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The mechanical properties of natural fibre based honeycomb core materials

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ABSTRACT

This paper investigates the compression properties of square and triangular honeycomb core materials based on co-mingled flax fibre reinforced polypropylene (PP) and polylactide (PLA) polymers. Initial testing focused on investigating the sensitivity of the tensile properties of the composites to variations in processing conditions. Following this, a range of triangular and square honeycomb structures were manufactured using a simple slotting technique. These structures were tested in compression at quasi-static rates of strain and their strength and specific energy absorption characteristics were determined. Finally, a finite element analysis was undertaken to accurately predict the strength, energy-absorbing characteristics, buckling behaviour and failure modes of these natural fibre based core materials.

1. Introduction

Increasing environmental concerns have encouraged researchers to develop a range of recyclable materials based on natural fibres such as flax, hemp, kenaf, jute, oil palm, coconut and many more. Natural fibres are low cost materials offering a low density, high specific properties, biodegradable characteristics and recyclability [1,2]. Over the years, a large amount of research has been conducted on these so-called 'green' or 'eco-friendly' materials. However, fundamental research on natural fibres has intensified only in recent years, due to increasing demands for greater environmental protection. Many researchers have shown that composites based on natural fibres can, if correctly designed, offer comparable properties to those based on conventional fibres. Mallaiah et al. [3] compared the properties of bio-based and synthetic fibre based sandwich structures and demonstrated that a hybrid structure based on bamboo and glass fibres offers higher values of core shear stress and face bending stress than those structures manufactured from either pure glass or bamboo fibres. Recently, the automotive industry has begun to employ natural fibres in the manufacture of both interior and exterior vehicle components in order to reduce the overall weight of the car whilst increasing its fuel efficiency and sustainability. A number of multinational companies, such as Daimler Chrysler, Mercedes Benz and Toyota, have introduced natural fibre composites into their products and plan to further increase their use in future components [4]. Jaguar and Land Rover [5] developed a prototype car door from flax/polypropylene and reported that the natural fibre component offers an excellence performance compared to current parts. Their results showed that this prototype is approximately 60% lighter than the equivalent steel part for the same stiffness, while Jaguar's prototype is roughly 35% lighter than a glass filled polypropylene component with the same thickness.

Recently, lightweight composite structures have seen dramatically increasing use in aircraft and satellites, where the drive for weight saving is greatest. Composite sandwich structures are recognised as offering a high strength to weight ratio as well as high specific bending stiffness and strength characteristics under distributed loads [6]. Previous research has shown that honeycombs based on square or triangular structures provide an impressive crush resistance and a high in-plane stretch strength. Dharmasena et al. [7] showed that square honeycombs exhibit strengths that are 27% higher than triangular honeycomb and other core designs. Yamashita and Gotoh [8] conducted quasi-static compression tests on aluminium honeycomb in the through-thickness direction. Following a numerical investigation, they showed that buckling failure occurs in all cases and established that the maximum strength is achieved when the cell shape is a regular hexagon. Gibson and Ashby [9] used both analytical and experimental techniques to investigate the mechanical properties of honeycomb structures subjected to transverse loading. Côté et al. [10–12] showed that the strain hardening behaviour of a stainless steel

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square honeycomb core offers a sustained resistance to out-of-plane compression and shear as well as through-thickness compression. The authors developed an analytical model for elastic and plastic buckling of the square-honeycombs. In addition, Wang and Yu studied energy absorption behaviour of paper honeycombs subjected to various strain rates [13] and ambient humidities [14]. It was shown that the load-carrying capacity and the energy absorption performance of paper honeycombs are insensitive to the low strain rate range (10^{-4}–10^{-2} s^{-1}). However, the initial peak stress, the plateau stress and the densification strain of paper honeycombs demonstrate a certain degree of strain rate sensitivity under intermediate strain rate impact (10^{-2}–10^{2} s^{-1}). Wang et al. [15] also presented energy absorption diagrams of paper honeycomb sandwich structures.

Numerical investigations into the structural response of natural fibre sandwich structures are limited [8,16]. Rao et al. [16] conducted a linear elastic finite element analysis on a hollow core sandwich structure manufactured from a sisal fibre composite. They found that the specific shear strength of the core is more than twice that associated with an unreinforced polypropylene core. Rao et al. [17] used both experimental tests and numerical modelling techniques to characterise the bond strength and energy absorption capabilities of recyclable sandwich panels made from sawdust polypropylene composites.

This paper presents investigation on the compression properties of square and triangular honeycomb core materials based on co-mingled flax fibre reinforced polypropylene (PP) and polylactide (PLA) polymers. Here, a range of triangular and square honeycomb structures were manufactured using a simple slotting technique. Initial testing to investigate the tensile properties of the composites and their sensitivity to variations in manufacturing temperature highlighted the relative superiority of the PP-based composites. Indeed, these materials were up to three times stronger than their PLA counterparts, in spite of the fact that their fibre architectures were nominally identical. It was noted, however, that the PP-based composites exhibited greater sensitivity to variations in the maximum processing temperature. Compression tests on both the square and triangular honeycomb structures once again highlighted the superiority of the PP composites, where differences similar to those noted following tensile testing were observed. Increasing the relative density of the honeycomb core resulted in an increase in both the compression properties and energy-absorbing capabilities of the core materials. It has been shown that for a given relative density, the square honeycombs significantly outperformed their triangular counterparts, with differences being in excess of 100% in certain cases. Finally, finite element models were developed to accurately predict the strength, energy-absorbing characteristics, buckling behaviour and failure modes of these natural fibre based core materials.

2. Experimental procedure

The core materials investigated in this study were based on flax fibre reinforced polypropylene (hereafter known as flax/PP) and biodegradable flax fibre reinforced polylactide (flax/PLA). Both composites were supplied in the form of plain weave co-mingled fabrics by Composites Evolution Ltd. Core structures based on two designs, a square hexagonal structure, Fig. 1a, and a triangular honeycomb structure, Fig. 1b, were considered. The flax/PP and flax/PLA laminates used to prepare core materials with different web thicknesses by compression moulding two, three and five layers of the co-mingled fabric. This procedure yielded flax/PP laminates with nominal thicknesses of 1.0, 1.5 and 2.3 mm and flax/PLA laminates with nominal thicknesses of 0.9, 1.3 and 2.0 mm. Initially, the influence of manufacturing temperature on the mechanical properties of the two types of composite was investigated by moulding panels based on three layers of woven fabric at temperatures of 170, 180, 190 and 200 °C for 60 min. The tensile properties of the composites were then evaluated through a series of tensile tests on 0/90° rectangular bars with length, width and thickness dimensions of 190, 20 and 1.3 mm respectively. The tests were undertaken on an Instron 4204 universal test machine at a crosshead displacement rate of 1 mm/min.

Following manufacture of the composite plates, the square and triangular honeycomb core structures were produced using the slotting procedure shown schematically in Fig. 2. Here, slots of equal width to the thickness of the composite were machined into 20 mm wide strips of composite material. The slots were cut to a depth of 10 mm and positioned 20 mm apart. An interference fit was assured at all intersections. The skins were bonded to the core at room temperature using a two part epoxy adhesive (Araldite 420 A/B). In principle, however, a thin thermoplastic film (either PP or PLA) could be used to achieve this bond.

The relative densities of the core materials were calculated from the ratio of the composite to the unit cell volume. For the square hexagonal structure this can be approximated by [7]:

$$\bar{\rho} = \frac{2t}{l} \tag{1}$$

Similarly, the relative density of the triangular honeycomb can be estimated using [7]:

$$\bar{\rho} = \frac{2\sqrt{3}t}{l} \tag{2}$$

Tables 1 and 2 summarise the relative densities of the six configurations investigated here, where it can be seen that for a given web thickness, the relative density is higher for the triangular core. The energy – absorption characteristics of the honeycomb cores were investigated by conducting compression tests on square blocks with an edge length of 50 mm. The tests were undertaken at a crosshead displacement rate of 1 mm/min and stopped when the specimen was fully crushed and the force began to rise rapidly. The energy absorbed in crushing the honeycombs was calculated by measuring the area under the force–displacement trace and the associated failure mechanisms were elucidated by photographing the edges of the panel during testing.

3. Finite element modelling

Numerical models were developed to simulate the mechanical response of the square and triangular honeycomb core sandwich structures subjected to compression. The flax/PP was modelled as an isotropic material with strain hardening prior to the core buckling. Using this approach, the plastic strain can be expressed as:

$$\varepsilon_{pl} = \varepsilon_{total} - \frac{\sigma_{total}}{E}, \sigma > \sigma_y \tag{3}$$

where σ_y is the initial yield stress. However, due to the thin nature of the honeycomb cell, the flax/PP experiences buckling before the core finally collapses. Here, a geometrical imperfection pattern was introduced into the model in order to accurately simulate the collapse behaviour of the honeycomb core. A geometric imperfection pattern is defined as a linear superposition of buckling eigenmodes obtained from a previous eigenvalue buckling prediction performed with Abaqus/Standard [18]. This was conducted using the *IMPERFECTION function in a linear perturbation step in ABAQUS/Standard. The buckling modes were predicted and then used to introduce a small imperfection in the straightness of the