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FINITE ELEMENT SIMULATION OF SELF-HEATING EFFECT AND THERMAL FATIGUE OF VISCOELASTIC POLYMER COMPOSITES

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Abstract

The self-heating effect, occurred in the viscoelastic media due to the mechanical energy dissipation during cyclic loading of a structure and its transformation into heat, is one of crucial problems of operation of elements made of polymeric composites. In some special cases of loading parameters the self-heating effect could dominate fatigue process, which results in intensification of structural degradation. The paper deals with finite element formulation of the self-heating effect and thermal fatigue of polymer composites. The definition of material properties was based on experimentally determined dynamic moduli of the material, which were converted to Prony series for implementation in the computational algorithm realized in commercial finite element software. Implementation procedure of the numerical simulation and exemplary results were presented. Obtained numerical results were compared with experimental results and reveal good convergence.

Key words: self-heating effect, thermal fatigue, Prony series, finite element method

1. INTRODUCTION

Polymers and polymeric composites found wide application in many engineering systems and constructions. They gained such a popularity thanks to the excellent strength-to-weight ratio and resistance to various environmental conditions. However, the behaviour of polymeric materials is different in comparison with traditional engineering materials (e.g. metals and alloys); polymeric materials reveal mainly viscoelastic behaviour (i.e. sensitivity to the frequency magnitude and temperature) with some derivative phenomena, including self-heating effect. For proper designing and operation of elements made of polymeric composites (especially for very responsible elements, like turbine blades or elements of turbojet engines) their specific behaviour in various loading and environmental conditions should be considered and well described.

The phenomena of self-heating and thermal fatigue occur in viscoelastic media in the high-amplitude periodic loading conditions due to the energy dissipation resulted from out-of-phase oscillations between stress and strain histories. The heat generated during this process is stored into the structure and causes a local temperature growth in the high-stressed regions. Considering a fact that the most of polymeric composites used as constructional materials are characterized by low thermal conductivity and relatively low glass-transition temperature, their application is able in a limited temperature range. The self-heating effect is a negative phenomenon in the operation of polymeric materials – even insignificant increase of a self-heating temperature

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causes structural changes and intensifies structural degradation much. In the cases of high and/or intensive loading the self-heating effect may dominate fatigue process, which is called thermal fatigue. During occurrence of thermal fatigue the self-heating temperature increased exponentially in the first phase, then the slow linear increase of temperature is caused by the mechanical degradation and after occurrence of the first damage the temperature increases rapidly until breakdown (Katunin, 2012). The lifetime of the element during thermal fatigue is much shorter than during fatigue, which is not combined with a self-heating effect occurrence.

Basing on literature survey it could be concluded, that the effect occurs in many engineering solutions and constitutes real danger during operation of composite elements. The authors of (Senchenkov & Karnaukhov, 2001) reported that the self-heating effect occurs in elements of turbojet engines, which were subjected to short-time overloads. Considering quick evolution of the degradation process occurrence of the self-heating effect should be prevented during designing phase. The problem of self-heating is present in propeller fans and turbine blades made of polymer composites (Adzima et al., 2010), where the local increase of temperature intensifies crack propagation. Additional problem with the self-heating effect occurrence was presented by Roos and Bakis (2011). Composite Cardan shaft, which drive back propeller of the Blackhawk helicopter is heated-up as a result of high-amplitude vibrations. Elimination of heating-up in such cases has crucial importance, because even small increase of temperature causes structural changes in a composite and intensifies its degradation. The self-heating effect occurs also in wind turbine blades as it was reported by the authors of (Fan & Kang, 2009). In some specific conditions (e.g. under the influence of a wind blowing with high speeds) the resonant vibrations are forced, which increase a stress level and initiate self-heating effect. The effect occurs in gear pairs made of polymers during workloads (Ramkumar et al., 2010), increase of temperature is observed on surfaces of contact of teeth. The authors of (Boyarov, 2010; Faghri & Guo, 2005) reported a possible danger regard to the self-heating effect occurred in composite reservoirs for storing liquid fuels and methanol, even slight increase of temperature may cause self-ignition and explosion of reservoirs.

The problem of self-heating is formulated by the several authors using phenomenological approach as a problem of thermoviscoelasticity represented by constitutive equations in the light of mechanics of continuous media. The first studies on a theoretical model of the phenomenon were introduced in the works of a research group from the Institute of Mechanics of the Ukrainian Academy of Science (Kovalenko & Karnaukhov, 1969). Later, the authors generalized presented formulation to different shapes of investigated models and multiple dimensions (e.g. Senchenkov et al., 2004). The problem was investigated analytically also by a group from the Paul Verlaine University in Metz (Dinzart & Molinari, 2005; Dinzart et al., 2008), where the authors modeled behaviour of simple one-dimensional systems. Some analytical models of self-heating were presented by the author of following article for cyclically loaded beam (Katunin, 2009), cyclically loaded rectangular (Katunin, 2010), circular and annular plate (Katunin, 2011) and for rectangular plate loaded on resonant frequencies (Katunin & Fidali, 2012). However, the analytical modeling is limited to solving models only for regular shapes and with many simplifications and assumptions, which are necessary to obtain an explicit analytical solution. Moreover, a coupled problem of thermoviscoelasticity could be solved analytically only for steady state.

For modeling the phenomena of the self-heating and thermal fatigue the finite element method (FEM) could be used as well. The application of FEM allows for obtaining numerical solution for non-steady state problems with non-linear geometry. The self-heating problem was formulated by the several authors for solving some engineering problems. Lesieutre and Govindswamy (1996) presented a FE formulation of viscoelastic thermo-rheologically simple medium subjected to the cyclic simple shear. The self-heating problem was solved using FEM for polycrystalline silicon thin film transistors (Wang et al., 2009) and for viscoelastic dampers (de Cazenove et al., 2009). The results of FE modeling of polyethylene and polyurethane media under the cyclic compression loading were presented by Avanzini (2011) and Pichon et al. (2012), respectively. Basing on literature survey the FE formulation of the thermal fatigue problem was not found, which motivated the author of this paper to develop such a model.

The aim of this paper is to present modeling procedure of the self-heating effect and thermal fatigue of polymeric composite plate subjected to the cyclic bending in the cantilever mode. For the material characterization the frequency-, temperature- and heating rate-dependent dynamic moduli (determined experimentally) were used after conversion to the Prony series form. For simulation of typical behaviour of a plate during thermal fatigue a damage criterion was applied. The implementation procedure was presented for MSC Marc/Mentat® commercial software. Obtained results of simulation were presented and compared with experimental results. The differences between simulation and experimental results were explained and discussed.

2. PROBLEM FORMULATION

The thermoviscoelastic behaviour in a stress relaxation mode of a polymeric laminate considering small strain formulation could be presented following the Boltzmann superposition principle as a hereditary integral equation (Katunin, 2010):

$$\sigma_{ij}(t) = G_{ijkl}(t,\theta)\varepsilon_{kl}(0) + \int_0^t G_{ijkl}(t-\tau,\theta)\dot{\varepsilon}_{kl}(\tau)\,\mathrm{d}\tau\,, \tag{1}$$

where $\sigma_{ij}(t)$ is a time dependent stress tensor, $G_{ijkl}(t,\theta)$ and $G_{ijkl}(t-\tau,\theta)$ are temperature dependent relaxation kernels tensors, $\varepsilon_{kl}(0)$ and $\dot{\varepsilon}_{kl}(\tau)$ are the short-term and the long-term strain tensors (derivative of a strain tensor with respect to relaxation time), respectively, τ is the relaxation time.

In the FE commercial packages which are able to solve the problem of thermoviscoelasticity the relaxation moduli are usually presented in the form of a series expansion in exponential terms known as Prony series. For the isotropic linear viscoelastic material it could be presented as follows:

$$g(t) = 1 - \sum_{i=1}^{N} g_i\left(1 - \exp\left(\frac{-t}{\tau_i}\right)\right), \tag{2}$$

where $g(t)$ is a dimensionless relaxation modulus, N is a number of terms taken into consideration, g_i and τ_i are the relaxation moduli and the relaxation time spectra. The elements g_i and τ_i could be determined experimentally during the relaxation tests or basing on Dynamic Mechanical Analysis (DMA) measurements under cyclic loading from the dynamic moduli based on the following relations:

$$G'(f,\theta,\beta) = G_0(\theta,\beta)\left(1 - \sum_{i=1}^{N} g_i\right) + G_0(\theta,\beta)\sum_{i=1}^{N}\frac{4g_i\pi^2\tau_i^2 f^2}{1+4\pi^2\tau_i^2 f^2}\,, \tag{3}$$

$$G''(\omega,\theta,\beta) = G_0(\theta,\beta)\sum_{i=1}^{N}\frac{4g_i\pi^2\tau_i^2 f^2}{1+4\pi^2\tau_i^2 f^2}\,, \tag{4}$$

where f is a frequency, $G'(f,\theta,\beta)$ and $G''(f,\theta,\beta)$ are frequency-, temperature- and heating rate-dependent dynamic storage and loss moduli, respectively. The sum of the moduli gives a complex modulus:

$$G^*(f,\theta,\beta) = G'(f,\theta,\beta) + iG''(f,\theta,\beta)\,, \tag{5}$$

where $G'(f,\theta,\beta)$ represents elastic behaviour, while $G''(f,\theta,\beta)$ represents viscous behaviour of the material.

Solving (1) with appropriate boundary conditions the dissipation function could be determined, cf. (Katunin & Gnatowski, 2012):

$$Q(X,t) = 3\pi f\sigma_0^2 G''(f,\theta,\beta)\,, \tag{6}$$

where X denotes Cartesian coordinates and σ_0 is an initial stress. For the determination of the self-heating temperature evolution the heat transfer equation with convection boundary conditions must be solved, where $Q(X,t)$ is substituted as a source function:

$$\lambda\nabla^2\theta(X,t) = c\rho\dot{\theta}(X,t) + Q(X,t)\,, \tag{7}$$

where λ is the coefficient of thermal conductivity, c is the volumetric heat capacity and ρ is the mass density.

The thermal fatigue problem could be modeled regarding to various criteria: evolution of stress values, material parameters or temperature values. Considering that the stress relaxation mode of cyclically loaded viscoelastic medium is assumed the thermal fatigue problem could be formulated basing on damage function S, which describes reduction of temperature-, frequency- and heating rate-dependent storage modulus of the material (Katunin, 2012):

$$S = 1 - \frac{G_0'(f,\theta,\beta) - G'(f,\theta,\beta)}{G_0'(f,\theta,\beta) - G_c'(f,\theta_c,\beta)}\,, \tag{8}$$

where $G_i'(f,\theta,\beta)$ without lower index denotes current value of the storage modulus and for $i = 0$ and $i = c$ there are an initial value and critical values of the storage modulus, θ_c denotes critical self-heating temperature.

3. FE PROBLEM FORMULATION AND IMPLEMENTATION

The elemental equations of the coupled non-stationary self-heating problem have the following general form, cf. (Lesieutre & Govindswamy, 1996):

$$[\mathbf{M}]\{\ddot{\mathbf{x}}\}+[\mathbf{C}]\{\dot{\mathbf{x}}\}+[\mathbf{K}]\{\mathbf{x}\}=\{\mathbf{f}\}, \qquad (9)$$

where [**M**] is the mass matrix, {**x**} is the displacements vector, [**C**] is the coupled thermomechanical matrix, [**K**] is the stiffness matrix and {**f**} is the force vector. The individual matrices have the following structure:

$$\begin{bmatrix} m & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}\begin{Bmatrix} \ddot{u} \\ \ddot{u}_I \\ \ddot{\theta} \end{Bmatrix}+\begin{bmatrix} 0 & 0 & 0 \\ 0 & \lambda/Q & 0 \\ 0 & \ddot{u}_I\,\lambda/Q & cV_{el} \end{bmatrix}\begin{Bmatrix} \dot{u} \\ \dot{u}_I \\ \dot{\theta} \end{Bmatrix}+\begin{bmatrix} G_uV_{el} & -G_uV_{el} & 0 \\ -G_uV_{el} & G_uV_{el} & 0 \\ 0 & 0 & \lambda V_{el} \end{bmatrix}\begin{Bmatrix} u \\ u_I \\ \theta \end{Bmatrix}=\begin{Bmatrix} F \\ 0 \\ 0 \end{Bmatrix}, \qquad (10)$$

where V_{el} denotes volume of a single element and u_I denotes inelastic displacements.

The formulated problem was implemented in the MSC Marc/Mentat® commercial software. The self-heating and thermal fatigue of the rectangular cantilever laminated plate with the following dimensions: length of 50 mm, width of 10 mm and thickness of 2.4 mm, was investigated. The modeled plate was made of glass/epoxy 12-layered laminate. The geometric model was meshed using 8-node hexagonal elements and the resulted mesh consisted of 1500 elements and 3744 nodes. The material properties were assumed for an isotropic (in-plane) medium with the shear modulus G = 633.2 MPa, Poisson ratio ν = 0.36 and mass density ρ = 1700 kg/m^3 following the experimental data presented in Katunin and Gnatowski (2012). The viscoelastic properties were modeled as for thermo-rheologically simple material due to the linear viscoelastic behaviour of the investigated composite and defined by 15 terms of Prony series presented in table 1, determined from the master curve of the storage modulus basing on DMA experiments (Katunin & Gnatowski, 2012). The reference temperature was assumed basing on the glass-transition temperature with the reference heating rate $\theta_r(\beta_r)$ = 134.36°C. The Williams-Lander-Ferry constants were determined from the master curve: C_1 = 79.094°C and C_2 = 405.817°C (Katunin et al., 2010). The loading frequency was assumed as f = 30 Hz.

The plasticity condition was defined by the initial yield stress equaled 9.6 MPa for taking into consideration inelastic displacements following to the experimental results. Such a condition allows taking into consideration a degradation evolution resulted by the self-heating temperature. The thermal expansion was defined as a function $\alpha(\theta)$ following the empiric formula (McElroy et al., 1988):

$$\alpha(\theta)=10^{-6}(54.8+0.163\theta). \qquad (11)$$

The thermal properties were assumed as isotropic: conductivity of 0.29 W/m·K, specific heat capacity of 1286 J/mol·K and emissivity of 0.85 (Katunin, 2010). The layers of the laminate were defined as deformable bodies with a contact condition without possibility of interlayer displacement.

The boundary conditions were defined as follows. On the one edge the fixed displacement was applied and on the opposite edge the force load of 100 N and table driven sine function was defined. For all of the elements the plastic heat generation boundary condition, which was driven by the CUPFLX user subroutine compiled in Fortran®, was defined together with the volumetric heat flux boundary condition. The initial condition was defined for initial temperature of 25°C.

Table 1. *Relaxation moduli and relaxation times for the investigated composite*

i	λ_i [MPa]	τ_i [s]	i	λ_i [MPa]	τ_i [s]	i	λ_i [MPa]	τ_i [s]
1	0.400135	$1.35008\cdot10^{-16}$	6	0.39011	$9.23148\cdot10^{-5}$	11	0.138988	2.5595
2	0.399143	$2.23091\cdot10^{-13}$	7	0.354449	$8.72457\cdot10^{-4}$	12	0.132368	15.0413
3	0.396655	$1.49878\cdot10^{-10}$	8	0.280924	$7.44511\cdot10^{-3}$	13	0.129665	81.6795
4	0.390505	$4.86245\cdot10^{-8}$	9	0.21778	0.05732	14	0.128225	412.734
5	0.385833	$8.46815\cdot10^{-6}$	10	0.156642	0.40044	15	0.126875	3037.54

The analysis was defined as quasi-static coupled one with a single-step Houbolt algorithm. A heat generation conversion factor was assumed as 0.8 (Rittel, 2000).

4. ANALYSIS OF RESULTS

The numerical study was carried out in order to analyze temperature distributions in the investigated composite plate and their time evolution. The maximal self-heating temperature values in the node of the FE model were extracted and compared with experimentally determined self-heating temperature during thermal fatigue loading of specimens (Katunin, 2012). An exemplary plot was presented in figure 1. The results of a temperature distribution at the beginning of the thermal fatigue process and before the damage initiation were presented in figure 2.

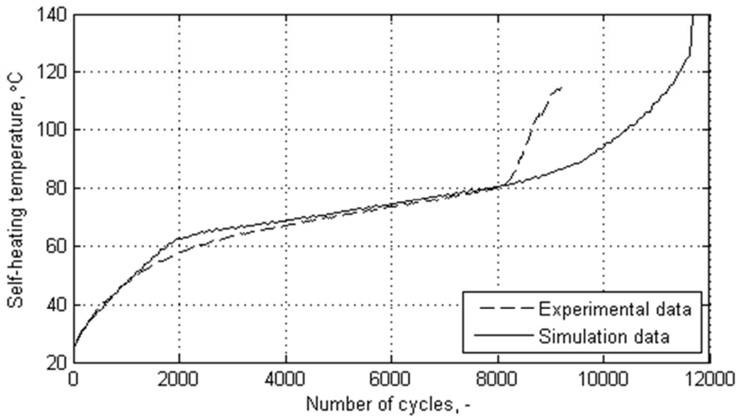

Fig. 1. Comparison of the simulation and experimental data of the thermal fatigue self-heating temperature evolution.

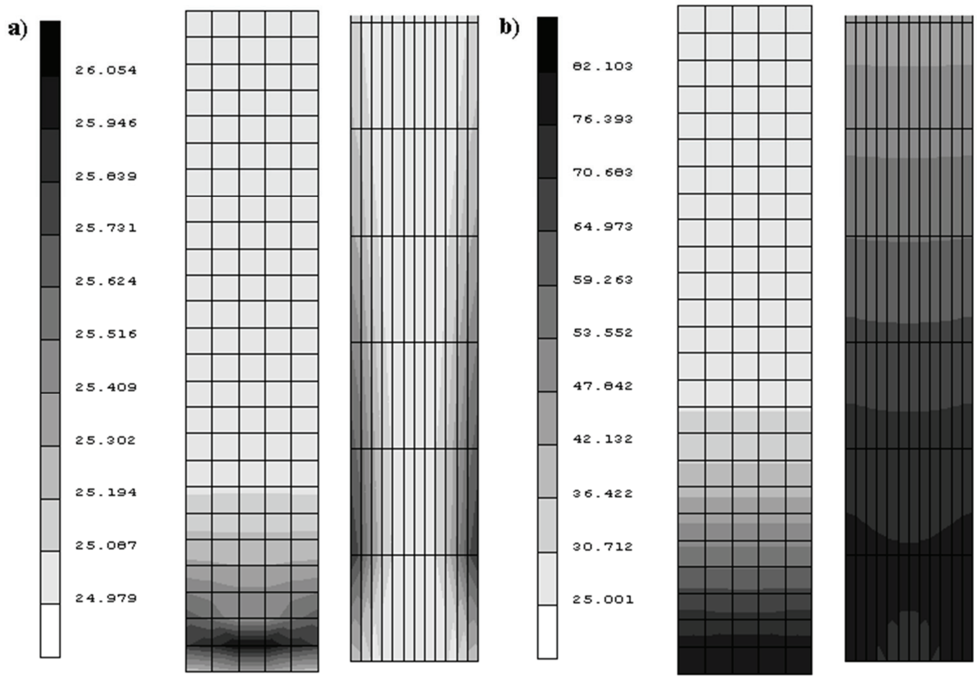

Fig. 2. Temperature distributions on the top of the plate and on the thickness (enlarged): a) at the beginning of the thermal fatigue process (after 90 cycles) and b) before the moment of damage initiation (after 7500 cycles)

As it could be noticed the experimental and simulation curves presented in figure 1 reveal a good agreement in the first (exponential temperature increase ~0÷2000 cycles) and second (linear temperature increase ~2000÷8000 cycles) phases of the thermal fatigue. Basing on experimental observations (Katunin, 2012) it was conducted that at the end of a second phase the damage initiation occurred. Therefore the temperature evolution in the third phase of a thermal fatigue influenced also by heating energy resulted by friction in the gap. Moreover, the numerical model did not considered the initiation of the damage, thus the simulation curve in figure 1 increased monotonically, while the experimental curve reveals a sudden change in the region of a damage initiation.

5. CONCLUSIONS

The theoretical considerations and simulation model presented in this paper allow for taking into consideration the self-heating effect and modeling the thermal fatigue process of viscoelastic media as well. The relaxation moduli were achieved from the master curve of a storage modulus and converted to the form of Prony series. The accuracy of obtained results is determined by the number of terms of Prony series taken into consideration. The most of physical phenomena accompanied with the investigated process were considered, which gives a good convergence between numerical and experimental results The differences in a comparison in the first and second phases of the thermal fatigue resulted also by experimental parameters, i.e. moment of clamping, possible manufacturing microdefects, loss of mechanical energy in friction in clamp regions, etc. However, one of the crucial parameter influenced on the accuracy of results is the heat generation conversion factor, which is a ratio of a mechanical energy converted into heat. Some authors proposed assuming this factor constant, e.g. (Handa et al., 1999; Rittel & Rabin, 2000), but Pichon et al. (2012) posed that the factor is not constant, which was confirmed by experimental results. Additional study of determination of the heat generation conversion factor and its functional dependencies will be carried out.

Additional research shows that more accurate model could be formulated in terms of micropolar theories. Such a model will allow to take into consideration deformations and displacements caused by the self-heating effect on the molecular level, which creates a new direction of research of the investigated phenomena.

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SYMULACJA METODĄ ELEMENTÓW SKOŃCZONYCH EFEKTU SAMOROZGRZANIA I ZMĘCZENIA CIEPLNEGO LEPKOSPRĘŻYSTYCH KOMPOZYTÓW POLIMEROWYCH

Streszczenie

Efekt samorozgrzania, występujący w ośrodkach lepkosprężystych ze względu na dyssypację energii mechanicznej podczas obciążeń cyklicznych struktury i jej przemiany w ciepło, jest podstawowym problemem eksploatacji elementów wykonanych z kompozytów polimerowych. W niektórych szczególnych przypadkach parametrów obciążenia efekt samorozgrzania może zdominować proces zmęczenia, co będzie skutkowało intensyfikacją degradacji strukturalnej. Artykuł przedstawia sformułowanie modelu numerycznego efektu samorozgrzania i zmęczenia cieplnego kompozytów polimerowych. Definiowanie właściwości materiałowych jest oparte na modułach dynamicznych materiału wyznaczonych eksperymentalnie, które przekształcono do postaci szeregów Prony'ego w celu ich implementacji w algorytmie obliczeniowym realizowanym w komercyjnym środowisku opartym o metodę elementów skończonych. Przedstawiono procedurę implementacji oraz przykładowe wyniki. Otrzymane wyniki numeryczne porównano z wynikami eksperymentalnymi, wyniki cechują się dobrą zbieżnością.

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