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Mechanical characterization of the flax/epoxy composite material

Camelia Cerbu*

Transilvania University of Brasov, B-dul Eroilor, Nr. 29, Brasov, 500036, Romania

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Abstract

The paper focuses on the mechanical characterization of the composite material made of epoxy resin reinforced with flax fabric. The mechanical behavior of flax / epoxy composite material was analyzed by using tensile test, flexural (bending) test and impact test (Charpy method). After the statistical processing of the experimental data recorded for all specimens tested, the average values of the following properties are determinate: Young's modulus E in tension, tensile normal stress at failure, tensile normal strain at failure,Young's modulus in bending, flexural normal stress at failure, strain energy in all tests (tension, bending, Charpy), resilience recorded in Charpy test. Finally, it reports the average values of the mechanical properties of the flax / epoxy composite material tested. The results show that the average values of the mechanical characteristics recorded on the weft direction of the flax fabric are greater than the ones recorded on the warp direction.

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Keywords: composite material; flax; tensile test; bending; Charpy.

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1. Introduction

In recent years, the natural fiber-reinforced composite materials are increasingly used for applications in the automotive field (interior design elements, board parts) or construction (panels). Such a type of material is the flax / epoxy resin composite material. Thus, it is important to know the performance of these types of materials in terms of their strength and stiffness. Therefore, during the last years the works focused on the using of both the wood flour [1, 2] of different species or natural fibres - hemp, jute, flax [3, 4, 5] in order to reinforce the polymer composite materials.

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* Corresponding author. Tel.: +40-268-412921; fax: +40-268-474761.
E-mail address: cerbu@unitbv.ro

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A recent paper published [3] showed that that in case of an epoxy matrix composites reinforced with woven flax fibre textiles, the effects of both the linear density of the weft yarn and the direction of crack propagation upon the fracture behaviour and fracture toughness were are significant.

Moreover, scientific literature reported about the trend of using of the natural textile fibers in order to reinforce the biodegradable composite materials. It was shown the effects of the reinforcing with natural fibers upon the improving of the acoustic properties [6].

The first of all, the paper presents the structure of the composite material tested and some properties of the component materials (flax fibers, epoxy resin). It was manufactured a plate made of flax/epoxy composite materials. All kinds of specimens (tensile specimens, specimens for bending and Charpy tests) are cut from the according with the European standards. In the following, the experimental tests, the equipment used and the results obtained are described.

Nomenclature

E	modulus of elasticity
σ	normal tensile stress or normal stress in bending
W	work done until maximum force or failure energy in impact test by using Charpy
K	resilience measured in impact test by using Charpy

2. Materials and test method

2.1. Materials

In this paper, flax woven fabric whose density is equal to $\rho = 280\, g/m^2$ was used to reinforce a polymer composite material. The composite material contained eight plies made of flax fabric and weight fiber was equal to 40%. It is known that different kinds of flax yarns were used on weft and warp directions to manufacture the flax woven fabric.

The mechanical characteristics of the epoxy resin used without reinforcing are given in the Table 1.

Table 1 Mechanical characteristics of the epoxy resin Epolam 2015 (with hardener) without reinforcing

Characteristic	Value	Unit of measure	Method
Tensile stress in tension	70	MPa	ISO 527: 1993
Flexural stress	120	MPa	ISO 178: 2001
Modulus of elasticity E	3100	MPa	ISO 178 :2001
Impact strength - Charpy (unnotch specimen)	40	kJ/m^2	ISO 179
Elongation in tensile test	5	%	ISO 527: 1993
Toughness	83	Shore D15	ISO 868: 2003

Table 2. Specimens tested

Direction of the length of specimen is parallel to	Number of specimens		
	Tensile test	Flexural test	Charpy test
Weft direction	10	10	10
Warp direction	5	5	5

The first, it was made a laminated composite board by using hand lay-up technology. The conditioning time for the plate was two weeks at room temperature. A vacuum system was used to eliminate the voids. The thickness of the composite board was equal to 5 mm.

Then, the plates made was cut to obtain: specimens for tensile test according to [7]; rectangular specimens for bending whose dimensions were 15x100 mm^2 according to [8]; rectangular specimens for Charpy test whose dimensions were 10x100 mm^2 according to [9]. In case of the Charpy test, a notch is made on the specimen in order to produce a stress concentration and thus promote failure in the case of the ductile materials. Herein, the all specimens are unnnotched according to [9].

The number of the specimens prepared for each test is shown in the Table 2. It may be remarked that two sets of specimens were manufactured in case of each mechanical test: a set of specimens whose length is parallel to the weft direction of the flax fabric while the other one set contains specimens whose length is parallel with the warp direction. This consideration was made taking into account that the flax yarns used for weft and warp directions are different according with the technical sheet of the flax woven fabric.

2.2. Test method

The dimensions of the cross-sections were recorded for each specimen before mechanical testing.

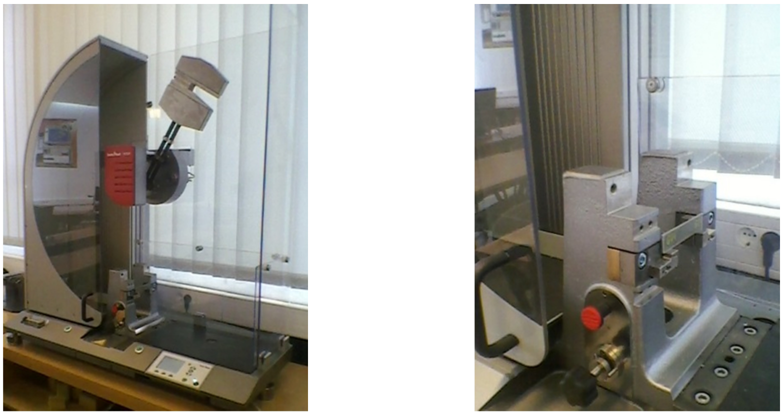
The testing equipment used for both tensile test and flexural test consists of hydraulic power supply. The maximum force capacity is ±15 kN. The speed of loading was equal to 1 mm/min or 1.5 mm/min during the tensile test or during the flexural, respectively. The method of the three points was used for testing in bending (flexural test).

Before each mechanical test of a specimen, the dimensions of the cross-section were accurately measured and then, they were considered as input data in the software program of the machine.

The testing equipment allowed us to record pairs of values in form of text files having 200-300 lines: tensile force F and extension of the specimen; bending force F and deflection v at midpoint of the flexural specimen. The experimental data were statistically processed in order to determine the mechanical properties. The modulus of elasticity E in tensile test and bending test was determinate on the linear portion of the loading curve; Therefore, the average values of the following quantities could be accuracy computed for tensile test: Young's modulus E in tensile test; maximum tensile stress; elongation Δl to the maximum force $F_{\max}$; normal strain ε to the maximum force $F_{\max}$; mechanical work W done until the maximum force $F_{\max}$.

The average values determinate in bending test are the following: Young's modulus E in flexural test; flexural rigidity EI_z; maximum bending stress $\sigma_{\max}$ at maximum load; mechanical work W done until the maximum force $F_{\max}$.

Another set of specimens were subjected to Charpy test to record the failure energy in impact.



a. b.

Fig. 1. Equipment used for Charpy test: (a) Pendulum impact tester HIT50P; (b) Charpy specimen tested

A pendulum impact tester HIT50P manufactured by Zwich was used for Charpy test (Figure 1). The technical data for this equipment are: angle of release 147.96°; impact velocity 3.807 m/s; height of release 739.07 mm; pendulum length 400 mm; swing duration at t =50 – 63.45 s; test data recording rate – 500 Hz; PC connection – USB; pneumatic release by using compressed air connection 6 *bar* (± 1 *bar*).

The impact is produced by swinging the pendulum hummer (Figure 1, a) against the test specimen from a height *h*. When it is released the hammer swings through an arc, hits the target specimen and after fracturing, it reaches a height *h'*.

When the pendulum drops, all impulses are counted up until the pendulum reverses its direction. The angle of deflection is obtained if the number of impulses corresponding to the pendulum direction is subtracted after impact. The height of the reversal point and thus, the absorbed impact energy are determined from this angle of deflection.

The angle of deflection must be adjusted exactly. It is not possible to equal out possible friction loss by a larger angle of deflection.

The difference between the initial energy and the remaining energy represents a measure of the energy required to fracture the specimen. This quantity is called failure energy in Charpy test and it is denoted by W .

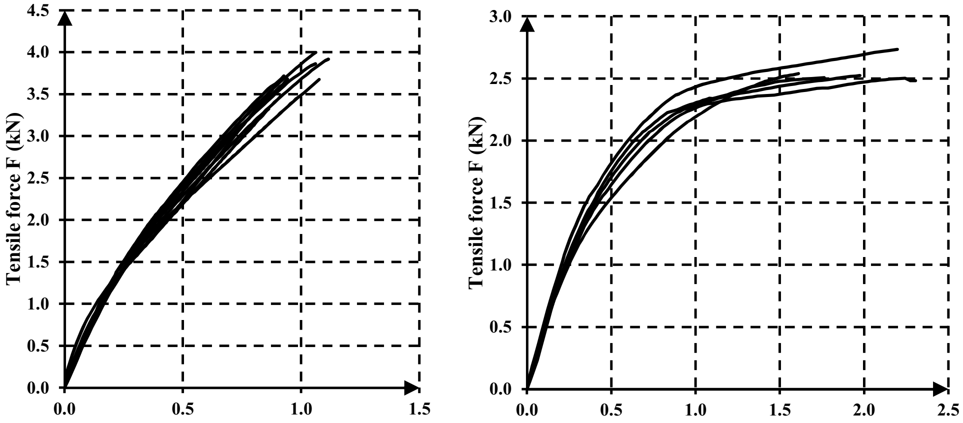
Finally, the resilience K of each composite specimen was computed by using the following formula:

$$K = \frac{W}{A} \tag{1}$$

where W represents the failure energy recorded in case of each specimen tested; A represents the aria of the specimen cross-section where the notch is manufactured.

3. Results

The force – elongation $(F - \Delta l)$ curves recorded in tensile test are shown in case of the both cases: the axial force is parallel to the weft direction of the flax fabric (Fig. 2, a); the axial force is parallel to the warp direction of the flax fabric (Fig. 2, b). Analyzing these figures we may observe that the maximum values of the tensile force are greater when the applied force is parallel to the weft direction of the flax fabric.

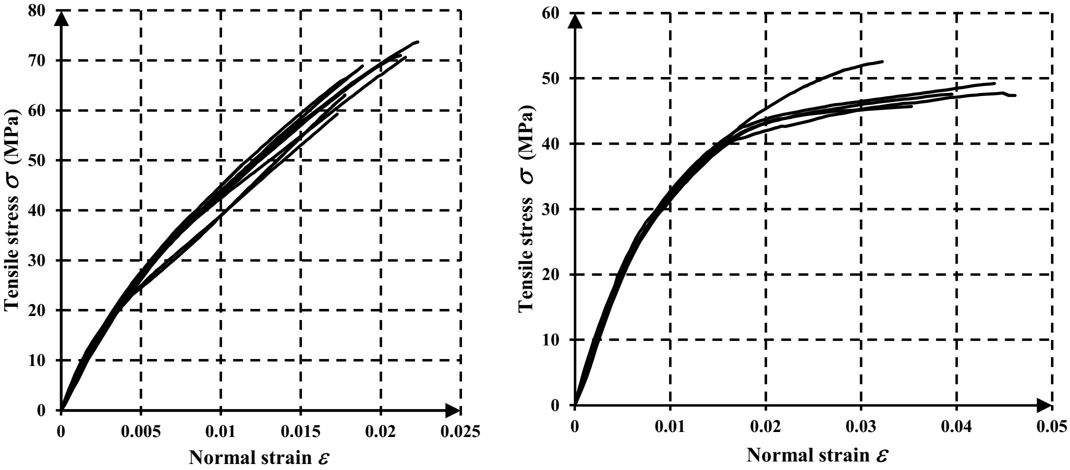


a. b.

Fig. 2. Force – elongation $(F - \Delta l)$ curves: (a) weft direction; (b) warp direction.

The stress-strain $(\sigma - \varepsilon)$ curves determinate in tensile test are also shown in the Fig. 3, where normal stress σ is the ratio between the axial force F and the area of the cross-section while the normal strain is the ratio between the elongation Δl and the initial length of the specimen.

It may be remarked again that the specimens are more stronger on the weft direction of the flax fabric.



a.

b.

Fig. 3. Stress - strain $(\sigma - \varepsilon)$ curves: (a) weft direction; (b) warp direction.

The $\sigma - \varepsilon$ curve recorded in case of each tensile specimen was used in order to determine the modulus of elasticity E. Approximation of the experimental data was made by linear regression which means approximation by a linear function (Fig. 4). So that the approximation to be considered "the best", sum of squares of the distances from each point to the curve that approximates the data, must be minimal. This is known as squares regression method. A measure of the quality of the curve fitting is called R-squared value that may be computed by using the formula:

$$R^2 = 1 - \sum_{i=1}^{n} (y_i - f_i)^2 \Big/ \sum_{i=1}^{n} (y_i - \bar{y})^2 \tag{2}$$

where n represents the number of the data points; y_i represents the real value (ordinate of the point i); f_i is the value of the function of linear regression and are sometimes called the predicted values.

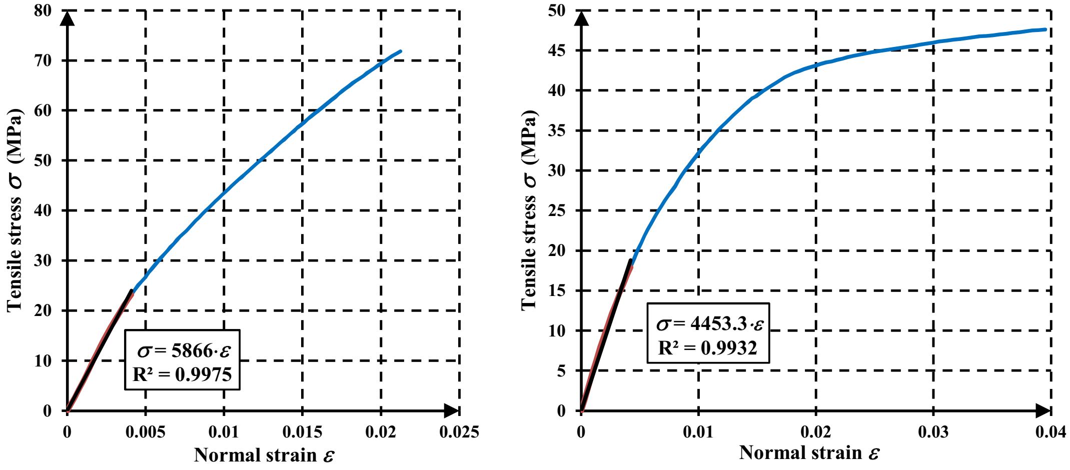
In the above equation (1), $\bar{y}$ is the mean of the observed data:

$$\bar{y} = \frac{1}{n} \sum_{i=1}^{n} y_i \tag{3}$$

In regression, the R-squared value (R^2) is a measure of how well the regression line approximates the real data points. A trend-line (or curve fitting) is more accurate when R-squared value is equal to or near 1 $(R < 1)$. When one approximates the experimental data by using a linear function, its R-squared value should be computed.

In fact, the slope of the line that approximates the linear portion of the $\sigma - \varepsilon$ curve is the *Young*'s modulus E corresponding of the tested specimen. This procedure is repeated for each tensile specimen. Herein, this approximation is detailed only in case of two specimens. The result shown in the Fig. 4, a corresponds to the case when the axial force applied is parallel to the weft direction while Fig. 4, b shows the linear approximation of the data in case when the axial force is parallel to the warp direction.

After statistically processing of the experimental data recorded in tensile test, the average values of the mechanical properties are summarized in the Table 3.

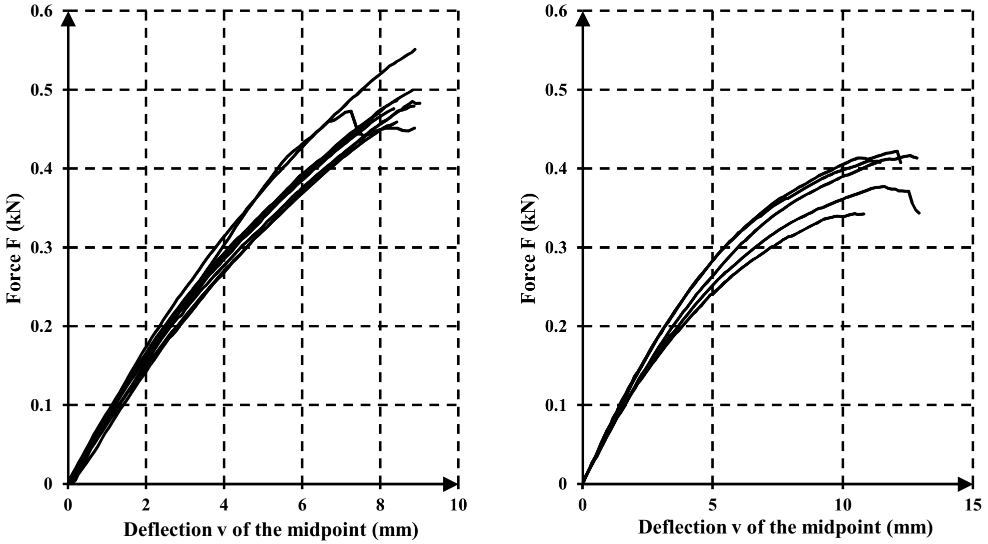


a. b.

Fig. 4. Determination of the Young's modulus in tensile test: (a) weft direction; (b) warp direction.

Table 3. The average values of the mechanical characteristics measured in the tensile test

Direction of the axial force	Fmax (kN)	Elongation Δl la Fmax (mm)	Strain to Fmax (%)	Max. tensile stress (MPa)	Young's modulus in tensile test (MPa)	Work to Maximum Load $(N \cdot mm)$
Warp direction	2.56	1.96	3.92	48.56	4386.22	4778.47
Weft direction	3.72	0.99	1.98	68.29	5870.64	3541.46



a. b.

Fig. 5. Force - deflection $(F - \mathrm{v})$ curves: (a) weft direction; (b) warp direction.

Fig. 5 shows the force – deflection $(F-\mathrm{v})$ curves recorded in bending test. The quantity v represents the vertical deflection of the cross-section located to the midpoint between the two simple supports in case of the bending test by using the method of the three points. It may be remarked again that the maximum bending force F recorded is greater in case of the specimens whose length is parallel to the weft direction. The modulus of elasticity E in bending was determinate taking into account the experimental data located on the linear portion of $F-\mathrm{v}$ curve. In this case, the linear portion was considered up to $v = 1.5\,mm$.

The mechanical characteristics determinate for each specimen in bending test are shown in the Table 4 while the average values are summarized in the Table 5.

Table 4. The average values of the mechanical characteristics measured in the bending test

Direction of the axial force	No. of Specimen	I_z (mm^4)	W_z (mm^3)	Max. Load F (kN)	Maximum Bending Stress (MPa)	Young's modulus in bending (MPa)	Work to Break $(N \cdot mm)$
Weft direction	1	204.53159	75.33392	0.44713	93.48	2379.95	1967.47
	2	200.76660	74.35800	0.55115	116.74	1927.55	2864.84
	3	193.22992	72.64283	0.48615	105.40	2384.36	2403.20
	4	203.91588	75.52440	0.45759	95.43	2262.63	2044.16
	5	202.43713	75.25544	0.45895	96.05	1958.26	2268.44
	6	201.81636	74.7468	0.4759	100.28	2389.99	2348.61
	7	201.02904	74.4552	0.49899	105.55	2077.55	1834.04
	8	203.39100	75.3300	0.47928	100.21	2186.46	2613.98
	9	190.19037	71.76995	0.48494	106.42	1909.95	2526.53
	10	210.62752	77.43659	0.47263	96.13	1891.84	2536.65
Warp direction	11	197.23637	73.595659	0.41000	87.74	1885.05	3150.37
	12	174.36839	67.584648	0.37726	87.92	1911.51	3393.15
	13	168.46677	66.0654	0.34266	81.69	1722.53	2485.24
	14	168.0246	65.892	0.40547	96.92	1971.22	3606.38
	15	179.2752	68.952	0.42187	96.36	1928.05	3498.62

Table 5. The average values of the mechanical characteristics measured in the bending test

Direction of the axial force	Max. Load (kN)	Maximum Bending Stress (MPa)	Young's modulus in bending (MPa)	Work to Break $(N \cdot mm)$
Warp direction	0.3915	90.13	1883.67	3226.8
Weft direction	0.4813	101.57	2136.85	2340.8

All specimens were completely broken after Charpy test. The average values recorded in Charpy test were: $W = 18.84J$ for the failure energy and $K = 0.3588\, J/mm^2 = 358.8\, kJ/m^2$ for resilience in case of the specimens whose length is parallel to the weft direction of the flax fabric. On the other one direction corresponding to the warp direction, the impact properties are: failure energy $W = 21.03J$ and resilience $K = 400.6\, kJ/m^2$.

4. Conclusion

Analyzing the results presented in the previous section it may observe that all mechanical properties corresponding to the weft direction of the flax fabric are greater than the ones recorded on the warp direction. More exactly, for example, the average value of the *Young*'s modulus E is greater with 33.84% on the weft direction (5870.64 *MPa*) than the one on the warp direction (4386.22 *MPa*). The maxim value of the normal tensile stress $\sigma_{\max}$ is greater with 40,63% on the weft direction (68.29 *MPa*) than the value corresponding to the warp direction (48.56 *MPa*). In case of the bending test, the average value of the *Young*'s modulus is greater with 13.44% on the weft direction (2136.85 *MPa*) than the value recorded on warp direction (1883.67 *MPa*). The maximum value of the flexural stress is also greater with 12.69% in case of the weft direction (101.57 *MPa*) than in case of the warp direction (90.13 *MPa*).

Contrary, the average value of the resilience that characterize the impact behavior, is greater with 11.65% in case of the specimens whose length is parallel with the warp direction $\left(400.6\,kJ/m^2\right)$ than the value recorded in case of the specimens whoese length is parallel to the weft direction $\left(358.8\,kJ/m^2\right)$. The reason is that both the failure energy W and the resilience K are inversely proportional with the modulus of elasticity in bending.

Taking into account the applications of such a composite material, the results shown within the present paper are useful in the modeling of the mechanical behavior of such a composite material reinforced with flax woven fabric. The paper shows different values of the mechanical characteristics depending on the direction of flax fabric – weft direction or warp direction.

Moreover, the behavior of the material is elastic-plastic. So, the stress-strain $(\sigma - \varepsilon)$ curves recorded on the both directions (weft and warp), in tensile test are required to define the material on the plastic domain.

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