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CALIBRATION OF FOUR FRACTURE MODELS AND DUCTILE FRACTURE SIMULATION POSSIBILITY

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Summary: *The paper deals with material models calibration from experiment tests on cylindrical bar. There are calibrated four ductile damage criteria, which seem to be generally well-known and successful at damage prediction. Four criteria –Strain Limit, Johnson-Cook, Rice-Tracey and EWK are described too. In the paper are discussed alternative damage simulation possibilities as Arbitrary Lagrangian Euler formulation and meshless method. The computations are realised in explicit FEM codes to simulation of bar cutting process. Numerical analysis of the problem was realized by the ANSYS/LS-Dyna and Abaqus-Explicit FEM package.*

1. Introduction

The ductile damage simulation is used not only for automotive, aerospace industry but it is often used for forming processes too. There are defined two models of material behavior at simulations of ductile damage. The material models and damage criteria are bounded with material calibration because of material constants in equations. The models are very sensitive to material constants and it should be paid better attention to them. The best way would be to calibrate the models for every kind of material, including the materials with the same mark. It is unfortunately very expensive, therefore simple criteria are still preferred. Wierzbicki et al. (2005) have shown possible calibration of seven criteria. There have not been defined any general guide in literature until now. The tests for the calibration were made with Czech commercial steel no.41 2050.3.

There are more ways for ductile fracture FEM simulation. The first method describes damage creation with help of element deletion. This method is the most common. If the Fracture criterion is reached, the element will be deleted. There is the problem with deletion of volume, the material is lost at simulation and this could be a problem.

Next fracture simulation method is Arbitrary Lagrange Euler (ALE) method formulation. The method combines advantages of Lagrange's and Euler's methods. In this case the elements are not deleted. The method is used often at large plasticity simulations that are typical for forming process.

The last approach to fracture problem simulation is meshless method. There are defined two types of meshless method in LS-Dyna, SPH (Smooth Particle Hydrodynamics), EFG (Element Free Galerkin). This paper is dealing with ALE and elements deletion methods.

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2. Calibration of material models

It is generally known that we need true stress-strain curve as plasticity model in FE simulation (Fig.1). Static tensile test is usually used for material model calibration. It is not easy to acquire stress-strain curve. The uniaxial state of stress is valid until the neck appears in sample. There are some empirical corrections such as MLR or Bridgman's. Borkovec (2008) has described material models calibration well. It has been calibrated using multilinear and favorite Johnson-Cook (J-C) material model. J-C material model takes note of strain rate and temperature material.

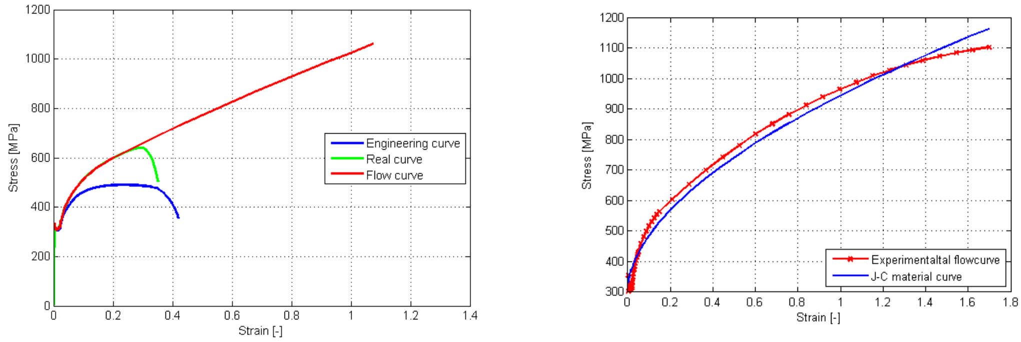


Fig.1. Multilinear flow curve and Johnson-Cook material model

3. Presentation of four fracture criteria and calibration

3.1 Equivalent strain

This criterion is one of the oldest. Fracture is assumed to occur in material when the plastic reduced strain reaches defined value $\bar{\varepsilon} = \bar{\varepsilon}_f$. This criterion is not difficult to calibrate and it is implemented almost at all commercial software. Disadvantage is that the criterion does not affect any kind of loading.

$$\bar{\varepsilon} = \sqrt{\frac{2}{3}}\sqrt{\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2} \qquad (1)$$

This criterion is used very often for easy understanding and calibration.

3.2 Johnson-Cook fracture model (J-C)

Johnson and Cook developed in 1985 fracture model which describes strain, triaxiality parameter and also strain rate and temperature influence.

$$\bar{\varepsilon}_f = \left(D_1 + D_2 exp(D_3\eta)\right)(1 + D_4 ln\dot{\varepsilon})(1 + D_5T^*) \qquad (2)$$

$$D = \sum \frac{\Delta\bar{\varepsilon}^p}{\bar{\varepsilon}_f} \qquad (3)$$

In the equation is defined triaxiality parameter $\eta = \frac{\sigma_m}{\bar{\sigma}}$ which is defined as hydrostatic and reduced stress quotient. It should be noted that there is difference among triaxiality definitions in commercial software. In equation is defined strain rate $\dot{\varepsilon}$ and homological temperature T^*.

There are also five material constants, only three of them are usually used in case of quasi-static isothermal processes.

3.3 Rice – Tracey fracture model (R-T)

Race and Tracey have studied ductile fracture during tensile tests. They defined criterion as

$$C_{RT} = \int_0^{\bar{\varepsilon}_f} \left(\frac{3}{2}\eta\right) d\,\bar{\varepsilon}. \tag{4}$$

There is only one material constant in criterion. Borkovec (2008) and Wierzbicki et al. (2005) refer good results good results of criterion.

3.4 ESI – Wilkins - Kamoulakos model (EWK)

This model is defined as product of two weight functions (w_1, w_2) that are dependent on hydrostatic stress and ratio among deviator stresses (S_1, S_2, S_3).

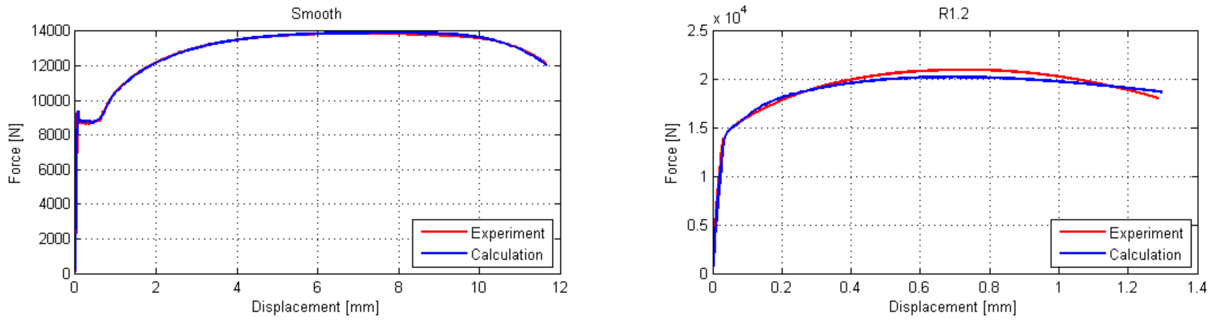
$$D = \int w_1 w_2 d\bar{\varepsilon}^p \tag{5}$$

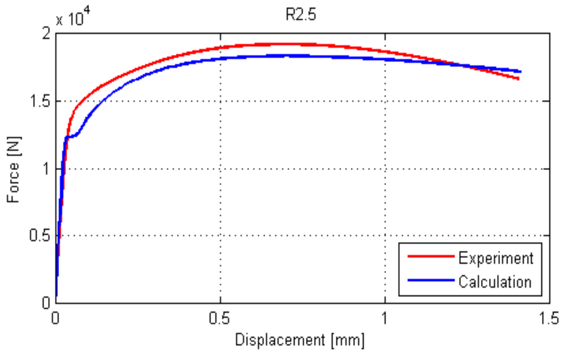
$$w_1 = \left(\frac{1}{1-\frac{\sigma_m}{P_{lim}}}\right)^{\alpha} \qquad w_2 = (2-A)^{\beta} \qquad A = max\left(\frac{S_2}{S_3}, \frac{S_2}{S_1}\right) \tag{6}$$

The parameters α, β and P_{lim} are material constants. This model is implemented only in PAM-Crash.

3.5 Ductile fracture model calibration

It is generally known, that we need to have as many material tests as material model constants. It is necessary to describe maximum range of triaxiality parameter in the place of failure in sample. We have chosen four cylindrical bar samples. The first sample is smooth and the others are with notch of radius 1.2mm, 2.5mm and 5mm. Experimental and computational results of tensile test are compared in Figure 2.





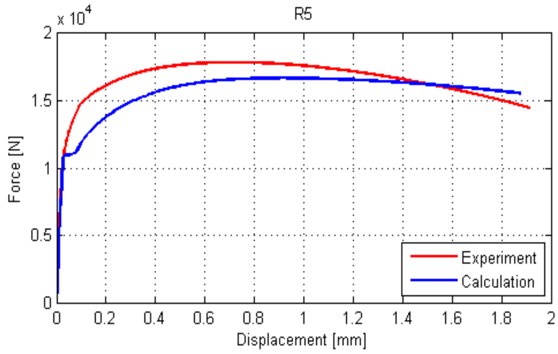


Fig.2: Force responses of tensile test

The experiment of smooth sample and computational curves are very similar. This is because of the data have been used for material model calibration. The difference between computed and experimental curves in each diagram is less than 10%. The reason for this has been investigated and it was found, that the geometrical deviations have the largest influence to results. We get about five percent difference of response forces by neck diameter difference $\mp 0.05mm$. The other reason could be material difference behavior.

We assume that the calculation tensile tests are acceptable and the data are used in calibration. The fracture criteria are mainly dependent on hydrostatic stress (σ_m), reduced stress ($\bar{\sigma}$) and plastic strain ($\bar{\varepsilon}^p$). It should be noted that it is not easy to define optimal model. For example, results of $\bar{\varepsilon}^p$ are very sensitive to mesh density, geometry imperfection and the number of substeps. Saanouki (2004) describes the same problem. The mesh density was investigated and it was chosen thirty elements through neck of sample. LS-Dyna has been chosen to tensile test simulation.

Tab.1: The average value of triaxiality and red. strain from comp. simulation

Type of sample	Average triaxiality η_{av}	Failure strain $\bar{\varepsilon}_f$
Smooth	0.41	0.95
R = 1.2 mm	1.0	0.32
R = 2.5 mm	0.78	0.49
R = 5 mm	0.62	0.59

Nonlinear least-squares method is used to criterions of calibrations. We have used command *lsqnonlin* in program Matlab.

Furthermore, there are plots of fracture parameters – strain dependences. It should be noted, how well the criteria describe different loading.

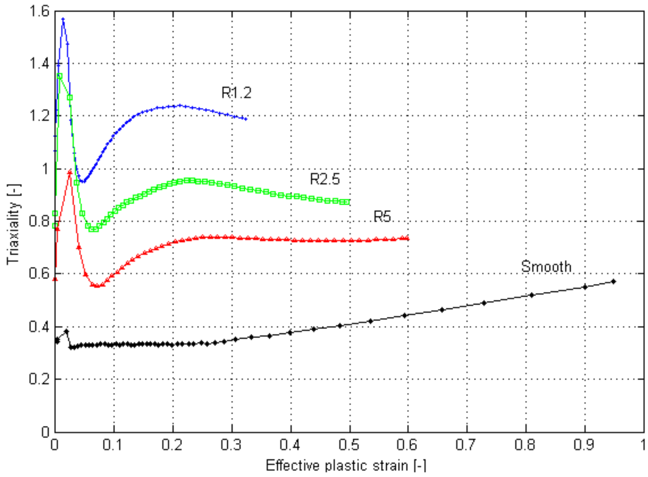


Fig.3: Triaxiality parameter vs. effective plastic strain in the centre of sample

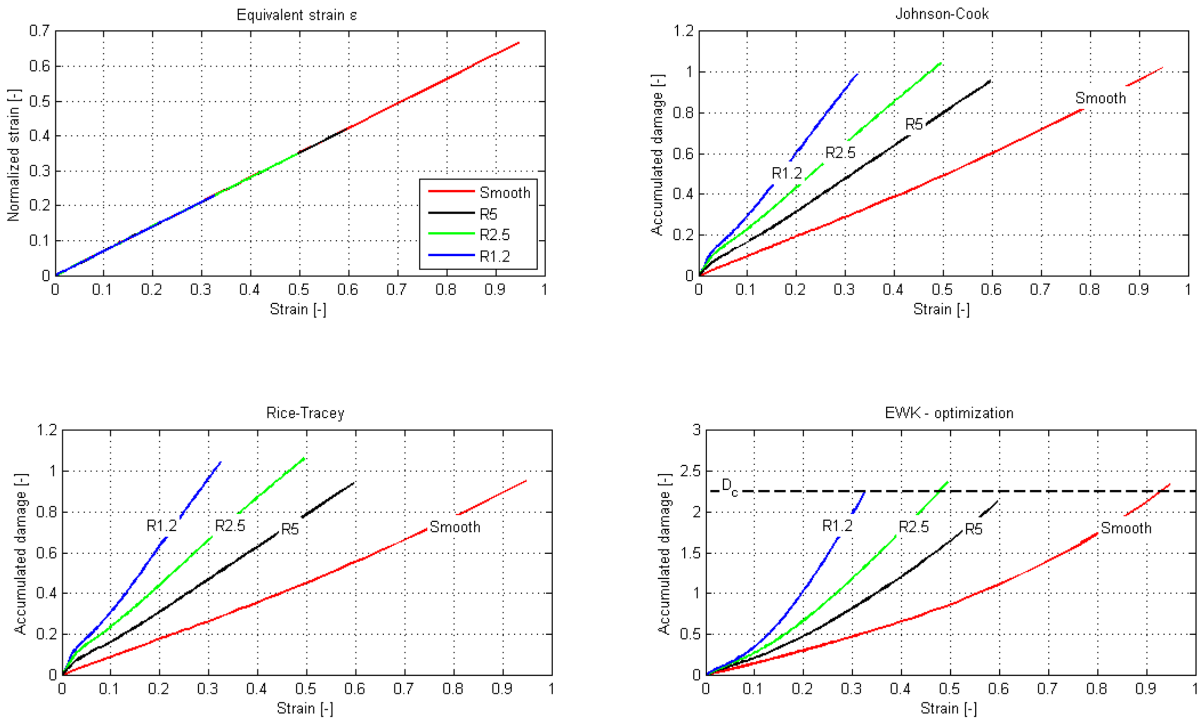


Fig.4: Damage parameter in center of sample

It is evident from the diagrams, that all criteria are able to describe ductile fracture at different loading well, except reduced strain criterion. Ideally, all curves should finish at one line. It is value 1 in most cases except criterion EWK. The line is critical fracture parameter. Reduced strain and J-C criterion will be validated on bar cutting model. They are implemented in Abaqus/Explicit.

4. Computational simulation of rod cutting

The FEM program Abaqus/Explicit was used to simulate the rod cutting. Two new calibrate models were used and verified by experiments data. The multilinear material model with reduced strain fracture criterion and Johnson-Cook material model with J-C fracture criterion were used. The rod cutting simulation is made as adiabatic process and friction is included too. The models and criteria are implemented in Abaqus 6.7.

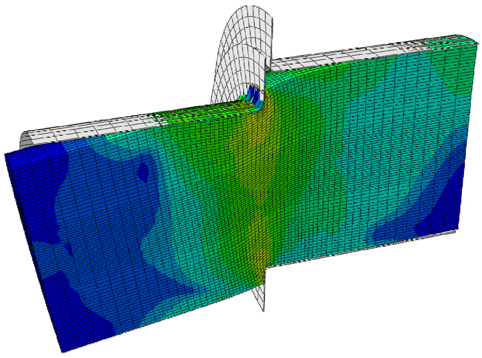


Fig.5: Model of rod cutting

5. ALE application at rod cutting problem

The ALE method was developed originally for fluid mechanics, for modeling the solid-fluid interaction and free-surface problems. However, it is used in solid mechanics problems and it is implemented in commercial implicit and explicit codes (LS-Dyna, Abaqus). ALE approach combines advantage of Lagrangian and Eulerian methods. The basic difference to classical method is, that the computational domain (grid) can move arbitrary and independently of the material. ALE easily describes different types of boundary conditions and large deformation without element distortion because of remesh at every n^{th} time-step. This approach could be used with success in technological operation. Contact boundary definition is not easy in ALE. We have been interested in ALE implemented in Abaqus/Explicit.

2D cutting model of cylindrical bar was made. It is necessary to define segment of deformable part of geometry as Euler domain. It is because of dynamic stability. It is generally not easy to define boundary conditions. The boundary conditions are combination of Euler and Lagrange methods.

ALE method does not strictly need element deletion. Initial state of the cutting process can seen in Fig.6. Cussing forces of ALE and Lagrange simulation are compared in Fig.7. Two damage models reduced strain and J-C were used in the Lagr. simulation. There are compared reaction cutting forces of Lagrange simulation and ALE definition.

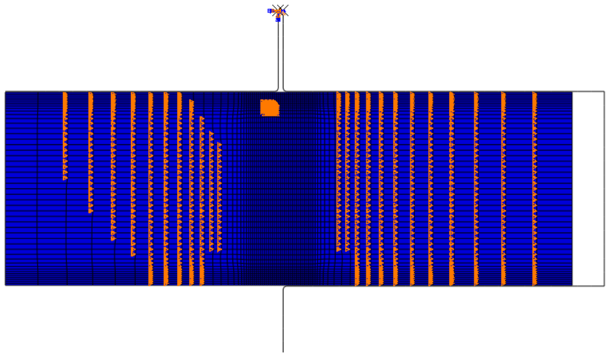


Fig.5: Boundary conditions in ALE method

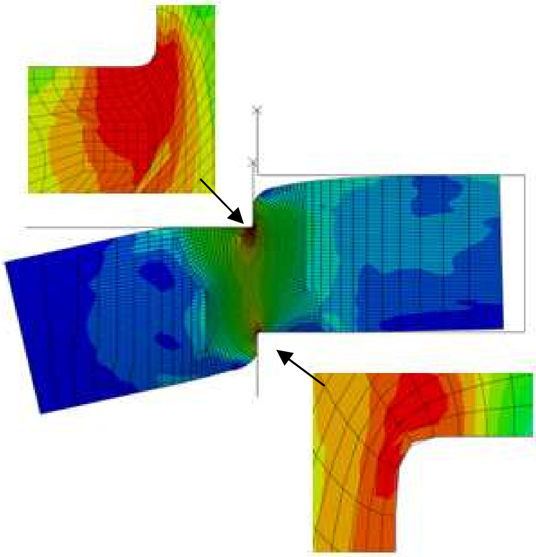


Fig.6: Part of cutting

ALE method gives us realistic result. This method could give us hopeful results in 3D modeling. The problem is, that ALE method implemented in Abaqus run only one CPU and the computation in 3D is extremely time-consuming.

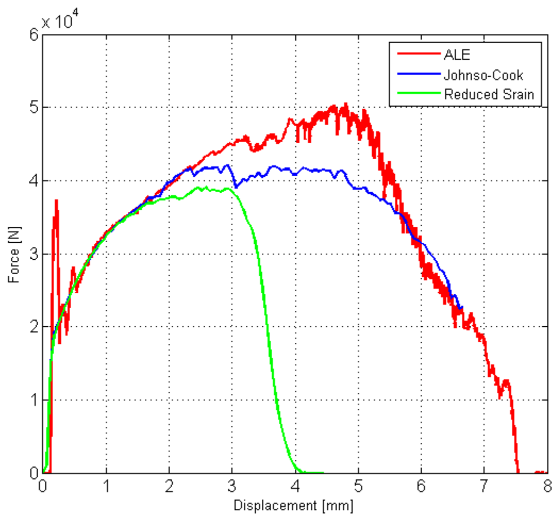


Fig.7: Cutting reaction forces comparison

6. Conclusion

The paper describes briefly the damage model calibration. The calibration is time-consuming process and it is important to debug the calibration model. Two calibrated criteria were used for rod cutting simulation which is verified by experiment. Criterion Rice-Tracey and EWK are going to be tested in the cutting simulation. It will be used in Abaqus subroutine VUMAT.

Further, application of ALE method in 2D to cutting process simulation was demonstrated and the possibility of fracture simulation without element deletion. Specific problems connected to this type of analysis were detected and solved. Next we shall continue with a full 3D ALE model. Meshless method will be tested as another possibility of material separation simulation.

4. Acknowledgement

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