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Effects of aluminum foam filling on the low-velocity impact response of sandwich panels with corrugated cores

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Abstract

In this study, a closed-cell aluminum foam was filled into the interspaces of a sandwich panel with corrugated cores to form a composite structure. The novel structure is expected to have enhanced foam-filled cores with high specific strength and energy absorption capacity. An out-of-plane compressive load under low-velocity impact was experimentally and numerically carried out on both the empty and foam-filled sandwich panels as well as on the aluminum foam. It is found that the empty corrugated sandwich panel has poor energy absorption capacity due to the core member buckling compared to that of the aluminum foam. However, by the filling of the aluminum foam, the impact load resistance of the corrugated panel was increased dramatically. The loading-time response of the foam-filled panel performs a plateau region like the aluminum foam, which has been proved to be an excellent energy absorption material. Numerical results demonstrated that the aluminum foam filling can decrease the corrugated core member defects sensitivity and increase its stability dramatically. The plastic energy dissipation of the core member for the foam-filled panel is much higher than that of the empty one due to the reduced buckling wavelength caused by the aluminum foam filling.

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Sandwich panel, corrugated core, foam-filled, low-velocity impact, energy absorption

Introduction

Structures applied as primary load carrying component subjected to both the quasi-static and impact load require high specific strength and energy absorption as well as low density [1–3]. Lightweight sandwich structures with metallic lattice cores such as honeycombs [4–6], corrugated cores [7–9], pyramidal cores [10–12], as well as laminated sandwich panels [13–16] are proposed to have such features compared with acoustic damping, thermal insulation, and other multifunctional properties. For the laminated sandwich composite panel, the delamination is also very important, and efforts have been down to study and improve its mechanical [3], vibration [13,14], and thermal buckling [15,16] properties. However, such sandwich panels usually invalidated with the node failure or core buckling which will lead to a rapid decrease in loading force immediately after it reached its peak; thus, their load-carrying capabilities are rather limited [17]. Therefore, the improving of core strength and energy absorption capacity of sandwich structure with lattice cores is urgently needed. In contrast, metallic foams are attractive for energy absorption applications when subjected to crushing and impulsive loads [18–21]. But their topological core defects induced by the processing method lead to lower crushing strength, which limit their application as load carrying constructions [22,23]. Therefore, sandwich structures with individual lattice core or foam core seem insufficient. It has been demonstrated that the hybrid core with combination of the two types of cores may have achieved the aim of both high specific strength and energy absorption [8].

Metallic foams have already been selected as the filling material to form foam-filled structures with increased impact energy absorption capacities, such as foam-filled tubes [24,25]. The enhancement mechanism was suggested to be the reduced buckling wavelength of the foam-filled tube under axial compression caused by the metallic foam filling [25]. However, the metallic foam-filled tubes are only attractive in axial crushing loading resistance applications and limited in other loading conditions, such as bending. Polymeric foams have also been chosen as the filling material to form hybrid cores and attempted to increase its strength and energy absorption capacity. Experimental, theoretical, and numerical studies were focused on the polyurethane foam-filled hexagonal [26–28] and square [29] honeycombs as well as corrugated [29,30] and truss [31] cores subjected to the quasi-static and dynamic loading. The effect of polyurethane foam filling on the stabilization of pyramidal lattice cores was also investigated [30,32]. Those results showed that the polymeric foam-filled lattice cores are attractive in energy absorption.

However, due to the low strength of the polymeric foam compared with metallic lattice cores, the improvements of peak loading force and energy absorption are rather limited. When applied as weight sensitive structures with the density considered, the results of polymeric foam-filled structures were even disappointing [28,29].

Instead of a weaker polymeric foam, a closed-cell aluminum foam was used as the filling material to form hybrid metallic lattice cores and found that the filling of the metallic foam can increase the peak loading strength, energy absorption capacity as well as bending resistance properties of the corrugated sandwich panel dramatically in our previous study [8,33]. Besides aluminum foam, metallic honeycombs were also used as the filling material to form novel structures, and demonstrated as having significant benefits on energy absorption [34,35], vibration control [36], thermal buckling resistance [37], and even acoustic absorption [38] properties. In order to increase the strength and energy absorption of lattice-cored sandwich structures, a hierarchical corrugated core sandwich panel was designed [39]. Mechanical performances including compressive [39–42], bending [40,43], shear [40,42], and failure modes [40] were studied theoretically, numerically, and experimentally. The results show that the hierarchical design can significantly increase the stability of the corrugated core web member causing increase of mechanical properties. However, the hierarchical designed corrugated panel can be further reinforced by the filling of metallic foams or honeycombs.

When structures are subjected to low-velocity impact load, such as airdropping energy absorption is important to protect the equipment and humans. Weight drop impact test was often used to study the low-velocity impact responses of materials and structures. Therefore, in the present study, due to manufacturing advantages over square or hexagonal honeycomb cores, sandwich structures with two-dimensional corrugated cores were selected and filled with the closed-cell aluminum foam to form hybrid composite cores. The low-velocity impact load was carried out on sandwich panels with the hybrid corrugated cores via weight drop test experimentally and numerically to study the effects of the aluminum foam filling on its impact responses, as well as empty panel and aluminum foam for contrast.

Experiment

Materials fabrication

The foam-filled corrugated sandwich panel was processed via the filling of the closed-cell aluminum foam into the space of the empty corrugated core; thus, the empty panel should be fabricated first. The face sheets and corrugated core webs of the sandwich panel were all made of 304 stainless steel with density of $\rho_s = 7900\,\text{kg/m}^3$. After the folding and laser welding processing methods, the empty corrugated sandwich panel was formed. Triangular foam prisms with the same shape of corrugated core space cut by electro-discharge machining (EDM) from a commercial closed-cell aluminum foam sheet [23] were used as the filling material. The prepared triangular foam prisms were inserted into the corrugated core spaces and fixed by epoxy glue. Surface cleaning of both the corrugated panel and foam prisms was required before assembling. The prepared foam-filled sandwich panel was held at 25°C for 4 hours, heated up to 80°C for 2 hours, and then cooled to the ambient temperature. After these processing methods, the foam-filled sandwich panel was obtained. Typical specimen images of the empty and foam-filled panels for the low-velocity impact test were shown in Figure 1 as well as the geometric parameters of a unit cell. Note that the interface between the foam prisms and steel corrugated sandwich panel may have a significant effect on the load-carrying and energy absorption properties; such interfaces were treated carefully to minimize the gaps, Figure 1(b). More details of the processing method of the materials can be seen in [8].

All the specimens have fixed inclination angle ($\alpha = 45°$), core height ($H = 17$ mm), and width ($B = 20$ mm) in the present study. With the densities of steel and aluminum foam denoted separately by ρ_s and ρ_f, the average density of the core ρ_c was defined as

$$\rho_c = \nu_s \rho_s + \rho_f (1 - \nu_s) \tag{1}$$

where ν_s is the volume proportion of the core occupied by the steel which is [29]

$$\nu_s = \frac{t/H}{t/H + \cos\alpha} \tag{2}$$

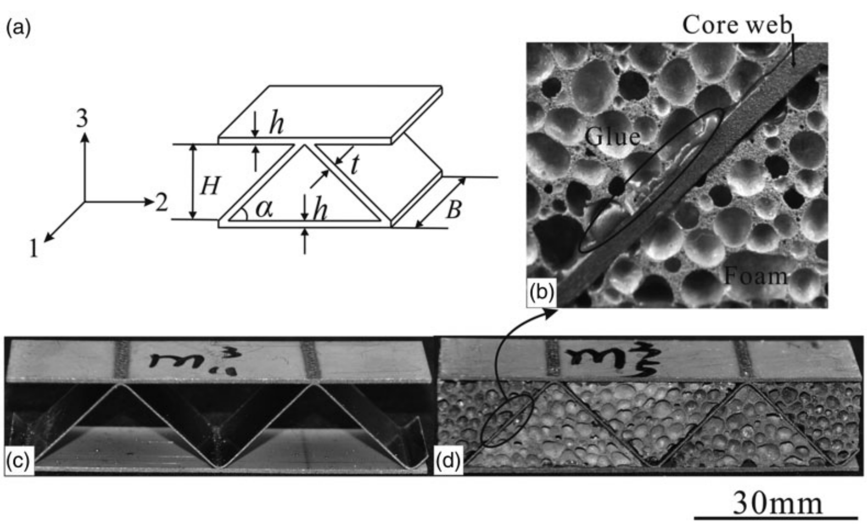

Figure 1. Specimens of sandwich panels with the empty and aluminum foam-filled corrugated cores: (a) schematic of a unit cell; (b) details of bonding condition; (c) empty panel; (d) foam-filled panel.

For the empty corrugated sandwiches, $\rho_f = 0$, whilst for the foam-cored sandwiches, $\nu_s = 0$. The density of aluminum foam ρ_f used in the present study was fixed as 540 kg/m^3. As defined, ρ_c for the empty corrugated sandwich panels were 198 kg/m^3 and 537 kg/m^3 with core web thickness $t = 0.3$ and 0.82, respectively, and for the foam-filled sandwich panels, it increased to 725 kg/m^3 and 1064 kg/m^3.

Low-velocity impact test

The typical specimens of both the empty and the foam-filled sandwich panels for low-velocity impact tests were shown in Figure 1(c) and (d). The specimens of sandwich panels have dimensions of $76 \times 20 \times 20$ mm while the aluminum foam specimens have dimensions of $\phi 35 \times 40$ mm.

The low-velocity impact load was carried out by on Instron 9250 HV weight drop impact test machine as shown in Figure 2(a). The specimen was placed in a rigid base and impacted by the free falling of an impactor, see Figure 2(b) and (c).

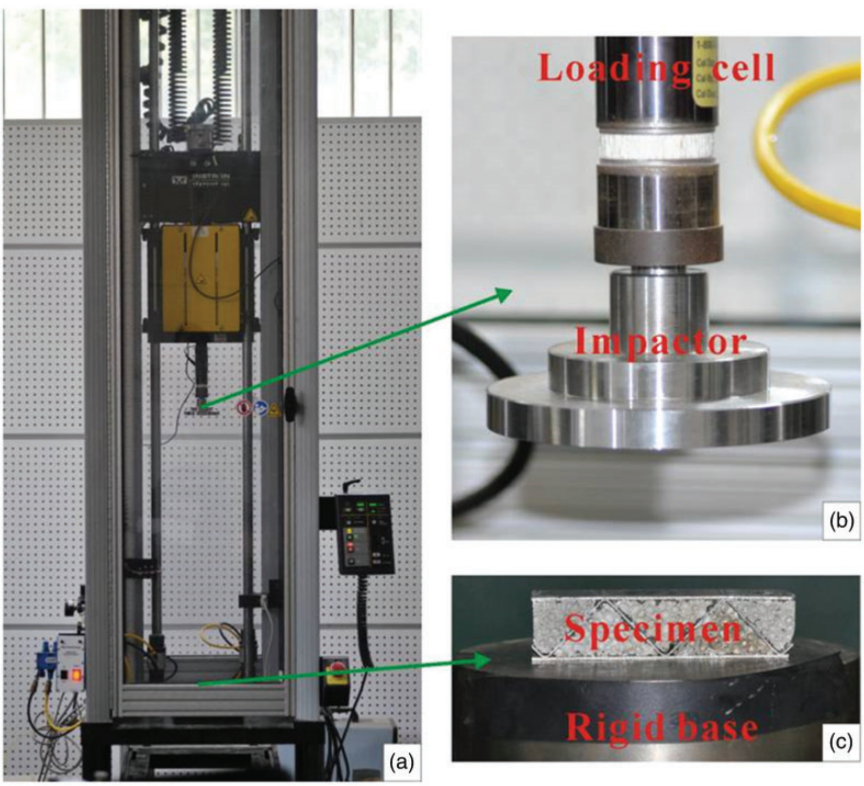

Figure 2. Instron 9250 HV weight drop impact test machine: (a) experimental setup; (b) impactor; (c) impact base.

Table 1. Summary of the experimental parameters for the low-velocity impact tests.

Specimen	Type	t (mm)	M (kg)	V_0 (m/s)	E_0 (KJ)
1	Aluminum foam		20.04	2.7947	78.29
2				3.427	117.73
3				3.699	137.16
4	Empty panel	0.3	5.05	1.3981	4.93
5				1.9774	9.85
6				2.783	19.51
7		0.3	20.04	1.9829	39.42
8		0.82	5.05	3.1077	24.33
9				3.4041	29.2
10				3.6773	34.07
11		0.82	20.04	1.9789	39.26
12				2.9752	78.33
13	Foam-filled panel	0.3	20.04	1.9785	39.24
14				3.1355	98.56
15				3.7074	137.79
16		0.82	20.04	3.1284	98.11
17				3.4284	117.83
18				3.6985	137.13

The specimens have fixed inclination angle ($\alpha = 45^\circ$), core height ($H = 17$ mm), width ($B = 20$ mm), and face sheet thickness ($h = 0.82$ mm). Where M is impactor weight, V_0 is initial impact velocity, and $E_0 = \frac{1}{2} M {V_0}^2$ is initial impact energy.

The impact load was measured by the loading cell integrated in the impactor of the machine. The initial velocity V_0 was measured by a photoelectric sensor with precision accuracy $\pm 0.1\%$. A pneumatic clamping fixture was used to prevent repeated impact. The impact energy E_0 can be altered by varying of velocity V_0 (altering weight drop height) and impactor weight M. No breakage of the welding joints was observed during the whole tests showing good weld bonding conditions. The photographs of the specimens after the impact were obtained to study their failure modes. The detailed experimental parameters for the low-velocity impact tests were summarized in Table 1.

Experimental results and discussion

In this section, the low-velocity impact responses of the novel foam-filled corrugated sandwich panels obtained via the weight drop test were discussed. The deformed images of specimens after the impact test were also shown to study the failure mechanisms. In contrast, the low-velocity impact performances of sandwich panels with empty corrugated cores as well as the closed-cell aluminum foam which act as the filling material in the present study were also discussed.

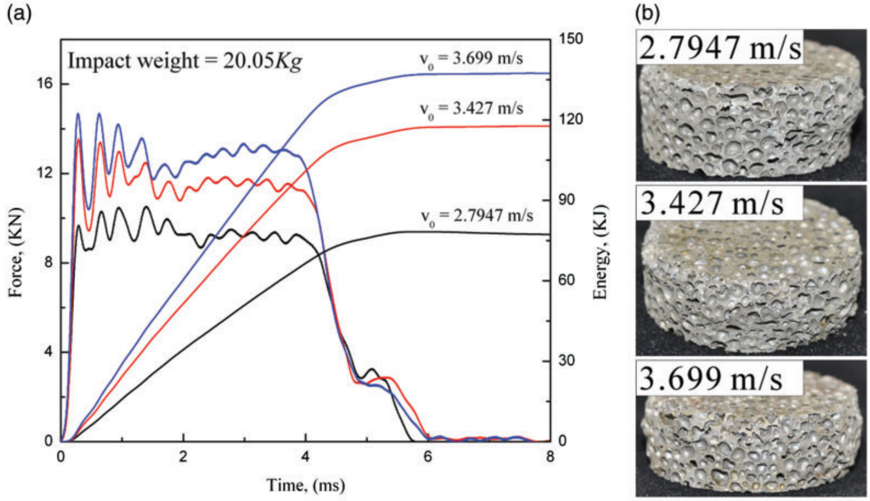

Figure 3. Impact of aluminum foam: (a) force–time curve; (b) specimens after impact. $M = 20.05$ kg.

Aluminum foam

The low-velocity impact responses of the closed-cell aluminum foam with different initial impact velocities were shown in Figure 3(a), while Figure 3(b) shows the images of residual specimens after the impact. The loading force versus time curves present three typical regions: (i) elastic region, which start from the impactor contacted with the specimen to the initial crushing of aluminum foam, where the foam deformed elastically and linearly; (ii) deformation region, where the foam deformed plastically and core crushing occurred layer by layer. At this region, the foam absorbed most of the impact energy, and the curve undergoes near plateau region; (iii) final region, where the impactor stops and the impact process ended. As anticipated, by increasing the initial impact velocity, the peak loading force and the absorbed energy E as well as the deformation of specimen increased, as shown in Figure 3. The deformed specimens after impact showning in Figure 3(b) indicates that the given impact energy E_0 is enough to make the aluminum foam crushing, but unable to make densification occurred. In other words, the specimen can absorb more impact energy, and the deformed foam still has energy absorption capacity. Accordingly, a closed-cell aluminum foam is an excellent impact energy absorption material and this is the main reason we chose it as the filling material to form a composite structure.

Empty corrugated sandwich panel. Figures 4 and 5 show the low-velocity impact responses of empty corrugated sandwich panels with different core web thickness, impact velocity, and impact weight. The corresponded deformed specimens after

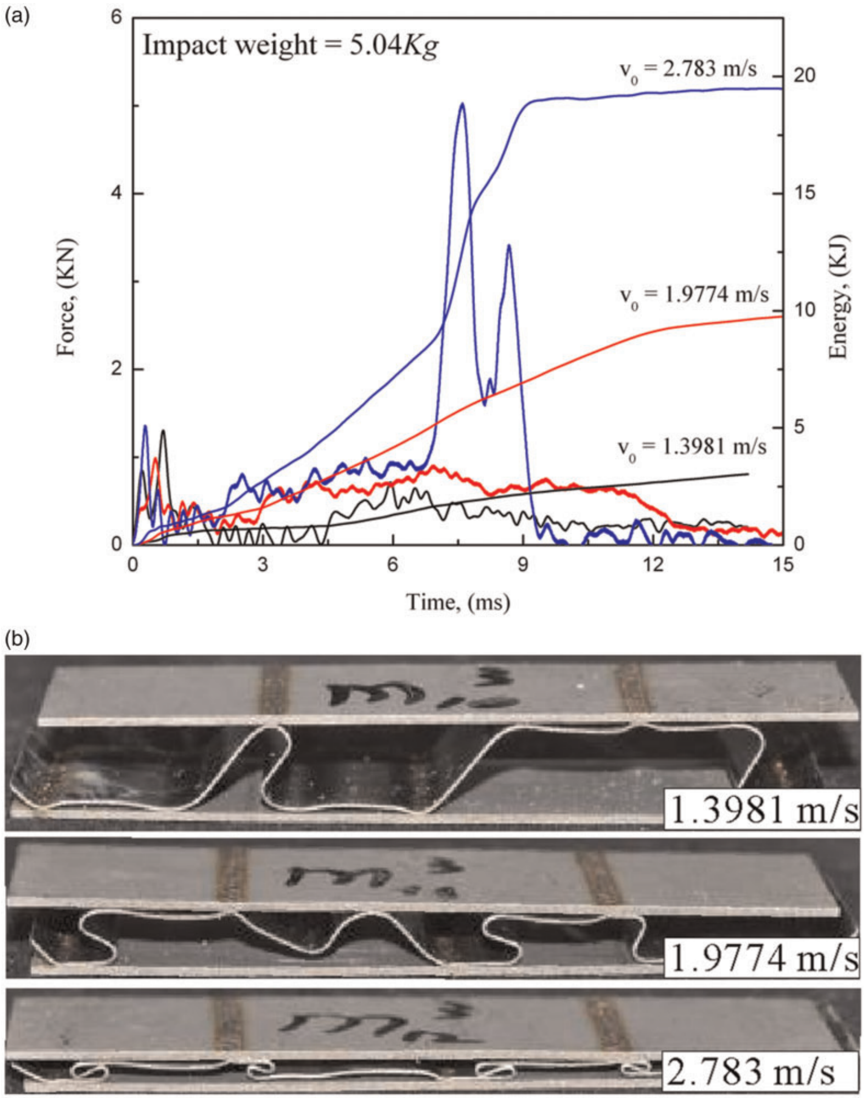

Figure 4. Impact of sandwich panel with the empty corrugated core, $\rho_c = 198$ kg/m^3: (a) force–time curve; (b) specimens after impact. $M = 5.04$ kg.

the impact were also displayed. As expected the loading force history of the empty corrugated sandwich panels are similar to that of the quasi-static one. As discussed for the aluminum foam earlier, three typical region of the impact loading history of the empty corrugated sandwich panels can also be seen. All the specimens have a linear elastic region before the deformation region occurred, but the deformation region differs to that of the aluminum foam. Note that two steps at this region can

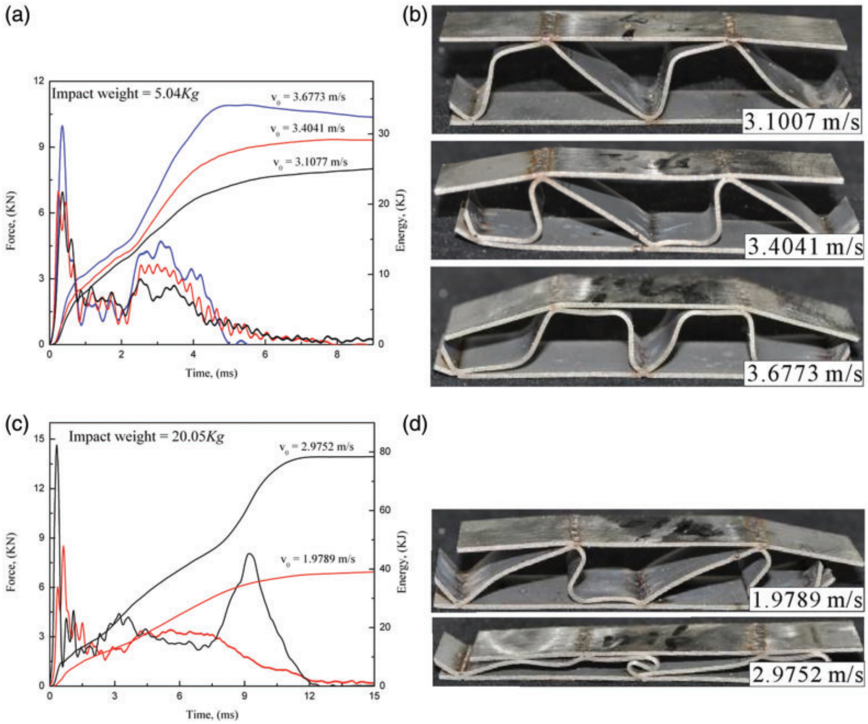

Figure 5. Impact of sandwich panel with the empty corrugated core, ρ_c = 537 kg/m^3: (a) force–time curve, (b) specimens after impact, $M = 5.04$ kg; (c) force–time curve, (d) specimens after impact, $M = 20.05$ kg.

be seen (like its quasi-static results shown [8]): the first step is core member soften immediately after peaking load reached due to buckling, which leads to the dramatically declined loading force; the second step is the impact loading force increasing again, caused by further deformation of specimens. Core member contact with face sheet at this stage causes the increase. After deformation region, the loading force decreased to zero, the impactor stops, and the impact process ended.

Note that specimens with densities of $\rho_c =$ 198 kg/m^3 have weak core members with strength of only 0.59 MPa. Therefore, the second step of the deformation region occurred and even the impact energy E_0 is as low as 4.93 KJ (see Figure 4, $V_0 =$ 1.3981 m/s). As increasing E_0 to 19.51 KJ, densification of the specimen occurred leading to the dramatically increased impact loading force (see Figure 4, $V_0 =$ 2.783 m/s). When E_0 increased further, the energy absorbed by the specimen before densification can be ignored, and the impact is just like the rigid board impact. The contact of the core web member and face sheet can be seen in Figure 4(b). For the specimens with densities of $\rho_c =$ 537 kg/m^3 with compressive strength of 5.94 MPa, similar impact loading history and deformation modes of the specimens are shown in Figure 5. In contrast, the impact energy E_0 and loading force are much larger, and the densification only occurred when E_0 reached about 78.33 KJ instead of 19.51 KJ. In general, the empty sandwich panel presents poor impact loading resistance and energy absorption compared with the aluminum foam.

As discussed before, the buckling of the core web member is the dominant failure mode of the empty corrugated sandwich panel subjected to both the quasi-static [8] and low-velocity impact load. Therefore, increasing the stabilization of the core web member became critical for its engineering applications, and this is the main aim of the present study. Filling of a closed-cell aluminum foam into the space of the empty corrugated core was demonstrated to be an effective way under the quasi-static loading conditions [8]; thus, under the low-velocity impact, advantaged impact energy absorption performances are anticipated and will be discussed in the following section.

Aluminum foam-filled sandwich panel. The low-velocity impact responses and specimen images after the impact of the aluminum foam-filled sandwich panels with average densities of $\rho_c = 725$ and 1064 kg/m^3 were shown in Figures 6 and 7, respectively. The deformed images of specimens show that the core web member of each foam-filled corrugated sandwich panel deforms with multiple plastic hinges instead of one for the empty ones. However, distinct crushing deformation of the inserted aluminum foam can be observed only when the impact energy E_0 reached 137.79 KJ of specimen with $\rho_c = 725$ kg/m^3 (see Figure 6(b) ($V_0 = 3.7074$ m/s)). The limitation of the impact energy E_0 due to the limited impact height of the weight drop set-up causes the insufficient deformation unfortunately in the present study. Thus, when the impact energy E_0 is further increased, the deformation of the aluminum foam-filled sandwich panel is expected to be much larger and will absorb more impact energy. Nevertheless, the qualitative discussion of the low-velocity impact response of the aluminum foam-filled sandwich panel and comparison of the empty corrugated panel and aluminum foam are beneficial to understand the mechanisms and helpful for its engineering applications.

In general, the impact loading force responses show three typical regions: linear elastic, deformation, and final region which are similar to that of the aluminum foam discussed earlier. Note that the near plateau deformation region is totally different to that of the empty corrugated sandwich panels which with dramatically declined loading force after its peak reached. As shown in Figures 6(b) and 7(b), the core web member deformed with much increased number of plastic hinges due to the aluminum foam filling. Therefore, the core web members were much more strengthened with mechanisms similar to the aluminum foam-filled tubes demonstrated to be the reducing of the buckling wavelength [25]. Similar results can also be seen in polyurethane foam-filled metal hexagonal honeycombs, which reduce the peak loading force to mean crushing force ratio when subjected to the low-velocity impact load [27]. For the aluminum foam-filled corrugated sandwich panels under the quasi-static compressive load, a dramatically increased peak

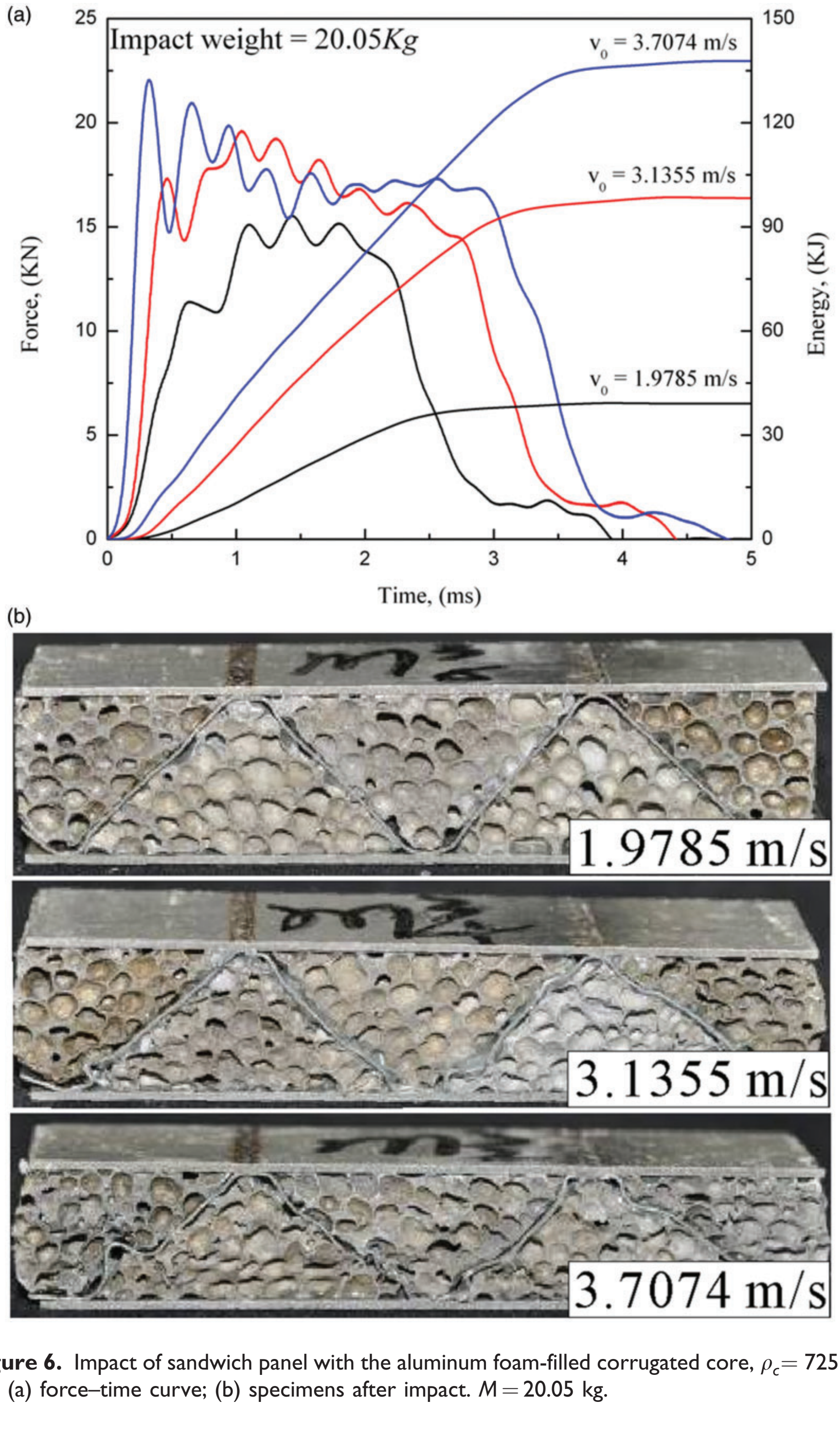

Figure 6. Impact of sandwich panel with the aluminum foam-filled corrugated core, $\rho_c = 725$ kg/m^3: (a) force–time curve; (b) specimens after impact. $M = 20.05$ kg.

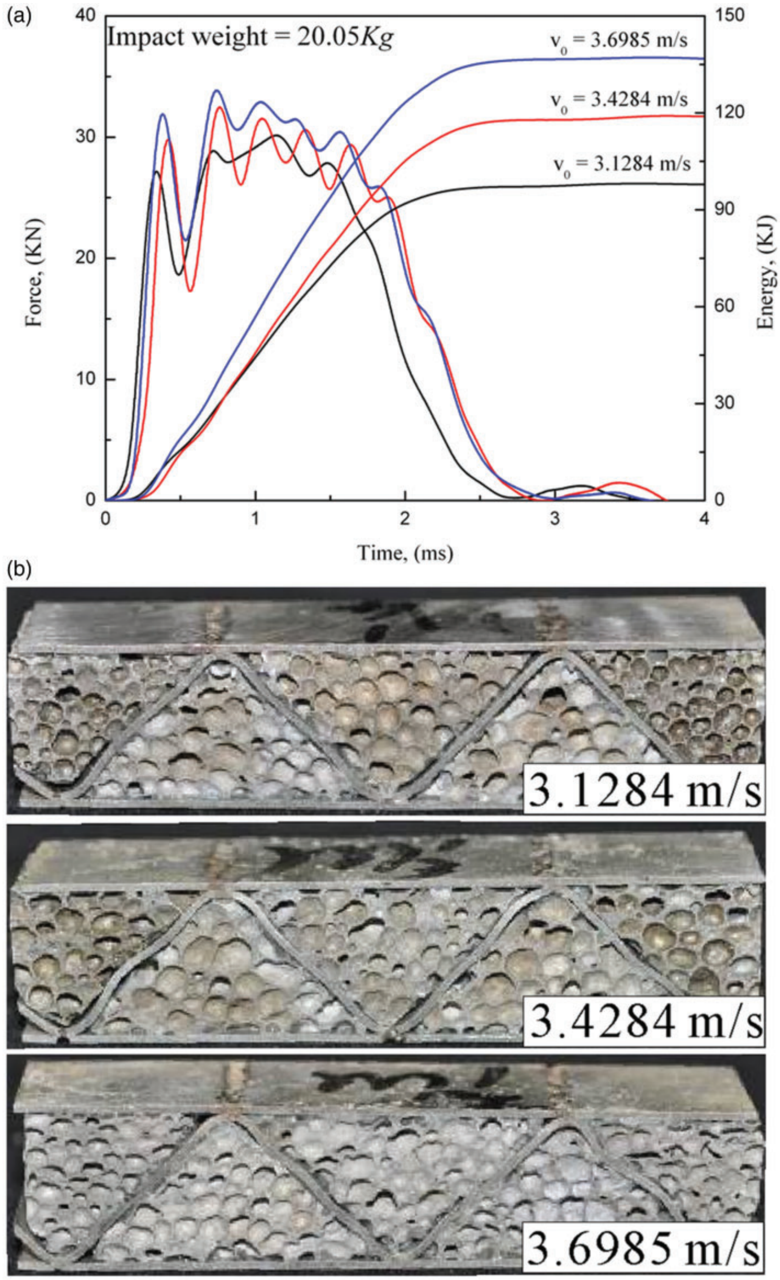

Figure 7. Impact of sandwich panel with the aluminum foam-filled corrugated core, $\rho_c = 1064$ kg/m^3: (a) force–time curve; (b) specimens after impact. $M = 20.05$ kg.

loading force and energy absorption was obtained [8]. Aluminum foam supplies sufficient lateral support to the core web members which changing its buckling modes and was suggested to be the enhancement mechanism. Thus, besides aluminum foam, the enhanced core web member due to the foam filling contributed more impact loading resistance and energy absorption compared with the empty ones. It was denoted that the aluminum foam-filled sandwich panel has superior impact loading resistance performances compared with the poorly performed empty corrugated ones. The excellent foam-like impact loading resistance performance of the aluminum foam-filled sandwich panel endows it with impact energy absorption applications other than load carrying applications.

Numerical investigation

Material properties and FE model

The core members of both the empty and foam-filled corrugated panels were modeled by an isotropic and homogeneous elastic-plastic solid mode, with density = 7900 kg/m^3, Young's modulus = 210 GPa, Poison ratio $\nu = 0.3$, and yield stress = 210 MPa. The quasi-static stress–strain curve of AIS304 stainless steel taken from Stout and Follansbee [44] was used in the FE simulations.

The aluminum foam was molded using a crushable foam constitutive model of Deshpande [45] and with Young's modulus = 2.61 GPa, Poisson ratio = 0.3, and plastic Poisson ratio = 0. The stress versus strain curve obtained from uniaxial compression tests was adopted in the simulations.

Both the empty and aluminum foam-filled corrugated panels under the low-velocity impact were numerically studied using ABAQUS/Explicit, and the geometrical parameters were the same as those of the experimental specimens (Figure 1).

The face sheets are stiff enough compared with the empty and foam-filled corrugated cores, and thus considered as rigid bodies. Both the corrugated core members and the filling foam are represented by four-node plain strain elements with reduced integration (CPE4R). An average element size of 1/10 of the thickness of the corrugated core member is attributed to both the core members and foam. A mesh size sensitivity study has been conducted and showed that further refining of the mesh has little influence on the results.

The face sheets, core members, and foam are assumed to be perfectly bonded, and the cohesive layers are not modeled. Symmetry boundary condition was applied on the two side faces of the foam insertion. The back face sheet of the panel was fixed, with no displacement or rotation allowed. A constant velocity V was imposed on the front face sheet so that the core was uniaxially compressed. Much more modeling details can be seen in our previous study [8,46].

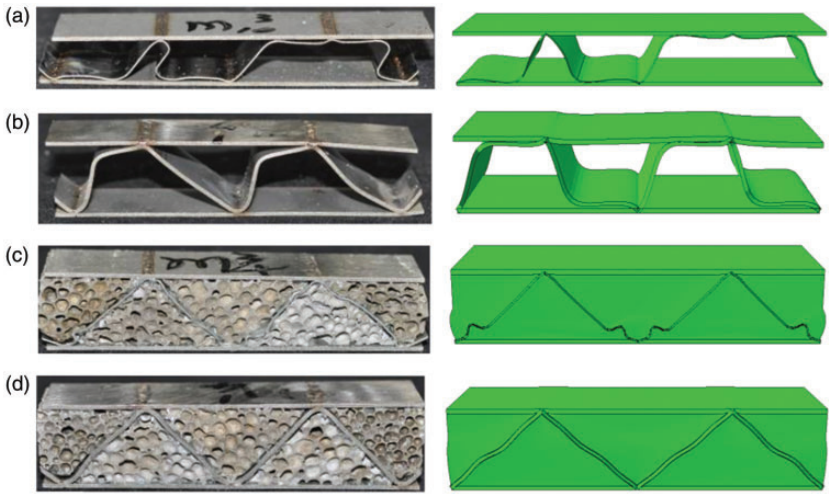

Figure 8. Deformation modes comparison of numerical and experimental results: (a) empty, $\rho_c = 198$ kg/m^3; (b) empty, $\rho_c = 537$ kg/m^3; (c) foam-filled, $\rho_c = 725$ kg/m^3; (d) foam-filled, $\rho_c = 1064$ kg/m^3.

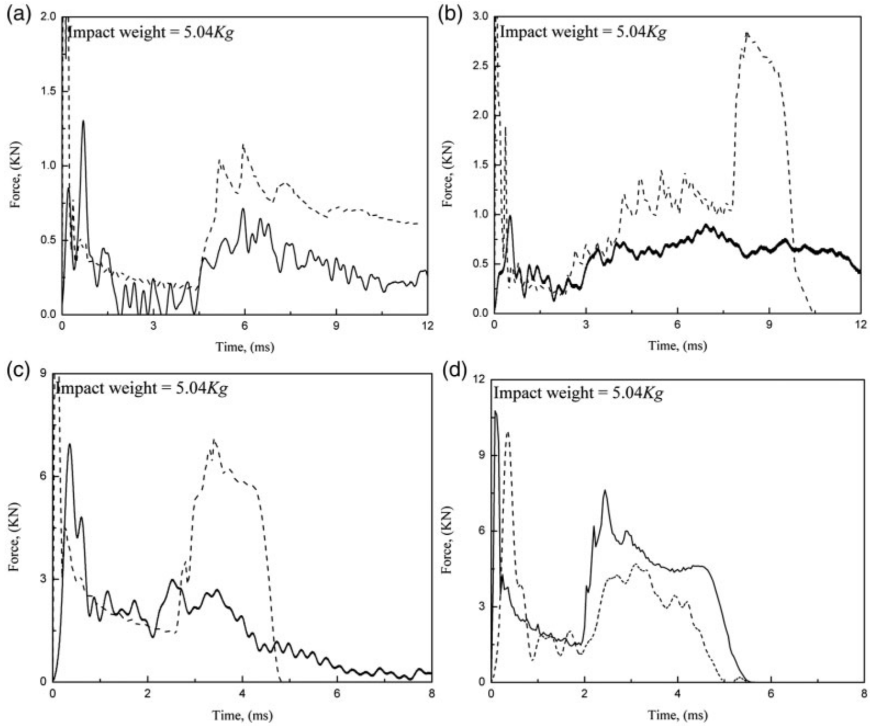

Figure 9. Force–time curve of empty sandwich panels with corrugated cores. Dense line: experimental, dash line: numerical. (a) $t = 0.3$ mm, $V_0 = 1.4$ m/s, (b) $t = 0.83$ mm, $V_0 = 2.0$ m/s, (c) $t = 0.83$ mm, $V_0 = 2.\ 8$ m/s and (d) $t = 0.82$ mm, $V_0 = 3.7$ m/s.

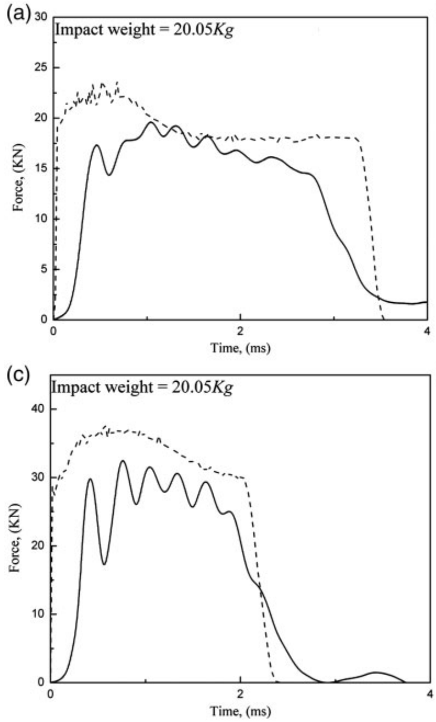

Figure 10. Force–time curve of the sandwich panel with the aluminum foam-filled corrugated core. Dense line: experimental, dash line: numerical. (a) $t = 0.3$ mm, $V_0 = 3.1$ m/s, (b) $t = 0.3$ mm, $V_0 = 3.7$ m/s, (c) $t = 0.8$ 2mm, $V_0 = 3.4$ m/s and (d) $t = 0.82$ mm, $V_0 = 3.7$ m/s.

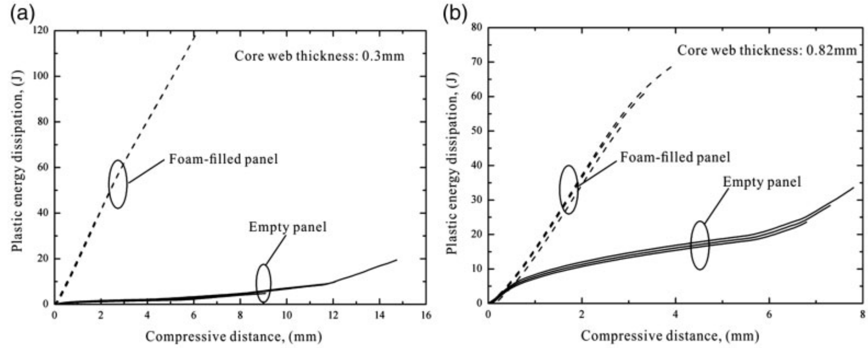

Figure 11. Plastic energy dissipation of both the empty and aluminum foam-filled corrugated sandwich panels with core web thickness: (a) 0.3 mm; (b) 0.82 mm.

FE results and discussion

The comparison of the deformation modes of both the empty and foam-filled sandwich panels can be seen in Figure 8(a) and (b), and the simulated result matching well with the experimental observation. Particularly, due to the foam filling, the buckling mode of the corrugated core member changed into a much shorter buckling wavelength, as shown clearly in Figure 8(a) and (b). The numerical and experimental force–time curves of sandwich panels with both empty and foam-filled corrugated cores under different impact velocities were shown in Figures 9 and 10, respectively. As shown in Figure 9, for the empty panel, the force–time curves of the numerical results were generally higher than that of the experimental ones, and the main cause of the inconformity may be the initial buckling of the corrugated core member due to materials fabrication, such as folding and welding processes. However, the numerical results of the aluminum foam-filled panel fit well with the experimental ones due to the foam filling, which reduces the defects sensitivity dramatically.

It was found that the plastic energy dissipation of the aluminum foam-filled corrugated sandwich panels was much higher than that of the empty one as shown in Figure 11 and increases as the increase of compressive strain. The filled aluminum foam supplies sufficient lateral support which limit and delay the buckling of the corrugated core members and causes the increase of the buckling load, and this may be the main cause of the increase of the energy dissipation for the aluminum foam-filled corrugated panels.

Conclusions

Metallic sandwich panels with corrugated cores were fabricated and filled with a closed-cell aluminum foam to form a novel hybrid composite panel. Such sandwich panels were experimentally and numerically carried out on a uniaxial out-of-plane compression impact load via weight drop. It was found that the filling of aluminum foam has a significant enhancement on the impact loading force and energy absorption of the hybrid composite sandwich panel when subjected to the low-velocity impact load. The aluminum foam-filled corrugated sandwich panel has superior impact loading resistance performances compared with the poorly performed empty ones which with the core web buckling occurred immediately after its peak loading reached. Besides the attributions of aluminum foam itself, the mechanisms underlying the enhancement of the peak stress and energy absorption were also attributed to the lateral support supplied by the aluminum foam to the corrugated core members. The lateral support alters the deformation modes, considerably delaying the core member buckling of corrugated sandwich panel. The numerical results indicate that the filling of the aluminum foam also can dramatically reduce the defects sensitivity of corrugated cores. With excellent quasi-static and impact loading resistance performances, the novel designed sandwich structure with metallic foam-filled hybrid cores has great potential as lightweight structural material in the impact energy absorption and load carrying applications.

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Declaration of conflicting interests

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