CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Considerable research work has been done to improve the dynamic properties (damping, frequency, moduli, etc.) of fiber reinforced polymer (FRP) laminated composite in which the material damping is studied either with macro-mechanical analysis alone or the same with micro-mechanical analysis, i.e., in the former analysis, the dynamic properties of the laminated composites are found out from the properties of lamina, obtained from the mechanical testing, layups sequence, boundary conditions, etc.; whereas in the later analysis, the properties of lamina are found out from its constituent properties of fiber and matrix, obtained from the mechanical testing, orientation of fibers, etc., and then the lamina properties are substituted as input to the macro-analysis to calculate the dynamic properties of the FRP laminated composites. Damping is associated with the dynamic characteristics of the laminated composites and it can be achieved by the influence of various parameters like the different orientations of fiber and layups, fiber - matrix interfaces, fiber - matrix interphases, visco-elastic behaviour of the polymer materials, damages, temperature (Chandra et al. 1999) interleaving of thermoplastic materials or honeycomb core or foam materials with fiber reinforced thermosetting composite materials, thicknesses, width and breath of the FRP and sandwich specimens.
In this chapter, research papers on many aspects and details of the constituent materials, fabrication methods, experimental setups, many parameters influencing the damping or dynamic characteristics related to FRP laminated composites and FRP-honeycomb sandwich panels have been thoroughly reviewed.

2.2 MATERIALS FOR DAMPING

Materials that possess high damping and high stiffness are not common in any mechanical components. Their vibration damping depends on the visco-elastic nature of the materials. They are mainly obtained from all categories of materials such as the damping by rubber, polymers (Thomas and George 1992, Nazarenko et al. 1995) and, metals (Wei et al. 2002, Wu et al. 2011, Wu et al. 2013) etc.. Rubber is commonly used as a vibration damping material (Das et al. 1993, Ganeriwala 1995). There are some other categories of the energy dissipation of materials such as honeycomb or foam materials. The hollow holes in the honeycomb or foam materials help in dissipating the absorbed energy.

Polymer–matrix composites (PMC) with the continuous glass/ carbon/ boron fibers are widely used for lightweight structures. Damping can be improved in the PMC materials (1) by the use of the visco-elastic layer or the interleaved layers in the interlaminar region of the laminated structures, and (2) by the tailoring of the constituent materials of the structure itself such as the fibers and the matrix materials (Chung 2003).

2.2.1 Improving damping by use of viscoelastic layer

While using the visco-elastic interlayer in the longitudinal configured composite (it means the continuous fibers are configured in the longitudinal direction), the loss tangent values are increased but the storage
modulus values are decreased. In order to increase the storage modulus to some extent, fibers can be used with surface treatments. In the transverse configured composites too, the loss tangent values are increased and the storage modulus values are decreased, but these effects are much larger in the longitudinal configured composite. The loss tangent and the loss modulus of the above configured composites can be increased with the increase in temperatures, but the storage modulus of the above composites is decreased with the increase in temperatures. But the above conditions are slightly favourable when the treated fibers are used (Chung 2003).

Electro-rheological (ER) fluids can also be used for constrained layer damping (Oyadiji 1996), due to their visco-elasticity. The damping properties of ER fluids can be varied by controlling the electric field. Magneto-rheological (MR) fluid can also be used for this purpose and the damping properties of (MR) fluids can be varied by controlling the magnetic field (Joshi 2012).

The use of a smart constrained layer in the form of a viscoelastic layer sandwiched by two piezoelectric layers can make the idea of having active and passive damping.

2.2.2 Improving damping by the tailoring of the fibers and the matrix materials

Since the epoxy–matrix has good adhesive capability and a long lasting of service, they are the dominant matrix for continuous fiber composites. Hence, the thermosets such as epoxy matrix are better for making the structural composite. However, thermosets tend to be more brittle and less tougher than thermoplastics (Fu & Chung, 2001).
Even though the rubber is exceptional in its damping capacity (loss tangent = 1.1 at 1 Hz in the case of Neoprene rubber), its storage modulus (7.8 MPa at 1 Hz) is very low (Luo & Chung 2000). Hence they are not suitable for structural applications. Polytetrafluoroethylene (PTFE) is a thermoplastic material which gives moderately high values of both loss tangent (0.22 at 1 Hz) and storage modulus (1.3 GPa at 1 Hz) (Fu and Chung, 2001). The polymethylmeth-acrylate (PMMA) is another thermoplastic which provides a lower loss tangent (0.10 at 1 Hz) and a higher storage modulus (3.5 GPa at 1 Hz) values than that of PTFE (Fu and Chung 2001) materials.

There are also the commonly used thermoplastic matrix materials such as Polyamide - 66 (Nylon) for making the composite. But the loss tangent of the material is comparatively low (0.08 at 1 Hz) (Fu & Chung, 2001). Therefore, PTFE and PMMA are attractive matrices for structural composites which provide larger damping. In addition, the polymer blends and interpenetrating networks are also pretty good. They are good due to the interface between the components in the blend or network providing a mechanism for damping (Chartoff et al. 1983, Sasaki et al. 1990, Tung & Hsu 1992).

When the dynamic properties of fibers are reviewed for the properties other than the damping, the carbon fibers are considered to be dominant among the various fiber materials due to their high modulus and low density. Despite the fact that glass fibers and polymer fibers are more ductile than carbon fibers, they may be alternated along with or in place of carbon fibers for the purpose of improving the damping effect for lightweight structural composites.

The damping behaviours of aluminum 2024 alloy, aluminum 2024 alloy/carbon fiber/epoxy (hybrid 1) and aluminum 2024 alloy/glass fiber/epoxy composites (hybrid 2) were investigated by Botelho et al. 2006.
They showed that the damping behaviour of hybrid 2 composite was higher than that of the hybrid 1 composite due to the difference of mechanical or visco-elastic properties of glass and carbon fibers.

Higher damping values can be achieved in flexible fiber materials at the expense of stiffness. For an instance, Hanselka and Hoffmann (1999) used carbon, aramid and dyneema fibers as reinforcing fibers embedded in the matrix and stated that the aramid fiber reinforced composite produced higher damping values than that of carbon and dyneema fiber reinforced composites. They also stated that the same composite produced lesser storage modulus values than that of the others.

Many research papers reveal that the damping loss factors of the FRP composites decrease with increase in the volume fraction of fiber in the composite. This effect on the volume fraction of fiber is more apparent in the longitudinal component of damping than their transverse and shear components. But, the storage modulus values of the same increase with increase in the volume fraction of fiber (Saravanos & Chamis 1990 a & b, Kaliske & Rothert 1995).

The material damping of laminated composites was derived analytically by Sun et al. (1987). The derivation was based on the classical laminated theory in which there were eighteen material constants in the constitutive equations of laminated composites. They discussed that the damping and stiffness always behaved in opposite manners and the designers should make some compromise in order to achieve optimum performance of composite structures.
2.3 FABRICATION PROCESS

There are many fabrication processes available to make the laminated composites. Among the fabrication processes, the hand-layup process is preferred for the preparation of FRP composite specimens by many researchers as it is very simple, economical, effective and also easy to remove the entrapped air manually by pressing the rollers against each lamina. The layup process is normally followed by molding under pressure for thermosetting polymer matrices. The molding pressure can also be accompanied with heating to speed up the curing. For instance, Tita et al. (2003) used the hand-layup process followed by molding under pressure and heating, to prepare the fiber (glass) reinforced polymer (epoxy resin) composite.

As far as the fabrication process is concerned in preparing the honeycomb core interleaved fiber reinforced polymer (FRP) composite specimens, many papers have reported the complicated, higher time consuming and the expensive method like the vacuum bag molding process. The use or the explanation of the simplest process is scarce in those papers. For example, Cabrera et al. (2008) fabricated Polypropylene honeycomb sandwich Panel (PP skins and PP honeycomb core) by vacuum bag molding process.

2.4 EXPERIMENTAL ANALYSIS

The modal properties such as natural frequencies, damping loss factors, etc. in different modes, are calculated experimentally in the setup with the association of suitable software in the system.

With regard to experimental analysis, Schwarz and Richardson (1999) have elaborately reviewed all the main topics associated with
experimental modal analysis (or modal testing), including making Frequency Response Function (FRF) measurements with a Fast Fourier Transform (FFT) analyzer, modal excitation technique, and modal parameter estimation method from a set of FRFs (curve fitting). From the experimental setups, the modal parameters are obtained by artificially exciting a machine or structure, measuring its operating deflection shapes (motion at two or more degrees of freedom), and post-processing the vibration data. The Frequency Response Function (FRF), which actually describes the input-output relationship between two points on a structure as a function of frequency is mainly measured from the inherent dynamic properties of a mechanical structure. The experimental modal parameters such as the natural frequency, damping loss factors, etc. are obtained from a set of FRF measurements. FRF is also defined as the ratio of the Fourier transform of an output response to the Fourier transform of the input force that caused the output.

Schwarz & Richardson (1999) have also discussed the different types of FRF measurements which are as follows:

**Impact Testing** is typical of a roving hammer impact test. The output i.e., the response obtained after hitting the specimens is constant or fixed and FRFs are measured for multiple inputs, i.e., hitting the specimens with varied amplitude forces.

**Shaker Testing** is another method where the input i.e., hitting the specimens with constant amplitude forces is fixed, and FRFs are measured for multiple output i.e., the response that obtained after hitting the specimens is varied.

**Single Reference (or SIMO) Testing** is called when single input and multiple outputs are used for either the impact or shaker testing.
Multiple Reference (or MIMO) Testing is called when two or more inputs and outputs are used for either the impact or shaker testing.

With the ability to compute FRF measurements in an FFT analyzer, impact testing shown in Figure 2.1 has become the most popular modal testing method used today, since it is a fast, convenient, and low cost way of finding the modes of machines and structures.

![Impact Testing Diagram](image)

**Figure 2.1 Impact testing (Schwarz & Richardson (1999))**

The following equipments are required to carry out an impact test;

1. An *impact hammer* with a load cell attached to its head to measure the input force.

2. An *accelerometer* to measure the response acceleration at a fixed point and direction.

3. A 2 or 4 channel *FFT analyzer* to compute FRFs.
4. **Post-processing modal software** for identifying modal parameters and displaying the mode shapes in animation.

Though the impact testing has many advantages as stated above, some of the structures which have the delicate surfaces cannot be impact tested, or because of its limited frequency range or low energy density over a wide spectrum, the impacting force is not to be sufficient to adequately excite the modes of interest.

![Shaker testing diagram](image)

**Figure 2.2 Shaker testing (Schwarz & Richardson (1999))**

When impact testing cannot be used, FRF measurements are made by providing artificial excitation with one or more shakers, attached to the structure (shown in Figure 2.2). A shaker is usually attached to the structure using a stinger (long slender rod), so that the shaker will only impart force to the structure along the axis of the stinger, the axis of force measurement. A load cell is then attached between the structure and the stinger to measure the excitation force.
Thwaites & Clark (1995) carried out shaker testing (referred to as non-destructive testing in this paper) method in which they detected and identified core damage and skin delamination of honeycomb sandwich structures at the positional accuracy of ± 2 mm with the help of measurements of the local phase velocity obtaining from the propagation phase of the frequency response function (FRF) between two points on the sandwich panel (shown in Figure 2.3).

![Shaker testing diagram](image)

**Figure 2.3 Shaker testing (Thwaites & Clark (1995))**

Using the impulse testing method, Deobald & Gibson (1987) measured the natural frequencies of square aluminium and graphite/epoxy plates. The measured natural frequencies were then used to determine two Young's moduli, the in-plane shear modulus, and a Poisson ratio by the Rayleigh-Ritz technique. Natural frequencies and mode shapes were also verified by finite element analysis and modal analysis for the plates.

Gibson (2000) has discussed that the modal testing by the use of impulsive excitation methods would have the potential to be a fast and accurate approach not only for the characterization of intrinsic material
properties, but for quality control and inspection as well. He has further discussed that the measurements from the testing had been used to characterize the global elastic constants of composites, the distribution of reinforcing fibers within composites, time-domain creep response of composites, elevated-temperature behaviour of composites and their constituents, interlaminar fracture toughness of composites; and the presence of defects, damage, and degradation in composites and adhesively-bonded composite structures.

Boundary conditions for the test specimens also play a very important role in influencing the dynamic behaviour of the composites. For instance, Ganapathi et al. (1999) has claimed that the rate of decrease in the system loss factor against the decrease in the thickness ratio of face-to-core of sandwich specimen was more for the simply supported case when compared to the clamped sandwich beams.

From the two methods of frequency response function (FRF) measurements described above, most of the researchers have chosen the impulse testing method due to its convenient in use, cost, time, etc. Related to this case, Suarez et al. (1984), Volnei tita et al. (2001), Shokrieh & Najafi (2006), Mahi et al. (2008), Boudjemai et al. (2012), Hong et al. (2012), Emadoddin et al. (2012), Singh et al. (2012), Senthil Kumar et al. (2014) have used the impulse testing method in their studies.

2.5 VARIOUS FACTORS INFLUENCING THE VIBRATIONAL DAMPING CHARACTERISTICS OF POLYMER COMPOSITES

2.5.1 Influence of the fiber orientations and layups

Fiber orientations and fiber layups play a vital role in influencing the dynamic characteristics of the polymer composite materials. The
properties like bending stiffness, strength, storage modulus, the damping loss factors, etc. are mainly influenced by the fiber orientations and layups.

In order to analyse the dynamic behaviour of the FRP composite under the influence of different orientations of fiber, it is essential to determine the anisotropic composite properties with lamination geometry, i.e., the dynamic properties like moduli $E_L, E_T, E_{LT}$ and the specific damping coefficients $\Psi_L, \Psi_T, \Psi_{LT}$ are required to be evaluated as functions of stress.

A series of laminated composite plates of 254 mm x 254 mm by 2.54 mm thick with the orientations of layers of $0^\circ, 5^\circ, 10^\circ, 20^\circ, 30^\circ, 35^\circ, 40^\circ, 45^\circ, 60^\circ, 70^\circ,$ and $90^\circ$ moulded from carbon fiber reinforced shell epikote DX209 resin were used by Adams and Bacon (1973) for the dynamic analysis at free flexure loading conditions. An another series of laminated composite plates of 254 mm x 76.2 mm by 2.54 mm thick with the orientations of layers, alternatively plus and minus (angle ply) of $0^\circ, 10^\circ, 20^\circ, 30^\circ, 45^\circ, 60^\circ$ and $90^\circ,$ moulded from the same materials were used by them for the same loading conditions. In this theory, the values of Young's modulus and damping coefficients $\Psi_x, \Psi_y, \Psi_{xy}$ were found with respect to the fiber orientations in which the later was assumed to be independent of stress.

In both the cases of the laminated plates, the Young's modulus values rapidly dropped over the fiber orientations i.e., from $0^\circ$ to $45^\circ$, and became very low at the orientation of $50^\circ$ and was almost constant till its $90^\circ$ orientation. In the first case of the laminated plates, the damping coefficient $\Psi_x$ was maximum at zero degree and reached zero at $20^\circ$ orientation and remained the same for the rest of the orientations. On the other hand the damping coefficient $\Psi_y$ was zero at $0^\circ$ orientation and got gradually increased over different orientations and reached maximum at its $90^\circ$ orientation. The damping coefficient $\Psi_{xy}$ was maximum at $30^\circ$ and gradually dropped for the rest of the orientations.
As the shear modulus was quite small at $30^\circ$ fiber orientation, it led to large energy dissipation in shear and hence, the damping was comparatively high at this orientation. The resultant damping coefficient i.e., SDC (specific damping capacity coefficient $= \Psi_x + \Psi_y + \Psi_{xy}$) peaked at $35^\circ$ and remained same till $45^\circ$, and slightly dropped and maintained constant for the rest of the orientations.

The moduli and the specific damping capacity (SDC) of the anisotropic beams under different fiber orientations were also predicted by Adams & Maheri (1994) using the same Adams and Bacon’s (1973) criterion with the basic plane stress relations. They showed that the damping values increased at a faster rate from $0^\circ$ to $60^\circ$, and increased slightly from $60^\circ$ to $90^\circ$ orientation of fibers.

The contribution of longitudinal, shear and transverse components of SDCs at low stress amplitude which were stated under different orientations of the fibers in the laminate are shown in Table 2.1.

**Table 2.1 Components and contribution of SDC under the fiber orientations (Adams & Maheri, 1994).**

<table>
<thead>
<tr>
<th>Component of SDC</th>
<th>Contribution of SDC</th>
<th>Orientations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal SDC ($\Psi_x$)</td>
<td>Sole contributor</td>
<td>@ the $0^\circ$ fiber orientations</td>
</tr>
<tr>
<td></td>
<td>Major contributor</td>
<td>@ the $15^\circ$ fiber orientations</td>
</tr>
<tr>
<td>Shear SDC ($\Psi_{xy}$)</td>
<td>Major contributor</td>
<td>@ the $45^\circ$ fiber orientations</td>
</tr>
<tr>
<td>Transverse SDC ($\Psi_y$)</td>
<td>Major contributor</td>
<td>@ the $60^\circ$-$75^\circ$ fiber orientations</td>
</tr>
<tr>
<td></td>
<td>Sole contributor</td>
<td>@ the $90^\circ$ fiber orientations</td>
</tr>
</tbody>
</table>

The theoretical and experimental SDC results of glass fiber reinforced polymer (GFRP) and carbon fiber reinforced polymer (CFRP) of
the off-axis and angle-ply laminates (off-axis means that all the plies or the lamina are oriented at an angle '0' and angle-ply means that the plies are alternately oriented at +0 and -0 from the principal axis of the laminate) are shown in the Figure 2.4.

Hwang & Gibson (1992) described the strain energy method in three-dimensional finite element form for characterizing the effects of interlaminar stresses on damping in thick angle-ply laminated composites under uniaxial extension. The energy dissipation of a vibrating laminate was computed on the basis of three-dimensional states of stress to account for the effects of interlaminar stresses on damping. The interlaminar damping was found to be particularly important over a particular range of ply angles or fiber orientations. They also pointed out to the existence of an optimal value of the laminate width-to-thickness ratio for maximizing the contribution of interlaminar damping and the total laminate damping.

Yim (1999) has predicted the damping of symmetric, balanced laminated composites in terms of volume fractions of constituent materials and different fiber orientations. From the basic damping of Poisson's ratio, the modified classical laminated theory was utilized to predict the damping of laminated composite beams and compared with Ni and Adams' (1984) model. Six typical laminated composites with different stacking sequences were engaged for this study. The results showed that the damping is highly affected by fiber orientation and stacking sequence in each model.

Maher et al. (1999) have indicated that the orientation of the fiber in the outer laminate had considerable effects on their modal parameters compared with the inner laminate and the laminate with 45° fiber orientation at which the shearing parameter would reach highest values, had the highest influence on the modal parameters compared with the other fiber orientations.
Figure 2.4 (Continued)
Figure 2.4 'Fiber orientations' Vs 'SDC' of (a) CFRP (Angle-ply), (b) CFRP (Off-axis), (c) GFRP (Angle-ply), (d) GFRP (Off-axis) (Adams & Maheri, 1994).
To examine the effect of transverse shear as a function of aspect ratio of fiber (length of fiber / thickness of fiber) on the damping of composites, Yim & Gillespie (2000) have determined material damping of unidirectional continuous fiber 0° and 90° laminates analytically by the strain energy weighted dissipation method and experimentally by the half-power bandwidth method for cantilever beam specimens hit by an impulse excitation. The laminates were fabricated from graphite/epoxy (Hercules AS4/3501-6). The outcome of theory and experiments showed that the loss factor of 0° composites exhibits a linear increase with decreasing aspect ratio. It was shown that the predicted loss factor of 90° composites increased with decreasing aspect ratio, but the experimental values didn't vary consistently with the aspect ratio. It was also shown that the 90° laminates exhibited much higher damping than the 0° laminates and the transverse shear stress (\(\tau_{xz}\)) had a considerable effect on the damping mechanisms in 0° unidirectional polymer composites but the same transverse shear stress didn't exhibit a considerable effect in 90° unidirectional polymer composites.

Adams & Maheri (2003) have further predicted the theoretical and experimental SDC results of CFRP of the cross-ply laminates (cross-ply means that the plies are alternately oriented at 0° and 90° from the principal axis of the laminate) in first four modes using basic laminate theory and a simple damping criterion. The effect of fibre orientation and stacking sequence (0°, 90°, 0°, 90°) of the layers in FRP laminates on SDC results were discussed for the second and fourth modes. They revealed that SDC of the second mode was more than twice that of the fourth mode. According to them, it was due to the fact that the stacking sequence number of the layers whose fibre lay in the second mode was lateral to the bending axis was one above the stacking sequence number of the layers whose fibre lay was parallel to the bending axis, but the situation was reversed in the fourth mode. They
also discussed that the bending stiffness of the second mode became lower than that of the fourth mode.

Berthelot (2006) has evaluated the damping loss factors in the case of unidirectional beams of glass and kevlar fibre composites using the Ritz method under different natural frequencies and fibre orientations. The results obtained for the loss factors of the unidirectional materials demonstrated a remarkable increase of material damping with the fiber orientations and the natural frequency.

2.5.2 Visco-Elastic Behaviour of the Solid Interleaving Layers

It is understood that the damping effects depend on the viscoelastic properties of the interleaved polymer material and the arrangements of the reinforcing fiber in the laminates influencing the stiffness of the intralaminar zone. The research works related to the behaviour of this layer are as follows:

Kishi et al. (2004) have studied the damping characteristics of carbon fiber-reinforced interleaved epoxy composites. Several types of thermoplastic-elastomer films, such as polyurethane elastomers, polyethylene-based ionomers and polyamide elastomers were used as the interleaving materials. The mechanical impedance method was used to determine the damping properties of the composite laminates with/without the interleaved films. The effects of the different layup arrangements of the carbon-fiber prepregs on the damping properties of the interleaved laminates were also studied. The viscoelastic properties of interleaved polymer films were reflected in the damping properties of the corresponding interleaved laminates. The loss tangent of the interleaved films at the test temperature played an important role in the loss factor of the interleaved laminates. Also, the stiffness of the films at the resonant frequency of the laminates was also important parameters influencing the loss factor of the laminates.
Hence, it was understood from this work that the damping effects depended not only on the viscoelastic properties of the interleaved polymer material but also on the arrangements of the reinforcing carbon fiber in the laminates influencing the stiffness of the intralaminar zone and the strain of the interleaved films.

Hui & Ling (2006) have predicted the damping behaviour of the laminated composites with integral viscoelastic layers using an integrated three-dimensional FEM (the commercial finite element software ANSYS 7.0) / strain energy approach. They pointed out that the reason for using 3-D FEM in this paper was to get a more realistic analysis by including the three-dimensional stress state. The contribution of energy dissipation due to the integral viscoelastic layers and the fiber-reinforced composites to viscoelastic materials were taken into account in this work. They have studied the impact of different parameters, such as damping of fiber-reinforced composite materials, ply angle of compliant layers and location of viscoelastic layers on the modal loss factor and frequency of damped composites. The modal behaviour of structures covered with a complex pattern of visco-elastic material in terms of damping performance was studied by Cura et al. (2012) with the new modified strain energy method. Different visco-elastic distributions were evaluated for the best damping effect.

Yim et al. (2003) have predicted the loss factor of 0° laminated composite sandwich cantilever beams with interleaving of a solid visco-elastic layer. They considered both the in-plane and transverse damping effect on the sandwich. The variation in the loss factor with the aspect ratio (length/thickness) was determined. As the 0° laminated composite only was used in this study, they considered the transverse shear damping effect in the out of deformation of XZ direction only. Hence, the loss factor equation was used as given below:
\[ \eta = \frac{\Psi}{2\pi} = \frac{\Delta W}{2\pi W} = \frac{\Delta W_x + \Delta W_y + \Delta W_{xy} + \Delta W_{xz}}{W_b + W_{xz} + W_{yz}} \]

where

\( \eta \) is damping loss factor of the sandwich; \( \Psi \) is SDC of the sandwich;

\( \Delta W_x, \Delta W_y, \Delta W_{xy} \) and \( \Delta W_{xz} \) are dissipated energies in X, Y, XY and XZ directions respectively;

\( W_b \) is bending strain energy;

\( W_{xy} \) and \( W_{xz} \) are shear strain energies in XY and XZ directions respectively.

Lin (2010) presented the dynamic characteristic and modelling of vibration for a sandwich beam consisting principal laminate or core at centre of the sandwich and surface laminate of pure epoxy matrix at top and bottom of the sandwich. The silica with nanoparticles of size 12–235 nm at various filler fraction (10–50 wt.%); three different polymer matrices: polyacrylate, polyimide and polypropylene, were closely packed in the core. It was indicated that the stiffness and damping in composite structure were given by nanofiller and polymer matrix respectively. They also discussed that the silica’s small particle size features and strain difference between principal and surface (top and bottom) layers could improve the energy dissipation of the sandwich structure.

Ghinet & Atalla (2011) described the modelling of the dynamic response of thick composite laminate plates and beams with linear viscoelastic damping layer under unit force or displacement excitation. They used the equation of motion following a wave approach based on discrete layer description and handled symmetrical and asymmetrical layouts of
unlimited number of transversal incompressible layers. This paper concluded with a sensitivity study to highlight the influence of the Poisson’s ratio of the core material on the input mobility and showed that only the dilatational (symmetric) mode of motion, separately from the asymmetric mode of motion, was affected by the Poisson’s ratio of the soft core.

Maout et al. (2011) maximized or optimized the passive damping of a hybrid elastomer/composite sandwich plate structure: with respect to the design variables of the total number of layers of the structure, their respective thicknesses and fiber orientations, the position(s) of the viscoelastic core(s) and the stacking sequence using the Method of Strain Energy (MSE). Illustrating the approach, a simple structure composed of layers of composite and viscoelastic rubber has been optimized.

Schwaar et al. (2012) have developed a mixed numerical–experimental identification procedure for characterising the storage and loss properties in sandwich structures with a relatively stiff core. The proposed method was based on the minimisation of the discrepancies between modal quantities computed with a highly accurate orthotropic shell FE model with adjustable elastic and structural damping properties, and the corresponding experimental data measured with a precise measurement setup.

Niyari (2013) presented a novel composite with high damping capacity for which, he has investigated the flexural damping responses of triple core (aluminium foam, Polymethacrylimide (PMI) foam and H100 PVC foam) sandwich panels using finite element analysis. He derived the different strain energies stored in the material directions of the constituents of composite materials and the energy dissipated by damping in the materials and the composite structure.
Using the modal strain energy approach, Yang et al. (2013) have investigated the vibration and damping performances of hybrid carbon fiber composite pyramidal truss sandwich panels with viscoelastic layers embedded in the face sheets. The modal tests were done to study the vibration and damping characteristics of the hybrid sandwich panels with or without viscoelastic layers. The damping loss factors of composite slender beams with different fiber orientations were tested to determine the constitutive damping properties of parent materials for such hybrid sandwich panels. It was shown that the damping loss factors of hybrid sandwich panels increased distinctly as compared with previous sandwich panels due to the viscoelastic layer embedded in the face sheets.

### 2.5.3 The Effect of the Interleaved Honeycomb Core Materials on Damping

The interleaving of a honeycomb core in composite laminate materials is being widely used in many key industries like automobile, aerospace, marine, sports, audio (Jiang et al. 2014), defence works, building constructions, etc. Many honeycomb core materials such as Polypropylene, Nomex, aluminium, etc., are being used by many of the above said industries and various researches. Due to the provision of high flexural rigidity with negligible weight, the honeycomb core interleaved sandwiches are attracted by the above industries in designing the structures (Wang and Yang 2000, Bassani et al. 2013). The laminated honeycomb sandwich materials possess high load carrying capacity, stiffness and high energy-absorption capability (Maheri et al. 2008). The FRP composite has a high in-plane stiffness-to-weight ratio, whereas the honeycomb FRP sandwich has a high bending stiffness-to-weight ratio, apart from the high in-plane stiffness to weight ratio. Due to the in-plane and the out-of-plane shear deformation of laminae of FRP skins and core, more energy is dissipated in all directions of the sandwiches.
It is known that the relative density of the foam/honeycomb core materials are lower. Having the advantage of the lower weight of core, it would also increase in sound absorbing or energy absorbing capability with decrease in the relative density of core materials (Hung et al. 2012).

Adams & Maheri (1993) have dealt with the steady-state vibration damping of composite/honeycomb sandwich beams. They showed the variation in the SDC with shear stress amplitudes for aluminium and Nomex honeycomb sandwiches and found that a sound honeycomb would experience linear damping at low stress amplitudes. Due to the lack of data on dynamic shear properties of honeycomb, the authors have adopted a new method of measuring these properties in a more systematic manner. The double-lap shear test-piece which ensures minimum extraneous damping was an effective arrangement for measuring the dynamic properties of honeycomb in shear. They concluded that the orthotropy of both the honeycombs was manifested only in the considerable difference in the shear moduli; there was little difference between the low amplitude damping of the shear vibration along the two principal directions.

Maheri & Adams (1994) have constructed sandwich beams from CFRP and GFRP skins, and Nomex or aluminium honeycomb cores for the prediction of the damping in the sandwich beams. In this paper, Timoshenko beam equations were proved to be capable of accounting for energy mechanisms of simple bending/shearing in a shear soft beam and used for the steady-state measurement of the SDC in a sandwich beam, and used for determining the bending/shearing proportion to the overall damping. The damping contribution of the constituent parts in the aluminium honeycomb sandwich under flexural loading conditions was considered with respect to skin fibre orientations. They found a high degree of interdependence between the skins and the core, contributing to the overall damping.
Wang & Yang (2000) have carried out the experimental study of the damping of laminated sandwich honeycomb beams with fine solder balls inserted in the honeycomb cells, losing the advantages of the lightweight nature of honeycomb structures. These solder balls were inserted in the cells before the composite was cured and the cantilever single-point excitation test was used on the first two modes of vibrations in this study. They recommended a tailor-make composite by inserting balls into particular cells where the maximum amplitude would normally occur. They have also discussed that the tailor-make composite process could be expensive and affect the mass production and the damping was quite effective on measuring the reduction in amplitude from the first two modes of vibration. They also did the peeling tests and claimed that there was no noticeable deterioration in the bonding strength between the core and the face sheets due to the collisions.

Maheri & Adams (2008) have used the basic laminate theory, together with the Rayleigh–Ritz method, the finite element analysis to predict damping and frequency of honeycomb sandwich for space applications (The honeycomb sandwich was used by ALCATEL SPACE as structural panels). The inherent damping of aluminium honeycomb core and carbon fibre-reinforced plastic (CFRP) skins materials was considered in this study. As the transverse shearing in a relatively thin sandwich skin was negligible, it was ignored here. Since the data for modal damping of the sandwich panels were of particular interest in space applications, it was concluded that tests would have to be carried out in vacuum (According to them, the sandwich specimens had experienced enormous damping when tested in air, owing to acoustic radiation).

Instead of using both the damping and natural frequency values together to predict the dynamic characteristics of sandwich panel which were
discussed in the previous paragraphs, the frequency values alone were used to study the vibration characteristics of sandwich panel. Jiang et al. (1995) also investigated the vibration behaviour of honeycomb structures with disbands under the influence of different boundary conditions by a mesh dependency study which was carried out to decide upon the optimum mesh density. They have concluded that the boundary conditions of honeycomb structures have a certain effect on their natural frequencies, especially in a higher mode and the honeycomb structures with disband requires a denser grid than the one without disband i.e the natural frequency values were affected by the changes in the disband size in higher mode (when the natural frequency values exceeds 1000 Hz).

2.5.4 The Effect of Temperatures on the Damping Characteristics

Though temperature is one of the influential factors to enhance the damping of the polymers, the latter is achieved only at the expense of strength, storage modulus, thermal properties, etc. Hence, the improvement of strength, modulus and thermal properties of the materials can be done by incorporating fibers with high strength, storage modulus and low heat conductivity in a thermosetting matrix with adequate thermal properties.

Even after this, the polymers are reinforced by very high heat resistant fibers. The modal loss factor can only be improved with a small reduction in the stiffness and strength on increasing the temperature. It was studied by Mohan et al. (1997) who used the finite element technique and strain energy method, to determine the modal frequencies and damping loss factors of the laminated composite under the effect of different temperatures.

The glass-transition point or temperature of the polymer composites also plays an important role in determining the level of damping values with respect to the temperatures. The glass-transition point or temperature, loss
factors, storage modulus, etc., of the polymer composite materials are determined by the Dynamic mechanical analysis (DMA) equipment. It is being widely used by many researchers.

For an instance, Melo & Radford (2005) have used it to investigate the visco-elastic properties of the unidirectional carbon fiber reinforced laminae and cross-ply laminates under different frequency ranges and at different temperatures, and observed that the storage moduli decreased with an increase in the damping loss factor under the effect of temperatures. The viscoelastic model which was used in this study provided valid lamina properties. Since laminate properties were predicted based on correctly measured laminae properties, they were closely matched with the measured laminate values. The storage modulus and loss factor values were also determined under different fiber orientations.

The material becomes soft and yields high damping characteristics near the glass-transition point of the polymer. This statement was proved by Youssef & Berthelot (2006) who analysed the damping and bending stiffness of unidirectional glass fibre composites with respect to different fibre orientations ranging 0° to 90°, and temperatures ranging 20° C to 120° C. They described that the damping loss factors and bending stiffness increased and decreased respectively with the fiber orientations and temperatures. They also studied the variation of the loss factor with the frequencies.

The thermal characteristics of the fiber reinforced Polyether ether ketone (PEEK), and the amorphous Poly ether sulphone (PES) materials, were investigated by Maheri et al. (1996) under different temperatures ranging from -250°C to 250°C, and it was reported that the modulus values remained stable at 0° fiber orientation, and reduced significantly at 90° fiber orientation under a different temperature range. They have also found that the amorphous PES material is more stable than the PEEK in the thermal condition, and
showed a small variation in the dynamic properties near 250°C. According to them, these materials showed similar cryogenic behaviour, i.e., there was a low level of damping at the lower end of the temperature range, and rising towards the peak with increasing temperature.

Pradeep et al. (2007) dealt with thermal buckling and vibration of sandwich beams and plates with composite facings and viscoelastic core and compared the effects of sandwich plate and beam elements. The effect of fiber angle, the effect of aspect ratio and the effect of the core thickness on the performance of the elements were actually studied by them. They concluded that there was a significant difference between the predictions of sandwich beam and plate elements due to some deficient in predicting the exact damping mechanism in beam elements, i.e., there was transverse shear, $\gamma_{yz}$, generated in the core in case of composite sandwich beams which was not accounted in the beam element formulation. They also pointed out that the same behaviour continued even under thermal environment.

Vijayakumar & Sundareswaran (2011) have studied the dynamic properties of polymer (epoxy) matrix composite under different temperatures. They found that the damping factor and the natural frequency of epoxy/glass fiber composite could be increased from 10% to 40% at 150°C when the epoxy was modified with cyanate content. The vibrational behaviour of fiber glass/epoxy specimen is also influenced by the temperature and moisture, i.e., the natural frequency of the specimen is reduced with the increase in the temperature and moisture content (Rath & Sahu 2012).

2.5.5 The Effect of Interfaces, Inter-Phase and Damages on Damping

The contribution of energy dissipation due to sliding at the fiber–matrix interface is also considered in fiber reinforced polymer composite having micro or nano gap in the form of hairline debonding between the
fiber–matrix interface. Since the weak interface provides more damping than that of the strong interface only at the expense of the strength and stiffness, the strong interface is normally preferred. For instance, Vantomme (1995) has developed a three-phase model (fiber, matrix and interface) which clearly showed that a poor quality interface with low elastic stiffness, had a significant effect on the energy damping capacity of the unidirectional laminate. The effect of interphase between the fiber and matrix also plays an important role in damping calculations. But, this effect is normally ignored in most of the research works.

In relation to this case, Gu et al. (1998) has evaluated the interfacial damping between the fiber and matrix of a fiber polymer composite from the interfacial shearing force that obtained from the fiber pullout or de-bond test. The interface damping loss factor was calculated from those stored and dissipated energy equations.

Damping can also be improved even in the metal or the metal matrix composites with the increase of interfaces in terms of joints or layers. For instance, Nanda (2006) has studied the effect of interface damping on the copper cantilever structures joined with the equi-spaced bolts. He found that the interface damping effect would improve considerably by increasing the number of layers with the uniform intensity of pressures at those interfaces.

Chandra et al. (2003) have used the FEM/Strain energy method to predict anisotropic damping matrix comprising of loss factors $\eta_{11}$, $\eta_{12}$, $\eta_{22}$ and $\eta_{23}$ considering the dissipation of energy due to fiber and matrix (two phase). Damping in three phase (i.e., fiber – interphase – matrix) composites was also calculated as an attempt to understand the effect of inter-phase. The effect of damping or the dissipation of energy at the fiber–matrix interfaces was also evaluated in the composite, presuming that the composite had hairline crack at those interfaces.
2.5.5.1. Fiber–interphase–matrix

The loss factor of composite for three-phase model can be stated as follows:

$$\eta_c = \frac{(\eta_f W_f + \eta_m W_m + \eta_i W_i)}{W_c}$$

where $W_c$ is the total strain energy of composite from the strain energy of its constituents, i.e., fiber, matrix and inter-phase $W_f$, $W_m$, and $W_i$.

$$W_c = W_f + W_m + W_i$$

The energy dissipated at the interface due to discontinuity is given by the following equation:

$$D = 2 \times \left( \frac{1}{2} \times F_i \times d_s \right)$$

where $F_i$ is step load and $d_s$ is the relative displacement between the nodes of the discontinuity at the interface.

The total loss factor of the composite can be stated as follows:

$$\eta_{total} = \frac{(D_f + D_m) + \sum_{j=1}^{n} (D_{id})_j}{W_{id}}$$

where $j$=index of friction element and $n$=being their total number; $D_f$ and $D_m$=energy dissipated by fiber and matrix, respectively; $D_{id}$=energy dissipation due to individual discontinuity at the interface, and $W_{id}$=total strain energy with interfacial discontinuity.
Recently, Idriss et al. (2013) have found that the damping effect and stiffness of the sandwich composites were sensitive to the debonding length under static and dynamic loadings. Though, the damping is increased, the interfacial debonding between top skin and core is one of the major causes in decreasing the specimens stiffness during fatigue. Hence, the interfacial forces are one of the major concerns in designing of the composites.

To enhance the interfacial bonding, the interfacial forces between Reinforcement/matrix interface nanostructures can be introduced into composite materials. Gan (2009) formed the nanopores on metal surface to increase the bonding strength of the metal/polymer interface.

Interfacial shear strength between the fiber/polymer materials over the entire service life of the composites is also needed to be retained. This strength would be gradually deteriorated if water is present at the fiber-matrix interfaces for the prolong time (Nguyen et al. 1998).

It was learnt that the energy could be dissipated from the minor damage/hairline crack/tiny blow hole of the solid or composite materials. The amount of the dissipated energy/damping can be computed using the vibrational analysis. Further, it is also possible to detect local structural damage and deteriorations in the beam materials from the vibrational analysis/with the association of the structural dynamic properties of the natural frequency and the damping ratio (Urgessa 2011). The vibrational analysis can also be applied to determine the elastic constants (longitudinal, transverse and shear modulus with respect to the fiber directions) and the modal damping ratio of a unidirectional composite beam (Yesilyurt et al. 2013).

A non-destructive test was also carried out using the vibration techniques by Cawley & Adams (1995) to detect the defects like de-
lamination of skins and honeycomb core, micro cracks, damages, tiny blow holes etc. from the laminates by comparing the difference in frequency and damping values measured from good and defected specimens. Thwaites & Clark (1995) also used the vibration based non-destructive test to detect delamination of skin, crushing of core and the ribbon separation of core by measuring the frequency response function along and across the panel and finding of the scattering the wave from the defect.

Dealing with the delamination damage or crack, the dynamic characteristics of composite laminates, including the natural frequencies, mode shapes and modal damping were investigated analytically and experimentally by Saravanos & Hopkins (1996). Depending on this generalized laminate theory, an exact methodology where the in-plane and out-of-plane relative motion between the delaminated sublaminates which are applicable to general laminate configurations was developed for predicting the natural frequencies and modal damping of composite beams. The cantilever experimental setup was used to measure natural frequencies and modal damping on composite beams with a single delamination.

Chirica et al. (2011) have analyzed the influence of the material damping properties of the composite plates with delaminations where the linear elastic behaviour of the laminate plates was predicted from the properties of the individual plies using laminate theory (that could also be used to predict the damping properties of such plates). An orthotropic delamination model, describing delaminating mode, using COSMOS/M soft package, was presented in this paper for analyzing the behaviour of the delaminated composite plates during vibrations. The damaged part of the structures and the undamaged part have been represented in this work.

Burlayenko & Sadowski (2014) have studied the dynamics of the debonded foam-cored sandwich plate subjected to both impulse and harmonic
loads using the finite element analysis by taking into account the intermittent contact between the detached segments within the damaged skin-to-core interface. The frequency response curves were extracted for sandwich plates with and without debonded region. The results of both the plates were compared, to specify the effects associated with the presence of debond on the forced vibrations of the sandwich plate. It was understood that the applied finite element model would be useful for non-destructive evaluation of defects in composite sandwich plates.

2.5.6 Influences of the Dimensions of the Composites on Damping

According to many researchers, the influence of the dimensions of the composite specimens has little effect on the improvement of damping of the fiber reinforced composite specimens.

Related to the above case, Suarez et al. (1986) have described the theoretical and experimental analysis on the influence of fiber length and fiber orientation on damping and stiffness of polymer composite materials. They finally predicted that the control of lamina orientation in the FRP laminated composites could be a better approach to the improvement of damping than controlling the fiber aspect ratio.

For thin laminated specimens, the transverse shear stress is normally ignored in many studies of the damping prediction. For illustration, using modal strain energy (MSE) based finite element method; Lin et al. (1984) considered only the interlaminar stresses, neglecting the transverse shear stress, for the prediction of specific damping capacity (SDC) of the composites under flexural vibration.

Ganapathi et al. (1999) have emphasized the influences of various parameters such as aspect ratio (l/h), thickness ratio of face-to-core (h_f/h_c),
shear modulus of the core, boundary conditions and amplitude of vibration on the damping characteristics of constrained layered/sandwich beam and laminated anisotropic beam.

They have listed the following general observations:

(i) The value of damping factor decreases with an increase in mode numbers up to a certain value of the aspect ratio, and then it increases with an increase in the mode numbers.

(ii) At the low range of aspect ratio, the effect of increasing the core thickness enhances the damping values significantly. But at the higher aspect ratio and core modulus, the difference in the loss factor values is less among the resonant frequencies.

(iii) The system loss factor ratio decreases with an increase in the amplitude of vibration and is more so when the aspect ratio and shear modulus are less.

(iv) The rate of decrease in the system loss factor is, in general, more for the simply supported case compared to the clamped beams.

(v) The loss factor ratio is more for the multi-layered symmetric laminates compared to those of orthotropic case.

The effect of the beam aspect ratio was considered in their predictions; i.e., the tests on different widths of beams showed no significant effect on the SDC or the modulus.

By using the finite-element method based laminated plate theories, the variation of modal properties (the natural frequencies and the damping
loss factors) with plate dimensions, number of glass- and carbon-fibre/epoxy based composites, as well as the thermoplastic poly (ether ether ketone) (PEEK) composites were shown by Maheri & Adams (1995). According to them, there was no significant variation in the damping loss factors with respect to the plate dimensions or the aspect ratio (side $a$ / side $b$) and the natural frequencies linearly varied with the same. The same properties were also estimated for different fiber orientations and layups.

Ohta et al. (2002) have presented the damping analysis of fiber reinforced plastics laminated composite plates with different thickness ratios and stacking sequence. In their numerical calculations, they have determined the natural frequencies and modal damping ratios based on the three-dimensional theory of elasticity and compared their results with the results of the plate theories such as the classical laminate theory. With reference to the plate theories, the damping predication obtained from the three-dimensional theory of elasticity were more accurate for thicker plates than that of thin plates, but, the natural frequency predication were more accurate for both thick and thin plates when referred to the plate theories.

2.5.7 Miscellaneous Aspects on the Dynamic Characteristics (Damping loss Factors and the Natural Frequencies) of the Composites

Gibson & Plunkett (1976) have studied the internal damping and elastic stiffness of E-glass fiber reinforced elastic beams under flexural vibrations. A rational method for obtaining the dynamic mechanical properties of lamina for laminates and beams was provided by Ni and Adams (1984). The dynamic properties of hybrid (carbon-glass fiber laminated) composites were estimated by Ni et al. (1984). They used the energy method and the Finite Element (FE) Technique and demonstrated that the addition of
a small amount of CFRP to the surface of the GFRP composite would improve the flexural modulus.

Two different damping models, i.e. the viscoelastic damping (VED) model and the specific damping capacity (SDC) model were used by Hu & Dokainish (1993) to carry out the damping study of the polymer-matrix and metal-matrix composites. They have shown that both the models were valid in the prediction of modal damping because there were no significant differences in the natural frequency, damping, and mode shapes between both models if the system was slightly damped. They have also shown the parametric effects of side-to-thickness ratio, principal moduli ratio, the total number of layers, lamination arrangement, and boundary conditions.

Talbot & Woodhouse (1997) have used the laminate and thin-plate bending theories to predict the vibration behaviour of free-edged, CFRP laminates. They have claimed that the laminate theory was capable of predicting the elastic behaviour, i.e., predictions of frequency and mode shape with sufficient accuracy. The same theory could also be extended to predict the damping properties with accuracy level of 30% which was adequate for most engineering purposes. They have also discussed that the properties of the plies of a laminate could be deduced from measurements on the complete laminate, using inverse laminate theory.

Sargianis & Suhr (2012) have studied the effect of core thickness on wave number and damping properties in sandwich composites using the half-power bandwidth method. A drastic increase in coincidence frequency was observed for the sandwich beam with the thinnest core thickness due to the low bending stiffness which resulted in low damping values, and consequently high wave number amplitude responses at low frequency ranges.
Moita et al. (2012) have developed a simple and efficient triangular plate/shell finite element model and optimization of damped multilayer sandwich plates, with a viscoelastic core sandwiched between elastic layers, including piezoelectric layers. The damping maximization of sandwich plate was conducted as an optimization problem where the reciprocal of the first modal loss factor was the objective function, and the elastic ply angles and the thicknesses of elastic and viscoelastic layers were the design variables.

Alijani et al. (2013) have experimentally investigated the large amplitude vibrations of completely free sandwich rectangular plates by using a Polytec scanning laser doppler vibrometer, and nonlinear frequency–response curves were obtained from performing the nonlinear tests. Damping ratio of sandwich plates was found to vary nonlinearly and increased significantly for large amplitude vibrations, more than doubling its initial value for vibration amplitude around 1.5 times the plate thickness.

Zhang et al. (2014) have studied the nonlinear dynamic behaviour of a simply supported 3D-Kagome truss core sandwich plate subjected to the transverse and the in-plane excitations using the governing equation of motion derived by the von Karman type equation for the geometric nonlinearity and the Reddy’s third-order shear deformation plate theory. The influence of the amplitudes for the in-plane and transverse excitations on the frequency–response curves was studied. The results of numerical simulations exhibited the existence of the period, multi-period and chaotic responses with the variation of the excitations.