783. Comparison of the mechanical properties of flax and glass fiber composite materials

Garip Genc[1, 2, a], **Ali El Hafidi**[1, b], **Papa Birame Gning**[1, c]
[1]University of Bourgogne, the Institute of Automotive and Transport Engineering (ISAT), Nevers, France
[2]Marmara University, Vocational School of Technical Sciences, Istanbul, Turkey
E-mail: [a]*ggenc@marmara.edu.tr*, [b]*aehafidi@u-bourgogne.fr*, [c]*papa-birame.gning@u-bourgogne.fr*

(Received 30 January 2012; accepted 14 May 2012)

Abstract. In this paper, the comparison of static and dynamic properties of flax and glass fiber composite materials is presented. For this comparison, dynamic and quasi-static experimental studies were carried out. As a dynamic test, vibration tests were fulfilled using the Oberst apparatus and the tensile test was fulfilled by a quasi-static test. The vibration tests were carried out under different temperatures by using temperature and climatic test cabinets. Flax and glass fibers were used as reinforcements, and polyester resin was used as a matrix to make up the composite specimens. According to the obtained results, the strength of flax fiber composite is lower than the glass fiber under tensile loading, but approximately the same under vibration excitation. On the other hand, damping characteristics of flax fiber composite is higher than glass fiber composite materials. These results demonstrated that natural fiber materials can be used instead of chemical materials for vibration absorption due to their high damping.

Keywords: flax fiber, glass fiber, Young’s modulus, vibration, damping.

1. Introduction

Today, petroleum-based materials are widely used in the industry due to their features, such as high strength, low weight and low density. However, when the potential harm inflicted to the nature is taken into account, finding and developing new materials that may be alternatives to the chemical materials have become a necessity for the science and the industry. Therefore, the question “Natural fibers: can they replace glass in fiber reinforced plastics?” [1] began to be asked by the scientists. Hence, the natural fibers have become the focus of attention of the researchers in the recent years.

Table 1. Comparison between natural and glass fibers [1]

	Natural fibers	Glass fibers
Density	Low	Twice that of natural
Cost	Low	Low, but higher than
Renewability	Yes	No
Recyclability	Yes	No
Energy consumption	Low	High
Distribution	Wide	Wide
CO_2 neutral	Yes	No
Abrasion to machines	No	Yes
Health risk when inhaled	No	Yes
Disposal	Biodegradable	Not biodegradable

Table 1 compares natural and glass fibers and clearly shows areas where the former have distinct advantages over the latter. Carbon dioxide neutrality of natural fibers is particularly significant. The burning of substances derived from petroleum products releases enormous amounts of carbon dioxide into the atmosphere. This phenomenon is believed to be the major cause of the greenhouse effect and consequently, the world’s climatic changes [1].

The use of natural fibers for the reinforcement of composites has lately received increasing attention, both by the academia and by the industry [2]. Flax fibers, which originate from renewable resources, are a noteworthy alternative to the mineral fibers. Their low cost together with their low density, high specific stiffness and biodegradability constitute the major factors for their use in composites. However, their physical-chemical properties as well as their mechanical behavior need to be known in order to optimize their performance [3].

In previous studies, Missoum et al. [4] performed vibration tests to identify the elasticity modulus in two directions of composite materials glass / polyester. Qian et al. [5] studied a method for identifying elastic and damping properties of composite laminates by using vibration test data. Baley [3] indicated that the knowledge of the behavior of flax fibers is of crucial importance for their use as reinforcements for composite materials. He tested the flax fibers under tensile loading and in repetitive loading–unloading experiments. In this study, it is shown that fiber stiffness increases with the strain. Charlet et al. [6] studied the tensile mechanical properties of flax fibers from the Herme's variety, according to their diameters and their locations in the stems. They revealed from SEM observations that the large scattering of these properties is ascribed to the variation of the fiber size along its longitudinal axis. They stated that the higher values of the mechanical properties for the fibers issued from the middle of the stems are associated with the chemical composition of their cell walls. Baley et al. [7] studied the transverse tensile behavior of a UD ply reinforced with flax fibers, in order to characterize the behavior of these materials for structural applications. Bodros et al. [8] studied the tensile properties of natural fiber-biopolymer composites in order to determine whether or not bio-composites may replace glass fiber reinforced unsaturated polyester resins. Charlet et al. [9] investigated the tensile properties of a natural composite material: the flax fiber. They studied the fiber size in order to check their influence on the property scatter, and the decrease of the fiber mechanical properties as a result of the fiber diameter. Andersons et al. [10] studied the elementary flax fibers of different gauge lengths in order to obtain the stress–strain response, strength and failure strain distributions. They considered the applicability of the single fiber fragmentation test for flax fiber failure strain and strength characterization. Charlet et al. [11] studied the mechanical properties of flax fibers to analyze the function of their biochemical and morphological characteristics. O'Donnell et al. [12] used vacuum-assisted resin transfer molding or resin vacuum infusion process to make composite panels out of plant oil based resin (acrylated epoxidized soybean oil (AESO)) and natural fiber mats made of flax, cellulose, pulp and hemp.

The development of natural fibers instead of chemical materials is vital due to environmental reasons. Thus, reducing the use of petroleum-based materials that are harmful to nature and increasing the use of bio-materials instead will be realized in the future. The purpose of this study is to determine the mechanical properties of natural fiber, in order to compare them with the chemical fiber materials. Vibration and tensile tests will be carried out to determine the mechanical properties. Flax fiber as a natural fiber, and glass fiber as a chemical fiber were used as reinforcements, and polyester resin was used as a matrix to produce the composite parts.

2. Materials and Specimens

The materials used in this study are a commercial flax fabric of Hermes variety and woven type glass fiber. The flax roller is made of a double cross-ply of UD layers with a fiber arrangement of ±45° and the glass fiber roller is made of a double woven-ply with fiber arrangement of 0° to 90° with respect to the roller axis. The areal weight of the flax roller is 237 g/m² and of the glass roller is 280 g/m².

The compression molding machine that was used to produce flat specimen's plates is an ENERPAC machine. The lower plate is fixed to the machine frame while the upper plate is controlled by a hydraulic cylinder of 5 bars pressure, to compress the stacked laminates. Squareshaped 4 layers (double ply) of 250 mm side were cut from the rollers and were manually impregnated with the liquid resin, before being stacked in steel rigid moulds and compressed between the plates. It is important to use the same matrix while comparing the properties of natural and chemical fibers. Therefore, polyester resin (Synolite 0179-N-1) was used as a matrix to make up the composite specimens. The properties of the composite materials are listed in Table 2.

Table 2. Properties of composite materials [3, 6, 13]

	Glass Fiber Composite		Flax Fiber Composite	
	Glass Fiber	Polyester Resin	Flax Fiber	Polyester Resin
Density (kg/m^3)	2560	1120	1498	1120
Young Modulus (GPa)	74	4	30	4
Volume Fraction (%)	28	72	38	62

To determine the characteristics of the composite materials, a quasi-static test and a dynamic test were performed. Therefore, two kinds of specimens are prepared, as shown in Fig. 1.

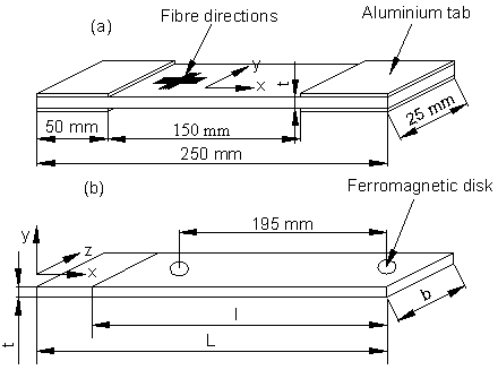

Fig. 1. Schematics drawing of specimens (a) tensile test specimen (b) vibration specimen

The specimens for tensile testing are prepared according to the ISO 527-4 [14] standard. The geometry, notations and coordinate system of these specimens are shown in Fig. 1a. All specimens are equipped with aluminum tabs of 50 mm long and 2 mm thick. Five specimens of each material were tested in quasi-static uni-axial tensile test. The specimens that are used in the vibration test are prepared according to D 45 1809 standard [15]. The geometry and coordinate system of these specimens are shown in Fig. 1b.

Vibration tests are fulfilled by Oberst vibration apparatus, which uses the ferromagnetic properties of materials for excitation and measurement of the resulting vibration. Because of the fact that the composite materials are not ferromagnetic, two ferromagnetic disks were glued on the composite specimens. As shown in Fig. 1b. the distance between two ferromagnetic disks is 195 mm, L and l represent the total length and length from fixation point of specimens respectively.

3. Experimental Tests

3. 1. Quasi Static Tests

Tensile testing is the most useful method to determinate the mechanical properties of materials. Therefore, in this study, tensile testing method is used to determine the elasticity modulus of composite materials. This test was carried out under 2 mm/min pulling speed, and the Young's modulus was calculated by using the area where the deformations were between 0.05 % and 0.25 % of the obtained stress-strain curves, according to the standard [14]. As shown in Fig. 2 typical stress-strain curves are obtained for flax and glass fiber composite materials.

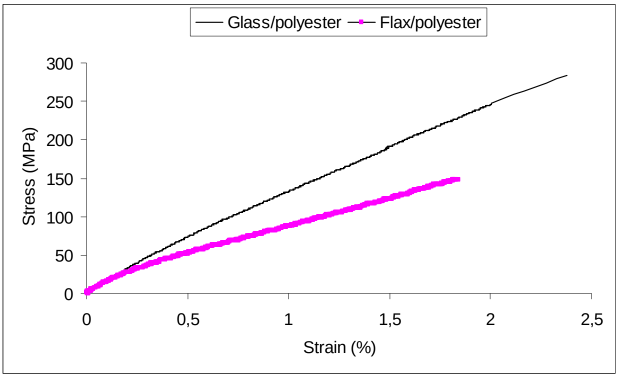

Fig. 2. Typical stress-strain curves of composite specimens

Young's modulus of glass fiber composite material is calculated as 15.1 GPa and the Young's modulus of flax fiber composite material is calculated as 10.2 GPa. These results demonstrate that the strength of glass fiber composite is higher than flax fiber composite materials under tensional loading.

3. 2. Dynamic Tests

Oberst method is well known and widely used as a vibration test to determinate dynamic properties such as rigidity and damping of materials. In this method, the dynamic response of a structure is related to characteristics of material, fixation type and its geometry.

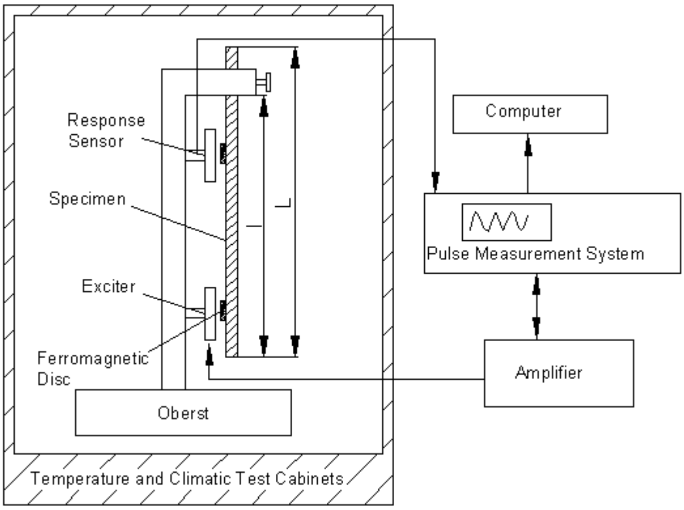

Fig. 3. Schematic experimental setup of Oberst vibration apparatus with temperature and climatic test cabinet

Fig. 3 shows the schematic experimental setup of Oberst vibration apparatus with temperature and climatic test cabinet used to perform the vibration tests. In this setup, the response sensor is placed close to the fixed end and the exciter is placed close to the free end of the composite beam. The signal given by the PULSE system generator is amplified and then sends the exciter. To accurately measure the modal damping ratios, a ”swept sine” signal with a small increase in frequency was used.

To adjust the temperature of measurement environment ”Temperature and Climatic Test Cabinet” is used. Frequency responses are obtained from the exciter and sensor signals. These frequency responses were used to determine Young’s modulus and damping characteristics of the composite materials.

3. 2. 1. Determination the Young’s modulus

Composite structures are widely used in the industry because of their high strength and low weight properties. Particularly, in automotive industry some applications of composite materials are used around the engine, such as internal engine covers. When the automotive applications of the composite parts are considered, the temperature effects on the materials have to be examined. Therefore, the temperature effects on the Young’s modulus of composite materials are investigated by using temperature and climatic test cabinet, which has the temperature capacity from –40 °C to +180 °C. Vibration tests were carried out for composite beams under fixed-free fixation type condition to determine the elasticity modulus under each temperature. The Young’s modulus was calculated by the equation (1) [16] using measured resonance frequency of composite materials:

$$f_n = \frac{X_n^{\ 2}}{2\pi l^2}\sqrt{\frac{EI}{\rho s}} \tag{1}$$

where:

- f_n: measured frequency of nth mode by examining the maxima of the amplitude or phase change of the measured frequency response functions,
- X^2_n: constant for the nth mode that depends on boundary condition [16],
- l: length of specimen from the fixation point,
- E: Young’s modulus,
- I: inertia moment ($bt^3/12$),
- ρ: density,
- s: cross-sectional area of beam (bt).

The thicknesses for flax and glass composite specimens are 1.8 mm and 1.9 mm. The width b and the length l of specimens are 15.5 mm and 228 mm.

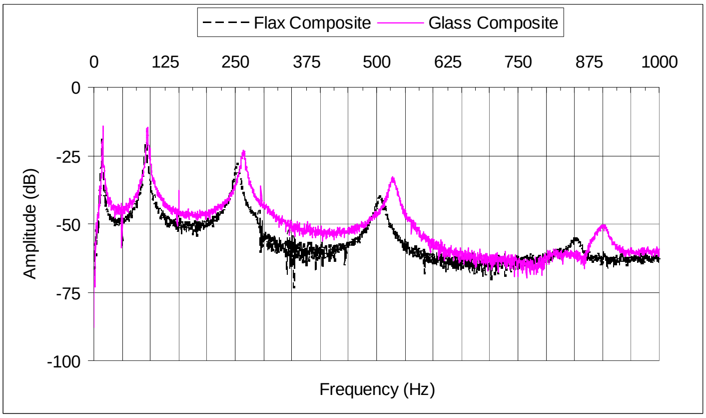

Fig. 4. Typical frequency response functions of flax and glass composite materials

Typical frequency response functions of flax and glass composite materials are provided in Fig. 4. Young’s modulus is calculated by equation 1 using measured resonance frequency. Vibration test results of glass and flax composite materials are given in Table 3 with the temperature effect. These results demonstrate that the elasticity of glass fiber composite is higher than for the case of flax fiber and the Young’s modulus of composite materials decrease when the temperatures increase.

Table 3. Vibration test results of Young’s modulus of glass (GFC) and flax fiber composite (FFC) materials with temperature effect (standard deviations in brackets)

Temperature (°C)	Mode Number	Resonance Frequency f_m (Hz)		Young’s Modulus E (GPa)		Average Young’s Modulus (GPa)	
		GFC	FFC	GFC	FFC	GFC	FFC
0	1	17.3	15.5	13.7	9.8	12.6 (0.8)	10.3 (0.3)
	2	101.5	99.5	12.1	10.3		
	3	283.8	279.5	12.1	10.4		
	4	564.8	553.3	12.4	10.6		
20	1	16.8	15.0	12.9	9.2	12.1 (0.6)	9.8 (0.4)
	2	100.0	98.3	11.7	10.1		
	3	279.5	272.0	11.7	9.8		
	4	556.3	540.8	12.1	10.1		
40	1	16.5	14.5	12.6	8.6	11.6 (0.7)	9.1 (0.4)
	2	97.5	94.3	11.2	9.3		
	3	272.8	260.0	11.2	9.0		
	4	544.5	521.5	11.6	9.4		
60	1	15.8	14.3	11.4	8.3	10.8 (0.7)	8.7 (0.3)
	2	94.8	92.3	10.5	8.9		
	3	264.5	254.3	10.5	8.6		
	4	529.0	506.0	10.9	8.9		

3. 2. 2. Determination of the damping

Fiber reinforced composite parts that are used around the engine must have high damping characteristics to absorb the vibration that is induced by the engine. When we consider an application of that sort, the temperature effects on damping have to be investigated. Hence, the temperature effects on the damping are examined under four values (from 0 °C to 60 °C), which are generally the working condition of an engine. The damping properties are calculated according to the Bandwidth theory [16] of measured resonance frequencies:

$$d_{(200)} = 200 \cdot \left(\frac{d_2 - d_1}{f_2 - f_1} \right) + d_2 - \left(f_2 \cdot \frac{d_2 - d_1}{f_2 - f_1} \right) \tag{2}$$

where:

- f_1: measured resonance frequency ($f_1 < 200$ Hz),
- f_2: measured resonance frequency ($f_2 > 200$ Hz),
- d_1: measured modal damping on f_1,
- d_2: measured modal damping on f_2.

The damping $d_{(200)}$ values are calculated by the equation (2) to compare the damping properties of glass and flax composite materials. According to the standard [15], resonance frequencies that are greater and smaller than 200 Hz ($f_2 > 200 > f_1$) should be used to calculate $d_{(200)}$ values.

Table 4. Vibration test results of damping of glass (GFC) and flax fiber composite (FFC) materials with temperature effect

Temperature (°C)	Mode Number	Resonance Frequency f_m (Hz)		Modal damping d_n (%)		Modal damping $d_{(200)}$ (%)	
		GFC	FFC	GFC	FFC	GFC	FFC
0	1	17.3	15.5	0.5	1.5	0.3	0.8
	2	101.5	99.5	0.3	0.7		
	3	283.8	279.5	0.3	0.9		
	4	564.8	553.3	0.3	0.9		
20	1	16.8	15.0	0.7	1.2	0.4	0.8
	2	100.0	98.3	0.4	0.7		
	3	279.5	272.0	0.4	0.8		
	4	556.3	540.8	0.3	0.8		
40	1	16.5	14.5	0.8	1.5	0.6	0.9
	2	97.5	94.3	0.5	1.0		
	3	272.8	260.0	0.6	0.8		
	4	544.5	521.5	0.5	0.8		
60	1	15.8	14.3	1.0	1.7	0.9	1.3
	2	94.8	92.3	1.0	1.3		
	3	264.5	254.3	0.9	1.2		
	4	529.0	506.0	1.0	1.4		

As given in Table 4, the results demonstrate that the damping of flax fiber composite is higher than for the glass fiber composite materials between the temperatures of 0 °C and 60 °C, and the damping of composite materials increases when the temperature rises. Natural fiber composite materials have significant damping characteristics than the chemical fiber composites at each temperature.

4. Results and Analysis

4. 1. Young’s Modulus

In this section of the study, experimental Young’s modulus of flax and glass composite materials, which is obtained by vibration and tensile tests, are compared. Besides, temperature effects on the Young’s modulus were examined by using climate cabinet under vibration excitation.

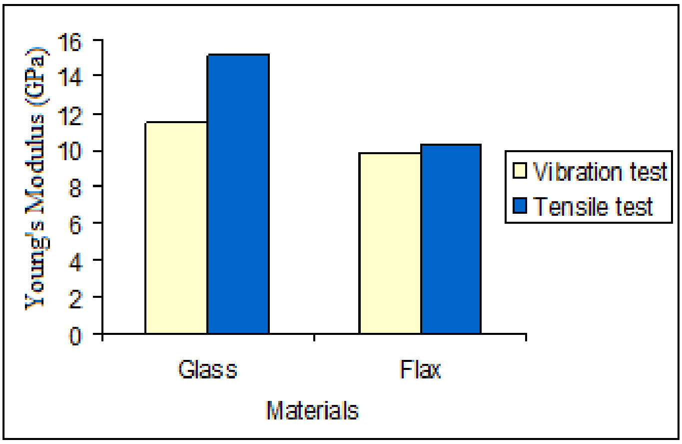

Fig. 5. Comparison of the experimental Young’s modulus of flax and glass composite materials

As given in Fig. 5, Young's modulus of glass fiber composite material is calculated as 11.4 GPa from vibration test and measured as 15.1 GPa by tensile testing, and the Young's modulus of flax fiber composite material is calculated as 9.8 GPa from vibration test and measured as 10.2 GPa by tensile testing. The deviation between the results of tensile test and vibration test can be explained by the different structures of the used materials. The differences of the structure of two kinds of reinforcement can give rise to this deviation. That is because used flax fibers have fabric combination, while the structure of the glass fiber consists of woven type fibers. Thus, these two diverse structures can act differently under tensile loading and vibration excitation.

These obtained results clearly reflect that the strength of glass fiber composite is higher than the flax fiber composite under tensile loading, whereas they have approximately the same strength under vibration excitation. In addition to that, determination of the temperature effect on the Young's modulus of composite materials under vibration excitation, which is important for automotive applications, is examined.

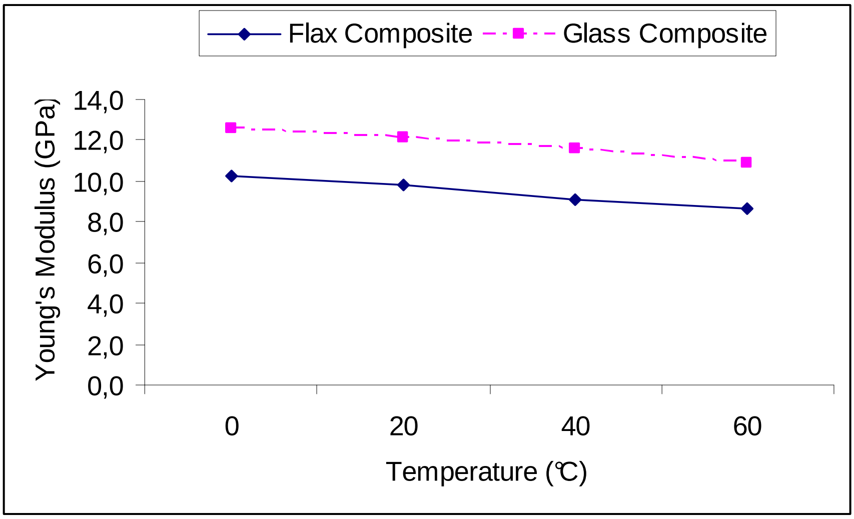

Fig. 6. Vibration test results of Young's modulus of flax and glass composite materials with temperature effect

As indicated in Fig. 6, experimental Young's modulus of composite materials decreases when the temperature increases, and the composite parts will loose strength under high temperature. According to these results, plant based materials have approximately the same strength with petroleum based materials.

4. 2. Damping characteristics

In this section of the study, the damping characteristic of flax and glass composite, which determines the absorption properties of the materials, is compared. In addition to that, the temperature effect on damping characteristic of composite materials is examined.

As indicated in Fig. 7, the damping characteristic of composite materials increases when the temperature rises. These results demonstrate that the damping characteristic of plant-based materials is clearly higher than in the case of petroleum-based materials under different temperatures. When we consider the working condition of the engine, the damping properties of structure that will be used around the engine become crucial.

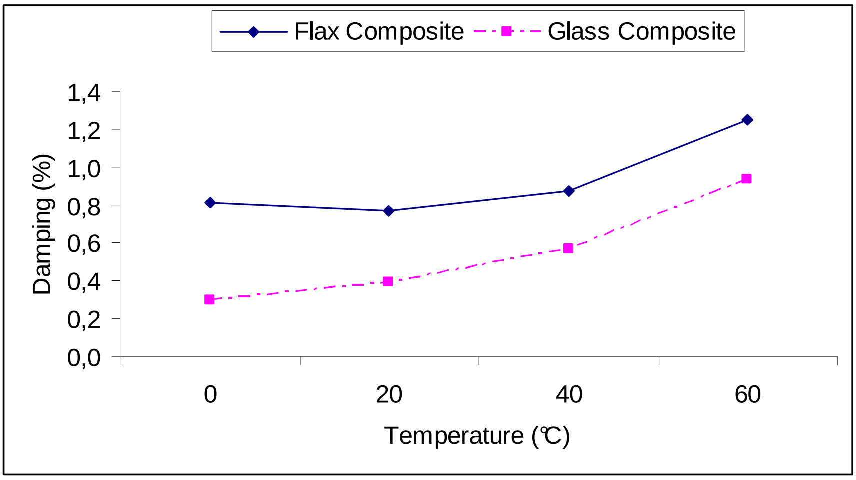

Fig. 7. Vibration test results for damping characteristic of flax and glass composite materials with the temperature effect

5. Conclusion

The objective of this study is to find alternative materials that will be used instead of petroleum-based materials. This study presented a comparison between quasi-static and dynamic properties of flax and glass composite materials. Vibration tests are carried out under different temperatures that are suitable for the working conditions of the engine. Temperature and climatic testing as well as tensile tests are carried out to determine the mechanical properties under room temperature.

The following conclusions were reached in the present study:

1. Young’s modulus of glass fiber composite materials is higher than flax fiber composite materials under tensile loading. However, under vibration excitation the values are approximately the same.
2. Damping characteristic of flax fiber composite materials is higher than in the case of glass fiber.

These results demonstrate that natural fibers can replace mineral fibers as reinforcement in applications where the structures are exposed to vibration excitation and in applications where vibration absorption has a major importance. To find an alternative reinforcement to the chemical materials, plant-based fibers have significant properties which need to be improved. Certainly, not only the reinforcement but also the matrixes have to be improved from biodegradable materials such as L-poly lactic acid (PLLA), to reduce the usage of petroleum-based materials.

Acknowledgement

This research is supported by University of Bourgogne, The Institute of Automotive and Transport Engineering (ISAT), Nevers, France and The Scientific and Technological Research Council (TUBITAK), Ankara, Turkey.

References

[1] **Wambua P., Ivens J., Verpoest I.** Natural fibers: can they replace glass in fiber reinforced plastics?. Composites Science and Technology, Vol. 63, 2003, p. 1259–1264.

[2] **Bos H. L., Mussig J., Oever M. J. A.** Mechanical properties of short-flax-fiber reinforced compounds. Composites: Part A, Vol. 37, 2006, p. 1591–1604.

[3] **Baley C.** Analysis of the flax fibers tensile behaviour and analysis of the tensile stiffness increase. Composites: Part A, Vol. 33, 2002, p. 939–948.

[4] **Missoum L., Labbaci B., Djermane M., Moudden B., Abdeldjebar R.** Identification of Young modulus by a vibration experimental method. Premier Collogue International (IMPACT 2010), Djerba, Tunisie, 22-24 March 2010.

[5] **Qian G. L., Hoa S. V., Xiao X.** A vibration method for measuring mechanical properties of composite, theory and experiment. Composite Structures, Vol. 39, No. l-2, 1997, p. 31–38.

[6] **Charlet K., Baley C., Morvan C., Jernot J. P., Gomina M., Breard J.** Characteristics of Hermes flax fibers as a function of their location in the stem and properties of the derived unidirectional composites. Composites: Part A, Vol. 38, 2007, p. 1912–1921.

[7] **Baley C., Perrot P., Busnel F., Guezenoc H., Davies P.** Transverse tensile behaviour of unidirectional plies reinforced with flax fibers. Materials Letters, Vol. 60, 2006, p. 2984–2987.

[8] **Bodros E., Pillin I., Montrelay N., Baley C.** Could biopolymers reinforced by randomly scattered flax fiber be used in structural applications?. Composites Science and Technology, Vol. 67, 2007, p. 462–470.

[9] **Charlet K., Eve S., Jernot J. P., Gomina M., Breard J.** Tensile deformation of a flax fiber. Procedia Engineering, Vol. 1, 2009, p. 233–236.

[10] **Andersons J., Sparnins E., Joffe R., Wallstrom L.** Strength distribution of elementary flax fibers. Composites Science and Technology, Vol. 65, 2005, p. 693–702.

[11] **Charlet K., Jernot J. P., Gomina M., Breard J., Morvan C., Baley C.** Influence of an Agatha flax fiber location in a stem on its mechanical, chemical and morphological properties. Composites Science and Technology, Vol. 69, 2009, p. 1399–1403.

[12] **O’Donnell A., Dweib M. A., Wool R. P.** Natural fiber composites with plant oil-based resin. Composites Science and Technology, Vol. 64, 2004, p. 1135–1145.

[13] **Gay D.** Matériaux Composites. ISBN-10: 2746210983, 5th édition, Hermès Science Publications, 2005.

[14] EN ISO 527-4. Determination of Tensile Properties - Test Conditions for Isotropic and Orthotropic Fiber - Reinforced Plastic Composites. July, 1997.

[15] Renault Automobiles Standard. Amortissants Vibratoires Mesure Du Facture D’Amortissement (Méthode OBERST). D 45 1809, Régie RENAULT, 1992.

[16] **Lalanne M., Berthier O., Hagopian J. D., Nelson F. C.** Mechanical Vibration for Engineers. John Wiley, New York, 1983.