



## Damping of carbon fibre and flax fibre angle-ply composite laminates

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## ABSTRACT

The damping behaviour of continuous carbon fibre and flax fibre reinforced polymer (CFRP and FFRP) composites was studied by comparing angle-ply laminates. Using logarithmic decrement measurements, dynamic mechanical analysis and vibration beam measurements, the damping was described as the specific damping capacity  $\psi$  in order to compare data using the different methods.

Our results show approximately 2–3 times better damping of FFRP compared to CFRP at low frequency and low strain. We show that the damping of both materials increases with increasing angle-ply orientation below 300 Hz. While the matrix and interface seems to contribute mainly to damping at lower frequencies, the fibre shows an increasing contribution with  $\psi = 64.4\%$  for unidirectional FFRP at 1259 Hz in the 5th mode of vibration, without a notable change in the elastic modulus. This work demonstrates that the FFRP may be simultaneously stiff and efficient at damping.

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## 1. Introduction

The high specific elastic modulus and specific strength of carbon fibre reinforced polymer composites (CFRPs) make them attractive for lightweight applications. Lightweight structures are however, prone to vibrations which lead to unwanted instability, reduced efficiency or in severe cases, structural failure. This can lead to conservative design, or the need of additional vibration damping which adds weight.

Flax fibre reinforced polymer composites (FFRPs) have gained interest due to their low environmental footprint and relatively good specific mechanical properties [1]. In flax fibres, semi-crystalline cellulose microfibrils are embedded in pectin and hemicellulose matrix [2]. These are ordered into cell walls enclosing a lumen to form the fibre microstructure. Stiffness and strength is primarily given by the secondary wall, ordered with an acute angle of  $10^\circ$  to the fibre direction. In turn, these elementary fibres are bundled with a lignin matrix and twisted together to form the structural fibre [3]. The combination of stiff discontinuous fibres connected with soft matrices means that such hierarchical flax

fibre-epoxy composites have an order of magnitude higher damping than aluminium and exhibit three times higher damping than carbon- or glass-fibre composites [4], making it a very attractive composite material to simultaneously provide structural damping and stiffness [5]. We build on this work by studying the effect of frequency and strain on FFRPs.

Several effects need to be considered to describe the damping behavior of such hierarchical composite materials. Fibre deformation [6], interphase viscoelasticity [7], matrix modification [8], coulumb friction at the interface [9], moisture, temperature [10] and ply angle are known to contribute to the overall damping [11]. Known methods to reduce and shift eigenmodes in composites have included viscoelastic layers [12], bolting or joining of structures [13], and damage or delamination [14], which add weight and/or are undesired. Previous works show that damping experiments can provide trends, but do not always yield comparable quantitative results due the test set up, excitation and material interaction across length scales. We aim to compare damping across sample size, excitation frequencies and applied strain by reducing the measurements to a common damping description, the specific damping capacity.

The specific damping capacity  $\psi$  may be defined as

$$\psi = \frac{\Delta U}{U} \quad (1)$$

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where  $\Delta U$  is the total energy loss per cycle and  $U$  is the maximum elastic stored energy [11]. This measure is useful as its energy definition is applicable to any damping measurement method.

## 2. Materials

Carbon fibre reinforced polymer composites were produced from unidirectional pre-preg Toray M40JB fibre ThinPreg TM 80EP-736/CF with an areal weight of 30 g/m<sup>2</sup> (North Thin Ply Technology, Switzerland, [15]). Unidirectional non-crimp flax fibre fabric with an areal weight of 300g/m<sup>2</sup>, type 5009 (Bcomp AG, Switzerland) with a twist angle of 20°, was used in combination with ThinPreg TM 80EP-736 (North Thin Ply Technology, Switzerland) epoxy matrix for consistency in our measurements.

The CFRPs were produced with 80 layers of 0.03 mm prepreg and FFRP composites were produced with 8 layers of 0.3 mm to produce lay ups with angle-ply orientations of 0°, ±10°, ±20°, ±30°, ±60° and 90° resulting in approximately 2.4 – 2.5 mm thick laminates. The composites were prepared (after a flax fibre pre-drying process of 110° C for 30 min) using autoclave manufacturing for the CFRP or compression resin transfer moulding for the FFRP and cured at 100° C for 2 h using a pressure of 1 MPa. Subsequent differential scanning calorimetry was used to ensure that the composites were indeed fully cured with a glass transition temperature of 115°C and optical microscopy of polished cross sections confirmed a porosity of less than 2 % in the water-jet cut samples. All of the samples were dried at 40° C in a vacuum overnight prior to testing.

## 3. Experimental methodology

Three measurement methods were studied to characterise the damping behaviour of FFRP with CFRP as a reference material for comparison, as shown in Table 1. The logarithmic decrement measurement method (LDM) measures the decay of vibration of a beam oscillating at its natural frequency  $f_n$ . Dynamic mechanical analysis (DMA) was performed to provide a clamp free measurement using the non-resonant damping experiment. Lastly, vibration beam measurements (VBM) were conducted to allow measurement of resonant damping at very large amplitudes, identify many modes of vibration and the study of a broad frequency range. The dynamic behaviour, elastic modulus  $E$  was derived using these methods, then damping was related to the specific damping capacity  $\psi$  in order to compare damping in CFRP and FFRP composites.

### 3.1. Logarithmic decrement measurement

The logarithmic decrement  $\delta$  is a damping measure for linear systems in the time domain. The test was performed on beams of vibrating length  $L = 290$  mm, declining at their natural frequency  $f_n$  from a pre-defined deflection. The specimens were clamped at one end with a fixed torque of 15 Nm. A fixed displacement  $X_0 = 5$  mm was applied to a point  $l = 150$  mm along the beam and then the decline in amplitude was recorded as a function of time using an OptoNCDT 1700 Laser displacement sensor. Two samples

were tested from a single plate and each sample was removed and re-clamped until three repeat measurements were obtained for each material (total six tests). Typically, an exponential function may be fit to the recorded amplitude decay in order to describe the vibration decline. Additionally, one may analyse the Fourier spectra to obtain the natural frequencies and damping via the quality factor  $Q$  which is the reciprocal of the dimensionless bandwidth, that describes the magnitude of under-damping of the system in resonance [16].

For linear under-damped systems in the time domain, defined by a parallel spring-damper material model with an attached mass  $m$

$$0 = m\ddot{x}(t) + c\dot{x}(t) + kx(t) \quad (2)$$

where  $c$  is the damper coefficient and  $k$  is the spring constant. The solution  $x(t)$  to (2) is

$$x(t) = X_0 \exp(-\tau t) \cos(T t) \quad (3)$$

with the initial displacement  $X_0$ , the decline rate  $\tau$  and the period  $T$ . The decrement  $\delta$  for a one dimensional decline can be determined by the decline of a free vibrating beam from one maximum amplitude  $\hat{x}(t)$ , to the next  $\hat{x}(t + T)$  [17].

$$\delta := \ln \frac{\hat{x}(t)}{\hat{x}(t + T)} \quad (4)$$

with the period  $T = 1/f_n$  the eigenfrequency  $f_n$  the decay rate  $\tau$  and time  $t$ . Using (3), the decrement becomes

$$\delta = \ln \frac{X_0 \exp(-\tau t)}{X_0 \exp(-\tau(t + T))} = \tau T = \frac{\tau}{f_n} \quad (5)$$

Further, solving the following system of equations, one may convert  $\delta$  to the specific damping capacity  $\psi$ .

$$\zeta = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}} \quad (6)$$

$$Q^{-1} = \sqrt{\left(1 - 2\zeta^2 + 2\zeta\sqrt{1 + \zeta^2}\right)} - \sqrt{\left(1 - 2\zeta^2 - 2\zeta\sqrt{1 + \zeta^2}\right)} \quad (7)$$

$$Q^{-1} = \sqrt{1 + \frac{\psi}{2\pi}} - \sqrt{1 - \frac{\psi}{2\pi}} \quad (8)$$

Using Taylor expansions for  $\delta$  close to zero, i.e. low damping, one may find the commonly used approximation  $\psi_{LDM} \approx 2\delta$  [4]. Representative LDM measurements of 0° CFRP and FFRP in are shown in Fig. 1. The time domain envelopes of these measured declining vibrations did not follow the one dimensional linear vibration posed by equation (2). When analysing the Fourier spectra, more than one resonance frequency  $f_n$  with notable and significant power was identified. As is evident in Fig. 1. Model (2) was therefore extended to a two dimensional space. The solution  $x(t)$  and resulting envelope  $g(t)$  of the free vibration becomes

$$x(t) = \sum_{i=1}^2 c_i \exp(-\tau_i t) \cos\left(\sqrt{\omega_{n_i}^2 - \tau_i^2} t\right) \quad (9)$$

$$g(t) = (c_1 \exp(-\tau_1 t) + c_2 \exp(-\tau_2 t)) \quad c_1 + c_2 = X_0 \quad (10)$$

The envelope  $g(t)$  is the sum of the two exponential declines.

**Table 1**  
Properties of the damping measurement methods studied.

Method	Sample size	Frequency	Clamping torque	Measure
LDM	360 × 45mm <sup>2</sup>	$f_n$	15 Nm	$\delta$
DMA	60 × 10mm <sup>2</sup>	0.1–100 Hz	–	$\tan(\gamma)$
VBM	360 × 45mm <sup>2</sup>	5–3000 Hz	15 Nm	Q factor

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