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The Vibrational Behavior of Hybrid Matrix Composites Based on Rosin and Reinforcement from Agricultural Waste and Natural Fiber Fabric

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Abstract. *Due to their high energy dissipation properties, in recent years, composite materials based on natural resins and fibers have been increasingly used. The paper studies the vibration behavior of composite bars reinforced with chopped wheat straw and, respectively, chopped sunflower seed shells. As matrix, an epoxy resin and, respectively, a hybrid resin based on rosin were used. A mathematical model useful for the study of damped vibrations is presented. For each of the analyzed bars, the frequency and damping factor for the first natural vibration mode are experimentally determined. Based on the experimental data, a coefficient that characterizes the vibration damping capacity for each bar is determined.*

Keywords: *sandwich composites, agricultural waste, 3-point bending behavior, vibration behavior*

1. Introduction

The activities related to the cultivation and processing of agricultural products generate a significant amount of waste that can be used for the production of composite materials. The use of these materials offers economic benefits while also contributing to environmental protection [1]. Wheat straw leftovers from the harvesting process and the shells resulting from the industrial processing of sunflower seeds are two examples of agricultural residues that can be used as natural reinforcements in polymer composites. Since the husk accounts for approximately 30% of the weight of a sunflower seed [2], and approximately 1.3 – 1.4 kg of straw is produced for every kilogram of wheat [3], millions of tons of agricultural waste are generated annually. The main advantages of using these agricultural residues include their low cost, low density, non-toxic nature, as well as their renewable and abundant availability [4].

In recent years, there has been an increased interest in using natural or hybrid resins to make composite materials reinforced with natural fibers [5-7]. A natural resin that is suitable for obtaining composite materials is rosin. The use of rosin to improve the mechanical properties of epoxy resins has been demonstrated in [8]. Three different methods of mixing epoxy resin with rosin powder were used. These methods were based on the use of two stirrers, one magnetic, one with ultrasonic and both respectively. Tests were conducted to determine density, hardness, and tensile compressive strength, and it was found that the method in which both agitators were used gave the best results. In the same context, [9] presents a comparative study between epoxy resin composites reinforced with rosin-based imid diacids and imid diacids based on trimellitic anhydride. Investigations into the mechanical properties of tensile strength and thermal stability showed that rosin-based reinforcing agents yield better results than those derived from trimellitic anhydride. In [10], a composite laminate made of epoxy resin reinforced with rosin anhydride and carbon fiber was developed. The composite was further strengthened by inter-leaving specially created polyamide veils between layers. Interlaminar shear strength and compression strength after impact were investigated. The results showed significant improvements in the samples

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with intermediate layers. Overall, the bio-composite exhibited mechanical properties comparable to those of the commercial petroleum-based equivalent.

The presence of energy dissipation mechanisms is now a widely accepted fact in all models used for simulating mechanical vibrations in elastic systems. Two types of energy loss causes are distinguished: external (through interaction with the surrounding environment or other physical systems) and internal (caused by processes within the system, such as the increase of thermal energy at the expense of mechanical energy due to internal friction) [11, 12]. Energy dissipation mechanisms are often suggested by experimental results [13]. Energy loss mechanisms are taken into account by introducing additional damping terms into the original conservative equations [14].

The damping of composite materials can be several orders of magnitude higher than that of traditional engineering materials, making them attractive for components subjected to dynamic loads. Exploiting material damping could also enhance the overall performance of composite structures compared to traditional methods of vibration absorption. Damping models proposed for composite materials originate from models for viscoelastic materials. The main reason is that most of the dissipation comes from the polymeric matrix. The simplest way to represent damping is by using linear viscoelastic models, such as Kelvin-Voigt, Maxwell, or Zener models [15]. However, the energy dissipation mechanism is more complex. Damping is influenced by fiber orientation, fiber/matrix interface conditions, as well as external excitation frequency or amplitude, environmental temperature, and other factors [16].

The analysis of specialized literature regarding the mechanical properties and vibration behaviour of natural fiber-reinforced composite materials highlights results that are sometimes contradictory. Therefore, damping must be derived from experimental data, appropriate to physical damping models. The damping properties of composite materials with hybrid rosin-based resin, reinforced with chopped wheat straw and crushed sunflower seed hulls, are investigated in this paper. Since the natural frequencies depend on the stiffness of the bars, the analyzed composite bars were subjected to three-point bending.

2. Materials and methods

2.1. Theoretical considerations

In general, the damped vibration of a bar is a combination of functions of the form $Ae^{-\mu t}\sin(\omega t+\varphi)$ [17, 18], where μ represents the damping factor, and ω represents the damped vibration frequency. These parameters are determined using the relations [17-20]:

$$\mu = \xi\omega_n,\ \omega = \omega_n\sqrt{1-\xi^2}, \qquad (1)$$

where ξ is the damping ratio, and ω_n is the natural frequency of the undamped vibration.

A challenge in the study of vibrations lies in how energy dissipation is accounted for in the equations of motion. For a composite bar, depending on the type of damping, the damping factor is constant, inversely proportional to the square of the bar's length, or inversely proportional to the fourth power of the bar's length [21]. Experimental observations have shown that, in the case of damped vibrations of composite materials, the predominant mechanism involves a damping force proportional to the bending velocity. Under these conditions, by specifying the equation of motion for transverse vibrations of a thin bar from [21], one obtains:

$$\ddot{w}(x;t) - 2\lambda b^2 \cdot \frac{\partial^2 \dot{w}(x;t)}{\partial x^2} + b^4\frac{\partial^4 w(x;t)}{\partial x^4} = 0, \qquad (2)$$

where λ is a parameter characterizing the damping capacity of the bar material and

$$b = \sqrt[4]{\frac{\langle EI\rangle}{\langle \rho A\rangle}}, \qquad (3)$$

$$\langle \rho A \rangle = \iint_{(S)} \rho \, dS , \tag{4}$$

$$\langle EI \rangle = \iint_{(S)} y^2 E \, dS . \tag{5}$$

Using the notations

$$\alpha = \frac{b\sqrt{1+\lambda}}{\sqrt{2}} \text{ and } \beta = \frac{b\sqrt{1-\lambda}}{\sqrt{2}} \tag{6}$$

the equation (2) turns into

$$\ddot{w}(x;t) - (a^2 + \bar{a}^2) \cdot \frac{\partial^2 \dot{w}(x;t)}{\partial x^2} + a^2 \bar{a}^2 \frac{\partial^4 w(x;t)}{\partial x^4} = 0 , \tag{7}$$

where $a = \alpha - i\beta$ and $\bar{a} = \alpha + i\beta$.

The solution to equation (7) is

$$w(x;t) = e^{p^2 t}\left(C_1 \cosh \frac{px}{a} + C_2 \sinh \frac{px}{a} + C_3 \cosh \frac{px}{\bar{a}} + C_4 \sinh \frac{px}{\bar{a}} \right). \tag{8}$$

The determination of constants C_1, C_2, C_3 and C_4 is done on the basis of the boundary conditions provided by the configuration of the bar support. For a bar fixed at one end and free at the other, the boundary conditions are:

$$\frac{\partial^2 w(0;t)}{\partial x^2} = 0 , \ \frac{\partial^3 w(0;t)}{\partial x^3} = 0 , \tag{9}$$

$$w(l;t) = 0 , \ \frac{\partial w(l;t)}{\partial x} = 0 . \tag{10}$$

From (9) it follows that

$$C_3 = -\frac{\bar{a}^2}{a^2} C_1, C_4 = -\frac{\bar{a}^3}{a^3} C_2. \tag{11}$$

From (10), considering (11), it follows that

$$\begin{aligned} &C_1\left(\cosh \frac{pl}{a} - \frac{\bar{a}^2}{a^2} \cosh \frac{pl}{\bar{a}} \right) + C_2\left(\sinh \frac{pl}{a} - \frac{\bar{a}^3}{a^3} \sinh \frac{pl}{\bar{a}} \right) = 0, \\ &C_1\left(\sinh \frac{pl}{a} - \frac{\bar{a}}{a} \sinh \frac{pl}{\bar{a}} \right) + C_2\left(\cosh \frac{pl}{a} - \frac{\bar{a}^2}{a^2} \cosh \frac{pl}{\bar{a}} \right) = 0. \end{aligned} \tag{12}$$

The system (12) has a nontrivial solution if

$$1 + \frac{\bar{a}^4}{a^4} - 2\frac{\bar{a}^2}{a^2} \cosh \frac{pl}{a} \cosh \frac{pl}{\bar{a}} + \left(\frac{\bar{a}}{a} + \frac{\bar{a}^3}{a^3} \right) \sinh \frac{pl}{a} \sinh \frac{pl}{\bar{a}} = 0 . \tag{13}$$

If we denote $\frac{pl\sqrt{2}}{b} = u + iy$, where $u, y \in \mathbf{R}$, from equation (13) we obtain the equations

$$\begin{aligned} &2 - 4\lambda^2 + (1-\lambda) \cosh(\sqrt{1+\lambda} \cdot u) \cos(\sqrt{1+\lambda} \cdot y) + \\ &+ (1+\lambda) \cosh(\sqrt{1-\lambda} \cdot y) \cos(\sqrt{1-\lambda} \cdot u) = 0, \end{aligned} \tag{14}$$

respectively

$$(1-\lambda)\sinh(\sqrt{1+\lambda}\cdot u)\sin(\sqrt{1+\lambda}\cdot y)- \\ -(1+\lambda)\sinh(\sqrt{1-\lambda}\cdot y)\sin(\sqrt{1-\lambda}\cdot u)=0. \quad (15)$$

For each natural mode of vibration, u and y are determined from equations (14) and (15), and then, the following characteristics are calculated: logarithmic decrement, loss factor, and damping ratio. Their values are obtained based on the relations:

- logarithmic decrement

$$\delta=\pi\left(\frac{y}{u}-\frac{u}{y}\right); \quad (16)$$

- damping ratio

$$\xi=\frac{y^2-u^2}{y^2+u^2}; \quad (17)$$

- loss factor

$$\eta=2\xi . \quad (18)$$

Table 1 shows the values of these characteristics for the first natural mode of vibration in the case of a bar fixed at one end and free at the other. The characteristics are calculated for various values of the parameter λ.

Table 1. The characteristic values δ,η,ξ corresponding to the first natural mode of vibration of a bar fixed at one end and free at the other, which are calculated for various values of the parameter λ

	u	y	**Logarithmic decrement** (δ)	**Damping ratio** (ξ)	**Loss factor** (η)
0	1.875104	1.875104	0	0	0
0.01	1.870111	1.880215	0.033854	0.0053880	0.0107760
0.02	1.865242	1.885441	0.067676	0.0107704	0.0215408
0.03	1.860500	1.890778	0.101433	0.0161415	0.0322830
0.04	1.855889	1.896221	0.135093	0.0214959	0.0429918
0.05	1.851412	1.901766	0.168625	0.0268278	0.0536556
0.06	1.847072	1.907407	0.201995	0.0321319	0.0642638
0.07	1.842873	1.913140	0.235173	0.0374028	0.0748056
0.08	1.838818	1.918961	0.268127	0.0426350	0.0852700
0.09	1.834908	1.924862	0.300827	0.0478233	0.0956466
0.10	1.831148	1.930841	0.333242	0.0529627	0.1059254
0.11	1.827539	1.936890	0.365342	0.0580480	0.1160960
0.12	1.824083	1.943005	0.397099	0.0630745	0.1261490
0.13	1.820782	1.949180	0.428483	0.0680372	0.1360744
0.14	1.817638	1.955409	0.459467	0.0729317	0.1458634
0.15	1.814653	1.961688	0.490023	0.0777535	0.1555070
0.16	1.811828	1.968009	0.520124	0.0824982	0.1649964
0.17	1.809164	1.974368	0.549746	0.0871618	0.1743236
0.18	1.806661	1.980758	0.578862	0.0917403	0.1834806
0.19	1.804322	1.987174	0.607449	0.0962299	0.1924598
0.20	1.802146	1.993609	0.635484	0.1006270	0.2012540

2.2. Preparation of samples

The following types of resins were used for creating the composite materials:

- Epoxy resin - Resoltech 1050, and its corresponding hardener Resoltech 1058S, abbreviated as E;
- Hybrid resin with 50% rosin and 50% epoxy resin, abbreviated as Co5;
- Hybrid resin with 60% rosin and 40% epoxy resin, abbreviated as Co6.

The reinforcement was made with:
- Chopped wheat straws, abbreviated as PT;
- Chopped sunflower seed shells, abbreviated as ST.

The abbreviations for the obtained composite materials are: EPT, Co5PT, Co6PT, EST, Co5ST and Co6ST respectively.

For the study of bending behaviour and vibration damping properties, two plates were made from each specified composite material. One of the two plates was kept in its initial state, while on the other plate, four layers of fabric made from a blend of 40% cotton and 60% flax, with 240 g/m^2 specific mass value, were applied on both face sheets. These layers were impregnated with the same type of resin used for the specimen, which was added. The plates with applied fabric layers were abbreviated as EPTF, Co5PTF, Co6PTF, ESTF, Co5STF, and Co6STF, respectively. From all the plates made, with or without fabric layers, samples were cut for bending testing and for studying vibration damping. The samples subjected to bending, cut from the plates without face sheets, had dimensions of 160 *x* 13 *x* 12.1 (*mm x mm x mm*) while those cut from the plates with face sheets had dimensions of 160 *x* 13 *x* 13.8 (*mm x mm x mm*) (according ASTM D790 and ASTM D638 standards).

The composite materials made had a mass ratio of 60% matrix and 40% reinforcement. The produced plates were subjected, in the technological process, to a uniform pressure of 10 N/cm². As a result, a small amount of resin was eliminated, and therefore, in the resulting composite plates, the resin mass ratio was 59-60%. The mixing of the components and the pouring of the composite plates were carried out at an ambient temperature of 21-23°C, and the samples were cut after 5 days from molding.

Figure 1 shows the samples for which the vibrational behaviour was studied.

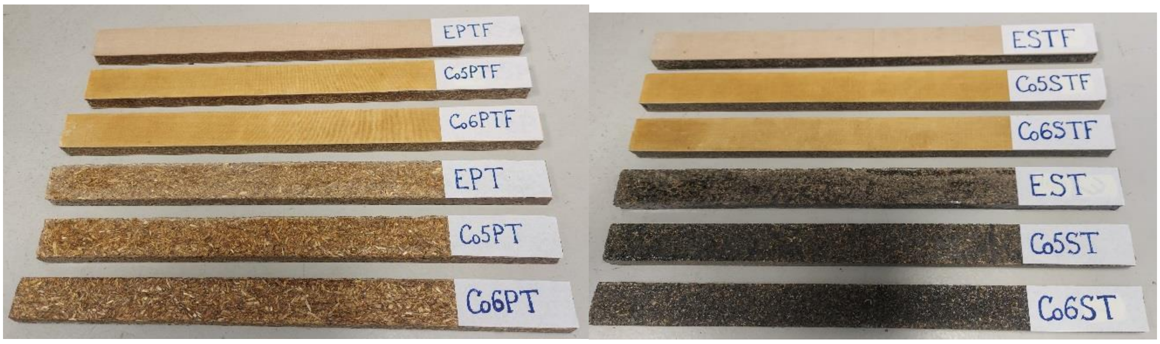

Figure 1. Samples used for the study of vibrational behaviour

The proportions of resins and types of reinforcing agent, together with the abbreviation, for the composite materials made are presented synthetically in Table 2.

Table 2. The types of resin and reinforcements used to make composite materials and their abbreviations

No.	Percentage by volume of resin Resoltech 1050 epoxy + Resoltech 1058S hardener	Percentage by volume natural resin	Reinforcing type core	Fabric type	Abbreviation
1	100%	-	chopped straw	-	EPT
2	50%	50%	chopped straw	-	Co5PT
3	40%	60%	chopped straw	-	Co6PT
4	100%	-	chopped seeds	-	EST
5	50%	50%	chopped seeds	-	Co5ST
6	40%	60%	chopped seeds	-	Co6ST
7	100%	-	chopped straw	flax + cotton	EPTF
8	50%	50%	chopped straw	flax + cotton	Co5PTF
9	40%	60%	chopped straw	flax + cotton	Co6PTF
10	100%	-	chopped seeds	flax + cotton	ESTF
11	50%	50%	chopped seeds	flax + cotton	Co5STF
12	40%	60%	chopped seeds	flax + cotton	Co6STF

In Table 3, the main characteristics of the samples used for studying vibration damping are presented.

Table 3. Characteristics of the samples used for studying vibration damping

Specimen	Resin mass ratio (%)	Dimensions (mm x mm x mm)	Mass (g)	Density (g/cm^3)
EPT	60	27x12.1x350	119	1.041
Co5PT	60	27x12.1x350	111	0.971
Co6PT	59	27x12.1x350	109	0.954
EST	59	27x12.1x350	129	1.128
Co5ST	60	27x12.1x350	126	1.102
Co6ST	60	27x12.1x350	123	1.076
EPTF	60	27x13.8x350	144	1.104
Co5PTF	60	27x13.8x350	137	1.051
Co6PTF	59	27x13.8x350	135	1.035
ESTF	59	27x13.8x350	155	1.188
Co5STF	60	27x13.8x350	152	1.165
Co6STF	60	27x13.8x350	149	1.142

2.3. Testing equipment

Bending tests were conducted using the material testing machine mounted on a bench, with a single-column Lloyd Instruments LRX type for mechanical tests, featuring the following specifications: maximum force of 2.5 *kN*; applied speed of 0.1-500 *mm/min*; 50 *mm* extensometer; 3-point bending test fixture; data acquisition and analysis software NEXYGEN-Plus.

The vibration behaviour was studied using a data acquisition system SPIDER 8, connected to a laptop. The acquisition system was interfaced with a signal conditioner NEXUS 2692-A-0I4 equipped with an accelerometer with a sensitivity of 0.04 *g*. The frequency measurement range was set between 0 – 2.400 *Hz* in SPIDER 8. Measurement errors introduced by the experimental system were eliminated using a Butterworth "High Pass" filter at a frequency of 3 *Hz*. The connection between the acquisition system and the laptop was established using CATMAN EASY software.

3. Results and discussions

3.1. Bending test

Based on the 3-point bending test, the following data were obtained: force-deformation diagrams, maximum load force F_{max} [*N*] and maximum deformation *e* [*mm*].

The force-deformation diagrams for representative samples from the sets of composite materials reinforced with chopped wheat straws without face sheets (a) and with face sheets (b) are presented in Figure 2.

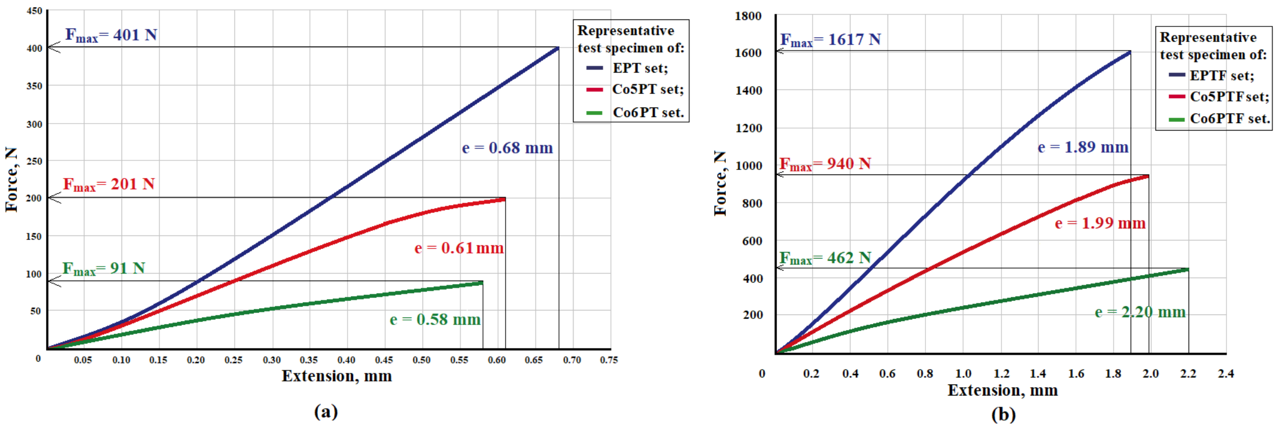

Figure 2. Force-deformation diagrams for representative samples from composite sets: (a) EPT, Co5PT and Co6PT; (b) EPTF, Co5PTF and Co6PTF

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The average value and standard deviation for maximum loading force F_{max} [*N*] and maximum deformation *e* [*mm*], for the sets of samples made from straw-reinforced composite materials, are given in Table 4.

Table 4. Average value and standard deviation for maximum loading force and maximum deformation for the sets of samples made from straw-reinforced composite materials

Specimen type	**Maximum load F_{max} [N]**	**Maximum extension at F_{max} L_{max} [mm]**
EPT	425 (± 41)	0.67 (± 0.07)
Co5PT	199 (± 18)	0.62 (± 0.05)
Co6PT	91 (± 8)	0.58 (± 0.04)
EPTF	1655 (± 120)	1.92 (± 0.18)
Co5PTF	953 (± 89)	2.03 (± 0.20)
Co6PTF	470 (± 39)	2.22 (± 0.21)

The force-deformation diagrams for representative samples from the sets of composite materials reinforced with crushed sunflower seed shells without face sheets (a) and with face sheets (b) are presented in Figure 3.

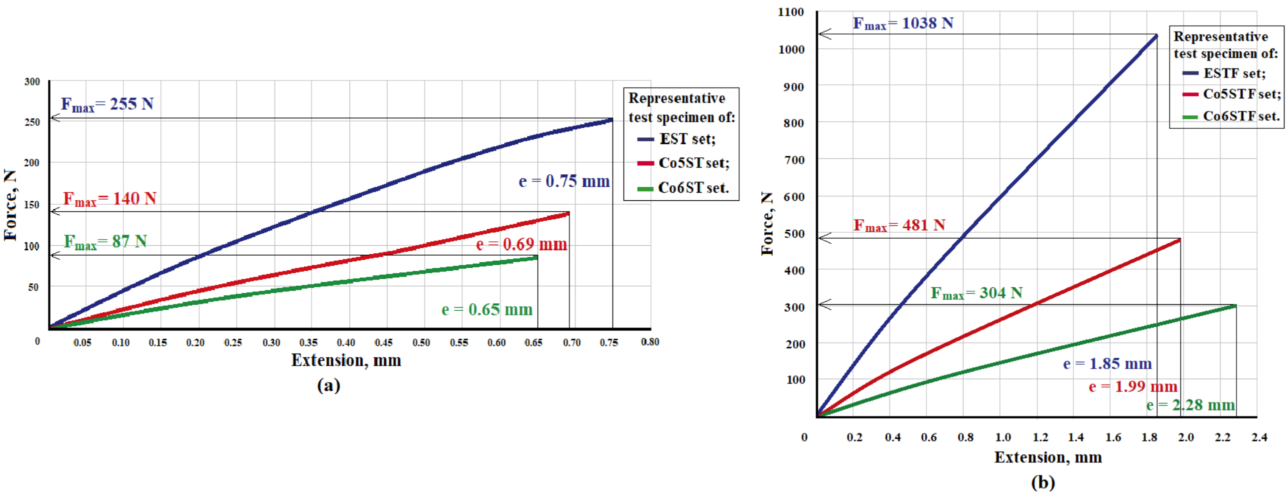

Figure 3. Force-deformation diagrams for representative samples from composite sets: (a) EST, Co5ST and Co6ST; (b) ESTF, Co5STF and Co6STF

The average value and standard deviation for maximum loading force F_{max} [*N*] and maximum deformation *e* [*mm*], for the sets of samples made from composite materials reinforced with crushed sunflower seed shells, are provided in Table 5.

Table 5. Average value and standard deviation for maximum loading force *Fmax* [*N*] and maximum deformation *e* [*mm*] for the sets of samples made from composite materials reinforced with crushed sunflower seed shells

Specimen type	**Maximum load** F_{max} [N]	**Maximum extension at F_{max}** e [mm]
EST	255 (± 20)	0.75 (± 0.06)
Co5ST	143 (± 13)	0.69 (± 0.04)
Co6ST	88 (± 8)	0.66 (± 0.04)
ESTF	1065 (± 73)	1.81 (± 0.12)
Co5STF	473 (± 35)	2.00 (± 0.14)
Co6STF	296 (± 28)	2.26 (± 0.14)

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In the three-point bending test, the upper part of the bar above the median plane is subjected to compression, while the lower part of the bar below the median plane is subjected to tension. All six types of analysed composite materials had significantly higher compressive strength than tensile strength. Since the stress distribution in bending is symmetrical about the median plane, the samples without face sheets break when the resultant stress on the lower outer surface equals the tensile strength. This is justified by the fact that, for samples without face sheets, the maximum bending forces are proportional to the tensile strengths. Composite materials with hybrid resin matrices have significantly lower tensile strengths than those with epoxy resin. Therefore, the strains at break decrease with the increase in the proportion of rosin in the hybrid resins.

Adding layers of flax and cotton fabric led to a modification in the behaviour of the bars subjected to bending. There was a fourfold increase in the maximum force that the samples could withstand. This is because the added fabric layers have much higher tensile strengths than the composites forming the core. Therefore, the samples break when the tensile strength in the flax and cotton fabric layers is reached. Unlike the bars without face sheets, it is observed that the strain at break increases with the increase in the proportion of rosin in the resin used as the matrix. This is because as the percentage of rosin in the matrix increases, the elasticity modulus of the core-forming composites decreases, leading to reduced bar stiffness and consequently, larger deformations.

3.2. Study of vibration damping

The vibrations of the 12 bars, which were fixed at one end and free at the other, were studied. For each bar, the vibration at the free end was measured. The free lengths of the bars were 200 *mm*, 220 *mm*, 240 *mm*, 260 *mm*, 280 *mm*, and 300 *mm*.

Figure 4 shows an experimental record for specimen Co6STF, for the free length of 200 *mm*. The damping factor μ and the vibration frequency ν were determined using the method detailed in [22, 23], based on 5 cycles.

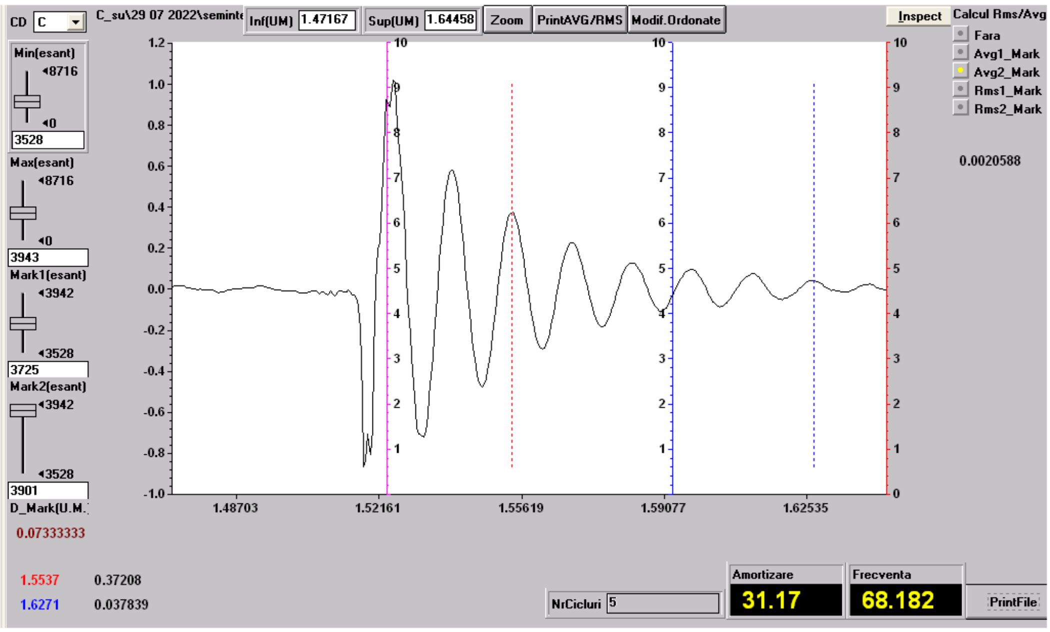

Figure 4. Vibration record (natural frequency and damping factor) of a representative specimen from the Co6STF set with a free length of 200 *mm*

Tables 6 - 9 present the results of experimental vibration determinations for the 12 types of samples made from composite materials reinforced with chopped wheat straw or chopped sunflower seed shells. The values shown represent the arithmetic mean for three measurements.

Table 6. Vibration behaviour of representative test specimens from sets EPT, Co5PT and Co6PT

Free Length [mm]	**EPT**		**Co5PT**		**Co6PT**	
	Frequency $\nu\,[Hz]$	Damping $\mu\,[s^{-1}]$	Frequency $\nu\,[Hz]$	Damping $\mu\,[s^{-1}]$	Frequency $\nu\,[Hz]$	Damping $\mu\,[s^{-1}]$
200	83.3	7.97	67.4	18.96	57.7	26.95
220	69.3	6.84	55.9	15.84	47.1	20.54
240	57.4	5.84	46.3	12.86	39.5	15.98
260	48.8	4.97	38.8	10.84	33.5	13.27
280	42.1	4.10	35.3	9.65	28.1	11.32
300	36.9	3.53	29.8	7.65	24.1	9.17

Table 7. Vibration behaviour of representative test specimens from sets EST, Co5ST and Co6ST

Free Length [mm]	**EST**		**Co5ST**		**Co6ST**	
	Frequency $\nu\,[Hz]$	Damping $\mu\,[s^{-1}]$	Frequency $\nu\,[Hz]$	Damping $\mu\,[s^{-1}]$	Frequency $\nu\,[Hz]$	Damping $\mu\,[s^{-1}]$
200	60.8	10.99	50.6	23.96	41.6	28.53
220	50.3	8.75	42.1	20.25	33.9	24.68
240	43.1	7.96	34.2	15.70	30.3	21.71
260	37.3	7.07	30.1	13.56	26.0	18.41
280	31.7	6.12	26.3	11.92	22.3	16.08
300	27.4	5.21	23.1	9.77	19.8	13.91

Table 8. Vibration behaviour of representative test specimens from sets EPTF, Co5PTF and Co6PTF

Free Length [mm]	**EPTF**		**Co5PTF**		**Co6PTF**	
	Frequency $\nu\,[Hz]$	Damping $\mu\,[s^{-1}]$	Frequency $\nu\,[Hz]$	Damping $\mu\,[s^{-1}]$	Frequency $\nu\,[Hz]$	Damping $\mu\,[s^{-1}]$
200	106.2	10.29	85.4	23.93	78.4	27.95
220	88.2	8.51	68.9	19.28	64.5	24.73
240	73.3	7.14	60.3	16.57	55.3	21.96
260	64.5	5.95	51.8	13.49	46.7	19.06
280	55.1	5.01	45.1	11.87	40.9	16.59
300	49.0	4.23	39.3	10.37	33.9	14.47

Table 9. Vibration behaviour of representative test specimens from sets ESTF, Co5STF and Co6STF

Free Length [mm]	**ESTF**		**Co5STF**		**Co6STF**	
	Frequency $\nu\,[Hz]$	Damping $\mu\,[s^{-1}]$	Frequency $\nu\,[Hz]$	Damping $\mu\,[s^{-1}]$	Frequency $\nu\,[Hz]$	Damping $\mu\,[s^{-1}]$
200	92.3	11.74	77.4	22.54	68.6	31.47
220	76.4	9.19	63.2	17.55	56.5	28.24
240	63.8	7.07	54.1	14.68	47.2	23.45
260	55.9	6.17	48.8	12.91	41.5	19.52
280	48.5	5.19	40.6	10.66	36.2	17.91
300	42.2	4.63	35.3	8.66	31.2	15.69

Based on the experimental data that were obtained and presented in Tables 5 - 8, variation of the frequency and the damping factor is illustrated in Figures 5 and 6 for samples reinforced with chopped wheat straw (a) and chopped sunflower seed shells (b).

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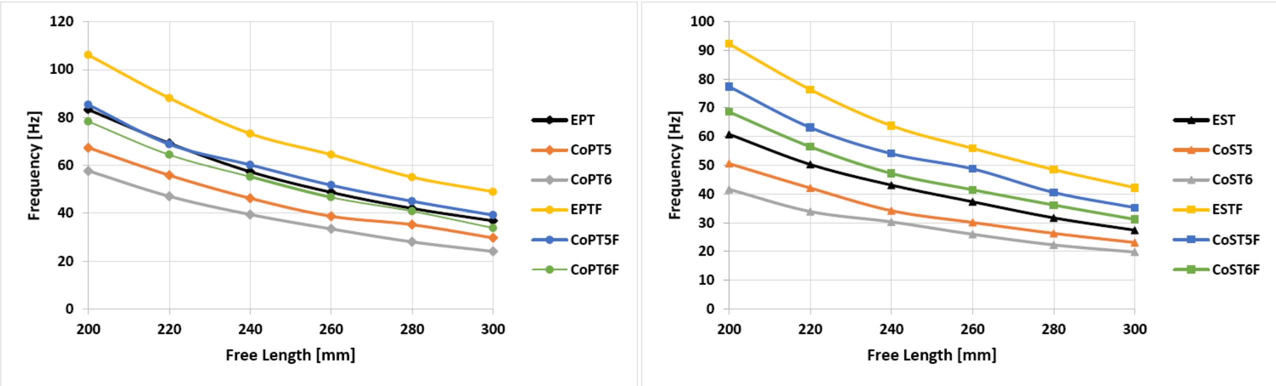
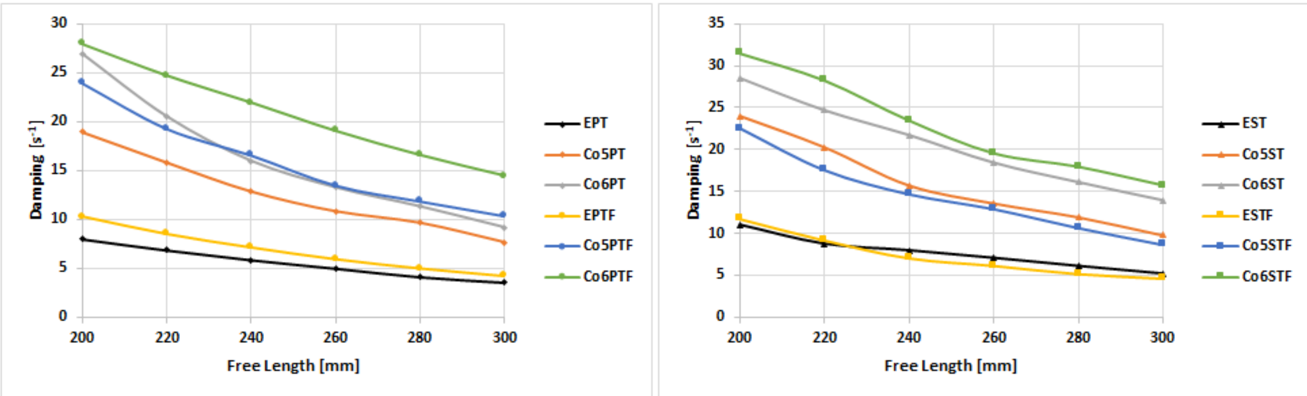


(a) **(b)**

Figure 5. The variation of the frequency for the samples sets: EPT, Co5PT, Co6PT, EPTF, Co5PTF, and Co6PTF (a); EST, Co5ST, Co6ST, ESTF, Co5STF, and Co6STF (b)



(a) **(b)**

Figure 6. The variation of the damping factor for the samples sets: EPT, Co5PT, Co6PT, EPTF, Co5PTF, and Co6PTF (a); EST, Co5ST, Co6ST, ESTF, Co5STF, and Co6STF (b)

The damping factor and the frequency depend on the dimensions of the cross-sectional area, the elastic properties of the bar material, and its free length. These two characteristics do not describe the damping properties of the material from which the bar is made; instead, they characterize the overall vibration behaviour of the bar as a whole.

To address this issue, the logarithmic decrement, damping ratio, and loss factor were calculated using the relationships [24–26]:

- logarithmic decrement

$$\delta = \frac{1}{n}\ln\frac{w_0}{w_n} = \frac{\mu}{\nu}; \tag{19}$$

- damping ratio

$$\xi = \frac{\delta}{\sqrt{\delta^2 + 4\pi^2}} \approx \frac{\delta}{2\pi}; \tag{20}$$

- loss factor

$$\eta \approx 2\xi. \tag{21}$$

where n is the number of cycles, w_0 is the maximum value at the beginning of the measurement interval, and w_n is the maximum value at the end of the measurement interval.

Table 10 presents the values for logarithmic decrement, damping ratio, and loss factor. These values are calculated as the average of the 6 values obtained for each bar and the values of the parameter λ that needs to be used in equation (1) to obtain these damping characteristics.

Table 10. Vibration damping parameters for the specimens under study

Sample	Logarithmic decrement (δ)	Damping ratio (ξ)	Loss factor (η)	Parameter (λ)
EPT	0.0985	0.01567	0.03135	0.0291
Co5PT	0.2704	0.04304	0.08607	0.0806
Co6PT	0.4145	0.06597	0.13195	0.1266
EST	0.1853	0.02949	0.05899	0.0550
Co5ST	0.4514	0.07184	0.14396	0.1375
Co6ST	0.7103	0.11305	0.22611	0.2259
EPTF	0.0934	0.01486	0.02972	0.0276
Co5PTF	0.2698	0.04294	0.08588	0.0805
Co6PTF	0.3963	0.06306	0.11613	0.1158
ESTF	0.1142	0.01818	0.03636	0.0339
Co5STF	0.2729	0.04344	0.08687	0.0813
Co6STF	0.4872	0.07754	0.15508	0.1547

We found that increasing the proportion of rosin in the hybrid resin leads to enhanced damping properties of the resulting composite materials. For the straw-reinforced composites with matrices of epoxy resin or hybrid resin with 50% rosin, adding outer layers on both sides did not significantly alter the vibration damping capacity. However, for the hybrid resin with 60% rosin, adding outer layers resulted in a 12% decrease in vibration damping capacity. In the case of the sunflower seed shell-reinforced beams, the decrease in vibration damping parameters upon adding outer layers is much more significant: 39% for the epoxy resin bar, 39% for the bar with hybrid resin containing 50% rosin, and 31% for the bar with hybrid resin containing 60% rosin.

The theoretical study of composite bar vibrations using equation (1) involves using a parameter λ with values smaller than the experimentally determined loss factor η. Thus, for the EPTF bar, which had the weakest damping properties, the parameter λ is 7.1 % smaller than the loss factor, and for the Co6ST bar, which had the best damping properties, the parameter λ is practically equal to the loss factor.

4. Conclusions

The sequence of eigenfrequencies depends on the elastic properties of the material of the bar, the dimensions of its cross-sectional area, and is inversely proportional to the square of the length of the bar. In the case of the studied bars, it is observed that the damping factor decreases, in turn, with the square of the bar's length. This shows that, predominantly, the damping force depends on the bending velocity of the bar, as considered in the analyzed mathematical model.

Adding outer layers made of flax and cotton fabric to the initially manufactured composite materials resulted in increased stiffness. Specifically, for the sandwich composites, the maximum bending force in three-point bending was approximately 4 times higher than that of the composites without the outer layers from which they originated.

Adding outer fabric layers on both sides did not bring significant changes to the vibration damping capacity (compared to the initially manufactured composites) in the case of wheat straw chopped reinforcements. However, we observed a significant decrease in the vibration damping parameters for sunflower seed shell chopped reinforcements.

The vibration damping capacity increases with the proportion of rosin in the hybrid resin used as the matrix. This suggests that the matrix plays a key role in determining the energy dissipation capacity of the composite materials.

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