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Experimental Investigation of Influence of Fibre Orientation on the Dynamic Properties of Carbon Fibre and Intra-Ply Woven Carbon-Kevlar/Epoxy Hybrid Composite

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Abstract: Composite materials are popular substitutes for conventional materials owing to their high strength-to-weight ratio. Reinforcements in the form of woven fabric clothes are common due to their ease of availability and preparation. The use of hybrid intra-ply as reinforcements synergises the advantages of more than one type of fibre. The current work focuses on the preparation of woven carbon fibre (CF) and carbon-Kevlar (CF-K) intra-ply hybrid fibre-based composites. Epoxy resin was used as the matrix and balsa sheet was used as the sandwich material. The angle of orientation of the woven fibre cloth was varied from 0° to 45° along the direction of loading. The dynamic properties of prepared samples were experimentally investigated using an impact hammer test. The natural frequency and damping ratio were influenced by the angle of orientation and the fibre reinforcement. The CF-K hybrid composite showed better dynamic properties when compared with the CF composite. The natural frequency was highest for the 0° sample, it reduced with the angle of orientation, and a reverse trend was observed for damping ratio. Both CF- and CF-K-based composites showed similar trends. The storage modulus variation also showed a similar trend as that of the natural frequency for both types of samples with orientation, but a reverse trend was observed for loss modulus, i.e., the loss modulus increased with the change in the angle of orientation, indicating the improvement in energy storage ability of the composite.

Keywords: hybrid composites; Carbo-Kevlar hybrid; vibration test; fibre orientation; intra-ply fibres



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1. Introduction

Fiber-reinforced composite materials have gained increased interest in recent years due to their superior properties in terms of light weight, high specific strength, and increased load-bearing capacity. These materials are a potential alternative to conventional materials such as metals and concrete. The use of a fibre-reinforced composite requires a deeper understanding of its properties, not only in terms of static but also under dynamic loading, which is critical. In general, predicting the natural frequency for the static test is acceptable; however, the energy dissipation could not be assessed effectively [1–3].

Generally, fibres can be short, long, or woven. The woven configuration can induce a greater strength damping compared to the other two cases. The performance is greatly affected by the orientation with respect to the loading direction. Additionally, based on the synthesis, the fibres are characterised as synthetic and natural fibres. The natural fibres are inherently less stiff and have a lower load-bearing capacity. Carbon fibres are versatile and widely used. However, its energy absorption is lower. To improve the damping, without compromising the strength, hybridisation would be the promising option. Past research has reported the hybridisation of the carbon fibre-reinforced composites with different fibres like glass, basalt, Kevlar, and even natural fibres like hemp and banana fibres. The

Kevlar-based fibre would be more advantageous as it has strong damping properties but a lower stiffness. Hybridisation is a trade-off that can be clearly used to obtain the balanced configuration to attain the desired properties [4–8].

Composites are widely used in automobile, aerospace, defence, and sports applications, where the applied load varies with time. Carbon-fibre-based composite materials have also been used as excellent fire-retardant materials. Hence, a study of its response to dynamic loading is vital. Composites are predominantly used in applications requiring low weight and load-bearing capacity. The rigidity of the structure increases as it becomes light and compact. The natural frequency of the system increases, which amplifies the problems associated with the vibration. This necessitates the need for a mechanism to reduce the effects of vibrations in the system. A rational approach would be to introduce a secondary damping treatment. The external damping treatment is not effective, as it is an additional feature that needs to be incorporated into the system. Rather, a focus on improving the inherent damping in the system would be more advantageous. The damping properties of the fibre-reinforced composites can be attributed to the interaction between the matrix, the fibre, and the fibre–matrix interface interaction. In many applications, when a constraint is imposed on the matrix material, the obvious choice would be to use different reinforcing fibres. This subsequently modifies the internal structure, the mechanism of interface interactions, and the load-bearing capacity. Reinforcing fibres with good inherent damping offers a greater potential for increasing material damping. Carbon fibre reinforced with chlorinated aramid nanofiber has been proven to improve the interfacial shear strength. However, the fibres in question have too little strength, which limits their load-bearing capabilities. This problem can be addressed by hybridisation, where ordinary reinforcing fibres are combined with fibres having higher damping [9–12].

In general, the composites exhibit viscoelastic properties, which implies that under dynamic loading, the response would be partly viscous and partly elastic. The viscous part is associated with the energy-absorbing ability, while energy dissipation is associated with the elastic part of the response. This typical response is referred to as viscoelasticity. The viscoelastic properties are expressed as the dynamic stiffness and the loss factor. The dynamic stiffness describes the ability of the material to absorb the energy, and the loss factor depicts the ability to dissipate the energy. Often, cyclic tests or dynamic mechanical analyser (DMA) tests would be performed on the composites to characterise the stiffness and damping characteristics. These properties can be extracted from the response over the frequency spectrum or the hysteresis response for the specific frequency of interest. Alternatively, the forced vibration test or impact-hammer-based tests can be employed to characterise the dynamic properties. These approaches are effective in terms of response and are economical. The impact hammer tests have been previously compared with forced vibration tests by employing an electrodynamic shaker and the results were similar. The response from these tests is assessed in terms of receptance or accelerance plots, which subsequently depends on the sensors employed to measure the response [13–22].

For fibre-reinforced composites, the dynamic stiffness and the damping are of greater significance. These properties can be tailor-made by incorporating the hybrid fibres. To study the effect of hybridisation on the dynamic viscoelastic properties, the present work focuses on exploring the influence of the orientation of fibres on the dynamic viscoelastic properties. A carbon–Kevlar hybrid fibre-reinforced composite is synthesised. The orientations of the fibres are varied from 0° to 45° in steps of 15° . From the impact hammer tests, the stiffness and damping properties are evaluated. To investigate the property variation with respect to the hybridisation, composites with woven carbon fibre reinforcement are prepared with the same orientation as that of the hybrid intra-ply. The effectiveness of hybridisation is assessed by comparing these property alterations.

2. Experimental Section

Viscoelastic Material Behaviour

By virtue of the matrix material, polymer composites exhibit viscoelastic behaviour. In response to the mechanical loading, it exhibits the attributes of an elastic solid at some instances and a viscous fluid at other instances. In general, its characteristics are intermediate between the ideal solid governed by Hooke’s law and ideal liquid behaviour described by Newton’s law of viscosity. In most cases, the properties of viscoelastic materials are characterised by harmonic behaviour with respect to time. Assuming that the behaviour of the composite under consideration is linear, the strain is harmonic (Equation (2)), and the stress is also harmonic with an angular velocity of ω . A phase difference exists between the given phase difference ($\delta = \omega\Delta t$) with respect to the strain (Figure 1).

$$\varepsilon(t) = \varepsilon_0 e^{j\omega t} \tag{1}$$

$$\sigma(t) = \sigma_0 e^{j(\omega t + \delta)} \tag{2}$$

where ε_0 is the amplitude of the shear strain and σ_0 is the amplitude of the shear stress.

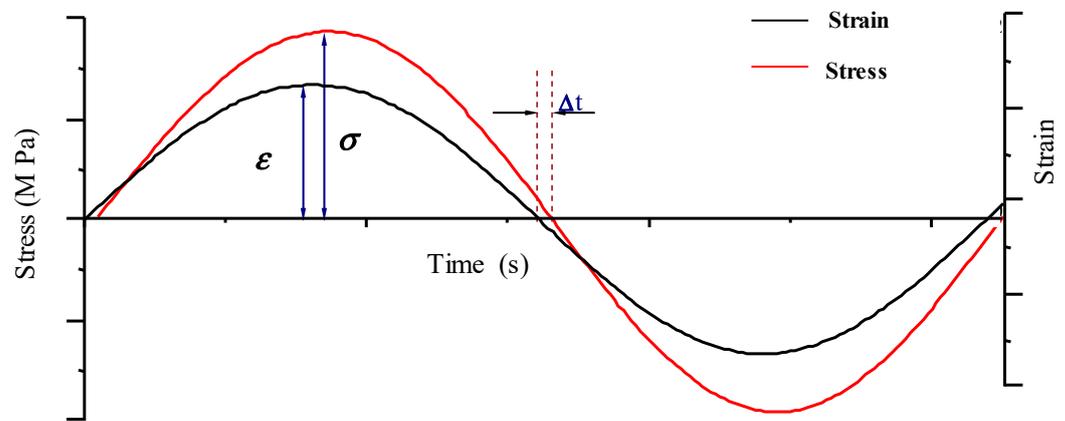


Figure 1. Phase difference between the stress and strain.

The properties of a viscoelastic material are expressed in terms of the complex modulus [23]. The complex modulus (E^*) is the response of a viscoelastic material under the dynamic loading condition. It represents the resistance offered in response to the applied strain, and it is expressed mathematically as [24,25],

$$E^* = \frac{\sigma(t)}{\varepsilon(t)} = \frac{\sigma_0 e^{j(\omega t + \delta)}}{\varepsilon_0 e^{j\omega t}} = \frac{\sigma_0}{\varepsilon_0} (\cos \delta + i \sin \delta) \tag{3}$$

The response of viscoelastic material for an external loading comprises two terms. The first term represents the instantaneous response of the continuous medium, and the second term signifies the delayed response involving the loading history at the preceding instant [26].

$$E' = \frac{\sigma_0}{\varepsilon_0} \cos \delta \text{ and } E'' = \frac{\sigma_0}{\varepsilon_0} \sin \delta \tag{4}$$

E' is the storage modulus and E'' is the loss modulus. The storage modulus represents the ability of the viscoelastic material to store the energy during deformation, which could be recovered later. The ability of a viscoelastic material to dissipate the energy is expressed in terms of loss modulus [27].

The loss factor η relation between the storage and the loss modulus is given by

$$\eta = \tan \delta = \frac{E''}{E'} \tag{5}$$

In terms of the loss factor, the complex modulus is expressed as

$$E^* = E' + iE'' = E'(1 + i\eta) \tag{6}$$

3. Methodology

The dynamic viscoelastic properties of composites can be characterised by adopting conventional vibration measurement techniques. Generally, forced or free vibration tests can be implemented. From the free vibration tests, the frequency-domain signals would be analysed to extract the natural frequency, and the logarithmic decay would be employed to estimate the damping factor. Alternatively, a shaker excitation test or an impact hammer test can be employed. In the shaker vibration tests, the input response would be measured. The properties can be extracted from the frequency response plots obtained in the form of receptance or transmissibility. A simplified form of the above-stated test would be impulse excitation. According to this method, an input impulse excitation would be given, and the corresponding response would be measured. From these measurements, the frequency response would be obtained (Figure 2).

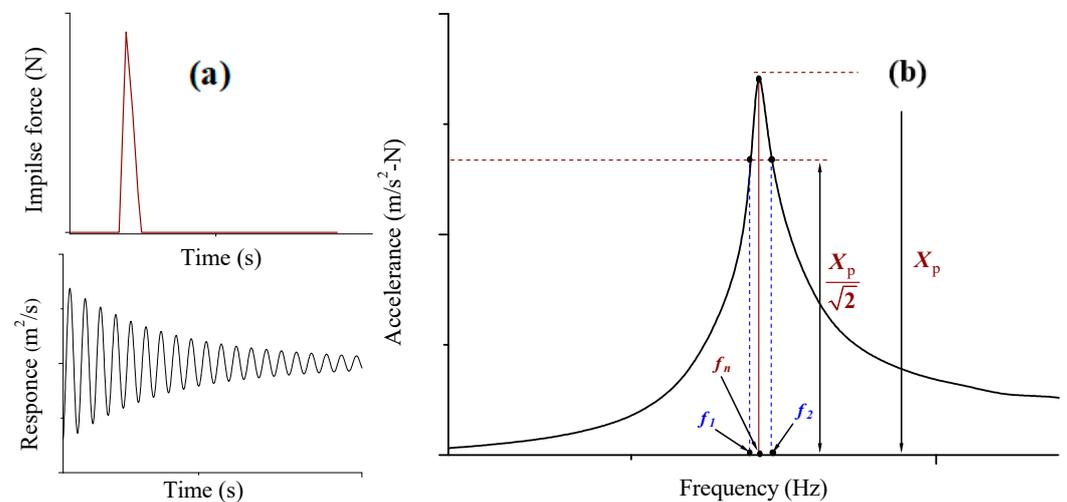


Figure 2. (a) Impulse input and time domain response of the system and (b) frequency domain system response.

The frequency response would be in terms of receptance or accelerance, which ultimately depends on the sensor used to acquire the response. From these plots, natural frequency (f_n) would be obtained corresponding to peak amplitude. The damping ratio (loss factor) is estimated according to the half-power bandwidth method (Figure 2b). The expression for calculating the loss factor from the half-power bandwidth method is given by

$$\eta = \frac{f_2 - f_1}{f_n} \tag{7}$$

where f_2 and f_1 are the frequencies corresponding to the half-power points.

The storage modulus of the fabricated composite beams is evaluated from the natural frequency estimated using the vibration test results. The expression for the storage modulus is obtained by equating the experimental fundamental frequency of the beam to the theoretical frequency of the Euler–Bernoulli beam. It is expressed as [28,29]

$$E = \frac{\omega_n^2 mL^3}{I \times 1.875^4} \tag{8}$$

where ω is the fundamental natural frequency, I is the moment of inertia, ρ is the mass density, L is the free length of the beam, and A is the cross-sectional area of the beam.

4. Material Preparation

4.1. Laminate Preparation

Carbon fibre (210 gsm 2×2 Twill 3k Carbon Fibre Cloth) and carbon–Kevlar (188 gsm Plain Weave 3k Carbon Kevlar Cloth) procured from Easy Composites Ltd., Stoke-on-Trent, UK were used for the laminate preparation. Balsa wood (2 mm thick) sourced from Udupi was used for the sandwich material. The photographs of the fibre cloth are shown in Figure 3. Four configurations of laminates were prepared by employing both fibre sheets by varying the angle of the fibre in steps of 0°, 15°, 30°, and 45°. Fibre sheets with dimensions of 300 mm × 300 mm were cut as per the orientations [0/0/Balsa/0/0], [15/0/Balsa/0/15], [30/0/Balsa/0/30], and [45/0/Balsa/0/45], respectively.

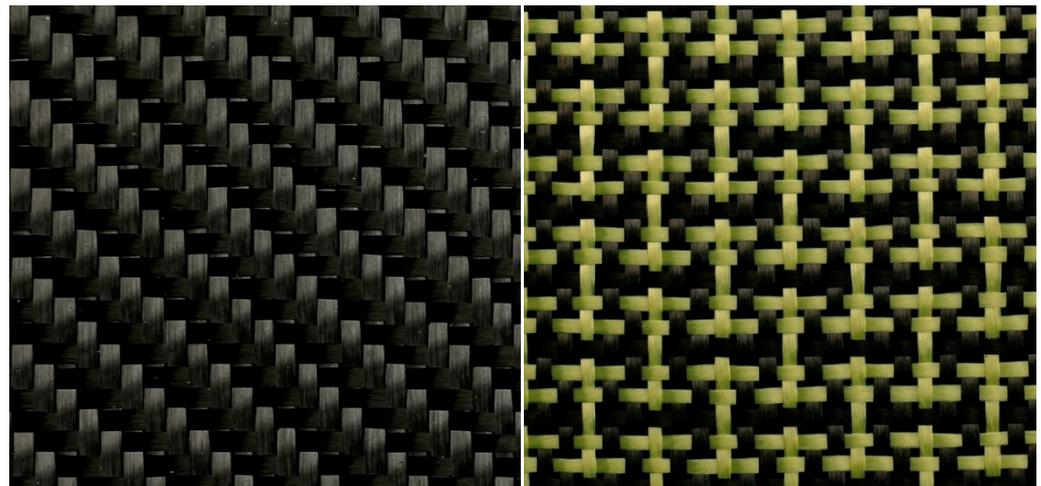


Figure 3. Carbon fibre cloth and carbon–Kevlar intra-ply cloth.

These combinations were maintained for both types of fibre sheets, and 8 samples were fabricated in total. Here, the angle was measured in the clockwise direction with respect to the direction of loading. A schematic of the stacking sequence of the [45/0/Balsa/0/45] sample is shown in Figure 4. The same technique was followed for other configurations.

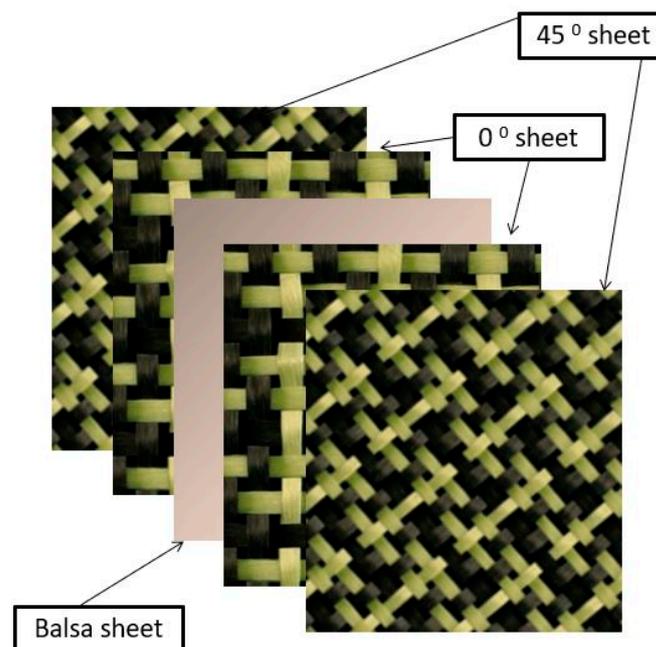


Figure 4. Schematic of stacking sequence.

The fabrication was performed using the hand layup technique, followed by the vacuum bagging process. A 300 mm × 300 mm fabric was first cut according to the angle required for the stacking sequence. The conventional hand layup technique was employed by laying up the layers in the stacking sequence mentioned on an open flat plate mould. Lapox L-12 epoxy resin was chosen as the matrix with a 45 min pot life at room temperature. Lapox K-6 was the curing agent applied and it was acquired from Yuje Enterprises, Bangalore, India. To achieve a uniform distribution of resin, the vacuum bagging technique was used. Once the samples were cured, the required samples were cut from the finished product. Samples with sizes of 230 mm × 30 mm were used for the impact hammer test. The test samples are displayed in Figure 5 below.



Figure 5. Test samples: (a) carbon fibre 0° and 45°, (b) carbon–Kevlar 0° and 45°.

The carbon fibre samples are named CF-0 and CF-45 for the 0° and 45° orientations, respectively, and for the intra-ply, CF-K 0 and CF-K 45 for the 0° and 45° orientations, respectively. Details of the prepared samples are given in Table 1.

Table 1. Details of the prepared samples.

Fibre	Angle of Orientation	Nomenclature	Dimension
Carbon fibre (CF)	0°, 15°, 30°, 45°	CF-0, CF-15, CF-30, CF-45	250 mm × 30 mm × 3 mm
Carbon–Kevlar fibre		CF-K 0, CF-K 15, CF-K 30, CF-K 45	

4.2. Experimental Set Up

The dynamic response of the composite beam was evaluated from impact-hammer-based experimental modal analysis [18–20]. These measurements are in compliance with the ASTM E756–05 standard [30]. The specimens were measured to be 230 mm × 30 mm. The schematic of the experimental set up is illustrated in Figure 6. An impact hammer (PCB, type-086C40) of sensitivity 2.25 mV/N was employed to give the input excitation near the fixed end of the beam. The response signals were measured from an accelerometer (PCB, sensitivity of 101.6 mV/g) attached at the free end of the beam. The impulse force and the acceleration signals were acquired from the NI-9234 data-acquisition module through NI-LabVIEW graphical programming.

From the impulse and response signals, the transfer function in the form of acceleration was measured. These measurements were repeated for the samples listed in Table 1. To maintain consistency in the test results, the clamping torque was carefully monitored. The experiments were conducted on three identical beam samples. A total of 15 averages were considered to ensure the consistency in measurement. To verify the consistency of the response, experiments were repeated three times under the same working conditions, and the average response was considered for analysis.

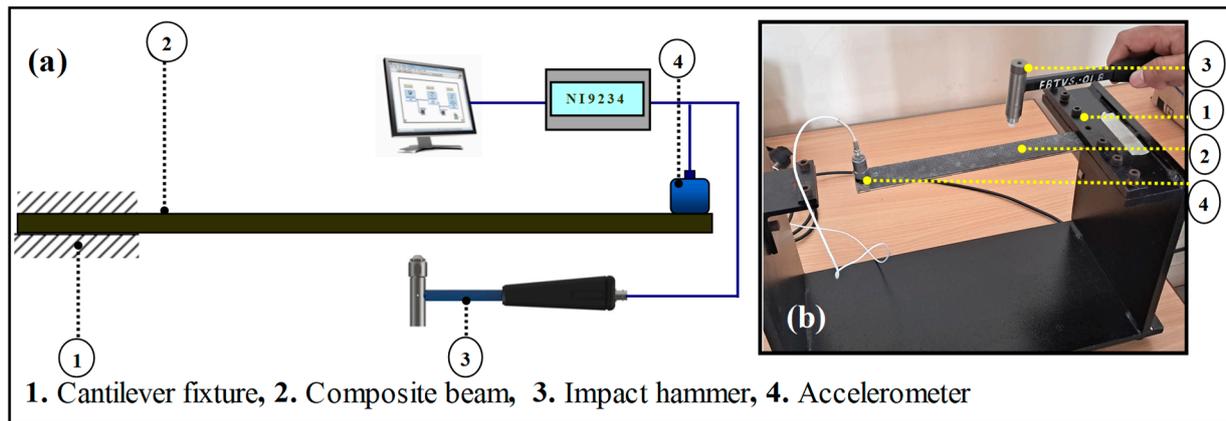


Figure 6. (a) Schematic of the experiment; (b) photograph of the impact test set up.

5. Results

The frequency response plots obtained from the impact hammer test are presented in Figures 7 and 8. As evident from the accelerance vs. frequency plots, the dynamic response was distinctly different for the CF composite and the CF-K composite beams. For CF beams with a fibre orientation of 0 degrees, the natural frequency was observed at 26.5 Hz. The corresponding value for the orientation of 45 degrees was 19.5 Hz. This indicates that natural frequency is a function of the orientation of the fibres. For CF-K beams, similar trends were noticed, with the natural frequency decreasing from 32 Hz to 22.5 Hz, as the fibre orientation was varied from 0 degrees to 45 degrees, respectively. These plots confirm the fact that the hybridisation has a positive impact on the resonance frequency of the composite beams. For the CF-K beam, for 0-degree fibre orientation, the natural frequency increased from 26.5 Hz to 32 Hz as the fibre type was modified. In other words, the hybridisation of the fibres improves the overall stiffness of the structure, which improves the rigidity and load-bearing capacity of the structure.

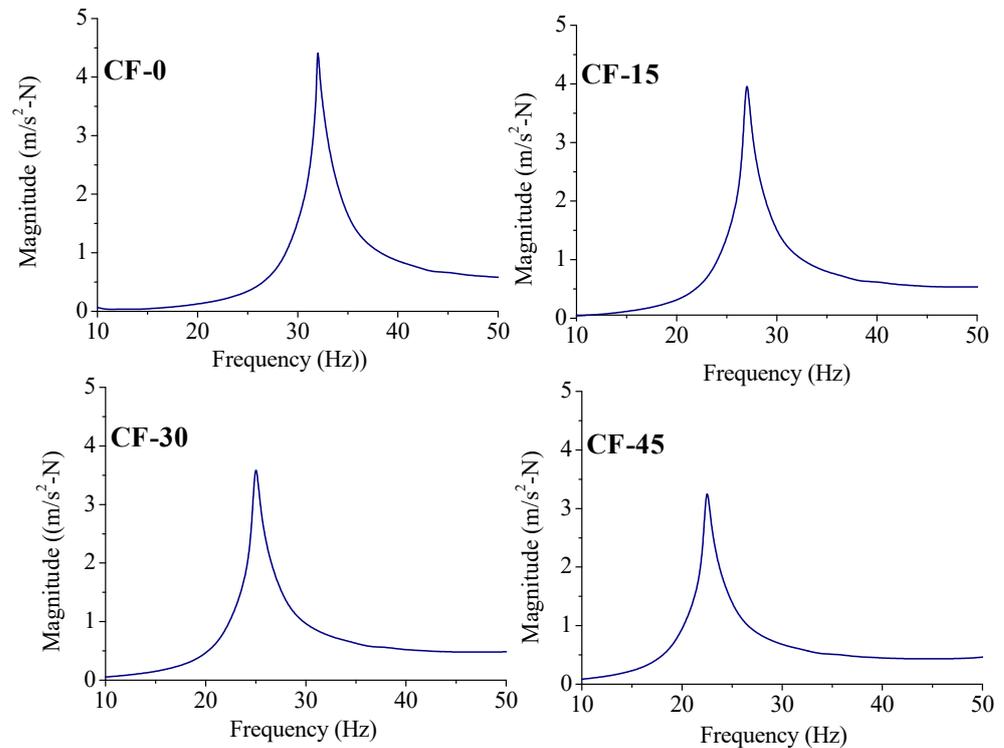


Figure 7. Frequency response plots of CF composite.

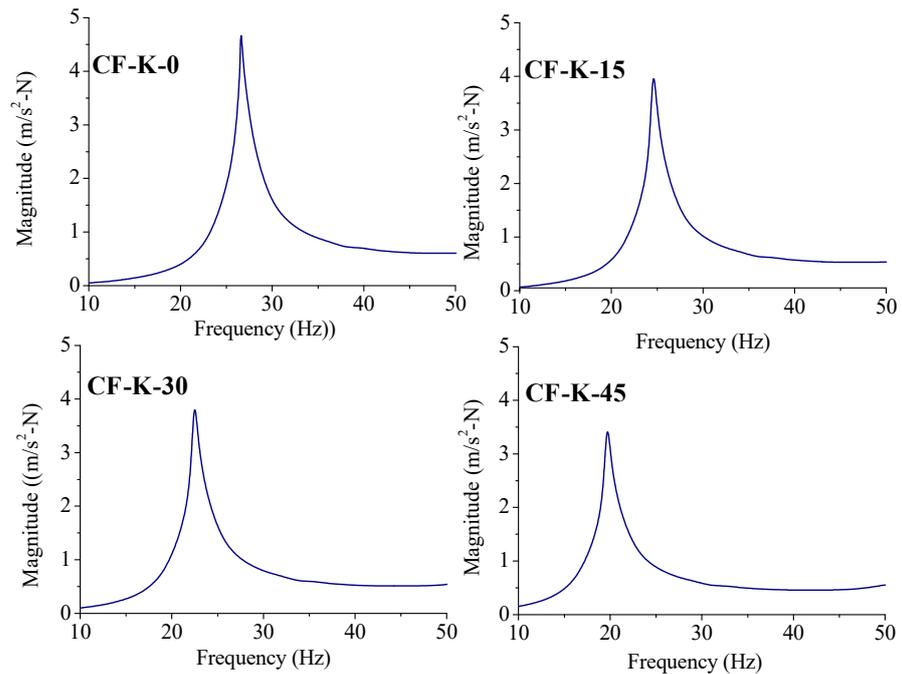


Figure 8. Frequency response plots of CF-K composite.

A comparison between the natural frequency variation of the beam with respect to the change in the fibre orientation and the fibre type is presented in Figure 9. As stated earlier, the natural frequency is higher for composites reinforced with hybrid fibres. With the increase in orientation, the natural frequency is decreased for both CF- and CF-K-reinforced composites, which substantiates the fact that the rigidity of the composite is reduced. For the same level of matrix loading, the natural frequency of CF-reinforced composite is reduced by 4% corresponding to the change in the fibre orientation from 0 degrees to 15 degrees. The reduction in natural frequency for the CF composites for 30- and 45-degree fibre reinforcement (with respect to 0-degree orientation) is 15% and 27%, respectively. For the CF-K composites, the natural frequency is reduced by 15%, 21%, and 29, corresponding to the change in orientation of the fibres from 0 to 15, 0 to 30, and 0 to 45 degrees. These values confirm that both CF and CFK composites exhibit properties which are sensitive to the fibre orientation. However, the hybridisation of fibres could induce a higher reinforcing effect, which results in a larger natural frequency and subsequently makes the composites more sensitive to the change in the orientation fibres.

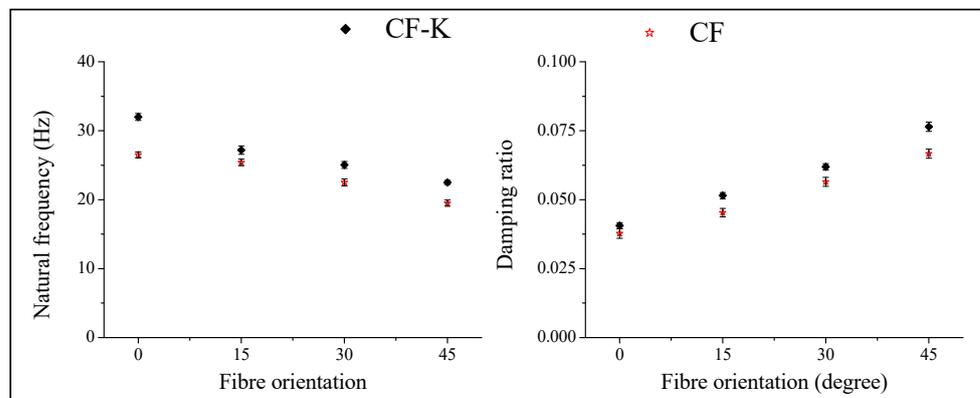


Figure 9. Natural frequency and damping ratio variation with fibre orientation.

Damping is a measure of the energy dissipation capacity of the material. For the composites, the variation in dynamic damping is assessed with respect to the change in fibre

orientation and the hybridisation. For the CF composites, the loss factor is enhanced by 0.0075 as the orientation is changed from 0 degrees to 15 degrees. The corresponding variations for the change in orientation of 0–30 and 0–45 degrees are 0.01 and 0.011, respectively. For hybrid composites, the loss factor is increased by 0.0108 for the change in orientation from 0 to 15 degrees. The corresponding values registered for the change in orientation of 0–30 and 0–45 degrees are 0.01 and 0.014, respectively. These variations confirm that the energy dissipation capabilities increase as the fibre orientation is increased. The maximum energy dissipation is noticed to correspond to the fibre reinforced at 45 degrees. Hybridisation has a significant impact on the energy dissipation characteristics of the composites. For CF-K composites, the maximum loss factor of 0.0765 is registered for the fibre orientation of 45 degrees. For the CF composites, a maximum loss factor of 0.0667 is observed.

The storage and loss modulus of composites estimated according to Equations (5) and (8) are presented in Figure 10. Among the CF composites, the maximum value of the storage modulus is registered for the fibres oriented at 0 degrees and the least for the composites prepared with a fibre orientation of 45 degrees. However, the trend is reversed as with respect to the variation in loss modulus with respect to the fibre orientation. This indicates that, for the same level of matrix loading, the energy dissipation characteristics can be varied by varying the orientation of the fibre. However, a compromise should be made with respect to the ability to store the energy.

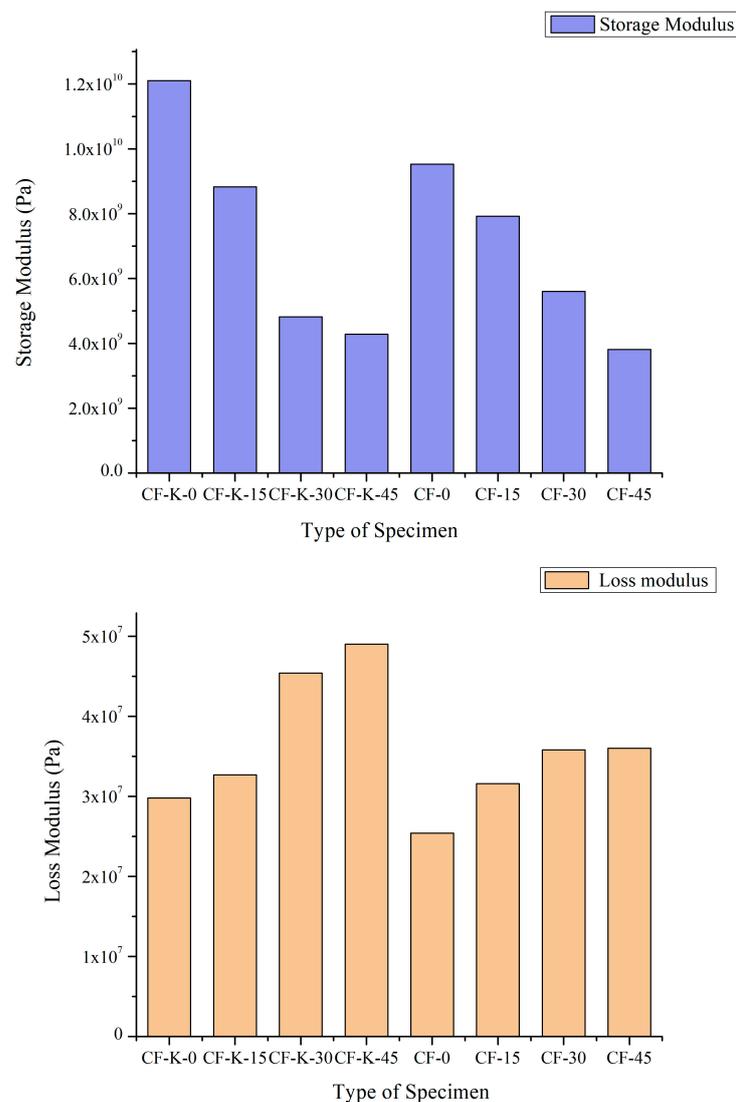


Figure 10. Comparison of storage and loss modulus variation with fibre orientation.

Compared to the CF fibres, the CF-K-based fibres have a superior energy dissipation ability and can absorb a larger amount of energy. The maximum storage modulus is registered for the composites with an orientation of 0, and the maximum energy dissipation can be attained for the composites with 45-degree reinforcement. Additionally, the hybridisation could yield superior properties compared to the composites synthesised with a single type of fibre reinforcement.

6. Discussion

Stiffness and damping are the important parameters of a structure that define the response of the structure under dynamic loading. The stiffness accounts for the ability to absorb the energy, and the damping depicts its ability to dissipate the energy. Generally, for any material, damping is inherently present, and the magnitude of the damping varies depending on the internal structure of the material. Composites are break-through materials that overcome the limitations of conventional materials. The unique attributes of composites are their ability to carry the load and their weight. With the decrease in weight, it is important that the damping be incorporated to protect the structure when it is exposed to the resonance condition. The composites have inherent damping due to the reinforcing fibres. In general, the properties of composites are a function of the matrix and the fibre. The fibres impart a reinforcing effect, which subsequently increases their stiffness as the modulus is enhanced. For the same level of matrix loading and the type of fibre, a change in the orientation of the fibres could modify the distribution of the load along the longitudinal and transverse directions, which subsequently reduces the stiffness. With the inclusion of hybrid fibres, the stiffness of the composites is further increased. Like carbon fibre-reinforced composites, a change in orientation results in similar effects in composites reinforced with hybrid fillers. This effect can be visualised from the change in the storage modulus of the samples as the fibre orientation is modified. The storage modulus is a direct indication of the stiffness of the sample. As evident from the graphs in Figure 9, the storage modulus is found to decrease with fibre orientation, with the maximum value of the storage modulus registered for the fibres oriented at 0 degrees and the least for the composites prepared with the fibre orientation of 45 degrees. However, the storage modulus corresponding to the hybrid fillers is lower compared to the carbon fibre-reinforced composite, which is a composite reinforced with a single type of fibre reinforcement.

The damping characteristics of the composites depend on the type of fibre, type of matrix, and the interface interaction. Under dynamic loading, the matrix and the fibres readily interact, which subsequently increases the energy dissipation. For a hybrid composite, the dissipation is pronounced as it has larger loss modulus values. This variation can be attributed to the variation in the interface interaction between the matrix and the fillers, which alters the mechanism at the micro-level. Additionally, the presence of two types of fibres could induce additional fibre-to-fibre interaction, which contributes to the energy dissipation.

The loss factor of the composites depends on the orientation of the fibres. For the fibre orientation of 45 degrees, the loss factor is higher compared to the 0-degree orientation. This typical response can be attributed to the variation in the storage and the loss modulus. According to the equation, the loss factor is a function of the storage and loss moduli. With the increase in angle of inclination, the storage modulus decreases and the loss modulus increases. This implies the fact that the cumulative contribution of the storage and loss modulus results in an increase in the loss factor of the composites. As the composite becomes stiffer (0-degree fibre orientation), interface interactions are not pronounced. With the increase in angle of orientation, the composite becomes softer, and the ability to absorb the energy decreases. Contrarily, the interface interaction would be enhanced. This subsequently increases the E'' . These variations contribute to the enhancement in the loss factor of composites as the angle of orientation of the fibres is increased. The mechanism can be visualised by considering a schematic of a 0-degree-orientation sample (Figure 11a) and the cross-section of a unit cell of the same (Figure 11b). As the fibres

are perfectly aligned parallel to the direction of loading, the 0-degree sample has the best damping ratio; however, as the angle of orientation is increased, the damping ratio reduces as the alignment is not parallel.

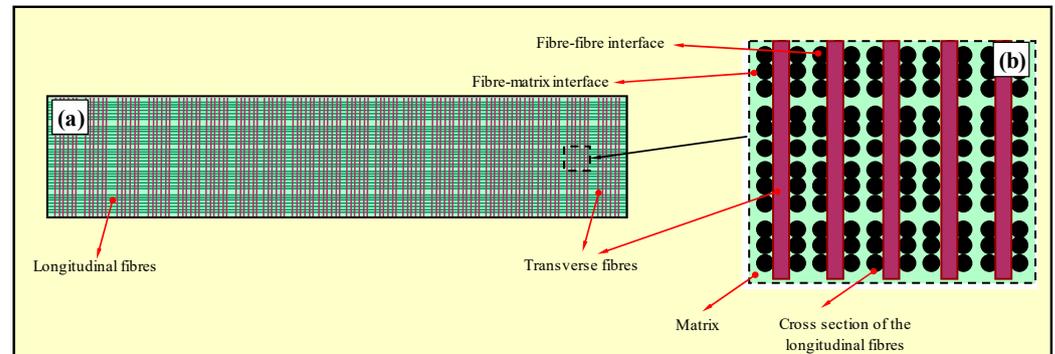


Figure 11. Schematic of the 0-degree fibre: (a) beam and (b) a unit cell of the cross-section of the beam.

Similar trends are noticed for the composites reinforced with hybrid fibres. The hybrid fibre results in a larger stiffness, which increases the ability of the composite to absorb energy. The ability of composites to dissipate the energy is higher compared to single-type fibre-reinforced composites. These factors cumulatively contribute to enhancing the damping characteristics of the hybrid composites. Overall, it can be evident that composites are the ideal alternative for conventional materials. The properties of composites can be tailor-made to meet the requirements of a specific application. Additionally, hybrid composites can modify the properties of composites when a constraint is imposed on the matrix. This study validates that hybridisation is beneficial. It can simultaneously improve the strength and the energy dissipation characteristics. Hybridisation could open up new possibilities where it can synergise the attributes of base fibres to attain superior properties.

7. Conclusions

Epoxy-based composite samples were prepared by reinforcing with carbon fibre-woven cloth and carbon-Kevlar fibre intra-ply. The influence of the angle of orientation on the dynamic properties was investigated by conducting an impact-hammer-based dynamic test. Viscoelastic material behaviour was analysed by analysing the variation in storage modulus and loss modulus of the samples as the fibre orientation was varied from 0° to 45° . The investigation of the results revealed the following conclusions.

The natural frequency of the samples reduced as the angle of orientation was increased, and the 0° sample showed the highest and the 45° sample showed the lowest natural frequency. This trend was consistent for both CF- and CF-K-reinforced samples. It was also observed that the natural frequency of CF-K intra-ply samples was higher than that of the CF specimen, indicating the enhancement in the stiffness by inclusion of the hybrid fibre.

By conducting viscoelastic analysis of the samples, it was clear that the storage modulus, which represents the energy storage capacity, increased with orientation. This result followed a similar trend as that of the natural frequency. However, a reverse trend was observed with respect to the loss modulus, which represents the energy dissipating capacity of the sample. This is also in line with the damping ratio, which was calculated using the half-power bandwidth method. Both types of samples showed the same trend, i.e., the damping ratio increased with orientation, and 45° samples showed the best damping property among the tested samples. However, the damping ratios of hybrid samples were higher. Thus, the CF-K intra-ply hybrid sample is a good material and has the potential to be a vibration damping material with good strength.

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