Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 2 August 2022 doi:10.20944/preprints202208.0060.v1

Bending Analysis of Integrated Multilayer Corrugated Sandwich Panel Based on 3D Printing

Wen Dang,[1] Xuan-Ting Liu,[1] and Bo-Hua Sun[1]

[1]*School of Civil Engineering & Institute of Mechanics and Technology*
Xi'an University of Architecture and Technology, Xi'an 710055, China
Corresponding author: email: sunbohua@xauat.edu.cn

Single-layer core corrugated sandwich panels generally consist of a corrugated core and two layers of panels, while multi-layer core corrugated sandwich panels are formed by stacking multiple layers of panels with multiple layers of core layers. 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. Parametric design of multilayer triangular core corrugated sandwich panels was also carried out by finite element software ABAQUS. It was found that a new multilayer corrugated sandwich panel with a multi-layer core is better than the single core shape multilayer corrugated sandwich panel in terms of bending load capacity, energy dissipation capacity and deformation capacity can be obtained through the combination design of different core shapes.

Keywords: Multi-layer core corrugated sandwich panel ,three-point bending , 3D printing , core shape, number of core layers

I. 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 of sandwich structures[1][2][3][4][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][7][8][9][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. In addition, in practice, most the sandwich structures are connected by bonding between two panels and the core layer for the convenience of fabrication, so the interface peeling between the core layer and the panel is the most common failure mode of sandwich structures [21][22][23].

In this study, integrated multilayer core corrugated core sandwich panels with three core shapes were fabricated by 3D printing technology and tested under transverse bending loads. The effects of the number of core layers and core shapes, on the deformation and failure modes, peak loads, and energy absorption of multilayer core corrugated sandwich panels under transverse bending loads were parametrically investigated. Both peak force and specific energy absorption vary with geometric parameters. At the same time, the structure of the multilayer triangular core corrugated sandwich panel was parametrically designed considering its damage pattern.

II. STRUCTURAL DESIGN AND MANUFACTURING

In this paper, three geometric configurations of corrugated sandwich panels with triangular (Figure 1a), trapezoidal (Figure 1b), and rectangular (Figure 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 (Figure 2). The overall size of the structure of the corrugated sandwich panel is 140mm24mmh,and the panel thickness$t_f$core thickness$t_c$core height$h_c$is taken as 1mm,0.6mm,and6mm respectively. Each core layer has 23 units and the length of individual unit$l_c$is 6mm. Numbering for various types of corrugated sandwich panels, such as S-1 for the single-layer triangular core sandwich panel, T-1 for the single-layer trapezoidal core sandwich panel, J-1 for the single-layer rectangular core sandwich panel, and so on, the specific dimensions are shown in Table 1.

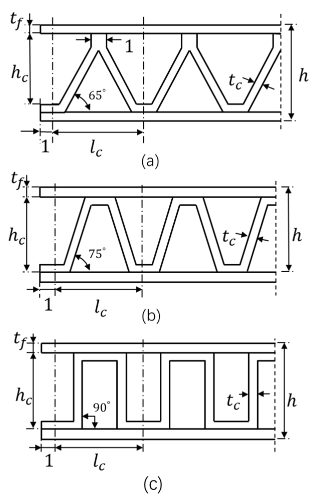

FIG. 1: Corrugated core geometry configuration

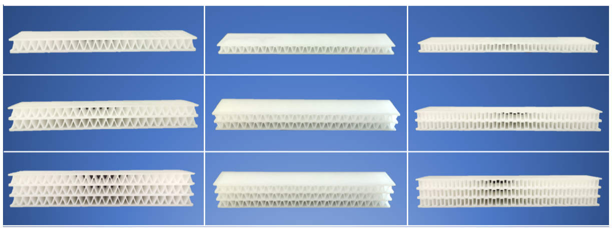

FIG. 2: Multi-layer core corrugated sandwich panel specimens with different core shapes

After determining the configuration and size of the multi-layer corrugated sandwich panel, the 3D modeling software SOLIDWORKS was used to build the model, and then the SLA light-curing 3D printer was used for printing and manufacturing(The printer model used in this paper is Z-RUI SLA880 (Figure 3), and the printing material used is resin 9400E tough material). Corrugated sandwich panels are formed in one piece by 3D printing technology, so the panels of corrugated sandwich panels do not need to be connected to the core layer by adhesives, avoiding structural failure due to interface peeling. Based on the processing process, the conventional triangular core was partially modified in design in order to increase the contact between the triangular core and the upper panel, as shown in Figure 1(a).

FIG. 3: Z-RUI SLA880 type 3d printer

III. EXPERIMENT AND RESULTS ANALYSIS

A. 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.

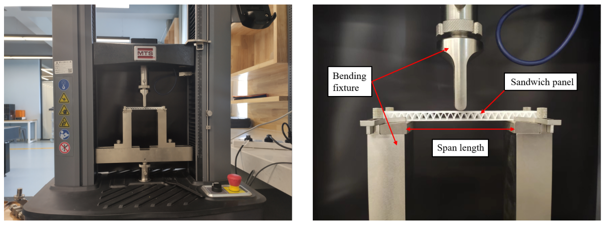

FIG. 4: Corrugated sandwich panel quasi-static three-point bending test

B. 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 (EA) absorbed by the structure to the mass (m) during the bending process, where the total energy absorption is the integral of the indenter load and the applied displacement.

$$EA = \int Fds \tag{1}$$

Therefore, the specific energy absorption of the structure is

$$SEA = \frac{\int Fds}{m} \tag{2}$$

TABLE I: Geometric dimensions of corrugated sandwich panels

Sample	t(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

Where s is the pressure head displacement at mid-span position and F is the pressure head reaction force at mid-span.

1. *Influence of core shape on the bending mechanical properties of multilayer corrugated sandwich panels*

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 panels, and triple-layer corrugated core sandwich panels, respectively.

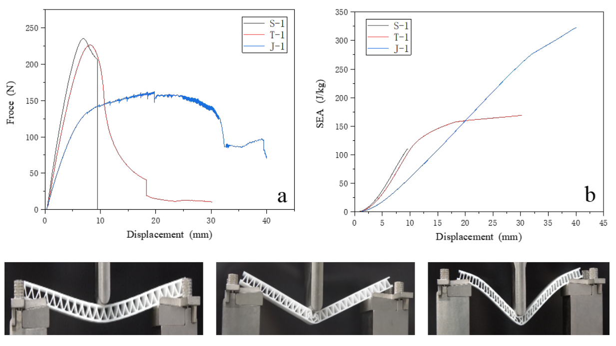

FIG. 5: Load and SEA variation curves with displacement for single-layer core corrugated sandwich panels with different core shapes

For the integrated single-layer core corrugated sandwich panels, it can be seen from Figure 5(a) 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 (Figure 5(c,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 (Figure 5(e)) 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. 5 (b), it can be found that in terms of energy dissipation, the 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 corru-

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 2 August 2022 doi:10.20944/preprints202208.0060.v1

gated sandwich panels exhibit better continuous energy dissipation.

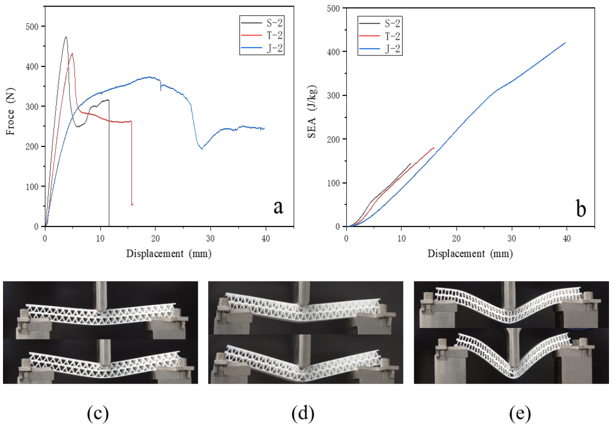

FIG. 6: Variation curves of load and SEA with displacement for corrugated sandwich panels with double cores of different core shapes

As for the integrated double-layer core corrugated sandwich panel, it can be seen from Fig. 6(a,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 (Figure 6 (c)) 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. 6 (d)), 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 (Figure 6 (e)) 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 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.

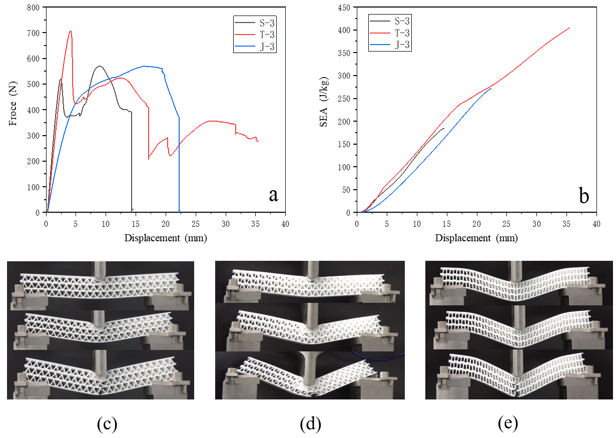

FIG. 7: Load and SEA variation curves with displacement for three-layer core corrugated sandwich panels with different core shapes

For the integrated three-layer core corrugated sandwich panel, it can be seen from Figure 7(a,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 (Figure 7(c)) 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

doi:10.20944/preprints202208.0060.v1

completely.And the deformation with displacement loading to damage mode of the three-layer trapezoidal core sandwich panel (Figure 7 (d)) 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 (Figure 7 (e)) during 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 sheer 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.

2. Effect of the number of core layers on the bending mechanical properties of multilayer corrugated sandwich panels

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.

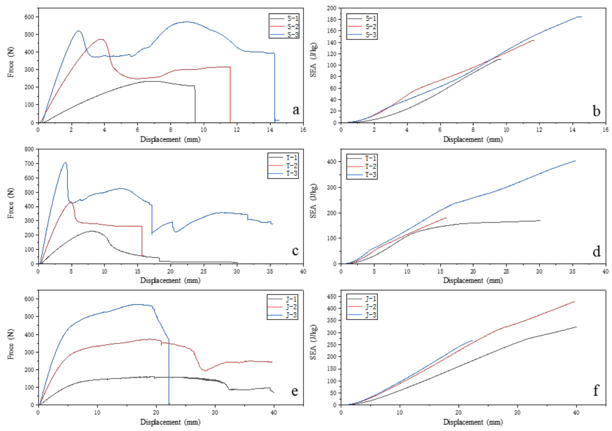

FIG. 8: Variation curves of load and SEA with displacement for multilayer corrugated sandwich panels with different number of core layers

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

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 2 August 2022 doi:10.20944/preprints202208.0060.v1

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.

IV. PARAMETRIC DESIGN OF MULTILAYER TRIANGULAR CORE CORRUGATED SANDWICH PANELS BASED ON ABAQUS

A. Destruction process of integrated multi-layer triangular core corrugated sandwich panel

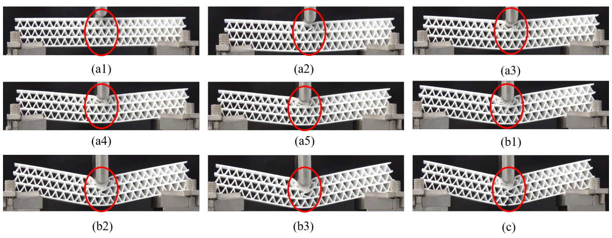

FIG. 9: Three layers of triangular core corrugated sandwich panel destruction process

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 (Figure 9 (a2)), 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 (Figure 9 (a3, 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 (Figure 9(a5)).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 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 (Figure 9(b1-b3)), after which the lowermost core lower panel and upper panel successively yield and fracture under tension (Figure 9(c)), 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.

B. 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 finite element model uses a material with an elastic modulus of 1300 MPa, a density of $1.12g/cm^3$, and a Poisson's ratio of 0.4.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

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 2 August 2022 doi:10.20944/preprints202208.0060.v1

ABAQUS dynamic display solver was used. A friction coefficient of 0.15 is also assumed to simulate the contact behavior between the pressure head support and the corrugated sandwich plate.To avoid the shear self-locking phenomenon under bending load, an 8-node hexahedral linear reduced integral unit (C3D8R) is used for discretization.The mesh size of 0.5 mm was chosen to balance the computational accuracy with the computational cost, so the number of mesh cells of the corrugated sandwich panel ranged from about 100,000 to 200,000. The finite element model is shown in Figure 10.

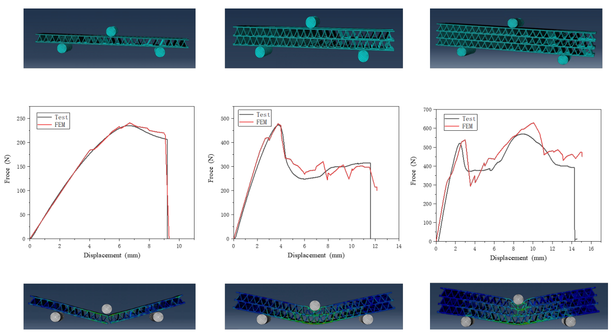

FIG. 10: Finite element model and analytical results of multi-layer triangular core corrugated sandwich panels under three-point bending load

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 Figure 10. 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.

C. 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 thr 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.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 2 August 2022 doi:10.20944/preprints202208.0060.v1

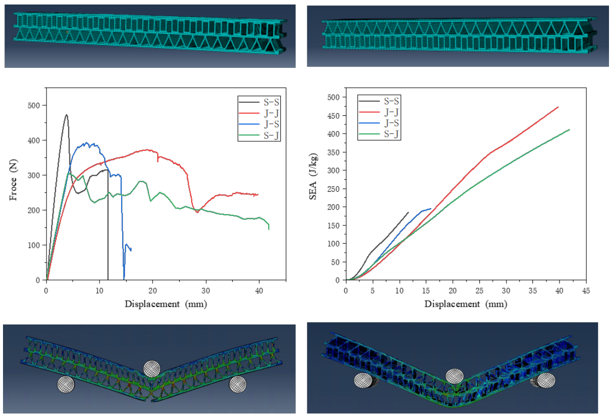

FIG. 11: Model and finite element simulation results of double-layer corrugated sandwich panel with triangular core after the introduction of rectangular core

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 Figure 11. 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 2).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 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.

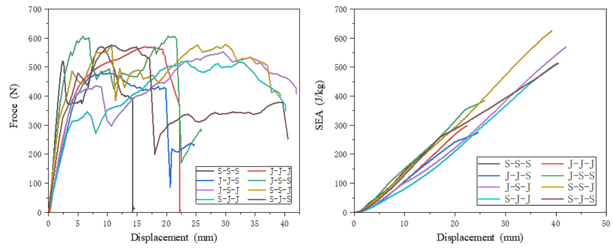

FIG. 12: Finite element simulation results of three-layer corrugated sandwich panel with triangular core after the introduction of rectangular core

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, and the simulation results are shown in Figure 12.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 3).Through comparison, we can find that the three-layer core corrugated sandwich panels with two triangular cores, including J-S-S,

TABLE II: 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

TABLE III: 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	2.4506	14.544	142.795
J-J-J	569.87	16.414	22.381	106.531
J-J-S	480.537	8.973	20.627	106.028
J-S-S	606.14	5.838	22.553	149.95
J-S-J	435.624	8.0267	>35	100.285
S-S-J	576.297	10.698	>35	134.85
S-J-J	345.788	6.573	>35	80.693
S-J-S	575.131	10.651	>35	126.313

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 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.

V. CONCLUSION

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) Among the three core shapes of multilayer core sandwich structures studied, multilayer triangular core and trapezoidal core corrugated sandwich panels tend to have higher bending load carrying capacity and energy dissipation capacity under small deformation, and multilayer rectangular core corrugated sandwich panels tend to show more stable bending deformation capacity under large deformation.

(3) Multi-layer triangular and trapezoidal core corrugated sandwich panel damage mode for layer by layer damage, the damage often occurs first in the uppermost core layer, with the upper core layer by layer bending damage, the lower core layer under the panel yield damage, so multi-layer triangular and trapezoidal core corrugated sandwich panel can withstand greater bending deformation compared to the single-layer core corrugated sandwich panel.

(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 panels, some of the new multilayer corrugated sandwich panels obtained not only improve the bending deformation capacity of multilayer triangular core corrugated sandwich panels under large deflection, but also their flexural bearing capacity is improved, and their bending mechanical properties are affected by the location and number of layers of rectangular core layers.

Acknowledgement This work was supported by Xi'an University of Architecture and Technology (Grant No. 002/2040221134). **Conflict of interest** The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

[1] Birman, V, Kardomateas, GA. Review of current trends in research and applications of sandwich structures. Compos B Eng 2018; 142: 221C240.

[2] Liu, Z, Chen, H, Xing, S. Mechanical performances of metal-polymer sandwich structures with 3D-printed lattice cores subjected to bending load. Arch Civ Mech Eng 2020; 20(3): 368C384.

[3] Kaviani boroujeni, A, Cloutier, A, Rodrigue, D. Low velocity impact behaviour of asymmetric three-layer sandwich composite structures with and without foam core. Polym Polym Compos 2017; 25(5): 381C394.

[4] Mansourinik, M, Taheri-Behrooz, F. The effect of interface debonding on flexural behaviour of composite sandwich beams. J Sandw Struct Mater 2018; 22(4): 1132C1156.

[5] Shahbazi, A, Zeinedini, A. Impact response of e-glass/epoxy composite bi-directional corrugated core sandwich panels. Polym Polym Compos 2020; 29: 1563C1574.

[6] Man Chun, L, Kowalik, M. Preliminary studies for alter-

native lattice core design for FDM 3D printed sandwich panels. Mater Today Proc 2018; 5(13): 26519C26525.

[7] Lubombo, C, Huneault, M. Effect of infill patterns on the mechanical performance of lightweight 3D-printed cellular PLA parts. Mater Today Commun 2018; 17(4): 214C228.

[8] Essassi, K, Rebiere, JL, El Mahi, A, et al. Experimental and analytical investigation of the bending behaviour of 3D-printed bio-based sandwich structures composites with auxetic core under cyclic fatigue tests.Compos A 2020; 131: 105775.

[9] Li, T, Wang, L. Bending behavior of sandwich composite structures with tunable 3D-printed core materials. Compos Struct 2017; 175: 46C57.

[10] Shahkarami M, Zeinedini A. Flexural Properties of 3D-printed hierarchical-sinusoidal corrugated core sandwich panels with natural fiber reinforced skins[J]. Polymers and Polymer Composites, 2022, 30: 09673911221101299.

[11] Rong, Y, Liu, J, Luo, W, et al. Effects of geometric configurations of corrugated cores on the local impact and planar compression of sandwich panels. Compos Part B Eng 2018; 152: 324C335.

[12] Dahiwale N B, Panigrahi S K, Akella K. Numerical analyses of sandwich panels with triangular core subjected to impact loading[J]. Journal of Sandwich Structures & Materials, 2015, 17(3): 238-257.

[13] Zhang P, Liu J, Cheng Y, et al. Dynamic response of metallic trapezoidal corrugated-core sandwich panels subjected to air blast loadingCAn experimental study[J]. Materials & Design (1980-2015), 2015, 65: 221-230.

[14] Rubino V , Deshpande V S , Fleck N A . The three-point bending of Y-frame and corrugated core sandwich beams[J]. International Journal of Mechanical Sciences, 2010, 52(3):485-494.

[15] Xia F, Pang T, Sun G, et al. Longitudinal bending of corrugated sandwich panels with cores of various shapes[J]. Thin-Walled Structures, 2022, 173: 109001.

[16] Abedzade Atar H, Zarrebini M, Hasani H, et al. The effect of core geometry on flexural stiffness and transverse shear rigidity of weight-wise identical corrugated core sandwich panels reinforced with 3D flat spacer knitted fabric[J]. Polymer Composites, 2020, 41(9): 3638-3648.

[17] Kilicaslan C , Gueden M , Odaci I K , et al. The impact responses and the finite element modeling of layered trapezoidal corrugated aluminum core and aluminum sheet interlayer sandwich structures[J]. Materials and Design, 2013, 46(4):121-133.

[18] Hou S, Shu C, Zhao S, et al. Experimental and numerical studies on multi-layered corrugated sandwich panels under crushing loading[J]. Composite Structures, 2015, 126: 371-385.

[19] Cao B T, Hou B, Li Y L, et al. An experimental study on the impact behavior of multilayer sandwich with corrugated cores[J]. International Journal of Solids and Structures, 2017, 109: 33-45.

[20] Farrokhabadi A, Taghizadeh S A, Madadi H, et al. Experimental and numerical analysis of novel multi-layer sandwich panels under three point bending load[J]. Composite Structures, 2020, 250: 112631.

[21] Yu, Y, Ying, L, Hou, W-b, et al. Failure analysis of adhesively bonded steel corrugated sandwich structures under three-point bending. Compos Structures 2018; 184: 256C268.

[22] Du, B, Chen, L, Tan, J, et al. Fabrication and bending behavior of thermoplastic composite curved corrugated sandwich beam with interface enhancement. Int J Mech Sci 2018; 149: 101C111.

[23] Hu Y , Li W , An X , et al. Fabrication and mechanical behaviors of corrugated lattice truss composite sandwich panels[J]. Composites Science and Technology, 2016, 125(Mar.23):114-122.