

# Effect of Stacking Sequences on the Mechanical and Damping Properties of Flax Glass Fiber Hybrid

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**Abstract:** The aim of this study is to show the interest of the mechanical and dynamical properties of glass-flax hybrid composites. Therefore, various staking sequences of glass-flax hybrid composites were manufactured and tested in free vibrations. The damping coefficients were identified by fitting the experimental responses of free-free bending vibrations. The obtained results show that the staking sequences and the position of flax fiber layers in the hybrid composites changed the properties, so a classification of different stacking sequences was established. In fact, the hybrid laminate made of two glass external layers placed on both sides of four flax layers is very interesting in term of its mechanical and damping properties. Indeed, it showed better specific bending modulus and loss factor than glass composites with proportions of 31 and 39%, respectively. A study of a structure of this composite has been made to validate the obtained results.

Keywords: Flax fiber; glass fiber; hybrid composite; damping; mechanical properties

## **1** Introduction

Glass fibers reinforced polymer composites are used nowadays in various fields, since they offer many advantages. However, the low dissipative characteristics of glass fibers could limit their use particularly in composite applications needing vibration damping. Indeed, in the cases where a structure is subjected to permanent vibrations, it is necessary to take into account the structural damping of the material and to optimize it according to the different constituents. So, the damping control permits to reduce structural vibrations, which are undesirable and can generate several problems such as structural fatigue and internal or external noise due to acoustic radiation.

The hybridization between natural and synthetic fibers can constitute a promising solution to take advantage that offer natural fiber while keeping the interesting properties of synthetic fiber. The hybridization advantage of the reinforcement of a composite is that one type of fiber can complete what is missing in the other one. For example, by considering a hybrid composite, the mechanical performance of some synthetic fibers can be combined with the several advantages that offer natural fibers such as their easy availability, biodegradability, non-abrasivity, renewability and eco-friendly characteristics [1-3]. Consequently, several research works have studied the effect of hybridization according to various aspects [4-9]. For example, Ramesh et al. [4] evaluated the mechanical properties of sisal-jute-glass fibers reinforced polyester composites. They indicated that the addition of sisal and jute fibers in glass composite improved the mechanical properties of the hybrid composites. In another work, Sabeel et al. [5] studied the effect of glass fiber hybridization and stacking sequences on tensile and flexural of jute-glass hybrid composites. They showed that the incorporation of glass layers above and below jute composite enhanced some properties of hybrid composites. Sabeel et al. [5] also found that stacking sequences significantly affected the flexural properties the studied composites. Similar results were also found in the case of other

hybrid composites composed with glass fibers and natural fibers such as flax, sisal, kenaf and bamboo [6,10-11] or with carbon fibers and flax fibers [12].

These works clearly show the complementary potential between natural and synthetic fibers in terms of their mechanical performances. However, only mechanical performances could be, in some cases, insufficient particularly when used materials are subjected to permanent vibrations. Indeed, the problem of vibration damping constitutes an important factor in the mechanical design of structures. It is within this context that we propose in the present work to analyze both mechanical and dynamic properties of glass-flax hybrid composites. This choice is motivated by the high mechanical performance of carbon fiber as well as the interesting dynamic properties of flax fiber. The choice of flax fiber is motived by its interesting dynamic properties as showed in several works [13-19]. For example, Wielage et al. [13] analyzed the dynamic properties of flax, hemp and glass fibers reinforced polypropylene composites by considering the Dynamic Mechanical Analysis. They found that the damping properties of flax and hemp composites are significantly higher than the glass ones. In other works, Duc et al. [14] compared the damping of flax, carbon and glass fibers reinforced polymer composites. In particular, they showed that flax fiber reinforced composites present relatively higher damping properties of flax fiber reinforced polymer composites. Duc et al. [14,15] attributed the interesting damping properties of flax fiber reinforced polymer composites to the friction mechanisms at the different scales of the fiber in particular through its cell wells.

For this purpose, non-hybrid and hybrid glass and flax fiber laminates were first elaborated with different stacking sequences, then tested to analyze the effects of the adding of flax layers on the dynamic properties of hybrid composites. Next, we will show how the finite element analysis allows us to determine the damping characteristics of these hybrid composites. Obtained results showed that hybridization can offer composites with better dynamic and mechanical properties. It also showed that those performances depend on the position of flax layers in the laminates. So, this study allows to identify the more interesting stacking sequence with the better compromise of elastic and damping properties. Finally, a simple structure composed of this stacking sequence was studied in vibrations to confirm the relevance of this choice.

## **2** Experimental Procedure

## 2.1 Materials

The non-hybrid and hybrid composite materials studied in this work were laminated with flax and/or glass fiber reinforcement and epoxy matrix. The reinforcement was a quasi-unidirectional fabric with a warp and weft ratio of 91/9. The flax fiber fabric of 200 g/m<sup>2</sup> was marketed by Depestele Group and the glass fiber fabric of 300 g/m<sup>2</sup> by Sicomin Company. The epoxy matrix was a SR 1500 epoxy resin with SD 2503 hardener at a mixing ratio of 100:33 by weight. 8 types of laminates composed of 8 layers were prepared with different stacking sequences, namely: Flax and Glass for non-hybrid laminates,  $[F/G_3]_s$ ,  $[F_2/G_2]_s$ ,  $[G/F_3]_s$ ,  $[G_2/F_2]_s$  and  $[G_3/F]_s$  for hybrid laminates, where F represents a flax layer and G a glass layer. Their specifications are summarized in Tab. 1.

All materials were manufactured by press platen process. Firstly, the layers of dry fabrics were impregnated one by one with the epoxy matrix. Once impregnated, laminates were then cured in a compression molding machine (SATIM model) under 6-bar pressure at 40°C for three hours and a half. Finally, the laminate plates were cut and shaped in rectangular form by using a diamond saw blade. The non-hybrid plates were cut to obtain specimens with different lengths (240, 260 and 280 mm) and different fiber orientations (0°, 90° and 45°). The hybrid plates were tested in a single orientation at 0°. The width of both non-hybrid and hybrid specimens was 26 mm for all orientations and lengths.

Laminate	Ply number Flax/Glass	Stacking sequence F: Flax, G: Glass	Thickness Flax/Glass (mm)	Fiber volume fraction $(V_f)$ Flax/Glass
Flax	8/0	FFFFFFF	2.90/0.00	35/0
$[F/G_3]_s$	2/6	FGGGGGGF	0.70/0.90	15/40
$[F_2/G_2]_s$	4/4	FFGGGGFF	1.40/0.60	25/21
$[F_3/G]_s$	6/2	FFFGGFFF	2.10/0.30	32/9
$[G/F_3]_s$	6/2	GFFFFFG	2.10/0.30	34/9
$[G_2/F_2]_s$	4/4	GGFFFFGG	1.40/0.60	26/22
$[G_3/F]_s$	2/6	GGGFFGGG	0.70/0.90	15/40
Glass	0/8	GGGGGGGG	0.00/1.28	0/54

Table 1: Designation, thickness and fiber volume fraction of the non-hybrid and hybrid laminate composites

### 2.2 Experimental Protocol

The aim of the present work is to characterize dynamic properties of the studied materials using a free flexural vibrations analysis. Fig. 1 shows the experimental equipment. Note that more details about this equipment as well as the method used can be found in a previous work of the authors [20]. The specimen was tested in a free-free configuration by hanging the specimen in a vertical position with a rubber band.



Figure 1: Experimental equipment [20]

The specimen was excited at different points using an impulse hammer (PCB 086C03) and the flexural vibrations were detected using an accelerometer (PCB 352C23) fixed on the specimen with wax. Both excitation and response signals were digitalized by LMS SCADAS dynamic analyzer. The frequency response enabled us to identify the natural frequencies and loss factors from LMS PolyMAX method detailed in [21]. This required first defining the geometry of the specimen and the coordinates of the excited points in the analysis system. The results for each length, orientation and material shown in this work were the average of five specimens.

#### **3 Modelling of Damping**

The main purpose of this part is to apply the energy approach to evaluate the structural damping of hybrid composites with different stacking sequences. It is within this context that free vibrations of the tested specimens are investigated with a four-node multilayered shell finite element, named S4, of the commercial code Abaqus [22]. This element is a doubly-curved general purpose element based on the first-order laminate theory. Transverse shear stresses could be neglected since thicknesses of specimens are widely lower than their lengths.

For each natural mode, the finite element analysis calculates its corresponding values of stresses and strains on the lower (l) and the upper (u) faces of each layer k of the element e (Fig. 2),

$$\sigma_{il}^{k,e}, \sigma_{iu}^{k,e}, \varepsilon_{il}^{k,e}, \varepsilon_{iu}^{k,e}, \quad (i = 1, 2, 6)$$
(1)

The energy  $U^{k,e}$  of the layer k in the element e can be expressed as follow:

$$U^{k,e} = U_{11}^{k,e} + U_{22}^{k,e} + U_{66}^{k,e}$$
<sup>(2)</sup>

where

$$U_{ii}^{k,e} = \frac{1}{2} \iiint_k \sigma_i^{k,e} \,\varepsilon_i^{k,e} \,dx \,dy \,dz = \frac{S_e}{2} \int_k \sigma_i^{k,e} \,\varepsilon_i^{k,e} \,dz, \quad (i = 1, 2, 6)$$
(3)

And Se is the surface of the finite element e.

The evaluation of the loss factor deduced from the finite element analysis can be done with an energetic approach [24]. The total energy stored in the structure can be expressed as follow:

$$U = U_{11} + U_{22} + U_{66} \tag{4}$$

where

$$U_{ii} = \sum_{\text{elements},e} \sum_{\text{layers},k} U_{ii}^{k,e}, \quad (i = 1, 2, 6)$$
(5)

Then, the dissipated energy with the damping phenomena in the layer k of the element e can be expressed as a function of loss factors as follow:

$$\Delta U_k^e = \eta_{11k}^e U_{11k}^e + \eta_{22k}^e U_{22k}^e + \eta_{66k}^e U_{66k}^e \tag{6}$$



Figure 2: Multilayered finite element S4 [22,23]

Loss factors are evaluated in the axis (L,T) of the material in each layer:  $\eta_{11k}^e$  and  $\eta_{22k}^e$  are loss factors in *L* and *T* direction respectively, and  $\eta_{66k}^e$  is the loss factor in the plane (L,T).

The dissipated energy in the finite element e can be expressed by:

$$\Delta U^e = \sum_{k=1}^n \Delta U_k^e,\tag{7}$$

The total energy dissipation  $\Delta U$  in the whole structure is then:

$$\Delta U = \sum_{\text{él?ments}} \Delta U^e \tag{8}$$

Finally, loss factor estimated by finite element analysis can be deduced from:

$$\eta = \frac{\Delta U}{U} \tag{9}$$

Eq. (9) was used to estimate the loss factors of the flax-glass hybrid laminates. For this purpose, it was necessary to know the elastic and damping properties of the non-hybrid flax and glass layers first. The assessment of these two properties will be detailed in Subsections 4.1 and 4.2.

#### **4 Result and Discussion**

# 4.1 Mechanical and Damping Properties of Non-Hybrid Laminates

The elastic coefficients  $E_L$ ,  $E_T$  and  $G_{LT}$  of non-hybrid composites were deduced from free vibration tests performed on specimens oriented at different fiber orientations 0°, 45° and 90°. It should be noted that natural frequencies of the specimens oriented at 0° and 90° depend on the longitudinal modulus  $E_L$ and transverse modulus  $E_T$ , respectively. Thus, based on the natural frequencies obtained by experimental modal analysis, all moduli can be determined. Thereby for specimens with fiber oriented to 0°, the identification of the longitudinal modulus  $E_L$  was conducted using an iterative method. A variation of the modulus value at each iteration was done, until the equality was reached between natural frequencies obtained by the experimental method and the finite element analysis. This iterative procedure was also used for 90° fiber orientation so the transverse modulus  $E_T$  can be identified. Then, shear modulus  $G_{LT}$ was determined in the same way using results of the specimens with 45° fiber orientation and taking into account variations of both moduli  $E_L$  and  $E_T$  as a function of frequency.

For the damping properties, the loss factors  $\eta_{11}$  and  $\eta_{22}$  of glass and flax laminates were experimentally determined from free vibrations of tested beams oriented at 0° and 90°, respectively. Moreover, their loss factors  $\eta_{66}$  were deduced from the experimental damping of tested beams oriented at 45° and the energy approach developed in Section 3. It is worthy to note that the use of different lengths (240, 260 and 280 mm) of the beams enables us to evaluate the variation of the mechanical and damping properties according to the frequency. Tab. 2 summarizes the engineering constants and the damping properties obtained from the used procedure. The values of the Young's moduli seem to be almost constant with the frequency for the glass and flax laminates. For the damping coefficients, it is observed two different behaviors of both laminates. In fact, the loss factors  $\eta_{11}$ ,  $\eta_{22}$  and  $\eta_{66}$  increase with the frequency for glass laminate while they are found to decrease for flax laminates. Moreover, loss factors  $\eta_{11}$  of flax laminate is significantly higher than that of glass laminate (from 137% to 194%) with respect to the considered frequency domain. These differences could be attributed to the flax fiber morphology, which promotes energy dissipation as reported in several works [14,17].

Composite	Frequencies (Hz)	$E_L$ (GPa)	$E_T$ (GPa)	$G_{LT}$ (GPa)	$\eta_{11}$ (%)	η <sub>22</sub> (%)	$\eta_{66}(\%)$
Flax	< 500	$21.00\pm0.35$	$6.53\pm0.22$	$1.61\pm0.07$	$2.03\pm0.08$	$2.63\pm0.07$	$3.46\pm0.05$
	500 - 1000	$21.81\pm0.88$	$6.59\pm0.20$	$1.70\pm0.06$	$1.83\pm0.01$	$2.57\pm0.00$	$3.40\pm0.01$
	> 1000	$22.09\pm0.64$	$6.64\pm0.24$	$1.74\pm0.08$	$1.83\pm0.00$	$2.57\pm0.00$	$3.39\pm0.01$
Glass	< 500	$43.07\pm0.88$	$13.26\pm0.27$	$4.10\pm0.11$	$0.69\pm0.01$	$2.24\pm0.07$	$2.69\pm0.14$
	500 - 1000	$43.70\pm0.16$	$13.76\pm0.13$	$4.20\pm0.00$	$0.73\pm0.01$	$2.44\pm0.07$	$3.07\pm0.05$
	> 1000	$43.63\pm0.08$	$13.90\pm0.00$	$4.20\pm0.08$	$0.77\pm0.02$	$2.77\pm0.14$	$3.49\pm0.14$

 Table 2: Engineering constants and loss factors in the material directions of non-hybrid composites

## 4.2 Bending Modulus of the Hybrid Laminates

The measurement of the first four natural frequencies of the beams with two free ends leads to the estimation of the bending modulus  $E_{fx}$  as follows [25]:

$$\begin{cases}
\omega_{1} = 22.373\omega_{0} \\
\omega_{2} = 61.673\omega_{0} \\
\omega_{3} = 120.900\omega_{0} \\
\omega_{4} = 200.000\omega_{0}
\end{cases}$$
(10)  
with

W

$$\omega_0 = \frac{1}{L^2} \sqrt{\frac{E_{fx} h^3}{12\rho_s}},$$
(11)

where  $E_{fx}$  is the bending modulus of the beam, L is the length, h is the thickness and  $\rho_s$  is the surface density.

Tab. 3 resume the values of the bending modulus deduced from Eq. (11) for all studied composites. The values reported in Tab. 3 represent the average of the bending modulus of the three beam lengths and four natural frequencies. One can notice that the bending modulus decreases when the flax layer number increases. It can also be observed that the more layers of glass on the external side, the more the modulus increases. Finally, these results show that adding of two internal flax layers to the glass fiber reinforced composite does not significantly affect the bending modulus of the  $[G_2/F_2]_s$  since the difference is only 3%.

Natural fiber reinforced composites are lightweight compared to glass fiber composites. This is why it is interesting to make a comparison between the specific moduli ( $E/\rho$ ). Fig. 3 shows the evolution of the specific bending moduli as a function of flax fiber volume fraction in the hybrid composite. Note that the highest specific modulus is found for the  $[G_2/F_2]_s$  laminate while the lowest is found for the  $[F/G_3]_s$  laminate.

Unlike the tensile modulus that does not depend on the position of the layers in the hybrid composite, as shown by Zhang et al. [6], our results show clearly that the bending modulus and the corresponding specific modulus of the composites depend on the stacking sequence of flax and glass layers. To demonstrate this, we consider for example both stacking sequences of the hybrid composite containing 25% by volume of flax fibers. The specific modulus of the  $[G_2/F_2]_s$  laminate increases by about 32% and 61% compared to glass and flax composites, respectively. In contrast, the [F<sub>2</sub>/G<sub>2</sub>]<sub>s</sub> laminate has a lower specific modulus (27% and 11% lower than non-hybrid glass fiber and flax fiber materials). This result is explained by the fact that the layers with higher longitudinal modulus, i.e., glass layers, are further away from the medium plan (glass fiber composite:  $E_L$ =43 GPa vs. flax fiber composite:  $E_L$ =21 GPa).

	Flax	[F <sub>3</sub> /G] <sub>s</sub>	$[F_2/G_2]_s$	$[F/G_3]_s$	Glass	$[G_3/F]_s$	$[G_2/F_2]_s$	$[G/F_3]_s$
E <sub>fx</sub> (GPa)	$21.38\pm0.51$	$22.08\pm0.81$	$22.75\pm0.69$	25.11 ± 0.79	$43.21 \pm 0.66$	$42.64 \pm 0.35$	$41.63 \pm 0.47$	$33.19 \pm 0.70$
		30 30 28 28 29 24 24 20 20 20 20 20 20 20 20 20 20 20 20 20	ss 5 10 Volumic	$[G_3/F]_8$ $F$ $[F/G_3]_8$ $I_5$ 20 pue fraction of f	[G <sub>2</sub> /] [F <sub>2</sub> /G <sub>2</sub> ] <sub>8</sub> 25 30 flax fibre (%)	$F_{2} l_{s}$ $[G/F_{3}]_{s}$ $F_{ax}$ $[F_{3}/G]_{s}$ $35$		

**Table 3.** Bending moduli of flax-glass hybrid composites

Figure 3: Evolution of the specific modulus as a function of the volume fraction of flax fiber of hybrid materials

## 4.3 Loss Factor of the Hybrid Laminates

The procedure developed in Section 3 was applied to the hybrid laminates by introducing in each non-hybrid layer its elastic moduli ( $E_L$ ,  $E_T$ ,  $G_{LT}$ ) and its damping coefficients  $\eta_{11}$ ,  $\eta_{22}$  and  $\eta_{22}$ . The lengths 240, 260 and 280 mm of the free-free test specimens were considered in order to obtain a variation with the frequency. Fig. 4 compares the experimental results and those obtained by finite element method for the studied composites. Both methods show the same results, proving that the finite element method enables us to accurately identify the loss factor of the hybrid materials. Fig. 4 shows also that the variation of loss factor as a function of the frequency has two different behaviors. This difference is associated with the evolution of the distribution of the dissipated energies in the glass and flax layers as shown in Fig. 5.

Concerning the  $[G_3/F]_s$  laminate where the external layers are glass layers, the loss factor slightly increases with frequency. In fact, the energy stored in the laminate is mainly dissipated by the glass layers (Fig. 5(a)), that is why the evolution of the loss factor as a function of frequency is directed by that of the glass fiber. For the hybrid with flax external layers, the effect of the energy dissipated by the flax layers is predominant (Fig. 5(b)). Thus, the reduction of the loss factors as a function of frequency of the flax fiber composites leads to a decrease in the loss factors of the hybrid with flax external layers.



Figure 4: Loss factor as a function of frequency (experimental and finite element results)



**Figure 5:** Dissipated energy in flax layers and glass layers for a 500 Hz frequency as a function of volume fraction of flax fiber in hybrid with (a) internal flax layers and (b) external flax layers

In order to compare the damping of the different hybrid laminates, the evolution of the loss factors at a frequency of 500 Hz is plotted according to flax fiber volume fraction (Fig. 6).

A significant increase of loss factor is observed especially when the external layers are flax layers. For example, the loss factors of the  $[G_2/F_2]_s$  and  $[F_2/G_2]_s$  laminates are 40% and 146% higher than glass fiber composite, respectively. This growth of damping properties is mainly attributed to the presence of flax layers which have a better loss factor than glass ones. As depicted in Fig. 5, the loss factor induced by the flax layers in the  $[G_2/F_2]_s$  laminate only represents 30% of the global loss factor (Fig. 5(a)), whereas it represents 96% in the hybrid  $[F_2/G_2]_s$  (Fig. 5(b)).

This difference between the  $[G_n/F_m]_s$  and  $[F_m/G_n]_s$  stacking sequences is essentially attributed to the repartition of the energies stored in the different layers. In fact, according to the chosen stacking sequence, between 19% and 88% of the stored energy is dissipated by glass layers in the case of  $[G_n/F_m]_s$  hybrids. In the other hand, in the case of  $[F_m/G_n]_s$ , the energy dissipation is directed by flax layers which represent about 85% and 98% of the global energy.



Figure 6: Loss factor as a function of flax fiber volume fraction of hybrid composites for 500 Hz frequency

## 4.4 Application to a Structure

The choice of a composite material in a structure is governed by the achievement of interesting mechanical and damping performances, while minimizing the weight of the structure. Based on the results obtained on hybrid laminates, the hybridization of flax and glass must be analyzed to find the most appropriate stacking sequence that offers the best compromise between bending modulus, specific bending modulus and damping. Tabs. 4 and 5 show the properties of flax-glass hybrid composites, compared to flax composite when flax layers are external (Tab. 4) and to glass composite when glass layers are external (Tab. 5).

One can notice in Tab. 4 that replacing flax internal layers by glass layers in the flax laminate has a positive hybrid effect on bending modulus. The highest modulus is reached for the  $[F/G_3]_s$  laminate but it is significantly lower than the glass laminate (25.1 *vs.* 43.3 GPa). In contrast, this replacing leads to a lowering of both specific bending moduli and loss factors of the composites and thus to a negative hybrid effect. By adding the percentages for each hybrid laminate, the results show that there is overall deterioration and therefore hybridization has an overall negative effect in this case.

Otherwise, the results in Tab. 5 show that replacing glass internal layers by flax layers in the glass laminate has a positive hybrid effect on both specific bending modulus and damping property. In particular, the  $[G_2/F_2]_s$  laminate still has very interesting bending modulus compared to the glass laminate (41.6 vs. 43.3 GPa), while significantly improving specific bending modulus and loss factor. In fact, this material has a specific bending modulus and loss factor which exceed those of the glass fiber composite by about 31% and 39%, respectively.

Table 4: Mechanical and damping	properties	of hybrid	flax-glass	composites	with	flax	external	layers
compared to flax composite								

Composite	Flax	[F <sub>3</sub> /G] <sub>s</sub>	$[F_2/G_2]_s$	$[F/G_3]_s$
$E_{fx}$ (GPa)	21.39	+ 2.95%	+ 6.36%	+ 17.40%
$E_{fx}/ ho$	18.01	- 5.56%	- 11.11%	- 16.67%
η (%)	2.01	- 5.01%	- 9.01%	- 25.01%

Composite	Glass	$[G_3/F]_s$	$[G_2/F_2]_s$	$[G/F_3]_s$
$E_{fx}$ (GPa)	43.37	- 1.68%	- 4.01%	- 23.46%
$E_{fx}/ ho$	22.01	+ 18.18%	+ 31.82%	+ 13.64%
η (%)	0.74	+ 5.41%	+ 39.19%	+ 85.13%

**Table 5:** Mechanical and damping properties of hybrid flax-glass composites with glass external layers compared to glass composite

Based on the results obtained previously, the  $[G_2/F_2]_s$  laminate combines mechanical and dynamic performances with weight gain. Thus, we propose thereafter to compare, in the case of a simple structure, this  $[G_2/F_2]_s$  hybrid laminate with the two non-hybrid laminates (flax laminate and glass laminate). To this end, the energetic approach presented in the section 3 was applied to the structure presented in Fig. 7. The thickness of each glass and flax layer was 0.75 mm, i.e., a total thickness of 6 mm for each laminate composed of 8 layers. The structure was meshed by 7000 four-node multilayered shell element S<sub>4</sub> of the Finite Element Analysis (FEA) software Abaqus. Fig. 8 illustrates the six mode shapes derived from the FEA. A twisted deformation of the structure is observed for the first mode (frequency ~ 121 to 138 Hz) and a transverse bending deformation for the third mode (frequency  $\sim 161$  to 186 Hz). The other modes combine these deformations and present frequencies between 157 to 386 Hz. Tab. 6 shows the values of the frequencies and damping coefficients associated to the vibration modes of the three structures. The natural frequencies of the structure made of flax laminate are 8 to 13% lower than those of the glass structure. However, its damping coefficients are 40 to 80% higher than those of the structures made of glass laminate. On the other hand, the natural frequencies of the structure elaborated with the  $[G_2/F_2]_s$ laminate are comparable to those of the glass structure. According to the considered modes, the damping coefficients of the structure made of  $[G_2/F_2]_s$  laminate are 5 to 21% higher than those of the glass one. In addition to that, it also offers a weight gain of about 35% compared to glass structure.

_	Glass		[G <sub>2</sub> /	<b>F</b> <sub>2</sub> ] <sub>s</sub>	Fl	ax
	Frequency (Hz)	Damping η(%)	Frequency (Hz)	Damping η(%)	Frequency (Hz)	Damping η(%)
Mode 1	138	1.53	136	1.85	121	2.78
Mode 2	171	2.01	184	2.10	157	2.81
Mode 3	186	1.60	178	2.01	161	2.87
Mode 4	280	1.86	399	1.96	249	2.90
Mode 5	310	1.89	329	2.01	281	2.84
Mode 6	374	1.90	386	2.15	338	2.89

Table 6: Dynamic properties of the three studied structures







Figure 8: Shapes of the first six modes of the studied structures

## **5** Conclusion

This study aimed at showing the interest of the mechanical and dynamical properties of glass-flax hybrid composites. Various staking sequences of glass-flax hybrid composites were manufactured and tested in free vibrations. The damping coefficients were identified by fitting the experimental responses of free-free bending vibrations. The experimental results were also compared with those derived from a finite element analysis. The obtained results show that this analysis enables us to accurately identify the damping coefficient of the hybrid materials.

Flax and glass hybridization within the composite has been proposed in order to combine the specificities of flax and glass fibers. Flax fiber provides damping and weight gain characteristics (due to its density) while the glass fiber contributes in better bending modulus to the composite. The results showed that the hybrid composites have higher dynamic properties compared to glass fiber reinforced composites, with a higher specific bending modulus for some of them. In particular, the  $[G_2/F_2]_s$  laminate, a configuration characterized by internal flax layers, offers the best compromise in terms of performance, compared to the specific bending and damping. The study of a simple structure composed of this hybrid laminate confirmed the relevance of this choice. Indeed, the proposed hybrid composite configuration becomes competitive with glass composites, thanks to its significant gain in weight and damping power while having a similar bending modulus.

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