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APPLICATION OF A GRADIENT DUCTILE DAMAGE MODEL TO METAL FORMING PROCESSES INCLUDING CRACK PROPAGATION AND MESH ADAPTIVITY

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Summary. *The entire process of ductile failure is modelled, from the initiation of damage to crack propagation. The microscopic material degradation mechanisms which trigger cracks are modelled by a softening elastoplastic behaviour. Mesh objectivity is ensured by a gradient enhancement. The two governing partial differential equations, i.e. equilibrium and a nonlocal averaging equation, are solved in a staggered manner, which renders a relatively simple implementation in existing finite element codes. Adaptive remeshing fulfils a threefold purpose: (i) allowing to model the geometry of discrete cracks; (ii) optimising the use of finite elements, so that finer elements are used in the regions of high strain localisation; (iii) preventing large element distortions. A number of metal forming simulations are shown which illustrate the main model features.*

1 Introduction

In the design of blanking and other metal forming processes, it is not only important to predict when and where cracks will originate, but also their trajectories, since these trajectories determine the shape of the final products. Optimising this shape may allow to eliminate subsequent processing steps and may thus result in considerable savings.

The microscopic processes which are responsible for fracture can be modelled in the form of material softening, as in continuum damage mechanics or softening plasticity. In a finite element context, strongly mesh dependent results can be avoided by using regularising techniques. Among them, gradient models enjoy great popularity [1, 2].

When the material fails, new free surface is created and a continuous solution can no longer be used. To model discrete cracks different numerical methods can be used, e.g. remeshing, Partition of Unity Methods or element erosion. Remeshing has the advantage that besides tracing crack paths, it can also be used to keep the mesh well shaped, which is important in a large strain framework. Remeshing enables to optimise the use of finite elements in the mesh adaptively. Mesh adaptivity is desirable in combination with softening materials, since these tend to show highly localised deformations in relatively small narrow regions, in which a high element density is desired.

In this work a combined continuous softening – discontinuous crack model is presented. A gradient enhancement in the form of [2] is used, which introduces a length scale. A staggered computational approach is used, which circumvents the solution of the coupled problem (equilibrium plus nonlocal averaging), thus rendering its implementation together with existing elastoplastic models more straightforward.

2 Gradient enhanced damage coupled with elastoplasticity

Ductile damage is introduced using the notion of effective stress, which results in the degradation of the yield stress according to

$$f(\boldsymbol{\sigma}, \varepsilon_p, \omega_p) \equiv \sigma_{eq} - (1 - \omega_p)[\sigma_y(\varepsilon_p)] \leq 1 \tag{1}$$

and of the elastic constants. ω_p is a damage variable ($0 \leq \omega_p \leq 1$), f denotes the yield function, σ_{eq} the equivalent von Mises stress and $\sigma_y(\varepsilon_p)$ the undamaged yield stress as a function of the equivalent plastic strain.

This concept can be applied to any plasticity framework. Here, an existing hypoelastoplastic model of a commercial software, MSC.MARC, is used, which allows to take full advantage of features which are needed for forming processes, e.g. contact.

Strongly mesh dependent results are avoided by introducing a non local variable $\bar{\psi}$, which is related to ω_p via the Kuhn-Tucker loading-unloading conditions

$$\dot{\omega}_p \geq 0, \quad \bar{\psi} - \omega_p \leq 0, \quad \dot{\omega}_p\,(\bar{\psi} - \omega_p) = 0\ , \tag{2}$$

as well as an initial value $\omega_p(t = 0) = 0$ and the limit $\omega_p \leq 1$.

$\bar{\psi}$ and its local counterpart ψ are related by the partial differential equation (PDE)

$$\bar{\psi} - \ell^2\, \nabla^2 \bar{\psi} \; = \; \psi\ . \tag{3}$$

In this equation, ∇^2 denotes the Laplacian with respect to the current (Eulerian) configuration; ℓ is an internal length parameter.

The local variable ψ in (3) follows from the evolution law

$$\dot{\psi} \; = \; \frac{1}{C} \left\langle 1 + \; A \, \frac{\sigma_h}{\sigma_{eq}} \right\rangle \varepsilon_p^B \, \dot{\varepsilon}_p\ . \tag{4}$$

This expression has been inspired on Oyane's work for porous plastic materials [3], which accounts for the fact that damage is driven by the plastic strain and increases more rapidly for higher triaxiality.

3 Numerical aspects

The equilibrium equation and nonlocal averaging equation (3) form a coupled problem. A monolithic algorithm to solve these equations has been developed in [4]. For many applications, however, a staggered algorithm may be more practical. First, equilibrium is solved for a constant damage variable ω_p, which will give new stresses $\boldsymbol{\sigma}$ and equivalent plastic strain ε_p. After updating the local variable ψ, the second step is to compute the nonlocal variable $\bar{\psi}$ via the averaging equation. This will allow to update the damage ω_p and the new yield stress σ_y, which are then used in the following load increment.

Isodamage step:

For a constant damage, the equilibrium problem is solved in an updated Lagrangian form using the implicit commercial software MSC.MARC. Upon convergence, the local damage variable ψ (4) is updated numerically by employing a one-step integration rule

$$\Delta\psi = ((1-\theta)h^t_\omega + \theta\, h_\omega)\Delta\varepsilon_p\,, \quad \text{where} \quad h_\omega = \frac{1}{C}\left\langle 1 + A\,\frac{\sigma_h}{\sigma_{eq}}\right\rangle \varepsilon_p^B. \tag{5}$$

Nonlocal averaging at fixed configuration:

The damage variable follows by enforcing the weak form of Eq. (3), which after making use of the divergence theorem reads

$$\int_\Omega \left(\mathsf{w}\,\bar{\psi} + \ell^2\vec{\nabla}\mathsf{w}\cdot\vec{\nabla}\bar{\psi}\right)\,\mathrm{d}\Omega = \int_\Omega \mathsf{w}\,\psi\,\mathrm{d}\Omega\,, \tag{6}$$

where w is a standard test function. This weak form is discretised in a standard manner by inserting interpolated fields for w and $\bar{\psi}$. Solving the resulting linear algebraic system gives the nonlocal variables, which allows to update the damage variable ω_p, and subsequently the yield stress σ_y needed by MSC.MARC.

Since the plastic strains localise in the regions with strongest damage evolution, the mesh density is set depending on the spatial distribution of the damage rate.

Cracks are introduced upon total material failure, i.e. at $\omega_p = 1$, thus rendering a smooth transition from the continuous damage field to a discrete crack. The crack direction is computed from the damage distribution around the crack tip and full remeshing is performed to accommodate every new crack increment during the crack advancement. Remeshing is followed by the transfer of state variables. All the above operations is carried out outside MSC.MARC.

4 Application to blanking

Simulations of the blanking process have been carried out to illustrate the main model features. In these simulations, the standard contact options in MSC.MARC have been used.

During blanking one wishes to accurately predict the shape of the cut surface. Experiments have shown that the clearance between the punch and the die has an important effect on the final shape. In Fig. 1 the mesh and damage rate field in the metal sheet are shown before and after the onset of fracture. Mesh adaptivity was used to capture the gradients in the sheared zone.

5 Conclusions

To model ductile failure in forming processes, from the nucleation of voids to fully developed crack propagation, ductile damage is used in combination with discrete crack modelling. Mesh independent results are obtained by means of a gradient nonlocal damage variable. The staggered approach followed allows to add a gradient enhanced damage influence to the plasticity formulation of a commercial finite element software. This is of special interest for engineers who wish to have reliable

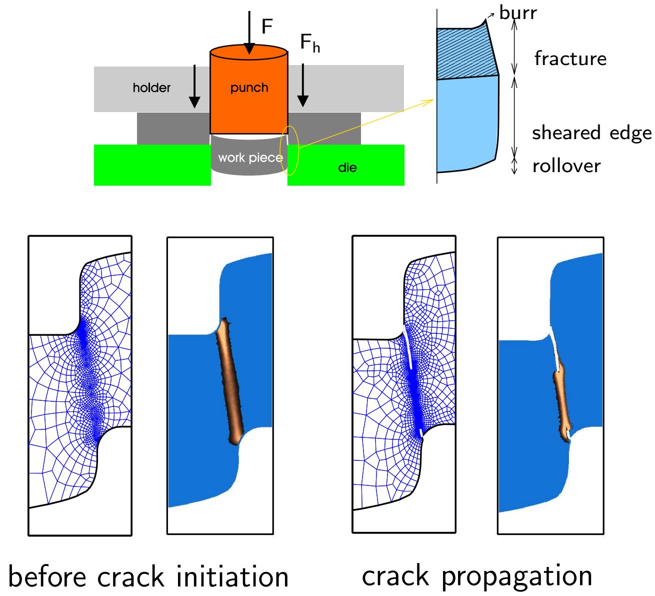

Figure 1: Top: blanking setup and schematic representation of a typical product edge after blanking; bottom: mesh and damage rate evolution.

results when using softening materials, since fully coupled implicit models are more difficult to implement.

In this framework, where large deformations, highly localised regions and discrete cracks are present, the use or remeshing has proven to be extremely useful. Adaptive remeshing is required when one does not know a priori where cracks originate, since it allows to have an optimum mesh density distribution.

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