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Dynamic response of metallic lattice sandwich structures to impulsive loading

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ABSTRACT

The dynamic response of metallic lattice sandwich plates under impulsive loading is studied by experimental investigation. The sandwich structures composed of two identical face sheets and tetrahedral lattice cores, were designed and fabricated through perforated metal sheet forming and welding technology. The air blast experiment of lattice sandwich structures was performed by use of a four-cable ballistic pendulum system. The deformation/failure mechanisms were investigated through experimental observation and analysis. The impulsive resistance of the tetrahedral lattice sandwich structures is quantified by the maximum permanent transverse deflection of the back face sheet as a function of transmitted impulse. The maximum transverse deflections of tetrahedral lattice sandwich plates are compared with that of hexagonal honeycomb ones with identical parent materials and core relative density. The comparison implies that the tetrahedral lattice sandwich structures possess a better impulsive resistance.

1. Introduction

With the fast development of modern technology in military area, the monolithic plates cannot meet the requirements of blast protection any longer. In such case, the lattice sandwich structures have attracted broad interest for their excellent impulsive resistant performance. The sandwich structures have various energy dissipation mechanisms, such as bending and stretching of the face sheet, compression and shear of the core. Especially, in the case of impulsive loading, the voids in the porous lattice core can provide adequate space for the large plastic deformation of the core, which is an efficient mechanism to dissipate the energy produced by blast impact [1–5].

For optimization and application of the lattice sandwich structures, it is necessary to have abundant experimental information. Recently in experimental investigation, Dharmasena et al. [6] and Zhu et al. [7] tested the dynamic response of square honeycomb sandwich plate made of stainless steel and hexagonal honeycomb sandwich plate made of aluminium alloy under explosion in the air, respectively. Wadley et al. [8] performed the underwater explosion experiment of rectangular pyramid lattice sandwich structure, which is made of stainless steel. McShane et al. used the impact of metal foam projectile to substitute the expensive and destructive blast experiment, and measured the impulsive resistance of square honeycomb and rectangular lattice sandwich structure, both made of stainless steel [9,10]. Lee at al. [11] and Tang et al. [12] tested the dynamic compression behaviour of pyramid and tetrahedral truss core respectively. However, no direct experimental comparison of impulsive resistance has been reported for the sandwich structures with different lattice cores under same condition. Theoretical studies also have been done by numbers of researchers previously. Fleck and Deshpande [5] divided the response of the sandwich structure into three sequential stages, and proposed an analytical model to predict the dynamic response of the clamped sandwich beam under impulsive loading. Based on the three-stage framework, studies on impulsive resistance of lattice sandwich structures were performed by many researchers [13–17].

In this study, we designed and fabricated the tetrahedral lattice sandwich square plate, which have the same material and core relative density as that of the hexagonal honeycomb sandwich plate tested by Zhu et al. [7], and performed air blast experiments to evaluate its impulsive resistance. The deformation and failure of lattice sandwich plate are investigated, and the comparison of three-dimensional and two-dimensional lattice sandwich structure with same material and relative density under air blast loading is

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derived by experimental investigation. The outline of this paper is as follows. The details of air blast experiment of lattice sandwich structure are introduced in Section 2. The specimens and testing set-up are presented at first, and the qualitative and quantitative experimental results are discussed subsequently. Finally, the general conclusions are summarized in Section 3.

2. Experiment

2.1. Specimens

The previous experimental investigation of lattice sandwich structures subject to air explosion was mainly focused on two-dimensional metal lattice materials; hence the present study concentrates on the three-dimensional metal lattice sandwich structure that exhibits a different core deformation characteristic.

The fabrication methods of three-dimensional metal lattice include sheet perforation and node folding method [18], investment casting method [19], and extrusion and electro-discharge machining method [20]. Due to the high metal fluidity of the investment casting method and strict equipment requirement of extrusion and exlectro-discharge machining method, the sheet perforation and node folding method is adopted in the fabrication of tetrahedral lattice material. The lattice core and face sheets are brazed together in inert gas atmosphere.

The metal material and geometry of the tetrahedral lattice is designed according to the aluminium alloy hexagonal honeycombs used in the experiment performed by Zhu et al. [7] for comparison. The face sheets were made of Al-2024-O aluminium alloy, and its mechanical properties are as follows: Young's modulus $E_f = 72.4$ GPa, Poisson's ratio $v_f = 0.33$, and yield stress $\sigma_f^Y = 75.8$ MPa. The lattice core were made of Al-5052-H39 aluminium alloy, and its mechanical properties are as follows: Young's modulus $E_c = 70$ GPa, Poisson's ratio $v_c = 0.33$, and yield stress $\sigma_c^Y = 265$ MPa. Preliminary testing results indicate that the mechanical properties of base material only have a tiny change after brazing.

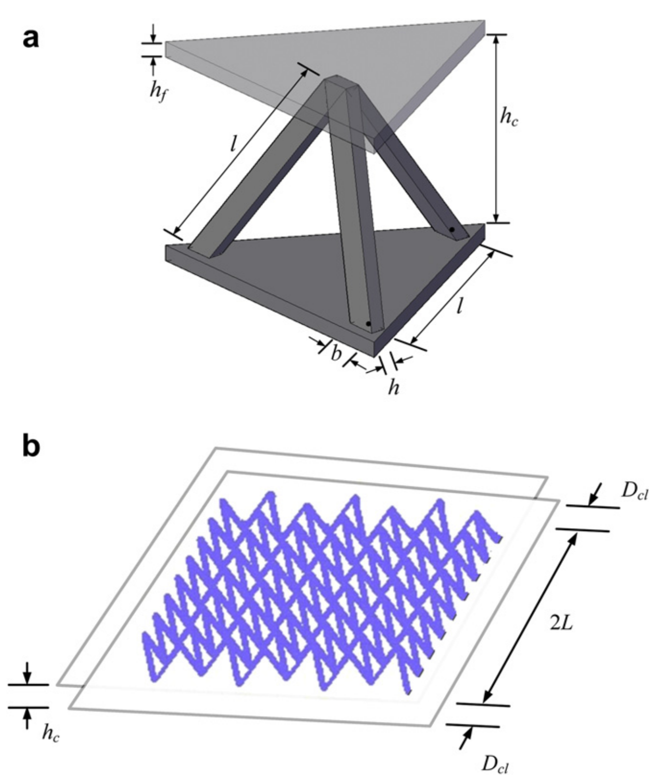

Fig. 1. Triangular lattice sandwich plate design for air blast tests: (a) unit cell of lattice sandwich structure; (b) sandwich plate.

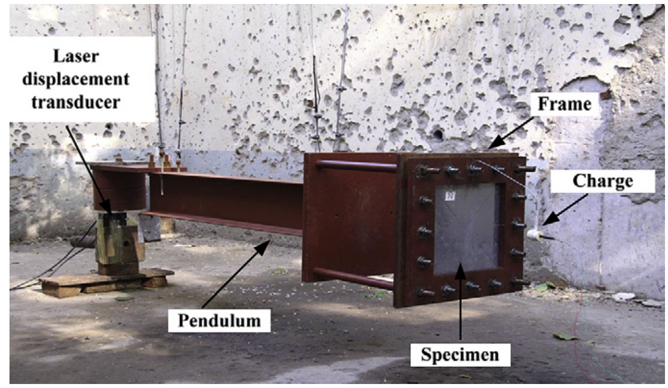

Fig. 2. Photograph of the four-cable ballistic pendulum system.

The design of the lattice is shown in Fig. 1. The thickness of the face sheets and the core are $h_f = 1$ mm and $h_c = 12.5$ mm, respectively. The lattice is a regular tetrahedron composed of three struts, with a length of $l = 15.3$ mm, a width of $b = 2$ mm and a thickness of $h = 2$ mm. The predicted relative density is given by

$$\bar{\rho} = \frac{3\sqrt{2}bt}{l^2} = 0.036. \tag{1}$$

The side length of the square sandwich plate is 310 mm, but the side length of the lattice core is only $2L = 250$ mm. The rest part of the core was filled with solid metal material to protect the specimen from collapse when clamping.

2.2. Set-up

The experiment was performed on a four-cable ballistic pendulum system, which has been used by Zhu et al. [1] for small explosive loading studies. A similar pendulum has been used by Nurick and Martin for explosive experiment [2–4]. A photograph of the pendulum system is shown in Fig. 2. The sandwich plate was clamped between two rectangular steel frames, which were fixed at the front of the pendulum. The TNT charge was placed in front of the specimen centre with a constant stand-off distance of 200 mm.

When the charge was detonated, the shock wave produced in the air impacted the specimen and the whole pendulum is pushed to translate. The oscillation amplitude of the pendulum was measured by a laser displacement transducer, and recorded by an

Table 1
The maximum deflection of the back face sheet and the transmitted impulse.

Number	Mass of charge (g)	Impulse (Ns)	Back face deflection (mm)
1	15	18.78	11.8
2	15	18.12	13.2
3	20	18.90	14.7
4	20	18.84	14.4
5	20	18.87	14.7
6	25	23.34	14.4
7	25	21.97	14.1
8	30	22.68	17.2
9	30	22.35	16.8
10	30	24.29	17.5
11	30	20.90	15.5
12[a]	20	22.96	24.7
13[a]	30	28.63	22.3

[a] The stand-off distance of the charge is 150 mm.

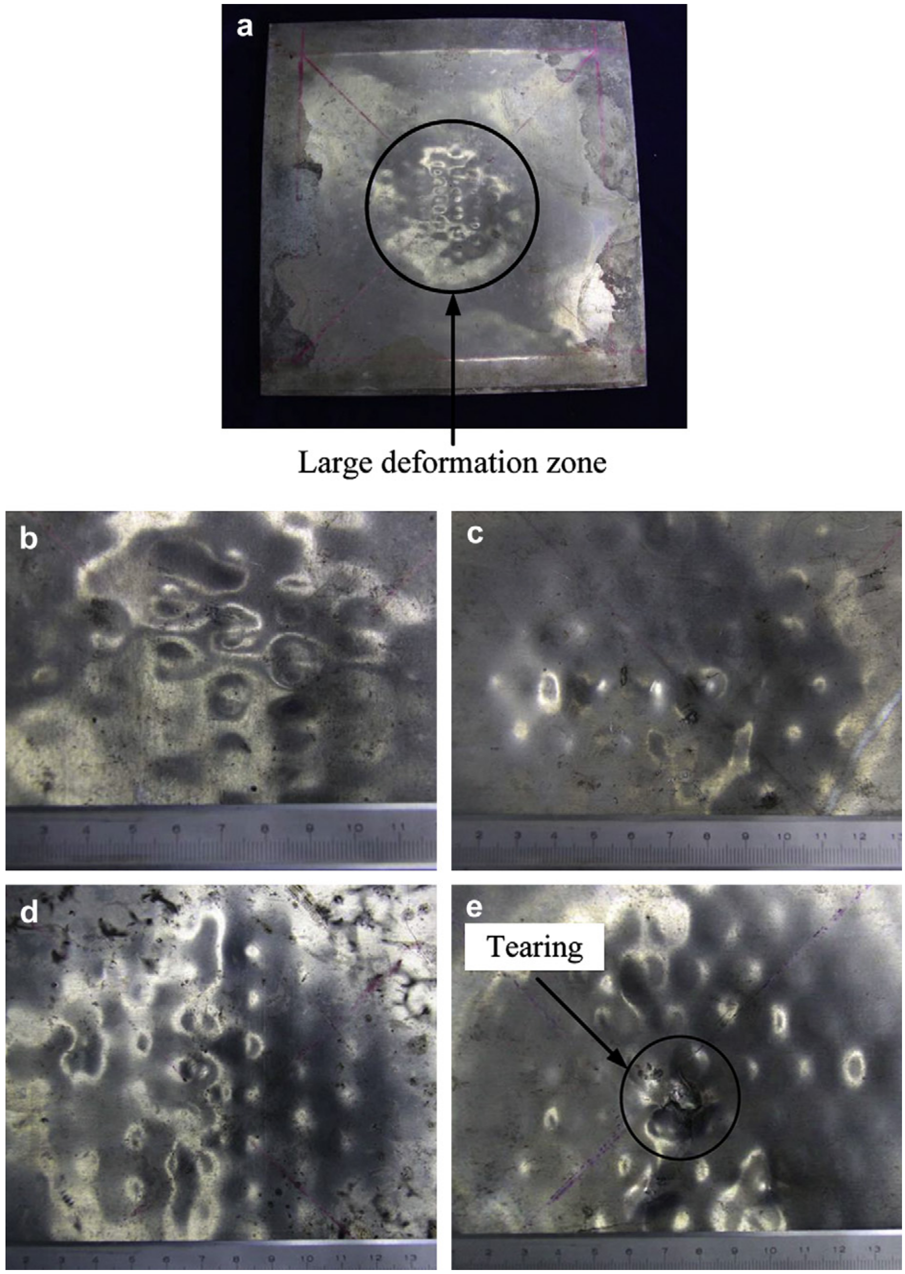

Fig. 3. (a) Global deformation of the front face sheet and large deformation zone in the centre of the lattice sandwich plate subjected to different impulses (b) 18.12 Ns; (c) 18.87 Ns; (d) 21.97 Ns; (e) 24.29 Ns.

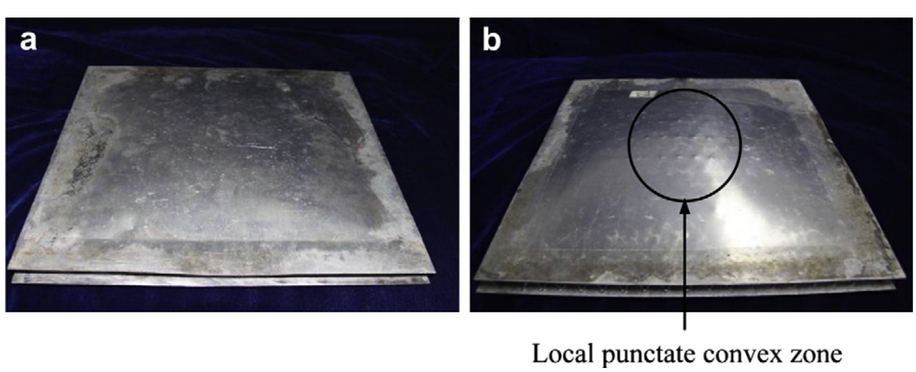

Fig. 4. Deformation of the back face sheet under different impulses: (a) 18.12 Ns; (b) 24.29 Ns.

oscilloscope. The impulse transmitted to the pendulum front face can be calculated according to the oscillation period, weight and length of the pendulum and the effective impulse on the specimen can be further estimated.

2.3. Experimental results

The relative density of the fabricated lattice sandwich specimen is 0.034, which is a little lower than the designed value due to the manufacturing error. A set of TNT charge mass, i.e. 15 g, 20 g, 25 g and 30 g, is used in the explosion experiment. The measured maximum deflection of the back face sheet and transmitted impulse are given in Table 1.

2.3.1. Deformation/failure modes

The impulses transmitted to the sandwich plate vary with the mass of charge, and the corresponding deformation/failure modes are discussed below for the front face sheet, back face and lattice core, respectively.

2.3.1.1. Deformation/failure modes of the front face sheet. The front face sheet of the lattice sandwich plate exhibits a large global deformation and local concave-convex deformation, as shown in Fig. 3. It can be seen that the local concave-convex deformation emerges at the central region of the front face sheet, and its area increases with the magnitude of the impulse transmitted to the sandwich plate as shown in Fig. 3(b–e). The front face sheet would suffer tearing failure at an abundant high impulse level. The contact of the core and face sheet can be regarded as point-surface contact, and thus intense impulsive impact could induce local concave–convex deformation for a relative thin face sheet. It implies that besides the global deformation, the front face sheet can also dissipate the impact energy by local deformation. Further efforts should be made to establish the analytical models including this mechanism.

2.3.1.2. Deformation/failure modes of the back face sheet. The deformation of the back face sheet is shown in Fig. 4. When the applied impulse has less intensity, only global deflection was observed, similar as that of the sandwich plates with other cores [6,7,21–23]. However, local punctate convex zone appears when the applied impulse is intense enough, as shown in Fig. 4(b). It is again because of the point-surface contact of the face sheet and lattice core. At the given mass of charge, the produced impulse is not intense enough to induce fracture in the back face sheet. Therefore, we adjusted the stand-off distance of the charge to 150 mm without changing its mass. A crack was then observed at the centre of back face sheet under an impulse of 28.63 Ns, as shown in Fig. 5.

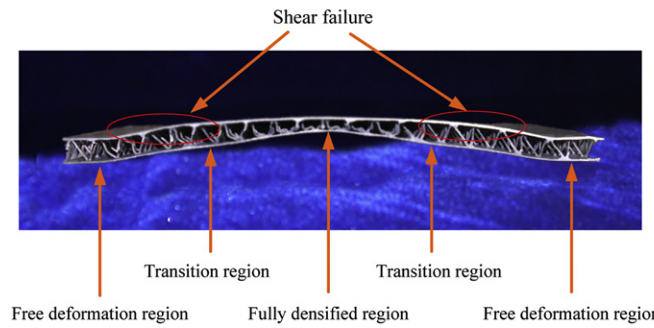

Fig. 6. Deformation of the lattice core.

2.3.1.3. Deformation/failure modes of the lattice core. The deformation of the lattice core is shown in Fig. 6. Three regions can be identified according to the deformation pattern of the core, from centre to the edge: (1) fully densified region in the centre; (2) free deformation region at the edge and (3) transition region between the centre and edge. Shear failure was observed in the transition region due to the incompatible deformation of the front and back face sheets.

In the blast experiment of hexagonal honeycomb sandwich plate, Zhu et al observed delamination failure between the front sheet and the honeycomb core [7], but no such delamination occurred in our experiment. Compared with the bonding connection between the honeycomb core and face sheets, the welded joints between the lattice core and face sheets possess higher connecting strength. Thus they can sustain much larger shear deformation.

2.3.2. Analysis and discussion

The tested maximum deflection of back face sheet of tetrahedral lattice sandwich plate is compared with that of hexagonal honeycomb obtained by Zhu et al. [7], as shown in Fig. 7. The

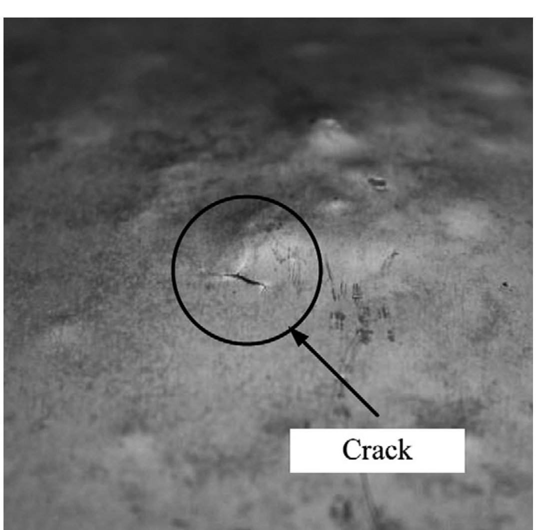

Fig. 5. Centre deformation zone of the back face sheet under an impulse of 28.63 Ns.

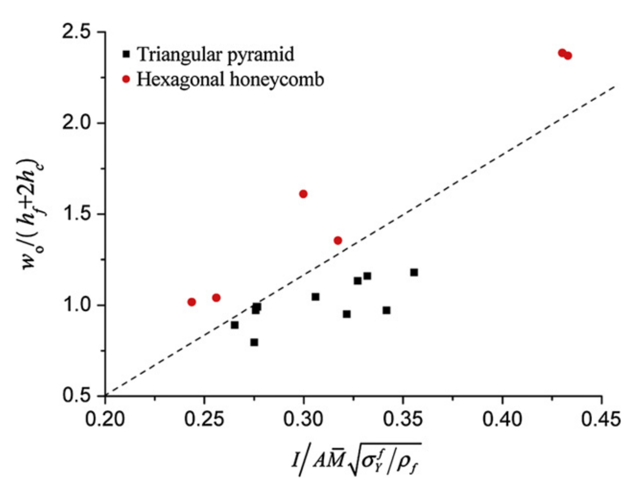

Fig. 7. The maximum non-dimensional deflections of the back face sheet vs non-dimensional impulse. (The experimental result of Hexagonal honeycomb is derived by Zhu et al. [7])

maximum deflection w_o and the applied impulse I are normalized by

$$\overline{w}_o = \frac{w_o}{2h_f + h_c} \tag{2}$$

and

$$\bar{I} = \frac{I}{A\overline{M}\sqrt{\sigma_f^Y/\rho_f}} \tag{3}$$

respectively, where A denotes the effective core area, and $\overline{M}$ denotes the sandwich mass per unit area.

It can be seen that the maximum deflection of the back face sheet increases with the applied impulse following an approximately linear relation for the tetrahedral lattice and hexagonal honeycomb sandwich plate. The maximum back face sheet deflection of the tetrahedral lattice sandwich plate is smaller than that of the hexagonal honeycomb sandwich plate. It indicates that the tetrahedral lattice sandwich plate possesses a better impulsive resistance.

3. Conclusions

The tetrahedral lattice sandwich structures are designed and fabricated through perforated metal sheet forming and welding technology. The dynamic response of the lattice sandwich structures is investigated by performing air explosion experiment. The transmitted impulses were measured by use of a four-cable ballistic pendulum system, and the maximum transverse deflection of the back face sheet is measured after test.

The experiment results indicate that, besides global transverse deflection, local concave-convex deformation and punctate convex deformation occur at the central region of the front face sheet and back face sheet, respectively. These deformation models are induced by the approximate point-surface contact between the core and the face sheet. Non-uniform compression deformation and shear deformation appear in the tetrahedral lattice core due to the inconsistent deformation of the front and back face sheets. The maximum permanent transverse deflection is engaged to evaluate the impulsive resistance of the tetrahedral lattice sandwich structures, and the measurement results of tetrahedral lattice sandwich plates are compared with that of hexagonal honeycomb ones with identical parent materials and core relative density. The comparison demonstrates that the tetrahedral lattice sandwich structures possess a better impulsive resistance.

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