Cellular Metal Truss Core Sandwich Structures**

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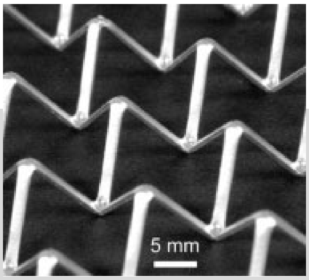

Closed cell honeycomb core structures are widely used for sandwich panel construction. Periodic open cell tetrahedral truss core structures have recently been shown to possess weight specific properties that compete with those of honeycomb core designs. In contrast to honeycomb, the open cell topologies provide many opportunities for multifunctionality. Past approaches to miniature tetrahedral truss fabrication from metals have utilized investment casting routes. Material choices are then constrained by the need for high fluidity during casting. Strength knockdown due to casting defects has been observed. Here, we utilize a comparatively simple wrought metal based approach. The truss cores are made by deformation shaping hexagonal perforated metal sheets. They are then bonded between thin facesheets using a transient liquid phase approach. When designed to minimize bending of members within the core, a linear dependence of core modulus and strength upon relative density is anticipated. Core relative densities of less than two percent have been obtained. With this approach, low cost truss core structures can be made from a wide variety of heat-treatable wrought alloys.

1. Introduction

Cellular metals have attracted interest as alternatives to honeycomb when used as the cores of sandwich structures designed to support in-plane compressive or bending loads.[1] For successful implementation, these cellular metal based approaches must compete against established panel stiffening and strengthening concepts. Conventional panel stiffening involves the attachment of stringers that increase the polar and second moment of cross-section area with modest added weight.[1] Panels of this type are often made by machining stiffeners from thick blanks and fastening to a sheet. When fabricated in this way, the panels can be quite light and stiff, however, they also show substantial anisotropy in the bending plane and are relatively expensive due to the poor utilization of material and high machining cost.

Other ways to stiffen a panel involve waffling or sandwich construction.[1–4] For the latter, thin strong skins are bonded to the sides of a lightweight core as shown in Figure 1. Like the flanges of an I-beam, the skins provide support in bending with one skin in compression and the other in tension. The core functions in a manner similar to the web of an I-beam. That is, it resists shear and compressive loads while separating the skins far apart to generate a high second moment cross-section area and therefore high rigidity.

Honeycomb core sandwich structures are the current state-of-the-art choice for weight sensitive applications such as aircraft and satellite structures.[2] But there are difficulties with forming them into complex (non-planar) shapes due to induced anticlastic curvature.[2] Also, the closed nature of the porosity can trap moisture leading to corrosion. In space applications, their skins are susceptible to interfacial debonding.

Open cell cores based upon tetrahedral truss concepts[5,6] allow fluids to readily pass through which could make them less susceptible to internal corrosion and depressurization

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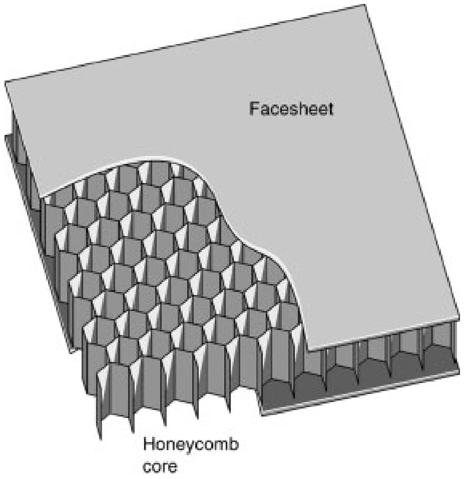

Fig. 1. Sandwich panel structure with a regular hexagonal honeycomb core.

induced delamination. When used as sandwich cores, they are more amenable to shaping into complex shapes. They are also attractive for multifunctional applications such as cross flow heat exchangers due to the interconnected nature of the porosity.[1]

Multifunctional materials designers seek to tailor load support properties of interest (e.g., stiffness and strength) in the most efficient way through adjustment of the open cell topology, relative density and material type. The intervening space can then be used for other functionalities.[7] For example, the porosity within a load supporting cellular metal structure could also be used to simultaneously enhance impact/blast energy absorption,[8,9] noise attenuation,[8] catalytic activity,[8] filtration efficiency,[8] electrical energy storage[10] or act as the host for the in-growth of biological tissue.[11] Stochastic open cell foams have been proposed for sandwich structure cores but their mechanical properties are inferior to honeycomb.[1] Figure 2 summarizes the Young's and shear moduli relative density relationships for various cellular concepts.

The elastic moduli of stochastic open cell foams are considerably lower than those of regular hexagonal honeycomb at low relative density. Similar trends are seen with the yield strength. These differences are a consequence of ligament bending.[12] For improved core performance, cellular topologies that deform by means of ligament stretching or compressing are preferred.[7] A prototypical example is the tetrahedral truss sandwich core[13] made by investment casting. However, high quality structures of this type are difficult to fabricate in miniature size at acceptable cost. Here, we describe the design, manufacture and properties of open cell tetrahedral truss core structures made from wrought metals. The cores are made using simple metal perforation and deformation shaping processes. They are bonded to thin metal facesheets using a transient liquid phase approach. Panel bending performance is assessed but multifunctional applications of the type described above are deferred to future studies.

2. Core Design

Cellular geodesic domes[5] are amongst the most structurally efficient cellular structures. Their favorable strength-to-weight geometry was extended to rectangular prismatic forms by way of the octahedral-tetrahedral truss.[6] These stiff, strong designs are based upon a triangulated architecture wherein truss members are elastically loaded in tension or compression only with no bending. Under this mode of deformation, the stiffness and strength have a linear dependence upon density making them a favored cellular topology for open cell structures intended for lightweight load support applications. Several studies have investigated the manufacture and performance of miniaturized versions of similar tetrahedral truss based structures as the cores of all metal sandwich panels.[13–15] They were made with legs of circular cross-section by investment casting.

Consider the design of a tetrahedral truss core made up of triad units with leg members of length L and rectangular cross-section dimensions w and h, Figure 3. The angle each member makes with a line extending from the center of the triad base to its peak is $\text{acos}(\sqrt{2/3})$, the triad height is about $L(\sqrt{2/3})$ and it provides support over a planar area $\sqrt{3}L^2/2$. The relative density of the core is close to

$$\frac{\rho_c}{\rho_s} = \frac{3\sqrt{2}wh}{L^2} \qquad (1)$$

where ρ_c is the density of the core and ρ_s is the density of its base material. To simplify, the base material will be treated as elastic-perfectly plastic. Point loading of a single tetrahedral triad unit can be used to establish core mechanical perfor-

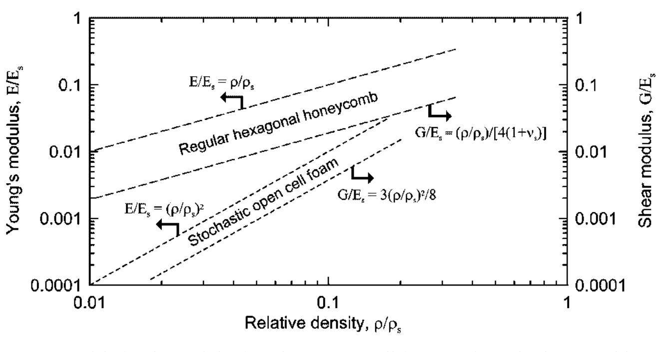

Fig. 2. Models for the moduli of stochastic open cell foams and regular hexagonal honeycombs (out-of-plane) [4]. For metals, Poisson's ratio is $v_s \approx 0.3$.

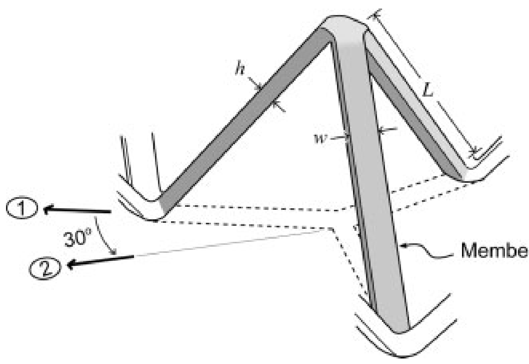

Fig. 3. Tetrahedral triad unit with leg members of rectangular cross-section.

mance. The elastic behavior of a pin-connected tetrahedral truss core is isotropic with relative moduli given by[14]

$$\frac{E_c}{E_s} = \frac{4}{9}\left(\frac{\rho_c}{\rho_s}\right) \tag{2}$$

$$\frac{G_c}{E_s} = \frac{1}{9}\left(\frac{\rho_c}{\rho_s}\right) \tag{3}$$

where E_c and G_c are the Young's and shear moduli for the core while E_s is the Young's modulus of its base material. The relative yield strengths are[14]

$$\frac{\sigma_{cy}}{\sigma_{ys}} = \frac{2}{3}\left(\frac{\rho_c}{\rho_s}\right) \tag{4}$$

$$\frac{1}{3\sqrt{2}}\left(\frac{\rho_c}{\rho_s}\right) \le \frac{\tau_{cy}}{\sigma_{ys}} \le \frac{\sqrt{6}}{9}\left(\frac{\rho_c}{\rho_s}\right) \tag{5}$$

where σ_{cy} and τ_{cy} are the compressive and shear yield strengths for the core while σ_{ys} is the yield strength of its base material. Here, the minimum shear strength occurs when shearing is parallel to the projection of one set of members onto the base-plane (one direction). The maximum occurs when shearing is oriented 30° to this projection (two direction).

For structural applications, a yielding mode of failure is preferred to the elastic buckling mode. For the lightest truss core, we seek the thinnest possible members that yield before they elastically buckle. These member dimensions lead to nearly simultaneous elastic buckling and yielding of members within. Elastic buckling of a single pin-connected member of solid rectangular section occurs at a member stress[16]

$$\sigma_b \le \frac{-\pi^2 E_s h^2}{12L^2} \tag{6}$$

where $h \le w$ and the negative sign indicates compression. Equating member buckling stress to compressive yield strength, $-\sigma_{ys}$, the member cross-section dimension for the lightest (pin-connected) truss core is given by

$$h_{\min} = \frac{L}{\pi}\left(\frac{12\sigma_{ys}}{E_s}\right)^{1/2} \tag{7}$$

Since elastic or plastic buckling occur about the thinnest cross-section dimension, square (circular or other equiaxed) sections are preferable to rectangular sections. Provided $h > h_{\min}$, failure initiates by yielding. The corresponding minimum relative density for the tetrahedral truss core (with square cross-section members) is then

$$\left(\frac{\rho_c}{\rho_s}\right)_{\min} = \frac{36\sqrt{2}\sigma_{ys}}{\pi^2 E_s} \tag{8}$$

where the ratio σ_{ys}/E_s is the material dependent yield strain. Observe that the lightest truss cores are made from low yield strain alloys.

Here, a pin-connected (conservative) approach to the buckling analysis has been used. For clamped members, the minimum cross-section dimension is divided by two and the core relative density by four. In practice, the joint normally behaves in a fashion intermediate to the pinned (no moment) and clamped (finite moment) conditions. In Figure 4, we plot minimum mass core relative density ranges for several common engineering alloys whose representative properties are given in Table 1.[17] Figure 4 indicates that the preferred relative density range is material specific. Tetrahedral truss cores with relative densities in the 0.1–0.5 % range are optimal for type 304 stainless steel but cores with relative densities in the 1–5 % range are optimal for Ti-6 Al-4 V.

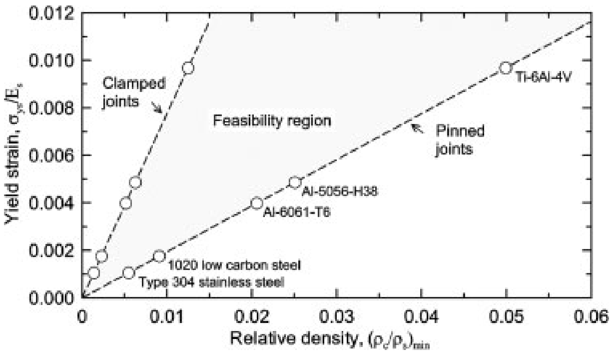

Fig. 4. Material dependent relative density relationships for minimum mass tetrahedral truss cores.

3. Sandwich Construction

Several approaches can be used to create miniature trusses with characteristics similar to those described above. Bending at the nodes of suitably perforated metal sheets provides one approach. Simple punching at alternate nodes provides another. The processes can be performed either under ambient or hot temperature conditions. In the latter, superplastic conditions can be utilized.

To illustrate the fabrication of miniature, wrought metal tetrahedral truss cores, hexagonal perforated type 304 stainless steel (Fe-18Cr-8Ni) sheet was obtained from Woven Metal Products, Inc. (Alvin, TX). The sheet was 0.74 mm thick and it contained 11.1 mm hexagonal holes (face distance) of 12.7 mm staggered centers spacing. The bar widths were 1.6 mm and the open area fraction was 77 %. With $L = 12.7$ mm, we estimate a triad height of 10.4 mm upon deforming the sheet out-of-plane to create tetrahedral trusses.

In Figure 5 we show an apparatus used to deformation shape the truss cores. Within the jig, bars were stretched by pushing (screw driven testing instrument at 5 mm min^{-1}) at their intersections (nodes) using hardened steel dowel pins of 1.6 mm diameter. Two intermediate annealing treatments (1100 °C for 15 min) were needed to soften the strain-hardened bars and prevent dowel pin punch through at the nodes. The final core heights were 10.0 mm (measured) and their relative densities were about 1.7 % (before sandwich construction). After shaping, truss members had $w = 1.26$ mm and $h = 0.59$ mm, Figure 6. Handbook values for annealed

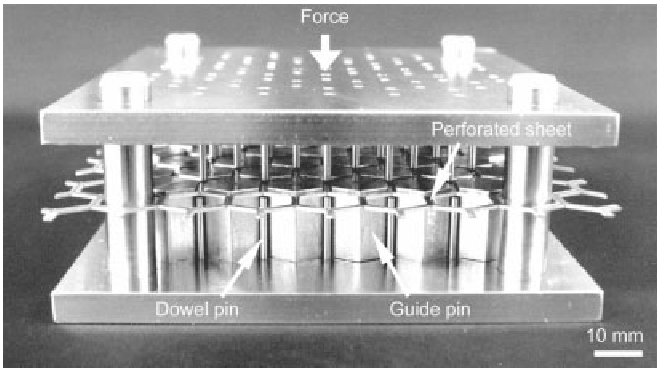

Fig. 5. Deformation shaping of the tetrahedral truss core.

Table 1. Properties of several common engineering alloys [17].

Wrought alloy	Density (g/cm^3)	Young's modulus [GPa]	Yield strength [MPa]	Yield strain
Al-6061-T6	2.7	69	275	0.0040
Al-5056-H38	2.7	71	345	0.0049
Ti-6Al-4V (solution + aging)	4.5	114	1103	0.0097
1020 low carbon steel (normalized)	7.9	196	345	0.0018
Type 304 stainless steel (annealed)	8.0	193	205	0.0011

type 304 stainless steel will be used throughout, Table 1. From Equation 7, we find $h_{\min} = 0.46$ mm and since $h_{\min} < h$, core failure is designed to initiate by yielding. This core has about three-times more mass than the lightest core with members of square cross-section. We note that other structurally attractive truss designs having pyramidal,[18] Kagomé[19] or other cellular architectures can be fabricated in a similar way.

A transient liquid phase approach was used for attaching thin facesheets to the cores. Truss cores were lightly sprayed with a mix of a polymer based cement (Nicrobraz® Cement 520) and –140 mesh (diameter ≤ 106 μm) Ni-25Cr-10P braze alloy powder (Nicrobraz® 51) both supplied by Wal Colmonoy Corp. (Madison Heights, MI). The solidus and liquidus of this alloy are 880 °C and 950 °C whereas the solidus of type 304 stainless steel is approximately 1400 °C. The coated cores were then placed between solid 0.75 mm thick type 304 stainless steel facesheets (the thickness, t, was chosen to promote failure by core shearing) and a small compressive pressure was applied. Perforated facesheets can also be used and when bonded to multiple core layers, multi-laminate and/or hierarchical structures are readily made.

Flexure panel cores were oriented for shearing to occur parallel to the projection of one set of members onto the facesheet (base-plane). The assemblies were then heated in a vacuum of better than 10^{-2} torr at 15 °C min^{-1} to 550 °C for 1 h to volatilize the polymer cement. An important feature of this cement/braze combination is that the braze alloy powders remain adhered after volatilization. The system was then evacuated to a vacuum level below 10^{-3} torr and the temperature was ramped at a rate of 15 °C min^{-1} to 1100 °C and held there for 1 h (for joint ductility enhancement).

At temperature, the braze alloy powders melted to coat the members (this seals microscopic defects) and the melt was drawn by capillary forces to points of core/facesheet contact. Interdiffusion then changed the contact composition and elevated its melting point causing solidification at the brazing temperature. Filleted joints of large curvature radius (to resist cracking) were obtained (Fig. 6b).

After furnace cooling to ambient, sandwich structures were machined for testing. The flexure panel length was 247 mm, its width was $b = 66.0$ mm, its thickness was $c + 2t = 11.3$ mm and its mass was 219 g. The final core height was slightly reduced to $c = 9.8$ mm owing to the compressive forces applied during heating. After sandwich construction, the measured relative density of the core, $\rho_c/\rho_s = 1.8\,\%$, was only slightly greater than before (1.7 %).

4. Beam-Flexure Analysis

Specific details of the midspan loading procedure can be found in.[15,20] The measured load-deflection curve is shown in Figure 7. A quasistatic unload-reload scheme was used to measure a beam stiffness, $F/\delta \approx 2500\ \text{N mm}^{-1}$, where F and δ are the midspan load and deflection. The deflection was expected to be about[1]

$$\delta = \frac{Fl^3}{24E_f bt(c+t)^2} + \frac{Fl}{4bcG_c} \tag{9}$$

where E_f is Young's modulus for the thin facesheets. From Equation 9, we obtain an estimate for the core shear modulus, $G_c \approx 1.01$ GPa, which corresponds to $G_c/E_s \approx 0.0053$.

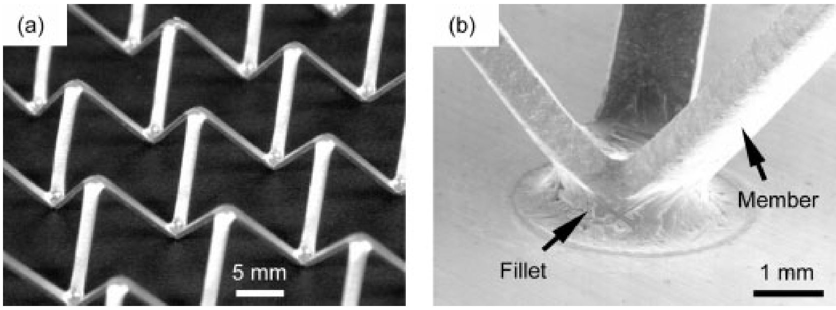

Fig. 6. a) Tetrahedral truss core after shaping. b) Typical core/facesheet bond.

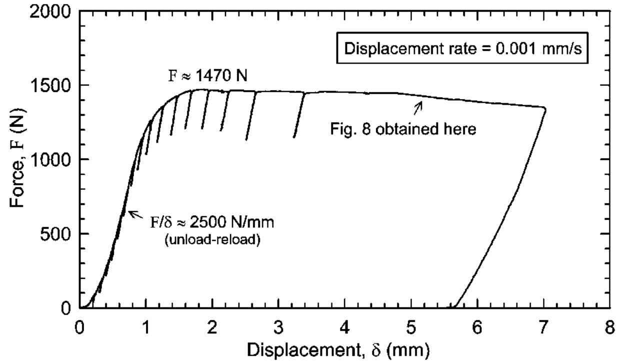

Fig. 7. Measured load-deflection data obtained during the beam-flexure test.

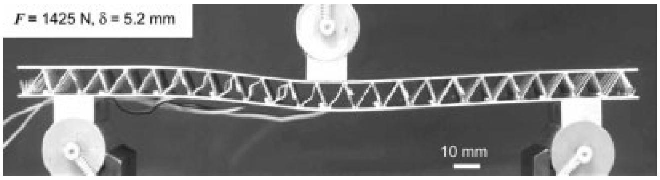

Fig. 8. Visual observations during the test. The span was l = 202 mm and the flat steel indenters were 16.0 mm wide.

During beam failure, the set of truss members on the left side of the beam (with facesheet projection parallel to the shearing direction) first yielded in compression and then plastically buckled about their thinnest cross-sections (Figure 8). A plastic hinge developed near the outer support on the left side. On the right side, members of this same set yielded in tension and work hardened. Neither plastic buckling or a hinge were observed there. Similar antisymmetric behavior has been seen in comparable investment cast systems.[15] Observe from Figures 7 and 8 that considerable stiffness and load bearing capacity are retained after initial plastic buckling.

The collapse load for beams having a small overhang, H (distance from the center of an outer indenter to the beam edge), is[1]

$$F_{\mathrm{A}} = \frac{2bt^2}{l}\sigma_{\mathrm{fy}} + 2bc\tau_{\mathrm{cy}}\left(1+\frac{2H}{l}\right) \tag{10}$$

where σ_{fy} is the facesheet yield strength. For large overhangs, plastic hinges form near the outer indenters and the collapse load becomes[1]

$$F_{B} = \frac{4bt^2}{l}\sigma_{\mathrm{fy}} + 2bc\tau_{\mathrm{cy}} \tag{11}$$

Since both failure modes were observed along the beam, we let $F_{\mathrm{A}} \approx F_{\mathrm{B}} \approx 1470$ N and obtain estimates for the core yield strength, $\tau_{\mathrm{cy}} \approx$ (0.88, 1.02) MPa, from Equations 10 and 11 where $H = 22.5$ mm. The mean of these values gives $\tau_{\mathrm{cy}} \approx$ 0.95 MPa and the corresponding relative core shear strength is approximately $\tau_{\mathrm{cy}}/\sigma_{\mathrm{ys}} \approx 0.0046$. We note that after testing, all core/facesheet bonds appeared intact with no visually observed cracking.

5. Discussion

In Figure 9, Hexcel Composites (Pleasanton, CA) 5056-H39 aluminum alloy honeycomb shear properties (plate shear test data)[2] are compared with measurements for the type 304 stainless steel tetrahedral truss core and model predictions, Equations 3 and 5. The honeycomb is normally made from rolled alloy 5056-H191 aluminum sheet ($E_{\mathrm{s}} = 71$ GPa, $\sigma_{\mathrm{ys}} = 435$ MPa and $\rho_{\mathrm{s}} = 2.6$ g cm^{-3}) onto which adhesive lines are drawn. This is followed by stacking, curing to form honeycomb before expansion (HOBE®) block and then expansion into honeycomb.[2] There is a doubling of wall thickness in the "L" direction as opposed to the other "W" direction and the mechanical properties are affected. In Figure 9, it can be seen that the measured and predicted relative shear modulus and strength of the tetrahedral truss core compare favorably with those of similar relative density honeycomb. Note however, that predictions for the truss core shear modulus are based upon pin-connected members. In practice, the added rotational resistance afforded by the nodes and braze alloy fillets could lead to stiffness enhancement. Plate shear test confirmation would be helpful since core shear values obtained from flexure tests are often higher than those obtained from plate shear tests.[2] Furthermore, inversion of Equation 9 for the shear modulus is sensitive to measurement error propagation. Nonetheless, the relative properties of the tetrahedral truss core significantly exceed stochastic foam systems, are

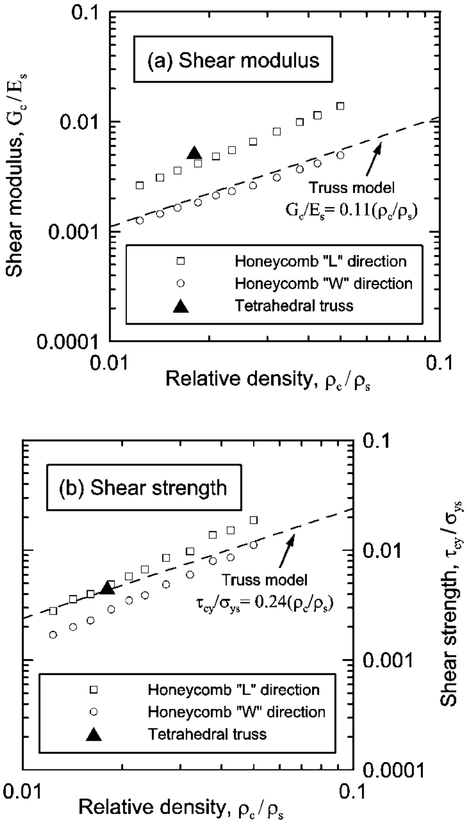

Fig. 9. Relative property comparisons for honeycomb and tetrahedral truss core systems. a) Shear modulus. b) Shear strength.

close to model predictions and show much promise as an open cell counterpart to honeycomb.

6. Summary

A metal deformation and assembly process has been used to fabricate periodic cellular metal truss core sandwich structures. Hexagonal perforated type 304 stainless steel sheets were deformation shaped to create miniature tetrahedral truss cores. Sandwich beams were constructed by bonding the cores between thin facesheets using a transient liquid phase approach. Bending properties were evaluated through a midspan loading procedure. Beam-flexure analysis revealed these materials to be exceptionally stiff and strong. The relative compressive and shear properties of the truss cores compare favorably to those of honeycomb however, their open cell architecture makes them particularly attractive for multifunctionality. Since the cores are flexible, the fabrication of complex curved sandwich structures appears feasible.

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