NUMERICAL STUDY OF THE FATIGUE DELAMINATION GROWTH CONSIDERING THERMAL PHENOMENA

Andrzej KATUNIN

Department of Fundamentals of Machinery Design, Silesian University of Technology
Konarskiego 18A, 44-100 Gliwice, Poland, email: andrzej.katunin@polsl.pl

Summary

The wide applicability of polymer-based laminates in the engineering practice causes the development of methods of their diagnosing. One of the most crucial faults in polymer-based laminates is their delamination. The problem becomes more complicated while thermal effects (e.g. self-heating and frictional heating) are taken into consideration. In the present study the numerical model of fatigue growth of the delamination in linearly viscoelastic polymer-based laminate was developed. The obtained results show, that the neglecting of the thermal effects in delamination process with some loading parameters for such structures can cause large inaccuracies in delamination growth evaluation and prediction.

Keywords: polymer-based laminates, self-heating, delamination growth, laminate diagnostics.

ANALIZA NUMERYCZNA ZMĘCZENIOWEGO PRZYROSTU DELAMINACJI Z UWZGLĘDNIENIEM ZJAWISK CIEPLNYCH

Streszczenie

Szerokie zastosowanie laminatów polimerowych w praktyce inżynierskiej wywołuje potrzebę rozwoju metod ich diagnostyki. Jednym z najbardziej krytycznych uszkodzeń w laminatach polimerowych jest delaminacja. Problem staje się bardziej skomplikowany, gdy pod uwagę bierze się efekty cieplne (samorozgrzanie, rozgrzanie od tarcia). W niniejszej pracy zaproponowano model numeryczny zmęczeniowego przyrostu delaminacji w liniowo-lepkosprężystym laminacie polimerowym. Otrzymane wyniki wskazują, że pominięcie efektów cieplnych w procesie delaminacji z pewnymi parametrami obciążenia dla takich struktur może powodować duże niedokładności w oszacowaniu i predykcji przyrostu delaminacji.

Słowa kluczowe: laminaty polimerowe, samorozgrzanie, przyrost delaminacji, diagnostyka laminatów.

1. INTRODUCTION

The wide applicability of polymer-based laminates, especially in automotive and aircraft applications, determines the necessity of development of diagnostic methods for the laminates. One of the most crucial faults is the delamination. The most valuable information during diagnosing such structures is the relation for an evaluation and prediction of the delamination growth and, based on this, estimation of the lifetime of the structure. In this case, when the cyclic loading is applied to the structure standard formulations of fracture mechanics based on the beam theory and its modifications cannot be applied. Results of previous works [1] show that the delamination growth depends on several factors: layer orientation, between which the delamination occurs, position on the thickness, type of boundary conditions, etc. During cyclic loading such laminates reveal viscoelastic state, which cause hysteretic behaviour. According to this, the self-heating effect caused by dissipated energy appears. Due to the problem complexity there is no strict theoretical formulation of the thermoviscoelastic fracture. The interesting approach was proposed in [2], which based on rheological-dynamical analogy, but generally the phenomenon was investigated numerically [3-5] using various numerical techniques: cohesive zone model (CZM), virtual crack closure technique (VCCT) or virtual crack extension technique (VCET).

The previous research [1] shows, that the layers orientation may have great influence on the delamination propagation. The steady self-heating in the delamination propagation process is negligible, because of low values of temperature increase. The non-steady self-heating and its influence on the fatigue delamination growth was investigated in this paper.

In the present study the fatigue delamination growth with thermal effects influence for ELS (End-Loaded Split) plate was considered. The critical energy release rates on the delamination front were calculated numerically using J-integral formulation. Then, the process of the delamination was modeled using VCCT with direct crack growth. The non-steady self-heating was presented by analytical formula and inputted to the numerical model as temperature-, frequency- and coordinates-dependent volumetric heat flux. The frictional heating was modeled basing on stick-slip Coulomb model. After numerical analysis the energy release rates and temperature distributions for the investigated configuration of boundary conditions were obtained and compared.

2. PREPARATION OF THE NUMERICAL MODEL

The numerical simulation was prepared using MSC.Marc/Mentat® commercial FE software. We considered ELS 24-layered plate (Fig.1) made of glass fiber reinforced epoxy resin with the length *l* of 0.125m, width *b* of 0.025m and thickness *h* of 0.00528m. Such configuration was subjected for mode II delamination.

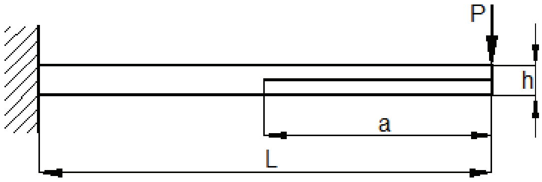

Fig. 1. Configuration of ELS plate

The layers orientation and material properties of the laminate were the same as in [1]. Each layer was modeled as deformable body with contact constraints except the initial delamination area. The model was meshed using 3000 three-dimensional eight-node thermomechanical elements. The viscoelasticity was modeled basing on Williams-Landel-Ferry (WLF) hypothesis and experimental data obtained from dynamic mechanical analysis [6] and represented as Prony series. The reference temperature (which coincides with glass-transition temperature) was 378 K and WLF constants C_1 and C_2 were 54.4745 K and 377.288 K, respectively [6]. Then the thermomechanical material properties were applied [7]. In this study one assumes the isotropy and temperature independence of above-mentioned properties. On the opposite sides of the plate mechanical boundary conditions of fixture on the one and loading force of 40 N on the other were applied.

The preliminary analysis of the critical energy release rates for different location of the crack front was performed using J-integral approach. The delamination in mid-plane (between 12th and 13th layer) was modelled as contact deactivation. Obtained values of critical energy release rates were presented in Fig. 2.

Then, the model of fatigue delamination growth was prepared. The above-mentioned parameters were defined the same as for previous model. The force was applied in sinusoidal cycles with the amplitude of 40 N. The initial delamination was assumed to 0.08 L and the delamination propagation was modeled using VCCT, where the crack growth resistance was defined as results presented in Fig.2. The direct crack propagation mode was chosen. The delamination propagation direction was defined using user subroutine (UCRACKGROW) compiled in Intel® Fortran Compiler®.

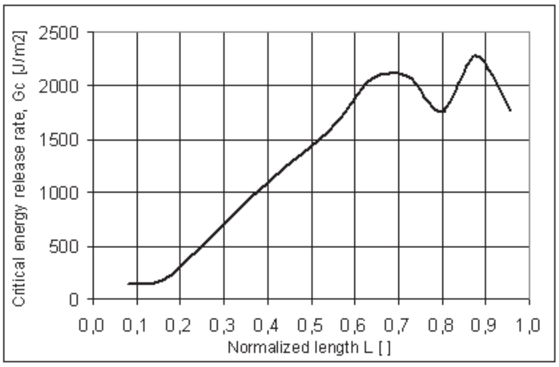

Fig.2. Critical energy release rates for investigated delamination growth

The initial temperature of the plate was assumed as 298 K. The friction in the delaminated area was modeled using Coulomb stick-slip model with the coefficient of friction equaling 0.15 (assumed following [8]). Due to the impossibility of modeling the self-heating, it was defined using the analytical formula proposed in [9]:

$$\Delta\theta(x,y)=6w^2(x,y)\varepsilon_{\max}^2\omega D''(\omega,\theta)\lambda^{-1}\cdot \sum_{m,n=1}^{\infty}\frac{\mathrm{sinc}\mu_m\mathrm{sinc}\gamma_n\cos\xi_m x\cos\xi_n y}{(1+\mathrm{sinc}2\mu_m)(1+\mathrm{sinc}2\gamma_n)(\xi_m^2+\xi_n^2)}\cdot (1-\kappa t\xi_{mn}) \quad (1)$$

where: *x* and *y* are Cartesian coordinates, θ is the temperature, *w* is the deflection function, ε_{max} is the maximal deflection, ω is the angular frequency, λ is the thermal conductivity, *D”* is the loss rigidity, κ is the thermal diffusivity, *t* is the time, μ and γ are subsequent roots of the boundary-value equations,

$$\xi_m=\frac{\mu_m}{l},\ \xi_n=\frac{\gamma_n}{b}\ \text{and}\ \xi_{mn}=\xi_m^2+\xi_n^2. \quad (2)$$

This expression was defined using multiple independent variable table as volumetric heat flux thermal boundary condition. The temperature dependence of *D”* (which was obtained experimentally using dynamic mechanical analysis [6]) for loading frequency of 200 Hz was fitted using the 4th order polynomial function ($R^2 = 1$):

$$D''(400\pi,\theta)=75.91\theta^4-14468.23\theta^3+1023044.75\theta^2-314824472.23\theta+588479316.65 \quad (3)$$

The analysis was defined as thermomechanical one with delamination growth. The analysis was continued until total delamination of the laminate for three cases: under self-heating and frictional heating, under frictional heating only and without considering any heating.

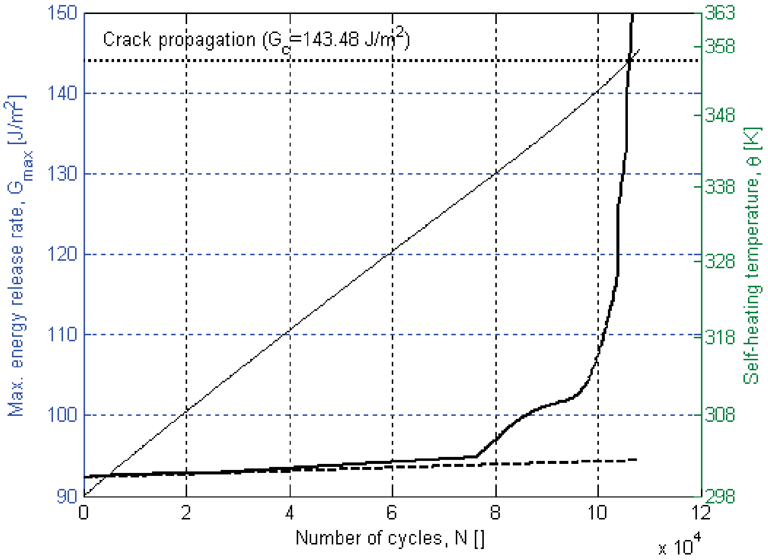

Fig. 3. Comparison of energy release rates for fatigue with and without consideration of the self-heating

3. RESULTS AND DISCUSSION

Numerical analyses were performed for $2 \cdot 10^5$ cycles for each investigated case. In Fig.3. were presented obtained results for maximal energy release rate $G_{\max}$ along the delamination front for cases with and without self-heating. During the delamination growth its front is irregular (Fig.4), therefore the maximum value of the energy release rates were considered. Also the temperature θ in the delamination front was presented for the case with self-heating (thin solid curve). As it can be noticed, the crack propagation occurred after $1.068 \cdot 10^5$ cycles with self-heating temperature of 357.48 K (intersection of bold solid and bold dashed curves), while in the case without taking into consideration the self-heating effect the energy release rate has still small value for the same number of cycles.

The observed nonlinearities of the energy release rate between $7.5 \cdot 10^4$ and 10^5 cycles appeared due to the relaxation process. After the first delamination, values of energy release rate in new delamination fronts were higher than critical ones, therefore the delamination propagated instantly in the whole area after few cycles. Fig.5. presents the energy release rates in new delamination fronts with the indication of critical energy release rates on the dimensionless normalized length of the plate.

The obtained characteristics of the energy release rate during delamination growth (Fig.5) are in good agreement with numerical and experimental results presented in other works [10].

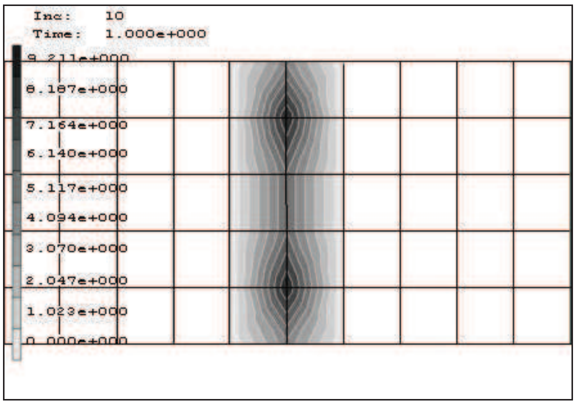

Fig. 4. Exemplary energy release rates distribution along the delamination front

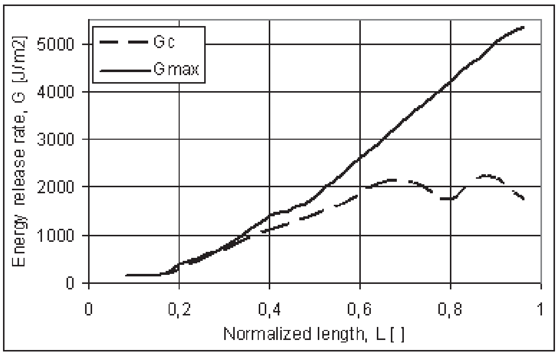

Fig. 5. Comparison of critical energy release rates and energy release rates during delamination growth

In case with frictional heating only values of the energy release rate practically were not differ than in case with self-heating. The temperature grown from the initial one to 304.6 K after $2 \cdot 10^5$ cycles and the maximal energy release rate was 101.52 J/m^2. Therefore, results for this case were omitted in Fig.3. However, in case of delamination bridging at the delamination front position value greater than in present case it may has greater influence on the structure heating up due to greater displacements in the delaminated region and also may cause the delamination growth.

The presented dependence of temperature and fatigue delamination growth shows, that the rapid increase of the energy release rates started at approximately 310 K. It shows, that the stiffness degradation of polymer-based laminates depends not only on loading parameters, but also on rheological characteristics.

4. CONCLUSIONS

In this work the numerical model of fatigue delamination growth in polymer-based laminates with thermal phenomena was developed. The research shows, that omitting self-heating in prediction of the delamination growth may cause large inaccuracies, especially when the laminate structure is subjected to intensive loading. The self-heating of the structure causes the stiffness decrease of the laminate and increase of the energy release rate along the delamination front. Moreover, the heating of the laminate causes the non-stationarity of the delamination propagation, which was observed in the present analysis.

For the numerical model validation the fatigue experiments will be carried out under laboratory conditions. After experiments it will be possible to use the Paris law in modeling the fatigue delamination growth. Then, the numerical model will be tuned by inserting i.a. temperature-dependent thermomechanical constants and coefficients from the experiments. After final calculations the empirical dependencies between fatigue, delamination growth and self-heating will be investigated. In the present work only the bending vibrations of the plate were discussed. Future research in the above-presented area consider other types of an excitation, e.g. self-heating and delamination growth under the torsional vibrations.

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Andrzej KATUNIN is a scientific assistant in the Department of Fundamentals of Machinery Design of Silesian University of Technology at Gliwice, Poland. His main areas of research are thermal phenomena in polymer-based laminates, laminates diagnostics, fatigue and life prediction of laminates, wavelets theory and applications.