Enhanced vibration damping and viscoelastic properties of flax/epoxy composites and their carbon fibre hybrid laminates

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Abstract

The damping and viscoelastic properties of flax/epoxy composites and their carbon fibre hybrid laminates are investigated. For this purpose, four different types of composite laminates using varied stacking sequences were fabricated by vacuum infusion process. The influence of various parameters on the vibration damping behaviour of flax and flax/carbon hybrid systems is investigated by using two techniques:shaker system utilising half-power bandwidth and dynamic mechanical analysis. In order to show the correlations between damping and mechanical properties, three-point bending tests are used to determine the bending stiffness of each stacking sequence. The results indicate that the location and number of flax plies contribute to the damping behaviour while the bending stiffness is mainly governed by location of carbon plies. Results show that the damping ratio varies for each vibration mode. Specimen type D, which contains the fewest number of carbon plies, exhibits higher values for both flexural stiffness and damping ratio compared to configuration B, which has the highest number of carbon layers. When comparing configurations B and C, it is observed that by trading off 8.1% of flexural stiffness, a substantial 34% increase in damping ratio was achieved in the second vibration mode.

Keywords: A: Hybrid, B. Vibration, C: Vacuum infusion, D: Natural fibre

1. Introduction

Fibre-reinforced composite materials have been increasingly used in many engineering applications. This trend is mainly due to their superior specific strength and stiffness compared to conventional metallic materials by providing a lower weight while maintaining adequate strength and stiffness. Glass and carbon fibres are the most common reinforcements used in polymer composites. However, the problems involving recycling these synthetic fibres and the growing global waste problem have led to considering natural fibres as more sustainable and environmentally friendly alternatives which are derived from low-cost renewable raw materials [1]. Flax fibres (FF) are one the most common natural fibres used in composite applications. The mechanical properties of FF are generally not as comparable as the synthetic ones. However, their specific mechanical properties are reported to be comparable to or even better than those of glass fibres [2]. Various aspects of flax fibre-reinforced composites are investigated by researchers and some reviews of these studies can be found in [3-5].

Hybrid composites having more than one reinforcing material, are used to benefit from the advantages of each reinforcement. The advantage can be a compromise between cost, strength, stiffness or other properties. Some studies on the hybridisation of flax fibres with synthetic ones are available in the literature [6-11].

The energy dissipation capability of a material is an important characteristic in the design of composites, especially during dynamic or cyclic loadings. This characteristic can be quantified by damping in the form of the quality factor, loss factor, specific damping capacity and the logarithmic decrement or the damping ratio [12].

Different aspects of the damping behaviour of flax fibre-reinforced composites are investigated [13-17] and superior damping properties of these fibres over the synthetic ones are reported in the literature [4,12,18-20]. It has been suggested that the efficient dissipation of energy in FF (fibrillar-fibrillar) materials can be attributed primarily to the hierarchical structure of their individual components. This includes the friction between the cellulose microfibrils within the cell wall, as well as the interaction between the hemicellulose/lignin matrix and the friction between adjacent cell walls [14].

Combining the superior intrinsic damping properties of flax fibres with the high strength and stiffness of carbon fibres has made these reinforcements excellent candidates for hybridisation which can provide a good balance between damping and mechanical properties for advanced applications [21-27]. Assarar et.al [21] showed that addition of two flax layers to the exterior of a carbon laminate resulted in a significant increase in damping, albeit at the cost of reduced bending modulus. However, in certain flax-carbon hybridizations, the study demonstrated improved damping properties while maintaining bending stiffness that was comparable to that of a carbon laminate.

Le Guen et al. [22] conducted research on the relationship between damping and modulus in hybrid composites made of flax and carbon fibres. They employed a hybrid mixed rule and laminate theory approach based on the mechanical properties of non-hybrid composites to accurately describe the correlation between vibration damping and elastic modulus in both longitudinal and flexural modes. Flynn et.al [23] utilized tensile, flexural, impact and vibration tests to investigate the damping and mechanical properties of hybridized carbon and flax composites with varying flax fibre volume fractions.

Assarar et.al [24] incorporated interleaving flax and viscoelastic layers into carbon fibre-reinforced composites to enhance their damping capabilities. They found that the addition of these layers on one side of the carbon-epoxy laminate did not alter its natural frequencies, while improving its damping properties by a significant margin of 36-117%. The effect of stacking sequences and fibre orientation on the damping properties of six-layer layups of unidirectional carbon/flax fibre reinforced epoxy composites was studied by Ben Ameur [25]. The comparison between damping of composites which they obtained by free vibration tests with an impulse technique showed that the vibration behaviour depends essentially on the stacking sequence of flax and carbon plies where the dynamic properties depend on fibre direction and content of flax and carbon.

Fairlie and Njuguna [26] conducted a study to explore the damping characteristics of an eight-layer composite material consisting of flax/carbon hybrid epoxy/fibre reinforcement for potential use in semi-structural applications in the automotive industry. The study employed an impulse hammer and a Laser Doppler Vibrometer. The results showed that adding one or two flax layers to the outer layer of a carbon fibre laminate reduced Young's modulus by 28% and 45%, respectively. Additionally, replacing the orientation of the internal layer of [C/F2/C]s with two ±45◦ layers did not have a significant effect on Young's modulus, but reduced the ultimate tensile strength by 61%. The study revealed that the external layers had the most substantial impact on damping properties. The inclusion of a flax layer in an epoxy/carbon fibre-reinforced composite as an external layer significantly increased its damping ratio by 53.6%, while adding two layers improved it by 94%. These findings suggest that incorporating flax layers in composite materials could enhance the damping properties of vehicles, making them more suitable for semi-structural applications in the automotive industry.

Another study focusing on the effect of stacking sequence on damping properties was conducted by Wang et. al [27]. The authors of the study used dynamic mechanical analysis (DMA) to analyze a five-layer scheme of flax and carbon plies. They found that the sandwich hybrid composite with carbon fibre on the surface exhibited higher material damping properties compared to the hybrid composite with flax fibre alternately stacked on the surface. The study further concluded that the structural damping performance of hybrid composites is influenced by the type of surface fibre used.

Despite having a significant development in this field, some important aspects still need to be investigated. These studies have not explored the correlation between vibrational properties and Dynamic Mechanical Analysis (DMA) results in the context of hybrid laminates. Furthermore, there is a lack of research aiming to simultaneously tailor tensile, bending, vibrational, and DMA properties. Previous studies in the literature have predominantly focused on relatively thin laminates with a maximum of eight plies. The authors believe that thin laminates with a low number of plies present two main challenges. Firstly, the reduced distance from the neutral axis amplifies the impact of any variations in ply properties. Secondly, even small changes in a low ply count, such as adding or modifying one or two layers out of maximum eight, result in significant percentage differences.

The primary objective of this study is to investigate the influence of flax ply positions and the number of carbon layers in the hybrid layup with a flax core on the vibration damping, mechanical, and thermo-mechanical properties of the resulting hybrid laminates. To accomplish this, four different layups are examined through cantilever vibration tests and dynamic mechanical analysis. Additionally, the flexural stiffness of each lay-up is precisely measured to establish a quantitative correlation between mechanical performance and damping properties. The findings of this study hold great promise for advancing the development and application of sustainable flax-based hybrid composites in various advanced lightweight applications. By comprehensively exploring the vibrational and mechanical characteristics of these materials, this research contributes to a deeper understanding of their dynamic behavior and potential performance advantages, driving the progress towards more efficient and environmentally friendly composites.

2. Method

2.1 Materials

Unidirectional (UD) carbon, UD flax and ± 45° flax plies with Sicomin Infugreen 810 + SD 8824 hardener bio-epoxy resin are utilised to produce four different laminates with different lay-ups. The specifications and suppliers of each component are summarised as follows:

- Carbon UD fabric (296g/m²): commercial name "UD Carbone Tissé 300g/m² T700", supplier : Sicomin (France), type : T700SC 12K 50, 800 tex
- Flax fabric ±45° (312g/m²), experimental product, name "FBX 312", supplier: Depestele (France), type: stitched non-twisted roving
- Flax UD Fabric (200g/m²): commercial name "Lincore© FWUD 200", supplier: Depestele (France), type: twill2/2, 3.6 threads/cm, Weight distribution : 93% warp direction and 7% weft direction.
- Resin: bio-epoxy infusion resin, commercial name "Infugreen 810" , 38% biosourced with its hardener : commercial name "SD8824", supplier: Sicomin (France).

The nominal properties of the individual plies are shown in Table 1.

Table 1. Properties of individual lamina used in this study.

Material	**E_1 (GPa)**	**E_2 (GPa)**	**G_{12} (GPa)**	**ν_{12}**	**Thickness (mm)**	**Density (g/cm^3)**
Carbon (UD)	112.22	5.54	5.32	0.35	0.36	1.47
Flax (UD)	19.96	4.42	2.47	0.32	0.36	1.30
Flax (± 45°)	7.27	7.27	5.46	0.47	0.54	1.30

The values in Table 1 are the nominal cured properties for a single lamina which are provided by Kairos ; issued from Classical Laminate Theory (rule of mixture) computation with a fibre volume content equal to 37% for flax plies and 48% for the carbon ply. E_1 and E_2 are the Young modulus in fabric direction and perpendicular to fabric direction respectively. G_{12} is the in-plane shear modulus. ν_{12} is Poisson ratio.

In this study, four different specimen types to investigate the effects of carbon ply number and locations within hybrid composites on damping behaviour are utilised. The stacking sequences were carefully chosen to maintain a constant bending stiffness and thickness while analyzing the impact of varying carbon ply locations and numbers. As a reference material, a specimen composed entirely of unidirectional (UD) flax plies is used. To explore the combined influence of carbon ply locations and numbers on damping/viscoelastic behaviour, we selected configurations where both parameters were simultaneously altered. It is worth mentioning that investigating each effect independently, while keeping one parameter constant and varying the other, would require a considerable increase in the number of samples resulting in a substantial increase in manufacturing cost, conducting the experiments and analysing the data. To address this issue and reduce the number of specimens and configurations, we adopted the current arrangement, despite introducing some level of uncertainty in the results.

All specimen types obtained from the composite laminates consist of 18 plies. In specimen type *A*, only UD flax is used as reinforcement which is used as the reference configuration. In other configurations, a ± 45° flax ply is placed in three different positions in the lay-up, while the number of carbon layers is reduced from 10 to 6 by changing the position of ± 45° flax from the surface toward the inside of the laminate. The configuration of each lay-up is shown schematically in Fig. 1.

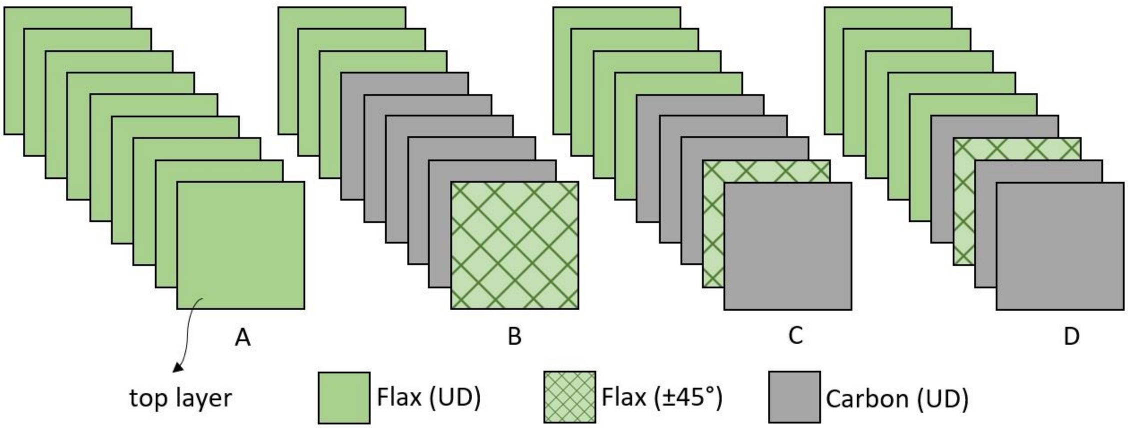

Fig.1 *Lay-ups configuration of each specimen type showing 9 of the 18 plies.*

2.2 Composite laminates fabrication

Four different laminate types (flax epoxy and flax/carbon epoxy hybrid) each consisting of 18 plies are manufactured to conduct three-point bending, vibration and DMA experiments. These laminates are produced by a vacuum-bag infusion process (Fig.2), in a controlled temperature and air-moisture environment. Flax fabrics were dried before lay-up. The resin was at room temperature before infusion. All the laminates were infused at once next to each other. For post-curing, the samples were kept at 40 °C for 24 hours in the oven. Finally, the laminates were cut into samples with 10 mm × 530 mm, 15 mm × 200 mm, and 10 mm × 35 mm for vibration, three-point bending and DMA tests respectively.

The plies were individually pre-cut using scissors and then dried in an oven equipped with heating lamps and an air dryer that continuously blew dry air. The room was closed and heated to a temperature of 22 °C and a relative humidity of 34% RH.

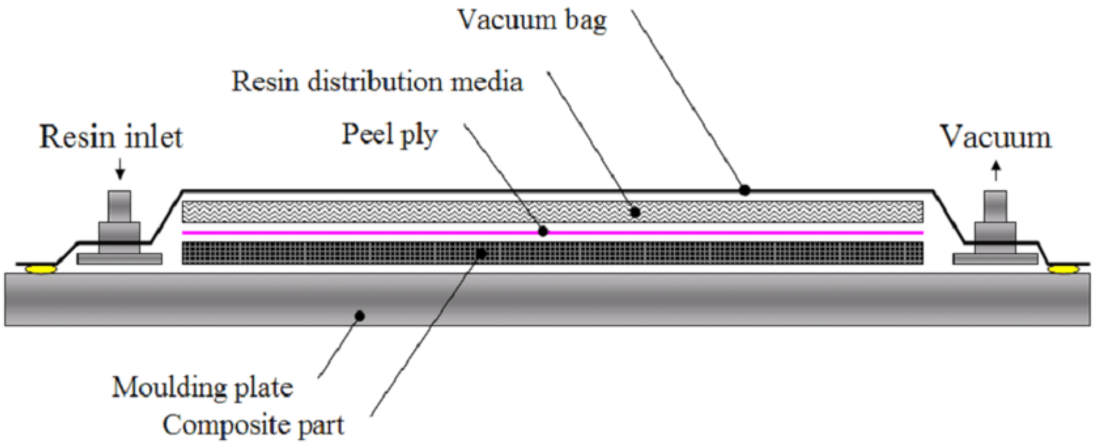

Fig.2 *Illustration of the layers needed for infusion process.*

The infusion consumables are obtained from Diatex supplier as summurised:

- Peel ply reference: PES 85
- Flow media reference: Infuplex Isonet
- Vacuum chanel reference: Diadrain
- Vacuum bag reference: PO120

A vacuum was applied and the bag was sealed, a drop-test was performed to ensure the quality of the seals. The pressure inside the vacuum bag was measured, the vacuum pump (model RA0025 from BUSH with electronic controller) was turned off, and the pressure was measured again ten minutes later. The pressure increase was 4.5 mbar in ten minutes, which was deemed satisfactory. The vacuum pump was then turned on again and the plies were left in this state for 20 hours to compact and remove as much air as possible.

A second drop-test was performed before preparing the resin mix, with a reading of +3.5 mbar in 10 minutes, indicating the test had been passed and the resin mix was prepared. The resin and hardener were at room temperature (22 °C). The resin mix was placed in a container located 0.8m below the molding plate, which helped to reduce the flow rate and limit occlusions and dry spots.

At last the samples were cut from the plates using a computer numerical control (CNC) machine with a 2 mm solid carbide milling cutter.

2.3 Vibration damping testing

The frequencies and damping ratios are determined using the vibration cantilever beam method, with a Derritron Electronics Electro-magnetic shaker system (type VP85). This system is powered by a DataPhysics DSA5-1K power amplifier with 1000W of maximum power. It is controlled by a DataPhysics Abacus, Quattro control and data acquisition module. The vibration signal was swept from 10 to 1000 Hz with 400 data points (linear distribution). Following the full-range vibration scan, in order to measure the resonance frequencies more accurately, several scans were conducted around the range of each resonance frequency.

Two accelerometers were used to record the response of the specimen. One accelerometer was attached to the moving tip of the beam to measure the dynamic response of the composite beam. Another accelerometer was attached to the shaker's moving platform, i.e.

the campled base of the composite beam, to control and obtain a constant acceleration r.m.s. magnitude of 0.5 g. The base or shaker control accelerometer was a B&K 4507 B ICP-type accelerator with a weight of 4.8 gm. However, for the specimen tip acceleration measuremnt, the lighter B&K 4517 ICP-type accelerometer weighing 0.6 gm was used to minimize the effect of the mass of the accelerometer. Initially the same accelerometer types with mass of 4.8 gm were used for both shaker and specimen. But since this mass was not negligible compared to the mass of the specimen, and the considerations should be made like vibration of a cantilever beam with additional mass, the second accelerometer with negligible mass of 0.6 gm was utilised.

The accelerometer was attached to the specimens at a 0.3 x length distance from the clamped end to measure the dynamic response of the beam. If the accelerometer is placed at the free-end of the beam, there is a higher amplitude and speed which increases the added-mass of the sensor and hence disturbs the coupon's response. Conversely, if the sensor is too close to the clamped end, the amplitude gets smaller and hence the errors increase. The chosen position of the sensor on the beam is a trade-off between these two extreme cases. It is to be noted that sensor placement can also force a specific vibration mode if placed near a node position. To avoid these issues, a contactless measurement could be done using video analysis, laser or ultrasound beams. The experimental setup for the vibration test is shown in Fig. 3.

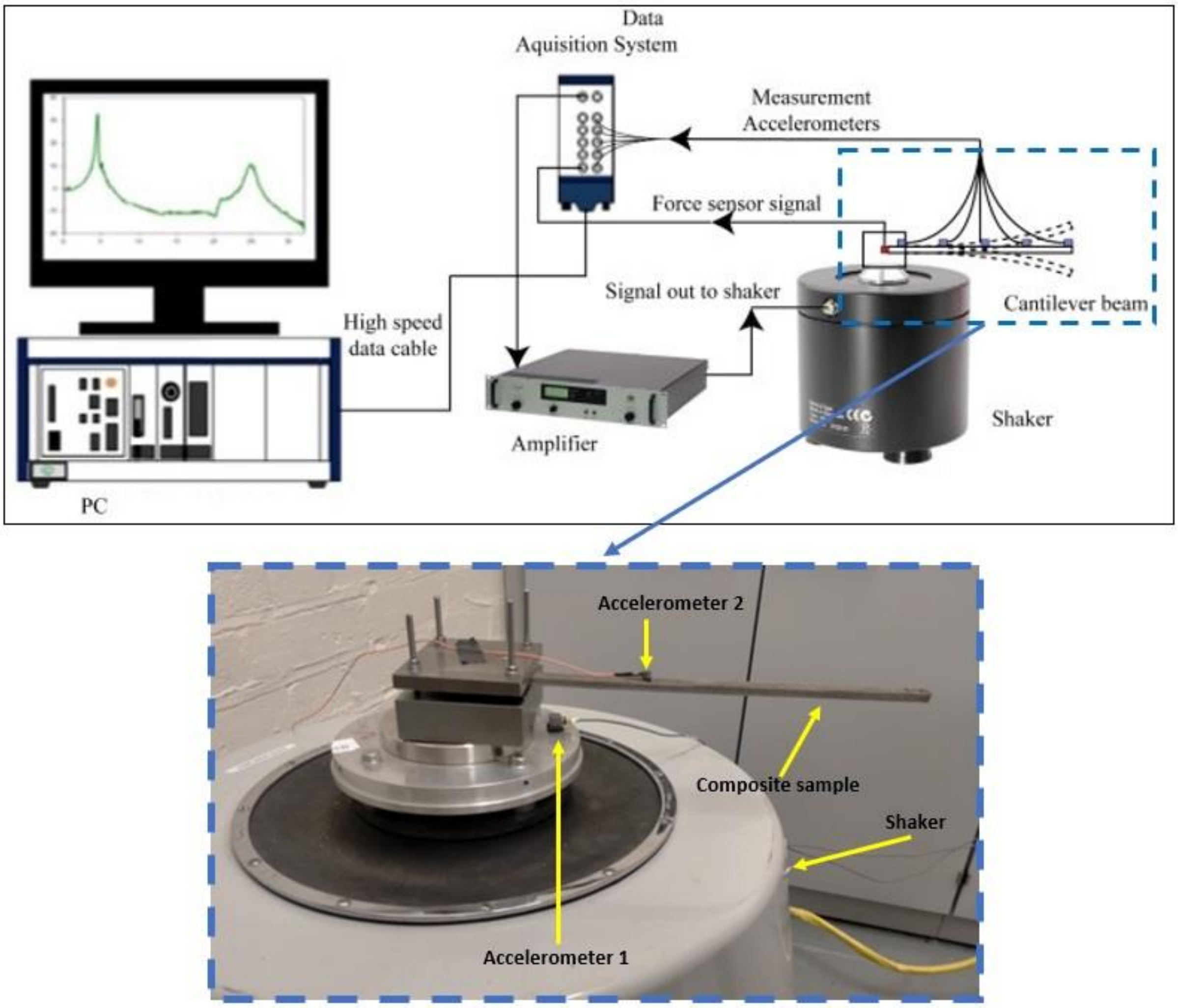

Fig.3. *The schematic illustration of the experimental setup for vibration testing.*

The dynamic properties corresponding to the first three resonance peaks were determined by using the 3-dB bandwidth (cut-off frequency) method also known as the half-power bandwidth method, as shown in Fig. 4.

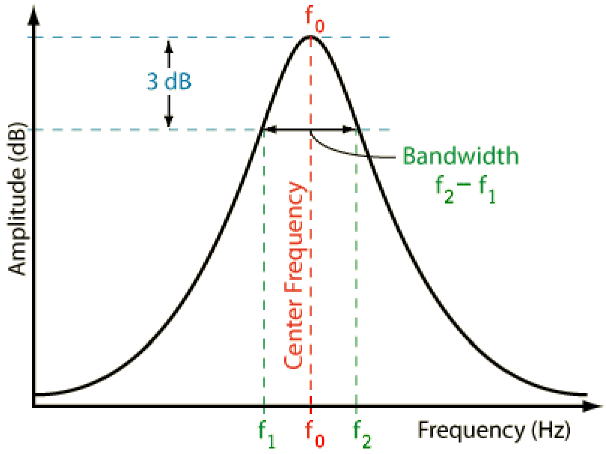

Fig.4 *The 3 dB method diagram for calculating the damping factor Q_n [25].*

In a frequency response function (FRF), the damping factor is proportional to the width of the resonant peak about the peak's centre frequency. The damping factor (Q_n) can be found by equation (4) [25]:

$$Q_n = \frac{f_0}{f_2 - f_1} \qquad (1)$$

where, f_0 is the frequency of the resonant peak and f_1 and f_2 are frequency values 3 dB down from peak value lower than and higher than f_0 respectively. The relationship between the damping factor (Q), damping ratio (ζ), and loss factor (η) is given in equation (2) [25]:

$$\eta_n = \frac{1}{Q_n} = 2 \cdot \zeta_n = \frac{\Delta f_{3dB}}{f_n} \qquad (2)$$

where n is the mode number. Also the half-power points are utilised to determine the damping ratio.

The experimental results for the first three natural frequencies are compared to the theoretical values explained in the following. Natural frequencies for a cantilever beam can be calculated from equation (3) [28]:

$$f_n = \frac{{k_n}^2}{2\pi L^2}\left(\frac{EI}{\rho A}\right)^{1/2} \qquad (3)$$

where, A, L, E, I and ρ are cross-section area, the free length of the beam, equivalent modulus of elasticity, second moment of area and density of the beam, respectively. K_n is obtained from the eigenvalue solution of the differential equation for free vibration of a cantilever beam and subscript n refers to the mode number.

Using classical laminate theory (CLT) the effective Young's modulus of the laminate, E_x can be calculated as equation (4) [29]:

$$E_x = \frac{(A_{11}A_{22} - {A_{12}}^2)}{tA_{22}} \qquad (4)$$

where the components of A_{ij} in equation (5) can be calculated from :

$$A_{ij} = \int_{-t/2}^{t/2} (\bar{Q}_{ij})_k \, dz = \sum_{k=1}^{n} (\bar{Q}_{ij})_k (z_k - z_{k-1}) \qquad (5)$$

where the $\bar{Q}_{ij}$ are the components of the transformed lamina stiffness matrix.

2.4 Dynamic mechanical analysis

Utilising DMA, the storage modulus, loss modulus and damping property (tan δ) of the material can be measured as they are deformed under dynamic stress. Moreover, these data provide quantitative information about the viscoelastic performance of materials.

To analyze the dynamic properties of the materials, temperature sweep tests were performed using a dual cantilever configuration on a TA Instruments (New Castle, Delaware, United States) *DMA Q800* dynamic mechanical analyser. The instrument utilized a 35 mm span for support, enabling characterization of the response of each material during dynamic mechanical analysis. The damping behavior of the composites was evaluated at specific frequencies, with testing conducted at 1 Hz and 10 Hz for each composite. At each frequency, the composites were heated from 23 °C to 150 °C at the rate of 3 °C/min.

2.5 Three-point bending test

The flexural bending stiffness was assessed using the three-point bending test. Specimens with size of 15 mm × 200 mm (width × length) were selected for this purpose, with a span length set at 16 times the specimen's thickness. The thickness for each specimen is provided in Table 1. Displacement-controlled loading, at a rate of 2 mm/min, was applied using a Zwick/Roell testing machine. The flexural stiffness of each sample was measured according to BS EN ISO 14125 standard and was calculated using the equation 6 [30]:

$$E_f = \frac{mL^3}{4bt^3} \qquad (6)$$

where *L*, *b* and *t* are the span length, width and thickness of the specimen, respectively, and *m* is the initial slope of the load-displacement curve obtained from the experimental data.

3. Results and discussions

3.1 Vibration damping behaviour

The frequency response functions, defined by the ratio between the specimen tip acceleration (output) and the base acceleration (input or excitation) in the frequency domain, for the samples from each configuration is presented in Fig.5.

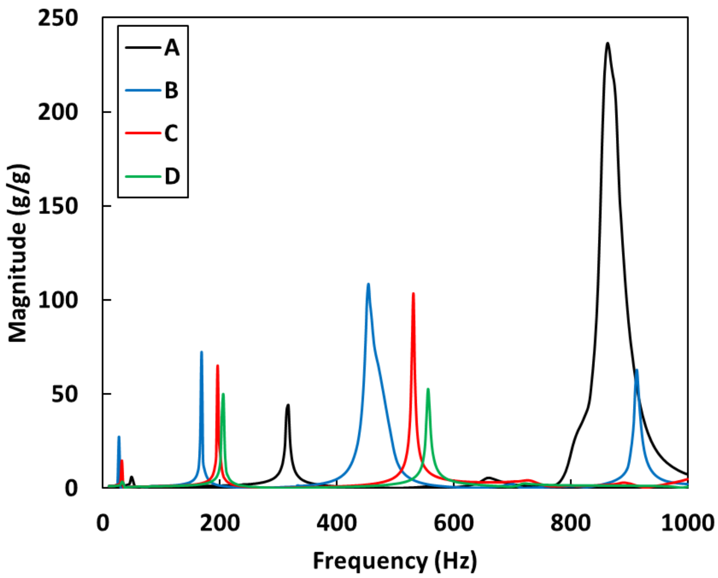

Fig.5 *Frequency response functions for swept sine signal (10 Hz to 1000 Hz) for different samples.*

Following the full-range scan, in order to measure the resonance frequencies more accurately, individual scans were conducted around the range of each resonance frequency. The resonance frequencies are presented in Table 2 and are compared with those obtained from theoretical values using the nominal material properties in Table 1.

Table 2. Resonance frequencies of laminates obtained from experiment and theoretical calculations.

Sample	**First three resonance frequencies (Hz)**								
	Experimental			**Analytical**			**Error (%)**		
	1st	**2nd**	**3rd**	**1st**	**2nd**	**3rd**	**1st**	**2nd**	**3rd**
A	51.4	317	863	55.3	336	970	7.5	6	12.4
B	28.1	172	464	31.6	198	555	12.4	15.1	19.6
C	31.9	197	531	31.5	197	553	1.2	1	4.1
D	33.6	207	563	30.0	187	525	10.7	9.6	6.7

The results show that the theoretical value from equation (1) gives a good estimation for natural frequencies. The high variation in sample B could have been due to differences between the lower thickness of the cured specimen and the higher nominal thickness used in theoretical calculations.

The damping properties can vary in different modes. Therefore, instead of considering the damping ratio of material just in first vibration mode, it is important to measure the damping property at other frequencies as well. Therefore, the first three modes are considered in this study, which provides better understanding about the damping properties of the materials.

The damping ratio (ζ) obtained from the experimental results in each first three resonance frequencies are calculated according to equations (1) and (2) and are summarised in Table 3.

Table 3. Modal damping ratios calculated by 3dB method for different samples.

	Damping ratio (ζ) %		
Sample	**1st**	**2nd**	**3rd**
A	0.49	0.76	1.72
B	0.47	0.18	0.75
C	0.52	0.24	0.51
D	0.51	0.24	0.35

As shown in Table 3, the damping ratio varies in each vibration mode. For specimen A, the damping ratio increases, while for other specimen types, it is minimum in the second mode of vibration. This implies that in each vibration mode, the damping mechanisim is not the same for each specimen. In the first mode, the damping ratio values are close to each other. Since the frequency in the first mode is low, the energy dissipiation in this frequency is not well stablished. Due to this nature, the first mode of vibration was not used to compare the damping mechanisms.

The 3-dB method results in second vibration modes show that specimen A with all flax layers exhibits the highest damping ratio and configuration B with the highest number (five) of UD carbon plies has the lowest. The better energy dissipation performance of sample A is due to higher damping properties of individual flax layers which is consistent with [21-27]. However, the conclusion for the mechanism of damping for other configurations needs more discussions. The damping ratios for configurations C and D are found to be similar, and they are about 37 % higher than specimen type B, and 68 % lower than configuration A.

It is reported [21-27] that flax layers in surface layers can dissipate more energy than a sequence with the same flax content in inner layers. The lower damping ratio in specimen type B with less number of flax plies with ± 45° layer on surface to specimen type C with higher flax content and ± 45° layer below surface may imply that the effect of flax fibre content is more important than its location. However, the same amount of increase in damping ratio is not found for configuration D. This shows that in addition to the flax content another parameter makes the difference. In specimen type B, the five carbon layers are consecutive and through the lay-up, but for case C, a flax ply exists between the carbon layers. Therefore, this local effect may have a significant effect on the energy dissipation capability of the laminate.

In the third mode of vibration, the damping ratio value is higher than the second mode for all specimen types. Considering the viscous behaviour as the governing damping mechanism, this increase can be related to velocity changes in higher frequency, resulting in the dissipation of more energy. Like the previous modes, sample A shows the highest damping ratio. However, in this mode, the damping ratio for sample B is higher than C and D. This shows that, in the third vibration mode, the location of the ± 45° flax layer and its distance from the neutral axis is more dominant than other parameters in higher frequencies. Therefore, in sample B, since the ± 45° flax layer has the highest distance from the neutral axis, the damping ratio is higher than C and D. In a similar way, the higher distance of ± 45° flax layer in C compared to D, makes its damping ratio to be considerably higher (45 %) in the third vibration mode. The dominant effect of flax fibre location can be magnified by considering the close damping ratio for these samples in the second vibration mode.

3.2 Dynamic mechanical analysis

The DMA results in terms of storage modulus, loss modulus and tan δ graphs through the temperature sweep in 25-150 °C are shown in Fig.6.

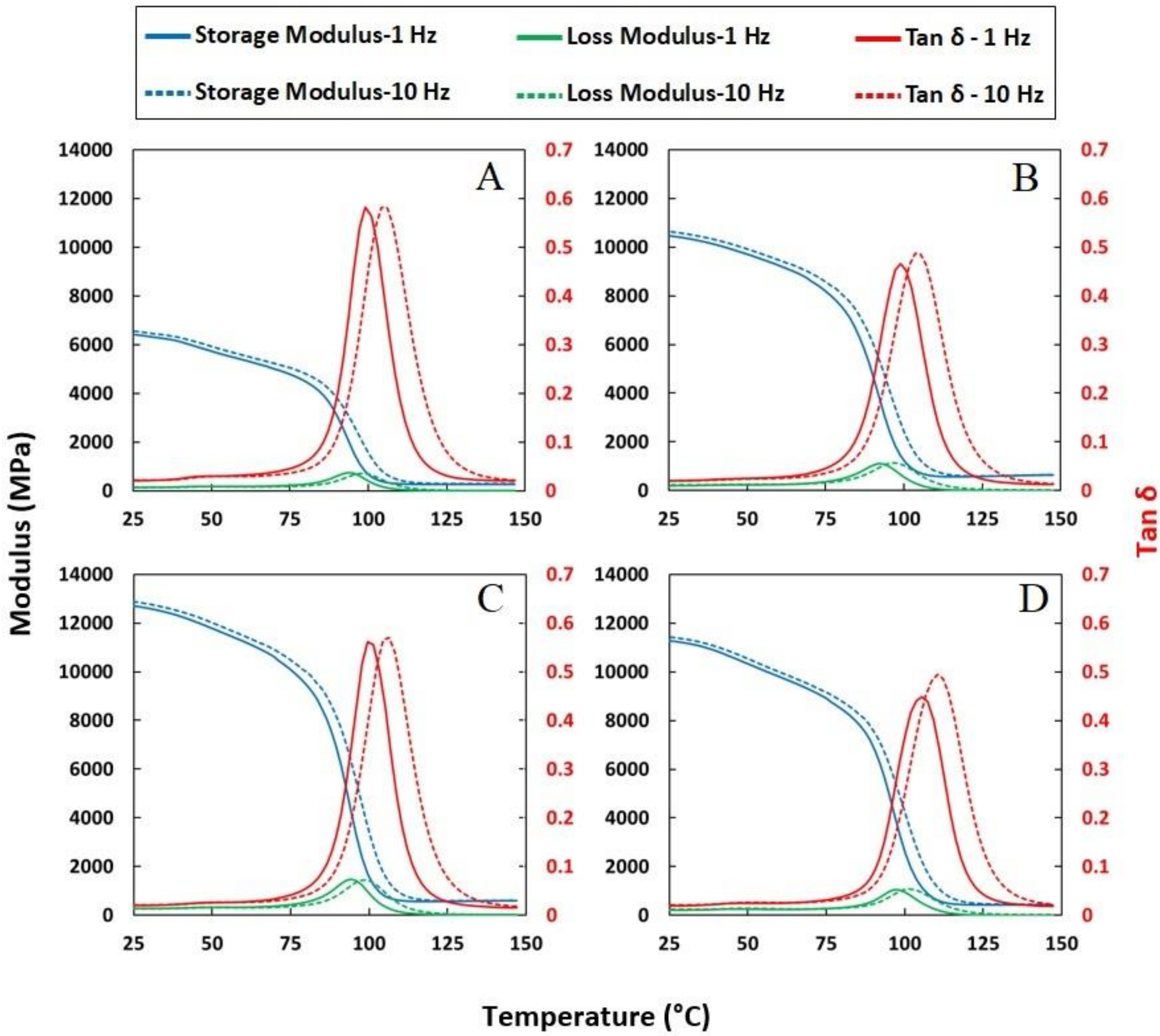

Fig.6 *Storage modulus, loss modulus and tan δ graphs of different samples.*

The loss modulus to storage modulus ratio, δ, can be used as an indicator of damping capability of a material. The tan δ values obtained from DMA of each specimen type at room temperature are summarized in Fig.7. For the frequency of 10 Hz, the tan δ values show a similar trend to the damping values measured by the 3-dB method, where this value is found to be maximum for configuration A (with all flax layers) and minimum for configuration B (with the highest number of UD carbon plies). Also like damping ratio, the tanδ for specimen C and D is between the maximum and minimum values for configurations A and B. However the differences in tanδ values is not as significant as damping ratios.

Damping defined by a DMA behaves somewhat differently from damping measurement from vibration test. DMA damping is proportional to the displacement amplitude, whereas viscous damping from vibration is proportional to the velocity. Thus, it is not possible to directly convert one number into the other.

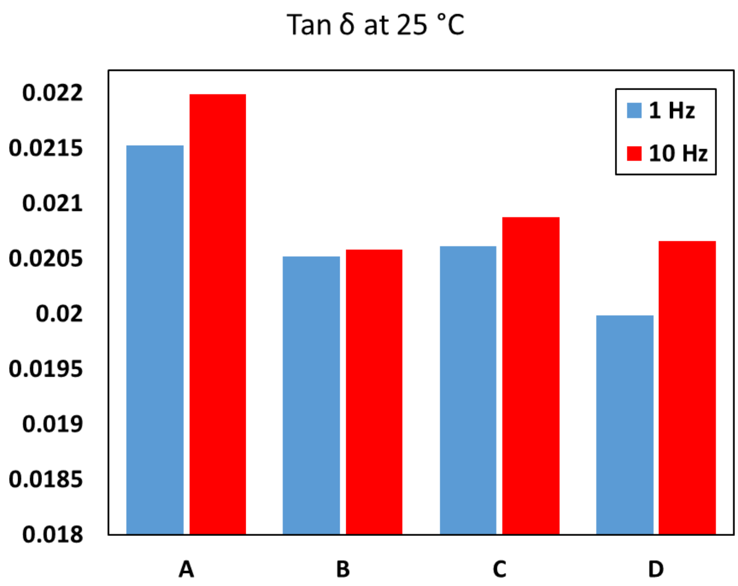

Fig.7 *tan δ values for all configurations at room temperature.*

The graphs of dynamic viscosity through the temperature scan of DMA results for all specimen configurations in 1 Hz and 10 Hz are presented in Fig.8. The results show that the dynamic viscosity values for all configurations 1 Hz is almost ten times of the 10 Hz.

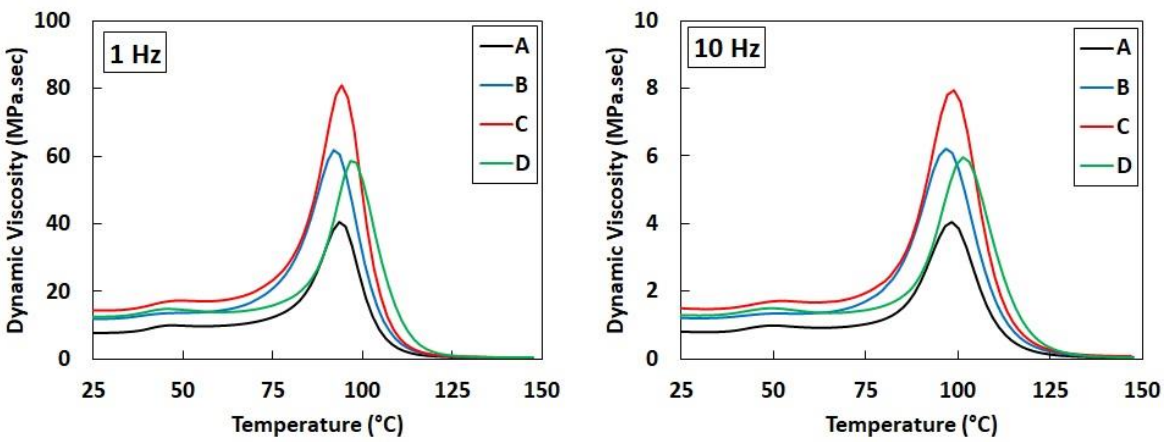

Fig.8 *Dynamic viscosity graphs for two different frequencies.*

The dynamic viscosity values for all samples are presented in Fig.9. Except specimen type C, an inverse relation between dynamic viscosity and damping value measured in vibration tests is found.

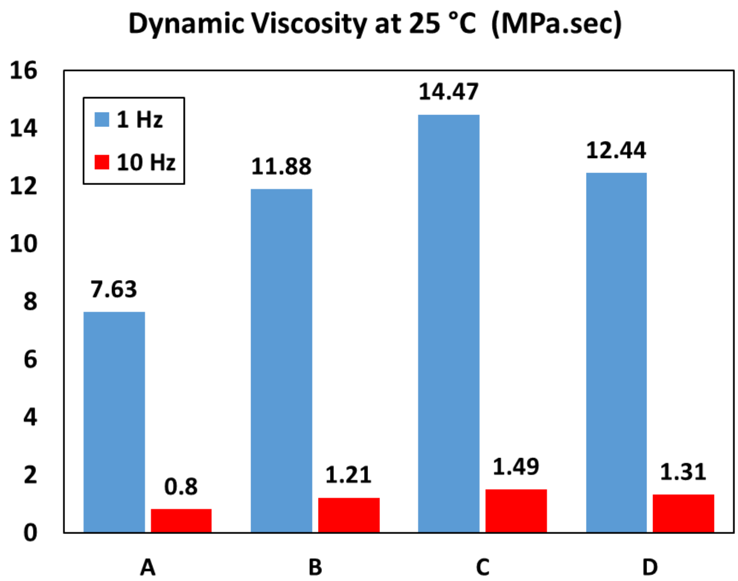

Fig.9 *Dynamic viscosity values for different samples.*

3.3 Mechanical properteis

The flexural stiffness of each lay-up measured by 3dB test is presented in Fig.10. Configuration A, with all UD flax plies, has the lowest flexural stiffness where configuration D, with two carbon plies in outer layers has the highest. Considering the number of carbon layers, configuration B has the highest. However, its flexural stiffness is 2.3 MPa lower than specimen type D with less carbon layers.

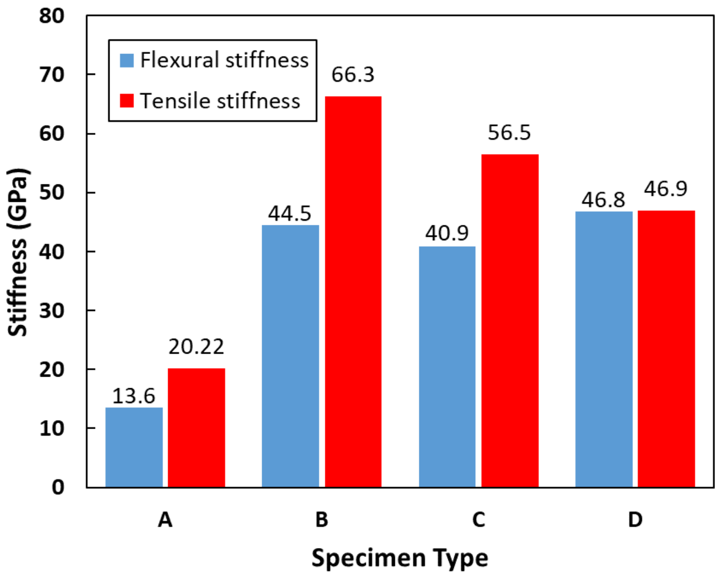

Fig.10 *Flexural and tensile stifness for all configurations.*

The extentional moduli are calculated using equation (4) and are shown in Fig.10. As expected, this property is proportional to the number of carbon layers. Comparing configurations B with C, shows that by sacrificing 8.1% flexural stiffness, an increase of 34% damping ratio was achieved in the second vibration mode. However, the most interesting result is found for sample D which contains the lowest number of carbon plies. Both the flexural stiffness and damping ratio of this sample are higher than configuration B. This shows that a hybrid composite can be stacked in a way that with higher flax fibre content, not only the damping property is enhanced, but also the flexural stiffness is improved. However, since the longitudinal stiffness could not be monitored, it can be beneficial to apply these in structures sensitive to bending, rather than longitudinal loading.

4. Conclusions

The influence of various stacking sequences on the damping behaviour of four different sets of flax and flax/carbon reinforced hybrid epoxy composites was investigated using vibration and dynamic mechanical analysis. The results from both tests (vibration and DMA) show that the damping properties are highly influenced by the location of each individual layer and the number of flax layers. In addition to these two parameters, the local position of the flax layer inside a group of carbon layers also plays a significant role in determining the damping behaviour as well as overall mechanical performance. However, the dominant damping mechanism is found to be different in each vibration mode. Three-point bending tests were carried out to correlate between the mechanical and damping properties of the hybrid composite laminates. For some specific configurations with sacrificing only 8.1% loss in flexural stiffness, an increase of 34 % in damping ratio was achieved. More interestingly, a lay-up with higher content of flax was shown to have higher damping properties attributed to the morphological structure of flax fibre. The lightweight hybrid composites developed in this study can be used in various advanced applications including marine, automotive and wind turbine where enhanced mechanical performance and damping properties are important.

The implications of this study lie in the development of hybrid composites based on renewable flax fibre hybridised with conventional carbon fibre taking the benefit of synergic effects.the results can be utilised to design components which go under the vibration damping loading scenarios.

CRediT authorship contribution statement:

SH Dashatan: Original Draft Preparation, Testing, Editinng, **M Sit:** Testing, Writing, Editing. **Z Zhang**: Conceptulisation, Funding Acquisition, Supervision, Writing, Editing. **E Grossmann**: Conceptulisation, Funding Acquisition, Supervision, Writing, Editing. **J Millot:**

Testing, Writing, Editing, **Y Huang**: Testing, Editing. **HN Dhakal:** Conceptulisation, Funding Acquisition, Supervision, Writing, Review and Editing.

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