Calibration of ductile damage model based on one single test

Steven Cooreman
ArcelorMittal Global R&D Gent / OCAS NV

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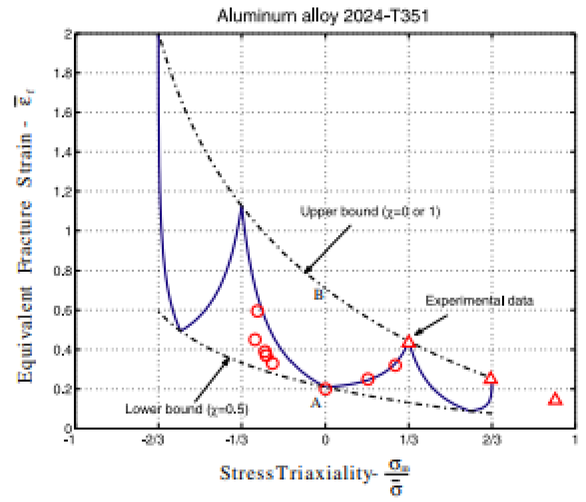
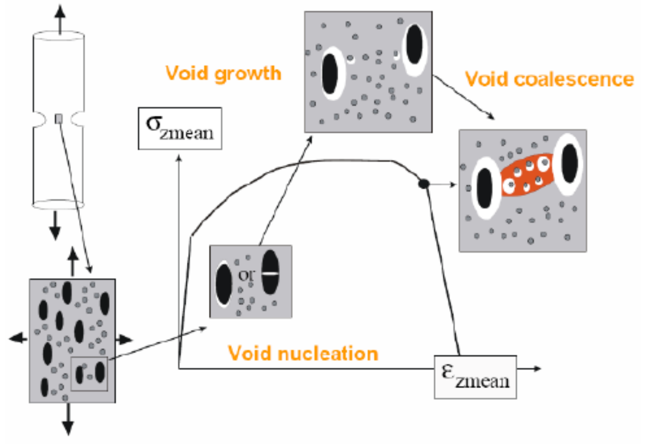
Prediction of ductile damage initiation and accumulation

- Ductile damage in metals:
  - Dependent on stress triaxiality (η) and Lode angle ($\bar{\theta}$)

- Prediction of ductile damage in FEA:
  - Porous metal plasticity models
    - Micromechanically informed
    - Process of void nucleation, growth and coalescence
    - e.g. GTN (Gurson-Tvergaard-Needleman)
  - Continuum damage mechanics models
    - Scalar damage variable *D*
    - e.g. Lemaitre damage model, Modified Bai-Wierzbicki model



From [1]



From [2]

[1] L. Xue, *Damage accumulation and fracture initiation in uncracked ductile solids subject to triaxial loading*, International Journal of Solids and Structures, Vol. 44, 2007, pp. 5163-5181
[2] D. Lassance , F. Scheyvaerts and T. Pardoen, *Growth and coalescence of penny-shaped voids in metallic alloys*, Engineering Fracture Mechanics, Vol. 73, 2006, pp. 1009-1035

Modified Bai-Wierzbicki ductile damage model

- Modified Bai-Wierzbicki model for ductile damage
  - Proposed by prof. T. Wierzbicki and co-workers [3] and further developed by prof. S. Münstermann and co-workers [4, 5]
  - Ductile damage initiates if I_{ddi} reaches 1.

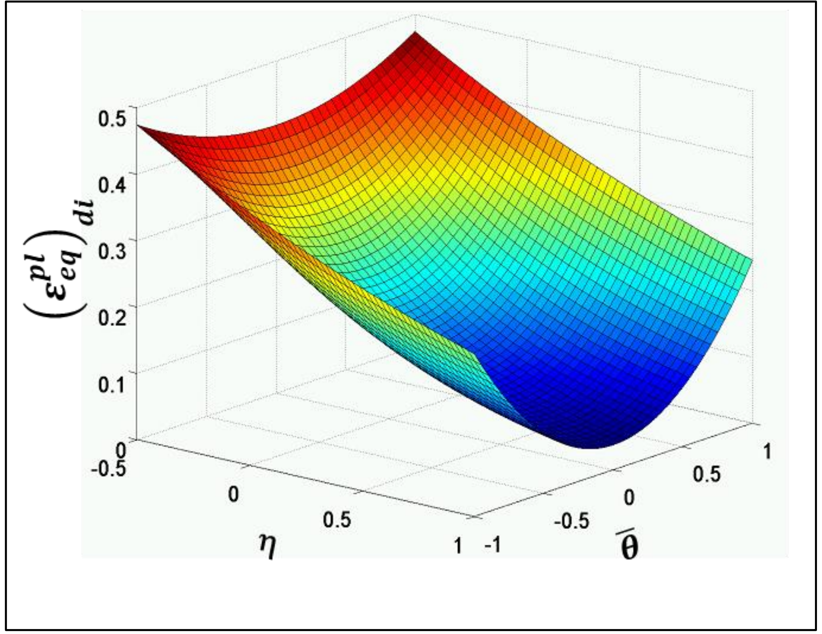
$$I_{ddi} = \sum_{i=0}^{n} \frac{\left(\Delta\varepsilon_{eq}^{pl}\right)_i}{\left(\varepsilon_{eq}^{pl}\right)_{ddi}(\eta_i,\bar{\theta}_i)} \quad \text{with } \left(\varepsilon_{eq}^{pl}\right)_{ddi}(\eta,\bar{\theta}) = \left[D_1 \cdot e^{-D_2\cdot\eta} - D_3 \cdot e^{-D_4\cdot\eta}\right]\cdot\bar{\theta}^2 + D_3 \cdot e^{-D_4\cdot\eta}$$

  - Ductile failure occurs if I_{df} reaches 1.

$$I_{df} = \sum_{i=n_{ddi}}^{n} \frac{\left(\Delta\varepsilon_{eq}^{pl}\right)_i}{\left(\varepsilon_{eq}^{pl}\right)_{df}(\eta_i,\bar{\theta}_i)} \quad \text{with } \left(\varepsilon_{eq}^{pl}\right)_{df}(\eta,\bar{\theta}) = \left[F_1 \cdot e^{-F_2\cdot\eta} - F_3 \cdot e^{-F_4\cdot\eta}\right]\cdot\bar{\theta}^2 + F_3 \cdot e^{-F_4\cdot\eta}$$

  - Evolution of scalar damage variable D

$$(\Delta D)_i = \frac{(\sigma_{eq})_{ddi}}{G_f}\left(\left(\varepsilon_{eq}^{pl}\right)_{df}(\eta_i,\bar{\theta}_i) - \left(\varepsilon_{eq}^{pl}\right)_{ddi}(\eta_i,\bar{\theta}_i)\right)\frac{\left(\Delta\varepsilon_{eq}^{pl}\right)_i}{\left(\varepsilon_{eq}^{pl}\right)_{df}(\eta_i,\bar{\theta}_i)}$$

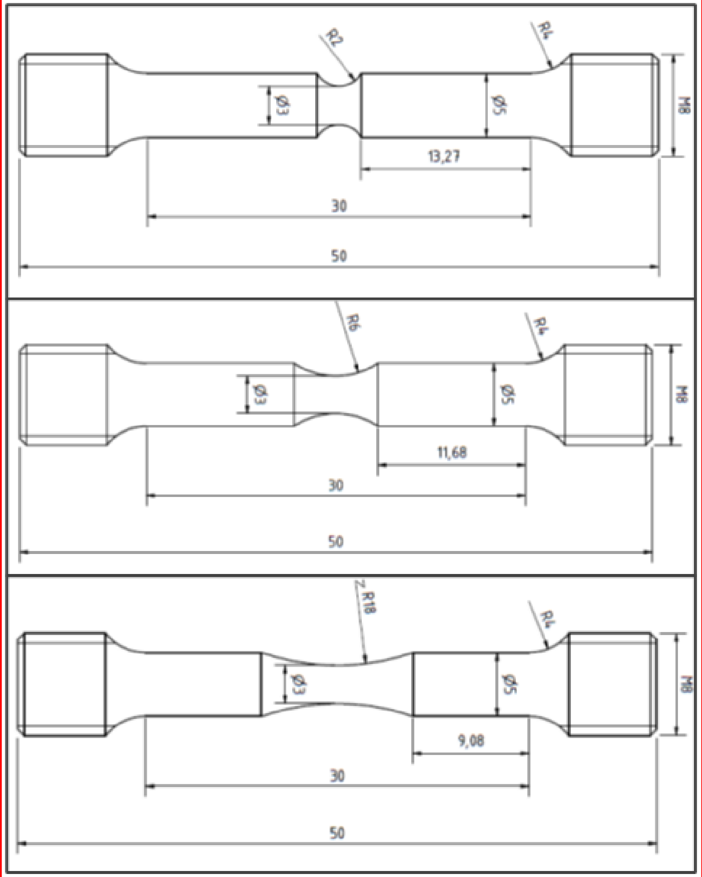


[3] Y. Bai and . Wierzbicki, *A new model of metal plasticity and fracture with pressure and Lode dependence*, International Journal of Plasticity, Vol. 24 (6), 2008, pp. 1071-1096
[4] J. Lian, M. Sharaf, F. Archie and S. Münstermann, A hybrid approach for modelling of plasticity and failure behaviour of advanced high-strength steel sheets, International Journal of Damage Mechanics, Vol. 22 (2), 2013, pp. 188-218
[5] F. Pütz, F. Shen, M. Könemann and S. Münstermann, *The differences of damage initiation and accumulation of DP steels: a numerical and experimental analysis*, International Journal of Fracture, Vol. 226, 2020, pp. 1-15

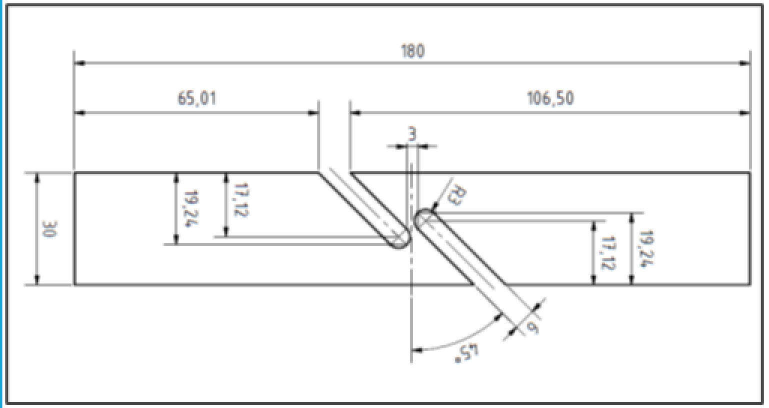
Default calibration procedure

- Extensive set of mechanical tests, generating different $(\eta, \bar{\theta})$ combinations

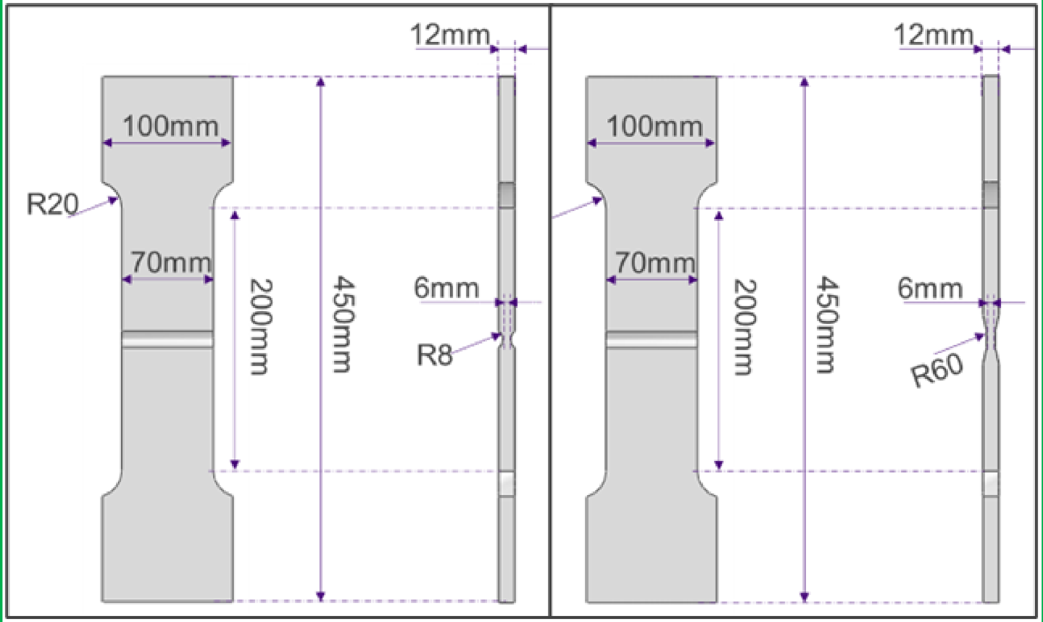
Notched round bar samples



In-plane shear sample



Notched plane strain samples



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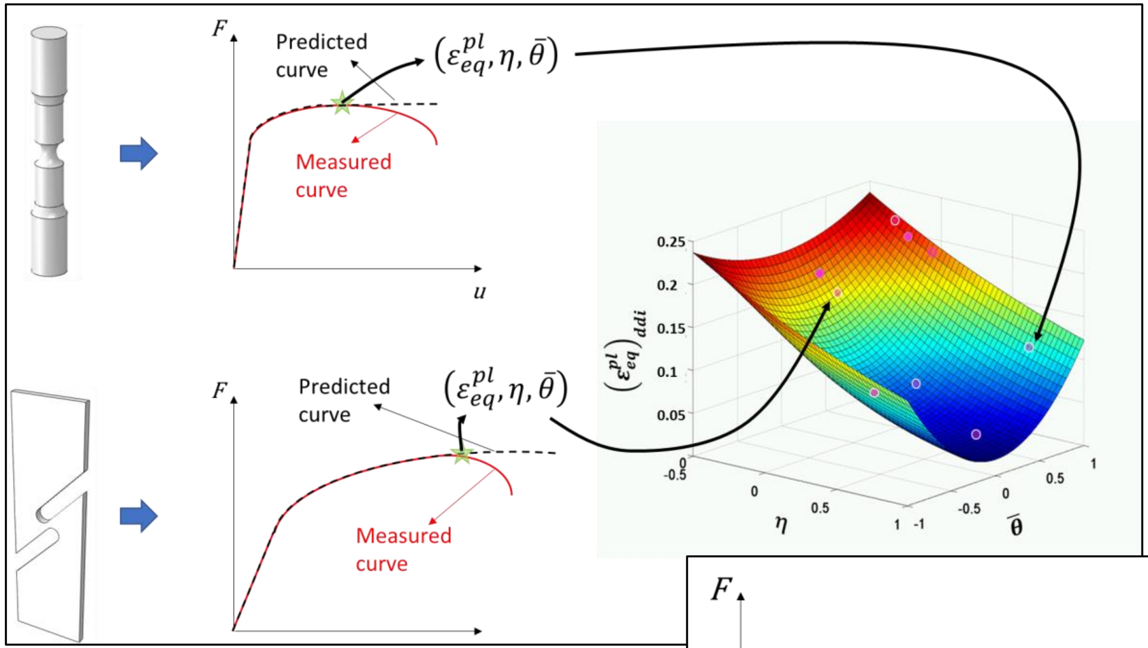
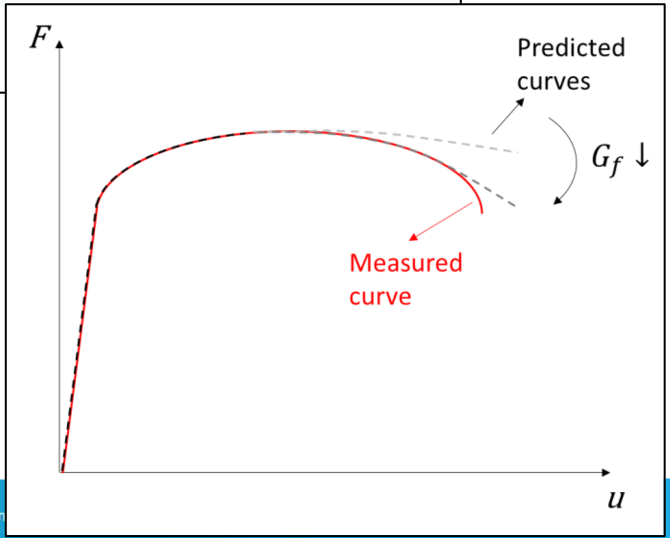
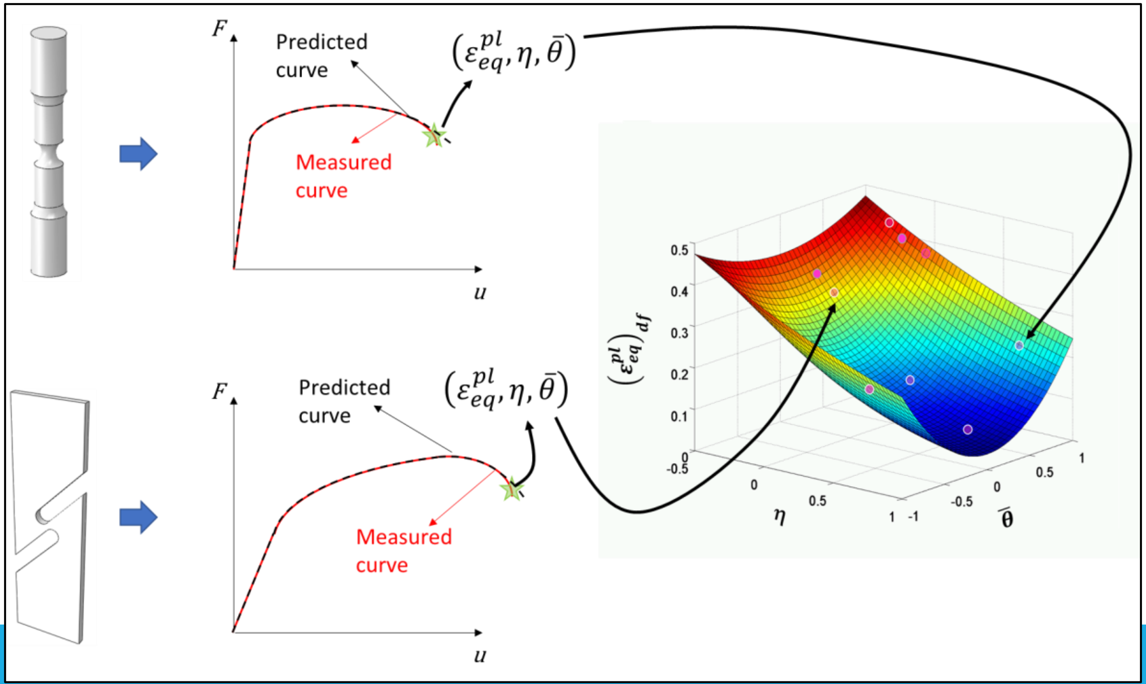
Default calibration procedure

- Extensive set of mechanical tests, generating different $(\eta, \bar{\theta})$ combinations







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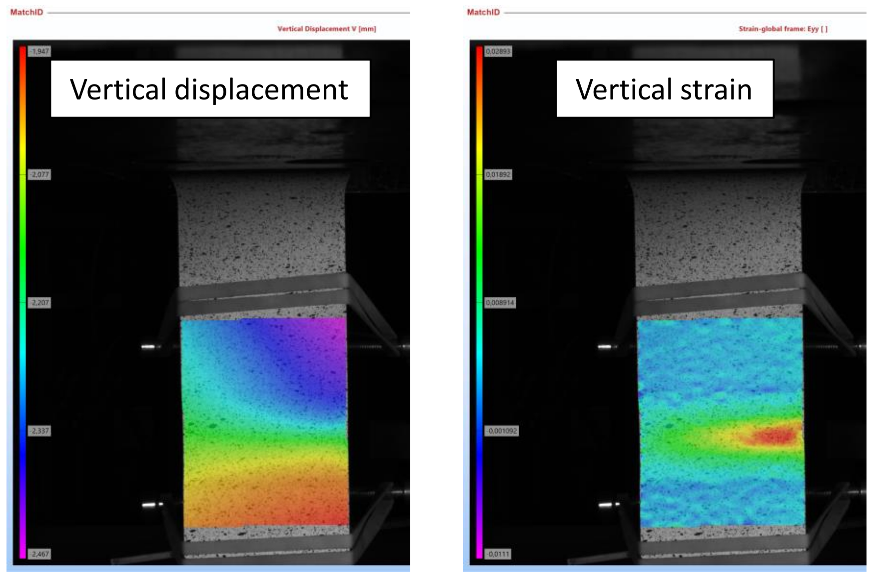
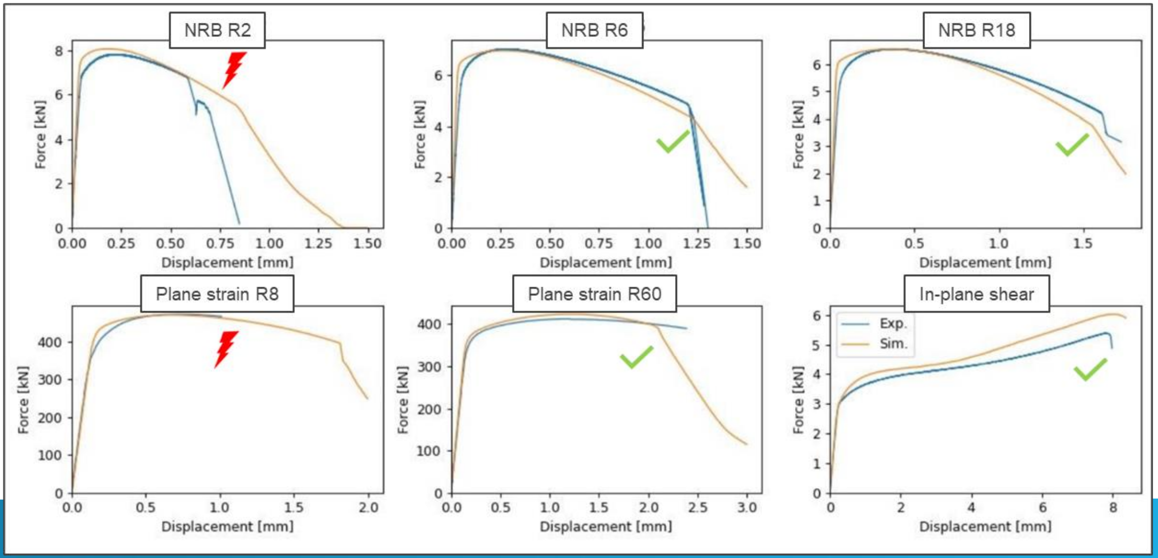
Default calibration procedure

- Challenges / shortcomings / disadvantages
  - When does damage initiate?
    - Only one point $((\varepsilon_{eq}^{pl})_{ddi}(\eta, \bar{\theta}))$ is considered.
  - Boundary conditions?
  - Effect of order in which parameters are calibrated.
    - Post-necking hardening behaviour?
  - Extensive manual intervention
  - User dependent (visual evaluation, no cost function minimization)

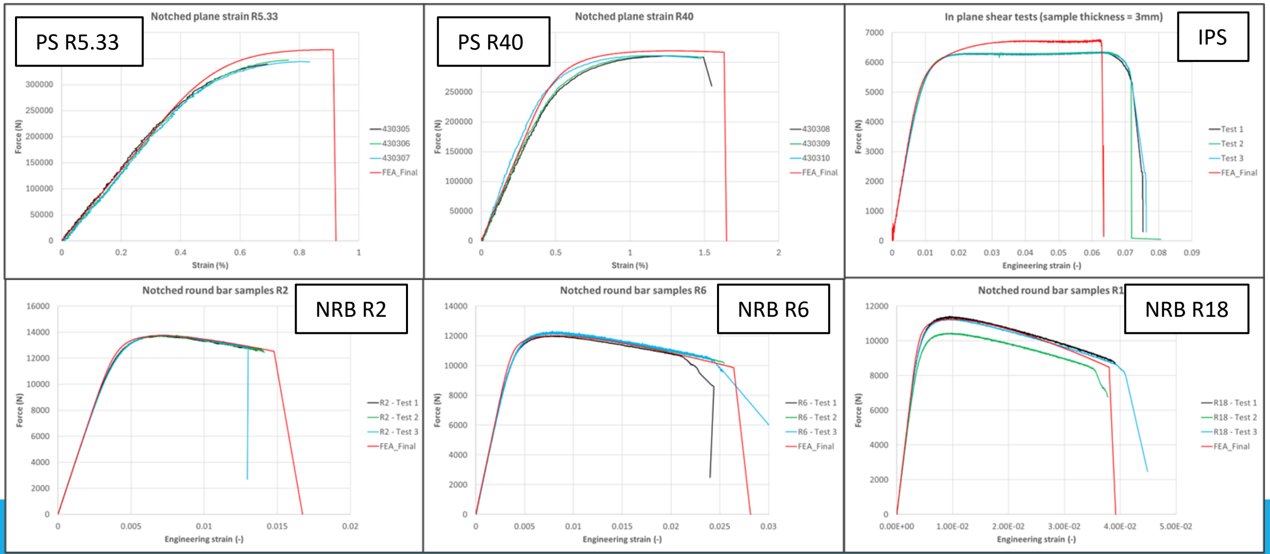
Plane strain sample – Effect of boundary condition



S700 – 12mm

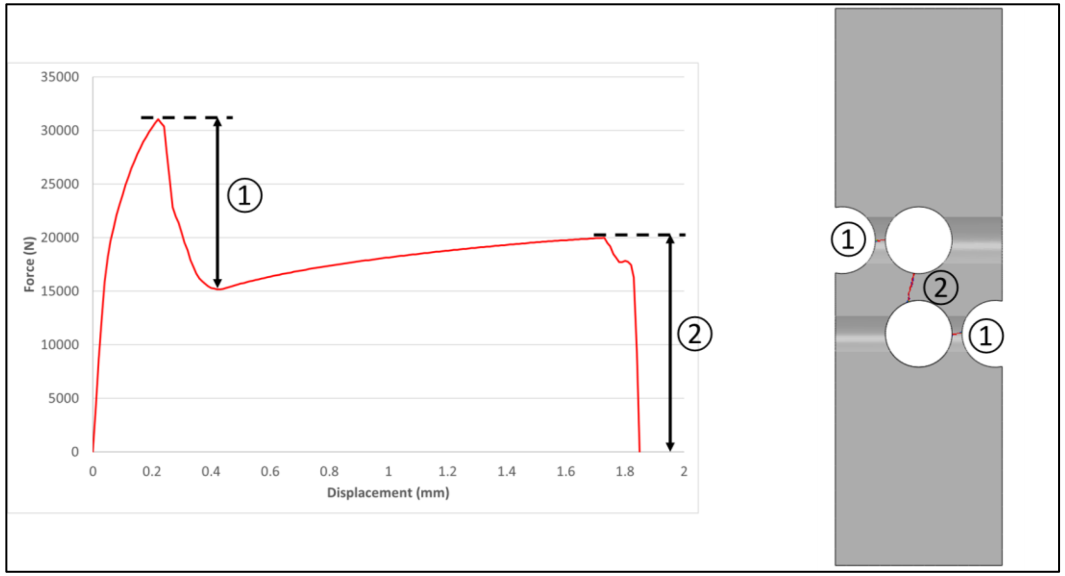


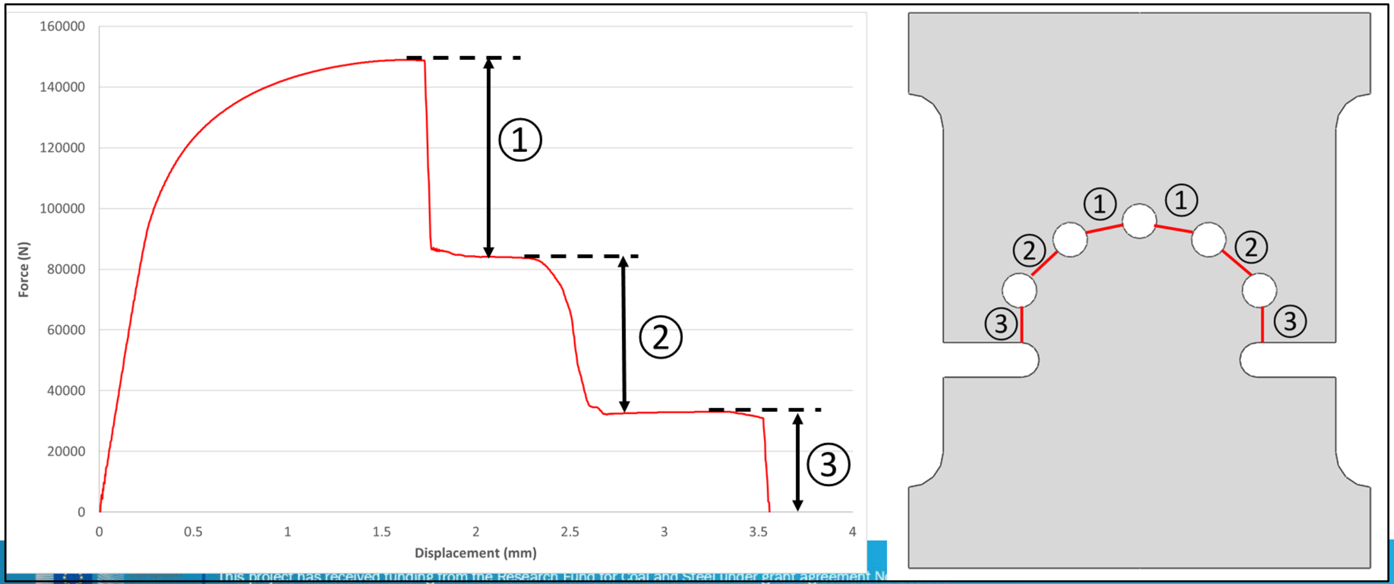
Relia 450 – 8mm

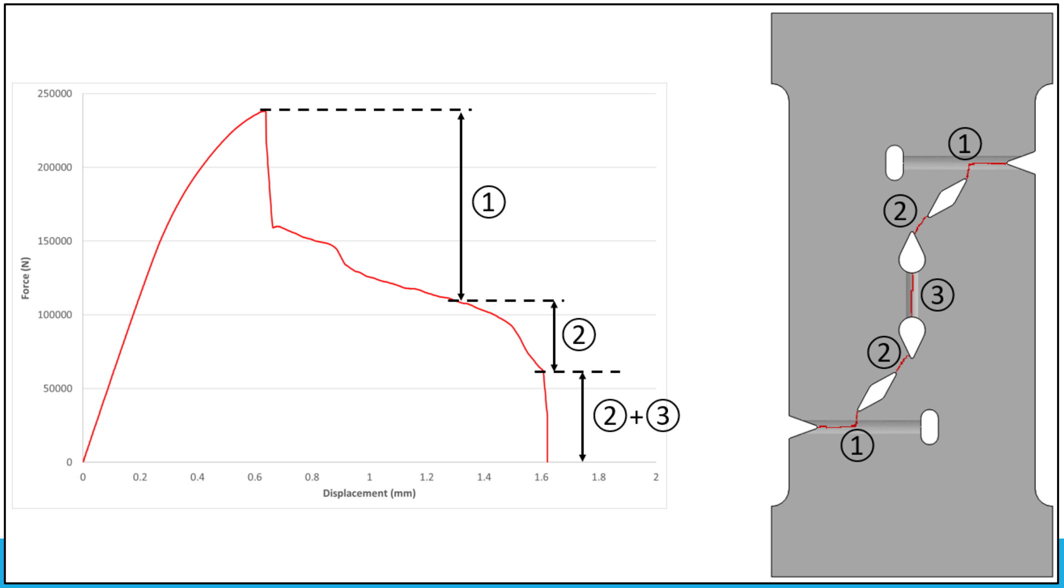


FEMU methodology

- Development of FEMU methodology for calibration of ductile damage model
  - Specimen design:
    - Wide range of stress triaxiality and Lode angle values
    - Testing on uni-axial tensile bench
    - Machinability







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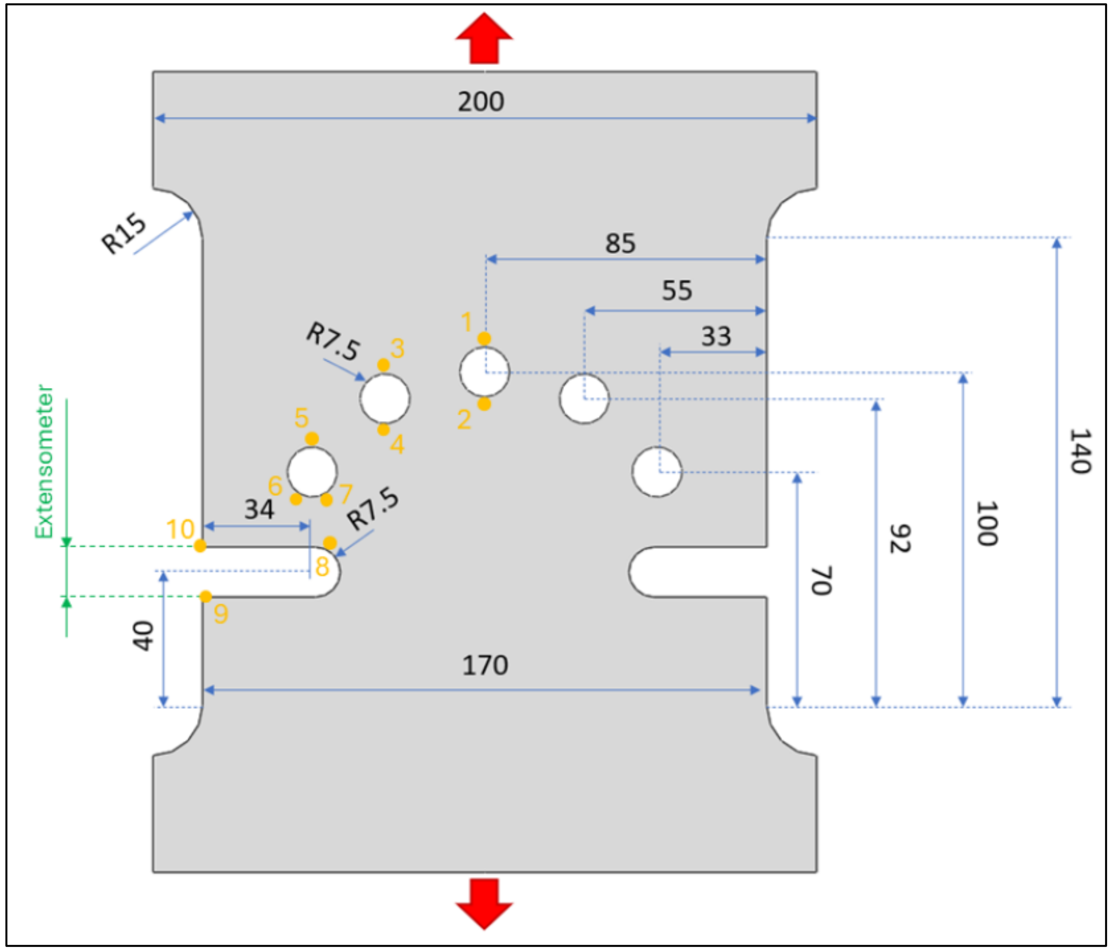
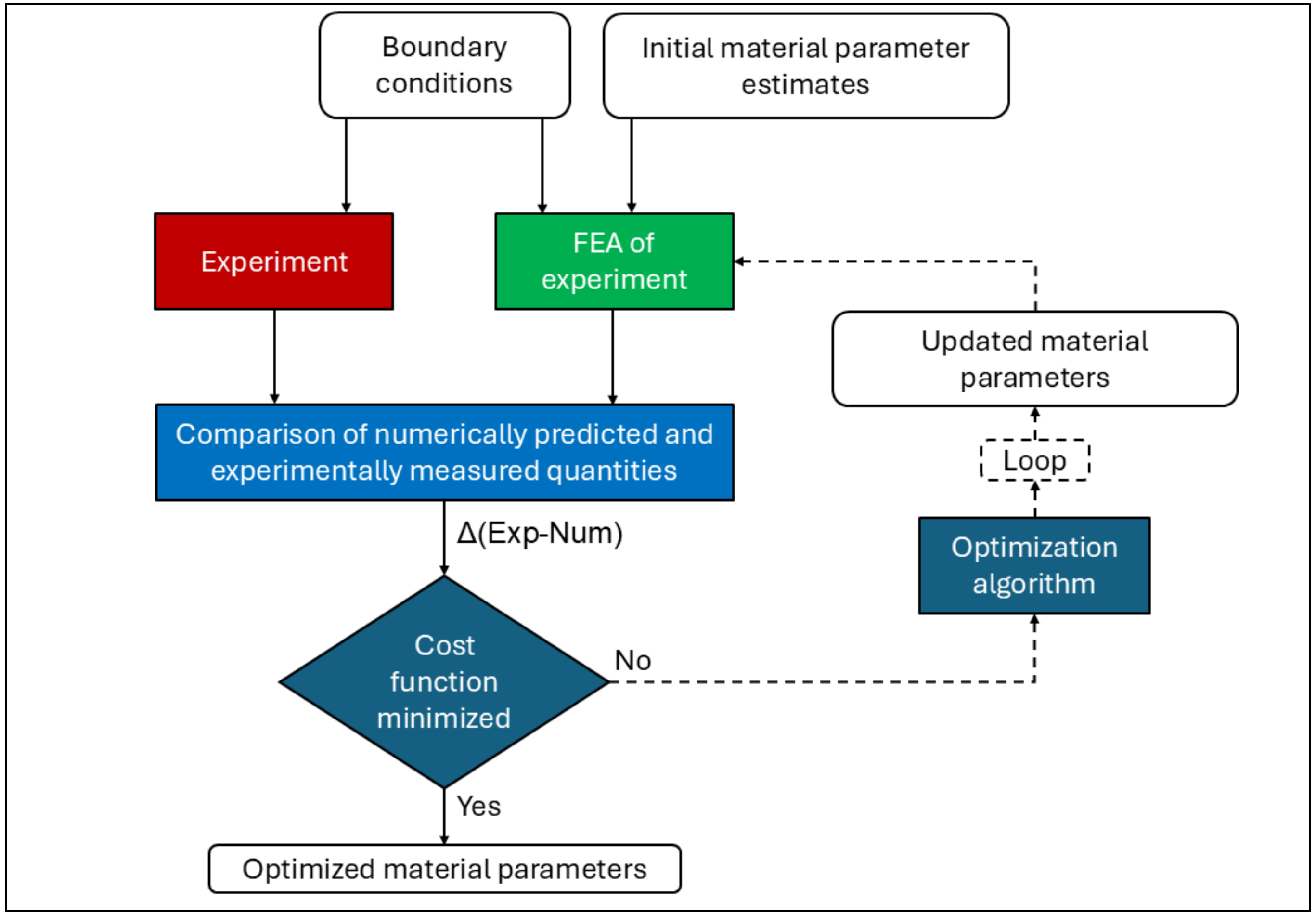
FEMU methodology

- Numerical validation





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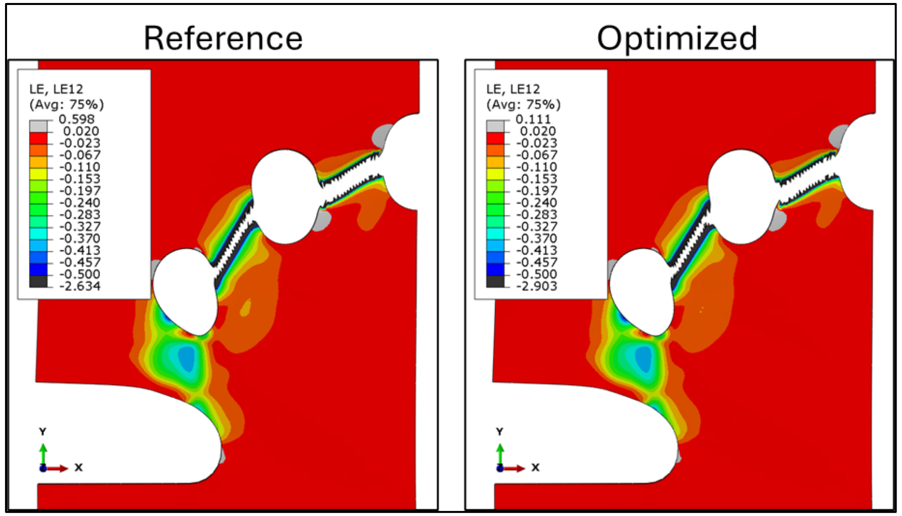
FEMU methodology

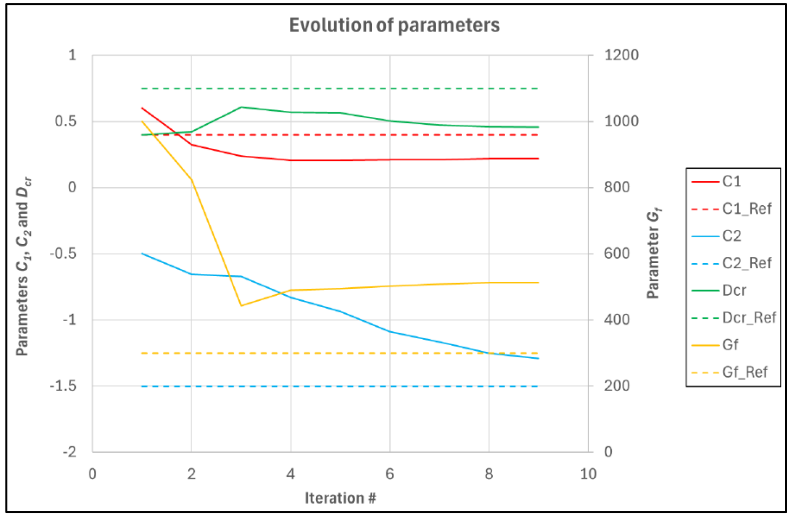
- Numerical validation
  - Constitutive model
    - Isotropic hardening
    - Ductile damage

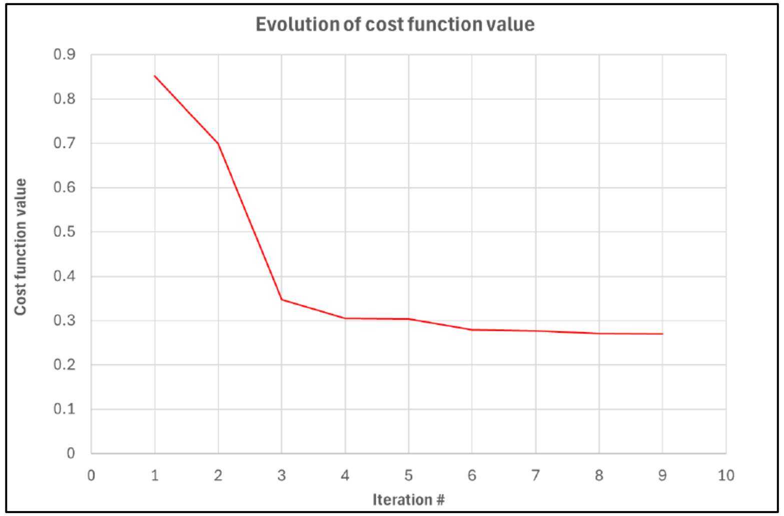
$$I_{ddi} = \int_0^{\varepsilon_{eq}^{pl}} \frac{d\varepsilon_{eq}^{pl}}{\left(\varepsilon_{eq}^{pl}\right)_{ddi}\left(\eta, \dot{\varepsilon}_{eq}^{pl}\right)} = 1$$

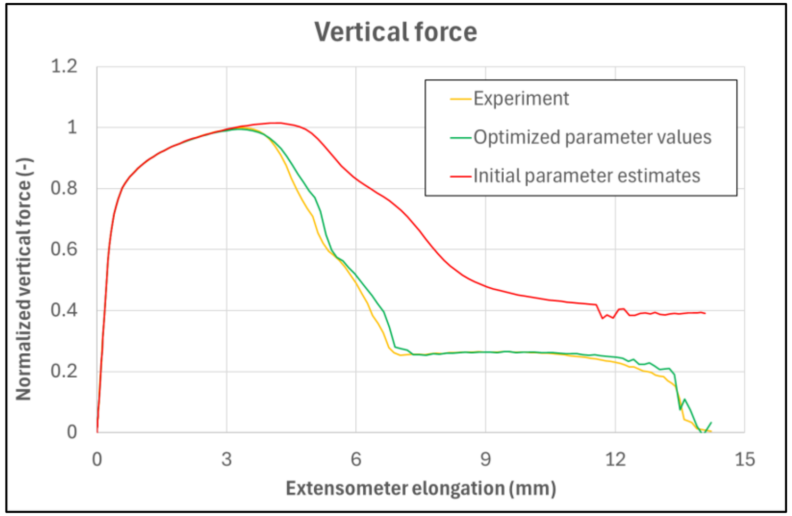
$$\left(\varepsilon_{eq}^{pl}\right)_{ddi}(\eta) = C_1 \cdot e^{C_2 \cdot \eta}$$

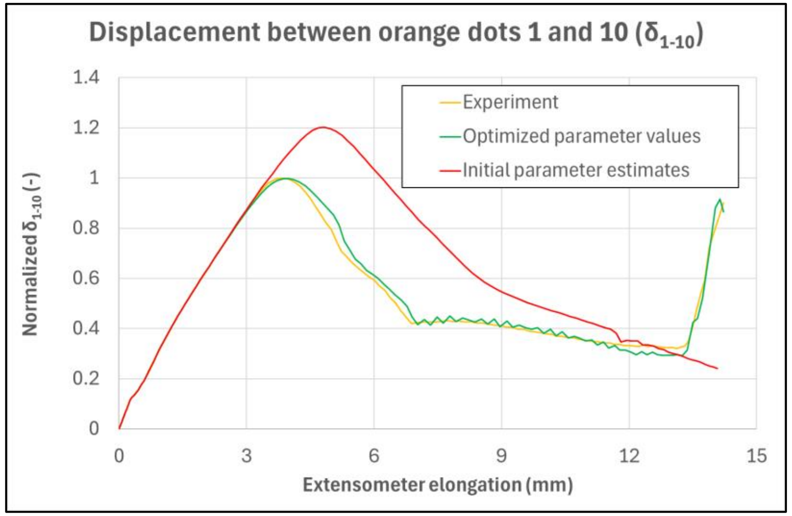
$$\dot{D} = \frac{L \cdot \dot{\varepsilon}_{eq}^{pl}}{\frac{2 \cdot G_f}{\sigma_{eq}^0}}$$











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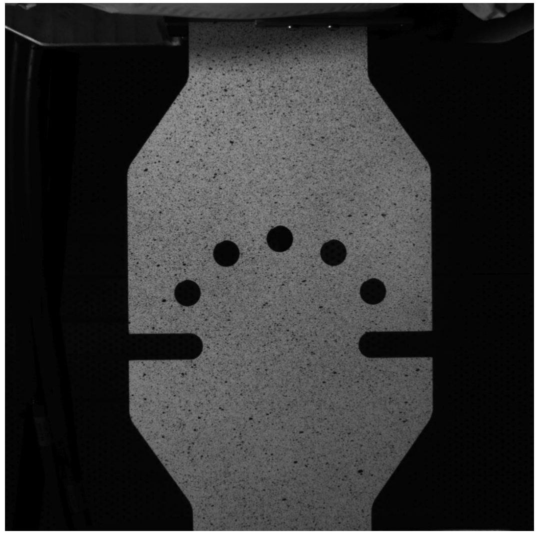
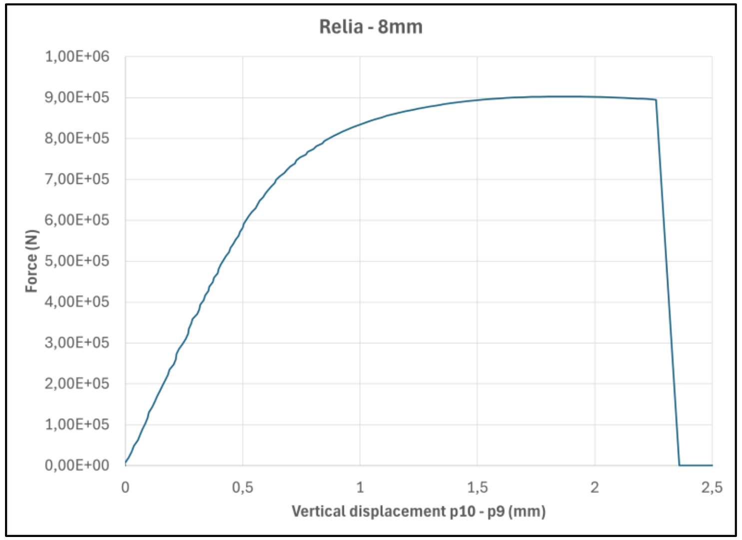
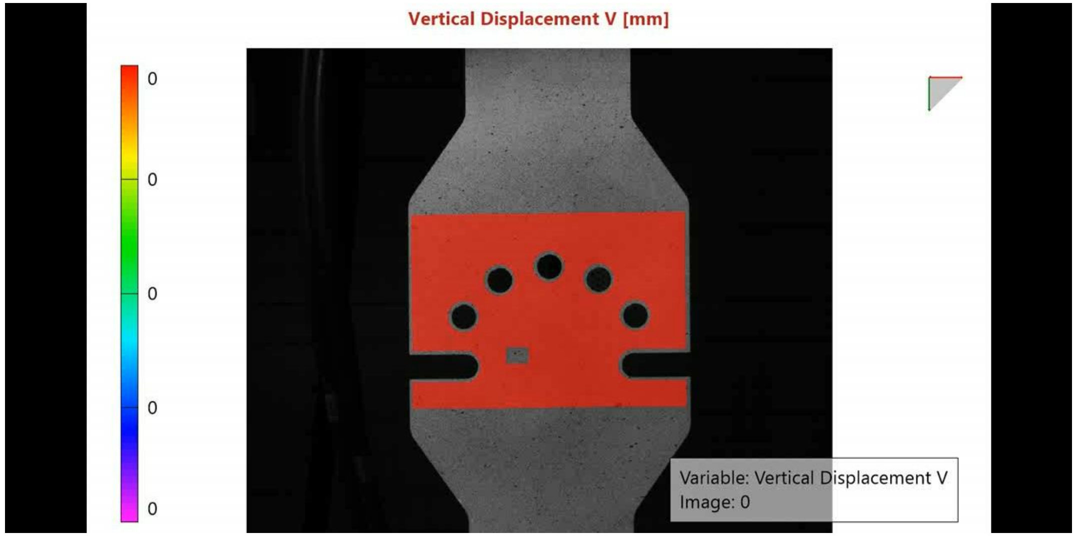
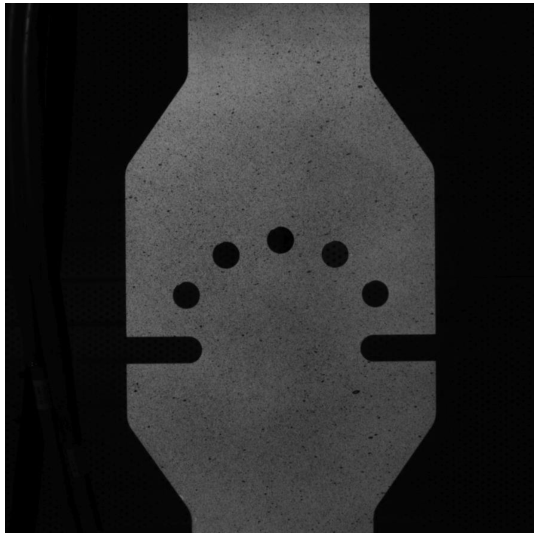
FEMU methodology

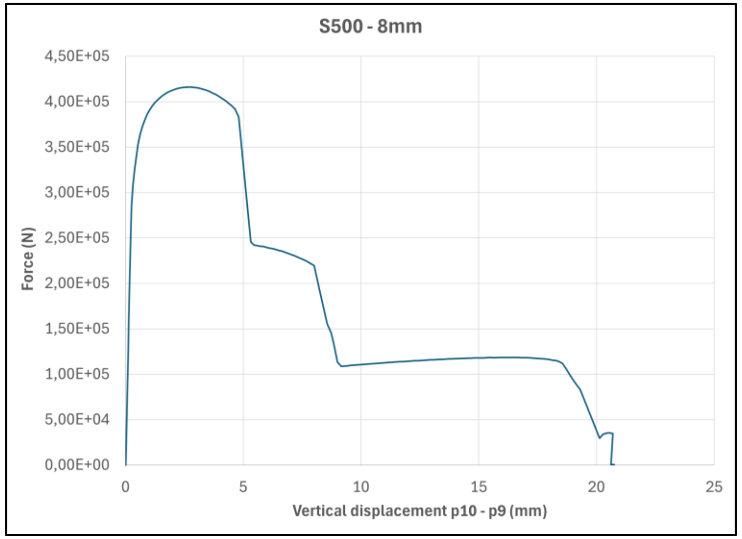
- Experimental work – ongoing
  - 8mm S500
  - 12mm S700
  - 8mm Relia 450











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FEMU methodology

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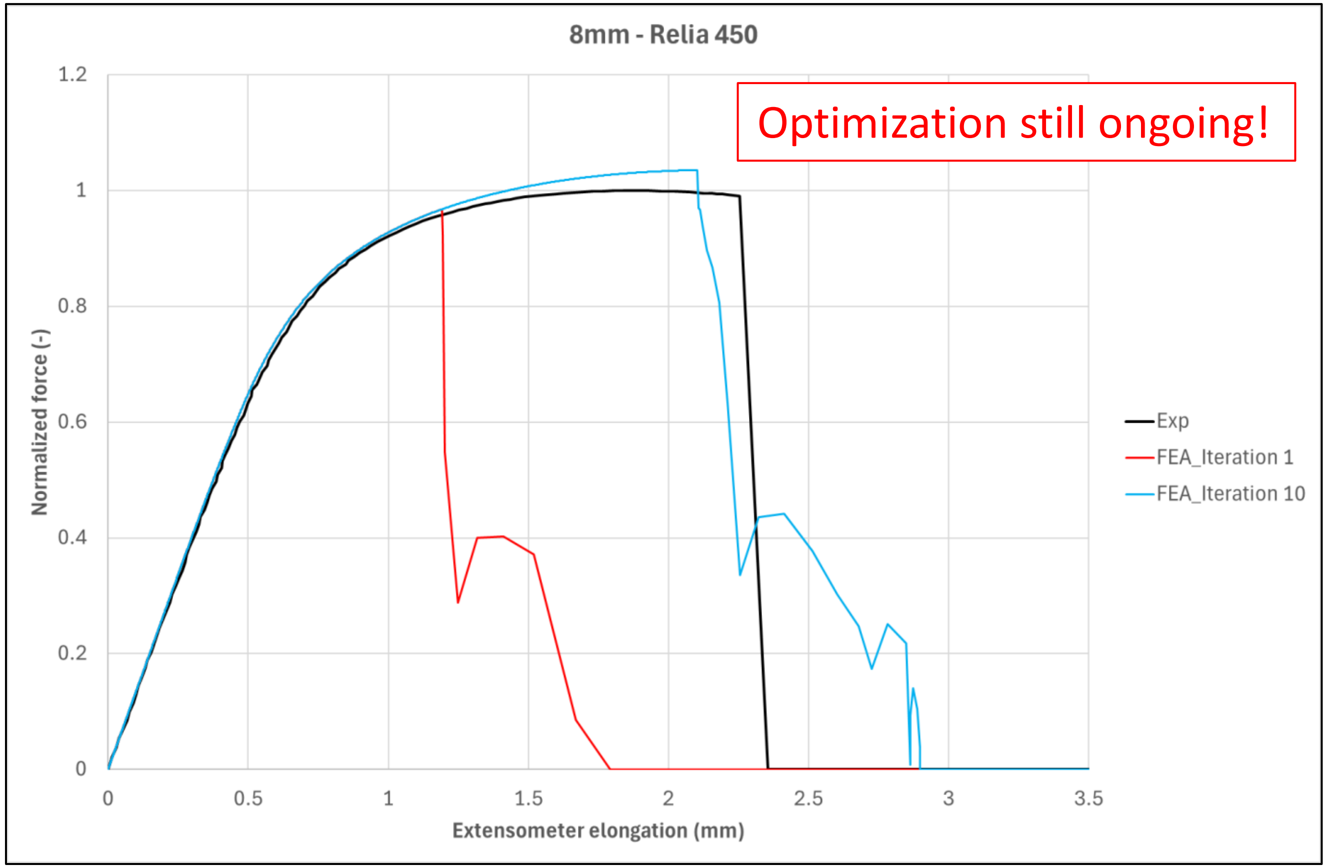
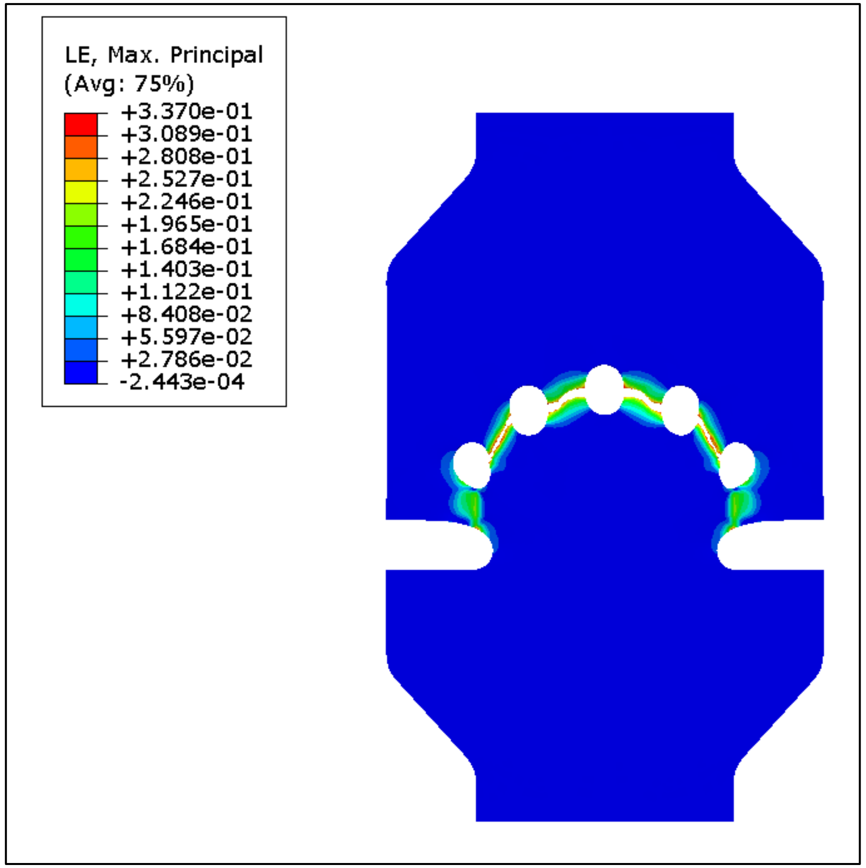
  - 8mm Relia 450





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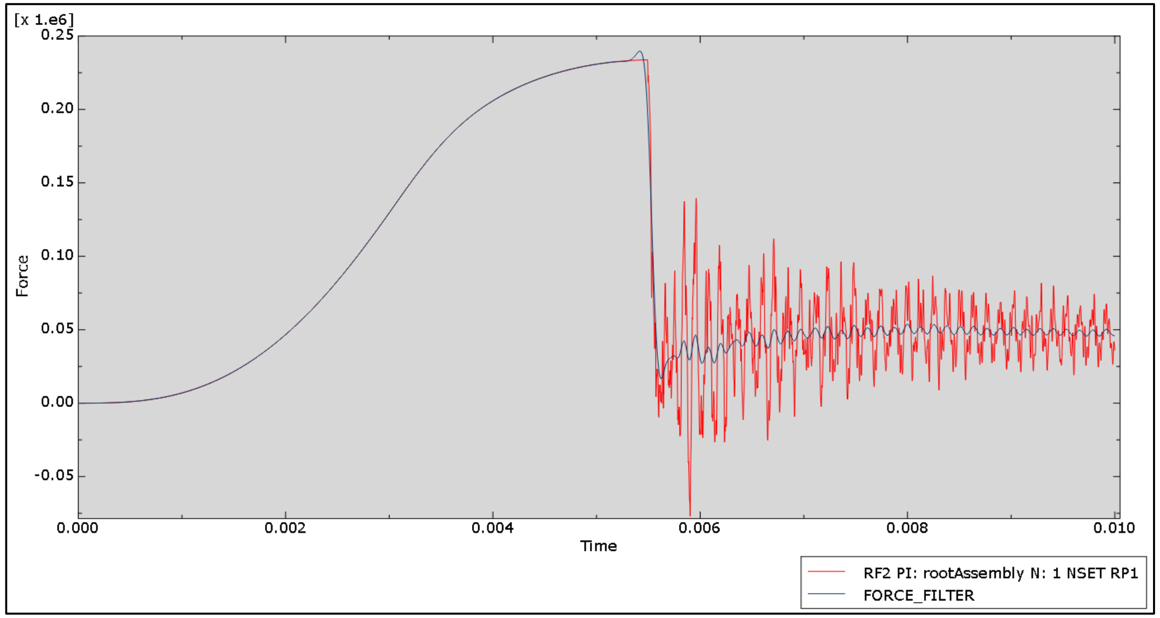
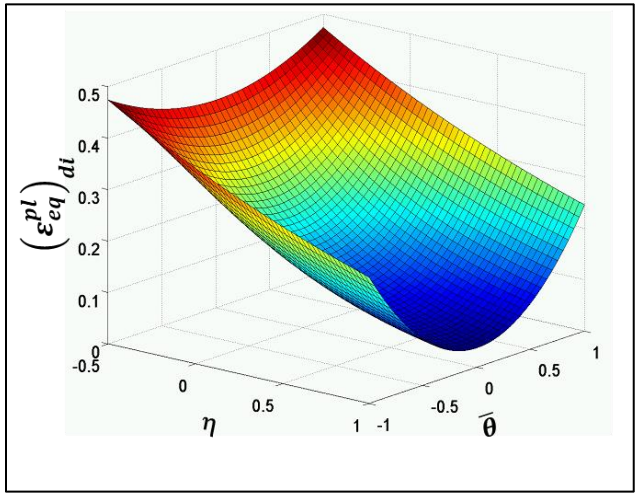
FEMU methodology

- Challenges
  - Gradient based optimization algorithm
    - Initial parameter estimates?
    - Local or global minimum?
    - Parameter sensitivity
      - To be studied beforehand.
      - Final failure is a discrete process.
  - Formulation of cost function
    - Consider more or other quantities?
  - FE model
    - Explicit simulation → How to deal with noise?
    - Should machine stiffness be considered?
  - How to guarantee convex damage initiation and failure loci?
    - Cannot be imposed by means of linear parameter constraints.
    - Reformulate damage model?





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