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Compressive and shear properties of carbon fiber composite square honeycombs with optimized high-modulus hierarchical phases

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ABSTRACT

This paper focuses on strengthening carbon fiber hierarchical composite square honeycomb structures (HCSH) by selecting high-modulus hierarchical phase and optimizing its thickness. HCSH have been manufactured from carbon fiber composite foam sandwich structures by a simple snap-fit and bonding method. The measured compressive and shear strengths are shown to be well predicted by micromechanics failure models of HCSH. Compared to the monolithic composite square honeycomb structures (CSH), the measured specific out-of-plane compressive strength of HCSH improves to approximately 330% and the specific shear strength improves to about 180%. Furthermore, the relationships between hierarchical phase modulus and its optimum thickness are developed to design the optimum HCSH. Carbon fiber HCSH are found to exhibit better mechanical properties than other cellular structures, and thus provide new opportunities for light-weight multifunctional sandwich structures.

1. Introduction

Composite periodic structures encompassing closed cell honeycombs and lattice truss structures, owing to their ultra-lightweight, high capability-loading and vast undeveloped inner space, are considered as the most one of promising candidates for multifunctional sandwich structure materials. Recently, a variety of composite periodic structures have been manufactured such as square honeycombs[1–4], hierarchical honeycombs [5–7], pyramidal lattices [8–11], octet-trusses [12,13], and other lattices [14–17]. Their experimental results have been added to the modified material property charts [8], as shown in Fig. 1. It was not difficult to find that carbon fiber composite honeycombs have significantly higher compressive modulus than the other competing materials with an equal mass. Meanwhile, at the core densities of more than 150 kg/m^3, CSH have the superior out-of-plane compressive strength over most known materials. Nevertheless, there are also two key challenges that limits the application of CSH. One is the elastic buckling of the honeycomb walls as the core density is less than 150 kg/m^3, which cause low out-of-plane compressive strengths. The other is the low shear strength of the core-to-facesheet bonding area where is generally the “weakest link” of the panels.

Russell et al. [4] designed and manufactured the square honeycomb sandwich structures from carbon fiber composites. Their out-of-plane compressive and in-plane shear responses were measured as a function of the relative density. The measurements and predictions reported here indicate that composite cellular materials with a square honeycomb topology reside in a gap in the strength versus density material property space (Fig. 1), providing new opportunities for lightweight, high strength structural design.

Recently, scholars have been trying to develop new methods to enhance compressive and shear strengths of composite sandwich structures. They found that hierarchical structure sandwiched by corrugated plate [15,18], foam [7,19,20], lattice truss [6,21] or other topology [22–25] is an efficient way to enhance the strengths of lightweight porous materials. Hierarchical structure has been designed to improve the buckling resistance because of its reinforced bending stiffness of the sandwich wall. The compressive strength of the hierarchical structure can be therefore vastly improved.

Kooistra et al. [18] designed the hierarchical corrugated core sandwich panel. The experiments indicated that the predicted strength of the second order truss is about ten times greater than that of a first order truss of the same relative density. Kazemahvazi et al. [19] designed and manufactured all-composite corrugated sandwich beams. Experimental results showed that the hierarchical structures can offer at least seven times higher specific strength compared to a monolithic corrugation.

Fang [23] found that the hierarchical design could improve the energy absorption of ultralight structures. The second order hexagon

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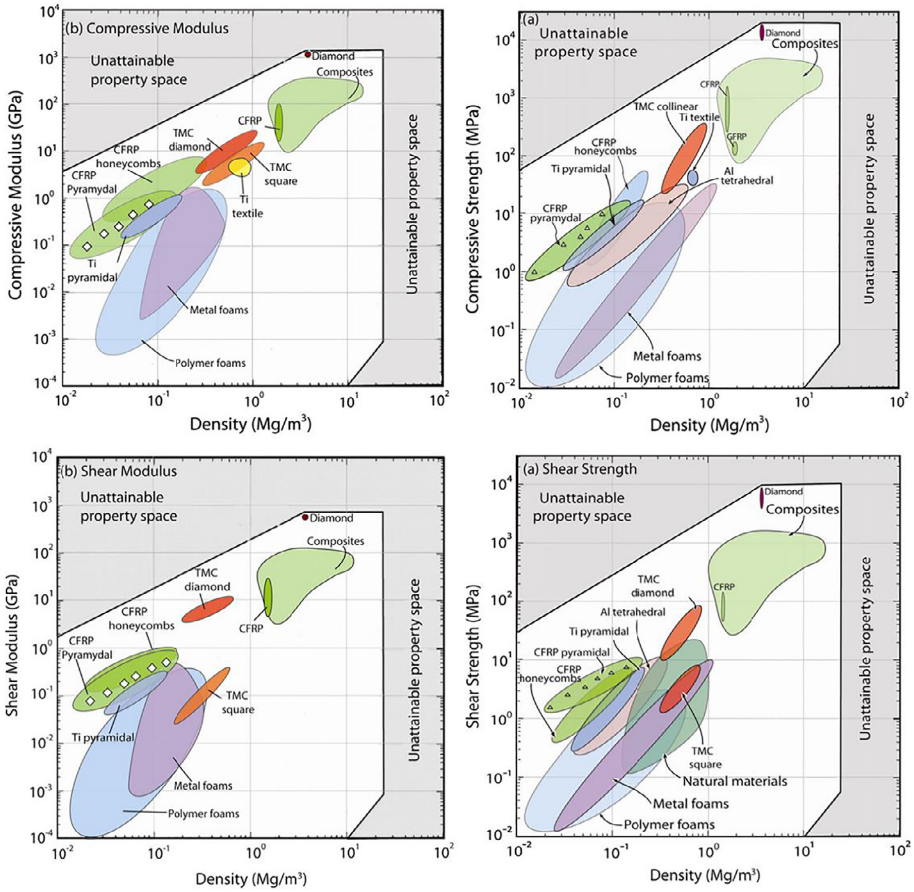

Fig. 1. Modified Ashby material strength versus density map for engineering materials [8].

honeycomb can provide a higher plateau stress than the regular honeycomb and the aluminium foam. Hierarchical structures can be used to design novel ultralight structures with excellent energy absorption capacity.

To enhance compressive strength of CSH, Cote et al. [7] manufactured the composite hierarchical square honeycombs sandwiched a polymethacrylimide (PMI) foam between E-glass fiber/epoxy composites. The hierarchical sandwich panel had a higher out-of-plane compressive strength than that of a monolithic composite sandwich panel. The result indicated that the extra hierarchical phase dramatically increased the specific strengths of CSH because of the increased elastic buckling resistance of the honeycomb walls. However, strengthening mechanism of the hierarchical structure have not been detailly discussed in this literature. Moreover, the low-modulus hierarchical phases resulted in low-level failure modes (Wrinkling or Shear buckling), which could not fully develop the advantages of hierarchical structures and then weakened its mechanical properties. Apart from that, the thick foam has increased the unit cell width, which resulted in the weak geometric continuity of the hierarchical structure. In addition, the in-plane shear properties of hierarchical structures, one of the important factors characterizing mechanical properties of HCSH, have not been researched in the article as well.

To improve the energy absorption of the woven honeycomb panels, Fan et al. [5,6] designed and fabricated hierarchical square honeycomb panels. The hierarchical square honeycomb panels owned lightweight, high compressive strengths and stable stress plateau at a relative high stress level. It was shown that the hierarchy obviously enhanced the energy absorption capability of composite honeycombs.

In addition, Yin et al. [26] investigated the mechanical properties of hollow lattice truss reinforced honeycombs. The measured results indicated that hollow lattice increased the buckling resistance of honeycombs. This work revealed that hybrid designs that capitalize on micro-topologies can fill the vacant regions in mechanical property charts.

And yet for all that, further improvements appear feasible for hierarchical structures by selecting high-modulus hierarchical phase and optimizing its thickness. Here, we take advantage of the hierarchical structure to enhance the elastic buckling resistance of the honeycomb walls. The honeycomb walls are made by woven carbon fiber/epoxy composite panels sandwiched by a high-modulus PMI foam. Here, we explore the application of a simple “snap-fit” assembly method for fabricating the HCSH panels. The mechanical properties of the HCSH have been characterized as a function of the core density and compared to micromechanical predictions. Finally, the measurements are added to the modified Ashby material property chart and compared with those of the other composite sandwich structures.

2. Materials and fabrication

2.1. Manufacture technique

The plain woven Toray T300-3k carbon fiber epoxy prepreg with 45% resin content (Liso Composite Material Technology Co. Ltd, China) is used to fabricate the square honeycomb core. The closed-cell PMI foam with the density $\rho_c = 205\,kg/m^3$ is selected due to its high modulus and its capacity to sustain a pressure up to 3.6 MPa at 130 °C, allowing autoclave curing. In this paper, square honeycomb cores are fabricated from the composite panels sandwiched by PMI foam by using a snap-fit and assemble procedure.

(I) PMI foam (Hunan Zhaoheng Material Technology Co., Ltd) are dried for 2 h in an autoclave at 130 °C with the vacuum negative pressure of 0.1 MPa, as shown in Fig. 2a.