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The fabrication and mechanical properties of novel composite lattice structures

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A B S T R A C T

A range of lattice structures, based on a carbon fiber reinforced epoxy composite, have for the first time been manufactured using a lost-mold technique. Here, core structures for potential use in sandwich panels were prepared by drilling holes in a well-defined pattern through either a high quality wax block or a machined salt slab. Continuous carbon fiber strands were then inserted through each of the holes in the perforated array, ensuring that one continuous tow extended through all of the elements within a given core structure. Two threading techniques were used to prepare the composite columns. Initial attention focuses on vertical truss cores and this is then extended to consider more complex structures.

Following infusion, using the VARTM manufacturing procedure, individual specimens were removed from the resulting sandwich panels in preparation for subsequent mechanical testing.

Compression showed that the strength of individual struts and the corresponding cores increases with strut diameter and fiber volume fraction. Smaller diameter struts failed in buckling, whereas the larger diameter columns failed in a crushing mode involving high levels of energy absorption. Finally, the properties of the various lattice structures considered here were predicted using finite element modeling techniques.

1. Introduction

In recent years, there has been a growing interest in manufacturing and characterizing the properties of metallic lattice structures, based on architectures such as the Kagomé structure [1], pyramidal designs [2] and the octet truss configuration [3]. A number of manufacturing techniques have been used to produce these metallic structures, including a rapid processing and brazing procedure [4], investment casting [5] and selective laser melting [6]. Subsequent mechanical testing has shown that many of these structures offer a range of attractive mechanical properties [1–7].

Recently, attention has focused on developing composite lattice structures that should, in principle, out-perform their metallic counterparts. Indeed, Finnegan et al. [8] showed that by combining optimum lattice designs with high-performance lightweight materials, it is possible to expand the material property space. Indeed, when plotted on an Ashby diagram of strength versus density, the authors showed that the theoretical strength of composite lattices lies well above current material systems, approaching the unattainable materials space, particularly at high densities. Here, the authors used a snap-fitting method to produce pyramidal truss cores with relative densities in the range of 1 to 10%. Other techniques have also been developed to manufacture composite lattice structures. Schneider et al. [9] developed a manufacturing technique based on folding and cutting flat sheets of carbon fiber reinforced PET to produce lattice cores with attractive mechanical properties. Yin et al. [10] manufactured what are termed stretch–stretch-hybrid hierarchical composite lattice cores by employing a two-step approach that involved assembling pyramidal lattice sandwiches into macroscopic truss configurations. Xiong et al. [11] manufactured pyramidal carbon fiber reinforced epoxy lattices using an EDM plunge cutting technique that employed a suitably-shaped cuprite electrode. Finally, Li et al. [12] used a series of triangulated molds with slots machined into them to produce carbon fiber/epoxy pyramidal lattice cores and showed that such structures outperform their metallic counterparts in terms of specific strength and stiffness.

Given the many difficulties associated with manufacturing composite lattice structures, defects and other forms of stress concentration are likely to occur. Chen et al. [13] investigated the effect of defects on the compressive properties of carbon fiber pyramidal lattice structures and showed that, compared to open cell foams and honeycombs, pyramidal cores offer a superior defect tolerance.

The aim of the study presented here is to use a lost-mold manufacturing technique to produce truss structures of varying complexity. Initial attention is given to assessing the effect of fiber volume fraction and strut diameter on the compression properties of vertical

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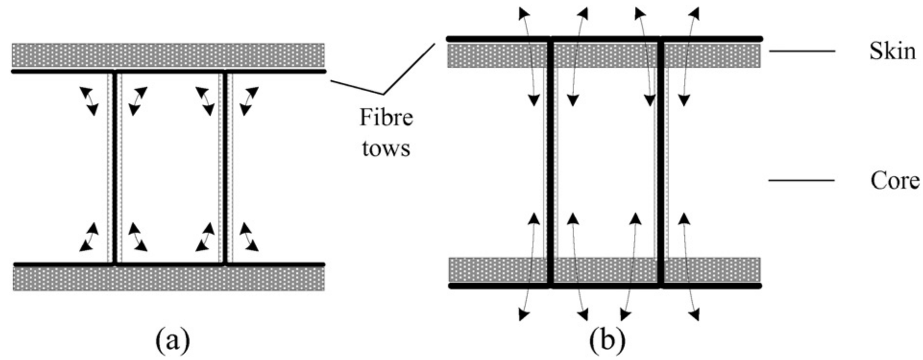

Fig. 1. Schematic drawings of the two procedures used to thread the samples. In Configuration A, the fibers extend through the holes and then between the wax core and the skins, whereas in Configuration B the fibers extend through the holes and the skins and then back.

truss structures and their individual reinforcing members. The study concludes by focusing on the manufacture and testing of all-composite pyramidal and octet truss-type structures.

2. Experimental procedure

The composite column truss cores investigated in this study were manufactured using a lost mold procedure. Here, a series of holes were drilled into wax blocks with length, width and thickness dimensions of 150 × 90 × 36 mm respectively. Four drill diameters were used, these being 2, 2.5, 3 and 4 mm. The 2 mm and 2.5 mm diameter holes were drilled in six by six arrays to form a unit cell, the 3 mm holes in five by six arrays and the 4 mm holes in four by five arrays, yielding cores with relative densities of 16.3, 26.7, 30.4 and 34.9% respectively. Carbon fiber tows were then threaded through the holes in order to reinforce the structure in the through-thickness direction. Two weaving patterns were adopted and these are shown schematically in Fig. 1. The first procedure involved threading the fibers through the array of holes and then across the top of the lost mold, as shown schematically in Fig. 1a. It is worth noting that the same fiber tow is used to link all of the holes in a unit cell, thereby ensuring that there are no fiber breaks in the entire structure. The fiber volume fraction within an individual hole was varied by using increasing numbers of fiber tows during the threading process. The second weaving pattern involved threading the fibers through the carbon fiber fabric that formed the facings in the resulting sandwich structures. This is shown schematically in Fig. 1b. Anchoring the through-thickness fibers to the facings has the effect of reducing lateral movement of the composite columns during compression loading.

Following the threading process, the reinforced core blocks were infused with resin using the VARTM manufacturing technique. Here, two layers of distribution, Gurit Knitflow40®, were placed over the stack to facilitate the flow of resin through the structure (top to bottom), saturating the fiber reinforced holes. A two-part toughened epoxy, Prime™ 20LV (Gurit Ltd.), with a fast hardener, was used in the VARTM procedure. A glass mold, with a line injection and a line vent permitted the observation of the resin flow process in the lower skin as it arrives after saturating the holes during the infusion process. A schematic of the lay-up arrangement for the VARTM process is shown in Fig. 2. The skins in the sandwich structures were based on four layers of carbon fiber fabric. The edges of the mold were sealed using a vacuum bagging material and a sealant tape. The mold was then infused with resin under vacuum at a pressure of 1 atm. The panels were allowed to cure at room temperature for approximately 12 h and then post-cured at 65 °C for 7 h.

Tests were also undertaken on sandwich panels based on a pyramidal core, Fig. 3a, and a modified pyramidal core, in which the unit cell included a central vertical member through its apex, Fig. 3b. These structures were manufactured using lost molds based on 200 mm square, 28 mm thick salt blocks. Here, the carbon fibers were woven through holes with diameters of 3 mm, according to Configuration A. Following resin infusion, the salt mold was dissolved using a continuous stream of water.

In the final part of this investigation, the possibility of manufacturing more complex lattice structures was investigated. Here, octet truss structures with strut diameters of 4 mm were prepared by drilling an array of holes through 56 mm thick salt blocks. Additionally, BCC, BCCZ, F2BCC and FCC structures (25% V_f), similar to those manufactured from metal powder [14], were prepared by drilling 3 mm diameter holes in 37 mm thick wax blocks.

The compression strengths of the composite cores and columns were measured by loading the specimens between circular steel platens at a crosshead displacement rate of 2 mm/min. Typically, four repeat tests were conducted on each core structure.

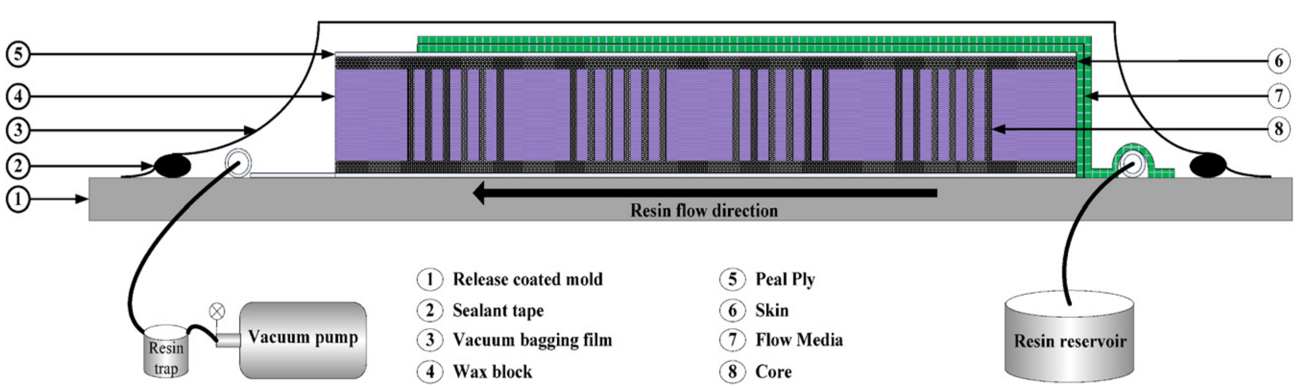

Fig. 2. Schematic of the VARTM process used to infuse the skins and core.