Mechanical and dynamic performance of woven flax/E-glass hybrid composites

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Abstract

Flax composites demonstrate superior damping properties to conventional fibres. These materials are already being utilised in some products but the mechanical properties they exhibit are too low for many structural applications. Hybridization of flax with higher strength fibres has been shown to yield materials, which balance damping and load carrying capabilities alongside improved environmental credentials for flax/carbon hybrids. However, the most used composite material is E-glass but the current literature does not facilitate the prediction of damping properties for these hybrid composites, where it is expected that they will behave differently due to the difference in material properties. The woven flax and E-glass fibres specimens embedded with epoxy resin are manufactured via resin infusion to understand the damping and mechanical properties possible from an industrial process and the dominant factors affecting them, rather than the relationships between individual variables and these properties. These experiments allow the hybrids to be profiled for the first time and it is observed that hybridization of flax and E-glass fibres results in an increase in damping, from 1.97 % to 2.63 % for the best hybrid, especially when the flax plies are placed on the outer skin, however the compromise in tensile properties is significant, from 473.28 MPa to 166.53 MPa.

Keywords: A. Flax composites, Hybrid composites, Textile Composites, B. Vibration, Mechanical properties

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1. Introduction

Vibrations in structures are a critical concern for engineers. This is especially the case in large structures such as yachts and aircraft where the presence of vibrations may cause undesirable consequences such as structural failure, noise and discomfort. For some applications, the vibration damping can be deployed without considering its strength or shape change under loading. However, for many structures this is not the case and the composite material properties must be a compromise between stiffness and vibration damping properties [1].

Flax fibres have been proposed for a number of applications as they exhibit excellent damping properties. Duc et al. [2] performed experiments which show that unidirectional flax fibres exhibit a 133 % increase in damping compared to E-glass fibre composite. This increase is attributed to the friction in the cell walls between the cellulose and hemicellulose whilst Guen et al. [3] links the excellent damping properties of flax to the friction between the cellulose fibrils and the polysaccharide's matrix, e.g. hemicellulose and pectin, in the fibre bundles. In addition to the damping properties flax fibres are also a more sustainable option and they have a low carbon footprint during production with 9.55 MJ/kg for flax fibre mat compared to 54.7 MJ/kg for E-glass fibre mat [4]. However, there are concerns about their strength and stiffness. Recent research [5], [6] and [7] shows that flax fibre composites demonstrate much lower mechanical properties than E-glass fibre composites leading to high deflections, due to their low stiffness and low strength [8].

To improve the mechanical properties of flax composites hybrids have been used by incorporating higher strength fibres, such as carbon. Guen et al. [9] characterised the damping-tensile modulus relationships in twill flax/carbon hybrid composites manufactured via the compression moulding method. The authors report that the damping coefficient of flax reinforced composites is four times higher than that of carbon reinforced composites but the addition of flax leads to a lower strength material, the tensile strength of the $[0_C/90_C/0_C/90_C/0_C]$ layup and the $[0_C/90_C/0_F/90_C/0_C]$ layup are 516.4 and 329.9 MPa, respectively. Hybridization for damping is evaluated by Assarar et al. [10] showing the effects of stacking sequences on the damping properties of flax-carbon twill epoxy composites. A noticeable increase in damping is observed when the flax layer is on the outside of the composite, however little contribution to damping is made when the flax layer is employed in the middle of the composite. Figure1 reproduces these findings showing the trade-off between the tensile strength and the damping ratio of flax/carbon hybrid samples. The tensile strength of the flax/carbon hybrid samples is between that of the FFFFF and the CCCCCC layups but the damping properties are shown to be highly dependent on the position of the flax fibres. Whilst the data available for flax/carbon shows substantial differences for different flax/carbon materials there are no papers documenting the dynamic behaviour of E-glass/flax hybrids. Due to the difference in material properties between E-glass and carbon there is an expectation that there will be a difference in behaviour between E-glass/flax hybrids and carbon/flax ones, meaning that a prediction of the behaviour is not possible from the current data. Therefore, this paper investigates this difference and compares it to the mechanical properties. The specimens are manufactured via resin infusion providing realistic characteristics, such as volume fraction and void content. This allows characterisation of the damping and mechanical properties from a realistic process and to determine the dominant factors affecting them. While the covariation in properties provides realistic mechanical and damping properties it is not possible to derive the relationships between the individual variables and these properties.

2. Experimental

2.1. Materials and manufacturing

The flax fibres considered for manufacture are FLAXPLY BL200, woven cross-ply [0°/90°] with a mean yarn tensile modulus of 11.4 ± 2.11 GPa [7] and a density of 200 g/m^2 from Lineo, Belgium. The E-glass fibres are WRE581T 2x2 twill woven roving [0°/90°] with a density of 590 g/m^2 from Gurit, UK. The matrix system is the Gurit Prime 20 LV Epoxy resin and Prime hardener, with a suggested cured system tensile modulus of 3.5 GPa from the material data sheet. Six laminates of different stacking sequences are fabricated using a resin infusion method, namely:

$[G_6]$, $[G_2/F]_s$, $[G/F/G]_s$ $[F/G/F]_s$, $[F_2/G]_s$ and $[F_6]$, where F represents a flax layer and G an E-glass layer, shown in Figure 2. 1 bar of vacuum was applied during the manufacturing process. Once the resin infusion process is completed the laminate is left to cure at an ambient temperature of 20 °C for 24 hours. This process is followed by the recommended post curing schedule with the laminates placed into an oven at 65 °C for 7 hours.

The theoretical and the experimental densities are obtained to estimate the void content of the samples. The theoretical density is obtained as per ASTM D2734-09 using both the weight fractions and the densities of the constituents. The experimental density of the samples is determined through a water displacement method in accordance with BS EN ISO 1183-1:2012 and compared to the theoretical value, giving the void content. The stacking sequences and the final physical properties of the composite specimens are presented in Table 1.

Table 1: Stacking sequences and manufacturing quality of the composite samples.

Laminates	Stacking sequences	Thickness (mm)	Experimental density (g/cm^3)	Void content (%)
$[G_6]$	GGGGGG	3.03	1.73	1.68
$[G_2/F]_s$	GGFFGG	3.35	1.48	1.63
$[G/F/G]_s$	GFGGFG	3.46	1.46	2.96
$[F/G/F]_s$	FGFFGF	3.44	1.41	2.60
$[F_2/G]_s$	FFGGFF	3.44	1.42	2.75
$[F_6]$	FFFFFF	3.40	1.17	2.36

Some variation in the thickness is shown between the specimens due to the manufacturing method and change in volume fraction between the fibre types. However, the effect of specimen thickness on damping loss factor was investigated by Crane et al. [11] using graphite/epoxy composites. It is reported that there is a little influence from the thickness on the damping properties of the composites. The source of this minimal contribution to the damping is attributed to the thermoelastic damping which is due to the cyclic heat flow which accounts for all the energy dissipation in metals whilst the influence of this phenomenon is too little to be taken into account in composites [11, 12]. The variation between the extreme thickness values is around 10 % in this study and therefore the effect of thickness on the damping of the samples is neglected. The void content of the composites show a good manufacturing quality having a void content of between 1.63 % and 2.96 %. This demonstrates an acceptable level of quality as the void content of the composites is below the void content, 4 %, where the void content starts to have an effect on the tensile properties of plant fibre composites [13].It is important to quantify the constituents of the samples due to the strong correlation between the fibre volume fraction and both the mechanical and damping properties.

It is important to quantify the constituents of the samples due to the strong correlation between the fibre volume fraction and both the mechanical and damping properties. The E-glass fibre content of the composites was experimentally determined by performing burn-off tests. The flax fibre content of the composites was determined using the weight content of the fibre used in the composite, as burn-off tests were not possible as the ignition temperature of the flax fibre and epoxy resin is too similar. The burn-off method was performed using three samples in an oven at 565 °C for 6 hours as per ASTM 3171-15. The volume fractions of these composite samples can be seen in Table 2.

Table 2: Fibre volume fractions of the composite samples.

	$[G_6]$	$[G_2/F]_s$	$[G/F/G]_s$	$[F/G/F]_s$	$[F_2/G]_s$	$[F_6]$
V_{fflax}	0	11.46 ±0.18	12.07 ±0.05	24.06 ±0.25	23.20 ±0.50	36.28 ±1.50
$V_{fE-glass}$	47.00 ± 0.67	26.75 ±0.41	28.17 ±0.11	14.04 ±0.14	13.54 ±0.29	0
V_{ftotal}	47.00 ± 0.67	38.21 ±0.59	40.24 ± 0.16	38.10 ±0.39	36.74 ±0.80	36.28 ±1.50

The mean volume fraction of the flax samples manufactured via a resin infusion is considerably lower than that of E-glass samples: 36.28 % and 47.00 % respectively. The flax samples also demonstrate more variability with a standard deviation of 1.50 %, which is the highest deviation among all the samples, compared to 0.67 % for E-glass samples. This difference in the fibre volume fractions is at least in part due to the yarn packing geometry of flax fibres: twisted yarns allow a maximum theoretical fibre volume fraction of 58.9 % for a quadratic arrangement of yarns whilst the maximum fibre volume fraction for the same arrangement of synthetic fibres is 78.5 % [13]. This is supported by other literature employing the resin infusion process where a flax fibre volume fraction of 24.82 % is obtained in [14] and between 32.7 % and 34.0 % is obtained in [15], and 37.24 % is obtained in [7].

The cost for the manufacturing process is also determined to allow a comparison between the different layups. It should be noted that this cost analysis is an approximation based on the cost at purchase which will vary based on time and location. For the E-glass fibres the material costs, the resin and fibre, represent a small percentage of the total cost of £34.84 at 25 %. The flax composites have a higher resin cost, almost double, and fibre cost, four times, leading to a laminate where the material costs are higher at 48 % of the total cost of £49.80. The hybrid composites fall between these costs with the cost dominated by the percentage of flax fibre used compared to the E-glass. The price of flax has been reported as cheap by [16] and [17], but is more expensive than the E-glass counterpart per meter square when it is purchased from the market. In addition it requires an increased quantity of resin, though this accounts only a small percentage of the cost and a negative impact on the environment. This high cost might reduce with economies of scale but at the current stage the cost of flax fibres in the market is not appealing.

3. Results

3.1. Mechanical properties

The manufactured composite laminates were cut into coupons for tensile testing as per ASTM D638-14: 250 mm in length and 25 mm in width. The tensile testing was carried out at 22 °C and at a relative humidity of 70 %. Five coupons for each composite sample were tested until failure under uniaxial tension at a constant crosshead displacement rate of 2 mm/min as suggested by the standard. Strain values were measured using an extensometer, Instron 2630 - 113, with a 50 mm gauge. The resultant mechanical properties are obtained as shown in Table 3. E-glass fibre specimens exhibit the highest tensile strength of 473.28 ± 4.23 MPa whilst the flax fibre specimens have the lowest tensile strength of 86.43 ± 4.39 MPa, showing a low variation of the material. Blanchard et al.[7] tested the samples manufactured using the identical fibres and epoxy used in this study and reported a tensile strength of 90.9 ± 7.18 MPa for flax samples, demonstrating similar results and confirming the quality of the manufacture and experiments. It is observed that replacing 2 plies of flax in the FFFFFF layup with 2 plies of E-glass as in the FGFFGF and FFGGFF layups increases the strength by between 48 % and 56 %, depending on the fibre volume fraction. Replacing 2 plies of E-glass in the GGGGGG layup with 2 plies of flax as in the GFGGFG and the GGFFGG layups produced a decrease in strength of between 42 % and 47 %. This is a large drop in strength for a relatively small change in the proportion of flax added to the hybrid.

Table 3: Tensile properties of the laminates at a crosshead displacement rate of 2 mm/min.

	$[G_6]$	$[G_2/F]_s$	$[G/F/G]_s$	$[F/G/F]_s$	$[F_2/G]_s$	$[F_6]$
Tensile Strength (MPa)	473.28	273.66	252.20	195.20	166.53	86.43
CoV (%)	2.05	3.40	5.06	2.40	2.41	5.08
Tensile Modulus (GPa)	34.25	24.22	23.21	13.48	12.86	8.89
CoV(%)	3.63	3.93	3.96	4.50	3.67	5.87

The coefficient of variations (CoV) of the tensile properties are also given in Table 3. The highest variation in tensile strength is seen in the FFFFFF specimens by 5.08 % and the lowest variation is in the GGGGGG specimens which vary by 2.05 % whilst the variations for the hybrid samples lie between 2.40 % and 5.06 %.

It is observed that the main failure modes for all of the samples are brittle fibre failures and fibre pull-out. However different levels of delamination are observed with the highest in the hybrid samples. When the E-glass samples fail they separate into many pieces leaving a large white area around the cross-section of the samples where the fracture occurs and broken, sharp, fibres. The flax samples do not exhibit whitening around the failure cross-section and the splinters are observed to be small and blunt after the failure.

3.2. Damping properties

Experimental modal analysis, which is the most common method for the determination of the damping properties of structures, was carried out to obtain the damping properties of the samples. The tests were carried out at 22 °C and at a relative humidity of 70 % as in the tensile testing. A fixed-free boundary condition was reproduced by clamping the samples at one end to simulate a cantilever beam where vibrations are potentially destructive. An external load was applied with an impact hammer on the samples and the response was measured by means of an accelerometer attached to the free end of each sample as illustrated in Figure 4. The accelerometer was a PCB 352C22 model, which has a sensitivity of 10.0 mV/g and a weight of 0.5 grams.

As the samples were clamped with bolts, the applied clamping torque can differ. This potential variation in the clamping torque may cause discrepancies in the frequency response function (FRFs) of the system. To investigate the effect of the torque on the clamping bolts, measurements were performed on the same sample. Each for the three samples were clamped at four different clamping torques by means of a torque wrench. The bolts are tightened to a torque of 7.75 Nm, 13.56, 31.00 and 40.68 Nm. It is observed that there is a considerable variation in the measured FRFs when the torque is set to be 7.75 Nm. However, the variations tend to be smaller as the torque is increased. There is no significant variation above 13.56, 31.00 and 40.68 Nm. Therefore, each bolt in the clamping system is tightened to a torque of 31.00 Nm.

For each stacking sequence three samples were tested. Each sample was discretized into three hitting points in the length direction and each hitting point was excited five times by a hammer. The average of the response was acquired by a Data Physics Quatro analyzer which digitalizes and processes the excitation and the response signals. Then the frequency response function of each system is identified by Signalcalc software. In principle, the FRF characterises how the samples respond to the applied forces. The FRF of a system contains the dynamic characteristics of the system that can be extracted by curve fitting. In the time domain analysis, where the acceleration time history is known, the damping ratio of a system is obtained using a logarithmic decrement, δ, which represents the rate at which the amplitude of a free damped vibration decreases. The damping ratio ζ, which is dimensionless quantity that represents how vibrations in a system decay after an impact, is shown in Eq. 1,

$$\zeta = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}}. \tag{1}$$

The logarithmic decrement, δ, is obtained using Eq. 2,

$$\delta = \frac{1}{n} \ln \frac{g_i}{g_{i+n}}, \tag{2}$$

where, n is the number of periods on which the amplitude is observed, g_i is the ith peak in acceleration, g_{i+n} is the (i+n)th peak in acceleration. The mean damping ratios obtained from the samples are given in table 4.

Table 4: Damping ratio of the samples

	$[G_6]$	$[G_2/F]_s$	$[G/F/G]_s$	$[F/G/F]_s$	$[F_2/G]_s$	$[F_6]$
Damping Ratio (%)	1.97	2.31	1.86	2.35	2.63	3.61
CoV (%)	1.01	1.32	1.74	1.59	1.36	2.56

Three samples for each six different layups were tested and every hit was repeated three times and the mean value was obtained. The repeatability of the experiments is shown to be good in Table 4 with all coefficient of variations (CoVs) below 3% over the experiment. The maximum variation in the damping experiment is seen in the FFFFFF samples that can be attributed to the inhomogeneity of the flax composites over the manufactured plate. The other variations are between 1.01 - 1.74% for the GGGGGG and GFGGFG, respectively. The FFFFFF samples offer the highest damping among the samples whilst the GFGGFG samples have the lowest damping ratio although they contain 2 plies of flax.

4. Discussion

4.1. Understanding the degradation of mechanical properties

Plotting the tensile strength against the E-glass fibre volume fraction of the samples in Figure 3, shows a correlation between increasing tensile strength in the samples and increasing E-glass fibre content with an exception in the strength of the GGFFGG and the GFGGFG layups. Having already determined that these layups have a void content of below 4 %, meaning that the void content should have little effect, this difference is more likely to be due to the change in the failure modes, the quality of the interfacial bonding and the nesting effect.

The interfacial bonding quality is the key factor influencing the strength of the composite materials. The strength of flax fibres is influenced by their hydrophilic nature, which causes weak interface regions and reduces the stress transfer between the fibres and the epoxy [18, 19, 20]. This chemical incompatibility yields composites with reduced mechanical properties. Without chemical treatments to modify the surface of the flax yarns, and improve the compatibility with the matrix, the interface properties are expected to be weak in a hybrid composite [21, 22]. As the flax fibres are not treated in the experiment it is expected that the interface is weaker between the flax fibres and the matrix than in the E-glass fibres. The fracture of the hybrid samples initiates with the flax fibres breaking at 90° where they separate from the matrix causing debonding that propagates through the fibre-matrix interface. In the hybrid specimens this propagation discontinues once it reaches the neighbouring ply. As the load increases this crack tip causes a stress concentration at the interface of the two plies, producing interlaminar stresses that lead to delamination cracks at the interface. This is followed by the 0° fibres which is a similar process to that documented in the literature [23]. This delamination crack between the flax and E-glass plies are observed in the current hybrid samples by visual inspection in the current hybrid samples along with extensive whitening the E-glass samples, however no delamination is observed in the pure flax samples but brittle fibre fracture and fibre pull-out.

Another potential source for this difference could be attiributed to the nesting effect where the woven fibre bundles are interlocked to each other. Kureemun et al. [23] claim that grouping woven fibres increases the possibility for nesting resulting in higher tensile properties. This suggestion is supported by the thickness difference observed in the GGFFGG and GFGGFG specimens, 3.35 and 3.46 mm, as E-glass fibre bundles are interlocked to neighbouring plies reducing the zone for the matrix. Similar sensitivity to the volume fraction is also obtained in the tensile modulus of the samples. Higher volume fractions lead to higher tensile moduli with the same effect seen in the tensile strength. The tensile moduli of the pairs of hybrid composites, with the same fibre volume fractions, are ascertained to be similar as the tensile modulus is a low strain measurement at which the two types of fabric show equivalent deformation responses.

It is found that the effect of the stacking sequences on the tensile properties is minimal compared to the effect on the damping properties. Zhang et al. [24] claim the stacking sequence has an influence on the tensile strength of UD flax/E-glass hybrid composites due to the increased number of fibre interactions which lead to higher tensile strengths. However, Kureemun et al. [23] find an inconsistency between the stacking sequences and the tensile strength of woven flax/carbon hybrid samples and claim that blocking carbon plies leads higher tensile properties as nesting of woven carbon plies leads higher tensile properties. Likewise, Li et al. [25] claim that changing stacking sequences of the flax/carbon hybrid composites did not influence the tensile properties too much. This disagreement in the results could be attributed to type of the fabric and the manufacturing method as woven fabric is manufactured via the resin infusion method in [23] and this current study whilst UD fabric is manufactured via the compression moulding in [24] which generally results in an improved interface between the layers.

4.2. Understanding the improvement in damping properties

Whilst stacking sequence does not play a large role in the strength of the laminate it does have a significant effect on the damping ratio, which tends to increase when the flax plies are on the outer side of the samples. This is attributed to the different energy dissipation mechanisms of flax and E-glass fibres. When flax plies are employed on the outer side, the induced energy is dissipated through various mechanisms, including the intrinsic characteristics of flax fibre: the presence of lumen and entanglement of the fibres and heterogeneity of the cell wall [9]. Therefore, improved damping properties are seen in such samples. Conversely, when E-glass plies are placed on the outer side the the composite responses as if the energy is dissipated through E-glass plies that do not possess complex energy mechanism systems. Therefore the damping of composites that E-glass plies placed on the outer side is governed by their resin content and the prediction of their damping properties is not as difficult as that of flax fibres composites.

The highest damping is in the FFFFFF samples whose fibre volume fraction is 36.28 % which is similar to the fibre volume fraction of the FFGGFF sample, 36.74 %. However, there is an increase in the damping ratio for the FFFFFF samples of about 27 % over the FFGGFF samples and 35 % over the FGFFGF samples, which also have a similar volume fraction of 38.10 %. This contradicts Flynn et al. [26] where the performance of hybridized carbon and flax composites are investigated using the same stacking sequence, CFCFC, but using a different number of plies manufactured via the vacuum assisted resin transfer moulding. The authors claim that the damping ratio of the flax composites tends to decrease as the flax fibre volume fraction reaches 27 % and this decrease is more pronounced when the flax volume fraction reaches 40 %. This was attributed to the poor compatibility between the fibres and the epoxy resin. No decrease in damping is observed in this study despite reaching 36 % of flax fibre volume fraction. The results are also compared to Li et al. [25] to determine the differences between flax/E-glass hybrids and flax/carbon hybrids; Figure 1 is updated as Figure 5 with the findings in these study. In both sets of tests the flax fibre only samples exhibit the best damping properties, though there is a difference between the damping ratios. This is most likely due to the different fibre volume fractions, 60 % and 36.28 %, as resin volume fractions is the main contributor to the damping of a composite. A change of behaviour is observed between the two hybrids with a more rapid decline in damping properties for the E-glass hybrids from the pure flax, showing that the hybridization is less beneficial for these materials. Both sets of hybrids are dependent on the stacking sequence, requiring flax on the outer side for the best results.

To investigate the damping of composite samples a simple analytical model is employed based on the rule of mixtures. A model derived by Hashin [27], shown in Eq. 3, is used to analytically predict the damping of the composite samples in this study,

$$\psi_c = \psi_m V_m E_m / E_c, \tag{3}$$

where, ψ_c is the damping of the composites, ψ_m is the damping of the matrix, V_m is the matix volume fraction, E_m is the Young's modulus of the matrix and E_c is the Young's modulus of the composite. Yim and Jang [28] claim that Hashin's model markedly underestimates the experimental results as it does not account for several factors that they propose influence the damping of composites: fibre diameter, fibre misalignment, the quality of the composite samples, the interlaminar shear effect, and the fibre volume fractions. The Hashin equation is modified to introduce a curve fitting parameter (α) to account for these factors, shown in Eq. 4,

$$\psi_c = \frac{\psi_m (V_m)}{V_m + V_f (E_c / E_m)^{\alpha}}. \tag{4}$$

The damping experimental results are replicated by determining the alpha value using trial and error, with the results shown in Figure 6. A good agreement is achieved in the E-glass samples when α is set to zero and the effects of the composite fibres are removed. When the flax fibres are added as a hybrid then small values of alpha provide a better estimate. The flax fibres show good agreement between the experiments and the model when a value of -4.0 is used, showing that there is a strong effect from the fibres. The factors effecting damping proposed by Yim and Jang [28] are investigated to determine the reasons for the inaccuracy in damping prediction for the FGFFGF, FFGGFF and FFFFFF layups.

The effect of fibre diameter on damping was investigated by [29] who show that the difference in specific damping coefficient values for fibre diameter values of 50 and 10 μm is 0.3-0.4 %. The difference in these experiments is expected to be much lower than these values as the average fibre diameter of flax and E-glass fibres are close: 23 and 19 μm, respectively. Fibre misalignment is also proposed as an element that increases the damping as it creates shear stresses in the composites. Although there is not an available standard for measuring the fibre misalignment a visual observation is made of the polished samples. No significant fibre misalignment is observed, therefore the effect of fibre misalignment and fibre diameter on the damping are treated as minimal or null. The void content is also proposed as a contributing factor to the damping and the void content is compared to the damping ratios of the samples in Figure 7. It is observed that the damping is not sensitive to the void content or that it has no effect. This might be due to the small void content in the samples reducing the contribution, but the manufacturing technique used for these samples, resin infusion, gives larger void contents than most processes, and is therefore considered to be a worst case scenario. The interlaminar stresses are also seen as a contributor to the damping, but these stresses only become significant when the width/thickness (w/t) ratio is below 2 [30]. The width/thickness ratio is much higher than 2 in this study, around 8, and therefore the contribution of the interlaminar shear stresses are considered to be limited. The volume fractions of the constituents are a dominant contributor to the damping which is demonstrated in Figure 8 where the fibre volume fraction of each specimen is plotted against the damping ratio. It is seen that there is an inverse relationship between the fibre volume fraction and the damping of the samples, where the damping is sensitive to the change in volume fraction, with more resin leading to increased damping. At similar volume fractions such as in the pair of the GGFFGG and GFGGFG or the pair of the FGFFGF and FFGGFF the damping ratios show only small fluctuations. In both pairs, the samples with lower fibre volume fractions exhibit better damping properties. However, the GFGGFG samples has a lower damping than the GGGGGG samples despite the fact that it exhibits a lower fibre volume fraction but these are only small variations.

Of these five factors the volume fraction is the dominant factor, but it would appear the minor fluctuations are unlikely to be from interlaminar stresses, voids or fibre misalignment. More complex models are required to determine the damping of flax but this model illustrates the change in behaviour between E-glass and flax, where the flax fibres provide additional damping whereas the E-glass fibres work against the flax fibres and damp this energy dissipation.

A radar chart is plotted to characterise the difference in properties between E-glass, flax and its hybrids, shown in Figure 9. The axes are aligned with the most beneficial values to the outside of the figure, meaning that large swept out areas represent materials with better properties. The GGGGGG layup sweeps the largest area on the left side of the figure where mechanical properties and the cost are presented. The FFFFFF layup covers more area on the right side of the figure where the density and the damping properties are presented. When the E-glass is turned into a hybrid the area on the right side of the chart, specific properties and damping, are increased only by a small amount, while a heavy penalty is incurred on the left side of the chart, mechanical properties and cost. The laminates with more E-glass, GGFFGG and GFGGFG, cover more area on the left side of the chart whilst those with more flax, FFGGFF and FGFFGF, cover more area on the right side of the chart. In this compromise the more flax plies in a sample the more is sacrificed in terms of the mechanical properties regardless of where the flax plies are placed. However, having more flax plies in a sample does not always mean more damping in the sample, unless flax plies are placed on the outer side of the sample. While the hybrids can be used to increase performance in some areas, it would seem the respective loss in properties is more than the gain and the overall profile of the material is reduced.

5. Conclusion

The damping and mechanical properties, tensile strength and tensile modulus, are determined and the paper confirms that the flax fibre composite samples, and hybrids, exhibit better vibration damping characteristics than E-glass fibre composites, but only when the flax layers are placed on the outer side of the specimen. However, the reduction in damping properties for the hybrids in comparison to flax is greater than seen between the carbon hybrids and flax, demonstrating a change in behaviour. It is shown that volume fraction is the dominant determinant of the damping, with hybrid and E-glass composites almost totally dependent on the matrix damping, but in the flax only samples the fibre properties also have an effect, unlike in the E-glass samples. A simple model is used to illustrate this behaviour and to show that flax plies provide some additional energy dissipation mechanisms which are inhibited when the plies are on the inside of a hybrid with no current explanation in the literature to describe this change. A number of factors are not included in this simple model and more complex models that accounts for various energy dissipation mechanisms are required to replicate the experimental data for flax composites; this includes investigating the effect of the woven fibres in comparison to unidirectional ones. In addition the experiments performed within the paper allow the hybrid material to be profiled and compared for the first time. It is shown that hybridization of flax and E-glass fibres ends up with positive hybrid effect in damping when flax plies are placed on the outer, however the compromise in tensile properties are substantial.

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References

[1] F. Duc, P.-E. Bourban, C. Plummer, J.-A. Månson, Damping of thermoset and thermoplastic flax fibre composites, Composites Part A: Applied Science and Manufacturing 64 (2014) 115–123.

[2] F. Duc, P. Bourban, J.-A. Månson, The role of twist and crimp on the vibration behaviour of flax fibre composites, Composites Science and Technology 102 (2014) 94–99.

[3] M.-J. Le Guen, R. H. Newman, A. Fernyhough, M. P. Staiger, Tailoring the vibration damping behaviour of flax fibre-reinforced epoxy composite laminates via polyol additions, Composites Part A: Applied Science and Manufacturing 67 (2014) 37–43.

[4] S. V. Joshi, L. Drzal, A. Mohanty, S. Arora, Are natural fiber composites environmentally superior to glass fiber reinforced composites?, Composites Part A: Applied science and manufacturing 35 (3) (2004) 371–376.

[5] B. Bax, J. Müssig, Impact and tensile properties of pla/cordenka and pla/flax composites, Composites Science and Technology 68 (7) (2008) 1601–1607.

[6] D. U. Shah, P. J. Schubel, M. J. Clifford, Can flax replace e-glass in structural composites? a small wind turbine blade case study, Composites Part B: Engineering 52 (2013) 172–181.

[7] J. Blanchard, A. Sobey, J. Blake, Multi-scale investigation into the mechanical behaviour of flax in yarn, cloth and laminate form, Composites Part B: Engineering 84 (2016) 228–235.

[8] D. U. Shah, Damage in biocomposites: Stiffness evolution of aligned plant fibre composites during monotonic and cyclic fatigue loading, Composites Part A: Applied Science and Manufacturing 83 (2016) 160–168.

[9] M. J. Le Guen, R. H. Newman, A. Fernyhough, G. W. Emms, M. P. Staiger, The damping–modulus relationship in flax–carbon fibre hybrid composites, Composites Part B: Engineering 89 (2016) 27–33.

[10] M. Assarar, W. Zouari, H. Sabhi, R. Ayad, J.-M. Berthelot, Evaluation of the damping of hybrid carbon–flax reinforced composites, Composite Structures 132 (2015) 148–154.

[11] R. M. Crane, J. W. Gillespie Jr, Characterization of the vibration damping loss factor of glass and graphite fiber composites, Composites science and technology 40 (4) (1991) 355–375.

[12] R. Chandra, S. Singh, K. Gupta, Damping studies in fiber-reinforced composites–a review, Composite

structures 46 (1) (1999) 41–51.

[13] D. U. Shah, P. J. Schubel, P. Licence, M. J. Clifford, Determining the minimum, critical and maximum fibre content for twisted yarn reinforced plant fibre composites, Composites Science and Technology 72 (15) (2012) 1909–1917.

[14] R. Petrucci, C. Santulli, D. Puglia, F. Sarasini, L. Torre, J. Kenny, Mechanical characterisation of hybrid composite laminates based on basalt fibres in combination with flax, hemp and glass fibres manufactured by vacuum infusion, Materials & Design 49 (2013) 728–735.

[15] Q. Liu, M. Hughes, The fracture behaviour and toughness of woven flax fibre reinforced epoxy composites, Composites Part A: Applied Science and Manufacturing 39 (10) (2008) 1644–1652.

[16] S. N. Monteiro, F. P. D. Lopes, A. S. Ferreira, D. C. O. Nascimento, Natural-fiber polymer-matrix composites: cheaper, tougher, and environmentally friendly, JOM Journal of the Minerals, Metals and Materials Society 61 (1) (2009) 17–22.

[17] H. L. Bos, The potential of flax fibres as reinforcement for composite materials, Technische Universiteit Eindhoven Eindhoven, 2004.

[18] H. Dhakal, Z. Zhang, M. Richardson, Effect of water absorption on the mechanical properties of hemp fibre reinforced unsaturated polyester composites, Composites science and technology 67 (7-8) (2007) 1674–1683.

[19] S. H. Ghaffar, O. A. Madyan, M. Fan, J. Corker, The influence of additives on the interfacial bonding mechanisms between natural fibre and biopolymer composites, Macromolecular Research (2018) 1–13.

[20] A. Le Duigou, A. Bourmaud, E. Balnois, P. Davies, C. Baley, Improving the interfacial properties between flax fibres and plla by a water fibre treatment and drying cycle, Industrial Crops and Products 39 (2012) 31–39.

[21] A. Le Duigou, P. Davies, C. Baley, Interfacial bonding of flax fibre/poly (l-lactide) bio-composites, Composites Science and technology 70 (2) (2010) 231–239.

[22] F. Almansour, H. Dhakal, Z. Y. Zhang, Investigation into mode ii interlaminar fracture toughness characteristics of flax/basalt reinforced vinyl ester hybrid composites, Composites Science and Technology 154 (2018) 117–127.

[23] U. Kureemun, M. Ravandi, L. Tran, W. Teo, T. Tay, H. Lee, Effects of hybridization and hybrid fibre dispersion on the mechanical properties of woven flax-carbon epoxy at low carbon fibre volume fractions, Composites Part B: Engineering 134 (2018) 28–38.

[24] Y. Zhang, Y. Li, H. Ma, T. Yu, Tensile and interfacial properties of unidirectional flax/glass fiber reinforced hybrid composites, Composites Science and Technology 88 (2013) 172–177.

[25] Y. Li, S. Cai, X. Huang, Multi-scaled enhancement of damping property for carbon fiber reinforced composites, Composites Science and Technology 143 (2017) 89–97.

[26] J. Flynn, A. Amiri, C. Ulven, Hybridized carbon and flax fiber composites for tailored performance, Materials & Design 102 (2016) 21–29.

[27] Z. Hashin, Complex moduli of viscoelastic composites—ii. fiber reinforced materials, International Journal of Solids and Structures 6 (6) (1970) 797–807.

[28] J. H. Yim, B. Z. Jang, An analytical method for prediction of the damping in symmetric balanced laminated composites, Polymer composites 20 (2) (1999) 192–199.

[29] R. Adams, D. Short, The effect of fibre diameter on the dynamic properties of glass-fibre-reinforced polyester resin, Journal of Physics D: Applied Physics 6 (9) (1973) 1032.

[30] S. Hwang, R. Gibson, Contribution of interlaminar stresses to damping in thick laminated composites under uniaxial extension, Composite structures 20 (1) (1992) 29–35.

6. Figures

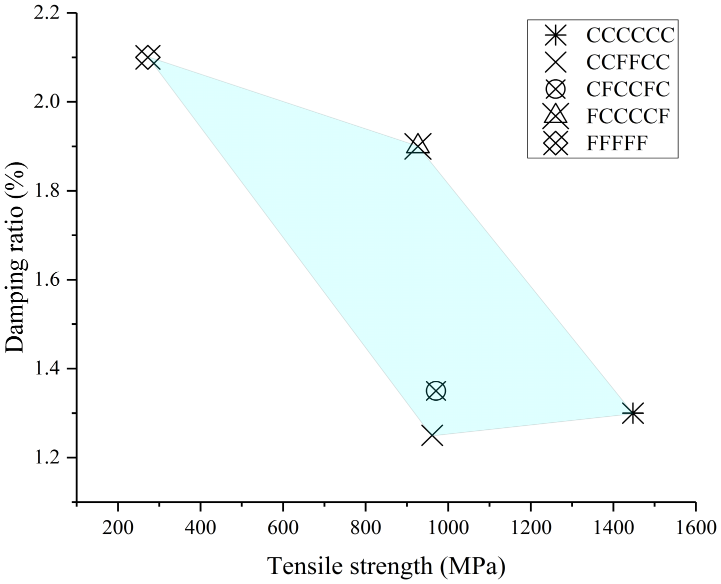

Figure 1: Comparison of tensile strength against damping ratio from tests performed by [25], where F represents a flax layer and C a carbon layer.

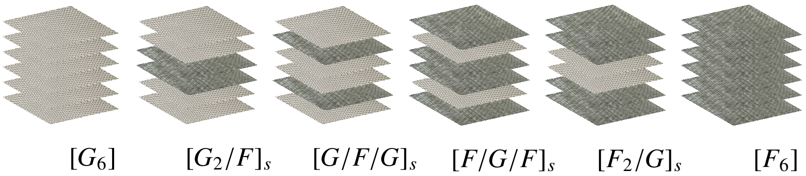
$[G_6]$ $[G_2/F]_s$ $[G/F/G]_s$ $[F/G/F]_s$ $[F_2/G]_s$ $[F_6]$

Figure 2: Stacking sequences of the laminates

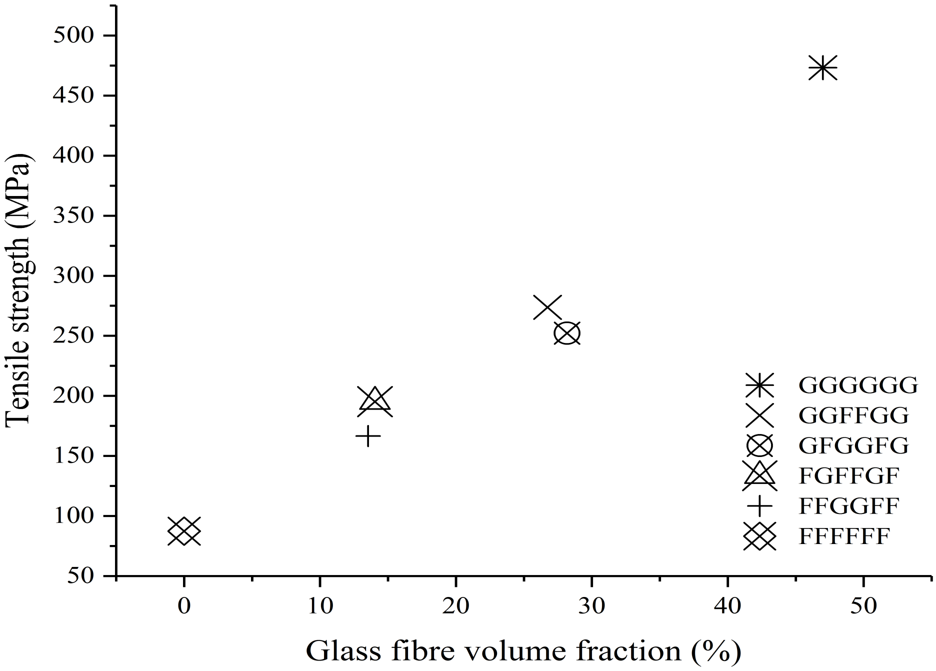

Figure 3: Effect of the E-glass fibre volume fraction on the tensile strength.

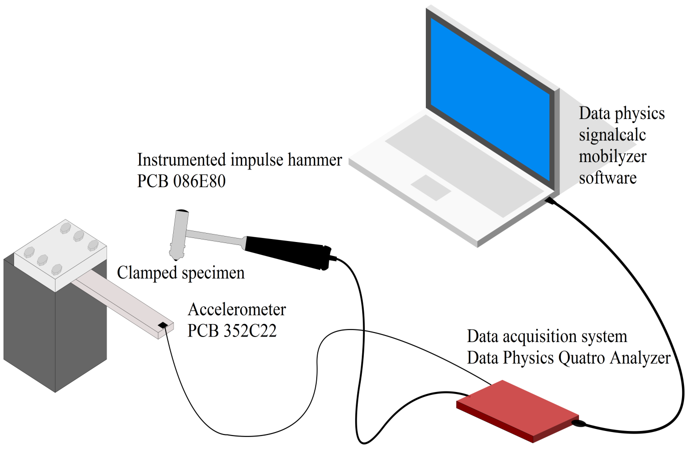

Figure 4: A schematic drawing of the set-up for experimental modal analysis.

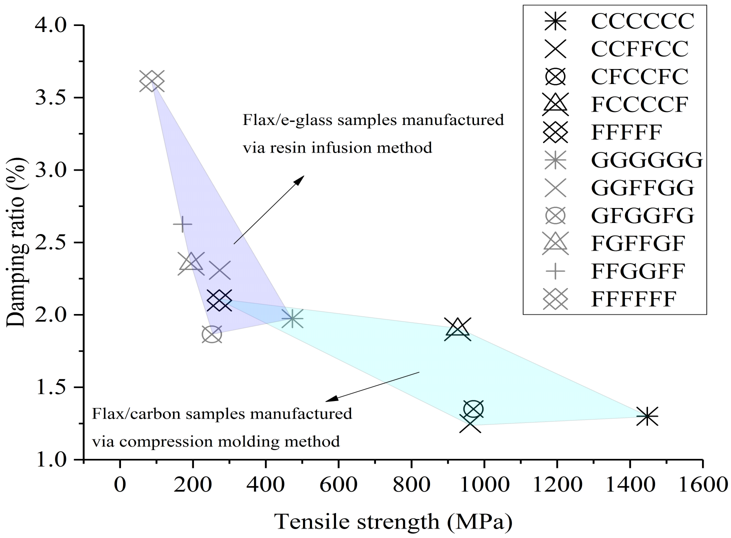

Figure 5: Tensile strength vs. damping ratio of flax/carbon hybrid samples [25] vs. tensile strength vs. damping ratio of flax/carbon hybrid samples.

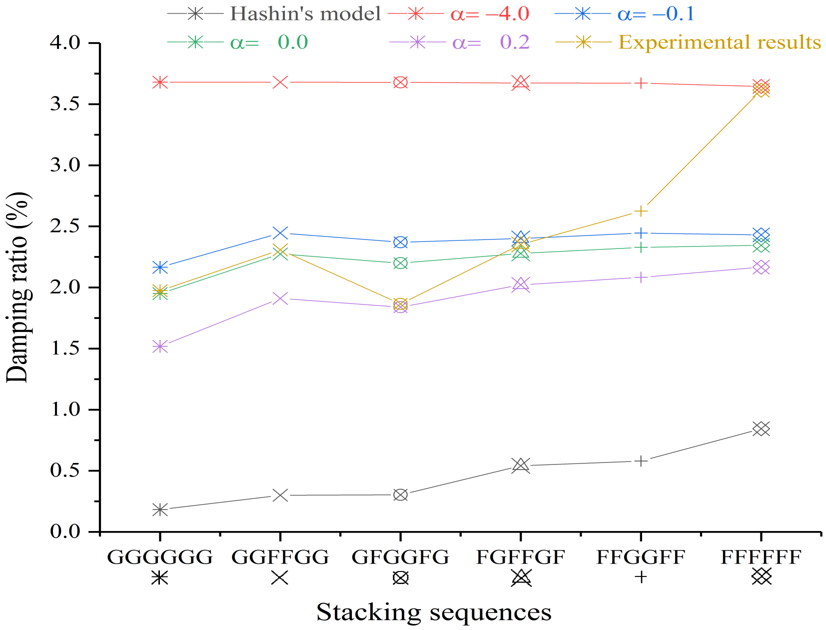

Figure 6: Experimental results and the damping prediction for the composite samples by employing Hashin's model [27] and Yim and Jang's model [28].

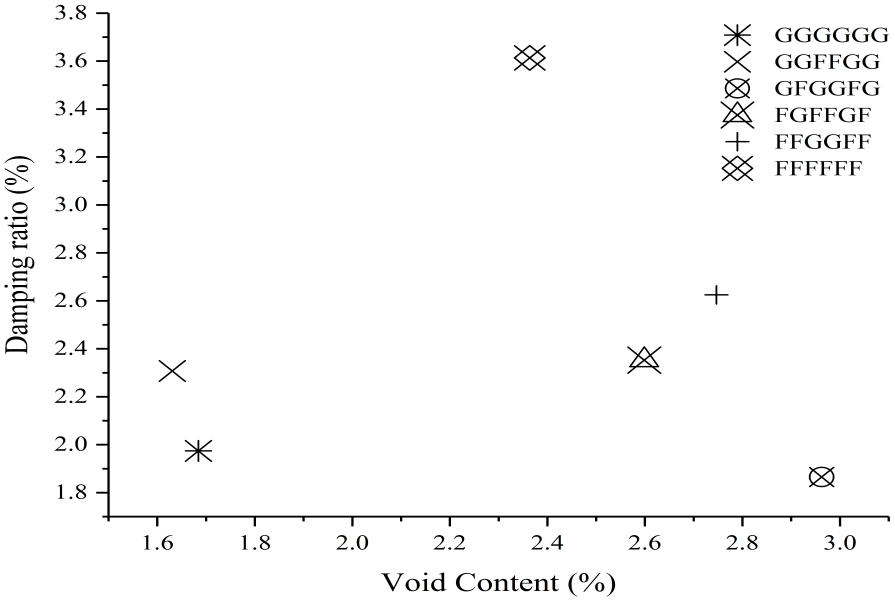

Figure 7: Effect of the void content on the damping ratio of the samples.

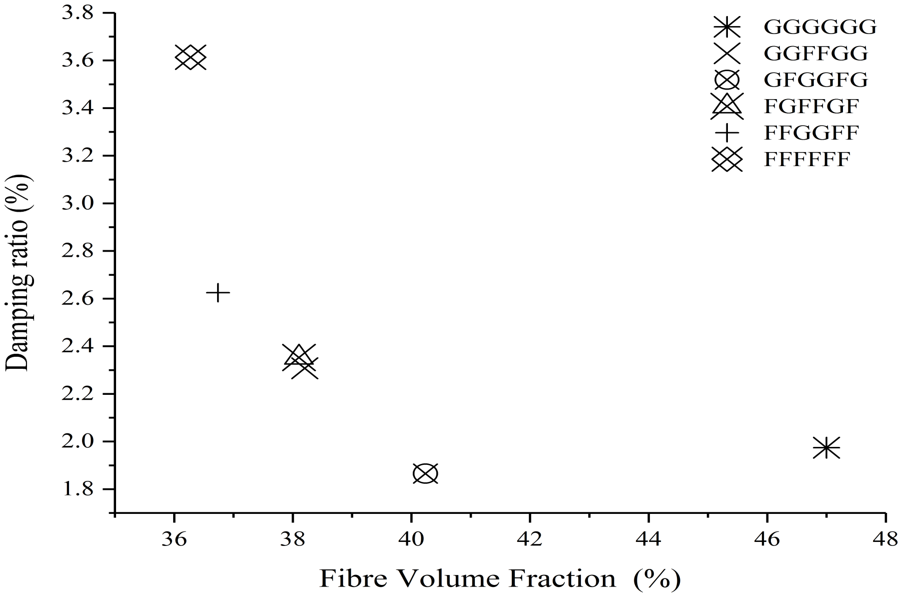

Figure 8: Effect of the total fibre volume fraction on the damping ratio of the samples.

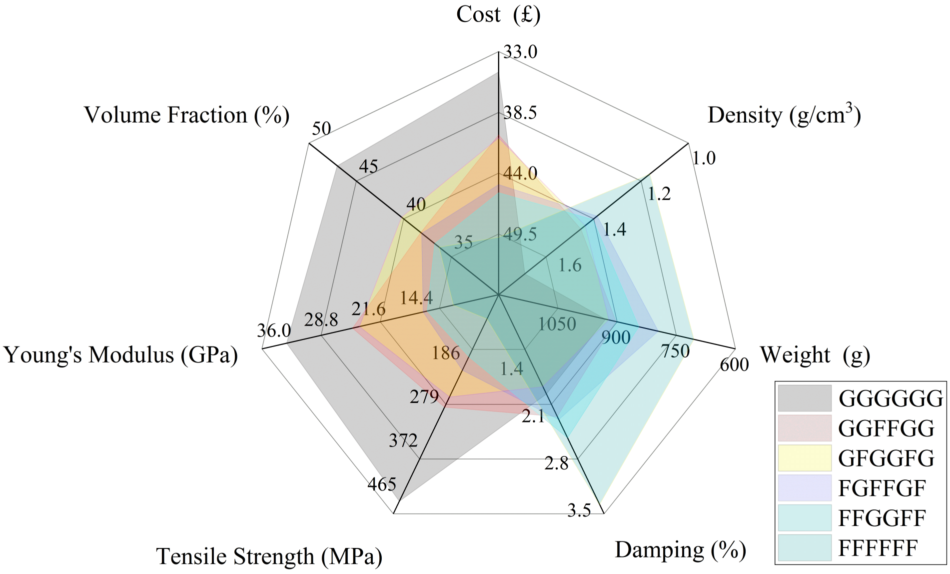

Figure 9: Summary of the findings on a radar chart.