DAMPING OF CARBON FIBRE AND FLAX FIBRE REINFORCED ANGLE PLY POLYMERS

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Abstract
The objective of this paper was to understand the damping of carbon- and flax-fibre reinforce polymers. We analysed carbon and flax symmetric angle ply laminates for a series of layup angles of 0°, ±10°, ±20°, ±30°, ±60°, 90°. We measured both series using dynamic mechanical analysis (DMA) and vibration beam measurements (VBM). Our results showed that the VBM and DMA elastic results can be converted from one into the other, and we found a mathematical formulation to relate the damping results of both. We discussed the underlining mathematical models of each measurement method and the physical interpretation. For both methods, we relate the elastic properties to the elastic modulus and the damping properties to the specific damping capacity (SDC), ψ. We concluded that within a certain frequency range micro-mechanical (DMA) and macro-mechanical (VBM) damping may be compared and even converted into one another.

1. Introduction

The high specific strength make materials such as carbon fibre reinforced polymers (CFRPs) attractive for light weight structures. These however, are prone to vibrations leading to unwanted instability, reduced efficiency or in the worst case, structural failure. This leads to conservative designs with reduced efficiency and higher weight.
Flax fibre reinforced polymers (FFRPs) have recently been gaining attention again due to their low environmental footprint and relatively good specific performance [1]. The hierarcherical microstructure in flax fibres consists of crystalline cellulose microfibrils embedded in pectin and a hemicellulose matrix [2]. This structure lends itself to improved damping performance compared to carbon and glass fibres. The damping of FFRP is an order of magnitude higher than aluminium and exhibit three times higher damping than glass-FRP or CFRP [3], making it very attractive to provide stiffness and damping simultaneously. However, many questions concerning the damping of FFRPs still remain unanswered, and most importantly many damping test methods exist, but are rarely comparable.
To address this dynamic problem, we present a methodology to compare across what we call micro- and macro-mechanical damping test-methods and excitation frequencies. We do this using dynamic mechanical analysis (DMA) for the micro-mechanical scale and vibration beam measurements (VBM) for the macro-mechanical scale. Our methodology is applied to study CFRPs and FFRPs where we describe an analytical approach to reduce the measurements to the specific damping capacity (SDC)

$$\psi := \frac{\Delta U}{U} \tag{1}$$

where ΔU is the total energy loss per cycle and U is the maximum elastic stored energy [4].

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2. Materials

Carbon fibre polymers were produced from prepreg from North Thin Ply Technology, Switzerland. For the FFRPs unidirectional (UD) non-crimp flax fibre fabric type 5009 (300g/m²) from Bcomp AG, Switzerland was used in combination with the same epoxy system in a resin transfer moulding process. CFRP laminates were produced with 80 layers of thin-ply UD prepreg (30g/m²) into balanced anti-symmetric lay ups and 8 layers of UD flax fabric into balanced symmetric lay ups with angle configurations (0°, ±10°, ±20°, ±30°, ±60°, 90°) resulting in approximately 2.4 – 2.5 mm thick laminates. Microscopy was used to ensure that the composites were fully cured. Porosity was less than 2% for all samples.

3. Measurement Methods

The micro-mechanical damping analysis was done using the dynamic mechanical analysis (DMA). It is a clamping free measurement requiring small coupons. For the macro-mechanical damping measurements, vibration beam measurements (VBM) were conducted. This method allows for measurements over a large frequency range. These methods are discussed in further detail, followed by the damping results, which are then related to the specific damping capacity, ψ. Additionally the elastic modulus E is extracted using these dynamic test methods.

Table 1. Damping measurement methods that were studied.

Method	Scale	Air damping	Frequency	Damping Measure
DMA	micro-mecanical	low	0.1-100 Hz	tan(δ)
VBM	macro-mechanical	high	5-3000 Hz	Q factor

3.1. Dynamic Mechanical Analysis

The DMA measurements were performed on a TA Instruments Q800 with the three point bending set up. The CFRP coupons were 60 mm by 6 mm, while the FFRP samples measured 60 mm by 10 mm. Each test was done three times at a temperature of 30°C. Measurements were taken at 1 Hz and 25 Hz at a preload of 0.05 N. The complex modulus **E**, consisting of the storage modulus E' and the loss modulus E'' was recorded and the tangent of the complex modulus, tan(δ), computed.

3.2. Vibration Beam Measurements

The VBM were performed on a Tira 57315/LS-340 shaker. Four beams of 350 mm by 45 mm were tested per run by clamping radially at a 90° offset with a fixed torque. Accelerometers were fixed to their free edges and one to the centre of the shaker. The sensor in the middle of the shaker was used for master motor-control and as the reference input for all other four accelerometers. Each run was a frequency sweep from 5 Hz to 3000 Hz at a constant acceleration amplitude throughout. The fast Fourier transform of each accelerometer was computed for data analysis.

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4. Results

4.1. Dynamic Mechanical Analysis

We used the micro-mechanical test method Dynamic Mechanical Analysis (DMA) to measure the complex modulus, **E**, consisting of the storage modulus, $E^{'}$, and the loss modulus, $E^{''}$, which are the reversible elastic part and the loss per cycle, respectively. The tangent of the complex moduli is

$$\tan(\delta) := \frac{E^{''}}{E^{'}} \tag{2}$$

which is the damping measure of the DMA. We found that this damping measure is related to the following forced vibration equation of motion

$$f(t) = m\ddot{x}(t) + (E^{'} - iE^{''})x(t) \tag{3}$$

with the imaginary unit, i. This can be shown using the transfer function H of system (3). The Fourier Transform (FT) is

$$F(\omega) = X(\omega)(m\omega^2 + E^{'} - i\omega E^{''}) \tag{4}$$

with the FT of the input $F(\omega) = \mathfrak{F}(f(t))$ and the output $X(\omega) = \mathfrak{F}(x(t))$. Thus, the transfer function H of (3) with the phase ϕ is

$$H(\omega) = \frac{X(\omega)}{F(\omega)} = \frac{1}{E^{'} + m\omega^2 - i\omega E^{''}} \quad \phi(\omega) = \arctan(\frac{-E^{''}}{E^{'} + m\omega^2}) \tag{5}$$

for a massless system, $m = 0$, these equations simplify to

$$H(\omega) = \frac{1}{E^{'} - i\omega E^{''}} \quad \phi(\omega) = \arctan(\frac{E^{''}}{E^{'}}) \tag{6}$$

which reproduces the definition of the $\tan(\delta)$. Thus δ, can be interpreted as the phase shift ϕ of the massless version of system (3). This means that the phase lag of the displacement to the input force is the measure for this damping measurement technique.

$$\tan(\phi(\omega)) = \frac{E^{''}}{E^{'}} = \tan(\delta) \tag{7}$$

Further to find a relation to the SDC, the tangent, $\tan(\delta)$, may be first related to the loss factor, η, which is feasible for viscoelastic materials [5]. Then the SDC, ψ_{DMA}, can be related to the loss factor

$$\psi_{DMA} := 2\pi\eta = 2\pi\tan(\delta) \tag{8}$$

The elastic modulus, E_{DMA}, is extracted as the real part of the complex modulus

$$E_{DMA} = \mathfrak{R}(\mathbf{E}) = E^{'} \tag{9}$$

The elastic modulus, E_{DMA}, and the SDC, ψ_{DMA}, were measured on two series of angle-ply CFRP- and FFRP-laminates. The DMA measurements of the elastic modulus, E_{DMA}, versus the layup angle were found to present decline in stiffness with a higher stiffness for the lower angles and a lower stiffness for the higher fibre angles (Fig. 1). The DMA results of the specific damping capacity, ψ_{DMA}, versus the layup angle generally show a rise in damping with a higher orientation angle of the fibres. This rise flattens for the higher frequency of 25 Hz. For all orientations the FFRP damps more than CFRP while CFRP is stiffer.

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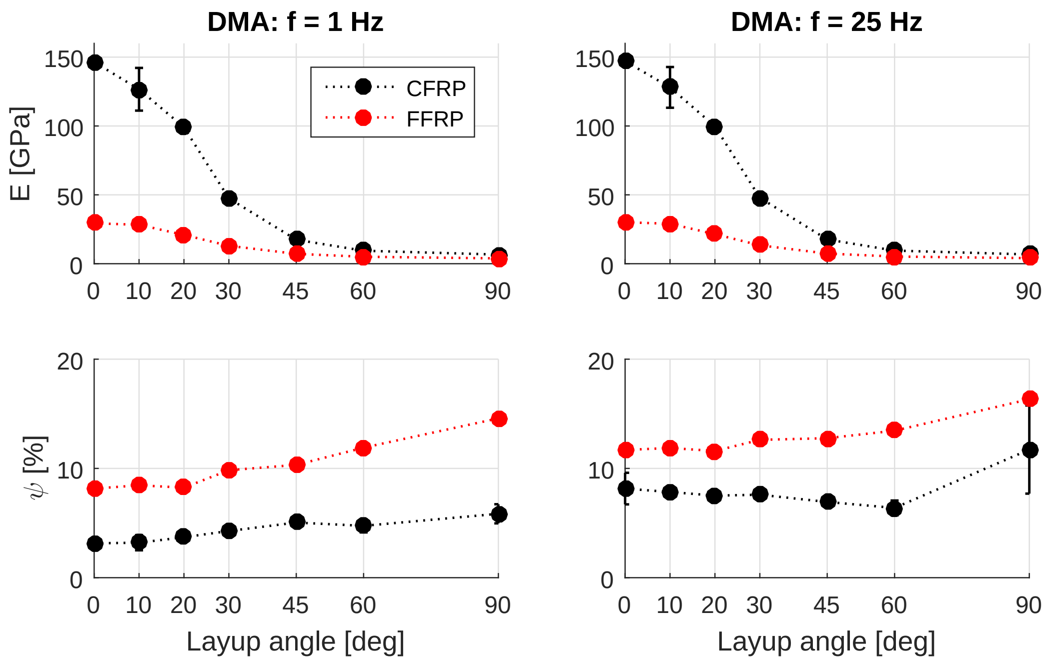

Figure 1. Dynamic mechanical analysis of carbon and flax fibre reinforced polymers at various different layup angles at 1 Hz and 25 Hz. E_{DMA} is the elastic modulus and ψ_{DMA} the specific damping capacity.

4.2. Vibration Beam Measurements

As a second damping measurement method we used the macro-mechanical approach Vibration Beam Measurements (VBM). We recorded the transfer function, $H(\omega)$, which is the Fast Fourier Transform (FFT) of the accelerometer output, $Y(\omega)$, divided by the FFT of the excitation, the acceleration of the input, $X(\omega)$

$$H(\omega) = \frac{Y(\omega)}{X(\omega)} \tag{10}$$

For analysis and data processing, $H(\omega)$ is divided into the gain and phase. From this transfer function We extracted the resonance frequencies for each beam by using the phase, which at resonance is at $90° + n180°$, $n \in \mathbb{N}$ at each resonance, n. From each resonance the maximum gain and the halfpowerpoints, ω_i with $i = h_1, h_2$, were extracted and used for the computation of the Quality factor, Q, which is then converted to the modal specific damping capacity, ψ_{VBM}, for each mode, n,

$$\psi_{VBM_n} = 2\pi\sqrt{1 - \frac{(2 - \frac{1}{Q_n^2})^2}{4}} \qquad Q_n := \frac{\omega_n}{\omega_{h_1} - \omega_{h_2}} \tag{11}$$

This method is based on the evaluation of resonance peaks and is computed purely in the frequency domain. The Quality factor is the maximum amplitude of a beam tip when sweeping through the resonance divided by the width of this peak. Thus, the faster a beam is excited and the higher the amplitude the higher the Q factor and therefore smaller damping, ψ_{VBM}.

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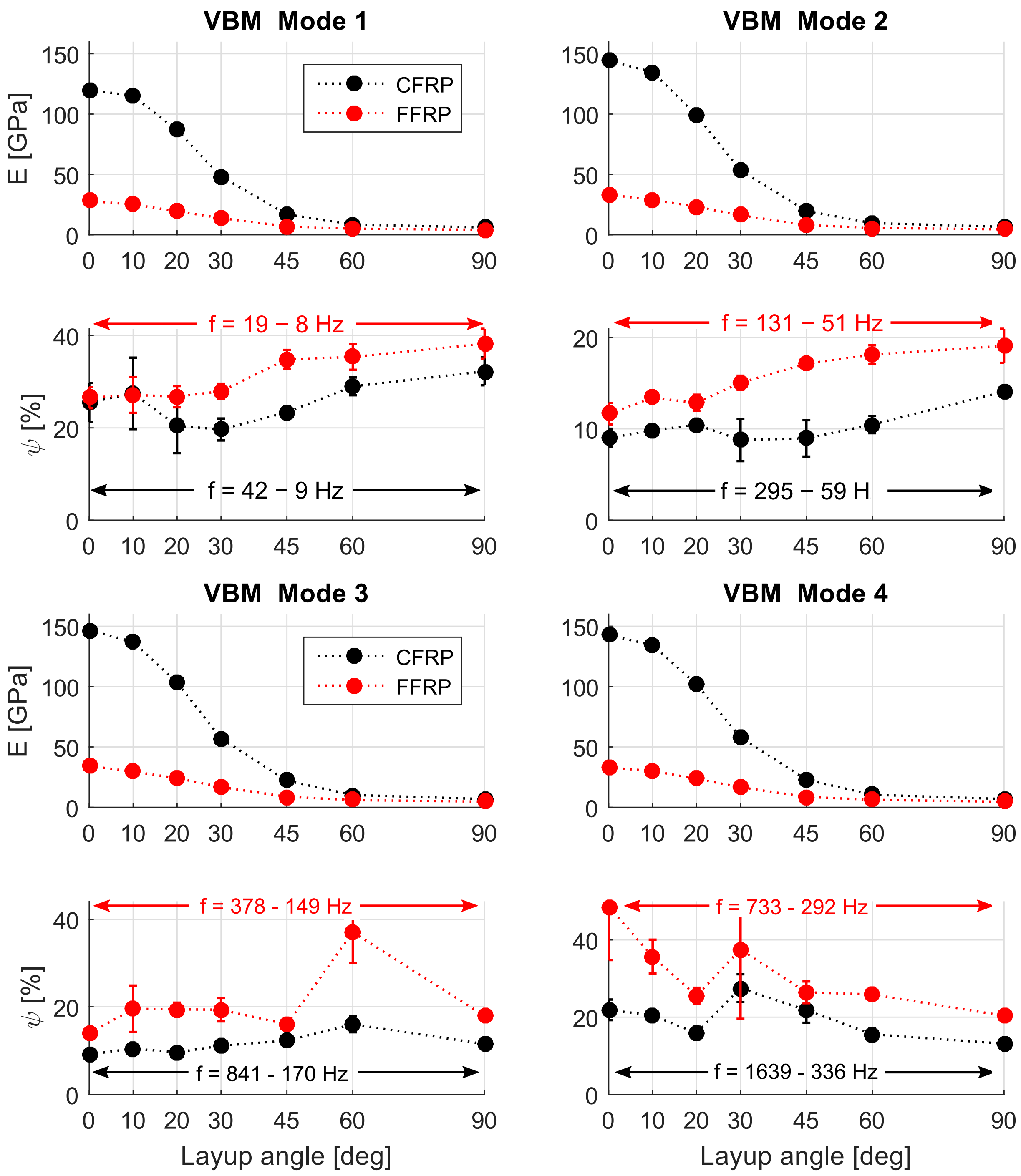

Figure 2. Vibration beam measurements of the specific damping capacity, ψ_{VBM}, and the elastic modulus, E_{VBM}, of carbon and flax fibre reinforced polymers (CFRP/FFRP) at different layup angles. The first four modes are shown and the range of the corresponding resonance frequencies, f.

To extract the elastic modulus, E_{VBM}, the resonance frequency must be converted to an elastic property based on a model. For this the Euler Beam Equation is used

$$\frac{\delta^4 w}{\delta x^4} + \frac{\rho A}{E_{VBM} I_x} \frac{\delta^2 w}{\delta t^2} = \frac{F(x,t)}{EI_x} \tag{12}$$

with the displacement, w, area, A, density, ρ, second area moment of inertia, I_x, and the force, F. Equa-

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tion (12) may be posed as an eigenvalue problem to calculate the resonance frequency of these vibration beams [6].
This results in the following equation, relating the elastic modulus, E_{VBM_n}, corresponding to each mode, n, and angular resonance frequency, ω_n,

$$E_{VBM_n} = \frac{\rho A \omega_n^2}{(\beta_{L_n}/L)^4 I_x} \tag{13}$$

with the Euler beam equation parameter, β_{L_n}, and the beam length, L. Using equation (13) resonance frequencies may be directly related to the elastic modulus. Each modes parameter β_{L_n}, is found by solving (12). The angular eigenfrequencies ω_n, are a mixed, geometric and material, property of the beam. The eigenfrequency is $f_n = \omega_n/2\pi$.

The elastic modulus, E_{VBM}, and the SDC, ψ_{VBM}, were measured on the same two series of angle-ply CFRP- and FFRP-laminates, as with the DMA (Fig. 2). The elastic modulus, E_{VBM}, versus the layup angle display the same trend as with the DMA. Classical Laminate Theory also confirms this trend. The moduli of mode 1 are slightly lower, most likely due to the presence of air-damping which is the highest at mode 1. The additional damping shifts the eigenfrequencies to lower values than where the less damped eigenfrequency would be.
The measured damping, ψ_{VBM}, versus the layup angle θ shows different dynamics per mode. As damping is a frequency dependant phenomena it is important to keep in mind that each mode occurs at a different frequency for each layup angle. This is due to the different elastic moduli of the samples. In Figure 2 each mode is noted with a frequency band within which all the n resonances occurred. At mode 1 the damping is high with its maximum at the 90° sample. For CFRP this trend is consistent with literature [7]. The generally higher damping in this mode is most likely due to the higher airdamping, because airdamping is know for its large contribution for high amplitudes [8]. The second modes damping dynamics are similar to the first mode, including the lower values at 30°. In the third modes damping plot we may observe a local maximum for the 60° samples for CFRP and FFRP. Most interestingly, for the fourth mode, the maximum damping shows for the 0° samples and the minimum for the 90° samples.

5. Discussion of Micro- vs Macro-Mechanical Damping Measurement

The underlining dynamic models of the DMA and VBM are different and therefore present different dynamic methods with different elastic and damping measures. (Tab. 2). We propose a methodology to convert each method to E respectively ψ.

Table 2. Damping measurement methods compared.

Method	Dynamic Model	Elastic Modulus	Damping ψ
DMA	$f(t) = m\ddot{x}(t) + (E' - iE'')x(t)$	$\Re(\mathbf{E})$	$2\pi\tan(\delta)$
VBM	$\frac{\delta^4 w}{\delta x^4} + \frac{\rho A}{E_{VBM} I_x}\frac{\delta^2 w}{\delta t^2} = \frac{F(x,t)}{EIx}$	$\frac{\rho A \omega_n^2}{(\beta_{L_n}/L)^4 I_x}$	$2\pi\sqrt{1 - \frac{(2-\frac{1}{Q^2})^2}{4}}$

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For the elastic modulus the conversion is

$$\Re(\mathbf{E}) = E_{DMA} = E_{VBM} = \frac{\rho A \omega_n^2}{(\beta_{L_n}/L)^4 I_x} \tag{14}$$

For the ψ_{DMA} and the ψ_{VBM} we assume they differ by a function, ψ_c of frequency f

$$\psi_{DMA} + \psi_c(f) = \psi_{VBM} \tag{15}$$

which quantifies the difference of micro-mechanical and macro-mechanical damping and the methods. We assume that this function $\psi_c(f)$ would need to take account for differences in air-damping, clamping and size effects. The quantification of this this function will be subject of further research.

6. Conclusion

We showed that FFRP damps better than CFRP up to frequencies of 1600 Hz for all tested angle-ply laminates. We suggest that this superior damping, together with the higher stiffness of CFRP, combines the two most important factors for light weight structures. The high stiffness to weight ratio and high damping to avoid structural failure at resonance. Therefore flax and carbon fibre hybrids are high potential candidates for future light weight structures.
We showed the possibility to convert DMA and VBM results to the elastic modulus, E, and specific damping capacity, ψ, potentially making them comparable. For the elastic modulus this means that two different models of two different measurement techniques yield the same result. For the SDC only further research will show how these two methods exactly relate. We conclude that within certain frequency range micro- and macro-mechanical damping test methods respectively resonant and non-resonant damping test methods may be compared and even converted into one other, however further results will need to quantify this relation. This comparison is helpful firstly to relate mathematical models and methods within a study and secondly for future studies to be able to compare new results to older, even if they are acquired with a different method.

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