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GLOBAL IDENTIFICATION OF THE LAMINATES' MATERIAL PARAMETERS

Summary – The paper is devoted to the global identification of material parameters of the single layer of the laminate. The measurement data for identification are derived from the laminate strength tests in the form of the three-point flexure test and the tensile test with a video extensometer. The evolutionary algorithm is applied to perform the identification procedure. Finite element method commercial software is employed to solve a boundary-value problem for laminates. Examples presenting effectiveness of the proposed method are included.

Keywords: identification, laminate, strength tests, finite element method, evolutionary algorithm

1 Introduction

Composite materials are common in modern structures, especially in such domains as: aerospace, watercraft, automotive, furniture industry, sports and many others. The reason is that composites have excellent mechanical and strength properties while having low specific gravity [1,2].

An important group of composites state laminates. Laminates are composite materials made of many layers called plies. Reinforcement in form of fibres is typically unidirectional in each ply, but may be differently arranged in particular plies. Laminates are characterized by the highest strength/weight ratio among composites. It is also possible to obtain required properties of them manipulating the constituent materials, fibre orientations and layer thicknesses [3].

As composites are inhomogeneous and very often anisotropic materials, it is necessary to take into account different dependencies than for traditional structural materials. The properties of laminates, including mechanical ones, are a function of the volume element position and the direction of acting load [1].

Manufacturers of laminate panels typically provide information about parameters (e.g. mechanical) of the product while the information about ply properties is not available. In order to perform a shape or topological optimization of a structural element made of laminate panel, one needs to create a numerical model of the laminate. In these cases, available information is not sufficient and it is necessary to identify material parameters of the single ply.

To solve the identification problems different optimization methods may be applied. Application of global optimization methods, like evolutionary algorithms, artificial immune systems or particle optimizers [4], can reduce the risk of getting stuck in local optima. Moreover, such methods do not require calculation of the objective function gradient and may be applied if such information is impossible or hard to obtain. The evolutionary algorithm has been used in the present work to solve the identification task.

Proposed attitude allows identification of the parameters necessary for preparation of the numerical model of the laminate. As typical material tests are employed, collecting of such data is relatively simple. Adequate numerical model allows proper designing of structural elements made of considered laminate panels and the further optimization of them.

2 Formulation of the problem

The aim of the paper is the identification of the material parameters of the single ply in existing laminate structure. According to the classical theory of lamination, it is assumed that a single layer of the laminate may be treated as an orthotropic material in plane stress state. Such material may be described by four independent material constants: a longitudinal Young's modulus E_1, transverse Young's modulus E2, shear modulus G_{12} and a major Poisson ratio ν_{12}. The constitutive equation has the form [2]:

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{Bmatrix} = \begin{bmatrix} \dfrac{E_1}{1-\nu_{12}\nu_{21}} & \dfrac{\nu_{21}E_1}{1-\nu_{12}\nu_{21}} & 0 \\ \dfrac{\nu_{12}E_2}{1-\nu_{12}\nu_{21}} & \dfrac{E_2}{1-\nu_{12}\nu_{21}} & 0 \\ 0 & 0 & G_{12} \end{bmatrix} \begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{12} \end{Bmatrix} \tag{1}$$

where: σ_{ij} – stress vector, ε_{ij} – strain vector; both in Voight notation.

An identification problem may be formulated as a minimization of the objective function J_0 with respect to the vector of the design variables **x** representing identified material constants. In the present paper the minimization of the following objective function is performed:

$$arg\,\min\left\{ J_0 = \sum_{i=1}^{N} \left[\hat{\mathbf{q}}_i(\mathbf{x}) - \mathbf{q}_i(\mathbf{x}) \right]^2 \right\} \tag{2}$$

where:

$\mathbf{x} = (x_r)$, $r = 1...N$ – vector of parameters representing identified constants;

$\hat{\mathbf{q}}_i$ – measured values of a state fields;

q_j – values of the same state fields computed from the mathematical model.

Four material constants of a single laminate ply are identified: two Young moduli E_1, E_2, Poisson ratio ν_{12} and shear modulus G_{12}. It is assumed that measurement data will be collected during standard strength tests like tensile and bending tests.

3 Distributed Evolutionary Algorithm

Evolutionary algorithms (EAs) are computational intelligence methods inspired by a process of natural evolution. EAs are global optimization methods which require only the objective function value of each potential solution to work. EAs process a set (population) of individuals also called chromosomes. Each chromosome is composed of genes representing design variables [5]. An initial population is usually randomly generated. The selection procedure promotes better solutions directing searching process while evolutionary operators, like crossover and mutation, generate new solutions and cause exploration of the design space. The algorithm runs until a termination condition is satisfied.

The applied distributed EA (DPEA) belongs to a group of co-evolutionary algorithms in which the total population of chromosomes is divided into subpopulations [6]. Each subpopulation evolves nearly independently interchanging some individuals during so called migration phase. Such attitude very often speeds up the evolution process. The floating-point chromosome coding is implemented. Simple crossover and two mutation operators: uniform mutation and Gaussian mutation are applied. The selection is performed by means of the ranking selection method. The block diagram of the DPEA is presented in

Fig. 1.

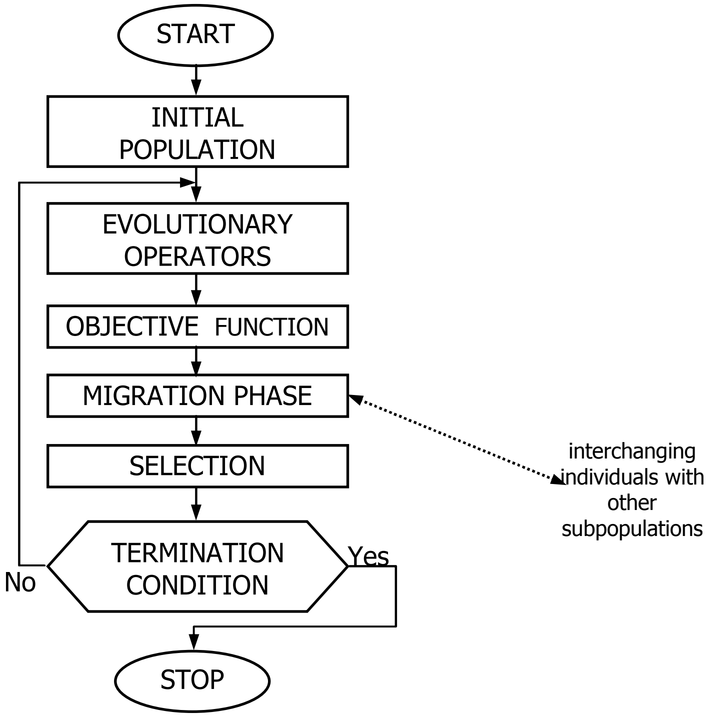


Fig. 1. The block diagram od DPEA

4 Laminate tests

To determine the number of layers and their arrangement within the laminate, the burning process in the temperature of 500 ℃ has been performed. The burning process in a laboratory oven lasted 15 minute, which allowed to fully burn out the resin. An application of the optical microscope allowed to determine the glass fabric orientation in each layer. A microscopic view of a single layer of glass fabric obtained after burning is presented in

Fig. 2.

Three-point flexure test allows to determine e.g. strains and stresses in a sample subjected to simple beam loading. The dimensions of the samples, the test speed, the distance between supports (set based on the thickness of the material) and the number of samples have been set according to the standard [7]. The samples were cut out from the laminate plate in two perpendicular directions and marked as “=” and “||”.

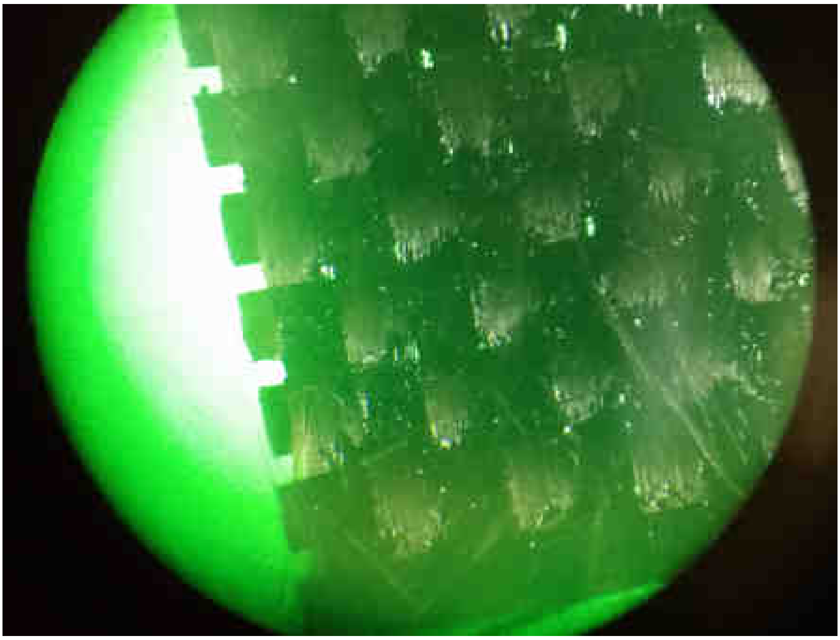


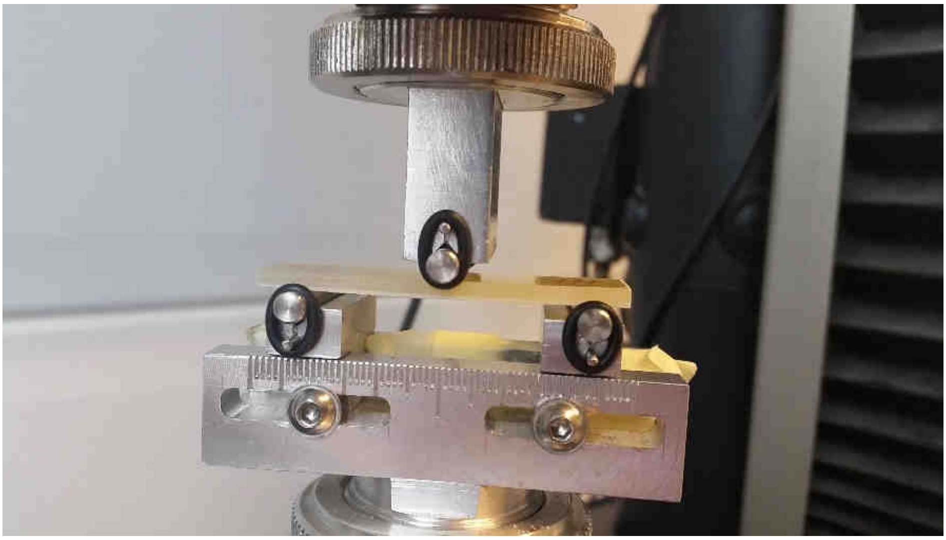
Fig. 2. Single layer of the glass fabric after burning (zoom 30x)

The tests were carried out using Zwick z050 testing machine with TestXpert II software (Fig. 3). The selected averaged test results for 10 samples are collected in Tab. 1.

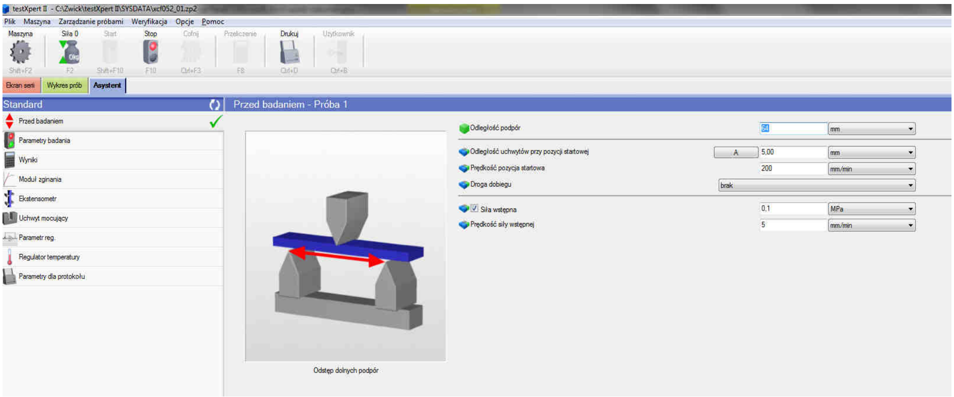
Tabela. 1. Average flexure test results from TesXpert software

laminate direction	numer of samples		E_f [MPa]	ε_{fM} [%]	Lv [mm]	h [mm]	b [mm]
„=”	5	avg value	14900	1.3	46	2.9	15.02
		standard deviation	7800	0.45	0.00	0.00	0.076
“||”	5	avg value	18600	1.3	46	2.9	14.8
		standard deviation	606	0.015	0.00	0.00	0.071

The symbols in Tab. 1 denote: E_f – flexural modulus, ε_{fM} – fiber elongation zone,Lv – distance between supports, h, b – sample thickness and width



a)



Odległość podpór	64	mm
Odległość uchwytów przy pozycji startowej	5,00	mm
Prędkość pozycja startowa	200	mm/min
Droga dobiegu	brak	
☑ Siła wstępna	0,1	MPa
Prędkość siły wstępnej	5	mm/min

b)

Fig. 3. Flexure test: a) loaded sample, b) exemplary TestXpert II window

The deflection for the given load may be calculated on the basis of the TestXpert II strain-force diagram (Fig. 4) as [7]:

$$f = \frac{\varepsilon \cdot (Lv)^2}{600h} \; [mm] \tag{3}$$

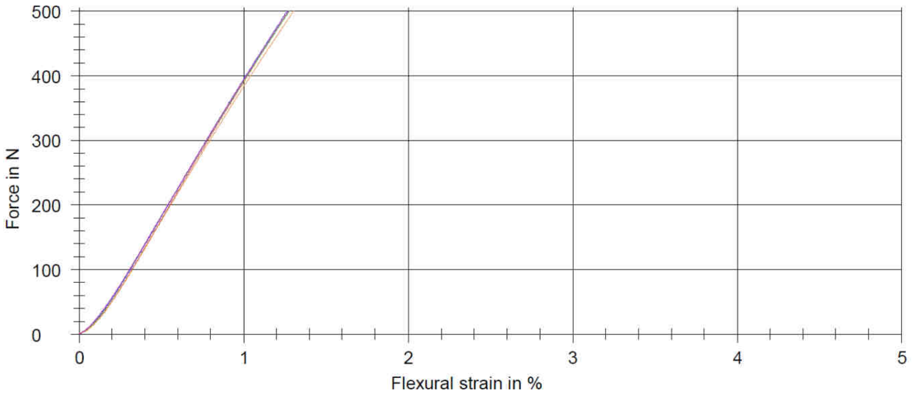


Fig. 4. Exemplary strain-force diagram from TestXpert II software ("=" direction)

To acquire additional measurement data, the tensile test was carried out on the same testing machine according to standard [8]. The standard defines e.g. sample shape and dimensions, loading speed and the way of Young modulus determination.

In order to measure the strains in the sample an extensometer should be used. In the presented case a video extensometer MessPhysik ME46 has been employed [9]. The video extensometer provides non-contact measurement of tensile and compressive deformations on different material samples, including composites. It is typically used to record longitudinal strain but may be also suitable for recording transverse strain. As a pattern is necessary for being tracked by video extensometer, it was necessary to apply the patterns of points to the samples (Fig. 5). Fig. 6 shows the test stand with the selected elements described.

Fig. 5. The patterns marked on the samples

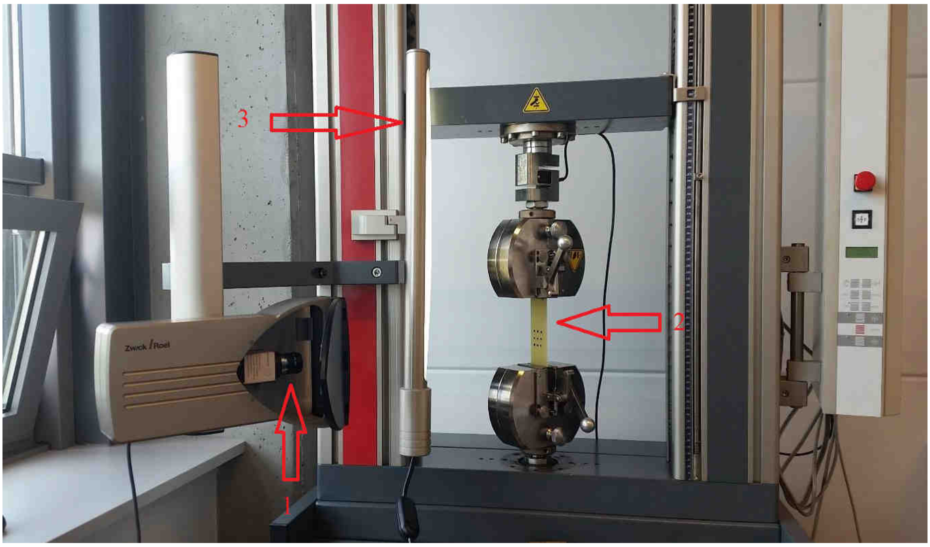


Fig. 6. Tensile test: video extensometer camera (1), mounted sample (2) and illumination lamp (3).

Applied 9 points allow tracing strains of 6 lines in two perpendicular directions: sections 1-3, 4-6 and 7-9 in longitudinal direction *x* and sections 1-3, 4-6 and 7-9 in transverse direction y (Fig. 7).

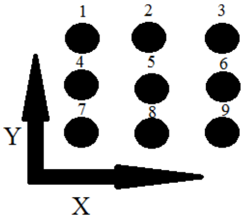


Fig. 7. Axes and pattern points' numbering.

The Dotmeasurement for Windows software has been used to trace the pattern of points during the tensile test [10]. The exemplary results of the video extensometer strain measurements are collected in Tab. 2.

Considered laminates are materials for which strain values are relatively low, even for quite high values of tensile forces. It can be observed in Tab. 2 that although the accuracy of the strain measurements is greatly higher for higher loading force, the measurement precision for transverse strains is not satisfactory for the applied video extensometer. The solution of the problem may be an application of the more precise strain measurement method, like digital image correlation (DIC) [11].

Tabela. 2. The tensile test strain measurement results

Force [N]	axis	strain			avg.	standard dev.
2000	longitudinal	1-3	4-6	7-9		
		-0.011%	0.049%	0.010%	0.016%	0.025%
	transverse	1-7	2-8	3-9		
		2.467%	-0.098%	-0.080%	0.763%	1.205%
14200	longitudinal	1-3	4-6	7-9		.
		0.428%	0.324%	0.471%	0.408%	0.062%
	transverse	1-7	2-8	3-9		
		-0.137%	-0.047%	-0.112%	-0.099%	0.038%

5 Numerical experiments

The correctness of the proposed identification procedure was verified by means of the numerical experiment. Numerical models of the reference samples have been prepared using the MSC Patran software [12]. 4 models of the samples for 2 different tests with two orientations of the laminate for each test have been created. Each of the laminate layer was modeled as an orthotropic material of known material parameters. 2D rectangular QUAD-4 elements have been employed. Boundary conditions represented the perfect supports and the uniformly distributed loads in both cases. The load F_t = 2000 N and F_f = 500N have been applied for tensile and flexure tests, respectively. MSC Nastran software [12] has been used to solve the boundary-value problem for the laminates.

The results obtained with the reference samples were treated in the numerical experimental as the measurement data. These data have been applied together with the results obtained for the potential solutions generated by DPEA algorithm for calculation of the objective function values.

The following ranges of the identified constants have been assumed:
E_1 = 13÷22 GPa, E_2 = 12÷17 GPa, v_{12} = 0.25÷0.32, G_{12} = 4÷6 GPa.
The identified values of the elastic constants (reference samples) are:
E_1 = 18 GPa, E_2 = 14.9 GPa, v_{12} = 0.28, G_{12} = 5 GPa.
The following parameters of the DPEA have been applied:

- the number of subpopulations n_{sub} = 2;
- the number of chromosomes in each subpopulation n_{ch} = 20;
- the number of genes in each chromosome: n_g = 4;
- the uniform mutation probability: um_p = 0.1;

- the simple crossover probability: $sc_p = 0.9$;
- the termination condition: the generation number $gen_{max} = 100$.

The best identification results and the average results for 10 independent runs of the evolutionary algorithm are collected in Tab. 3.

Tabela. 3. The results of the evolutionary identification

Identified constant	Actual values	The best results		Average results	
		Found values	Error [%]	Found values	Error [%]
E_1 [GPa]	18.0	17.962	0.21	17.813	2.21
E_2 [GPa]	14.9	14.927	0.18	14. 907	2.78
v_{12}	0.28	0.278	0.71	0.273	3.67
G_{12} [GPa]	5.0	5.020	0.41	4.955	8.45
Average error			0.38		4.28

It can be observed in Tab. 3 that very good identification results have been obtained. The identification error values for the best run of the DPEA are lower than 1%. The average identification error for all identified constant is equal to 4.28% which is also satisfactory result. It can be also seen that the best identification result have been obtained for both Young moduli. It should be emphasized that in practice the best run of the algorithm (with the lowest value of the objective function) is taken into account.

Real measurements are never precise, which should be taken into account in practice. Previous research [13] suggest that the measurement error up to 5% usually not significantly worsen the identification results.

6 Summary

The aim of this work was to develop a method of the identification of material parameters of the single laminate layer using data taken from typical strength tests. Such information allows modelling of the structures made of the laminate for which such information is not provided by the manufacturer. The preparation of the proper models allows e.g. a shape optimization or a topological optimization of the laminate structures.

Two standard test in the form of the flexure test and the tensile test tensile test and have been conducted to collect identification data. The data taken from the available video extensometer during tensile test turned out to be not accurate enough and the more precise strain measurement method should be applied.

The global optimization method in the form of the evolutionary algorithm has been applied to solve the identification task. Numerical experiment data have been taken as measurements results to verify the efficiency of proposed method. The identification result turned out to be very satisfactory. Consequently it should be noted that the assumed kind and number of measurement data is sufficient to identify the material constants of a single layer of existing laminate.

The research is planned to be extended in by future by taking into account the inaccuracy of measurements and the speed-up of the calculations by means of the parallel computations.

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GLOBALNA IDENTYFIKACJA PARAMETRÓW MATERIAŁOWYCH LAMINATÓW

Streszczenie – Artykuł jest poświęcony globalnej identyfikacji parametrów materiałowych pojedynczej warstwy laminatu. Dane pomiarowe dla identyfikacji pochodzą z prób wytrzymałościowych w postaci próby trójpunktowego zginania oraz próby rozciągania z zastosowaniem wideo-ekstensometru. Algorytm ewolucyjny został zastosowany jako metoda optymalizacji. Komercyjne oprogramowanie metody elementów skończonych zostało użyte w celu rozwiązania zadania brzegowego dla laminatów. Zamieszczono przykłady prezentujące skuteczność proponowanego podejścia.

Słowa kluczowe: identyfikacja, laminat, próby wytrzymałościowe, metoda elementów skończonych, algorytm ewolucyjny