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Research Article

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Prediction of Dynamic Mechanical Properties of Viscoelastic Composites

Sandeep Kumar Gautam and Rabindra Kumar Patel[*]

Motilal Nehru National Institute of Technology Allahabad, Prayagraj, Uttar Pradesh, India

[*]**Correspondence to:**
Rabindra Kumar Patel
Motilal Nehru National Institute of Technology
Allahabad, Prayagraj, Uttar Pradesh, India.
E-mail: rkpatel@mnnit.ac.in

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Abstract

In this paper, prediction of dynamic mechanical properties of viscoelastic composites has been done by using finite element-based software ABAQUS. Viscoelastic material has been considered matrix and elastic as reinforcement phase. In this composite, epoxy has been chosen as matrix and alumina as reinforcement. Viscoelastic phase has been modelled by generalized Maxwell model. A stress relaxation test has been performed on the composite sample using ABAQUS. Relaxation data obtained from the test have been used to predict the storage modulus, loss modulus, and loss tangent of the viscoelastic composite

Keywords

Storage modulus, Loss modulus, Loss tangent

Introduction

Most of the polymers show viscoelastic behaviour that combines both viscous and elastic characteristics. Because viscoelastic materials are neither totally viscous nor entirely elastic, their modulus is represented by a complex variable called the “complex modulus”, which has both storage and energy dissipation components [1].

Viscoelastic material can be represented by behavior of viscous material and the elastic material. Mechanically the viscoelastic material can be modelled by spring and dashpot. Spring exhibits the behavior of elastic part and dashpot the behavior of viscous part. A spring and a dashpot can be connected in two ways. One in which spring and dashpot is connected in series is called Maxwell model and in other where the spring and dashpot connected in parallel is called Voigt-Kelvin model. These two models have their use and limitations. There is one more model in that one Maxwell element is connected with a spring in parallel and is called standard linear solid [1].

Viscoelastic materials are used for damping of vibration as passive material. They are used in the form of layers with the host structure [2]. Keeping in view of such applications study on damping behavior of viscoelastic composites is being done.

Chandra et al. has reviewed the literature on damping in fiber-reinforced composite materials and structures with emphasis on polymer composites [3]. Fisher and Brinson investigated the mechanical property for a three-phase viscoelastic composite by the use of two micromechanical models: the original Mori–Tanaka method and an extension of the Mori–Tanaka solution developed by Benveniste to treat fibers with interphase regions [4]. Xia et al. [5] has presented an explicit unified form of displacement-difference periodic boundary conditions for repeated unit cell model. Kurnatowski and Matzenmiller [6] have performed two-scale simulation of viscoelastic composite structures. They modelled the macrostructure with standard finite element tools, the simultaneous microscale analysis was done with the numerically efficient generalized method of cells. Patel et al. [7] studied the effect of interphase on damping property of polymer nanocomposites using finite element-based programs. Qiao and Brinson [8] focused on modelling gradients and interphase percolation in polymer nanocomposites. Yadollahpour et al. [9] has calculated the damping capacity numerically using a micro-mechanical modelling approach. Katiyar and Kumar [10] have investigated the loss factor of the epoxy/alumina nanocomposite experimentally. Vakilifard and Mahmoodi [11] estimated the dynamic moduli and creep damping capacity of short carbon fiber reinforced polymer hybrid nanocomposite using micromechanical approach. Sarikaya et al. [12] studied the vibration damping behavior of graphene nanocomposites via dynamic mechanical analysis. Pan et al. [13] studied the damping behavior of epoxy nanocomposite beams reinforced with carbon nanotubes and graphene nanoplatelets.

In the present work authors use similar procedure as given in the literature [7] and predicted the dynamic mechanical properties of viscoelastic composite using ABAQUS.

Materials and Methods

Modelling viscoelastic composite material

In viscoelastic composite the matrix has been considered as viscoelastic material and reinforcement as elastic.

Modelling strategy

For simplicity the elastic fiber has been distributed uniformly in the viscoelastic matrix. Distribution of fiber has been considered to be in square arrangement as shown in figure 1a. From this arrangement the representative volume element has been taken as a square (100 x 100 μm^2) with one fiber (volume fraction 10%) in it as shown in the figure 1b. This representative volume element has been taken for the analysis.

Figure 2a shows the mesh of the model which has been done in ABAQUS. Boundary conditions have been shown in figure 2b. Displacement on edge AB in the y-direction is zero and displacement on AC in x-direction is zero. Displacement is applied on boundary BD which varies linearly from zero to maximum value of 1 μm. It reaches its maximum value in 2 s.

Material model for viscoelastic matrix

For modelling viscoelastic matrix generalized Maxwell model has been selected. The reason for the selection of this model is that it explains both the phenomena of viscoelastic materials i.e., stress relaxation and creep in better way. Relaxation modulus for this material can be given by the expression.

$$E(t) = E_\infty + \sum_{i=1}^{N} E_i e^{-t/\rho_i}$$

Where, E_∞ is long term elastic modulus, E_i are the moduli of the spring elements, $\rho_i = {}_i/E_i$ the relaxation times and N is the number of terms in Prony series.

Material properties of viscoelastic matrix (epoxy) and reinforcement (alumina) have been given in table 1 and table 2.

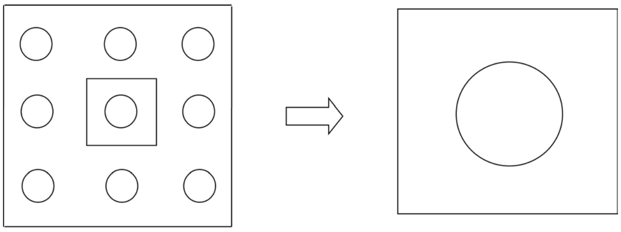
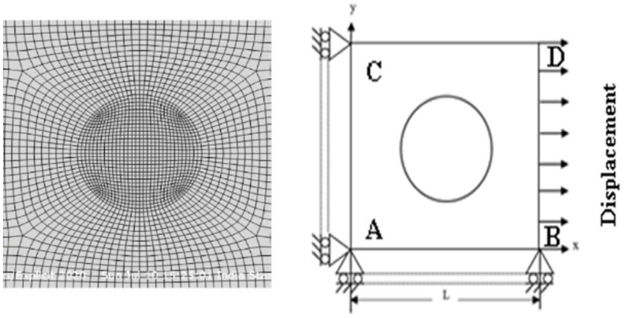

(a) (b)

Figure 1: Shows **(a)** regular arrangement of fiber in a matrix and **(b)** unit cell.



(a) **(b)**

Figure 2: Shows **(a)** mesh of the unit cell and **(b)** boundary conditions.

Table 1: Material properties of alumina and epoxy [10].

Material	Young's Modulus (GPa)	Poisson's ratio	Density (kg/m^3)
Alumina	500	0.33	3900
Epoxy	4	0.37	1180

Table 2: Prony series parameters for matrix (epoxy) as used in ABAQUS [10].

g_i	k_i	$_i$ (s)
0.0738	0	463.4
0.1470	0	0.06407
0.3134	0	0.0001163
0.3786	0	7.321 x 10^{-7}

Convergence test

Convergence test has been carried out. Result converges at 2000 elements.

Results and Discussion

Unit cell of viscoelastic composite has been analyzed in ABAQUS. Stress relaxation test has been done.

Stress relaxation test

Stress relaxation test on the viscoelastic composite sample has been done in ABAQUS. For carrying out the test, time dependent displacement has been applied on the unit cell. Data obtained from the test have been fitted by using the least squares curve fit. For this a function of MATLAB 'lsqcurvefit' has been used. Fit is very sensitive to the initial guess.

Expressions used for fitting the data are given below. These have been derived using the constitutive equation for the viscoelastic material. Here it is assumed that the composite which is made of viscoelastic matrix and elastic reinforcement will behave as viscoelastic material.

$$\sigma(t) = R_\varepsilon E_\infty t_1 = \sum_{i=1}^{N} E_i R_\varepsilon \rho_i e^{-\frac{}{\rho i}} \left(e^{\frac{t_1}{\rho i}} - 1 \right) \qquad \text{for } t > t_1$$

$$\sigma(t) = E_\infty R_\varepsilon t = \sum_{i=1}^{N} \rho_i E_i R_\varepsilon \left(1 - e^{-\frac{t}{\rho i}} \right) \qquad \text{for } t < t_1$$

Where, R_ε is strain rate and t_1 is time up to which displacement is gradually increasing to its maximum value.

Determination of prony series parameter

From the fit Prony series parameters E_∞, E_i, and ρ_i can be obtained for the viscoelastic composite. As the best fit has been obtained from one term Prony series. So, these parameters E_∞, E_1, and ρ_1 are obtained from the fit. The fitted curve has been shown in figure 3. From the fit, values of E_∞, E_1, and ρ_1 are obtained as 10.8 MPa, 8.8 MPa, and 5 s, respectively. These parameters are used to calculate the storage modulus, loss modulus, and loss tangent for the viscoelastic composite.

Validation of result

Maximum value of loss tangent for matrix material is obtained as 0.3069 theoretically. Maximum value of loss tangent for the same from the present analysis 0.3124. Percentage error is -1.8.

Variation of storage modulus w.r.t. frequency

Determination of storage modulus ($E'(\omega)$) has been done by the expression given below [1]:

$$E'(\omega) = E_\infty + \sum_{i=1}^{N} \frac{\left(E_i \omega^2 \rho_i^2\right)}{1 + \omega^2 \rho_i^2}$$

Storage modulus has been calculated from the above expression. In the above expression Prony series parameters are used. They have already been obtained from fitting the stress relaxation data. Nature of variation of storage modulus with respect to frequency for matrix and composite is same. It can be seen from figure 4a. Magnitude of storage modulus for composite is more than that of viscoelastic matrix. It is because of the presence of elastic reinforcement of high modulus as compared to matrix.

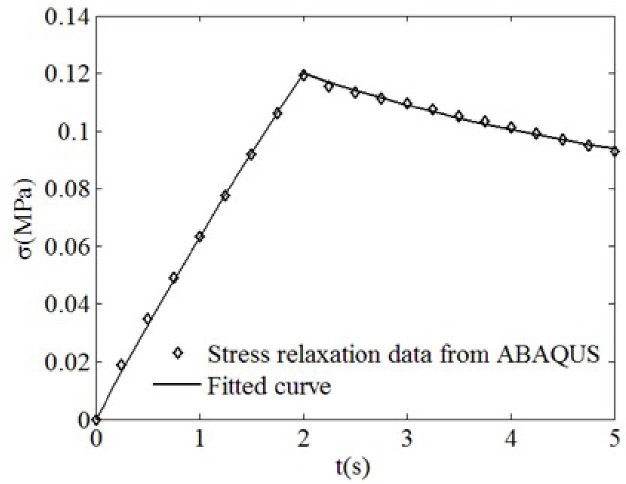


Figure 3: Shows fitting of relaxation data obtained from relaxation test.

Variation of loss modulus w.r.t. frequency

Determination of loss modulus ($E''(\omega)$) has been done by the expression given below [1]:

$$E''(\omega) = \sum_{i=1}^{N} \frac{\left(E_i \omega \rho_i\right)}{1 + \omega^2 \rho_i^2}$$

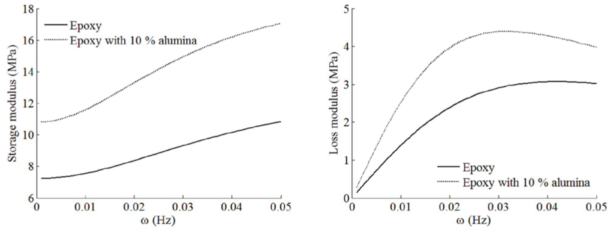
Loss moduli for the composite as well as for the matrix have been obtained by using the above expression. It can be seen from figure 4b loss modulus for the composite is more than that of matrix. The reason behind it is same i.e., the elastic reinforcement of high modulus as compared to matrix.

Variation of Loss Tangent w.r.t Frequency

Loss tangent or tan δ can be calculated by the expression given below [1]:

$$\tan\delta = E''(\omega) / E'(\omega)$$

Variation of loss tangent with respect to frequency has been shown in figure 5. From the figure, it can be seen that nature of variation of loss tangent for viscoelastic matrix and composite is same. The only difference is in the peak value.



(a) (b)

Figure 4: Shows variation of **(a)** storage modulus and **(b)** loss modulus with respect to frequency.

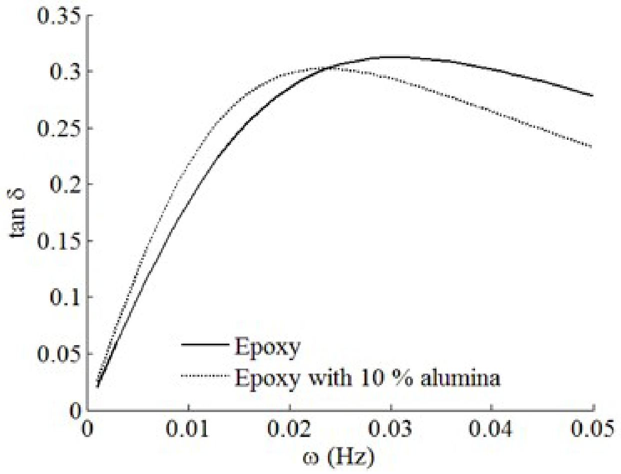


Figure 5: Shows variation of loss tangent with respect to frequency.

The peak value of loss tangent for composite is less than that for the matrix. This is also because of the presence of elastic reinforcement, which reduces the loss tangent value for the composite.

Conclusion

Loss tangent of the viscoelastic matrix obtained from the analysis in ABAQUS is found to be in good agreement with the that obtained from the given expression. Variation of storage modulus, loss modulus and loss tangent with respect to frequency have been predicted for the viscoelastic composite. Based on the results it can also be concluded that this method can be used to predict the dynamic material properties of viscoelastic composites.

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None.

Conflict of Interest

The authors declare no conflict of interests to disclose.

Credit Author Statement

Sandeep Kumar Gautam: Modeling, Analysis; Rabindra Kumar Patel: Writing - original draft preparation, Supervision. All the authors read and approved the manuscript.

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