MICRO-SCALE FINITE ELEMENT STUDY OF THE DAMPING IN UNIDIRECTIONAL FIBER REINFORCED COMPOSITES

A. Rezaei[1,2,3], D. Garoz[1,3], J. Faes[1], F. A. Gilabert[1,3], W. Desmet[2], and W. Van Paepegem[1]

[1]Department of Material Science and Engineering, Faculty of Engineering and Architecture, Ghent University, Tech Lane Ghent Science Park - Campus A, Technologiepark 903, Zwijnaarde, Belgium
Email: ali.rezaei@ugent.be, ali.rezaei@kuleuven.be
[2]Production Engineering, Machine Design and Automation (PMA) Section, Department of Mechanical Engineering, KULeuven, Leuven, Belgium
[3]SIM Program M3Strength, Technologiepark Zwijnaarde 935, B-9052 Zwijnaarde, Belgium

Keywords: Damping, Composites, Micro-Scale, Finite Element Method

Abstract

This article employs the strain energy finite element method to study the anisotropic damping of unidirectional fiber reinforced composites in micro-scale. The simulations have been performed on a Representative Volume Element composed of randomly distributed glass fibers in an epoxy polymer matrix. The models include also Periodic Boundary Conditions. Influence of the fiber volume fraction on the loss factors of a unidirectional fiber reinforced composite is investigated. At the end of the article, using a simplified model, effect of a homogeneous and isotropic hard or soft interphases on the loss factors of a composite is studied.

1. Introduction

Damping is a very crucial parameter in the dynamic behavior of materials. Nevertheless, currently there are only few studies about the damping behavior of fiber reinforced composites. Growing the use of composite materials for dynamic applications, such as automotive industry, demands more comprehensive studies on the damping in composite materials.

Among the different sources of energy dissipation in fiber reinforced polymer composites, viscoelastic behavior of constituents (polymer matrix and fibers) has a major contribution. Micromechanical damping analysis aims to determine the contribution of the viscoelastic damping of each constituent in the damping behavior of a composite [1].

This article employs the finite element method to study the anisotropic damping of unidirectional fiber reinforced composites in the micro-scale, using the strain energy approach. In this method the axial, transverse, and shear loss factors of a composite are expressed as the ratio of summation of the product of the strain energy stored in an individual element and the element's loss factor to the total strain energy.
The previous relevant studies consider unit cells with a single fiber or basic fiber packing with simplified boundary conditions [2, 3]. In this work, the simulations have been performed on a periodic Representative Volume Element (RVE) composed of randomly distributed fibers in a polymer matrix including Periodic Boundary Conditions (PBC).

Excerpt from ISBN 978-3-00-053387-7

In this research, the boundary problem is solved through the finite element method and the damping loss factors are computed and homogenized through a post-processing algorithm. The case study is a glass fiber reinforced epoxy composite. At the first stage, it is presumed that there is a perfect bonding between the fiber and the matrix meaning that the composite is made up of two phases. Since the inhomogeneity of a unidirectional fiber reinforced composite is defined by fiber volume fraction, a parametric study is performed to evaluate the effect of the fiber volume fraction on the loss factors of the composite.

At the end of the article, effect of the interface damping on the various damping coefficients of the composite is studied. To this purpose the interface is presumed as an extra phase in the composite. This part of study is also performed on a randomly distributed representative volume element including periodic boundary conditions.

2. Strain Energy method

The strain energy method is a widely used approach to calculate the damping factors of a system. In this method, proposed by Ungar and Kerwin [4], the system loss factor is expressed as a summation of the products of the individual element loss factors and the fraction of the total strain energy stored in each element.

$$\eta = \frac{\sum_{i=1}^{n} \eta_i W_i}{\sum_{i=1}^{n} W_i} \tag{1}$$

Where η is the total loss factor of the system, η_i denotes the loss factor of i^{th} element in the system, W_i expresses the strain energy stored in the i^{th} element at maximum vibratory displacement and n is the total number of elements in the system.

Accordingly, in the micromechanical analysis of a fiber reinforced composite material with a perfect bonding between fibers and matrix, the composite loss factors can be written as:

$$\eta_c = \frac{\eta_f W_f + \eta_m W_m}{W} \tag{2}$$

Where η_c denotes the loss factor of the composite for the axial, transverse or shear loading, η_f is the damping factor of the fiber, W_f is the total strain energy stored in the fibers, η_m is the damping factor of the matrix and W_m is the total strain energy stored in the matrix.

The strain energy equation is very well suited for the finite element analysis of complex structures like composites [5]. In the finite element implementation of equation (1), the index i denotes the element number, n refers to the total number of finite elements, and the strain energy terms W_i are obtained from the finite element analysis for the loading case of interest.

This article employs the strain energy method to study the damping of unidirectional fiber reinforced composites.

3. Finite element model

The simulations have been performed on periodic RVEs composed of randomly distributed fibers. As it is known, in the modern micromechanical modeling of composites, one of the major concerns is to build up a realistic RVE including appropriate fibers distribution [6]. In this article we use an in-house developed software that can generate random distributions of fibers for high values of fiber volume fractions.

Moreover, Periodic Boundary Conditions (PBCs) have been applied to the RVEs. Here we use a surface coupling technique to introduce the periodic boundary conditions to the finite element models. Figure 1 explains the principle of this approach. When the geometry is complex and mesh is non-conformal, surface

Excerpt from ISBN 978-3-00-053387-7

coupling technique is very efficient to apply the periodic boundary conditions. In this method the nodes of one side of a RVE are copied to the opposite side and thereby a virtual node-based surface is built up. For example, in figure 1 the nodes from the edge AB are copied to the opposite edge and called EF. Afterwards the periodic equations are applied between the nodes of the edge AB and the edge EF. Finally, the copied nodes are coupled with the mesh nodes on the edge CD [7].

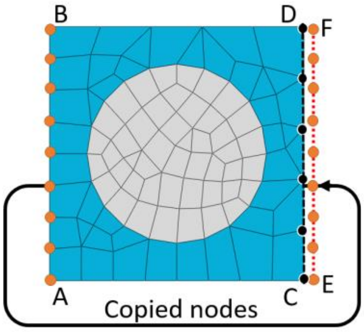

Figure 1. Concept of the unit cell with surface-coupling PBCs.

This study has been performed on a glass fiber reinforced epoxy with the elastic stiffness and damping properties represented in table 1 [2].

Table 1. Material properties of the studied glass fiber and epoxy.

Properties	*Glass fiber*	*Epoxy*
E	*72.4 GPa*	*2.76 GPa*
ν	*0.2*	*0.35*
η	*0.0018*	*0.015*

RVEs with the fiber volume fractions of 0.4, 0.5, 0.6, 0.7 and 0.8 are studied (Figure 2). The geometry of each RVE is discretized with about 60000 fully integrated solid elements. The fiber cross section is circular, and the fiber diameter is 5 µm.

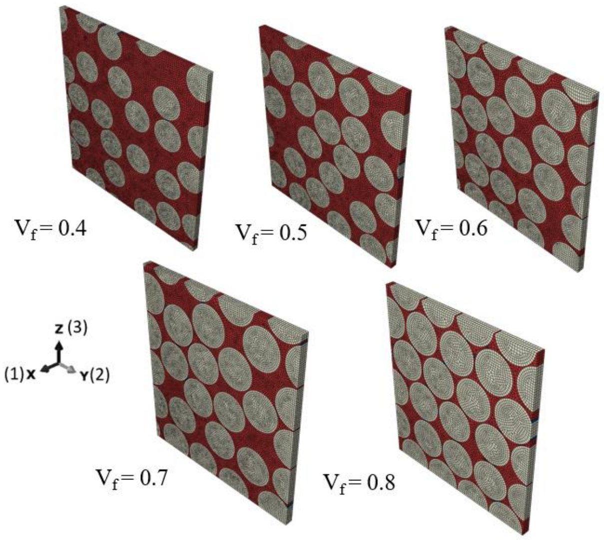

Figure 2. RVEs with different fiber volume fraction.

Excerpt from ISBN 978-3-00-053387-7

4. Results and discussion

For an axial strain of 0.005, figure 3 shows how the loss factor η_{11} decreases while the fiber volume fraction increases. For the fiber volume fraction of 0.4 the axial loss factor is 0.0024. By increasing the volume fraction, the loss factor decreases down to 0.0019. Overall, 40% increase in the fiber volume fraction causes about 20 % decrease in the axial loss factor.

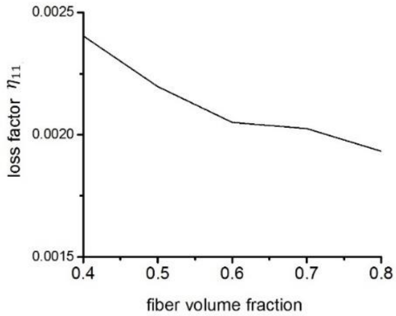

Figure 3. Influence of the fiber volume fraction on the axial loss factor η_{11}

For the transverse strain of 0.005 in y direction, 40 % increase in the fiber volume fraction results in about 24 % decrease in the loss factor η_{22} (figure 4). Similarly, for the transverse strain of 0.005 in z direction, 28% decrease is observed in the loss factor η_{33}.

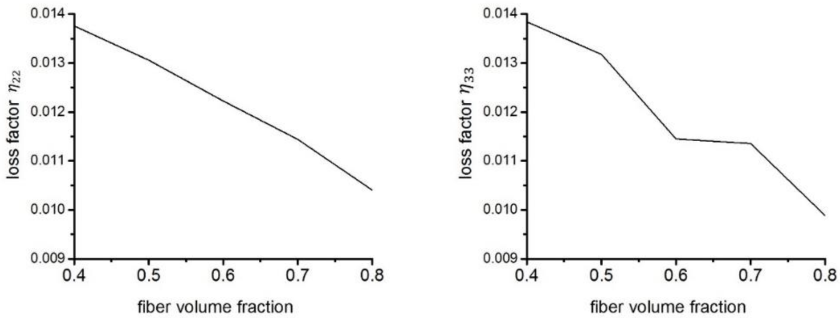

Figure 4. Influence of the fiber volume fraction on the transverse loss factors η_{22} and η_{33}.

Figure 5 shows that for the in-plane shear strain, an increase of 40% in the fiber volume fraction results in a decrease of 28% in the shear loss factor η_{23}.

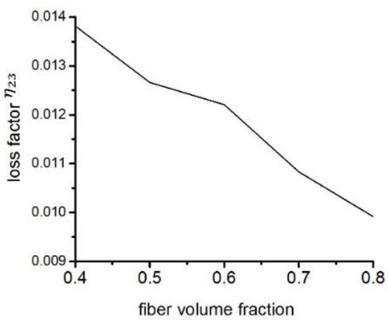

Figure 5. Influence of the fiber volume fraction on the in-plane shear loss factors η_{23}

Excerpt from ISBN 978-3-00-053387-7

5. FEM model with interphase

Here we consider a thin solid layer between the fiber and the matrix in order to study the effect of hard and soft interphases on the loss factors. These models are constructed for an RVE with the volume fraction of $V_f = 0.7$ and the interphase layer with the thickness of 0.1 µm (figure 6).

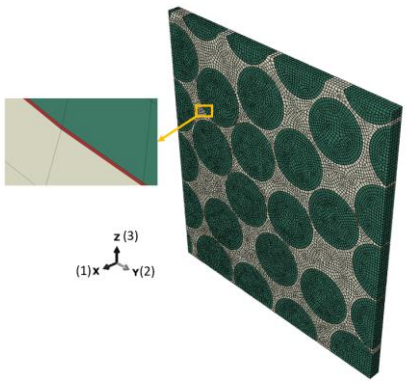

Figure 6. RVE with a thin interphase layer

In this model the hard interphase properties are taken as average of the elastic properties of the fiber and matrix and the soft interphase properties are lower than that of the matrix (table 2).

Table 2. Hard and soft interphase properties.

Properties	*Hard Interphase*	*Soft interphase*
E	*37.58 GPa*	*0.5 GPa*
ν	*0.204*	*0.4*
η	*0.0084*	*0.0084*

The simulations have been performed for the axial, transverse and in-plane shear strain values of 0.005. The results show that the axial loss factor η_{11} is about 0.0020 for both of the hard and soft interphase. For the transverse loading in y direction the loss factor η_{22} equals to 0.0114 and 0.01126, respectively for the hard and soft interphases. For the in-plane shear strain, loss factor η_{23} is about 0.0108 for the both interphases. These results indicate that stiffness of the interphase does not affect the loss factors significantly.

6. Conclusions

Effect of the fiber volume fraction on the loss factors of a unidirectional glass fiber composite has been studied. The models have been performed on the RVEs with randomly distributed fibers and non-conformal periodic boundary conditions.

It is shown that the fiber volume fraction plays an important role in the damping parameters of a composite. Moreover, a simplified simulation describes that a soft or hard interphase does not influence the loss factors meaningfully. However, further studies are required for a more detailed investigation.

Excerpt from ISBN 978-3-00-053387-7

Acknowledgments

The authors gratefully acknowledge SIM (Strategic Initiative Materials in Flanders) and IWT (Flemish government agency for Innovation by Science and Technology) for their support of the ICON project M3NVH, which is part of the research program MacroModelMat (M3). The authors also would like to highly acknowledge SIEMENS PLM for its important supportive and cooperative role in the project.

References

[1] R. Chandra, S.P. Singh, and K. Gupta, Damping studies in fiber-reinforced composites – a review. *Composite Structures,* 1999. 46(1): p. 41-51.

[2] R. Chandra, S.P. Singh, and K. Gupta, Prediction of Damping in Three-phase Fibre-reinforced Composites. . *Defence Science Journal,* 2003. Vol. 53. 2003.

[3] R. Chandra, S.P. Singh, and K. Gupta, A study of damping in fiber-reinforced composites. *Journal of Sound and Vibration,* 2003. 262(3): p. 475-496.

[4] Ungar, E.E. and E.M. Kerwin, Loss Factors of Viscoelastic Systems in Terms of Energy Concepts. *The Journal of the Acoustical Society of America,* 1962. 34(7): p. 954-957.

[5] H. Guan, and R.F. Gibson, Micromechanical Models for Damping in Woven Fabric-Reinforced Polymer Matrix Composites. *Journal of Composite Materials, 2001.* 35(16): p. 1417-1434.

[6] A.R. Melro, P.P. Camanho, and S.T. Pinho, Generation of random distribution of fibres in long-fibre reinforced composites. *Composites Science and Technology,* 2008. 68(9): p. 2092-2102.

[7] G. Al Kassem, and D. Weichert, Micromechanical material models for polymer composites through advanced numerical simulation techniques. *PAMM,* 2009. 9(1): p. 413-414.

Excerpt from ISBN 978-3-00-053387-7