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Numerical Modeling of the Flax / Glass / Epoxy Hybrid Composite Materials in Bending

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Abstract

The main purpose of this paper is the numerical analysis of the mechanical behaviour in bending of the both flax / epoxy composite material and E-glass / flax / epoxy hybrid composite material. Theoretical results are compared with the experimental results obtained in bending tests in case of the both kinds of composites. The finite element analysis (FEA) is used for simulation of the mechanical behaviour of the beams. Three kinds of beams made of laminated composite materials are modelled with finite element method: a beam made of eight flax /epoxy layers; a sandwich beam having two glass / epoxy layers as bottom shell layers, four flax / epoxy layers as core, and again two glass / epoxy layers as top shell layers (*Hybrid 1*); a beam made of four flax /epoxy layers and four glass / epoxy layers alternately arranged (*Hybrid 2*). The composite layers are modelled as orthotropic materials because the layers are reinforced either with glass or with flax bidirectional woven fabrics. The theoretical results obtained in finite element analysis were compared with the experimental results obtained in bending tests in terms of both the force-displacement curves *(F-w)* on the elastic domain and the equivalent modulus of elasticity E_x of the beam. Regarding the equivalent modulus of elasticity E_x it was found that the greater values of the errors were 6.11% and 5.58% and these correspond to the *E*-glass / flax / epoxy hybrid composite in weft direction and warp direction of the flax fabric, respectively.

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Keywords: Composite material; flax; glass; modeling; bending.

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1. Introduction

During the last years the works published in the field of the composite materials focus on the composites reinforced with vegetable fibers (jute, flax, hemp, wood fibers) and composites based on reinforcement or filler materials obtained by processing of the wastes (rubber, aluminum, PETs, plastics etc.) [1-4].

Herein, in order to increase the rigidity of the panels reinforced with flax fabric, the flax reinforced panels were additionally reinforced with glass fabric. Therefore, glass / flax hybrid composite panels are obtained.

Numerical modelling of the composite materials reinforced with flax fabric became a necessity taking into account the widely using of such kind of composite material in different applications in automotive industry and in civil engineering (panels for in-door or out-door design) [1, 2]. Carbon reinforcement was combined with flax reinforcement in order to improve the damping in case of the hybrid carbon–flax reinforced composites [5].

The modelling with finite elements of the laminated composite materials is used for numerical analysis and simulation of the mechanical behaviour of the beam made of flax / epoxy composite and glass / flax / epoxy hybrid composite material. The main target is to show the advantages of the additionally reinforcement with glass fabric in case of the hybrid composite comparatively with the composite material reinforced only with flax fabric from both flexural strength and flexural modulus E_x point of view.

The properties of the layers were defined in Abaqus (student edition, Dassault Systemes), by taking into account the experimental results obtained in bending in case of the following composite materials: flax / epoxy and glass / epoxy composites. The composite layers are modelled as orthotropic materials. In case of the flax / epoxy layer, the values of the moduli of elasticity corresponding to the warp and weft directions of the flax fabric are different because the flax yarn used in warp direction is not the same with the yarn used in weft direction. It was simulated the bending of three kinds of beams (one is made of flax / epoxy laminated composite, two kinds of glass / flax / epoxy hybrid composites) defined by using the method of the three points according with the experimental set-up used in the in bending test of the composite materials.

The theoretical results obtained in finite element analysis (FEA) were compared with the experimental results obtained in bending tests in terms of both the force-displacement $(F-w)$ curves on the elastic domain and the equivalent modulus of elasticity E_x of the beam.

The work also shows the methodology used in numerical modelling of the beams made of laminated composite materials.

Nomenclature

E_1, E_2	equivalent elasticity moduli corresponding to the composite material with respect with the *1* and *2* axes respectively, of the material coordinate system whose axes are aligned with the reinforcement directions with fibers as axis *1* and weft direction of the flax fabric coincide;
E_x	equivalent elasticity modulus of the fictitious orthotropic material that is equivalent with the laminated composite material, with respect to the *Ox* axis;
ν_{12}, ν_{21}	*Poisson*'s ratios, corresponding to the reinforcement plane *12* with fibers, with respect to the local (material) coordinate system;
$\sigma_{\max}$	maximum value of the normal stress recorded in bending test;
$\sigma_x, \sigma_y, \sigma_z$	normal stresses that develop at the level of an arbitrary point of the composite beam mechanically loaded with respect to the axes of the global coordinate system *xOyz*;
w	displacement with respect to the direction of the axis *Oz* of the global coordinate system.

2. Materials and test method

2.1. Materials

In this investigation, two kinds of composite materials are analysed: one composite material is made of eight flax / epoxy layers; the other one is a sandwich having two glass / epoxy layers as bottom shell layers, four flax / epoxy layers as core, and again two glass / epoxy layers as top shell layers. All laminated composite materials are symmetrical with respect to the median surface. The both kinds of reinforcement consist in bidirectional woven fabrics. The density of the glass fabric is $\rho = 200\ g/m^2$ while the density of the flax fabric is $\rho = 280\ g/m^2$.

The epoxy resin Epolam 2015 was used as matrix (binder) and some of its mechanical properties without reinforcement are: tensile strength in tension $\sigma_t = 70\,MPa$; flexural strength $120MPa$; modulus of elasticity $E = 3100MPa$ in flexural test.

One panel whose dimensions are $1m$ x $1m$ was made of each composite material tested by using hand-layup technology. The content of the fibres was equal to 40 %wt. The thickness of the flax / epoxy composite panel was equal to $5.4 \pm 0.1mm$ while the thickness of the hybrid composite panel was equal to $3.9 \pm 0.1mm$. The thickness of the layers reinforced with flax fabric is equal to $0.675mm$ while the thickness is equal to $0.3mm$ in case of the layer reinforced with glass fabric.

The both panels were dried at room temperature (about $20 \div 22^\circ C$) for two weeks before the cutting of the flexural specimens. The dimensions of the specimens were $15\,\mathrm{x}\,100\,mm^2$ according to [6].

The flax fabric is made of different kinds of flax yarns in weft and warp directions and this aspect was taken into account when the flexural specimens are cut because the properties depend on the fibre orientation [7]. Two sets of specimens were cut in case of each composite material: 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 to the warp direction.

2.2. Test method

In flexural test it was used the testing equipment machine manufactured by Walter & Bay was used having a hydraulic power supply. The maximum force capacity was ±100 kN. The method of the three points was used for testing in bending. The speed of loading was equal to 1.5 mm/min until to the maximum force according to [6].

3. Theoretical approach

It is shown the model with finite elements used in simulation of the mechanical behaviour (analysis of stresses, strains and displacements) of the laminated composite material in bending. The results obtained by finite element analysis are compared with the experimental results only for the elastic domain. The Abaqus soft, student edition (Dassault Systemes), was used in finite element analysis. Because in Abaqus soft the laminated structure (called Composite Layup) may be associated just to the shell parts, it was defined a shell whose dimensions are 15mm x 80mm corresponding to the flexural specimens that was experimentally tested [6]. The scheme of loading is shown in the figure 1a and the spam between the simple supports was equal with 64 mm according to the flexural tests [6]. The resultant force of the uniformly distributed pressure is $F = 100N$ that is in the elastic domain.

The finite element model (Fig. 1, b) uses Shell S4R elements that are recommended to analyse thin or thick plates. The finite element model consists in 520 Shell S4R elements. It was defined two kinds of lamina material corresponding to the both kinds of layers: layer made of flax / epoxy composite material; layer made of glass / epoxy composite material. These materials were associated to the thin layers which make up the laminated structure of the specific composite materials involved in the theoretical study: flax / epoxy composite material (Fig. 2, a); *Hybrid 1* glass / flax / epoxy which is a sandwich composite material having two glass / epoxy layers as bottom shell layers, four flax / epoxy layers as core, and again two glass / epoxy layers as top shell layers (Fig. 2, b); *Hybrid 2* glass / flax / epoxy composite material whose flax / epoxy and glass / epoxy layers are laid out alternatively (Fig. 2, c). All laminated composite materials are symmetrical.

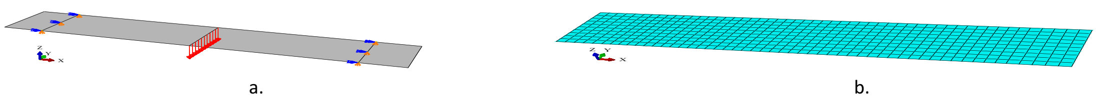
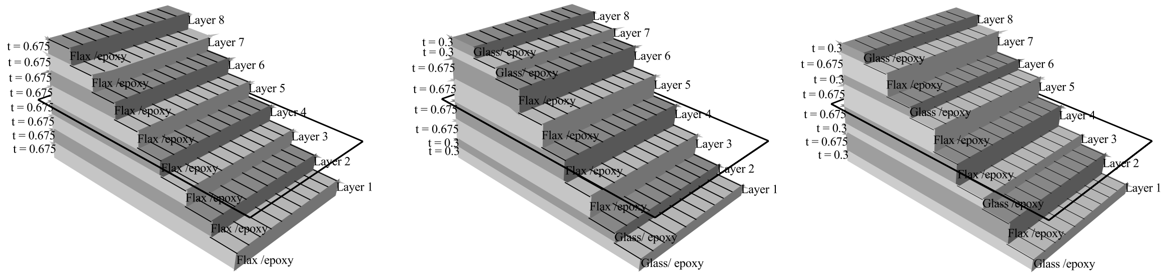


Fig. 1. Model of the laminated composite material: (a) scheme of loading; (b) meshing with shell elements



a. b. c.

Fig. 2. Defining the layout layers in case of the three composite materials theoretically analyzed:
(a) flax / epoxy composite material; (b) *Hybrid 1* composite material; (c) *Hybrid 2* composite material

a.  b.

Fig. 3. (a) axis 1 of the material (weft direction) is parallel to the length; (b) axis 2 of the material (warp direction) is parallel to the length

In case of the flax / epoxy layer, the properties of the layer in warp and weft directions of the flax fabric are different. It was considered that the weft direction coincides with the axis 1 of the material coordinate system while the warp direction and axis 2 also coincide. Two cases were analysed in case of each composite material analysed: case 1 when the axis 1 of the material coordinate system (weft direction corresponding to the flax fabric) is parallel to the direction of the specimen length (Fig. 3, a); case 2 when the axis 2 of the material coordinate system (warp direction corresponding to the flax fabric) is parallel to the direction of the specimen length (Fig. 3, b). This option is possible in Abaqus due to the command called Assign material orientation.

Taking into account the above convention, the properties of the layer made of flax / epoxy composite material are: $E_1 = 2136.85\,MPa$ (weft direction); $E_2 = 1883.67\,MPa$ (warp direction); $\nu_{12} = 0.337$; $\nu_{21} = 0.297$. The flexural properties of the flax / epoxy layer were defined according to both the results obtained in flexural test shown in this paper and the results published by the authors in other works [8, 9, 10]. Since to manufacture the glass fabrics the same glass yarns were used in both weft and warp directions, the properties of the glass / epoxy layer were defined according to [9]: $E_1 = E_2 = 6155\,MPa$; $\nu_{12} = \nu_{21} = 0.15$.

Abaqus soft reports output data (stresses and strains) for three integration points of each layer (the black points marked in figure 2): the integration point located to the top surface of the layer; the integration point located in median surface of the layer; the integration point located in bottom surface of the layer.

The force-displacement curves $(F - w)$ experimentally recorded are compared with the ones obtained by using FEA model in order to validate the theoretical model. Moreover, by using the slopes of the linear force-displacement curves $(F - w)$ theoretically obtained by using FEA model, the equivalent modulus of elasticity E_x in bending may be computed in case of all composite structures analysed by using the following relation:

$$E_x = \frac{F}{\mathrm{v}} \cdot \frac{l^3}{48 I_z} = tg\beta \cdot \frac{l^3}{4bh^3} \text{ [MPa]} \tag{1}$$

where F [N] is the bending force; v [mm] - vertical displacement of the cross-section located to the midpoint between the supports; β - slope of $(F - w)$ curve; l [mm] - span between the simple supports; b [mm] – width of the cross-section; h [mm] - height of the cross section that is equal with the thickness of the composite panel.

4. Results

4.1. Theoretical results

The first, the distributions of the vertical displacement w in the direction of the axis Oz are plotted in case of all composite structures theoretically analyzed: flax / epoxy composite material (Fig. 4); *Hybrid 1* composite (Fig. 5); *Hybrid 2* composite (Fig. 6).

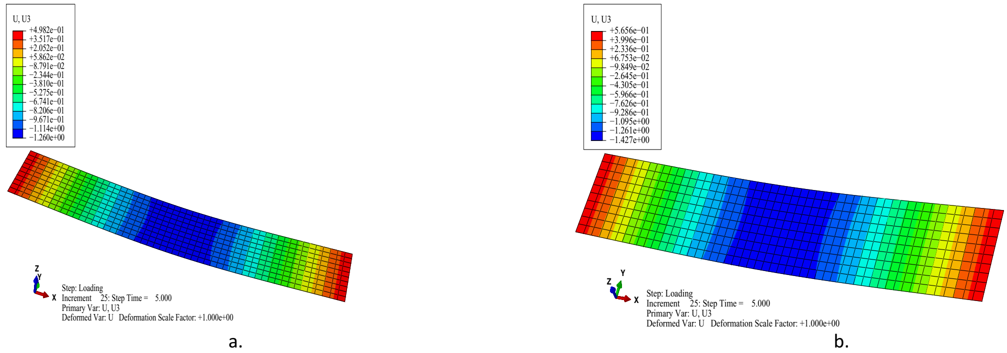


Fig. 4. Distribution of the vertical displacement w in the direction of the axis Oz in case of the flax / epoxy composite material: (a)length of the model is parallel to the weft direction of the flax fabric; (b) length is parallel to the warp direction of the flax fabric

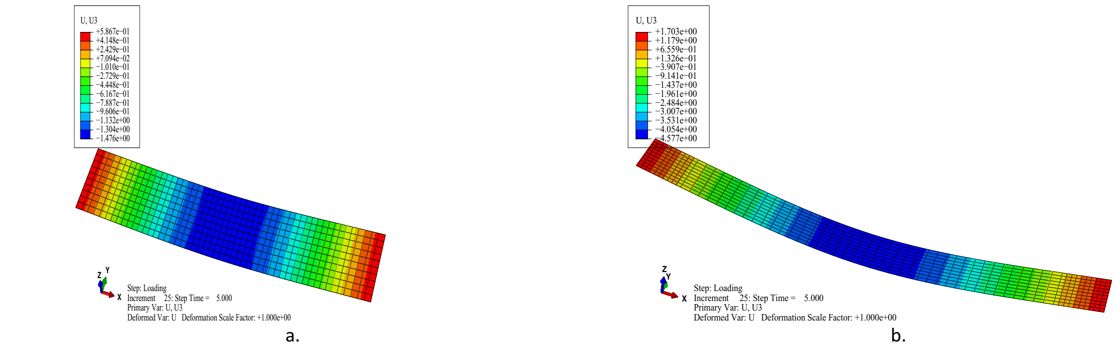


Fig. 5. Distribution of the vertical displacement w in the direction of the axis Oz in case of the *Hybrid 1* glass / flax / epoxy composite: (a)length of the model is parallel to the weft direction of the flax fabric; (b) length of the model is parallel to the warp direction of the flax fabric

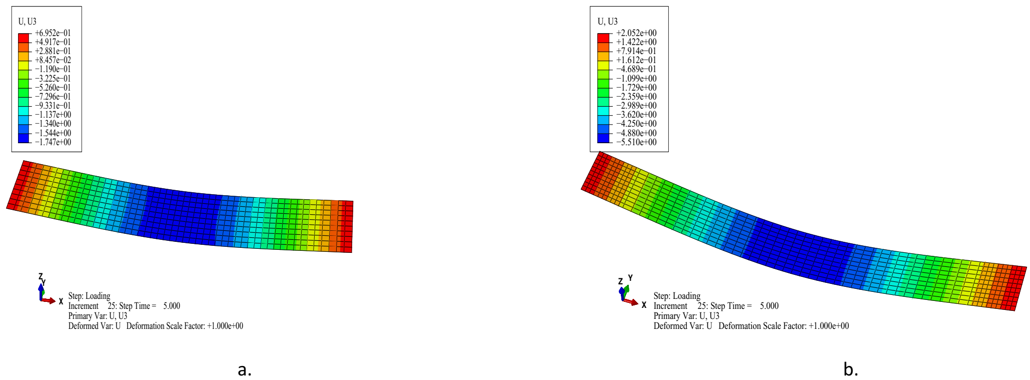


Fig. 6. Distribution of the vertical displacement w in the direction of the axis Oz in case of the *Hybrid 2* glass / flax / epoxy composite: (a)length of the model is parallel to the weft direction of the flax fabric; (b) length of the model is parallel to the warp direction of the flax fabric

In the figure 7 it is plot by using Abaqus, the distribution of the normal stress $\sigma_1 = S_{11}$ across the thickness of the composite structures in case of all composite materials that were theoretically analysed: flax / epoxy composite material (Fig. 7, a); *Hybrid 1* composite (Fig. 7, b); *Hybrid 2* composite (Fig. 7, c). It may be remarked that the graphs shown in the figure 7 were plotted across the thickness of the same laminated shell element for which the maxim normal stress σ_1 was recorded at the level of bottom surface of the plate. It may remark the sudden change of the normal stress at the interface between two different layers (flax / epoxy layer and glass / epoxy layer) in case of the hybrid composite materials (Fig. 7, b and c).

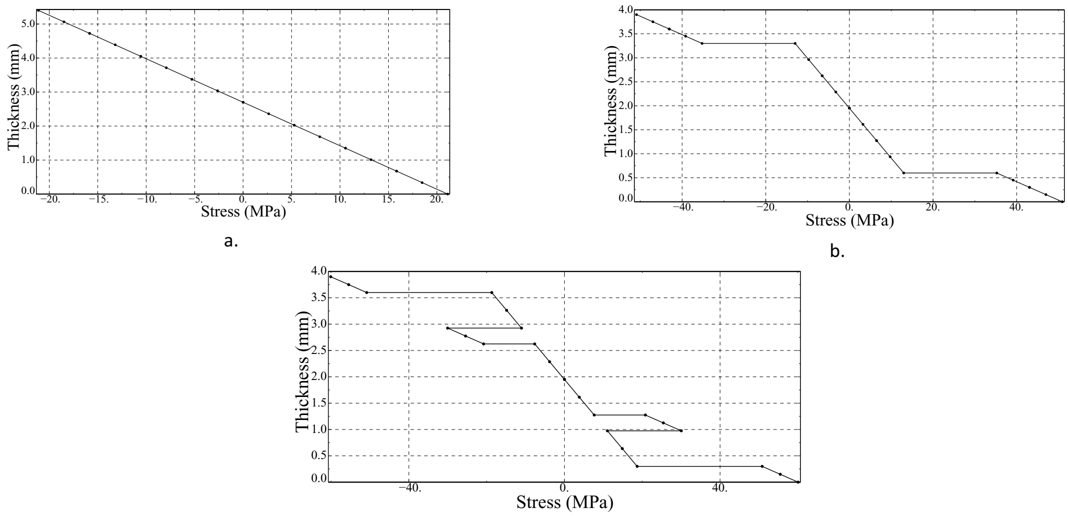


Fig. 7. Distribution of the normal stress $\sigma_1 = S_{11}$ (parallel to the weft direction of the flax fabric) across the thickness in case of all composite structures analyzed $(F = 100\,N)$: (a) flax / epoxy composite material; (b) *Hybrid 1* composite material; (c) *Hybrid 2* composite material

4.2. Experimental results

In the table 1 are shown the average values of the mechanical characteristics (maximum flexural stress σ_{max}, modulus of elasticity E_x) experimentally determined in case of the composite materials tested: flax / epoxy composite material; *Hybrid 1* – E-glass / flax / epoxy. It may remark that the greatest values of the mechanical properties correspond to the *Hybrid 1* E-glass / flax / epoxy composite and these were measured in the weft direction of the flax fabric. It may also be noted that the modulus of elasticity E_x in bending is with 136.18% higher in weft direction corresponding to the flax fabric in case of the *Hybrid 1* composite than in case of the flax / epoxy composite material. The maximum flexural stress σ_{max} corresponding to *Hybrid 1* in the weft direction also increased with 91.08% comparatively with the flax / epoxy composite material. This remark clearly shows the advantage of the reinforcement with glass fabric of the both top and bottom shell layers.

Table 1. The average values of the mechanical characteristics measured in bending test in case of the composite materials tested

No.	Type of the composite material		Bending test		Poisson's ratio ν_{12}
			Maximum flexural stress σ_{max} (MPa)	Modulus of elasticity E_x (MPa)	
1	Flax / epoxy Epolam 2015	Weft	101.57 (C)	2136.85 (C)	0.337
		Warp	90.13 (D)	1883.67 (D)	0.297
2	*Hybrid 1* – E-glass / Flax / epoxy Epolam 2015	Weft	194.08 (A)	5046.92 (A)	-
		Warp	137.92 (B)	4966.85 (B)	-

4.3. Theoretical versus experimental results

The first of all, the experimental curves force-displacement $(F-w)$ were graphically compared with theoretical curve obtained by using FEA model in the elastic domain in case of the both composite materials tested: flax / epoxy composite (Fig. 8); *Hybrid 1* – E-glass / flax / epoxy composite (Fig. 9). The data experimentally obtained are shown with marks having different shapes while the theoretical curves $(F-w)$ are drawn by using blue lines.

It can be observed that the theoretical curve force-displacement $(F-w)$ fits very well with experimental data in the case of flax / epoxy composite material both in weft and warp direction corresponding to the flax fabric. A good match with the experimental data is recorded also in the case when the length of the specimen made of *Hybrid 1* composite material (glass / flax / epoxy) is parallel to the weft direction of the flax fabric. But the match is not so good when the specimen length is parallel to the warp direction.

In the Table 2, the average values of the equivalent modulus of elasticity E_x determined in bending tests are compared with the theoretical values computed by using the relation (1) after it was computed the slope β of the theoretical force-displacement curves plotted by using FEA model in Abaqus. In case of the *Hybrid 2* – E-glass / flax / epoxy composite only the theoretical value of the equivalent modulus of elasticity E_x is reported in this work. It may remark that the maximum value of the error for the equivalent modulus of elasticity E_x is equal to 6.111%.

This value was recorded in case of the *Hybrid 1* composite and corresponds to the direction of the specimen length that coincides with the weft direction of the flax fabric.

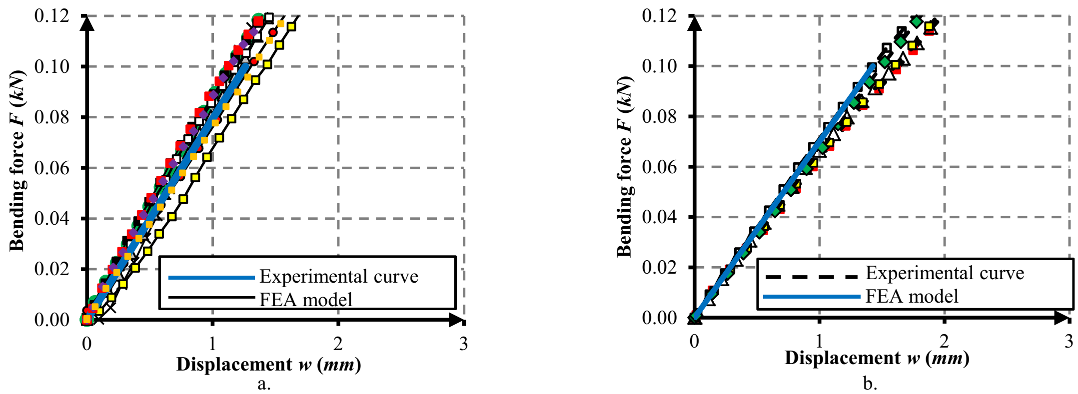


Fig. 8. Comparison between the results experimentally obtained and the ones obtained by FEA concerning the force-displacement curve $(F-w)$ in case of the flax / epoxy composite material: (a) specimen length is parallel to the weft direction; (b) length is parallel to the warp direction

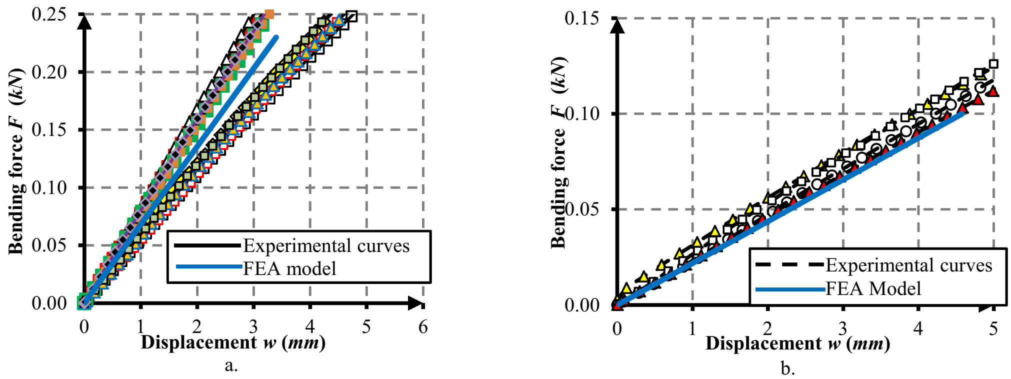


Fig. 9. Comparison between the results experimentally obtained and the ones obtained by FEA concerning the force-displacement curve $(F-w)$ in case of the *Hybrid 1* glass/ flax/ epoxy composite material: (a) length is parallel to the weft direction; (b) length is parallel to the warp direction

Table 2. Comparison between the experimental results and the ones obtained by using FEA

Type of the composite material	Direction	Equivalent modulus of elasticity E_x in bending (MPa)		Error Exp. versus FEA (%)
		FEA Model	Experimentally	
Flax / epoxy composite material (8 layers)	Weft	2101.40	2136.85	1.687
	Warp	1855.27	1883.67	1.531
Hybrid 1 – E-glass / flax / epoxy (8 layers)	Weft	4756.26	5046.92	6.111
	Warp	4704.06	4966.85	5.586
Hybrid 2 – E-glass / Flax / epoxy (8 layers)	Weft	4018.58***	-	-
	Warp	3905.66***	-	-

*** *Equivalent modulus of elasticity* E_x *was computed only theoretically by using FEA model.*

5. Conclusions

The work reports results obtained in numerical modelling of the mechanical behaviour in bending in case of three kinds of structures of composite materials and these results are experimentally validated in case of two types among the composites tested. The hybrid composite (glass / flax / epoxy) proposed within this paper, whose equivalent modulus of elasticity $E_x = 5046.92\,MPa$ is greater than the value $E_x = 2136.85\,MPa$ recorded in case of flax / epoxy composite, should be used to manufacture innovative products in automotive industry or in civil engineering.

The work has also contributions from the point of view of the innovative design of the composite materials because it comparatively analyses the equivalent modulus of elasticity E_x in case of two hybrid composites composed by the same number of layers (4 glass / epoxy layers, 4 flax / epoxy layers) but these were differently arranged. The issue presented in this paper is situated at the border of two different areas: materials engineering and mechanical engineering.

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