MULTISCALE MODELING AND EXPERIMENTAL ASSESSMENT OF DAMPING IN UNIDIRECTIONAL FIBER REINFORCED COMPOSITES

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Abstract

The dynamic mechanical properties of fiber reinforced composites could depend on several factors including geometrical parameters, fiber volume fraction, orientation and other aspects. This paper focuses on determining the impact of volumetric fraction of fibers on the dynamic mechanical properties of composites. The study involves analyzing the dynamic properties of composites reinforced with unidirectional fibers using a multiscale numerical model. Additionally, the results are compared with experimental approaches to assess and validate the accuracy of the model.

1. Introduction

Composite materials are increasingly crucial in various sectors as the demand for materials with enhanced properties growths. Recent improvements have focused on enhancing properties such as high damping capacity, flexural modulus, specific strength, and corrosion resistance to compete with some conventional materials [1]. These enhancements are influenced by several factors, including the fabrication method, fiber length, fiber weight ratio, fiber orientation, fiber and matrix nature, and the interfacial interaction between the fiber and matrix [2].

With a growing need for materials sourced from renewable origins, bio-based composites are becoming increasingly popular. Plant fibers, serving as an alternative to widely used glass fibers and even in certain conditions carbon fibers, are gaining attention due to their sustainability, renewability, environmental friendliness, lightweight nature, and cost-effectiveness [3]. The distinctive focus lies on the unique properties of these plant fibers, highlighting their contribution to the overall composite's profile. Additionally, bio-based composites exhibit superior damping properties compared to conventional alternatives [4]. Despite these promising advantages, there remains a gap in our comprehensive understanding about the origin of the damping in plant fiber composites.

In addressing this gap, a multi-scale finite element method is proposed in this study to assess the damping behavior of composite materials. This approach operates on two distinct scales: micro-level and macro-level. The micromechanical approach examines the overall composite behavior by analyzing the properties of its constituents (fiber and matrix) within a representative volume element (RVE). Conversely, the macromechanical approach simplifies the composite's heterogeneous structure by substituting it with a homogeneous medium possessing anisotropic properties [5]. Homogenization plays a pivotal role in multiscale modeling, enabling the derivation of properties for a homogeneous model at a specific scale from a heterogeneous model constructed at a lower scale [6].

This proposed modeling methodology serves as a complementary approach to experimental techniques for assessing composite damping behavior. Commonly used techniques in the experimental approach include dynamic mechanical analysis (DMA) and modal analysis [7]. DMA, conducted within a lower frequency range, focuses on controlled volume fractions of fibers in both synthetic and bio-based composites, aiming to measure their viscoelastic properties. Meanwhile, modal analysis, performed under free-free boundary conditions and covering a broad frequency spectrum, is employed to identify the dynamic properties of the composites at the macroscale.

2. Finite element model

Understanding and modeling natural fiber reinforced composites has become a significant challenge in bio-based materials research. Both bio-based and synthetic composites possess complex properties, making it difficult to accurately evaluate their overall characteristics using traditional methods designed for metals [8]. Consequently, more efficient techniques are needed to characterize composite materials due to their intricate microstructure. Among the methods proposed multi-scale modeling is employed to analyze the constituent materials (fibers and matrices) and predict their characteristic behavior.

2.1. Multi-scale modeling

Analyzing the dynamic behavior of a complex structure can pose challenges, especially when dealing with numerous small components or when assembly properties are unknown. In such cases, the concept of homogenization becomes crucial [9]. Homogenization techniques offer a solution by simplifying the complex structure into a single material with macroscopic properties that reflect its overall behavior. This simplification proves especially useful within composite laminas, where the distribution of fibers across the cross-section tends to be random. To simplify analysis, many micromechanical models presume a periodic layout of fibers, enabling isolation of a RVE or unit cell. This RVE shares identical elastic constants and fiber volume fraction with the composite.

In order to analyze an RVE, careful consideration of the applied boundary conditions is essential. Additionally, selecting the appropriate RVE that matches the assumed fiber distribution is critical for obtaining reliable results [10]. Commonly employed periodic fiber arrangements include the square array and the hexagonal array. As shown in Figure 1, we have chosen to investigate a unidirectional fiber inside a square array of quadrilateral elements, which correspond to the fiber volume fraction of interest.

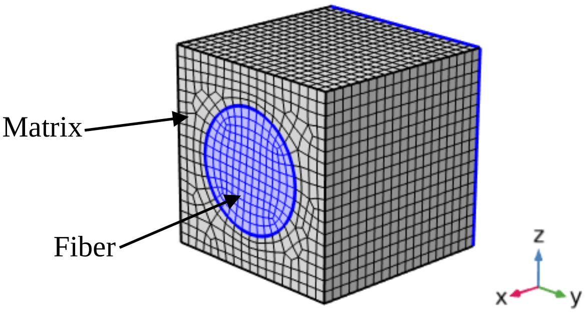

Figure 1. RVE meshed with COMSOL®

One way to think of composite materials is as a periodic array of RVEs. Therefore, applying periodic boundary conditions (PBC) to the RVE models becomes imperative. These boundary conditions require the imposition of continuity criteria at the RVE boundaries connected to neighboring RVEs, ensuring the integration of all individual RVEs into a structural continuum body [11]. The periodic boundary conditions are expressed as:

$$u_{dst} - u_{src} = \bar{\varepsilon}\,(X_{dst} - X_{src}). \tag{1}$$

where $\bar{\varepsilon}$ is the average strain, u_{dst} and u_{src} are the displacement components at the destination and source faces of the RVE respectively, and X is the postion. To fulfill this requirement, we utilized the cell periodicity feature in COMSOL®, with steps provided in Figure 2. At the microscale, homogenized properties are computed through a complex stationary analysis, neglecting the dynamics effects occuring at the scale of the cell.

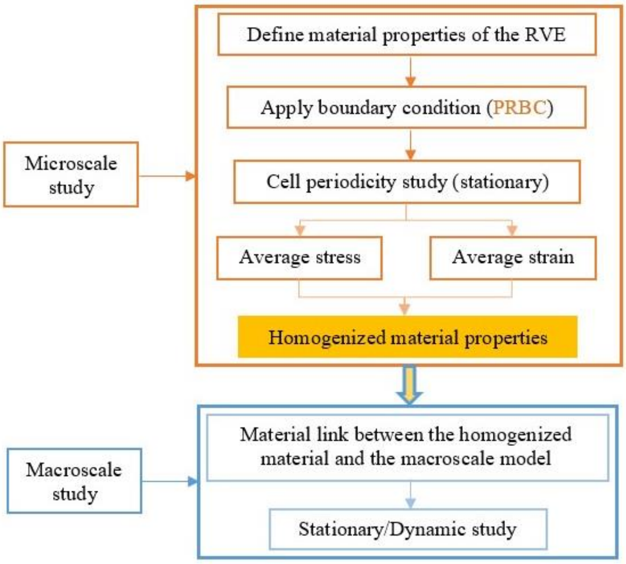

Figure 2. Steps performed on COMSOL®

In the study of the micromechanics of fiber-reinforced materials, it is convenient to use an orthogonal coordinate system that has one axis aligned with the fiber direction. In this setup, the x-axis coincides with the fiber direction, while the y and z axes lie within the plane of the RVE and are perpendicular to the fibers, as illustrated in Figure 1. For our analysis, we consider dimensions of $l = 10$ µm for a square RVE, with fiber radii corresponding to volume fractions ranging from 30 to 70%. The simulations have been performed on a glass fiber reinforced epoxy with the elastic stiffness and damping properties represented in table 1 [12].

Table 1. Basic properties of glass fibre-reinforced epoxy

Properties	Glass fiber	Epoxy
$\boldsymbol{E}\ (\boldsymbol{GPa})$	72.4	2.76
$\boldsymbol{G}\ (\boldsymbol{GPa})$	30.2	1.02
$\boldsymbol{\nu}$	0.2	0.35
$\boldsymbol{\eta}$	0.0018	0.015

3. Results

In Figure 3, as expected, we observe that as the volume fraction of fiber varies between 30% to 70%, the stiffness of the composite increases by 58% in the longitudinal direction and by 70% in the transverse direction. In terms of shear modulus, there is a 68% increase in the fiber direction and a 62% increase in the transverse direction. To confirm our findings, we compare them with those from Devireddy, S. B. R., & Biswas, S. [13], showing a strong agreement between the two sets of results.

Once we obtain the complex modulus from the elasticity matrix, we proceed to calculate the loss factor by taking the ratio between the imaginary and real parts of the modulus. As shown in figure 4, it is evident that the damping of the composite decreases by 39% for 0° orientation of the fiber as the volume fraction of the fiber increases from 30% to 70%, with a similar decrease of 24% observed in the transverse direction of the fiber. Similarly, examining the shear modulus reveals a decrease of 17% in the longitudinal direction and 6.9% in the transverse direction of the fiber. These results are then compared with the findings presented by Rezaei A. et al. [14].

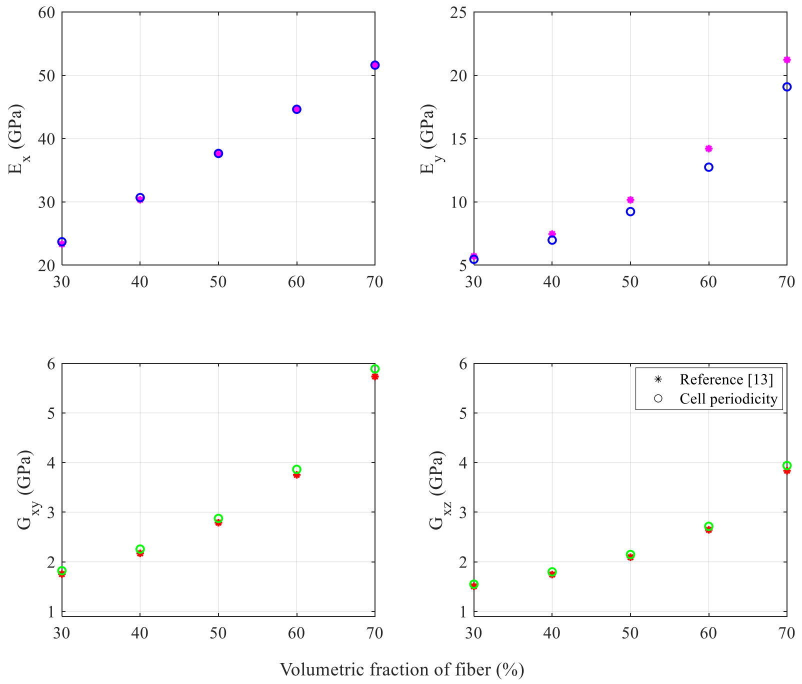

Figure 3. Evolution of Young's modulus and shear modulus with increasing volume fraction

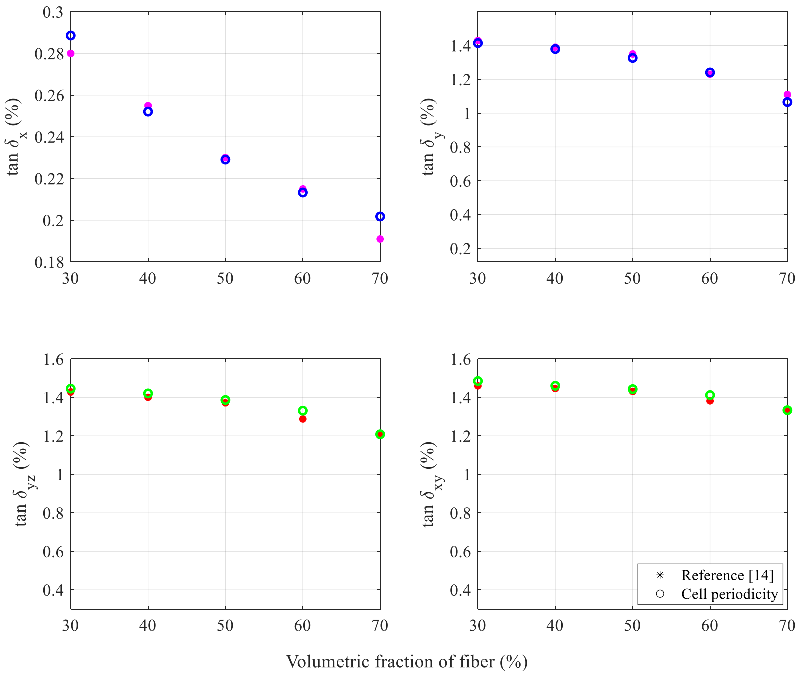

Figure 4. Evolution of damping with increasing volume fraction

Now that we have obtained the effective properties of the composite material from our micro-scale study, we can construct a macro-scale model where the composite consists of homogeneous effective properties determined from the homogenization study. We considered the same glass-epoxy composite, modeled as a solid plate measuring 300 mm * 200 mm * 1.5 mm, and subjected to fixed-free boundary conditions. Here, we conducted a complex eigenfrequency analysis to determine the composite's overall damping property.

We conduct a similar study for the flax fiber reinforced epoxy composite. Although information on the damping properties of flax fibers is limited, some literatures suggest that the damping value ranges from 0.9% to 11% [15,16]. For our simulations, we selected a value of 0.9%. Figure 5 illustrates a comparison between the damping values of glass fiber reinforced epoxy composites and those of flax fiber reinforced epoxy composites. Eigenfrequency study indicates that at each frequency, the loss factor for the flax-epoxy composite exceeds that of the glass-epoxy composite.

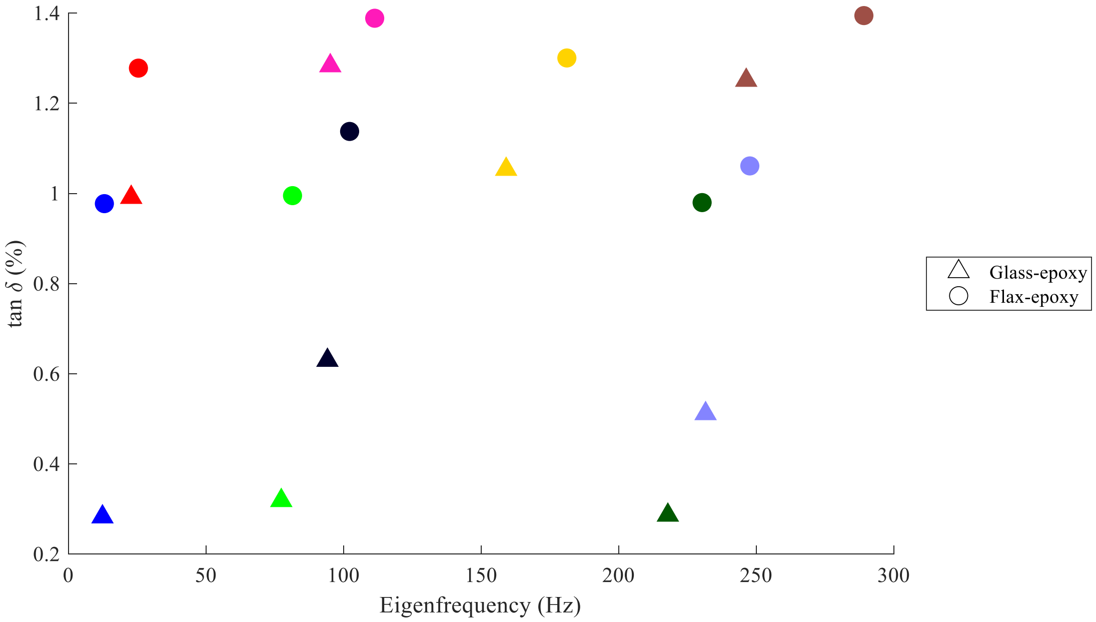

Figure 5. Damping properties of unidirectional fiber reinforced epoxy composites

These findings are consistent with the experimental research conducted by Duc F. et al [4], where they perfomed DMA tests at 1 Hz and ambient temperature. The incorporation of flax fibers into epoxy leads to a notable increase of 52% in the composite’s damping values compared to those achieved with glass fibers. This highlights the enhanced damping characteristics offered by flax fiber reinforcement, affirming its potential for improving composite materials' performance in various applications.

4. Conclusions

In this paper, we propose a multi-scale model to simulate the damping behavior of fiber reinforced composite materials. At the micro-scale, the constituents of a composite are simulated as isotropic materials to obtain homogenized elastic properties. These properties are then utilized in a macro-scale study to determine the overall damping of the composites.

Using the proposed method, we investigated the impact of fiber volume fraction on the behavior of a unidirectional fiber reinforced composite. Our findings highlight the significant role of fiber volume fraction, showing that higher fiber fractions result in increased stiffness and decreased damping, considering that the damping values of the matrix is dominant over the damping of the fiber.

Our analysis suggests that with accurate information, the multi-scale approach can serve as an effective tool for predicting the dynamic mechanical properties of composites. This numerical method can also incorporate an interface between the fiber and the matrix, aiming for an optimal balance between rigidity and damping in the composite.

Acknowledgments

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