Multifunctional periodic cellular metals

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Periodic cellular metals with honeycomb and corrugated topologies are widely used for the cores of light weight sandwich panel structures. Honeycombs have closed cell pores and are well suited for thermal protection while also providing efficient load support. Corrugated core structures provide less efficient and highly anisotropic load support, but enable cross flow heat exchange opportunities because their pores are continuous in one direction. Recent advances in topology design and fabrication have led to the emergence of lattice truss structures with open cell structures. These three classes of periodic cellular metals can now be fabricated from a wide variety of structural alloys. Many topologies are found to provide adequate stiffness and strength for structural load support when configured as the cores of sandwich panels. Sandwich panels with core relative densities of 2–10% and cell sizes in the millimetre range are being assessed for use as multifunctional structures. The open, three-dimensional interconnected pore networks of lattice truss topologies provide opportunities for simultaneously supporting high stresses while also enabling cross flow heat exchange. These highly compressible structures also provide opportunities for the mitigation of high intensity dynamic loads created by impacts and shock waves in air or water. By filling the voids with polymers and hard ceramics, these structures have also been found to offer significant resistance to penetration by projectiles.

Keywords: cellular materials; sandwich panel structures; cross flow heat exchange; stainless steel; light metals

1. Introduction

Periodic cellular metals are highly porous structures with 20% or less of their interior volume occupied by metals (Evans et al. 2001; Wadley et al. 2003). Some, such as hexagonal honeycomb, are widely used to enable the design of light weight sandwich panel structures (Bitzer 1997), for creating unidirectional fluid flows (Lu 1999), for absorbing the energy of impacts (Zhang & Ashby 1992), to impede thermal transport across the faces of sandwich panels and for acoustic damping. Corrugated (prismatic) metals are also a form of periodic cellular metal structure (Wadley et al. 2003). They have their voids arranged in one direction enabling fluid flow in one direction but not the others. They are widely used in buildings and in ship construction (Royal Schelde Shipbuilding) and for cross flow heat exchangers. More recently, significant interest has emerged in lattice structures which have three-dimensional interconnected void spaces well suited
for allowing fluid flow through them (Evans et al. 2001; Wadley et al. 2003). The structures of interest here are composed of repeating unit cells with cell diameters that range from tens of micrometres to tens of millimetres.

Honeycomb structures are composed of plates or sheets that form the edges of unit cells. These can be arranged to create triangular, square, hexagonal or related shapes. Their unit cells are repeated in two dimensions to create a cellular solid, figure 1. One of the manufacturing methods used to create hexagonal honeycomb leads to a doubling in wall thickness of every other web, which results

Figure 1. Examples of the three forms of honeycomb shown as core structures in sandwich panels: (a) hexagonal honeycomb, (b) square honeycomb and (c) triangular honeycomb.
in anisotropic mechanical behaviour. All honeycombs are closed cell structures. By identifying a unit cell and deriving the volume fraction occupied by metal, it is possible to obtain simple relations between the relative density \( \rho/\rho_s \) and the topology of the structure (see Table 1).

Table 1. Unit cells and relative densities of honeycomb topology structures.

<table>
<thead>
<tr>
<th>Honeycomb</th>
<th>Relative Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hexagonal Honeycomb</td>
<td>( \rho/\rho_s = \frac{8t}{3(\sqrt{3}l + 2t)} ) for ( l \gg t )</td>
</tr>
<tr>
<td>Square Honeycomb</td>
<td>( \rho/\rho_s = \frac{(2l-t)t}{l^2} ) for ( l \gg t )</td>
</tr>
<tr>
<td>Triangular Honeycomb</td>
<td>( \rho/\rho_s = \frac{(2\sqrt{3}l-t)t}{l^2} ) for ( l \gg t )</td>
</tr>
</tbody>
</table>
If the cores shown in figure 1 are rotated 90° about their horizontal axis, they become prismatic structures with open (easy flow) cells in one direction and a closed cell structure in the two orthogonal directions. Other prismatic structures are also easy to make. Figure 2 shows three examples. In these figures, the prismatic layers are shown laminated with a 90° in-plane rotation (0/90°) between the layers illustrating the possibility of varying the anisotropy of the structure and enabling the cell size to be made independent of the distance between face sheets when used in sandwich panels. Table 2 shows the relative density—unit cell geometry relations for prismatic cellular structures.

Figure 2. Prismatic (corrugation) topology structures. (a) Triangular corrugation, (b) a diamond topology (equivalent to a square corrugation rotated by 45°) and (c) a steeper web truss corrugation with a flat top that is widely used in buildings and for marine applications where it is called Navtruss.

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Closed cell honeycombs and partially open prismatic structures are constructed from plate or sheet elements. Fully open cell structures can be created from slender beams (trusses) that in principle can be of any cross-sectional shape: circular (Deshpande & Fleck 2001; Chiras et al. 2002; table 2.

Table 2. Prismatic topology unit cells and relative density relations.

<table>
<thead>
<tr>
<th>Relative Density</th>
<th>Triangular Corrugation</th>
<th>Diamond Prismatic Corrugation</th>
<th>Navtruss Corrugation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho/\rho_2$</td>
<td>$\frac{t}{\frac{1}{2}l \sin 2\omega + t \cos \omega}$</td>
<td>$\approx \frac{2t}{t}$ for $\omega = 45^\circ$, $l \gg t$</td>
<td>$\rho/\rho_3 = \frac{2t}{l \sin 2\omega} = \frac{2t}{l}$ for $\omega = 45^\circ$</td>
</tr>
<tr>
<td>$\rho/\rho_3$</td>
<td>$\frac{(l_1 + l_2) t}{(l_2 + l_1 \cos \omega)(l_1 \sin \omega + t)}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Wang et al. 2003), square (Kooistra et al. 2004; Rathbun et al. 2004), rectangular, I-beam, or hollow (Queheillalt & Wadley 2005a,b). The trusses can be arranged in many different configurations depending upon the intended application (Evans et al. 2001). Figure 3 shows six examples of micro truss cellular topologies used as the cores of sandwich panels. Table 3 identifies pertinent unit cells and relative density relations.

The tetrahedral structure, figure 3a, has three trusses each meeting at a face sheet node (Deshpande & Fleck 2001; Chiras et al. 2002; Wadley et al. 2003; Kooistra et al. 2004). The pyramidal structure has four trusses meeting at a face sheet node, figure 3b (Deshpande & Fleck 2001; Wadley et al. 2003; Zok et al. 2004). In both topologies, the trusses form a continuous network. Both also have directions of unobscured ‘easy flow’. There are three of these channels in a single layer of the tetrahedral structure and two in the pyramidal system. A slightly different topology has been proposed by Salvatore Torquato at Princeton and is referred to as a three-dimensional Kagome topology (Hyun et al. 2003), figure 3c. Kagome is a Japanese term for the basket weave pattern created by in-plane weaving in three directions. Such two-dimensional weaves have been found to be very strong. In Torquato’s

Figure 3. Examples of lattice truss topologies configured as the cores of sandwich panel structures. (a) Tetrahedral lattice, (b) pyramidal lattice, (c) three-dimensional Kagome lattice, (d) diamond textile, (e) diamond collinear lattice and (f) square collinear lattice. Many can be made with solid or hollow trusses. The truss cross sections can also be shaped (e.g. square as opposed to circular).
Table 3. Unit cells and relative densities for micro trusses used as cores in sandwich panels with solid face sheets.

relative density

<table>
<thead>
<tr>
<th>Unit Cell Type</th>
<th>Relative Density Equation</th>
<th>Angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tetrahedral</td>
<td>( \frac{\rho}{\rho_s} = \frac{2}{\sqrt{3}} \left( \frac{wt}{l^2 \cos^3 \omega \sin \omega} \right) = 3\sqrt{2} \frac{wt}{l^2} ) for ( \omega = 54.7356^\circ )</td>
<td></td>
</tr>
<tr>
<td>Pyramidal</td>
<td>( \frac{\rho}{\rho_s} = \frac{2wt}{l^2 \cos^3 \omega \sin \omega} = 4\sqrt{2} \frac{wt}{l^2} ) for ( \omega = 45^\circ )</td>
<td></td>
</tr>
<tr>
<td>Diamond Textile</td>
<td>( \frac{\rho}{\rho_s} = \frac{\pi d}{l \sin 2\omega} = \frac{\pi}{4} \frac{d}{l} ) for ( \omega = 45^\circ )</td>
<td></td>
</tr>
<tr>
<td>Hollow Diamond</td>
<td>( \frac{\rho}{\rho_s} = \frac{\pi}{4} \frac{(d_o^2 - d_i^2)}{l d_o \sin 2\omega} = \frac{\pi}{4} \frac{(d_o^2 - d_i^2)}{ld_o} ) for ( \omega = 45^\circ )</td>
<td></td>
</tr>
</tbody>
</table>
structure, the nodes that are formed at the face sheets have the two-dimensional Kagome weave pattern. Pairs of tetrahedrons are inverted and rotationally offset from each other by 60° to create the three-dimensional topology shown in figure 3c. Each of the three topologies shown in figure 3a–c is efficient at supporting structural loads—especially the shear loads encountered in panel bending.

Other lattice truss topologies have also been proposed based upon manufacturing considerations. Figure 3d–f shows examples that are easy to make from wires. The diamond textile structure is made from layers of a plain weave metal fabric that have been bonded to each other (Sypeck & Wadley 2001). A simple wire lay up process can be used to create diamond and square truss structures (Queheillalt & Wadley 2005a) shown in figure 3e,f. Their unit cells and relative density relations are also summarized in table 3.

The micro truss topologies shown above are all configured as the cores of sandwich panels. However, they can also be terminated by open truss faces. Examples are shown in figure 4a–c. In this case, the tetrahedral structure (figure 4a) becomes Fuller’s octet truss (Fuller 1961; Despande et al. 2001); a truss structure consisting of four tetrahedrons arranged to form a larger tetrahedron with an interior octahedral hole. The pyramidal structure with a truss face (figure 4b) is also known as a lattice block material (Wallach & Gibson 2001). The three-dimensional Kagome topology (figure 4c) clearly reveals the basket weave pattern formed by connecting the nodes to the exterior of the structure. All of the structures can be repeated vertically to create true, three-dimensionally periodic lattice truss topologies.

This paper reviews recent developments in topology design and the fabrication of periodic cellular metals, and summarizes some of the emerging interests in their use as multifunctional structures. Emphasis is placed upon their application as load supporting structures with added functionalities including thermal management, blast wave mitigation and ballistic resistance.

2. Fabrication approaches

The applications of periodic cellular metals can be only realized if affordable fabrication routes exist for the topologies and metal alloys of interest. Many
sheet forming, perforated sheet folding/drawing (Sypeck & Wadley 2002; Kooistra & Wadley in press), wire assembly (Sypeck & Wadley 2001; Queheillalt et al. submitted), and investment casting methods (Deshpande & Fleck 2001; Chiras et al. 2002; Wang et al. 2003) are emerging for the shaping of the topologies discussed above. Numerous ways for bonding these structures are also being developed including laser and other micro-welding techniques for steels, superalloys and many refractory metals, diffusion bonding for titanium alloys and transient liquid phase processes such as brazing for copper (Tian et al. 2004a) and some aluminium alloys (Kooistra et al. 2004).

(a) Honeycomb structures

Several approaches for making metallic honeycomb structures have been developed (Bitzer 1997). Hexagonal honeycombs are usually fabricated by an expansion manufacturing process, especially when the relative density is low ($\tilde{\rho} < 0.1$). In this process, thin metal sheet is first cut into panels, bent as desired and strip bonded (figure 5). This results in a so-called ‘honeycomb before expansion’ or HOBE block. This can be cut and stretched perpendicular to the strip bonds to create a hexagonal structure. The expansion process requires moderately high inter-sheet bond strengths (sufficient to enable sheet stretching). For low-density honeycombs with very thin webs, the required bond strengths are readily achievable with modern adhesives or by laser welding or diffusion bonding processes (Bitzer 1997). However, as the web (sheet) thickness to cell size ratio increases (i.e. as the relative density increases) the force needed to stretch the metal sheets eventually approaches the inter-sheet bond fracture strength. The manufacture of higher relative density hexagonal honeycombs then requires the use of other manufacturing methods.
One based on a corrugation process is illustrated in figure 6. In this approach, a metal sheet is first corrugated, and then stacked. The sheets are welded together and the core sliced to the desired thickness and the corrugated layers either adhesively bonded or welded as shown in figure 6. Figure 7 shows examples of the use of a slotted metal strip approach for the assembly of square (Dharmasena et al. submitted) and triangular honeycombs (D. T. Queheillalt 2003, private communication). Since no metal bending is required, this slotted sheet process is also well suited for making honeycombs from less ductile materials. Even brittle composite or ceramic honeycombs can in principle be made by this approach.

\( b \) Prismatic topologies

Prismatic topology structures can be manufactured by sheet bending or progressive rolling operations, figure 8, or by extrusion techniques. The corrugation approach is often preferred for low relative density structures made from alloys with high formability. Triangular, flat topped, square or sinusoidal corrugations can all be fabricated by this approach. The flat-topped structures have steeper webs than their triangular counterparts making them a preferred topology for many structural applications. The corrugated sheets can be stacked either collinearly, figure 8a, b or in a cross ply manner as shown in figure 8c and then bonded by similar techniques to those used to make honeycombs.

For high relative density structures, the slotted sheet methods shown in figure 9 can be used to create short lengths of a prismatic structure (Cote et al. in press). Metal extrusion through complex dies can also be used to make collinear channel structures from metals with high ductility. A group at Georgia Tech (Cochran et al. 2000) has developed an ingenious extrusion process for systems that lack
Figure 7. A strip slotting method for making (a) square honeycomb and (b) triangular honeycombs. The strips can be bonded by brazing.

Figure 8. Corrugation methods can be used to make prismatic cellular structures. Some metals can also be extruded to create prismatic cellular cores. (a) Single layer corrugation, (b) double layer corrugation, (c) cross-ply double layer corrugation.
sufficient hot ductility. In this approach, a metal oxide or metal hydride powder slurry is first fabricated. This is then extrusion-shaped, dried and subsequently either reduced or oxidized to convert the oxide or hydride to a metal. A final sintering step is used to densify the structure and increase its strength.

(c) Lattice truss structures

Lattice truss topology structures can be made by investment casting, perforated metal sheet forming, wire/hollow tube lay-up or by snap fitting laser cut out lattices. All but the investment casting approach require assembly and bonding steps to create the cellular structure and for later attaching it to face sheets.

Investment casting begins with the creation of a wax or polymer pattern of the lattice truss structure (and face sheets). The patterns for the lattices used in flat panel structures can be made by injection moulding. Those for complex shaped objects can be made by rapid prototyping methods such as fused deposition

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modelling (Crump 1992). The truss and face sheet pattern is then attached to a system of liquid metal gates, runners and risers that are made from a casting wax and coated with a ceramic casting slurry. The pattern is removed and the empty (negative) pattern filled with liquid metal (figure 9). After solidification the ceramic is removed, the gates and runners are removed, and the component is inspected to ensure that complete liquid metal infiltration has occurred and that casting porosity has not compromised structural integrity. Lattice block and more recently the pyramidal, tetrahedral and three-dimensional Kagome cell topology structures have all been made by this investment casting route (Deshpande & Fleck 2001; Wallach & Gibson 2001; Chiras et al. 2002; Wang et al. 2003).

In principle, the investment casting approach can be used to fabricate complex, non-planar shaped structures of significant size (1–5 m) and weight (up to several hundred kilograms). Structures made from high fluidity casting alloys such as Al–Si (Deshpande & Fleck 2001; Wallach & Gibson 2001), Cu–Be (Chiras et al. 2002; Wang et al. 2003) and some super alloys have all been made this way. Most have relatively high core relative densities (greater than 5%), a consequence of the difficulty of reliably filling moulds containing very small diameter, high aspect ratio (truss) channels. Periodic cellular metals with lower relative densities can be fabricated from a wide variety of structural alloys using sheet or wire forming methods.

The folding of a perforated or expanded metal sheet provides a simple means to make lattice trusses. A variety of die stamping, laser or water jet cutting methods can be used to cut patterns into metal sheets. For example, a tetrahedral lattice truss can be made by folding a hexagonally perforated sheet in such a way that alternate nodes are displaced in and out of the sheet plane as shown in figure 10. By starting with a diamond perforation, a similar process can be used to make a pyramidal lattice. A photograph of a representative aluminium alloy structure is shown in figure 11.

There is considerable waste material created during the perforation of the sheets used to create low relative density lattices and this contributes significantly to the cost of making cellular materials this way. These costs can be greatly reduced by the use of either clever folding techniques that more efficiently utilize the sheet material or methods for creating perforation patterns that do not result in material waste. Figure 12 shows an example of the use of metal expansion techniques, followed by folding, that provides a means for creating lattice truss topologies with little or no waste.

The weaving and braiding of metallic wires provides a simple, inexpensive means for controlling the placement of metal trusses. It is applicable to any alloy that can be drawn into wire. Plain weave (0/90°) fabrics are the simplest to envision. The included angle (normally 90°) can be modified after weaving by shearing the fabric and a wide range of cell width to fibre diameter ratios are available. Cellular structures are made from these metal textiles by simply stacking and bonding layers of the fabric. The best structures are achieved by aligning the layers so that the nodes of adjacent layers are in contact (figure 13). Sandwich panels can be fabricated from these cores with the wires oriented at any angle to the face sheet normal by a transient liquid phase bonding process. Examples of 0°/90° and ±45° configurations made this way are shown in figure 13.
Figure 10. A perforated metal sheet can be bent and bonded to create a tetrahedral lattice truss structure.

Figure 11. Example of a multilayer tetrahedral structure constructed from folded perforated aluminium sheet with open cell faces. The cell size is approximately 10 mm.
Figure 12. A pyramidal lattice truss structure can be made by periodically slitting a metal sheet and then stretching (expanding) it. Alternate bending rows of nodes converts the expanded metal sheet into a pyramidal lattice truss structure.
Lattice truss structures with similar topologies to textiles can be fabricated by a wire lay up process followed by transient liquid phase bonding or node fusion welding. Using a slotted tool to control wire spacing and orientation it is a simple matter to lay down collinear wires and to alternate the direction of successive layers (figure 14). This procedure results in square or diamond lattice truss topologies that can be machined and bonded to face sheets. The approach has a number of attractions. Compared to the textile approach, it is more

Figure 13. Copper textile core sandwich panels. (a) $0^\circ/90^\circ$ wire (square) orientation. (b) $+45^\circ/-45^\circ$ wire (diamond) orientation.

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Figure 14. Wires or hollow tubes can be used to create cellular structures by bonding layers of collinear assemblies.
straightforward to maintain the cell alignment throughout the structure at low relative densities. Moreover, hollow tubes can be used instead of solid wires and this enables very low-density lattices to be achieved and truss compressive buckling strengths to be increased by increasing the truss moment of inertia. The emergence of precision drilling methods also enables hollow pyramidal lattices to be fabricated (figure 15).

Many processes are available to metallically bond honeycomb, prismatic and lattice truss structures from the sub assemblies described above. For titanium alloys diffusion bonding methods have been successfully developed. For example, lattice truss core sandwich panels can be made from Ti6Al4V alloys by applying...
a pressure of 5–10 MPa to each of the truss-face sheet nodes while the panels are held at 850–930 °C for about an hour. For other materials, electrical resistance, laser, friction stir and other common fusion welding methods can be used to assemble the structures.

For many stainless steels, super alloys, titanium, copper and some aluminium alloys, brazing methods can be used to fabricate periodic cellular lattices. Brazing usually involves coating (by dipping or spraying) the materials to be bonded with a melting temperature suppressing alloy dispersed in a binder/adhesive. For some materials, this can be applied as a thin clad layer to the sheets prior to their assembly into cellular structures. In other cases the brazing alloy is suspended as a powder in a sticky polymer resin and is applied by spraying. Numerous brazing alloy compositions have been developed for the various engineering alloy systems of interest. A Ni–25Cr–10P alloy is widely used for stainless steels (Sypeck & Wadley 2001; Sypeck & Wadley 2002; Queheillalt & Wadley 2005a) while Al–Si alloys are used to join some aluminium alloys (Kooistra et al. 2004).

3. Lattice truss mechanical properties

(a) Stiffness predictions

Periodic cellular structures are stretch dominated and their elastic properties are predicted to scale linearly with the relative density. The modulus also scales linearly with that of the parent alloy. Lattice truss structures have inclined trusses, which introduce resolved force and load supporting area factors that depend upon the topology of the truss structure and the direction of applied load. For a single layer tetrahedral lattice truss two independent stiffness constants (the out-of-plane compression and shear stiffness) are important for the mechanical performance of a sandwich panel, figure 16. The out of plane compressive stiffness of the tetrahedral lattice, $E_{33}$, is given by (Deshpande & Fleck 2001)

$$E_{33} = E_s \sin^4 \omega \bar{\rho},$$

where $E_s$ is the Young’s modulus of the parent alloy, $\omega$ is the included angle and $\bar{\rho}$ is the relative density as defined in table 3.

The out-of-plane shear stiffness of the tetrahedral lattice truss is given by (Deshpande & Fleck 2001)

$$G_{13} = G_{23} = \frac{E_s}{8} \sin^2 2 \omega \bar{\rho}.$$  

(3.2)

Similar expressions have been derived for pyramidal and three-dimensional Kagome lattices.

During out-of-plane compression of a square collinear lattice, only the vertical wires carry load and the Young’s modulus of the collinear sandwich lattice is then simply given by (Queheillalt & Wadley 2005a)

$$\frac{E^*}{E_s} = \frac{\pi}{4} \left( \frac{a}{l} \right) = \frac{\bar{\rho}}{2}.$$  

(3.3)

All of the trusses that are connected to the top and bottom faces of a sandwich panel contribute to load support in a diamond collinear or textile lattice. However, those at the sides of the specimen are unconnected and so the modulus of finite width
specimens will be reduced by a factor that depends upon the length, \( L \), to height, \( H \), ratio of the specimen. Zupan et al. (2004) have shown that the effective Young’s modulus, \( E^* \), of the diamond collinear lattice is given by

\[
\frac{E^*}{E_s} = \frac{\pi}{4} \left( \frac{\alpha}{t} \right) \left( 1 - \frac{1}{A \tan \omega} \right) \sin^3 \omega \cos^4 \omega \equiv \bar{\rho} \left( 1 - \frac{1}{A \tan \omega} \right) \sin^4 \omega, \tag{3.4}
\]

where \( A \equiv L/H \) is the aspect ratio of the sandwich plate. Note that \( 1 - 1/A \tan \omega \to 1 \) as \( A \to \infty \) and the lattice asymptotically attains its maximum modulus of \( E^* = E_s \bar{\rho} \sin^4 \omega \) (equation (3.1)) for samples that are long compared to their thickness.

The trusses of textile structures cross each other and are, therefore, wavy. If the waviness amplitude is equal to the strut diameter, \( a \), Queheillalt et al. (submitted) have shown that a work balance gives the effective modulus, \( E_w \), of a wavy strut as

\[
\frac{E_w}{E_s} = \frac{1}{1 + \left( \frac{10}{3} - \frac{32}{\pi} \right) + 8(1 + v)\left( \frac{\alpha}{t} \right)^2}, \tag{3.5}
\]

where \( v \) is poisons ratio. The out-of-plane modulus of the textile structure is then obtained by substituting \( E_w \) from equation (3.5) for \( E_s \) in equations (3.3) and (3.4).

(b) Modulus comparisons

The out-of-plane modulus is plotted versus relative density for a variety of periodic cellular materials in figure 17. Honeycombs have the highest modulus and are, therefore, preferred for stiffness dominated design. However, the reduction in modulus for some of the other topologies is not large, and the compromise between this property and others that might be critical may be
acceptable. Figure 17 shows predictions for the modulus of metal foams. These are bending dominated structures and their experimentally measured compressive modulus is fitted by (Ashby et al. 2000)

\[
\frac{E^*}{E_s} = \alpha(\bar{\rho})^n,
\]

where \(\alpha\) is a coefficient with a value that lies between 0.1 and 4 and the exponent, \(n\), has a value of approximately 2.

It is worth noting that many experimentally measured moduli for lattice trusses are well below the predicted values. Finite element analyses of these lattice structures indicate that the predictions above are reasonable estimates. The discrepancy appears to be a consequence of imperfections whose origin is not yet fully resolved. One effect could be truss waviness created during fabrication. Another might be related to small variations in the lengths of the trusses. During initial loading the applied load would then be disproportionately shared between the trusses.

(c) Strength predictions

Consider the tetrahedral lattice truss made from a rigid perfectly plastic material with tensile yield strength, \(\sigma_y\). In this case, yielding of the lattice is coincident with the peak strength of the lattice and must scale linearly with
relative density (load supporting area) and the yield strength of the parent metal. Deshpande & Fleck (2001) have shown that the peak strength, $\sigma_{33}^{pk}$, is given by

$$\sigma_{33}^{pk} = \sigma_y \sin^2 \omega \bar{\rho}. \quad (3.7)$$

However, at low relative densities, the trusses become increasingly slender and under some conditions the peak strength of the lattice is controlled by elastic buckling rather than yield. The peak compressive strength in this situation is obtained by replacing $\sigma_y$ in equation (3.7) with the elastic buckling strength of a truss member. The peak compressive strength is then given by

$$\sigma_{33}^{pk} = \frac{k^2 \pi^2}{8 \sqrt{3}} E_s \sin^3 \omega \cos^2 \omega \rho^2, \quad (3.8)$$

where $E_s$ is the Young’s modulus of the solid (parent) material and $k$ is a factor accounting for the rotational stiffness of the ends of the struts: $k=1$ or 2 for pin-ended or built-in end conditions, respectively.

By equating (3.7) and (3.8) it can be shown that tetrahedral lattice trusses made from an elastic ideally plastic material will collapse by elastic buckling of the constituent truss members when the relative density

$$\bar{\rho} < \frac{8 \sqrt{3}}{\pi^2 k^2 \sin \omega \cos^2 \omega} \frac{\sigma_y}{E_s}. \quad (3.9)$$

If a tetrahedral lattice is constructed from a material with a positive strain hardening rate, it begins to plastically deform (yield) at a strength given by equation (3.7), but continues to support increased stress due to strain hardening of the trusses. The trusses eventually collapse by plastic buckling at a plastic bifurcation stress, $\sigma_{cr}$, given by Shanley–Engesser tangent modulus theory (Gere & Timoshenko 1984). For square cross-section trusses with a cross-sectional area, $t^2$, and length, $l$, the plastic bifurcation stress is given by

$$\sigma_{cr} = \frac{k^2 \pi^2 E_t}{12} \left( \frac{t}{l} \right)^2, \quad (3.10)$$

where $E_t$ is the tangent modulus defined as the slope of the uniaxial stress versus strain response of the solid material at the critical stress, $\sigma_{cr}$.

The compressive strength of the lattice truss is obtained by replacing $\sigma_y$ in equation (3.7) by $\sigma_{cr}$ defined by equation (3.10). For a linear strain hardening material, $E_t$ is a constant and $\sigma_{33}^{pk}$ scales with $\rho^2$, whereas $\sigma_{33}^{pk}$ of a tetrahedral core that is constructed from an ideally plastic solid material scales linearly with relative density when yielding controls the strength.

The strength of a cellular metal whose collapse is controlled by plastic buckling can be increased by using metals with high $E_t$ values at the buckling stress of the struts. Redistributing the material of the strut to increase its moment of inertia can also increase the critical buckling stress for both elastic and inelastic buckling. Hollow trusses provide a convenient means for accomplishing this. The elastic bifurcation stress, $\sigma_{cr}$, for an axially loaded column is given by

$$\sigma_{cr} = \frac{\pi^2 k^2 E_s}{Al^2}, \quad (3.11)$$
where $E_s$ is the elastic modulus, $I$ is the second area moment of inertia of the truss and $A$ is its cross-sectional area. The inelastic bifurcation stress of a compressively loaded column is obtained by replacing $E_s$ with $E_t$, in equation (3.11)

$$\sigma_{cr} = \frac{\pi^2 E_t k^2 I}{AL^2}.$$  \hspace{1cm} (3.12)

In both buckling cases, the critical strength can be increased at constant relative density by redistributing the material of a solid strut as a tube. For example, by equating the metal cross-sectional area of a solid truss and hollow truss with a wall thickness that is a tenth that of the tube outer radius, results in a tubular truss whose outer radius is $5^{1/2}$ times that of the solid. The resulting ratio of the hollow to solid truss second moment is then 10. Strength increases of this order are unlikely to be fully achieved in practice because other, localized modes of tube buckling can set in. Nevertheless, significant strength increases are achievable and are beginning to be realized in hollow truss lattice structures.

The out-of-plane shear strength of a tetrahedral lattice has a minimum and maximum strength direction (figure 16). The former corresponds to a situation where one of the trusses is loaded in axial tension while the later is controlled by axial truss compression. For a linear, perfectly plastic material, the minimum out-of-plane shear strength is given by

$$\tau_{\text{min}} = \sigma_{13}^y = \frac{\sigma_y}{4} \sin 2 \omega \bar{p},$$ \hspace{1cm} (3.13)

where $\sigma_y$ is the material yield strength. The maximum out-of-plane lattice truss shear strength is

$$\tau_{\text{max}} = \sigma_{23}^y = \frac{\sigma_y}{2\sqrt{3}} \sin 2 \omega \bar{p}.$$ \hspace{1cm} (3.14)

For a strain hardening material with a tensile strength, $\sigma_{TS}$, the shear strength of the lattice in the weak shear direction is obtained by replacing $\sigma_y$ in equation (3.8) by $\sigma_{TS}$

$$\sigma_{13}^{pk} = \frac{\sigma_{TS}}{4} \sin 2 \omega \bar{p}.$$ \hspace{1cm} (3.15)

In the maximum shear strength direction, the shear strength is obtained by replacing $\sigma_y$ in equation (3.9) by $\sigma_{cr}$

$$\sigma_{31}^{pk} = \frac{\sigma_{cr}}{4} \sin 2 \omega \bar{p},$$ \hspace{1cm} (3.16)

where $\sigma_{cr}$ again corresponds to the column (truss member) bifurcation stress. Note that a difference in $\sigma_{TS}$ and $\sigma_{cr}$ associated with strain hardening materials will lead to an asymmetric shear strength of the tetrahedral lattice truss in the 1–3 (minimum strength) type directions. Similar results have been obtained for pyramidal and Kagome lattices.

The compressive strength or tensile out-of-plane strength of a square collinear or textile lattice is easily determined since half the trusses do not contribute to the compressive strength of sandwich panel structures and the remainder are aligned with the loading direction. If the metal is elastic–perfectly plastic, vertical wires undergo compressive or tensile yield, and the effective out-of-plane...
yield strength of the collinear lattice is given by

$$\frac{\sigma^*}{\sigma_{ys}} = \frac{\pi}{4} \left(\frac{a}{l}\right) = \frac{\rho}{2}. \quad (3.17)$$

If the trusses are sufficiently slender, the compressive strength of the square lattice is governed by buckling of the wavy struts and is obtained by replacing $\sigma_{ys}$ in the above equation with the compressive strength of a wavy truss, $\sigma_w$. Queheillalt et al. have recently shown that the collapse strength of a wavy strut, $\sigma_w$, is given by

$$\frac{\sigma_w}{\sigma_{ys}} = \frac{\lambda \pi + \sqrt{\lambda^2 \pi^2 + 64/9}}{8/3}, \quad (3.18)$$

where

$$\lambda = \left[\left(1 - \sqrt{1 - \frac{4}{\pi^2}}\right) - \frac{2}{\pi} \sin^{-1}\left(\frac{2}{\pi}\right)\right]. \quad (3.19)$$

In the square orientation of the collinear lattice, experimental studies indicate the lattice collapses by co-operative Euler buckling of the constituent struts over the full height of the sandwich. Assuming that the struts are built into the sandwich faces, the elastic buckling collapse load of a collinear square lattice is given by

$$\frac{\sigma^*}{\sigma_{ys}} = \frac{\pi}{4 \epsilon_y} \left(\frac{a}{l}\right)^3 \left(\frac{l}{H}\right)^2 = \frac{2 \rho^3}{\pi^2 \epsilon_y} \left(\frac{l}{H}\right)^2. \quad (3.20)$$

Elastic buckling is the operative collapse mode for sandwich lattice relative densities satisfying the inequality

$$\rho^2 < \frac{\pi^2 \epsilon_y}{4} \left(\frac{H}{l}\right)^2. \quad (3.21)$$

It is important to note that the elastic buckling strength of square collinear lattice materials is not an intrinsic material property; it decreases with increasing lattice height, $H$, for a fixed value of the relative density.

The yield strength, $\sigma^*$, of the diamond lattice can be determined directly from equilibrium. If the lattice is constructed from an elastic perfectly plastic material and struts are sufficiently stocky that failure occurs by yielding, the macroscopic compressive yield strength of the lattice is given by

$$\frac{\sigma^*}{\sigma_{ys}} = \frac{\pi}{4} \left(\frac{a}{l}\right) \left(1 - \frac{1}{A \tan \omega}\right) \tan \omega = \rho \left(1 - \frac{1}{A \tan \omega}\right) \sin^2 \omega. \quad (3.22)$$

The collinear lattice collapses by elastic buckling of the constituent trusses if the Euler buckling load, $P_{\text{euler}}$, of the constituent struts is less than their plastic yield strength. The Euler buckling load of the struts is given by

$$P_{\text{euler}} = \frac{k^3 \pi^3 E_s a^4}{4l^2}, \quad (3.23)$$

while the plastic yield load, $P_{\text{yield}} = \pi a^2 \sigma_{ys}$. The factor $k$ in equation (3.23) depends on the rotational stiffness of the end nodes of the strut. The lowest
strength buckling mode under uniaxial compression corresponds to struts of length, \( l \), buckling as pin-ended (freely rotating) struts. Thus, \( k = 1 \) and the collinear lattice collapses by elastic buckling of the constituent struts if the yield strain, \( \varepsilon_y \), of the solid material satisfies the inequality

\[
\varepsilon_y \equiv \frac{\sigma_{ys}}{E_s} > \frac{\pi^2}{4} \left( \frac{a}{l} \right)^2 \equiv \rho^2 \sin^2 2\omega.
\] (3.24)

In the regime of relative density where buckling dominates, the collapse strength is given by

\[
\frac{\sigma^*}{\sigma_{ys}} = \frac{\pi^3}{16\varepsilon_y} \left( \frac{a}{l} \right)^3 \left( 1 - \frac{1}{A \tan \omega} \right) \tan \omega \equiv \frac{\rho^3}{\varepsilon_y} \left( 1 - \frac{1}{A \tan \omega} \right) \sin^2 2\omega \sin^2 \omega.
\] (3.25)

(d) Strength comparisons

The core relative density regime where sandwich panel structures are optimized for bending is \( \sim 2–10\% \). Out-of-plane compressive strength measurements for periodic cellular metals with a variety of topologies are summarized in figure 18 for this range of relative densities. Most of the samples were constructed from stainless steel. The strength of periodic cellular structures made from high modulus, medium strength alloys (e.g. 304 stainless steel), is then plastic buckling controlled. Strain hardening has significant effects and results in an elevation of the strength above elastic–perfectly plastic predictions. At low relative density, pyramidal lattices are competitive with honeycombs because slender columns have superior buckling resistance to thin sheets.

Diamond woven textiles are found to have strengths significantly less than collinear materials with the same relative density and topology. This appears to be a consequence of their wavy struts. However, both are still significantly superior to equivalent weight open cell foams.

Data for the strength of hollow truss structures agree well with predictions of increased strength arising from the delayed onset of buckling. For example, the strength of a hollow pyramidal lattice with a relative density of 1.8\% is more than three times that of a solid truss structure of identical relative density. These structures are significantly superior to honeycomb structures in this relative density region.

Recent studies by Wicks & Hutchinson (2001, 2004) and Valdevit et al. (2004) have begun to explore optimized sandwich panel designs for bend load support applications. The various modes of failure of failure have been identified and material is redistributed between the core and face sheets to maximize the bending resistance. The weight of simple and diamond corrugated structures subjected to simple longitudinal bend loading are then found to be comparable to truss core structures assuming elastic–perfectly plastic material responses. Honeycombs are predicted to be about 40\% lighter. The introduction of strain hardening may have a significant effect upon these optimizations.

Kooistra et al. (submitted) have recently reported significant increases (factors of ten or more) in the strength of simple corrugations by redistributing the material in a hierarchical design. Essentially, they made each web of the corrugation from corrugated plates. Optimization studies for these hierarchical designs

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designs and comparisons with the hollow truss structures may lead to further improvements in mechanical performance.

4. Multifunctional applications

Periodic cellular metals with honeycomb and corrugated topologies are widely used core structures for light weight sandwich panels. Recent fabrication developments now enable lattice truss core structures to be fabricated with similar, and in some cases superior mechanical performance. All these cellular structures can be exploited for multifunctional applications. Three illustrative examples are considered below.

(a) Thermal management

Sandwich panel structures based upon highly porous, periodic cellular metal structures have attracted significant interest for load supporting structural applications. Cellular metals with open cell topologies are also attractive heat exchange media, where dissipation of high intensity heat in relatively small spaces is required (Evans et al. 1999; Gu et al. 2001). Consider a typical application, where a high heat flux is deposited on one of the face sheets of a sandwich panel structure. Corrugated or prismatic core structures are widely used to dissipate heat because they provide ample opportunity to conduct the

Figure 18. Normalized strength variation with relative density for cellular metals.
heat from the hot face sheet into the web structure (Lu 1999; Brantsch et al. 2002; Yeh et al. 2003; Tronconi et al. 2004; Boger & Heibel 2005; Dempsey & Eisele 2005). This results in a temperature gradient through the thickness of the core. If a coolant flows through the core, heat transfer at the metal–coolant interface occurs and this heat is transported away from the webs raising the average temperature of the coolant and reducing that of the metal core.

The performance of a corrugated core heat exchanger can be characterized by the heat removed under constant fluid flow velocity and by the pressure difference required to propagate the coolant at that velocity through the flow channels. These can be quantified by two topology dependent dimensionless parameters. The Nusselt number, $Nu_H$, characterizes the heat removed from the structure and is defined by

$$Nu_H = \frac{hH}{k_f}, \quad (4.1)$$

where $h$ is the heat transfer coefficient between the metal webs and the coolant, $H$ is a characteristic dimension (e.g. the cell or core height) and $k_f$ the thermal conductivity of the coolant. The friction factor, $f$, characterizes the resistance to flow and is defined by

$$f = \left( \frac{\Delta P}{L} H \right) \left( \frac{1}{\rho U_{m}^2/2} \right), \quad (4.2)$$

where $U_{m}$ is the mean coolant velocity at the inlet of the heat exchanger, and $\Delta P/L$ is the pressure drop per unit length. The coolant velocity can also be expressed in dimensionless form by the Reynolds number of the flow defined as

$$Re_H = \frac{\rho_f U_{m} H}{\mu_f}, \quad (4.3)$$

where $\rho_f$ and $\mu_f$ are the coolant density and viscosity.

Any open cell metal structure that allows a coolant flow to pass through the pore structure can be used as a heat exchange medium. Both stochastic (metal foams and sintered powders) and the periodic topology structures described above have been made from a wide variety of metals and their heat exchange performance explored. Metal foams with open cells have inferior load supporting capability compared to periodic structures of the same weight because their deformation under mechanical loading is dominated by cell wall bending as opposed to cell wall stretching in most periodic structures (Deshpande et al. 2001). However, they provide a high thermal conductivity path for thermal transport, possess a very high surface area for heat transfer to a cooling fluid and provide a contiguous (though tortuous) path for coolant flow through the structure (Boomsa & Poulilakos 2001; Battacharyya et al. 2002; Phanikumar & Mahajan 2002; Singh & Kasana 2004; Zhao et al. 2004). Periodic cellular structures have anisotropic pore structures. For instance, prismatic structures have one low friction flow direction. Pyramidal lattices have two, and the three-dimensional Kagome and tetrahedral topologies have three easy flow directions. Textile and collinear structures have one very easy flow direction while flow in others lies between that of the lattices and prismatic structures. Their thermal characteristics are, therefore, orientation dependent, leading to optimization opportunities.
Numerous studies have sought to characterize the cross flow heat exchange performance of the various cellular structures. Several recent attempts have been made to compare them in terms of the dimensionless metrics described above as a function of the flow velocity expressed in the form of the dimensionless Reynolds number based upon $H$ defined as the core thickness used for measurements \((\text{Kim et al. 2004a,b, 2005; Tian et al. 2004a})\). Figure 19 shows a recent comparison of the performance of aluminium, copper and iron base alloy foams, copper textile structures and various truss structures measured in the easiest flow direction \((\text{Tian et al. 2004b; Lu et al. 2005})\). The metrics for various reference configurations are also shown including Moody’s result for an empty channel (a panel with the core removed), a corrugated duct and a louvered fin structure. The most promising structures have a high Nusselt number and low friction factor at the coolant velocity of interest (set by the input thermal flux, the coolant, the required operating temperature and the available fluid pumping capacity).

Several observations can be deduced from these preliminary efforts to compare structures. If heat removal and friction factor are equally important, louvered fins and prismatic structures have the best performance because of their low frictional losses. As friction becomes less of a constraint, or the need to remove heat dominates, the textile structures and smaller cell size diamond prismatic structures become interesting because they have a large area of contact with the hot face sheet and present a high surface area to the flow. There are important caveats yet to be resolved for multifunctional structures which must support loads and enable heat transfer to a cross flow. The optimum heat exchanger structures balance the conduction of heat through webs and trusses (maximized by increasing the relative density) against the need to create easy flow paths (maximized by minimizing relative density). The optimum is material selection and application specific but lies in the 10–20% relative density range. Light weight sandwich panel optimizations for bending typically result in structures with much lower core relative densities (around 2%).

One approach to resolving this dilemma is to increase the thermal conductivity of the cellular structure. This then enables the conductive transport of the thermal flux using smaller cross-sectional area webs or trusses. Heat pipes and plates offer a novel potential route. Preliminary results are encouraging \((\text{Tian et al. 2004b})\). An additional advantage of the approach arises when hollow truss structures are utilized, since these also possess exceptional strength compared to their solid equivalent relative density counterparts.

\[(b)\] Blast wave mitigation

The need to protect structures from the high intensity dynamic loads created by explosions in air or water has stimulated interest in the periodic cellular structures to replace monolithic load supporting structures \((\text{Xue & Hutchinson 2003; Fleck & Deshpande 2004})\). When an explosive charge is detonated in air, the rapidly expanding gaseous reaction products compress the surrounding air and move it outwards with a high velocity that is initially close to the detonation velocity of the explosive \((\sim 7200 \text{ m s}^{-1})\). The rapid expansion of the detonation products creates a shock wave with discontinuities in pressure, density, temperature and velocity \((\text{Baker 1973})\). The pre and post shock states are
Figure 19. Comparisons of (a) the Nusselt number (heat removal rate) and (b) friction factor as a function of Reynolds number for cellular metals (adapted from Tian et al. 2004b; Lu et al. 2005).

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described by conservation equations for mass, momentum and energy, and are collectively referred to as the Rankine–Hugoniot jump equations (Baker 1973).

The shock wave that travels through the air consists of highly compressed air particles that exert pressure on all surfaces they encounter. There is a discontinuous ‘jump’ of the shock front pressure, with the pressure rising from ambient \((p_a)\) to \(p_s\). The pressure difference \((p_s - p_a)\) is referred to as the blast overpressure. At a fixed location in space, the pressure decays exponentially with time after the arrival of the shock and is followed by a negative (i.e. suction) phase. A blast wave pressure pulse has a very short time duration, typically measured in fractions of a millisecond. The free-field pressure–time response can be described by a modified Friedlander equation,

\[
p(t) = (p_s - p_a) \left[ 1 - \frac{t - t_a}{t_d} \right] e^{-(t-t_a)/\theta},
\]

where \(t_a\) is the arrival time, \(t_d\), the time duration of the positive phase, and \(\theta\) the time decay constant (ConWep blast simulation software). The impulse \((I)\) is given by the time integral of the applied pressure time response during the positive phase.

When the shock wave encounters a surface, it is reflected, amplifying the incident overpressure. In air the magnification can be highly nonlinear and depends upon the incident shock strength and the angle of incidence. For a weak air supported shock, the resultant blast loads are doubled upon reflection of the shock wave. For strong shocks, reflection coefficients of 8 have been reported assuming ideal gas conditions and up to 20 when real gas effects such as the dissociation and ionization of air molecules are considered (Baker 1973).

The most promising cellular metals mitigation approach utilizes sandwich panel concepts to disperse the mechanical impulse transmitted into structures thereby reducing the pressure applied to a protected structure located behind. A schematic illustration of the concept is shown in figure 20. Detailed finite element calculations using fully meshed geometries with square honeycomb, prismatic corrugations and pyramidal truss topologies made from materials defined by their yield strength, strain hardening rate, and strain rate sensitivity have been conducted (Xue & Hutchinson 2003; Fleck & Deshpande 2004; Qiu et al. 2004; Xue & Hutchinson 2004; Hutchinson & Xue 2005; Rathbun et al. in press). These studies indicate significant performance improvements compared to equivalent mass per unit monolithic plates. They arise from three beneficial effects (two for air loading): (i) a fluid structure interaction effect for water loading that reduces the momentum impulse transmitted to the structure, (ii) kinetic energy dissipation in the cellular material by core crushing and (iii) the increased bending resistance of the sandwich panel structure.

For near field air blasts, a shock wave propagates from the source of the explosion to the front face and is reflected. The pressure resulting from the shock wave decays with distance (from the explosion source) and time. When the shock is incident upon a rigid surface, the shock wave front undergoes a reflection. This requires the forward moving air molecules comprising the shock wave to be brought to rest and further compressed inducing a reflected overpressure on the wall, which is of higher magnitude than the incident overpressure. The impulse imparted to the front face of the structure causes it to acquire a velocity that varies inversely with the mass per unit area of the face sheet. In the acoustic limit, the
pressure pulse applied to the sample front face during this process is twice that of the free-field shock (large stand-off distances and for weak explosions). In the near field where nonlinear effects are present in the shock front, the pressure reflection coefficient can rise to a value of eight (under an ideal gas assumption). Even larger pressure reflection coefficients result when real gas effects (dissociation and ionization of the air molecules) occur in the free field shock. Deshpande & Fleck refer to this initial phase of the blast shock–structure interaction as stage I. In water, thin face sheets have a low inertia and able to deflect during the initial shock loading. Cavitation then occurs in the water at some finite distance from the

Figure 20. Air blast mitigation concept using a sandwich panel and its response to blast loading.
face sheet–water interface and the momentum imparted to the structure is established by that of the face sheet and attached water. This can be as little as a half the impulse that would be acquired by a rigidly supported solid plate of identical mass per unit area to the sandwich panel.

For an ideal blast with no delayed (reflected) shock arrivals (e.g. due to the ground), a front face of mass $m_f$, will be moving at a velocity, $v_o$, towards the back face sheet, and will have acquired its full momentum ($m_f v_o$) at the end of stage I. For sandwich panel structures, this front face motion is resisted by compression of the cellular core. A region of densified core is then created at the front face and this propagates at the core plastic wave speed towards the back face. This plastic wave speed, $V_p = (E_t/\rho_s)^{1/2}$ where $E_t$ is the parent alloy tangent modulus and $\rho_s$ its density. $V_p$ is typically ~500 m s$^{-1}$ for stainless steel alloys subjected to plastic strains of around 10%. It is about a tenth of the elastic wave speed of the materials used to make the structure.

The core crushing occurs at a characteristic pressure and this pressure resists the front plate movement and slows the front face motion. The magnitude of the explosive shock that can be resisted depends upon the strength of the core and its thickness and the face sheet thickness (i.e. mass per unit area). Several groups have sought to identify the optimal cellular structure relative density. Results are somewhat dependent upon the core topology but in general identify the 2–5% relative density range as an optimum. Figure 18 shows that at this relative density, the quasi-static compressive strength of honeycombs and pyramidal (and tetrahedral) lattices are comparable and recent experiments and detailed finite element modelling indicate that each of these structures have promising attributes for blast wave mitigation.

The momentum $m_f v_o$ acquired by the front face results in front face (initial core crushing) velocities ($v_o$) in the 100–200 m s$^{-1}$ range. At these velocities dynamic effects can increase the cellular structures, dynamic strength significantly. Three effects contribute to this elevation of crush stress: the inertial resistance of the core, strain rate hardening of the alloy used to make the core webs/trusses and inertial increases in the buckling strength of the core webs or truss members. Recent results indicate that these effects can increase the crush resistance by up to an order of magnitude (J. W. Hutchinson 2005, private communication).

For large, spatially localized shock loadings, the impulse transmitted to the back face sheet can be sufficient to cause an edge supported panel to bend. During this panel bending process (stage III), figure 20, further mechanical energy dissipation occurs by a combination of core collapse and core/race sheet stretching. In a well designed system, the restraining forces accompanying this plastic dissipation are sufficient to arrest the motion of the panel before the loads applied to the support structure exceed design objectives, or front face tearing or shear off occurs. It is important to recognize that core crushing continues to play an important role during stage III because highly crush resistant cores maintain a larger face sheet separation and, therefore, a higher panel bend resistance.

These various effects combine to enable large reductions in the back face deflections of sandwich panels compared to solid plates of equivalent mass. Figure 21 shows measurements of a honeycomb core sandwich panel fabricated from high ductility stainless steel subjected to strong air blast shock loadings and

compares them to the response of a solid plate. It can be seen that large improvements through the use of periodic cellular materials can be achieved. Several groups are investigating how to optimize cell topology, select the alloy system and choose the various geometrical details to further improve this performance increase.

(c) Hybrid ballistic lattices

Several groups have begun to investigate the ballistic properties of cellular metals. Gama et al. (2001) have investigated the use of closed cell aluminium foams in layered, integral armour concepts and find potentially significant improvements in system performance. These improvements appear to be related to the delay and attenuation of stress wave propagation. Layers of the foam were found to decouple the underlying structure from the high intensity stress waves created by projectile impacts. The mechanism appeared to be a consequence of: (i) the high crushability of these materials which enable shock isolation until the foam had reached its densification strain and (ii) the high acoustic damping of partially crushed closed cell aluminium foams.

Honeycomb topologies are significantly more efficient at supporting stress than their equivalent relative density metal foams, and have been shown to be very

Figure 21. Measurements of the sandwich panel front and back face deflections as a function of applied impulse compared with solid plate centre deflections.
effective at dissipating the energy of projectiles provided the area of the impact is large compared to the cell size (Frank 1981; Goldsmith & Louie 1995). They offer much less resistance if the projectiles do not interact with the webs in these structures.

The projectile penetration of sandwich panels with periodic cellular metal cores has begun to be investigated experimentally by Yungwirth et al. (submitted). He finds that when the cell size is large compared to the diameter of the projectile, the sandwich panels provide about the same resistance to penetration as the solid face sheets alone. Additional small projectile velocity reductions occur when the projectiles strike the trusses, and are a consequence of projectile energy dissipation by truss plastic deformation.

Yungwirth et al. (submitted) noted that the void spaces in periodic cellular metal sandwich structures provided opportunities to insert materials that could improve ballistic performance. Preliminary studies of hybrid structures containing elastomers with glass transition temperatures in excess of the ambient temperature and/or hard ceramics led to very significant increases in ballistic performance. Figure 22 shows cross-sections of a pyramidal lattice core sandwich panel after impact with a 12.5 mm diameter steel projectile with an impact velocity of 600 m s$^{-1}$. The empty lattice and a lattice filled with an elastomer with low glass transition temperature were easily penetrated. Similar lattices infiltrated with a high glass transition temperature elastomer or metal encased alumina were much more effective at resisting projectile penetration. These early studies suggest interesting possibilities for tailoring the performance of new composite systems based upon metallic lattices.

5. Summary

Periodic cellular metals encompassing closed cell honeycombs, prismatic corrugations and lattice structures with solid and hollow trusses and cell sizes in the millimetre range can now be fabricated from a wide range of engineering alloys. When used for the cores of light weight sandwich panels, low relative density variants of all cell topology classes can result in panels with high bend resistance, significant out-of-plane compressive strength/stiffness and excellent in-plane shear stiffness and strength. When constructed from medium strength, high work hardening rate alloys with large Young’s moduli, these cellular structures collapse by inelastic buckling under compressive loading. Hierarchical corrugated and hollow truss structures with enhanced second moments of inertia provide very significant additional strength improvements over systems explored to date.

Closed cell honeycomb structures can be used to impede heat flow through the thickness of sandwich panels. Corrugated structures provide an easy coolant flow path for cross flow heat exchange. Lattice truss structures have several of these easy flow directions and very high specific surface areas for contact with a coolant flow. As a result, they can provide superior heat removal but at the cost of sometimes significantly higher resistance to coolant flow. These structures are very compressible and show significant promise for the mitigation of high intensity shock waves such as those created by the detonation of explosives in air or water. Their resistance to the penetration of
projectiles is comparable to that of their face sheet structures. However, significant enhancements appear feasible by inserting polymers and hard ceramics into the aligned pore spaces of these structures. Generalizations of these hybrid lattice structures appear to offer a promising route for the development of novel multifunctional structures.

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