Andrzej KATUNIN
Wojciech MOCZULSKI

KONCEPCJA METODOLOGII OCENY STOPNIA DEGRADACJI LAMINATÓW

THE CONCEPTION OF A METHODOLOGY OF DEGRADATION DEGREE EVALUATION OF LAMINATES

Praca dotyczy detekcji i identyfikacji uszkodzeń w elementach maszyn z laminatów oraz prognozowania ich propagacji podczas pracy elementu. Rozpatruje się dwa przypadki uszkodzeń: delaminacje i nieciągłość włókien zbrojących. Przy modelowaniu rozpartuje się dwa przypadki modeli: płytę kołową utwierdzoną na brzegu oraz belkę wspornikową. Materiałem modeli oraz próbek jest transwersalnie izotropowy laminat. W piewszej fazie badań są budowane modele matematyczne dla identyfikacji częstości podstawowej drgań dla płyty i belki i weryfikowane na podstawie modeli MES oraz eksperymentu. W kolejnej fazie badań najpierw jest przeprowadzana analiza zmęczeniowa belki dla określenia parametrów obciążenia i liczby cykli do wystąpienia uszkodzeń. Budowany jest także model numeryczny do termomechanicznej analizy sprzężonej w celu identyfikacji optymalnej częstości wymuszenia w teście zmęczeniowym z uwzględnieniem temperatury samowzbudnej powstającej między warstwami na skutek tarcia. Podczas testu zmęczeniowego jest mierzona siła wymuszenia, przemieszczenia i temperatura samowzbudna, a tażle zliczana jest liczba cykli. Na podstawie badań można wnioskować o wpływie uszkodzeń i ich propagacji na cykl życia laminatu.

Słowa kluczowe: *diagnostyka laminatów, modelowanie MES, temperatura samowzbudna.*

This paper aims at recognizing and classifying faults in laminate elements of machines and predicting propagation of faults during operation of the element. In the pre-processing phase we built mathematical models of identification of the first natural frequency for the plate and beam and then verified it using the frequency numerical analysis based on FEM and the experiment. During the processing phase the fatigue test must take place. First the element is analysed in the fatigue numerical analysis in order to identify the parameters of loading and the number of cycles before crack initialization. Also at this time we are able to analyse the thermal mechanical coupling. This analysis is needed to identify the optimal loading frequency in the fatigue experimental test whilst considering the self-activating temperature between laminas in the laminate evoked by friction. In fatigue test the loading force, displacements and self-activating temperature are measured and the number of cycles is counted. Also we can conclude about the influence of the faults and its propagation to the life cycle of laminate.

Keywords: *diagnosis of laminates, FEM modelling, self-activating temperature.*

1. Introduction

The laminates are used in many different branches like automotive, aerospace, shipbuilding etc. Nowadays, laminate materials are used even for most responsible parts of machinery and equipment, such as fan blades of turbojet engines, propeller blades, basic parts of car bodies, and other. Therefore, their behavior in different conditions, especially in varying application environment and workloads, must be predictable. This problem becomes more complicated, when the part concerned contains defects and faults. It is necessary to decide whether the part must be repaired or it must be substituted. The decisions could be made in situations, when the rheological properties and behavior of composite material and parts made of it are sufficiently well known.

Therefore, we need to carryout a comprehensive research involving several tests. In this paper we focus our attention on modeling natural frequency of vibrations, fundamental fatigue test and detecting the character of variability of self-activating temperature in the laminate of exemplary design. These factors are involved in the most important criteria for evaluating the life cycle of investigated laminate.

The paper is organized as follows. In the next section we deal with problem description, taking into account a particular design of the laminate composite. Further on, we give an overview of techniques used to-date for detecting faults in laminates. Then we provide an outline of the own method of detecting faults in the laminates, which combines two approaches: the experimental one and the other complementary one taking advantage of modeling the behavior by means of FEM. Then we present selected results obtained in the course of investigations in the Department. Finally, we conclude and give some ideas concerning future work.

2. Problem description

The subject of research is the 24-layered symmetric laminate with epoxy matrix and glass fiber reinforcement. The material model of it is transversal isotropic or "in-plane": layers of laminate can be described by structural formula $[0/60/-60/-60/60/0]_{4S}$. This model gives some mechanical and technological advantages and permits to construct composite elements easier with no loosing the stiffness and lightweight of construction. Also, the transversal isotropic model can be described by comparatively simple mathematical model, which allows simply describing the behavior of the composite material..

The modern composite parts are becoming "intelligent structures", which can be understood as a structure capable of carrying out measurements, and actuating systems, sometimes – operating systems, which gives the opportunity of autonomous reaction to loading of the elements. The newest integrated systems can even prevent the faults and its propagation using the influence on material stiffness and even damping.

The research problem, which the authors are going to discuss in this paper concerned answers to the questions as follows:

1. Which methods and techniques can be used for detection and location of faults in composite parts?
2. How the degradation degree of the investigated element during its exploitation can be evaluated?

The subject of research is to try defining the methodology with some additional conditions as follows:

- The methods and techniques used must give the opportunity to detect the degradation of composite elements and possibly must be non-destructive;
- The element under evaluation should operate in its normal way.

3. Techniques used to-date

Mechanical degradation processes of polymer composites are conduced to changing the material structure in local and global ranges. These changes have different forms: cracks of matrix and reinforcement, adhesive cracks, delaminations etc. The plastic deformations, changing the properties of composite elements can also take place. In case of degradation caused by long-term static and fatigue loading with approximately homogenous distribution over the volume of the part, changes of structure cover large areas. The propagation can be observed in a macroscopic scale. Decrease of stiffness coefficients and strength factors and increase of friction characteristics may take place.

The degradation degree evaluation can be processed by [1]:

- measurement of values of material stiffness coefficients,
- measurement of geometrical characteristics of dominated crack types,
- evaluation of permanent strength and fatigue.

The oldest method for controlling composite parts quality is tap test consisting in knocking the composite by special hummer and interpreting the obtained response. It gives the opportunity to detect voids in structure. The sensitivity of the method decreases with increasing depth of fault [6].

The next group of methods, which is used for detection of faults in composites, is created by ultrasound resonance techniques based on resonance vibrations measurement of the investigated structure. A piezoelectric sensor is activated for vibrations by sinusoidal tension and leads into material continuous wave, which repulse from its surface and is being amplified or damped. The amplitude and phase of vibrations on the surface of material depends on stiffness module and thickness of material under sensor. In case when delamination takes place the effective thickness of material decreases, which changes the amplitude and phase of the vibrations. These changes can be observed by the measurement system as a change of electrical impedance of the piezoelectric sensor. By scaling the system on the specimens it could be possible to define the range of vibration parameters for acceptable and inacceptable areas of the composite. Sensitivity and accuracy of the method decreased with increasing depth of faults under surface [6].

The newest techniques in composite research are thermography and inteferometry. The thermography method is based on impulse heating the composite surface and observing the changes of temperature distribution on surface using termovision camera. Areas, which contain delaminations, loose heat slowly. Based on distribution and dynamics of changes it can be possible to localize dimensions and depth of delaminations and other types of faults [6].

Interferometric techniques are based on laser light interference for showing small deformations of material surface under constraint mechanical loads influence. The typical method of loading composite materials consists in creating an underpressure on the surface using special suckers. In consequence pressure differences between pressure inside delaminations and air outside composite areas are swelled. Those deformations can be illustrated on holographic images by series of interference peaks around swelled areas. The thermographic and interferometric techniques can be successfully applied for control measurement. Its fundamental advantage is a possibility of quick research of large single-sided available areas without the need to breakup elements.

4. Conception of proceeding

The two types of models are considered: a thin circular clamped plate and cantilever beam, which were made from 24-layered epoxy based composite whose layers have been rotated according to the global coordinate system.

In investigated research the following algorithm of proceeding is proposed. In the pre-processing phase natural frequencies of vibrations of the investigated models based on a theoretical model (using Cauchy's influence function method for the plate and Timoshenko's formulas for the beam) were investigated. Then, obtained results were compared with the ones obtained using the numerical model based on FEM and the experimental results. FEM modeling was accomplished in MSC.Patran/Nastran. The models were created using 2D shell elements and material properties were defined in the Laminate Modeler module, which transforms inputted material constants and angles of rotating to the whole material. In the experiment the natural frequencies of model were identified using piezoelectric sensor placed in the center of the plate and on the actuation pipe in the beam case and computer vibrations analyzer KSD-400 with PC. Also in the experiment the problem of detecting faults was investigated. The experimental faults are assessed and if the first natural frequency value is near the theoretical value of the natural frequency it can be concluded that the faults do not occur in the tested element. However, if the values significantly differ then the research must be continued to reveal reasons of the differences.

In the processing phase the fatigue test must take place. Firstly, the fatigue numerical analysis was carried out in order to locate the most subjected faults places. The fatigue module from CosmosWorks was used for the analysis. The beam was modeled as one solid, and material properties were averaged. During the complete simulation corresponding to 10^7 cycles the model was subject to the point load. The self-activated temperature in the laminate was also investigated. The respective model was prepared and analyzed in MSC.Marc/Mentat. There were 24 deformable bodies (modeled as laminate laminas) with "touching" contact, which allows to model displacements between the laminas and friction between them. Contact with friction was based on the stick-slip method and Coulomb model. Material properties were defined using the anisotropic model by respective definition of the matrix of elastic coefficients. It allows defining true transversal isotropic material for the model. Then, the model was meshed using solid elements with shell properties for eliminating big differences between element dimensions. Mechanical boundary conditions were defined as a fixed displacement on the first side of the beam and a varying sinusoidal force on the other side. Thermal boundary conditions were defined as plastic heat generation. Then, initial conditions were defined as the initial temperature 293 K for the whole model. The analysis type was defined as thermo-mechanically coupled and calculations were made using the full Newton-Raphson iterative algorithm. After this research the fatigue test has been carried out. In this test we measured the temperature continuously using a termovision camera, loading force measured by a force gauge, and determined material properties using a laser scanning vibrometer and modal analysis. A crack and its propagation is discovered using ultrasound measurements.

In the post-processing phase we can conclude about and evaluate degradation degree of the investigated laminate. The data from modeling and experiments is the basis for creating a new fatigue mathematical model with consideration of faults propagation and self-activating temperature.

5. Results obtained to-date

In the research the analytical model of natural frequency vibrations for transversal isotropic plate was developed. The clamped circular plate with the radius R, flexural rigidity D_0 and constant thickness was considered (in isotropic case) [3]:

$$D_0 = \frac{Eh_0^3}{12\left(1-\nu^2\right)} \tag{1}$$

ν – Poisson's ratio, E – Young's flexural modulus.

The investigation of free axi-symmetrical vibrations of a plate consists of the boundary problem [3]:

$$L_0[u] - pr^{-\frac{2}{3}m}u = 0 \qquad p = \frac{\rho h_0}{D_0}R^{\frac{2}{3}m}\omega^2 \tag{2}$$

$$u(R) = 0 \qquad u'(R) = 0 \tag{3}$$

$$L_0[u] \equiv u^{IV} + 2r^{-1}(m+1)u^{III} + r^{-2}(m^2+m)u^{II} \tag{4}$$

where: u – flexural amplitude, $u=u(r)$, ρ – density, ω – frequency parameter.

In the transversal isotropy case the flexural rigidity (1) becomes a matrix (5) [2]:

$$[D] = \begin{bmatrix} D_{11} & D_{12} & 0 \\ D_{21} & D_{22} & 0 \\ 0 & 0 & D_{33} \end{bmatrix} \tag{5}$$

where [8]:

$$D_{ij} = \frac{1}{3}\sum_{k=1}^{n}\left\{Q_{ij}\right\}_k\left(z_k^3 - z_{k-1}^3\right) \tag{6}$$

where z is a distance from the investigated lamina to the axis of symmetry of the laminate. The elasticity matrix Q can be displayed as:

$$[\bar{Q}] = \begin{bmatrix} \frac{E_1}{1-\nu_{12}\nu_{21}} & \frac{\nu_{21}E_2}{1-\nu_{12}\nu_{21}} & 0 \\ \frac{\nu_{21}E_2}{1-\nu_{12}\nu_{21}} & \frac{E_2}{1-\nu_{12}\nu_{21}} & 0 \\ 0 & 0 & G \end{bmatrix} \tag{7}$$

When angles of rotation were taken into consideration we had to use the cosines matrix, which transforms material properties for tho layers into direction different that 0^0.

$$[T] = \begin{bmatrix} \cos^2\theta & \sin^2\theta & 2\sin\theta\cos\theta \\ \sin^2\theta & \cos^2\theta & -2\sin\theta\cos\theta \\ -\sin\theta\cos\theta & \sin\theta\cos\theta & \cos^2\theta - \sin^2\theta \end{bmatrix} \tag{8}$$

After taking into consideration formulas (5)-(8) it can be possible to obtain the dependence for rigidity of a lamina (9):

$$\left[D_{ij}\right]_k = [T][Q][T]^T\left(z_k^3 - z_{k-1}^3\right) \tag{9}$$

and the rigidity of the whole laminate [4]:

$$D = \sum_{k=1}^{n}\left(\frac{D_{11}+D_{22}}{2}\right)_k \tag{10}$$

which can be presented as a sum of averaged rigidities of laminas. Finally, the first natural frequency can be calculated as:

$$\omega_1 = \gamma_{\pm}\frac{1}{R^2}\sqrt{\frac{D_0}{\rho h_0}} \tag{11}$$

For the cantilever beam the Timoshenko's formulas were used [7]:

$$\omega_1 = \frac{\lambda_1}{L^2}\sqrt{\frac{D}{\rho h}} \tag{12}$$

where: L is a length of the beam. $L = a$.

$$\lambda_1 = 3{,}52 - 0{,}0967\beta + 0{,}03\beta^2 - 0{,}00476\beta^3 \tag{13}$$

$$\beta = \frac{b}{a} \tag{14}$$

Then, analytical models were verified using FEM. Normal modes maps are shown in Fig. 1. and Fig. 2.

Then, results of the models were verified experimentally using resonance method, computer vibration analyzer and FFT method. Results of comparison are shown in Table 1.

Table 1. Comparison of obtained results

Model	*Analytical method*	*Numer. method*	*Experim. method*	*Error*
Units	f_{t1} *[Hz]*	f_{t2} *[Hz]*	f_e *[Hz]*	*Δ [%]*
Plate	*213,46*	*220,91*	*218,95*	*2,57*
Beam	*17,824*	*17,534*	*17,996*	*0,96*

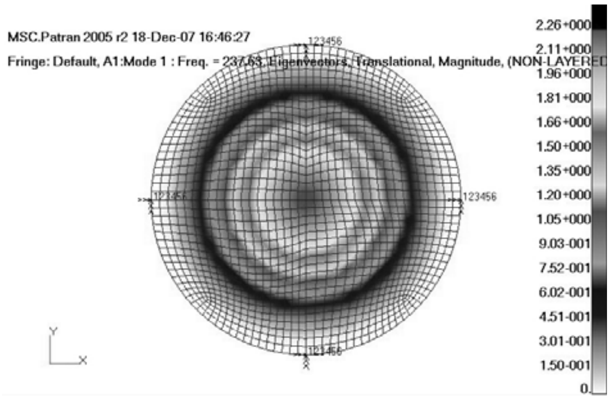

Fig. 1. Map of the normal mode of the laminate plate

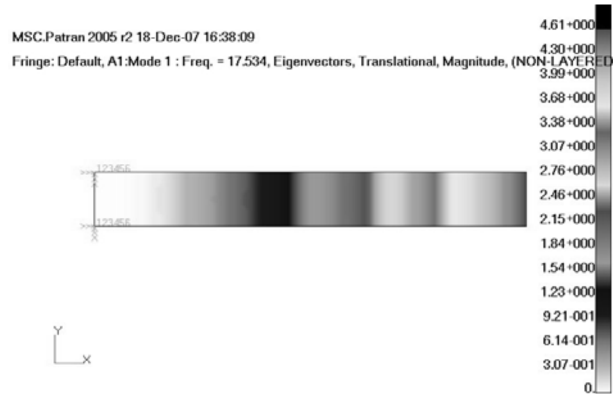

Fig. 2. Map of the normal mode of the laminate beam

In the experiment natural frequencies of samples with and without faults were investigated. Results are shown in Table 2 and Table 3.

Tab. 2. Comparison of the experimental results of the plate

Without faults	*With faults*	*Error*
f_1 [Hz]	*f_{1f} [Hz]*	*Δ [%]*
218,95	*236,94*	*8,22*

Then, the results from fatigue numerical analysis were obtained. The life cycle map is shown in Fig. 3.

The glass transition temperature of epoxy of a laminate was obtained using DSC 822^e Mettler Toledo by differential scanning calorimetry method. An analysis showed, that the first glass transition temperature of epoxy is equal to 54,09 ^{0}C.

Based on these results the numerical thermo-mechanical coupled analysis was carried out. The aim of the analysis was to investigate the character of increasing the self-activating temperature to the glass transition temperature and to evaluate the number of cycles to the transition. The number of time steps in the analysis was 4000, corresponding to 1000 seconds and processed in 26090 computational cycles. In the Fig. 4. the map of the self-activating temperature after 1000 seconds was presented and in Fig. 5. the temperature increasing of each lamina was shown (node numbers are equaled to maximal temperature in laminas).

After analysis an increase of the temperature to 293,08 K was observed. As the results show, we cannot make any conclusions based on this temperature. Furthermore, the analysis itself requires very long time to complete, thus it is infeasible for the computer resources available to the authors. Therefore, an approximation of the obtained results was needed. For the approximation the Optimization model from Maple was used. We took into consideration the maximal obtained temperature (in the 6th layer). Then, the obtained results were inputted to Maple workspace and the approximation function was modeled by formula (15) [5]:

$$T=a\text{-}b\exp(\text{-}cn) \qquad (15)$$

where: *a, b, c* – constants, *n* – number of cycles.

Tab. 3. Comparison of the experimental results of the beam

Without faults	*Delami-nation*	*Fiber discontin.*	*Error $f_1 - f_{1d}$*	*Error $f_1 - f_{1fd}$*
f_1 [Hz]	*f_{1d} [Hz]*	*f_{1fd} [Hz]*	*Δ_1 [%]*	*Δ_2 [%]*
17,996	*22,994*	*26,993*	*27,77*	*49,99*

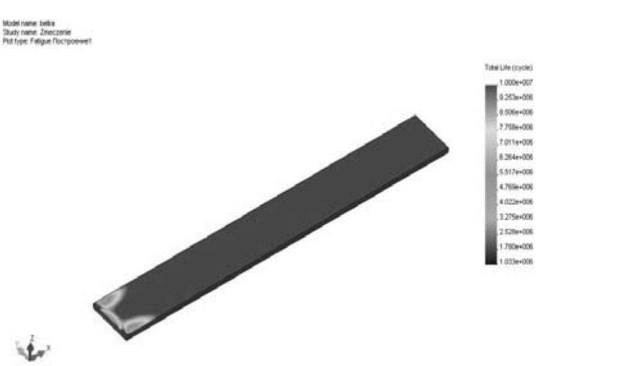

Fig. 3. Life cycle fatigue map of the laminate beam

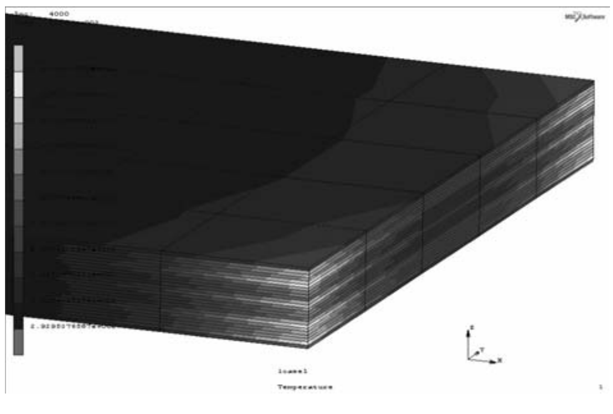

Fig. 4. Map of self-activating temperature after 1000 seconds

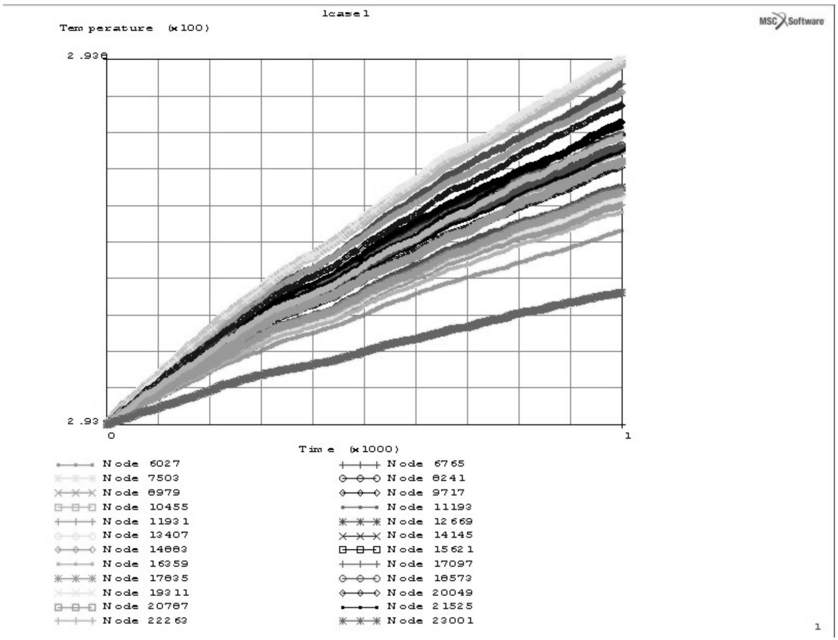

Fig. 5. Temperature increasing in laminas after 1000 seconds

After generation of residues the LLSolve function, was applied, which approximates using least squares method. The obtained characteristics was presented by formula (16) and illustrated in Fig. 6.

$$T=327{,}04-34{,}04\exp(-0{,}000024n) \qquad (16)$$

Then, the approximation results were compared with the results obtained from numerical modeling. The maximal error was near 0,02% (Fig. 7).

The glass transition temperature was achieved after approximately 560000 cycles based on approximation model.

6. Summary and conclusions

The subjects of research were two composite structures: circular clamped plate and cantilever beam. Both the theoretical models and samples from transversal isotropic laminate were investigated.

Comparison of natural frequencies of vibrations of the plate and beam presented in Table 1. shows, that errors of comparison between theoretical and experimental results are low: 2,57% in the plate case and 0,96% in the beam case. Therefore, the presented theoretical model can be applied for obtaining natural frequencies of the models. Also, it can be applied for detecting faults in laminates, however, the theoretical model cannot be applicable for microfaults, because it needs a different method of signal processing, e.g. Wavelet transform.

The point of fatigue numerical analysis is to identify load condition and the number of cycles when cracks initiation takes place.

The results obtained from DSC analysis show that the first glass transition temperature is approximately low for the investigated laminate. After the glass transition the rheological model changes from elastic to viscoelastic one. For the laminate the transition point can be often a critical work border. However, many parts of machines work in conditions, when the transition

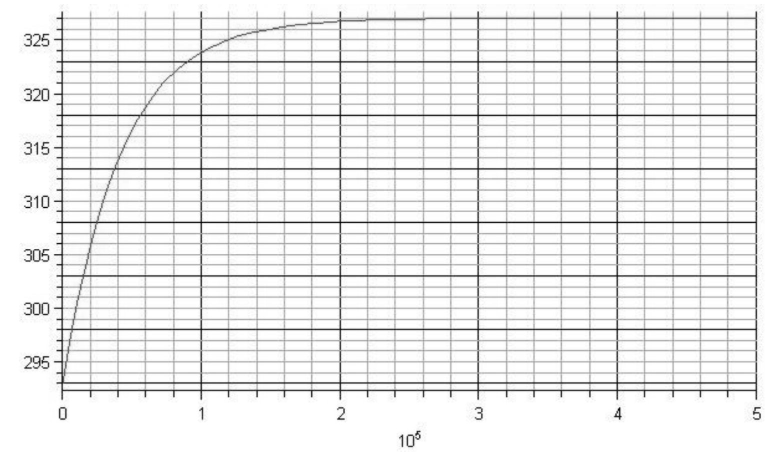

Fig. 6. Self-activating temperature characteristics obtained by means of approximation

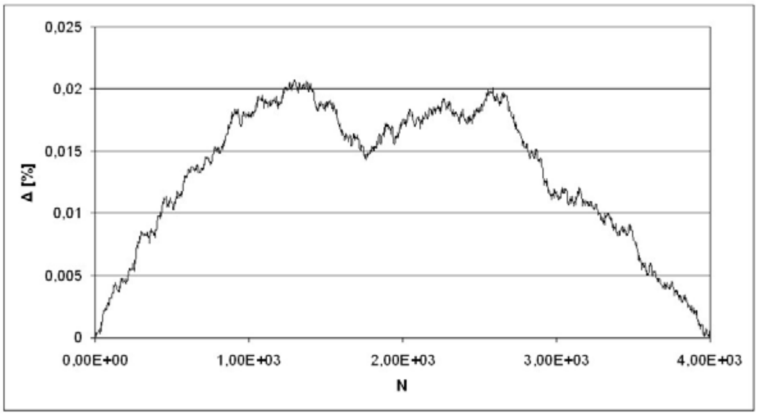

Fig. 7. Approximation error

takes place. Therefore, it is necessary to know the behavior of laminate during self-activating temperature increase, especially during the transition and after transition.

By means of the thermo-mechanical numerical analysis of the self-activating temperature we can obtain an approximative number of cycles till transition. Based on this data we can collate the loading force in the experiment. Also, self-activating temperature characteristics gives an opportunity to obtain a realistic model, which can be applied in fatigue, crack and delamination propagation numerical tests.

In the further research the numerical models of fatigue with self-activating temperatures and crack growth will be developed. Then, they will be verified experimentally, as it has been presented in Chapter 4. In the test three types of samples will be investigated: a sample without faults, sample with local delaminations and sample with discontinuity of reinforced fiber. After the experiment it can be possible to correct obtained numerical models and to conclude about degradation degree evaluation. Based on theoretical and experimental results the new mathematical fatigue model is likely to be developed.

The research is in progress now. Presented results in this paper determine the fundamentals for a new methodology of degradation degree evaluation in laminates.

7. References

[1] Bełzowski A.: *Degradacja mechaniczna kompozytów polimerowych. Metody oceny wytrzymałości długotrwałej i stopnia uszkodzenia*, Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław 2002, 176 s.
[2] Hyla I., Śleziona J.: *Kompozyty. Elementy mechaniki i projektowania*, Wydawnictwo Politechniki Śląskiej, Gliwice 2004, 258 s.
[3] Jaroszewicz J., Zoryj L.: *Metody analizy drgań osiowosymetrycznych płyt kołowych z zastosowaniem funkcji wpływu Cauchy'ego*, Wydawnictwo Politechniki Białostockiej, Białystok 2005, 120 s.
[4] Katunin A.: *Modelowanie częstości drgań własnych płyty kołowej transwersalnie izotropowej*, II Studencka Konferencja Naukowa „Metody Komputerowe – 2008", Gliwice 2008, s. 17-20.
[5] Katunin A.: *O modelowaniu temperatury samowzbudnej w laminacie*, II Studencka Konferencja Naukowa „Metody Komputerowe – 2008", Gliwice 2008, s. 21-24.
[6] Mackiewicz S., Góra G.: *Ultradźwiękowe badania konstrukcji kompozytowych w przemyśle lotniczym*, XI Seminarium „Nieniszczące badania materiałów", Zakopane 2005.
[7] Pilker W.D.: *Formulas for stress, stain and structural matrices (2nd edition),* John Wiley and Sons, 2005, 1571 p.
[8] Woźniak Cz. (red.): *Mechanika sprężystych płyt i powłok*, Mechanika Techniczna, VIII tom, Wydawnictwo Naukowe PWN, Warszawa 2001, 768 s.

Mgr inż. Andrzej KATUNIN
Prof. dr hab. inż. Wojciech MOCZULSKI
Department of Fundamentals of Machinery Design
Faculty of Mechanical Engineering
Silesian University of Technology
Konarskiego 18A, 44-100 Gliwice, Poland,
e-mail: andykatunin@yahoo.com, wm@polsl.pl,