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IDENTIFICATION OF MATERIAL PROPERTIES OF COMPOSITE MATERIALS

Paulius Ragauskas[1], Rimantas Belevičius[2]

Vilnius Gediminas Technical University, Saulėtekio al. 11, Lithuania
E-mails: [1]Paulius.Ragauskas@vgtu.lt; [2]Rimantas.Belevicius@vgtu.lt

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Paulius RAGAUSKAS
Education: BA Honours in Mechanical Engineering, 2003; MA in Informatics Engineering, 2005 at Vilnius Gediminas Technical University.
Scientific interests: finite element method, genetic algorithms.

Rimantas BELEVIČIUS, Prof
Education: In 1976 a graduate of civil engineering studies at Vilnius Gediminas Technical University (formerly Vilnius Civil Engineering Institute).
Affiliations and functions: PhD in 1986, doctor habil degree in 1994. Since 1996 – professor.
Scientific interests: finite element method, optimization of structures.

Abstract. Present paper describes the facilities of composite material properties identification technique using specimen vibration tests, genetic algorithms, finite elements analysis and specimen shape optimization. In identification process the elastic constants in a numerical model is updated so that the output from the numerical code fits the results from vibration testing. Main problem analysed in this paper is that Poisson's ratio is the worst determined elastic characteristic due to its low influence on specimen eigenfrequencies. It is shown that it is possible to increase its influence by choosing specific test specimen characteristics (side aspect ratio, orthotropy angle, etc.) via optimization routine. In this paper are presented test results of some experiments wherein glass-epoxy and carbon-epoxy material properties were identified.

Keywords: identification of material properties, genetic algorithm, shape optimization, vibration test.

1. Introduction

Composite materials are one of the important applications of technological progress to modern aircraft.

Composite materials consist of fibres embedded in an epoxy matrix. Composites provide major weight savings in airplane structures due to their high strength-to-weight ratio and high corrosion resistance, as well as resistance to damage from cyclic loading.

Knowledge of the elastic properties of composite materials is essential for design and application in manufacture, and the measurement of these properties during the manufacturing process allows obtaining the desired material properties. The determination of the

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material properties of composite materials is much more complicated than that of isotropic or orthotropic materials (Ragauskas *et al.* 2008).

Vibration testing combined with a numerical method is a potential alternative approach to determine the elastic constants of materials because of its non-destructive character, single test, and ability to produce average properties (Ayorinde *et al.* 1993; Ayorinde 1995; Hwang *et al.* 2006).

Traditional test procedures based on static loading of test specimens are slow and expensive. At least three separate static tests are required to measure the four elastic constants describing the linear-elastic stress-strain relationship of thin unidirectional laminates (Berthelot 1999; Bledzki *et al.* 1999; Carlsson *et al*. 1997). Moreover, for properties such as shear modulus and Poisson's ratio, these tests often yield poor results (Maletta *et al.* 2004; Ragauskas *et al.* 2008; Rikards *et al.* 1999). Poisson's ratio is the worst determined elastic characteristic of all because its influence on the eigenfrequencies of the specimen is sufficiently lower than other elastic characteristics and is difficult to measure by classical tests (Frederiksen 1998). In order to increase its influence on the eigenfrequencies, the dimension optimization of specimen side aspect ratio and orthotropy angle is performed. It is known that certain specimen side aspect ratios and orthotropy angles affect the influence of Poisson's ratio (Frederiksen 1999).

Thus, we propose the following technology for the identification material properties: the first stage of the proposed technology is to determine an advantageous specimen side ratio and orthotropy angle for better identification of Poisson's ratio. The second stage is an ordinary process of identifying material properties using optimized specimens.

Identifying the material properties of unidirectional single layer plates has carried out the testing of the technique based on vibration tests. It is well known: if a specimen is square, it has duplex eigenfrequencies. It means that one eigenfrequency of the specimen has two same mode shapes, rotated at 90° respectively. This results in the distortion of the objective function (chapter 2.6). This phenomenon was circumvented automatically because the optimization of the side ratio and angle of orthotropy of the specimen always yields a rectangular shape and non-zero angle of orthotropy.

2. Identification procedure

Our approach for determining the elastic constants of materials combines vibration testing with a numerical method. Natural frequencies and the corresponding mode shapes are obtained from vibration testing, and the elastic constants in the numerical model are updated so that the predicted dynamic properties fit the results from vibration testing. With this approach, elastic constants obtained always represent the global, averaged properties of a structure.

In earlier research practice, the method used to determine the elastic constants of materials was usually a simple searching method, e.g. the least-squares or gradient method. To obtain more accurate and reliable results, it is necessary to use more efficient searching methods. Thus, an identification method combining experiment design, the response-surface function, and finite element analysis has been used for the elastic constants of composite laminates (Rikards *et al.* 1999; Ma *et al.* 1999). The works of Cunha, Maletta, Hwang, and Lee clearly show the potential of genetic algorithms (GAs) for the procedure of identifying material properties (Cunha *et al.* 1997; Hwang *et al.* 2006; Lee *et al.* 2006). Also, some special techniques can enhance the GAs, e.g., Hwang uses a hybrid real parameter GA (RGA) for inverse determination. RGA overcomes parameter encoding and decoding and saves computational time (Hwang 2000; Hwang *et al.* 2006; Hwang 2006).

In this work, the GA library (obtained from Wall, Massachusetts Institute of Technology) is used in the inverse determination method to search for the elastic constants.

In the present investigation, the finite element method is used for the modelling and dynamic analysis.

2.1. Finite element models

Modelling using the finite element method (FEM) is based on the first-order shear deformation theory including rotation around the normal. The FEM program ANSYS was used in calculations. The element SHELL63 was employed in the mathematical model. The element has a bending and membrane capability; both in-plane and normal-to-the-plane loads are permitted. It has six degrees of freedom at each node: translations in the *x, y* (in-plane axes), and *z* (normal) directions and rotations about the *x, y,* and *z* axes.

2.2. Dynamic analysis

The Block Lanczos eigenvalue solver is default for modal analysis (Grant 1997). The Block Lanczos method is especially powerful when searching for eigenfrequencies in a given part of the eigenvalue spectrum of the given system. The convergence rate of eigenfrequencies will be approximately the same when extracting modes in the midrange and higher end of the spectrum, as well as extracting the lowest modes.

2.3. ANSYS parametric design language

ANSYS Parametric Design Language (APDL) is internal language for the creation of a numerical material model. It is efficient when performing a huge amount of calculations with different material properties (MP). With APDL one can automate the calculation process, changing variables without intervention in the sequence of calculation. To identify MP using GA, it is convenient to change the input data file in every iteration via the APDL program without any interruption in the process (Ragauskas *et al.* 2008).

2.4. Genetic algorithm

GA is an exploration algorithm based on the principles of natural selection and genetics. According to this, the stronger individuals in a population survive and generate offspring that transmit their heredity to new generations. A simple GA involves a set of individuals (population) and a set of genetic operators. Each individual (chromosome) in the population represents a solution for a problem in the code of a string. The genetic operators allow the genetic manipulation process (reproduction) to be carried out.

In the current identification problem, the process of identification starts with the generation of a random initial population of sets of MP values. The population is formed of individuals, each of which represents a particular material, i.e. it is composed of a set of predicted material properties. In the genetic process, the decimal material properties are converted to a binary string and are put to a chromosome. After genetic manipulation, the binary string is converted back to a decimal expression, and the new material properties are put to a numerical model to obtain the eigenfrequencies of the updated specimen.

A fitness function is a particular type of objective function that quantifies the optimality of a solution so that a particular individual may be ranked against all the other individuals. More optimal individuals are allowed to breed and mix their datasets, producing a new generation. An ideal fitness function correlates closely with the goal of the algorithm.

2.5. Proposed technique

The detailed optimization scheme is presented in figure 1. The main consideration should be applied to the service application. This part is the main coordinating segment in the identification process. It manipulates data, runs additional programs (e.g. ANSYS), and outputs information.

The great advantage of material properties identification method based on GA is the possibility to define each identifiable parameter in a quite wide range. This will cause longer calculations but will allow revising more possible solutions.

The GA method is sensitive to GA parameters (population size, mutation, and crossover probabilities). Some tests of parameter identification were performed with a low number of generations to find out the best of each GA parameter value. Then assumptions about favourable parameter magnitudes were derived, the best combinations of parameters were chosen, and the calculations were repeated with a higher number of generations.

Our results correspond to international experience and recommendations, which propose 5 % of mutation, 90 % of crossover probabilities, and a population size as large as possible. A population size of 40 individuals proved to be sufficient for the current problem. Hereafter the mathematical model of material is developed and material properties are identified.

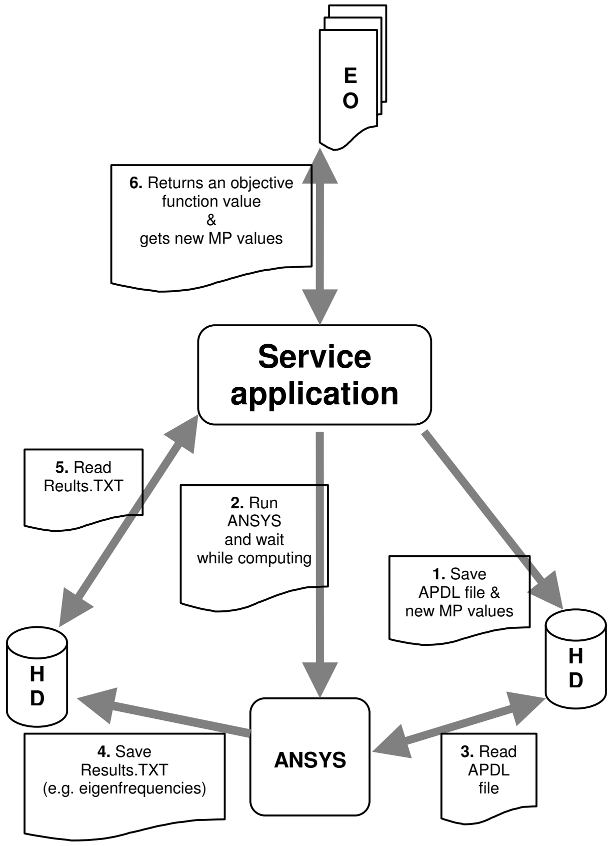

Fig 1. Detailed optimisation scheme

2.6. Identification problem

Poisson's ratios and transverse shear module are not as sensitive to the change in eigenfrequencies as other material parameters are. However, the influence of those parameters on the vibration data can be highlighted adjusting the specific characteristics of the test specimen (plate side aspect ratio, orthotropy angles, thickness), and choosing proper number and set of the frequencies taken for the identification. These characteristics differ remarkably for different composite materials of the same laminate class (Frederiksen 1998).

First, the rough identification of material properties using a test specimen of random characteristics is performed; here only the approximate values of Poisson's ratios and shear module are ascertained. Then the optimization problem is posed to maximize the sensitivity of natural frequencies to those material properties:

$$\max \quad \partial T(x) / \partial x_i \ , \quad \text{s.t.} \ \ x \in D \tag{1}$$

where the objective function *T(x)* includes the residuals between experimental (measured) and calculated natural frequencies:

$$T(x) = \sum_{i=1}^{n} \frac{\left(f_i^e - f_i^c\right)^2}{f_i^{e2}}, \tag{2}$$

where the set of design parameters x includes the specimen characteristics and the set of frequencies to be taken for identification; D is a feasible "shape" of the problem; f^e are the experimental eigenfrequencies; and f^c are calculated eigenfrequencies.

For example, for the one-layer unidirectional composite material, design parameters comprise only of the aspect ratio of plate dimensions and the angle of orthotropy direction; the thickness of the plate and the set of frequencies to be used can be added for thick multi-layer composite laminates. The optimization problem is solved using GA with tuned genetic parameters and the package ANSYS; the derivatives are calculated numerically.

In the second step of identification, the adequate test specimen is prepared and ordinary MP identification process is performed. In some cases, several specimens of one material with different geometry might be necessary due to the unequal influence of certain identifiable parameters on natural frequencies. The results are verified by comparing the elastic properties identified with the available experimental data for the tested materials.

3. Numerical examples and comments

The technology is tested using unidirectional composites: glass-epoxy (E-Glass) and carbon-epoxy (E-Carbon). These materials were chosen in consideration of their wide use in the aircraft industry and the presence of their characteristics in the literature (Berthelot 1999; Bledzki *et al.* 1999). These materials are determined by five independent elastic characteristics:

$$E_1, E_2 = E_3, \nu_{12} = \nu_{13}, \nu_{23}, \quad G_{12} = G_{13}, G_{23} = E_2/2(1+\nu_{23}), \tag{3}$$

where the longitudinal direction is denoted by 1 and the two transverse directions are denoted by 2 and 3 (Fig. 2; the orthotropy angle is zero). Here Young's modulus is represented as E, Poisson's ratio is represented as ν, and the shear modulus is represented as G. Commonly, having in mind the poor accuracy of the identification of Poisson's ratios and to simplify the three-dimensional identification problem to a two-dimensional one, assumptions about the additional parity of elastic constants are introduced:

$$E_1, E_2 = E_3, \nu_{12} = \nu_{13} = \nu_{23}, \quad G_{12} = G_{13} = G_{23} \tag{4}$$

However, we will use all six elastic constants as the design parameters for our identification in order to show the possible discrepancies on all material properties (Tab. 2). Our task is to increase the identification accuracy of the in-plane Poisson's ratio.

First, the material properties of square specimens were identified. These test show the quite poor accuracy of the identification of the in-plane Poisson's ratio for both materials: for the E-Glass it was identified with an average error of ~3.4 % (the smallest error achieved is 1.9 %), and for E-Carbon it was identified with an average error of 8.0 % (smallest error 1.5 %). Geometry optimization of specimens was performed and the optimal side ratio and orthotropy angle were obtained. Then the material properties of optimized (rectangular) specimens were identified. After geometry optimization, the identification of Poisson's ratio showed very good accuracy and confirmed the presumption made above.

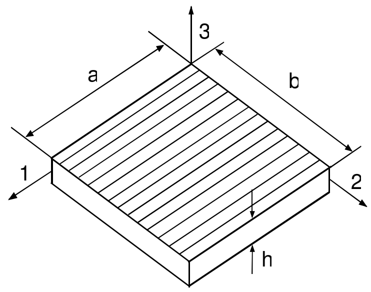

Fig 2. Specimen geometry

The geometry of initial and optimized specimens is rendered in table 1.

Table 1. Geometry of specimens

Specimen properties	Square	Rectangular	
		E-Glass	E-Carbon
a mm	250		
b mm	250	167.725	120.215
h mm	2.0		
ρ kg/m3	1375		

Table 2 shows the identifiable material properties and their bounds (Berthelot 1999).

Table 2. Material properties and range of identifiable parameters

Material properties	E-Glass		E-Carbon	
	min	max	min	max
E_1, *GPa*	20	60	100	300
E_2=E_3, *GPa*	5	14	7	14
G_{12} =G_{13}, *GPa*	1	10	1	10
G_{23}, *GPa*	1	10	1	10
ν_{12}=ν_{13}	0.1	0.5	0.1	0.5
ν_{23}	0.1	0.5	0.1	0.5

3.1. Numerical example No 1

The first numerical example is carried out using glass-epoxy composite material. The first step of the proposed technique, the specimen side ratio optimization and the orthotropy angle optimization, reveals the influence of these parameters on the identification of the in-plane Poisson's ratio. That can be seen in the pictures (Fig. 3, 4) below; the graphics beyond the depicted interval can be obtained by mirroring the curves shown. In these figures (and also Fig. 5 and 6), the curve is plotted using second order polynomial approximation.

Since GA is a stochastic algorithm, 20 tests were performed to ensure the reliability of the solution for every specimen. In the tables below, the typical five solutions for each specimen are shown (1, 2, … 5), average values of MP are given, and the identification error is calculated in the following way:

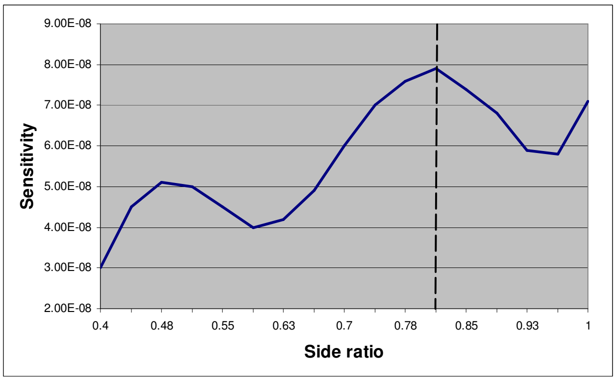

Fig 3. Approximated values of sensitivity of in-plane Poisson's ratio to the side ratio

$$\Delta = \frac{MP^{REF.} - MP^{FEM}}{MP^{FEM}} \times 100\,, \qquad (5)$$

where MP^{REF} are the reference material properties taken from literature and MP^{FEM} are calculated material properties.

In conclusion, the optimal specimen geometry for the identification of the major Poisson's ratio of glass-epoxy material is:

- side ratio $a/b = 0.7375$ ($b = 167.725$ mm);
- orthotropy angle γ=0.693979°.

As seen from table 4, after the shape optimization of the glass-epoxy specimen, the error of identifying the major Poisson's ratio decreases to an average error of 0.9 % (0.03 % in the best solution).

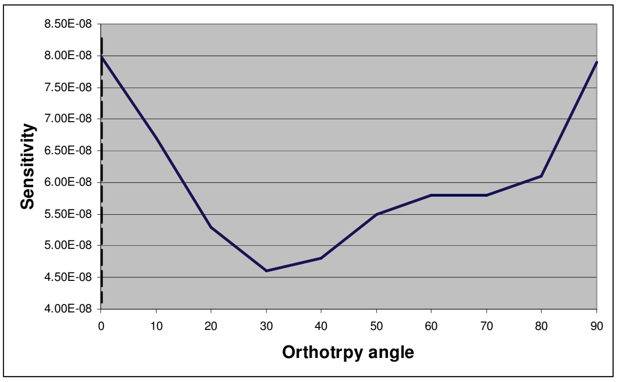

Fig 4. Approximated values of sensitivity of in-plane Poisson's ratio to the orthotropy angle

Table 3. Identified material properties of glass-epoxy (square specimen)

Material properties	E- Glass (square specimen)								
	ref. [3]	1	2	3	4 (best)	Δ %	5	average	Δ %
E_1, GPa	45.2	44.9229	46.0032	45.2055	45.1835	0.04	44.9613	45.3	0.22
$E_2=E_3$, GPa	10.8	10.6249	11.1876	10.6249	10.8016	0.01	10.6249	10.8	0.00
$G_{12}=G_{13}$, GPa	4.57	4.58599	4.37491	4.58585	4.58599	0.35	4.57281	4.54	0.66
G_{23}, GPa	3.96	8.34365	7.35651	9.67796	1.25873	214.60	4.42422	6.21	36.23
$\nu_{12}=\nu_{13}$	0.31	0.368775	0.237496	0.324997	0.304334	1.86	0.368849	0.320890	3.39
ν_{23}	0.36	0.154484	0.54388	0.596059	0.38713	7.01	0.242019	0.384714	6.42
T*e-5		9.5341	130.522	15.2971	0.458346		9.15845		

Table 4. Identified material properties of glass-epoxy specimen (rectangular specimen)

Material properties	E- Glass (rectangular specimen)								
	ref. [3]	1(best)	Δ %	2	3	4	5	average	Δ %
E_1, GPa	45.2	45.2018	0.00	45.2006	45.2042	45.1536	45.2219	45.2	0.01
$E_2=E_3$, GPa	10.8	10.7994	0.01	10.7998	10.8013	10.8125	10.7617	10.8	0.05
$G_{12}=G_{13}$, GPa	4.57	4.56951	0.01	4.57047	4.56965	4.57089	4.56841	4.57	0.00
G_{23}, GPa	3.96	9.71366	59.23	2.75702	1.64257	2.98842	8.81236	5.18	23.59
$\nu_{12}=\nu_{13}$	0.31	0.310081	0.03	0.310305	0.309686	0.309152	0.325067	0.312858	0.91
ν_{23}	0.36	0.44875	19.78	0.169123	0.458473	0.545253	0.479499	0.420220	14.33
T *e-7		0.059		0.108378	0.105444	8.84193	67.7368		

3.2. Numerical example No 2

A second numerical example is carried out using carbon-epoxy composite material. As the E-Glass, this one similarly showed poor accuracy identifying Poisson's ratio if the specimen is square (Tab. 5). As one can see in figures 5 and 6 below, by optimization of the specimen geometry, more accuracy identifying Poisson's ratio at particular side ratio and orthotropy angle values can be achieved (Tab. 6).

In conclusion, the optimal data of carbon-epoxy material specimen geometry for the identification of the in-plane Poisson's ratio is:

- side ratio $a/b = 0.481$ ($b = 0.120215$ mm);
- orthotropy angle γ=15.355°.

As seen from the figures for the carbon-epoxy, geometry optimization is clearly needed in this case: the optimal geometry is far from the initially chosen square shape.

Again, after the shape optimization of the carbon-epoxy specimen, the error of identification of the major Poisson's ratio decreases to an average error of 0.04 % (0.02 % in the best solution) (Tab. 5).

All the results of the identification of the major Poisson's ratio for glass-epoxy and carbon-epoxy are summarized in table 7.

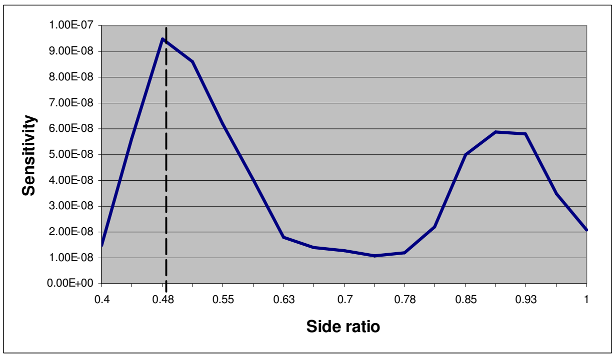

Fig 5. Approximated values of sensitivity of in-plane Poisson's ratio to the side ratio

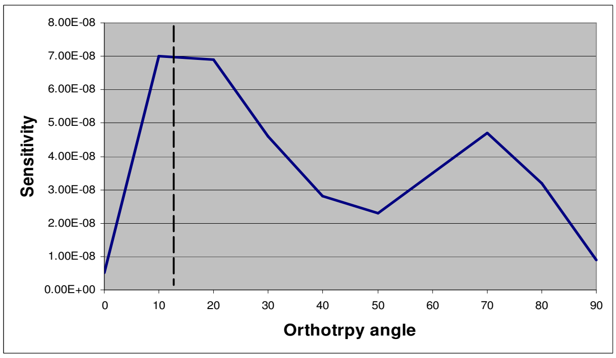

Fig 6. Approximated values of sensitivity of in-plane Poisson's ratio to the orthotropy angle

Table 5. Identified material properties of carbon-epoxy specimen (square specimen)

Material properties	E- Carbon (square specimen)								
	ref. [3]	1	2	3	4 (best)	Δ %	5	average	Δ %
E_1, GPa	229.4	228.124	228.124	224.999	229.296	0.05	229.934	228	0.61
$E_2=E_3$, GPa	10.8	11.9713	12.0004	11.9221	11.9952	9.96	12.0314	12	10.00
$G_{12}=G_{13}$, GPa	4.57	5.13971	5.1485	5.21881	5.1485	11.24	5.1485	5.16	11.43
G_{23}, GPa	3.96	9.15912	8.00993	8.03383	1.25983	214.33	7.13994	6.72	41.07
$\nu_{12}=\nu_{13}$	0.32	0.390655	0.324997	0.461163	0.325008	1.54	0.237496	0.347864	8.01
ν_{23}	0.39	0.164667	0.470799	0.463369	0.269327	44.81	0.388249	0.351282	11.02
T *e-5		1.14	1.60999	20.2394	0.100369		0.58575		

Table 6. Identified material properties of carbon-epoxy specimen (rectangular specimen)

Material properties	E- Carbon (rectangular specimen)								
	ref. [3]	1	2(best)	Δ %	3	4	5	average	Δ %
E_1, GPa	229.4	228.988	229.003	0.17	228.997	229.006	229.015	229	0.17
$E_2=E_3$, GPa	10.8	12.0042	11.9999	10.00	12.0004	11.9996	11.9993	12	10.01
$G_{12}=G_{13}$, GPa	4.57	5.13957	5.13999	11.09	5.14026	5.13985	5.14012	5.14	11.09
G_{23}, GPa	3.96	1.90405	6.58924	39.90	1.70272	1.23909	8.96425	4.08	2.94
$\nu_{12}=\nu_{13}$	0.32	0.320212	0.319993	0.00219	0.319801	0.319913	0.319507	0.319885	0.04
ν_{23}	0.39	0.554337	0.567981	31.34	0.47369	0.324273	0.519181	0.487892	20.06
T *e-9		58.3853	0.0885775		1.74095	1.10375	5.56644		

Table 7. Results of identification of material properties

Material properties	E-Glass					E-Carbon				
	ref. [3]	square	Δ %	optim.	Δ %	ref. [3]	square	Δ, %	optim.	Δ %
E_1, GPa	45.2	45.1835	0.04	45.2018	0.00	229.4	229.296	0.05	229.003	0.17
$E_2=E_3$, GPa	10.8	10.8016	0.01	10.7994	0.01	10.8	11.9952	9.96	11.9999	10.00
$G_{12}=G_{13}$, GPa	4.57	4.58599	0.35	4.56951	0.01	4.57	5.1485	11.24	5.13999	11.09
G_{23}, GPa	3.96	1.25873	214.60	9.71366	59.23	3.96	1.25983	214.33	6.58924	39.90
$\nu_{12}=\nu_{13}$	0.31	0.304334	1.86	0.310081	0.03	0.32	0.325008	1.54	0.319993	0.002
ν_{23}	0.36	0.38713	7.01	0.44875	19.78	0.39	0.269327	44.81	0.567981	36.62
T *e-9		4583.46		5.9006			1003.69		0.088577	

Conclusions

A two-step technology for the identification of material properties is proposed. It consists of the optimization of the geometric parameters of the specimen and the identification of the elastic properties of the material.

The main advantage of the proposed technology is much higher accuracy in the desired MP identification. Thus the in-plane Poisson's ratio for E-Glass can be identified with less than 0.03 % of error compared to an error of ~2% if the specimen geometry is not optimized.

The proposed technology presupposes repeating the identification process with several specimens that are optimized for the desired MP parameters, since the specimen optimized for a certain parameter may yield worse identification results for the remaining parameters. Thus, for the optimized E-Carbon specimen, even the good identifiable longitudinal Young's modulus is identified with ~3 times larger error compared to the identification of a square specimen.

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KOMPOZITINIŲ MEDŽIAGŲ TAMPRUMO IDENTIFIKAVIMAS

P. Ragauskas, R. Belevičius

S a n t r a u k a

Straipsnyje aprašomas kompozitinių medžiagų tamprumo charakteristikų identifikavimo metodas naudojant bandinių vibracinius bandymus, genetinius algoritmus, baigtinių elementų metodą ir bandinių formos optimizavimą. Identifikavimo metu tamprumo charakteristikos skaitmeniniame modelyje yra atnaujinamos tol, kol skaitinio eksperimento rezultatai nustatytu tikslumu sutampa su vibracinio bandymo rezultatais. Šio straipsnio pagrindinis uždavinys yra padidinti Puasono koeficiento identifikavimo tikslumą, kadangi šis, palyginti su kitų tamprumo charakteristikų identifikavimo tikslumais, yra menkas dėl ypač mažos koeficiento įtakos bandinio tikriniams dažniams. Darbe parodyta, kad įmanoma padidinti Puasono koeficiento įtaką optimizavimo procedūromis, pasirenkant konkrečias bandinio savybes (kraštinių proporcijas, ortotropijos kampą ir t.t.). Pateikiami keleto stiklo ir anglies pluoštais armuotų kompozitinių medžiagų tamprumo charakteristikų identifikavimo rezultatai.

Reikšminiai žodžiai: medžiagų tamprumo identifikavimas, genetinis algoritmas, formos optimizavimas, vibracijos testas.