Theoretical and experimental study of foam-filled lattice composite panels under quasi-static compression loading

Zhimin Wu, Weiqing Liu, Lu Wang, Hai Fang, David Hui

Abstract

In this paper, a simple and innovative foam-filled lattice composite panel is proposed to upgrade the peak load and energy absorption capacity. Unlike other foam core sandwich panels, this kind of panels is manufactured through vacuum assisted resin infusion process rather than adhesive bonding. An experimental study was conducted to validate the effectiveness of this panel for increasing the peak strength. The effects of lattice web thickness, lattice web spacing and foam density on initial stiffness, deformability and energy absorbing capacity were also investigated. Test results show that compared to the foam-core composite panels, a maximum of an approximately 1600% increase in the peak strength can be achieved due to the use of lattice webs. Meanwhile, the energy absorption can be enhanced by increasing lattice web thickness and foam density. Furthermore, by using lattice webs, the specimens had higher initial stiffness. A theoretical model was also developed to predict the ultimate peak strength of panels.

1. Introduction

Sandwich panels have been widely used for constructing bridge decks, temporary landing mats and thermal insulation wall boards due to better performance in comparison to other structural materials in terms of enhanced stability, higher strength to weight ratios, better energy absorbing capacity and ease of manufacture and repair. In sandwich panels, low density material, known as core, is usually adopted in combination with high stiffness face sheets to resist high loads [1]. The most common types of core materials include polyvinyl chloride (PVC) foam, polyurethane (PU) foam, balsa wood, honeycombs, polyester foam coremat etc. The main functions of core materials are to absorb energy and provide resistance to face sheets to avoid local buckling.

Extensive experimental studies of composite sandwich panels with balsa wood core have been conducted in the past two decades [2–5]. Osei-Antwi et al. [6] investigated the shear mechanical characterization of composite sandwich panels with balsa wood core. Six specimens, cut from the panels in accordance with the three principal shear planes, were tested. The test results indicated that shear stiffness and strength increased with increasing density of the balsa wood, but they did not change with the use of different adhesive joints in the balsa panels between the lumber blocks. Bekisli and Grenestedt [7] developed a new manufacturing method for the balsa sandwich cores by vacuum assisted resin infusion, and conducted the experimental study on these cores under shear force. The test results revealed that the new manufacturing method can increase stiffness and strength of the balsa sandwich cores. However, the compressive and shear stiffness and strength of balsa wood have very large variations due to the natural and anisotropic characteristics of the material. Hence, a lot of material tests have to be carried out to obtain reliable values for practical design. Furthermore, appropriate fire and corrosion protections should be provided due to the use of wood.

Up to now, many investigations of geometric configurations have been conducted to find more effective lightweight energy absorbing structures [8–21]. Cartié and Fleck [22] studied the compressive strength of foam-cored sandwich panels with pin-reinforcements. The test results showed the compressive strength and energy absorption capacity of the sandwich panels were increased. In the buckling analysis of pin-reinforcements, the foam core was considered as an elastic Winkler foundation in supporting the pins. The compressive strength was governed by elastic buckling of the pins. Furthermore, the relationship between the compressive strength and loading rate was studied. Fan et al. [23] tested a series of multi-layered glass fiber reinforced composite woven textile sandwich panels under quasi-static compression loading. Their test results revealed that energy absorption of the multi-layered panel was greatly improved and far exceeded that...
of the monolayer panel of the same thickness, and the failure mode was progressively monolayer collapses. The authors also conducted the bending tests of multi-layered glass fiber reinforced composite woven textile sandwich panels [24]. The failure mode was associated with the crippling and shear failure within the face sheets, and the load capacity was dictated by the fracture strength of the face sheets. Meanwhile, the authors pointed that the plastic hinge mechanism made the panels to possess a long deflection plateau after the peak strength. As an effectively kind of energy absorbing structures, the egg-box shape has also extensively been investigated [25–27]. Yoo et al. [28] carried out the compressive tests on foam-filled composite egg-box panels to evaluate the energy absorbing capacity. The crack initiation and propagation of composite egg-box cores without foam were observed and analyzed. Furthermore, the possible use of foam-filled composite egg-box panels as a thermal insulation wall board for membrane type liquefied natural gas ships was also evaluated. Although a lot of geometric configurations for energy absorbing structures have been developed in recent years, the majority of them have been applied to various protective packaging and crashworthiness structures for automobiles, ships and aero planes rather than civil engineering structures, because the compressive, shear and bending stiffness of these composite panels are low, the manufacturing process of these geometric configurations is complicated, and the cost of production may stay at a relative high level. Choy et al. [29] developed two types of sandwich panels, namely the fiber inserted foam panels and the aluminum foil covered panels. Their test results proved that the bending stiffness of these panels was increased. However, these panels were used to reduce the noise and isolate the vibration in the air conditioning. Hence, the composite panels with these geometric configurations are hardly extended to civil engineering field.

Chen and Davalos have investigated the strength and stiffness properties of composite sandwich deck panels with sinusoidal core geometry in the past few years. The compressive and shear tests of FRP sandwich deck panels with sinusoidal core geometry have been conducted [30]. Chopped strand mat, composed of E-glass fibers and polyester resin, was used for the core material. The test results showed that the typical shear failure mode was delamination at the core-face sheet bonding interface, and the maximum strength of these panels was determined by the number of bonding layers and core thickness. An analytical model for the buckling capacity of FRP panels with two loaded edges partially constrained was proposed by Davalos and Chen [31]. By considering the skin effect, Chen and Davalos [32] obtained an accurate solution of the transverse shear modulus and the interfacial stress distribution for sandwich structures with sinusoidal core. However, in their studies, the critical buckling stress of sinusoidal core is usually low, which is obviously caused by the absence of restriction from foam core. Hence the compressive strength of panels cannot be improved. Meanwhile, the energy absorbing capacity of panels was not evaluated.

To address the aforementioned shortcoming, a simple and innovative foam-filled lattice composite panel, manufactured through vacuum assisted resin infusion process [33], is developed in this study, as shown in Fig. 1. The face sheets, lattice webs and foam cores are combined by vacuum infusing resin, which can enhance the peel resistance between face sheets and foam cores. Unlike other foam-core sandwich composite panels, the compressive strength of foam is improved due to the confinement effects provided by lattice webs, and the foam cores can also restrict the local buckling of the lattice webs. Hence, the compressive strength of foam-filled lattice composite panels can be improved significantly. An experimental study was conducted to validate the effectiveness of this new type of panel. The peak strength, initial stiffness, defor-mability and energy absorbing capacity were investigated. A theoretical model was also developed to predict the ultimate peak strength of panels.

2. Manufacture process

The manufacture process can be divided into the following six steps: (i) four GFRP mats are placed on a large flat board as shown in Fig. 2(a), and the fiber orientation angle is 0/90° to the panel horizontal axis; (ii) the foams are cut into cubes according to the design dimensions, and then wrapped using GFRP with ±45° fiber orientation angle see Fig. 2(b); (iii) to place four GFRP mats on the foam cores, and the fiber orientation angle is also 0/90° to the panel horizontal axis; (iv) before vacuum infusing UPR, the stripping cloth, diversion cloth and a thicker cover plate which is used to make the face board flat are installed, respectively, as shown in Fig. 2(d); (v) the unsaturated polyester resin is infused into the vacuum bag due to the effect of atmospheric pressure (see Fig. 2(e)); (vi) After UPR curing, the manufacture of foam-filled lattice composite panels is completed, and then the panels are cut in accordance with special requirements, as shown in Fig. 2(f).

3. Theoretical model

3.1. Local buckling of the GFRP web

The local buckling of the GFRP web can be analyzed using elastic foundation model, as shown in Fig. 3(a). The foam is represented by the spring with a stiffness of k (per unit width and length). In accordance with classical theory of elastic stability [34], the governing differential equation for the stability analysis of web is expressed as

![Fig. 1. The foam-filled lattice composite panels (a) photo of Specimen HST25SD6 and (b) schematic diagram.](image-url)
Fig. 2. The vacuum infusion molding process (a) manufacturing step i, (b) manufacturing step ii, (c) manufacturing step iii, (d) manufacturing step iv, (e) manufacturing step v and (f) manufacturing step vi.

Fig. 3. Theoretical model (a) elastic foundation model; (b) local buckling calculation and (c) closed web-foam core element (Part I) and unclosed web-foam core element (Part II).
\[ \begin{align*}
D &= \frac{E}{2(1-\nu)} \left( \frac{\partial^2 w}{\partial x^2} + 2\frac{\partial^2 w}{\partial x \partial y} + \frac{\partial^2 w}{\partial y^2} \right) = N_x \left( \frac{\partial^2 w}{\partial x^2} \right) + 2N_{xy} \frac{\partial^2 w}{\partial x \partial y} + N_y \frac{\partial^2 w}{\partial y^2} 
\end{align*} \]

where \( D \) is the bending stiffness of the web, which can be determined by

\[ D = \frac{E t^3}{12(1-\nu^2)} \]

where \( E \) and \( \nu \) are Young’s modulus and Poisson’s ratio of web, respectively.

The energy associated with the web deforming \((U_1)\) and the energy associated with the applied loading \((U_2)\) are respectively given by

\[ \begin{align*}
U_1 &= \frac{D}{2} \int \int \left\{ \left( \frac{\partial^2 w}{\partial x^2} \right)^2 + \frac{2}{(1-\nu)} \left[ \left( \frac{\partial^2 w}{\partial x \partial y} \right)^2 - \left( \frac{\partial^2 w}{\partial y^2} \right)^2 \right] \right\} d_x d_y \\
U_2 &= \frac{1}{2} \int \int \left[ N_x \left( \frac{\partial w}{\partial x} \right)^2 + 2N_{xy} \left( \frac{\partial w}{\partial x} \frac{\partial w}{\partial y} \right) + N_y \left( \frac{\partial w}{\partial y} \right)^2 \right] d_x d_y
\end{align*} \]

The loaded edges of web are fixed supports, and unloaded edges are simply supports. The web is only subjected to a uniform axial compression in the \( x \)-direction. A half buckling wave length in the \( x \)-direction, the boundary conditions of web at the loaded and unloaded edges are

when \( x = 0 \) or \( x = h \), \( w = 0 \) and \( dw/dx = 0 \)

when \( y = 0 \) or \( y = b \), \( w = 0 \) and \( \partial^2 w/\partial x^2 = 0 \)

Assuming that the deflection functions in the \( x \) and \( y \) directions are the cosine and sine functions, respectively, the deformed shape can be expressed as

\[ w = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} A_{mn} \left( 1 - \cos \frac{2m\pi x}{h} \right) \sin \frac{n\pi y}{b} \]

The total potential energy of the GFRP web \((E)\) is given as

\[ E = U_1 + U_2 + U_3 \]

where \( U_3 \) is the energy associated with elastic foundation, defined as

\[ U_3 = \frac{1}{2} \int \int kw^2 d_x d_y \]

According to the principle of minimum potential energy,

\[ \frac{\partial E}{\partial A_{mn}} = 0 \]

The critical buckling stress \((f_c)\) can be calculated by

\[ f_c = \frac{D \pi^4 (16b^4 m^4 + 8k^2 b^2 m^2 n^2 + 6h^2 n^4) + 3kh^2 b^4}{4\pi^2 h^2 b^2 m^2 t} \]

3.2. Ultimate axial load capacity

The panel can be considered as consisting of closed web-foam core (CWFC) element (Part I) and unclosed web-foam core (UWFC) element (Part II), as shown in Fig. 3(c). For the CWFC element, the depth and width are \( a \) and \( b \), respectively. The thickness of web is \( t/2 \). By considering force equilibrium, the theoretical peak strength of the CWFC element \((P_{c,pre})\) can be expressed as

\[ P_{c,pre} = 0.85 f_w A_t + f_w A_w \]

where \( A_w \) and \( A_t \) are cross-sectional areas of the web and foam, respectively, \( f_w \) is the axial compressive strength of web, and \( f_{ct} \) is the axial compression strength of the confined foam, which can be calculated by

\[ f_{ct} = 1 + k_f \frac{f_l}{f_w} \]

where \( f_l \) is the compressive strength of the unconfined foam, \( k_f \) is the effectiveness coefficient of confinement, which is equal to 2.98 \([35]\), \( f_l \) is the lateral confining pressure, and \( k_f \) is the shape factor, which can be calculated by

\[ k_f = \frac{b A_t}{A_w} \]

\[ A_w = \frac{1 - [((b/a)(a - 2R_s) + (a/b)(b - 2R_s)^2)]}{3A_y} \]

where \( A_w \) is the effective confinement area, and \( R_s \) is the corner radius.

Teng et al. \([35]\) proposed the following formula to calculate the lateral confining pressure \( f_l \) of confined foam:

\[ f_l = \frac{f_{w,t}}{2\sqrt{a^2 + b^2}} \]

where \( f_{w,t} \) is the tension strength of web.

For the UWFC element, because the GFRP web cannot provide the effective lateral confinement pressure to the foam, the effect of compressive strength of foam on the ultimate peak strength can be ignored. Hence, the theoretical peak strength of the UWFC element \((P_{w,pre})\) can be expressed as

\[ P_{w,pre} = f_w A_w \]

If a local buckling failure occurs, the \( f_w \) should be replaced by \( f_{ct} \) in Eq. (15).

Then, the theoretical ultimate peak strength of panels \((P_{pre})\) can be expressed as

\[ P_{pre} = \sum P_{c,pre} + \sum P_{w,pre} \]

4. Experimental program

4.1. Test specimens

The specimens were manufactured using a vacuum assisted resin infusion process at Nanjing University of Technology. The E-glass weave fabrics, referred to simply as GFRP, and HS-2101-G100 unsaturated polyester resin (UPR) were used for face sheets and webs. The panels were filled urethane foams (UF) with variation density (40 kg/m³, 60 kg/m³ and 80 kg/m³). During vacuum infusion molding process, methyl ethyl ketone peroxide (MEKP) was used to be the initiator of the unsaturated polyester resin.

In this study, 20 specimens were manufactured and tested. The specimen was cut from the panels, and it was representative of a symmetric volume element of the structure when subjected to compression loading, as shown in Fig. 1(a). All specimens had the same width \((w = 200 \text{ mm})\) and length \((d = 200 \text{ mm})\). Specimens HS4D, HS6D, H7D6 and H5D8 were control specimens without webs to demonstrate the mechanical performance of the normal foam core GFRP sandwich panels. The other specimens were strengthened by webs with varying foam density (\( \rho \)), thickness of the lattice web (\( t \)) and spacing of the lattice web (\( s \)). The details of specimens are given in Table 1.
The initial stiffness of a panel is defined as the slope of the load–displacement curve. The initial stiffness $K_1$ is given by Eq. (17):

$$K_1 = \frac{P_y}{\Delta_y}$$  \hspace{1cm} (17)

where $P_y$ and $\Delta_y$ are yield load and corresponding yield displacement, respectively. According to the load–displacement curves as shown in Figs. 5–7, it should be noted that the specimens exhibited an approximate linear behavior until failure occurs, hence, the yield load ($P_y$) could be replaced by peak load ($P_u$) in Eq. (17).

The test results of all the specimens, including the peak strength ($P_u$), initial stiffness ($K_1$), stroke efficiency ($S_E$) and specific energy absorption ($S_A$), are summarized in Table 4. Figs. 5 and 8(a) show the effects of lattice web thickness on the $P_u$ and $K_1$ of panels. Compared to Specimen H5D6 ($P_u = 18.09$ kN, $K_1 = 2.99$ kN/mm), the $P_u$ of Specimens H7T2S7D6, H7T4S7D6 and H7T7S7D6 increased by 447.8%, 1317.3% and 2377.3%, respectively, and the $K_1$ of Specimens H7T2S7D6, H7T4S7D6 and H7T7S7D6 increased by 2051.8%, 4535.1% and 6416.4%, respectively. Compared to Specimen H5D6 ($P_u = 20.15$ kN, $K_1 = 4.01$ kN/mm), the $P_u$ of Specimens H7T2S7D6, H7T4S7D6 and H7T7S7D6 increased by 698.9%, 1523.7% and 1581.3%, respectively, and the $K_1$ of Specimens H7T2S7D6, H7T4S7D6 and H7T7S7D6 increased by 1375.8%, 3062.3% and 4700.2%, respectively. Compared to...
Specimen H5D4 ($P_u = 4.66$ kN) and H5D8 ($P_u = 35.23$ kN), the $P_u$ of Specimens H5T2S5D4 and H5T2S5D8 increased by 5314.4% and 807.2%, respectively. This may be due to the fact that thicker web can provide higher lateral confining pressure to the foam as presented in Eq. (14), then the compressive strength of the confined foam can be enhanced. Meanwhile, the thicker web can lead to a larger axial stiffness. Hence, the use of thicker web can improve the strength and initial stiffness of panels significantly.

Figs. 6 and 8(b) illustrate the effects of lattice web spacing on the $P_u$ and $K_1$ of panels. According to Figs. 6(a) and 8(b), for the specimens with 70 mm web height, 2.4 mm web thickness and 60 kg/m$^3$ foam density, the $P_u$ and $K_1$ of Specimen H7T2S5D6 ($s = 50$ mm) were 278.23 kN and 102.67 kN/mm, respectively, which were 72.8% and 1700.5% larger than the $P_u$ of Specimen H7T2S7D6 ($s = 70$ mm) and H7T2S1D6 ($s = 100$ mm), respectively, and 73.5% and 84.4% larger than the $K_1$ of Specimen H7T2S7D6.
and H7T2S1D6, respectively. According to Figs. 6(b) and 8(b), for the specimens with 70 mm web height, 6.8 mm web thickness and 60 kg/m$^3$ foam density, the $P_u$ and $K_1$ of Specimen H7T7S5D6 ($s = 50$ mm) were 624.31 kN and 219.09 kN/mm, respectively, which were 84.3% and 118.6% larger than the $P_u$ of Specimen H7T7S7D6 ($s = 70$ mm) and H7T2S1D6 ($s = 100$ mm), respectively, and 13.8% and 91.8% larger than the $K_1$ of Specimen H7T2S7D6 and H7T2S1D6, respectively. According to Eq. (14), the smaller web spacing can result in a larger lateral confining pressure to the foam, which can improve the compressive strength of the confined foam. Therefore, decreasing the web spacing can increase the peak strength of panels.

Figs. 7 and 8(c) illustrate the effects of foam density on the $P_u$ and $K_1$ of the panels. Compared to Specimen H5T2S5D4 ($P_u = 252.31$ kN, $K_1 = 162.78$ kN/mm), the $P_u$ of Specimens H5T2S5D6 and H5T2S5D8 increased by 5.1% and 26.7%, respectively, and the $K_1$ of Specimens H5T2S5D6 and H5T2S5D8 increased by 14.7% and 24.3%, respectively. Compared to Specimen H1T2S1D4 ($P_u = 308.10$ kN, $K_1 = 174.07$ kN/mm), the $P_u$ of Specimens H1T2S1D6 and H1T2S1D8 increased by 6.4% and 15.9%, respectively, and the $K_1$ of Specimens H1T2S1D6 and H1T2S1D8 increased by 8.2% and 22.1%, respectively. The foam with higher density also behaves stiffer. Hence higher density foam can provide much more resistance to the applied loads. Therefore, a larger foam density can give a higher peak strength and initial stiffness.

5.2. Compressive behavior and failure modes

According to the load–displacement curves, the deformation of specimens can be divided into three stages: linear-elastic stage, post-yield stage and foam densification stage. All specimens exhibited a linear-elastic response up to failure at the elastic stage. In the post-yield stage, the compressive load capacity decreased sharply, which was associated with buckling of lattice webs, as shown in Fig. 9(b). The compressive load capacity of lattice composite panels roughly stayed at a half of peak strength level, while the compressive load capacity of control specimens kept peak load level. In the foam densification stage, the compressive load capacity of panels increased, but the deformation of panels was very large. With an increasing applied load, the buckled webs violently extruded the foam, which resulted in crushing of the foam, as shown in Fig. 9(c).

For the sandwich members, there are usually five failure modes including face sheet compressive/tensile failure, core shear failure, delamination, face sheet wrinkling and core indentation failure. But all of them usually occurred in the bending tests. The core shear and indentation failure usually occurred when the sandwich...
panels subjected to the concentrated compression loading. In this study, the failure mode of all the specimens was quite similar. However, the mentioned failure modes were not observed in this study because sandwich panels were tested under uniform distributed axial compression loading. Due to the use of the GFRP web, the failure modes can be categorized as two primary types: (1) GFRP web compressive failure and (2) GFRP web local buckling failure. The microscopic phenomena which originate the corresponding failure modes can be summarized, respectively, as follows: (1) the compressive stress of the web reaches its yield stress before the occurrence of the local buckling, and (2) the critical buckling stress of the web is less than its yield stress. According to the critical buckling stress obtained from Eq. (9), the failure mode of panels can be judged.

5.3. Stroke efficiency

The stroke efficiency \( \left( S_{te} \right) \) is introduced to evaluate the deformability of a panel. The load–displacement responses of the specimens as shown in Figs. 4–6 can be idealized as a quadrilateral curve (Fig. 10). Because specimens exhibited an approximate linear response up to failure, a line OA can be considered as a tangent line to the load–displacement curve before reaching the peak strength. The line BC can be drawn according to the average value of the compressive strength in the post-yield part. A tangent line CD to the load–displacement curve in the region of densification of foam can be drawn and its intersection point with line BC is point C. The horizontal coordinate value corresponding to point C is the stroke length \( \left( \Delta_s \right) \). The stroke efficiency \([39]\) is defined as the ratio of the stroke length to the height of a panel \( H \), thus

\[ S_{te} = \frac{\Delta_s}{H} \]  \hspace{1cm} (18)
Fig. 11(a) shows a distinct decrease of the measured stroke efficiencies with increasing web thickness. The $S_{te}$ of Specimens H5D6 and H7D6 (without web) were largest compared to the corresponding lattice web composite panels. The $S_{te}$ of Specimens H5T2S7D6 and H7T7S7D6 with 2.4 mm lattice web thickness reduced to 62.6% and 67.9%, respectively. The panels with the thickest lattice webs had the lowest values of $S_{te}$ (57.9% for H5T5S7D6, and 59.8% for H7T5S7D6). The reason of this phenomenon was that the thicker webs can lead to the larger axial stiffness of the panel, hence, the stroke length becomes small for a given compressive load.

Fig. 11(b) shows a slight increase of the measured stroke efficiencies with increasing lattice web spacing. Compared to Specimen H7T2S5D6 ($s = 50$ mm), the $S_{te}$ of Specimens H7T2S7D6 ($s = 70$ mm) and H7T2S1D6 ($s = 100$ mm) increased by 4.3% and 12.1%, respectively. Compared to Specimen H7T2S5D6 ($s = 50$ mm), the $S_{te}$ of Specimens H7T7S7D6 ($s = 70$ mm) and H7T7S1D6 ($s = 100$ mm) increased by 6.9% and 14.9%, respectively. Because the larger web spacing can give a smaller volume ratio of the web to the whole panel, hence, the axial stiffness of the panel decrease, which lead to an increase in the stroke length.

Fig. 11(c) shows a reduction of the measured stroke efficiencies with increasing foam density.

For Specimen H5T2S5D4 with 40 kg/m$^3$ foam density, the measured stroke efficiency was 56.1%, while for Specimen H5T2S5D8, the $S_{te}$ reduced to value of 44.7% due to the higher foam density ($\rho = 80$ kg/m$^3$). Although the difference in the web height and spacing, both curves in Fig. 10(c) shows a similar trend. The $S_{te}$ of Specimen H1T2S1D4 with 40 kg/m$^3$ foam density was 28.0%, which was 12.4% and 15.1% larger than that of Specimen H1T2S1D6 ($\rho = 60$ kg/m$^3$) and Specimen H1T2S1D6 ($\rho = 60$ kg/m$^3$), respectively. Seitzberger et al. [39] proposed that the reduction of the stroke efficiency is related to the foam behavior. With increasing foam density, the region of densification, where the compressive force starts to increase steeply, was shifted to lower values of the compressive strain. The foam suffered very large compressive strains and prevented the deformation of the lattice webs, which reduced the stroke length of the panels.

5.4. Specific energy absorption

The specific energy absorption ($S_e$) was adopted to evaluate the “mass efficiency” of a panel, which is defined as [39]:

$$S_e = \frac{W(\Delta e)}{m}$$

Fig. 11. The stroke efficiency of the panels (a) the effects of lattice web thickness; (b) the effects of lattice web spacing and (c) the effects of foam density.
where $m$ is the total mass of a panel, and $W$ is the total energy, which is given by Eq. (20):

$$W(\Delta) = \int_0^P (\Delta) d\Delta \tag{20}$$

where $P$ is the applied compressive force, and $\Delta$ is the displacement of specimen with integration variable $\Delta$. Assuming that the contribution due to elastic deformations is negligible, $W$ can approximately be regarded as the energy dissipated by plastic deformation.

Fig. 12(a) shows the effects of lattice web thickness on the specific energy absorption of the panels. For the specimens with 70 mm web height, 70 mm web spacing and 60 kg/m$^3$ foam density, the $S_e$ of Specimen H7T7S7D6 ($t=7.2$ mm) was 4.3, which was 207.1%, 30.3% and 10.3% larger than that of Specimen H7D6 (without lattice webs), H7T2S7D6 ($t=2.4$ mm) and H7T4S7D6 ($t=4.8$ mm), respectively. For the specimens with 50 mm web height, 70 mm web spacing and 60 kg/m$^3$ foam density, the $S_e$ of Specimen H5T7S7D6 ($t=7.2$ mm) was 4.1, which was 485.7%, 141.2% and 17.1% larger than the $S_e$ of Specimen H5D6 (without lattice webs), H5T2S7D6 ($t=2.4$ mm) and H5T4S7D6 ($t=4.8$ mm), respectively. Hence, the lattice web thickness can play an important role in increasing the energy absorption of the panels.

Fig. 12(b) shows the effects of lattice web spacing on the specific energy absorption of the panels. For the specimens with 70 mm web height, 2.4 mm web thickness and 60 kg/m$^3$ foam density, the $S_e$ of Specimen H7T2S5D6 ($s=50$ mm) was largest, which was equal to 3.9, the $S_e$ of Specimens H7T7S5D6 ($s=70$ mm) and H7T8S5D6 ($s=100$ mm) were 3.3 and 2.4, respectively. For the specimens with 70 mm web height, 7.2 mm web thickness and 60 kg/m$^3$ foam density, the $S_e$ of Specimen H7T7S5D6 ($s=50$ mm) was largest, which was equal to 5.2, the $S_e$ of Specimens H7T7S7D6 ($s=70$ mm) and H7T7S1D6 ($s=100$ mm) were 4.3 and 3.6, respectively. The test results indicated that the smaller lattice web spacing of the panels can achieve the larger energy absorption.

Fig. 12(c) shows the effects of foam density on the specific energy absorption of the panels. For the specimens with 50 mm web height, 2.4 mm web thickness and 50 mm web spacing, the $S_e$ of Specimen H1T2S5D4 ($\rho=40$ kg/m$^3$) was 2.6, which was 19.2% and 34.6% smaller than that of Specimen H1T2S5D6 ($\rho=60$ kg/m$^3$) and H1T2S5D8 ($\rho=80$ kg/m$^3$), respectively. For the specimens with 100 mm web height, 2.4 mm web thickness and 100 mm web spacing, the $S_e$ of Specimens H1T2S1D4 ($\rho=40$ kg/m$^3$) was 3.7, which was 8.1% and 18.9% smaller than that of Specimen H1T2S1D6 ($\rho=60$ kg/m$^3$) and H1T2S1D8 ($\rho=80$ kg/m$^3$), respectively. Thus, the energy absorption of the panels can be enhanced using the foam with the higher density.

6. Comparison with available experimental results

Chen and Davalos [30] tested three FRP sandwich deck panels with sinusoidal core geometry under compression loading. The face sheets and cores consisted of chopped strand mat. For each specimen, the volume ratio of the core respect to the whole panel ($\eta$) was calculated. Table 5 compares the peak strength and initial stiffness presented in Chen and Davalos [30] with those of Specimen H5T7S7D6 because the value of $\eta$ of Specimen H5T7S7D6 is similar with their specimens. Compared to Specimen H5T7S7D6,
the $P_\text{l,chen}$ of Specimens B1C2, B2C2 and B3C2 decrease to 34.7%, 36.4% and 39.5%, respectively, meanwhile, the $K_\text{l,chen}$ of Specimens B1C2, B2C2 and B3C2 decrease to 44.3%, 76.1% and 70.0%, respectively. The reason is that for the specimen H5T7S7D6, the critical buckling stress of web can be increased due to the restriction from foam cores, and the compressive strength of the foam is also improved because of the confinement provided by webs. Hence, even the value of $\eta$ of Specimen H5T7S7D6 is slightly smaller, larger peak strength and initial stiffness can be achieved.

7. Comparison with available experimental results

Table 4 summarized the theoretical ultimate peak strength of panels. During the calculation, Specimens H5T2S5D4, H5T2S5D6, H5T2S5D8 and H7T2S5D8 failed by local buckling of web. The critical buckling stresses of them were 36 MPa, 40 MPa, 54 MPa and 51 MPa, respectively. For the foam-filled lattice composite panels, the largest variation between theoretical and experimental results in the ultimate peak strength was 18%, which occurred in Specimen H5T2S5D8. In general, comparing the theoretical and experimental ultimate peak strengths reveals that the proposed theoretical model is able to conservatively estimate the actual ultimate peak strength of panels under quasi-static compression loading with an average underestimation of 3%.

8. Conclusions

This paper presents an experimental investigation on the foam-filled lattice composite panels under quasi-static axial compression loading. The main findings of this study are summarized as follows:

(1) A kind of foam-filled lattice composite panels applied to civil engineering field was developed through vacuum assisted resin infusion process. The comparison between the available test results of Chen and Davalos [30] and the test results were presented. These panels had the characteristics of high compressive stiffness and strength, and strong energy absorbing capacity.

(2) The experimental results show that compared to the foam-filled composite panels, a maximum of an approximately 1600% increase in the peak load of panels can be achieved due to the use of lattice webs.

(3) The thicker lattice web and smaller lattice web spacing can enhance the peak load of panels significantly, but the effects of foam density on the peak load of panels are small.

(4) A quadri-linear curve was proposed to idealize the load–displacement responses of panels. The stroke length can be determined according to the quadri-linear curve.

(5) The thinner lattice web and larger lattice web spacing can improve stroke efficiency of panels, while the larger foam density can decrease the stroke efficiency of panels because the larger density foam, suffered larger compressive strain, can provide much more resistance to prevent the folds from touching each other.

(6) The energy absorption of panels is affected by lattice web thickness, lattice web spacing and foam density. Larger energy absorption can be achieved by increasing the lattice web thickness and foam density and decreasing the web spacing.

(7) Overall, it has been demonstrated that the foam-filled lattice composite panels exhibited better performance than the normal foam-core sandwich panels. It is expected that the foam-filled lattice composite panels can be widely used as bridge decks, formworks and wall boards.

Acknowledgements

The research described here was supported by the Key Program of National Natural Science Foundation of China (Grant No. 51238003), Natural Natural Science Foundation for the Youth (Grant No. 51008157) and Key University Science Research Project of Jiangsu Province (Grant No. 12KJA580002).

References