

Investigation of dynamic properties of a polymer matrix composite with different angles of fiber orientations

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Abstract. For the dynamic values of fiber-reinforced polymer matrix composite materials, elastic modulus and damping values are emphasized, and the two are desired to be high as much as possible, as the first is related to load bearing capacity, the latter provides the capability of energy absorption. In the composites, while fibers are usually utilized for reinforcement providing high elastic modulus and so high strength, matrix introduces a medium for high damping. Correct measurement of damping values is a critical step in designing composite materials. The aim of the current study is to measure the dynamic values of a glass fiber-reinforced polymer matrix composite, Hexply 913/33%/UD280, produced by Hexcel, using a vibrating beam technique. The specimens with different angles of fiber orientations (0, $\pm 10^\circ$, $\pm 20^\circ$, $\pm 35^\circ$, $\pm 45^\circ$, $\pm 55^\circ$, $\pm 70^\circ$, $\pm 80^\circ$ and 90°) were manufactured from the composite prepreg and subjected to the clamped-free boundary conditions. Two different methods, the half power bandwidth and the logarithmic free decay, were used to measure the damping values to be able to compare the results. It has been revealed that the dynamic values are affected by the fiber orientations; for high flexural modulus the specimens with small angles of orientation, but for high damping those with large angles of orientation should be preferred. In general, the results are comparable, and the free decay method gave smaller values compared to the bandwidth method, with a little exception. It is suggested that the results (data) obtained from the test can be used for modal analysis reliably.

1. Introduction

Use of fiber-reinforced polymer matrix composites find many applications especially in aerospace and automotive sectors, due to their strength to weight ratio, damping properties, impact performance, fatigue life and resistance to corrosion etc. Therefore, their dynamical behaviors at low and high stress levels are investigated by many researchers [1-5]. In such materials, high strength capability is provided by the fibers and manipulated by their angles of orientations. On the other hand, matrix as a constituent material introduces high damping into the structures and serves for load transfer [6,7]. It is known that aerospace vehicles and automobiles are always under mechanical vibrations during their service life, which makes the components made out of composite materials to be handled. There are many efforts to increase damping value of the materials using different techniques [6-11]. Their points of interest mainly focus on matrix, interfacial between fiber and matrix, inter-laminar effects and stacking sequences [8,9]. Koratkar *et al* [10] measured more than 1000% increases in the loss modulus but a little reduction in the storage modulus when polycarbonate was enhanced by 2% weight fraction of single-walled carbon nanotubes (SWNTs). It was believed that frictional sliding at the SWNT



interfaces was the reason for the enhanced energy dissipation. This was supported by the analysis of Zhou *et al* [11], who developed a model for the frictional sliding damping mechanism based on interfacial frictional motion between the nanotubes and the polymer matrix. Somen *et al* [12] used a novel liquid Methylmethacrylate (MMA) thermoplastic resin to enhance vibration damping of a composite made up of thick and thin plies of carbon fibers. After developing the novel composite system, the liquid MMA was found to be 27% more efficient in improving the structural damping compared to the epoxy resin. In another work [7], the damping behavior of continuous carbon fiber and flax fiber reinforced polymer (CFRP and FFRP) composites was studied by comparing angle-ply laminates. The results showed that about 2-3 times better damping of FFRP compared to CFRP at low frequency and low strain, and that the damping of both materials increases with increasing angle-ply orientation below 300 Hz. In a similar works [4], a multi-scaled methodology by using flax fibers and carbon nanotubes (CNTs) was proposed to enhance the damping property of carbon fiber reinforced epoxy composites. The damping property was measured by free vibration test and the strength and modulus were obtained by tensile and flexural tests. Effects of stacking sequences of flax fibers and the addition of CNTs on both the damping property and the mechanical properties of carbon fiber reinforced composites were investigated. Results clearly showed that the damping property of carbon fiber reinforced composites was improved greatly by laying flax fibers on the outmost layers of the composites. With the addition of CNTs, the damping property was further enhanced.

It is well known that reliable measurements of damping can only be possible via sophisticated measurement systems, and therefore it has been a subject of investigations for many researchers [13-15]. Some alternatives techniques were developed using such systems, which are able to give the results by a non-contact system [16,17].

As mentioned above, many efforts have been made by many researchers so far to increase damping values in the composite structures using different methods. The aim of this work is to obtain a desired damping and vibration capability in the structures by altering the orientation angles of fibers, balanced and symmetric. For this purpose, the dynamic properties of the composite materials were investigated via an experimental test set-up with an impact hammer and a vibration laser head. A non-contact response from the impacted specimens with clamped-free end conditions was obtained, thanks to the laser head. It is believed the data obtained by the set-up could be used for the modal analysis.

2. The experimental works

2.1. The specimens

The material used in this study was a glass fiber reinforced polymer matrix composite, Hexply 913/33%/UD280, produced by Hexcel, and the cure conditions for the prepreg of the composite was 130 °C for 120 minutes under a pressure of 5 bars. The specimens with 0, ±10°, ±20°, ±35°, ±45°, ±55°, ±70°, ±80° and 90 fiber orientations were machined from the cured plates with 10 layers, and some details of them are shown in table 1. The test was carried out under a controlled environment, at room temperature (23°C) and 50% relative humidity, to avoid environmental effects on the specimens, and about four specimens of each type were tested to see if the results are repeatable.

Table 1. The details of the composite specimens used for the experimental work.

Fiber Angle	Width [mm]	Thickness [mm]	Length [mm]	Mass [g]	Density [kg/m ³]
0 °	25.44	1.909	202.8	17.70	1797.46
± 10 °	24.98	1.873	200.4	16.68	1778.91
± 20 °	24.97	1.842	196.5	16.24	1796.58
± 35 °	24.89	1.853	200.1	16.52	1789.72
± 45 °	25.64	1.937	200.5	17.62	1769.14
± 55 °	25.76	1.833	199.9	16.46	1744.20
± 70 °	25.62	1.932	201.0	17.61	1770.47
± 80 °	25.65	1.958	199.4	17.50	1747.68
90 °	25.82	1.881	201.0	16.91	1732.60

2.2. The test set-up

For the dynamic measurements of the specimens, a vibrating beam technique was used, shown in figure 1. The experimental set-up includes a manual impact hammer to generate impulse and a non-contact laser head to pick up the response from the specimen. The impacted specimen is aimed to give its natural frequencies within a required frequency domain, via some distinguished peak values of the amplitude, depending on the mode shapes. A sophisticated data acquisition card was used to collect the digital values of velocity (amplitude) versus time, provided by the laser head which is also able to give displacement values. The set-up is supported by a software to process the data according to the required output format for visualization and analysis. The natural frequency, elastic modulus and damping values of the specimens could be measured easily via the technique. For the damping values, two different methods, the half power bandwidth and the logarithmic free decay, were used, and more details about the methods are explained below.

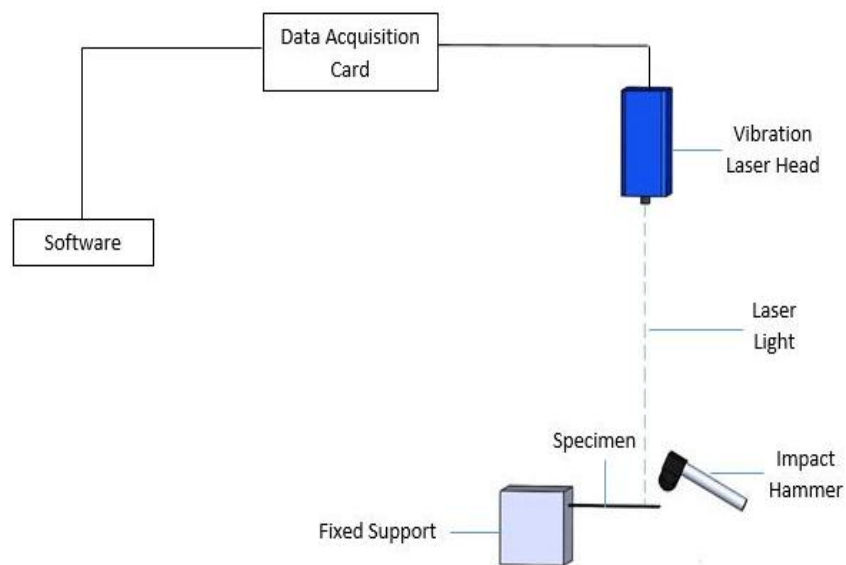


Figure 1. Experimental set-up for the specimens with clamped-free end conditions.

3. Theory

3.1. Measurement of flexural modulus

For every solid obeying Hook's Law, there is a specific natural frequency which is a function of its elastic modulus, geometry, density and the mode number. The natural frequency of a beam, f_n , is found as [18]:

$$f_n = \frac{1}{2\pi} \left(\frac{\lambda_n}{l} \right)^2 \sqrt{\frac{EI}{\rho tb}} \quad (1)$$

where $\lambda_n = 1.875$ is the 1st eigenvalue for clamped-free end conditions, n is the mode number, E is the flexural modulus, I is the second moment of area, l is the length, ρ is the mass density, t is the thickness, and b is the width of the beam. The flexural modulus of the specimen was measured using equation (1), and only the first (fundamental) mode was taken into account for all the measurements.

3.2. Measurement of damping

For an elastic solid structure, damping is defined as the conversion of mechanical energy into thermal energy, and it is defined in a number of different, yet related ways [19]. In this study, the half-power

bandwidth method and the free decay method were used for measuring the damping values, and the results were compared to see if they are in agreement.

3.2.1. The half-power bandwidth method. This is determined from the curve of velocity amplitude against frequency, obtained when the specimen is impacted by the hammer. The ‘half-power bandwidth’ is $(f_2 - f_1)$ where f_2, f_1 are the frequencies at which the amplitude falls to $1/\sqrt{2}$ of its maximum value, reached at f_n , the resonant frequency. The loss factor, η is defined as,

$$\eta = \frac{f_2 - f_1}{f_n} \quad (2)$$

A schematic representation of the definition is illustrated in figure 2(a).

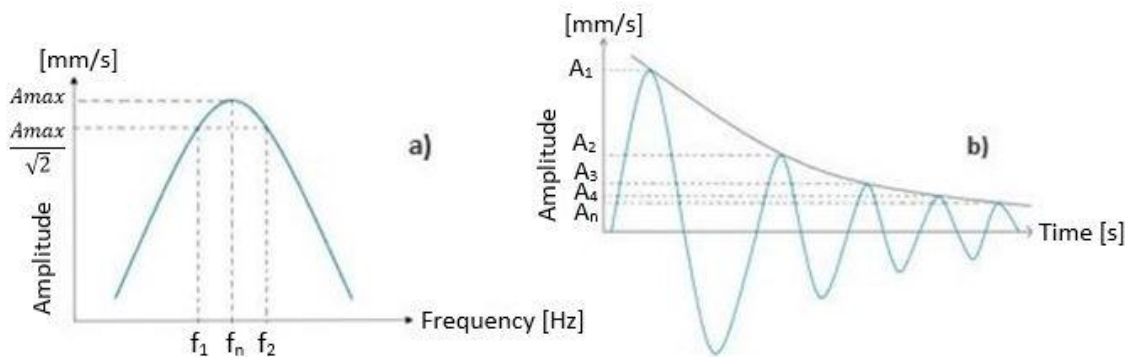


Figure 2. Schematic representations of the definitions of a) the half-power bandwidth method, b) the logarithmic free decay method.

3.2.2. The logarithmic free decay method. This is found by observing the decay of free vibrations (a ‘free decay’ method). The specimen is vibrated using the hammer, and a trace obtained of vibration amplitude against time, as illustrated in figure 2(b), is obtained. The logarithmic decrement, δ is then given by:

$$\delta = \frac{1}{n} \ln\left(\frac{A_1}{A_{n+1}}\right) \quad (3)$$

Where A_1 is the amplitude of the first cycle, and A_{n+1} is the amplitude of the $(n+1)^{th}$ cycle.

For convenience, damping is usually presented in Specific Damping Capacity (SDC), Y , which is defined as the ratio of the energy dissipated per cycle to the maximum elastic energy stored per cycle, per unit volume [20]. This ratio is usually expressed as a percentage.

For small damping, it is known there is relationship as follows [19],

$$h = \frac{Y}{2\rho} = \frac{f_2 - f_1}{f_n} = \frac{d}{\rho} \quad (4)$$

4. Results and discussions

The variation of natural frequencies of the specimens with different angles of fiber orientation is shown in figure 3(a). It is seen from the figure that the natural frequency is greatly dependent on the fiber orientations, and that small angles of fibers result in relatively high natural frequencies. From equation (1), it is clear that the frequency is affected by the dimensions of the specimens under test, to eliminate this, the specimens tested have almost the same dimensions (see table 1), which implies

the change in the frequency is only attributed to the different angles of orientation. While the maximum natural frequency is about 47 Hz for the specimens with the 0° orientation, the minimum value is around 25 Hz for those with the 90° . The figure clearly shows that there is a linear decrease in the frequency for the specimens with from the 0° up to the 55° orientations, and then it levels up for those with fiber orientation angles $\geq 55^\circ$.

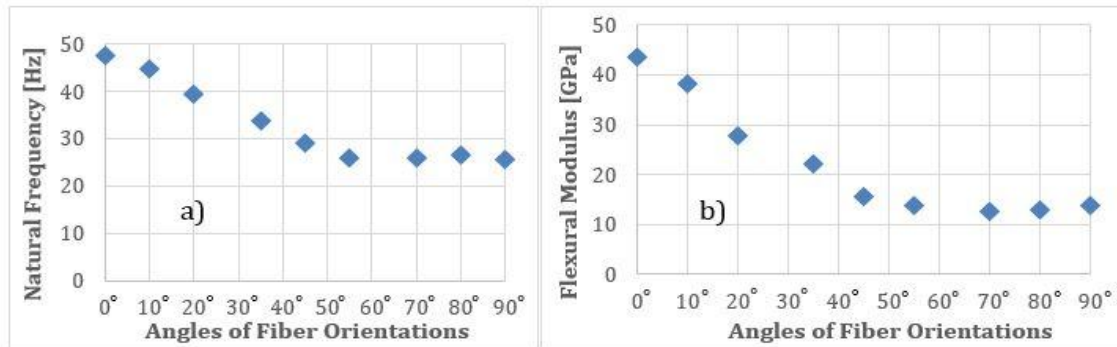


Figure 3. Variation of (a) the natural frequency, and (b) the flexural modulus of the composite specimens with different angles of fiber orientations.

The variation of flexural modulus with the fiber orientations are shown in figure 3(b), the response is similar to that shown in figure 3(a). A maximum value of the modulus, about 44 GPa, is found for the specimens with the 0° orientations, and the minimum value was about 15 GPa for those above the 55° orientations. The potential reason for this occurrence is because the specimens with from the 0° up to the 45° orientations are controlled mainly by the fibers, and those with the 45° orientations are in somewhere controlled by the both, fibers and matrix, and those with above 45° orientations are dominated by the matrix of the material. It is important to note that the specimens with high strength could only be possible for those with small angles, and these are especially recommended for high loading capacity.

As explained above, for the damping measurements of the specimens, two different methods, the logarithmic free decay and half power bandwidth, were used, and the results are presented in figure 4, which is the variation of SDC against the different fiber orientation angles. The figure shows that the results are totally opposite to that in figure 3(b); while the maximum values of the SDC are about 7% for the specimens with the higher angles, $\pm 45^\circ$, $\pm 55^\circ$, $\pm 70^\circ$, $\pm 80^\circ$ and $\pm 90^\circ$, the minimum value is about 2% for those with the 0° . These results are directly related to the mechanical behavior of the fiber and the matrix forming the content of the composite material. It is clear that the matrix as a polymer has a high damping value, but a low value of elastic modulus, however, the specimens controlled by the behavior of the fibers should give low damping, but high elastic modulus. The current results are in agreement with the results reported by Adams and Maheri [20].

As shown in figure 4 the damping results obtained from the two methods are comparable, in general, however, those with the $\pm 20^\circ$ orientations showed a little bit different value; the results from the logarithmic decrement method yields higher than those from the bandwidth method, opposite for the other specimens. Typical responses of the specimens measured by the laser head, after impacted by the hammer, are shown in figures 5(a) and 5(b), the cases for the bandwidth and for the free decay methods, respectively. It should be noted that the first figure (figure 5(a)) indicates the natural frequencies between 1st and 4th modes, and that only the 1st mode was used for the measurements. The damping values of the specimens were obtained by using equations (2) and (3), and then converted into SDC by using equation (4). A previous work showed that especially the specimens with $\pm 45^\circ$ fiber orientations could provide a high damping value with a reasonable high strength, which could be preferred for structural purposes and for vibratory conditions [16].

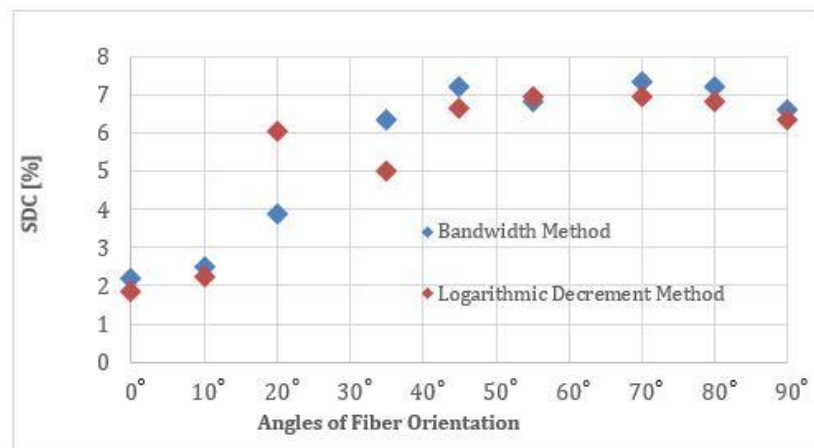


Figure 4. Variation of Specific Damping Capacity (SDC) with angles of fiber orientations from the two methods.

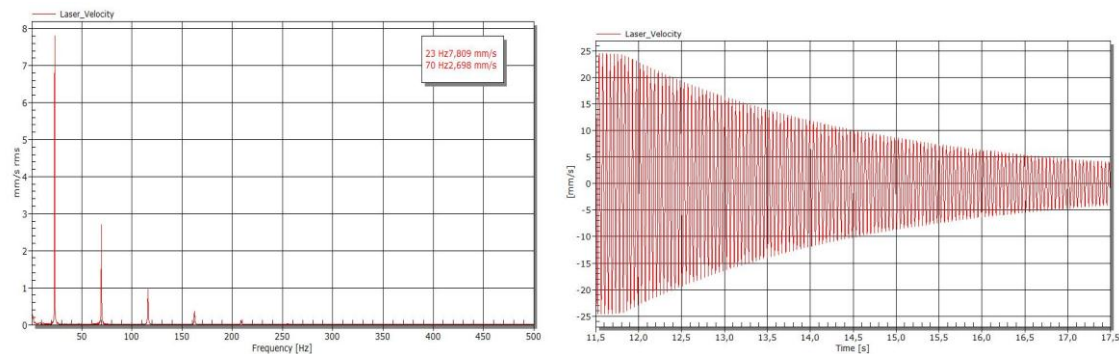


Figure 5. The response from the impacted specimens for the damping measurements of a) the half-power bandwidth method, and b) the logarithmic free decay method.

5. Conclusions

It is recommended that correct measurements of the dynamic properties of the composite materials are important for design purposes. The results obtained from the vibrating beam technique indicated that the dynamic values of the material were controlled by the angles of fiber orientations. While high values of the natural frequency and flexural modulus were provided by the specimens with the small angles, high damping values were obtained from those with the high angles, $\pm 45^\circ$, $\pm 55^\circ$, $\pm 70^\circ$, $\pm 80^\circ$ and $\pm 90^\circ$. In general, the results from the two methods, bandwidth and free decay, were in agreement, and the test set-up with the non-contact response measurement gave reliable and repeatable data which could be used for the modal analysis.

Acknowledgments

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