TRR285

Efficient Gradient-Enhancement of Ductile Damage for Implicit Time Integration

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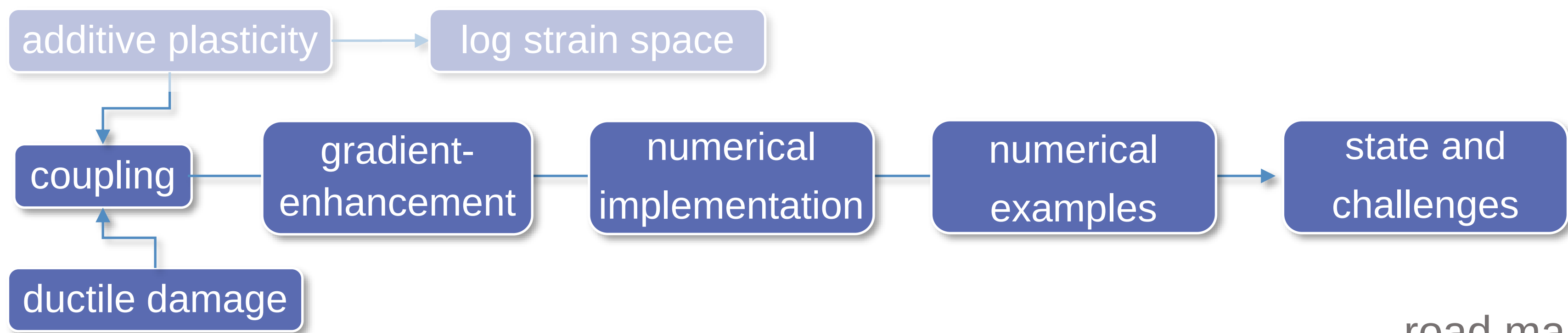
Material modelling for mechanical joining of sheet metal

- **materials: dual-phase steel HCT590X; aluminium alloy EN AW-6014**
- **locally severe plastic deformations (acc. plastic strains > 2)**
  → finite plasticity in the logarithmic strain space (“ln-space”)
  Miehe et al., 2001/2002; JF et al., 2022 (IJSS)
- **modelling of process-induced damage:** “damage is not failure”
  Tekkaya et al., 2020
  → phenomenological ductile continuum damage model
- **fully coupled plasticity-damage**
  → damage localisation
  → regularisation with gradient-enhancement to ensure mesh-independence
  → transfer to LS-Dyna using weakly staggered thermomechanical coupling

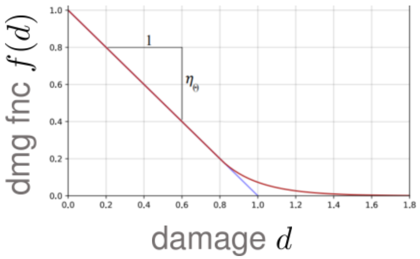


road map

Source code for logarithmic strain space available at: https://github.com/jfriedlein/Logarithmic_Strain_Space-Fortran

Damage and degradation

- damage variable
  $d = [0 \ldots \infty)$
- damage function

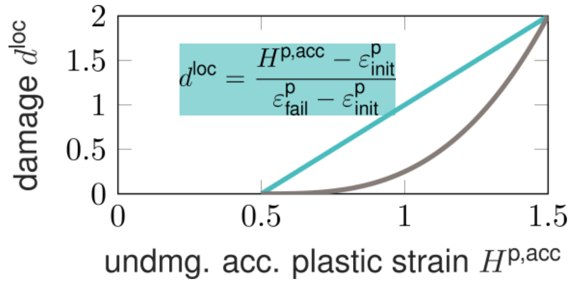


$$f_i = \begin{cases} 1 - \eta_i d, & \text{if } f_i > 0.01 \\ 0.001 + (0.01 - 0.001)\exp\left(\frac{1-0.01-\eta_i d}{0.01-0.001}\right), & \text{else} \end{cases} = [1 \ldots 0.001)$$

Ductile damage

ductile damage driven by plasticity: $d^{\text{loc}}(H^{\text{p,acc}})$
with undamaged acc. plastic strain

$$\dot{H}^{\text{p,acc}} = \sqrt{\tfrac{2}{3}}\dot{\gamma}^{\text{pd}} \geq 0$$

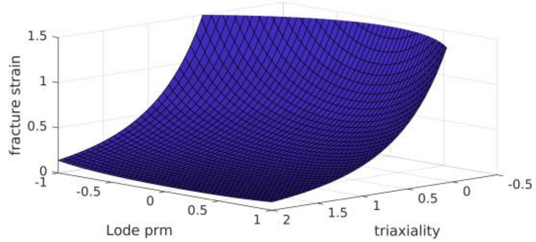


nonlinear damage accumulation:

$$d^{\text{loc}} = \left[\frac{H^{\text{p,acc}} - \varepsilon^{\text{p}}_{\text{init}}}{\varepsilon^{\text{p}}_{\text{fail}} - \varepsilon^{\text{p}}_{\text{init}}}\right]^{n_d}$$

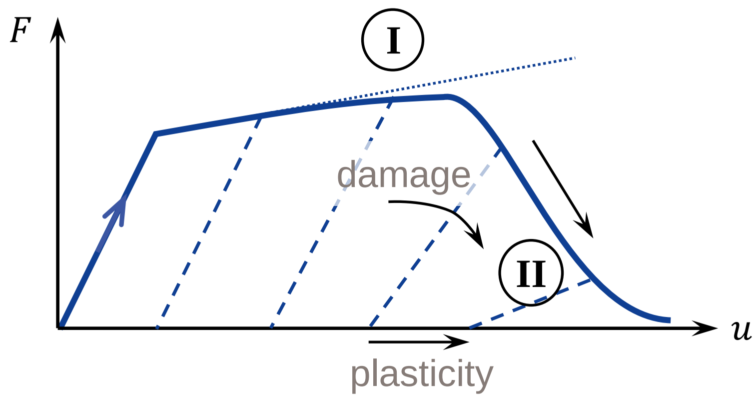
"truly" local damage

$\varepsilon^{\text{p}}_{(\bullet)}$: plastic strain
init: damage initation
fail: failure
n_d: damage exponent



Modified Mohr-Coulomb failure surface

Coupling elasticity, plasticity and damage

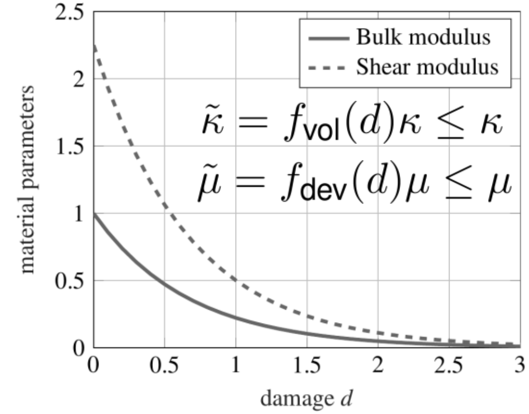


elasticity

plasticity ⟷ damage

concept of effective stress

material degradation



stress:

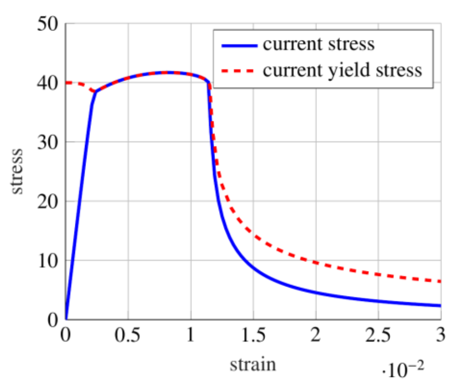
$$\tilde{\sigma}_{\text{flow}} = f_{\text{p}}(d)\sigma_{\text{flow}} \leq \sigma_{\text{flow}}$$

plastic strain tensor:

$$\dot{\boldsymbol{H}}^{\text{pd}} = \dot{\gamma}^{\text{pd}}\boldsymbol{n} = \dot{\boldsymbol{H}}^{\text{p}}$$

plastic hardening variable:

$$\dot{\alpha} = f_{\text{p}}(d)\dot{\gamma}^{\text{pd}}$$



$$\Psi^{\text{elastic}}$$

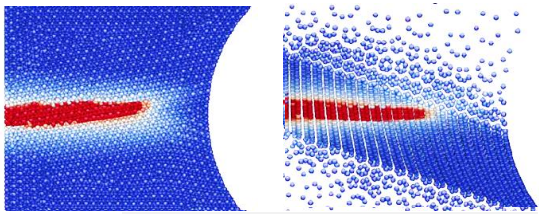
$$\Psi^{\text{plastic}} = \Psi^{\text{elastic}} + \Psi^{\text{hard}}$$

$$\Psi^{\text{locPD}} = f_i * \Psi^{\text{elastic}} + \Psi^{\text{hard}}$$

free energy

Regularisation and Gradient-enhancement

- Why regularisation?
  - Local damage models
    - mathematically ill-posed
    - mesh-dependent (mesh size/orientation/…)



Zhang&Lorentz&Besson, 2018

- Why gradient-enhancement?
  - more efficient than non-local integral model
  - more flexible than viscous regularisation

Nahrmann&Matzenmiller, 2021
Niazi et al., 2013

- Gradient-enhancement of free energy

$$\Psi = \Psi^{\text{loc}}(\boldsymbol{H}, \boldsymbol{H}^{\text{p}}, \alpha, d) + \Psi^{\text{nloc}}(d, \bar{d})$$

with $\Psi^{\text{nloc}} = c/2 \|\nabla_{\boldsymbol{X}} \bar{d}\|^2 + \beta/2\left[\bar{d} - d\right]^2$

$\bar{d}$: non-local damage variable
d: local damage variable
c: regularisation parameter
β: penalty parameter

Dimitrijevic&Hackl 2011;
Kiefer et al. 2018;
Langenfeld&Mosler 2019;
Brepols et al. 2020

- Partial Differential Equations (PDEs)

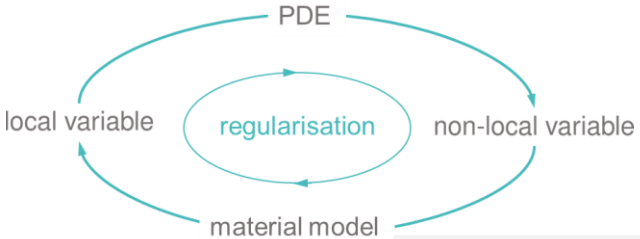
balance of linear momentum:

$$\nabla_{\boldsymbol{X}} \cdot [\boldsymbol{F} \cdot \boldsymbol{S}] = \boldsymbol{0}$$

regularisation

$$\nabla_{\boldsymbol{X}} \cdot \left[c \nabla_{\boldsymbol{X}} \bar{d}\right] - \beta\left[\bar{d} - d\right] = 0$$

Seupel et al., 2018
Ostwald et al., 2019

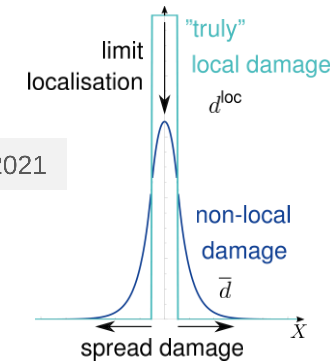


Friedlein et al. (PAMM21)

What variable to regularise? Many more options. Interested? Just ask.

Numerical implementation I

- weakly staggered thermomechanical coupling
- delayed non-local variable $\bar{d}_n$
  - explicit time integration → directly applicable (Nahrmann&Matzenmiller, 2021)
  - implicit time integration → step size dependency
- mimic change of non-local variable $\bar{d}_{\text{n+1}} = \bar{d}_n / d_n^{\text{loc}} \cdot d_{\text{n+1}}^{\text{loc}}$



Friedlein et al., 2021 (PAMM)

thumat1x

thermal solver with source term and IHVE=1

$$l^2 \Delta_X \bar{d}_n - \left[\bar{d}_n - d_n^{\text{loc}}\right] = 0$$

hsvm(d_n^{loc}) → thumat1x → temp($\bar{d}_n$) → umat4x → hsv($d_{\text{n+1}}^{\text{loc}}$)

umat4x

UMAT with ITHERM=1

$d_{\text{n+1}}^{\text{loc}} \leftarrow$ local damage model

$K_{\text{NL}} = \bar{d}_n / d_n^{\text{loc}}$

$\bar{d}_{\text{n+1}} = K_{\text{NL}} \cdot d_{\text{n+1}}^{\text{loc}}$

Non-local integral model: Tvergaard&Needleman, 1995; Andrade et al., 2011

$$d_{\text{n+1}} = \max(\max(\underbrace{d_n}_{\dot{d}\geq 0}, \underbrace{\bar{d}_n}_{\text{spread}}), \bar{d}_{\text{n+1}})$$

$f(d_{\text{n+1}}) \rightarrow$ material behaviour

IHVE=1: map mechanical history

Code soon available at: https://github.com/jfriedlein/Gradient-enhancement_thermomech_weaklyStaggered_Fortran_LS-Dyna

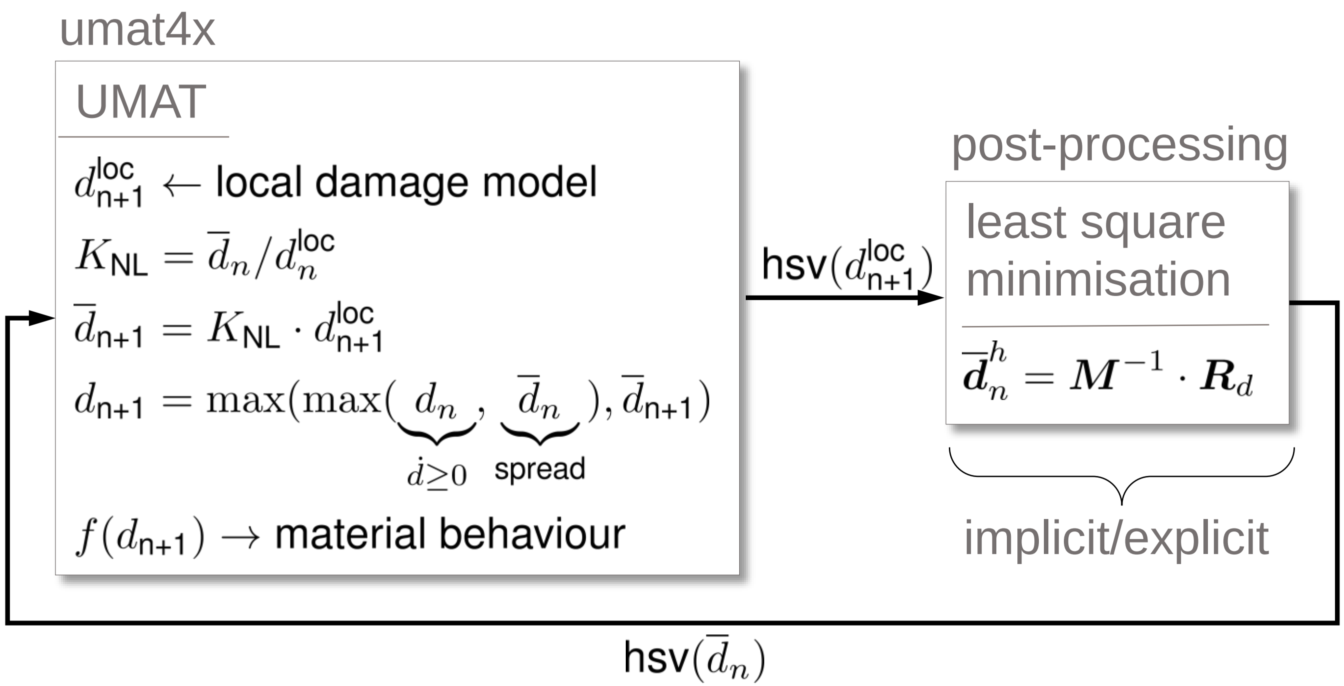
Numerical implementation II

- thermal step ideally done after/before each mechanical step
- PDE for regularisation

$$l^2 \Delta_X \bar{d}_n - \left[\bar{d}_n - d_n^{\text{loc}}\right] = 0$$

  - linear → single Newton-Raphson iteration $\bar{\boldsymbol{d}}_n^h = \boldsymbol{M}^{-1} \cdot \boldsymbol{R}_d$

→ gradient-enhancement by post-processing scheme



Numerical implementation III

- nonlinear damage evolution using midpoint rule
  - quadratic accuracy
  - suitable for implicit time integration with larger steps
  - exact for damage exponent $n_d = 2$ with constant damage parameters

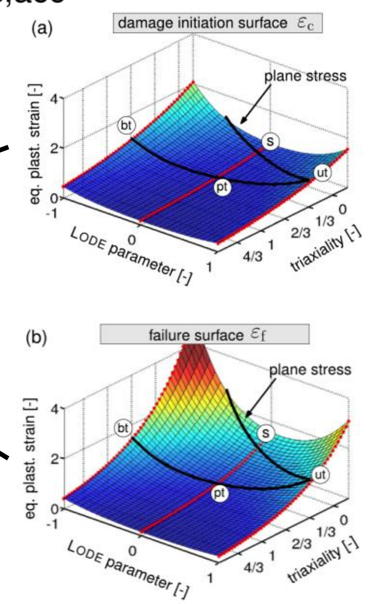
$$\Delta d^{\text{loc}} = \frac{n_d}{\left[\varepsilon^{\text{p}}_{\text{fail}} - \varepsilon^{\text{p}}_{\text{init}}\right]^{n_d}} \left[H^{\text{p,acc}}_n + 0.5\Delta H^{\text{p,acc}} - \varepsilon^{\text{p}}_{\text{init}}\right]^{n_d - 1} \Delta H^{\text{p,acc}}$$

with $H^{\text{p,acc}}$: undmg. acc. plastic strain

$\varepsilon^{\text{p}}_{\text{init}}$: plastic strain at damage initation

$\varepsilon^{\text{p}}_{\text{fail}}$: plastic strain at failure

n_d: damage exponent, e. g. =2



Nahrmann&Matzenmiller, 2021

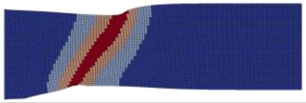
- Implementation
  - tensor-based→ tensor toolbox for Fortran (ttb)
  - modular implementation

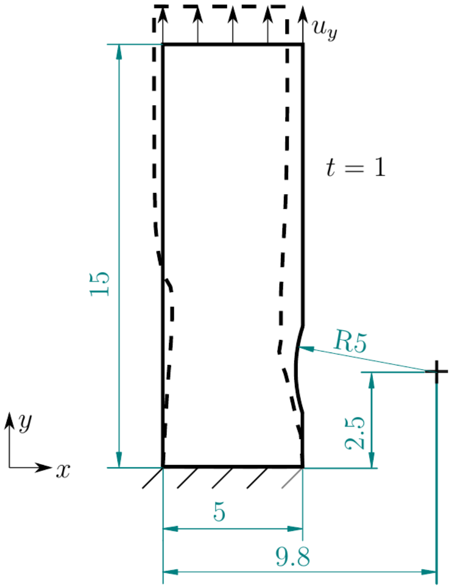
→ GitHub-user: jfriedlein

ttb.F Tensor Toolbox for Fortran

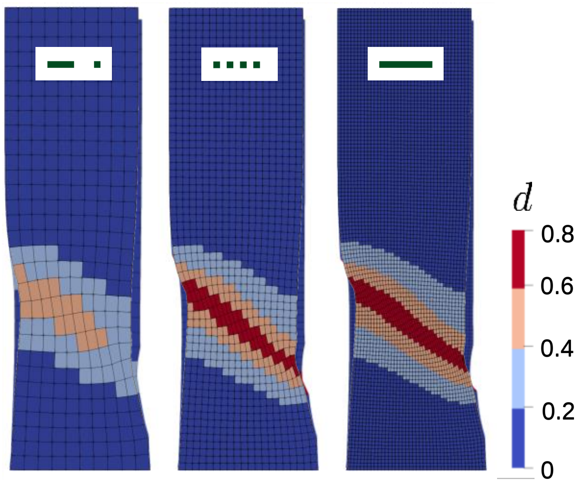
https://adtzlr.github.io/ttb/

Shear band specimen

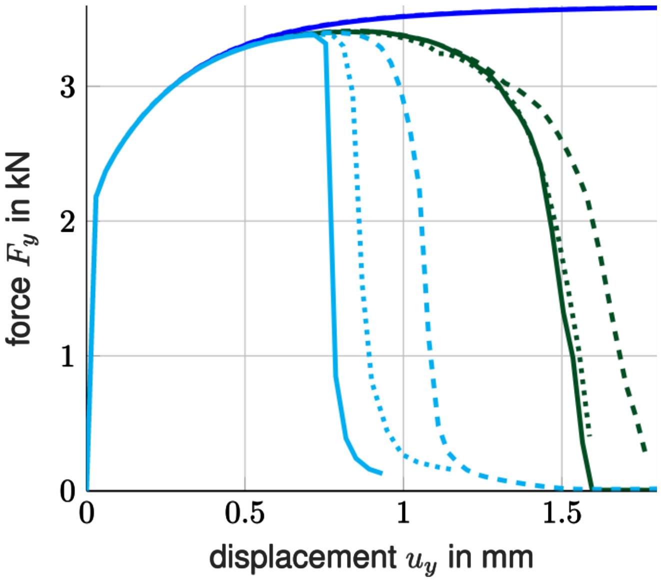




Seupel et al., 2018



gradient-enhanced model (green)
local model (cyan)



	gradient-damage
l/mm	1

pure plasticity
steel HCT590X
(identified from tensile tests)

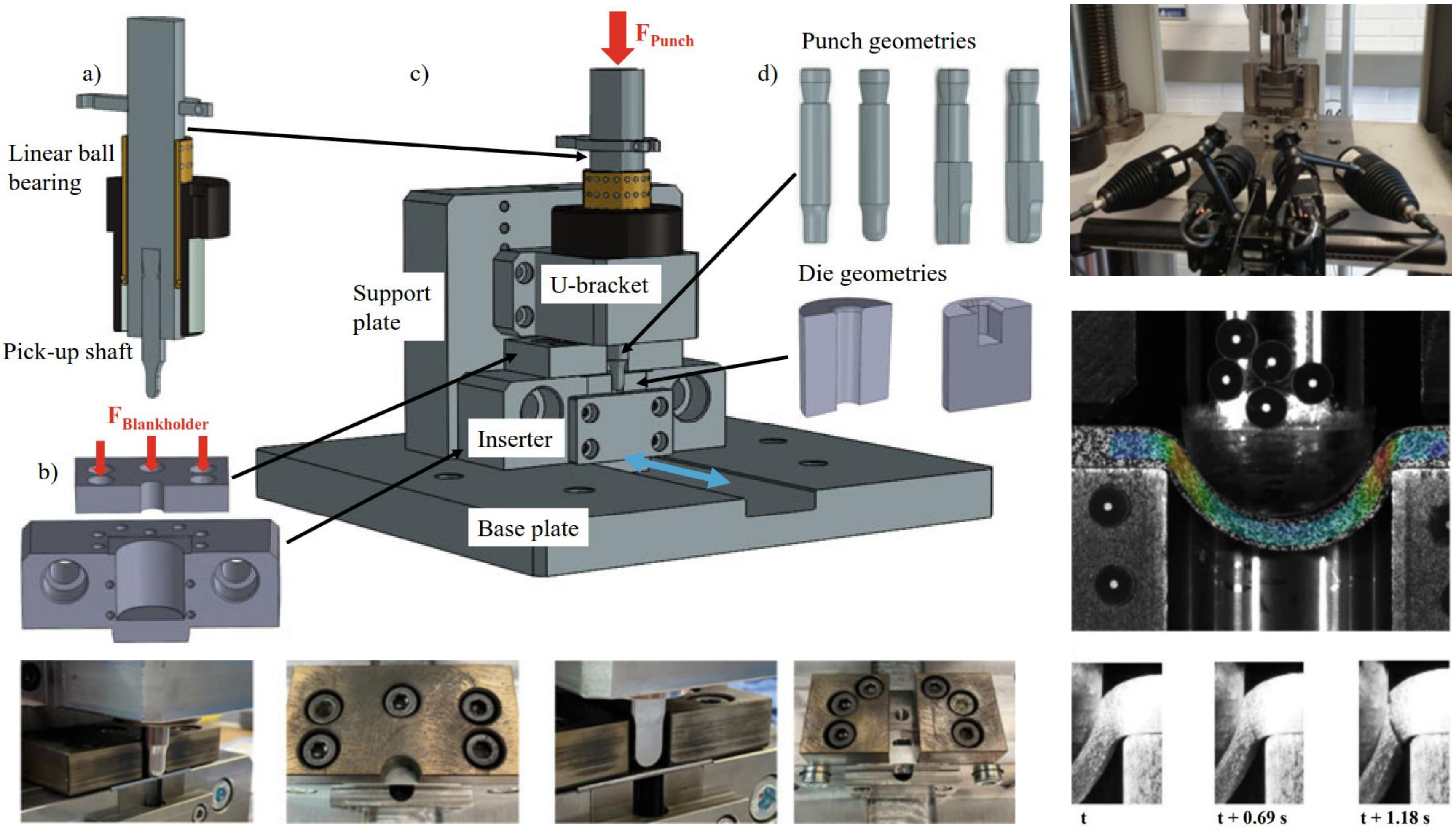
Friedlein et al., 2021 (IDDRG21)

$$d^{\text{loc}} = \left[\frac{H^{\text{p,acc}} - 0.01}{0.4 - 0.01}\right]^2$$

coarse mesh
medium mesh
fine mesh

comparison of local plasticity-damage and plasticity – gradient-damage on plane strain example

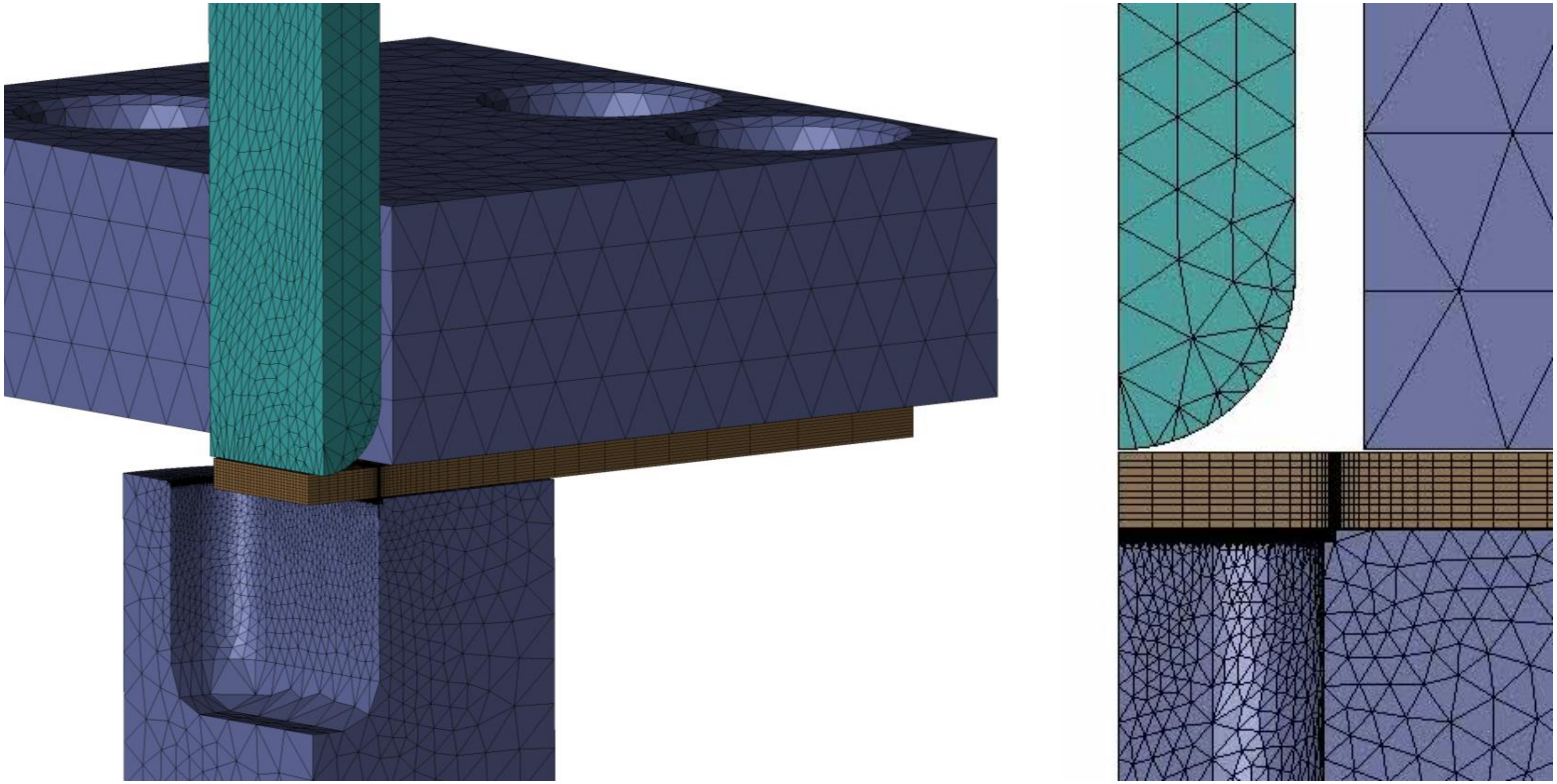
Modified punch test I



Böhnke et al. 2022 (NUMISHEET22

experimental setup of the modified punch test

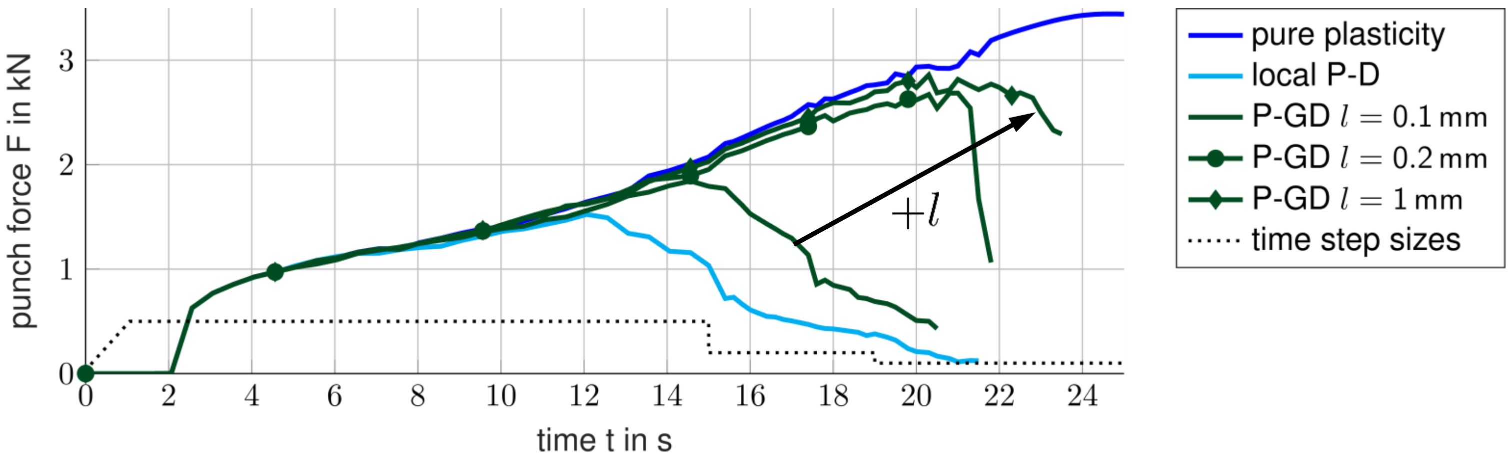
Modified punch test II

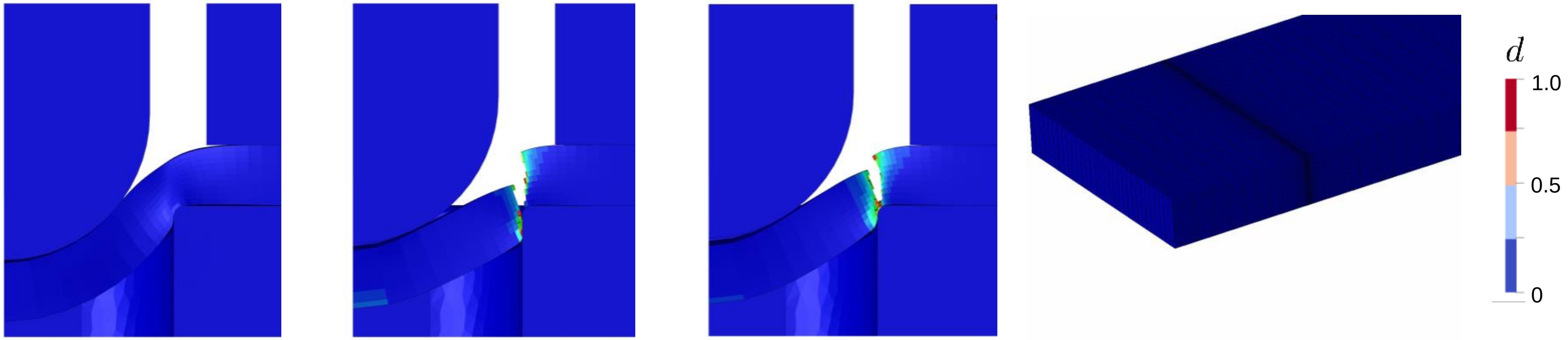


aluminium EN AW-6014 T4; sheet thickness 2 mm

numerical setup of the modified punch test with a prismatic round punch

Modified punch test III





pure plasticity local P-D plasticity – gradient-damage $l = 0.1\,\mathrm{mm}$

numerical results for the modified punch test with a prismatic round punch

State and challenges: Gradient-enhancement of ductile damage

Solution strategy

- monolithic
  - fully coupled
  - accurate
  - unlimited time steps
  - unsym. stiffness
  - usu. need for UEL

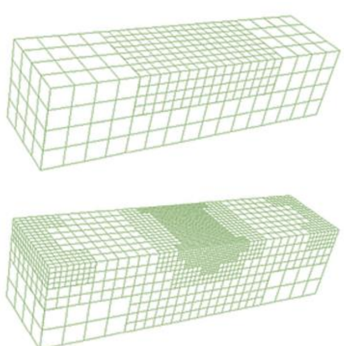
Kiefer et al. 2018
Brepols et al. 2020

- weakly staggered
  - approximate
  - limited time steps
  - efficient
  - flexible
  - existing solvers
  - existing ELFORMs

→ possibility for post-processing scheme freeing thermal solver

Mesh

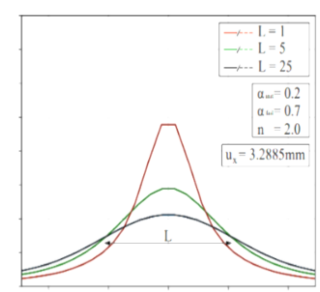
- regularisation requires fine mesh
- calls for mesh adaptivity
- regularisation copes well with changing mesh size
- gradient-enhancement can improve damage history transfer by inverse mapping



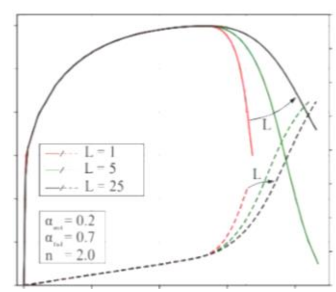
Parameter identification

- internal length
  - how to separate effects?
- challenging couplings
  - damage affects plasticity
  - damage affects stress state
  - gradient-damage affects local damage evolution
  - how to use existing strategies without inverse FEM?
- regularisation of alternative variables

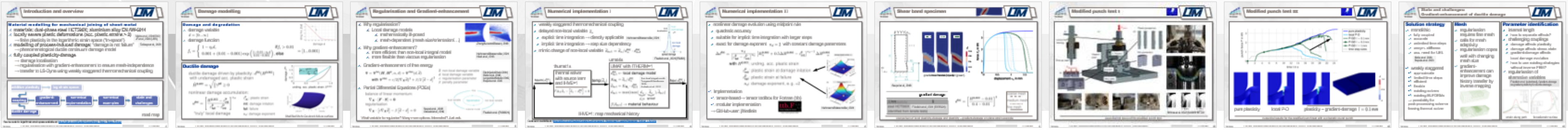
Friedlein et al. (submitted), Gradient-damage vs gradient-plasticity for ductile damage.



strain along path



force&strain vs time



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Thank you for your attention!

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