International Journal of Engineering Science Invention **(IJESI)**
ISSN (Online): 2319 – 6734, ISSN (Print): 2319 – 6726
www.ijesi.org || PP.89-97

Damping measurement in composite materials using combined finite element and frequency response method

B. S. Ben[a], B. A. Ben[b], Adarsh K[c] , K. A. Vikram [c] and Ch.Ratnam[d]

[a] Department of mechanical engineering, S.V.P Engineering College, Visakhapatnam, India, 530003
[b,d] Department of mechanical engineering (AUCE), Andhra University, Visakhapatnam, India, 530003
[c] Department of mechanical engineering, GITAM University, Visakhapatnam, India, 530003

ABSTRACT: *The article presents the methodology for finding material damping properties at higher frequency and at relatively lower amplitudes. The method employs combined Finite element and frequency response for finding the damping characteristics of composite materials, which are used in high frequency applications. The hybrid method has been implemented on carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) plates. The tests were conducted using ultrasonic pulse generator with scan view plus software as virtual controller. The dynamic mechanical analysis was carried out in high range frequency sweep mode using the hybrid method. The fiber reinforced composites have been characterized for damping parameters at low amplitudes and in a non-destructive mode.*

Keywords: *Carbon fibres, Glass fibres, Vibration, Acoustic emission, Damping*

I. INTRODUCTION

The damping capacity of a material is the fundamental property for designing and manufacturing structural components in dynamic applications. Materials with high damping properties are very desirable to suppress mechanical vibration and transmission of waves, thus decreasing noise and maintaining the stability of structural systems. Experimental and analytical characterization of damping is not easy, even with conventional structural materials, and the anisotropic nature of composite materials makes it even more difficult. Fiber-reinforced polymer composites (FRPC) has interesting properties such as light-weight, high specific strength and stiffness, compared with metals, which make it very attractive for many marine structures [1–2]. At the same time, the excellent material damping performance of FRPC, due to the viscoelastic characteristics of the polymer matrix, which make it plays an important role on improving the dynamic performance of the structure. Experimental approaches range from laboratory bench-top methods to portable field inspection techniques, whereas analytical techniques vary from simple mechanics-of-materials methods to sophisticated three-dimensional finite-element approaches.

In recent years, many of studies were focused on the damping analysis of composite materials and structures. Kyriazoglou and Guild [3] used finite element method to predict the damping characteristics of GFRP and CFRP laminates. Berthelot et al. [4–6] applied the Ritz Method to perform the damping calculations and experiments of various composites, including unidirectional glass/Kevlar fiber composites and orthotropic composites with interleaved viscoelastic layers, and further completed the damping analysis of composite plate and structures by using this method [7–9]. In the present work a hybrid method for finding damping properties of a material using ultrasonic pulse generator experimental setup is developed.

Damping in composites involves a variety of energy dissipation mechanisms that depend on vibrational parameters such as frequency and amplitude and these are studied with nondestructive evaluation. In fiber-reinforced polymers, the most important damping mechanisms have been studied by Y. Chen and R. F. Gibson [10].

The nondestructive evaluation (NDE) techniques such as radiography, acoustic emission, thermal NDE methods, optical methods, vibration damping techniques, corona discharge and chemical spectroscopy, have also been applied to characterize the fiber-reinforced composites [11]. Among these techniques, the vibration damping method, which is based on energy dissipation theory, has been increasingly used for measuring damping capacity. The principle of the method is based on the theory of energy dissipation. According to the theory, quality of interfacial adhesion in composites can be evaluated by measuring the part of energy dissipation contributed by the interfaces, assuming that the interface part can be obtained by separating those of matrix and fiber from the total composites. The energy dissipation of a material can be evaluated by the damping of the material.

Nowick and Berry summarized the techniques currently used for measuring vibration damping of materials and structures [12]. The techniques for the measurement of damping often deal with natural frequency or resonant frequency of a system. In general, all apparatus for the investigation of vibration can be categorized as free vibration (or free decay) and forced vibration. Free vibration is executed by a system in the absence of any external input except the initial condition inputs of displacement and velocity [13]. For example, it is possible to have a wire sample gripped at the top, and have a large weight hanging freely at the bottom; this system can be set either into longitudinal or torsional oscillation. The latter represents the well-known "torsion pendulum", developed by Ting-Sui K , in which the strain at any point can be expressed in terms of the angular twist of the inertia member.

For a forced vibration, a periodic exciting force is applied to the mass. When the resonant frequency is achieved, the loss angle is obtainable directly from the width of the resonance peak at half-maximum in a plot of (amplitude) versus frequency. Typical forced vibration techniques include the free-free beam technique [14] and the piezoelectric ultrasonic composite oscillator technique (PUCOT) [15-17]. These techniques have been applied to dynamic mechanical analysis (DMA) which is a widely used technique in polymer studies, and has attracted even more attention for interface characterization. However, the instrument is relatively expensive and cannot be operated at a high frequency which can reflect more information from the tested materials.

The damping of fiber reinforced composite materials has been studied extensively [18-20]. All of the published results for continuous fiber reinforced composites show that when strain levels are low the damping characteristics do not depend on strain amplitude but are dependent on fiber orientation, temperature, moisture absorption, frequency, and matrix properties. Fiber properties have only minimal effects. However, for discontinuous fiber reinforced composites it has been shown that the damping characteristics in the fiber direction are much greater than that obtained continuous fiber reinforced composites. It is commonly accepted that the main sources of damping in a composite material come from microplastic or viscoelastic phenomena associated with the matrix and slippage at the interface between the matrix and the reinforcement.

Composite materials fall into two categories: fiber reinforced and particle (or whisker) reinforced composite materials. Both are widely used in advanced structures. Among the various kinds of composites, glass fiber-reinforced polymer (GFRP) and carbon fiber-reinforced polymer (CFRP) composites have become more and more important in engineering applications because of their low cost, light weight, high specific strength and good corrosion resistance.

This paper will emphasize viscoelastic damping, which appears to be the dominant mechanism in undamaged polymer composites vibrating at small amplitudes. An ultrasonic based hybrid method employing combined finite element and frequency response was developed to measure the damping properties of composite material.

II. EXPERIMENTATION

In this work carbon fiber/epoxy (CFRP) and glass fiber/epoxy (GFRP) were tested for their damping properties. The specimens of dimensions 120 x 30 x 2 mm were fabricated by the standard process [21]. The laminate consists of 12 plys and each ply consisting of woven fiber mat with epoxy layer of thickness 0.2mm. A schematic diagram of the experimental setup is shown in Fig. 1. The test specimen is clamped at one end on a cantilever support. The transducers were placed on the test specimen at a distance of 80 mm from each other. The shear wave transducer was coupled to the specimen using a honey glycerine couplant made by Panametrics. The couplant was able to provide transmission of a normal incident shear wave to the specimen. We used the pitch-catch radio frequency (RF) test method, which uses dual-element sensors (DIC–0408) with a 1 KHz to 4 MHz frequency range. A point-contact sensor (DIC–0408) with an 8 mm diameter was used in the test setup where one element transmits a burst of acoustic waves into the test piece, and a separate element receives the sound propagated across the test piece between the transducer tips as shown in Fig. 2. Both the actuation and the data acquisition were performed using a portable Panametrics NDT™ EPOCH 4PLUS and a desktop PC running Scanview plus software as a virtual controller.

III. VISCOUS DAMPING AND RESPONSE OF A SYSTEM

Damping in composites involves a variety of energy dissipation mechanisms that depend on vibrational parameters such as frequency and amplitude and these are studied with nondestructive evaluation. Damping in a system can be determined by noting the maximum response.

The differential equation of motion for the System with viscous damping (c) when the excitation is a force $F = f_o \cos \omega t$ applied to the system is given by [22].

$$m\ddot{x} + c\dot{x} + kx = f(t) \tag{1}$$

$$\ddot{x} + \frac{c}{m}\dot{x} + \frac{k}{m}x = \frac{f_0}{m}\cos\omega t = u(t) \quad (2)$$

$$\ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n^2 x = a\cos\omega t = u(t) \quad (3)$$

Where $u(t)$ is the modified excitation, ω_n is natural frequency, ζ is damping ratio and here

$$2\zeta\omega_n = \frac{c}{m} \quad (4)$$

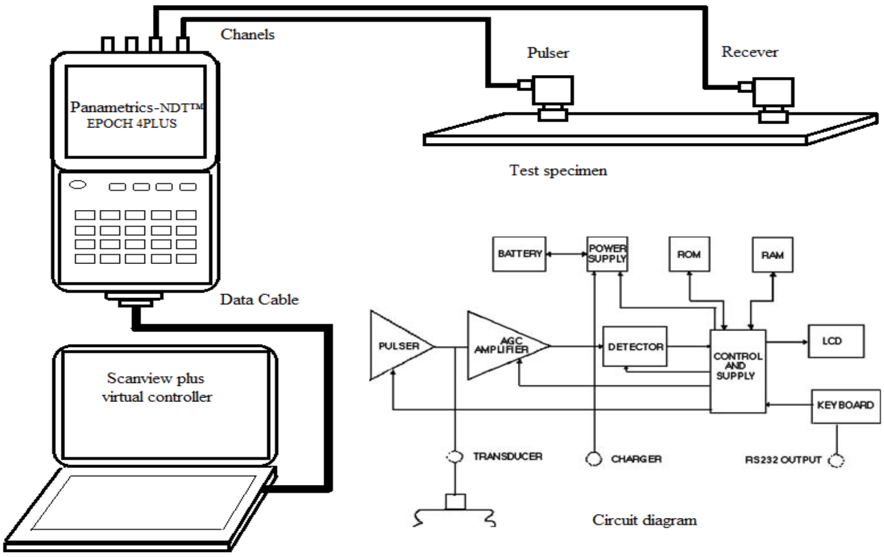

Fig. 1 Schematic representation of experimental setup

Fig. 2 Damping measurement experimental setup (EPOCH 4PLUS)

The differential equation of motion for the System when the excitation is complex is given by

$$\ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n x = ae^{j\omega t} \quad (5)$$

Where, $e^{j\omega t} = \cos\omega t + j\sin\omega t$

The resulting complex particular solution is

$$x_p = X(j\omega)e^{j\omega t} \quad (6)$$

True particular solution is

$$X[-\omega^2 + 2\zeta\omega_n j\omega + \omega_n^2]e^{j\omega t} = ae^{j\omega t} \quad (7)$$

Since $e^{j\omega t} \neq 0$

$$X = \frac{a}{[-\omega^2 + 2\zeta\omega_n j\omega + \omega_n^2]} \quad (8)$$

The characteristic polynomial of the system is

$$\Delta(\lambda) = \lambda^2 + 2\zeta\omega_n\lambda + \omega_n^2 \quad (9)$$

With the Laplace variable s

$$\Delta(s) = s^2 + 2\zeta\omega_n s + \omega_n^2 \quad (10)$$

Put $s = j\omega$

$$\Delta(j\omega) = -\omega^2 + 2\zeta\omega_n j\omega + \omega_n^2 \quad (11)$$

The response and excitation in the frequency domain of the system is:

$$G(j\omega) = \frac{1}{\Delta} = \left[\frac{1}{s^2 + 2\zeta\omega_n s + \omega_n^2}\right] \quad (12)$$

The amplification $\left(|G(j\omega)| = {}^{1}/_{|\Delta|}\right)$ is maximum (i.e, resonance) when $|\Delta|$ is a minimum or $|\Delta|^2$ is a minimum. The condition of peak amplification of system when excited by a sinusoidal input is called resonance and associated frequency of excitation is called resonant frequency and it is determined by

$$\Delta = \omega_n^2 - \omega^2 + 2\zeta\omega_n j\omega \quad (13)$$

$$|\Delta|^2 = (\omega_n^2 - \omega^2)^2 + (2\zeta\omega_n\omega)^2 = D \quad (14)$$

The resonance corresponds to a minimum value of D, or

$$\frac{dD}{d\omega} = 2(\omega_n^2 - \omega^2)(-2\omega) + (2\zeta\omega_n)^2\omega = 0 \quad (15)$$

Hence condition for resonance is

$$\omega_n^2 + \omega^2 + 2\zeta^2\omega_n^2 = 0 \quad (16)$$

At the resonant frequency

$$\omega_r = \sqrt{1 - 2\zeta^2}.\,\omega_n \quad (17)$$

From eq.(4) and eq.(17)

$$\sqrt{2(\omega_n^2 - \omega_r^2)} = \frac{c}{m} \quad (18)$$

When the damping coefficient *c* is greater than zero, the phase between the force and resulting motion is different than zero which leads to the transmissibility T and phase angle ψ, presented in eq. 19 and eq. 20 as a function of the frequency ratio ω_r/ω_n and for several values of the fraction of critical damping ζ [22].

$$T = \sqrt{\frac{1 + (2\zeta\omega_r/\omega_n)^2}{(1 - \omega_r^2/\omega_n^2)^2 + (2\zeta\omega_r/\omega_n)^2}} \quad (19)$$

$$\psi = \tan^{-1}\frac{2\zeta(\omega_r/\omega_n)^3}{1 - (\omega_r/\omega_n)^2 + (2\zeta\omega_r/\omega_n)^2} \quad (20)$$

IV. METHODOLOGY

In the present work a methodology has been developed for finding damping property of a material using combined finite element and frequency response method. Fig. 3 shows the process flow diagram of the dynamic mechanical analysis using present method. The basic material property Young's modulus is obtained from the ultrasonic pulse generator experimental setup. The instrument finds the Acoustic Emission (AE) velocities travelling in the material which will be very useful for determining the material properties [23-26]. The Young's modulus of the test specimen is determined using the relation given in eq. (21).

$$E_1 = \frac{V_T^{\,2}\rho(1+\upsilon_{12})(1-2\upsilon_{12})}{1-\upsilon_{12}}$$

$$E_2 = \frac{V_L^{\,2}\rho(1+\upsilon_{12})(1-2\upsilon_{12})}{1-\upsilon_{12}} \quad (21)$$

where V_L and V_T are longitudinal and transverse velocity of Lamb waves traveling in the material respectively, ρ is material density and υ_{12} is Poisson's ratio.

The calculated Young's modulus and Poisson's ratio are used as material inputs in ANSYS model to find natural frequencies. The natural frequencies and the response of the system at different mode number obtained from the experimental setup are substituted in eq.(18) to find viscous damping of the system.

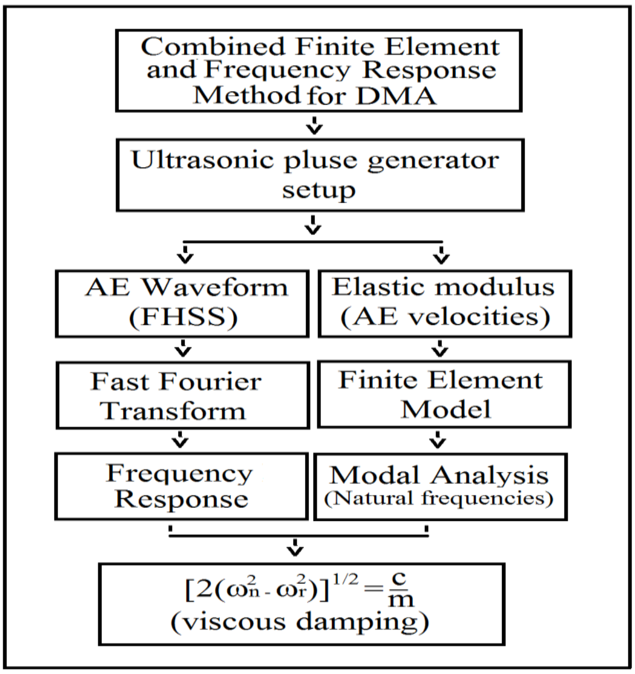

Fig. 3 Process flow diagram for Dynamic Mechanical Analysis by hybrid method

V. RESULTS AND DISCUSSION

Many researches carried damping measurements in temperature sweep mode but the present work involves frequency sweep since the damping is to eliminate the noise and vibrations resulting from natural frequencies in many industrial applications. In general conventional DMA techniques are used to determine thermomechanical behavior of polymers by typically employing dynamic shear or tensile loading modes at defined frequencies between 0.1 and 50 Hz. The hybrid method employed for DMA applications depends on type of wave propagated, and viscous damping is determined from the measured acoustic parameters sound velocity and amplitude. The primary advantage of hybrid method for DMA is that due to the compact sensor size it can easily be integrated into most manufacturing processes.

The oscillatory motion is a characteristic property of the structure and it depends on the distribution of mass and stiffness in the structure. The oscillatory motion occurs at certain frequencies known as natural frequencies or characteristic values, and it follows well defined deformation pattern known as mode shapes or characteristic modes. The study of such free vibration is very important in finding the dynamic response of elastic structures.

In the present work damping measurements were carried out using hybrid method combining finite element and frequency response of the system. The materials properties of the test specimen obtained from experimental setup are reported in table 1. The modal analysis was carried out using Block Lancozs method in ANSYS for thirty subsets and shell-190 has been used as meshing element. Fig. 4 and fig. 5 shows the first, tenth, twentieth and thirtieth mode of natural frequency of the two materials, GFRP and CFRP respectively. The continuous digital waveform from the instrument is processed through virtual controlling software scanview plus. The continuous waveform is subjected to fast Fourier transform (FFT) which yield a single peak from the calibrated optimal driving frequency, however for a few finite cycles, the FFT appears as a Gaussian curve. The influence of measurement frequency, dispersion, hysteresis, reflections at material boundaries, and changes in material density on the measured sound velocity and amplitude were taken into account. To support conclusions a wide range of experimental data was evaluated using sensors operating in the frequency ranges 50 Hz to 4 MHz. Fig. 6 shows the response curves of the materials being tested for damping properties obtained from experimental setup.

Table 1 Material properties calculated using experimental setup

Material	V_T (m/s)	V_L (m/s)	υ_{12}	E_1 (Gpa)	E_2 (Gpa)	Density (ρ) kg/m^3
GFRP	**6439**	**3128**	**0.346**	**47.31**	**11.26**	**1853**
CFRP	**8745**	**4628**	**0.307**	**77.74**	**21.73**	**1400**

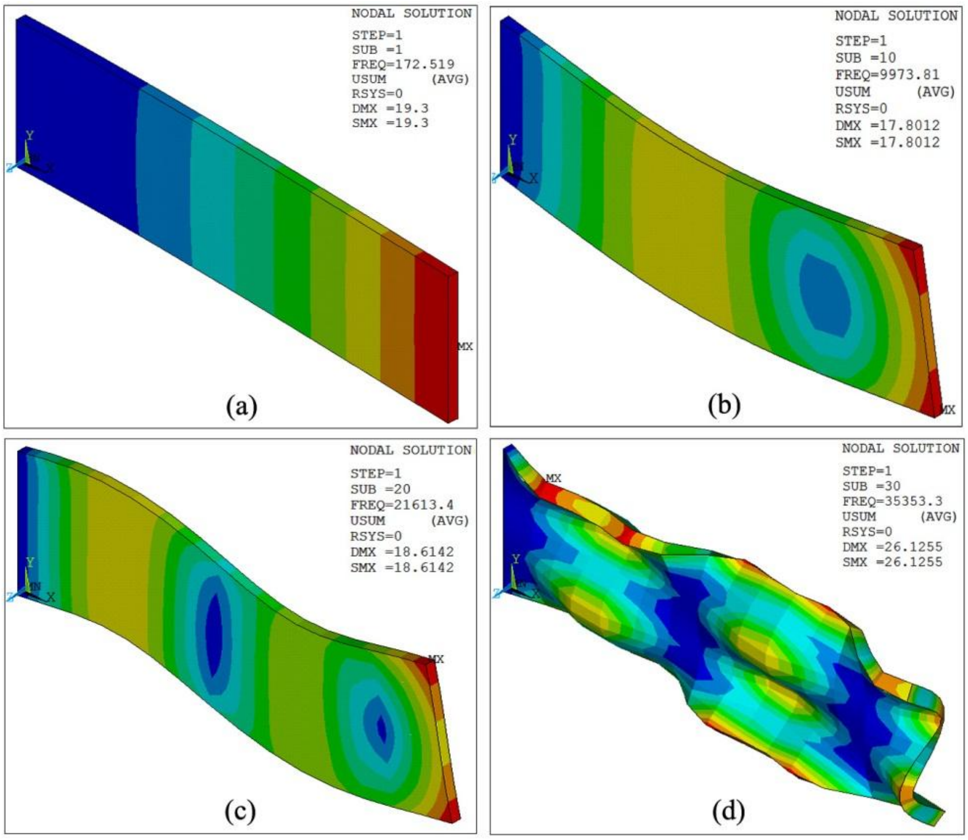

Fig. 4 GFRP specimen's 1st, 10th, 20th and 30th mode of natural frequency

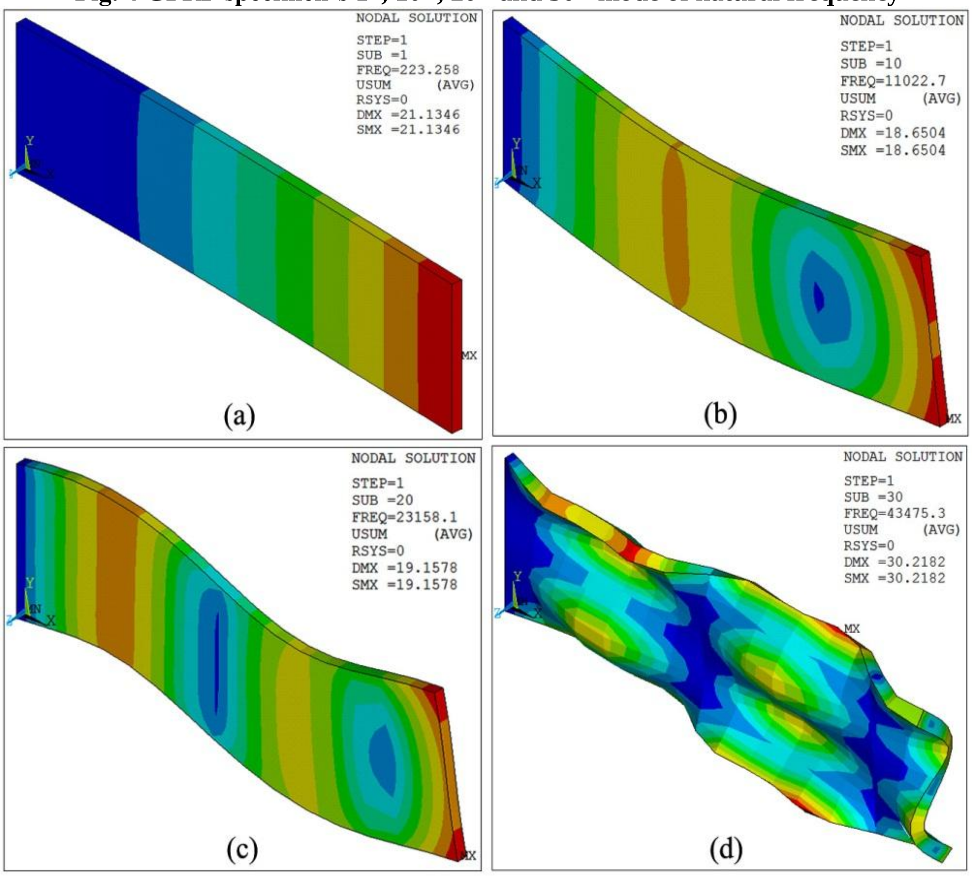

Fig. 5 CFRP specimen's 1st, 10th, 20th and 30th mode of natural frequency

The viscoelastic behavior is usually the basis for dynamic mechanical property analysis including damping. Polymer matrix composites in particular are known to exhibit viscoelastic behavior, which cause energy dissipation and frequency dependence of both stiffness and damping. The natural frequencies and frequency responses of the material used in the present research at different modes is shown in fig. 7. The frequency responses and the natural frequencies obtained from modal analysis are used to determine viscous damping (c) and damping capacity (tan ψ) at different modes. Fig. 8 shows the damping capacities and viscous damping of the tested specimens with respect to their mode frequencies. The material GFRP and CFRP exhibits similar damping capacity for most of the mode frequencies, and in between 2 kHz to 6 kHz GFRP has been dominating among the two and at higher range of frequencies CFRP is found to be good in damping capacity. In case of viscous damping the GFRP specimen has been dominating in entire range of mode frequencies. Transmissibility (T) and damping ratio (ς) are two important dimensionless quantities which are frequently used to express the damping behavior of the system. Fig. 9 shows the transmissibility and damping ratio of the tested specimens with respect to their mode frequencies. It has been observed from the results that the transmissibility and damping ratio were almost similar for entire range of mode frequencies; however CFRP specimen has better transmissibility and damping ratio in the range of 15 kHz to 26 kHz.

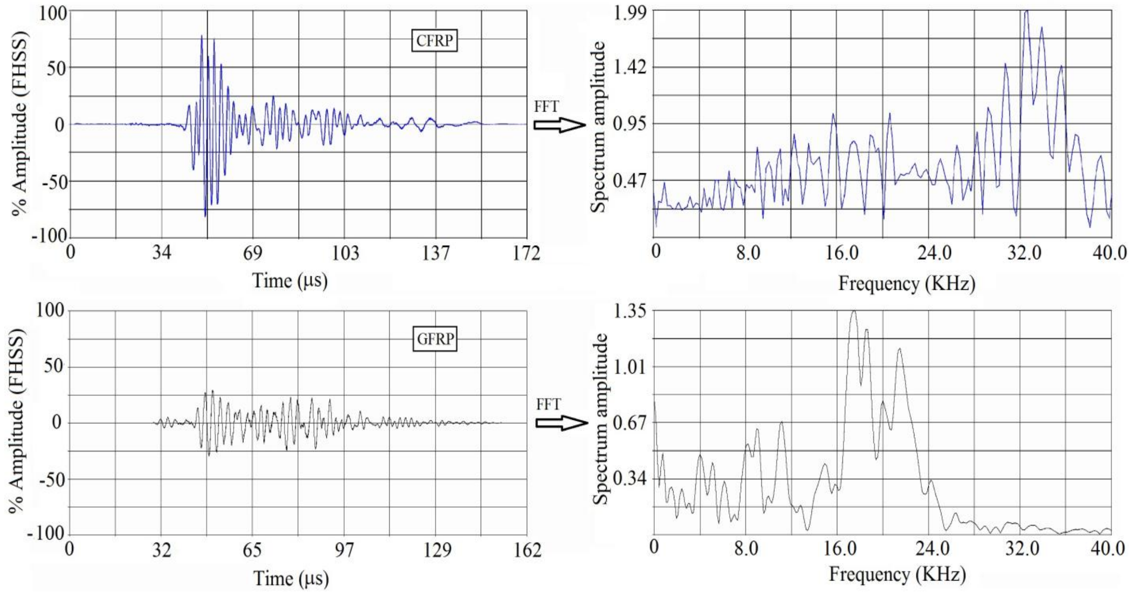

Fig. 6 Response curve of GFRP and CFRP specimen

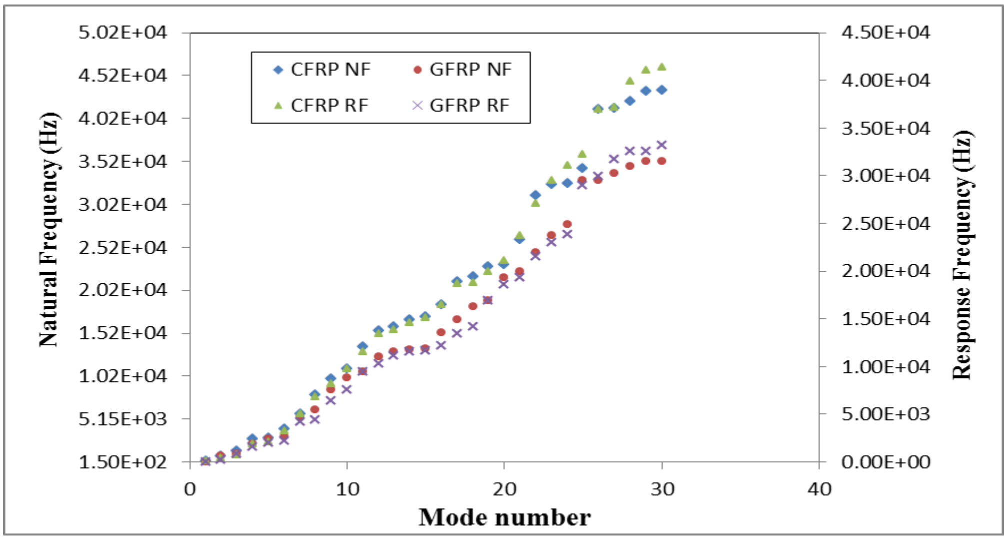

Fig. 7 Natural frequencies and frequency responses of CFRP and GFRP specimen

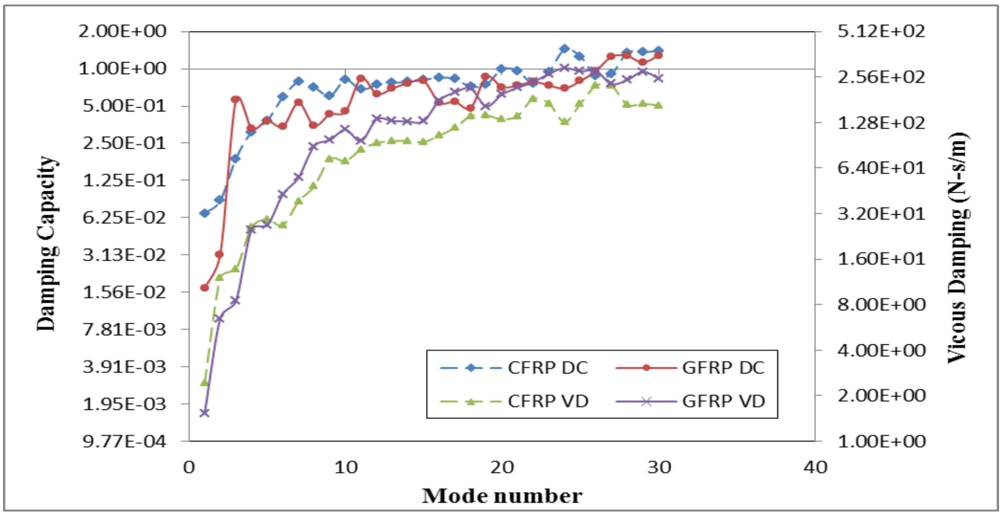

Fig.8 Damping capacity and viscous damping for CFRP and GFRP specimen

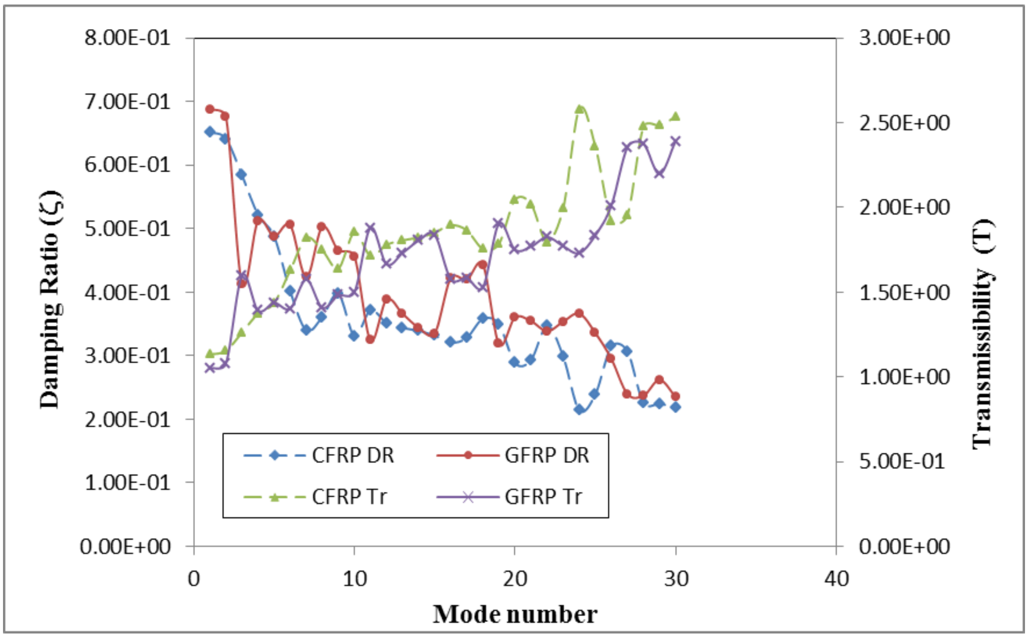

Fig. 9 Transmissibility and damping ratio for CFRP and GFRP specimen

VI. CONCLUSIONS

Dynamic mechanical analysis is a technique used to study and characterize materials. It is most useful for studying the viscoelastic behavior of polymers. Combined finite element and frequency response has been explored in this work and tests were carried out on CFRP and GFRP composite plates. The materials have been characterized for damping parameters at their mode frequencies. The main advantage of this method is that the materials can be tested in high frequency range, specifically at its natural frequencies and at relatively low amplitudes and in a non-distractive way.

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