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Dynamic behavior of aluminum honeycomb sandwich panels under air blast: Experiment and numerical analysis

Xin Li, Peiwen Zhang, Zhihua Wang*, Guiying Wu, Longmao Zhao

Institute of Applied Mechanics and Biomedical Engineering, Taiyuan University of Technology, Taiyuan 030024, PR China

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ABSTRACT

This paper presents a blast experiment to investigate the blast-resistance of square sandwich panels with hexagon aluminum honeycomb cores. Different heights and cell side length s for honeycomb core were considered in the experiment. The impulse loading on the panel was calculated by using the displacement history of ballistic pendulum. The interaction between the shockwave and panel, as well as the deformation/failure modes of face sheet and core, were discussed. Finite-element simulation was also conducted to investigate the dynamic response of the sandwich panel. The simulation captured most of the details of the deformation patterns. The velocity, displacement, strain history and energy absorption of the sandwich panel was analyzed.

1. Introduction

Sandwich structures, which can dissipate considerable energy by large plastic deformation under impact/blast loading, have extensively applied in a wide range of fields, including aerospace, marine and railway engineering [1,2]. Therefore, many researchers have focused on the dynamic mechanical behavior of such structures, particularly in the last decade. Fleck and Deshpande [3] first developed a rigid–plastic model to analyze the blast resistance of clamped sandwich beams. In their theory, the response of sandwich plate and beam can be split into three stages: Fluid–Structure Interaction, Core Compression and Structural Dynamic Response. This model was extended for clamped circular and square sandwich plates by Qiu et al. [4] and Zhu et al. [5], respectively. A number of simulations were also performed to investigate the responses of sandwich panels under shocks [6–11]. For example, Xue and Hutchinson [6] compared the performance of metal sandwich plates under impulsive blast loads with solid plates that are made of the same materials and have the same weight. The results showed that the sandwich plate outperforms the solid plate, particularly in water blasts. Andrews and Moussa [10] used a single-degree-of-freedom mass–spring system to model the sandwich panel and presented failure mode maps for sandwich panels with composite face sheets. By conducting a set of calculations, Ebrahimi and Vaziri [11] presented an empirical relationship to predict the deformation and fracture of solid plates and square honeycomb panels under two consecutive, but isolated shocks.

In addition to theoretical and numerical analyzes, several blast experiments were also performed to investigate sandwich structures. Dharmasena et al. [12] performed explosive tests to study the dynamic response of square honeycomb core sandwich panels and solid panels. Their results indicated that the honeycomb sandwich panels produce smaller back face deflections than solid plates with identical mass. Zhu et al. [13] conducted air blast experiments to study the dynamic response of honeycomb sandwich panels. The results showed that face sheet thickness and core density significantly influence deformation/failure patterns. Nurick et al. [14–16] conducted air blast experiments on unbonded honeycomb and metallic foam core sandwich panels. The failure modes, influence of core height and face sheet thickness and interaction among components are discussed. By comparing different core types, Theobald [15] found that face sheet thickness has a significant effect on the performance of panels relative to an equivalent monolithic plate. Cui et al. [17] tested the metallic lattice sandwich panels under air blast. Deformation/failure mechanisms were investigated by experimental observations and analyzes. Hassan et al. [18] investigated the influence of different core densities on the blast resistance of PVC sandwich panels with aluminum alloy skins. The results indicated that damage within the sandwich panels becomes more severe as the density of the foam core increases. Wadley et al. [19] studied the deformation and fracture of sandwich panels that are subjected to localized impulse loading by the impact of explosively accelerated water-saturated sand shells. During loading, the sandwich panels suffered global bending and localized core crushing and stretching. A discrete particle-based method was also used to simulate the interaction among the high explosive detonation products, the soil and the aluminum panel.

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* Corresponding author. Tel.: +86 351 6010560.
E-mail address: wangzhihua@tyut.edu.cn (Z. Wang).

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Although numerous studies have been conducted on the behavior of sandwich structures under blast loads, the interaction among shockwave and structure, deformation mechanism of the sandwich structure remains unclear. In this study, a four-cable ballistic pendulum system was employed to investigate the dynamic response of aluminum honeycomb sandwich panels under blast loads. Different dimensions of honeycomb sandwich panels were tested in the experiment. The interaction between the shockwave and front face sheet, as well as deformation/failure modes of the face sheets and core, were discussed in the experiment. Numerical simulations were also performed to investigate the response process of the sandwich panel. The details are presented in Sections 2 and 3, respectively.

2. Experiment

2.1. Experimental procedure

2.1.1. Material and configuration of specimen

The face sheets and core of the honeycomb sandwich panels are made of AL-1200 and AL-5052, respectively. The mechanical properties are provided in Table 1. The manufactured specimen and its core sketch are shown in Fig. 1. The core was composed of a standard hexagon honeycomb with a side length of a and height of H_c. The front and back face sheets (H_f) were both 0.8 mm thick. The total height of the panel was: $H = H_c + 2\ H_f$. The Face sheets and core were combined by hot melt adhesive membranes. The configurations of the sandwich panels are numbered as shown in Table 2.

2.1.2. Experimental set-up

To measure the exerted impulse, a four-cable ballistic pendulum system [13] was employed in the tests as shown in Fig. 2a. The system was composed of a clamp, steel beam, and counterweight and was suspended in free air by 4 wire ropes. The specimen was clamped in the clamp frame with 16 screws. The explosive charge and detonator were set ahead of the specimen. Details on the explosive charge geometry and detonator location are shown in Fig. 2b. In the experiment, when the explosive charge mass is varied, the diameter D and length L are almost keep the same. A laser displacement sensor (Micro-Epsilon LD1625-200) was set behind the pendulum system to measure the translation of pendulum. The impulse applied on the pendulum was calculated by measuring the displacement history of the pendulum by the laser displacement sensor. The effective impulse on the specimen could be further estimated based on the exposed area of the specimen [13]. The specimens were processed into squares with 300 mm × 300 mm size, and the effective action area of the blast was 250 mm × 250 mm.

2.2. Test result

In this section, deformation/failure modes of face sheets and core under different impulses are discussed respectively.

2.2.1. Deflection

The specimens can be divided into two Cases. Case 1 has the same side lengths ($a = 3$ mm) but different heights (Groups S1, S3 and S5). Case 2 has the same heights ($H = 20$ mm) but with different side lengths (Groups S2, S3 and S4). The center permanent deflections of the back face sheets were plotted against the impulse as shown in Fig. 3 (Results of the back face sheets with only plastic deformation are provided.). The results show that increasing the impulse by 22.5%, 48.3%, 83.4%, and 29.7% in groups S1, S3, S4 and S5 increase the permanent deflections of the back face sheet by 76.6%, 39.9%, 235.7% and 88.4%, respectively. The test results show that when the impulse remains at a certain level in Case 1, the permanent deflection decreases obviously with the decrease of the core height from 28.4 mm to 8.4 mm. Case 2 shows that when the impulse increases from 17.4NS to 24.5NS, the deflection decreases from 32.9 mm to 26.4 mm with the decrease of the side length from 5 mm to 1.5 mm (S4-4 to S3-2 to S2-3). It is evident that the increasing core height or decreasing side length increases the capacity of the core to absorb shock energy. Thus the permanent deflection of the back face decreases. However, the mass and volume of the panel increase with decreasing cell side length and increasing core height. Therefore, determining a compromise design for sandwich structures is one of the most important issues that need to be considered.

2.2.2. Failure modes of face sheets

Menkes and Opat [20] first defined three failure modes that were observed in blast-loaded beams: large inelastic deformation (Mode I), tensile tearing at the boundary (Mode II), and shearing at the supports (Mode III). By investigating the inelastic response of blast-loaded sandwich panels, Nurick [14] extended those modes for plates that are:

- Mode I – Large inelastic deformation.
- Mode II* – Partial tearing of the boundary, and
- Mode II – Tensile tearing around the full boundary.

However, based on the observation of the current experiments, the three deformation/failure modes of the face sheets are redefined as follows:

- Mode I: Large plastic deformation only. (Fig. 5b).
- Mode II: Large plastic deformation with tearing (either at the center or boundary of the face sheets). (Figs. 4b and 5a).
- Mode III: Erosion (pitting and fragment) with tearing and plastic deformation. (Fig. 4a).

The deformation/failure modes of the face sheets under different impulses are given in Table 3. Three modes were all observed in the tests and only Mode I and Mode II were produced at the back face sheet.

Table 3 shows that when Mode III emerges on the front face sheet, the impulse loading on the panel is not the largest in the same groups. However, the scaled distance between front face sheet and the charge is relatively small. As we know, when the scaled distance decreases, the peak pressure loaded on the panel will enhanced, hence the font sheet will be more prone to occur Mode III.

Fig. 6a shows the sketch of the wave fronts of different explosive charges used for specimen S2-1 and S2-3. Fig. 6b shows the reflected peak pressure (P_{ref}) and impulse (i) distributions on the

Table 1
Mechanical property of face sheet and core.

	Material	Yield stress (Mpa)	Tensile strength (Mpa)	Young's modulus (Gpa)	Density (g/cm^3)	Poisson ratio
Face sheet	AL1200	140	160	70	2.7	0.3
Core	AL5052	70	210	70	2.7	0.3