IDENTIFYING THE TEMPERATURE EFFECT ON THE DAMPED RESPONSE OF COMPOSITE BEAMS USING PIEZOCERAMIC ACTUATORS AND SENSORS

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ABSTRACT

Polymer-matrix composites are known to exhibit high and anisotropic material damping drastically affected due to environmental conditions. In order to efficiently study the effect of temperature on composite damping a new experimental framework is developed. A small circular piezoelectric actuator is used to excite composite beam specimens of various fiber orientations. The compliance of each specimen is measured with a small piezoceramic sensor and frequency response functions are calculated. Additionally, the experiment's temperature is continuously acquired. Modal frequencies and damping are estimated through correlation with a parametric model for a wide temperature range. The elastic properties are extracted through fitting with experimental data and composite damping coefficients are back-calculated using composite damping mechanics. Measured values illustrate the effect of temperature on the damped dynamic response of the composite beam specimens.

1. INTRODUCTION

Passive damping is a critical parameter in lightweight structures requiring tight vibration control, high fatigue endurance, impact resistance, aeroelastic stability and accurate positioning of devices and sensors. Polymer matrix composites are known to exhibit higher material damping compared with the most common metals, as a result of their polymer matrix and their inherent heterogeneity. Increased use of those materials in various environmental conditions signifies the need for a fast and reliable technique for mechanical and damping property measurement under any circumstances. The development of a damping measurement system implementing embedded or on-board actuators and sensors having minimum interference on the dynamic characteristics under varying environmental conditions is technically appealing.

Substantial analytical and experimental work has been reported on damping mechanics of composite laminates and damping characterization, e.g. Ni and Adams [1], Gibson and Plunkett [2], Yang and Gibson [3] and Wren and Kinra [4]. Saravanos and Chamis [5] studied the hygrothermal effect on the damped dynamic characteristic of composite beams and Lee and Saravanos [6] analyzed the temperature effect on piezoelectric composite plates. While the effect of low temperatures on the damped dynamic response of composite structures has been studied, very little experimental work has been reported regarding the temperature effect on composite damping and/or the damped dynamic response of smart composite structures. The current paper presents a mostly experimental work detecting the effect of lower than room temperatures on the damped dynamic characteristics of smart composite beams. The beams are self-excited and self-monitored using a pair of piezoelectric actuator and sensor. Emphasis is given on capturing the effect of temperature on the damping of the composite beams, while its effect on the elastic properties is also investigated.

2. EXPERIMENTAL CONFIGURATION AND MATERIALS

Off-axis composite beams were tested in nearly free-free configurations in order to minimize damping due to friction in the supports. Specimens were supported with strings attached

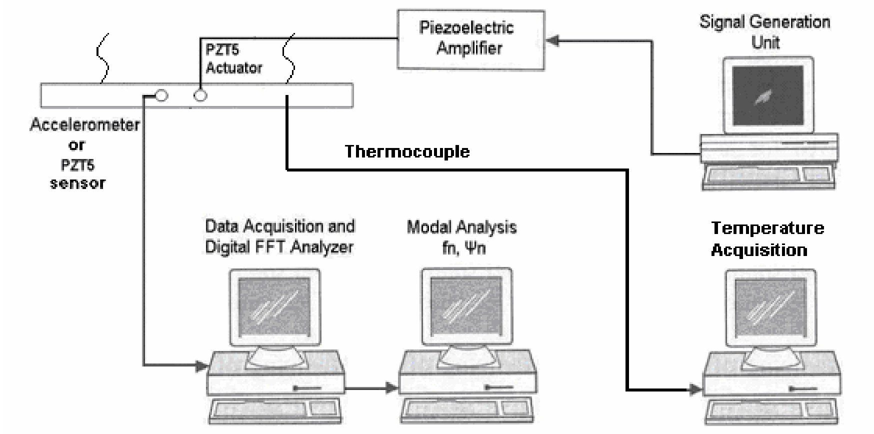

Fig. 1. Experimental setup

approximately at the modal lines of the first bending mode. A virtual instrument was developed based on Labview® to digitally generate swept-sine excitation functions with frequency range between 1Hz and 2.5 KHz, which was converted to analog signal using a 16 bit DAQ card. The actuator signal was amplified through a voltage amplifier and then applied across the terminals of a piezoceramic PZT5 disk with 12.7mm diameter and 0.5mm thickness, epoxied on the surface, at the center of the composite beam. The response of the beam was measured using a second PZT5 disc of same properties epoxied at the center of the specimen surface. The applied voltage at the terminals of the piezoactuator as well as the voltage measured at the piezosensor were digitized through a high speed DAQ card and processed using FFT software to obtain the frequency response functions (FRF) of the beam. The measured FRFs were further correlated using a parametric model consisting of a series of known complex exponential terms, each term approximating an individual mode with unknown modal parameters. In this manner the modal flexural frequencies and damping coefficients of the tested system were measured, such that the least squares error between the model and measured frequency response functions was minimized. Figure 1 presents the experimental setup.

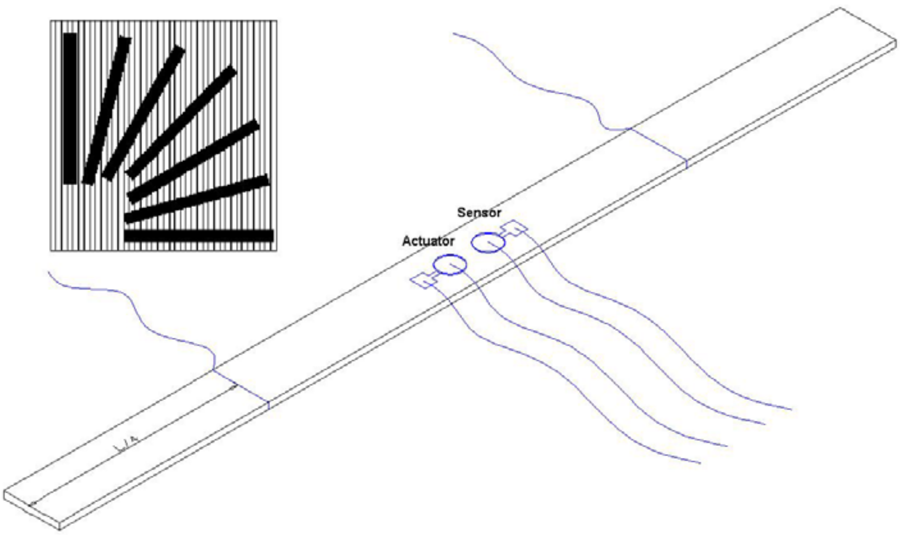

Fig 2. Sample Specimen

Additionally, in order to measure the environmental and surface temperature during the tests, flexible and sensitive thermocouples were used. Thermocouples having a diameter of 0.20mm and a constant mean time-response of 0.05sec were attached on the surface of each specimen, approximately at the modal points of the first bending mode, in order to achieve the minimum disturbance on the beam's free vibration. Another thermocouple was measuring the environmental temperature in the freezer or the refrigerator. Temperature data were amplified and then digitized using the DAQ card. While testing each beam, temperature data were acquired and stored for further processing.

All tested specimens were 3-ply-Glass-Polyester composite beams. An isofthalic polyester resin was used during the fabrication. The set of specimens used consisted of seven composite beams (Fig. 2) with fiber orientation angles of 0^o to 90^o by 15^o increments ($[0]_3$, $[15]_3$, $[30]_3$, $[45]_3$, $[60]_3$, $[75]_3$ and $[90]_3$). All tested beams were 450mm long, 30mm wide and had a nominal thickness of about 1.033mm. In order to record the effect of environmental parameters on the isofthalic matrix, another beam made of pure polyester resin was tested. This specimen was 750mm long, 20mm wide and had a mean thickness of about 2mm. For the imposition of low temperatures all specimens were issued in a common freezer or refrigerator at least 10 hours before testing in order to obtain a unique temperature through the specimens' thickness. The entire testing configuration was designed in such manner that in low temperatures the freezer remained closed in order to avoid interference of the measured system with the environment. Due to the long remaining of the specimens at low temperatures before testing, the difference between the measured surface and environmental temperature during the testing was negligible.

3. MEASUREMENT OF DAMPING COEFFICIENTS

This section describes briefly the composite damping mechanics required for the extraction of the basic damping coefficients of a composite material.

On-axis Ply Damping. The material coordinate system indicated with subscripts 1,2,3 with axis 1 parallel to the fibers and axis 3 through-thickness. It is assumed that the damping of the composite on the material coordinate system is orthotropic (in planes 1-2 and 1-3), described by six damping (loss) coefficients, [4]: (1) longitudinal loss coefficient, η_{l1} (direction 11); (2) transverse in-plane loss coefficient, η_{l2} (direction 22); (3) transverse through the thickness loss coefficient, η_{l3} (direction 33); (4) in plane shear loss coefficient, η_{l6} (direction 12); (5) interlaminar shear loss coefficient, η_{l4} (direction 23); and (6) interlaminar shear loss coefficient, η_{l5} (direction 13). We can further assume transverse isotropy on the 2-3 plane, which reduces the independent coefficients to four ($\eta_{l3} = \eta_{l2}$, $\eta_{l5} = \eta_{l6}$). For a material loaded in the plane of the ply the on-axis damping matrix $[\eta_l]$ is:

$$[n_l] = \begin{bmatrix} n_{l_1} & 0 & 0 \\ 0 & n_{l_2} & 0 \\ 0 & 0 & n_{l_6} \end{bmatrix} \tag{1}$$

Off-axis Ply Damping. For the case of rotated (off-axis) composites, which are loaded in-plane, the equivalent damping capacity of the composite in the structural coordinate system xyz is best described by the following off-axis damping matrix $[n_c]$

$$[n_c] = \begin{bmatrix} n_{c_{11}} & n_{c_{12}} & n_{c_{16}} \\ n_{c_{21}} & n_{c_{22}} & n_{c_{26}} \\ n_{c_{61}} & n_{c_{62}} & n_{c_{36}} \end{bmatrix} \tag{2}$$

which is provided by the following transformation:

$$[\eta_c] = [R]^T [\eta_l] [R]^{-T} \tag{3}$$

where η indicates loss factor and [R] are the ply rotation matrices.

Laminate Damping. The damping matrices, $[A_d]$, $[B_d]$ and $[D_d]$ representing the extensional, coupling and bending damping matrices, respectively, are calculated using the following expressions [4]:

$$[A_d] = 2\pi \sum_{k=1}^{N} \int_{h_{k-1}}^{h_k} [Q_c]_k \ [n_c]_k \, dz \tag{4}$$

$$[B_d] = 2\pi \sum_{k=1}^{N} \int_{h_{k-1}}^{h_k} \left([Q_c]_k \ [n_c]_k \right)_{in} z dz \tag{5}$$

$$[D_d] = 2\pi \sum_{k=1}^{N} \int_{h_{k-1}}^{h_k} \left([Q_c]_k \ [n_c]_k \right)_{in} z^2 dz \tag{6}$$

Where [Qc] is the off axis stiffness matrix. The laminate damping is measured using the equation:

$$n_L = \frac{1}{2\pi} \frac{\Delta W_L}{W_L} \tag{7}$$

Assuming that we have off-axis composites subjected to pure bending, $Mx \neq 0$, $M_y=M_{xy}=N_x=N_y=N_{xy}=0$, then $[B]=[B_d]=0$ and $\varepsilon^0=0$, thus

$$\{k\} = [D]^{-1} \begin{Bmatrix} M_x \\ 0 \\ 0 \end{Bmatrix} \tag{8}$$

where k is the curvature vector and [D] is the bending stiffness matrix of a laminated beam. The dissipated and maximum stored strain energies, ΔWL and WL respectively take the form:

$$\Delta W_L = \frac{1}{2} \{k_x\}^T \cdot [D_d] \cdot \{k_x\} \tag{9}$$

and,

$$W_L = \frac{1}{2} \{k_x\}^T \cdot [D] \cdot \{k_x\} \tag{10}$$

Equation (7) ultimately relates the flexural damping of the off-axis specimen to the ply angle and damping coefficients through equations (8-10),(6),(3) and (1).The flexural modal damping provided by equations (7),(9-10) and (1),(3) is correlated with measured damping of composite specimens with various fiber orientation angles using a least squares fitting method.

4. RESULTS

Seven off-axis specimens with fiber angles incrementing by 15 degrees were cut from a UD plate and tested using a small circular piezoelectric actuator attached to the middle of the span. A second piezosensor with the same characteristics was measuring the specimens' vibration. During the tests 5 different temperature levels were selected: the first one, 23.5^{o}C, was the room temperature, the second, 7.6^{o}C, was the temperature of a common refrigerator and -1, -14.8,-28.2 ^{o}C were three temperature levels obtained during the test in the freezer. These temperatures are the mean values acquired during the testing. All seven specimens were put together in the freezer or the refrigerator in order to obtain the same reference environmental conditions for every one. The measured values of the damping ratio versus frequency as a function of the environmental conditions for every one of the seven specimens are presented in Fig. 3.

These plots illustrate a reduction in damping ratio values with decrease of the temperature. The specimens' damping values become more sensitive to the environmental conditions as the fiber orientation angle increases from 0 to 90 degrees. The $[0]_3$ specimen is completely insensitive to the environmental conditions. In contrast, the matrix oriented specimens are strongly affected. However, the reduction in damping is mainly observed between the environmental temperature (23.5 ^{o}C) and the others. The curves describing the damping ratio values versus frequency for temperatures between 7.6 and -28.2 ^{o}C remain together without a significant decrease between them. These curves intersect in some cases and don't have a uniform variation as does the curve representing the room temperature. This trend is probably owed to the fact that the moisture inside the refrigerator and the freezer is too high compared with the rooms' moisture and is not taken into account. In addition, the piezoceramic actuators and sensors were attached on the specimens' surface using epoxy adhesive with unknown characteristics at low temperatures.

A specimen fabricated with pure isofthalic matrix was tested in various temperatures in the same way as described above. Fig. 4 presents the measured values. The trend observed in this case is the same as in the previous one and reinforces the conclusion that the damping is mainly a function of the matrix. Fig. 5 and 6 present the first bending frequency or the damping ratio value of the first mode, respectively, versus the fiber orientation angle in each one of the discrete temperature levels. Figure 5 shows a gradual increase at the first modal frequency with temperature decrease. All curves follow the same trend. Fig. 6 illustrates a reduction at the measured damping ratio values with temperature decrease. In Fig. 6 the reduction is not as clear as it was for the frequencies, some bad points exist and in some cases (28.2 ^{o}C) intersection between the curves is observed. Overall, the results indicate a gradual increase of the specimens' stiffness as the temperature becomes lower, which causes this increase at the modal frequencies and reduction at the damping ratio values.

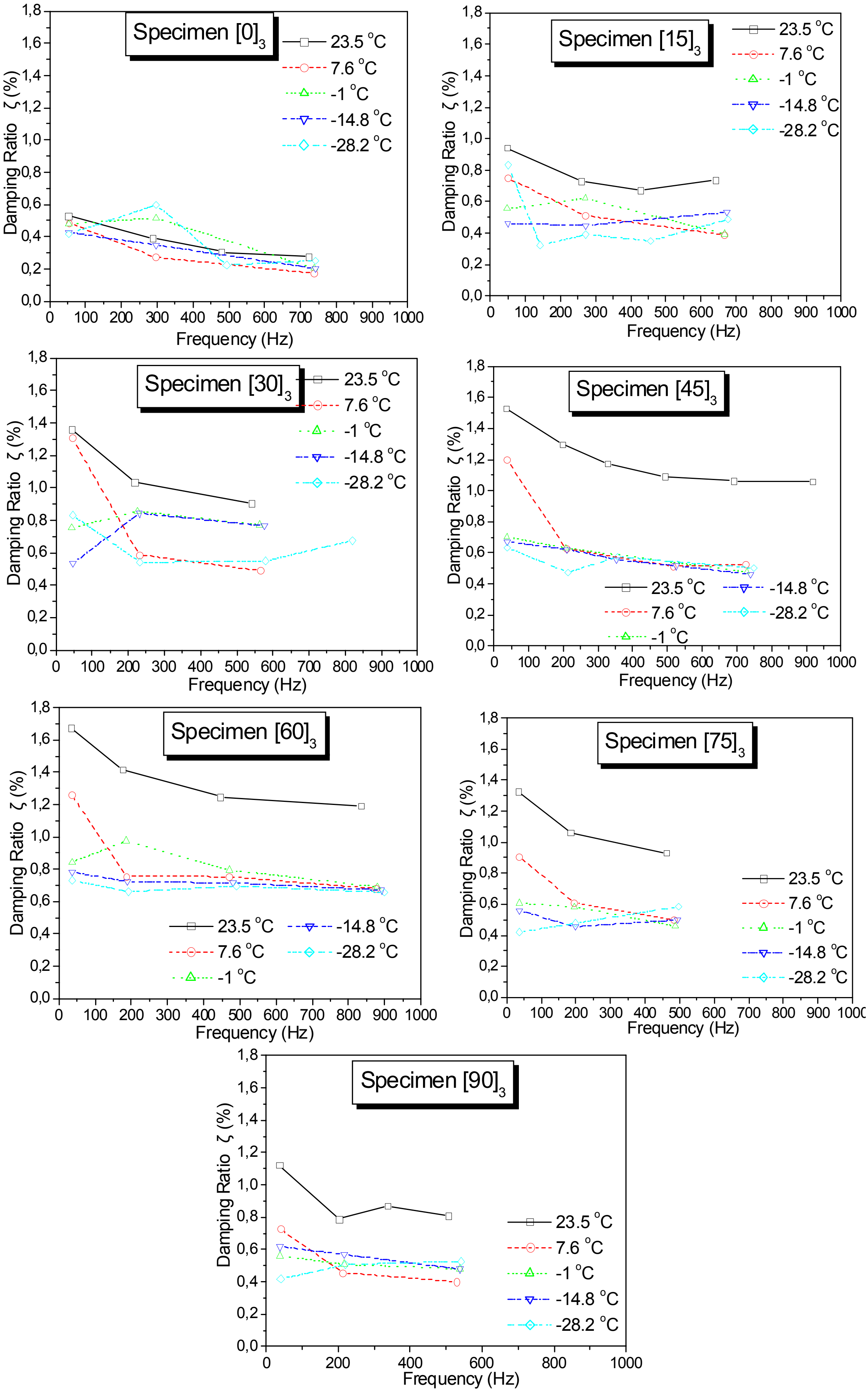

Fig 3. Damping ratio ζ versus frequency as a function of the temperature for every specimen.

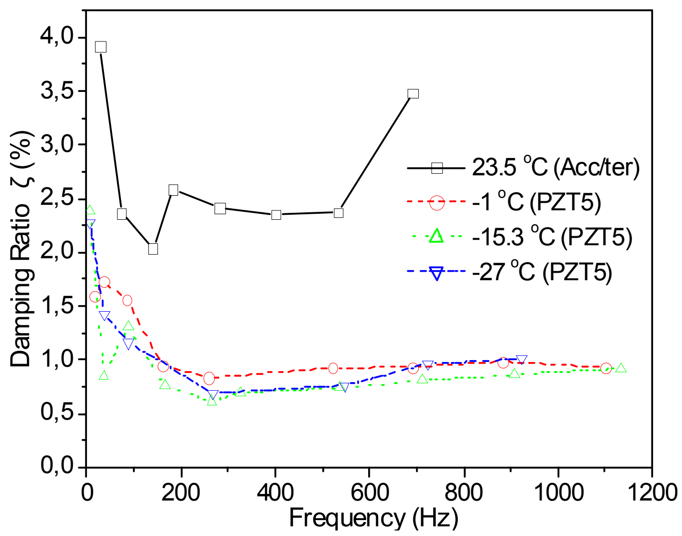

Fig 4. Damping ratio versus frequency for the isofthalic matrix

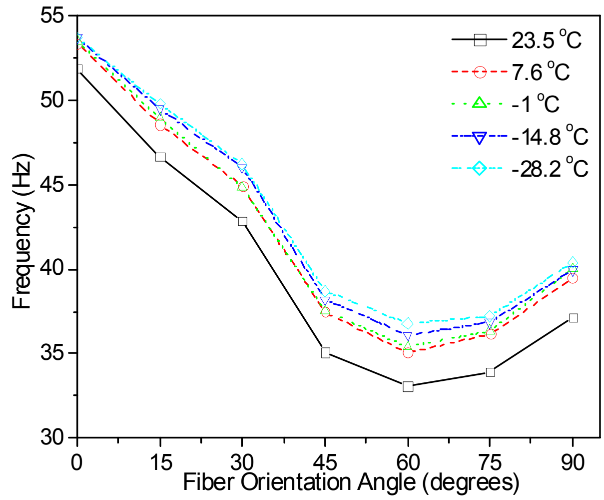

Fig 5. First bending frequency versus fiber orientation angle for each temperature level

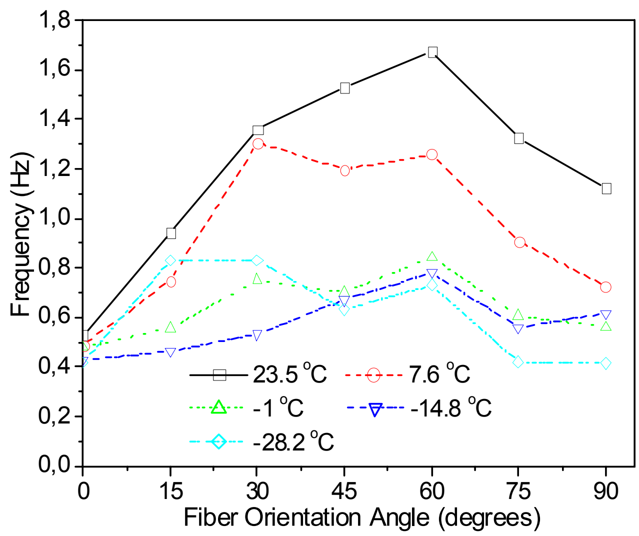

Fig 6. Damping ratio of the first bending frequency versus the fiber orientation angle for the five discrete temperatures.

Using the data presented in Fig. 5 the equivalent elasticity modulus values (flexural E_{11}, bending E_{22} , shear G_{12} and Poisson ratio v_{12}) are extracted for every temperature. Based on the methodology described above and using the previously extracted elasticity modulus and the values of the figure 6 the damping coefficients (longitudinal ζ_{l1}, transverse ζ_{l2} and shear ζ_{l6}) are extracted after the least squares fitting for every one of the temperature stages. The extracted values are presented at tables 1 and 2. Figures 7 and 8 illustrate the relative values of the equivalent elasticity modulus and damping coefficients as a function of temperature stage.

Table1. Extracted elastic properties of the first bending mode for every temperature

Mean Temperature (°C)	E_{11} (GPa)	E_{22}(GPa)	G_{12} (GPa)	v_{12}
23.5	11.702	5.441	2.076	0.309
7.6	12.407	6.159	2.297	0.349
-1	12.510	6.318	2.288	0.352
-14.8	12.595	6.315	2.435	0.378
-28.2	12.625	6.474	2.476	0.389

Table2. Extracted damping coefficients of the first bending mode for every temperature

Mean Temperature (°C)	ζ_{l1} (%)	ζ_{l2} (%)	ζ_{l6} (%)
23.5	0.0588	0.1517	0.2302
7.6	0.0433	0.0945	0.2045
-1	0.0578	0.0730	0.1104
-14.8	0.0495	0.0774	0.0894
-28.2	0.0717	0.0479	0.1179

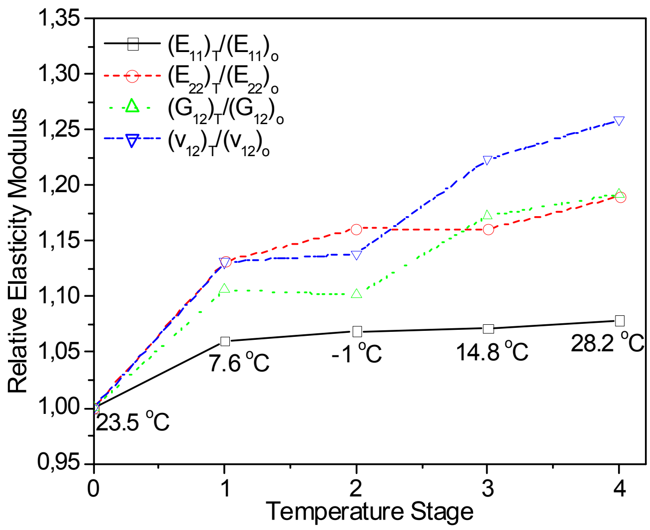

Fig.7. Effect of temperature on the relative equivalent modulus (o refers to the room temperature)

An increase in the equivalent elasticity modulus is observed with the temperature reduction representing the increase at the stiffness of the composite material at lower temperature levels. The more insensitive elastic property is the flexural elasticity modulus E_{11}, whose value is not a function of the polymer matrix. Similar results are presented in Fig. 8, where the transverse ζ_{l2} and shear ζ_{l6} damping coefficients decrease at lower temperature levels.

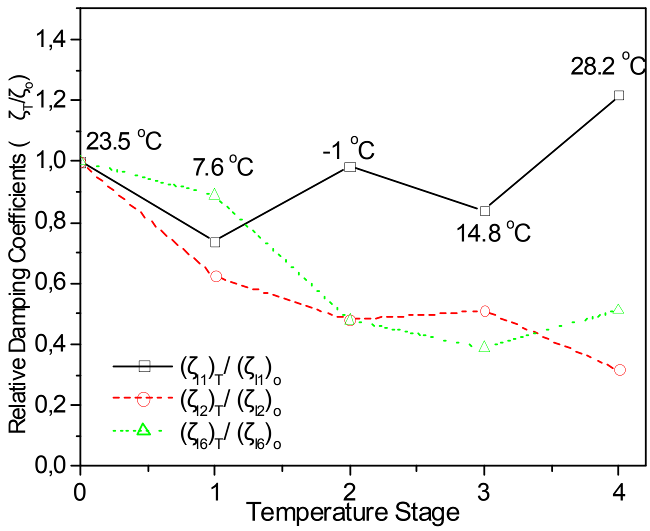

Fig 8. Effect of temperature on the extracted values of damping coefficients (o refers to the damping coefficients extracted using the measured values at the room environmental conditions)

5. SUMMARY

An experimental procedure utilizing piezoelectric actuator and sensor was presented for measuring the damping of composite beam specimens in room and low temperatures. This technique has many advantages including minimum interference of the measured system with the outer environment and high portability. The experimental framework indicated the ability of piezoceramics to work as sensors or actuators under low temperatures allowing minimum disturbance of the vibrated system. The effect of low temperatures on the measured modal frequencies and damping coefficients was recorded and compared with results at room temperature. Overall, the stiffness of the specimens was increased and their damping was decreased with decreasing temperature. The same trend was recorded at the extracted values of the equivalent elasticity modulus and damping coefficients, which have offered a better illustration of the temperature effect on the material's elastic and damping properties. The results did not reveal a significant change in damping between low temperature levels, which may be attributed to other environmental conditions like moisture, which are not taken into account in the current experimental methodology. Due to the fact that this is a work in process the need for additional experimental and analytical work has arisen, which will take into account more environmental parameters.

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