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DAMAGE AND FRACTURE MODELLING IN METAL FORMING PROCESSES

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Summary. *A non-local gradient damage formulation, based on an improved Lemaitre damage model, is adopted in order in order to prevent discretization dependence that generally accompanies the numerical solutions when local softening is introduced. The non-local gradient damage field is related to the local one via a diffusion differential equation, in which the diffusive term is a function of the characteristic length parameter of the material.*

1 INTRODUCTION

Commercial codes are, nowadays, a common tool for the design metal forming processes. For certain processes it is important to prevent the possibility that defective parts may be produced or that formability limits may be reached. In other processes, like cutting or sheet blanking, fracture is a part of the process itself and should be accounted for. Those codes rarely include the modelling of internal damage of the material and subsequent fracture that would help the designer on his task. In some cases they provide some a-posteriori damage criteria, in the sense that damage or fracture are only evaluated after an “undamaged” elasto-plastic analysis. Furthermore most of those criteria may be adequate for certain processes and inadequate for others and, most often, fail for manufacturing processes involving complex strain paths where, in the critical points of the workpiece, the principal stresses change in sign and direction during the forming process. The continuum damage models may capture in a better way the mutual influence between damage and plastic deformation. Nevertheless, when included in finite element codes, due to the local softening induced, standard damage formulations suffer, in their numerical implementation, from mesh dependence.

In this work a non-local continuum damage model is introduced. The model is implemented within a mixed enhanced finite element formulation appropriate for large strain elasto-plastic deformations and is based on the Lemaitre damage model which is enhanced by the introduction of a crack closure scalar parameter, allowing to treat differently the damage evolution in either traction or compression stress states. Its non-local aspect is introduced by a diffusion/adsorption type equation, relating the local and non-local damage fields. In this equation the diffusion term is linked to a characteristic length scale, a material parameter. The adsorption term is the difference between the local and non-local damage fields, providing the damage averaging on a localized zone, depending on the length scale (the diffusion coefficient) and regardless of the mesh size.

2 CONTITUTIVE MODELLING

Concomitantly with large plastic deformations that characterize almost all the forming processes, another process of dissipation may be present, usually termed as ductile damage, associated with the internal degradation of the material, due the initiation, growth and coalescence of voids that may preclude fracture. In the theory of Continuum Damage Mechanics the damage is assumed to be a continuum variable which may be of a scalar, vector or tensor type. Tensor and vector definitions of the damage are usually of difficult calibration and therefore scalar variables are preferred. Although simple these type of models may give very useful information on damage localization and prediction of the fracture initiation site.

In this work the Lemaitre damage model is adopted, in which the damage variable, D, is the effective surface density of micro defects and it is assumed that the constitutive equations of a damaged material are kept formally identical as for the undamaged material, but where the stress σ is replaced by the effective stress $\tilde{\sigma}$, i.e., the stress present in the resisting remaining area after damage has occurred. The effective stress is therefore written as

$$\tilde{\sigma} = \sigma / (1 - hD) \tag{1}$$

where h is another variable to take into account the different response and evolution of damage in traction or compression.

Although the two dissipation phenomena associated with damage and plastic deformation are different they are somewhat related. This is reflected in Lemaitre model by the adoption of strain equivalence hypothesis that affects the plastic flow rule which may written as

$$\dot{\boldsymbol{C}}^{p\text{-}1} = 2\dot{\alpha}\sqrt{\frac{3}{2}}\frac{\|dev(\boldsymbol{\tau})\|}{1 - D} - \left[\sigma_Y + \alpha\,\varepsilon_p\right] \tag{2}$$

where $\dot{\boldsymbol{C}}^p$ is the right Cauchy–Green plastic tensor, $\boldsymbol{\tau}$ is the Kirchhoff stress tensor, α is the internal variable associated with hardening and σ_Y the initial yield stress.

The other important governing equation is the damage evolution that, in this case may be written as

$$\dot{D} = \dot{\bar{\varepsilon}}_p \left(\frac{w_e^-}{S_0 \left(1 - hD\right)} + \frac{w_e^+}{S_0 \left(1 - D\right)} \right) H \left(\bar{\varepsilon}_p - \bar{\varepsilon}_{pD} \right) \tag{3}$$

where w_e^- and w_e^- are, respectively, the compressive and tensile elastic energy density, S_0 is the energy strength of damage, $\bar{\varepsilon}_p$ and $\bar{\varepsilon}_{pD}$ are respectively the equivalent plastic strain and its limit value that defines the initiation of damage and $H(\bullet)$ the Heaviside function.

3 NON-LOCAL GRADIENT DAMAGE MODEL

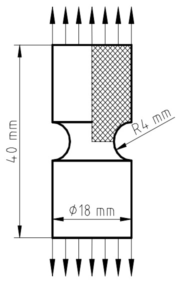
In the non-local model a non-local damage variable is introduced[1]. In the discretization of the two methods used in this work, namely the Finite Element Method and the Reproducing Kernel Particle Method, the non-local damage variable $\bar{D}$ is discretized according to the usual processes associated with the respective method and takes the place of the damage variable in the equations (1) and (2). The equilibrium equations are written using the non-constitutive damage variable $\bar{D}$ which is implicitly related to the constitutive damage variable, D, through a diffusion differential equation

$$\left(D - \bar{D}\right) + c_0 \nabla_0^2 \bar{D} = 0 \tag{4}$$

where c_0 is related to a material length scale parameter. The damage is therefore averaged over a finite length, irrespective of the numerical discretization.

4 NUMERICAL EXAMPLE

A tensile test is used to show how the non-local model removes the discretization dependence associated to the standard local model. The geometry and properties are shown in Figure 1.

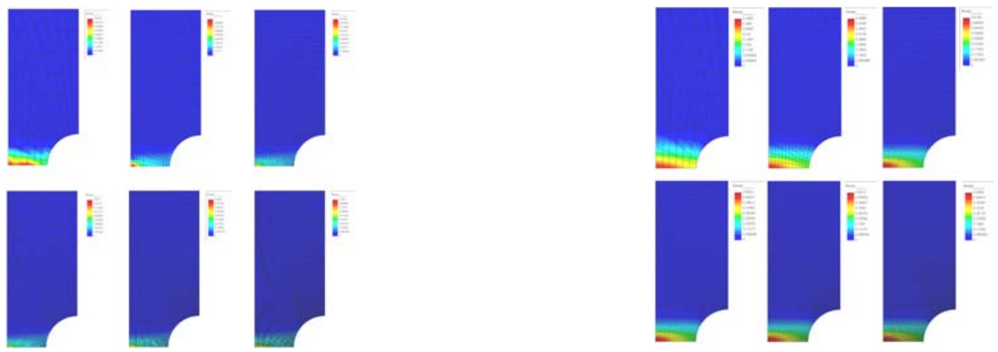


Bulk modulus	κ	$57503.3\ N/mm^2$
Shear modulus	μ	$26540\ N/mm^2$
Hardening law	σ_Y	$589(10^{-4}+\varepsilon_p)^{0.216}\ N/mm^2$
Damage threshold	ε_{pD}	0
Energy strength of damage, local model	S_0	$1.25\ N/mm^2$
Energy strength of damage, gradient model	S_0	$1.1\ N/mm^2$
Area ('length') scale	c_0	$0.4\ mm^2$
Crack closure parameter	h	$1.0/0.0$

Figure 1: Axisymmetric notched bar- geometry and properties.

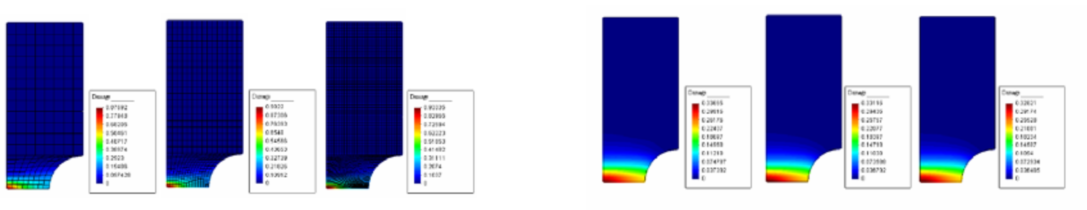
In Figures 2 and 3 the solutions for the local and non-local models in both the Finite Element Method and the Reproducing Kernel Particle Method are shown. In the Finite

Element case different meshes with 72, 288, 1152, 2592, 4608 and 7200 elements were used. In the Reproducing Kernel Particle Method different cases with 189, 576 and 2250 material points were used. There is pronounced discretization dependence in both methods for the local approach to damage, which is removed when the non-local approach is utilised. As the number of elements of the mesh or the number of material points increase the size of the damage zone reduces, accompanying the refinement of the discretization.



a) b)

Figure 2: Finite Element solution: a) Local model; b) Non-local model.



a) b)

Figure 3: Reproducing Kernel Particle Method solution: a) Local model (integration mesh represented); b) Non-local model.

5 CONCLUSIONS

- Numerical implementation of damage local models suffer from mesh dependence. This was verified in both the traditional Finite Element Method but also in a more recently proposed meshless method, namely the Reproducing Kernel Particle Method.
- The proposed non-local model removes the discretization dependence from the solution in both methods.

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