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Influence of the Characteristics of the 3D FE Mesh on the Evolution of Variables Used to Characterize the Stress State

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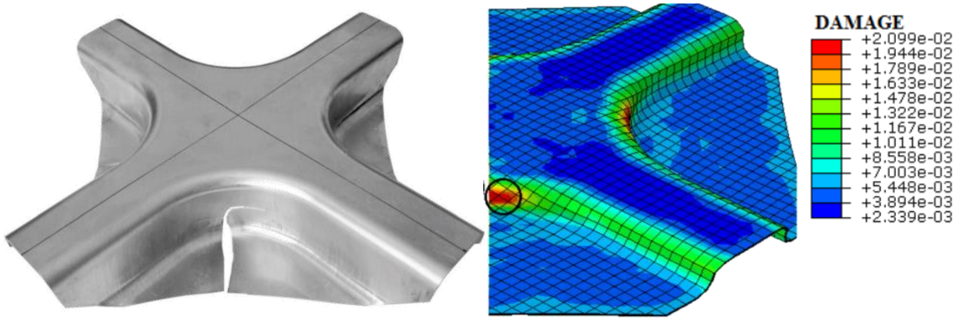
Prediction of ductile fracture in metallic material

- Increase usage of new materials with higher strength-to-weight ratio, e.g. AHSS.
  - Allows to produce lighter structures and components, while maintaining satisfactory strength and stiffness, which results in a reduction of the overall structure mass, a crucial step to meet the ever-stringent standards on passenger safety and gas emissions.
  - The increased mechanical strength of steels is usually accompanied by a reduction of their ductility. This phenomenon, complemented by the higher work hardening of AHSS, reduces the formability and crashworthiness of the components.

- It is of the utmost interest the development of reliable numerical tools that accurately describe internal damaging and failure of ductile materials, either by necking onset or premature ductile fracture.

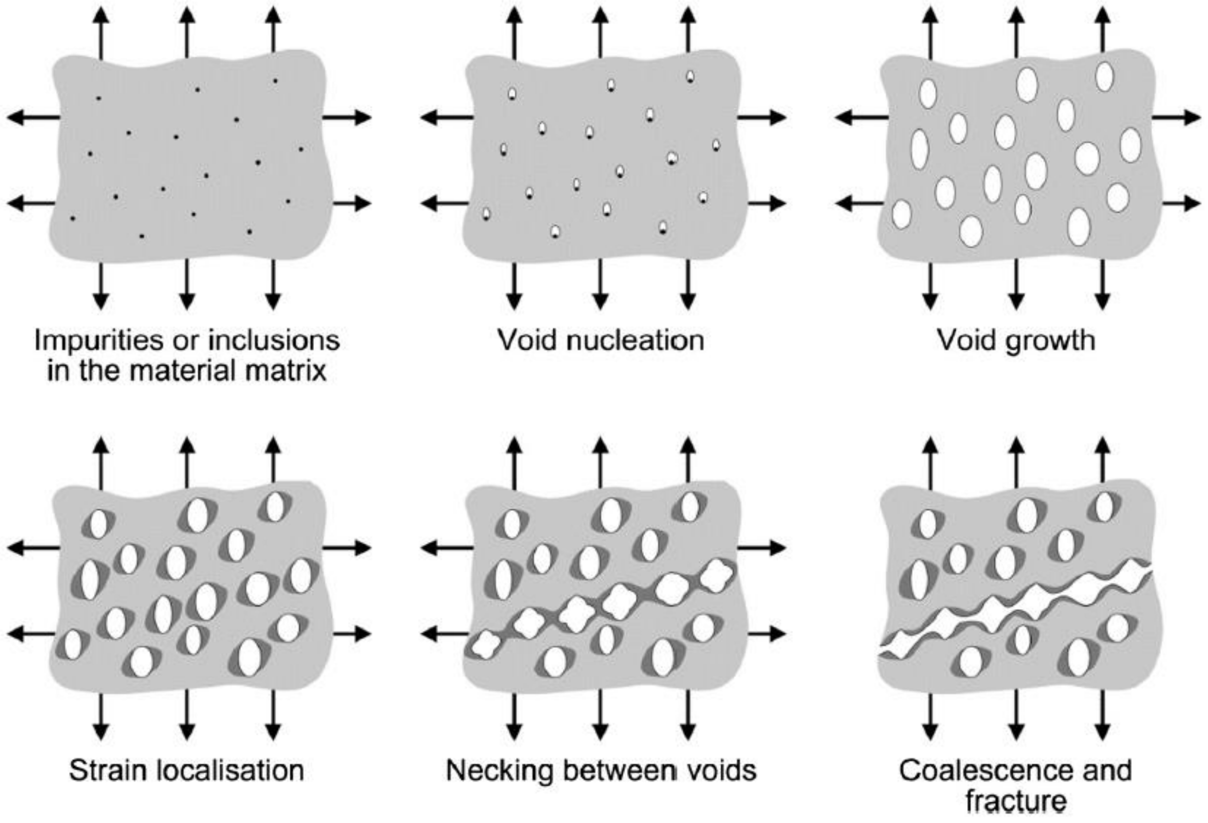


Amaral, R. *et al.*, *Evaluation of ductile failure models in Sheet Metal Forming*, MATEC Web of Conferences 80, 03004, 2016.

Prediction of ductile fracture in metallic material

- ***Ductile fracture*** describes the rupture of a material that experiences large plastic deformation, exhibiting high ductility in the region where structural failure occurs.

- ***Damage*** can be understood as the physical process of progressive deterioration of the material.
  - At the microscopic level, damage is related to the mechanism of nucleation, growth and coalescence of micro-cracks and micro-cavities, evidenced by experimental observations.
  - Macroscopically, damage translates into a decrease of the material stiffness, strength and a reduction of the remaining ductility.



Gatea, S. *et al.*, *Modelling of ductile fracture in single point incremental forming using a modified GTN model*, Engineering Fracture Mechanics, 186, 59–79, 2017.

Prediction of ductile fracture in metallic material

- ***Damage models*** are proposed to link the measurable field variables to the progressive deterioration towards fracture, i.e. the damage evolution.

Uncoupled Models	• The damage process is independent of the material plastic behaviour, i.e. the plastic properties of the material do not change with the damage accumulation; • Damage is evaluated as a post-processing step of the conventional FEM solution.
Coupled Models	• The damage accumulation is incorporated in the constitutive equations; • The plastic properties of the material are considered as a function of the accumulated damage.

Prediction of ductile fracture in metallic material

- A stress state is fully defined by the six independent components of the Cauchy stress tensor. Regarding the study of ductile fracture mechanics, the stress state is usually described by two dimensionless parameters:
  - Stress triaxiality:

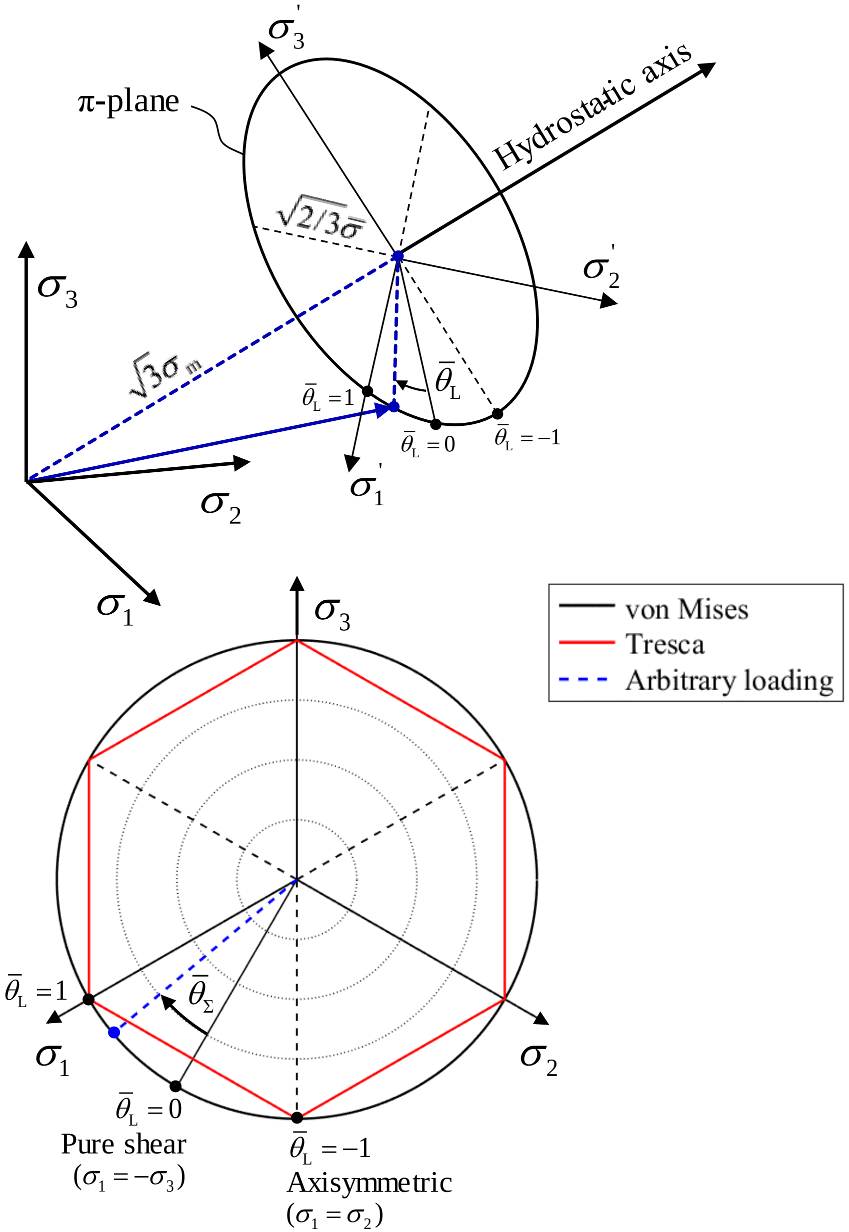
$$\eta = \frac{1}{3}\frac{I_1}{\sqrt{3J_2}} = \frac{\sigma_{\mathrm{m}}}{\bar{\sigma}_{\mathrm{Mises}}},\quad \text{where } \sigma_{\mathrm{m}} = \frac{1}{3}I_1 \text{ and } \bar{\sigma}_{\mathrm{Mises}} = \sqrt{3J_2},$$

  - Lode angle parameter:

$$\bar{\theta}_{\mathrm{L}} = \left(1 - \frac{2}{\pi}\arccos(\varphi)\right) = \frac{2}{\pi}\arcsin(\varphi),\quad \text{with } \varphi = \frac{3\sqrt{3}}{2}\frac{J_3}{(J_2)^{3/2}}.$$

where:

$$I_1 = \mathrm{tr}(\boldsymbol{\sigma}),\quad J_2 = \frac{1}{2}\boldsymbol{\sigma}':\boldsymbol{\sigma}',\quad J_3 = \det(\boldsymbol{\sigma}'),\quad \text{with } \boldsymbol{\sigma}' = \boldsymbol{\sigma} - \frac{1}{3}\mathrm{tr}(\boldsymbol{\sigma})\mathbf{I},$$

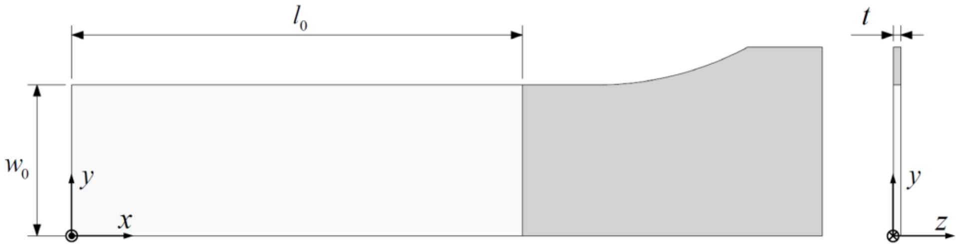


Goal

- Analyse the influence of the discretization adopted in the gauge area of test specimens, commonly used to calibrate ductile fracture models, in the evolution and distribution of the field variables $(\eta, \bar{\theta}_L)$.

- Two stress states of great importance to the sheet metal forming process were studied:

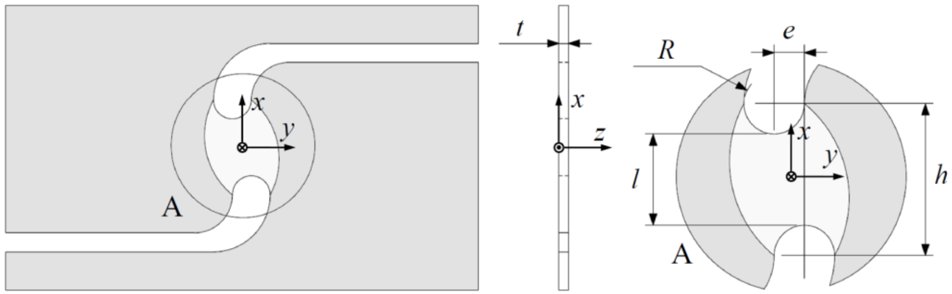
  - (i) uniaxial tension – (1/3,1)



Structured mesh
Unstructured mesh

Gauge section length	l_0 [mm]	30
Gauge section width	w_0 [mm]	10
Sheet thickness	t [mm]	0.5

  - (ii) simple shear – (0,0)



Structured mesh
Unstructured mesh

Notch eccentricity	e [mm]	1
Gauge section length	l [mm]	3
Notch radii	R [mm]	1
Dist. between axes	h [mm]	5
Sheet thickness	t [mm]	0.5

Material

- Dual phase steel DP780 (1 mm thick). The yield of the material is described using the isotropic von Mises criterion. The flow stress is modelled through a combined Swift-Voce isotropic hardening law:

$$Y(\bar{\varepsilon}_\text{p}) = \alpha Y_\text{Swift}(\bar{\varepsilon}_\text{p}) + (1-\alpha) Y_\text{Voce}(\bar{\varepsilon}_\text{p}), \quad \text{with} \quad \begin{aligned} Y_\text{Swift}(\bar{\varepsilon}_\text{p}) &= K(\varepsilon_0 + \bar{\varepsilon}_\text{p})^n, \\ Y_\text{Voce}(\bar{\varepsilon}_\text{p}) &= Y_0 + (Y_\text{sat} - Y_0)\left(1 - e^{-C_\text{Y}\bar{\varepsilon}_\text{p}}\right), \end{aligned}$$

Table 1. Elastic properties and combined Swift-Voce hardening law parameters of the DP780 steels (Roth, C.C.. and Mohr, D., *Ductile fracture experiments with locally proportional loading histories*, International Journal of Plasticity, 79, 328-354, 2016).

Elastic Properties		Voce Law			Swift Law			Combined Law
E [GPa]	v [-]	Y_0 [MPa]	Y_sat [MPa]	C_Y [-]	K [MPa]	ε_0 [-]	n [-]	α [-]
194	0.33	349.54	885.9	93.07	1315.4	$0.28\cdot10^{-4}$	0.146	0.7

Discretizations and element type

- Given the different length scale of the studied specimens, the average finite element size, l_{elem} is defined according to the dimensionless parameter $\mu=(l_{elem}/l_{char})$.
- Three in-plane (P) mesh discretizations are considered, corresponding to μ values of 20, 40 and 100. Additionally, three discretizations along the sheet thickness direction are employed, corresponding to 2, 4 and 8 layers (L).
- All meshes comprise eight-node hexahedral solid finite elements with a selective reduced integration (SRI) technique.

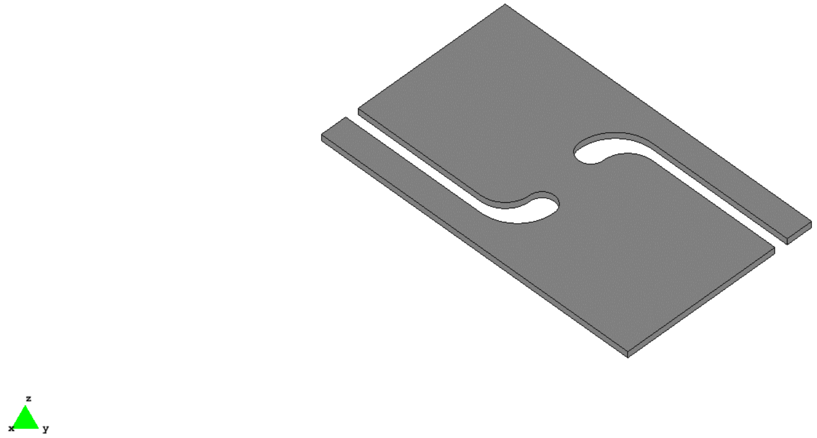
- **DD3IMP** in-house finite element code (implicit time integration).

Table 2. Mesh characteristics and corresponding computational time for the finite element simulations.

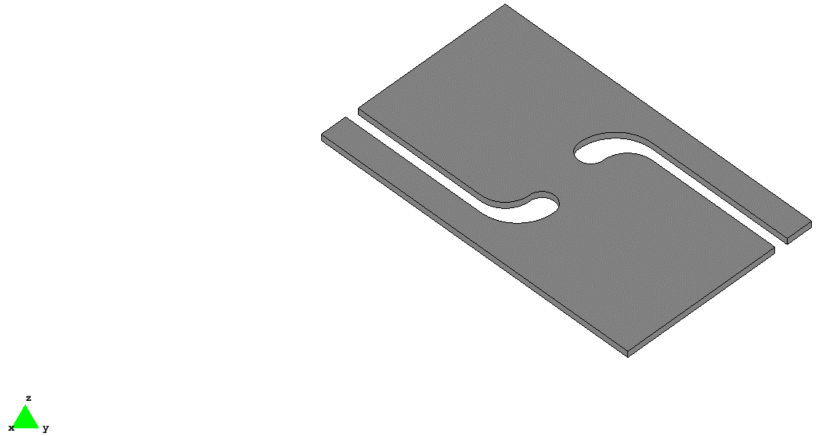
Mesh	Tensile specimen			Shear specimen		
	# Elements	# Nodes	CPU time [h]	# Elements	# Nodes	CPU time [h]
P020L2	2728	4380	0.02 (42 Steps)	3438	5502	0.01 (42 Steps)
P040L4	20212	26105	0.20 (49 Steps)	20032	25775	0.06 (42 Steps)
P100L4	122004	154410	1.69 (56 Steps)	109788	138420	0.46 (44 Steps)
P100L8	244008	277938	8.59 (58 Steps)	219576	249156	2.16 (46 Steps)

Evolution and distribution of the equivalent plastic strain

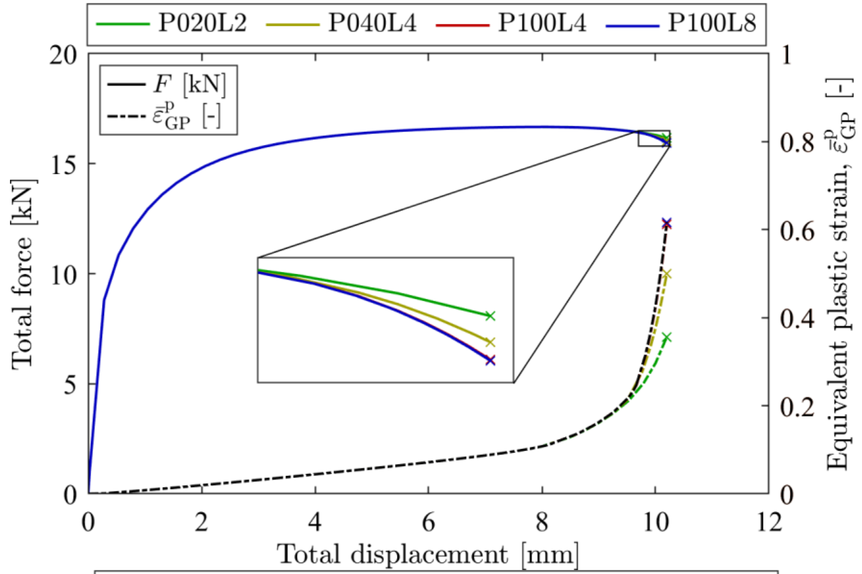
P040L4

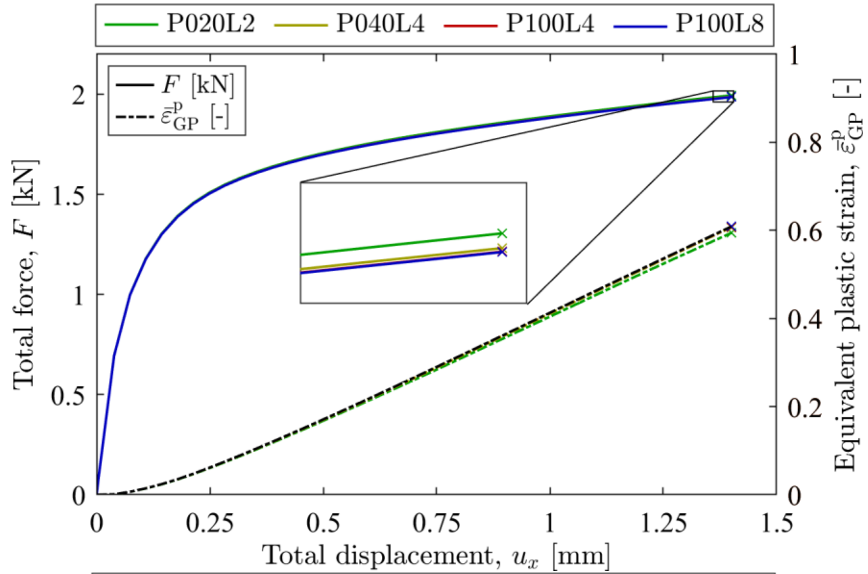


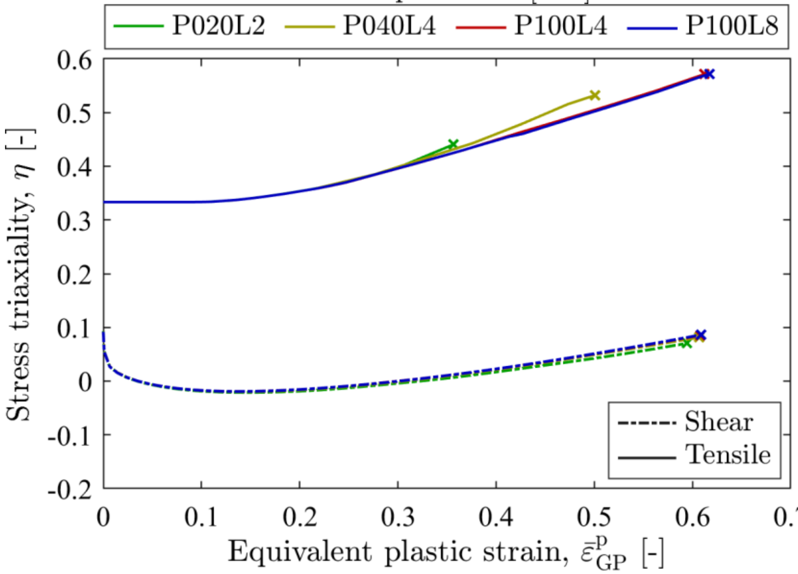
P100L4

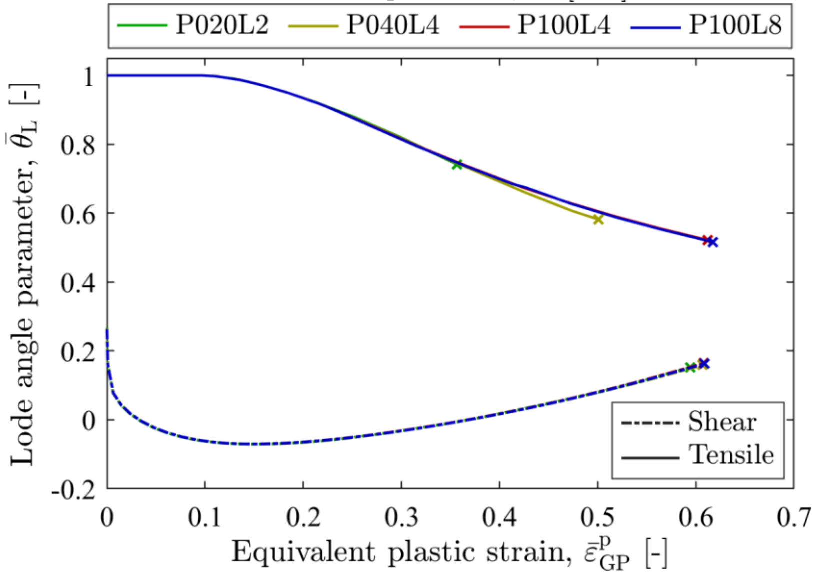


Influence of the FE mesh on the evolution of global and local variables

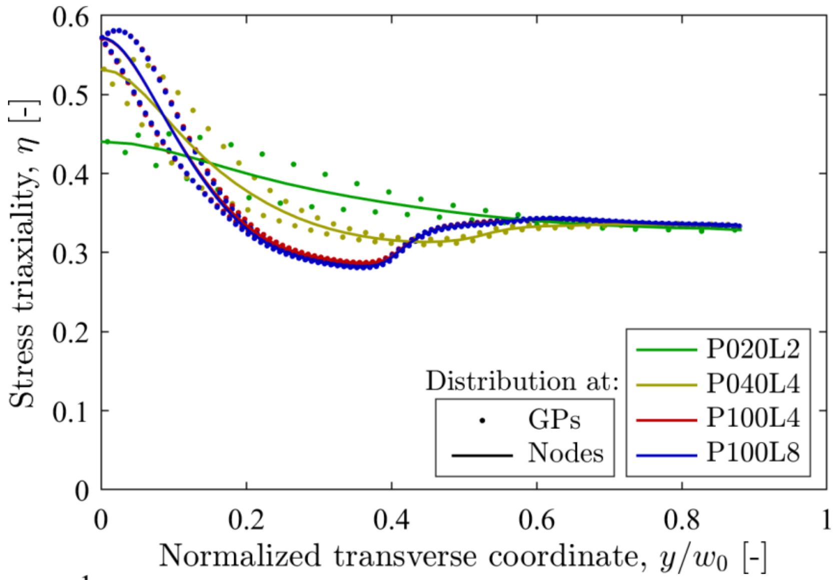


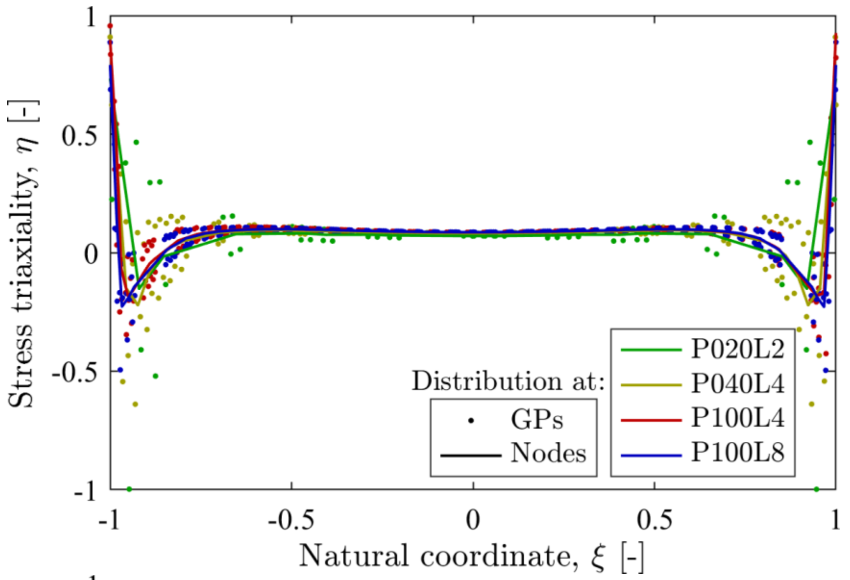


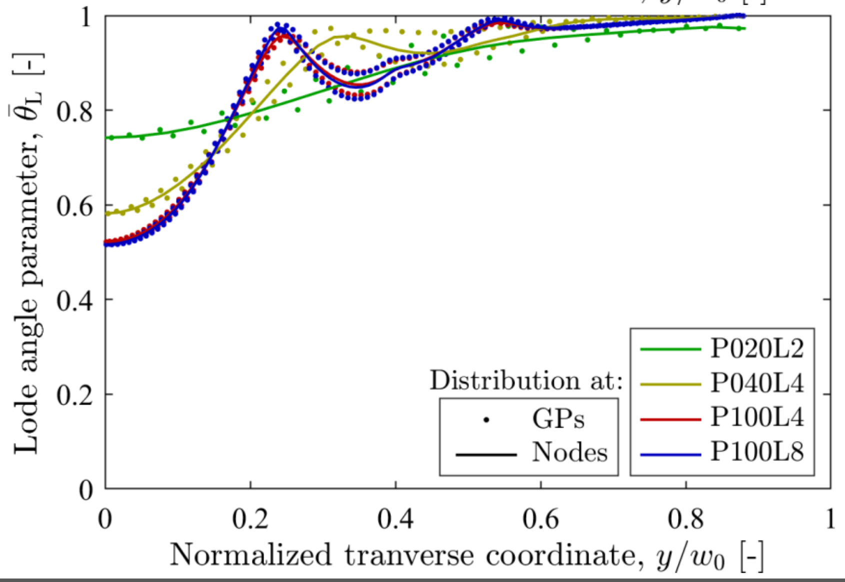


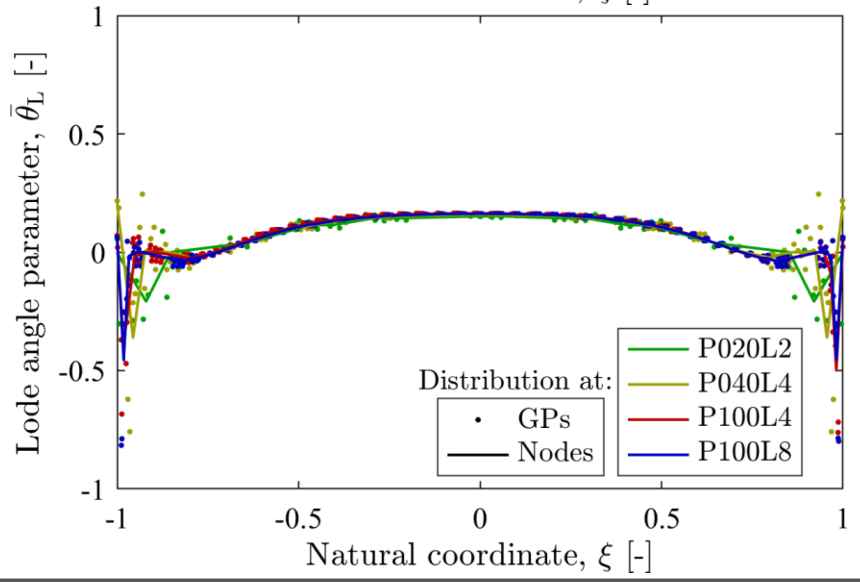


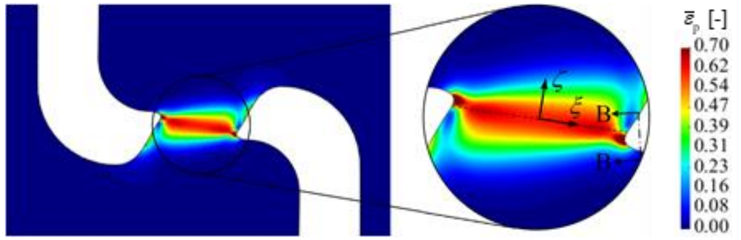
Influence of the FE mesh on the distribution of local variables

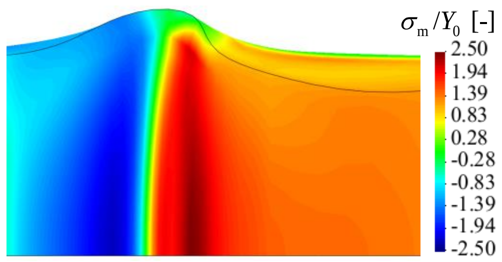




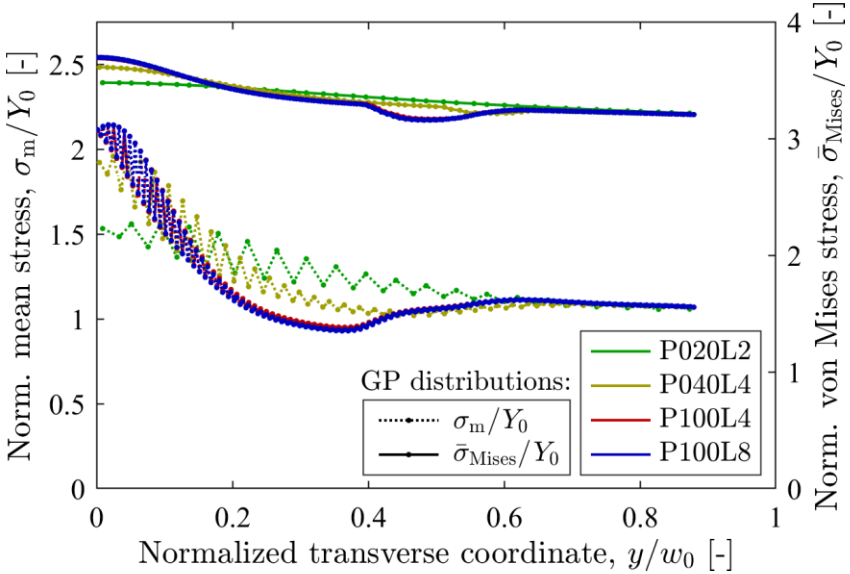


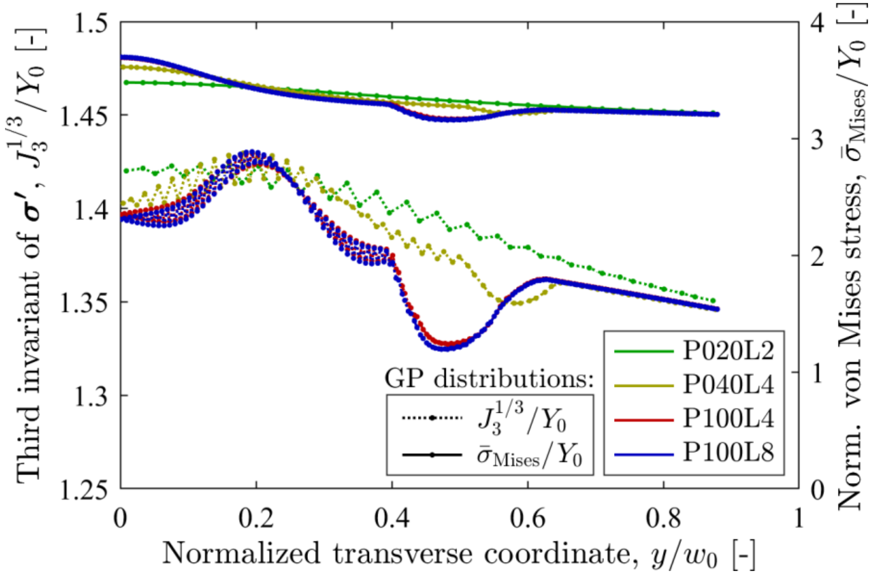


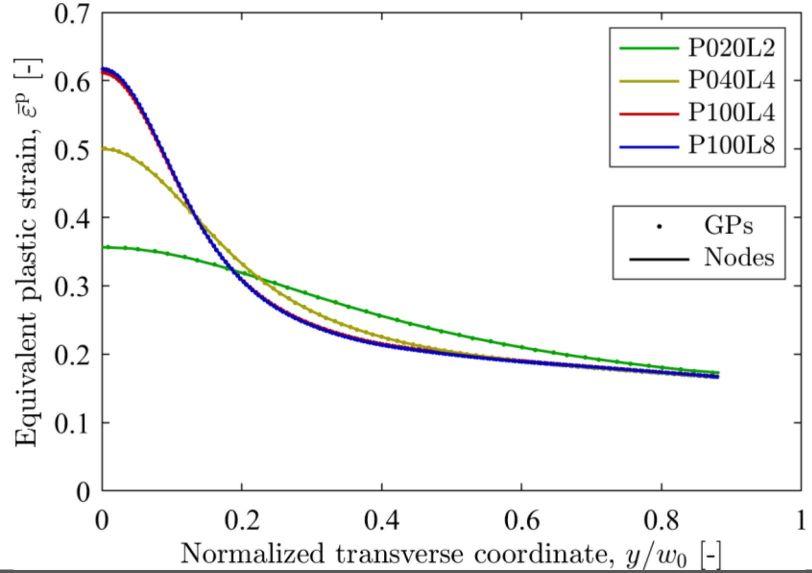


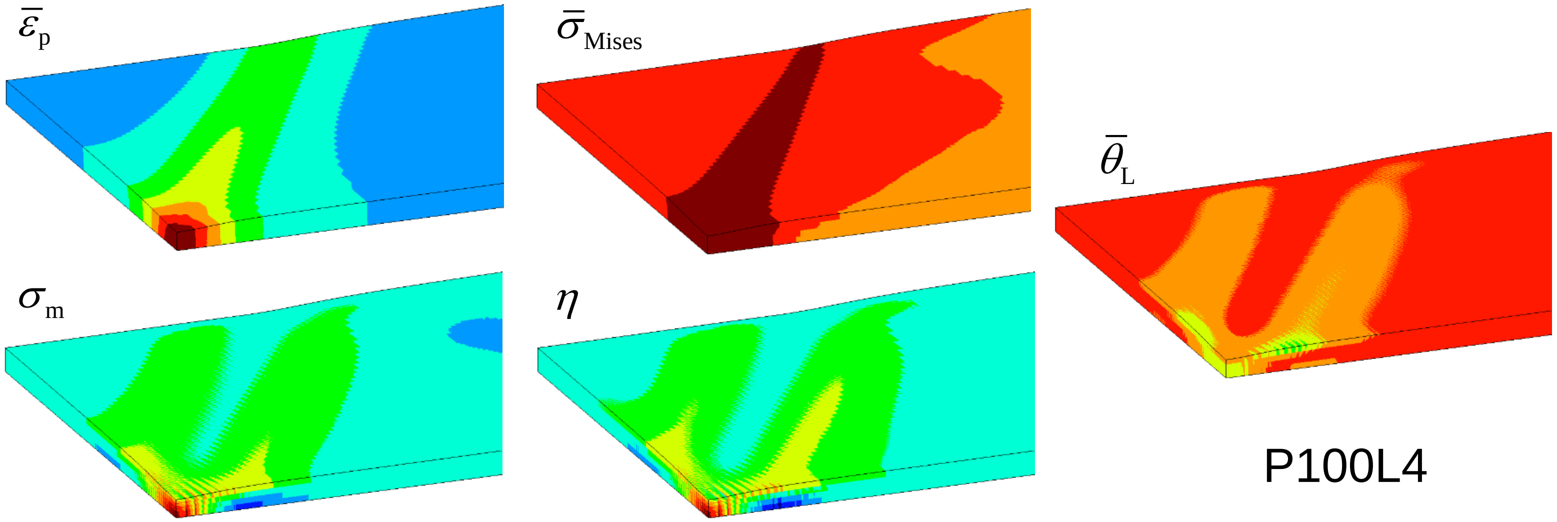


Influence of the FE mesh on the distribution of local variables

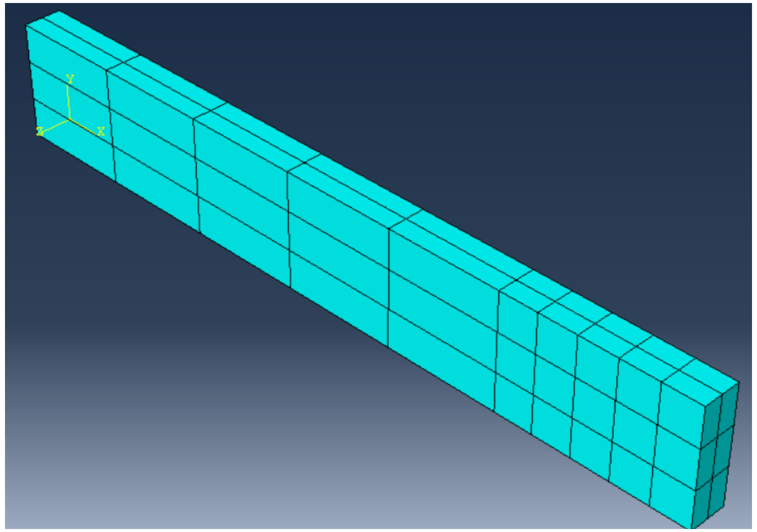


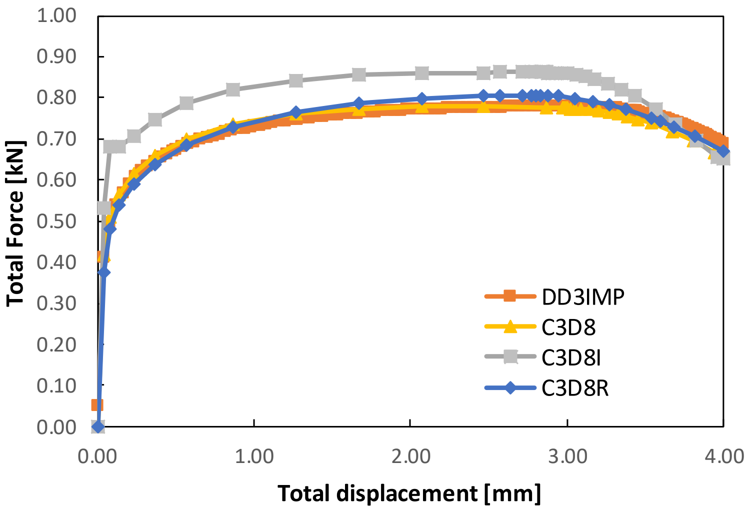


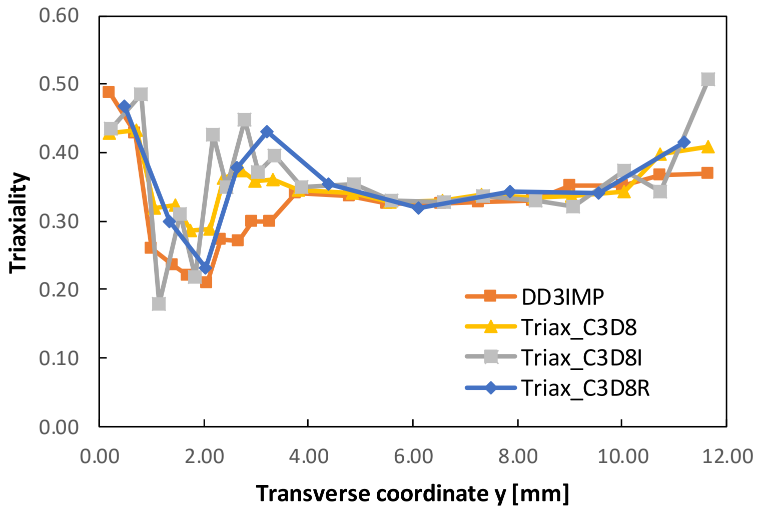




Influence of the integration rule on the distribution of local variables





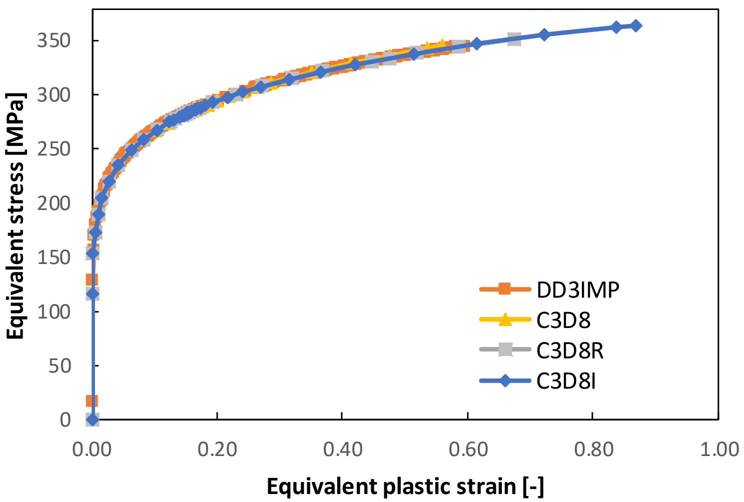


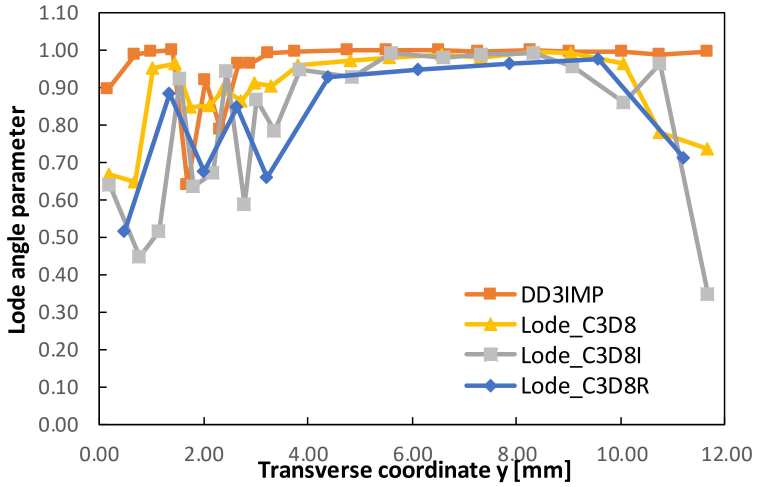
Eight-node brick elements:

C3D8 - Fully integrated

C3D8I - Incompatible mode

C3D8R - Reduced integration with hourglass control





Conclusions

- The required mesh refinement changes particularly when plastic instability occurs. The field variable distribution at the GPs shows that non-negligible oscillations can arise relative to the smoothed results at the nodes.

- Significant oscillations of the results at the GPs occur both between adjacent FE and within a FE itself. These discontinuities do not vanish with the mesh refinement and their amplitude vary throughout the domain.

- As a result of the non-uniform computation of the field variables at the GPs, uncoupled damage models may predict a highly local and equally discontinuous damage distribution at the GPs, which could lead to a somewhat misleading prediction of fracture.

- The evaluation of the FE results only at the nodes, i.e. in a smoothed way, can conceal problems of excessive heterogeneity of the distribution of local variables and, ultimately, of the ductile damage.

Acknowledgements

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Thank you for your attention!