Damping characteristics of glass fiber reinforced composite with viscoelastic layers

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Abstract— **Vibration and the composite material are two wildest growing research topics. The structural component subject to dynamic loading in their working life it causes vibration. It is very important in designing a structure to predict the vibration behavior in advance and to take necessary steps to control the structural vibration and its amplitude. Viscoelastic embedded composite material has been emphasized as an effective designing parameter for increasing damping performance of composite structure. This work presents Experimental and analytical model for energy dissipation in composite laminates embedded with viscoelastic layers at optimal position. Five different configurations for the embedded composite laminates had been fabricated as per ASTM Standards and have been compared with untreated specimen for vibration damping, strength, stiffness. The elastic and dissipative material function for shear modes has been experimentally characterised for the constituents of embedded laminates. The effects of damping layers for fiber-reinforced composite materials and location of viscoelastic layers on the loss factor and frequency of treated composite has been studied. Interleaving damping layers at various locations and numbers of layers shows dramatic enhancement in damping characteristics with permissible reduction in strength and stiffness.**

Keywords—Composite material, Modal analysis, Finite element analysis, FFT analyser.

I. INTRODUCTION

Fiber-reinforced composites are being increasingly used as alternatives for conventional materials primarily because of their, high specific strength specific stiffness and tolerable properties.

In addition the viscoelastic character of composites render them suitable for high performance structural applications like aerospace, marine aerospace, automobile, etc. However, these materials are somewhat distinct from metals because the former exhibit several peculiar modes of failure (delamination, fiber failure. matrix crazing, and interfacial bond failure due to deboning) and at micromechanical level, i.e., constituent level. Several analytical approaches are available in the form of micromechanical, structural and micromechanical models/theories as a result of Investigations carried out for both static and dynamic performance of composites.

Damping is an important parameter related to the study of dynamic behavior of fiber-reinforced composite structures. The perfect characterization of dynamic response of visco-elastically damped composite materials has to be analyzed by analytical model/method describing properties of composites based upon its constituents and their interaction condition of interphase [1]. The control of noise and vibrations in structures can be achieved by using active or passive damping systems. For active damping systems proper design arrangement of control systems and sensors are required. It increases the complexity of the system and hence less reliable, whereas the passive damping control is achieved by use of structural modifications, and damping layers. Because of reduced system complexity passive damping contributes more effectively with high reliability to the improvement of composite structures than the active damping. Shao Hui Zhang, Hua Ling Chen studied strain energy method in Finite Element analysis for predicting model loss factor of laminated composite beam with integral visco-elastic layer. Factors like contribution of energy dissipation due to fiber- reinforced composite and frequency of visco-elastic damping material are taken into account. The effect of ply angle of compliant layers, location of visco-elastic layer on the loss factor and frequency of damped composite beam studied using commercial software ANSYS7.0 by developing 3D Finite Element model [2]. Sen. Liang, Y.X. Zhang developed innovative composites from stage of design, location of damping layers. Manufacturing embedded and co-cured composite which mainly aims strong potential to resist impact. Study resulted that with visco-elastic film embedded plates can improve impact resistance greatly and with increasing thickness of viscoelastic film, plasticity also enhances greatly [3]. Jean-Marie Berthelot Studied damping characteristics of laminated unidirectional cantilever beam subjected to an impulse input. Size of specimen for investigation taken was 200mm wide and 300mm long with thickness of 2.4mm. Using Ritz's method for damping model flexural vibration of beam is investigated. In which Influence of beam width and vibration frequency is considered [4]. A. Martone et al studied configuration of composite material based on viscoelastic fiber integrated along traditional carbon tows within same lamina were studied and tested. Specimen was manufactured with two viscoelastic volume fraction (2.5% and 5%).Vacuum Infusion process (VIP) used to manufacture specimens and Dynamic Mechanical analysis (DMA) is carried performed. Analytical and experimental results gives significant enhancement (+80% and +56%) of the damping properties [5]. Nagasankar P. et al studied theoretical and experimental damping property of Glass fiber reinforce polymer (GFRP) matrix composites with reducing diameter of the glass fiber from 27.2μm,for various orientation and layup by keeping volume fraction constant. Impulse technique is used for evaluation of natural frequencies and loss factors. Blevins "formula for natural frequency and mode shape" and Ni & Adams's "the specific damping capacity (SDC) model" is used for evaluating the same properties [6]. Jinqiang Li, Yoshihiro Narita have studied optimal design and analysis for the damping loss factor of laminated plate under general edge conditions. Classical laminated theory has been used to obtain loss factor from energy formulation for symmetrically laminated thin plates comprised of fiber reinforce layers and visco-elastic layers by layup method

In fundamental mode results of numerical simulation shows that both thickness and location of viscoelastic core play important role in the model damping loss factor of laminated plate [7]. In the present study, both experimental and numerical study is conducted for woven roving G/E composite plates. Quantitative results are presented to show the effect of different Parameter like no. of layers, aspect ratio and fiber orientation in free-free boundary conditions. Based on the first order shear deformation theory, a finite element formulation is presented for the analysis of the free vibration of composite plates. The percentage of difference between numerical results and experimental results are due to non-uniformity in the specimens properties (Voids, variations in thickness, non-uniform surface finishing) and also positioning of the accelerometers. This experimental method represents to predict the dynamical behavior of woven composite, in order to design panels or other similarly structure used in different applications such as automotive industry, aerospace, civil, marine and other high performance structures.

In the present work, five different configurations for the embedded composite laminates have been fabricated using VARTM and basic properties are evaluated experimentally. The modal loss factor is calculated using half-power band width method from the FRF obtained in vibration test. These results are compared with untreated specimen's results to investigate different position of viscoelastic layer and the effect of viscoelastic layer thickness on modal loss factor. Further the Flexural and Impact test was performed to examine strength, stiffness of viscoelastic embedded composite material.

II. METHODOLOGY

A. Dissipative behavior of composite laminate

An elastic solid is deformed with strains (ε, ϒ) and loaded with stresses (s, τ) when external forces are applied. The work of external forces is stored as strain energy U, according to the following relationship:

$$U = \frac{1}{2}\int_V \sigma . \varepsilon \, dV$$

Stress (σ) and Strain (ε) tensors and dv representing the unit volume element. The total energy stored within the material can be computed as the sum of the energy stored in all constituent phases of the elastic body, as:

$$U = \frac{1}{2}\Sigma_{Vi}\left(\int_{Vi} \sigma . \varepsilon \, dV\right)$$

The mechanical energy dissipated by a material, is measured by the Specific Damping Capacity (SDC), which represents the ratio between the dissipated and total energy, as follows:

$$\psi = \frac{\delta U}{U} = 2\pi tan\delta = 2\pi \, \eta$$

The derivation of the equation could be finding elsewhere. The Strains and stresses generated by external forces, dissipate energy by different mechanisms, therefore damped energy can be evaluated for corresponding tensor element by summation of each term, as follows:

$$\delta U = \frac{1}{2}\int_V \psi(\sigma . \varepsilon) dV$$

Where ψ is the material specific damping capacity (SDC) as defined in equation.

B. Hybrid architectures for damping enhancement: Embedded configuration

The optimal position of the viscoelastic layer within the laminate is determined by the balance of five opposite design considerations. The maximum shear energy is experienced at the middle plane but a soft damping material here placed would dramatically affect the bending strength of the overall laminate. A tool is would be necessary to design the distribution of the damping layers within the laminate stacking sequence. Toward this aim, five different configurations of embedded composite laminates have been built and experimentally tested. Untreated Data have been compared with in the five different samples that are shown in table 1

The glass fiber properties are
E11 = 21GPa, E22 = E33=8.55GPa,
G12=G13=G23=3.5GPa,
ν12=ν13ν23=0.3,
ρ = 1566 Kg/m3, thickness of each layer t= 0.125mm
Viscoelastic material properties are

E = 2.2 x 105 Pa, ν = 0.3, ρ = 1200 Kg/m3, and
The material loss factor is 0.0586,
Thickness of each layer t=0.25mm

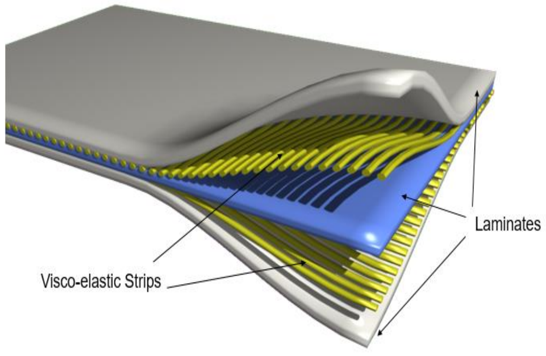


Fig 1 Design of concept of composite laminates

Specimen	Stacking sequence	VEM layer
Untreated	0/+30/-30/ 90/-30/+30/0	NA
Type 1	0/+30/-30/90/VM/ 90/-30/+30/0	1
Type 2	0/+30/-30/ VM /90 / 90/ VM /-30/+30/0	2
Type 3	0/+30/ VM /-30/90/ 90/-30/ VM +30/0	2
Type 4	0/+30/ VM /-30/90/VM/ 90/-30/ VM +30/0	3
Type 5	0/ VM /+30/-30/90/VM/ 90/-30/+30/ VM /0	3

Table No: 1 Stacking Sequence

The following materials such as Glass fiber, epoxy resin and Acrylonitrile Butadiene Rubber (NBR) as viscoelastic material are used. The E-glass mat fabric of 0.2 mm and Polyester resin with room temperature curing hardener (Methyl Ethyl Ketone peroxide) with diluents Cobalt Naphthenate mix was employed for the matrix material

Specimen	Epoxy (wt. %)	Glass (wt. %)	VEM (wt. %)
Untreated	30	70	NA
1	30	65	5
2	30	60	10
3	30	60	10
4	30	55	15
5	30	55	15

Table no.2 Details of Prepared Composite

Sample is fabricated with 8 numbers of layers and lied up and cured at room temperature for 24hr. The cross sectional area of rectangle is 220 x 220 x 3 mm then the cured specimens were cut in to the size of 200 x 20 x 3 mm3 by using computer Numerical control router machine in order to achieve uniformity in all cases.

C. Fabrication Method.

Vacuum assisted resin transfer molding VARTM has been developed as variant of traditional RTM process. To reduce the cost and design difficulties associated with large metal load.

First, the vacuum pump is turned on to remove air from preform assembly. The system has been equilibrated and all air leaks have been eliminated because air leakages can cause resin to improperly flow through the molds and also leads to formation of air bubbles. The resin is allowed to flow into preform. A pressure of 1atm is provided to both the driving forces for the resin to impregnate the rein-forcemeat and the compression-force to compact preform to desire fiber volume fraction.

The vacuum is left on until the resin has completely gelled. The plates are cured at room temperature. Figures shows schematic diagram of vacuum assisted resin transfer molding (VATRM) process.

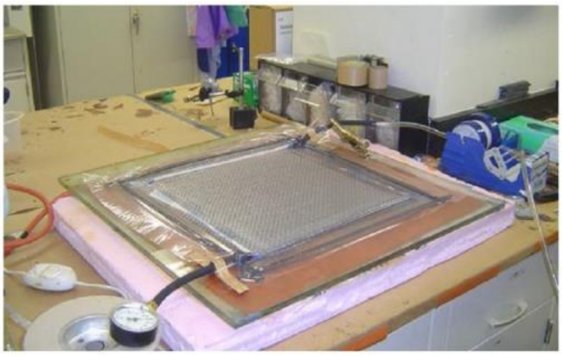


Fig. 2: Diagram of vacuum assisted resin transfer molding (VATRM) process

D. Determination of material constants

The characteristics of fiber glass/epoxy composites plate which can be determined completely by material constants Density (ρ), Young's modulus (E) and Poisson's ratio (υ). The specimens were cut by diamond cutter or by hex saw as per ASTM Standards D 638-08. After cutting in the hex saw, it was polished in the polishing machine. Those specimens were tested and value ware adapted.

III. NUMERICAL ANALYSIS

The composite plate consist layer of Acrylonitrile butadiene rubber (NBR) embedded within Glass fiber. For the analysis purpose dimensions of test specimen are finalized according to ASTM E756, which are shown in

Fig.3: VEM embedded composite plates

Table No.3 Dimensions of plate

A. Modal Strain Energy Method (MSEM)

Name of the part	Material	Thick (mm)	Length (mm)	Width (mm)
Damping Material	Viscoelastic material	0.25	220	10
Base material	Glass Fiber	0.4	220	220

The modal strain energy (MSE) method has been proposed to estimate the modal loss factors or modal damping ratios of structures with viscoelastic damping material. Modal analysis gives strain energy fraction at corresponding bending modes.

By using modal strain energy method the modal loss factor can be obtained using following equation. Material Loss Factor of VEM (η_{VEM}) = 0.0586

$$\eta_{Modal} = \eta_{VEM} \frac{U_{VEM}}{U_{Total}}$$

Where,

η_{Modal} = Modal Loss Factor

U_{VEM} = Strain Energy of VEM Rubber

η_{VEM} = Material Loss Factor of VEM

U_{Total} = Total Strain Energy of Structure

1) Finite Element Analysis Result for Specimen-1

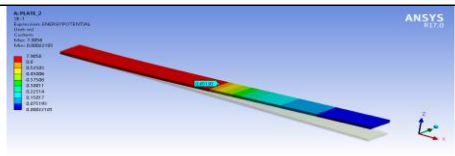
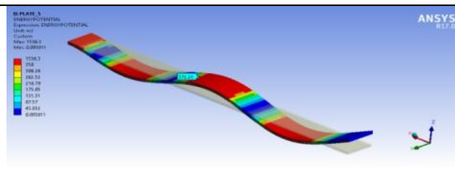
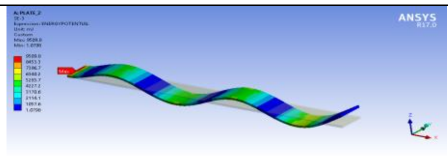
Mode	Specimen-1	(U_{Total})
1		0.65
2		71.28
3		9509

Table No. 4 Total Strain Energy of Structure

2) Sample Calculations for Specimen -1

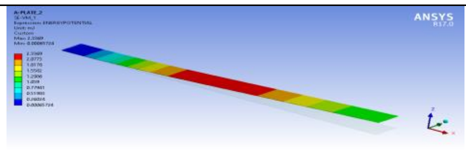
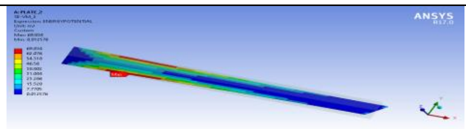
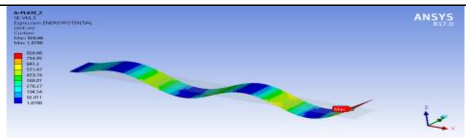
Mode	Specimen-1	(U_{VEM})
1		2.33
2		69.83
3		826.66

Table No. 5 Strain Energy of Viscoelastic layer

MODE NO.1

$$\eta = 0.0586 \times \frac{2.33}{0.65} = 0.21$$

MODE NO.2

$$\eta = 0.0586 \times \frac{69.83}{71.28} = 0.057$$

MODE NO.3

$$\eta = 0.0586 \times \frac{826.66}{95.9} = 0.005$$

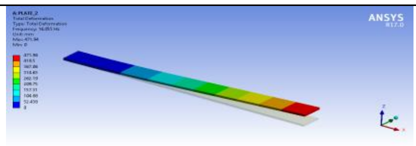
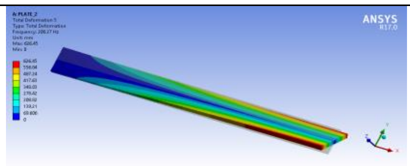
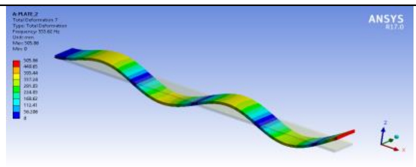
Mode	Specimen-1	Freq.	Loss F.
1		16.05	0.21
2		20.8.27	0.057
3		553.62	0.005

Table No.6 FEA Frequency and Loss factor

IV. EXPERIMENTAL ANALYSIS

A. Experimental Set-Up

Fig. 4 shows the experimental setup used to carry out the modal analysis of Viscoelastic embedded composite laminates using impact hammer. The accelerometer is at the end of rectangular composite laminate. The modally tuned impact hammer with sharp hardened tip is chosen forgetting higher frequencies. The displacement signal

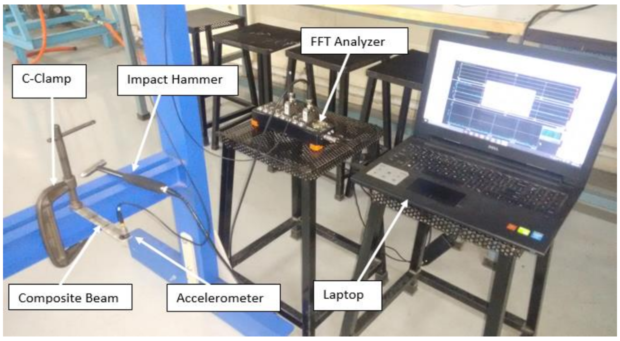


Fig.4: Experimental setup

From accelerometer has been recorded in personal computer through data acquisition system (DEWE soft FFT analyzer) and ICP conditioner. Two separate adaptors are used for capturing the output signal, one for receiving accelerometer signal and the other for measuring the magnitude of the response by the hammer from laminates. Results are displayed on computer screen.

B. Half-power bandwidth method for determining Modal loss factor

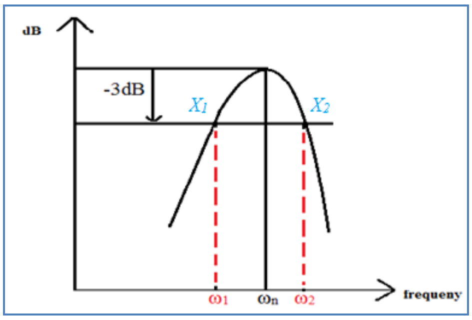


Fig.5: Half power bandwidth Method

The usual convention is to consider points X_1 and X_2 as in the Figure above, to be located at frequencies on the response curve where the amplitude of response of these points is $1/\sqrt{2}$ times the maximum amplitude. The bandwidth at these points is frequently referred as 'half-power bandwidth'. The half-power points or 3 dB points for small damping corresponds to the frequencies ω_1 and ω_2. The frequency interval between these two half power points is [9]

$$\Delta\omega = \omega_2 - \omega_1 .$$

Loss factor of this method is defined as

$$\eta = \frac{\Delta\omega}{\omega_n}$$

Modal damping factor $(\xi) = \eta/2$

The fig.6 shows the frequency response function (FRF) curve of Specimen 1 VEM embedded composite plate. Natural frequencies are:

17.090 Hz, 205.078 Hz, 595.703 Hz and 1177.979 Hz.

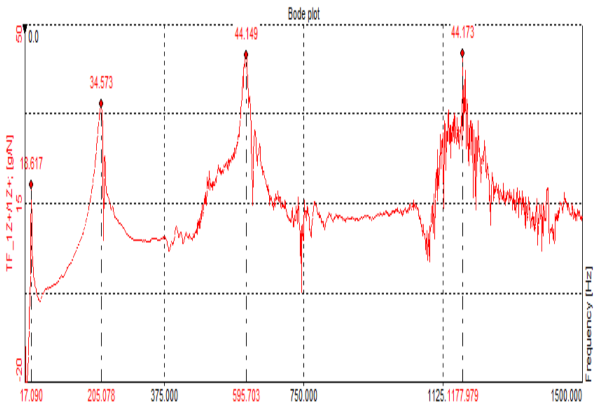


Fig.6: FRF curve of Specimen 1

Sample Identification	Mode 1		Mode 2		Mode 3	
	Exp. Frequency (Hz)	FEA Frequency (Hz)	Exp. Frequency (Hz)	FEA Frequency (Hz)	Exp. Frequency (Hz)	FEA Frequency (Hz)
Untreated	13.42	20.39	87.89	127.7	262.4	357.3
Specimen 1	17.09	16.05	205.0	208.2	595.0	553.6
Specimen 2	19.53	14.51	234.3	239.8	649.4	563.8
Specimen 3	24.41	15.58	246.6	275.1	721.4	649.1
Specimen 4	18.85	13.25	219.1	264.7	640.8	683.2
Specimen 5	19.53	12.88	205.0	187.4	588.3	568.7

Table No.7 Experimental and Numerical comparison for frequency at different modes

Sample Identification	Mode 1		Mode 2		Mode 3	
	Exp. Loss Factor	FEA Loss Factor	Exp. Loss Factor	Exp. Loss Factor	Exp. Loss Factor	Exp. Loss Factor
Specimen 1	0.2129	0.21	0.0594	0.057	0.0011	0.005
Specimen 2	0.5068	0.4976	0.1489	0.132	0.0825	0.013
Specimen 3	0.3001	0.16	0.0990	0.093	0.0067	0.07
Specimen 4	0.20	0.11	0.0434	0.07	0.003	0.076
Specimen 5	0.3008	0.25	0.0419	0.04	0.0062	0.0068

Table No 8 Experimental and Numerical comparison for frequency at different modes

1) Sample Calculations for Specimen-1

MODE NO.1

$$\eta = \frac{18.006 - 14.368}{17.09} = 0.219$$

MODE NO.2

$$\eta = \frac{210.067 - 198.89}{205.0} = 0.0594$$

MODE NO.3

$$\eta = \frac{595.143 - 594.489}{595} = 0.0011$$

V. MECHANICAL PROPERTIES

A. *Flexural Test-*

Flexural Strength is one of the important factors in composite material. It can be determine by performing flexural test using UTM with 3 point bending method. A span of 50 mm with the crosshead speed of 2mm /min has been taken for all the sample of dimension 127 x 13 x 3 mm as per ASTM D790-10 Test Standards. [10]

B. *Impact Test-*

The ability of polymer matrix composites to withstand high energy impact without fracturing or breaking is referred as impact strength. Magnitude of impact energy is mainly depends on interfacial adhesion between the fiber and matrix. That can be determine by performing Izod Impact Test according to ASTM D256-10 the specimen of 65 x 13 x 3 mm sized for used for measuring impact strength.[10]

VI. RESULT AND DISCUSSION

By using numerical and experimental analysis the comparison of modal frequency and modal loss factor of composite plate embedded with VEM are shown in Table No. 6 & Table No. 7 for different models Effect of crucial parameters like position of viscoelastic material Layer, number of VEM layers and effect of Rubber on strength and stiffness of Composite has been analyzed. Furthermore, a detailed mode shape study has been carried out.

C. *1) Effect of the viscoelastic layer relative position*

Case I -The relative position of the viscoelastic layer for the laminate is may be important parameter with a likely effect in the loss factor value. Five different specimen configurations were considered and compared with untreated laminates for analysis. For this case Glass fiber composite placing a viscoelastic material like rubber as one layer (Middle) between fiber layers is compared with untreated specimen. VEM embedded structure shows relatively improved loss factor shown in Figure 7

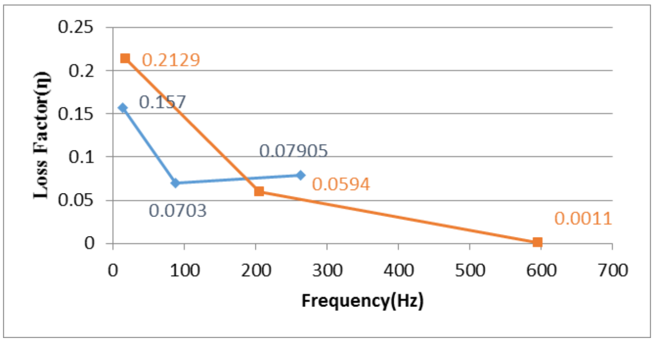


Fig.7: Loss factor variation as a function of the viscoelastic layer's relative position
(single layer compared with untreated case)

Case II- Another approach has been followed consisting in the simulation of the damping behavior of an identical laminate but with two viscoelastic layers. This allows us to strengthen the energy loss contribution of the damping material (as it is now two times thicker than the previous case) and therefore try to perceive any effect resulting from the variation of the position of the viscoelastic layer

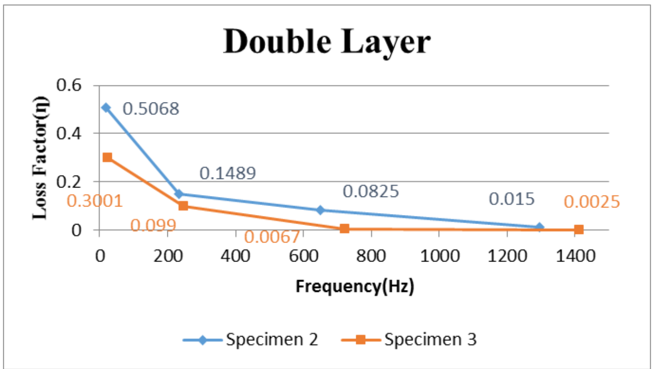


Fig.8: Loss factor variation as a function of the viscoelastic layer's relative position (double layer case)

The plots in Figure 8 refer to type of specimens having the Viscoelastic material (now in the form of two layers instead of the single one considered in the previous case) in two distinct positions: in the laminate's plane of symmetry (specimen 2); towards the laminate´s outer surface (specimen 3). Now, the effect of the relative position of the visco elastic layers in the loss factor variation is quite clear in Figure 8 Where the loss factor value is dramatically higher than that of specimens with one viscoelastic layer.

Case III- In order to obtain a maximum loss factor value anther configuration has been Designed with three layers of Viscoelastic material placing one layer at middle of symmetry and other two in two distinct positions: in the laminate's plane of symmetry (specimen 4) and towards the laminate´s outer surface (specimen 5). Plot in Figure 9 refers increase in loss factor but not as that of double Layer.

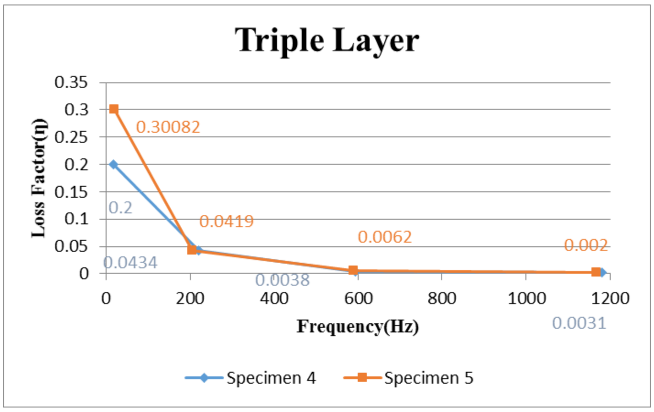


Fig.9: Loss factor variation as a function of the viscoelastic layer's relative position (Triple layer case)

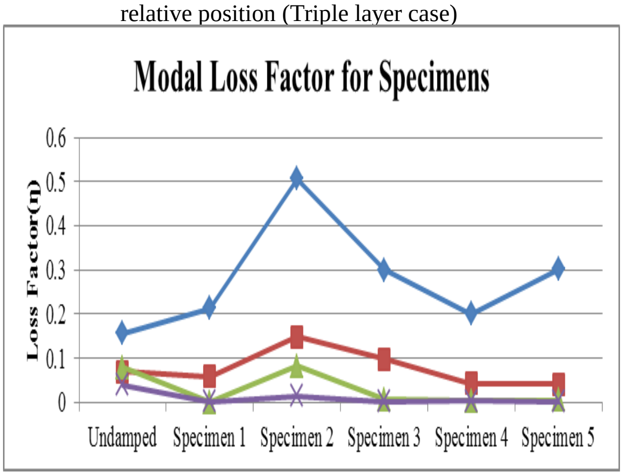


Fig.10: Experimental modal loss factor of Specimens

Specimen	Maximum loss factor (η_{max})	Percentage variation (With Untreated)
Untreated	0.157	0%
Specimen 1	0.2129	35.60%
Specimen 2	0.5068	222.80%
Specimen 3	0.3001	91.14%
Specimen 4	0.2	27.38%
Specimen 5	0.3008	91.082%

Table No.9 Best Specimen type configuration for optimum modal loss factor

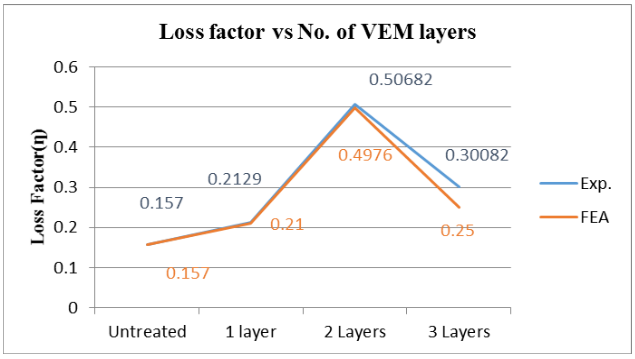


Fig.11 Graph of loss factor for Number of VEM Layer

The Number of viscoelastic layer has a strong influence in the loss factor value, showing a nearly linear dependency up to 2 number of layer. Beyond this threshold, the loss factor variation is much smaller and tends to a stable value, which means that the gain damping capabilities can be compromised by the considerable weight increase of the laminates

3) Error Percentage between Experimental & Numerical Results.

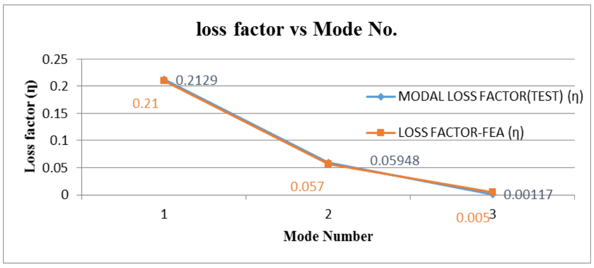


Fig 12: Experimental and FEA loss factor compare

Mode Number	1	2	3
Exp. Loss Factor	0.2129	0.05948	0.00117
FEA Loss Factor	0.21	0.057	0.0015
Error %	1.362%	4.1694%	10.648%

Table No. 10 Experimental and FEA Loss Factor percentage error

The results obtained for free vibration of composite plates for both experimental and ANSYS was in good agreement. It is observed from the above table shows that a number of layers increases the natural frequency also increases. Numbers of VEM layers have a large influence on geometry as well as the dynamic behavior of composite materials. An experimental and analytical result shows good agreement with each other, because of their calculation accuracy. FFT and ANSYS follow the iterative processes so they give more accurate results.

4) Effect of Viscoelastic material on Strength & stiffness.

Composite materials have wide acceptance because of it's their high strength-to-Weight and Stiffness-to-weight ratios. Interleaving Viscoelastic material in composite structure may cause reduction in strength and stiffness

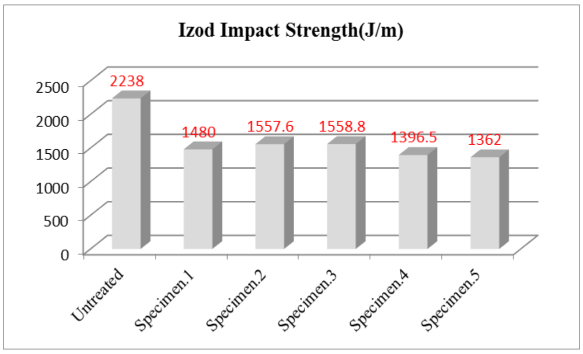


Fig.13: Impact strength of Glass composite embedded with VEM.

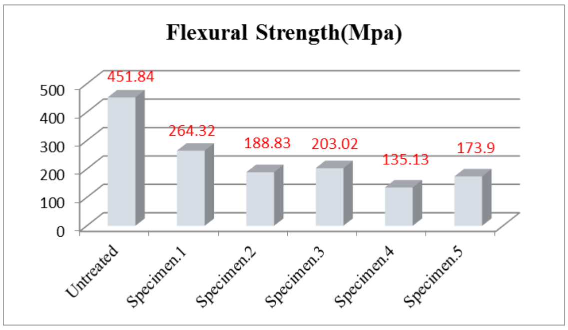


Fig.14: Flexural strength of Glass composite embedded with VEM.

CONCLUSION

- The damping performance is measured in terms of modal loss factor (η).
- Comparing Frequency and Modal loss factor for Untreated and treated composites it is found that Viscoelastically treated composites shows higher modal loss factor which is desirable.
- It is observed that the results obtained by FEA analysis and experiment analysis are well corroborated with error within 15%.
- By FEA & experimental analysis results, it is observed that percentage of modal loss factor of Specimen 2(105.28%) is more than Specimen 1(35.60%), Specimen 3(91.14%), Specimen 4(27.38%) and Specimen 5(91.082%) considering untreated as Loss Factor as base value.
- Modal loss investigation can state that different position of viscoelastic layer plays vital role to enhance damping characteristic of composites.
- Specimens with placing a viscoelastic material like rubber as one layer between fiber layers, damping ratio is improved. This may be because of high strength and shear modulus of the viscoelastic material. Loss factor

varied with respect to position of layer. Position of the VEM layers beside to middle compared to outer surface plane provide higher loss factor values than other relative positions.

- Flexural and Impact test shows weight percentage of viscoelastic material can enhance damping capacity of composites system with little reduction in strength and stiffness.

SCOPE OF FUTURE WORK

Others types of viscoelastic materials can be used to improve the model accuracy and to validate its applicability. Optimization procedure could be developed to provide additional information about important design aspects for this type of materials.

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