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Damping and Vibration Analysis of Polyethylene Fiber Composite under Varied Temperature

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Abstract

Damping and vibration properties of polyethylene fiber composite are investigated under varied temperature. A damping monitoring method is used to experimentally measure frequency response and the frequency is obtained numerically using a finite element program. The natural frequencies of a system are a function of its elastic properties, dimensions, and mass. This concept is used to calculate theoretical vibration modes of composites. The damping properties, in terms of the damping factor, are determined by the half-power bandwidth technique.

The time responses measured experimentally are compared with the numerically obtained ones. Good agreement between the 2 methods shows that numerical analysis can be used to determine the time response curve of polyethylene fiber composite. It is seen that polymer matrix composites have temperature-dependent mechanical properties. A functional relationship between temperature and damping properties of polyethylene fiber composite under varied temperature is obtained.

Key words: Polymer matrix composite, Polyethylene, Damping, Frequency, Temperature effects.

Introduction

Damping is an important modal parameter for the design of structures for which vibration control and cyclic loading are critical. Damping is also a significant factor for the fatigue life and impact resistance of structures. All engineering materials dissipate energy under cyclic load. Some of them, such as elastomer, plastic, and rubber, dissipate much more energy per cycle than metallic materials. Damping varies with different environmental effects, such as frequency, amplitude of stress, temperature, and static preload. Damping is also affected by corrosion fatigue, grain size, porosity, and number of fatigue cycles, especially for metallic materials (Çolakoğlu, 2004). There is a functional relationship between damping and all the effective factors. In addition, temperature is usually one of the most important factors for damping in polymers and polymeric materials.

Polymer matrix composites are commonly used in weight sensitive structures due to their high stiffness-to-weight ratios. They are especially significant in aircraft, aerospace, and military applications. On the other hand, polymers have temperature-dependent mechanical properties. If dynamic stability and positioning accuracy are design requirements in polymer matrix composite structures, their damping properties must be investigated under varied temperature for possible use in different seasons, climates, and regions.

Many studies have been carried out on the vibration properties of polymer matrix composite materials. Adams and Maheri (2003) investigated the damping capacity of fiber reinforced plastic and developed a damping energy equation for analysis. Using the finite element method, the Rayleigh-Ritz method, and an experimental method, the damping capacity and frequency of the fiber reinforced plastic composite plate with (0, 90, 0, 90)s cross-ply were compared at room temperature. Thermal and morphological characteristics of E-glass/Kevlar 49-reinforced siliconized epoxy composites were studied by Alagar et al. (2000). Variations with temperature of the tangent and storage modulus of maleic anhydride compatibilized short glass fiber/SEBS/polypropylene hybrid composites were investigated by Tjong et al. (2002). A study by Kim and Hwang (2002) examined the effect of debonding on the natural frequency and flexural rigidity, and on the changes in frequency response functions of sandwich beams. The elastic modulus of resin-based materials was determined as a function of the resonance frequency during polymerization by Meredith (1999). Also using an experimental method, the dynamic Young's modulus and damping factors for a Kevlar 49 fabric-reinforced polyester composite material were investigated (Wallace and Bert, 1979). Vinylester-resin-matrix composites reinforced with untreated and 5% NaOH-treated jute fibers with different fiber loading were subjected to dynamic mechanical and thermal analysis to determine their dynamic properties as a function of temperature (Ray et al., 2002). The storage modulus of all the examined composites decreased with increasing temperature, with a significant fall in the temperature range of 110-170 °C. Sefrani and Berthelot (2006) experimentally analyzed the effect of temperature on the damping properties of unidirectional glass fiber composites as a function of the frequency and fiber orientation using a cantilever beam test specimen and an impulse technique. They also performed an analytical calculation and evaluated the damping as a function of temperature using the Ritz method. Characterizing the damping properties of interleaved carbon-fiber/epoxy laminates, such as polyurethane elastomers, polyamide elastomers, and polyethylene-based ionomers, was the main objective of Kishi et al. (2004). Wei and Kukureka (2000) evaluated the damping and elastic properties of composites and composite structures experimentally by the resonance technique. The dynamic mechanical behavior of natural rubber and its composites reinforced with short coir fibers was studied by Geethamma et al. (2005). The elastic and tangent modulus against temperature was examined. It was found that there is a nonlinear relationship between the loss factor and temperature. Finally, Lopez-Manchado and Arroyo (2000) studied the thermal and dynamic mechanical properties of polypropylene and short organic fiber composites. The elastic modulus and the loss factor against temperature were also investigated. As a result, the studies concentrated on the dynamical behavior of polymer matrix composites under room temperature and/or varied temperature, but none of them examined polyethylene fiber composites. The researchers used several experimental techniques for the damping analysis. Some of them used analytical techniques to further analyze and model the behavior.

The objective of this study is to investigate the damping and frequency properties of polyethylene fiber composite under varied temperature. For this purpose, the tension test is first applied to the specimens to obtain the mechanical properties of the composite laminate. Then, the temperature-dependent frequency response is analyzed experimentally using a damping monitoring technique (Çolakoğlu and Jerina, 2003), and the damping factor and natural frequency are measured. In the experiment, 15 different temperatures were considered from –10 to 60 °C. The composite beam is also modeled numerically by the finite element method using the ANSYS program. To compare the numerical and experimental results, an impact load and damping factor, which are obtained experimentally, are added to the model. It is found that the numerical and experimental frequency responses are in good agreement.

Experimental and numerical methods

Materials

Polyethylene fiber composite (UHMW-PE UD-HB2) manufactured by Dyneema Company is used in the experiment. Every lamina of polyethylene has 0- and 90-degree fiber layers on it; therefore, the elastic modulus of the lamina is the same in the x and y directions ($E_x = E_y$). Composite beam specimens are pressed at 125 °C under 200 bar pressure, for a total pressing time of approximately 30 min.

Firstly, specimens are subjected to a tension test to obtain mechanical properties. Results for fiber and polyethylene laminate are shown in Table 1. Although polyethylene fibers are an almost perfectly linear elastic material, laminate specimens have a non-linear elastic structure and the elastic modulus decreases from 115 to 25.5 GPa due to the effect of the polymer matrix resin and fabrication. The elastic modulus is calculated using tensile strength and elongation, and it is regarded as linear up to this point. The measured, calculated, and numerically determined frequencies prove that the accuracy of this elastic modulus is almost perfect, as seen in Table 2.

The experiment was performed with 10-layered beam specimens. The length (L) and width (w) of the beams are 300 and 30 mm, respectively. The thickness (t) of the polyethylene specimens is between 2.8 and 2.9 mm. An impact load is applied to the specimen to induce vibration using a spherical steel ball hammer (see Figure 1). To measure the magnitude of the impact load, a strain gauge placed on the mid-point of the specimen, a strain gauge conditioner, and a voltmeter are used. The measured magnitude is between 3.5 and 4 N. This load level is also used in the numerical investigation to obtain the frequency response, and the numerical and experimental results are compared. The impact load is taken to be 3.65 N in the numerical investigation.

Measurement of damping

The damping factor and natural frequencies are measured experimentally from the frequency response using a damping monitoring technique (Çolakoğlu, 2003). In this process, the specimen is attached to a platform using a thin wire to measure the damping factor and natural frequency at free-free boundary conditions, as shown in Figure 1. The accelerometer is placed just below the mid-point to measure the peak of the second vibration mode. A vibration is induced in the specimen using a small steel ball hammer. The accelerometer (PCB 336C) measures the vibration and produces an electrical signal that is amplified by the charge amplifier (PCB 482 B11), which is then input to the computer. The amplified signal is measured with a Gravis ultrasound card for data acquisition. A Fast Fourier Transform (FFT) is performed for the signal and the software measures the lateral natural vibration modes. This damping monitoring device has 2 different programs: the first

Table 1. Mechanical properties of polyethylene fiber composite.

Materials	Type	Modulus (GPa)	Density ρ(kg/m^3)	Tensile Strength(MPa)	Failure Strain (%)
Polyethylene	Fiber	$E_1 = 115$	970	$\sigma_1 = 3500$	$\varepsilon_1 = 3.5$
	Laminate	$E_1 = 25.5$ $E_2 = 25.5$ $E_3 = 3.4$	900	$\sigma_1 = 860$ $\sigma_2 = 860$	$\varepsilon_1 = 8$ $\varepsilon_2 = 8$

Table 2. The first natural vibration modes of polyethylene fiber composite beam under varied temperature (the size of the specimen used in the measurement is 2.9 × 30 × 301 mm^3).

Temperature (°C)	Measured f_1 (Hz)	Analytical f_1 (Hz)	Numerical f_1 (Hz)
60	168.81	169.29	169.06
55	169.46	169.65	169.41
50	170.44	170.22	169.98
45	171.26	170.99	170.76
40	171.5	171.98	171.74
35	172.7	173.17	172.93
30	174.42	174.55	174.31
25	175.17	175.34	175.1
20	177.73	177.87	177.63
15	179.04	179.83	179.58
10	182.37	181.96	181.71
5	185.42	184.26	184.01
0	187.08	186.73	186.48
–5	190.18	189.36	189.1
–10	190.74	192.11	191.85

controls the hardware and the second is used to obtain frequency response from the time response using the FFT. The computer also determines the damping factor from the induced vibration by the half-power bandwidth method using a curve fitting technique.

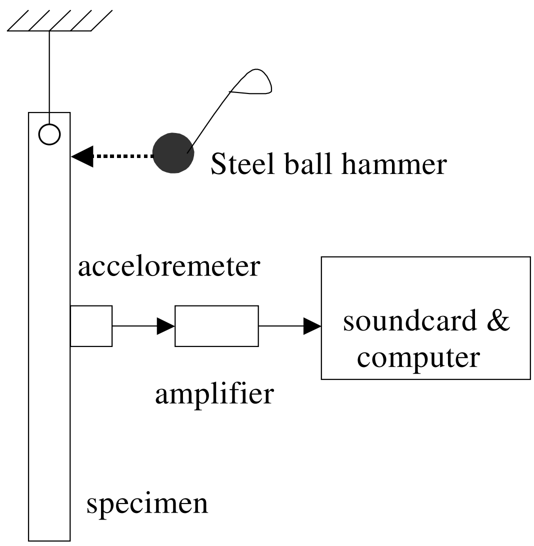

Figure 1. Measurement of the frequency response curve using the damping monitoring method.

Numerical analysis

Two different analyses, modal and harmonic, are carried out with ANSYS 9.0 finite element software. The linear elastic orthotropic model is used to investigate the cloth composite laminated beam. Only the elastic modulus of the laminate is necessary for the beam analysis. Mechanical properties of the composite beams are taken from Table 1. For this problem, the BEAM3 (Beam 2D elastic) element is used. This element has 3 degrees of freedom (translation along the X and Y axes, and rotation about the Z axis). To determine the natural frequencies, modal analysis is carried out using the subspace method with ANSYS in free-free boundary conditions. Harmonic analysis is also investigated to numerically obtain frequency response. The stepped load method is used to describe the response curve with 3.65 N load, which is also applied to the specimen experimentally, as explained in the Materials section. The number of substeps is taken to be 300 in the analysis for the 0-750 Hz frequency range. Finally, the measured damping factor is applied to the model to compare both frequency responses.

Theory

Lateral vibration of a beam can be derived from the Euler-Bernoulli equation (Dimaragonas, 1996). Using the free-free boundary conditions, the solution gives the frequency equation for the lateral vibration of the beam as

$$f_i = \frac{\beta_i^2}{2\pi L^2}\sqrt{\frac{EI}{\rho \mathrm{A}}} \tag{1}$$

where L is the length of the beam, E is the elastic modulus, I is the moment of inertia, A is the cross sectional area, and ρ is the density. In addition, β_i is a constant dependent on the boundary conditions, and i = 1, 2 ... n are the natural frequency modes. At free-free boundary conditions, $\beta_1 = 4.73$, $\beta_2 = 7.853$, and $\beta_3 = 10.996$ for the first, second, and third natural frequencies, respectively. To calculate the elastic modulus from the measured frequency response curve and to compare it with the result from tension test, E is derived as

$$E = \frac{\rho\, \mathrm{A}L^4}{I\beta_i^4}(2\pi\, f_i)^2 \tag{2}$$

Results and Discussion

Table 2 shows the first natural frequencies under varied temperature for a polyethylene fiber composite beam. The damping factor and natural frequency are experimentally measured 10 times for each temperature using the damping monitoring method in free-free boundary conditions. The mean of the measured results is shown in Table 2 and Figure 2. In addition, the numerical results in Table 2 are found by finite element analysis and analytical data are calculated using Eq. (1). To get analytical and numerical frequencies, the elastic modulus is calculated using Eq. (2), and those results are normalized using a second-order polynomial curve-fit equation. It is seen that polyethylene fiber composite is a temperature-dependent material. In addition, the numerical, analytical, and experimental results are in good agreement. The first natural frequency decreases with increasing temperature. There is also a functional relationship between temperature and the damping factor, but there is an inverse relationship between temperature and frequency, as seen in Figure 2. The damping factor in polyethylene fiber composite beam varies from approximately 0.0725 at –10 °C to 0.02 at 60 °C.

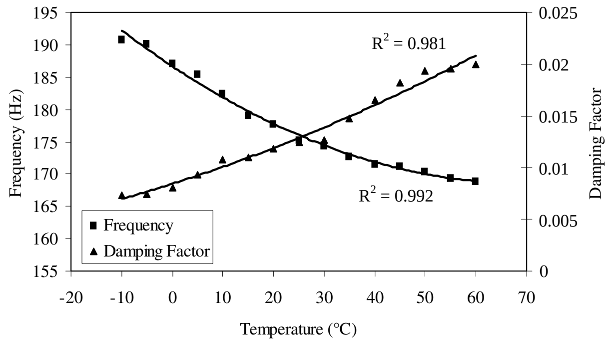

Figure 2. Variation in the damping factor and natural frequency in a polyethylene fiber composite beam specimen under varied temperature.

The mean of the first natural frequency of polyethylene fiber composite is $f_1 = 175.17$ Hz and the corresponding damping factor is $\zeta_1 = 0.0124$ at 25 °C. Those values for a 1018 hot-rolled carbon steel beam with different size are measured as $f_1 = 65$ Hz and $\zeta_1 = 0.0044$ (Çolakoğlu, 2001). $f_1\zeta_1$ gives a constant independent of beam size to compare the damping capacity with other materials. This constant for polyethylene is approximately 7.6 times more than that of the 1018 hot-rolled carbon steel beam.

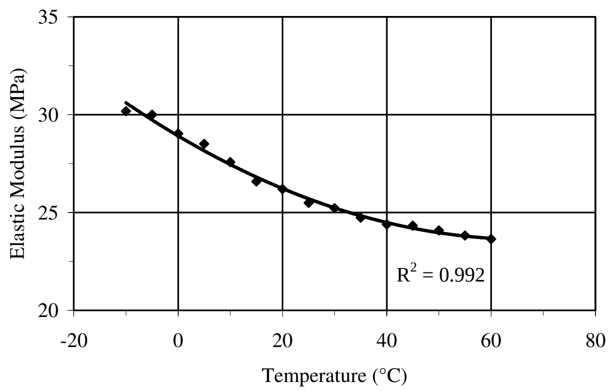

Figure 3. Temperature-dependent variation in elastic modulus of polyethylene fiber composite.

Another investigation in this study is the temperature-dependent elastic modulus (E) of polyethylene fiber composite, which is 25.6 GPa at room temperature. Using Eq. (2), E is also calculated from the frequency response curve. It is determined to be E = 25.5 GPa, which is in perfect agreement with the experiment. The temperature-dependent variation of E is shown in Figure 3. It is seen that both E and the natural frequency decrease with increasing temperature.

The output of the measured frequency response is shown in Figure 4, in free-free boundary conditions. It shows peaks, which correspond to the natural frequencies of the composite beam. Only the first and second peaks of the natural frequency are seen in Figure 4. The responses are measured more than 10 times and one of the best signals is used in this study. In this case, the damping is deduced from the half-power bandwidth. Moreover, the mean of the measured natural frequencies and damping factors are recorded as data. In addition, the measurement of the damping factor for the first frequency peak using the damping monitoring device is shown in Figure 5. Numerically modeled frequency response is also analyzed. Figure 6 shows the ANSYS output signal. In this process, the experimentally applied load, 3.65 N, and the measured damping factor are used in the numeric model to compare both frequency responses. As seen in Figures 4 and 6, the experimental and numerical results are in good agreement. Simultaneously, the first peak amplitude and the first natural frequency mode of the beam specimen are chosen to compare the experimental and numerical results, and they almost match perfectly (Figure 7). Finally, Figure 8 shows the response of the first natural frequency of the composite beam obtained for 3 different temperatures (–10, 25, and 60 °C). The natural frequency decreases when the test temperature is increased, but the damping factor increases. In addition, similar to the natural frequency, the peak amplitude decreases with increasing temperature.

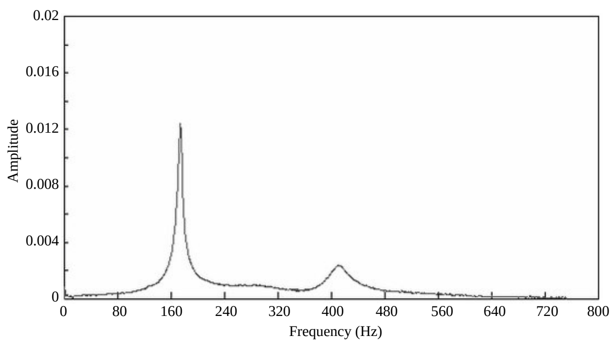

Figure 4. Measured frequency response curve for a polyethylene fiber composite beam specimen at room temperature.

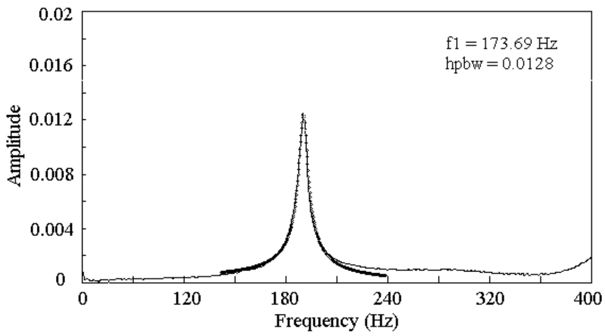

Figure 5. Measurement of the damping factor for the first natural vibration mode.

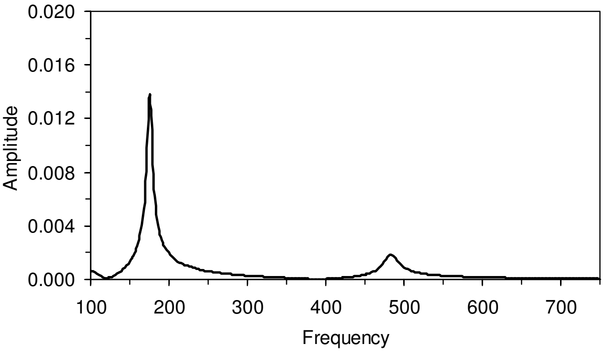

Figure 6. Numerical frequency response curve for the polyethylene fiber composite beam specimen at room temperature.

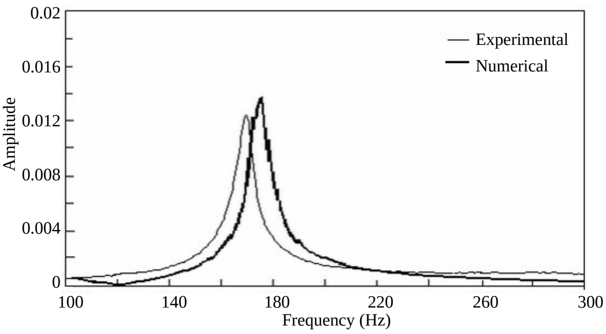

Figure 7. Comparison of the experimental and numerical frequency response curves for the first vibration mode at 25 °C.

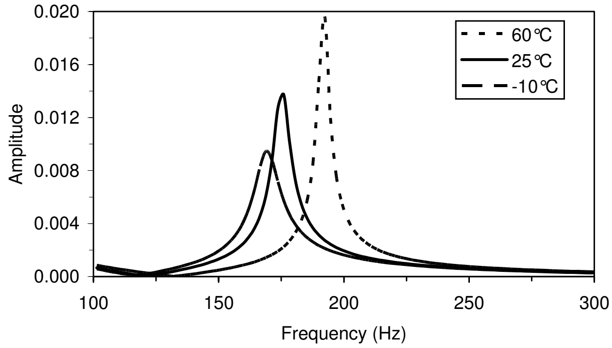

Figure 8. Comparison of the numerical frequency response curves for the first vibration mode at –10, 25, and 60 °C.

Conclusions

The damping behavior of polyethylene fiber composite is investigated experimentally and numerically in this study. The effect of temperature on the natural frequency and the damping factor are analyzed because polymer matrix composites have temperature-dependent mechanical properties. It is observed that the elastic modulus, frequency, and damping factor vary with temperature, but that functional relationships are different. The natural frequency decreases with increasing temperature and a similar effect is seen for the variation in the elastic modulus. On the other hand, the damping factor has an inverse relationship with frequency. Finally, the experimentally measured and numerically modeled frequency responses are examined. Experimental data are used in numeric analysis. It is seen that the frequency peaks, damping factors, and amplitudes in the frequency response are in good agreement. As a result, having found the material properties of polyethylene fiber composite experimentally, the numerical method could be used to determine the dynamic behavior of complex structures.

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