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Effects of Aluminum Foam Filling on Compressive Strength and Energy Absorption of Metallic Y-Shape Cored Sandwich Panel

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Abstract: The design of lightweight sandwich structures with high specific strength and energy absorption capability is valuable for weight sensitive applications. A novel all-metallic foam-filled Y-shape cored sandwich panel was designed and fabricated by using aluminum foam as filling material to prevent core member buckling. Experimental and numerical investigation of out-of-plane compressive loading was carried out on aluminum foam-filled Y-shape sandwich panels to study their compressive properties as well as on empty panels for comparison. The results show that due to aluminum foam filling, the specific structural stiffness, strength, and energy absorption of the Y-shape cored sandwich panel increased noticeably. For the foam-filled panel, aluminum foam can supply sufficient lateral support to the corrugated core and vertical leg of the Y-shaped core and causes a much more complicated deformation mode, which cannot occur in the empty panel. The complicated deformation mode leads to an obvious coupling effect, with the stress–strain curve of the foam-filled panel much higher than those of the empty panel and aluminum foam, which were tested separately. Metallic foam filling is an effective method to increase the specific strength and energy absorption of sandwich structures with lattice cores, making it competitive in load carrying and energy absorption applications.

Keywords: sandwich panel; Y-shape core; aluminum foam; compressive strength; energy absorption

1. Introduction

Lightweight sandwich structures with lattice cores [1,2] and foam cores [3,4] have been widely studied and applied due to their outstanding mechanical performance [5–7]. Lattice cored structures such as pyramidal [8,9], corrugated [10,11], Kagome [12], and honeycomb cores [13–15] have advantages in load carrying applications; however, after the loading force reaches its peak, core member softening occurs and leads to an immediate and dramatic decline of load-carrying capacity [8]. In contrast, foam structures have excellent energy absorption properties [16–18] and functional designs, such as acoustic absorption [19,20] and thermal insulation [21,22], but their mechanical strength is limited due to the microstructure of the core and defects during the foaming process and high porosity [23]. Therefore, designing structures resistant to core member buckling and increasing specific strength and energy absorption are important for applications of lightweight sandwich structures.

Recently, some effective structures have been proposed and designed to increase the specific strength and energy absorption of lattice structures and foam structures [24–27]. Metallic and polymeric foams are used as filling material to improve the mechanical performance of sandwich structures with lattice cores and have proved to be effective [25–28]. Yan et al. [25] designed an all-metallic foam-filled

2 of 11

sandwich panel with corrugated cores. These panels have considerably increased compressive [25], bending [29], and impact resistance [30] performance compared with empty panels. The foam-filled corrugated panel has also been demonstrated to have enhanced blast resistance behavior compared with empty panels [31]. Besides foam filling, metallic [32–34] and composite [35,36] tubes are also effective in enhancing the strength and energy absorption of metallic foams [32], polymeric foams [33,35,36], and aluminum honeycombs [34]. In conclusion, foam filling and tube enhancement are two effective methods of increasing the specific strength and energy absorption of lattice and foam structures.

Sandwich structures with Y-frame cores are developed in the hull design process to improve crash performance, and these structures have been proved to have advantages in load carrying and energy absorption applications [37–41]. Rubino et al. [37–39] experimentally and numerically studied the three-point bending and dynamic response of a clamped sandwich beam and plate with metallic Y-frame core, with the results showing notable advantages compared with the equal areal mass monolithic plate. St-Pierre et al. [40,41] investigated the low velocity impact [40] and dynamic indentation [41] response of the Y-frame cored sandwich structure and proved that the impact force transmitted to the back face by the Y-frame core is markedly lower, thus providing protective benefits to the underlying structure. In addition to metallic cores, all-composite sandwich structure with Y-shaped cores have also been designed and fabricated, and their mechanical performance under compressive [42], bending [43], and shear [44] load has been investigated experimentally, numerically, and analytically. However, both metallic and composite Y-shape cored structures [41,44] exhibit an immediate and dramatic decline of loading force after approaching the peak due to core member softening, as discussed before.

Therefore, the purpose of the present study was to increase the mechanical performance of the Y-shape cored sandwich panel, and aluminum foam-filing has been proved as an effective method of achieving this aim. The Y-shape cored sandwich panel is designed and fabricated via laser welding firstly, and then enhanced by filling of aluminum foam. Out-of-plane compressive behavior of both empty and foam-filled Y-shape cored sandwich panels was studied experimentally and numerically. The effect of foam filling on load carrying, energy absorption, and deformation modes was investigated, and the enhancement mechanisms are also discussed.

2. Experimental

2.1. Materials and Fabrication

The aluminum foam-filled metallic Y-shape cored sandwich panel with both of its face sheets and core members was made up of 304 stainless steel sheets with a density of $\rho_s = 7900 \text{ kg/m}^3$. For reference, the empty Y-shape cored sandwich panel was also considered and firstly fabricated via laser welding. The schematic of the Y-shape cored sandwich panel is shown in Figure 1. The panel consisted of corrugated cores, vertical legs, and two face sheets [39]. The length, width, and height of the specimen was $110 \times 20 \times 34$ mm. The corrugated cores were formed via procedural folding, and the legs and face sheets were cut by using wire electrical discharge machining (WEDM). The folded corrugated cores and vertical legs were firstly connected together by laser spot welding and then connected with the upper and lower face sheets, also with laser welding. After laser welding, the Y-shape cored sandwich panels were formed. To form good joining conditions, vacuum brazing technology was also used in the present study to strengthen the specimen after laser welding by applying brazing flux to the weld joint, which was then placed in a vacuum furnace for vacuum brazing. The details of vacuum brazing can be seen in Reference [45].

The aluminum foam-filled Y-shape cored sandwich panel was fabricated by filling of aluminum foam into the spaces of empty panel. Closed cell aluminum alloy foam (AlSi7) fabricated via the melt foaming route with a relative density of $\rho_f = 0.24$ in collaboration with the D.P. He Group of Southeast University, China, was used as the filling material with pore size of 1–3 mm [46]. Aluminum foam was cut by WEDM into prisms having the same shape of the core space of the empty Y-shape cored

sandwich panel. The foam prisms were inserted into the Y-shape core and fixed by using Ausbond A713 epoxy glue. Ultrasonic surface cleaning under alcohol conditions and gluing were applied to both the foam prisms and the empty panel before assembly. After holding at 25 °C for 4 h and 80 °C for 2 h, when cooled to ambient temperature the aluminum foam-filled Y-shape cored sandwich panels were formed. Figure 2 shows the final fabricated specimens of both empty and aluminum foam-filled Y-shape cored sandwich panels for the compressive tests.



Figure 1. Schematic of with Y-shape cored sandwich panel.



Figure 2. Specimen images of empty and aluminum foam-filled Y-shape cored sandwich panel, t = 0.41 mm.

In the present study, the face sheet thickness h = 0.82mm, specimen width B = 20 mm, core member length L = 24 mm, corrugated core and face sheet angle $\alpha = 45^{\circ}$, as shown in the schematic in Figure 1 were all fixed, as was the relative density of aluminum foam $\overline{\rho}_f = 0.24$. Core member thickness of 0.41 and 0.82 mm was chosen to form the Y-shape cored sandwich panel with different densities. The relative density of the empty Y-shape cored sandwich panel $\overline{\rho}_Y$ was defined as the volume proportion of the core occupied by the steel:

$$\overline{\rho}_{\rm Y} = \frac{V_S}{V_T} = \frac{2LBt + LBt}{2LB\cos\alpha(L + L\sin\alpha)} = \frac{3t}{2L\cos(1 + \sin\alpha)} \tag{1}$$

where V_s is the volume of the steel core, and V_T is the total volume of the core. For the aluminum foam-filled Y-shape cored sandwich panel, the relative density can be defined as the averaged relative density $\overline{\rho}_c$ compared with steel:

$$\overline{\rho}_{c} = \overline{\rho}_{Y} + (1 - \overline{\rho}_{Y})\overline{\rho}_{f}\rho_{AL}/\rho_{s}$$
⁽²⁾

where $\overline{\rho}_f$ is the relative density of aluminum foam and ρ_{AL} and ρ_s are the densities of aluminum alloy and 304 stainless steel, respectively. Equation (2) can be also applied to empty Y-shaped core without foam and aluminum foam core without the Y-shaped core, and for the empty Y-shape cored sandwich panel, $\overline{\rho}_f = 0$, while for aluminum foam without the Y-shape core, $\overline{\rho}_Y = 0$. The weight of the glue was neglected. Details of specimens for the compressive tests are summarized in Table 1.

Table 1. Summary of core member thickness *t*, relative density $\overline{\rho}_{c'}$ as well as experimental (Exp.) and numerical (Num.) results of specific structural stiffness $E_{33}/\overline{\rho}_{c'}$ compressive stress σ_{peak} , normalized compressive stress $\sigma_{33}^{\text{Peak}}/(\sigma_y \overline{\rho}_c)$, energy absorption per unit volume W_v , and per unit mass W_m of the specimens. All specimens had identical *L*, *B*, and α ; the density of foam aluminum relative to aluminum was 0.24.

Specimens	<i>t</i> (mm)	$\bar{ ho}_{c}$	$E_{33}/\rho_{c}(MPa)$	$\sigma^{Peak}_{33}({\rm MPa})$		$\sigma_{33}^{Peak}/(\sigma_y \rho_c)$		$W_{\mathbf{V}}(10^3 \mathbf{kJ/m}^3)$		$W_{\rm m}({\bf kJ/kg})$	
			Exp.	Exp.	Num.	Exp.	Num.	Exp.	Num.	Exp.	Num.
Empty-1	0.41	0.036	3083	0.78	0.93	0.10	0.12	0.11	0.097	0.39	0.34
Empty-2	0.82	0.072	2083	2.89	3.56	0.19	0.24	0.35	0.42	0.62	0.74
Filled-1	0.41	0.115	5609	13.78	16.29	0.57	0.67	7.08	8.27	7.79	9.10
Filled-2	0.82	0.148	5581	17.40	20.48	0.56	0.66	8.07	11.06	6.90	9.46

2.2. Compressive Test

Out-of-plane (direction 3 shown in Figure 1) quasi-static compressive load was carried on both empty and aluminum foam-filled Y-shape cored sandwich panels of specimens shown in Figure 2 using a hydraulic testing machine (MTS) at ambient temperature. For comparison, the strength of aluminum foam was also measured with specimen dimension of $24 \times 24 \times 40$ mm. The loading rate was fixed at 2 mm/min with a nominal strain rate of less than 10^{-3} s⁻¹. A compressive strain of at least 50% for each specimen was achieved to ensure the complete deformation and energy absorption. The loading force and displacement of specimens was obtained by the load sensor and transverse displacement of the machine. Digital images of each specimen were acquired with a video camera to study the deformation modes and explore the failure mechanisms. A Sony FDR-AX100E digital video camera was used in the experiment. The frame rate and resolution of the camera were 25 p and 4 K, respectively. No breakage of the welded joints was observed during the whole test, indicating good connecting conditions due to laser welding and vacuum brazing.

3. Numerical Models

To better understanding the effect of aluminum foam filling on compressive behavior of Y-shape cored sandwich panels and their failure mechanisms, 3D finite element (FE) simulations with ABAQUS/Explicit were also carried out for both empty and aluminum foam-filled sandwich panels. The Y-shape core members of the sandwich panel made of 304 stainless steel were modeled by using von Mises J2 flow elastoplastic theory, and with Young's modulus $E_s = 210$ Gpa, yield stress $\sigma_y = 210$ Gpa, and Poisson ratio $\nu = 0.3$. With consideration of plastic hardening of the 304 stainless steel, the plastic hardening stress versus strain curve taken from Stout and Follansbee [47] was used in the FE simulations. For aluminum foam, a crushable foam constitutive model of Deshpande and Fleck [48] was employed with the following material parameters: Young's modulus $E_{AL} = 2.61$ Gpa, Poisson ratio $\nu = 0.3$, and plastic Poisson ratio $\nu = 0$. The stress–strain curves of aluminum foam used in the FE model were obtained from the uniaxial compression test in the literature [25].

Figure 3 shows the geometry and boundary conditions of FE models for both empty and aluminum foam-filled Y-shape cored sandwich panels under compression. The face sheets are considered as rigid bodies for they are much stiffer than their cores. The face sheets, Y-shape core members, and aluminum foam are assumed to be perfectly bonded. The 304 stainless steel Y-shape core was modeled by using 4-node shell elements (S4R), aluminum foam prisms used an 8-node reduced integration element (C3D8R), while four-node rigid elements (R3D4) were used for the rigid bodies. All mesh sizes are less than 2 mm in the present FE model. As shown in Figure 3, symmetry boundary conditions were applied for both empty and foam-filled panels. The bottom rigid face sheet is fixed, and the top sheet has a displacement in the 3-direction with a slow axial velocity of 1.5 mm/s. General contact was applied for the present models, with a Coulomb friction coefficient of 0.28. More details of FE simulation can be seen in our previous study [25].



Figure 3. Geometry and boundary conditions of FE models for compression tests of both empty and aluminum foam-filled Y-shape cored sandwich panels.

4. Results and Discussion

4.1. Effect on Strength and Stiffness

Experimentally measured and numerically simulated stress–strain curves of empty and aluminum foam-filled Y-shape cored sandwich panels are shown in Figure 4. For the empty panel, after a linear elastic increase, the stress-strain curve declined to a very low level immediately after it reached its peak due to its core member buckling, similarly to the empty corrugated panel. However, for the foam-filled panel, the decline was much smaller and was sustained at a high level after its first peak stress approach compared with the empty panel. In general, the numerical results fit with the experimental results. For the FE model used in the present study with ideal bonding conditions between foam and steel, the simulated peak strength and stiffness were higher than those of the experimental results. The displacement measured by the transverse displacement of machine also led to considerable deviations.



Figure 4. Measured and simulated compressive stress–strain curves of the Y-shape cored sandwich panels. (**a**) Empty panel; (**b**) aluminum foam-filled panel.

As summarized in Table 1, due to aluminum foam filling, the peak compressive strength σ_{33}^{Peak} of the foam-filled panel can have a dramatic increase of over 16 and 5 times (Exp.) that of the empty panel with core member thickness *t* of 0.41 and 0.82 mm, respectively. As the filling of aluminum foam causes a significant increase of density, the peak compressive strength was normalized as $\sigma_{33}^{Peak}/(\sigma_y \overline{\rho_c})$, where σ_y is yield stress of the 304 stainless steel and $\overline{\rho_c}$ is the averaged relative density of core defined as Equation (2). Therefore, Table 1 shows that the normalized peak strength $\sigma_{33}^{Peak}/(\sigma_y \overline{\rho_c})$ of the foam-filled panels can also have an increase of 4.7 (Filled-1, Exp.) and 1.9 (Filled-2, Exp.) times that of the related empty panels. Note that with the increase of core member thickness from 0.41 to 0.82 mm, the peak load increased from 0.78 to 2.89 MPa (Exp.) for the empty panel; however, for the foam-filled panel, the increase was not so dramatic. The simulated numerical results (Num.) are also summarized in Table 1 and generally fit with the experimental results, and the deviation is caused by the less refined features of the present numerical model, such as the ideal bonding conditions considered.

Besides compressive strength, aluminum foam filling can also have a significant effect on the stiffness of specimens, which can be defined as slope of the linear stage of stress–strain curve $E_{33} = \sigma_{33}/\epsilon_{33}$, which can be specific as $E_{33}/\overline{\rho}_c$. As shown in Table 1, the specific structural stiffness $E_{33}/\overline{\rho}_c$ of foam-filled Y-shape cored sandwich panels was 1.82 and 2.68 times that of the empty panel with core member thickness *t* of 0.41 and 0.82 mm, respectively.

4.2. Effect on Energy Absorption

The energy absorption capacity of structures can be defined as energy absorption per unit volume (W_v) , which is the integration of stress-strain curves:

$$W_{\rm v} = \int_0^\varepsilon \sigma d\varepsilon \tag{3}$$

Figure 5 shows the energy absorption per unit volume W_v versus compressive strain of both empty and foam-filled Y-shape cored sandwich panels. The results show that the foam-filled structure is more efficient fir energy absorption, and the numerical results generally fit with the experimental results compared with the corresponding empty panels. The deviations may be caused by the lack of consideration of bonding condition between the foam and steel of the specimen, and accurate simulation of large deformation of the present specimens is rather difficult. When $\varepsilon = 0.5$, the calculated W_v of all specimens is summarized in Table 1. For weight sensitive applications, the specific energy absorption (SEA) is also very important and could be calculated as [25]:

$$W_{\rm m} = \frac{W_{\rm V}}{\overline{\rho}_{\rm c}} \tag{4}$$

where $\overline{\rho}_{c}$ is the averaged relative density of the core defined as Equation (2). The averaged energy absorption per unit mass W_{m} of specimens is also summarized in Table 1.



Figure 5. Measured and simulated energy absorption per volume of the Y-shape cored sandwich panels. (a) Empty panel; (b) aluminum foam-filled panel.

As shown in Table 1, due to aluminum foam filling, the energy absorption per unit volume W_v of foam-filled Y-shape cored sandwich panel was 64 and 23 times (Exp.) that of the empty panel with core member thickness *t* of 0.41 and 0.82 mm, respectively. In contrast, with consideration of the significant increase of core density caused by aluminum foam filling, the specific energy absorption W_m of the foam-filled panels was 20 and 11 times (Exp.) that of the empty panels.

4.3. Coupling Effect

Figure 6a,b shows the stress–strain curves of empty and foam-filled Y-shape cored sandwich panels with core member thickness t of 0.41 and 0.82 mm, respectively, as well as aluminum foam. Note that the dashed line represents the sum of the empty panel and aluminum foam, which were

tested separately. Therefore, a significant coupling effect can be seen in Figure 6a,b as the shadow area shows. A similar coupling effect is observed for sandwich structures with aluminum foam-filled corrugated cores [25] and aluminum foam-filled metallic tubes [1]. The enhancement mechanism was suggested to be a result of the filled aluminum foam giving sufficient lateral support to the core web members which shortened the buckling wavelength [1]. The mechanisms of the present coupling effect are discussed in the following deformation modes section.



Figure 6. Coupling effect between Y-shaped core members and aluminum foam. The dashed line shows the sum of the stress–strain curve of empty and aluminum foam, which were tested separately. Core member thickness: (a) t = 0.41 mm; (b) t = 0.82 mm.

4.4. Deformation Modes

As discussed before, aluminum foam filling can lead to a significant increase of compressive strength, structural stiffness, and energy absorption, and the core member and aluminum foam present an obvious coupling effect. The experimentally measured and numerically simulated deformation modes of both empty and aluminum foam-filled Y-shape cored sandwich panels under different compressive strain are shown in Figures 7 and 8, respectively.

As shown by the deformation mode of the empty panel in Figure 7, the buckling and post-buckling of corrugated core web members and vertical legs of the Y-shaped core dominated its compressive process. The corrugated core web member and vertical leg buckling caused the dramatic and immediate decline of compressive strength after it reached its peak, which is similar to the corrugated sandwich panel [25], and the loading capability and energy absorption efficiency were strongly limited. Thus, structure design against buckling is proposed to increase loading capability and energy absorption, which was the purpose of the present study.

In contrast, the foam-filled panel has a more complicated deformation mode as shown in Figure 7. As shown in the red ellipse area in Figure 7, compared with the empty panel, multiple plastic hinges can be seen from the Y-shaped core of the foam-filled core. A higher order buckling mode requires much higher buckling load. In other words, the corrugated core web members and vertical legs of the foam-filled panel have a much shorter wavelength, similar to the foam-filled metallic tubes [1]. The complicated deformation mode is caused by the sufficient lateral support supplied by aluminum foam, leading to the higher compressive peak loading force. In addition, aluminum foam can also support the corrugated core web members and vertical legs after buckling, therefore; the compressive load of the foam-filled panel can be kept at a high level after its peak. After the densification of the filled aluminum foam occurred locally, the stress-strain curve rose again. Therefore, the energy absorption per unit volume W_v and per unit mass W_m of the foam-filled panel increased dramatically due to aluminum foam filling.



Figure 7. Images of both empty and aluminum foam-filled Y-shape cored sandwich panels under different compressive strain illustrating the deformation history, t = 0.41 mm.



Figure 8. Simulated deformation modes of empty and aluminum foam-filled Y-shape cored sandwich panels under different compressive strains. The deformation of Y-shaped core member in the foam-filled panel shows more complicated deformation modes due to aluminum foam filling, t = 0.41 mm.

The numerically simulated deformation of both empty and aluminum foam-filled Y-shape cored sandwich panels under various compressive strains is shown in Figure 8. To clearly show the coupling effect, the deformation of the Y-shaped core member in the foam-filled panel is displayed separately. The simulated deformation modes match well with the experimental observation shown in Figure 7. Compared with the empty panels, the foam-filled panels have a much more complicated deformation mode with multiple plastic hinges instead of one as discussed before. In addition, the aluminum foam filling leads to the complicated deformation of the Y-shaped core member in the foam-filled panel,

as shown in Figure 8, which means that the core member in the foam-filled panel is more efficient in load carrying and energy absorption, and this can be suggested to be the main cause of the coupling effect shown in Figure 6.

5. Conclusions

Sandwich structures with aluminum foam-filled Y-shape cored sandwich panels are proposed were fabricated in this study. The effect of aluminum foam filling was studied numerically and experimentally under out-of-plane compressive loads. Conclusions from numerical and experimental results are as follows:

- (1) Aluminum foam filling leads to a significant increase in mechanical properties of Y-shape cored sandwich panels, with specific structural stiffness $E_{33}/\bar{\rho}_c$, normalized compressive stress $\sigma_{33}^{\text{peak}}/(\sigma_y\bar{\rho}_c)$, and specific energy absorption W_{m} increasing up to 2.68, 5.7, and 20 times that of the empty panel, respectively.
- (2) An obvious coupling effect of the foam-filled Y-shape cored sandwich panel was found. The stress–strain curve of the foam-filled sandwich panel was much higher than the sum stress–strain curve of the aluminum foam and empty Y-shape cored sandwich panel, tested separately.
- (3) The numerical results and experimental measurements agree well with each other on both stress-strain curves and deformation modes. The numerical and experimental results demonstrated that the coupling effect is caused by the sufficient lateral supports supplied by aluminum foam to the corrugated core and vertical leg of the Y-shaped core, which leads to a much more complicated deformation mode that may not occur in the empty panel. The coupling effect and excellent performance of aluminum foam caused the significant improvement of mechanical properties.
- (4) With dramatically increased specific strength, stiffness, and energy absorption, the present aluminum foam-filled Y-shape cored sandwich panel is suggested to be effective in load carrying and energy absorption applications.

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