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A new method for the determination of damping in cocured composite laminates with embedded viscoelastic layer

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Abstract

A new method for the determination of damping in cocured composite laminates with embedded viscoelastic layer is developed based on mode superposition and modal strain energy method. The calculated damping value is not modal loss factor but a combination of damping from the contributing modes. The dynamic mechanical properties of the viscoelastic material cocured with composites were investigated and were substituted in the present method for calculating the damping in cocured composites. The analytical results were compared with the experimental results by dynamic mechanical thermal analysis (DMTA). The results demonstrate a good agreement between analytical and experimental results. This work provides a means for the study of damping in this structure with different environment temperature and excited frequency.

1. Introduction

In recent years, cocuring damping materials in composites has been shown to be successful in greatly increasing the damping of composite structures with little reduction in stiffness and strength [1–5]. Cocuring refers to the process of inserting viscoelastic materials within composite laminates before the composite is cured, therefore the embedded viscoelastic materials should undergo temperature and pressure cycle which is necessary to cure the composite.

Pioneering work on the damping in cocured composite laminates with embedded viscoelastic layer was done by Barrett [6] in 1991. Saravanos and Penera [7] have developed discrete layer damping mechanics by using a semi-analytical method for predicting the modal damping of simply supported specialty composite plates. A comprehensive, yet simple model to study the dynamic behavior of multiple damping layer composite beams with anisotropic laminated constraining layers has been developed by Rao and He [8]. Liao et al. [9] carried out a theoretical approach based on a simple combination of the RKU model and the NA method to investigate the effect of a high-damping interleaf layer on the damping performance of composite beams. Yim et al. [10] investigated the damping behavior of a 0° laminated sandwich composite beam inserted with

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a viscoelastic layer with both in-plane stresses and transverse shear stress considered. Suzuki et al. [11] developed a finite element model based on the multilayer theory and the higher-order theory for free vibration and damping analysis of laminated plates with viscoelastic interlayers. More recently, Zhang and Chen [12] take both the frequency dependence of viscoelastic damping materials and the contribution of energy dissipation due to fiber-reinforced composites into account, predicted the modal loss factor of laminated composite beams with integral viscoelastic layers.

Since the damping properties of viscoelastic material are quite sensitive to frequency and temperature, the damping in cocured composites would also dependent on frequency and temperature with embedded viscoelastic material as a special layer. Although some works in this direction have taken the frequency dependence of viscoelastic material into account, the loss factor studied is the modal loss factor of each mode. It cannot approach the desired damping capabilities of the structure under excitation. In addition, few of analytical works have taken the temperature dependence of the viscoelastic material into account. Thus, it becomes indispensable to determine the actual damping over a range of temperatures under excitation with different frequency.

In this study, a new formulation for analyzing the damping in cocured composite laminates has been developed with different temperature and excitation frequency. The loss factor in this new method is not the modal loss factor but a summation of the product of the modal loss factor and the participation factor of each mode. The algorithm was applied in the determination for the loss factor of a simply supported beam with different environment temperature under a sinusoidal excitation with frequency 1 Hz. The loss factor measurements of the beam were carried out using dynamic mechanical thermal analysis (DMTA) [13] for the validation of the theory. Cocuring viscoelastic material not only decreases the damping capabilities, but also changes the modulus of the viscoelastic material. The dynamic mechanical properties of the viscoelastic material cocured with composites were investigated and were substituted in the present method to avoid the cocuring inducing some difference.

2. Specimen preparation and experimental method

The embedded viscoelastic material was the butadiene-acrylonitrile rubber (NBR) film with thickness 0.3 mm, while the fiber-reinforced composite laminate was T700/TT85 unidirectional prepreg tape. The surfaces of the NBR film were smeared with adhesive J67 to be bonded with composite laminates. The cocured composite laminates plate was produced in a hotpress with layup $[0_8/d/0_8]$ (d means the damping layer). The laminates were processed at temperature 120 °C for 120 min and at 160 °C for 240 min under an applied pressure of 200 kPa. The cocured composites beam specimens were cut from the processed laminates using a diamond abrasive saw. After the cutting procedure, all specimen edges were sanded flat for better dimensional precision. Accurate dimensions of each specimen were measured using a hand-held micrometer. The specimen dimensions of cocured composite laminate with embedded viscoelastic layer were nominally $38.0\,\text{mm} \times 5.0\,\text{mm}$ ($L \times W$). The specimen dimensions of viscoelastic material NBR film were $60.0\,\text{mm} \times 6.0\,\text{mm}$.

The loss factor measurements were carried out using dynamic mechanical thermal analysis (DMTA Q800). Two different testing modes were applied, one is 3-point bending testing mode for cocured composite laminates and the other is tension testing mode for NBR film. All tests were carried out under a sinusoidal strain-controlled mode. The strain amplitudes used were 0.008% for cocured composite laminates and 0.015% for NBR throughout the measurements. The assumption that the damping capacity is independent of the amplitude of strain is valid for very small strains. The specimens were pre-stressed with an applied force 10% larger than the force necessary to produce the desired strain amplitude for both cocured composite laminates and NBR. This procedure guarantees that the center probe is always in contact with the beam in 3-point bending tests. The force necessary to pre-stress the specimen is automatically calculated by the computer control of the DMTA and corrected, if necessary, throughout the experimental procedure.

The temperature scan measurements were conducted under a constant excited frequency. The temperature scan measurements were performed over the temperature range of -50 to 100 °C, with a heating rate of 5.0 °C/min and excited frequency of 1 Hz.

3. Influencing factors for loss factor

3.1. Temperature and frequency

Most of viscoelastic materials exhibit three different mechanical states, glassy state, viscous state and elastomeric state with different temperatures. In the glassy state, modulus is very high while loss factor is very low; in the viscous state, modulus decreases rapidly while loss factor increases rapidly to a peak value and then decreases rapidly; in the elastomeric state, both modulus and loss factor are very low as shown in Fig. 1.

Modulus and loss factor of viscoelastic materials are functions of frequency (f) and temperature (T). It can be written as

$$E(f,T) = E(f\alpha_T) \tag{1}$$

the relation between α_T and T can be written as (WLF equation)

$$lg\,\alpha_T = \frac{-C_1(T-T)_r}{C_2+T-T_r} \tag{2}$$

where C_1 and C_2 are constants depending on the reference temperature (T_r). Between temperature and frequency there exists an equivalent relation, i.e. high frequency is equivalent to low temperature, while low frequency is equivalent to high temperature.

3.2. Cocuring

Cocuring many viscoelastic damping materials decreases the damping capabilities of the material. It was proven that the reason for this decrease is the interaction between the damping material and epoxy during the cure cycle [14,15]. The interaction not only decreases the damping capabilities, but also changes the modulus of the viscoelastic material. To avoid the interaction-inducing difference, the dynamic mechanical properties of the NBR cocured with composites were obtained out by DMTA and were compared to that of the original NBR. The cocured NBR was separated from the cocured composite laminates with embedded viscoelastic layer.

Figs. 2 and 3 show, respectively, the temperature spectrum of loss factor and the storage modulus of the original and cocured NBR. It is observed that the cocuring decreases the loss factor especially in the viscous state of the viscoelastic layer. In addition, the cocuring increases the storage modulus of the viscoelastic layer. The result benefits the accurate prediction of the damping of the cocured composite laminates with viscoelastic layer.

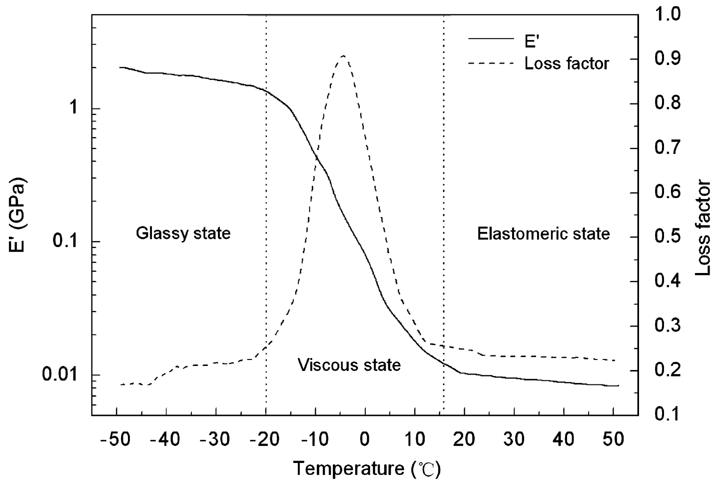

Fig. 1. Typical temperature spectrum of dynamic mechanical properties of viscoelastic material.

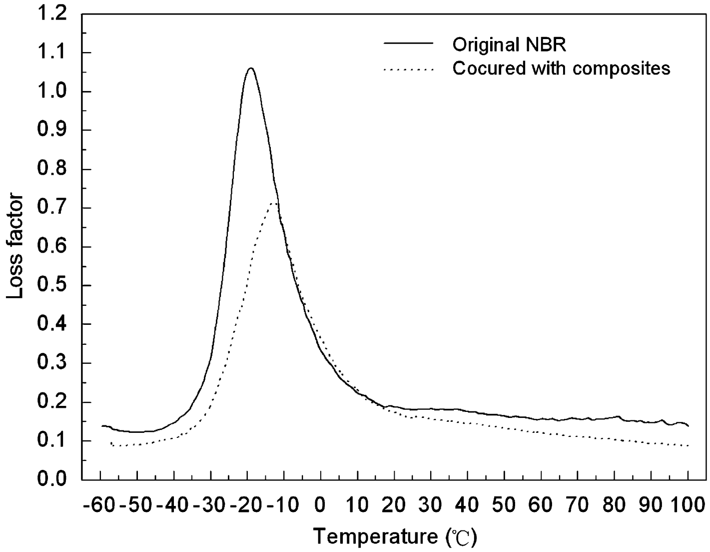

Fig. 2. Temperature spectrum of loss factor of original and cocured NBR.

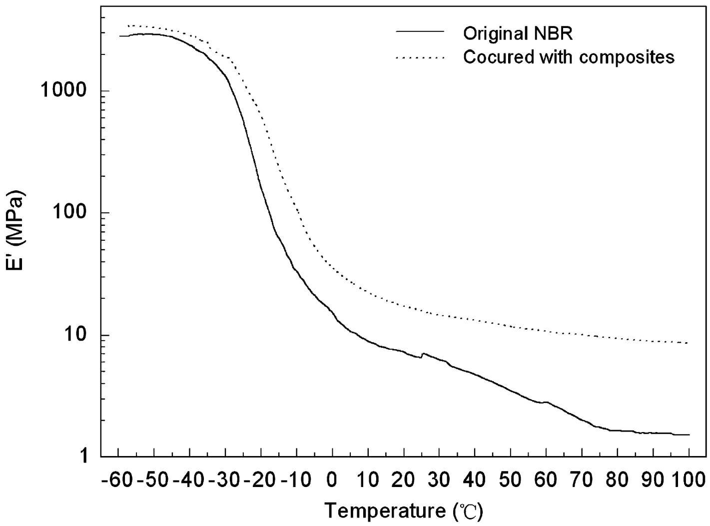

Fig. 3. Temperature spectrum of storage modulus of original and cocured NBR.

4. Theoretical approach

In the present section, all algorithms will be deduced for the determination of damping in cocured composite laminates with embedded viscoelastic layer with different environment temperatures and excited frequencies. In the energy method, the damping of structure is estimated as the ratio of dissipated energy to the stored energy at a given forcing function [16]:

$$\eta = \frac{\eta_v(\mathrm{SE})_v + \eta_c(\mathrm{SE})_c}{(\mathrm{SE})_t} \tag{3}$$

where η is the loss factor of the cocured compsosites; η_v is the loss factor of the viscoelastic layer; η_c is the loss factor of fiber-reinforced composites; $(\mathrm{SE})_v$ is the strain energy in the viscoelastic layer; $(\mathrm{SE})_c$ is the strain energy in the fiber-reinforced composites; $(\mathrm{SE})_t$ is the total strain energy in the integral structure; and

$$\mathrm{SE} = \tfrac{1}{2}\{x\}^{\mathrm{T}}[K]\{x\} \tag{4}$$

where $\{x\}$ is displacement vector. The displacement vector $\{x\}$ can be calculated by mode-superposition method. In this method, the displacement response of structure with n-degree freedom is described as follows:

$$\{x\} = \sum_{i=1}^{n} \xi_i \{\varphi\}_i \tag{5}$$

where $\{\varphi\}_i$ is the ith mode and ξ_i is the participation factor for the ith mode. Eq. (5) also can be written in matrix form as

$$\{x\} = [\Phi]\{\xi\} \tag{6}$$

where $[\Phi]$ is the modal matrix. By substituting Eq. (6) into Eq. (4), the strain energy of structure can be expressed in the following form:

$$\mathrm{SE} = \tfrac{1}{2}\{\xi\}^{\mathrm{T}}\{\Phi\}^{\mathrm{T}}[K]\{\Phi\}\{\xi\} = \tfrac{1}{2}\{\xi\}^{\mathrm{T}}[\bar{K}]\{\xi\} \tag{7}$$

$$[\bar{K}] = [\Phi]^{\mathrm{T}}[K][\Phi] = \begin{bmatrix} \bar{k}_1 & & & \\ & \bar{k}_2 & & \\ & & \ddots & \\ & & & \bar{k}_n \end{bmatrix} \tag{8}$$

where $\bar{k}_i$ is modal stiffness and can be written as

$$\bar{k}_i = \varphi_i^{\mathrm{T}}[K]\varphi_i \tag{9}$$

Then, the strain energy of structure also can be written in the form of liner combination of modal stiffness:

$$\mathrm{SE} = \frac{1}{2}\sum_{i=1}^{n} \xi_i^2 \bar{k}_i \tag{10}$$

The modal strain energy method makes use of the eigenvectors of the undamped system and it will generally give good estimations when the modal coupling is negligible. The modal loss factor of the ith mode can be defined as the ratio of the energy dissipated to the energy stored in the ith vibrational mode [17]. The strain energy is defined by

$$\mathrm{MSE}_i = \frac{1}{2}\sum_{r=1}^{N} \varphi_i^{r\mathrm{T}}[K]\varphi_i^r \tag{11}$$

where φ_i^r is the ith eigenvector associated with the rth element; N is the total number of elements. By comparing Eqs. (11) and (9), the relation of MSE_i and $\bar{k}_i$ can be written:

$$\mathrm{MSE}_i = \tfrac{1}{2}\bar{k}_i \tag{12}$$

By substituting Eq. (12) into Eq. (10), strain energy and modal strain energy can be seen to be related through the following relation:

$$\mathrm{SE} = \sum_{i=1}^{n} \xi_i^2 \mathrm{MSE}_i \tag{13}$$

According to Eq. (13), $(\mathrm{SE})_t$ and $(\mathrm{SE})_v$ can be written as in the same form:

$$(\mathrm{SE})_t = \sum_{i=1}^{n} \xi_i^2 \mathrm{MSE}_i^t \tag{14}$$

$$(\mathrm{SE})_v = \sum_{i=1}^{n} \xi_i^2 \mathrm{MSE}_i^v \tag{15}$$

The strain energies $(\mathrm{SE})_t$, $(\mathrm{SE})_v$ and $(\mathrm{SE})_c$ are in the following form:

$$(\mathrm{SE})_c = (\mathrm{SE})_t - (\mathrm{SE})_v \tag{16}$$

Finally, by substituting Eqs. (14)–(16) into Eq. (3) and neglecting the joint damping introduced by boundary effects between the layers and edge, the loss factor of integrated cocured composite laminates with embedded viscoelastic layer can be expressed in the following form:

$$\eta = \eta_c + (\eta_v - \eta_c)\varepsilon \tag{17}$$

$$\varepsilon = \frac{(\mathrm{SE})_v}{(\mathrm{SE})_t} = \frac{\sum_{i=1}^{n} \xi_i^2 \, \mathrm{MSE}_i^v}{\sum_{i=1}^{n} \xi_i^2 \, \mathrm{MSE}_i^t} \tag{18}$$

where ε is the ratio of strain energy in viscoelastic layer against the total strain energy in the integral structure.

The calculated damping value in Eq. (17) is clearly not the modal loss factor. This form of the damping value will approach the actual damping value as the displacement vector approaches the system's response by forcing the system at an excited frequency. This approach for the calculated damping will always be a combination of damping from the contributing modes.

The viscoelastic material properties of the viscoelastic material vary significantly with temperature and frequency. The analytical model developed takes these effects into consideration. These variations can be accounted for by separately solving the damping values with any temperature and frequency. Loss factor and storage modulus values of commonly available damping materials with different frequency and temperatures can be obtained using temperature–frequency nomogram charts supplied by the manufacturers.

5. Results, discussion and verification of the proposed method

5.1. Verification

Fig. 4 presents a freely supported beam. Suppose this beam is the same as the specimens beam in Section 2, and suppose the beam vibrates under the sinusoidal excitation $p = -q_0 \sin(\omega_0 t)$ at the center. We can get the participation factor for the ith mode applying the mode-superposition method as follows:

$$\xi_i = C_0 \frac{\sin(\mathrm{i}\pi/2)}{(\omega_i^2 - \omega_0^2)} \tag{19}$$

where C_0 is constant that depends on magnitude of load and the shape of the beam. According to Eq. (8), strain energy ratio ε is independent of the constant C_0. And then, the modal participation factor can be

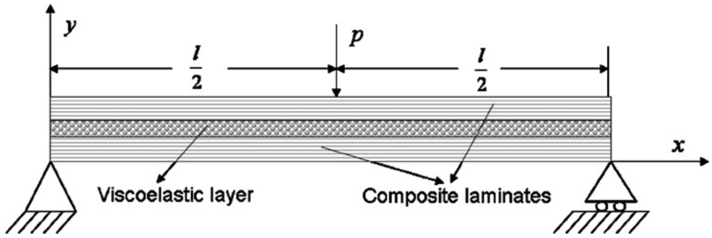

Fig. 4. The schematic diagram of specimen by DMTA in 3-point bending testing mode.

simplified and re-written as

$$\xi_i = \frac{1}{(\omega_i^2 - \omega_0^2)}, \quad i = 2k-1 \ (k = 1, 2, \ldots, n) \tag{20}$$

$$\xi_i = 0, \quad i = 2k, \ (k = 1, 2, \cdots n) \tag{21}$$

where ω_i is the natural frequency of ith mode of the freely supported beam.

The values of ω_i, MSE_i^v and MSE_i^t of ith mode were calculated using ANSYS finite element software package. As the dominant mechanism of damping in constrained layer beams is the shearing of the core, it is important that the finite element model accurately represents the strain energy due to shearing. A 3-D layered structural solid element named SOLID46 is selected to model the damped composite system. The real constant table is specified constituting the orthotropic material property, ply orientation angle and layer thickness. Element SOLID45 is selected to model the viscoelastic layer. The geometrical parameters of the beam are the same as test specimens by DMTA. All the elements meshed are rectangular solids. The dimension of each element for SOLID46 is 0.25 mm × 0.272 mm × 0.95 mm and the total element number is 8000. The dimention of each element for SOLID45 is 0.075 mm × 0.25 mm × 0.95 mm and the total element number is 3200. The carbon fiber-reinforced plastic (CFRP) properties considered here are assumed to be independent of frequency and temperature for simple, and are given by $E_{11} = 120\,\mathrm{GPa}$, $E_{22} = 9\,\mathrm{GPa}$, $G_{12} = 4.3\,\mathrm{GPa}$, $v_{12} = 0.29$, $\rho = 1635\,\mathrm{kg/m^3}$. The properties of viscoelastic material are given by $\rho_v = 1850\,\mathrm{kg/m^3}$ (Poisson's ratio) $v = 0.48$. These values were supplied separately by each manufacturer.

The modulus of viscoelastic layer was set one by one within the temperature range from −50 to 50 °C at excitation frequency of 1 Hz. To avoid difference, the performance parameters substituted are not of the original NBR but of the NBR cocured with composites. The loss factor and modulus of cocured NBR and the modal analysis results of cocured composites are listed in Table 1 with different temperature at excitation frequency of 1 Hz. The modal participation factor of each mode was determined by substituting natural frequency of each mode into Eqs. (20) and (21). The ratio ε was determined by substituting the modal participation factor and modal strain energy of each mode into Eq. (18). Considering the modal participation factor of higher-order mode is too small and that of the even order is zero, we take the first and the third modes for calculation. Finally, the loss factor of integral cocured composites is determined by substituting the loss factor of viscoelastic material and composites and the strain energy ratios ε into Eq. (17). The loss factor

Table 1
Loss factor and modulus of cocured NBR and the modal analysis results of cocured composites with a different temperature and excited frequency 1 Hz

Temperature (°C)	Loss factor	Tensile modulus (MPa)	First bending mode		Third bending mode		ε
			Frequency (Hz)	ξ_1 ($\times 10^{-8}$)	Frequency (Hz)	ξ_3 ($\times 10^{-8}$)	
−49.44	0.11507	2138.6	6553	2.328	13,271	0.568	0.122
−39.88	0.1235	1965.7	6521	2.352	13,189	0.575	0.129
−30.97	0.14037	1789.6	6481	2.381	13,091	0.584	0.138
−20.11	0.2313	1283.5	6318	2.505	12,726	0.617	0.172
−14.79	0.38817	804.7	6032	2.748	12,191	0.673	0.222
−9.9	0.54858	375.3	5425	3.397	11,385	0.771	0.291
−7.56	0.56092	269.6	5135	3.792	11,115	0.809	0.308
−5.12	0.53786	189.5	4826	4.293	10,882	0.844	0.316
−3.4	0.50047	151.2	4633	4.659	10,755	0.865	0.313
−1.65	0.46938	124.4	4477	4.990	10,659	0.881	0.305
0.26	0.40985	97.2	4297	5.415	10,553	0.898	0.291
5.17	0.35013	67.2	4061	6.063	10,411	0.923	0.259
10.12	0.29161	49.1	3892	6.601	10,298	0.943	0.226
20.24	0.21078	32.1	3714	7.249	10,153	0.971	0.181
30.11	0.16117	23.4	3611	7.667	10,042	0.992	0.149
40.2	0.14856	20.8	3579	7.808	9998	1.001	0.139
50.05	0.142	17.5	3534	7.998	9932	1.014	0.125

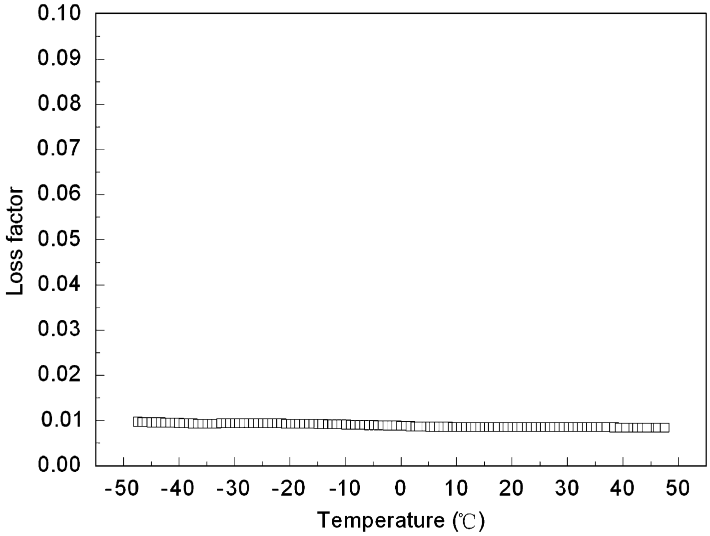

Fig. 5. The temperature spectrum of loss factor of fiber-reinforced composites.

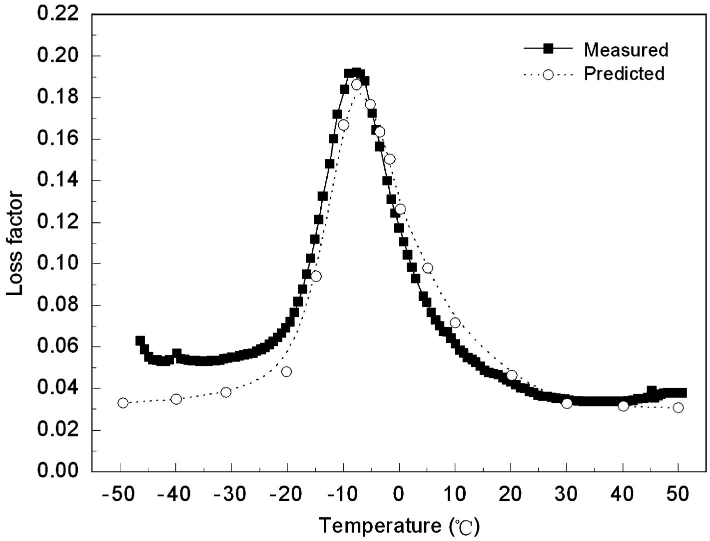

Fig. 6. Comparison of the loss factor that is measured and that is predicted at different temperatures with excited frequency 1 Hz.

of composites was also tested by DMTA as shown in Fig. 5. We can find that the loss factor of fiber-reinforced composites is much smaller and almost independent of the temperature compared to that of the NBR. So, we assumed the loss factor to be a constant 0.01. The loss factors of the viscoelastic layer are taken from the mechanical properties of the cocured NBR.

5.2. Result and discussion

Fig. 6 shows the comparison of calculated and measured (by DMTA for verification) loss factors of cocured composite laminates beam. Although there is some difference as the viscoelastic layer is in glassy state, the difference is due to joint damping. The boundary conditions introduce some joint damping [18]. However, it has been neglected in the method presented for simplicity. The joint damping models the energy loss due to the relative motion of the two contacting surfaces. This relative motion will occur at their interface when the shearing force is greater than frictional resistance. The greater the shearing stress introduced in the interface, the higher the modulus of the viscoelastic layer. Therefore, there is more joint damping as the viscoelastic material in glassy state due to the much higher modulus, while there is much less joint damping as the viscoelastic material in viscous state and elastomeric state because of the much smaller modulus.

Except for some difference in glassy state due to the joint damping, there is a good agreement between the loss factor predicted and that measured. The method put forward is validated. It has to be mentioned that there is a peak value at about $-7\,^{\circ}\mathrm{C}$. It is because the viscoelastic layer has a maximum loss factor and a proper modulus, which results in a large-strain energy ratio ε at about $-7\,^{\circ}\mathrm{C}$.

6. Conclusions

A new method for determination of damping in cocured composite laminates with embedded viscoelastic layer has been developed. The algorithm was applied in the determination of the loss factor of a simply supported beam over a temperature range under a sinusoidal excitation with frequency 1 Hz. The dynamic mechanical properties of the viscoelastic material cocured with composites were substituted in the present method for calculating damping in cocured composites. Although there is some difference as the viscoelastic layer in glassy state, the difference is due to the joint damping. Except for it, the loss factor calculated agrees well with that by DMTA. The method put forward is validated and it is important to the practical application of this structure. Moreover, the proposed method can be applied to any other type of viscoelastic damping structure.

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