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Numerical analysis of crack initiation and propagation in an aluminium sample

Analiza numeryczna procesu inicjacji i propagacji pękania próbki aluminiowej

Abstract
This paper reports an analysis of simulated crack propagation in an aluminium sample depending on the direction of external loads. The objective of the study was to perform a numerical analysis of crack propagation as well as to determine regions which are most susceptible to failure. The object of study was created from numerical analysis of material failure due to fibre separation using Abaqus 6.14. The modelling of crack propagation was performed using the numerical xFEM method for separating material fibres irrespective of the finite element mesh.

Keywords: Abaqus, xFEM, numerical analysis, crack initiation and propagation

Streszczenie
W ramach pracy przeprowadzono symulację numeryczną procesu propagacji pękania aluminiowej próbki, w zależności od kierunku obciążeń zewnętrznych. Celem pracy było wykonanie badania numerycznego propagacji pękania materiału oraz wykazanie obszarów najbardziej newralgicznych. Przedmiot badań przygotowano w ramach analizy numerycznej zniszczenia materiału na skutek rozdzielenia włókien w oparciu o środowisko Abaqus 6.14. Propagacja procesu pękania materiału została przeprowadzona na podstawie metody badań numerycznych xFEM, stanowiącej metodę rozdzielania włókien materiału niezależnie przebiegającego od siatki elementów skończonych.

Słowa kluczowe: Abaqus, xFEM, Analizy numeryczne, Inicjacja i propagacja pękania

1. Introduction

Nowadays, the phenomenon of the permanent separation of fibres in structures is a significant problem related to the long-term and proper operation of machinery. It is desirable to design solutions which offer immediate ways of preventing undesired phenomena such as fibre cracking due to excessive loads [6–8].

Previous numerical methods for investigating material failure enable the prediction of crack initiation regions – their results are highly compatible with experimental results. The popular methods for predicting material failure regions are connected with different calculation algorithms. One of the most popular methods for fibre separation in the Abaqus system is the cohesive zone method (CZM). Over the years, other methods for failure visualisation have been developed, for instance, the virtual crack closure technique (VCCT) for interlayer delamination. One more widely used method for investigating failure is the extended finite element method (xFEM) for determining crack propagation irrespective of the generated finite element mesh. There are also other methods for describing material failure; however, the above three methods are the most widely used ways of visualising material failure due to external loads.

Structures containing indentations are much more susceptible to damage during long-term operation. The process of permanent fibre separation in samples with indentations often begins in the regions above or below the indentation, and not, as it would seem, on the edge of the indentation. When designing structures, it is important that undesirable phenomena of material failure caused by loads are prevented, and if they occur, it is crucial to predict areas where failure propagation begins. There are numerous studies [4, 5, 11–16] on crack propagation processes and the use of the xFEM method. The innovative character of this method stems from the fact that the simulation of crack initiation and propagation processes runs independently of the applied FEM mesh type and density. The research works [4, 14, 16, 17] related only to the determination of crack progression for different types of material depending on one specific type of boundary condition. Regarding the current problems of machinery operation, it is necessary to adopt an approach which results in the improvement of the operational conditions of machines. As far as material strength is concerned, it is valuable to have the knowledge to predict failure initiation regions. These processes can be computer simulated without the necessity of conducting expensive strength tests or cyclic loading tests. The application of numerical tools such as ABAQUS enables the effective determination of critical regions of structures depending on the defined physical processes that are consistent with real phenomena leading to the loss of initial mechanical properties [2, 3, 9, 10].

2. Materials and research methods

The study was conducted on square samples with symmetrical incisions in the central region. The samples were made from aluminium 6082. The numerical model was designed using Abaqus 6.14. The structure was described by a selection of material properties – these are listed in table below [1].

Table 1. Characteristics of the aluminium

Material: Aluminium	
Young's Modulus [MPa]	70,000
Poisson's Ratio	0.3
Max Principal Stress [MPa]	300

The numerical model was designed only for the elastic range in order to determine the region of crack initiation and propagation due to applied loads. The geometrical parameters of the element are given in millimetres. The thickness of the sample was only 1 mm. The prepared model is shown below.

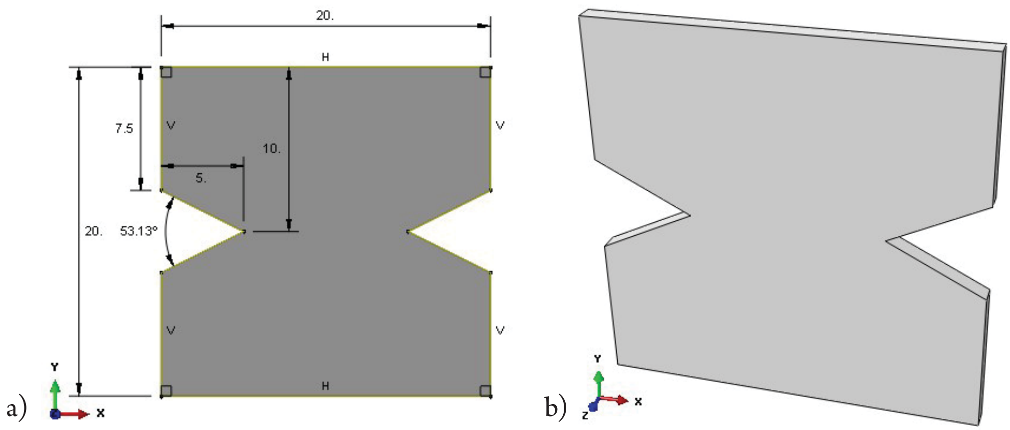

Fig. 1. Test sample: a) geometrical parameters, b) CAD model (source: own study)

The numerical model was defined by boundary conditions and external loads in the form of forced displacements causing tension and bending of the sample. The upper surface of the profile was fully fixed in each of three tested variants of load. In the first case, axial tension was defined by the application of forced displacement of the lower surface by 0.5 mm. The second variant involved the displacement of the bottom right surface towards the material (opposite to the X-axis) and downwards by 0.75 mm. The final variant corresponded to the second variant and involved the displacement of the bottom left surface relative to the X-axis and downwards by 0.75 mm. The objective of each case was to simulate failure of the FEM model under varying loads. The figures below illustrate the three variants of the applied boundary conditions.

The discretisation of the numerical model was performed using the best possible type of finite elements, i.e. C3D8R, with 550 mesh elements and 1224 nodes. The number of mesh elements is relatively small, yet the investigation of crack propagation by the xFEM method does not require increasing mesh density owing to the fact that the process does not depend on the FEM mesh. Eight-node elements with three degrees of freedom and reduced integration (C3D8R) are characterised by a very high degree of accuracy of the results. Its obtained due to removing false modes of deformation of numerical elements (by the application of higher-order polynomial equations to describe this process) [18]. Basically, the static measurements

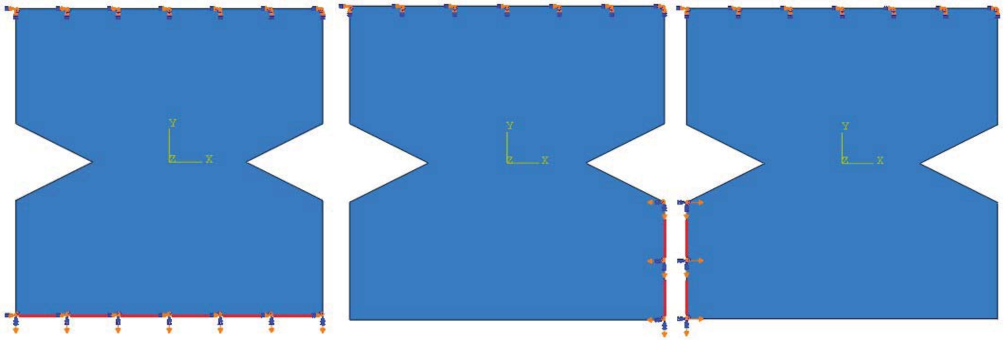

Fig. 2. Numerical model for three cases of boundary conditions (source: own study)

only involved the definition of mesh type and mesh density. The numerical model with the implemented mesh for the entire structure is shown in the figure below.

The objective of the study was to perform a complex analysis of structure effort until crack initiation. It then involved the modelling of the propagation of the crack in order to obtain the shapes of separated fibres under varying loads. The numerical results were constantly compared with the material properties of the sample to examine material effort.

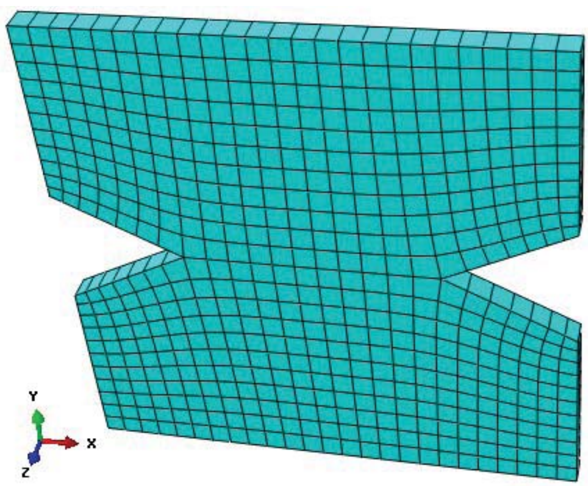

Fig. 3. Numerical model after discretisation (source: own study)

3. Results

The analysis of crack initiation and propagation performed by the innovative xFEM method enabled the identification of the region of crack initiation and the direction of shape of the propagating crack. Micro-failures of the element can occur when the element reaches the state of tensile strength. The moment when the material undergoes considerable elongation and loss of fibre cohesion due to the impact of tensile and bending forces, the irreversible failure of the element's structure begins to take place. Crack propagation is totally independent of a finite element mesh, and it is possible to investigate structures with the aim of predicting potential regions of failure initiation until their complete failure. The FEM analysis enabled the determination of the regions of crack initiation as well as the shape of the crack. The study investigated the regions of structure failure using three different variants of boundary conditions in order to compare fibre separation depending on applied external loads. All three cases of failure are illustrated in the figures below.

A solid model was used to map the crack propagation process with respect to the 3D solid structure; this model had eight-node finite elements with three translational degrees of freedom in each of the eight nodes per one finite element. The crack initiation occurred precisely in the spot of sample necking, right next to its incision. FEM analysis enabled showing research results dependent upon applied boundary conditions. The first result of structural failure results from the axial tension of the sample by 0.5 mm. The effect of tension was symmetrical crack propagation until the complete separation of fibres of the tested material. Following the complete failure of the sample, the stresses were concentrated in the

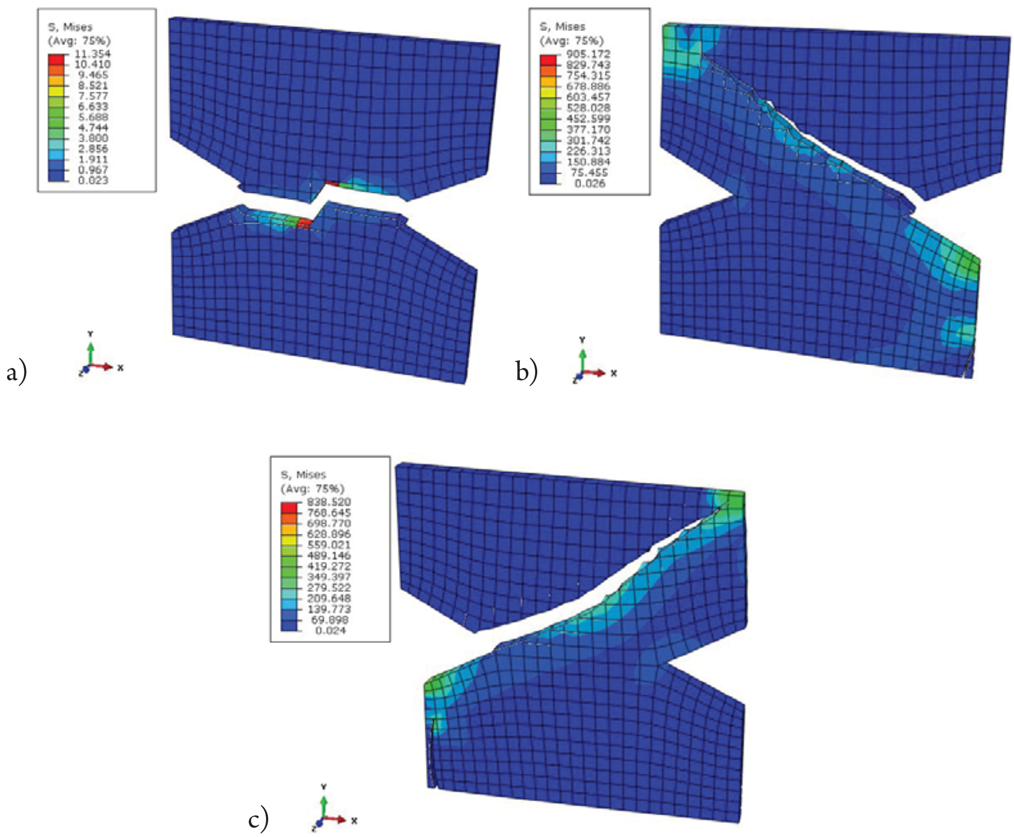

Fig. 4. Visualisation of failure: a) axial tension failure, b) failure under second load, c) failure under third load (source: own study)

central region of the crack, and the value of stress after total failure was slightly over 11 MPa. The stresses of 11 MPa were the residual stresses resulting from the elastic unloading. The second result is concerned with a partially bending and tensile force acting on the bottom right surface of the sample. It can be observed here that the cracking was initiated on the right side of the central incision of the sample. Regarding crack propagation in the upper left part of the sample, the stresses amounted to over 905 MPa (three times more than the max principal stress – value of crack initiation). The results of the third variant of the applied boundary conditions reveal that the crack propagation here was symmetrical to that in the previous case. Crack initiation also occurred in the region of the sample incision on the left. Due to the impact of tensile-bending loads, the crack propagated towards the right upper edge of the sample. The visualisation of structure failure additionally shows the regions of complete failure of selected finite elements depending on the applied variant of boundary conditions. When the value was 1, and thus met the xFEM criterion, specific regions of the structure underwent failure. The visualisation of the results below illustrates the numerically determined regions of complete failure of the structure.

Based on material data and crack propagation coefficients, the XFEM method enables simulation of complex failure processes for popular materials depending on external loads. The STATUSXFEM variable (i.e. the percentage of structure failure) describes regions of structure failure, where a value of 1 defines the region of complete failure of selected elements of the FEM mesh. In the first variant of the boundary conditions, the structure underwent total failure only in the region of central necking. The results of the second variant of boundary conditions reveal that the structure undergoes failure from the right side of central necking to the top left corner of the sample. The results of the last variant of boundary conditions demonstrate that the structure's failure is almost symmetrically identical to that observed in Variant 2.

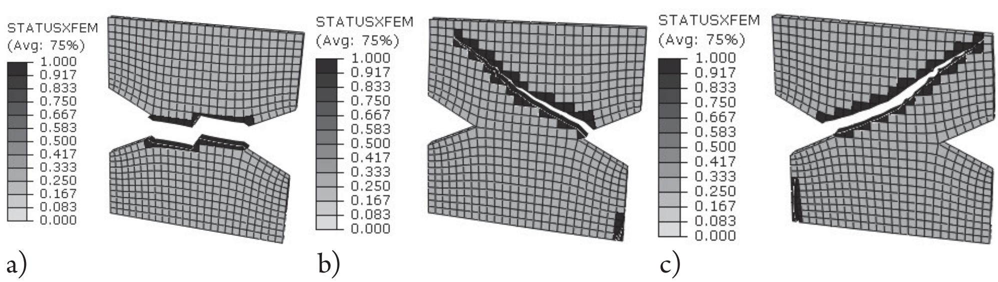

Fig. 5. Damage criterion determined by xFEM method: a) failure in case 1, b) failure in case 2, c) failure in case 3 (source: own study)

4. Conclusions

The investigation of structural failure based on numerical simulations enabled the identification of crucial regions of the structure. Nowadays, it is important to have information about regions that are problematic regarding the operation of these structures. The possibility of predicting regions that are critical for a given element by numerical simulation greatly facilitates the design and production processes. The simulation of complex physical processes enables the reduction of production costs and the time for manufacturing prototypes and their validation. Predictions of the potential areas of fracture of structures subjected to external loads can reduce the cost of part production by removing structural defects during design processes and advanced computer simulations. The results of the investigation of structural failure due to crack propagation depending on the applied boundary conditions demonstrate that further studies can be conducted in order to re-design this element such as to prevent its failure. The numerical results lead to the following conclusions:

- numerical analysis of the effort of structures enables the precise prediction of failure initiation regions in these structures;
- xFEM method for simulating structural failure enables the visualisation of crack initiation and propagation irrespective of the applied finite element mesh;
- FEM simulations of material cracking enable the determination of both the direction of crack propagation due to load and the degree of failure of mesh elements;
- it is possible to determine the relationship between the mode of structural failure and varying boundary conditions.

The above conclusions confirm the significance of FEM modelling in effort analysis. Systems for strength analysis offer wide opportunities for structural examination and further design optimisation.

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