TOWARDS VERIFICATION OF A GRADIENT-ENHANCED DUCTILE DAMAGE MODEL

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1. Introduction

Processes in the metal forming industry involve large plastic deformations accompanied by ductile damage. In order to better predict the properties of the finished product as well as the behaviour during the process, more accurate simulations are necessary. Damage models require a regularisation to obtain mesh independent results. In the following a specific gradient-enhancement strategy is discussed.

2. Nonlocal damage model

An elegant way to include gradients into a model was suggested in [1, 4]. In this context, the free Helmholtz energy is split into a local and nonlocal contribution

$$\varPsi = \varPsi^{\mathrm{loc}}(\boldsymbol{F}, d, \boldsymbol{\mathcal{I}}^{\mathrm{p}}) + \varPsi^{\mathrm{nl}}(\boldsymbol{F}, d, \phi, \nabla_{\boldsymbol{X}}\phi) \quad \text{with} \quad \varPsi^{\mathrm{nl}} = \frac{c_d}{2}\|\nabla_{\boldsymbol{X}}\phi\|^2 + \frac{\beta_d}{2}\,[\phi - d]^2 \ ,$$

where the quantity ϕ, an additional field variable in the context of the finite element method, represents nonlocal damage and is linked in penalty type fashion to the local damage variable d. Since the gradient of the local damage $\nabla_{\boldsymbol{X}} d$ is not required, many already established local damage models can be incorporated into this framework. Successful implementations can be found in, e.g. [2, 3, 5].
The material model uses a multiplicative split of the deformation gradient $\boldsymbol{F} = \boldsymbol{F}^{\mathrm{e}} \cdot \boldsymbol{F}^{\mathrm{p}}$ and logarithmic strains $\boldsymbol{\varepsilon}^{\mathrm{e}}$ for the elastic free Helmholtz energy

$$\varPsi^{\mathrm{loc}}\left(\boldsymbol{\varepsilon}^{\mathrm{e}}, d, \alpha\right) = \frac{K}{2}\, f^{\mathrm{vol}}(d)\,[\mathrm{tr}\left(\boldsymbol{\varepsilon}^{\mathrm{e}}\right)]^2 + \mu\, f^{\mathrm{iso}}(d)\, \boldsymbol{\varepsilon}^{\mathrm{e}} : \boldsymbol{\varepsilon}^{\mathrm{e}} + \varPsi^{\mathrm{p}}\left(\alpha\right) \ .$$

The volumetric and isochoric contributions are each multiplied with damage functions $f^{\bullet}(d)$ defined as

$$f^{\bullet}(d) := \left\{\mathbb{R}_0^+ \to]0, 1]\right\} \quad \text{with} \quad f^{\bullet}(d) = \exp(-\eta_{\bullet}\, d)\,,$$

such that the local damage d is positive but otherwise unbounded.
In this multisurface formulation the driving forces q, $\boldsymbol{m}$ and β have to lie in the elastic domain, which is bounded by a von Mises yield criterion including nonlinear isotropic hardening as well as a damage criterion with a variable damage threshold, i.e.

$$\varPhi^{\mathrm{p}}(\boldsymbol{m}^{\mathrm{t}}, \beta, d) = \|\,\mathrm{dev}(\boldsymbol{m}^{\mathrm{t}}_{\mathrm{eff}})\| - \sqrt{\frac{2}{3}}\left[\sigma_{\mathrm{y}}^0 - h\,\alpha^{n_{\mathrm{p}}}\right] \quad \text{and} \quad \varPhi^{\mathrm{d}}(q, d) = q_{\mathrm{eff}} - q_{\mathrm{max}}\left[1 - f^q(d)\right]^{n_{\mathrm{d}}} \ .$$

In both criterions effective driving forces are used to intensify the coupling — the spatial Mandel stresses $\boldsymbol{m}$ are divided by the damage function $f^{\boldsymbol{m}}$ and in an analogous way the damage driving force q is divided by an exponential function dependent on the hardening variable α.
Using standard thermodynamics and the postulate of maximum dissipation yields evolution equations which are transformed into an algorithmic update with an exponential scheme for the integration of $\boldsymbol{F}^{\mathrm{p}}$ and backward Euler integration for d. The resulting double set of Karush-Kuhn-Tucker conditions are solved using an active set scheme.

3. Parameter identification

The underlying experiment for the parameter identification (PI) is a tension test of a specimen cut from DP800 sheets, see Figure 2. The experiment was recorded by a suitable camera such that the inhomogeneous displacement field could be obtained from DIC software. The experimental displacement field components u_{tij}^{exp} at every point in time t, every point i and every dimension j considered together with the corresponding displacements from the simulation u_{tij}^{sim} enter the objective function

$$F = \sum_{t} \sum_{i=1}^{n_{\mathrm{np}}} \sum_{j=1}^{n_{\mathrm{dim}}} \left[\Delta u_{tij}^{\mathrm{exp}} - \Delta u_{tij}^{\mathrm{sim}} \right]^2 .$$

The objective function only consists of the squared error of relative displacements — the difference in displacement compared to neighbouring points — since the force measured in the experiment is directly applied as Neumann boundary condition in the finite element simulation. Relative displacements are chosen over the actual displacements to remove the influence of rigid body motions. After identifying the elastic parameters for DP800, a PI to determine the plastic parameters was carried out. The load displacement diagram shows a good agreement between experiment and simulation, see Figure 1. An additional simulation including unloading confirms the evolution of plastic strains. In future work the damage parameters shall be identified. The gradient parameter c_d will receive special focus in order to check its independence from geometry and specimen size.

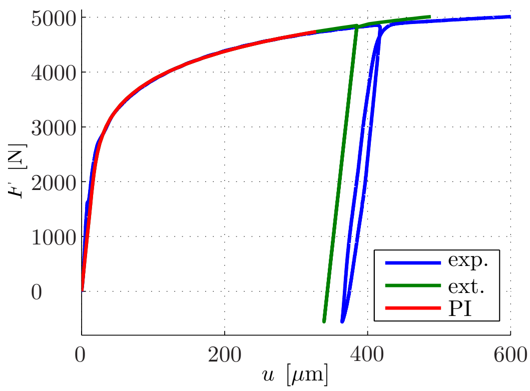

Figure 1: Load displacement diagram of the tension test including unloading underlying the PI. Experiment (blue), PI result (red) and simulation including the unloading (green).

Figure 2: Image of the specimen geometry. The specimens from $1.5\,\mathrm{mm}$ DP800 sheets are $50\,\mathrm{mm}$ long.

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