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Numerical study of delamination propagation in polymer-based laminates during quasi-static loading

Key words

Mode II delamination, polymer-based laminates, delamination propagation.

Słowa kluczowe

Delaminacja II rodzaju, laminaty polimerowe, propagacja delaminacji.

Summary

In this paper, the author presents the numerical investigation of the delamination propagation in polymer-based laminate rectangular plates subjected to bending with different configurations of initial delamination. Four cases of configurations of mode II initial delamination were investigated: End-Loaded Split, Cantilever Beam Enclosed Notch, End-Notched Flexure, and Centre-Notched Flexure. These configurations were chosen due to their most common occurrence in engineering practice. The author researched the possibility of delamination growth based on critical strain energy release rate and the dependence of its value from loading and initial delamination length. The author shows that classical methods of energy release rates calculation cannot be applied for multilayered composites in cases when the initial delamination occurs out of laminate mid-plane. The influence of the self-heating effect in steady-state to crack growth was also investigated. The energy release rates were obtained from numerical simulations using J-integral formulation. The character of the delamination propagation was modelled using the

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cohesive zone approach. Results of the simulation were presented as the damage function in dependence of loading and initial delamination length. The obtained results can be useful for the prediction of the delamination growth in quasi-static tests and for modelling the delamination propagation during dynamic excitation in fatigue tests.

1. Introduction

Wide applicability of polymer-based laminates determines the development of methods and techniques of their diagnosing and monitoring. Therefore, the behaviour of them in different operation states and conditions must be investigated. The problem becomes more complicated when these structures contain faults and imperfections.

One of the most crucial faults in polymer-based laminates is the delamination or the interlayer cracks. Delaminations can arise in significant phases of the exploitation of a laminate element and their initiation and propagation can be caused by different factors, like critical loads, high temperature, ageing of material, fatigue stiffness degradation, impacts or other sources of interlaminar stress concentrations. Moreover, delaminations can arise in manufacturing processes during lamination process, waterjet cutting, and other. Delaminations can cause stiffness losses of the laminate and its total failure. In fact, mechanisms of delamination propagation must be investigated for laminate structural performance evaluation.

It is well known that delaminations can initiate in three modes according to loading and boundary conditions. Various works were focused on the mode I delamination and it is already extensively studied [1,2]. The mode III delamination has special conditions of initiation, and in engineering practice it occurs rather rarely [2]. The largest and not fully investigated group of delamination is classified as mode II delaminations. It can be induced when the prenotched specimen is subjected to bending loads with different boundary conditions.

There are many theoretical and experimental studies concentrated on fracture mechanics of laminates. In such studies, the main parameter that must be identified is the delamination resistance. It can be obtained using significant approaches. The first approach consists in evaluation of the critical stress intensity factor $K_{II,c}$ for the initial delamination length a [2,3]. The most commonly used approach uses the critical energy release rate $G_{II,c}$ formulation, which was proposed by Irwin [4]. In many works there is a proposal of analytical evaluation of energy release rate based on simple beam theory and its further modifications [5]. Various computational techniques allow the determination of the energy release rate as the J-integral [6], virtual crack extension technique (VCET) or virtual crack closure technique (VCCT) [7]. These techniques found wide application in FEM simulations.

The author's works were concentrated on degradation degree evaluation [8] and fatigue processes in polymer-based laminates with additional phenomena.

The influence of self-heating on the laminate fatigue was investigated in [9,10]. In the present paper, the author focused on numerical simulation of delamination propagation when the prenotched specimens have different initial delamination length and when the delamination occurs between significant layers of the laminate. Four cases of mode II delamination were investigated: End-Loaded Split (ELS), Cantilever Beam Enclosed Notch (CBEN), End-Notched Flexure (ENF), and Centre-Notched Flexure (CNF). Results of numerical simulations of energy release rate values were presented as R-curves in Section 3. Then, the character of delamination propagation was investigated numerically based on the cohesive zone method. The delamination was presented as the damage function and dependencies of applied loading and initial crack length were studied.

2. Problem description and motivation

Definition and solution of problems of the fracture mechanics is based on equations of structural mechanics. Due to the consideration of polymer-based laminates, the material must be defined by viscoelastic constitutive relations. However, in many works, which were considered on fracture of polymer-based laminates (e.g. [5-7]), the author assumes the linear elastic delamination models. This assumption is true for quasi-static loading only.

In the present paper, the multidirectional CFRP laminate rectangular plate was taken into consideration. The structural formula of the laminate, characteristic dimensions and material properties were given by (1) and Table 1 [8], where E_1 and E_2 are Young's moduli, G_{12} is the shear modulus, ν_{12} is the Poisson ratio, ρ is the density and L, b, h, h_0 are length, width, height of the plate and height of the layer respectively, whose structure is represented by:

$$[0/60/-60/-60/60/0]_{4S} \tag{1}$$

Table 1. Material properties and characteristic dimensions of the plate
Tabela 1. Stałe materiałowe i charakterystyczne wymiary płyty

E_1 [GPa]	E_2 [GPa]	G_{12} [GPa]	ν_{12} [-]	ρ [kg/m^3]
38.283	10.141	3.533	0.366	1794
L [m]	B [m]	h [m]	h_0 [m]	
0.25	0.025	0.00528	0.00022	

2.1. Theoretical background

As it was noticed before, four mode II delamination configurations were chosen for the analysis: ELS, CBEN, ENF and CNF. These configurations are presented in Fig. 1.

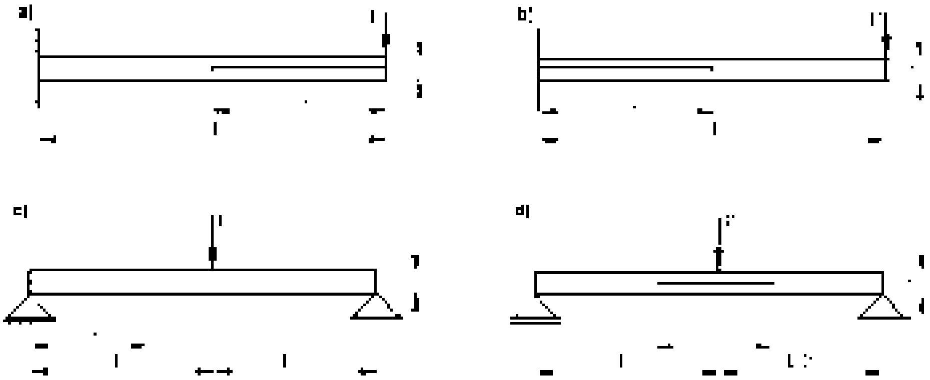

Fig. 1. Configurations of delamination, a) ELS, b) CBEN, c) ENF, d) CNF
Rys. 1. Konfiguracje delaminacji, a) ELS, b) CBEN, c) ENF, d) CNF

The presented configurations were based on typical experimental tests of delamination, which allow to determine delamination resistance given by critical stress intensity factors $K_{II,c}$ or critical energy release rates $G_{II,c}$, whereas there is the relation between the latter parameters. According to corrected beam theory $G_{II,c}$ can be presented by (2) for the investigated cases with respect to Fig. 1.

$$\text{a), b)} \qquad G_{II,c} = \frac{9P^2a^2}{4b^3E_1h^3},$$
$$\text{c), d)} \qquad G_{II,c} = \frac{9P^2a^2}{16b^3E_1h^3}, \tag{2}$$

where P is the applied load and a is the initial delamination length. The relation between $G_{II,c}$ and $K_{II,c}$ can be presented as:

$$G_{II,c} = \frac{K_{II,c}^2}{E'}, \; E' = E_1 \text{ for plane stress and } E' = \frac{E_1}{1-\nu^2} \text{ for plane strain.} \tag{3}$$

It is known that there is the equality between energy release rate and J-integral value. Therefore, there is a possibility to substitute the evaluation of $G_{II,c}$ values by J_c values in further investigations. The J-integral can be defined mathematically as path-independent contour integral and can be useful for crack analysis [11]. Physically, it is the measure of dissipative energy during crack propagation, which can be presented as:

$$J = -\frac{\partial U}{\partial a}, \tag{4}$$

where U is the potential energy [2].

For evaluation of delamination propagation character the cohesive zone method was used. This method is based on constitutive relationship between stress values and relative displacements value. The effective traction t is introduced as a function of effective opening displacement δ and is characterised by the initial reversible response followed by an irreversible response as soon as the critical effective opening displacement δ_c has been reached. The irreversible part is characterised by increasing the damage function ranging from 0 (onset delamination) to 1 (full delamination) [11]. In this study the exponential function (5) was used:

$$t = G_{II,c} \frac{\delta}{2\delta_c} \exp\left(-\frac{\delta}{\delta_c} \right), \tag{5}$$

where $G_{II,c}$ is the energy release rate or so-called cohesive energy.

2.2. Motivation

In investigations of the delamination of rectangular plates, there are several constraints if the analytical approach was chosen. First of all, the presented relations (2) assume that the delamination growth is stable; however, in the investigated case, the delamination growth instabilities can occur as well. Moreover, in (2), only the longitudinal Young modulus was taken into consideration, but in case of multidirectional laminate mechanical characteristics must be determined by four independent parameters. Referring to this, the 3-dimentional numerical model was prepared for solving the problem using MSC.Marc/Mentat commercial software, which allows one to model the delamination more realistically.

3. Numerical evaluation of energy release rates

The numerical model of the rectangular plate consists of 24 elastic bodies according to (1), which was meshed using hexagonal 8-node elements. Material properties were the same as in Table 1. The delamination in investigated cases between particular layers was modelled as a contact deactivation in interesting areas. Then, the delamination front was modelled using the crack tip node path along the width of the plate for 3-dimensional formulation. Boundary conditions were defined for each investigated case and the loading force P was applied as quarter-sine function (6) for defining it as a cyclic loading:

$$P = P_0 \sin(0.5\pi t), \tag{6}$$

where $P_0 = 10$ [N] is the static load and t is time variable defined as quasi-static time step for the analyses. The analysis was defined as mechanical static problem and J-integral values were calculated. In obtained results the values of energy release rates were chosen as a maximal value along the delamination front. Due to nonlinear distribution of energy release rates along the delamination front it is necessary to be sure that the delamination occurs. Results of critical energy release rates for the different initial delamination length were presented as R-curves in Fig. 2. The analyses were provided for the initial delamination with $H = 0.5$. Here and further A_0 is the non-dimensional initial delamination length, z denotes the distance from bottom surface of the laminate to the delaminated area and H is the non-dimensional thickness parameter:

$$A_0 = \frac{a_0}{L},\ H = \frac{z}{h}. \tag{7}$$

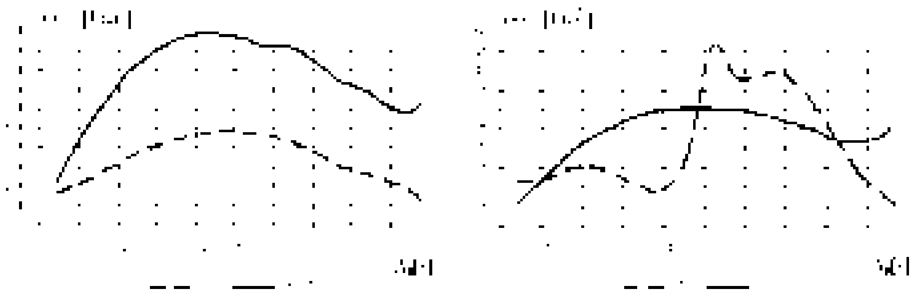

Fig. 2. R-curves for different initial delamination values
Rys. 2. Krzywe R dla różnych wartości delaminacji początkowej

According to the definition of delamination tests, which were taken into consideration and the modified beam theory, the initial delamination must be situated in the half thickness. In cases when the delamination occurs in different places, the values of energy release rates were not the same, therefore it was investigated in this study. R-curves were presented in Fig. 3 for ELS case.

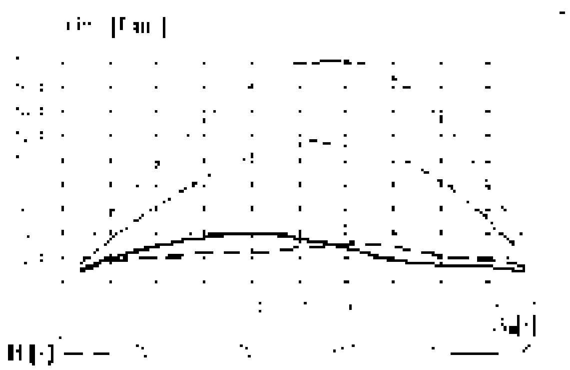

Fig. 3. R-curves for different initial delamination values and delaminated layers
Rys. 3. Krzywe R dla różnych wartości delaminacji początkowej i zdelaminowanych warstw

The H parameter values were chosen according to the orientation of pairs of layers between which the delamination occurs. Only five cases were chosen according to the symmetry of the laminate (see (1)). The investigated cases are presented in Table 2.

Table 2. Investigated cases of the delaminated layers
Tabela 2. Rozpartywane przypadki zdelaminowanych warstw

H [-]	0.5	0.75	0.875	0.917	0.958
Layers orientation [deg]	0/0	0/0	-60/-60	60/-60	0/60

For the investigated cases the dependence between applied loading P and displacements δ was also studied. Results were presented in Fig. 4.

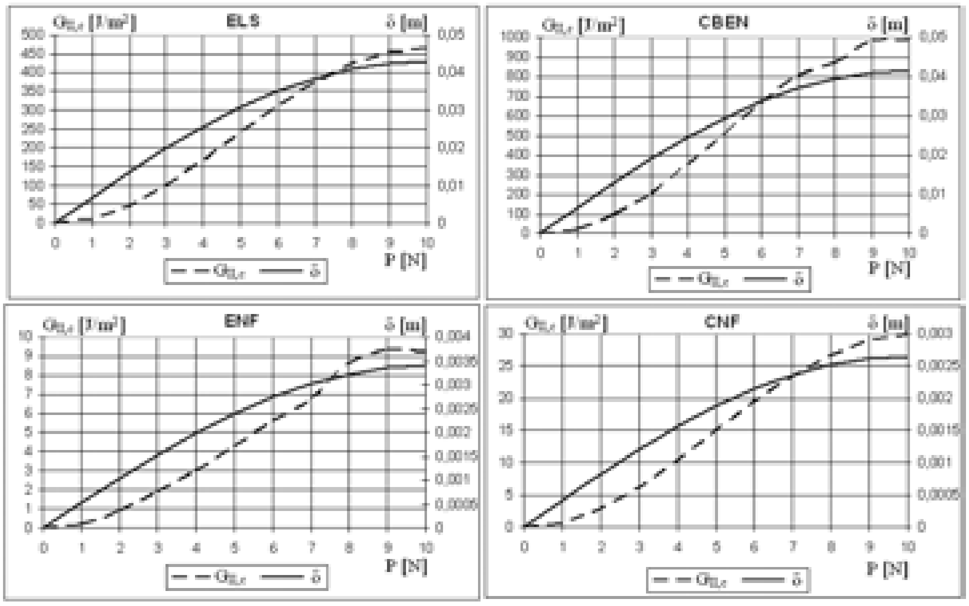

Fig. 4. Relations P-δ and P-$G_{II,c}$ for $A_0 = 0{,}4$
Rys. 4. Zależności P-δ oraz P-$G_{II,c}$ dla $A_0 = 0{,}4$

In the case of cyclic loading of the laminate, it reveals viscoelastic properties. During out-of-phase oscillations between stress and strain amplitudes, the mechanical energy is dissipated and transformed into the heat. According to low values of the thermal conductivity of the epoxy resin, the heat accumulates in the structure and the self-heating effect is performed [12]. Due to the quasi-static formulation of the present problem, only the steady-state of the self-heating was taken into consideration. The numerical model was redefined for solving the coupled thermal-mechanical work and supplemented by the initial condition of the ambient temperature (293 K) and boundary condition of the temperature defined as:

$$\theta = Q\frac{\mathrm{sinc}\mu_m \mathrm{sinc}\gamma_n \cos\xi_m x \cos\xi_n y}{(1+\mathrm{sinc}2\mu_m)(1+\mathrm{sinc}2\gamma_n)(\xi_m^2+\xi_n^2)} + \theta_0, \tag{8}$$

where θ is the temperature distribution, Q is the dissipative heating, μ_m and γ_n are subsequent roots of the boundary-value characteristic equations, x and y are Cartesian coordinates, θ_0 is the ambient temperature and $\xi_m = \mu_m/L$ and $\xi_n = \gamma_n/b$.

Results of analyses show, that the influence of the self-heating effect in all the investigated cases on J-integral values is rather low, in all cases it did not exceed 0.1%, therefore it was neglected in calculations.

4. Evaluation of damage functions during delamination

For the evaluation of the character of the delamination growth the cohesive zone method was used. The numerical model was defined as in the previous section with additional changes. The cohesive zone was modelled using zero-thickness hexagonal 8-node interface elements, contact options between two interested layers were deactivated and the glue “second-to-first” contact was defined between the cohesive zone and each of contacted layers. Then, the geometrical properties were defined for the cohesive zone: They were defined as 3D interface with integration points located in Gauss points. Material properties for cohesive zone were defined as follows: the exponential cohesive model (5) was applied with critical opening displacement δ_c = 10^{-5} [m] and the cohesive energy was set up in order to obtain full delamination when the maximal force has been applied (Table 3.). For each of investigated cases, the $G_{II,c}$ value was different. The problem was defined as the mechanical static.

The obtained results were presented as the damage function D, which takes values “0” for healthy area and “1” for fully delaminated area. Results for the investigated cases are presented in Fig.5 as contour line plots, which presented dependence between the energy release rate, the delamination length and the applied force for H = 0.5 and A_0 = 0.5.

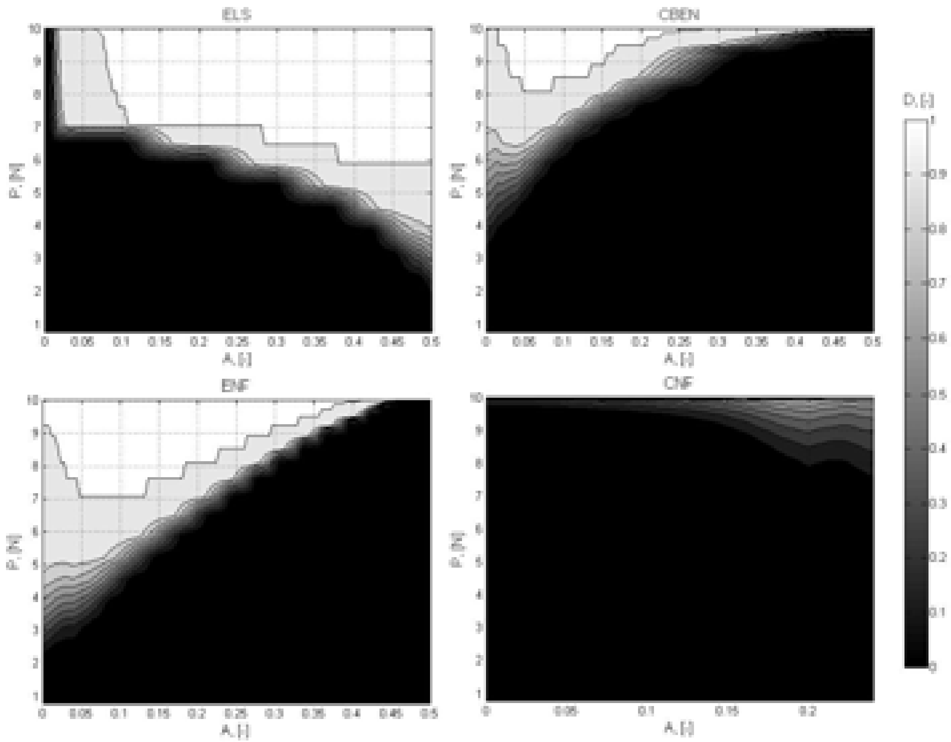

Fig. 5. Damage functions during delamination growth
Rys. 5. Funkcje uszkodzeń podczas przyrostu delaminacji

Table 3. Cohesive energy values of investigated cases
Tabela 3. Wartości energii dekohezji dla rozpatrywanych przypadków

Case identifier	ELS	CBEN	ENF	CNF
$G_{II,c}$ [J/m^2]	25	18	4.5	7.5

The next numerical research concerned the evaluation of the character of the delamination growth with different values of thickness of delamination occurring (Fig. 6) and different initial delamination values A_0 (Fig. 7). Results in Fig. 6 are presented for cases as in the previous section according to Table 2 for ELS models.

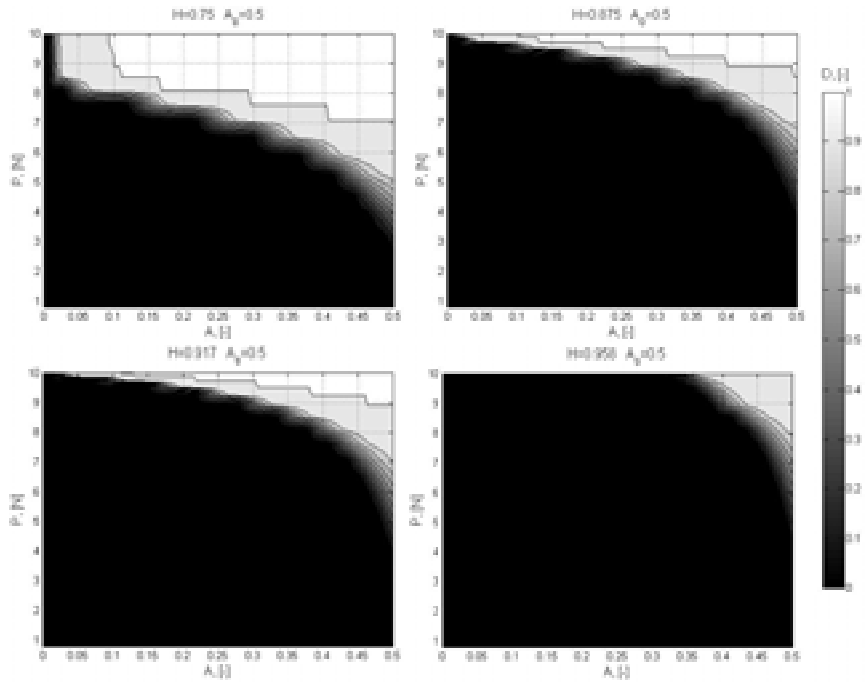

Fig. 6. Damage functions during delamination growth with different *H* parameter
Rys. 6. Funkcje uszkodzeń podczas przyrostu delaminacji z różnymi parametrami *H*

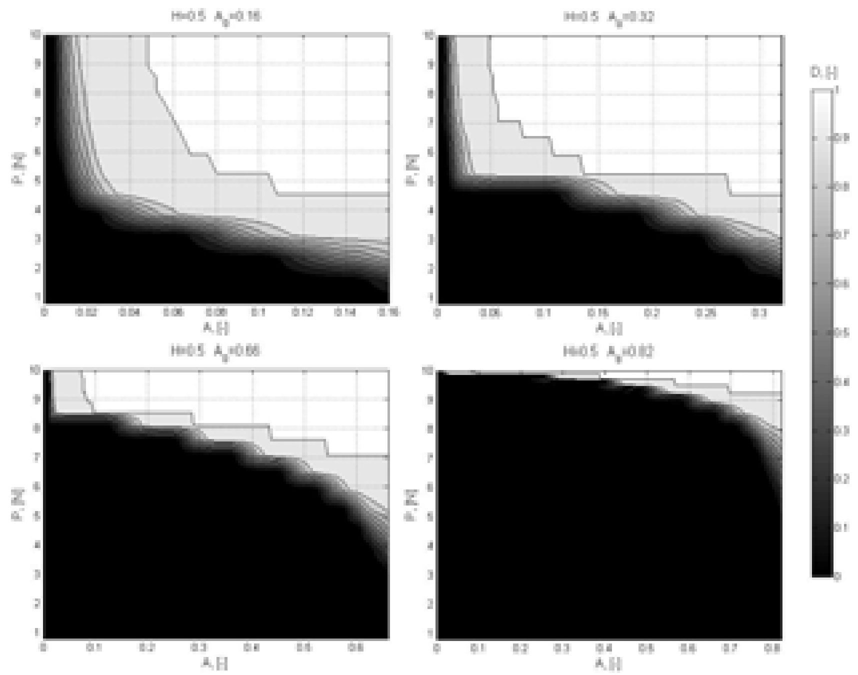

Fig. 7. Damage functions during delamination growth with different initial delamination
Rys. 7. Funkcje uszkodzeń podczas przyrostu delaminacji z różną delaminacją początkową

The delamination function is characterised by slow growth, when it attains near-one values. Figures presented below do not illustrate these small changes because of insufficient resolution of contour plots. Therefore, the fully delaminated regions in the given case can be presented as the delamination length in the function of the applied force. Such exemplary results are presented on Fig.8 for ELS configuration. The initial delamination A_0 in ELS, CBEN and ENF cases is equal to 0.5 and in CNF case is equal to 0.52.

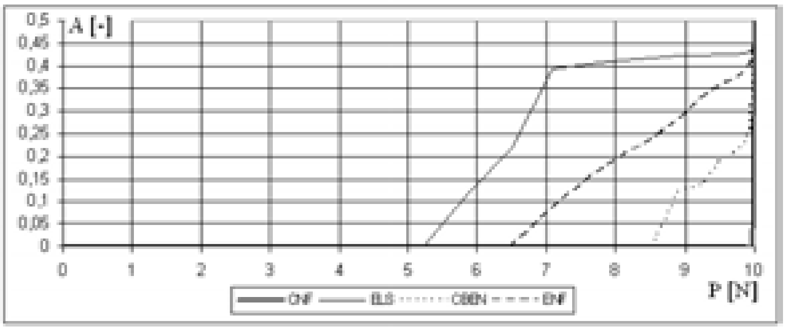

Fig. 8. Fully delaminated regions
Rys. 8. Całkowicie zdelaminowane obszary

5. Analysis of results

In the present work, the delamination process was studied numerically for four configurations of the initial delamination (Fig. 1). FE models were defined and calculated using MSC.Marc/Mentat commercial software. There are several directions of research presented in this work. We calculated the energy release rates on the delamination front in the dependence of the initial delamination length and in the dependence of the thickness, where the delamination occurs and presented results as R-curves (Fig. 2-3). Also, force-displacement and energy release rate-displacement dependencies were obtained (Fig. 4). Analyses were performed based on the J-integral formulation of the fracture. Then, the character of the delamination growth was studied using cohesive zone model formulation. Among others, the character of the delamination was studied for different values of the thickness where the delamination occurs (Fig. 6), and the initial delamination length (Fig. 7).

Analysing obtained R-curves for investigated cases (Fig. 2), one can notice that the delamination instability occurs at near half-length of the specimen, which is conformed with experimental results [2]. In case of ENF specimen (Fig. 2), there is a nonlinearity with higher order, which is caused by stress concentrations due to boundary conditions (Fig. 1). The next analyses for models with variable thickness parameter H show that, in cases when the delamination occurs out of mid-plane, the values of energy release rate are different and characterised by a decreasing tendency, which can be explained by larger stresses due to increasing the distance from neutral plane of the laminate ($z \to h/2$). This can be asserted based on R-curves with H = 0.5 and H = 0.75 in Fig.3 while taking into consideration the identical layers orientation for both cases (Table 2). We also compared pairs of layers with different orientation (see Table 2); and based on results presented in Fig.3, we can affirm the great influence of the layers orientation on energy release rates. This phenomenon occurs due to the influence of the layers' orientation on layers' rigidity and can be obtained from classical theory of lamination. Analysing results of force-displacement dependencies for investigated cases (Fig. 4), we obtain quadratic curves which coincides with modified beam theory and relations (2). Such curves were used for determining the damage energy in experimental studies [2]. Dependencies between energy release rates and the applied force also show quadratic behaviour, which is justified by linear beam theory.

In case of cyclic loading of the polymer-based laminate, there are some energy losses according to the hysteretic behaviour of the laminate, due to the theory of linear thermoviscoelasticity. According to the quasi-static study presented in this work, only the steady-state self-heating was investigated. Results of numerical simulations show that, in all investigated cases, the difference between models with and without self-heating did not exceed 0.1%; therefore, the self-heating effect has not been taken into account and could be neglected in such simulations and tests.

The study concerned the investigation of the character of delamination propagation shows stable growth of the delamination in all the investigated cases (Fig. 5), which verifies previous simulations and obtained R-curves. Stepping of the applied force caused the observed non-linearity. As it can be noticed, the character of the delamination growth in investigated cases is similar. In Fig.6, the exemplary damage function distribution for ELS configuration with variable parameter H is presented. The results confirm previous investigations. It can be observed that, for H = 0.5 (Fig.5) and H = 0.75 (Fig.6), the character of the damage function distributions are the same, but values vary according to the distance from the neutral plane of the laminate. In cases with other values of H, the influence of layer orientations can also be observed. Simulations of the delamination with variable initial delamination (Fig. 7) show the nonlinear behaviour of the damage function, especially in first two cases. It can be noticed that, after exceeding some critical force value, the delamination becomes unstable.

6. Conclusions

Analysing obtained results in several numerical studies, we can conclude the impossibility of using analytical methods based on beam theory for solving some specific problems of the delamination. The beam theory assumes that the material can be presented only by longitudinal Young's modulus, while in the case of non-isotropic structures, it behaves differently. Moreover, in standard tests for delamination evaluation, the initial delamination always is situated in mid-plane of the laminate. Therefore, the beam theory and dependencies (2) cannot be applied for evaluation of the energy release rates. Moreover, they cannot be used for a description of delamination behaviour, when it occurs in a plane other than the mid-plane (Fig. 6). Finally, the beam theory assumes growth stability during delamination process, but in many cases this assumption can give quite large differences.

The presented results are helpful for understanding the processes of the delamination propagation in multilayered structures. In further work, they will be used for modelling the high-cycle fatigue behaviour of such laminates. There are some additional effects that will be present in fatigue processes and constitute great scientific interest: hysteretic behaviour and thermal phenomena like non-steady self-heating and frictional heating in delaminated areas. The author's scientific group is going to carry out their research concerning these problems in the near future.

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Badania numeryczne propagacji delaminacji w polimerowych laminatach podczas obciążeń quasi-statycznych

S t r e s z c z e n i e

W niniejszej pracy autorzy prezentują badania numeryczne propagacji delaminacji w polimerowych laminatowych płytach prostokątnych poddanych zginaniu z różnymi konfiguracjami delaminacji wstępnej. Rozpatrzono cztery przypadki konfiguracji delaminacji wstępnej II rodzaju: End-Loaded Split, Cantilever Beam Enclosed Notch, End-Notched Flexure i Centre-Notched Flexure. Takie konfiguracje były wybrane ze względu na ich częste występowanie w praktyce inżynierskiej. Autorzy zbadali możliwość przyrostu delaminacji na podstawie krytycznego współczynnika uwalniania energii i zależności jego wartości od obciążenia i wstępnej długości delaminacji. Autorzy pokazali, że klasyczne metody wyznaczenia współczynników uwalniania energii nie mogą być zastosowane w przypadku wielowarstwowych kompozytów wtedy, gdy delaminacja inicjowana jest poza płaszczyzną środkową. Zbadano także wpływ efektu samorozgrzania w stanie ustalonym. Współczynniki uwalniania energii otrzymano z symulacji numerycznych z zastosowaniem sformułowania opartego na wyznaczeniu całki J. Charakter propagacji delaminacji był modelowany z wykorzystaniem modelu obszaru kohezji. Wyniki symulacji zaprezentowano w postaci funkcji zniszczenia w zależności od obciążenia i długości delaminacji wstępnej. Otrzymane wyniki mogą być wykorzystane przy predykcji przyrostu delaminacji w testach quasi-statycznych i przy modelowaniu propagacji delaminacji podczas wymuszenia dynamicznego i testów zmęczeniowych.