Quasi-static three-point bending of metallic sandwich panels

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Abstract. Sandwich panels become ideal candidates in industry applications due to their excellent energy absorption ability and light weight. The cellular core of sandwich panels may experience large plastic deformation at an almost constant stress, thus the panel has excellent energy absorption capability. The current paper examines and compares the mechanical performance of sandwich panels with three types of cores (corrugated, honeycomb and lattice truss) under quasi-static three-point bending. Finite element analysis (FEA) was performed in this study and the numerical models of each panel were developed using ABAQUS to predict the deformation mode and the bending response of panels (i.e. force-displacement curve and energy absorption) under three-point bending. Two deformation modes are predicted for all three types of sandwich panels. The honeycomb sandwich panel is expected to have the best energy absorption ability among the three types of sandwich panels with the same relative density. The outcomes of the present study will thereby provide useful information for their applications in industry.

Keywords: sandwich panels; numerical simulation; three-point bending; energy absorption; deformation mode.

1. Introduction
Sandwich panels are hybrid panels, that consist of a low-density core between two skin layers. Compared with their metal counterpart, sandwich panels usually have a much lower density. Due to their excellent energy absorption and lightweight, sandwich panels are widely used in engineering applications such as automobile, aerospace, shipbuilding, and rail [1, 2]. Based on the geometries and topologies of the micro panels, the core of sandwich panels can be classified as those with stochastic cells (open and closed cell foams) and periodic cells (honeycomb, truss, and corrugated core) [3].

Researches have been conducted on sandwich panels with various cores such as corrugated core, honeycomb core and lattice core. There are several shapes of corrugated core, such as triangular, trapezoidal, and curvilinear [4–6]. Corrugated sandwich panel can also be multi-layered [7–9]. Both the layers and configurations influence the mechanical response of panels. Lu et al. [10] firstly proposed four failure types and the failure criteria for the bending of triangular corrugated sandwich. The failure types are face yielding, core yielding, face buckling and core buckling.

The common feature of honeycomb panel geometry is an array of hollow cells formed between thin vertical walls. The geometry varies widely, and mostly commonly used cell shape is hexagonal, columnar [11] and square [12, 13]. A honeycomb panel has low density, relatively high out-of-plane compression strengths and out-of-plane shear strength [14]. The collapse modes of honeycomb sandwich panel under three-point bending test include core shear, face yield, indentation, and face
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wrinkling. The collapse mode changed with the geometric parameters of the sandwich panel and also the span [15–17].

The lattice truss core has several struts each meeting at a node. Unlike corrugated core and honeycomb core, the lattice truss core has fully open interior panel, which facilitates multifunctional applications [18]. The theoretical model of the lattice truss core has been built by many researchers [19, 20].

However, the aforementioned studies only investigated the performance of each individual sandwich panel with a specific core such as metal foam, honeycomb, corrugated core, and truss. The research on the comparison among different sandwich panels subjected to three-point bending is limited. Therefore, in the present study, sandwich panels with three types of cores (corrugated, honeycomb, and lattice truss) under three-point bending will be simulated numerically using ABAQUS. Parametric studies will firstly be conducted on each sandwich panel. Subsequently, the energy absorption of these sandwich panels will be compared.

2. Finite element analysis

ABAQUS/Explicit was used in this study to simulate the three-point bending of the sandwich panels. As shown in Figure 1, the diameters of the indenter and supports are 30 mm and 10 mm respectively. The span of the two supports is 200 mm. The thickness of the face-sheet is 1.6 mm. The material of the face-sheets and core are aluminum 5005 H34. The material properties can be found in the author’s previous study [21] and are listed in Table 1. The corrugated and honeycomb sandwich panels were meshed with four-node shell elements (S4R). For lattice truss sandwich panels, the face-sheets were meshed with shell elements (S4R), and the core was meshed with beam (B31) elements and 3D stress (C3D8R) elements, respectively. The force-displacement curves of the sandwich panels using two mesh methods are shown in Figure 3. The two curves are almost identical. While the computational time of the panel meshed by 3D stress elements was significantly longer than that of the panel meshed by beam elements. Therefore, in the subsequent study, the core of the lattice truss sandwich panel was meshed by beam elements. The indenter and supports were rigid body. General contact was applied in the simulation. The supports were fully fixed and the indenter moved downwards with a constant velocity of 50 mm/s, which could reduce the computational time.

| Property               | Value       |
|------------------------|-------------|
| Density (kg/m³)        | 2700        |
| Poisson’s ratio        | 0.33        |
| Young’s modulus (GPa)  | 65.0        |
| Yield stress (MPa)     | 138.0±7.2   |
| Hardening modulus $E_p$ (GPa) | 0.246       |
| Failure strain         | 0.044-0.057 |

Table 1. Material properties of aluminum 5005 H34 [21].
Figure 1. A sketch of the configuration of the three-point bending simulation.

Figure 2. The FE models of the lattice truss sandwich panels meshed with (a) beam (B31) elements and (b) 3D stress (C3D8R) elements.
3. Results and discussions

3.1 Corrugated sandwich panels

Figure 4 shows the three key parameters of the corrugated sandwich panel, namely core height, $h_c$, corrugation angle, $\theta$, and core thickness, $t_c$. In the parametric study, eight numerical models were developed and are listed in Table 2 (2 different core heights \( \times \) 2 different corrugation angles \( \times \) 2 different core thicknesses). Two deformation types of the corrugated core were observed in the simulation. The first one, which is shown in Figure 5(a), is overall collapse. Models C3 and C8 exhibited this deformation mode in which the whole core is deformed. Figure 5(b) shows the second deformation mode, which is local indentation of the core. The core is only indented in the central area of the panel. The remaining six models display this deformation mode. In Figure 6, when the core is overall crushed, the force increases at first, reaches the peak, and then drops to a trough. Subsequently, the force increases again and plateaus out at a slightly lower force. However, when the core is locally indented, the force decreases gradually and reaches a plateau after the peak force.
Table 2. FE models of corrugated sandwich panels with different geometric parameters.

| Model designation | $h_c$ | $\theta$ | $t_c$ |
|-------------------|-------|----------|-------|
| C1                | 15    | 25°      | 0.6   |
| C2                | 15    | 25°      | 1.0   |
| C3                | 15    | 65°      | 0.6   |
| C4                | 15    | 65°      | 1.0   |
| C5                | 20    | 25°      | 0.6   |
| C6                | 20    | 25°      | 1.0   |
| C7                | 20    | 65°      | 0.6   |
| C8                | 20    | 65°      | 1.0   |

Figure 5. Two deformation modes of the corrugated sandwich panels: (a) overall crushing (Model C5); (b) local indentation (Model C8).
Figure 6. Force-displacement curves of (a) Model C5 and (b) Model C8, respectively. Normalized force is calculated by dividing the force by the width of the panel.
3.2 Honeycomb sandwich panel

The configuration of a honeycomb sandwich panel is shown in Figure 7. The core height, $h_c$, side length of the cell, $l_c$, and cell wall thickness, $t_c$, are the three key geometric parameters for a honeycomb sandwich panel. In the parametric study, the core heights are 15 mm and 20 mm, the side lengths of the cell are 4.0 mm and 7.5 mm, the cell wall thicknesses are 0.05 mm and 0.10 mm, respectively. Totally eight models were developed. In Figure 8, the honeycomb panels also deform in two modes, overall crushing and local indentation, which are the same as that of corrugated panels. The force-displacement curves of corrugated and honeycomb sandwich panels deformed in local indentation mode are similar. While there is no evident peak on the force-displacement curve of honeycomb panels deformed in overall crushing mode. After the first linear increase, the force rises at a slow rate and then decreases gradually. Models H3 and H7 demonstrated overall crushing mode and the remaining models deformed in local indentation mode.

![Figure 7](image_url)

**Figure 7.** A sketch of the configuration of a honeycomb sandwich panel.
| Model designation | \( h_c \) | \( l_c \) | \( t_c \) |
|-------------------|---------|---------|--------|
| H1                | 15      | 4       | 0.05   |
| H2                | 15      | 4       | 0.1    |
| H3                | 15      | 7.5     | 0.05   |
| H4                | 15      | 7.5     | 0.1    |
| H5                | 20      | 4       | 0.05   |
| H6                | 20      | 4       | 0.1    |
| H7                | 20      | 7.5     | 0.05   |
| H8                | 20      | 7.5     | 0.1    |

Table 3. FE models of honeycomb sandwich panels with different geometric parameters.

Figure 8. Two deformation modes of the honeycomb sandwich panels: (a) overall crushing (Model H3); (b) local indentation (Model H2).
Figure 9. Force-displacement curves of (a) Model H3 and (b) Model H2. Normalized force is calculated by dividing the force by the panel width.

3.3 Lattice truss sandwich panel.
Figure 10 shows a sketch of the configuration of a lattice truss sandwich panel. The unit cell of the core is of pyramidal shape, and the angle between the truss and face-sheet is fixed to be 45°. Therefore, the key geometric parameters are only the core height, $h_c$, and the diameter of the truss cross section, $d_c$. Table 4 shows the parameters of the four FE models in the parametric study. The deformation modes of the lattice truss core can also be classified as overall collapse and local indentation. Figure 11 shows the progressive collapse of Model T1, which deformed in overall collapse mode. In Figure 11(a), the trusses near the centre of the core are bent, which leads to the first plummet of the force after the peak (Figure 13a). With the drop of the indenter, most of the trusses are bent (Figure 11b) and the force plummets again at an indenter displacement of 10 mm (Figure 13b). The deformation and force-displacement curve of the lattice truss panels deformed in local indentation are similar to those of corrugated and honeycomb panels. Models T1 and T3 exhibit overall crushing mode and Models T2 and T4 display local indentation.
Figure 10. A sketch of the configuration of a lattice truss sandwich panel.

Table 4. Lattice truss sandwich models with different geometric parameters.

| Model designation | $h_c$ | $d_c$ |
|-------------------|-------|-------|
| T1                | 15    | 1     |
| T2                | 15    | 2     |
| T3                | 20    | 1     |
| T4                | 20    | 2     |

Figure 11. Progressive collapse of the Model T1, which is in overall collapse deformation mode: (a) only the trusses near the centre are bent, (b) most of the trusses are bent.
Figure 12. Model T2 is deforming in local indentation mode.

Figure 13. Force-displacement curves of (a) Model T1 (the force is smoothed due to the dramatic fluctuation) and (b) Model T2. Normalized force is calculated by dividing the force by the panel width.
4. Specific energy absorption
The specific energy absorption (SEA) is calculated by dividing the energy absorption by the specimen mass. In this study, the energy absorption is determined as the area under the force–displacement curves when the indenter displacement is from 0 to 40 mm. The specimen mass is calculated using the dimensions of the specimen between the two supports.

The relative density of the corrugated core is:
\[
\tilde{\rho}_c = \frac{t_c}{h_c \cos \theta}
\] (1)

The relative density of the honeycomb core is:
\[
\tilde{\rho}_h = \frac{2t_c}{\sqrt{3}l_c}
\] (2)

The relative density of the lattice truss core is:
\[
\tilde{\rho}_l = \frac{\pi d_c^2}{\sqrt{2}h_c^2}
\] (3)

Figure 14 shows the SEA versus core relative density of the three types of sandwich panels. The honeycomb and truss cores in this study have lower relative densities (less than 0.03), while the relative densities of the corrugated sandwich panels are greater than 0.03. When the relative density are the same (for example, relative density \(\approx 0.03\)), the honeycomb sandwich panel has the highest SEA, followed by the lattice truss sandwich panel, and corrugated sandwich panel’s SEA is the lowest. For all three types of sandwich panels, the SEA of each type of sandwich panels increases with the increase of their relative density.

5. Conclusions
In this study, parametric studies have been conducted for corrugated, honeycomb, and lattice truss sandwich panels. A comparison in terms of the specific energy absorption is subsequently carried out to evaluate the performance of three sandwich panels. Within the parameter range studied, the following conclusions are drawn:

1. Two deformation modes have been observed in all three sandwich panels, namely overall collapse and local indentation. The panels with weak core tend to deform in overall collapse mode.
2. The force-displacement curves of all three sandwich panels in local indentation have similar trend - force firstly increases linearly, reaches the peak, and then drops gradually. The force-displacement curves of sandwich panels in overall collapse differ with the type of core.

3. When the relative densities are the same, the honeycomb sandwich panel has the highest specific energy absorption.

4. Specific energy absorption increases with the increase of the relative density of core for all three sandwich panels.

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