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STUDY ON PIEZO-DAMPING CYANATE MODIFIED EPOXY MATRIX GLASS FIBRE COMPOSITE WITH LEAD ZIRCONATE TITANATE

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ABSTRACT

Mechanical properties of piezo-damping cyanate modified epoxy matrix glass fibre composite are investigated under 60% cyanate ester with varied lead zirconate titanate. The mechanical properties like tensile strength, flexural strength and fracture toughness are measured as per ASTM D3039, D790 and D5528, respectively. Epoxy/glass fibre with 60% cyanate loading (60EPCY) with good mechanical properties is the system chosen for varying load of PZT material (0%, 10%, 20% and 30%). Finite element method is used to measure frequency response, damping factor were obtained for piezo-damping cyanate modified epoxy matrix glass fibre composite.

Keywords: glass fibre composite, damping, vibration, frequency, fracture toughness.

INTRODUCTION

Damping materials are routinely used in engineering applications to reduce the vibrational level in structural components. Viscoelastic materials have been extensively used for that purpose. However, the mechanical property of viscoelastic materials is so low that they cannot be used directly in engineering application. In order to get a structural and functional material, researchers have made great efforts to study fiber reinforced composites, which were reported in reference [1]. But the results in reference demonstrated that the damping of most composites decrease while their mechanical properties increase. The purpose of this paper is to improve the mechanical property and damping property of the composite simultaneously by designing its component and structure.

It is well known that the reinforcement can improve the mechanical property of the composite greatly. The damping property of the composite may also be improved, if the reinforcement is chosen properly and combined with the matrix in a special way to make varied damping mechanisms playing roles together in composite. In this paper, a quarternary composite is designed, called glass fiber reinforced PZT loaded cyanate modified epoxy composite.

Epoxy resin is widely used matrix material for composite applications. But the main drawback is its high brittleness. In order to improve the toughness of epoxy resin system an inherently tough cyanate ester resin is used [2]. This resin blend has very good mechanical properties when compared with rubbers. The damping property of the composite is improved by incorporation of PZT ceramic powder [3].

Thus the work presented in this paper throws light on studying the mechanical and damping properties of the quarternary composite with varying cyanate and PZT loading and analyzing their effect on cyanate and PZT loading on the properties.

MATERIALS AND METHODS

Materials

Epoxy resin LY556 (diglycidyl ether of bis phenol A), curing agent HT972 (DDM - diamino diphenyl methane), Arocy b10 (bis phenol dicyanate), E-glass fibre and lead zirconate titanate (PZT). All chemicals were used as purchased.

Fabrication of polymer composite laminates

The composites are fabricated from E-glass fiber and commercial epoxy resin/cyanate modified epoxy resin. The glass fiber with an aerial density of 200 g/m^2 was used as the reinforcement for composite laminate. The liquid epoxy was taken in a beaker, which was heated to 90^{o}C to lower the resin viscosity and desired amount of cyanate was added into resin. The Cyanate loading was varied between 0%, 20%, 40% and 60% by weight of epoxy resin (Table-1). The mixture was degassed in a vacuum oven followed by addition of DDM (curing agent) in 27% by weight of epoxy and stirred for 3 minutes at 90^{o}C. A steel cylindrical mould was coated with silicone release agent and then a layer of the resin was applied using a brush.

Necessary precautions were taken to keep the fabric well aligned. This process was repeated to construct a 14 ply laminate. The fabricated sheet was then cured at 120^{0}C for 1 hour and 180^{o}C for 1 hour in a hydraulic press. The laminate was then demoulded and post cured at 220^{o}C for 1 hour an oven [4]. A similar procedure was carried out for PZT with 10%, 20% and 30% loading with 60EPCY system (Table-1).

Table-1. Material composition (Lead Zirconate Titanate (PZT) loading).

Code name	**Epoxy** (g)	**Cyanate** (g)	**PZT** (g)	**DDM** (g)
60EPCY	100	60	--	27
60EPCY10PI	100	60	16	27
60EPCY20PI	100	60	32	27
60EPCY30PI	100	60	48	27

The tensile and flexural properties were investigated by using Universal Testing Machine (Model H50K-S, Hounsfield Test Equipment Ltd, UK). The cross head speed was 1mm / min The span length of the specimen was 150mm .Tensile modulus studies were evaluated as per ASTM D 3039.The flexural strength and flexural modulus of the composites were studied as per ASTM - D790. The crosshead speed was 1.0 mm / min. The double cantilever beam (DCB) test samples for G_{IC} fracture toughness measurements were prepared according to the ASTM D 5528 (dimension 125 x 25 x 3mm) with a pre-initiated crack of 50mm. Aluminium hinges were attached to the surfaces of the specimens to facilitate crack propagation. Measurements of load and crack displacement were taken at the initial crack propagation, at 1mm intervals for first 5mm, then at 5 mm interval up to a total crack length of 45 mm and at 1mm intervals for the last 5 mm giving a total of 19 readings. Three methods of data reduction were applied, using software programs, the data quoted being those obtained by compliance method at peak load [9]. The displacement of crack was observed using a camera and the test was carried out in universal testing machine [5].

Vibration analysis

The free vibration analysis for laminated plates from the piezoelectric actuation is formulated. Firstly a linear static analysis of the structure subjected to induce in plane piezoelectric stress is performed from where the stresses over the plate are determined. After the stresses are known a free vibration analysis is carried out, however considering the effects of the induced piezoelectric stress field in the geometric stiffness matrix.

This formulation consists of a free vibration problem for a composite plate subjected to initial piezoelectricity induced stress. The free vibration equations of motion can be derived from Hamilton's principle,

$$\int_{t_1}^{t_2} \delta(T - U - \Delta W) = 0 \tag{1}$$

Where, T - Kinetic energy
U - Strain energy
Δw - change in the potential energy due to work of in plane stresses

The in plane elastic stresses due to piezoelectric actuation can be made available from the static stress analysis described with the following definition:

$$\{\sigma\} = [\bar{Q}]\,(\bar{e} - e_T) - E_3\{e_p \tag{2}$$

The change in the bending potential energy is given by

$$\Delta w = \iiint (\sigma_x \bar{e}_x^2 + \sigma_y \bar{e}_y^2 + \sigma_{xy} \bar{e}_{xy}^2)dxdydz \tag{3}$$

In the above equation considering only the terms related to the bending is zeroing the mid surface in plane displacements then the change in to potential energy becomes,

Applying equation (4) in (3) and the work done due to pre buckling stress during buckling may be expressed as

$$\begin{aligned}\Delta w = \frac{1}{2}\iiint & [\sigma_x(U_x^2 + V_x^2 + W_x^2) + \sigma y^2(U_y^2 + V_y^2 + W_y^2) \\ & + 2\sigma_{xy}(U_x U_y + V_x V_y + W_x W_y)dxdydz\end{aligned} \tag{4}$$

then Δw becomes

$$\Delta w = \frac{1}{2}\iint \begin{Bmatrix} U_X \\ U_y \\ V_x \\ V_y \\ W_x \\ W_y \end{Bmatrix}^T \begin{pmatrix} \begin{matrix} N_{xx} N_{xy} \\ N_{xy} N_{yy} \end{matrix} & 0 & 0 \\ 0 & \begin{matrix} N_{xx} N_{xy} \\ N_{xy} N_{yy} \end{matrix} & 0 \\ 0 & 0 & \begin{matrix} N_{xx} N_{xy} \\ N_{xy} N_{yy} \end{matrix} \end{pmatrix} \begin{Bmatrix} U_X \\ U_y \\ V_x \\ V_y \\ W_x \\ W_y \end{Bmatrix} dxdy \tag{5}$$

In order to complete the Formulation, the Kinetic energy expression,

$$T = \frac{1}{2}\int_v \begin{Bmatrix} \bar{U} \\ \bar{V} \\ \bar{W} \end{Bmatrix}^T \begin{Bmatrix} \bar{U} \\ \bar{V} \\ \bar{W} \end{Bmatrix} \rho dv \tag{6}$$

Must be written in terms of the displacement field. Again assuming symmetry with respect to the Z-axis. The kinetic energy can be put in terms of the mid-surface displacement and mass related quantities.

$$T = \frac{1}{2}\int_v \begin{Bmatrix} \dot{U} \\ \dot{V} \\ \dot{W} \end{Bmatrix}^T \begin{bmatrix} \rho & 0 & 0 \\ 0 & \rho & 0 \\ 0 & 0 & \rho \end{bmatrix} \begin{Bmatrix} \dot{U} \\ \dot{V} \\ \dot{W} \end{Bmatrix} da \tag{7}$$

The mass related terms are defined by,

$$M = \int_{z_0}^{z_t} \rho dz \tag{8}$$

M represents the mass per unit area

The potential energy correspondences to piezoelectric induced unique strain problem for a laminated discretized in N finite elements results.

$$\pi=\frac{1}{2}\sum_{P=1}^{N}\{q\}_p^T[K]_p[q]_p+\sum_{p=1}^{n}\{q\}_P^T\{F_P\}_P+\sum_{p=1}^{N}\{q\}_p^T\{F_T\}_p \tag{9}$$

The Pth element stiffen matrix is given by

$$[K_p]=\int_{A_p}[B]^T[B][B]\,dA \tag{10}$$

While the vector of element equivalent nodal piezoelectric force is

$$\{F_P\}_P=\int_{Ap}[B]^T\begin{Bmatrix}\{N_p\}\\ 0\end{Bmatrix}dA \tag{11}$$

$$\{F_T\}_P=\int_{Ap}[B]^T\begin{Bmatrix}\{N_T\}\\ \{M_T\}\end{Bmatrix}dA \tag{12}$$

$$\{K\}\ \{q\}=\{F\} \tag{13}$$

In order to facilitate the formulation of the element geometric stiffer matrix the following relation is defined.

$$\begin{Bmatrix}U_x\\ U_y\\ V_x\\ V_y\\ W_x\\ W_y\end{Bmatrix}=[G_w]\{q\}_p \tag{14}$$

Also the following matrix is defined containing the resultant of forces corresponding to the initial in plane stresses.

$$[N]=\begin{pmatrix}\begin{matrix}N_{xx}N_{xy}\\ N_{xy}N_{yy}\end{matrix} & 0 & 0\\ 0 & \begin{matrix}N_{xx}N_{xy}\\ N_{xy}N_{yy}\end{matrix} & 0\\ 0 & 0 & \begin{matrix}N_{xx}N_{xy}\\ N_{xy}N_{yy}\end{matrix}\end{pmatrix} \tag{15}$$

The change in potential energy is finally written as,

$$\Delta w=-\frac{1}{2}\iint(\{q_p\}^T[G_w]^T[N][G_w]\{q_p\})dxdy \tag{16}$$

From where the geometric stiffness matrix is promptly recognized as,

$$\{K_G]=\iint[G_w]^T[N][G_w] \tag{17}$$

In order to establish the critical buckling state corresponding to the equilibrium condition, the second variation of total potential energy must be equal to zero.

$$[K]_s+\lambda[K]_G=0 \tag{18}$$

Where λ is the Eigen value which multiple the applied temperatures to give the critical buckling temperature. (T_{CR})

In order to complete the formulation the element mass matrix

$$[M]_P=\int_{Ap}[N]^T[\rho][N]dA \tag{19}$$

Total potential energy,

$$\pi=\frac{1}{2}\sum_{P=1}^{N}\{q\}_p^T[K]_p[q]_p+\frac{1}{2}\sum_{p=1}^{n}\{q\}_P^T\{K_G\}\{q\}_P+\frac{1}{2}\sum_{p=1}^{N}\{lq\}^T\{M\}\{q\}_p \tag{20}$$

Applying Hamilton's principle yields the equation of the motion for the plate under free vibration. This equation can be cast in the form of an Eigen value problem in terms of the vector of system nodal displacement {q} as

$$\{[K]+[K_G]-\omega^2[M]\}\{q\}=\{0\} \tag{21}$$

$$f_{n1}=\frac{3.53}{2\Pi}\sqrt{\frac{EI}{\rho AL^4}} \tag{22}$$

$$f_{n2}=\frac{34.80}{2\Pi}\sqrt{\frac{EI}{\rho AL^4}} \tag{23}$$

Based on the above formulation, we have developed a package COMSAP for smart composite plates.

RESULTS AND DISCUSSIONS

Effect of PZT dopant on static mechanical properties

The effect of PZT doping on static mechanical properties of cyanate modified epoxy glass fibre system is tabulated in Table-2. From the table, it is observed that the tensile strength of 60EPCY is 401MPa.On PZT loading tensile strength is found to reduce by 6.5%, 11.5% and 19.7% respectively for 10%, 20% and 30% PZT doping. A similar decreasing trend is observed with tensile modulus also. This drop in tensile properties may be attributed to poor interfacial adhesion between the PZT particles and matrix material.

The effect of PZT doping on flexural properties is shown in Table. From the Table it is obvious that the flexural strength is found to decrease by 4.9%, 7.9% and 15.7% respectively for 10%, 20% and 30% PZT loading when compared to neat EPCY system. Also a marginal reduction in flexural modulus is observed when compared to EPCY system. This reduction in flexural properties may be attributed to poor interfacial bonding PZT with fibre and matrix which cannot resist bending stress applied. However the drop in flexural property is only marginal. Much of the resin property is retained even after PZT loading.

Table-2. Effect of PZT dopant on static mechanical properties.

Name of sample	**Tensile strength** (MPa)	**Tensile modulus** (GPa)	**Flexural strength** (MPa)	**Flexural modulus** (GPa)	**Fracture toughness** (kJ/m^{2}s)
EP	320	3.8	402	8.5	0.7971
60EPCY	401	5.3	503	11.2	0.9315
60EPCY 10PI	375	5.1	478	9.8	0.911
60EPCY 20 PI	355	4.8	465	9.5	0.9
60EPCY 30 PI	322	4.1	424	9	0.84

The influence of PZT doping on mode I fracture toughness of EPCY system is given in Table. From the Table it is seen that ther is a marginal drop in the fracture toughness when compared to EPCY system. The fracture toughness which is imparted mainly due to the oxazolidone and triazine ring structure is retained to a greater extent even after PZT doping. Here also the marginal drop in fracture toughness is due to poor interfacial bonding.

EFFECT OF PZT LOADING ON DYNAMIC MECHANICAL PROPERTIES OF 60EPCY COMPOSITE UNDER VARIED TEMPERATURE

Effect of PZT loading on natural frequency of 60EPCY composite

The first natural frequencies under varied temperature for piezo-damping cyanate modified epoxy matrix glass fibre composite are experimentally determined using free vibration method. The natural frequencies are measured 5 times for each temperature and the mean of the measured results is shown in Figure-1.

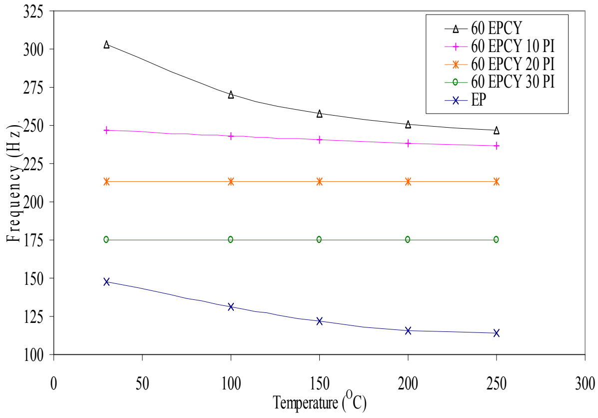
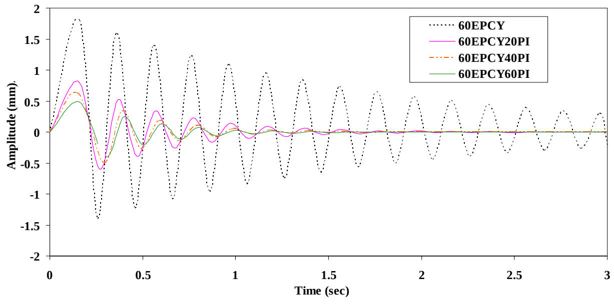


Figure-1. Effect of PZT loading on natural frequency vs. temperature.

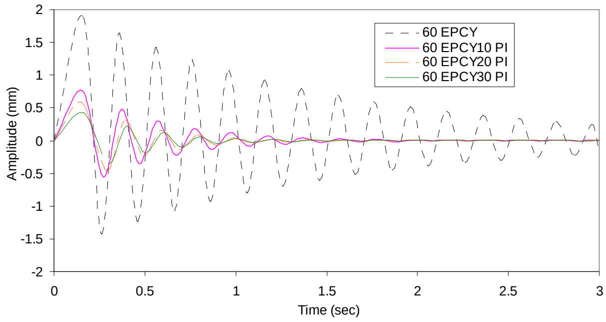
From the Figure it is seen that natural frequency of 60EPCY is 303 Hz at 30^{o}C. With increase in PZT loading natural frequency at 30^{o}C is found to decrease by 0.89 times, 0.81 times and 0.76 times for 60EPCY10PI, 60EPCY20PI and 60EPCY30PI respectively. With increase in temperature the natural frequency of 60EPCY is found to decrease from 303 Hz at 30^{o}C to 247Hz at 250^{0}C. This decreasing trend in natural frequency may be attributed to the softening of matrix material. In the case of PZT loaded EPCY increase in temperature does not significantly affect the natural frequency. The natural frequencies of 60EPCY10PI, 60EPCY20PI and 60EPCY30PI are 236.54Hz, 213.38Hz and 174.89Hz respectively at 250^{o}C. In 60EPCY20PI and 60EPCY30PI the natural frequency is maintained constant over a wide range of temperature. The constant trend in natural frequency with increase in temperature is due to piezoelectric effect.

Effect of PZT loading on damping factor of 60EPCY composite at varied temperature

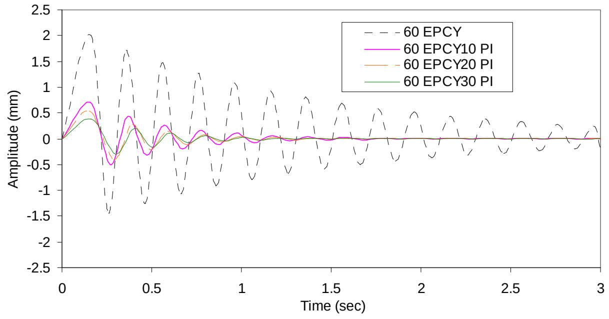
Figure-2 (a, b, c, d, e) shows the time response curve at different temperature (30^{0}C, 100^0 C, 150^0 C, 200^0 C, 250^0 C). It is observed that increase in PZT loading reduce in amplitude. Figure-3 shows the effect of PZT loading on damping factor of 60EPCY at varied temperature. The damping factor of neat 60EPCY composite is 0.02, 0.022, 0.024, 0.025 and 0.025 at 30^{o}C, 100^{o}C, 150^{o}C, 200^{o}C and 250^{o}C respectively. The PZT loaded 60EPCY shows an increase in the damping factor. The damping factor of 60EPCY10PI, 60EPCY20PI and 60EPCY30PI at 30^{o}C are 0.68, 0.1 and 0.102 respectively. The increase in damping factor is 2.4 times for 60EPCY10PI, 4 times for 60EPCY20PI and 4 times for 60EPCY30PI. From this it can be seen that 60EPCY20PI has better damping factor than other PZT loaded 60EPCY composites. Also with increase in temperature the damping factor is found to remain almost constant. Thus 20% PZT loaded 60EPCY composite has better damping property than neat 60EPCY and PZT loaded 60EPCY composites



(a)



(b)



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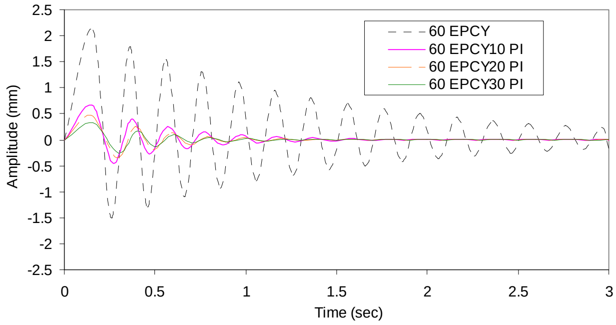

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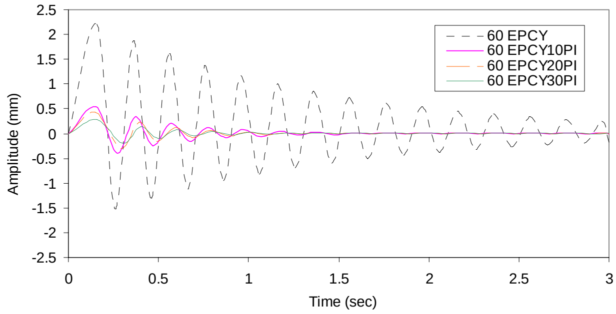

(e)

Figure-2 (a, b, c, d, e). Time response curve at different temperature (30°C, 100 °C, 150 °C, 200 °C, 250 °C).

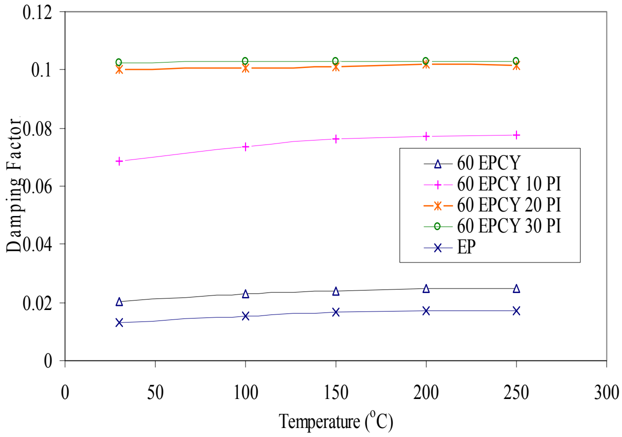

Figure-3. Effect of PZT loading on damping factor of 60EPCY composite at varied temperature.

The mean of the first natural frequency of 60EPCY composite is f_1= 303 Hz and the corresponding damping factor is ζ_1= 0.02036 at 30°C. The influence of PZT loading on the damping factor of 60EPCY and PZT modified 60EPCY system are shown in Figure-3. From the Figure it is seen that the damping factor increases with increase in PZT content up to 20%. The damping factors of 60EPCY10PI and 60EPCY20PI systems are found to increase by 2.2 times 3.4 times respectively when compared with 60EPCY system. But 60EPCY30PI system shows a decreasing trend in the damping factor value.

CONCLUSIONS

This study deals with the use of PZT particles as dopants for cyanate modified epoxy glass fibre system. The effects of filter loading on both static and mechanical properties were investigated using UTM and finite element method. From the results it was confirmed that there is a marginal drop in the mechanical properties with increase in PZT loading. About 75% of the mechanical properties are retained when compared to EPCY system. The drop in mechanical properties it attributed to poor interfacial bonding. The damping factor determined in this study reveals that 60EPCY 20PI is found to have high damping factor when compared to EPCY composite. The reason may be attributed to the piezo electric effect imparted by the ceramic PZT material.

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