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MULTISCALE APPROACH TO STRUCTURE DAMAGE MODELLING

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The paper deals with the problem of modelling of different types of damages in metallic and composite structures. The modelling of damage and fracture plays an important role in design and implementation of Structural Health Monitoring systems, particularly it is very important in prognosis of the rest of safe life of structures. The authors overview and analyse the existing methods and available tools of damage and fracture modelling. The application of selected models for structure damage and fracture modelling in macro and micro scale simulations is the main subject of this paper. Two groups of models are considered; the first group consists of models capable of predicting brittle fracture, second – models used for ductile damage evaluation. In the latter group, macro and multiscale models are presented. Finally, the multiscale damage model based on a representative volume element is presented. The grain structure modelling and its FE implementation are discussed in conjunction with application of ductile damage criterion for grain structures. Several numerical examples are presented.

Key words: multiscale damage modelling, delamination modelling, ductile damage modelling and experimental validation

1. Introduction

The safety of operation of critical mechanical structures is one of the main factors which are taken into account during a design process. Damages to these structures due to errors in design, faults in manufacturing, degradation of materials, unexpected loads and environmental conditions can all be reasons of catastrophic failure. To avoid or limit the number of catastrophic accidents, users of such structures employ Structural Health Monitoring (SHM) to detect possible damage at an early stage of damage initiation. The main four tasks for SHM systems are (Adams, 2007):

1) Damage detection
2) Damage localization
3) Assessment of damage size
4) Prognosis of the rest of safe life of the structure.

The first three tasks of SHM systems can be carried out using several existing methods based on particular measurements which depend on the type of structures and the condition of their operation (Adams, 2007). The prognosis of safe life of mechanical systems is the most difficult and it is based on simulation of the structure life. Nowadays engineering is firmly supported by CAD/CAM/CAE software (Boller *et al.*, 2009; Inman and Farrar, 2008). It allows one to assess the strength of parts remotely. Used in conjunction with sophisticated CAE software, even more complex problems such as manufacturing processes, explosions, wave propagation and many others can be simulated.

It is becoming more common for these systems to be used as they allow for analysing structures in terms of fracture mechanics, e.g. the calculation of stress intensity factors and energy release rates (Leski, 2007; Xie and Biggers, 2007). The finite element method is also widely used for such a purpose, but others, such as the boundary element method or finite volume method can also be found (Burczyński, 1995; Burczyński *et al.*, 2007; Kokot and Kuś, 2007). Recently, multiscale methods are becoming more and more popular (Madej *et al.*, 2008). They allow for formulating models at different scales: macro, meso, micro and even nano, what helps one to build a model of damage and to predict damage evolution. This list seems to be incomplete, since this is a very rapidly developing group of methods and they seem to have almost no limitations.

Because of the high demand for safety of mechanical structures; the capability of predicting damage, fracture and its evolution, is becoming more and more important. It is also important that together with structure health monitoring methods, the structure damage modelling becomes a common toolset for engineers.

The paper structure is as follows. Section 2 is devoted to the overview of structure damage and fracture modelling methods. Several advantages and drawbacks are listed. In Section 3, some computer tools that can be used for the modelling are discussed briefly and some theoretical considerations are presented. Section 4 contains numerical examples of application of selected models for delamination of composites and ductile fracture prediction. A multiscale damage model, based on a representative volume element is presented. Comparison of simulation results and experiments confirms correctness of the modelling approach. Finally, Section 5 follows with conclusions from the previous Sections.

2. State of the art in structure damage modelling methods

Structure damage modelling methods can be divided according to the level of model formulation level (Madej *et al.*, 2008). With such criterion we can distinguish between: macro models and multiscale models (meso, micro and nano models).

The former group is mainly based on typical phenomena known from fracture mechanics, where parameters such as stress intensity factor (Leski, 2007) or energy release rate (Xie and Biggers, 2007), can be used as damage indicators. We can also mention here phenomenological ductile damage models (Just and Behrens, 2004). These are mainly based on components of stress and strain tensors. Practical application of ductile damage models can be found in Just and Behrens (2004), Śleboda (2005-2008). In the macro models group, models based on cohesive zones can be listed (Xie and Biggers, 2006; Ural *et al.*, 2006). This solution is widely implemented in commercial CAE software as a special element type. Its constituent behaviour is described by traction vs. separation relation. Damage is therefore modelled as evolution of interface bonding parameters finally leading to surface separation. A model based on cohesive zones, which allows for lifecycle prediction of the structure and crack retardation is presented in Ural *et al.* (2006).

Damage models are based on different theories. There are a lot of models based on combination of quantities calculated at the macro scale to evaluate damage. This group contains phenomenological models frequently called damage indicators. There is also a group of micromechanical models (Gurson, 1997; Needleman and Tvergaard, 1984) which consider microstructural changes as the source of damage and predict its influence on the macro scale.

The implementation of models at lower scales (meso, micro and nano scales) and data flow between subsequent scales during analysis, allows for more precise results. As an example development of shear bands and strain localization (Madej *et al.*, 2008), the influence of grain boundaries and inter-phase boundaries on their behaviour in manufacturing processes (Milenin and Kustra, 2008) can be presented.

The large number of multiscale models requires their classification (Madej *et al.*, 2008). These models are classified into two groups – concurrent and upscaling models.

In the upscaling group (Madej *et al.*, 2008) the macro behaviour of the model is affected by appropriate phenomena at finer scales. Once the macro scale analysis step is calculated, the necessary data is transferred to a finer scale, and then the fine scale problem is solved. The data can be again transferred to a finer scale, or if it is at the finest level, the results can flow back to the previous level.

The idea of concurrent modelling methods can be found in Burczyński *et al.* (2007), Kokot and Kuś (2007). In concurrent methods, the problems are a priori divided into domains and solved simultaneously at different scales. The most common scales are the global and the fine ones. An example of a concurrent multiscale model is shown in Fig. 1 (Madej *et al.*, 2008). A notched cantilever beam is subjected to the end load. The vicinity of the notch is modelled at the atomic scale, while the rest of the beam is modelled at the macro scale (Fig. 1a). The force applied to the end causes bending of the beam and micro cracking at the bottom of the notch, which can be observed at the nanoscale (Fig. 1b).

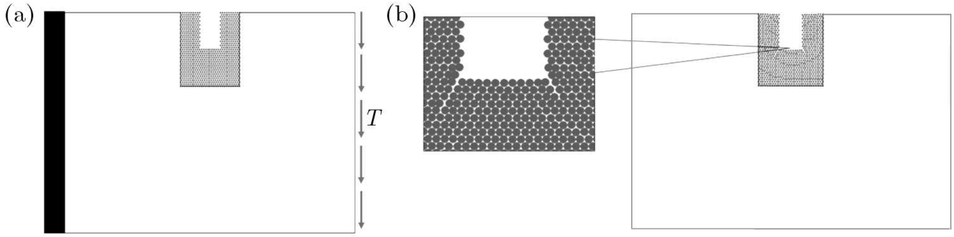

Fig. 1. Exemplary concurrent multiscale model (Madej *et al.*, 2008). (a) Notched cantilever beam subjected to end load. Vicinity of the notch modelled at atomic scale. (b) Simulation result. Cracks initiation in the corners of the notch

In both groups of models, solutions at different scales can be carried out with different techniques, the most common being the finite element method (Just and Behrens, 2004; Milenin and Kustra, 2008), cellular automata (Gandin and Rappaz, 1996), molecular dynamics and boundary element method (Burczyński, 1995).

The ideas of concurrent and upscaling multiscale methods presented above are summarised in Fig. 2 (Madej *et al.*, 2008).

These two approaches can be used to model different types of damage suitable for mechanical structures.

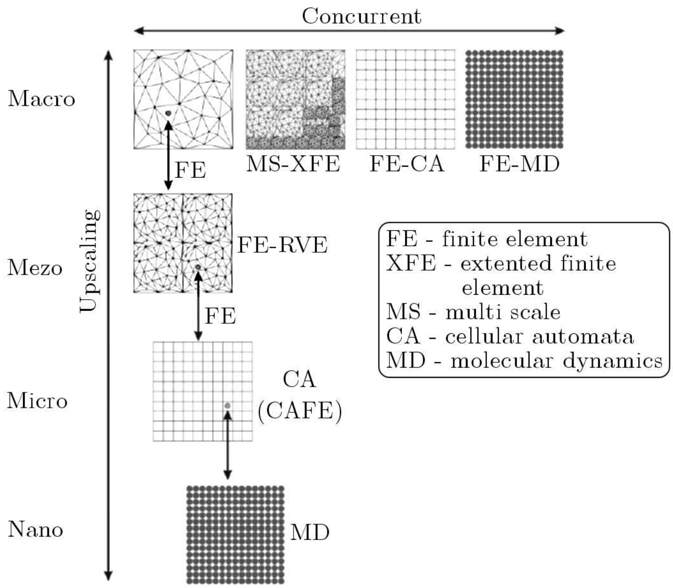

Fig. 2. Classification of multiscale modelling methods Madej *et al.*, 2008

3. Numerical tools for structure damage and fracture modelling

In literature, many papers on damage modelling can be found. Derivation of various ductile damage models, which can be regarded as damage indicators can be found in Cockcroft and Latham (1968), Gurson (1997), Lemaitre (1996), Needleman and Tvergaard (1984) and Oyane *et al.* (1980). The details of numerical implementation of the above models in commercial CAE software are presented in MSC.Marc Mentat (2008). Practical application of these models to manufacturing processes is described in details in Just and Behrens (2004), Milenin and Kustra (2008). Since damage accumulated in a material can lead to fracture, this kind of material failure requires different theoretical approaches (Krajcinovic, 1996; Wnuk, 1981). The problems of damage evolution and crack initiation and propagation will be discussed in this Section of the paper.

Due to different phenomena preceding and driving the fracture process in different types of materials, or even in the same materials under different conditions, it is necessary to consider different groups of models dedicated for damage evolution and crack initiation and propagation. The presented models are split into two groups: brittle fracture and ductile damage models. The first, considering brittle fracture, is especially important to evaluate crack risk and determine the crack propagation direction. The second group contains ductile damage models. The evolution of ductile damage consists of three distinct stages: pores nucleation, growth and coalescence finally leading to the fracture. Ductile damage mechanics provides a basis for phenomenological damage indicators and micromechanical models as well as giving the possibility of employing multiscale models for damage modelling and simulation. Numerical models belonging to both groups are implemented in software tools and can be applied for real life damage prediction problems.

3.1. Brittle fracture modelling

There are many solutions for fracture modelling which are commercially used for the assessment of brittle fracture risk. It is of particular importance to calculate stress the intensity factor (K), which is the easiest way to evaluate the possibility of brittle fracture. When K is known, the energy release rate (G) can be calculated, since in linear elastic fracture mechanics this is straightforward. Three numerical methods for calculating G will be presented – crack closure technique (CCT), virtual crack closure technique (VCCT) (MSC.Marc Mentat, 2008) and J-Integral (Rice, 1968).

Since, according to the definition, the energy release rate is the change in potential energy per unit crack growth length, two models shown in Fig. 3 should be considered. In the second model (b), the crack propagated by length a compared with model (a). F is then the force which is necessary to keep the crack surfaces together, and u is the displacement. The energy release rate (G) can be then calculated from the following formula (MSC.Marc Mentat, 2008)

$$G = \frac{Fu}{2a} \tag{3.1}$$

The force F and crack growth length a can be obtained from model (a), while the displacement u from model (b) (Fig. 3). Such a method is known as CCT – Crack Closure Technique. Two separate calculations of different models are necessary in this approach.

The modification of CCT is VCCT method. Instead of calculating two separate models for obtaining u, the displacement of closest nodes lying on the crack surfaces in the same model is taken to calculate G (Fig. 4). Thus VCCT is calculated in one step of a single model.

The last among the presented methods for calculating G is so-called J-Integral, formulated by Rice (1968). It can take into account plasticity near the crack tip, temperature and dynamic phenomena. It is very often a built-in tool in FEM solvers (MSC.Marc Mentat, 2008).

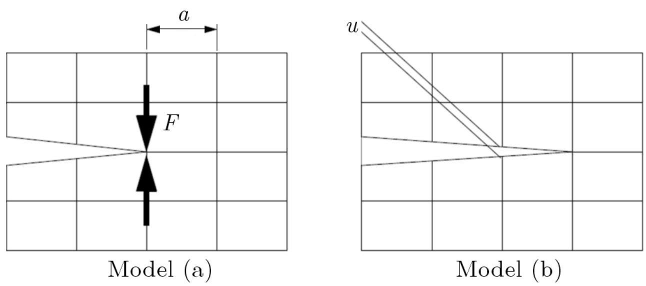

Fig. 3. Two simple models employed in CCT method (MSC.Marc Mentat, 2008)

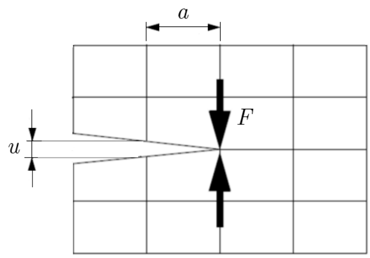

Fig. 4. Model employed for VCCT method (MSC.Marc Mentat, 2008)

Assuming small scale yielding, G can still be used as fracture criterion. It is then compared with critical energy release rate value (G_c). Because G_c can change its value, the so-called crack extension resistance curve, known also as r-curve can be used to find the critical energy release rate value.

Apart from the definition of crack propagation criteria, it is very important to assess its propagation path. There are two aspects influencing the crack propagation path – material properties and stress distribution. The second is of particular attention because, while the crack moves on, the state of stress changes. Among all theories predicting the crack propagation path, only two will be discussed (Wnuk, 1981):

- theory of maximum hoop stress
- theory of maximum energy release rate.

The above theories were chosen because of their mathematical simplicity, accurate results obtained and the fact that they are already implemented in many commercial CAE packages.

According to the maximum hoop stress theory, the crack will propagate in θ^* direction of the maximum hoop stress $\sigma_{\theta\theta}$, thus the criterion

$$\frac{\delta\sigma_{\theta\theta}}{\delta\theta} = 0 \qquad\qquad \frac{\delta^2\sigma_{\theta\theta}}{\delta\theta^2} = 0 \tag{3.2}$$

must be met.

This theory is equivalent to the theory of maximum tensile stress, which assumes that the crack will propagate perpendicularly to the direction of the maximum tensile stress.

Theory of maximum energy release rate shows that the crack will propagate in the direction which will maximize G. Recalling energy release rate definition (3.1)

$$G \equiv -\frac{\delta \Pi}{\delta a} \tag{3.3}$$

The above is equivalent to the whole system minimal potential energy.

The crack propagation direction can be calculated from the following formulas (Wnuk, 1981)

$$\frac{\delta G(\theta^*)}{\delta \theta} = 0 \qquad \frac{\delta^2 G(\theta^*)}{\delta \theta^2} = 0 \qquad G(\theta^*) \geqslant G_c \tag{3.4}$$

Independently of the fracture criterion, either crack propagation direction prediction theory can be used. In nonlinear analysis, the stress redistribution after crack growth is recalculated and the propagation direction can change. Thus implementation of the above theories in FEM solvers allow for reproducing of propagation paths in complex structures.

3.2. Ductile damage modelling

As mentioned before, there are many ductile damage models. A ductile damage model, accounting for void nucleation and coalescence is presented in Gurson (1997), Needleman and Tvergaard (1984). Phenomenological models based on strain and stress tensors components derived by Cockroft, Latham and Oyane can be found in Cockcroft and Latham (1968), Oyane *et al.* (1980). The model of effective stresses by Lemaitre, which can be regarded as a multiscale damage model is described in details in Lemaitre (1996). Numerical implementation details of the above models can be found in MSC.Marc Mentat (2008). Their practical applications in industrial processes is presented in Just and Behrens (2004).

Ductile damage occurs under high deformation conditions. Such conditions can seldom be met in structure operation, but are frequent in manufacturing processes. In the case of complicated manufacturing processes such as forging, rolling, etc., appropriate ductile damage model should be carefully chosen. Apart from location, ductile damage models can be used to predict time-to-damage. The threshold for the model is usually defined by a comparison of the real and virtual process and an assessment of the ductile damage model value corresponding to the time of fracture. The process can be optimised then, that is why most of ductile damage models are also called the relative models. Among many ductile damage indicators the following will be presented:

- Principal tension ductile damage model (MSC.Marc Mentat, 2008)
- Cockroft-Latham ductile damage model (Cockcroft and Latham, 1968)
- Oyane ductile damage model (Oyane *et al.*, 1980)
- Multiscale ductile damage model (Model of Effective Stresses by Lemaitre (1996)).

Principal Tension ductile damage model is one of the simplest ductile damage indicators. The damage value is expressed by the formula (MSC.Marc Mentat, 2008)

$$\int \frac{\sigma_{max}}{\overline{\sigma}}\, dt \tag{3.5}$$

where σ_{max} is the maximum principal stress, $\overline{\sigma}$ – is von Mises stress.

It assumes that damage will occur under conditions of high tensile stress, which is quite intuitive.

Cockroft-Latham damage indicator is in fact an enhancement of the principal tension model and is defined as follows (Cockcroft and Latham, 1968)

$$\int \frac{\sigma_{max}}{\overline{\sigma}}\dot{\overline{\varepsilon}}\, dt \tag{3.6}$$

where σ_{max} is the maximum principle stress, $\dot{\overline{\varepsilon}}$ – effective strain rate, $\overline{\sigma}$ – von Mises stress.

In addition to the principal tension indicator, it also takes into account the strain rate. The bigger strain rate, the more possible damage.

Oyane ductile damage model is defined by the formula (Oyane *et al.*, 1980)

$$\int \Big(\frac{\sigma_m}{\overline{\sigma}} + B\Big)\dot{\overline{\varepsilon}}\, dt \tag{3.7}$$

(7) where σ_m is mean stress and B is material constant. Consideration of the mean stress in ductile damage modelling is very important, as it is known that materials exhibit more plasticity while subjected to tri-axial compression, and even brittle materials such as marble can be deformed plastically (Karman's experiment).

Micromechanical damage models play a very important role in damage modelling (Krajcinovic, 1996). Micromechanical models assess damage in a material at the macroscopic level through changes in its microstructure. Since this approach sometimes requires solving models at a finer scale, it can be then regarded as amultiscale approach.

Among many micromechanical damage models, the model of effective stresses by Lemaitre (1996), Lemaitre and Chaboche (1990) will be mentioned.

The model of effective stresses is based on the idea of a representative volume element. The considered domain is divided into small regions – cells – in which certain damage evolution laws at the micro scale are applied. A detailed description of this model can be found in Just and Behrens (2004), Lemaitre (1996) and Lemaitre and Chaboche (1990).

The required model parameters can be obtained from a tension test, so it is not necessary to carry out expensive and time consuming experiments. The model has been implemented in commercial CAE solvers, and requires a set of the following parameters:

R_m – stress at uniform elongation (ultimate strength)

$\varepsilon^p_{eq,Rm}$ – equivalent strain at uniform elongation (used as the damage nucleation threshold)

$R_b/(1-D_{1c}) = R_m \rightarrow D_{1c} = 1 - R_B/R_m$ - critical damage under uniaxial conditions

S_D – damage resistance parameter, calculated from formula (Just and Behrens, 2004)

$$S_D = \frac{R_B^2}{2E(1-D_{1c})^2 \frac{dD}{d\varepsilon_{eq}}} = \frac{R_m^2}{2E\frac{dD}{d\varepsilon_{eq}}} \tag{3.8}$$

Both S_D and D_{1c} are evaluated from experimental data.

All of the models described above are used for damage and crack initiation and propagation modelling of metallic and composite structures; the results are presented in Section 4 of the paper. Most of them are already implemented in commercial CAE solvers. Simplicity of ductile damage indicator formulas (3.5)-(3.7) enables users to implement these models in other programs as postprocess values. Capability of calculating the strain energy release rate (G) or strain intensity factors (K) is more complicated.

4. Application of selected models for structure damage modelling in macro and micro scale

The applications of selected damage and fracture models are presented below. The following models are employed for simulations:

- brittle fracture
  - delamination model
- ductile damage models
  - tensile test analysis
  - ductile damage prognosis in a manufacturing process
  - multiscale damage model based on a representative volume element

4.1. Composite delamination modelling

Cohesive zone modelling is mostly employed for delamination analysis (Aymerich *et al.*, 2008). An eight-ply, three-dimensional model of laminate has been used in analysis. A rectangular plate has been constrained at edges and subjected to a displacement load at the centre of the top surface. While pressing the top surface, stresses exceed the strength of cohesive bonding between plies. There are two indicators describing the state of the material: delamination index and damage index. The delamination index has a value between 0 and 1, where 0 states for safe bonding, while 1 – beginning of damage. Value of 1, however, does not mean the loss of load capacity, but the transition to irreversible state of progressing damage, which is described by a decreasing slope of traction vs. separation relation. The damage index has values between 0 and 1, where the damage index value of 0 is equal to the value of 1 for the delamination index. If the damage index reaches the value of 1, it means that the load capacity has been exhausted. Results of analysis as distribution of delamination and damage indexes are shown in Fig. 5.

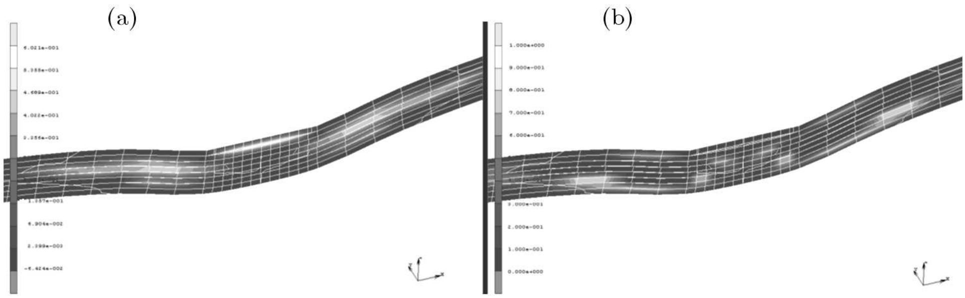

Fig. 5. Distribution of damage index (a), and delamination index (b)

Damage initiates under the first ply, caused by the applied displacement. After separation between the first and second ply, an immediate increase in the delamination index in the surrounding material is observed, which is caused by stress redistribution. As a consequence, other ply-to-ply bondings are damaged. The separation area is shown in Fig. 6.

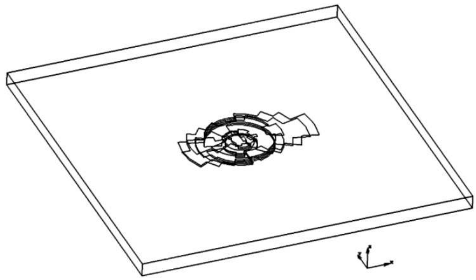

Fig. 6. Laminate plate with delamination

The modelling of cohesive zones provides a powerful tool for the modelling of delamination in composite plates. Nevertheless, it can be used at finer scales for bond modelling and other phenomena, such as atomic interactions, because of its natural traction vs. separation relation comparable to interatomic force vs. displacement relation.

4.2. Application of ductile damage modelling

The application of ductile damage models has been verified with tensile tests and drawing process simulations.

At first, a virtual tensile test is conducted, since no exact material data has been available, the results can be compared qualitatively.

Dynamic forces and material property variations with temperature were neglected, since according to standards, the test is conducted with a press velocity equal to 5 mm/min. The test was carried out with a Zwick/Roell Z250 machine.

Cylindrical specimens of different size and material parameters were used in the experiment. The goal was to obtain experimental data, especially force as a function of grip displacement.

The numerical analysis is assumed to be axisymmetric, but it is also assumed to be based after break-off of the specimen. MSC.Marc is employed as the solver and MSC.Marc Mentat as the pre and post processor.

The force as a function of grip displacement for the applied loads scenario, obtained in simulation, is presented in Fig. 7.

As can be seen from the results obtained, the plot is almost identical to one based on real tests. Characteristic points can be recognised in the chart

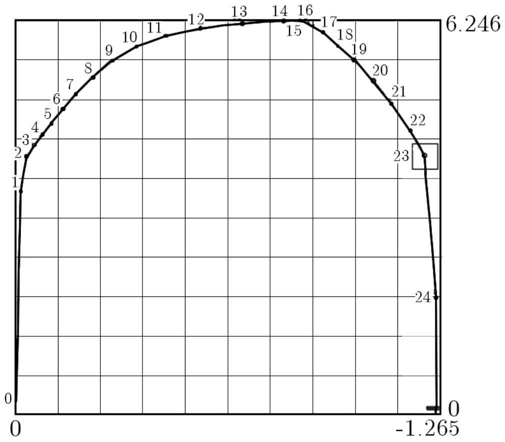

Fig. 7. Force as a function of grip displacement

such as linear-elastic region, strain hardening, tensile strength value and the break-off.

The time of break-off for the specimen can thus be obtained and is interesting from the application point of view. It is marked on the chart by a rectangle. The specimen is separated into two parts and the force suddenly drops to zero. This was captured by the simulation by means of application of the so-called "kill element" method which allows for removing elements while certain value of damage indicator had been reached. The used method allowed for modelling the fracture process following damage accumulation. Subsequent stages of the virtual tension test are presented in Fig. 8.

The above analysis confirms the real experimental tests; damage initiates in the specimen axis and propagates outwards causing break-off.

Identical simulations were carried out with Oyane and Principal Stress damage indicators. Similar results were obtained. The results of these analyses are shown in Fig. 9.

The results of numerical simulations with different ductile damage models are very close to the real process. In both, the place of damage initiation and time-to-damage are well reproduced, despite the fact that very simple damage models were used. The presented damage indicators are widely used in simulation of manufacturing processes because of their ability to recognise the reason of damage, thus helping to redesign a particular part of the process. Capability of ductile damage models for predicting damage initiation and evolution leading to fracture will be shown next in this section.

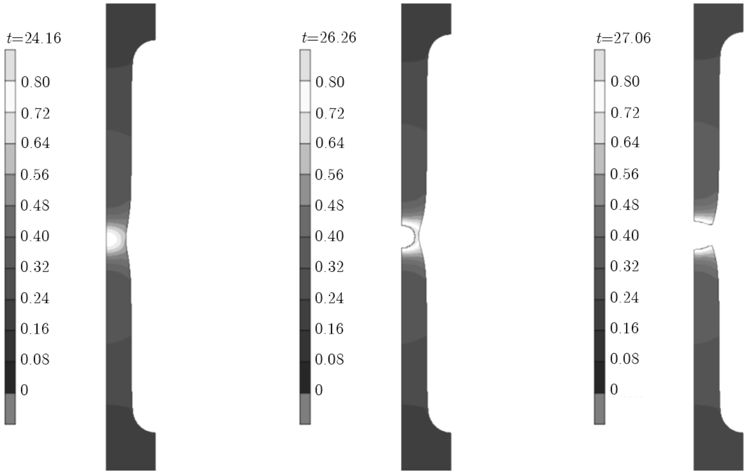

Fig. 8. Subsequent stages of tensile test

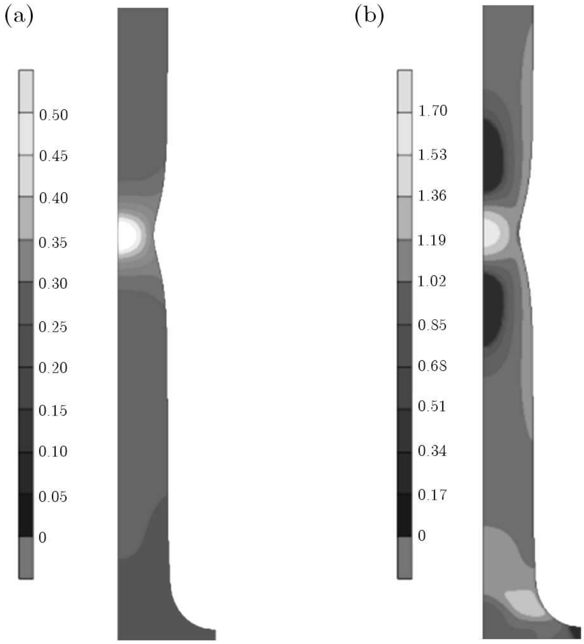

Fig. 9. Oyane (a) and Principal Stress (b) damage indicators during virtual tension test

In manufacturing processes, many faults may appear such as folds, laps, underfillings and fracture. While underfillings are easy to detect by a simple visual inspection, folds and laps are difficult to observe. That is why an inspection of final products covers not only a visual but also a sectional inspection in order to detect sub surface folds, laps and other failures. All of them can be caused by incorrect process parameters, and thus parameters like die geometry, lubrication, press kinematics, etc., should be adjusted. Among these failures, ductile fracture can be present. It occurs due to extremely disadvantageous process conditions, e.g. high tensile stresses.

All manufacturing processes are different, thus process conditions should be investigated and optimised individually. As an example, the drawing process is presented below, because the state of stresses can be quite easily recognised as a biaxial compression and axial tension state. Such a state of stresses can cause internal crack initiation and propagation. These chevron cracks are extremely dangerous since they cannot be investigated through visual inspection. Such cracks are shown in the cross section of the specimen in Fig. 10 (MSC.Marc Mentat, 2008).

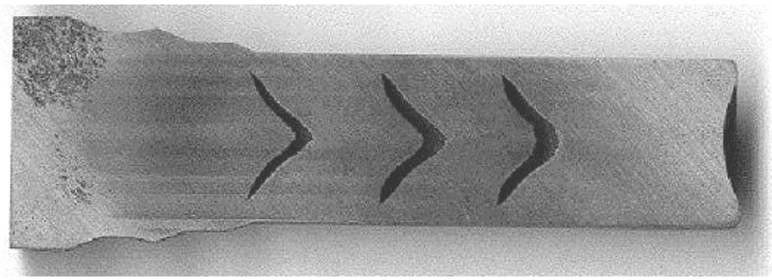

Fig. 10. Chevron cracks during drawing process (MSC.Marc Mentat, 2008)

In order to show the possibility of predicting this kind of failure, a simple drawing process has been modelled. For this purpose, also some process parameters were changed, i.e. the drawing angle has been increased. Oyane damage indicator has been introduced in the model with an appropriate damage threshold for the "kill element" method in order to capture the fracture. Subsequent stages of the process showing damage initiation and fracture evolution are presented in Fig. 11.

As can be seen in the above figure, fracture initiation starts in the middle of the part and propagates outwards forming a series of chevron cracks. The above results are in good accordance with the real process observations.

In Fig. 12, the force diagram for the above process simulation is shown. A characteristic decrease of force due to fracture initiation and propagation

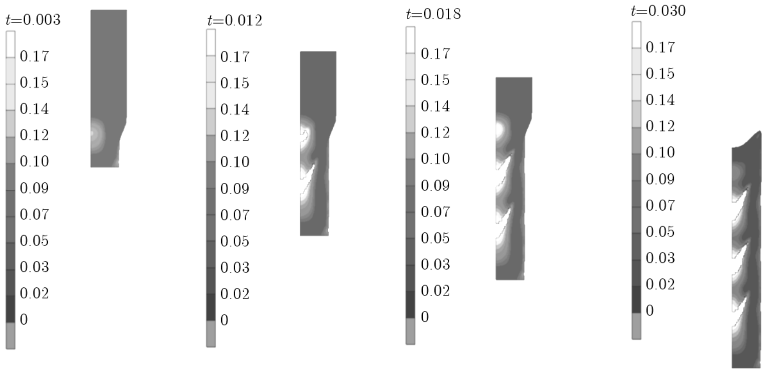

Fig. 11. Subsequent stages of virtual drawing process

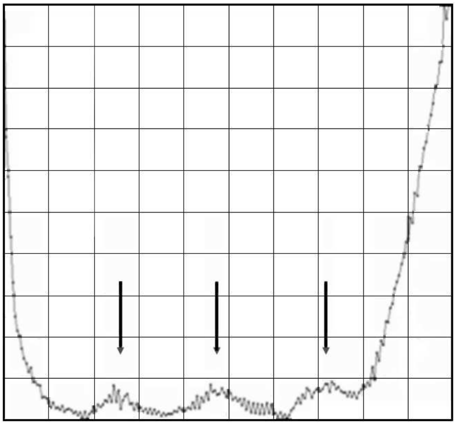

Fig. 12. Force diagram for drawing process with significant force drops related to ductile fracture

can be seen quite clearly. Such plots provide useful information about damage severity and localisation, and can be used for comparison with the experiment.

Simulation results are similar with the real process. Damage model parameters have been chosen based on the tension test.

4.3. Multiscale damage modelling

In the literature, the grain type of model is used for modelling of behaviour of metallic structures at the micro scale (Milenin and Kustra, 2008). This type of model is often employed with the idea of a representative volume element, where the material particles at the macro scale are modelled as a representative grain structure at the micro scale. The aim of the approach is to predict initiation and propagation of micro-cracks in metallic structures.

The idea of multiscale ductile damage model is shown in Fig. 13. At first, a grain structure with desired features, such as general pattern and average grain size, is generated. Subsequently, appropriate model properties are applied to the structure. Simultaneously, the global FE model is initialised and the first simulation step is calculated. Based on global FE model results, a particle subjected to critical loads is selected. The loads are then transferred to the micro scale and are applied to the grain model. Micro-scale simulation provides results of structure deformation, initiation and propagation of micro cracks. Information about load capacity or specific material properties changes can be transferred back to the macro scale and then affect the next step of the global analysis.

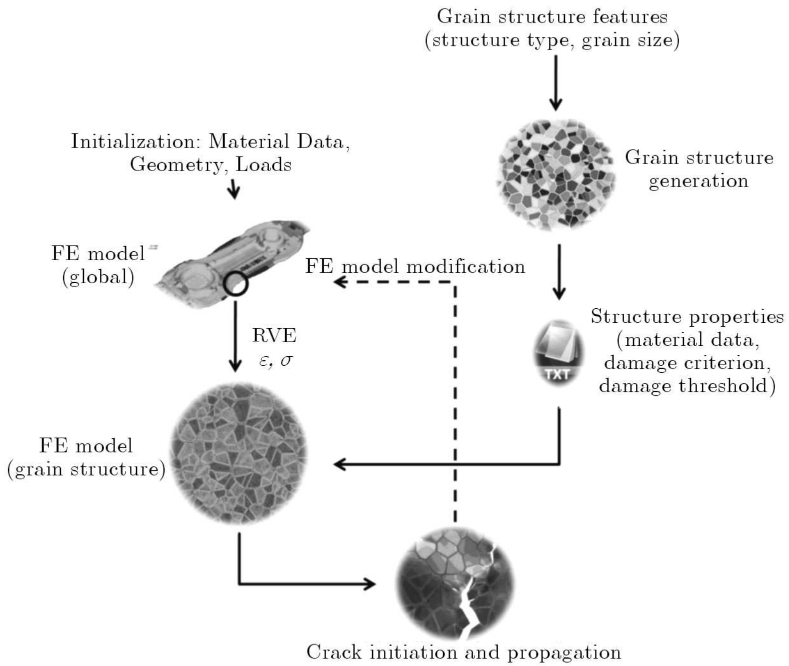

Fig. 13. Idea of multiscale ductile damage model

The Voronoi algorithm (Du *et al.*, 1999) has been used for structure generation. Different structure patterns can be obtained by using various site localisations, i.e. base points of the diagram. Moreover, the model allows for defining physical grain boundaries, which can be interpreted as a structural issue or just a technical solution for different damage criteria. An FE model is built automatically by a script translating the structure geometry to MSC.Marc Mentat. Mesh, material properties, and then other model parameters are also applied. The model with mesh is shown in Fig. 14. Each colour in Fig. 14 represents material properties assigned to the grain.

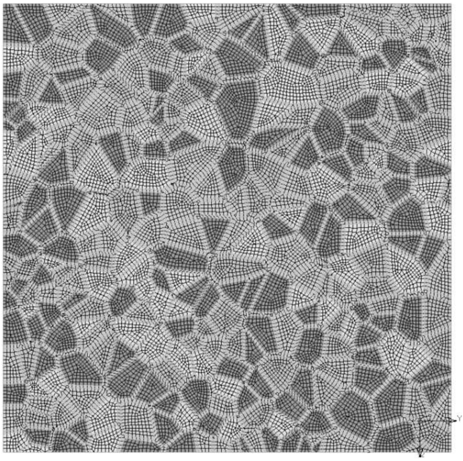

Fig. 14. Exemplary FEM model of the structure with 300 grains with grain boundaries (applied material data)

The ductile damage criterion has been used with the "kill-elements" method. The structure consisting of one hundred grains was subjected to a tensile load. The load was assumed to be equivalent to a certain strain for the macro scale model. Slightly different material properties of grains made the structure anisotropic. Grain boundaries were assumed to be the weakest region of the structure, so the "kill-element" criterion was applied only to this area. The results of simulation of tension of the structure are shown in Figs. 15 and 16.

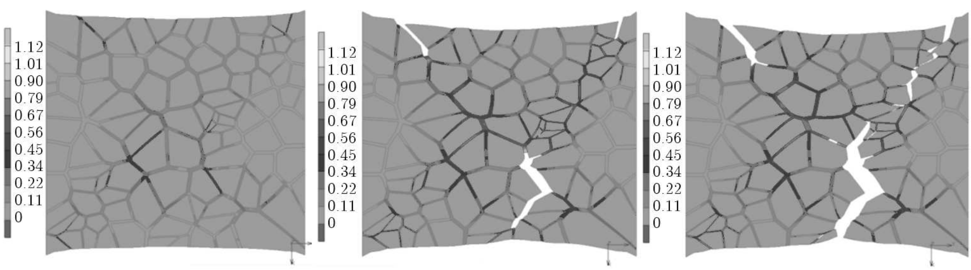

Fig. 15. Damage indicator distribution in simulation of tension of grain structure

As it is shown in Figs. 15 and 16, the fracture propagates along an angle of 45° with respect to the subjected load, which meets the direction of maxi-

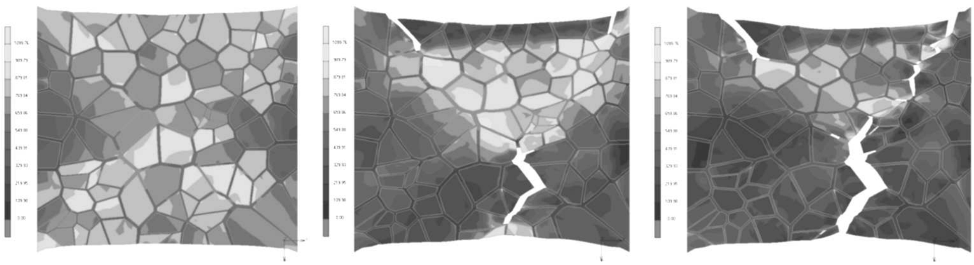

Fig. 16. Stress distribution in simulation of tension of grain structure

mum shear stress. Subsequently, micro cracks continue to propagate following the weakest path in the current state of stress.

Despite the fact that such a structure is pure virtual, it provides information about micro fracture risk, or can serve as a source of information about the structure features responsible for the susceptibility of fracture.

5. Conclusions

The finite element method is widely used for solving complex engineering problems with very a good accordance with the reality. The presented methods implemented in FEA packages serve as tools for damage and fracture evaluation as well as predicting crack propagation further, which becomes extremely important in the scope of SHM.

Amongst the mentioned failure types, brittle fracture is probably one of the most dangerous because, while breaking in a brittle manner, the crack grows rapidly (after reaching specific crack length) allowing no chance to prevent a catastrophe. Numerical techniques capable of modelling brittle fracture were presented in Sections 3.1 and 4.1. In the latter, the idea of cohesive zones was used to predict delamination in a composite structure. Lots of successful verifications of application of cohesive zones in the modelling of delamination were made e.g. (Xie and Biggers, 2006; Ural *et al.*, 2006). The results of the simulation are presented in Section 4.1 and are reasonable in relation to actuality. The modelling of composites failure is of particular interest due to high importance of laminates to the in modern industry.

The last group of models is the ductile damage group. Ductile damage occurs under high deformation conditions and is commonly faced in metal forming processes. An application of damage indicators was shown in Section 4.2. The numerical results obtained were compared with experimental tests.

Due to intensive development of multiscale methods, achievements in this field have also been summarised. A model of effective stress and multiscale modelling with the Voronoi diagram were shown in this group as a tool for micro cracking prediction and evaluation of a potential propagation path.

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Wieloskalowe podejście do modelowania uszkodzeń konstrukcji

Streszczenie

Modelowanie uszkodzeń i pęknięć konstrukcji odgrywa bardzo istotną rolę w projektowaniu i implementacji systemów monitorowania stanu konstrukcji (SHM) oraz jest szczególnie istotne dla prognozy czasu bezawaryjnej pracy obiektów. Autorzy prezentują przegląd i analizę dostępnych metod i narzędzi pozwalających na modelowanie uszkodzeń konstrukcji metalicznych i kompozytowych. Głównym tematem pracy jest zastosowanie wybranych modeli uszkodzeń konstrukcji do symulacji uszkodzeń w skalach mikro oraz makro. Przeanalizowane zostały dwie grupy modeli; modele pozwalające na symulację zjawiska pękania kruchego oraz modele wykorzystywane do analizy uszkodzeń plastycznych. W drugiej grupie rozpatrzono modele w skali makro oraz modele wieloskalowe. W pracy zaprezentowano wieloskalowy model bazujący na elemencie objętościowym (RVE). Omówione zostało modelowanie struktur ziarnistych oraz implementacja z wykorzystaniem metody elementów skończonych w połączeniu z zastosowaniem kryteriów pękania plastycznego dla struktur ziarnistych. W pracy zaprezentowane zostały wyniki symulacji numerycznych oraz ich weryfikacja eksperymentalna.

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