Composites Part B 134 (2018) 28–38

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Effects of hybridization and hybrid fibre dispersion on the mechanical properties of woven flax-carbon epoxy at low carbon fibre volume fractions

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ARTICLE INFO

Article history:
Received 15 November 2016
Received in revised form
9 May 2017
Accepted 16 September 2017
Available online 20 September 2017

Keywords:
Hybrid
Mechanical properties
Damage mechanics
Mechanical testing

ABSTRACT

Natural and synthetic fibers are increasingly being used as reinforcements in various applications. While the latter is popular for its generally superior mechanical properties, natural fibers are eco-friendly, cheap and have good vibro-acoustic properties. As more businesses are investing in green and sustainable technologies, natural fibers have been gaining attention in recent years and are already being used in various applications such as car interior, sporting equipment, etc. To date, their applications have been limited to those not requiring very demanding mechanical performance. In this paper, mechanical performance enhancement of natural fiber composites through hybridization with carbon fibers was benchmarked against one of the strongest and stiffest natural fibres, flax, through various interlayer flax-carbon hybrids at low carbon fibre volume fractions. Besides strength and stiffness characterization of hybrid laminates, this work investigates the effects of interlaminar hybrid fiber dispersion on tensile performance. The results suggested that morphology of mating hybrid plies might affect stiffness in woven fabrics. Hybrid laminates with single carbon plies interspersed with flax plies displayed lower tensile stiffness due to absence of nesting of the stiffer woven carbon plies and architectural crimp mismatch between flax and carbon woven fabrics. Comparisons with rule of hybrid mixture predictions showed reasonably good agreement in hybrid laminates exhibiting linear behavior, but significant over-predictions in highly dispersed laminates due to large deviations from linearity.

1. Introduction

Fibre reinforced composites are among the most advanced engineering materials in various industrial applications. Unlike traditional isotropic materials such as metals, the load bearing capability of fibre reinforced composites can be optimized for an intended application through embedding fibres in appropriate matrices and aligning them judiciously. With two or more types of fibre within the same matrix, an even wider range of optimized blended properties are possible. Although this idea, otherwise known as fibre hybridization, has been around for quite some time [1], recent emergence of new materials creates new and exciting possibilities for obtaining superior hybrid composites tailored for particular applications. The need for such material systems are becoming more important as modern composite structures are increasingly required to meet multiple and possibly even competing performance criteria. In many applications, for instance in transport vehicles [2,3], the requirements of stiffness, strength and impact resistance are critical and fundamental. However, lightweightness, lower cost, noise attenuation, and sustainability are also becoming important factors and composites products that can deliver optimal combination of desirable characteristics will be more attractive and competitive. In order to achieve this, some trade-off in properties and performance is usually necessary.

Driven essentially by the need for sustainable eco-friendly materials [4], natural fibres [5,6] have increasingly been used as composites reinforcements due to their low cost and their potential in meeting strength and stiffness [7–9] requirements for non-structural and semi-structural applications. Moreover, they have good vibro-acoustic damping properties [10–12] which make them suitable for various applications such as car interior, door panels, dashboards, etc. [13–15] and sporting equipment [16]. In spite of

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https://doi.org/10.1016/j.compositesb.2017.09.035
1359-8368/

these favorable properties, their hygroscopic behavior and relatively low mechanical properties [17–21] compared to synthetic counterparts, are some of the major impediments to their penetration into higher-end applications. Numerous studies have attempted to address these issues [22–26] in an effort to enhance the performance of natural fibre reinforced composites (NFCs) through improving (1) fiber-matrix adhesion [27,28], (2) processing technique [29], and through (3) hybridization of fibres derived from various plants [30–34]. Although many of these approaches have successfully improved properties of NFCs, performance is still not good enough [35] for most structural applications.

Due to the need for higher mechanical performance, lower cost and sustainability, hybridization of natural fibres with synthetic fibers such as glass [17,31,36–38] and carbon [39–43] have been of increasing interest recently. The objectives of these studies vary from assessing improvements in thermal stability, water absorption behavior, stiffness, strength and impact properties, to acoustic and vibration damping properties.

Dhakal et al. [40] investigated the water absorption behavior, thermal and mechanical properties of unidirectional and cross-ply hybrid laminates, and results showed significant improvements in each of these aspects compared to non-hybrid flax composites. Assarar et al. [44] studied the effects of hybridization and stacking sequences on the damping properties of flax–carbon epoxy composites, manufactured through platen press process. Results highlighted the major role that position of flax layers within the hybrid play on overall laminate bending stiffness and damping properties. Flynn et al. [39] characterized the mechanical properties and mechanical variability of a fixed layup of flax-carbon hybrids at various flax fiber volume fractions. In the biomedical field, flax sandwiched with thin sheets of carbon on either side has been proposed by Bagheri et al. [42,45] for use as an orthopedic long bone fracture plate since mechanical properties of the hybrid are closer to human cortical bone than clinically-used orthopedic metal plates, making the material a potential candidate for use in long bone fracture fixation.

These studies, although limited, collectively indicate a broadening potential for natural fibres as superior substitutes to existing materials through hybridization with synthetic fibres. As interests in hybrid composites involving natural fibers are expected to grow [46], proper understanding of the interactions between the various phases in the hybrids is necessary to derive maximum benefit from these advanced material systems which can potentially stand as superior candidates for design-specific solutions requiring a wider spectrum of properties such as high stiffness, strength, and impact resistance, in addition to good vibro-acoustic damping performance, and eco-friendliness.

In this paper, flax is hybridized with carbon fibres at low carbon fibre volume fractions. Dominance of flax by weight is maintained in order to retain a substantial component of the beneficial attributes of flax fibre – such as the low cost and eco-friendliness of the resulting hybrid, while concurrently gaining significant enhancements in stiffness, strength and impact resistance by virtue of the carbon fibres [47]. Tensile characteristics of various inter-layer hybrids are determined experimentally and compared against plain flax epoxy to quantify the achievable performance enhancement. The reliability of using simple volumetric rule-of-mixture approach in predicting hybrid strength and stiffness is assessed. Several hybrid configurations with dissimilar flax and carbon ply stacking sequences, at the same relative weight fractions, are also developed to study the effects of hybrid fiber dispersion.

2. Materials and method

Hybrid and non-hybrid composite laminates were fabricated from plain woven 4x4 hopsack flax fabric [48] with areal density of 500 g/m^2 (Composite Evolution, UK), and 197 g/m^2 plain woven carbon fabric (Hexcel-282 3K, US). The matrix used for the composites is low viscosity epoxy resin system, Epolam 5051 (Axson, France).

The hybrid laminates developed for this study are shown in Fig. 1, labeled as FC1 to FC5. Although the scope of this work is limited to the performance of flax-carbon hybrids under tension, these layups are developed for studying a wider range of mechanical and vibro-acoustic damping properties of flax-carbon hybrids.

FC1 consists of three plies of flax fiber reinforced with two plies of carbon fiber, stacked alternately. The carbon fiber volume fraction is increased in FC2 without altering the degree of hybrid fiber dispersion through insertion of an additional carbon ply on the laminate's upper and lower surfaces. The outer carbon plies are shifted towards the mid-plane of the laminate in FC3, while keeping the number of carbon fiber laminae unchanged. The location of carbon fiber reinforcement in FC3 and FC1 are similar, with the latter having a lower carbon fiber loading and higher hybrid fiber dispersion. Carbon plies in FC3 are shifted to the outer plies in FC4, resulting in a sandwich structure with three plies of flax fibers blocked at the center. All hybrid laminates studied are symmetric with the exception of FC5, where flax and carbon fibers interact at a single interface. Laminates FC2-FC5 have the same flax to carbon fiber ratio and thickness, with varying degrees of hybrid fiber dispersion; FC1 and FC2 are the most dispersed, followed by FC3, FC4 and FC5, respectively. In this paper, fiber dispersion refers to dispersion of the two fiber types (flax and carbon) throughout the laminate.

2.1. Composite fabrication

Flax fabrics were dried in a vacuum oven at 90 °C for 3 h prior to resin infusion, as natural fibers tend to have high moisture content, unlike carbon fibers, due to their hydrophilic nature. Preforms with stacking sequences specified in Table 1 were prepared and vacuum bagged for 2 h at room temperature to evacuate air trapped in the dry fabrics. The low viscosity resin system was used to facilitate fiber wetting. Resin-hardener mixture was allowed to degas for 30 min in a vacuum chamber, prior to preform impregnation through vacuum assisted resin infusion (VARI). Following the manufacturer's recommendations, curing was done at 25 °C over 24 h and post-cured at 80 °C for 16 h. Laminates thicknesses were measured and recorded in Table 1.

2.2. Fiber volume fractions

Samples of dry flax fibers, dry carbon fibers, pure cured matrix, and the hybrid composite laminates were taken for measurements of volume using a standard gas pycnometer, and weight, from which the densities were calculated. According to rule of hybrid mixtures, the density of the hybrid laminate can be expressed as

$$\rho_H = V_F\rho_F + V_C\rho_C + (1 - V_F - V_C)\rho_M \tag{1}$$

where ρ is density, V is fiber volume fraction, and subscripts F, C, M and H stands for flax, carbon, matrix and hybrid composite, respectively. For a particular hybrid laminate with n_F flax plies and n_C carbon plies,

$$\frac{V_C}{V_F} = \frac{n_C \cdot W_C \cdot \rho_F}{n_F \cdot W_F \cdot \rho_C} \tag{2}$$

where W is areal density (densities of flax and carbon fabrics are