Nonlocal damage modelling for finite element simulations of ductile steel sheets under multiaxial loading

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The finite element simulation of forming processes or vehicle crash scenarios involves multiaxial loading conditions in general. Thereby, damage and failure in ductile steel sheets is triggered by void growth under hydrostatic tensile loading or by void elongation within a narrow band under shear dominated loading. These different damage mechanisms are considered by a stress state dependent continuum damage model. The damage initiation and failure are represented by a critical and a failure strain. Both are HOSFORD-COULOMB type functions of the stress triaxiality and the LODE parameter and, thus, incorporate the stress state dependence of the damage mechanisms. Due to the pathological mesh sensitivity for continuum damage models, an enhancement towards nonlocal damage evolution is carried out. Thereby, two options are investigated and compared: the integral nonlocal formulation and the gradient enhanced approach. Finally, the proposed nonlocal ductile damage model is verified for a wide range of stress states by test data of various tensile and shear specimens.

1 Stress state dependent nonlocal ductile damage model

The proposed constitutive equations include a plasticity model, consisting of the VON MISES yield criterion and nonlinear isotropic hardening, see [1] and [2]. The plasticity model is coupled to a continuum damage mechanics based approach by the concept of effective stresses. Thereby, isotropic damage is represented by the damage variable D. Damage growth is proposed by means of an evolution equation for the damage variable, driven by the equivalent plastic strain $\bar{E}_{\mathrm{pl}}$. The damage exponent n_{D} controls the nonlinearity of the damage evolution behaviour. In order to consider stress state dependent damage and failure, the stress triaxiality $T = \frac{I_1}{3\sqrt{3J_2}}$ and the LODE parameter $\bar{L} = 1 - \frac{2}{\pi}\arccos(\frac{3\sqrt{3}}{2}\frac{J_3}{J_2^{3/2}})$ are applied for stress state characterisation, based on the first basic stress invariant I_1 and the second and third deviatoric stress invariants J_2 and J_3. Consequently, the damage initiation criterion $\varepsilon_{\mathrm{c}}(T,\bar{L})$ as well as the failure criterion $\varepsilon_{\mathrm{f}}(T,\bar{L})$ depend on the stress triaxiality and the LODE parameter, whereby the HOSFORD-COULOMB model from [3] is applied for both functions. Finally, the following set of equations is obtained for the stress state dependent ductile damage model:

$$\dot{D} = \frac{n_{\mathrm{D}}}{\varepsilon_{\mathrm{f}}(T,\bar{L}) - \varepsilon_{\mathrm{c}}(T,\bar{L})} \left\langle \frac{\bar{\mathrm{E}}_{\mathrm{pl}} - \varepsilon_{\mathrm{c}}(T,\bar{L})}{\varepsilon_{\mathrm{f}}(T,\bar{L}) - \varepsilon_{\mathrm{c}}(T,\bar{L})} \right\rangle^{n_{\mathrm{D}}-1} \dot{\bar{\mathrm{E}}}_{\mathrm{pl}}\,, \quad \varepsilon_{\mathrm{c/f}}(T,\bar{L}) = b_{\mathrm{c/f}} \left(\frac{1 + c_{\mathrm{c/f}}}{g_{\mathrm{c/f}}(T,\bar{L})} \right)^{\frac{1}{n}} \tag{1}$$

$$g_{\mathrm{c/f}}(T,\bar{L}) = \left[\frac{1}{2}(f_1 - f_2)^{a_{\mathrm{c/f}}} + \frac{1}{2}(f_2 - f_3)^{a_{\mathrm{c/f}}} + \frac{1}{2}(f_1 - f_3)^{a_{\mathrm{c/f}}} \right]^{\frac{1}{a_{\mathrm{c/f}}}} + c_{\mathrm{c/f}}\,(2T + f_1 + f_3) \tag{2}$$

$$f_1 = \frac{2}{3}\cos\left[\frac{\pi}{6}(1 - \bar{L})\right]\,, \quad f_2 = \frac{2}{3}\cos\left[\frac{\pi}{6}(3 + \bar{L})\right]\,, \quad f_3 = -\frac{2}{3}\cos\left[\frac{\pi}{6}(1 + \bar{L})\right] \tag{3}$$

The parameters a_{c}, b_{c}, c_{c} for damage initiation and a_{f}, b_{f}, c_{f} for failure have to be calibrated to test data, whereas the exponent is usually defined to $n = 0.1$.

In order to prevent the pathological mesh sensitivity for continuum damage models, an enhancement towards nonlocal damage evolution is carried out. By applying the integral nonlocal approach according to [4], the nonlocal damage $\tilde{D}(\mathbf{x})$ at the reference point $\mathbf{x}$ is obtained by weighting the local damage $D(\mathbf{y})$ at neighbouring points $\mathbf{y}$ over the integration region Ω. Therefore, the three-parameter weighting function $w(\mathbf{x},\mathbf{y})$ is employed with the parameters p and q and the characteristic length $l_{\mathrm{c,int}}$. Hereby, $\|\mathbf{x}-\mathbf{y}\|$ is the EUCLIDean norm of the distance between $\mathbf{x}$ and $\mathbf{y}$.

$$\tilde{D}(\mathbf{x}) = \frac{\int_\Omega D(\mathbf{y})\, w(\mathbf{x},\mathbf{y})\, \mathrm{d}\mathbf{y}}{\int_\Omega w(\mathbf{x},\mathbf{y})\, \mathrm{d}\mathbf{y}}\,, \quad w(\mathbf{x},\mathbf{y}) = \left[1 + \left(\frac{\|\mathbf{x}-\mathbf{y}\|}{l_{\mathrm{c,int}}} \right)^p \right]^{-q} \tag{4}$$

As alternative to the integral nonlocal formulation according to Eq. (4), the implicit gradient enhanced damage approach

$$\tilde{D}(\mathbf{x}) - l_{\mathrm{c,grad}}^2 \nabla^2 \tilde{D}(\mathbf{x}) = D(\mathbf{x}) \tag{5}$$

is applied for the nonlocal enhancement as well. The implementation into LS-DYNA® is carried out by exploiting the thermo-mechanical solver, due to the analogous field problem of the Helmholtz type inhomogeneous differential equation (5) with the steady-state heat equation.

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2 Model verification for a wide range of stress states

The model parameters are identified for the ductile steel HX340LAD on the basis of test data from the Fraunhofer Institute for Mechanics of Materials (IWM), see [6]. In order to capture a wide range of stress states, the design of experiments includes flat smooth and notched tensile specimens, various shear specimens and a NAKAZIMA biaxial punch test. The sheet thickness is 1.5 mm in all cases. The identified model parameters are already published in [1] and [2]. The simulation is carried out for the stress state dependent ductile damage model in combination with the integral nonlocal formulation denoted as (sim. int.) and the gradient enhanced damage approach with (sim. grad.) in Fig. 1 a) and b). The predicted stress-strain curves are compared to the test data in Fig. 1 a) for the tensile specimens and in b) for the shear specimens. A good overall accordance is achieved, verifying the proposed model for a wide range of stress states. Note that the numerical results, obtained by both different nonlocal methods, are nearly identical. However, a significant difference is found for the elapsed simulation time. Thereby, three different mesh sizes are evaluated for the smooth tension specimen in Fig. 1 c) and for the 0° shear specimen in d). Compared to the simulation with the gradient enhanced approach, the elapsed simulation time for the integral nonlocal formulation is noticeably higher, in particular for the very fine mesh, due to its the underlying costly search algorithm.

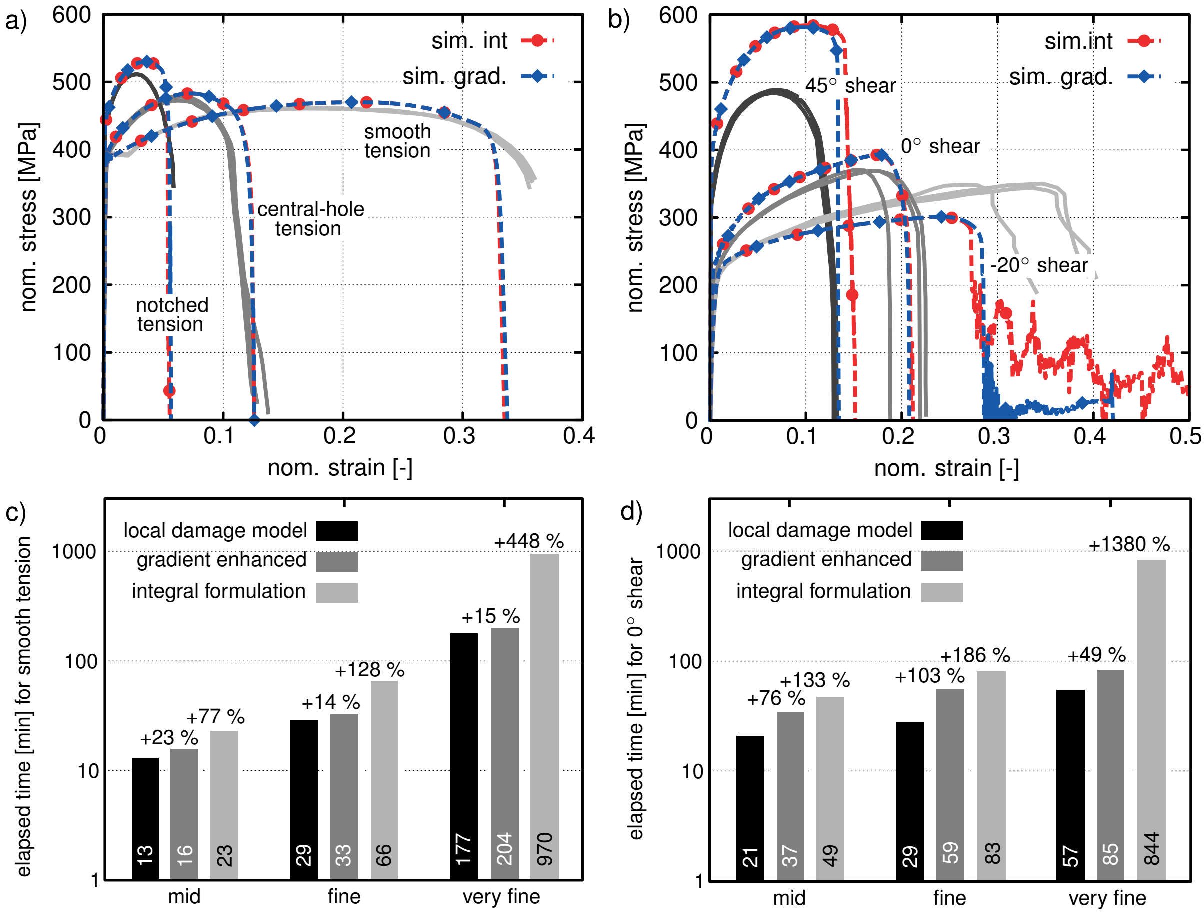

Abb. 1: Simulation results (dashed lines) compared to test data from [6] (solid lines) for tensile specimens in a) and shear specimens in b) as well as elapsed simulation time for the smooth tension specimen in c) and the 0° shear specimen in d) with three different mesh sizes (mid: 0.5 mm, fine: 0.25 mm, very fine: 0.125 mm)

Literatur

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