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Simultaneous Identification of Elastic and Damping Properties in Bio-Based Composites

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Abstract. *Conventional carbon- and glass-fibre reinforced composites provide high specific stiffness and strength but exhibit low vibration damping, which can affect structural durability under dynamic loading. Bio-based composites reinforced with hemp fibres and combined with recyclable thermoplastic resins such as Elium® offer a promising alternative due to their improved stiffness–damping trade-off and enhanced sustainability. This work focuses on the identification of both elastic and damping properties of bio-based composites. The main contribution lies in the development of a robust vibration-based methodology using Finite Element Model Updating (FEMU), enabling the simultaneous identification of stiffness and damping parameters. The approach combines experimental modal analysis and finite element simulations, where material parameters are identified by minimizing discrepancies in natural frequencies and modal damping ratios. A dedicated identification procedure, including sensitivity analysis and mode selection, ensures a stable and reliable process. The methodology is first validated on a reference composite plate, then applied to materials of interest, including pure resins (Elium® and GreenPoxy®) and hemp fibre composites, to investigate the influence of temperature on the identified properties. The proposed framework provides a stable and transferable strategy for the characterization of bio-based composites.*

1. INTRODUCTION

Vibration control has become a major research focus due to its importance across various industrial sectors, particularly those related to passenger comfort and structural safety, such as the automotive (Zhao *et al.*, 2025), railway (Connolly *et al.*, 2015), and aeronautical industries. Vibration mitigation can be achieved through active control strategies (Butaud *et al.*, 2016), (Daley *et al.*, 2004) or passive approaches (Raze and Kerschen, 2021), (Mrabet *et al.*, 2019). Among passive solutions, enhancing the intrinsic damping properties of materials represents an efficient strategy (Duc *et al.*, 2014), (Murray *et al.*, 2021), (Liu *et al.*, 2021). However, increasing damping must not compromise structural stiffness. Composite materials are increasingly employed in industrial applications, notably in wind turbine blades (Haselbach *et al.*, 2020). Conventional composites reinforced with carbon or glass fibres (Murray *et al.*, 2021), (Haselbach *et al.*, 2020) exhibit excellent stiffness but low damping, which can negatively affect dynamic performance and fatigue life.

Bio-based composites reinforced with plant fibres such as hemp or flax offer a promising alternative for a better stiffness–damping balance (Liu *et al.*, 2021). Enhanced damping arises from viscoelastic energy dissipation in the polymer matrix, intrinsic fibre characteristics, and fibre–matrix interfacial phenomena (Liu *et al.*, 2021). Material-scale studies show that replacing glass fibres with flax increases damping by over 100% while slightly reducing stiffness (Duc *et al.*, 2014), and substituting a thermoset epoxy matrix with Elium® resin increases damping by a factor of five (Porter *et al.*, 2026). Structural-scale studies confirm these trends; for instance, flax-based wind turbine blades withstand loads with increased flexibility, requiring stacking sequence optimisation to match stiffness of glass-based blades (Shah *et al.*, 2013), and Glass/Elium® thermoplastic blades maintain stiffness while increasing damping by 82% (Murray *et al.*, 2021).

Despite these advantages, damping remains complex to characterise (Treviso *et al.*, 2015), (Liu *et al.*, 2021). Experimental techniques include Dynamic Mechanical Analysis (DMA) (Butaud *et al.*, 2015), creep–relaxation tests, and vibration-based methods (Butaud *et al.*, 2016). Vibration-based techniques allow simultaneous identification of elastic and damping properties through FEMU (Finite Element Model Updating) (Mottershead *et al.*, 2011). FEMU is applicable to simple and complex geometries, enabling inverse vibration-based identification of mechanical properties (Viala *et al.*, 2018), while other methods are limited to simpler geometries such as plates (McIntyre and Woodhouse, 1988).

Since the thesis objective is to optimise elastic and damping performance of bio-based wind turbine blades, efficient identification tools are required at both material and structural scales. A key step is the investigation of frequency dependence, which can be analysed using DMA for thermorheologically simple materials (Butaud *et al.*, 2015), but is generally not directly applicable to composite materials.

In this context, the FEMU method (Viala *et al.*, 2018), (Mottershead *et al.*, 2011) is adopted and first applied to composite plates. A significant modification is introduced: material damping is explicitly incorporated as an identification parameter rather than relying solely on modal damping values from experimental measurements. Indeed, exploring higher frequency ranges requires an appropriate excitation system while maintaining free boundary conditions. An electromagnetic coil–magnet system is selected, enabling higher excitation frequencies, though it introduces additional mass, altering dynamics and preventing the use of some inverse methods based on idealised plate models (McIntyre and Woodhouse, 1988). This justifies incorporating material damping directly into the FEMU framework, which remains applicable under modified dynamic conditions.

Particular attention is devoted to identification stability. The first stage ensures that selected experimental modes lie in a quasi frequency-independent band, enabling robust parameter identification. Subsequent identifications explore higher frequency bands to analyse viscoelastic frequency dependence. Once stabilised, FEMU is applied to composites based on Elium® and GreenPoxy® resins to assess matrix influence on mechanical properties, particularly damping, and the effect of temperature is finally investigated.

2. MATERIALS AND METHODS

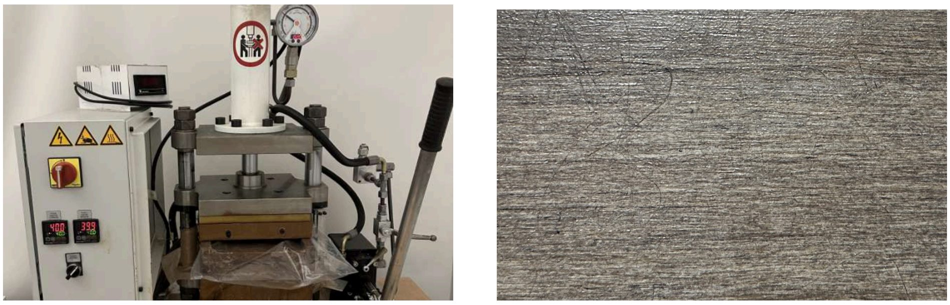
In order to achieve the objectives of this study, several materials and experimental–numerical methods are employed. The overall methodology follows a sequential approach: composite plates are first manufactured and prepared for testing, then subjected to vibration experiments. Subsequently, numerical simulations are performed, and the experimental data are integrated into an identification algorithm.

2.1 Manufacturing and conditioning 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 reinforcement are used in this research: HempTape® 150 supplied by EcoTechnilin, which is a unidirectional tape with an areal density of 150 g/m^2, and Quasi-UD hemp reinforcement supplied by Linificio, with an areal density of 200 g/m^2. However, the present study focuses primarily on the HempTape® 150 reinforcement. The matrix used in this work is Elium® resin supplied by Arkema (grade 191 SA with 191 XO initiator). Elium® is a liquid thermoplastic acrylic resin based on methyl methacrylate (MMA) monomer. Polymerisation occurs through a free-radical mechanism initiated by a peroxide-based initiator (191 XO), which activates the polymerisation of the MMA monomer at moderate temperature. For the manufacturing of Elium-based thermoplastic composites, a thermocompression process is adopted. The fibres are first dried at 80 °C for 30 minutes to remove residual moisture. The resin is subsequently degassed under vacuum at approximately -950 mbar in order to eliminate air bubbles and minimise porosity in the final composite. Manual lay-up is performed in an A4-sized mould. After resin impregnation and stacking, the mould is closed and sealed inside a bag to ensure airtight conditions. This step is essential because the MMA monomer is volatile; without proper sealing, significant resin loss due to evaporation can occur. Finally, the assembly is placed in a thermocompression press at 40 °C under a pressure of 2 bar (Fig. 1a) in order to accelerate polymerisation and ensure proper consolidation of the composite laminate. HempTape® 150/Elium® composite plates are obtained (Fig. 1b), exhibiting an average porosity of approximately 5.5%. The fibre volume fraction is about 40%, corresponding to a fibre mass fraction of 49%. After manufacturing, the plates are conditioned at 23 °C and 50% relative humidity (RH) until moisture equilibrium is reached, which requires approximately 14 days. Once conditioning is completed, the specimens are subjected to vibration testing.

2.2 Vibration Testing of the Composite Plates

Once the composite plates are fully prepared and conditioned, vibration tests are carried out. The objective of the experimental modal analysis is to identify the natural frequencies f_i^{exp}, the modal damping ratios ζ_i^{exp}, and the corresponding mode shapes (eigenvectors) $\{\psi_E\}_i$ associated with each natural frequency. The experimental setup is presented in (Fig. 2a). In order to approximate free–free boundary conditions, the plate is suspended from a rigid frame using thin nylon monofilament wires connected to springs. This configuration minimises boundary constraints and allows the structure to vibrate freely. The excitation system consists of an electromagnetic coil–magnet device (Fig 2b). A small

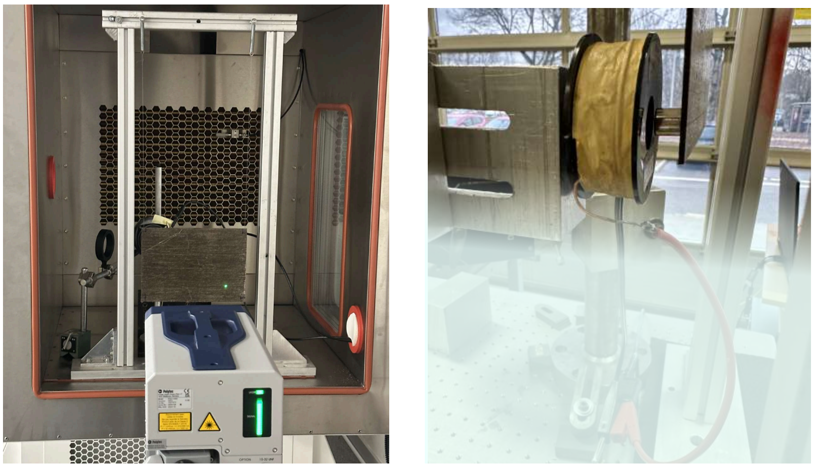


(a) Hot press used for the manufacturing of the composite plates.

(b) Hemptape150/Elium composite plate after manufacturing.

Figure 1: Manufacturing process of the Hemptape150/Elium composite plates.

permanent magnet is bonded to one corner of the plate, while the excitation coil is centred around the magnet without mechanical contact. The coil–magnet excitation system is therefore selected, as it enables wideband excitation while pre-



(a) Vibration experimental setup

(b) Electromagnetic coil–magnet system

Figure 2: Experimental setup

serving free–free boundary conditions. The only drawback of this method is the additional mass introduced by bonding the magnet to the plate, which modifies the structural dynamics and makes classical analytical plate models unsuitable. However, this issue does not affect the present identification strategy, since the magnet is explicitly included in the FE numerical model. A white noise excitation is applied over a frequency range of 20–2000 Hz (the bandwidth is adapted depending on the tested plate). The vibratory response is measured using a Polytec Q-tec laser Doppler vibrometer. For tests conducted under controlled temperature and humidity conditions, the entire setup is placed inside a CLIMATS climatic chamber (Fig. 3). A dedicated optical access allows vibration measurements to be performed with the laser vibrometer without disturbing the environmental conditions. The modal parameters f_i^{exp}, ζ_i^{exp}, and $\{\psi_E\}_i$ are identified using

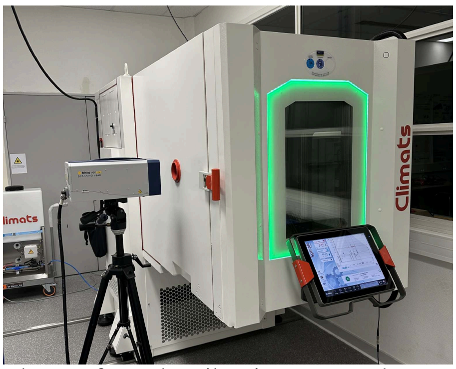


Figure 3: Climatic chamber used to perform the vibration tests under controlled temperature conditions.

Modan software developed at the Department of Applied Mechanics. Among the implemented identification techniques, the Least Squares Complex Frequency (LSCF) algorithm developed by Guillaume *et al.* (1998) is employed.

2.3 Numerical Modelling and Optimisation Procedure

2.3.1 Finite Element Simulation

In parallel with the experimental campaign, finite element simulations are performed using COMSOL Multiphysics®. The objective of the numerical modelling is to extract the same modal quantities as those obtained experimentally, namely the numerical natural frequencies f_i^{num}, the modal damping ratios ζ_i^{num}, and the numerical mode shapes $\{\psi_N\}_i$.
An eigenfrequency study is conducted under free–free boundary conditions in order to reproduce the experimental configuration. The permanent magnet used in the excitation system is explicitly included in the numerical model. Its geometry, mass, and material properties are introduced to ensure consistency between the numerical and experimental configurations. For the UD composite plates, the material is assumed to be transversely isotropic, reflecting the unidirectional fibre reinforcement. In contrast, the pure resin plates are modelled as isotropic materials. To introduce damping into the numerical model, hysteretic damping is considered through the elastic moduli of the unidirectional (UD) composite plates, namely the longitudinal modulus E_L, the transverse modulus E_T, and the in-plane shear modulus G_{LT}. Each complex modulus is defined as:

$$E_L^* = E_L\,(1 + i\,\eta_L), \quad E_T^* = E_T\,(1 + i\,\eta_T), \quad G_{LT}^* = G_{LT}\,(1 + i\,\eta_{LT}), \tag{1}$$

where:

- E_L is the elastic modulus in the longitudinal fibre direction,
- E_T is the elastic modulus in the transverse direction,
- G_{LT} is the shear modulus,
- η_L, η_T, and η_{LT} are the corresponding loss factors in the longitudinal, transverse, and shear directions, respectively,

2.3.2 FEMU – Inverse Problem and Optimisation Procedure

The objective of the FEMU (Finite Element Model Updating) procedure is to minimise the discrepancy between experimental and numerical results by adjusting the material parameters within the numerical model. This optimisation is performed using MATLAB®'s `fminsearch` function, which is based on the Nelder–Mead simplex method. However, varying these parameters may lead to mode switching (or mode shape inversion) during the optimisation process. To prevent this issue, a mode-tracking algorithm is incorporated into the optimisation framework. The entire identification procedure is implemented using LiveLink™ for COMSOL® with MATLAB®, and the identification strategy is carried out in two successive stages:

- A first stage dedicated to the identification of the elastic parameters E_L, E_T, and G_{LT} for the composite material.
- A second stage aimed at identifying the damping parameters (hysteretic loss factors).

Identification of Elastic Properties
In this first stage, only the real part of the eigenfrequencies is considered. The experimentally measured natural frequencies f_i^{exp} are taken as reference values, and the objective is to match the numerical natural frequencies f_i^{num} to the experimental ones.
The identification procedure is based on the minimisation of the following objective function:

$$F_E = \left\{ \begin{array}{l} \min \sqrt{\displaystyle\sum_{i=1}^{N_m} \left(\frac{f_i^{\mathrm{num}} - f_i^{\mathrm{exp}}}{f_i^{\mathrm{exp}}} \right)^2}, \\ E_L,\ E_T,\ G_{LT} \end{array} \right. \tag{2}$$

where N_m denotes the number of modes included in the identification process.
The optimisation is carried out by varying the elastic parameters E_L, E_T, and G_{LT}.

Identification of Damping Properties
Once the elastic properties are identified, they are fixed in the numerical model. Hysteretic damping is then introduced through the loss factors associated with the elastic moduli, and a second optimisation stage is performed to identify the

damping parameters. Introducing hysteretic damping into the model leads to the computation of complex eigenfrequencies in COMSOL. These complex frequencies are related to the modal damping ratio through the following relationship:

$$f_i^* = f_i\sqrt{1-\zeta_i^2} + i\,\zeta_i f_i, \tag{3}$$

where f_i is the undamped natural frequency and ζ_i denotes the associated modal damping ratio.
From the computed complex eigenfrequencies, the numerical modal damping ratios ζ_i^{num} are extracted. The optimisation procedure aims to minimise the discrepancy between the numerical and experimental modal damping ratios ζ_i^{exp}, which are taken as reference values, using the following objective function:

$$F_\zeta = \begin{cases} \min \sqrt{\displaystyle\sum_{i=1}^{N_m} \left(\frac{\zeta_i^{\mathrm{num}} - \zeta_i^{\mathrm{exp}}}{\zeta_i^{\mathrm{exp}}}\right)^2}, \\ \eta_L, \eta_T, \eta_{LT} \end{cases} \tag{4}$$

where N_m is the number of modes considered in the identification.

3. RESULTS AND DISCUSSIONS

3.1 Determination of the Number of Modes for Identification

In order to determine the necessary and sufficient number of modes to ensure a reliable identification, it is first essential to evaluate the sensitivity of the natural frequencies and modal damping ratios with respect to the mechanical properties to be identified. Furthermore, it is necessary to verify that the identification procedure is not affected by frequencies, which could bias the updating process. This verification is performed on the HempTape/Elium composite plate.

3.1.1 Sensitivity Analysis

In this work, the relative sensitivity approach is adopted to quantify the influence of elastic and damping parameters on the modal response. This formulation provides a normalized measure of the variation of the natural frequencies and modal damping ratios with respect to variations of the mechanical properties.
For the elastic parameters, the relative sensitivities are expressed as:

$$S_i(E_L^k) = \frac{E_L^k}{f_i^k}\frac{f_i^{k+1}-f_i^k}{E_L^{k+1}-E_L^k}, \quad S_i(E_T^k) = \frac{E_T^k}{f_i^k}\frac{f_i^{k+1}-f_i^k}{E_T^{k+1}-E_T^k}, \quad S_i(G_{LT}^k) = \frac{G_{LT}^k}{f_i^k}\frac{f_i^{k+1}-f_i^k}{G_{LT}^{k+1}-G_{LT}^k}. \tag{5}$$

Similarly, the relative sensitivities associated with the damping parameters are defined as:

$$S_i(\eta_L^k) = \frac{\eta_L^k}{\zeta_i^k}\frac{\zeta_i^{k+1}-\zeta_i^k}{\eta_L^{k+1}-\eta_L^k}, \quad S_i(\eta_T^k) = \frac{\eta_T^k}{\zeta_i^k}\frac{\zeta_i^{k+1}-\zeta_i^k}{\eta_T^{k+1}-\eta_T^k}, \quad S_i(\eta_{LT}^k) = \frac{\eta_{LT}^k}{\zeta_i^k}\frac{\zeta_i^{k+1}-\zeta_i^k}{\eta_{LT}^{k+1}-\eta_{LT}^k}. \tag{6}$$

These expressions allow the evaluation of the influence of each elastic and damping parameter on the i-th modal frequency f_i and modal damping ratio ζ_i.This enables the determination of the number of modes required for accurate identification.

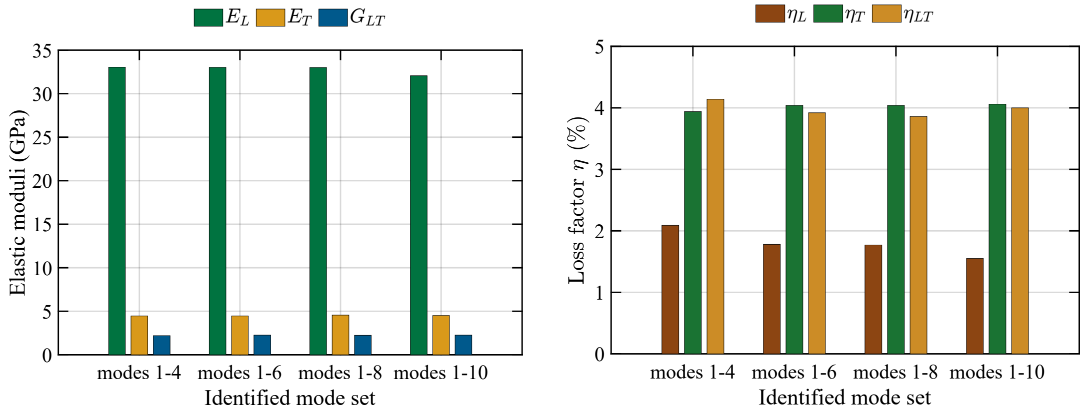
3.1.2 Selection of the Number of Modes

The FEMU procedure is performed using several subsets of modes, corresponding to different choices of the number of modes included in the identification, N_m (modes 1–4, 1–6, 1–8, and 1–10), as shown in Fig. 4. The choice of N_m also relies on the coherence between experimental and FE simulation results. For the HempTape/Elium plate, the complex MAC (Modal Assurance Criterion), which quantifies the correlation between experimental and numerical mode shapes, is defined as

$$\mathrm{MAC}(i,j) = \frac{\left|\{\psi_N\}_i^T \{\psi_E\}_j^*\right|^2}{\left(\{\psi_N\}_i^T\{\psi_N\}_i^*\right)\left(\{\psi_E\}_j^T\{\psi_E\}_j^*\right)}, \tag{7}$$

where $(\cdot)^T$ 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 shown in Fig. 5 illustrates that, thanks to the coil–magnet excitation, a sufficient number of modes (highlighted in red) can be captured for reliable identification.
The identification results remain stable up to 8 modes for the HempTape/Elium plate. However, noticeable variations

in the identified properties are observed when including mode 9 and above, indicating the onset of the influence of frequencies or at least deviations in the model hypotheses, such as boundary conditions or loading conditions. Therefore, it is recommended, for each tested structure, to perform a preliminary assessment in order to determine the optimal number of modes to be included, ensuring a reliable and physically meaningful identification.



(a) Evolution of the identified elastic properties as a function of the number of modes used in the identification process.

(b) Evolution of the identified damping properties as a function of the number of modes used in the identification process.

Figure 4: Influence of the number of modes considered in the identification procedure on the estimated elastic and damping properties.

3.1.3 Verification of the Identified Properties

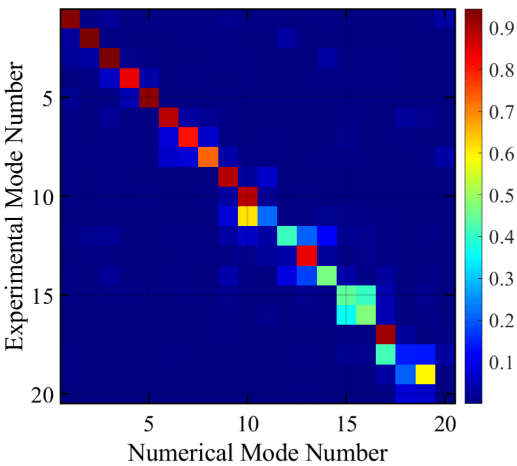


Figure 5: MAC matrix obtained using coil–magnet excitation.

To validate the identified mechanical properties, a numerical simulation is conducted using the identified parameters of the HempTape/Elium plate. The experimental boundary and excitation conditions are reproduced within the finite element model. The simulated Frequency Response Function (FRF) is then compared with the experimentally measured FRF for the same plate (Fig. 6). A good agreement is observed between numerical and experimental results, both in terms of natural frequencies and modal damping ratios, thereby confirming the accuracy and reliability of the identified material properties.

3.2 Identification Results

3.2.1 High Damping Performance of Elium Resin and Bio-Based Fibers

Composites manufactured using two different resins (Elium and GreenPoxy) and hemp fiber reinforcements (Hemptape and Quasi-UD), with a fiber volume fraction of 40% and a porosity of 5%, as well as pure resin plates, are experimentally characterized and compared (Fig. 7). For pure resin specimens, Elium exhibits a damping of 7.17% compared to

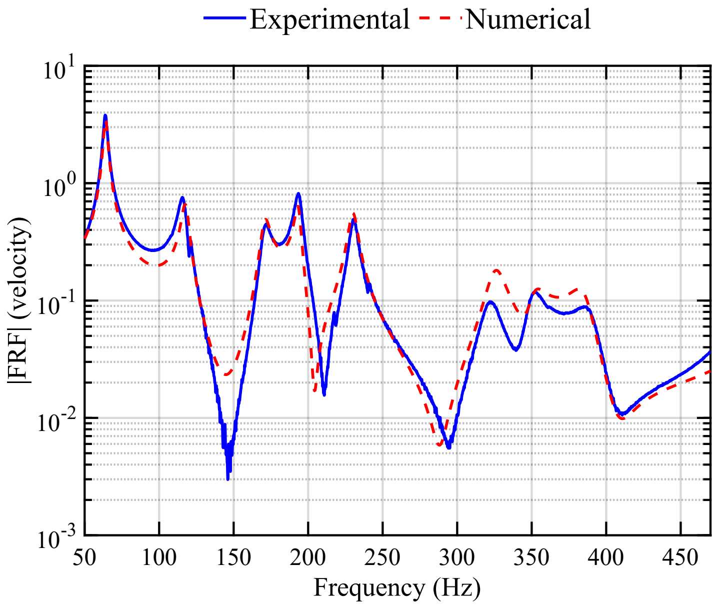
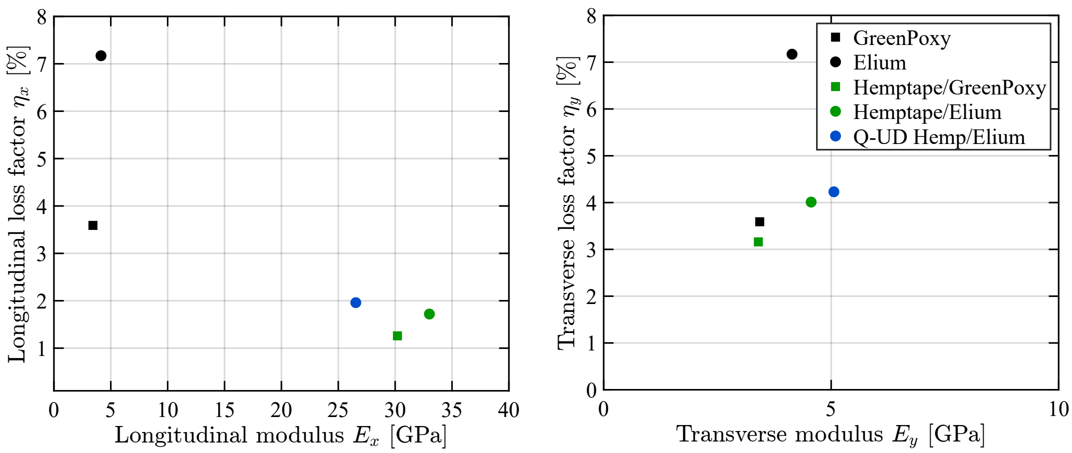


Figure 6: Comparison between the experimental FRF and the simulated FRF obtained using the identified material properties.

3.59% for GreenPoxy, corresponding to an increase of approximately 100%, while the stiffness increases from 3.43 GPa to 4.14 GPa (+21%). Figure 7a presents the longitudinal damping as a function of longitudinal stiffness.
For Hemptape composites, replacing GreenPoxy with Elium results in a damping increase from 1.26% to 1.72% (+37%), together with a stiffness increase from 30.20 GPa to 33.01 GPa (9%).
The Quasi-UD Hemp/Elium composite exhibits a longitudinal stiffness of 26.54 GPa and a damping of 1.96%. Compared to Hemptape/Elium, this corresponds to a 20% lower stiffness but a 14% higher damping. The reduced stiffness is attributed to the non-unidirectional architecture of the quasi-UD reinforcement. Moreover, the presence of transverse stitching yarns contributes to enhanced energy dissipation mechanisms, leading to higher damping levels.
Figure 7b shows the transverse damping as a function of transverse stiffness. In this direction, the influence of the matrix is more pronounced.
For Hemptape composites, the transverse damping increases from 3.16% (GreenPoxy) to 4.01% (Elium), corresponding to a 27% improvement, while stiffness increases significantly (from 3.4 GPa to 4.56 GPa), corresponding to an improvement of about 34%. The Quasi-UD Hemp/Elium composite exhibits a transverse damping of 4.23%, slightly higher than Hemptape/Elium (+5%), with a comparable transverse stiffness (5.06 GPa).
These results confirm the dominant role of the polymer matrix in matrix-dominated loading directions, while also highlighting the influence of reinforcement architecture on the stiffness–damping balance.



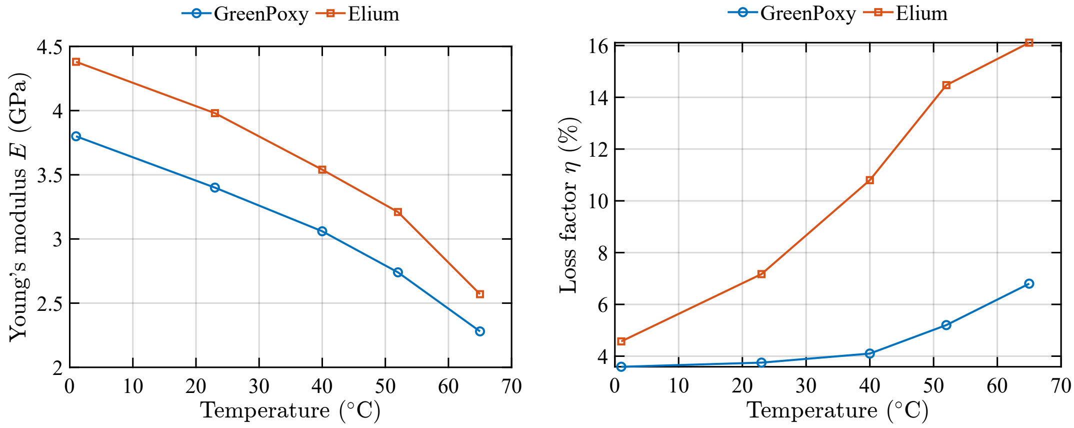
(a) Damping factor vs. elastic modulus in the longitudinal direction

(b) Damping factor vs. elastic modulus in the transverse direction

Figure 7: Comparison of experimental damping and stiffness for composites reinforced with hemp fibers, showing the influence of fiber and resin type (Elium and GreenPoxy).

3.2.2 Influence of Temperature on the Identified Properties

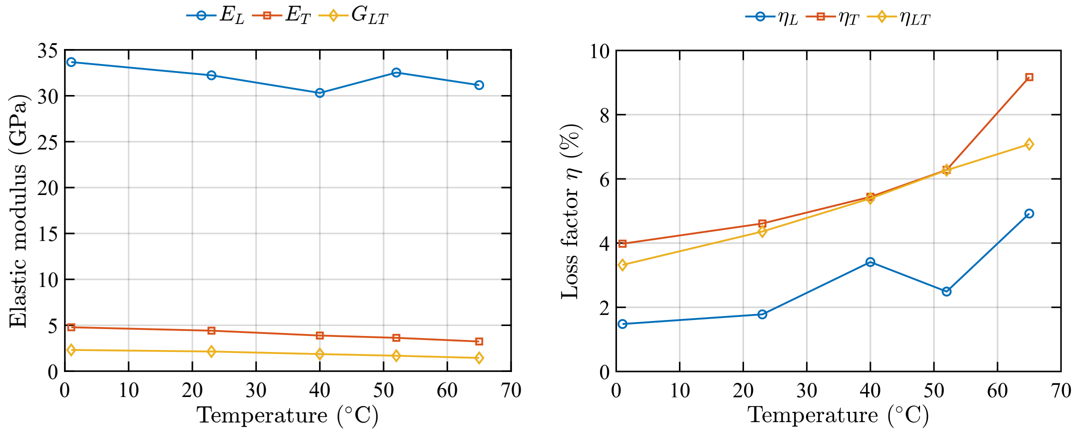
The influence of temperature on the identified dynamic properties is investigated over the range 1–65 °C under 50% relative humidity. The results show that Elium maintains its superiority over GreenPoxy in terms of both damping (Fig. 8b) and stiffness (Fig. 8a), for pure resin specimens and across the entire investigated temperature range. An increase in damping is observed with rising temperature, accompanied by a reduction in stiffness. This behavior is typical of viscoelastic polymers, in which increased molecular mobility at higher temperatures enhances energy dissipation while simultaneously reducing elastic stiffness. A similar trend is observed for the HempTape/Elium composite regarding the temperature dependence of damping (Fig. 9b). However, the stiffness reduction is less pronounced in the composite compared to the pure resin (Fig. 9a). This is attributed to the presence of reinforcing fibers, which mitigate the thermal softening of the matrix and help preserve the global mechanical response of the material. These findings confirm the stabilizing role of fibers in the thermo-mechanical behavior of composites, while highlighting the dominant contribution of the polymer matrix to temperature-dependent dissipation mechanisms.



(a) Evolution of Young's modulus with temperature for pure resins (Elium and GreenPoxy)

(b) Evolution of damping with temperature for pure resins (Elium and GreenPoxy)

Figure 8: Temperature-dependent mechanical properties of pure Elium and GreenPoxy resins: (a) Young's modulus, (b) Loss factor.



(a) Evolution of elastic moduli with temperature for Hemptape composites in L, T, and LT directions

(b) Evolution of damping with temperature for Hemptape composites in L, T, and LT directions

Figure 9: Temperature-dependent mechanical properties of Hemptape composites : (a) Elastic modulus, (b) Loss factor

4. CONCLUSIONS

The main objective of this work is to accurately identify both the elastic and damping properties of plates and structures with complex geometries. The identified damping and elastic properties exhibit consistent and physically meaningful trends, supporting the reliability of the proposed identification framework. Furthermore, the next step of this research aims to investigate the influence of frequency on these properties using a vibration-based method applied to plate structures. This requires the excitation of high-frequency modes, which necessitates the use of specific excitation devices. However, such excitation systems — particularly the coil–magnet device employed in this study — alter the intrinsic dynamics of the tested plates. Under these conditions, classical analytical plate models become unsuitable. In this context, a robust identification methodology independent of conventional plate models has been developed. An extension of the FEMU approach was therefore proposed to additionally incorporate the identification of damping parameters. This strategy enables the simultaneous identification of elastic and damping properties within the present study and provides a solid foundation for their characterization over a wider frequency range in future work.

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