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KOMPOZYTY
COMPOSITES

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NUMERICAL SIMULATION OF CRACKING PROCESS OF POLYMER COMPOSITES ON EXAMPLE OF SENB SAMPLE

The numerical calculations made in the work included the analysis of stress distribution near the rift top and determination of the stress intensity coefficient (WIN) as well as the J integral during three-point bending of SENB samples made from composites with a matrix of two well-known thermoplastics: PP and PA6 with a 25% content of glass fibre. Analysis of the composites crack development and propagation was also done performed. The numerical tool used for FEM calculations is the ABAQUS/Standard computer program that has modern calculation procedures in this field. The numerical calculations were made taking into consideration the experimental data determining the conditions of cracking process initiation of the composite material. The results of the numerical calculations were verified by the results of the experiments. The numerical calculations that were made concerned a geometrically non-linear problem. They were conducted with use of the incremental-iterative Newton-Raphson method. The numerical analysis was performed in two steps. The first step was a preliminary analysis that allowed estimation of the stress level in the composites near the rift top that initiated the cracking process, as well as forecasting the possibility of further propagation occurrence (or exclusion of this phenomenon) in the material region. In the second step of calculations corresponding to the critical value of deflection, numerical calculations taking into account the development and propagation of the crack were made using a more advanced technique for modeling cracking - the Cohesive Zone Method (CZM).

Keywords: **polymeric composites, cracking process, fracture toughness, numerical simulation, polypropylene, polyamide 6, glass fibre, SENB**

SYMULACJA NUMERYCZNA PROCESU PĘKANIA KOMPOZYTÓW POLIMEROWYCH NA PRZYKŁADZIE PRÓBKI SENB

Przeprowadzone w pracy obliczenia numeryczne obejmowały analizę rozkładów naprężenia w pobliżu wierzchołka rysy i wyznaczenie współczynnika intensywności naprężeń WIN oraz całki J podczas trójpunktowego zginania próbek SENB wykonanych z kompozytów na osnowie dwóch znanych tworzyw termoplastycznych PP i PA6 z 25% zawartością włókna szklanego. Dokonano również analizy rozwoju i propagacji pękania tych kompozytów polimerowych. Zastosowanym w obliczeniach MES narzędziem numerycznym jest program ABAQUS/Standard, posiadający nowoczesne procedury obliczeniowe w tym zakresie. Obliczenia numeryczne prowadzono z uwzględnieniem danych doświadczalnych określających warunki inicjacji procesu pękania danego kompozytu polimerowego. Wyniki obliczeń numerycznych zostały zweryfikowane z rezultatami badań eksperymentalnych. Wykonane obliczenia numeryczne stanowiły zagadnienie geometrycznie nieliniowe z wykorzystaniem przyrostowo-iteracyjnej metody Newtona-Raphsona. Analiza numeryczna prowadzona była w dwóch etapach. Pierwszy etap obliczeń stanowił wstępną analizę, pozwalającą oszacować poziom wytężenia kompozytów polimerowych w pobliżu wierzchołka rysy inicjującego proces pękania oraz dokonać oceny możliwości wystąpienia dalszej propagacji (lub jej wykluczenie) w obszarze materiału. W drugim etapie obliczeń, odpowiadającym osiągnięciu krytycznej wartości ugięcia, przeprowadzono obliczenia numeryczne uwzględniające rozwój i propagację pęknięcia z wykorzystaniem bardziej zaawansowanej techniki modelowania procesu pękania - Cohesive Zone Method (CZM).

Słowa kluczowe: **kompozyty polimerowe, proces pękania, odporność na pękanie, symulacje numeryczne, polipropylen, poliamid 6, włókno szklane, SENB**

INTRODUCTION

The Finite Element Method (FEM) is one of the most commonly used methods to solve different engineering problems. It is a modern calculation tool that supplements and widens the possibilities of stress state analysis of construction elements. In this method, a finite division of the Ω area (discretization) into finite elements averaging the physical state of the body is made and calculations are made only for nodes coming from this division. Beyond the nodes, the determined property is approximated on the basis of the values in the nearest nodes [1-3]. The numerical calculations made in the work included analysis of stress distribution near the rift top and determination of the stress intensity coefficient (WIN) as well as the J integral during three-point bending of SENB samples made from composites with a matrix of two well-known thermoplastics: PP and PA6 with a 25% content of glass fibre. Analysis of the polymeric composites crack development and propagation was also conducted. The numerical tool used for FEM calculations is the ABAQUS/Standard computer program that has modern calculation procedures in this field. The numerical calculations were made taking into consideration the experimental data determining the conditions of cracking process initiation of the composite material. The results of the numerical calculations were verified by the results of the experiments. The numerical calculations that were made concerned a geometrically non-linear problem. They were conducted with use of the incremental-iterative Newton-Raphson method. The numerical analysis was performed in two steps. The first step was a preliminary analysis that allowed estimation of the stress level in the composites near the rift top that initiated the cracking process, as well as forecasting the possibility of further propagation occurrence (or exclusion of this phenomenon) in the material region. In the second step of calculation, corresponding to the critical value of deflection, numerical calculations taking into account the development and propagation of cracks were made using a more advanced technique for modeling cracking - the Cohesive Zone Method (CZM) [4-10].

BASICS AND ASSUMPTIONS

Numerical analysis using the finite element method FEM was made on a spatial model of a SENB-type sample used for crack resistance tests. The sample was made from the composites PP and PA6 with a 25% content of glass fibre. The SENB sample was subjected to a 3-point bending test. The drawing of this sample with marked dimensions is presented in Figure 1.

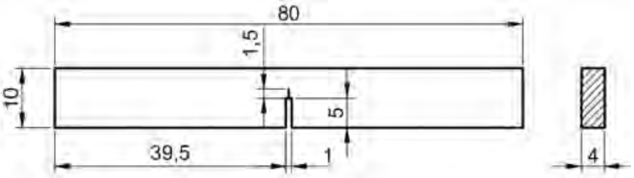

Fig. 1. Drawing of SENB sample for crack resistance tests

Rys. 1. Schemat próbki do badań odporności na pękanie typu SENB

In order to sharpen the vertex of the notch maximally, a fatigue pre-crack in the notch middle-width was made. A structural mesh of a hexagonal type was used to create the numerical model. Discretization of the SENB sample was based on 20-node solid elements of the C3D20R type, with a second order shape function that have 3 translation degrees of freedom in each node. The elements of the supports and pushing rod were imaged with use of non-deforming elements of the R3D4 type (rigid body). The overall view of the calculation model of the SENB-type sample for crack resistance testing is shown in Figure 2.

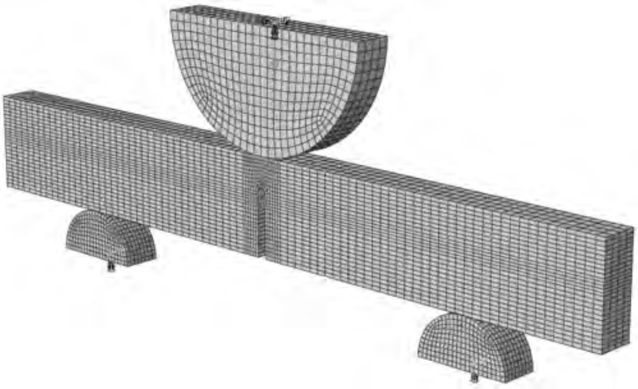

Fig. 2. General view of calculation model of SENB-type sample for crack resistance tests

Rys. 2. Widok ogólny modelu obliczeniowego próbki do badań odporności na pękanie typu SENB

The boundary conditions of the numerical model were defined by fixing the bottom supports and the load was realized by pushing the rod displacement in the vertical direction, according to the turn of the displacement vector. Contact interactions of a *surface-to-surface contact* type were defined between the supports and the pushing rod and the SENB sample. The numerical model required consideration of the mesh singularity near the rift (fatigue pre-cracking) top from the first calculation step. Splitting the region near the rift into smaller fragments is recommended. It was realized by a mesh consisting of elements in the shape of “circles” concentric at the rift top. In the first “circle”, 15-node solid elements of a *wedge* type - C3D15 with a second order shape function were used. In these elements, the nodes located in the middle of the side edges were “dragged” to 0.29 of the edge length, counting from the top of the fatigue pre-crack. As a result, singularity of the mesh in the rift top was assured. An example of the division into finite elements with the consideration of 8 circles is shown in Figure 3.

The model for the second step of numerical calculations was worked out considering the *surface-based cohesive behaviour* modelling technique. This model enables the observation of crack propagation along the initiating rift direction (Fig. 4). The crack propagation direction was determined along the direction of the initiating rift and perpendicularly to the upper edge of the sample. In the numerical model, the interactions of so-called “*cohesive* type contact” were taken into account. Determination of the *cohesive* type contact properties required definition of the material failure parameters that in this case were determined on the grounds of cracking initiation criterion.

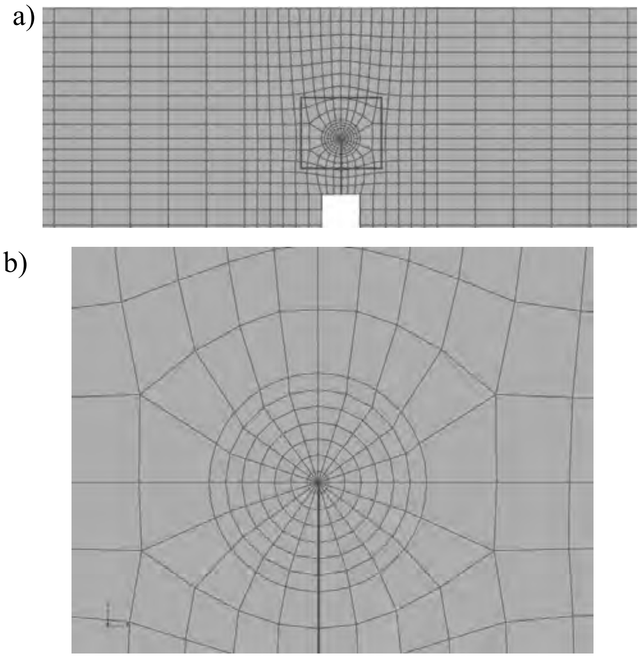

Fig. 3. Mesh near rift top: a) overall view, b) view of detail A

Rys. 3. Siatka elementów skończonych w pobliżu wierzchołka rysy: a) widok ogólny, b) widok szczegółu A

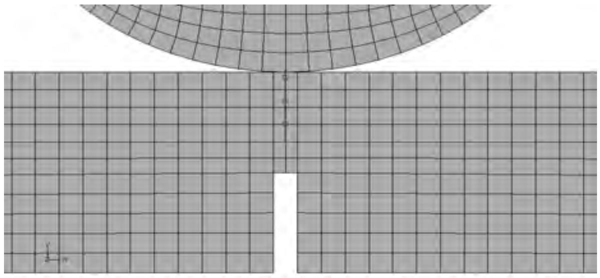

Fig. 4. Model of cohesive zone

Rys. 4. Model strefy cohesive

The model of linear elasticity was used to describe the properties of the tested composite. The composites of PP and PA6 with 25% of glass fibre content were considered as a quasi-isotropic body. The other assumption was that the strain values are proportional to the stress values in the model until the moment of total crack of the SENB sample. In the linear elastic model, it was assumed that the sample is broken without significant energy dissipation for plastic deformation. Plastic regions can only occur near the notch and are totally controlled by the surrounding elastic regions. Linear-elastic fracture mechanics is used for the analysis of stress and strain fields. For such defined material it is only necessary to determine the Young modulus of elasticity E and Poisson ratio ν (Table 1).

The numerical calculations enable determination of the crack intensity coefficient K_I and Rice integral J (first step of calculations) as well as observation and analysis of crack propagation (second step of calculations). In the first step of calculations, reduced stress distribution according to the Huber-Mises-Hencky (H-M-H) hypothesis was determined in the crack region (Fig. 5).

TABLE 1. **Values of Young modulus and Poisson's ratio ν**

TABELA 1. **Wartości modułu Younga i współczynnika Poissona ν**

Composite	Young's modulus E, MPa	Poisson's ratio ν
PA6 + 25GF	7434	0,4062
PP + 25GF	4525	0,4165

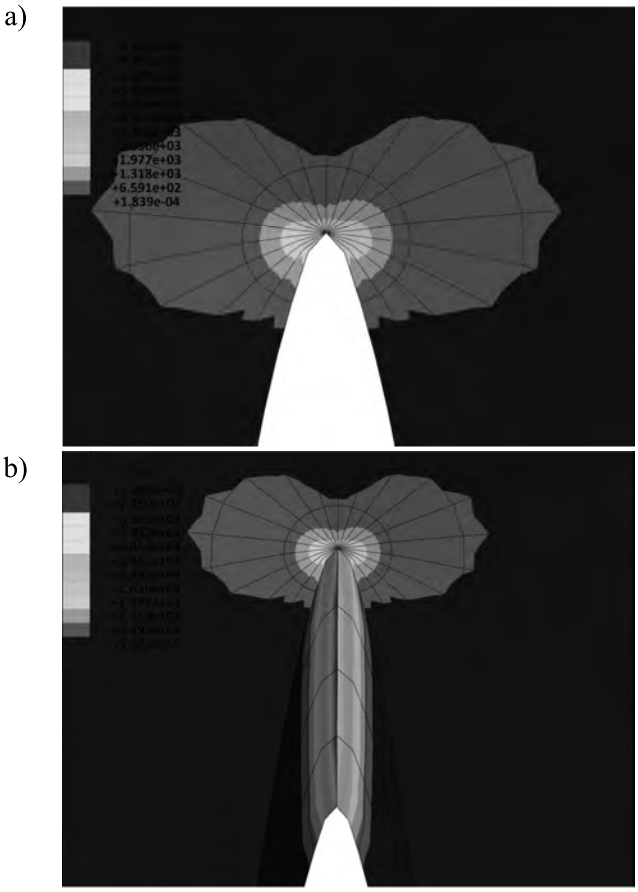

Fig. 5. Reduced stress distribution according to H-M-H hypothesis in rift top region for PA6 with 25% glass fibre content: a) front view, b) view from rift interior

Rys. 5. Rozkład naprężenia zredukowanego wg hipotezy H-M-H w okolicy wierzchołka rysy dla kompozytu PA6 z 25% zawartością włókna szklanego: a) widok od przodu, b) widok od wnętrza rysy

RESULTS OF NUMERICAL CALCULATIONS

The crack intensity coefficient and Rice integral values were read out for each of the 8 circles. On the basis of the authors' own experience and the data from literature, the values of the crack intensity coefficient and J integral were omitted for the first three circles in order to avoid the undesired influence of singularity near the rift top. The results for the circles from 4 to 8 were employed for the calculations of the crack intensity coefficient and J integral. The mean values of the crack intensity coefficient K_I and Rice integral J counted numerically for the circles from 4 to 8 are presented in Table 2.

For comparison, the values of the crack intensity coefficient K_I and Rice integral J arising from the experiments are also listed in Table 2.

TABLE 2. **Values of crack intensity coefficient K_I and Rice integral J**

TABELA 2. **Wartości współczynnika intensywności naprężeń K_I i całki Rice'a J**

Composite	K_I, MPa $\cdot \sqrt{m}$		Rice'a integral J, kJ/m^2	
	Numerical calculations	Experiment	Numerical calculations	Experiment
PA6 + 25GF	8.89	9.46	6.46	6.88
PP + 25GF	7.28	8.01	6.98	7.76

The results of the numerical calculations confirm the convergence of the obtained values of crack resistance parameters with the results obtained from the experiments. The best compatibility was obtained for the composites of PP with a 25% glass fibre content. For the composite with the PP matrix, a compatibility of 96% was obtained when comparing the numerical and experimental calculations. For the composite with the PA6 matrix, a compatibility lower by 2% was obtained. The numerically calculated values of crack intensity coefficient K_I and Rice integral near the rift top, for deflection referring to the cracking initiation moment are also presented in regard to SENB sample deflection *f* (Fig. 6).

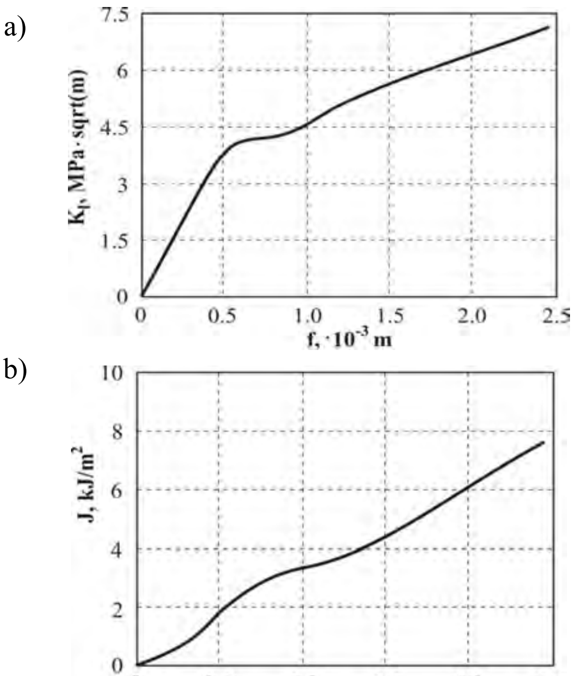

Fig. 6. Values of K_I (a) and Rice integral (b) for value of deflection referring to cracking initiation for PA6 with 25% glass fibre content (values for circle number 8)

Rys. 6. Wartości K_I (a) oraz całki Rice'a (b) dla wartości ugięcia odpowiadającej inicjacji pęknięcia dla PA6 z 25% zawartością włókna szklanego (wartości dla 8 okręgu)

The results of the CZM model analysis enable observation of the cracking process depending on the loading element movement - the pushing rod. The deflection value referring to the cracking initiation moment was verified as well as the value of deflection in the final phase of sample cracking were verified. The results of this analysis are presented in the form of colour contoured maps on the background of the deflected model with a plotted map of reduced stress H-M-H (Figs 7 and 8).

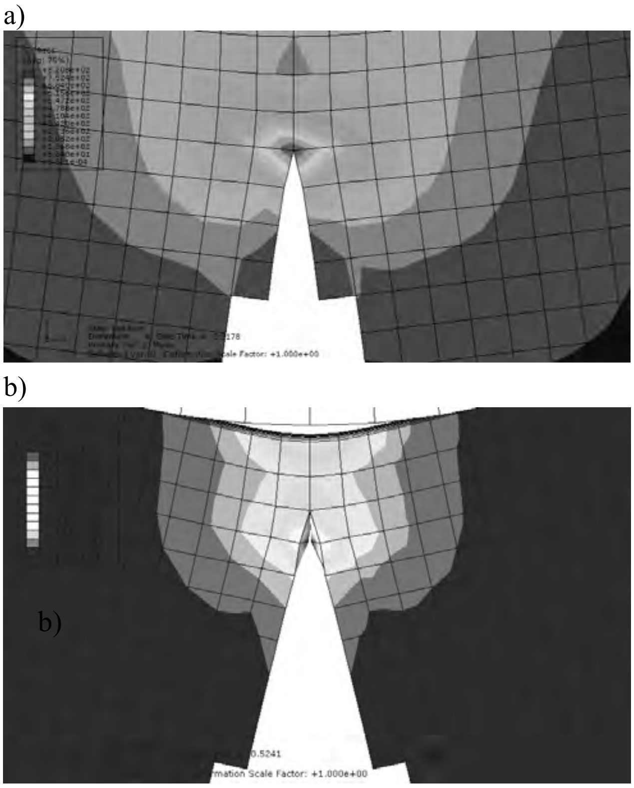

Fig. 7. Cracking process of SENB sample from PA6 with 25% glass fibre content composite: a) cracking initiation moment, b) final phase of cracking process

Rys. 7. Proces pękania próbki SENB wykonanej z kompozytu PA6 z 25% zawartością włókna szklanego: a) moment inicjacji pęknięcia, b) końcowa faza procesu pękania

As a result of the numerical calculations with the CZM modelling technique, the following values of deflection characterizing the cracking process were obtained:

- for PA6 with maximum content of glass fibre, the deflection value referring to the cracking initiation moment was *f* = 2.434 mm and failure of the sample occurred for deflection *f* = 5.421 mm,
- for PP with maximum glass fibre content, the deflection value referring to the cracking initiation moment was *f* = 1.039 mm and failure of the sample occurred for deflection *f* = 4.709 mm,

The deflection values obtained from the experiments were accordingly:

- for PA6 with 25% glass fibre content: cracking initiation of SENB sample occurred for deflection value *f* = 2.675 mm and the failure of the sample - at deflection *f* = 5.844 mm,
- for PP with 25% glass fibre content: cracking initiation of SENB sample occurred at deflection value *f* = 1.179 mm and the failure of the sample - at deflection *f* = 5.335 mm.

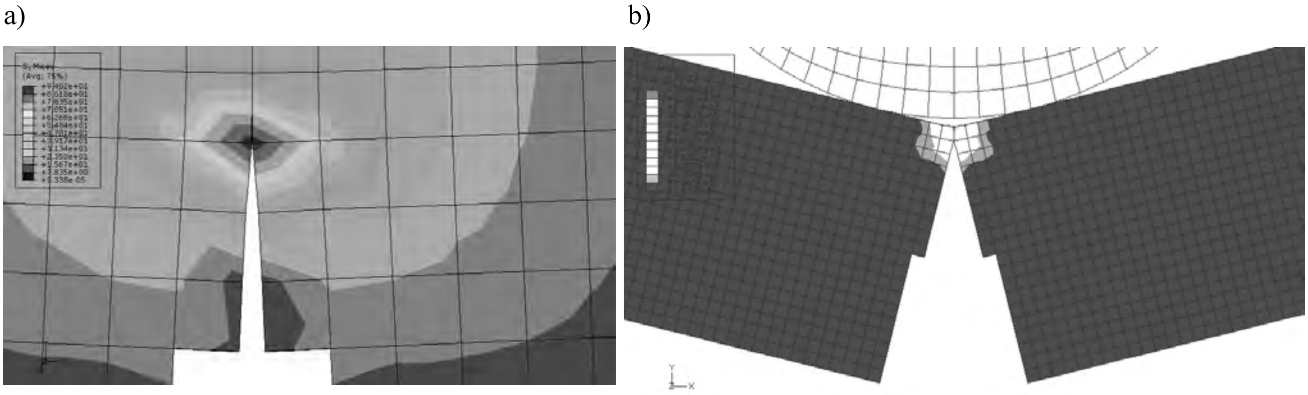

Fig. 8. Cracking process of SENB sample made of PP with 25% glass fibre content composite: a) cracking initiation moment, b) final phase of cracking process

Rys. 8. Proces pękania próbki SENB wykonanej z kompozytu PP z 25% zawartością włókna szklanego: a) moment inicjacji pęknięcia, b) końcowa faza procesu pękania

For the composite of PA6 with glass fibre, a convergence of 91% between the numerical calculations and experimental results was observed. A convergence lower by a few percent (88%) was obtained for the composite of PP with glass fibre. The results of the numerical simulation with the use of the CZM model confirmed the correctness of the failure mechanism used for the analysed composites.

CONCLUSIONS

The numerical modelling techniques used in the work for analysing the phenomena of the cracking process of SENB samples from PP and PA6 composites assure convergence of the calculation results with the results obtained from the experiments. It confirms the adequacy of the FEM discrete models that were devised and it is the grounds for further research in this field, with the use of numerical methods as an alternative investigation method that could be a completion and extension of crack resistance research. It is forecast that in the next phase of numerical simulations, some theoretical considerations of the cracking process will be made using other body models that can be representative for composites with thermoplastic polymer matrices.

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