VIBRATION DAMPING OF NATURAL FIBRE-REINFORCED COMPOSITE MATERIALS

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Abstract

This work investigates the effects of fibre orientation on the damping properties of flax fibre-reinforced polypropylene composites. Laminates were manufactured by a vacuum bagging process. The dynamic properties were then found from vibration measurements of beam test specimens and an impulse hammer technique to frequencies of 1 kHz. The frequency response of a sample was measured and the response at resonance used to estimate the natural frequency and damping loss factor. The single degree-of-freedom circle-fit method and the Newton divided difference formula were used to estimate natural frequency and loss factor. Experiments were subsequently conducted on a range of samples with different fibre orientations. If the fibre angle is 0º or 90º with respect to the beam axis, then, for an impact on the centreline, the motions are both bending and torsion. For other fibre orientations the impact induces predominantly bending. Numerical estimates of the response, and in particular the natural frequencies, were made using an ANSYS finite element model, with the beam being discretised into a number of shell elements. The experimental results showed significant variations in natural frequencies and loss factors with variations in fibre orientation. Composites containing 45°, 60° and 90° fibre orientation exhibited approximately the same natural frequencies. Composites with different fibre orientations exhibit different loss factor, and the maximum loss factor is obtained for the case of 45° fibre orientation, with the loss factor generally lying in the range of 2-7%. The loss factor increases with increasing frequency. These outcomes indicate that the flax fibre-reinforced composites could be a commercially viable material for applications in which noise and vibration are significant issues and significant damping is required.

1. Introduction

Increased environmental consciousness, reduced non-renewable sources and problems inherent to the disposal of waste materials have led to a growing interest in using natural fibre from renewable sources as reinforcement in polymeric composites. Natural fibres are composed of cellulose, hemicellulose, lignin and pectin. They are viscoelastic in nature which contributes to damping [1-3]. Viscoelastic materials have inherent ability to dissipate energy through mechanical deformation. Vibratory energy is converted into heat energy during the deformation of the material [4]. The most effective way to increase structural damping of a system is to employ materials having high-energy dissipation capacity [5]. High damping materials possess the ability to suppress mechanical vibrations and attenuate wave propagation [6, 7]. Generally, all-metal structures such as steel and aluminium have very low damping. [8-12], whereas composites have more damping, and the vibration energy

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dissipates through the viscoelastic nature of the polymeric composites, the friction at interfaces caused by relative motion between matrix and fibre, and the damping due to voids, cracks and delaminations [13, 14].

It is well known that polymers behave like viscoelastic materials and generally exhibit high damping compared to metallic materials [15]. Therefore, the incorporation of natural fibres into a polymeric matrix can have multifunctional capabilities such as vibration control, energy dissipation, heat dissipation and crash absorbance along with high stiffness to weight ratios. Hence, they can potentially be used in aerospace, sporting goods and military applications, where a combination of a structural function such as load-bearing and other non-structural functions such as vibration damping and fracture toughness are of great importance. Nevertheless, there have so far been few studies performed on composites especially for vibration damping, based on natural fibres which have significant intrinsic internal energy dissipation capacity. Therefore, the objective of this work is to investigate the dynamic behaviour of natural fibre-reinforced polymer composites (NFPCs) considering different fibre orientations and composite beam lengths.

2. Materials and Testing Technique

2.1. Materials

Sheets of polypropylene (PP) random copolymer (MOPLEN RP241G), with a melt flow rate (MFR) of 1.5 g/10 min determined by ISO 1133 and a thickness of 0.38 mm were used as matrix material. Polypropylene sheets were produced by Lyondell Basell Industries and supplied by Field International Ltd., Auckland, New Zealand. Unidirectional flax fabric (FlaxPly UD180) with a nominal specific weight of 180 g/m^2 and density of 1410 kg/m^3 was used as reinforcement. Flax fabric was supplied by Lineo, Meulebeke, Belgium.

2.1. Manufacturing of Composites

Flax fabrics were dried for 24 hours at 70°C in a vacuum dryer (Squaroid duo-vac vacuum oven) to reduce the moisture content. The vacuum bagging technique (Fig. 1) was used to manufacture the composite samples. This technique uses atmospheric pressure for holding the laminate in place during the cure cycle. Dry flax fabrics and PP sheets were interleaved by a hand lay-up process and placed on an aluminium plate. Then peel ply was used to separate the breather from the laminate, and the breather was employed to ensure all the air inside the vacuum bag could be drawn to a vacuum port. After sealing the materials stack, all the air was evacuated from inside the vacuum bag using a vacuum pump. The mould was subsequently placed inside the Elecfurn (FAC 100) oven and heated to a temperature of 190°C for 1 hour. After this, the mould was cooled to a room temperature of 25°C. The size of the panels was nominally 500 mm x 600 mm with a target thickness of 3 mm and a fibre volume fraction of 0.31. Beams (450 mm x 20 mm x the thickness of the material) with different fibre orientations such as 0°, 30°, 45°, 60° and 90° were cut from the panels using an automatic saw. Neat PP samples were also manufactured for comparison.

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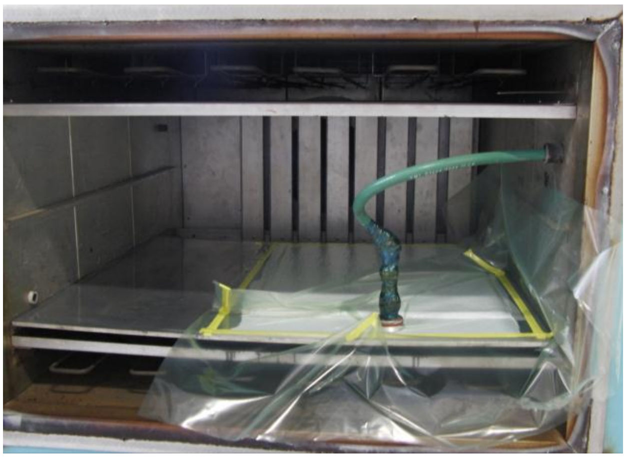

Figure 1. Vacuum bagging technique.

2.2. Testing Technique

An impulse hammer technique was used to measure the frequency response of the NFPC samples. One end of the composite beam was clamped in a fixed support and the other end was free to vibrate. The excitation was provided by an impact hammer (PCB model: 086E80) with a soft tip at a distance of around 5 mm from the free end of the beam, and the beam response was measured by a laser vibrometer (Polytec model: PDV-100) at a distance of 20 mm from the free end of the beam. The excitation and response were then processed by a spectrum analyser which gives the frequency response functions. Subsequent data processing was performed in MATLAB [16].

2.3. Data Processing

The extraction of modal parameters such as natural frequencies and loss factors from measured frequency responses (see Fig. 2) was performed using the single degree-of-freedom (SDoF) circle-fit method [17] and the Newton divided difference formula [18, 19]. A portion of the data in a narrow frequency range around each resonance was analysed. A circle was fitted through the use of a least-squares error fit to the data when plotted in the complex plane. The centre and radius of the circle were estimated. The loss factor (η_r) was estimated from frequency response measurements at frequencies ω_a and ω_b above and below the natural frequency (ω_r) using the expression [17].

$$\eta_r = \frac{\omega_a^2 - \omega_b^2}{\omega_r^{\,2}\left(\tan\left(\theta_a/2\right) + \tan\left(\theta_b/2\right)\right)} \tag{1}$$

where $\theta_{a,b}$ are the angles between the radii from the centre of the circle to the natural frequency and the frequency response at the chosen frequencies ω_a and ω_b, respectively. The mean loss factors were then calculated from 100 estimates by considering 20 data points, 10 data points below the natural frequency and 10 data points above the natural frequency.

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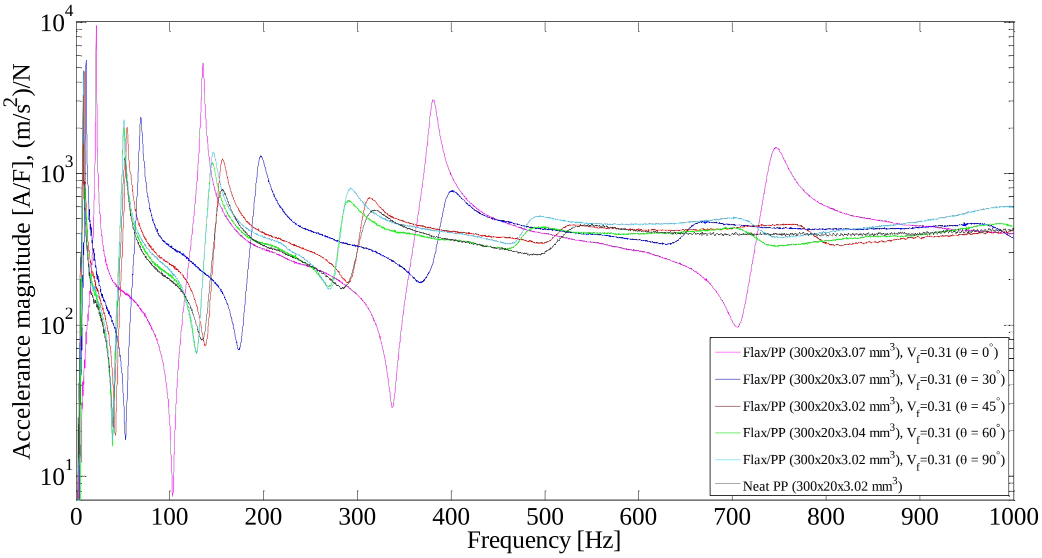

Figure 2. Accelerance magnitude for the different fibre orientations of flax/PP composite and neat PP beams.

3. Results and Discussion

The estimation of natural frequencies and loss factors was performed on composite beams of lengths 300, 350, and 400 mm with five different fibre orientations (0°, 30°, 45°, 60° and 90°) and a fibre volume fraction of 0.31. Figure 2 shows an illustrative example of the magnitude of the measured accelerance for the flax/PP samples of various fibre orientations and the neat PP sample. Clean resonance peaks can be identified. The data in the vicinity of these peaks was then post-processed to determine the natural frequencies and loss factors.

3.1. Natural Frequencies

The variations of natural frequency with fibre orientation for a fibre volume fraction of 0.31 are shown in Fig. 3. In general, the natural frequencies of neat PP beam are lower than the composite beams, and this is expected as the stiffness of the neat PP sample is lower. The highest resonant frequency happens for 0° fibre orientation because the fibres are stiffer in tension than the matrix. The drop in natural frequencies is substantial as the angle between the longitudinal and fibre axes increases. However, the decrease reduces when the angle between them is greater than 30°. For the composite orientations of 30°, 45° and 60°, the natural frequency either decreases by a small amount or is nearly constant. Increasing the angle of fibres from 0° to 60° reduces the natural frequency by 63.72% (from 21.64 Hz to 7.85 Hz) in the case of first mode. In the frequency range of interest, the maximum natural frequency of 906.79 Hz occurs for the beam length of 350 mm. The magnitude of the peak value of the response at resonance decreases with increasing length in the cases of all fibre orientations.

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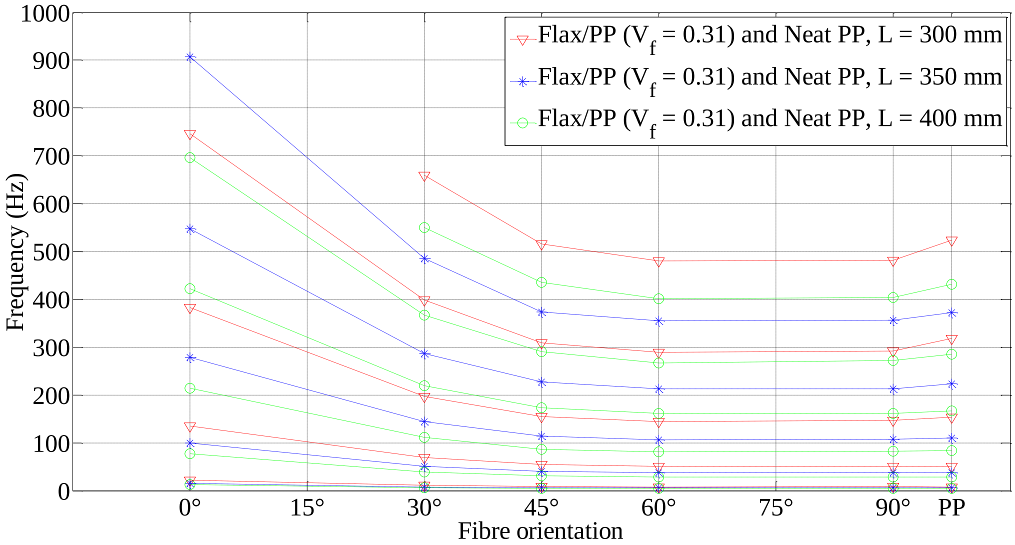

Figure 3. Variation of natural frequency with fibre orientation of flax/PP composite and neat PP beams.

3.2. Loss Factors

The mean loss factors of flax/PP composite and neat PP beams are shown in Fig. 4. The linear fits are also shown for each set of data.

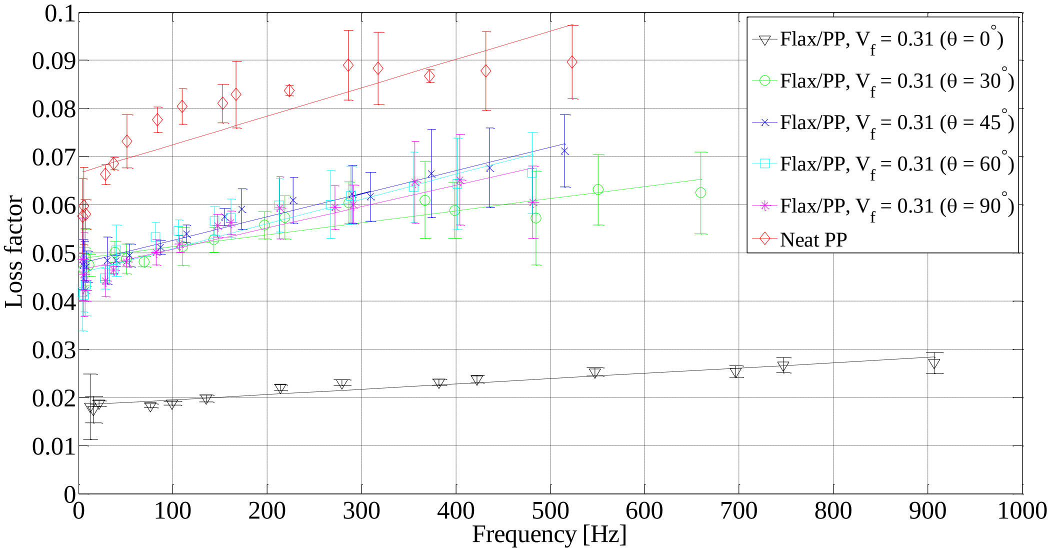

Figure 4. Variation of loss factor with natural frequency of flax/PP composite and neat PP beams.

The loss factor of neat PP is 0.06 approximately at low frequencies. This value matches with the value reported by a number of authors [1, 20, 21]. As frequency increases, the loss factor of neat PP increases, rising to 0.090 at approximately 500 Hz.

Damping increases when the frequency is increased, and the increase in energy dissipation with frequency may come from fibres and/or fibre/matrix interactions. However, the loss factor of composites is lower than that of neat PP because of the lower amount of viscoelastic PP. When

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compared to the base PP samples, the loss factor decreases by about 30% (from 0.077 to 0.054) in the case of 30° fibre oriented samples.

The effect of the reinforcement orientation on the damping of the composites is noticeable. The 0° oriented samples demonstrate sharper resonance peaks (Fig. 2), while 30°, 45°, 60°, and 90° fibre oriented samples exhibit broader peaks except for the first two peaks. This indicates that the damping effect is greater for such orientations.

The loss factor increases with increasing fibre orientation up to 45°, and it can then be seen to decrease as the fibre orientation increases above 45°. The maximum damping was obtained for the fibre orientation of 45°. A similar trend was observed by Berthelot et al. [22], Ying et al. [23] and Adams and Maheri [24] in the case of glass serge fabric-reinforced epoxy, carbon fibre-reinforced epoxy, and carbon and glass fibre-reinforced plastic composites, respectively. This is because the total energy is dominated by the in-plane shear strain energy [25], and in-plane shear strain energy is maximised at this fibre orientation in NFPCs. The average loss factor for the 45° orientation samples showed a significant increase in loss factor of around 150% (from 0.021 to 0.052) when compared to the 0° fibre orientated samples. At very low frequency, different fibre orientations other than 0° fibre orientation exhibit almost the same damping. Damping is minimum and stiffness is maximum at 0°, i.e., in the fibre direction. This is very reasonable, since the fibres play a dominant role at 0° fibre orientation and fibres exhibit less damping and much higher stiffness than the matrix material. As the orientation angle is increased, the general trends are for the damping to increase (up to a certain angle) and the stiffness to drop.

A slight increase in damping for higher frequency was observed. This observation is consistent with what has been mentioned earlier [22, 26-30]. The maximum loss factor of 0.071 was observed for the for the 45° fibre oriented beam at approximately 500 Hz. Overall, the loss factor of NFPC is in the range of 2-7% irrespective of various fibre orientations and beam lengths.

The standard deviation of the estimated loss factor at each resonance is in the range of 0.04-0.98%, which is small compared to the mean. In relation to this deviation, some possible measurement errors include measurement noise, clamping pressure, air damping and nonuniformity in the laminate (voids, variations in thickness and improper bonding).

3.3. Comparison between the Experimental and Simulated Natural Frequencies

Natural frequencies predicted from finite element analysis using ANSYS are compared to the experimental results in Fig. 5. The comparisons are made only for out-of-plane bending natural frequencies.

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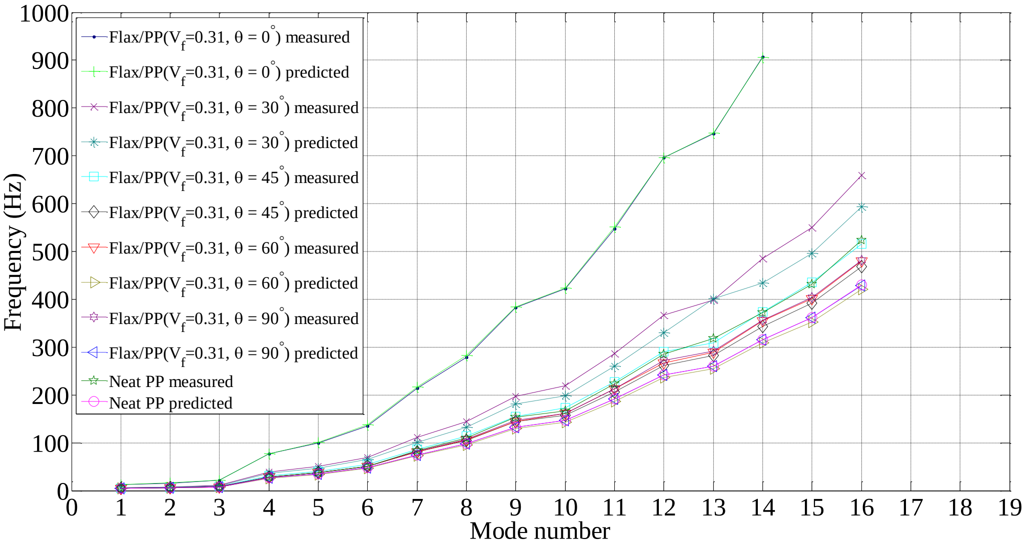

Figure 5 Comparison between the experimental and predicted natural frequencies of flax/PP composite and neat PP beams.

It can be seen that natural frequencies decrease with increasing fibre orientation. This is because the natural frequencies are associated with the stiffness of the structure, and the 0° fibre orientation is stiffer in flexural vibration than other fibre orientations. The results from finite element analysis are in reasonable agreement with the measured natural frequencies, where the maximum errors are 14.98% and 22.14% for the fibre orientation of 60° composite and neat PP samples, respectively.

3.4. Mode Shapes of Composite Beams

Three types of mode shapes such as out-of-plane bending, in-plane bending and twisting are observed as shown in Fig. 6 with mode shapes being a combination of all these motions. Among all mode shapes, only out-of-plane bending natural frequencies were strongly excited. Some out-of-plane bending frequencies were not observed. In case of 0° and 90° fibre orientations, more twisting mode shapes are observed than other fibre orientations. It may be due to less effect of bending-twisting coupling modes as the samples are symmetric. For other fibre orientations (30°, 45° and 60°), mode shapes are predominantly out-of-plane bending and in-plane bending. The maximum out-of-plane and in-plane bending frequencies occurred at 0° fibre orientation. The beams with a fibre orientation of 0° have a lower first twisting natural frequency, whereas the 30° oriented beams have higher twisting natural frequencies.

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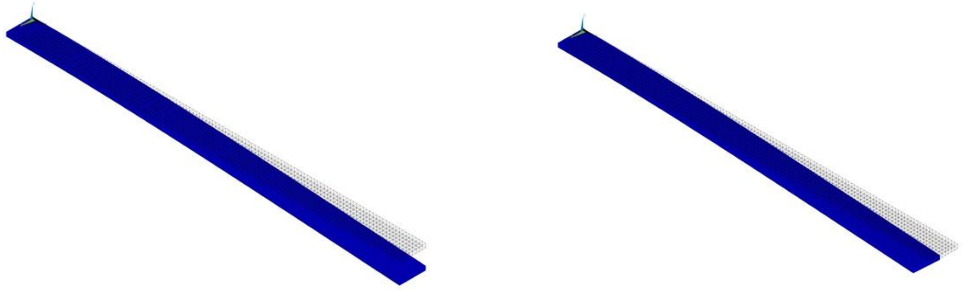
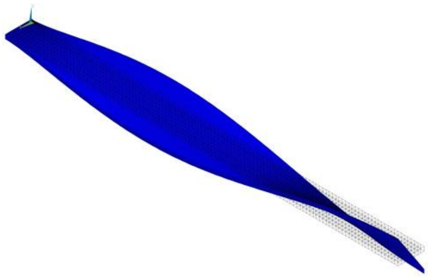


Mode 1: 22.07 Hz (Out-of-plane bending) Mode 3: 139.68 Hz (In-plane bending)



Mode 6: 667.26 Hz (Twisting)

Figure 6. Mode shapes of a composite beam.

4. Concluding Remarks

The effect of fibre orientations of NFPCs on damping was estimated from vibration measurements. The loss factor was found to increase up to fibre orientation of 45° and then decrease. The loss factor generally lies in the range of 2-7%, and the maximum loss factor was for 45° fibre orientation. The standard deviation of the loss factor estimated at each resonance was in the range of 0.04-0.98%. The natural frequencies from the finite element analysis showed reasonably good agreement with measured natural frequencies.

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