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REMARKABLY STABLE DAMPING IN UD FLAX/EPOXY COMPOSITES AT INCREASING FIBER VOLUME FRACTIONS

Tsilat Shiferaw[1*], Pauline Butaud[1], Morvan Ouisse[1], Vincent Placet[1]

[1] *Université Marie et Louis Pasteur, SUPMICROTECH, CNRS, Institut FEMTO-ST, F-25000 Besançon, France*
** tsilat.shiferaw@femto-st.fr*

Abstract

Plant fiber composites are increasingly considered as sustainable alternatives to glass and carbon composites due to their low density, reduced environmental impact, and inherently high damping capacity. However, the mechanisms governing their dynamic behavior remain insufficiently understood, and existing models struggle to predict damping reliably at the composite scale. In composites reinforced with synthetic fibers, increasing fiber volume fraction typically enhances stiffness while reducing damping, raising the question of whether plant fiber composites follow a similar trend. In this study, flax fiber-reinforced thermoset composites with fiber volume fractions of 25%, 35%, and 47% are investigated using dynamic mechanical analysis and vibration testing. The results show a stiffness increase of approximately 30% across this range, while damping remains nearly constant at $\eta \approx 0.015 \pm 0.005$, indicating a clear deviation from the classical stiffness–damping trade-off. To extend these findings, a multiscale finite element model incorporating intrinsic fiber damping properties is developed. Simulations confirm that plant fiber composites maintain stable damping levels with increasing fiber content, unlike composites reinforced with synthetic fibers, which exhibit a significant decrease. These results highlight the potential of plant fiber composites to achieve a favorable balance between stiffness and damping, making them promising candidates for vibration-sensitive lightweight structures.

Keywords: *Plant based composites; Damping; Multiscale; Homogenization*

1 Introduction

The increasing demand for environmentally sustainable materials has driven significant interest in plant fiber-reinforced composites. Compared to conventional synthetic fibers such as glass and carbon, plant fibers offer advantages including low density, renewability, and reduced environmental impact. However, these benefits are often accompanied by lower stiffness, moisture sensitivity, and variability in mechanical properties [1–4]. Because of these limitations, plant fiber composites are predominantly used in non-structural components, such as automotive interior parts and sporting goods [5]. Nevertheless, recent studies have highlighted the capability of bast fiber composites; particularly flax, hemp, jute, and kenaf to meet the mechanical requirements of more demanding applications, including load-bearing structures like wind turbine blades, owing to their favorable specific stiffness and strength [6–8].

In addition to static mechanical performance, the dynamic behavior of composites is critical in many applications. Damping plays a key role in vibration attenuation, noise reduction, and fatigue resistance, and plant fiber composites generally exhibit higher intrinsic damping than their synthetic counterparts [9–12]. However, this behavior is strongly influenced by microstructural parameters such as fiber orientation, fiber volume fraction, and interfacial properties [13–15]. Among these parameters, fiber volume fraction is known to have a major influence on composite behavior. Increasing fiber content typically leads to improved stiffness in fiber-reinforced composites [16, 17] but its effect on damping is less straightforward. In composites reinforced with synthetic fibers, a consistent decrease in longitudinal damping with increasing fiber volume fraction has been reported [18]. In contrast, studies on plant fiber composites, particularly in thermoplastic matrix, suggest more complex trends. For example, Etaati et al. [19] observed an initial increase in damping with fiber content in short hemp/PP composites, attributed to enhanced interfacial dissipation, followed by a decrease at higher fractions. Other studies on flax/PP composites report negligible variation in damping over a range of fiber contents [15]. However, the behavior of continuous plant fiber composites in thermoset matrices remains insufficiently explored, leaving open the question of whether similar trends apply.

A comprehensive understanding of the relationship between microstructure and macroscopic response is therefore required to fully exploit these materials. Experimental techniques, such as dynamic mechanical analysis, provide valuable insight into viscoelastic behavior across a range of loading conditions and reveal sensitivities to defects like porosity or fiber misalignment [11]. However, experimental studies are generally limited to specific material types and cannot easily be extended to a broader design space. Analytical models have been proposed to estimate the viscoelastic response of composites based on constituent properties. In particular, formulations by Berthelot and Sefrani [20] describe the contributions of fiber and matrix phases to damping, although they often neglect fiber dissipation in the longitudinal direction for composites reinforced with synthetic fibers due to their low intrinsic damping. While such assumptions are reasonable for glass and carbon fibers, they may not be valid for plant fibers, whose higher intrinsic damping and complex microstructure can significantly influence the overall composite response. As a consequence, a gap persists between experimental observations and predictive modelling, especially for plant fiber composites. Existing approaches struggle to capture the variability of damping behavior and to describe its evolution with key parameters such as fiber volume fraction. This motivates the use of multiscale modelling strategies, which enable the prediction of macroscopic properties from microstructural characteristics and provide a framework to investigate a wider range of material configurations [21].

The objective of this study is to investigate the influence of fiber volume fraction on the dynamic mechanical behavior of flax fiber-reinforced composites. Experimental characterization is conducted to quantify the evolution of stiffness and damping with fiber content, and to provide validation data for the modelling approach. A multiscale finite element framework is then employed to relate microstructural features to macroscopic viscoelastic properties, enabling a comparison between plant fiber and conventional synthetic fiber composites. The paper is organized as follows: Section 2 presents the methods to characterize the viscoelastic properties of composites, Section 3 discusses the results, and Section 5 summarizes the main conclusions.

2 Materials and methods

2.1 Materials and sample preparation

Flax fiber-reinforced epoxy composites are manufactured using SR Greenpoxy 56 resin with SD 7561 hardener (Sicomin). The resin and hardener are mixed at a mass ratio of 100:37 and cured under thermocompression at 60 °C for 1 h, followed by post-curing at 100 °C for 1 h. Unidirectional flax reinforcements (FlaxTape 110, Ecotechnilin) are dried at 50 °C for 1 h to minimize moisture effects prior to processing. The composites are then produced by hand impregnation followed by compression moulding, targeting fiber volume fractions of 25%, 35%, and 47% through thickness control of the laminate. After manufacturing, samples are conditioned at 23 °C and 50% relative humidity for at least two weeks prior to testing.

2.2 Modal analysis

Modal analysis is performed to characterize the damping behavior of flax-Greenpoxy composites over a broad frequency range. Square plates are extracted from the laminates, with dimensions of $100 \times 100 \times 1.2\ \mathrm{mm}^3$, $110 \times 110 \times 1.45\ \mathrm{mm}^3$ and $125 \times 125 \times 1.8\ \mathrm{mm}^3$ for fiber volume fractions of 47%, 35%, and 25%, respectively, in order to obtain comparable natural frequencies across the different fiber content. The specimens are suspended using thin wires to approximate free–free boundary conditions as shown in Figure 1. The plates are excited using an acoustic source, and the response is measured with a scanning laser vibrometer. Frequency response functions are obtained, from which modal frequencies, damping ratios, and mode shapes are identified using an in-house analysis tool.

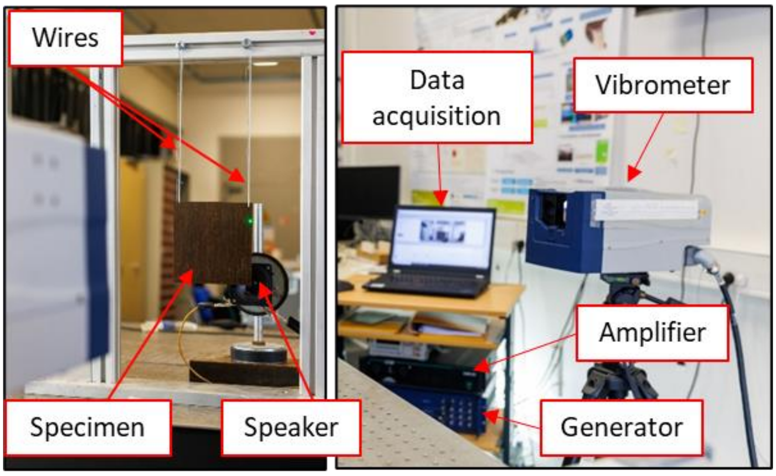

Figure 1. Vibration test experimental setup

To determine the directional damping properties, a model updating approach based on an orthotropic finite element model is employed. Following the method proposed by McIntyre and Woodhouse [22], initial estimates of the viscoelastic constants are derived from the measured modal frequencies, specimen geometry, and density. These properties are then iteratively refined by minimizing the difference between numerical and experimental frequencies until convergence is achieved. The final model provides the effective orthotropic stiffnesses and associated loss factors for each composite configuration. These values are further used to validate or compare the results coming from the numerical approach.

2.3 Multiscale modelling

The dynamic behavior of unidirectional fiber reinforced composites is investigated using a multiscale finite element approach implemented in COMSOL Multiphysics. This framework relies on homogenization techniques to link microstructural features to macroscopic viscoelastic properties. The modelling procedure follows two successive steps: microscale analysis based on a Representative Volume Element (RVE), and macroscale structural modelling.

2.3.1 Microscale modelling

At the microscale, an RVE composed of a unidirectional fiber embedded in a matrix is used to estimate the effective properties of the composite. The fiber and matrix are modelled using complex-valued material properties in order to account for energy dissipation and to simultaneously predict storage and loss components.

Periodic boundary conditions are applied to ensure displacement continuity across opposite faces of the RVE, enabling consistent homogenization of the mechanical response. From the simulations, the homogenized complex modulus and loss factors is obtained.

2.3.2 Macroscale modelling

The effective viscoelastic properties obtained at the microscale are used as input for a macroscale finite element model, where the composite is represented as an equivalent homogeneous orthotropic material. This step enables the prediction of structural dynamic behavior at the plate scale and allows direct comparison with modal analysis results. The multiscale approach therefore provides a consistent framework to relate microstructural parameters, such as fiber content and constituent properties, to the overall stiffness and damping response of the composites.

3 Results and discussion

The multiscale study is performed on flax, glass, and carbon fiber composites to predict their effective elastic moduli and loss factors. This approach enables both validation of the numerical model against experimental data and a direct comparison between plant based and conventional fiber reinforcements, providing insight into stiffness–damping trade-offs across different composite types. The material properties used in the simulations are summarized in Table 1.

Table 1. Material properties used in the numerical model.

Material	E_L **[GPa]**	E_T **[GPa]**	η_L **[%]**	η_T **[%]**
Greenpoxy	3 [11]	3 [11]	1.5 [23]	1.5 [23]
Flax	55 [24]	8 [25]	0.66 [24]	1.32*
Glass	66 [20]	66 [20]	0.19 [20]	0.083 [20]
Carbon	345 [20]	15 [26]	0.25 [20, 27]	0.13 [20, 27]
			***Arbitrary values**	

Figure 2a and 2c presents the evolution of the longitudinal modulus E_L and longitudinal loss factor η_L as a function of fiber volume fraction V_f. The increase in E_L with increasing fiber content is accurately captured by the numerical model, showing good agreement with experimental measurements. The evolution of η_L differs depending on the fiber type. For glass fiber composites, η_L decreases from about 0.4% at 20% V_f to approximately 0.2% at 70% V_f, consistent with their low damping capacity. This trend agrees with experimental data from the literature, which show a reduction from 0.33% to 0.28% as V_f increases from 35% to 60% [27]. Carbon fiber composites exhibit a slight decrease from 0.29% to 0.2%, in line with experimental observations above 30% V_f [27]. In contrast, flax fiber composites show significantly higher damping, with η_L in the range of 0.7–0.8% in the numerical model. Experimental measurements obtained in this study (green square markers) indicate higher values, with an approximately constant η_L of 1.5% as V_f increases from 25% to 47%. These results indicate that flax fiber composites achieve stiffness levels comparable to glass fiber composites while exhibiting approximately three times higher damping than composites reinforced with synthetic fibers.

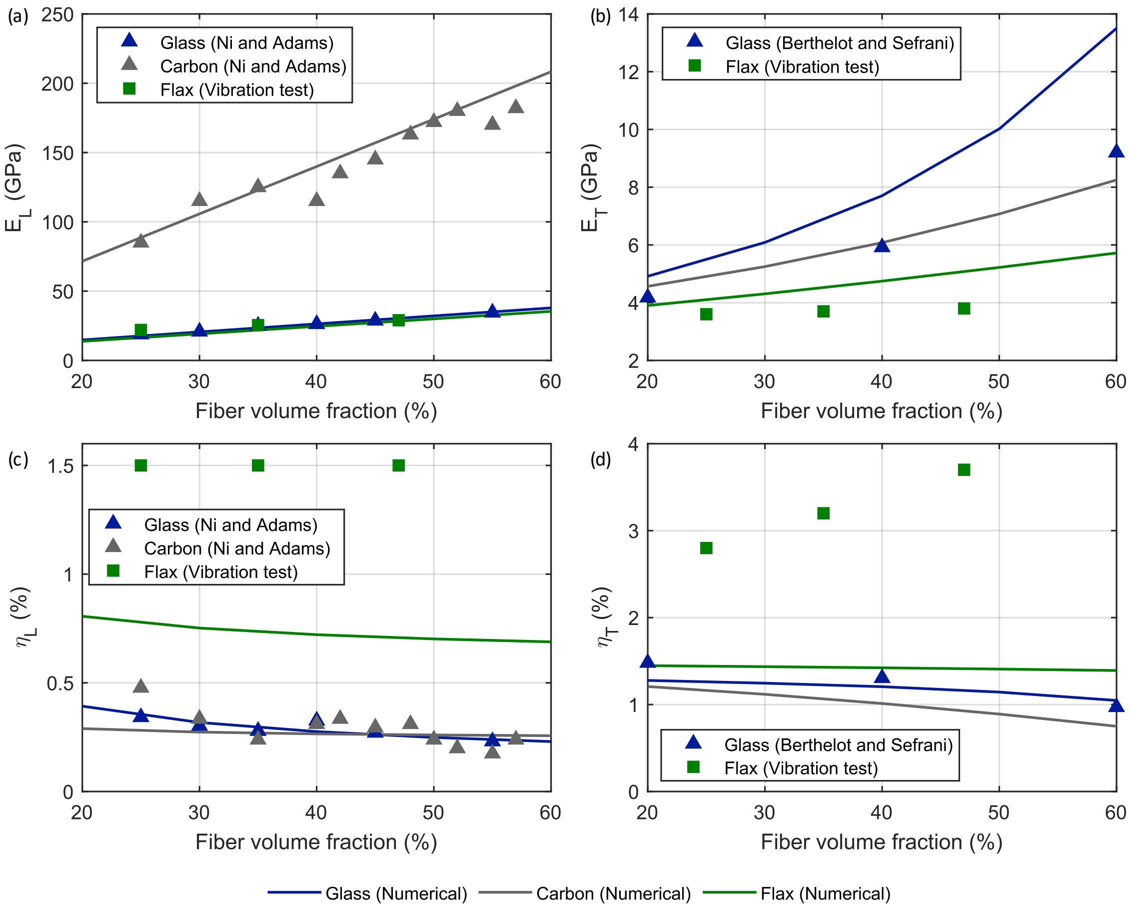

Figure 2. Numerical and experimental comparison of stiffness and damping for glass, carbon, and flax fiber composites: (a) longitudinal modulus E_L, (b) transverse modulus E_T, (c) longitudinal loss factor η_L, and (d) transverse loss factor η_T. Markers represent experimental values, and continuous lines show the numerical predictions for different fiber types.

Figure 2b and 2d show the transverse modulus E_T and loss factor η_T. The numerical model predicts an increase in E_T with increasing V_f for all cases. This trend is consistent with the experimental observations for glass fiber composites, where the transverse stiffness increases with fiber content. In contrast, flax fiber composites exhibit an almost constant transverse modulus with increasing V_f, as the transverse stiffness of flax fibers is relatively close to that of the matrix. As a result, the reinforcement effect remains limited in the transverse direction. The discrepancy between numerical and experimental results can be attributed to idealized assumptions regarding stress transfer mechanisms. Similarly, the transverse damping is not accurately reproduced by the numerical model. For flax/epoxy composites, the predicted η_T values are significantly underestimated compared to experimental measurements, as the influence of additional dissipation mechanisms is not fully captured by the current modeling approach. These results indicate that further model developments are required to better capture the transverse damping behavior of natural fiber composites.

4 Conclusions

This study investigated the influence of fiber volume fraction on the stiffness and damping behavior of unidirectional flax–greenpoxy composites using a combined experimental and multiscale numerical approach. The results show that the longitudinal stiffness increases with fiber content and is well predicted by the numerical model, while the longitudinal damping remains nearly constant. In contrast, the transverse response exhibits limited sensitivity of stiffness to fiber volume fraction and higher damping levels, which are not accurately captured by the model.

The comparison with glass and carbon fiber composites highlights that flax fiber reinforced composite achieve comparable stiffness to glass fiber reinforced composite, while exhibiting significantly higher damping. However, the numerical model overestimates transverse stiffness and underestimates transverse damping, indicating that additional mechanisms such as shear and interfacial effects need to be incorporated.

Overall, this work provides insight into the role of fiber content in governing the dynamic behavior of plant-based composites and highlights the need for improved modelling approaches to accurately describe their transverse viscoelastic response.

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