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The damping–modulus relationship in flax–carbon fibre hybrid composites

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ABSTRACT

The trade-off between the elastic modulus and damping capacity as a function of fibre composition in carbon–flax hybrid composite laminates was investigated. Hybrid composite laminates with varying carbon–flax fibre–epoxy content were prepared using a combination of compression moulding and vacuum bagging. The elastic modulus and damping loss coefficients were determined by free-vibration in longitudinal and flexural modes, and modelled using a rule of hybrid mixtures (ROHM) and laminate theory. The models were in close agreement with the experimental data for both the longitudinal and flexural modes and thus appeared to be a feasible method of predicting the stiffness–damping relationship in this system of hybrid composite laminates. The experimental data of the tensile strength was found to also follow the ROHM. However, the experimental data of the flexural strength deviated negatively from the theoretical prediction, exhibiting lower values than the predicted ones.

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1. Introduction

Vibration damping and stiffness are antagonist properties and the improvement of one of the property is generally concurrent with the decrease of the other one [1]. In some applications (e.g. automotive and aeronautic), both properties are required and there is a necessity to understand this compromise, especially, in the field of composites where hybrids can be tailored to suit specific functions [2]. Hoa and Ouellette investigated aramid–carbon–epoxy composites and reported that flexural stiffness was increased by increasing the volume fraction of carbon fibres at the expense of the vibration damping properties [3]. Similar findings were reported by Martone et al., where viscoelastic fibres were commingled with carbon fibres in epoxy composites. They found that micromechanical hybridisation increases damping absorption by 82% but also decreases the elastic modulus by 37% [4]. Recently, Duc et al. reported the stiffness and damping coefficient of carbon and flax fibres epoxy composites [5]. They found that the carbon twill composite was 3.6 times stiffer and 7.1 times stronger than the flax composite with a 50% reduction in the damping coefficient [5].

The use of natural cellulosic fibres as reinforcement for polymer composite materials presents some key advantages over synthetic fibres, including reduced occupational health issues in manufacturing, lower environmental impact and improved vibration damping [6–10]. Damping was associated to intrinsic properties of plant fibres e.g. entanglement of the fibres, void in the lumen, heterogeneity of the cell wall and reversible hydrogen bonding between the different components of the cell wall [10,11]. Such advantages have popularised the utilisation of flax fibres in commercial items such as bikes frames, snowboards and racquets. However, the mechanical properties of natural fibre-reinforced plastics are often not sufficient for structural applications [12]. Therefore, the hybridisation of plant fibres with man-made fibres is necessary. Presently, there are no systematic studies of the trade-off between improvements in damping and loss in stiffness and strength with regard to hybrid plant fibre and man-made fibre-reinforced polymer composites. The present study investigates the relationship between the loss coefficient and modulus/strength in tensile and flexural modes in flax–carbon fibre hybrid composite laminates.

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2. Experimental procedures

2.1. Materials

The resin system was based on diglycidyl ether of bisphenol A (EPON 828, Shell Chemical Company, Texas, USA) and methyltetrahydrophthalic anhydride (Lindride 52, Lindau Chemicals Ltd. Columbia, USA), and methyl-imidazole was used as the accelerator (Sigma Aldrich, Auckland, New Zealand). The ratio of resin to curing agent to accelerator was 100:87.5:1.5. The flax 2/2 twill, flax 4/4 hopsack (Composite Evolution, Chesterfield, UK) and carbon fibre 2/2 twill (Fibretech Solutions Ltd., Rotorua, New Zealand) had areal weights of 420, 500 and 240 g/m^2, respectively.

2.2. Preparation of composite laminates

The resin was mixed at room temperature and degassed for 1 h in a desiccator. The laminae were impregnated by hand and pre-cured separately at 105 °C for 10 min. The preforms were then stacked in 0/90° cross-ply configurations resulting in both non-symmetric and symmetric laminates. The laminate stack was then vacuum-bagged for 1 h at room temperature, followed by compression moulding using two step temperature and pressure profiles (Fig. 1) and left to cool overnight. Post curing was carried out at 110 °C for 24 h and then 150 °C for 5 h.

The combinations of fibres are listed in Table 1. The carbon–epoxy laminae content of the hybrid laminates was calculated using the mean thickness of the single flax–epoxy and carbon–epoxy laminae. The average thickness of a single cured carbon–epoxy and flax–epoxy lamina was 0.256 and 0.743 mm, respectively. Both values were determined using the experimental values of the single fibre type composites.

2.3. Quasi-static mechanical properties of flax composites

Quasi-static mechanical tests were determined on an Instron 5566 Universal Testing Machine (Norwood, Massachusetts, USA) with a 10 kN load cell, with the exception of the carbon hybrid laminates that were tested using a 40 kN load cell.

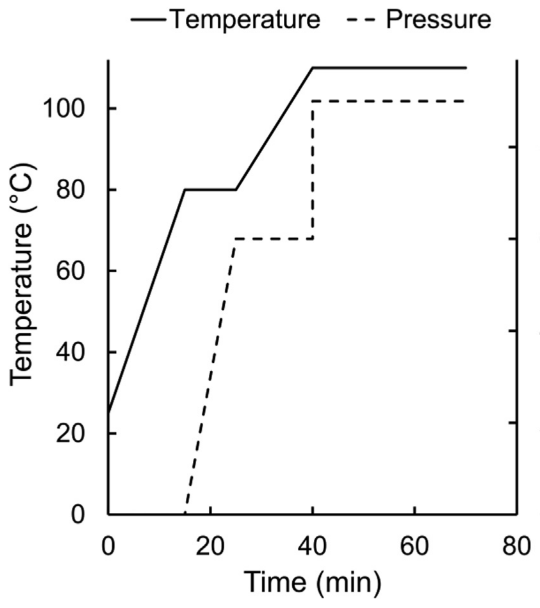

Fig. 1. Temperature and pressure profiles for forming the composites.

The flexural properties were determined *via* 3-point bending at a displacement speed of 1.1 mm/min in accordance with ASTM D790-03. Three-point bending specimens were prepared as 100 × 12.6 mm coupons. Tensile test coupons (220 × 25 mm) were tested at a displacement speed of 2 mm/min, while strain was measured using a 25 mm extensometer in accordance with ASTM D3039/D3039M-00. Three to five replicates were conditioned for 48 h at 23 °C and 50% relative humidity prior to mechanical testing.

2.4. Acoustic properties

The moduli of elasticity (MOE) of the composites were determined using resonant frequency in longitudinal and flexural mode. Each specimen was excited by a manual impulse and the resulting vibration decay was recorded with a microphone (THS 130P10 SN6156) plugged to an amplifier from National Instruments (NI USB-4431) as described in ASTM E1876-09. In the case of flexural mode testing, the specimens were suspended at nodal points to minimise the influence of the system suspensions, and the exciter and sensor were placed at anti-nodes.

The sample rate was 50 kHz and sampling durations were 0.1 or 5 s for longitudinal or flexural mode testing, respectively. The resonant frequencies were obtained from the Fourier-transformed signal. Loss coefficients (η) were calculated from the half-power bandwidth of the fundamental resonance (b) at frequency f, using the relationship $\eta = b/f$ [13]. The values of MOE are referred as E_l for longitudinal mode and E_f for flexural mode. The MOE were calculated as shown in Eqs. (1) and (2) [13,14]:

$$E_\mathrm{l} = 4\rho L^2 f^2 \quad \text{(longitudinal)} \tag{1}$$

$$E_\mathrm{f} = \left(48\pi^2 \rho L^4 f^2\right) \Big/ \left(\beta^4 h^2\right) \quad \text{(flexural)} \tag{2}$$

where ρ is the density, L the length of the beam, and $\beta = 4.73$ is the constant associated with free–free boundary condition and the first flexural mode.

3. Derivation of rule of hybrid mixtures

3.1. E_l and longitudinal vibrations damping

The rule of hybrid mixtures (ROHM) was used to predict the elastic modulus (E) and loss coefficient (η) of the hybrid laminates. The calculation of the elastic modulus was based on a macro-mechanics approach in which composite properties are based on E and η of the flax–epoxy and carbon–epoxy composites at the lamina level. Thus, the elastic modulus of a hybrid composite laminate can be determined using Eq. (3):

$$E_\mathrm{l} = \sum_i V_i E_i \tag{3}$$

where V is the relative volume fraction (*i.e.* $\sum_i V_i = 1$). The subscripts l and i indicate longitudinal mode and fibre type used in the composite lamina, respectively. Thus, i indicates either a flax–epoxy (F) or carbon–epoxy (C) lamina in the present work.

For lightly damped structures, the structural damping can be described as a function of the energy stored in each of the constitutive elements [15]. When applying this concept to the different components using ROHM, the damping of the composite can be written as Eq. (4) [16]:

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