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Effect of hybrid composite structure and environmental aging on dynamic properties

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ABSTRACT

Natural fibres, particularly flax, are gaining attention as sustainable alternatives to synthetic reinforcements due to their low density, biodegradability, and reduced environmental impact. Their relatively high damping capacity makes them attractive for vibration-sensitive applications; however, their susceptibility to environmental conditions and lower thermal stability require further investigation. This study examined the effect of laminate configuration and environmental aging on the dynamic behaviour of flax, carbon, and flax–carbon hybrid laminates with a stacking sequence [0/45/–45/90] s. Five configurations were analysed, differing in the placement of carbon layers within the laminate. Specimens were subjected to accelerated aging through thermal shocks and UV radiation. Dynamic tests were performed using an electromagnetic shaker, with frequency ranges selected to capture the first two resonance modes. Measurements were conducted in the initial state and after each aging procedure. The results indicate that the location of carbon plies significantly influences both natural frequencies and vibration amplitudes. Among all configurations, the hybrid configuration with carbon layers at 0° exhibits the highest stiffness – a 36% increase compared to the flax configuration and a 29% increase compared to the carbon configuration. The highest amplitude values were also observed for this hybrid configuration. Environmental exposure generally reduces amplitudes, suggesting changes in effective damping. After both aging processes, a significant decrease in vibration amplitude was observed for all configurations – ranging from approximately 20% to 75%, depending on the laminate configuration and type of aging. In contrast, the effect of aging on beam stiffness is limited; for most configurations, changes in stiffness within the range of ±1–7% were observed.

Keywords: flax, carbon, hybrid composites, dynamic performance, resonance zone.

INTRODUCTION

In recent years, there has been a dynamic increase in attention to composite materials in many industries. Composites are characterised by a unique combination of low weight and high strength, which makes them extremely attractive in the structures where it is important to reduce weight while maintaining adequate durability and resistance to loads, including dynamic loads [1, 2]. In response to the challenges of the global economy, including the reduction of environmental pollution, increased energy efficiency, and the implementation of sustainable development policies, there is a growing trend towards materials based on natural resources that can potentially replace traditional synthetic fibres, such as glass or carbon fibre [3, 4]. From this perspective, composite materials reinforced with natural fibres, as well as hybrid systems combining natural and synthetic fibers, are becoming the subject of intensive research.

Natural fibres, such as flax, hemp, or jute fibres have many advantages that make them a competitive choice compared to traditional fibres used in laminate production. They are characterised by low density, are biodegradable, low-cost and easily available, while their production consumes less energy and generates a reduced carbon footprint [5, 6]. An additional benefit of natural fibres is their relatively good vibration damping capacity, which makes them interesting for the dynamic applications where energy dissipation and vibration reduction are important [7, 8]. On the other hand, natural fibres have some limitations – they have lower strength and stiffness than glass or carbon fibres, are sensitive to moisture, and have lower thermal resistance [9]. These disadvantages result in challenges to their widespread use in high-performance engineering applications.

An essential aspect of composite design must be to consider the impact of the external environment on the properties of the material, because every real object, depending on its intended use, is exposed to various external factors. Environmental conditions such as moisture absorption, temperature shocks, UV radiation, and chemical exposure may lead to degradation of the matrix and fibre-matrix interface, resulting in changes in stiffness, damping and dynamic response of composite structures [10, 11]. Natural fibre composites typically offer better vibration damping but lower stiffness, while synthetic fibre composites offer high stiffness at the expense of vibration damping [12, 13]. The most popular fibres used in laminates and the connection between their stiffness and damping are shown in Figure 1. Environmental aging typically leads to a decrease in stiffness and an increase in vibration damping due to matrix plasticisation and deterioration of interlaminar bonds [14]. Due to the characteristic of natural fibres and their sensitivity to external conditions, it is extremely important to evaluate the impact of environmental aging on the properties of natural and hybrid composites.

This would allow for a detailed assessment of the properties of these materials and their potential applicability in the design of practical engineering structures that are exposed to external conditions.

A solution that can combine the advantages of natural fibres with the high strength of synthetic fibres is offered by hybrid composites. These types of materials combine two types of reinforcement – natural and synthetic – in a single matrix, which results in a good compromise between low weight, environmental benefits, and mechanical properties [15, 16]. This makes it possible to design materials that are durable, resistant, and more eco-friendly. These types of composites are particularly interesting in the dynamic applications where a combination of vibration resistance, energy absorption capacity, and structural stability under fluctuating loads is required. In this study, flax-epoxy and carbon-epoxy laminates, as well as three hybrid flax-carbon-epoxy configurations, were examined in order to compare the dynamic characteristics of natural and synthetic composites. The samples were also exposed to environmental aging – UV radiation and thermal shocks – to determine the impact of external factors on these materials.

Object of the study

The tested structures were composite beams with various material compositions. Five configurations were used for the tests: K1, K2, K3, K4, and K5. All had the same symmetrical layer arrangement [0/45/-45/90]s, but the individual configurations were different in terms of the materials used to make the individual layers of the laminate.

Configuration K1 was made fully of flax laminate, K2 fully of carbon laminate, while K3, K4, and K5 combined flax and carbon layers, resulting in hybrid configurations. Epoxy resin was used as a matrix for all samples. For each of the K1-K5 configurations, 9 or 10 samples were tested (depending on the type of configuration). Each beam was 200 mm long and 20 mm wide, while the wall thickness varied depending on the configuration due to the different thicknesses of the individual flax and carbon layers. The details of each configuration are presented in Table 1.

The composite laminates were manufactured using unidirectional (UD) epoxy prepreg with an areal density of 150 g/m². The reinforcement

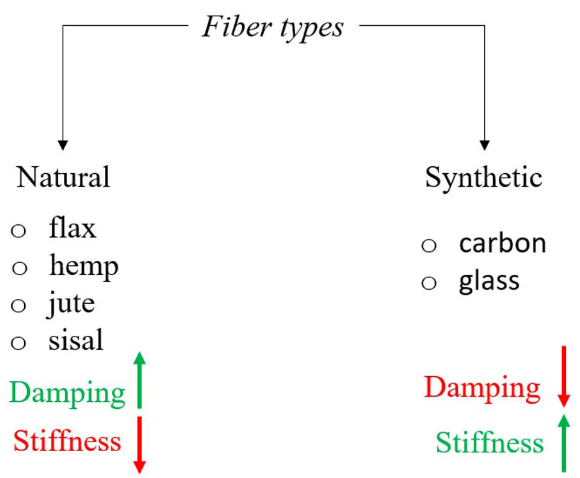

Figure 1. Classification of main fibre types used in laminates and their influence on damping and stiffness (arrows indicate qualitative trends in damping and stiffness)

Table 1. Symbols for individual profile configurations

Symbol	Configuration	Average wall thickness [mm]
K1	[0/45/-45/90]s – all layers made from flax	2.11
K2	[0/45/-45/90]s – all layers made from carbon	1.54
K3	[0/45/-45/90]s – layers 0° made from carbon, the rest from flax	1.97
K4	[0/45/-45/90]s – layers 45° made from carbon, the rest from flax	1.97
K5	[0/45/-45/90]s – layers -45° made from carbon, the rest from flax	1.97

was composed of continuous fibres aligned in a single direction, without any weave. The prepreg material consisted of fibres pre-impregnated with epoxy resin. Individual plies were cut and arranged according to the required laminate configurations. The laminates were cured in an autoclave under elevated temperature and pressure, within a temperature range of 80–140°C, ensuring low porosity. After curing, the composite plates were cut to obtain the samples with final dimensions using a three-axis CNC milling process. Diamond-coated milling cutting tools were used to minimise delamination and ensure as high-quality edges as possible.

Due to the different components of the individual samples, clear differences can be observed between the carbon fibre samples and the flax and hybrid samples. The edges of the carbon laminate are smooth, while the edges of the hybrid samples and fully flax samples are frayed and irregular. This is a direct result of the different nature of the fibres. Carbon fibres are characterised by high stiffness and brittleness, which gives them smooth, sharp edges. Flax fibres perform differently: they are softer, more malleable, and composed of many microfibers, which causes their edges to be frayed and irregular. It would appear that these differences in edge morphology may influence the dynamic response of the samples, particularly in terms of vibration damping and energy dissipation. The frayed edges of the flax and hybrid laminates may enhance friction and micro-sliding mechanisms, resulting in higher damping compared to carbon fibre laminates. Figure 2 shows sample specimens for each configuration.

In dynamic tests, the first and second modes of vibration were analysed, as they represent the dominant part of the structure's vibration energy and are most often excited under operating conditions. The first vibration mode represents the overall stiffness and mass of the system, while the second mode captures more complex deformations and the influence of material distribution and damping properties. Analysis of these modes provides a reliable assessment of dynamic characteristics while reducing measurement uncertainty associated with higher modes [17].

Using a single layer layout configuration ([0/45/-45/90]s) for all samples allowed for a representative comparison of flax and carbon laminates and an extensive analysis of hybrid arrangements – determining how a modification of a specific layer material impacts the dynamic response. Figure 3 shows the laminate layer structure used for testing and the analysed vibration modes.

Laboratory stand for dynamical behaviour

To test the beams for dynamic loads, the electromagnetic shaker system, TIRAvib 50101, was used. The beam was mounted in the shaker holder in a way that the free end was 150 mm long (50 mm was mounted in the holder). To obtain comparable beam vibration responses, excitations were applied using a sinusoidal input signal with a constant level corresponding to a gravitational acceleration of 1 g (g is taken as g = 9.81 m/s^2). The behaviour of the composite beam was recorded using two acceleration sensors, which were configured for the assumed frequency range. The use of two sensors (at the end and along the length of the beam) made it possible to read the maximum amplitudes for the first and second modes of vibration in the flexural direction of the beam. The third sensor was installed on the holder of the shaker, which monitored the reference signal. The specific items of the test stand are shown in Figure 4.

Environmental aging

To determine the impact of selected environmental factors on the dynamic properties of flax, carbon, and hybrid laminates, two independent types of aging tests were conducted. The first involved subjecting the samples to thermal

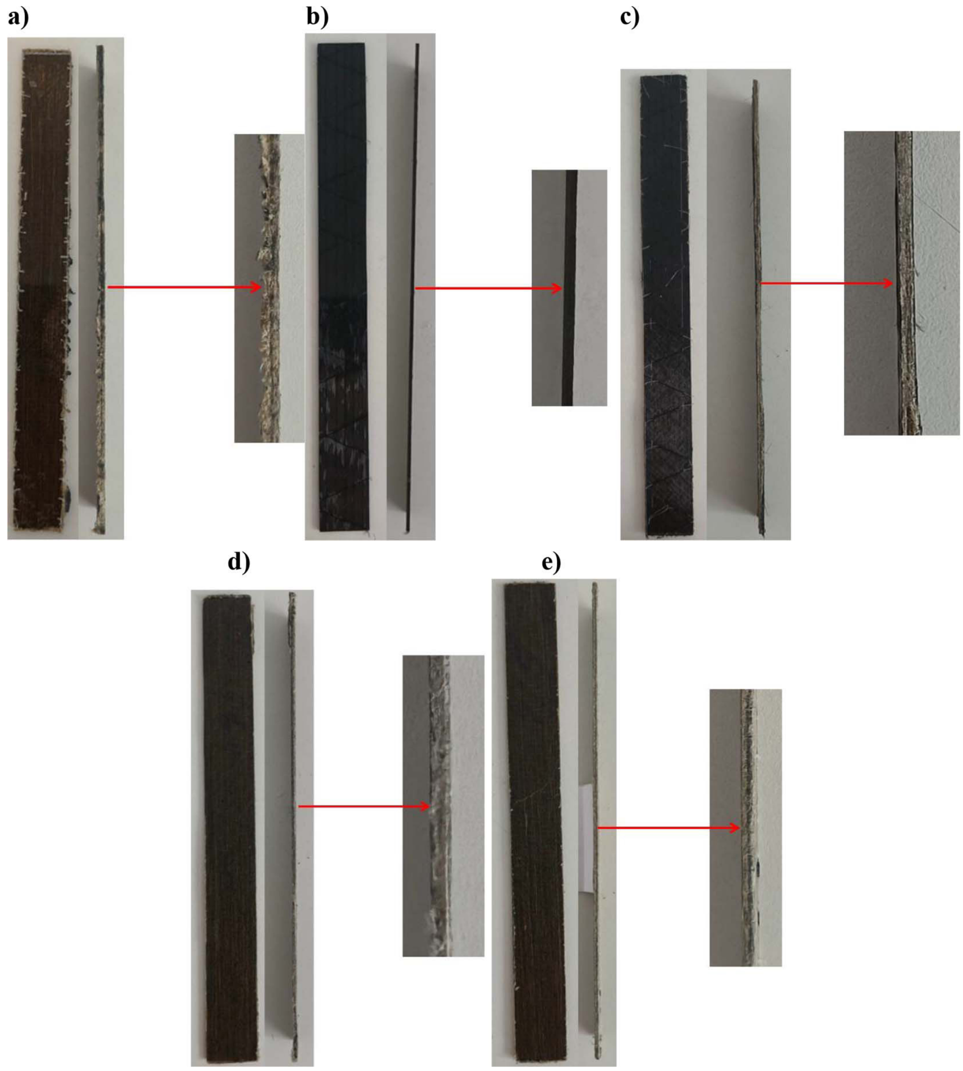

Figure 2. Structure of representative samples provided for the experiment: (a) K1, (b) K2, (c) K3, (d) K4, (e) K5

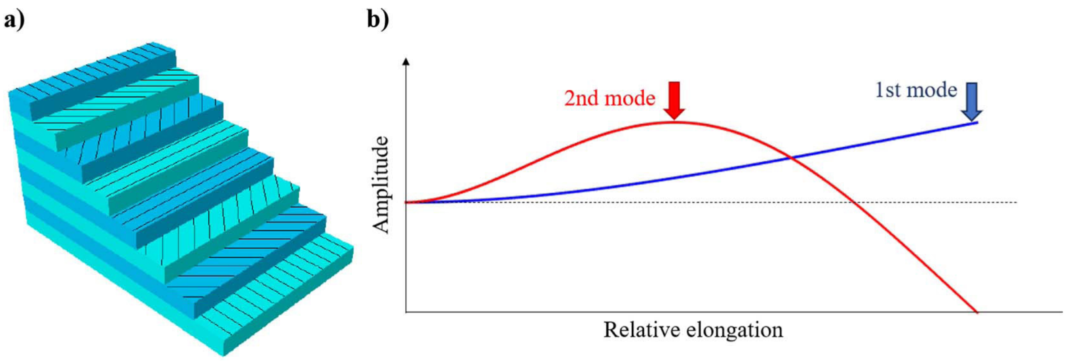

Figure 3. Schematic diagram of the beams examined: (a) laminate layer arrangement [0/45/-45/90]s, (b) analysed vibration modes with indication of maximum vibration amplitudes

shocks (thermal conditioning), while the second involved exposure to UV radiation. For every configuration, 5 specimens were subjected to thermal shocks and 4 or 5 specimens (depending on the configuration) were subjected to UV radiation. Thermal conditioning was performed in a T/60/V2 Weisstechnik chamber (Weiss Umwelttechnik GmbH, Heuchelheim, Germany), with tests

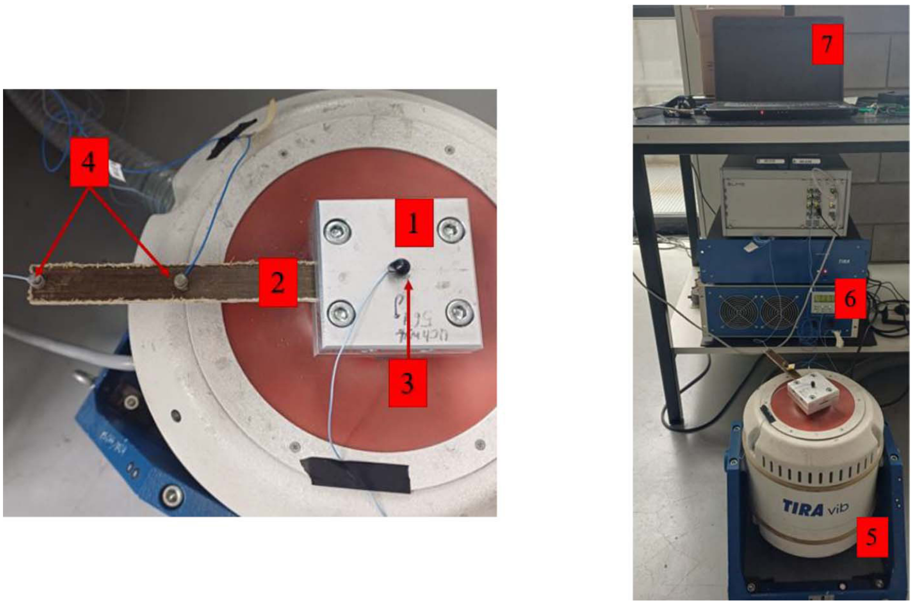

Figure 4. Laboratory stand equipment: holder (1), beam (2), reference sensor (3), system response measuring sensors (4), electromagnetic shaker system (5), amplifier (6), computer with software LMS Test.Lab (7)

performed in the range from −50 °C to +50 °C. The samples were exposed to both low and high temperatures for 30 minutes. The change in conditions between high and low temperatures took place within 6 seconds. The second aging process of the material, under the impact of UV radiation, was conducted in a QUV/SPRAY/RP accelerated atmospheric aging chamber. The source of radiation was UV-A 340 lamps, which simulate daylight. The parameters during UV radiation were as follows: temperature 60 °C, radiation intensity 0.83 W/m². For both tests – thermal shocks and UV radiation – the conditions simulated a two-month exposure to these effects. The devices used to carry out the sample aging processes are shown in Figure 5.

Experimental research

For each configuration, presented in Figures 6–9 a series of amplitude–frequency response measurements was performed. The obtained curves exhibited high repeatability both in terms of the locations of the resonance

a) b)

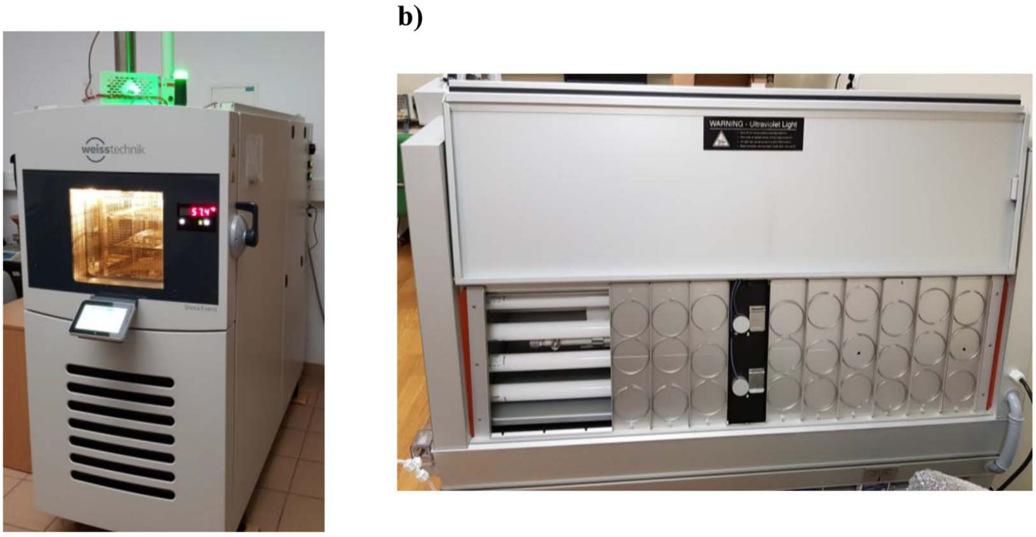

Figure 5. The chambers used to conduct the sample aging processes: (a) thermal shock chamber, (b) atmospheric aging chamber (UV aging tests)

frequencies and the amplitude values. Therefore, a representative curve was selected from the recorded characteristics based on the consistency of the main peak locations and amplitude levels with the remaining measurements. The selected characteristics correspond to the median (typical) behaviour of the system and they form the basis for further analysis.

The amplitude–frequency characteristics presented in Figure 6 illustrate clear differences in the dynamic response between flax, carbon, and hybrid laminates. In the unaged condition (Figure 6a), the carbon laminate (K2) exhibits higher natural frequencies compared to the flax laminate (K1), which reflects the higher stiffness of carbon fibres. At the same time, the flax laminate shows lower

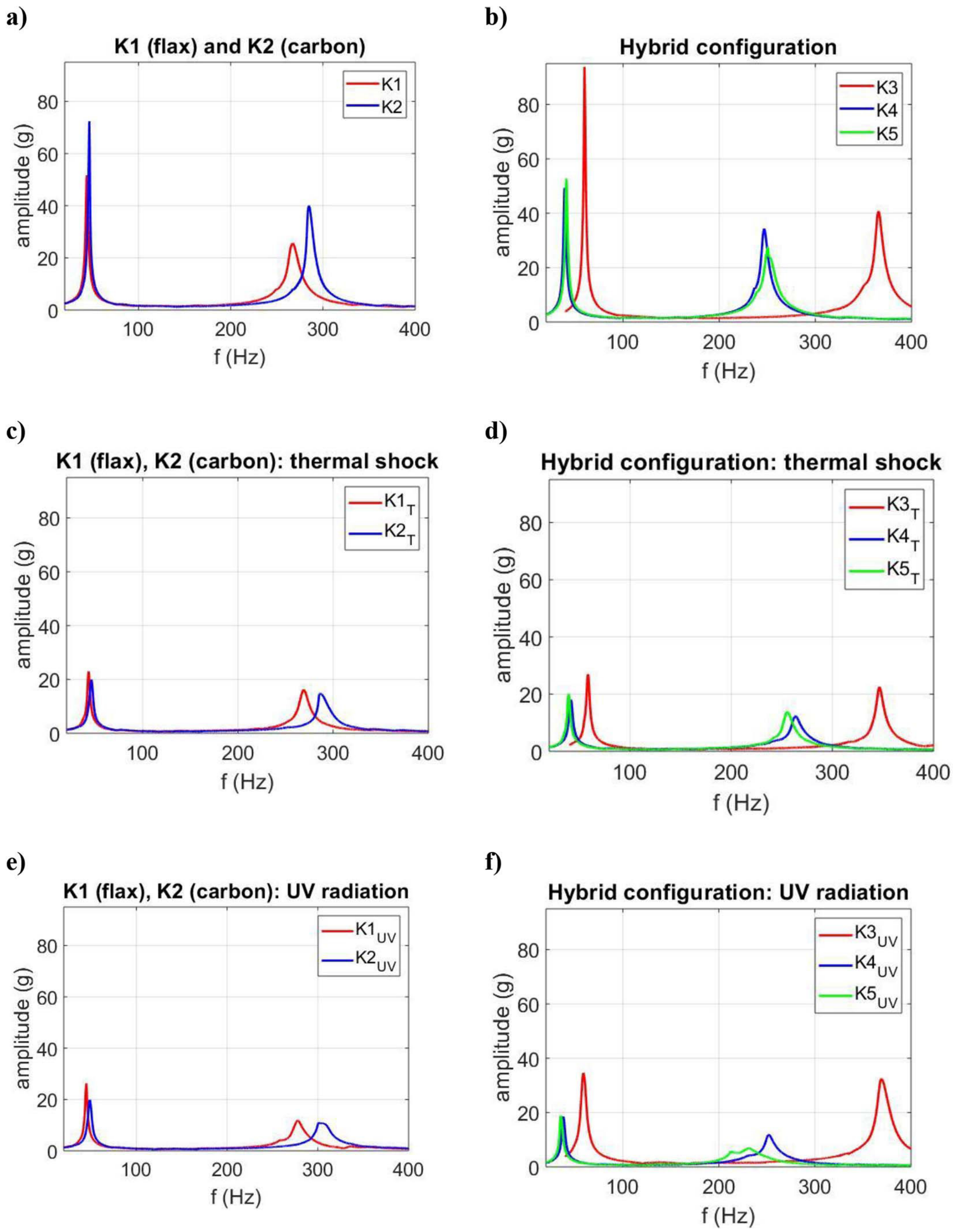

Figure 6. Response amplitude versus excitation frequency at $A_{exc}=1\,g$ for: (a) comparison of flax and carbon composites; (b) hybrid composites; (c) comparison of flax and carbon composites after thermal shocks; (d) hybrid composites after thermal shocks; (e) comparison of flax and carbon composites after UV radiation; and (f) hybrid composites after UV radiation

resonance frequencies and generally lower peak amplitudes, which is consistent with its lower stiffness and higher intrinsic damping capacity.

The hybrid configurations (Figure 6b) demonstrate intermediate behaviour between the fully flax and fully carbon laminates, confirming that the dynamic response can be effectively tuned by modifying the material composition of selected layers. Among the hybrid variants, noticeable differences in peak amplitudes and slight shifts in resonance frequencies can be observed, indicating that the position of carbon plies influences both stiffness distribution and energy dissipation mechanisms. When analysing the resonance frequencies of the unaged samples, the hybrid configuration K3 exhibits the highest values for the first and second resonance ranges, at 60.1 Hz and 365 Hz, respectively. When compared to the all-flax configuration (K1), these values are approximately 36% higher, while compared to the all-carbon configuration (K2), they are approximately 29% higher. The amplitude values are also highest for K3, reaching 93.5 g for the first resonance and 40.7 g for the second resonance. When comparing this to the other configurations, the deviation depends on the resonance range. Generally, greater differences were observed for the first resonance - 82% compared to K1 and 30% compared to K2. For the second resonance, the differences were 59% (K1) and 2% (K2), respectively.

After thermal shock aging (Figure 6c and Figure 6d), a general reduction in resonance amplitudes is observed for all laminate types. This effect is more pronounced in carbon and hybrid laminates, suggesting increased internal damping, possibly due to microstructural changes in the matrix and at the fibre–matrix interface. Slight shifts in resonance frequencies may also indicate changes in effective stiffness caused by thermal cycling.

A similar trend is observed after UV exposure (Figure 6e and Figure 6f), where all configurations show reduced peak amplitudes compared to the initial state. The decrease in amplitudes suggests enhanced damping due to matrix degradation or interfacial weakening. The flax laminate appears less sensitive to environmental aging, while carbon and hybrid laminates show more noticeable changes, confirming their higher susceptibility to environmental factors.

Dynamic response with detailed comparison of individual configurations is provided in the figures. The detailed comparisons presented in Figures 7–9 allow for a clearer interpretation of how environmental aging affects individual laminate configurations and provide further insight into the governing physical mechanisms. Figure 7 shows the resonance curves for the fully flax (K1) and fully carbon (K2) laminates before and after environmental aging. For the flax laminate (Figure 7a), both thermal shocks and UV exposure lead to a noticeable reduction in resonance amplitudes, indicating an increase in effective damping. This behaviour is likely associated with microcracking of the epoxy matrix, degradation of the fibre–matrix interface, and possible microstructural changes within the natural fibres. In comparison, the carbon laminate (Figure 7b) exhibits a greater decrease in vibration amplitude after both aging processes. This is most likely due to matrix degradation and weakening of the fibre–matrix interface under thermal shocks and

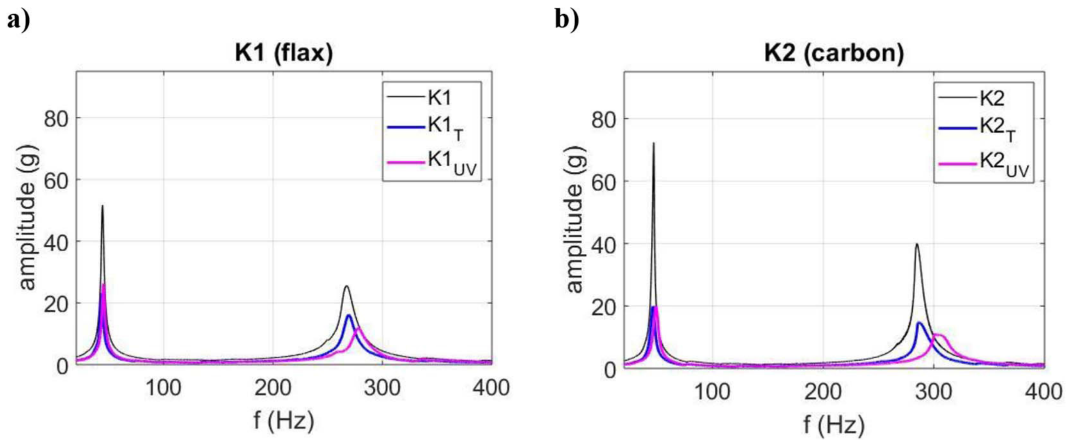

Figure 7. Response amplitude versus excitation frequency f at $A_{exc}=1\,g$ for composite beams before and after aging under thermal shocks (T) and UV radiation (UV), shown for flax fibre–reinforced (a) and carbon fibre–reinforced configurations (b)

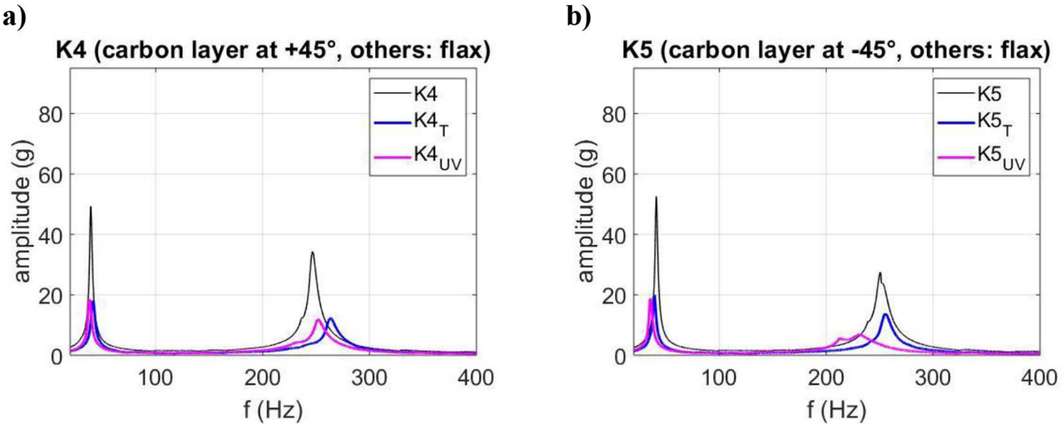

Figure 8. Response amplitude versus excitation frequency at Aexc = 1g for the composite both before and after aging under thermal shocks (T) and UV radiation (UV), shown for hybrid fibre-reinforced composite configurations consisting of flax layers with one carbon layer oriented at +45° (a) and -45° (b)

UV exposure, leading to microcrack formation and increased damping. In contrast, the flax laminate shows a smaller relative change in dynamic properties, which can be attributed to its higher initial damping and more compliant structure, allowing for more effective energy dissipation without significant loss of structural integrity. Figure 8 presents the hybrid configurations with carbon layers oriented at +45° (K4) and −45° (K5). In both cases, environmental aging leads to a reduction in resonance amplitudes, confirming increased damping due to microdamage and interfacial degradation. However, the magnitude of changes remains moderate, indicating that off-axis carbon layers contribute less to global bending stiffness and therefore the dynamic response is more strongly influenced by the surrounding flax layers.

The similarity of trends for K4 and K5 suggests that the sign of the off-axis orientation has a limited effect on global dynamic properties, while the presence of carbon layers still improves structural stability compared to the fully flax laminate. Figure 9 shows the configuration with carbon layers oriented along the beam axis (K3). This configuration exhibits the highest resonance amplitudes among the hybrid laminates, both before and after aging, indicating the strongest contribution of carbon plies to bending stiffness when aligned with the principal deformation direction.

Although environmental aging leads to a reduction in amplitudes, the changes observed in the hybrid laminate are less pronounced than in the fully carbon laminate but more significant than in the flax laminate, indicating an intermediate sensitivity to aging effects. This suggests that

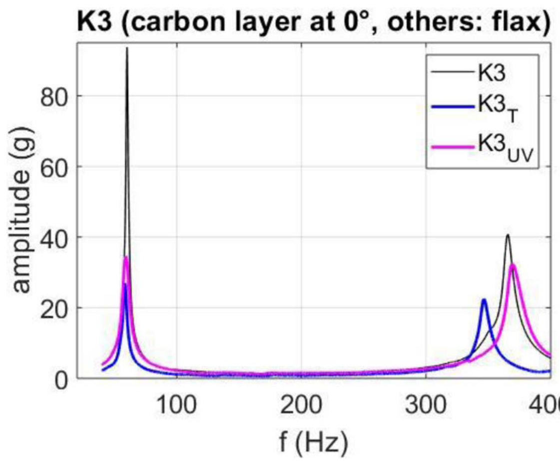

Figure 9. Response amplitude versus excitation frequency at Aexc = 1g for the composite both before and after aging under thermal shocks (T) and UV radiation (UV), shown for hybrid fibre-reinforced composite configurations consisting of flax layers with one carbon layer oriented at 0°

the incorporation of carbon layers aligned with the main load direction enhances stiffness, while the presence of flax layers contributes to maintaining more stable damping characteristics under environmental exposure.

Tables 2 and 3 summarise the values for resonance frequency and vibration amplitudes as well as the percentage changes for these parameters after the environmental aging for all configurations. The quantitative results indicate that resonance frequencies exhibit relatively small variations for all configurations, generally within ±7%, confirming that environmental aging has a limited effect on the global stiffness of the laminates. In contrast, vibration amplitudes are

Table 2. Resonance frequencies of samples: non-aged, after thermal shock, and after UV exposure, as well as the percentage changes after aging compared to non-aged samples

Configuration	Before aging [Hz]	After thermal shocks [Hz]	After UV exposure [Hz]	Change after thermal shocks [%]	Change after UV exposure [%]
1st resonance range					
K1	44.1	43.3	44.7	-1.81	1.36
K2	46.7	45.9	48.9	-1.71	4.71
K3	60.1	58.5	58.7	-2.66	-2.33
K4	39.2	41.5	37.9	5.87	-3.32
K5	41.1	39.4	35.7	-4.14	-13.14
2nd resonance range					
K1	267.3	269.3	277.9	0.75	3.97
K2	285.0	286.2	301.8	0.42	5.89
K3	365.4	346.4	369.7	-5.20	1.18
K4	246.5	263.5	252.4	6.90	2.39
K5	250.3	255.6	231.5	2.12	-7.51

Table 3. Vibration amplitudes for samples: non-aged, after thermal shocks, and after UV exposure, as well as the percentage changes after aging compared to non-aged samples

Configuration	Before aging [g]	After thermal shocks [g]	After UV exposure [g]	Change after thermal shocks [%]	Change after UV exposure [%]
1st resonance range					
K1	51.4	22.8	26.1	-55.64	-49.22
K2	72.4	19.8	19.7	-72.65	-72.79
K3	93.5	26.8	34.6	-71.34	-62.99
K4	49.2	18.0	18.5	-63.41	-62.40
K5	52.6	19.8	18.8	-62.36	-64.26
2nd resonance range					
K1	25.6	16.2	11.8	-36.72	-53.91
K2	39.9	14.7	10.8	-63.16	-72.93
K3	40.7	22.4	32.4	-44.96	-20.39
K4	34.2	12.3	11.8	-64.04	-65.50
K5	27.2	13.7	6.8	-49.63	-75.00

significantly reduced for all configurations and aging conditions, with decreases ranging from approximately 50% to over 70% in the first resonance range. In the second resonance range, amplitude reductions remain substantial, but exhibit a wider variability (from about 20% to 75%), indicating a stronger dependence on laminate configuration and aging type.

Among the analysed materials, the carbon laminate (K2) shows the largest amplitude reductions about 63–72%, while the flax laminate (K1) exhibits the smallest changes about 36–55% - depending on the aging type and resonance range. These values confirm that flax laminate is more resistant to environmental aging than carbon laminate.

CONCLUSIONS

The conducted experimental study demonstrated that the dynamic response of composite beams strongly depends on the type of reinforcement and laminate configuration. Carbon fibre laminates exhibit higher natural frequencies, confirming their higher stiffness, while flax laminates show lower resonance frequencies combined with higher damping capacity.

Hybrid laminates present intermediate dynamic behaviour, indicating that their properties can be effectively tailored by modifying the position and orientation of carbon layers within the laminate. The configuration with carbon layers aligned along the beam axis provides the most significant stiffness contribution among all variants – including hybrid, full-flax and full-carbon configurations.

Environmental aging in the form of thermal shocks and UV radiation leads to a general reduction in vibration amplitudes for all tested configurations, indicating an increase in effective damping. The values are significantly reduced for all tested configurations, compared to non-aged samples, and vary more widely, from approximately 20% to 75%, depending on the configuration and aging type. These changes are more pronounced in carbon and hybrid laminates, which confirms their higher sensitivity to environmental conditions compared to flax laminates. In contrast, the changes in resonance frequencies remain relatively limited for most configurations, typically within approximately ±1-7%, with a maximum decrease of 13.14% observed after UV exposure for hybrid configuration K5. The results indicate that environmental exposure mainly affects damping-related mechanisms, while global stiffness remains relatively stable, particularly in laminates containing flax reinforcement. Overall, the study confirms that the dynamic performance of hybrid composites can be controlled through appropriate laminate architecture, enabling a balance between stiffness and vibration damping while maintaining acceptable environmental resistance.

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