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STUDIES ON DAMPING PROPERTIES OF EPOXY-CYANATE/ GLASS FIBRE COMPOSITES BY PASSIVE CONTROL

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ABSTRACT

Polymer composite as a novel damping material has attracted great interest in the development because of its excellent stiffness and damping characteristics. The methodology for vibration suppression of structures can be categorized into two groups, namely passive and active controls. In passive control, the material properties of structure such as damping and stiffness are modified so as to change the response of structure. A typical example of passive control is tailoring of composite materials. A lot of research on tailoring of the composite material has been carried out actively in terms of the effect of fiber orientation on stiffness, strength and damping ratio. In the present investigation tailoring of composite material is done by addition of another inherently tough material (cyanate ester resin) to conventional epoxy resin system. The effect of cyanate loading on natural frequency and damping coefficient are determined. The experimental studies are further confirmed by FEM analysis.

Key words: *Cyanate / Epoxy Composites, Damping Factor, FEM, Vibration.*

1. Introduction

Damping materials have good ability to dissipate elastic strain energy when subjected to vibratory loads and have been widely used in the fields of high performance structural applications such as aerospace, marine, construction, etc [1]. 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 elastomeric, 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 [2]. 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 structure due to their high stiffness to weight ratios. They are especially significant in air craft, aerospace, and military applications. On the other hand, polymer has 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 temperatures for passable use in different seasons, climates, and regions.

In aerospace and many other lightweight structures, there are many vibration inputs that can lead to resonance [3], so it is necessary to have a sound methodology to control the vibration. During the past few decades, it has become technically and ecologically important to suppress vibration and impact noise [4]. From this scope, many mechanical dampers have been investigated and developed, and there, the exploitation of damping materials is a key point to produce efficient damping to eliminate vibration and noise [5]. In particular, the polymer composite, as a novel damping material, has attracted great interest in development because of its excellent stiffness and damping characteristics [6]. Among the thermosetting polymers, epoxy resins are the most widely used for high-performance applications such as, matrices for fibre reinforced composites, coatings, structural adhesives and other engineering applications. Epoxy resins are characterized by excellent mechanical and thermal properties, high chemical and corrosion resistance, low shrinkage on curing and the ability to be processed under a variety of conditions [7]. Once fully cured, epoxies form highly cross linked, three dimensional networks. The densely cross linked nature of the material enables many of its superior properties.

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However, the high level cross linking in epoxy networks leads to inherent brittle materials and that constraints many of its applications. Several studies have been made to improve the toughness and crack resistance of epoxy resin. One successful modification method is the incorporation of secondary rubbery phase that separates from the matrix during curing, leading to different morphologies [8–12]. The advantage of rubber toughening in thermosets is that, fracture toughness can be improved dramatically. However, elastomer modification will lead to significant reduction in the modulus and thermal stability of the material. In recent years, high-performance thermoplastics have been used to modify epoxy resin such as, PES, PEI, PEEK, ABS, etc. [13], because of their high modulus and glass transition temperatures. The incorporation of thermoplastic, initially miscible, which phase separates during the epoxy-hardener curing reaction, leads to toughness improved epoxy networks. But processing of thermoplastic resin is difficult.

Thermosets have historically been the principal matrix material for composites although thermoplastics are used in many applications. The properties of the composites and the factors influencing their properties were extensively studied. The use of epoxy resin as the matrix for fibre-reinforced composites in structural applications has been increased significantly. High specific stiffness, strength, dimensional stability, selective electrical properties, lightweight and excellent corrosion resistance make them valuable for automobile and aerospace industries. Most of the fibre-reinforced composites offer a combination of strength and modulus that are either comparable or better than many of the conventional and traditional metallic materials. The extent of adhesion of polymer blend matrix to the reinforcing elements, especially fibres, is very important. It is well known that stress passes from the fibres to the matrix through the interface. Therefore, the adhesive force affects the strength and rigidity of the reinforced plastics and their fracture behavior. Glass fibre is one among the high strength and high modulus material used for the preparation of large varieties of composites. Glass fibres have found very extensive use in plastics, most commonly, in continuous form, in catalyst-activated thermosetting resins and in short form, in thermoplastics. The principal advantages of glass fibres are low cost, high tensile strength, high chemical resistance and excellent insulating properties. There are mainly two types of glass fibres commonly used in fibre reinforced plastic industry, namely E-glass and S-glass. E-glass has the lowest cost of all commercially available reinforcing fibres, which is the reason, its widespread application in fibre reinforced composite (FRP) industry[14]. Current research is also directed towards the use of thermoset – thermoset polymer blends, in particular the incorporation of inherently tough polymers into brittle polymer systems in order to impart improvements in fracture toughness in the resulting blends [15]. Here toughening of epoxy resin is tried with an inherent tough polymer cyanate ester resin.

The objective of the present work is to investigate the effect of thermoset modification of epoxy resin on damping properties of glass fibre reinforced composites.

2. Experimental Details

2.1 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. All chemicals were used as purchased.

2.2 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 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.

Table 1: Material Composition

S.No	**Name**	**Epoxy (g)**	**Cyanate (g)**	**DDM (g)**
1	EP	100	--	27
2	20EPCY	100	20	27
3	40EPCY	100	40	27
4	60EPCY	100	60	27

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°C for 1 hour in a hydraulic press. The laminate was then demoulded and post cured at 220°C for 1 hour in an oven [15]. The style of weave is of plain woven fabrics type.

2.3 Vibration analysis (Theory)

Vibration refers to mechanical oscillations about an equilibrium point. The oscillations may be periodic such as the motion of a pendulum or random such as the movement of a tyre on a gravel road. Vibration is occasionally desirable. For example, the motion of a tuning fork, the reed in a woodwind instrument, harmonica and the cone of a loudspeaker are the desirable vibrations, necessary for the correct functioning. More often, vibration is undesirable, wasting energy and creating unwanted sound and noise. For example, the vibrational motions of engines, electric motors, or any mechanical devices in operation are typically unwanted. Such vibrations can be caused by imbalances in the rotating parts, uneven friction, meshing of gear teeth, etc. Careful designs usually minimise unwanted vibrations.The fundamentals of vibration analysis can be understood by studying the simple mass-spring-damper model. Indeed, even a complex structure such as an automobile body can be modeled as a summation of simple mass-spring-damper models. The frequency of a free vibration system is called the natural frequency (fn). fn is one of the most important quantities in vibration analysis and is called the undamped natural frequency. To start the investigation of the mass-spring-damper, we assume that the damping is negligible and that there is no external force applied to the mass (i.e. un-damped free vibration). Let us consider a mass-spring system with stiffness (K) and mass (m). The spring deflects Δx due to the mass (m). In equilibrium position, the forces acting on the mass are the vertical downward force (mg) and vertical upward force ($K.\Delta x$). When the body is in equilibrium, we have:

$$K.\Delta x = mg \quad (1)$$

When the mass is given at displacement of x, the vertical upward force is $K(\Delta x+x)$. Due to the displacement of x, the body experiences a downward acceleration a. The net force (taking upward as negative and downward as positive) acting on the system is

$$F = mg - K(\Delta x+x) \quad (2)$$

By Newton's second law of motion

$$F = ma \quad (3)$$

Implies,

$$mg - K(\Delta x+x) = ma \quad (4)$$

from equation (1), ($mg-K.\Delta x$) is zero.

Therefore,

$$ma + Kx = 0 \text{ (or) } m\,(d^2x / dt^2) + Kx \quad (5)$$

The equation (5) is the basic differential equation for the motion of a spring-mass system. The fundamental equation of harmonic motion is

$$(d^2x / dt^2) + \omega^2 x \quad (6)$$

Comparing differential equation (5) with the fundamental equation of harmonic motion (6) we have.

$$\omega = (K / m)^{1/2} \quad (7)$$

Also the time period,

$$tp = 2\Pi / \omega \quad (8)$$

and the natural frequency,

$$fn = 1 / tp = 1 / 2\,\Pi\,(K / m)^{1/2}$$

$$= 1 / 2\,\Pi\,(g / \delta)^{1/2} \quad (9)$$

If the mass and stiffness of the system are known, we can determine the frequency at which the system will vibrate once it is set in motion. Every vibrating system has one or more natural frequencies at which it will vibrate immediately when it is disturbed.

This simple relation can be used to understand in general what will happen to a more complex system, once we add mass or stiffness. For example, the above formula explains why when a car or truck is fully loaded, the suspension is felt "softer" than when empty because the mass is increased when loaded, resulting in the reduction of natural frequency of the system.

These formulae describe the resulting motion, but they do not explain why the system oscillates. The reason for the oscillation is due to the conservation of energy. In the above example we have extended the spring and therefore have stored potential energy in the spring. Once we let go of the spring, the spring tries to return to its unstretched state and in the process accelerates the mass. At the point where the spring has reached its un-stretched state, it no longer has any energy stored, but the mass has reached its maximum speed and hence all the energy has been transformed into kinetic energy. The mass then begins to decelerate because it is now compressing the spring and in the process transferring the kinetic energy back into potential energy. This transferring back and forth of the kinetic energy in the mass and the potential energy in the spring causes the mass to oscillate. In our simple model, the mass will continue to oscillate for ever at the same magnitude, but in a real system there is always something called damping that dissipates the energy and therefore the system eventually comes to rest.

We now add a viscous damper to the model that outputs a force that is proportional to the velocity of the mass. The damping is called viscous because it models the effects of an object in a fluid. The basic differential equation (5) for un-damped free vibration must be modified by adding the damping force also.

$$\text{Damping force} = c\,(dx / dt) \qquad (10)$$

The proportionality constant c is called the damping coefficient and has units of Force over velocity (N s/m). Now the basic differential equation is

$$m\,(d^2x / dt^2) + Kx + c\,(dx / dt) = 0 \qquad (11)$$

The solution to this equation is

$$x = e^{At} \qquad (12)$$

Substituting x in equation (11) we get

$$A^2 e^{At} + (c/m)\,A\,e^{At} + (K/m)\,e^{At} = 0 \qquad (13)$$

Implies,

$$A^2 + (c / m)\,A + (K / m) = 0 \qquad (14)$$

The roots for the equation (14) are

$$A_1 = (-c/2m) + ((c/2m)^2 - (K/m))^{1/2} \qquad (15)$$

&

$$A_2 = (-c/2m) - ((c/2m)^2 - (K/m))^{1/2} \qquad (16)$$

Therefore, the most general solution for the equation (11) is

$$x = C_1 e^{A_1 t} + C_2 e^{A_2 t} \qquad (17)$$

Here C_1 and C_2 are two arbitrary constants which are to be determined from the initial conditions of the motion of the mass. The roots K_1 and K_2 may be real, complex or equal. If the roots are complex conjugate, damping is small; the system will still vibrate, but will stop vibrating over time. This case is called under-damping. If the roots are real, the damping is more; the system no longer oscillates. This is called over-damping. If the roots are equal, the system is critically damped.

To characterize the amount of damping in a system, a ratio called the 'damping ratio' is used. This damping ratio (ζ) is just a ratio of the actual damping coefficient over the critical damping coefficient. The formula for the damping ratio (ζ) is

$$\zeta = c / c_c \qquad (18)$$

where, cc is called critical damping coefficient and is expressed as

$$c_c = 2m\omega_n \qquad (19)$$

The logarithmic decrement method is often used to find the amount of damping in a mechanical system. Logarithmic decrement is defined as the natural logarithm of the amplitude reduction factor. Logarithmic decrement is given by

$$\ln(x_n / x_{n+1}) = 2\Pi\,\zeta / (1-\zeta^2)^{1/2} \qquad (20)$$

Where, x_n and x_{n+1} are any two successive amplitude on the same side of the mean position.

2.4 Vibration analysis (Experimental)

Four mode natural frequencies of the composite plates was found using vibration testing equipment. The vibration testing equipment contains an accelerometer, impulse hammer, dynamic signal analyzer and a PC with RT-pro software to display the analysis result. The equipments are shown in Fig. 1 & Fig 2.

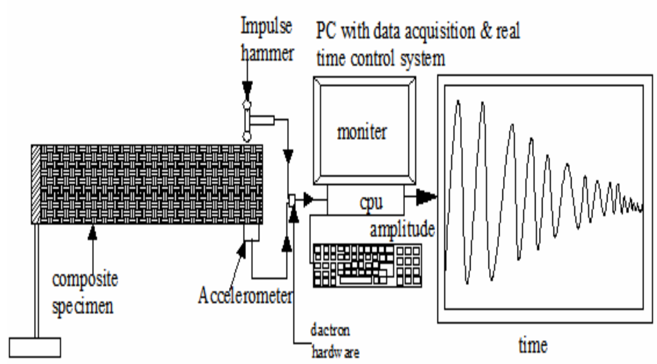

Fig.1 Experimental Setup for Vibration Analysis

The accelerometers contain seismic element and piezoceramic crystal which converts acceleration to analogue signals. Impulse hammer is used to excite structures with definable impulse force for the purpose of studying their dynamic behavior. Experimental modal analysis, deals with the determination of natural frequencies, damping ratios and mode shapes through vibration. The system to be tested is excited with an impact hammer, which generates the required exciting function.

Fig. 2 Experimental Setup for Vibration Analysis

The impact hammer produces different excitations of different magnitude. The same is sensed by a force transducer attached to the tip of the impact hammer and fed as input signal to the FFT analyzer. Dynamic signal analyzers analyze the vibration characteristics. The frequencies versus displacement graph were obtained. From the graph the damping coefficients were calculated.

2.5 Measurements

The composite laminates were cut to required dimension. The laminates were then subjected to vibrations tests to determine the natural frequencies and damping factors.

3. Results and Discussion

3.1 Effect of cyanate loading on natural frequency of composite laminates

The first, second, third and fourth fundamental frequencies are obtained experimentally and given in the Table 2.

The mode 1, mode 2, mode 3 and mode 4 frequencies of pure epoxy system are 148, 430, 1167 and 2915 Hz respectively. On increasing the cyanate loading from 20% to 40% and 60% the mode1 frequency is found to increase by 1.5 times, 1.9 times and 2.0 times respectively. A similar increasing trend is found in the case of mode 2, mode 3 and mode 4 frequencies of 20EPCY, 40EPCY and 60EPCY. The increase in natural frequency of cyanate modified epoxy system when compared to neat epoxy composite may be attributed to increase in stiffness of cyanate ester resin system.

Table 2: Fundamental Natural Frequency of Epoxy/ Cyanate/Glass Fibre Composite

Matrix composition	Mode 1	Mode 2	Mode 3	Mode 4
	f1 (Hz)	f2 (Hz)	f3 (Hz)	f4 (Hz)
EP	148	430	1167	2915
20 EPCY	225	616	1550	3717
40 EPCY	278	755	1900	4945
60EPCY	303	818	2060	5320

3.2 Effect of cyanate loading on damping coefficient of composite laminates

The natural frequencies and the corresponding displacements are given in the Table 3.

Table 3: Natural Frequency and Amplitude of Composite Plates

Matrix composition	Mode 1		Mode2		Mode3	
	X1 (mm)	f1 (Hz)	X2 (mm)	f2 (Hz)	X3 (mm)	f3 (Hz)
EP	24.6	148	23	430	21.5	1167
20 EPCY	24	225	22.6	616	21.4	1550
40 EPCY	22.5	278	20.5	755	18.9	1900
60EPCY	18	303	15.5	818	8	2060

These natural frequencies and the corresponding displacements are used to determine the damping coefficients and the calculated values are given in Table 4.

Table 4: Damping Coefficient

Matrix composition	Damping coefficient
EP	0.071
20 EPCY	0.096
40 EPCY	0.184
60EPCY	0.323

From the Table 4 it is observed that the damping coefficient of pure epoxy composite to be 0.026. With cyanate loading the damping coefficient is found to increase by 1.4 times for 20% loading, 2.6 times for 40% loading and 4.5 times for 60% cyanate loading respectively. The reason for increased damping coefficient may be attributed to increased stiffness of cyanate modified epoxy system when compared to neat epoxy system.

3.3 Finite element method

The free vibration analysis was also done in SOLID WORKS. The element used is tetrahedral element. Tetrahedron shaped element supports a polynomial with a maximum order of eight. It is well suited to model irregular meshes. Tetrahedral element is shown in the Figure 3

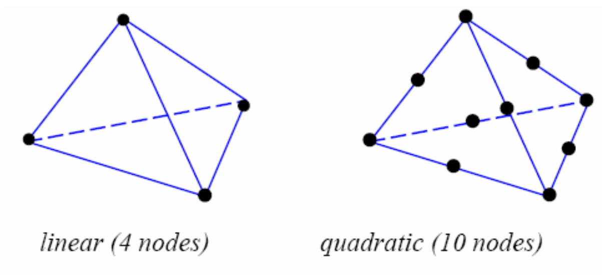

Fig. 3 Tetrahedral Element

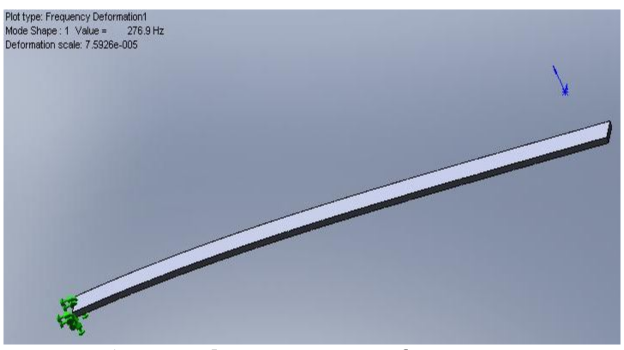

Fig. 4 Mode 1 Frequency of 40EPCY

A sketch of dimension 15mm X 3mm is first drawn in sketcher work bench. The sketch is then extruded in part to 300mm. Then a frequency analysis is done in Cosmos express. The material for each matrix composition is defined by entering the value for density and Young's modulus. The model is the restrained in cantilever configuration. No load is applied. A fine meshing is done to get more accurate result. The analysis for each composition of the matrix was done and the representative figures of mode 1, mode 2, mode 3 and mode 4 for 40% cyanate loading are shown in Figures 4, 5, 6 and 7 respectively.

The experimentally determined natural frequencies were verified theoretically by FEM and the values are presented in Table 5. The theoretical values are found be in good agreement with the experimental values.

The computer aided analysis result was compared with the experimental result and the error for the first mode alone is tabulated in the Table 6.The experimental results are in close agreement with natural frequencies calculated by solid works.

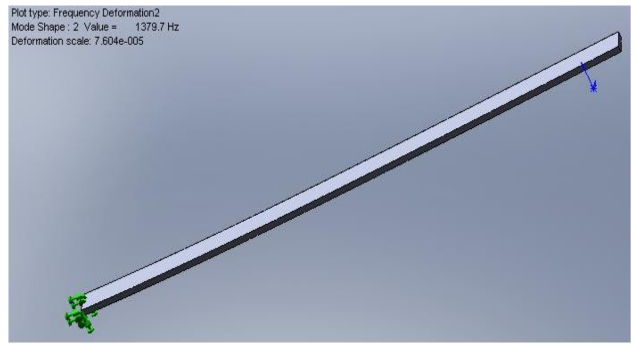

Fig. 5 Mode 2 Frequency of 40EPCY

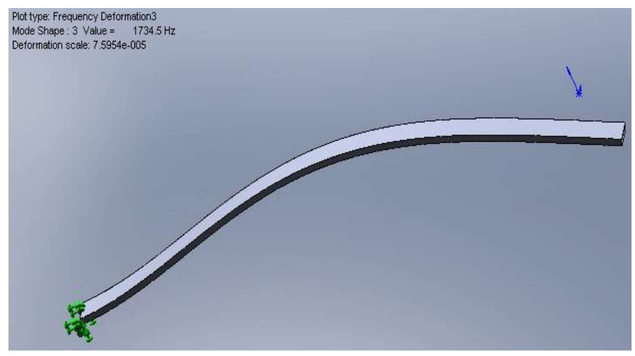

Fig. 6 Mode 3 Frequency of 40EPCY

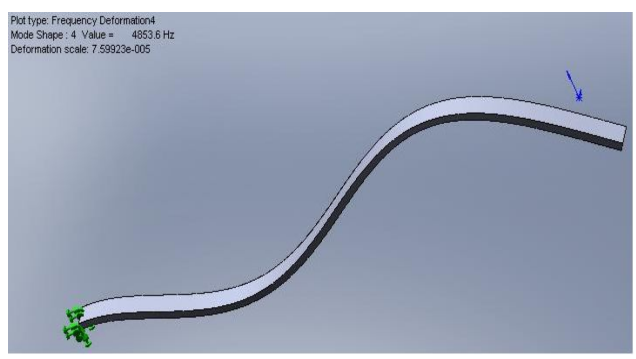

Fig. 7 Mode 4 Frequency of 40EPCY

Table 5: Fundamental Natural Frequency of Epoxy/ Cyanate/Glass Fibre Composite (by FEM)

Matrix composition	Mode 1	Mode2	Mode3	Mode 4
	f1 (Hz)	f2 (Hz)	f3 (Hz)	f4 (Hz)
EP	158	787	970	2770
20 EPCY	237	1179	1481	4146
40 EPCY	277	1380	1735	4854
60EPCY	306	1527	1919	5371

Table 6: Comparison of Experimental and Solid Works Result

Matrix composition	Experimental results (Hz)	Computer aided analysis result (Hz)	Error
EP	148	158.03	10.03
20 EPCY	225	236.52	11.52
40 EPCY	278	276.9	1.11
60EPCY	303	306.41	3.41

4. Conclusion

Testing the free vibration of the composite plates was done by excited vibrating hammer. Using this method, the fundamental natural frequency of the epoxy and cyanate modified epoxy composites were determined. From the work, it is obvious that the fundamental natural frequencies of cyanate modified epoxy/ glass fibre composites were found to increase with the increase in cyanate content. The reason may be attributed to the increase in stiffness of the composite material. Logarithmic decrement method is used to find the damping coefficient of the composites. The damping coefficients of cyanate modified epoxy/ glass fibre composites were found to increase with the increase in cyanate content. From the results of the present study, it is obvious that the cyanate modified epoxy composite can be used for engineering and aerospace applications to provide better performance

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