Journal of Materials Science and Engineering A 6 (1-2) (2016) 35-42
doi: 10.17265/2161-6213/2016.1-2.005

DAVID PUBLISHING

Passive Damping Characteristics of Carbon Epoxy Composite Plates

Dileep Kumar K* and V V Subba Rao

Faculty of Mechanical Engineering, JNT University Kakinada, Kakinada-533 003, India

Abstract: Vibration damping is an important phenomenon in the field of engineering design while predicting the dynamic analysis of the most of the structures. It is one of the typical dynamic responses of structural members, which allows the members fail due to larger amplitudes. Composite materials are replacing conventional structural materials due to attractive, superior mechanical properties such as high strength to weight ratio, high modulus, high corrosion resistance and good fatigue resistance. Composite materials possess high degree of material damping compared with conventional materials. One of the advanced technique employed to safe guard against the severe intensity of vibrations by controlling the dynamics of the structures is the provision of enhancing energy dissipation by the design of a constrain layer. When a constrain layer is made of a non actuating stiff layer of material introduced in the structure, say a viscoelastic material called a PCLD (Passive constrained layer damping). In the present work, an analytical solution for damping of a FRP (Fiber reinforced polymer) plates with a single or double interleaved viscoelastic layers in is obtained. Ritz method is employed to predict the damping nature of the plate under several boundary conditions. Specific damping capacity and a loss factor are deduced from the method of energy formulation for viscoelastic layers interleaved in laminated fiber reinforced plate. The loss factor of constrain layered plate is calculated as a function of fiber orientation in its orthotropic layers. An isotropic constrain layers are configured at midplane, symmetric, asymmetric and outer positions across the thickness of the plate. A parametric study also carried out to observe the effect of position of a constant thickness viscoelastic layer on the damping characteristics of passively constrain orthotropic plate.

Key words: Thin plate theory, specific damping capacity, loss factor and viscoelastic materials.

Nomenclature

U:	Energy dissipated
ΔU:	Maximum strain energy
A_{mn}:	Fourier Co-efficient of deflection
R:	Aspect ratio
e_0:	Viscoelastic layer of thickness
a:	Length of the plate
b:	Width of the plate
e:	Thickness of the orthotropic lamina
iQ_{pq}^{v}:	Reduced stiffness constants
d_1:	Up Distance of VEL from laminate Midplane
d_2:	Down of VEL from laminate Midplane
w_0:	Transverse displacement
A_{ij}:	Series Co-efficient
C_{minj}^{pqrs}:	Product of integrals I and J
D_{pq}^{v}:	Time
E:	Young's modulus
D_{pq}^{ort}:	Bending Moment in y direction
$f_{pq}(\theta)$:	Orientation function

Greek Letters

υ :	Poisons ratio of VEM
ψ_x:	Specific Damping Co-efficient
λ_m:	Boundary values of the plate in x-direction
γ_m:	Boundary values of the plate in y-direction
η:	Loss factor
α:	Longitudinal modulus
α_1:	A constant for VEM position Up Distance
α_2:	A constant for VEM position down Distance

1. Introduction

Nowadays an increased demand for the control of acoustics and vibration in structures had enforced the designers to take damping into account even from the preliminary design phase. A designer always looks for a material which shows superior or optimum properties under given operating environment. It is very difficult task to search for an optimal material for

*Corresponding author: Dileep Kumar K, assistant professor, research field: damping of composite structure.

every new design. In such cases a composite material will be the best practical solution owing to reason that its properties can be tailored according to desired degree of magnitude by providing geometric and material symmetry conditions. The advantages of composites can be made utilized by the rational choice of stacking sequence. In many aerospace, commercial and automotive components, sports and structures composites have been successfully used. Advanced composite materials not only have high stiffness but also have greater damping capacity compared to metals. For example, in a FRP composite, the damping is enhanced due to the internal friction among the constituents and interfacial slip at the fiber-matrix interfaces, where as the fiber contributes to the stiffness. However, the damping capacity of the composite laminates can be increased many fold by incorporating viscoelastic layers between the laminae of the host composite. In this hybrid approach, the dominant mechanism of damping is the shear induced between the damping layer and the constraining layers. The trade-offs in using damping layers are a slight reduction in stiffness and a small increase in the weight of the composite system. The desirable damping characteristics and design flexibility make the viscoelastic materials to be embedded as an important isotropic constituent layer in the composites.

Adams R D [1] consider the basic elasticity relationships for unidirectional composites, together with the Adams-Bacon damping criterion, are utilised for prediction of moduli and flexural damping of anisotropic CFRP (Carbon fiber reinforced polymer) and GRP beams with respect to fibre orientation. Billups E K [2] works on several two-dimensional theories for investigating the SDC (Specific damping capacity) of composite materials and theories are compared with those of Adams and Bacon, Adams and Maheri, Ni and Adams [3] and Saravanos and Chamis. No interlaminar effects are considered. The analysis considers the variations of Young's modulus and damping of viscoelastic layers with the frequency. Finally, the article presents the effects of Young's modulus and the damping of a viscoelastic layer interleaved in the middle plane of unidirectional laminate by Jean-Marie Berthelot [4]. The optimal lay-up design problem, a layer wise optimization (LO) method is applied to the orthotropic plates comprised of two different laminates, and an optimal fiber angles are determined to obtain the maximum loss factor in the first mode by Jinqiang Li [5]. Jean-Marie Berthelot [6] also predicted various damping parameters and are investigated using cantilever beam test specimens using an impulse hammer technique. Damping modeling is developed by a finite element analysis which evaluated the different energies dissipated in the material as a function of fiber directions of the layers is the work of Ni, R. G. and Adams, R. D [7]. Advanced FRP composites are prime candidates for several interesting applications where damping is a key parameter. Improvement of vibration damping characteristics of such materials makes them qualify even more attractive applications. Since most of composite structural elements in military, automotive and space applications are subject to severe dynamic loads an additional vibration control becomes necessary. This can be achieved by using different damping treatments. High degree of damping in a structure can often improve performance in a dynamic load environment. Various methods for predicting damping in a structure are proposed, the Ritz method is the most efficient method.

In composite base structures, several factors influence its structural vibration response. For example, the constituents, the fiber orientation and stacking sequence in the host structure, and the position from midplane, amount and type of treatment of embedded layer, influence the response strongly. The effect of some of such parameters is presented here using Ritz method.

2. Modeling of FRP Plate Using Ritz Method

Passive damping has been recognized as an important mechanism for controlling the elastodynamic performance of flexible structures. The arrangement of different layers in a PCLD plate is shown in Fig. 1. Among various passive damping techniques, it is known that the material damping can effectively improves the capabilities for suppressing vibration, sound, fatigue endurance and impact resistance, and can be easily implemented as viscoelastic layers in the laminated plate structures. The goal of an effective damping treatment is to add the viscoelastic material in such a way and in such location so as to ensure that the greatest possible cyclic deformation of the damping materials will occur as the structure vibrates in the modes of interest, to dissipate as much vibrational energy during each cycle as possible. This requires an understanding of the dynamic behavior of the structure or machine and an understanding of the deformation of the viscoelastic material which occurs during vibration of the structure, and by no means least, an understanding of the complex modulus properties of the candidate damping materials in order that a proper treatment can be developed.

Two types of laminates with viscoelastic layers were considered. Laminates with a single viscoelastic layer of thickness e_0 interleaved in the middle plane of laminates (Fig. 2) and laminates with two viscoelastic layers of thickness e_0 interleaved away from the middle plane (Fig. 3). The layers of the initial laminates are constituted of unidirectional or orthotropic materials with material directions making an angle θ with the x direction oriented along the length of plates under consideration. The total thickness of the unidirectional or orthotropic layers is ‘e’ and the interlaminar layers are assumed to have an isotropic behavior

2.1 Interlaminar Viscoelastic Layer

The laminate is constituted of a unidirectional or orthotropic material of thickness e in which a single viscoelastic layer of thickness e_0 is interleaved (Fig. 2). Material directions make an angle θ with the plate directions. According to the results established in Berthelot, the total strain energy stored in the laminate with the viscoelastic layers can be expressed as

$$U = U_{11} + 2U_{12} + U_{22} + U_{66}$$
$$U_{pq} = U_{pq}^{ort} + U_{pq}^{v} \quad pq = 11,12,22,66 \qquad (1)$$

The energies U_{11} and U_{22} are the strain energies stored in tension-compression in the material directions, U_{12} is the coupling energy induced by the Poisson’s effect, and U_{66} is the strain energy stored in in-plane shear. The energy is separated as the strain energy U_{pq}^{ort} stored in the orthotropic layer and the strain energy U_{pq}^{v} stored in the viscoelastic layer. Applying the results obtained by Berthelot and Sefrani et al and Berthelot, the energy stored in the orthotropic layers 1 and 3 (Fig. 2) can be written as

$$U_{pq}^{ort} = U_{pq}^{1} + U_{pq}^{3} =$$
$$\frac{1}{2Ra^2}\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{i=1}^{M}\sum_{j=1}^{N} A_{mn}A_{ij}f_{pq}(\theta)Q_{pq}\frac{e^3}{12}\Big[\Big(1 +$$
$$e0e3 - e0e3 \qquad (2)$$

where, a is the length and R the length-to-width ratio of the plate, U_{pq}^{1} and U_{pq}^{3} are the strain energies stored in layers 1 and 3, are the reduced stiffness constants of the materials, and $f_{pq}(\theta)$ are functions of the material directions obtained by Berthelot et. al. In the same way, the strain energy stored in the viscoelastic layer is given by

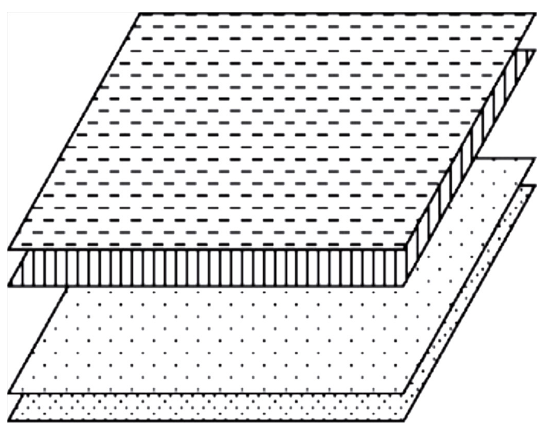

Fig. 1 Laminate with viscoelastic layer.

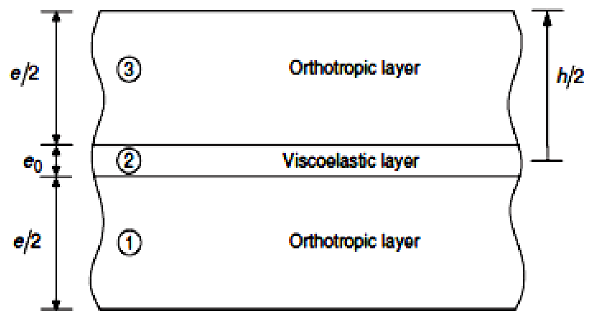

Fig. 2 Laminate with a single viscoelastic layer.

$$U_{pq}^{v}=U_{pq}^{2}$$
$$=\frac{1}{2Ra^2}\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{i=1}^{M}\sum_{j=1}^{N}A_{mn}A_{ij}f_{pq}^{v}(\theta_v)iQ_{pq}^{v}\frac{{e_0}^3}{12} \quad (3)$$

where, the reduced stiffness constants iQ_{pq}^{v} are expressed as

$$iQ_{pq}^{v}=\begin{bmatrix}\frac{E}{(1-\upsilon^2)} & \frac{E}{(1-\upsilon^2)} & 0\\ \frac{E}{(1-\upsilon^2)} & \frac{E}{(1-\upsilon^2)} & 0\\ 0 & 0 & \frac{E}{(2(1+\upsilon))}\end{bmatrix} \quad (4)$$

Introducing the Young's modulus E and the Poisson's ratio υ of the viscoelastic layer. This layer being considered as isotropic, the results are independent of the direction. Thus, the function $f_{pq}^{v}(\theta_v)$ can be deduced by considering an orientation equal to zero, which leads to

$$f_{11}^{v}(\theta_v)=C_{minj}^{2200};\ f_{12}^{v}(\theta_v)=C_{minj}^{2002}R^2;$$
$$f_{22}^{v}(\theta_v)=C_{minj}^{0022}R^4;\ f_{66}^{v}(\theta_v)=4C_{minj}^{1111}R^2; \quad (5)$$

The energy dissipated by viscous damping is then expressed by

$$\Delta U=\sum_{pq}^{n}(\psi_{pq}^{ort}U_{pq}^{ort}+\psi_{pq}^{v}U_{pq}^{v}) \quad (6)$$

Introducing the specific damping coefficients of the orthotropic material considered and the coefficients of the viscoelastic layer. The damping coefficients are the in-plane damping coefficients of the orthotropic layer considered in Berthelot and Sefrani et al. They will be simply noted. The damping of the viscoelastic layer is related essentially to the Young's modulus and it can be written as

$$\psi_{11}^{v}\approx\psi_{22}^{v}\approx\psi_{66}^{v}\approx\psi_v;\ \psi_{12}^{v}=0 \quad (7)$$

Next, the damping of laminated plate with a single viscoelastic layer is evaluated by

$$\psi_x=\frac{\Delta U}{U} \quad (8a)$$

Finally the loss factor is obtained as follows

$$\eta=\frac{\psi_x}{2\pi} \quad (8b)$$

2.2 Two Interlaminar Viscoelastic Layers

This subsection considers the case of a unidirectional or orthotropic material of thickness e in which two viscoelastic layers of thicknesses e_0 are interleaved in the initial material (Fig. 3). To obtain a general analysis, the viscoelastic layers are considered to be interleaved at distances d_1 and d_2 from the middle plane, respectively. These distances will be expressed as

$$d_1=\alpha_1\frac{e}{2},d_2=\alpha_2\frac{e}{2} \quad (9)$$

As previously mentioned, the strain energy stored in the laminate with the two interleaved viscoelastic layers can be expressed by Eqn.1 where U_{pq}^{ort} is the strain energy stored in the orthotropic layers and U_{pq}^{v} is the strain energy stored in the two viscoelastic layers. The strain energy stored in the orthotropic layers 1, 3 and 5 can be expressed as

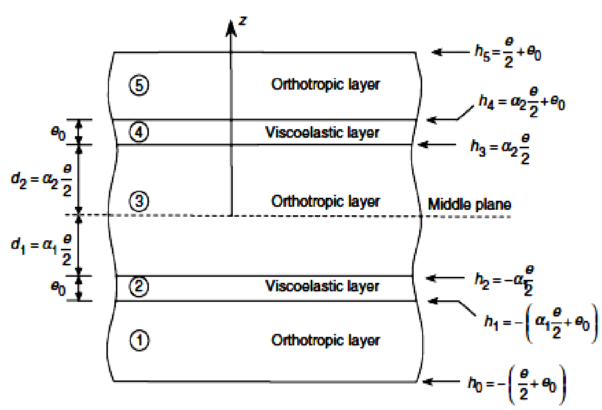

Fig. 3 Laminate with two interleaved viscoelastic layer.

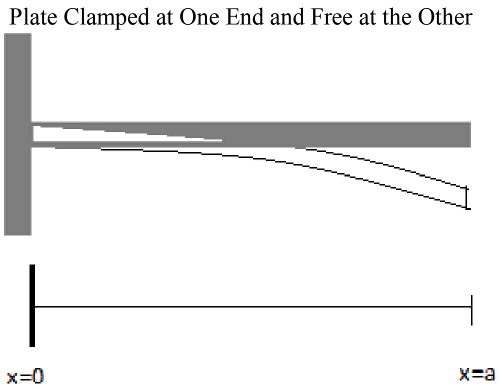

Fig. 4 Clamped Free Beam condition.

$$U_{pq}^{ort} = U_{pq}^{1} + U_{pq}^{3} + U_{pq}^{5} = \sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{i=1}^{M}\sum_{j=1}^{N} A_{mn}A_{ij}f_{pq}(\theta)D_{pq}^{ort} \tag{10}$$

pq = 11,12,22,66

With, $D_{pq}^{ort} =$

$$\left[2\left(1+2\frac{e_0}{e}\right)^3 + \alpha_1^3 + \alpha_2^3 - \left(\alpha_1 + 2\frac{e_0}{e}\right)^3 - \left(\alpha_2 + 2\frac{e_0}{e}\right)^3\right] Q_{pq}\frac{e^3}{24} \tag{11}$$

The strain energy stored in the two viscoelastic layers 2 and 4 can be written as

$$U_{pq}^{v} = \frac{1}{2Ra^2}\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{i=1}^{M}\sum_{j=1}^{N} A_{mn}A_{ij}f_{pq}^{v}(\theta_v)D_{pq}^{v} \tag{12}$$

With,

$$D_{pq}^{v} = \left[\left(\alpha_1 + 2\frac{e_0}{e}\right)^3 + \left(\alpha_2 + 2\frac{e_0}{e}\right)^3 - (\alpha_1+\alpha_2)^3\right] iQ_{pq}^{v}\frac{e^3}{24} \tag{13}$$

where, the functions $f_{pq}^{v}(\theta_v)$ are given by Eq. (5). In the particular case of two viscoelastic layers which are interleaved at the same distance from the middle plane

$$d_1 = d_2 = \alpha\frac{e}{2} \tag{14}$$

Hence the bending stiffness induced by the viscoelastic layers are simply written as

$$D_{pq}^{v} = \left[\left(\alpha + 2\frac{e_0}{e}\right)^3 - (\alpha)^3\right] iQ_{pq}^{v}\frac{e^3}{12} \tag{15}$$

3. Plate Boundary Condition

In the case of a beam clamped at the end *x* = 0 and free at the other end *x* = *L,* its geometric representation is shown in Fig. 4 and the boundary conditions are

At the end x = 0:

$$w_0(\mathrm{x}=0) = 0, \frac{dw_0}{dx}(\mathrm{x}=0) = 0 \tag{16}$$

At the end x = L:

$$w_0(x=L) = 0, M(x=L) = 0, \tag{17}$$

Also,

$$\frac{d^2w_0}{dx^2}(x=L) = 0, \frac{d^3w_0}{dx^3}(x=L) = 0, \tag{18}$$

The first eight solutions of Equation for clamped free beam are listed in Table 1 with the corresponding values of γ_m. For high enough values of γ_m the approximate values can be written in the form

$$\lambda_m = (m+0.25)\pi \tag{19}$$

In the case of a beam that is free at both ends its geometric representation is shown in figure. 5 and the boundary conditions are:

$$\begin{aligned} &\frac{d^2X_m}{dx^2}(x=0) = 0, \frac{d^3X_m}{dx^3}(x=0) = 0, \\ &\frac{d^2X_m}{dx^2}(x=L) = 0, \frac{d^3X_m}{dx^3}(x=L) = 0, \end{aligned} \tag{20}$$

With,

$$\begin{aligned} X_1(x) &= 1, \\ X_2(x) &= 2\sqrt{3}\left(\frac{x}{L} - 1\right) \end{aligned} \tag{21}$$

These functions correspond to the rigid modes of translation and rotation. The two roots $\lambda_1 = 0$ and $\lambda_2 = 0$ are associated with these functions. The other roots λ_m and the corresponding values γ_m are identical to those found in the case of two clamped ends. The values of λ_m and γ_m are given in Table 2 for m varying from 1 to 9. The first mode of free vibrations is obtained for m = 3. The free vibration frequencies are identical to those of a beam with clamped ends.

4. Materials Selection

Each of the composite plates was chosen to have the following physical and geometric configuration:

Table 1 Coefficients of a clamped-free beam function.

m	1	2	3	4	5	6	7	8
λ_m	1.87	4.69	7.85	10.99	14.13	17.27	20.42	23.56
γ_m	0.73	1.01	0.99	1.000	1.000	1.000	1.000	1.000
$((m\text{-}0.5)\pi$	1.57	4.71	7.85	10.99	10.99	17.27	20.42	23.56

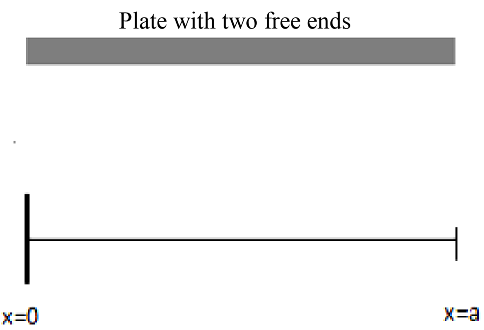

Fig. 5 Free- Free Beam condition.

Length (a) = 300 mm

Breadth (b) = 200 mm

No of plies (n) = 8

Thickness of each ply (t) = 0.3 mm

Force (q_0) = 500 N

Thickness of Viscoelastic material (e_0) = 0.2 mm

The materials properties of chosen materials listed in Table 3.

5. Results and Discussion

Loss factor (η) of unidirectional carbon fibre/epoxy laminate with different boundary conditions and at various fibre orientations for a single and multiple viscoelastic layer positions from the laminate mid plane.

Case I: (CFFF) One edge clamped all other edges free.

Case II: (CCCC) All edges clamped.

Case III: (CFCF) Adjacent edges clamped.

The loss factor (η) of Unidirectional Carbon Fibres/Epoxy with different boundary conditions and at various fibre orientations without and with Viscoelastic Layers is shown in Table 4. and Table 5 respevtively. Figs 6 and 7 are the plot of results displayed in Tables 4 and 5 i.e loss factor as a function of fiber orientation.

Table 2 Coefficients of a free-free beam function.

m	3	4	5	6	7	8	9
λ_m	4.730	7.853	10.99	14.13	17.27	20.420	23.562
γ_m	0.982	1.000	1.000	1.000	1.000	1.000	1.000

Table 3 Materials properties of glass/epoxy and viscoelastic layer.

Material	E_L (GPa)	E_T (GPa)	G_{LT} (GPa)	υ_{LT}	η_{11}(%)	η_{22}(%)	η_{66}(%)
Carbon/Epoxy	110	8.6	6.0	0.28	0.14	0.66	0.80
Viscoelastic	50 (MPa)	50 (MPa)	50 (Mpa)	0.3	29.95	29.9	29.95

Table 4 Loss factor (η) of unidirectional carbon fibres/epoxy with different boundary conditions and at various fibre orientations without viscoelastic layers.

Angle	0	15	30	45	60	75	90
CCCC	0.24	0.27	0.33	0.37	0.40	0.41	0.40
CFFF	0.10	0.12	0.24	0.40	0.47	0.50	0.49
CFCF	0.24	0.27	0.33	0.37	0.40	0.41	0.40

Table 5 Loss factor (η) of unidirectional carbon fibres/epoxy with CFCF boundary conditions and at various fibre orientations with viscoelastic layers.

Angle	Loss factor (η) of carbon/ epoxy laminate			
	CFCF			
	Mid	Sym	Asym	Outer
0	0.61	1.12	1.25	1.84
15	0.47	0.74	0.80	1.11
30	0.50	0.68	0.73	0.97
45	0.68	0.87	0.95	1.28
60	0.87	1.13	1.23	1.67
75	0.81	1.21	1.32	1.86
90	0.79	1.26	1.39	1.97

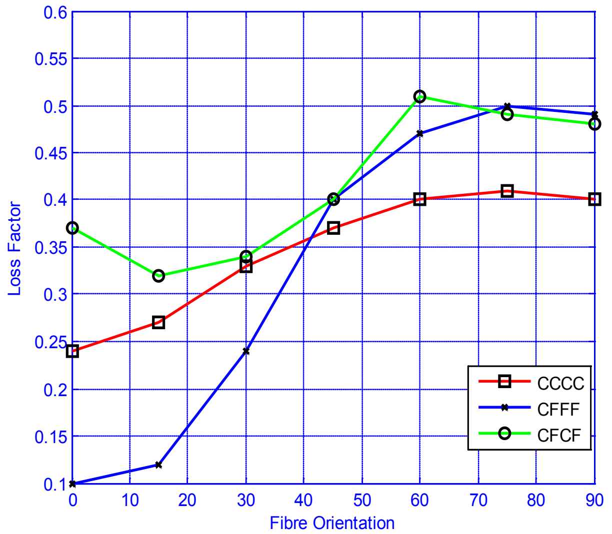

Fig. 6 Variation of Loss factor (η) of unidirectional carbon fibres with fibre orientation without viscoelastic layers.

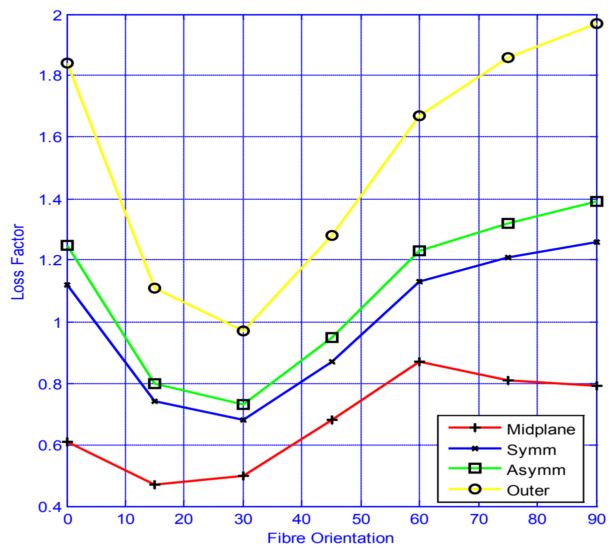

Fig. 7 Loss factor (η) of unidirectional carbon fibres (CFCF) with viscoelastic material inserted at various positions with fibre orientation.

6. Conclusions

This study investigates the damping properties of unidirectional carbon reinforced laminates shows very poor damping values when compared with glass and Kevlar reinforced laminates [3]. But, when it is provided with interleaved constrain layer with a single or two its damping values obtain are considerably high. For a given laminate without constrain layer, the CFCF (Fig. 6) will have maximum value of loss factor at 60^0. Whereas the minimum value for the same boundary conditions recorded at 15^0 if a constrain layer is used at midplane position. For all other positions of constrain layer the loss factor is in between 0.5% at 30^0 single midplane to 1.97% at 90^0 two outer position. It shows that damping nature of carbon laminates and 90^0 enhanced four folds. It is also realized that the provision of constrain layer in the FRP lamination process is highly compatible. It is noticed that a trend of increase in the damping of laminates significant as the viscoelastic layers are placed from the mid layer to outer layer. Also it showed that, the least value of loss factor found at 30^0 when two layers are used irrespective of their locations.

References

[1] Adams, R. D. and Maheri, M. R. 1994. "Dynamic Flexural Properties of Anisotropic FIbrous Composite Beams." *Compos Sci Technol* 50 (4): 497-514.

[2] Billups, E. K. and Cavalli, M. N. 2007. "2D-Damping Predictions of Fibre Composite Plates: Layup Effects." *Compos. Sci. Technol.* 68 : 727-33.

[3] Maheri, A. M., Assarar, M., Sefrani, Y. and Berthelot, J.-M. 2008. "Damping Analysis of Orthotropic Composite Materials and Laminates Composites." 39: 1069-76.

[4] Berthelot, J.-M. and Sefrani, Y. 2004. "Damping Analysis of Unidirectional Glass and Kevlar Fibre Composites." *Composites Science and Technology* 64: 1261-78.

[5] Li, J.-Q. and Narita, Y. 2013. "Analysis and Optimal Design for the Damping Property of Laminated Viscoelastic Plates under General Edge Conditions." *Composites: Part B* 45: 972-80.

[6] Berthelot, J.-M. 2006. "Damping Analysis of Orthotropic Composites with Interleaved Viscoelastic Layers: Modelling." *Journal of Composite Materials* 40 (21): 1889-909.

[7] Ni, R. G. and Adams, R. D. 1984. "The Damping and Dynamic Moduli of Symmetric Laminated Composite Beams-Theoretical and Experimental Results." *J. Compos Mater* 18 (2): 104-21.