Paper ID:

Multi-Scale Assessment of the Stiffness–Damping Trade-Off in Hemp/Elium® Composites for Wind Turbine Applications

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Abstract

Conventional composites reinforced with carbon or glass fibers exhibit excellent specific mechanical properties but suffer from limited vibration damping capability, which can negatively impact performance and fatigue life. Overcoming this limitation often requires complex and costly solutions, increasing both weight and cost of the system. Plant fibres, such as hemp, offer a promising alternative due to superior damping properties. The aim of this study is to investigate the potential of a bio-based composite made of hemp fibers and Elium® thermoplastic resin (Arkema), focusing on the balance between stiffness and damping at material scale. The central question addressed is how the elastic and damping properties of these constituents influence the global behavior of the composite material. More specifically, can a reactive thermoplastic such as Elium® enhance composite damping, and do hemp fibers offer a relevant compromise between stiffness and damping?
To answer these questions, a material-scale comparison is performed using two reference benchmarks: a glass fiber reinforcement and an epoxy resin system. This approach enables the respective effects of fibers and matrix on stiffness–damping balance to be isolated and analysed. Elastic and damping properties are identified using an inverse approach based on Finite Element Model Updating applied to vibration tests. Initial results on pure resins show Elium® exhibits a loss factor twice that of epoxy (~6% vs. ~3%), highlighting its damping potential. At composite scale, this increase translates into an improvement in damping, typically between 30% and 50%. Finally, extension of these findings to structural scale is considered as perspective.

Keywords: *Bio-based composites; Damping properties; Inverse identification; Hemp fibers*

1 Introduction

Thanks to their low density and attractive mechanical properties, composite materials have become widely used in many industrial sectors, including aerospace [1], automotive [2], and energy [3]. Among them, conventional composites based on carbon or glass fibers are currently the most widely used. These materials offer excellent specific stiffness and strength [4]. However, beyond their non-ecological nature due to the use of synthetic fibers, they generally exhibit limited damping capacity. This drawback often requires additional and complex vibration reduction solutions.

Such strategies may involve either active control systems [5, 6] or passive approaches. In the latter case, additional devices such as tuned mass dampers (TMDs) can be implemented [7, 8, 9]. Another passive strategy consists in designing materials with intrinsic damping capability. In this context, plant fibers appear as a promising alternative due to their high damping capacity [10], combined with their low density, which leads to attractive specific stiffness. Bio-based composites therefore offer a relevant compromise between stiffness and damping [11].
Regarding damping behavior, and contrary to the commonly accepted assumption for glass- and carbon-fiber composites, where the contribution of fibers to longitudinal damping is generally considered negligible, Berthelot and Safrani [12], showed that fibers can, in fact, play a crucial role in the damping response of composites, along the fiber direction. In this context, the contribution of plant-fiber reinforcements to longitudinal damping warrants particular attention. Their polymeric nature fundamentally distinguishes them from inorganic glass and carbon fibers, potentially challenging the validity of conventional assumptions established for synthetic fiber composites.
In addition to the role of fibers, the matrix type has also a significant influence on both transverse elastic and damping properties [13, 14]. This question is even more pertinent in the case of a reactive thermoplastic matrix such as Elium. Indeed, although it is liquid prior to polymerization and can be processed using manufacturing routes typically reserved for thermoset composites, it remains a thermoplastic system, potentially exhibiting a larger viscous contribution than crosslinked thermoset matrices.

The objective of this study is therefore, first, to investigate to what extent the elastic and damping properties of the constituents influence the behavior at the composite scale, and then to consider, as a perspective, their impact at the structural scale. More specifically, the study addresses whether a thermoplastic resin such as Elium® can significantly enhance damping at the composite level, and whether hemp fibers can improve damping while maintaining a suitable stiffness–damping balance.

To answer these questions, an identification campaign is conducted using a Finite Element Model Updating (FEMU) approach [15], based on vibration test results and finite element model updating. In this study, the FEMU methodology is developed and extended to allow the simultaneous identification of both stiffness and damping properties, building on previous work [16], which was limited to stiffness identification.

Using this developed methodology, the anisotropic elastic and damping properties of the materials of interest can be identified, allowing a deeper understanding of the influence of both fiber and matrix on the viscoelastic behavior of composites.

2 Materials and Methods

2.1 Manufacturing of composite plates

The composite plates are first manufactured prior to mechanical testing. As mentioned previously, hemp fibres are selected for this application. Two types of hemp reinforcements are used in this study: HempTape® 150 supplied by EcoTechnilin, which is a unidirectional tape with an areal density of 150 g/m², and a quasi-unidirectional (QUD) hemp reinforcement supplied by Linificio, with an areal density of 200 g/m². In addition, a unidirectional glass fibre reinforcement (Saertex, 1182 g/m²) is used as a reference.

Two matrix systems are considered: Elium® resin supplied by Arkema (grade 191 SA with 191 XO initiator) and GreenPoxy®, used as a benchmark epoxy resin. Elium® is a liquid thermoplastic acrylic resin based on methyl methacrylate (MMA) monomer, which polymerises through a free-radical mechanism initiated by a peroxide-based initiator. For the manufacturing of Elium-based composites, a thermocompression process is adopted. The fibres are first dried at 80 °C for 30 minutes to remove residual moisture (this step is not applied to glass fibres). The resin is subsequently degassed under vacuum at approximately −950 mbar to minimise porosity.

Manual lay-up is performed in an A4-sized mould. After impregnation and stacking, the mould is placed in a sealed bag to prevent evaporation of the volatile MMA monomer. The assembly is then placed in a thermocompression press at 40 °C under a pressure of 2.5 bar to ensure polymerisation and consolidation. For GreenPoxy-based composites, no sealed bag is required, as the resin is non-volatile; however, the same thermocompression protocol is applied.

The resulting composite plates exhibit a porosity lower than 5%. The fibre volume fraction is approximately 40% for hemp-based composites (10 plies) and around 65% for glass fibre composites (3 plies). After manufacturing, the hemp-based composites are conditioned at 23 °C and 50% relative humidity until equilibrium is reached (approximately 14 days), before being subjected to vibration testing.

2.2 Vibration Testing of the Plates

Vibration tests are performed to identify the modal properties of the composite plates, namely the natural frequencies f_i^{exp}, damping ratios ζ_i^{exp}, and mode shapes $\{\psi_{exp}\}_i$, where "i" denotes the mode number and "exp" refers to experimental measurements.

The plate is suspended using thin nylon wires and springs in order to approximate free–free boundary conditions. Excitation is provided by a coil–magnet system: a small permanent magnet is bonded to the plate, while an electromagnetic coil generates a non-contact excitation. A white noise signal is applied over a frequency range of 20–2000 Hz.

The vibratory response is measured using a laser Doppler vibrometer, ensuring non-contact measurements. The experimental setup can be placed inside a climatic chamber for tests under controlled environmental conditions.

Modal parameters are identified using the MODAN software, developed at the Department of Applied Mechanics, based on the Least Squares Complex Frequency (LSCF) method.

2.3 Numerical Modelling and Optimisation Procedure (FEMU)

The idea is to develop a non-destructive identification method capable of simultaneously identifying the anisotropic elastic and damping properties of composite materials, and applicable to complex structures over a wide frequency range.

The approach relies on experimental modal analysis, from which the following quantities are identified: the natural frequencies f_i^{exp}, damping ratios ζ_i^{exp}, and mode shapes $\{\psi_{exp}\}_i$. In parallel, a finite element model is developed, reproducing as closely as possible the experimental boundary conditions. In particular, the FE model enables a more accurate representation of the experimental setup, especially the presence of the magnet, which alters the dynamic behavior of the tested plates. Such effects cannot be taken into account by analytical plate models, making their use unsuitable in this context and highlighting the advantage of the proposed approach.

The corresponding numerical "num" modal parameters — natural frequencies f_i^{num}, damping ratios ζ_i^{num}, and mode shapes $\{\psi_{num}\}_i$ — are then computed. An optimization process is implemented. The objective is to minimize the discrepancy between experimental and numerical modal quantities. The material parameters (elastic and damping properties) are iteratively updated through this process.

A mode tracking procedure is incorporated to ensure correct correspondence between experimental and numerical modes throughout the optimization, which is essential for robust identification.

3 Results and Discussions

3.1 Validation of the FEMU procedure

The Modal Assurance Criterion (MAC) is widely used to quantify the correlation between experimental and numerical mode shapes. It is defined as Eq. (1):

$$MAC(i,j) = \frac{\left|\{\psi_N\}_i^T\{\psi_E\}_j^*\right|^2}{(\{\psi_N\}_i^T\{\psi_N\}_i^*)(\{\psi_E\}_i^T\{\psi_E\}_i^*)} \quad (1)$$

where $(\cdot)^{\mathrm{T}}$ denotes the transpose, $(\cdot)^*$ denotes the complex conjugate, $\{\psi_N\}_i$ is the i-th numerical mode shape, and $\{\psi_E\}_j$ is the j-th experimental mode shape.

The MAC matrix is computed between experimental and numerical mode shapes obtained using the identified parameters. This enables the assessment of the quality of the correlation and ensures that the modes considered in the FEMU procedure are physically relevant. In particular, it helps verify that higher-order modes included in the identification process remain well correlated with experimental observations

For instance, in the case of the HempTape/Elium plate, the MAC matrix is used to evaluate the consistency between experimental and numerical mode shapes obtained after identification. As shown in Figure 1 the MAC matrix illustrates that, thanks to the coil–magnet excitation, a sufficient number of modes (highlighted in red) are captured, ensuring a reliable identification.

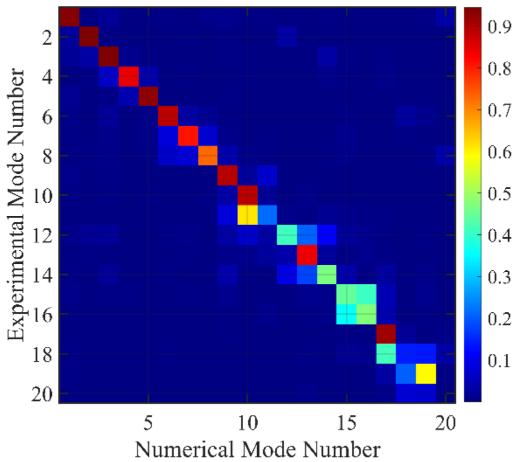

Figure 1. MAC matrix obtained using coil–magnet excitation.

To validate the identified mechanical properties, a numerical simulation is performed using the identified parameters. The experimental boundary and excitation conditions are reproduced in the finite element model.

The simulated Frequency Response Function (FRF) is then compared with the experimentally measured FRF (Figure 2). The response is evaluated at a measurement point located at one of the free corners of the plate, with the same point location used for both the numerical and experimental FRFs. A good agreement between numerical and experimental results, both in terms of natural frequencies and modal damping ratios, confirms the accuracy and reliability of the identified stiffness and damping properties.

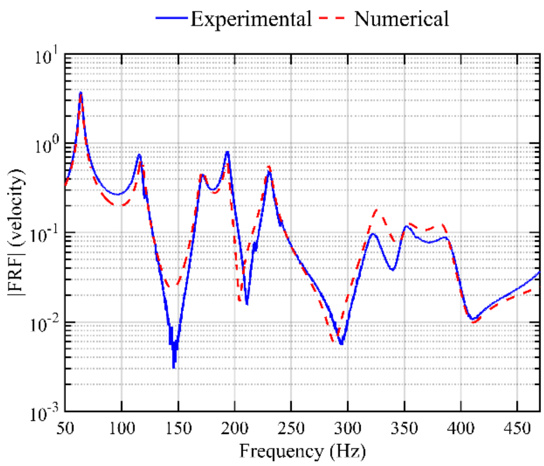

Figure 2. Comparison between the experimental FRF and the simulated FRF obtained using the identified material properties.

3.2 Influence of Constituent Type on Composite Properties

As shown in Figure 3, the influence of both matrix and fiber types on stiffness and damping properties can be clearly observed in both longitudinal and transverse directions. The influence of the matrix type is first analyzed at the resin scale. For the neat materials, Elium exhibits a damping that is approximately +100% higher than that of GreenPoxy (7.2% vs 3.6%), while maintaining a higher stiffness (+21%). At the scale of UD composite, the use of Elium leads to an increase in longitudinal damping of about +37% compared to GreenPoxy (1.7% vs 1.3%). This increase is significantly lower than that observed at the resin scale, highlighting the dominant role of hemp fibers in the longitudinal direction. This result suggests that, contrary to conventional assumptions reported in the literature for synthetic fibers, plant fibers such as hemp significantly contribute to damping in the fiber direction.

In the transverse direction, where the matrix governs the mechanical behavior, the effect of the resin becomes more pronounced, with an increase of +31% in stiffness (4.45 vs 3.40 GPa) and +30% in damping (4.1% vs 3.2%) when using Elium instead of GreenPoxy.

The influence of the fiber architecture is also evident. When comparing unidirectional hemp (UD) and quasi-unidirectional hemp (QUD), an increase in longitudinal damping is observed for the QUD configuration (+12%, 1.9% vs 1.7%), despite a reduction in stiffness. This behavior can be attributed to the woven nature of the QUD architecture, which involves two main directions (warp and weft). The resulting fiber undulation (crimp) induces local variations in fiber orientation, promoting additional internal friction mechanisms and thus increased energy dissipation.

Finally, when comparing the different fiber types, glass fiber composites exhibit a longitudinal stiffness approximately +60% higher than UD hemp composites (52 vs 33 GPa). However, this increase is associated with higher density and fiber volume fraction (approximately 65% for glass fiber composites compared to 40% for hemp composites). As hemp composites have a lower mass density, the specific stiffness (stiffness-to-density ratio) becomes comparable between the two materials. In terms of damping, glass fiber composites show significantly lower longitudinal damping (0.61%, i.e., about −65% compared to hemp), whereas in the transverse direction, similar damping levels are observed (~4%). This confirms that, in the transverse direction, the mechanical behavior is primarily governed by the matrix properties.

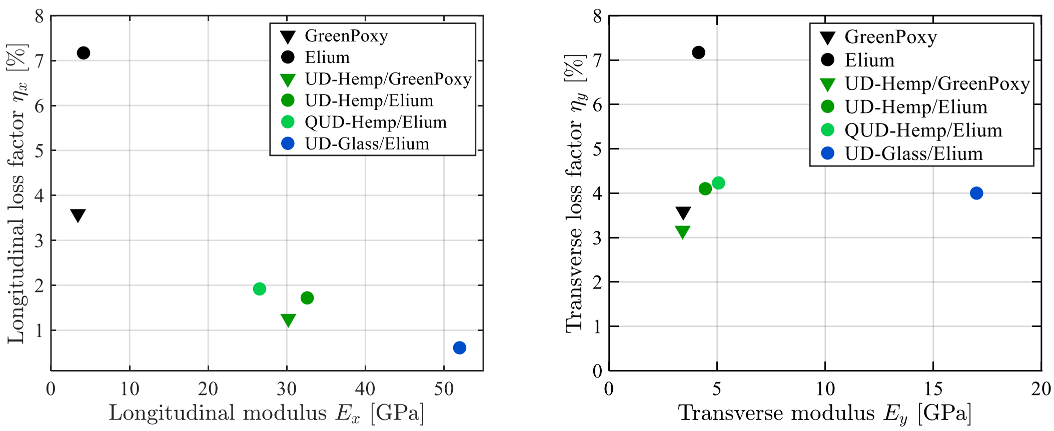

Figure 3. Damping factor vs. elastic modulus in the longitudinal and transversal directions

4 Conclusions

The objective of this study was to investigate the extent to what the elastic and damping properties of composite constituents influence the behavior of the resulting composites at the material scale, with a view toward future extension to the structural scale. To this end, a comparative analysis was carried out on different material systems combining two types of fibers (hemp and glass), two hemp fiber architectures (unidirectional (UD) and quasi-unidirectional (QUD)), and two types of resins (thermoset GreenPoxy and thermoplastic Elium). The analysis was performed in both longitudinal and transverse directions to identify the governing trends.

The results clearly demonstrate that both matrix and fiber characteristics significantly influence the stiffness–damping balance. At the resin scale, Elium exhibits a substantially higher damping capacity than GreenPoxy, confirming its strong viscoelastic potential, while maintaining a higher rigidity than epoxy. However, at the composite scale, this effect is attenuated in the longitudinal direction, where fibers play a dominant role. In particular, the relatively moderate increase in damping observed for hemp/Elium composites compared to the neat resin highlights the strong prevalence of plant fibers to energy dissipation along the fiber direction. These finding challenges conventional assumptions established for synthetic fiber composites, where the contribution of fiber to longitudinal damping is often considered as negligible.

In contrast, in the transverse direction, the matrix is shown to govern both stiffness and damping properties, leading to a more pronounced influence of the resin type. The fiber–matrix interface may also play a significant role, as interfacial mechanisms such as debonding or micro-slip can contribute to energy dissipation. Additionally, the results emphasize the importance of fiber architecture: the QUD hemp configuration significantly enhances damping, which can be attributed to fiber undulation (crimp) inducing local misalignment and promoting additional dissipation mechanisms.

Finally, the comparison between hemp and glass fiber composites highlights an interesting trade-off. While glass fibers provide higher stiffness, they exhibit significantly lower damping in the longitudinal direction. When considering specific stiffness, hemp-based composites become competitive, while offering superior damping performance.

Acknowledgements

This project has received funding from the Circular Bio-based Europe Joint Undertaking (CBE JU) under grant agreement No 101157517. The JU receives support from the European Union Horizon Europe research and innovation program and the Bio-Based Industries Consortium. The authors also thank the FEMTO-ST laboratory, Applied Mechanics Department, and notably the AMETISTE platform, for providing the support, experimental facilities, and infrastructure used in this research.

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