Shear behavior of aluminum lattice truss sandwich panel structures

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Abstract

Age hardenable 6061 aluminum tetrahedral lattice truss core sandwich panels have been fabricated by folding perforated sheets to form highly flexible cellular cores. Flat or curved sandwich panels can be fabricated by furnace brazing the cores to facesheets. Flat sandwich panels with core relative densities between 2 and 10% have been fabricated and tested in the \( \sigma_{\pm 13} \) shear orientation (minimum shear strength orientation for a tetrahedral lattice) in the fully annealed (O) and aged (T6) conditions. The shear strength of the lattices increased with relative density, parent alloy yield strength and work hardening rate. Analytical stiffness and strength predictions agree well with measured values for all relative densities and parent alloy heat treatments investigated. The stiffness and strength of 6061-T6 aluminum tetrahedral lattice structures are shown to be comparable to those of conventional 5052-H38 aluminum closed cell hexagonal honeycombs and more than 40% stiffer and stronger than flexible honeycombs used for the cores of curved sandwich panels.

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1. Introduction

Millimeter cell size, aluminum alloy lattice structures with various open cell topologies are attracting interest as lightweight core structures for sandwich panel constructions. For bending dominated applications of sandwich panels; the facesheets carry the bending stresses with one facesheet in compression and one in tension and the flexural strength of the panel is governed by the shear response of the core and by the strength of its attachment points (nodes) to the facesheets. The core also increases the flexural stiffness of the panel by providing a separation between the two facesheets.

Lattices appear to be mechanically competitive alternatives to prismatic (corrugated) and perhaps honeycomb structures when configured as the core of a sandwich panel. These lattice sandwich structures are of particular current interest because of their potential fully open interior structure which facilitates multifunctional applications [1–4]. For example, lattice core sandwich panels appear capable of supporting significant structural loads while also facilitating cross flow heat exchange [5–8]. Some structures also enable high authority shape morphing [9–14] and all appear to provide significant high intensity dynamic load protection [15–21]. Lattices are also flexible and are amenable to the creation of singly or compound curved sandwich panels. They may also alleviate some of the delamination and corrosion concerns associated with the use of traditional closed cell honeycomb sandwich panels [22,23].

The emergence of microscale lattice truss structures originally envisioned at the meter scale by Buckminster Fuller [24] has been paced by the development of practical methods for their manufacture [4,25]. Initial efforts to fabricate millimeter scale structures employed investment casting of high fluidity casting alloys such as copper/beryllium [26], aluminum/silicon [27–30] and silicon brass [27]. However, the tortuosity of the lattices and ensuing casting porosity made it difficult to fabricate high quality structures at low relative densities (2–10%) identified as optimal for sandwich panel constructions [31]. While some lattice constructions appear to possess significant tolerance to defects such as occasional weak trusses or nodes [32,33], the low toughness of the materials used to make these as-cast lattice materials have often lacked the mechanical robustness required for the most demanding structural applications [34].

Efforts to exploit the inherent toughness of many wrought engineering alloys led to the development of alternative lattice fabrication approaches based upon perforated metal sheet folding [35]. These folded truss structures can be bonded to each
other or to facesheets by conventional joining techniques such as brazing, transient liquid phase (TLP) bonding or welding techniques to form all metallic lattice truss sandwich panels. Panels fabricated from austenitic stainless steels with tetrahedral [35–37] and pyramidal lattice truss [38–41] topologies have been made by node row folding of a patterned sheet to form the core and TLP bonding to facesheets. Because of the high temperatures normally encountered with TLP bonding, this process results in sandwich panels which remain in a low strength, annealed condition. While these structures appear much more robust than their investment cast counterparts, the reduced strength of their annealed microstructure can limit their potential uses for some structural applications.

The perforated sheet folding method has recently been extended to age hardenable aluminium alloys such as the 6061 system, and tetrahedral lattices made from this alloy have been shown to exhibit high specific compressive strengths (Fig. 1) [42]. Comparisons with other cellular aluminum topologies (Fig. 1), confirm that 6061 aluminum alloy tetrahedral lattice structures are far superior to aluminum open cell metal foams and prismatic corrugations. The compressive response of the tetrahedral lattice was comparable to that of honeycomb panels of similar specific mass and found to be sensitive to the lattices heat treatment condition. Annealed cores with high tangent moduli were more efficient than age hardened structures and significantly exceeded elastic-ideally plastic strength predictions. Inelastic column-buckling models robustly predict the through thickness compressive strengths and resolved the important role of the parent materials post-yield tangent modulus in delaying the onset of unstable inelastic buckling.

Here, we explore the in-plane shear stiffness and strength of these 6061 aluminum tetrahedral lattice structures described above. The measured shear stiffness and strengths of the lattice truss structures are compared to analytical predictions and shown to be comparable to those of other topologies for aluminum based sandwich structures.

2. Fabrication methodology

2.1. Tetrahedral lattice truss fabrication

A detailed description of the fabrication approach for making 6061 aluminum alloy lattice truss structures can be found in Kooistra et al. [42]. Briefly, a folding process was used to bend elongated hexagonal perforated 6061 sheet to create a single layer tetrahedral truss lattice. The folding was accomplished using a paired punch and die tool to fold node rows into regular tetrahedrons with three trusses emanating from each node resulting in a highly flexible core structure.

The unit cell of a tetrahedral lattice is shown in Fig. 2. The relative density, $\bar{\rho}$, of a tetrahedral lattice with 50% occupancy of the available tetrahedral sites is given by ref. [27]:

$$\bar{\rho} = \frac{2}{\sqrt{3} \cos^2 \omega \sin \omega} \left( \frac{t}{l} \right)^2$$  \hspace{1cm} (1)

where $\omega$ is the angle between the truss members and the tetrahedron base plane ($\omega = 54.7^\circ$ for regular tetrahedrons) and $t$ and $l$ are the sheet thickness and truss member length, respectively. The relative density of the lattice was varied here by modification of the sheet thickness and the perforation dimensions to maintain a square truss cross section and a constant truss length (Table 1).

2.2. Sandwich panel fabrication

Sandwich panels were constructed from the folded lattice structures by placing them between 6951 aluminum alloy face sheets clad with a 4343 aluminum–silicon braze alloy. The

![Fig. 2. Tetrahedral unit cell used to derive relative density and mechanical properties. The positive and negative shear directions are also shown. They result in different stress–strain behaviors because of the different truss tensile stretching and compressive buckling configurations.](image-url)
Table 1: Predicted and measured relative densities of tetrahedral lattice truss structures

<table>
<thead>
<tr>
<th>Condition</th>
<th>Model</th>
<th>Pre-braze measurement</th>
<th>Post-braze measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eq. (1)</td>
<td>0.063</td>
<td>0.017 ± 0.003</td>
<td>0.020 ± 0.001</td>
</tr>
<tr>
<td></td>
<td>0.079</td>
<td>0.027 ± 0.004</td>
<td>0.030 ± 0.002</td>
</tr>
<tr>
<td></td>
<td>0.099</td>
<td>0.042 ± 0.004</td>
<td>0.039 ± 0.001</td>
</tr>
<tr>
<td></td>
<td>0.125</td>
<td>0.067 ± 0.003</td>
<td>0.069 ± 0.002</td>
</tr>
<tr>
<td></td>
<td>0.178</td>
<td>0.136 ± 0.002</td>
<td>0.106 ± 0.003</td>
</tr>
</tbody>
</table>

assemblies were coated with a metal-halide flux and placed in a furnace for brazing in air at 595 ± 5 °C for between 5 and 10 min [43]. After air-cooling, the samples were solutionized at 530 °C for 60 min and either furnace cooled for the fully annealed (O) condition or water quenched and aged at 165 °C for 19 h for the aged (T6) condition [44]. Fig. 3 shows an example of one of the sandwich panels with a core relative density, \( \bar{\rho} = 0.039 \).

The nodes of the lattice truss core were ground flat prior to brazing to ensure good contact between the lattice core and the face sheets. This resulted in post-braze measurements of the relative densities slightly higher than those predicted by Eq. (1). Table 1 summarizes the truss geometries, the measured and predicted relative densities. The mean post-braze relative density (reported at a confidence level of 95%) was used to identify the test specimens and for subsequent experimental data normalizations.

Tensile coupons of the 6061 alloy accompanied the cores through each thermal process step and were used to determine the mechanical properties of the parent aluminum alloy in both the O and T6 tempers. Three tensile tests were performed according to ASTM E8 at a strain rate of 10^{-3} s^{-1} for each heat treatment condition [45]. Table 2 shows the mechanical property data for 6061 aluminum in the O and T6 tempers.

### 3. Shear experiments

The sandwich panels were tested according to ASTM C273 using a compression shear plate configuration at a nominal strain rate 10^{-3} s^{-1} at an ambient temperature of 22 °C [46]. The applied force was used to calculate the stress imparted to the sandwich structure, while shear displacement data of the rigid plates was obtained by laser extensometry and the shear strain is simply the displacement divided by the height of the sandwich core.

Initial experiments indicated the need for a rigid bond between the sandwich panel facesheets and shear plates, especially during evaluation of the highest relative density (strongest) cores. The test samples were attached using four mechanisms to prevent premature debonding and/or movement during testing. The grit blasted surfaces were adhesively bonded using an epoxy adhesive (Loctite Hysol® E-120HP). The facesheets were also fastened to the shear plates using steel machine screws. Finally, mechanical locking utilizing a leading edge stop machined into the shear plate and a trailing edge adjustable clamping bar was used to reduce load transfer stresses.

### 4. Results

Fig. 4a and *b shows representative shear stress–strain behavior for the annealed and aged samples loaded in the \( \sigma_{+13} \) direction (see Fig. 2), which corresponds to one truss loaded in compression and the other two in tension (positive orientation). Fig. 4c and d shows representative shear stress–strain behavior for the annealed and aged samples loaded in the negative \( \sigma_{-13} \) direction, where one truss member is loaded in tension and the other two in compression.

The annealed samples tested in the \( \sigma_{+13} \) direction (Fig. 4a) sustained large macroscopic shear strains (as high as 35%) without rupture of the tensile loaded truss members. For these samples there was a small linear response during initial loading, followed by yielding and increased load support. After large deformations (which increased with sample relative density) the tensile truss members underwent strain localization (necking) followed by rupture and a decrease in the load support. Fig. 5 shows photograph of strain localization in a truss member (at 34.1% macroscopic strain) for an annealed sample with \( \bar{\rho} = 0.069 \) sample.

The aged samples (Fig. 4b) exhibited a better defined linear elastic region followed by observable plastic yielding of the tensile truss members. Load support continued to increase until a peak strength was reached. Initiation of truss member rupture then coincided with a sharp decrease in its load carrying capacity. These tensile ruptures were observed to occur at various locations along the truss member length independent of relative density. Fig. 6 shows photographs of an aged sample with a relative density, \( \bar{\rho} = 0.039 \) at various stages of deformation.

### Table 2: Mechanical property data for 6061 aluminum in the O and T6 tempers from the uniaxial Cauchy (true) stress–true strain curves

<table>
<thead>
<tr>
<th>Heat treatment condition</th>
<th>Young’s modulus, ( E_i ) (GPa)</th>
<th>Yield strength, ( \sigma_{ys} ) (MPa)</th>
<th>Ultimate tensile strength, ( \sigma_{Ts} ) (MPa)</th>
<th>Strain at failure, ( \epsilon_f ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annealed (O)</td>
<td>68.6</td>
<td>70</td>
<td>208</td>
<td>21.2</td>
</tr>
<tr>
<td>Aged (T6)</td>
<td>69.1</td>
<td>268</td>
<td>306</td>
<td>15.1</td>
</tr>
</tbody>
</table>
Fig. 4. Shear stress–strain responses for tetrahedral lattice structures. Representative responses are shown for the $\sigma_{+13}$ orientation in the (a) annealed and (b) aged hardened condition and for the $\sigma_{-13}$ orientation in the (c) annealed and (d) aged hardened condition. Note the change in strain axes for the age hardened samples.

The annealed shear samples tested in the (negative) $\sigma_{-13}$ direction (Fig. 4c), also sustained very large macroscopic strains. For these samples there was an initial linear response, followed by yielding and then a period of stably increasing load support. A peak strength was eventually reached, corresponding with the buckling of the compressively loaded truss members. The aged samples tested in the $\sigma_{-13}$ direction (Fig. 4d), also behaved similarly. However, truss buckling was observed to occur at a significantly lower plastic shear strain consistent with the lower tangent modulus of the heat treated condition. Some node debonding was observed in the higher relative density samples as indicated in Fig. 4d.

The stiffnesses for both orientations were determined from unload/reload measurements in the nominally elastic portion of the shear stress strain response. There was no effect of loading direction or heat treatment. Fig. 7 shows a plot of the normalized shear stiffness, $\Gamma = G/(E_s \bar{\rho})$, where $G$ is the shear modulus and $E_s$ is the Young’s modulus. The shear modulus measurements shown in Fig. 7 are the average of two experiments conducted for each orientation and heat treatment (eight measurements per relative density) shown. The data indicate a linear dependence of shear modulus upon relative density and is well fitted by a relation of the form: $G = 0.11 E_s \bar{\rho}$.

The normalized shear 0.2% offset yield strength for the $\sigma_{\pm13}$ orientations for both the annealed and aged samples is plotted versus $\bar{\rho}$ in Fig. 8. The experimental data for the normalized yield strength of both the annealed and aged cores indicate a mild dependence upon relative density for both the positive and
negative oriented shear directions and it can be seen in Fig. 8 that the normalized yield strength increases with relative density. Note that the normalized coefficients shown in Fig. 8 are nearly equivalent for both the annealed and aged lattice cores, indicating a linear dependence upon $\sigma_{ys}$ of the parent alloy.

The normalized peak shear strength $T = \sigma_{pk}/(\sigma_{ys}\bar{\rho})$ of the annealed and aged samples in the $\sigma_{\pm 13}$ orientation is plotted versus $\bar{\rho}$ in Fig. 9. The experimental data for the normalized peak strength of both the annealed and aged cores indicate a mild dependence upon relative density for both the positive and negative oriented shear samples. It can be seen in Fig. 9 that the normalized peak strengths increase with relative density and the rate of increase in the annealed cores is nearly double that of the aged cores. This is indicative of the higher strain hardening rate of 6061 in the annealed condition. For example, the ratio of $\sigma_{TS}/\sigma_{ys}$ is 2.97 for the annealed condition and 1.14 for the aged condition.

5. Micromechanical predictions

Deshpande and Fleck have developed analytical expressions for the mechanical properties of tetrahedral lattice truss cores assuming elastic-ideally plastic struts [27]. Table 3 summarizes their analytical expressions for the shear stiffness, Eqs. (2) and (3), and strength, Eqs. (4) and (5). If the lattice is constructed from slender trusses, they can collapse by elastic buckling. In this case, the shear strength is found by replacing $\sigma_{ys}$ in Eqs. (4) and (5) with the elastic bifurcation stress $\sigma_{cr}$ of the struts, Eq. (6). The factor $k$ depends on the rotational stiffness of the nodes; for a pin-joint that can freely rotate $k = 1$ where $k = 2$ corresponds to a built-in rigid joint. If the truss material has a non-zero post-yield strain hardening rate, inelastic buckling defined by Shanley–Engesser tangent modulus theory determines the lattice strength [47]. The peak compressive strength is then obtained by replacing $\sigma_{ys}$ in Eqs. (4) and (5) with the inelastic bifurcation stress $\sigma_{cr}$ of a compressively loaded column. The inelastic bifurcation stress $\sigma_{cr}$ is given by Eq. (7) where, $E_t$ is the tangent modulus defined as the slope $d\sigma/d\varepsilon$ of the uniaxial stress versus strain curve of the parent material at a stress level, $\sigma_{cr}$ [48].

The shear stiffness in the $\sigma_{\pm 13}$ directions is predicted to be the same and its dependence upon $\bar{\rho}$ is in very good agreement with the experimental data (Fig. 7). The normalized shear strength prediction, Eq. (5), is compared with the experimental data in Fig. 8 using the measured yield strength of the parent aluminum to normalize the results. The experimental results approach the yield strength predictions as the relative density increases for both heat treated conditions and orientations. The discrepancy between predicted and measured yield strengths at low relative density appears to be a manifestation of manufacturing defects introduced during fabrication.

The peak strength of lattice structures is determined by their mechanism of strut failure. This in turn depends on the truss slenderness (cell geometry), strut material properties (i.e. yield strength, Young’s and tangent moduli) and the mode of loading. Peak shear strength predictions are also given in Table 3 for both elastic and inelastic truss buckling. A comparison between
the measured and predicted normalized peak shear strength is shown in Fig. 9 for both test orientations and heat treatment conditions. The peak shear strength prediction drawn on the figures assumes inelastic buckling of the compressed truss members for both node conditions \( k = 1 \) and \( 2 \). Deshpande and Fleck have shown that the in-plane shear strength is periodic for the tetrahedral lattice core and it follows from symmetry conditions that shear strength in the \( \sigma_{\pm 13} \) orientations are equivalent [27]. It is apparent that the plastic buckling model predicts the higher relative density response of both the annealed and age hardened lattices reasonably well using a built-in node assumption. The lower relative density data is better approximated by a pin-jointed truss-facesheet connection condition consistent with less end constraint of slender trusses.

6. Discussion

Numerous studies have addressed sandwich panel design for various lattice truss sandwich structures [41,49–53]. Optimal designs are ascertained by minimization of an objective function (normally weight) for panel bending, subject to multiple constraints [41]. These constraints are normally defined by the operative failure mechanisms: facesheet yielding and buckling and truss member yielding and buckling. For most practical core

Table 3
Analytical expressions for the in-plane shear stiffness and strength of the tetrahedral lattice [27]

<table>
<thead>
<tr>
<th>Mechanical property</th>
<th>Analytical expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear stiffness</td>
<td>( G = G_{13} = \frac{1}{2} E_s \sin^2 2\omega \bar{\rho} )</td>
</tr>
<tr>
<td>Normalized shear stiffness</td>
<td>( \frac{G}{E_s} = \frac{1}{8} \sin^2 2\omega = 0.11 ), for ( \omega = 54.7^\circ )</td>
</tr>
<tr>
<td>Shear strength (plastic yielding)</td>
<td>( \sigma = \sigma_{\pm 13} = \frac{1}{4} \sigma_{ys} \sin 2\omega \bar{\rho} )</td>
</tr>
<tr>
<td>Normalized shear strength (plastic yielding)</td>
<td>( \frac{T}{\sigma_{ys}} = \frac{1}{4} \sin 2\omega = 0.24 ), for ( \omega = 54.7^\circ )</td>
</tr>
<tr>
<td>Shear strength (elastic buckling)</td>
<td>( \sigma = \sigma_{\pm 13} = \frac{1}{4} \sigma_{cr} \sin 2\omega \bar{\rho} ), where ( \sigma_{cr} = \frac{k^2 \pi^2 E_s}{12 \left( \frac{t}{\bar{t}} \right)^2} )</td>
</tr>
<tr>
<td>Shear strength (plastic buckling)</td>
<td>( \sigma = \sigma_{\pm 13} = \frac{1}{4} \sigma_{cr} \sin 2\omega \bar{\rho} ), where ( \sigma_{cr} = \frac{k^2 \pi^2 E_t}{12 \left( \frac{t}{\bar{t}} \right)^2} )</td>
</tr>
</tbody>
</table>
topologies, optimal sandwich panel designs distribute 17–34% of the metal mass in the core, depending on topology with core relative densities <10% and the remainder equally between the top and bottom facesheets [52].

The panels tested here are not optimized in this formal sense, but it is still instructive to compare their response with honeycomb cores made from aluminum alloys of similar strength. The tetrahedral lattice is compared to an aluminum hexagonal honeycomb, and a (reentrant) flexible honeycomb both available from Hexcel Composites (Stamford, CT, USA) under the trade names of HEXWEB® and FLEXCORE®. These honeycombs are made from a 5052-H38 aluminum alloy for which $E_s = 69$ GPa, $\sigma_{ys} = 255$ MPa and $\sigma_{TS} = 290$ MPa [54]. The ratio of $\sigma_{TS}/\sigma_{ys}$ is an indication of the alloy strain hardening capacity. The ratio $\sigma_{TS}/\sigma_{ys}$ for 5052-H38 is very similar to that of the 6061-T6, 1.14 and 1.13, respectively. Both alloys also have similar tensile failure strain values (14 and 17%, respectively) in their high strength conditions. It is therefore possible to assess the normalized lattice truss stiffness and strengths on a purely topological basis.

Fig. 10 shows the stiffness of the tetrahedral lattice together with that of both the regular and flexible honeycomb. The shear stiffness values in the figure correspond to the minimum shear stiffness for both topologies. The tetrahedral lattice shear stiffness is nearly equivalent to the hexagonal honeycomb data and is ~40% stiffer than that of flexible honeycombs of the same core relative density. The tetrahedral lattices therefore appear to be attractive alternatives to conventional and especially flexible honeycombs, for deflection limited applications.

Fig. 11 shows the normalized peak shear strengths for the two honeycomb topologies loaded in the direction corresponding to the honeycombs minimum shear strength. The tetrahedral lattice data is shown for both negative and positive orientations. The two alloys have similar strain hardening characteristics and so we conclude that the tetrahedral lattice topology has an efficiency approaching that of a conventional hexagonal honeycomb.

Fig. 10. The shear stiffness of the 6061-T6 tetrahedral lattices compared to commercially available 5052-H38 honeycomb cores.
and appears significantly superior to flexible honeycomb structures. Recalling the earlier study’s conclusion of comparable compressive strengths for the two topologies, we conclude that tetrahedral lattice structures appear to be promising alternatives for load supporting sandwich panel structures, especially when the structures possess significant curvature.

7. Conclusions

- Tetrahedral lattice cores have been made by folding hexagonally perforated 6061 aluminum alloy sheets. A simple open air furnace brazing technique has then been used to metallurgically bond the tetrahedral cores to 6951 solid facesheets to form sandwich panel structures.

- The shear stiffness and strength was experimentally measured and their behavior was adequately captured by Deshpande and Fleck’s analytical expressions for modulus and strength of tetrahedral lattice truss structures.

- The structural performance of the 6061 tetrahedral lattices lie within the upper and lower bounds of conventional hexagonal honeycomb shear stiffness and are competitive with honeycomb topologies when loaded in the minimum shear strength directions.

- The tetrahedral lattice core is highly flexible prior to bonding to facesheets and it is more than 40% stiffer and stronger than equivalent relative density flexible honeycombs used for the cores of curved sandwich panels.

- The tetrahedral lattice structure offers many ancillary benefits to traditional closed-celled honeycombs all at an equivalent specific stiffness and strength while possessing the formability of flexible honeycomb topologies.

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