Mechanical behavior of sandwich panels with hollow Al–Si tubes core construction

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Abstract

A new type of lightweight sandwich panels consisting of vertically aligned hollow Al–Si alloy tubes as core construction and carbon fiber composite face sheets was designed. The hollow Al–Si alloy tubes were fabricated using precision casting and were bonded to the face sheets using an epoxy adhesive. The out-of-plane compression (i.e. core crushing), in-plane compression, and three-point bending response of the panels were tested until failure. The hollow Al–Si alloy tubes core configuration show superior specific strength under crushing compared to common metallic and stochastic foam cores. Under in-plane compression and three-point bending, the buckling of face sheets and debonding of hollow cores from the face sheets were observed. Simple analytical relationships based on the concepts of mechanics of materials were provided for the compression tests, which estimate the sandwich panels’ strength with high fidelity. For three-point bending, detailed finite element analysis was used to model the response and initial failure of the sandwich panels.

1. Introduction

The interest in metallic sandwich panels with cellular cores has grown rapidly over the last decade for lightweight multi-functional structural systems [1–5]. Metallic sandwich panels have been traditionally made of stochastic cores such as aluminum alloy foams [6,7] or micro-architecture lattice materials such as the hexagonal honeycomb [8,9]. These sandwich panels have superior mechanical properties to their solid plate counterpart (of equal mass); however, their closed-cell configuration limits their multi-functional applications [10–14]. On the other hand, open-cell cellular structures and lattices possess mechanical properties comparable to most closed-cell cellular structures [15–21]. In addition, their open-cell configuration allows heat exchange along the panel core, making them attractive candidates for development of multi-functional structural systems. This includes three-dimensional periodic truss cores, such as pyramidal, tetrahedral or octet-truss core with high nodal connectivity [22,23].

In the present paper, a new type of lightweight sandwich panel with hollow Al–Si alloy tubes core is designed and manufactured. The Al–Si alloys are widely used in aerospace, marine, automotive and other engineering applications due to their low weight, excellent casting properties and corrosion resistance [24]. The details of the fabrication method for the Al–Si alloy tubes and sandwich panels are provided in Section 2. In Section 3, we study the behavior of the core under crushing (e.g. out-of-plane compression of the sandwich panels), as well the mechanical response of the sandwich panel under in-plane compression and three-point bending. In all experiments, the specimens were loaded up to large deformation and failure to gain insight into the mechanisms of deformation, failure and fracture of the sandwich panels under different mechanical loadings.

2. Design and fabrication

The core construction of the sandwich panels consists of Al–Si alloy hollow tubes, made using the precision casting, as shown in Fig. 1. The casting process involves a furnace, pattern (a hollow rubber tube), and a sand mold. The pattern has the same dimensions as the Al–Si alloy tubes and was used to form the casting cavities in the sand mold. The Al–Si alloy was melted in the furnace, ladled and poured into the cavity of the sand mold. After the solidification of the alloy, the casted Al–Si tube was removed from the sand mold.

The chemical composition (wt.%) of the Al–Si alloy is as follows: Mg (0.8–1.2%), Si (0.4–0.8%), iron (0.7%), copper (0.15–0.4%), zinc (0.25%), titanium (0.15%) and manganese (0.04–0.35%). The material properties of the Al–Si alloy depend the solidification parameters (e.g. the crystallization rate and the temperature gradient) [25–27]. Here, the Al–Si alloy has the Young’s modulus of E = 72 GPa and the tensile strength, σ = 251 MPa [28]. The flat face sheets were made of continuous carbon fiber reinforced epoxy resin composite prepreg sheets with thickness 0.175 mm. The tubes were bonded to the face sheets using an adhesive (08–57, Heilongjiang...
Institute of Petrochemical) and were aligned at constant distances in the two in-plane direction of sandwich panels, denoted by \(a\) and \(b\), in both in-plane directions of the panel. Table 1 gives the material properties of the Al–Si alloy, the carbon fiber-reinforced composite and adhesive used in the fabrication of the sandwich panel.

Fig. 2a shows the schematic of a unit cell of the sandwich panel, where \(r\), \(R\), and \(h\) are the inner radius, outer radius and height of each Al–Si hollow tube, respectively, \(d\) and \(L\) are the thickness and radius of the rings at the two ends of the tube. The relative density of the core \(\rho\) is given by

\[
\rho = \frac{\pi(R^2 - r^2)h + 2(L^2 - R^2)d}{abh}
\]

In our study, the tube's geometry was constant with \(r = 2\) mm, \(R = 3\) mm, \(h = 10\) mm, \(d = 1\) mm and \(L = 4\) mm and \(a\) and \(b\) are varying in this study to obtain different core densities. The relative density of the sandwich core was varied by changing the number of tubes per unit surface area of panel (i.e. changing the unit cell dimensions, \(a\) and \(b\)). Fig. 2 shows a sandwich panel with a core relative density \(\rho = 3.35\%\) and face sheet thickness 1 mm. In this case the unit cell of the sandwich panel has the dimensions, \(a = 20\) mm and \(b = 30\) mm.

3. Core behavior and strength

Out-of-plane compression tests were performed to determine the compressive stiffness and strength of the Al–Si tubes core construction, using a screw-driven testing machine (INSTRON 5569). The sandwich panels tested were 80 mm × 80 mm, with a total height of 12.8 mm. Each face sheet was a composite laminate with 8 plies with a sequence [0/45/-45/0]s and thickness 1.4 mm. Fig. 3 shows the crushing response of two sandwich panels with \(\rho = 2.83\%\) (\(a = 26.67\) mm and \(b = 26.67\) mm) and \(\rho = 5.03\%\) (\(a = 20\) mm and \(b = 20\) mm). A simple analytical relation for a tube cores Young's modulus gives

\[
E_c = \frac{\pi R^2 - \pi r^2}{a \times b} E
\]

which yield the Young module, \(E_c = 133.0\) MPa and 236.4 MPa, for the core relative densities, \(\rho = 2.83\%\) and \(\rho = 5.03\%\), respectively. Based on the measured unloading curves, Young's module of the same sandwich cores are 115.1 MPa and 211.5 MPa, respectively, which demonstrates a relatively good agreement with the analytical estimates.

For both sandwich cores, the initial linear response is followed by a nonlinear response regime, which is associated with the plastic deformation of the hollow tubes. Generally, the peak stress (marked by the arrows in Fig. 3) occurs when the failure of tubes is originally observed. The measured peak stresses of 5.46 MPa and 9.38 MPa were measured for tube cores with \(\rho = 2.83\%\) and \(\rho = 5.03\%\), respectively. Fig. 4 displays an image of a failed hollow Al–Si alloy tubes under crushing, showing cracks at approximately 45° that extend between the two ends of the tubes. The analytical relations of the maximum strength can be obtained as follows.

Table 1

<table>
<thead>
<tr>
<th>Material</th>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>T700/TDE85</td>
<td>E11 (GPa)</td>
<td>132</td>
</tr>
<tr>
<td></td>
<td>E12 (GPa)</td>
<td>10.3</td>
</tr>
<tr>
<td>Al–Si alloy (6061)</td>
<td>E22 (GPa)</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>G12 (GPa)</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>G22 (GPa)</td>
<td>3.91</td>
</tr>
<tr>
<td>08–57 Adhesion</td>
<td>Young's modulus (GPa)</td>
<td>251</td>
</tr>
<tr>
<td></td>
<td>Poisson's ratio</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>Room temperature shear strength (MPa)</td>
<td>86.83</td>
</tr>
</tbody>
</table>

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4. In-plane compression of sandwich panels

In this section, we studied the response and failure of the sandwich panels with a hollow Al–Si tube core construction under in-plane compression using a screw-driven testing machine (Instron 5569). The axial compression tests were carried out in the quasi-static regime with a nominal displacement rate of 0.5 mm/min. Fig. 6a shows the load–displacement response of a sandwich panel with $h = 10$ mm, width, $w = 60$ mm, length, $L = 210$ mm and core relative density $\rho = 3.35\%$. Each face sheet had 8 composite plies with the ply sequence $[0/0/90/0]_8$, and thickness $1.4$ mm. The in-plane effective stiffness of the panel is $5.81$ MPa and the effective in-plane strength of the panel, calculated based on the measured peak load of $21451.6$ N, is $\sim 21.7$ MPa. Fig. 6b shows the sandwich panel before and after loading.

Under in-plane compression, the skins remain intact but tend to buckle and bend outward. By neglecting the contribution of the hollow Al–Si alloy tube core, the Euler buckling load $P_b$ can be expressed as

$$P_b = \frac{k^2 \pi^2 D}{L^2}$$

(4)

where $k = 2$ for a panel with built-in ends to prevent rotation, and $D$ is the flexural rigidity of the panel. Assuming that the Poisson ratios of the core in the in-plane direction are negligible, the equivalent flexural rigidity of the composite column can be estimated from the classical laminate composite beam [34], as

$$(EI)_{eq} = \frac{w}{3} \sum_{k=1}^{N} \frac{E_k}{1 - v_{12}^k v_{21}^k} \left( z_k^2 - z_{k-1}^2 \right) + \frac{w}{12} E_p h^3$$

(5)

where the first term is the contribution of face sheets to the flexural rigidity of the composite column and the last term is the contribution of the core, where $N$ is the number of laminate plies, $E_k$ is the Young’s modulus of ply $k$ in the direction of loading, $v_{12}^k$ and $v_{21}^k$ are the Poisson’s ratio of ply $k$ and $z_k$ and $z_{k-1}$ are the distances of the outer and inner surface of the laminate from the panel neutral axis (the middle height of the panel due to symmetry). $E_p$ is the Young’s modulus of the core in the direction of loading. For sandwich panels with a low core density, the contribution of the core in the overall flexural rigidity of the panel is negligible and can be ignored.

When the flexural and shear rigidities are of the same order of magnitude, the interaction between the Euler and shear buckling modes must be taken into consideration for the prediction of the critical load and strength of the sandwich panel. The shear
According to Eq. (7), the critical load of the panel under in-plane compression is 25.2 MPa, about 13.9% larger than the measured strength. The occurrence of the buckling mode at the lower compression load suggests the weakness of the bonding – see Fig. 6b. Initially, the debonding occurs between a few tubes and the face sheets, which results in a small reduction in the load-carrying capacity of the panel, as observed in the force–displacement response shown in Fig. 6a. As the compression test proceeds, the complete debonding of the core from the face sheet occurs abruptly, the face sheet burst apart with a sharp sound and the load–displacement curve drops sharply. The hollow tubes stay intact with no apparent fracture or significant plastic deformation.

5. Three-point bending of sandwich panels

Three-point bending experiments were carried out for sandwich panels using the same test machine as previous sections under the displacement controlled condition. Fig. 7a shows the load–displacement responses obtained in two different trails for a sandwich panel with \( L = 210 \) mm, the span length 150 mm, \( w = 60 \) mm, height 12.8 mm and relative density \( \rho = 1.26\% \). Each face sheet was a composite laminate with eight plies with a sequence \([0/45/-45/0]\), and overall thickness 1.4 mm. Two test results are presented in Fig. 7a and labeled as curve A and curve B, respectively. At the initial stage of deformation, the response curves approximately coincide and the slope of the load–deflection curve is \( \approx 600 \) N/mm. The initial elastic response is followed by a nonlinear regime, where debonding, face wrinkling, delamination and core shearing were observed – see Fig. 7b.

After the initial elastic behavior, the adhesion strength between face sheets and the core is insufficient to sustain the complete integrity of the sandwich panel, and the tubes debond from the top face sheet as it undergoes compression during bending. This debonding is the first apparent failure in the panel and results in a sudden drop in the load-carrying capacity of the panels (at 901.5 N and 1080 N in the two trials of Fig. 7a), while the lower face sheet and the core are still adhered together. As the experiment proceeds, the top face sheet buckles and delamination occurs and propagates between tubes and the shearing force increases in the core. At final stage of the experiment, several cracks were observed in the Al–Si alloy tubes and the tubes completely debond.

Fig. 5. Modified Ashby’s strength–density chart for a wide range of materials with a low relative density. We have added to this chart, the measured properties of the Al–Si hollow tubes core construction.

Fig. 6. In-plane compression of sandwich panels: (a) load–displacement response up to failure and (b) a sandwich panel with the relative density \( \rho = 3.35\% \) before the load is applied and after failure. The deformed panel shows overall buckling and also debonding of the hollow tubes from the composite face sheets.

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Fig. 7. Bending behavior of the sandwich panel: (a) load–displacement response under three-point bending for two different specimens and (b) the deformed configuration in (top) in the elastic regime and (bottom) at the final stage of experiment (deflection = 7 mm, curve B), showing buckling and delamination of the top face sheet, debonding, delamination and core shear.

Fig. 8. (a) Finite element mesh for a sandwich panel with hollow tubes core; (b) deformed configuration and the distribution of von-Mises stress for a sandwich panel with $\rho = 1.26\%$ subjected to $P = 1080$ N in three-point bending.
from the top face sheets. The observed failure mode of the sandwich panel combines debonding, delamination, core shearing and face wrinkling.

The total elastic displacement of the mid-span of a sandwich beam in three-point bending, \( \delta \), is the sum of the flexural and shear deflections [36],

\[
\delta = \frac{PL^3}{48EI_{eq}} + \frac{PL}{4(AG)_{eq}}
\]  

(7)

where \( P \) is the applied load, \( (EI)_{eq} \) the equivalent flexural rigidity of the sandwich panel, Eq. (6) and \( (AG)_{eq} \) is the equivalent shear rigidity, which is dictated by the core shear stiffness [37] and is in the order of \( \nu_hGc \). The deformation of the sandwich panel is mainly due to core shear deflection. Assuming \( (AG)_{eq} = whGc \), the slope of the load–deflection curve is \( \approx 434 \text{ N/mm} \), which is smaller than the experimental value. As the next step, we carried out detailed finite element calculations to simulate the behavior of the sandwich panel subjected to three-point bending. The calculations were carried out using commercial software, ANSYS. In our model, the face sheets were modeled using 8-node shell elements. The tubes were modeled as three-dimensional parts and meshed using 20-node brick solid elements. We also modeled the adhesive layer using 8-node quad solid elements. The mesh size was refined systematically to obtain reliable convergence and mesh size independency. Fig. 8a shows a typical finite element mesh used in our calculations. The boundary condition in the finite element calculations is the same as experiments and discussed above. Fig. 7b shows the deformed configuration and the distribution of the von-Mises stress due to core shear deflection. Assuming \( P = 1080 \text{ N} \) – which was the maximum load measured in our experiment, see Fig. 6a. This load results in the displacement of 1.68 mm in the middle of the top face, which is comparable with the measured value of 1.7 mm. To estimate the failure load of the sandwich panel under three-point bending, we monitored the maximum shear stress in the adhesive layer. At \( P = 1182 \text{ N} \), the maximum shear stress reaches the failure shear strength of the adhesive, given in Table 1. The response obtained from the finite element calculation is shown in Fig. 7a, which, in general, is in a good agreement with the experimental results.

6. Conclusions

Light weight sandwich panels with hollow Al–Si alloy tubes core and carbon fiber reinforced laminated panels were manufactured. The mechanical behavior and failure of the sandwich panel were studied under out-of-plane compression, in-plane compression, and three-point bending tests. The tube core offers high specific strength compared to stochastic and metallic cellular cores and thus, can be used to design light weight multi-functional structures.

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