated core panels are 140 mm long, 24 mm wide, and the panel thickness t_f Take 1 mm. Height of all single-layer corrugated core layers h_c and width of single corrugated cell l_c are all 6 mm. There are 23 corrugated cells in the single-layer corrugated core layer, and the cells at both ends of the core layer extend outward for a distance of 1 mm, so that the length of the corrugated core layer is the same as that of the panel (Fig. 1). Various types of corrugated sandwich panels are numbered, for example, S-1 represents single-layer triangular core sandwich panel, T-1 represents single-layer trapezoidal core sandwich panel, J-1 represents single-layer rectangular core sandwich panel, and so on. See Table 1 for specific dimensions.

Considering that at present, the sandwich structure panel and the core layer are mostly bonded or welded into a whole, which not only requires high processing quality, but also easily leads to the failure of the interface peeling structure [21–25]. Therefore, this paper uses 3D printing technology to prepare a corrugated sandwich structure with integrated core and panel. According to the configuration and size of the multi-layer corrugated sandwich board, the 3D modeling software SOLIDWORKS is used to build the model, and then the SLA light curing 3D printer is used for printing and manufacturing. SLA is one of the most widely used printing technologies at present [26]. Compared with other printing technologies (such as FDM [27, 28]), SLA has higher accuracy and printing efficiency.

Table 1 Geometric dimensions of corrugated sandwich panels

Sample	t_f (mm)	t_c (mm)	h(mm)	h_c (mm)	l_c (mm)	θ	Weight(g)
S-1	1	0.6	8	6	6	65	13.68
S-2	1	0.6	15	6	6	65	23.23
S-3	1	0.6	22	6	6	65	32.71
T-1	1	0.6	8	6	6	75	13.62
T-2	1	0.6	15	6	6	75	23.22
T-3	1	0.6	22	6	6	75	33.15
J-1	1	0.6	8	6	6	90	15.39
J-2	1	0.6	15	6	6	90	26.64
J-3	1	0.6	22	6	6	90	37.84

The printer model used in this paper is Z-RUI SLA 880 (Fig. 3), and the printing material used is resin 9400 E ductile material. 9400 E is an ABS like stereo light molding resin with precise and durable properties, which is often used for printing precise and high tenacity structures. According to ASTM D638, the mechanical properties of 9400 E resin are shown in Table 2. SLA printing controls the laser beam to scan on the resin surface to solidify the resin surface. After one layer of curing, a layer of liquid resin is covered on the newly formed layer film, and the scanning continues to make it solidify and combine on the section of the part formed before curing. In this way, it increases layer by layer, thus printing out a complete three-dimensional structure. According to the manufacturer's regulations, the specific printing parameters are as follows: the main laser emission wavelength is 354.7 nm, the layer thickness is 0.1 mm, the laser power is 58 W, and the printing speed is 40 mm/h. In addition, based on the processing technology, in order to increase the contact between the triangular core and the upper panel, the traditional triangular core has been partially modified and designed, as shown in Fig. 1a.

3 Experiment and Results Analysis

3.1 Three-point Bending Test

The bending test of the corrugated sandwich panel was carried out according to ASTM D790 standard by taking the span distance of 90 mm and using MTS electronic universal testing machine with a fixture for displacement loading at a speed of 2 mm/min. where the radius of the circle at the indenter and the support was 4.5 mm. the loading device was shown in Fig. 4, and the mid-span load and the corresponding deflection values were obtained by displacement loading.

Fig. 3 Z-RUI SLA880 type 3d printer



Table 2 Mechanical properties of specimens

parameters	Unit	value
Density	g/cm^3	1.12
Elastic Modulus	MPa	1300
Poisson ratio	–	0.4
Yield stress	MPa	49

3.2 Test Results and Analysis

A total of nine types of corrugated sandwich panels corresponding to the three types of units were subjected to three-point bending displacement loading tests to obtain their corresponding mid-span load-displacement curves. At the same time, to understand the energy dissipation capacity of these corrugated sandwich panels, the respective specific energy absorption (SEA) and displacement curves were extracted from the load-displacement curves. Specific energy absorption is an important parameter to measure the energy absorption capacity of the structure and is the ratio of the total energy (E) absorbed by the structure to the mass (m) during the bending process, where the total energy absorption is the area of the load-displacement curve [29].

$$E = \int_0^d F d \quad (1)$$

Therefore, the specific energy absorption of the structure is

$$SEA = \frac{E}{m} \quad (2)$$

where E is the energy absorbed by the structure when the deformation is d ; F is the bending force; m is the mass of the sample.

3.2.1 The Influence of Different Layers of Corrugated Core

We first studied the effect of corrugated cores of different core shapes on the bending mechanical properties of multilayer sandwich panels, and here we discuss the integrated single-layer corrugated core sandwich panels, double-layer corrugated core sandwich

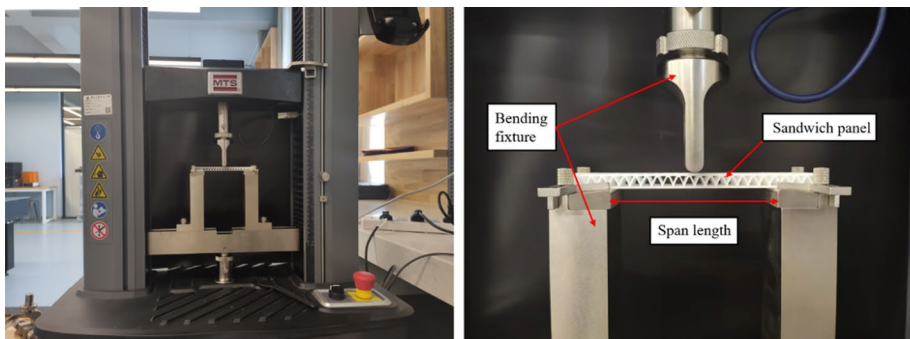


Fig. 4 Setting requirements for quasi-static three-point bending test of corrugated sandwich panel

panels, and triple-layer corrugated core sandwich panels, respectively. We obtain the specific energy absorption of the structure by integrating the mid-span load-displacement curve, and draw the curve of specific energy absorption changing with the mid-span deflection to evaluate the energy absorption capacity of the structure.

For the integrated single-layer core corrugated sandwich panels, it can be seen from Fig. 5a that all three different types of single-layer core corrugated sandwich panels undergo an elastic phase in which the load grows linearly with displacement and then enters the elastoplastic phase. As the displacement continues to load and reaches the ultimate load, the load starts to decrease with the increase of displacement until a fracture occurs and the structure fails. The difference is that due to the effect of the vertical angle of the core cell element webs of the triangular and trapezoidal cores (Fig. 5c, d), the triangular and trapezoidal core sandwich panels exhibit higher bending load capacity compared to the rectangular core corrugated sandwich panels, but at the same time, the vertical angle of these core cell element webs leads to over-concentration of forces on the upper panel near the loading location, while the lower panel is subjected to greater tensile forces and tends to fracture first, resulting in earlier structural failure. In particular, the triangular core sandwich panel, due to its structural influence, although it exhibits higher load-bearing capacity, the upper and lower panels of the structure fail after instantaneous brittle fracture when the displacement loading is small, and the core layer does not show obvious deformation. While the rectangular core (Fig. 5e) due to its core layer vertical angle-vertical force transfer, so that the loading position of the upper and lower panels are relatively uniform force, the core layer inner cell wall also multi-cell bending deformation at the same time, which leads to the overall deformation of the structure, but also make the structure in the three-point bending action can withstand continuous loading, until the core layer vertical support fracture occurred, the structure failural. Also from Fig. 5b, it can be found that in terms of energy dissipation, the

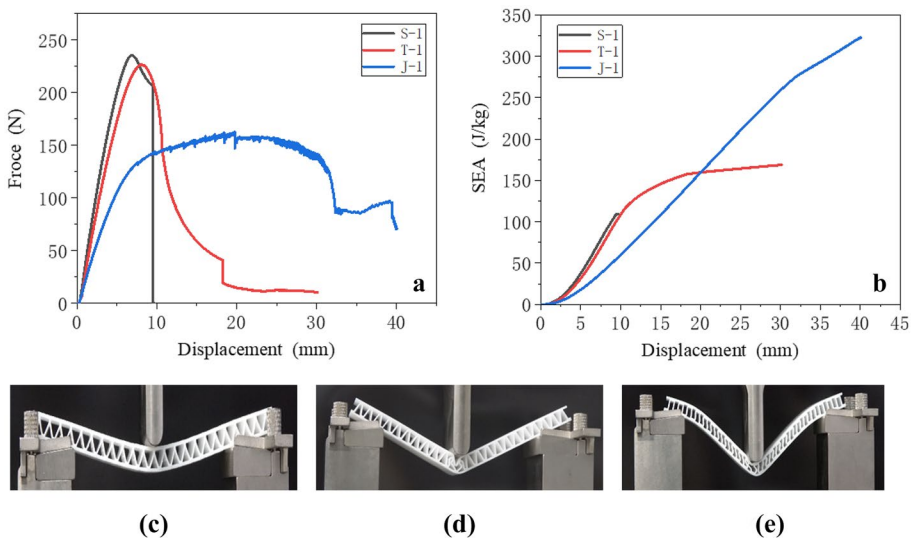


Fig. 5 For single-layer core corrugated sandwich panels with different core shapes: (a) load-displacement curve; (b) SEA - displacement change curve. (c) Triangle core deformation diagram (d) trapezoidal core deformation diagram (e) rectangular core deformation diagram.

triangular and trapezoidal core single-layer corrugated sandwich panels exhibit better bending energy dissipation than the rectangular core corrugated sandwich panels under small displacement loading, especially when the structure is in the relatively elastic phase, while the rectangular core corrugated sandwich panels exhibit better continuous energy dissipation.

As for the integrated double-layer core corrugated sandwich panel, it can be seen from Fig. 6a, b that similar to the single-layer core corrugated sandwich panel, the double-layer triangular core corrugated sandwich panel has better performance both in terms of structure and energy consumption, followed by the double-layer trapezoidal core corrugated sandwich panel and finally the double-layer rectangular core corrugated sandwich panel. The difference is that the double-layer triangular core corrugated sandwich panel (Fig. 6c) has a relatively slow deformation process of the upper core with the increase of displacement after reaching the ultimate load until fracture, when the upper core fractures, the lower core starts to be stressed, at which time the load has a slow rise with the displacement curve, followed by a brittle fracture of the lowermost panel like the single-layer core corrugated sandwich panel, and the structure fails. In the case of a double-layer corrugated sandwich panel with a trapezoidal core (Fig. 6d), the upper core also experienced the process of slow deformation with displacement loading until fracture, during which the lower core did not deform significantly, but with continuous displacement loading, the lower panel of the lower core fractured under tension and the structure failed. Double-layer rectangular core corrugated sandwich panel (Fig. 6e) upper and lower cores bend almost simultaneously with displacement loading in the loading process, and as the displacement of the span position continues to load, shear

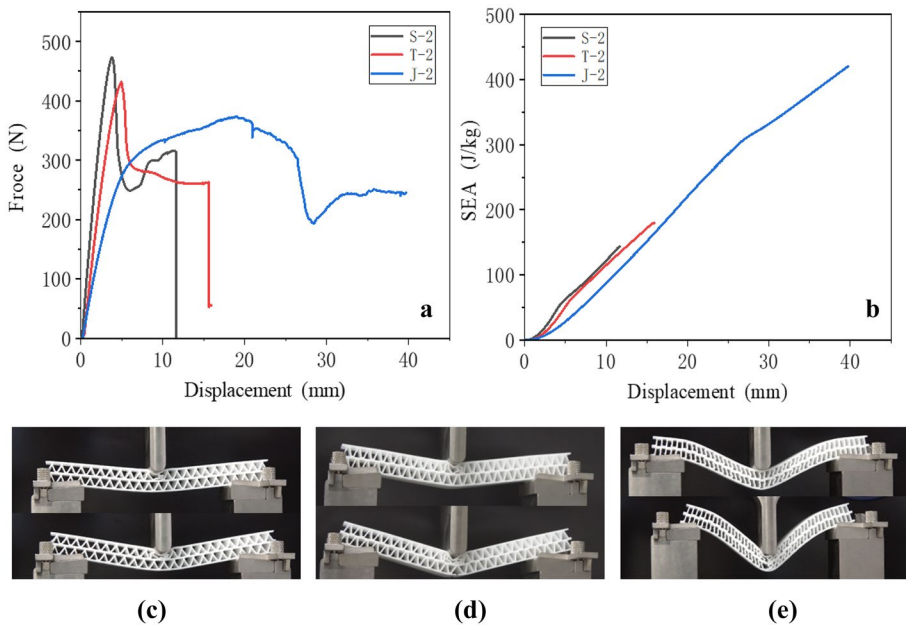


Fig. 6 For double-layer core corrugated sandwich panel with different core shapes: (a) load-displacement curve; (b) SEA - displacement change curve. (c) Triangle core deformation diagram (d) trapezoidal core deformation diagram (e) rectangular core deformation diagram.

damage occurs in the middle panel of the upper and lower cores, and some core units are damaged due to excessive bending deformation, and the structure fails here.

For the integrated three-layer core corrugated sandwich panel, it can be seen from Fig. 7a, b that the triangular core has better bearing capacity and energy dissipation capacity than the single-layer core and double-layer core corrugated sandwich panels, the three-layer trapezoidal core corrugated sandwich panel has better initial bearing capacity and bending energy dissipation capacity under small deflection, followed by the three-layer triangular core corrugated sandwich panel, while the three-layer rectangular core corrugated sandwich panel has the slightly lower bearing capacity and energy dissipation than the other two types of three-layer core corrugated sandwich panels. In the case of displacement loading, the three-layer triangular core corrugated sandwich panel (Fig. 7c) is continuously loaded with displacement, and the uppermost core is firstly deformed and fractured after reaching the peak load, and when the upper core is damaged by compression, the upper core is gradually densified with continuous loading, and the middle core layer starts to be deformed by force, and the load-displacement curve appears to rise for the second time, and even shows higher bending resistance bearing capacity than before the uppermost core is damaged, and then the span displacement continues to be loaded, and the lowermost core's lower panel and upper panel are successively fractured by tension and the structure fails completely. And the deformation with displacement loading to damage mode of the three-layer trapezoidal core sandwich panel (Fig. 7d) is similar to that of the three-layer triangular core sandwich panel, although its secondary peak load is much lower than that of the first. And the deformation of the three-layer rectangular core sandwich panel (Fig. 7e) during

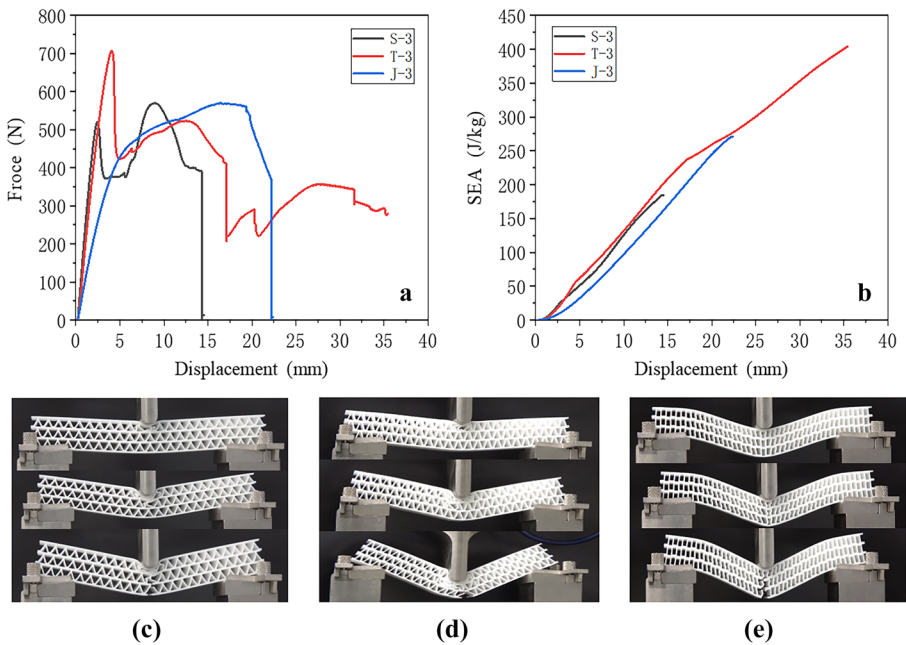


Fig. 7 For three-layer core corrugated sandwich panel with different core shapes: (a) load-displacement curve; (b) SEA - displacement change curve. (c) Triangle core deformation diagram (d) trapezoidal core deformation diagram (e) rectangular core deformation diagram.

displacement loading is similar to that of the single-layer and double-layer rectangular core corrugated panels, in which the bending deformation of the three-layer core occurs almost simultaneously during the displacement increase, and the shear damage occurs in the upper and lower panels of the middle core layer with the continuous increase in displacement loading, followed by the fracture of the lowermost core lower panel and complete structural failure.

By analyzing the multi-layer corrugated sandwich panels with different core shapes, it can be seen from the test results that the existence of the vertical angle of the core shaped cell element web makes the triangular core and trapezoidal core sandwich panels significantly better than the rectangular core corrugated sandwich panels both in terms of structural bearing capacity and energy dissipation capacity, but in the case of larger displacement loading, compared with the triangular core and trapezoidal core corrugated sandwich panels in the displacement of the three-point bending displacement loading process in part of the core layer damage brought about by the load-displacement curve fluctuations, rectangular core corrugated sandwich panels tend to show more stable bending deformation capacity and energy dissipation capacity due to the relative uniformity of the core layer. In addition, compared with the other two configurations of core layers, triangular core corrugated sandwich panels are often the first to reach the first peak load during bending displacement loading, and the structure is often the first to fail. The final failure causes of the multi-layer corrugated sandwich panel structures with different core shapes are also different, among which triangular core and trapezoidal core corrugated sandwich panel structures fail mostly due to tensile fracture of the lower panel, while multi-layer rectangular core corrugated sandwich panel is due to shear damage of the inner panel of the structure.

3.2.2 The Influence of Different Geometric Shapes of Corrugated Cores

This section discusses the effect of the number of core layers on the bending mechanical properties of integrated corrugated sandwich panels and compares the mid-span load-displacement curves and the change in specific energy absorption with displacement curves of corrugated sandwich panel structures with three core shapes for different core layer numbers.

As shown in Fig. 8, the flexural load capacity of the corrugated core sandwich structure increases with the number of core plies regardless of the geometric configuration of the core plies, and the structural energy dissipation capacity also increases with the number of core plies. In addition, in most cases, because of the multi-layer corrugated core sandwich panel in the case of displacement loading upper core force deformation of the lower core often does not have obvious deformation, until the upper core after the destruction of the middle position of the span continues to be compressed tends to dense, the lower core unit will not occur obvious deformation, which makes compared with the single-layer core corrugated sandwich panel, the multi-layer core corrugated sandwich panel in the structure after partial destruction can still maintain a good load-bearing capacity, the structure can often withstand greater deformation. The difference is that multi-layer rectangular core corrugated sandwich panel due to its relatively balanced force transfer between the panel and the core layer, its broken ring often first appears in the structure of the internal core layer between the panel by shear damage, and internal damage will often accelerate the failure of the overall structure, so for the rectangular core corrugated sandwich panel, single-layer rectangular core corrugated sandwich panel deformation capacity is often better than the multi-layer rectangular core corrugated sandwich panel.

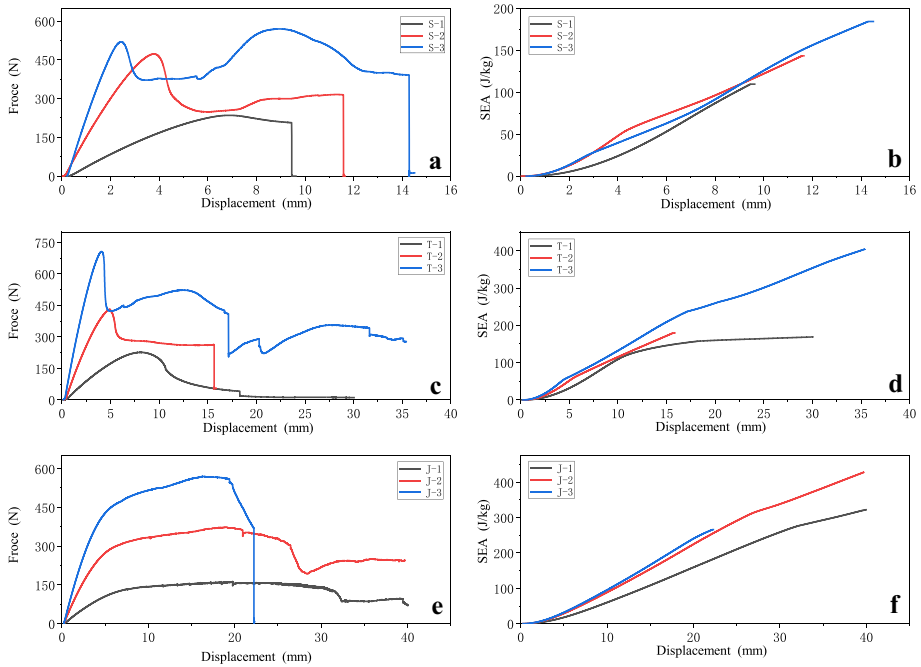


Fig. 8 Variation curves of load and SEA with displacement for multilayer corrugated sandwich panels with different number of core layers

4 Parametric Design of Multi-Layer Triangular Core Corrugated Sandwich Panels Based on ABAQUS

4.1 Destruction Process of Integrated Multi-Layer Triangular Core Corrugated Sandwich Panel

The damage process of integrated multi-layer triangular core corrugated sandwich panels is often manifested as layer-by-layer damage from top to bottom, and the damaged area is mainly concentrated in the mid-span area. The factors affecting the damage of corrugated sandwich panels include flexure, fracture, and breakage of core layer single cell web, and flexure and fracture of the panel. Take the three-layer triangular core corrugated sandwich plate as an example, after the structure is subjected to a three-point bending load, the triangular core single cell directly below the indenter at the uppermost core mid-span position first undergoes bending deformation (Fig. 9a2), with the bending displacement continues to load, the triangular single cell web directly below the indenter fractures, while the triangular single cells at adjacent positions also undergo bending deformation one after another (Fig. 9a3, a4), Then, the webs of the triangular elements of the uppermost core near the indenter are broken successively. The triangular cell loses its load-bearing capacity after the cell web fracture, the compression head invades the corrugated core sandwich plate, and the upper core starts to compact with the invasion of the compression head (Fig. 9a5). In this process, the overall structure of the multi-layer corrugated sheet is slightly bent and deformed, while the structure of the two core layers below does not show significant bending deformation. After the uppermost core fails

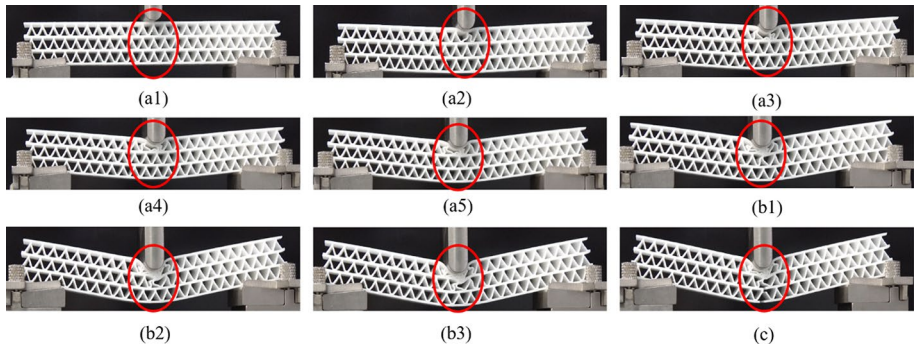


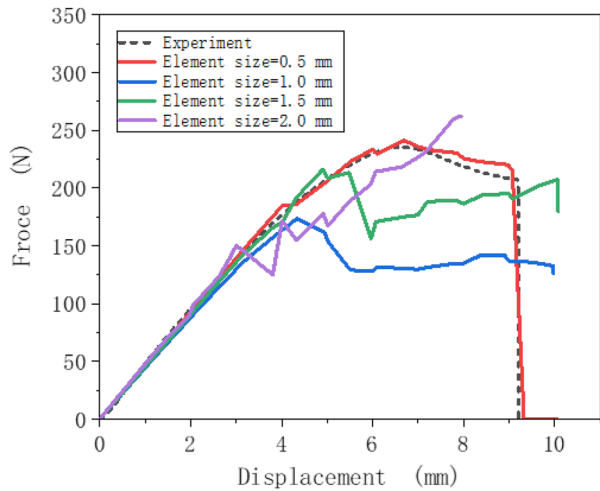
Fig. 9 Failure Process of the integrated three-layer core corrugated sandwich panel under Three-point Bending Test

near the span-center position and tends to be dense under compression, the bending damage process of the three-layer triangular core corrugated sandwich panel is similar to that of the two-layer triangular core corrugated sandwich panel. With the continuous loading of displacement, the triangular single cell wall directly below the second core indenter begins to bend and deform (Fig. 9b1,b2,b3), after which the lowermost core lower panel and upper panel successively yield and fracture under tension (Fig. 9c). Up to this point the structure fails. No major deformation occurred during the whole damage process of the three-layer triangular core corrugated sandwich panel, and the upper panel of the overall structure did not fracture.

4.2 Finite Element Analysis of Multi-Layer Triangular Core Corrugated Sandwich Panels

To better study the bending performance of multilayer core corrugated sandwich panels, this paper uses the finite element software ABAQUS to simulate multilayer triangular core corrugated sandwich panels. To better approach the experimental effect, this paper uses the 3D modeling software SOLIDWORKS for corrugated sandwich panel modeling, after which the ABAQUS program is imported. The material model of resin 9400 E is used for the input parameters of the finite element model. See Table 2 in Section II of the article for the relevant material parameters. To simulate and restore the damage and fracture behavior of corrugated sandwich panels in bending deformation, the model adopts the built-in flexible damage model of ABAQUS, whose ductility criterion is obtained by integrating the MISES, Johnson-Cook, Hill, and Drucker-Prager plasticity models. Since the deformation between the indenter and the support is neglected during the bending process, the rigid body restraint is used to restrain it as a rigid body. To satisfy the quasi-static loading conditions of the simulation as well as to obtain better convergence, the ABAQUS dynamic display solver was used. ABAQUS general contact is used to simulate the contact between the indenter, the support and the panel, the contact between the panel and the core layer, and the possible self-contact of the core layer during the bending process of the sandwich plate. The contact friction coefficient is set to 0.15. To avoid the shear self-locking phenomenon under bending load, an 8-node hexahedral linear reduced integral unit (C3D8R) is used for discretization [30]. Conduct mesh convergence analysis to select appropriate simulation model element size. The results are shown in Fig 10. When the Mesh size is 0.5 mm, the load-displacement curve converges. Therefore, the element size of the simulation model is

Fig. 10 Load-displacement curve of different element sizes



fixed at 0.5 mm. The computer processor used for finite element analysis is AMD Ryzen Threadripper 3970X 32-Core Processor 3.69 GHz, and the RAM is 128GB, which meets the relevant operational requirements. The finite element model is shown in Fig 11.

Through the finite element software, the three-point bending test simulation of the single-layer triangular core corrugated sandwich panel, double-layer triangular core corrugated sandwich panel, and the three-layer triangular core corrugated sandwich panel is carried out respectively, and the load-displacement curve at the midspan is extracted and compared with the load-displacement curve obtained from the test. The results are shown in Fig 11. Through comparison, it can be seen that the finite element can better simulate the bending mechanical properties and damage forms of multilayer corrugated sandwich panels, indicating that it is feasible to study the bending mechanical properties and damage modes of multilayer corrugated sandwich panels by finite element.

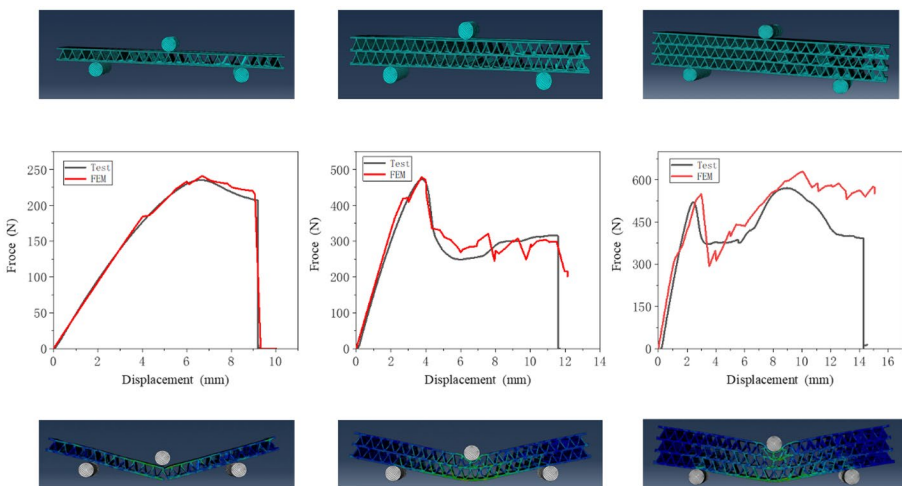


Fig. 11 Finite element model and analytical results of multilayer triangular core corrugated sandwich panels under three-point bending load

4.3 Parametric Design of Multi-layer Triangular Core Corrugated Sandwich Panels

Through the previous study, we found that the triangular core brings excellent flexural load bearing capacity to the multi-layer triangular core corrugated sandwich panel due to its own relatively stable geometric configuration. While the rectangular core is not as stable as the triangular core under bending load, it is the core web is very prone to bending deformation, this feature limits its bending load capacity but greatly enhances the bending deformation capacity of the structure, allowing the structure to maintain the relative stability of the overall structure under large bending deformation, with continuous bending energy dissipation capacity. At the same time, through the analysis of the damage process of multi-layer triangular core corrugated sandwich panels, we found that the triangular core brings excellent load-bearing capacity but limits the overall deformation capacity of multi-layer triangular core corrugated sandwich panels, and its structural damage process is generally layer-by-layer damage. Considering the respective characteristics of the triangular core and rectangular core corrugated sandwich panel, and the characteristics of the multi-layer triangular core corrugated sandwich panel of layer by layer destruction, we consider introducing part of the rectangular core layer inside the multi-layer triangular core corrugated sandwich panel to balance the load bearing capacity and bending deformation capacity of multi-layer triangular core corrugated sandwich panel, hoping to get a new multi-layer core corrugated sandwich panel with high load bearing capacity and continuous bending energy dissipation capacity. Given the above objectives, we reassembled the two-layer triangular core corrugated sandwich panel and the three-layer triangular core corrugated sandwich panel after introducing the rectangular core and simulated the designed new multi-layer core corrugated sandwich panel with three-point bending loading through the finite element software ABAQUS. To distinguish easily, we name multi-layer corrugated sandwich panels by core shape in this section. For example, a double-layer triangular core corrugated sandwich panel is S-S, while S-J-S is a three-layer core corrugated sandwich panel with an uppermost triangular core, middle rectangular core, and lower triangular core.

Firstly, we redesigned the double-layer triangular core corrugated core sandwich panel and designed a double-layer core corrugated sandwich panel with a rectangular core on top and a triangular core on the bottom (J-S type), and a double-layer core corrugated sandwich panel with a triangular core on top and rectangular core on the bottom (S-J type) respectively, as shown in Fig. 12. The initial peak load of the structure, the displacement corresponding to the initial peak load, the maximum deformation before failure of the structure and the specific energy absorption at a mid-span indentation head displacement of 10 mm were extracted to evaluate the load carrying capacity, deformation capacity and bending energy dissipation capacity of the structure, respectively (Table 3). The results of the three-point bending finite element simulation of these two types of bilayer core sandwich panels show that the bilayer core corrugated sandwich panels exhibit different bending properties after the combination of core layers. First of all, J-S corrugated sandwich panel, in the three-point bending process, the upper rectangular core almost bends and deforms simultaneously with the overall structure, while the lower triangular core almost has no obvious bending deformation, resulting in the overall bending deformation of the structure is limited, which makes J-S corrugated sandwich panel, relative to S-S corrugated sandwich panel, show better bending deformation capacity, while relative to J-J corrugated sandwich panel shows higher load-bearing capacity, achieving a better balance of load-bearing capacity and bending deformation. In the process of three-point bending, the upper and lower core layers are deformed simultaneously with the overall

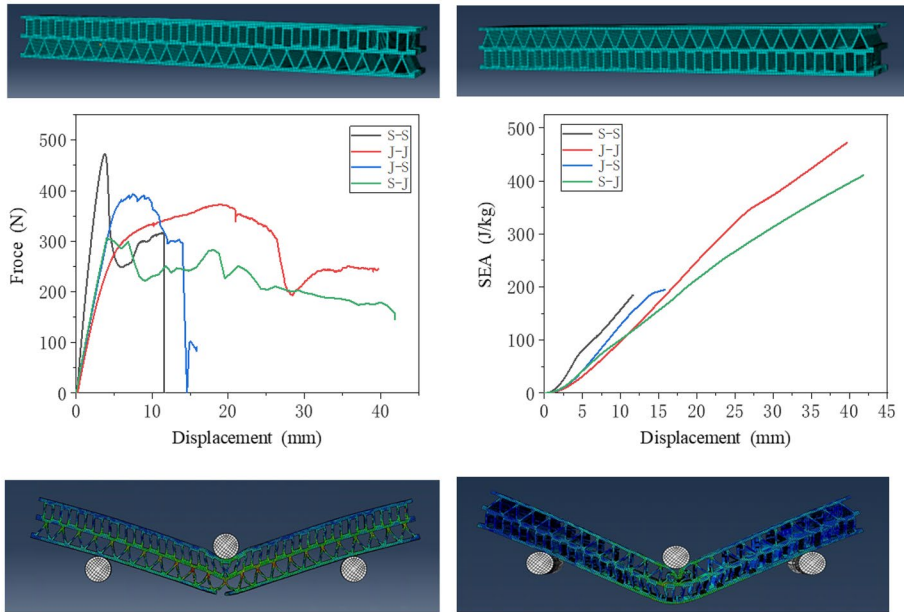


Fig. 12 Model and finite element simulation results of double-layer corrugated sandwich panel with triangular core after the introduction of rectangular core

bending deformation of the structure, and the weaker resistance to deformation of the lower rectangular core leads to faster deformation of the core layer than the upper layer, which makes the overall structure deform rapidly. Although this structure exhibits the same large deformation capacity as the J-J corrugated sandwich panel, the load capacity is much lower than that of the other configurations of double-core corrugated sandwich panels. In terms of bending energy consumption, the bending energy consumption of the J-S corrugated sandwich panel is higher than that of the S-J corrugated sandwich panel under the same deformation conditions, between the highest S-S corrugated sandwich panel and the lowest J-J corrugated sandwich panel. The S-J corrugated sandwich panel also has a similar sustained bending energy dissipation capacity as the J-J corrugated sandwich panel under large deformation.

For three-layer core corrugated sandwich panels, we have designed six types of three-layer core corrugated sandwich panels, including J-J-S, J-S-S, J-S-J, S-S-J, S-J-J, and S-J-S types, in addition to the original S-S-S and J-J-J types. We performed three-point bending finite element simulations of these six types of three-layer corrugated sandwich panels,

Table3 Simulation data of double core corrugated sandwich panel

Sample	Initial peak loading (N)	Displacement corresponding to the initial peak load (mm)	Maximum deformation before failure (mm)	SEA(D=10mm) (J/kg)
S-S	473.003	3.777	11.597	156.641
J-J	373.291	18.977	>35	97.802
J-S	393.189	7.488	13.984	129.409
S-J	306.501	4.044	>35	100.248

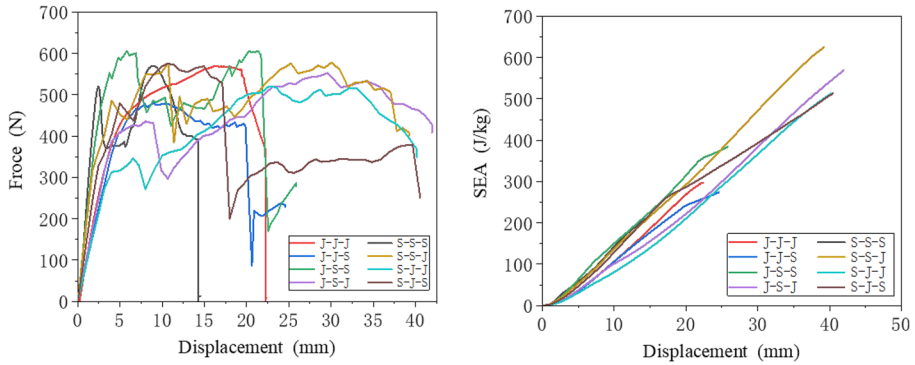


Fig. 13 Finite element simulation results of three-layer corrugated sandwich panel with triangular core after the introduction of rectangular core

and the simulation results are shown in Fig. 13. The initial peak load of the structure, the displacement corresponding to the initial peak load, and the maximum deformation of the structure before failure and the specific energy absorption at a mid-span indentation head displacement of 10 mm were likewise extracted to assess the load carrying capacity, deformation capacity and bending energy dissipation capacity of the structure respectively (Table 4). Through comparison, we can find that the three-layer core corrugated sandwich panels with two triangular cores, including J-S-S, S-S-J, and S-J-S type corrugated sandwich panels, after the introduction of one layer of the rectangular core, not only show better bending load capacity and bending deformation capacity than S-S-S type corrugated sandwich panels, their bending energy dissipation capacity under the same displacement is also close to that of S-S-S type, and the better bending deformation capacity also provides them with continuous bending energy dissipation capacity. Among them, J-S-S corrugated sandwich panel cannot help but show the best initial bearing capacity, and its bending deformation capacity is almost the same as that of J-J-J, while S-S-J and S-J-S have almost the same performance in all aspects, although the bearing capacity is not as good as that of J-S-S corrugated sandwich panel, its deformation capacity is better than that of J-S-S corrugated sandwich panel. The three-layer core corrugated sandwich panels with the introduction of two rectangular cores, including J-J-S, S-J-J, and J-S-J corrugated sandwich panels, are significantly inferior to the three-layer core corrugated sandwich panels of

Table 4 Simulation data of three-layer core corrugated sandwich panel

Sample	Initial peak loading (N)	Displacement corresponding to the initial peak load (mm)	Maximum deformation before failure (mm)	SEA(D=10mm) (J/kg)
S-S-S	519.909	2.451	14.544	142.795
J-J-J	569.870	16.414	22.381	106.531
J-J-S	480.537	8.973	20.627	106.028
J-S-S	606.140	5.838	22.553	149.950
J-S-J	435.624	8.027	>35	100.285
S-S-J	576.297	10.698	>35	134.850
S-J-J	345.788	6.573	>35	80.693
S-J-S	575.131	10.651	>35	126.313

several other configurations in terms of bearing capacity and bending energy dissipation under the same displacement, but their bending deformation capacity is better than that of J-J-J multilayer core corrugated sandwich panels.

We found that the number of layers and the location of the introduced rectangular core have a significant effect on the bending mechanical properties of this new multilayer corrugated sandwich panel by using the finite element software ABAQUS to simulate the three-point bending of the new multilayer corrugated sandwich panel with a rectangular core. For double-layer core corrugated sandwich panels, the upper rectangular core and the lower triangular core corrugated sandwich panels (J-S type) show a more balanced balance of load-bearing capacity and bending deformation capacity. As for the three-layer corrugated sandwich panel, after the introduction of one layer of the rectangular core into the three-layer triangular core corrugated sandwich panel with high bearing capacity, not only the structural bearing capacity becomes larger, but also its structural bending deformation capacity is significantly improved, and when the rectangular core is located in different positions, its bending mechanical properties are also different. And when two layers of rectangular cores are introduced, the structural bearing capacity decreases significantly, while the bending deformation capacity of the overall structure differs between the two layers of rectangular cores with different positions. Therefore, we can optimize the design of multi-layer triangular core corrugated sandwich panels with better load-bearing capacity and poorer bending deformation capacity by introducing some rectangular cores with better bending deformation capacity.

5 Conclusions

In this paper, single-core, double-core, and triple-core corrugated sandwich panels of three configurations including triangular, trapezoidal, and rectangular were manufactured with the help of 3D printing technology. The mechanical properties and damage modes of these multilayer corrugated sandwich panels under transverse bending loads were also investigated by three-point bending tests and ABAQUS finite element simulations, respectively. The change of bending mechanical properties of multilayer triangular core corrugated sandwich panel after adding rectangular core with better bending deformation capacity was also studied by finite element. The following conclusions can be drawn from the study.

1. Multi-layer core corrugated sandwich panel, with the increase in the number of core layers, its flexural bearing capacity will be significantly increased, while its bending deformation and energy dissipation capacity will also be increased.
2. Multilayer triangular core and trapezoidal core corrugated sandwich panels tend to have higher bending bearing capacity and energy consumption capacity under small deformation, while multilayer rectangular core corrugated sandwich panels tend to show more stable bending deformation capacity under large deformation.
3. The failure mode of multi-layer triangular and trapezoidal core corrugated sandwich panels is layer-by-layer failure. After the upper core layer is bended and damaged layer by layer, the lower panel of the lower core layer is yielding and damaged. Therefore, the multi-layer triangular and trapezoidal core corrugated sandwich panels can bear large bending deformation compared with the single-layer core corrugated sandwich panels.
4. The failure of multi-layer rectangular core corrugated sandwich panels often occurs first in the span of the position of the middle core layer of the upper and lower panels shear

damage, followed by the structure of the lowermost core layer of the lower panel yield damage, and then the structure completely failed.

5. After introducing some rectangular core layers into the multilayer triangular core corrugated sandwich panel, some new multilayer corrugated sandwich panels obtained not only improve the bending deformation capacity of the multilayer triangular core corrugated sandwich panel with large deflection, but also improve its bending bearing capacity, and its bending mechanical properties are affected by the position and number of rectangular core layers. For example, for double-core corrugated sandwich panels, the bearing capacity and energy consumption capacity of J-S type are higher than that of J-J type, while the deformation capacity is higher than that of S-S type; For three-layer triangular core corrugated sandwich panels, after introducing a layer of rectangular core, the bearing capacity and deformation capacity of S-J-S, S-S-J and J-S-S corrugated sandwich panels are significantly better than S-S-S.

6 Limitations and application discussion

In this study, the bending mechanical properties of the integrated multi-layer corrugated sandwich panel were studied, but there are still the following limitations:

1. Due to the limitation of manufacturing process, the resin 9400 E material has good toughness, but the processed overall structure still has brittleness, and the research on large deformation of multilayer core corrugated sandwich panel with partial shape core is not friendly.
2. Due to the space limitation, the related fracture energy problems in the bending process will be studied in the future work.
3. The change of the size and style of the indenter and the position of the corrugated core cell corresponding to the indenter during the bending process will have an impact on the failure mode of the corrugated sandwich plate. This is a detailed research direction, which is not studied in this paper due to the limited space, which will be reflected in the future research.

At the same time, this study has potential in some aspects:

1. Compared with single-layer sandwich structure, multi-layer core sandwich structure has excellent bearing capacity, deformation performance and energy absorption performance. Its uncomplicated design can easily be widely used in aviation, aerospace, civil engineering and other related fields.
2. Multi-layer composite core corrugated core sandwich panel provides a new idea for the research of emerging functional sandwich structure. Through the combination design of simple configuration and the combination of its advantages, the effect of $1+1>2$ can be achieved at low cost.

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Availability of Data and Material The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics Approval and Consent to Participate This article does not address ethical issues. the authors confirm that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Conflict of interest The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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