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APPLICATION OF NONLOCAL DAMAGE MODELS TO SHEET FORMING APPLICATIONS

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1 INTRODUCTION

Damage and fracture are important criteria in the design of products and processes. Traditional assessments of the formability of sheet metal materials are based on the appearance of geometrical instabilities, the necking of the sheet. A commonly used method to predict geometrical instabilities in sheet metal forming processes is the Forming Limit Curve (FLC). However, the use of an FLC has some limitations in case of small radius over thickness ratios, non proportional strain paths and non-traditional forming materials with less formability, such as aluminium and high-strength steels. These materials often fail due to physical instabilities, even before necking starts. For crash simulations the FLC is too conservative as also during necking energy is absorbed.

Ductile damage models can be used complementary to the FLC approach to improve the failure predictions. A nonlocal damage model will be presented in Section 2 and some results will be shown in Section 3. The extension of this model to shells is discussed in Section 4.

2 NONLOCAL DAMAGE MODEL

Nonlocal damage models are used to avoid the mesh dependency problems of local damage models. The nonlocal damage model presented here is based on [1, 2]. The local damage driving variable z is a function of the local stress and strain history as defined in Equation 1. The triaxiality $\frac{\sigma_h}{\sigma_{eq}}$ in this equation proves to be important factor [3].

$$z = \int_{\varepsilon_p} \langle 1 + A\frac{\sigma_h}{\sigma_{eq}} \rangle \varepsilon_p^B d\varepsilon_p \tag{1}$$

The nonlocal damage driving variable $\bar{z}$ is obtained using a Helmholtz partial differential equation with a Neumann boundary condition (Equation 2). l is the internal length scale, which controls the width of the localisation bands.

$$\bar{z} - l^2\nabla^2\bar{z} = z; \quad \nabla\bar{z}\cdot n = 0 \quad \text{on}\,\Gamma \tag{2}$$

The evolution of history parameter κ is according the Kuhn-Tucker loading-unloading conditions.

$$\dot{\kappa} \geq 0; \quad \bar{z} - \kappa \leq 0; \quad \dot{\kappa}(\bar{z} - \kappa) = 0 \tag{3}$$

The degradation of the material properties ω is calculated from the history parameter κ using a damage evolution law. Here a linear law is used, the degradation initiates at κ_i and the material fails completely at κ_u.

$$\omega = 0 \quad \text{for} \quad \kappa < \kappa_i; \quad \omega = \frac{\kappa - \kappa_i}{\kappa_u - \kappa_i} \quad \kappa_i \leq \kappa \leq \kappa_u; \quad \omega = 1 \quad \text{for} \quad \kappa > \kappa_u \tag{4}$$

The yield stress is calculated using a strain hardening function h, which competes with the softening due to damage.

$$\sigma_y = (1-\omega)h(\varepsilon_p) \tag{5}$$

The nonlocal damage model is implemented using user subroutines into a commercial explicit Finite Element code [4] as well as a private implicit code [5] using an operator split approach. This method is relatively easy to implement into existing codes. The local and nonlocal damage driving variables z and $\bar{z}$ are updated only at the end of an increment. This means that the degradation ω is kept constant during an increment. Therefore the results become stepsize dependent, but will converge for decreasing stepsize. The increment size used in an explicit simulation is normally much smaller than used in an implicit simulation. Therefore the stepsize dependency is negligible for explicit codes.

The discretisation of Equation 2 results in a symmetric linear system of equations, which has to be solved every increment to calculate the nonlocal variable $\bar{z}$. The calculation time of the nonlocal values is less than the time needed for one increment in an implicit simulation. Contrary to this, for an explicit simulation the calculation of the nonlocal values takes more time than an increment (depending on the problem size). Therefore, in order to reduce the total calculation times using an explicit code, the nonlocal values are calculated only every n increments (typically 100).

Cracks initiate as the degradation (ω) is equal to one and there is no stiffness left. Crack growth is often modelled by element erosion, i.e. failed elements are removed from the problem and the simulation is continued on this updated geometry. Element erosion results in mass loss and a faceted crack surface. This may have a strong influence on the local stress and strain distributions and may lead to to numerical instabilities. This may result in convergence problems using implicit integration, but is attractive for explicit codes due to its simplicity, compared to alternative computational techniques to describe evolving cracks, such as remeshing [2].

The nonlocal model has a number of extra material parameters (l, κ_i, κ_u,A,B) besides the normal ones, which have to be determined experimentally. Microhardness measurements or inverse modelling can be used for this purpose [3, 6], but no standard identification method exists. The element size in the damaged areas should be smaller than the length scale to capture the gradients properly in the nonlocal model. Ideally this length scale is related to the microstructure. However, a small length scale leads to a large number of elements. In practice the length scale might be chosen larger in order to decrease the problem size. Adaptive remeshing of the damaged area might solve this problem [2].

3 BENDING APPLICATION

The nonlocal model has been applied to a three point sheet bending case with a punch radius of 0.2 mm and a die radius of 5 mm. The sheet of 1 mm thickness has been modelled with 40 plane strain elements in thickness direction. An elasto-plastic VonMises material model is combined with the nonlocal damage model. The used material properties are $\kappa_i = 0.05, \kappa_u = 0.5, A = 3, B = 0, h = 983(\varepsilon_p + 4.1e^{-2})^{0.256}$. The length scale l has been varied from 0.0 (local damage) to 0.2 mm.

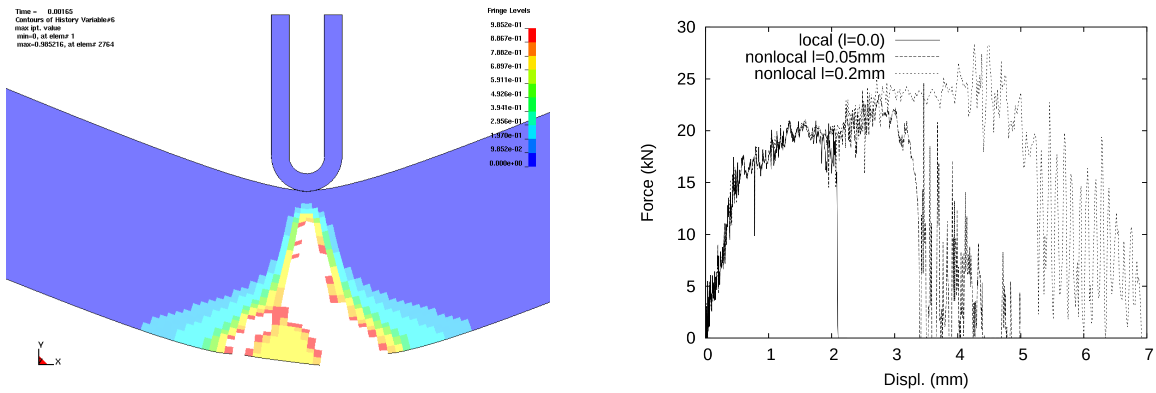


Figure 1: Results of bending simulations. Left: ω for $l = 0.05mm$. Right: force-displacement diagram for various l.

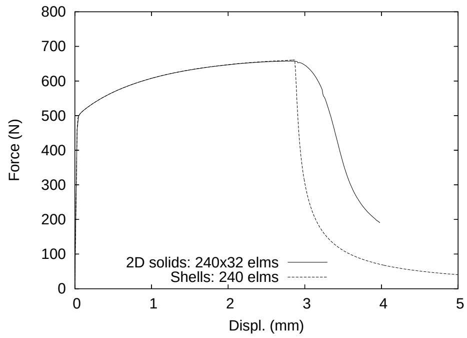
Figure 1 shows the resulting crack shape. During bending shearbands develop at the outer fibers. This results in a crack inclined to the outer surface, which grows along the symmetry line until separation of the parts. These shear bands disappear for larger values of the length scale ($l = 0.2mm$) and the crack follows the symmetry line completely. From the force-displacement graph can be seen that an increasing length scale leads to a more ductile response. These detailed 2D simulations of bending (and combinations with tension) can serve as a reference for simulations with shell elements.

4 SHELL ELEMENTS

For large scale simulations of forming or crash of sheet products shell elements are the most efficient method. Shell elements have a limited description of the kinematics, as normals remain straight during the deformation. Therefore these types of elements are not capable of describing failure with through thickness shear bands as shown in Figure 1. However, often such local details are not of interest and only the correct moment of failure and the energy absorption is important. Furthermore the result should be independent of the used meshsize.

The extension of the nonlocal damage model from solid elements to shell elements is not straight forward. The size of shells elements is normally larger than the sheet thickness. Therefore it is not possible anymore to use the same length scale as in simulations with solid elements. Often the nonlocal model is applied independently for every layer of integration points of the shell element.

Even without damage the necking in simulations with shell elements is mesh size dependent as illustrated in Figure 2. The necking of a tensile bar with an imperfection has been modelled with 2D solids and shells with the same plane strain boundary condition. In the 2D case the neck has a fixed width where for the shells the neck has a width of one element, because the thickness of two neighbouring elements is not coupled. The described nonlocal damage model is not capable of solving this type of mesh dependency completely.



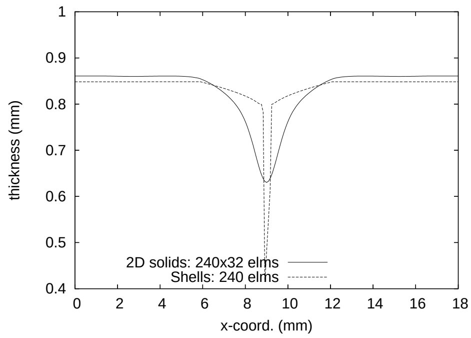


Figure 2: Results of tensile test simulation of a strip of 15x1 mm. Left: force-displacement diagram. Right: thickness distribution at displacement of 3 mm.

5 CONCLUSIONS

A nonlocal damage model has been presented, which gives mesh independent results for solid elements. Some issues concerning the extension of this nonlocal damage models to shell elements have been discussed. A solution for the observed problems with thin shells might be the use of solid shells or cohesive zones [7].

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