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# Hybrid core carbon fiber composite sandwich panels: Fabrication and mechanical response

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## ABSTRACT

Carbon fiber reinforced polymer (CFRP) composite sandwich panels with hybrid foam filled CFRP pyramidal lattice cores have been assembled from a carbon fiber braided net, 3D woven face sheets and various polymeric foams, and infused with an epoxy resin using a vacuum assisted resin transfer process. Sandwich panels with a fixed CFRP truss mass have been fabricated using a variety of closed cell polymer and syntactic foams, resulting in core densities ranging from 44–482 kg m$^{-3}$. The through thickness and in-plane shear modulus and strength of the cores increased with increasing foam density. The use of low compressive strength foams within the core was found to result in a significant reduction in the compressive strength contributed by the CFRP trusses. X-ray tomography led to the discovery that the trusses develop an elliptical cross-section shape during pressure assisted resin transfer. The ellipticity of the truss cross-sections increased, and the lattice contribution to the core strength decreased as the foam density was reduced. Micromechanical modeling was used to investigate the relationships between the mechanical properties and volume fractions of the core materials and truss topology of the hybrid core. The specific strength and moduli of the hybrid cores lay between those of the CFRP lattices and foams used to fabricate them. However, their volumetric and gravimetric energy absorptions significantly exceeded those of the materials from which they were fabricated. They compare favorably with other lightweight energy absorbing materials and structures.

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## 1. Introduction

An ongoing effort to increase the structural efficiency and impact energy absorption of weight sensitive structures continues to motivate interest in ultra-light sandwich panel structures [1]. A number of light, stiff, and sometimes strong, concepts have emerged for such applications. They utilize faces made of materials with high specific stiffness and strength separated by low density cellular cores with either a honeycomb topology fabricated from Nomex [2], light metals and composites [3], or a closed cell topology foam made from rigid polymers [4,5]. Various groups have also attempted to use metal foams as a stiffer and stronger replacement for lower cost polymer foams, and as a less costly alternative to honeycombs [6,7].

Open cell foams have a low nodal connectivity and are usually bend-dominated structures. As a result they have low elastic moduli and compressive strengths; especially at low density. Gibson and Ashby [8] have shown that the Young's elastic modulus, $E$ of foams depends on the foams cell topology (open or closed cell), its relative density $\bar{\rho}$ defined as the ratio of the density of foam to that of the solid from which it is made, and the elastic modulus of the solid material from which it is made, $E_s$. For open cell foams, the modulus-relative density relationship can be written:

$$\frac{E}{E_s} = C\bar{\rho}^2 \tag{1a}$$

where $C$ is a cell topology dependent constant (approximately equal to unity for many open cell foams). The inelastic crushing of polymeric foams usually occurs at a near constant "plateau" stress over a large plastic strain (of order 0.6) terminated by the onset of densification at a densification strain, $\varepsilon_D = 1 - 2\bar{\rho}$. For open cell foams, the plateau strength, $\sigma_{pl}$ is proportional to the yield strength of the material from which the foam is made, $\sigma_{ys}$ but has a power law dependence upon relative density [8]:

$$\frac{\sigma_{pl}}{\sigma_{ys}} = C_1\bar{\rho}^{3/2} \tag{1b}$$

where $C_1$ is a constant of proportionality. The energy absorbed per unit volume during crushing of foams to their densification strain, is given by the integral of the stress strain response up to the onset of densification. For an ideal foam with rectangular stress versus strain

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relation, the volumetric stored energy is $\sigma_{pl}(1-2\bar{\rho})$ [8,9]. The rapid loss in energy storage as the relative density (and plateau strength) decreases can be mitigated by the use of closed cell foams.

Closed cell foams have cell edges which both bend and stretch during compression and have cell faces which also stretch. The relationship between the Young's modulus and relative density of closed cell foam includes contributions from the cell edges and faces, resulting in a foam modulus – relative density relation of the form [8]:

$$\frac{E}{E_s} = C_2\phi^2\bar{\rho}^2 + C_2'(1-\phi)\bar{\rho} \tag{2a}$$

where $C_2$ and $C_2'$ are the constants of proportionality for the cell edges(bending structures) and cell faces (which deform by membrane stretching), and $\phi$ is the fraction of the solid in the cell edges.

The plastic collapse strength of the closed cell foam also contains contributions from the stretching of the cell faces and is given by:

$$\frac{\sigma_{pl}}{\sigma_{ys}} = C_3(\phi\bar{\rho})^{3/2} + C_3'(1-\phi)\bar{\rho} \tag{2b}$$

As a result of the stretching, the moduli and plateau strengths of closed cell foams are higher than open cell equivalents, and are therefore preferred for impact protection. While these foams are excellent impact energy absorbers, the structural efficiency of foam core sandwich structures are inferior to honeycomb and some other core topology concepts [10].

The search for structurally efficient cellular cores has led to the development of lattice truss structures made from high specific strength alloys such as titanium [11] and aluminum [12]. They have been shown to exhibit superior stiffness and strength to identical denzsity closed cell foams made of the same material [13,14]. This arises because lattice structures have high nodal connectivity and are fully stretch dominated. Deshpande and Fleck [15] have analyzed the load redistribution process for tetrahedral and pyramidal truss structures, and predict a linear relation between the lattice modulus and that of the solid and the relative density of the core given by:

$$\frac{E}{E_s} = \bar{\rho}\sin^4\omega \tag{3}$$

where $\omega$ is the angle of inclination of the truss (typically 45–55°). They also show that for low aspect ratio trusses that do not buckle, the lattice strength was proportional to that of the solid material used to make the truss, $\sigma_Y$, and the lattice relative density:

$$\frac{\sigma}{\sigma_Y} = \bar{\rho}\sin^2\omega \tag{4}$$

Since the modulus and strength of lattice structures significantly exceeds those of equivalent foams, a number of fabrication approaches have been devised to utilize lattice structures for the cores of sandwich structures. For instance, aluminum truss cores manufactured via extrusion or folding have been shown to have good mechanical performance in both compression and shear [12,16]. Titanium alloy lattices have also been shown to have high compressive strengths and stiffness's, and are well suited for use in higher temperature applications [17,18]. Low density carbon fiber reinforced composite (CFRP) lattices have also attracted significant recent interest for the cores of ultra-light sandwich structures [19–26]. For example, CFRP honeycomb core sandwich structures have been made from 0°/90° fiber reinforced laminates using a slotting and adhesive bonding approach, and have been found to have high compressive and shear strengths [19]. Carbon fiber truss structures have also been made by hot-press molding of carbon fiber pre-preg materials [20–22] and by a mechanical "snap-fit" method [23,24].

The compressive strength of CFRP lattice structures made from laminates is governed by elastic buckling of the struts at low relative densities, or truss delamination (inter-ply splitting). In shear, the strength of the adhesive used to attach the truss to the face sheet is also a limiting factor. In addition, the use of 0°/90° laminates results in at most only half of the fibers being oriented in the direction of the load applied to the truss. The strength of CFRP truss structures could therefore be increased by; (i) increasing the fraction of fibers aligned in the loading direction, (ii) creating trusses better able to withstand interplay delamination failure, and (iii) developing a more robust node-face sheet bonding method. However, once a brittle CFRP strut failure occurs, the remnant strength of the lattices would be low, and so a CFRP core structure might be ill-suited for impact energy absorption applications.

Here we explore the use of braided carbon fiber approach for fabricating CFRP pyramidal lattice structures that reinforce closed cell polymer foams in a hybrid CFRP truss/foam core sandwich panel. The braided trusses are non-laminated materials. In principle this eliminates the delamination failure mode. In addition, all the fibers are aligned within a few degrees of the braid axis which may increase the axial compressive strength of the strut. We have investigated the effect of varying the foam strength upon mechanical response of the hybrid and empty lattice panels in compression and shear. We find that the hybrid composite/foam structures have a strength that is the sum of the foam and pyramidal lattice. Interestingly, we also find that the cross sectional shape, and thus compressive strength contributed by the composite struts, is governed by the foams resistance to crushing during the (pressure assisted) resin transfer fabrication process. This led to a synergistic increase in strut strength as the foams compressive strength was increased. The energy absorbed during crushing of these hybrid structures then substantially exceeded that of CFRP lattices and the foams.

## 2. Panel design and fabrication

### 2.1. Design concept

The sandwich panel concept explored here is schematically illustrated in Fig. 1. The panel cores were assembled from a braided carbon fiber net and prismatic, closed cell polymer foam inserts to

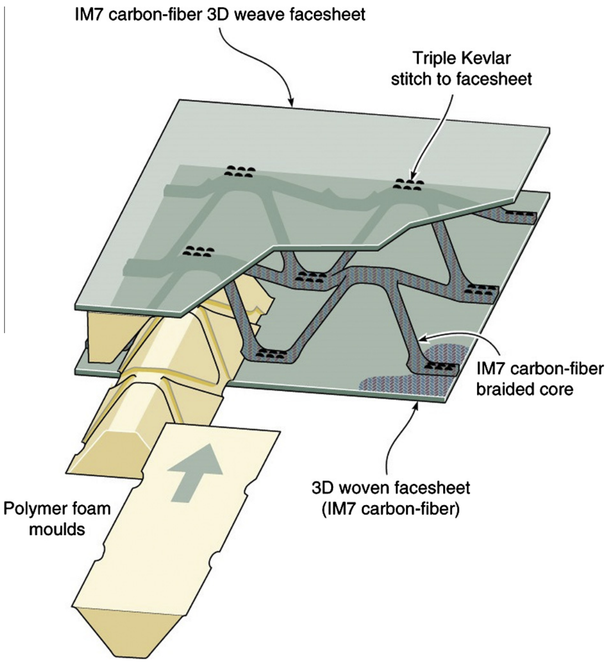

**Fig. 1.** Hybrid composite core structure consisting of a braided CFRP pyramidal lattice with polymer foam inserts configured as the core of a sandwich panel with 3D woven carbon fiber composite face sheets.