Prediction of ductile fracture of a DP780 steel using uncoupled damage models

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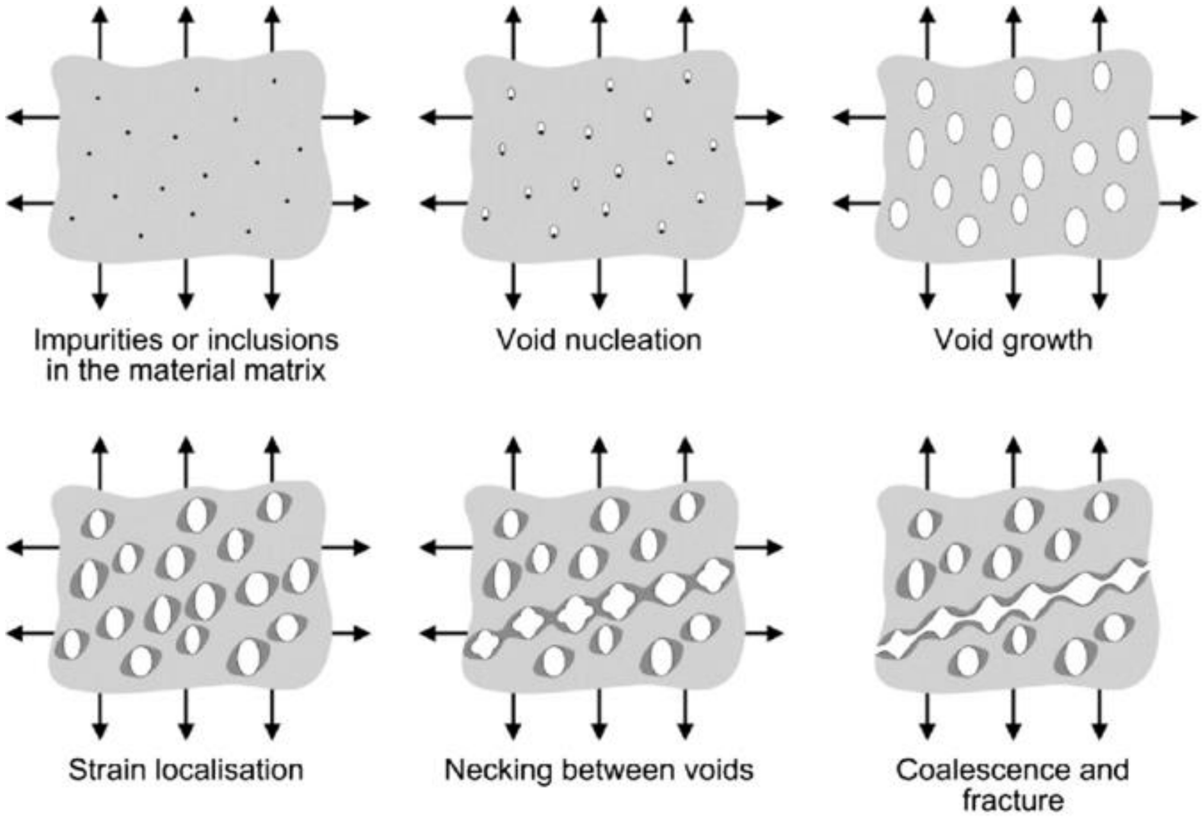
Damage

- A ductile material undergoes gradual internal deterioration (accumulated damage) as it is formed by plastic deformation

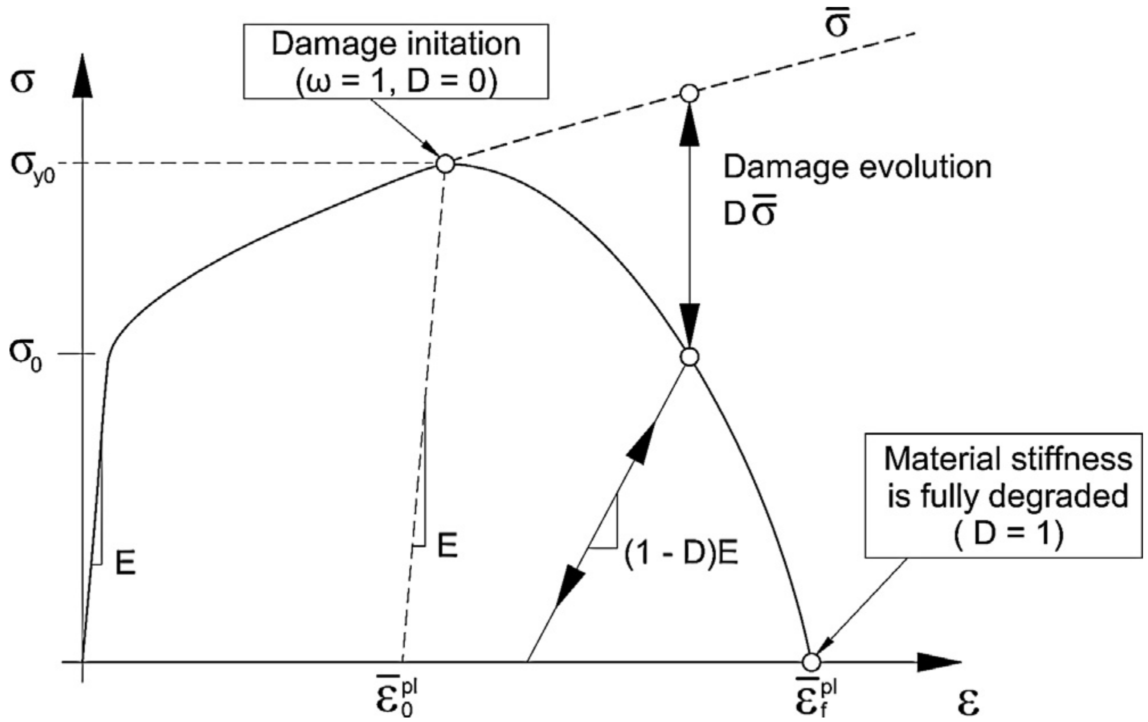
- Damage is a result of the nucleation, growth and coalescence of voids



Gatea, S., Ou, H., Lu, B. and Mccartney, D. (2017). "Modelling of ductile fracture in single point incremental forming using a modified GTN model". Engineering Fracture Mechanics. 186. 10.1016/j.engfracmech.2017.09.021.

Damage

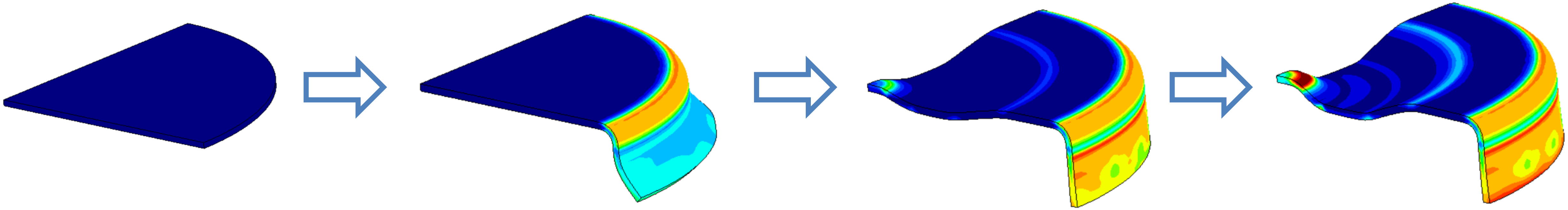
- Macroscopically, the accumulation of damage reduces the material's load carrying capacity
- Damage accumulation in the material leads, in the limit, to the occurrence of ductile fracture



Preś, P., Skoczyński, W., and Jaśkiewicz, K. (2014). "Research and Modeling Workpiece Edge Formation Process during Orthogonal Cutting". Archives of Civil and Mechanical Engineering 14 (4): 622–35.

Damage models

- The accurate prediction of ductile fracture *locus* is fundamental to the design and optimization of sheet metal forming processes
- Numerical simulation using FEM is used to reduce products' development time and cost
- Damage models are numerical tools that allow to identify the onset of fracture in terms of a damage variable



Uncoupled damage models

- Typically, phenomenological models consider the accumulation of damage as a phenomenon independent of the plastic behavior of the material
- Materials' mechanical properties do not vary as it is deformed and accumulates damage
- The damage variable is, therefore, used as an indicator of the occurrence of fracture and treated as a scalar

$$D = \int_0^{\bar{\varepsilon}_f} f(\sigma_{ij})\, d\bar{\varepsilon}^p$$

D = 0 → No damage accumulated

D = 1 → Occurrence of fracture

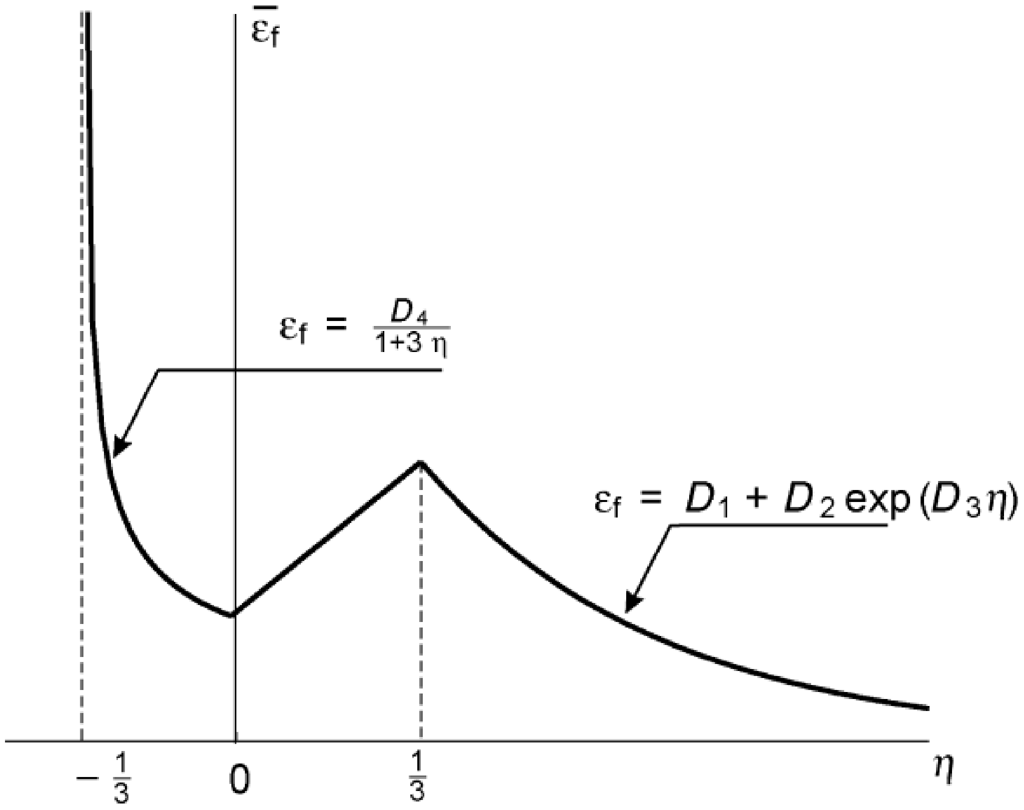
Bao-Wierzbicki's damage model

$$\bar{\varepsilon}_f = \begin{cases} \dfrac{D_4}{1+3\eta}, & -\dfrac{1}{3} < \eta \leq 0 \\ \bar{\varepsilon}_{f,t} + \left(\bar{\varepsilon}_{f,t} - \bar{\varepsilon}_{f,s}\right)(3\eta - 1), & 0 \leq \eta \leq \dfrac{1}{3} \\ D_1 + D_2 \exp(D_3\eta), & \eta \geq \dfrac{1}{3} \end{cases}$$

η – stress triaxiality

$$\eta = \frac{\sigma_m}{\bar{\sigma}}$$

- 4 Parameters: D_1, D_2, D_3 and D_4
- $D = \int_0^{\bar{\varepsilon}^p} \frac{1}{\bar{\varepsilon}_f} d\bar{\varepsilon}^p$



Mae, H., Teng, X., Bai, Y. and Wierzbicki, T. (2007). "Calibration of Ductile Fracture Properties of a Cast Aluminum Alloy". Materials Science and Engineering: A 459 (1–2). Elsevier: 156–66.

Xue-Wierzbicki's damage model

$$\bar{\varepsilon}_f = \bar{\varepsilon}_{f_0}\mu_p\mu_\theta$$

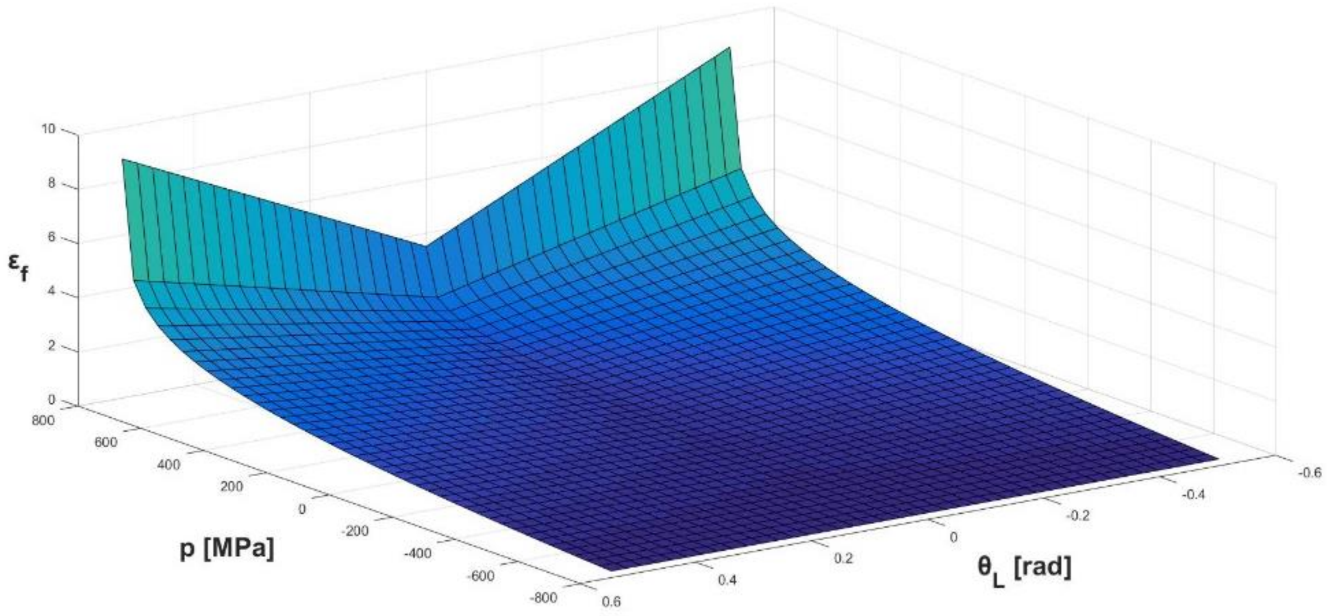
p – hydrostatic pressure [MPa]

θ_L – Lode angle [rad]

$$p = -\sigma_m$$

$$\theta_L = -\frac{1}{3}arcsen\left(\frac{27}{2}\frac{J_3}{\bar{\sigma}^3}\right)$$

$$-\frac{\pi}{6} \leq \theta_L \leq \frac{\pi}{6}$$



$$\mu_p = \begin{cases} 1 - q\ln\left(1 - \frac{p}{p_{lim}}\right), & p \geq p_{lim}\left[1 - \exp\left(\frac{1}{q}\right)\right] \\ 0, & p < p_{lim}\left[1 - \exp\left(\frac{1}{q}\right)\right] \end{cases}$$

$$\mu_\theta = \gamma + (1-\gamma)\left(\frac{6|\theta_L|}{\pi}\right)^k$$

- 6 Parameters: $\bar{\varepsilon}_{f_0}$, q, p_{lim}, γ, k and m
- $D = m\int_0^{\bar{\varepsilon}_c}\left(\frac{\bar{\varepsilon}^p}{\bar{\varepsilon}_f}\right)^{(m-1)}\frac{1}{\bar{\varepsilon}_f}d\bar{\varepsilon}^p$

Xue-Wierzbicki's damage model

$$\mu_p = \begin{cases} 1 - q \ln\left(1 - \frac{p}{p_{lim}}\right), & p \geq p_{lim}\left[1 - \exp\left(\frac{1}{q}\right)\right] \\ 0, & p < p_{lim}\left[1 - \exp\left(\frac{1}{q}\right)\right] \end{cases}$$

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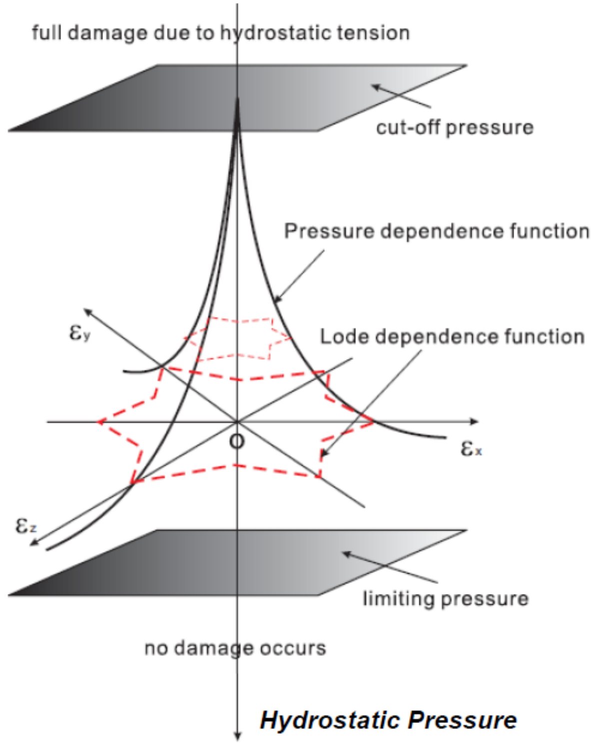
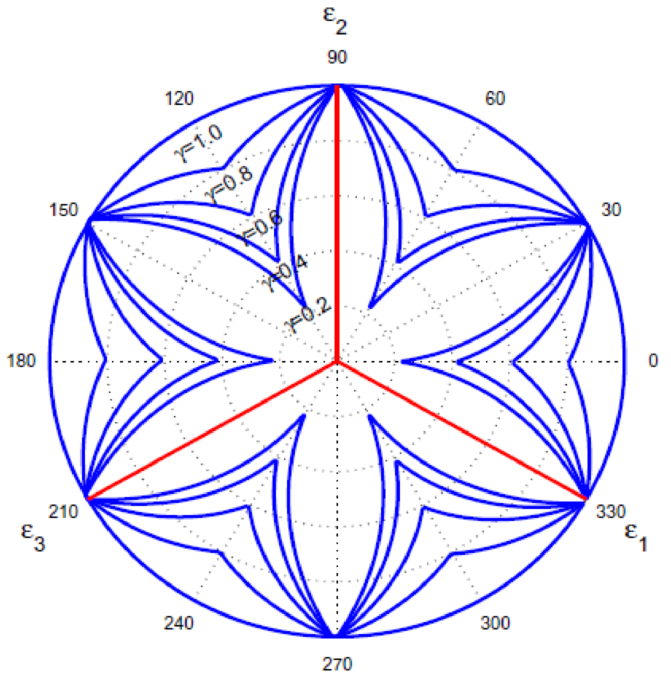
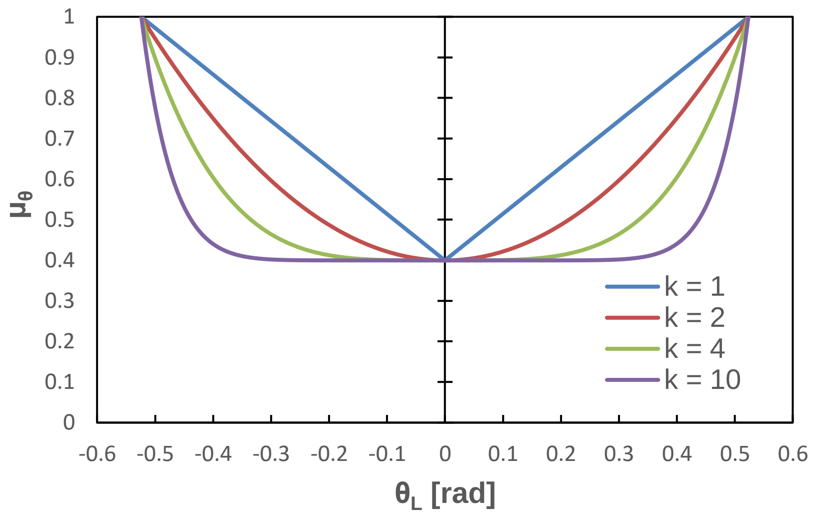






Xue, L., and Wierzbicki, T. (2008). "Ductile Fracture Initiation and Propagation Modeling Using Damage Plasticity Theory". Engineering Fracture Mechanics 75 (11). Pergamon: 3276–93.

Numerical modeling of the material

DP780 steel

- Isotropic material ⇨ von Mises yield criterion

- Strain hardening ⇨ Swift + Voce law

- Hybrid numerical-experimental results conducted by Roth and Mohr (2016)

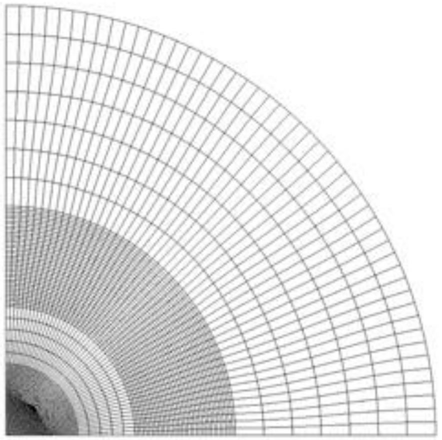
  - $\bar{\varepsilon}_f$ is determined experimentally by digital image correlation
  - η and θ_L are evaluated numerically to match the experimental $\bar{\varepsilon}_f$
  - Experiments designed such that η and θ_L remain constant as the specimen is loaded to fracture

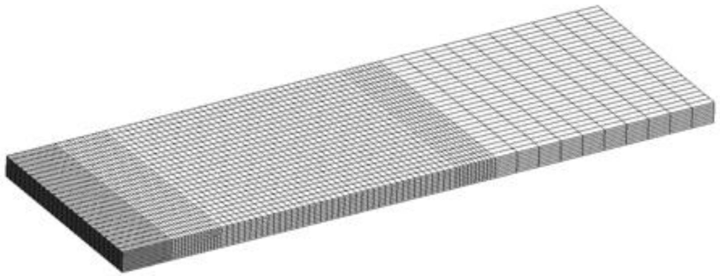
- Simulations performed using DD3IMP finite element solver

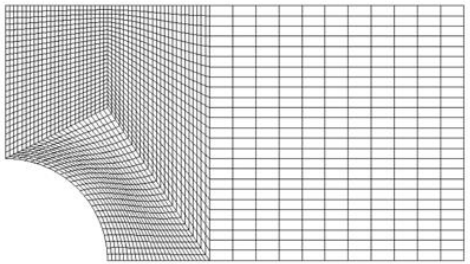
Mechanical tests

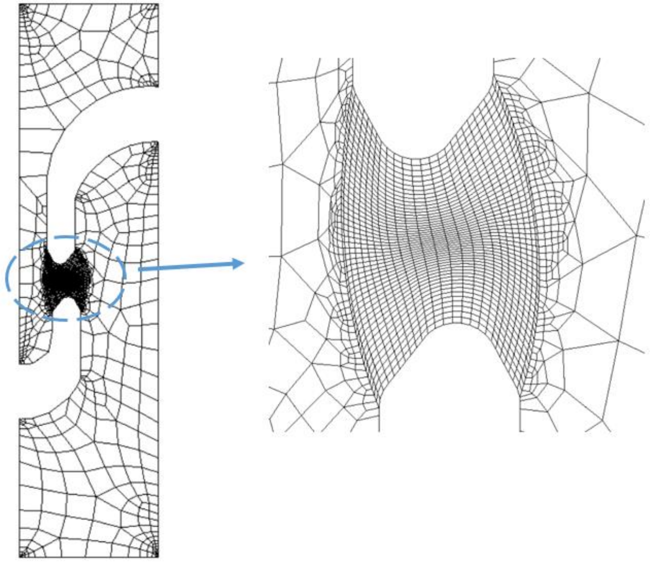
- Four different mechanical tests are analyzed:

	$\bar{\varepsilon}_f$	η	$\bar{\theta}_L$
Equi-biaxial tension	0,72	2/3	-1
V-bending	0,518	0,57735	0
Tension with a central hole	0,79	0,53	0,244825
In-plane shear	0,86	0,12	0,32

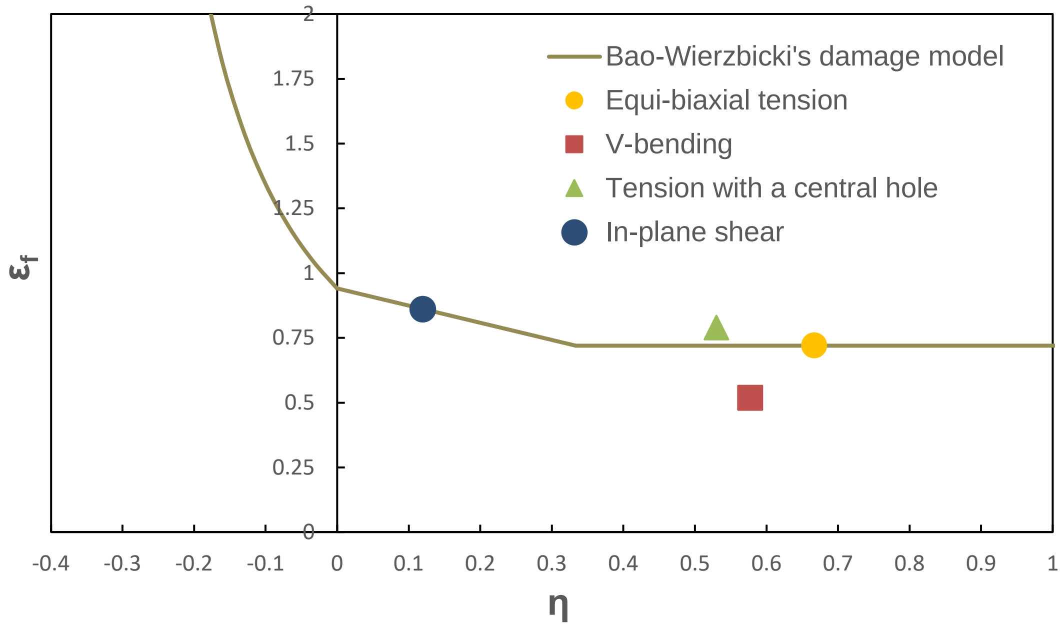


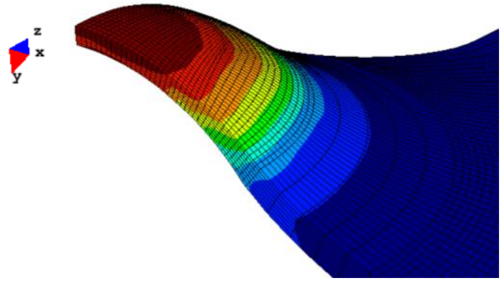




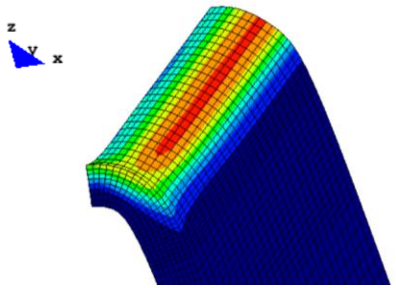


Bao-Wierzbicki's damage model

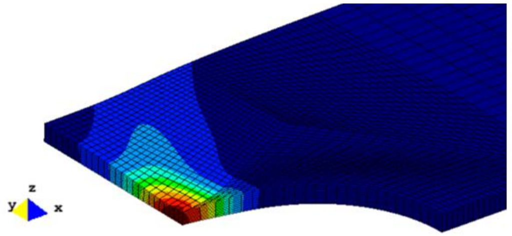




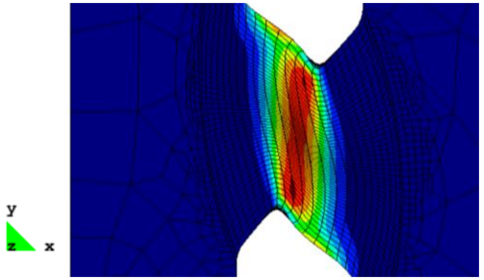
Equi-biaxial tension



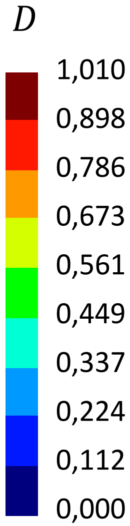
V-bending



Tension with a central hole



In-plane shear

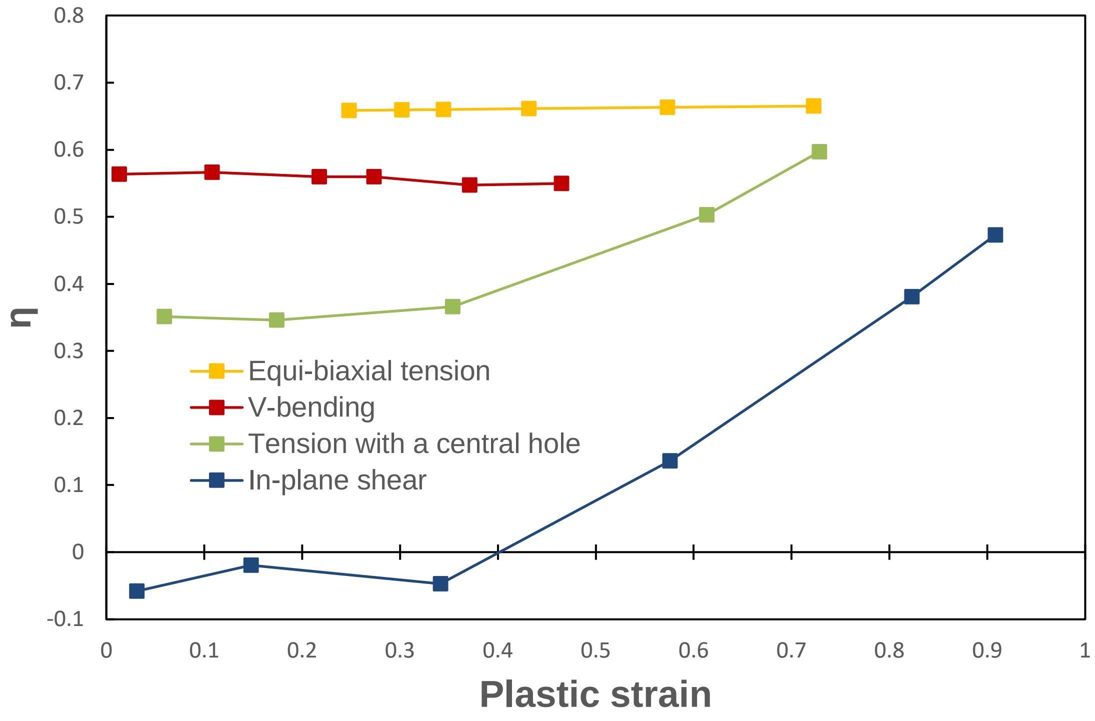


- Calibrated parameters:

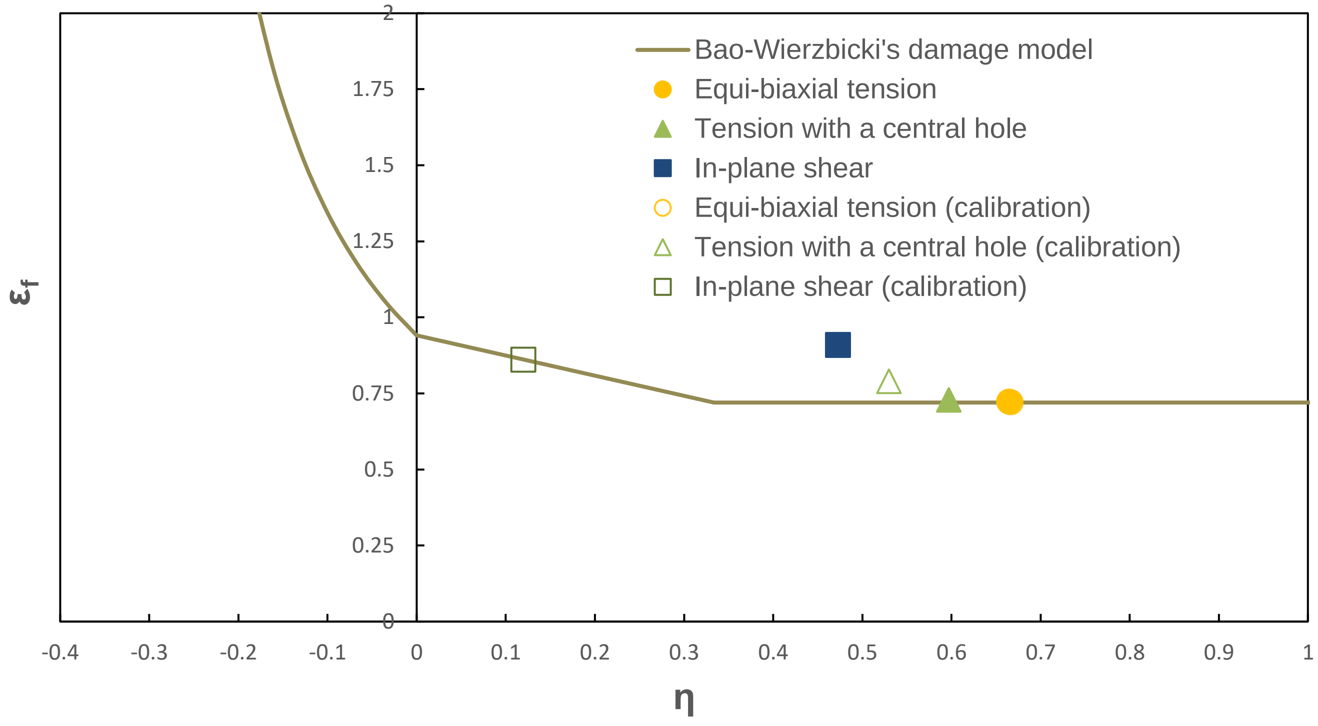
D_1	D_2	D_3	D_4
0,5686	0,1519	0,0	0,9408

Numerical results: Bao-Wierzbicki's damage model

Stress triaxiality evolution

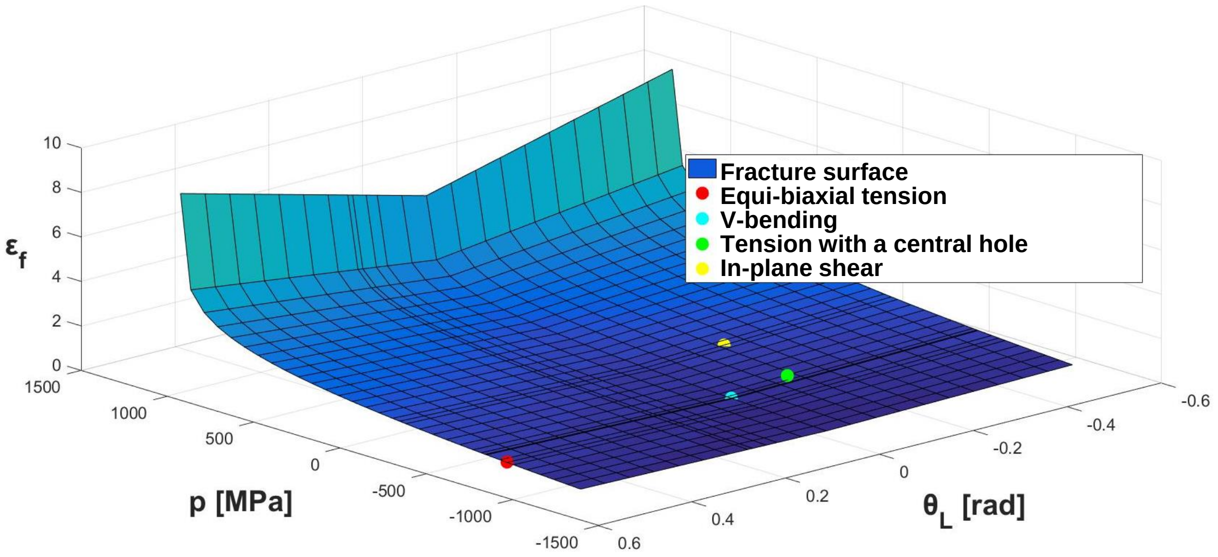


Numerical results vs calibration



- Fracture was not predicted for the V-bending test

Xue-Wierzbicki's damage model

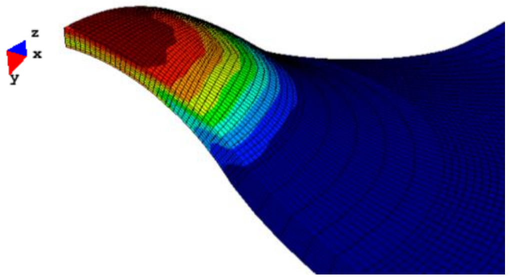


- Values indicated by the authors:

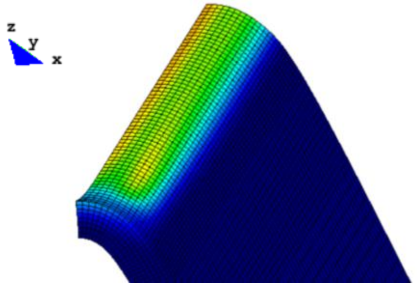
m	k
2	1

- Calibrated parameters:

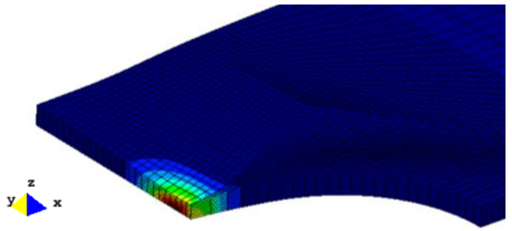
$\bar{\varepsilon}_{f_0}$	p_{lim} [MPa]	q	γ
1,24	1131,949	0,8146	0,6562



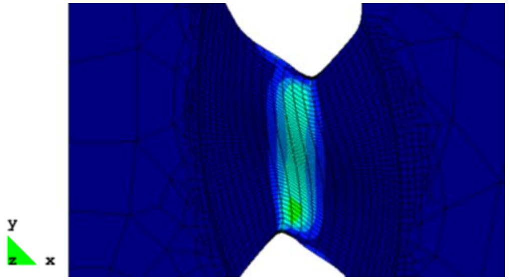
Equi-biaxial tension



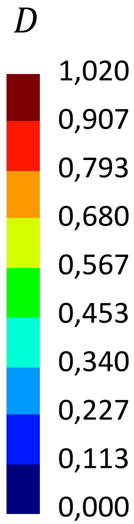
V-bending



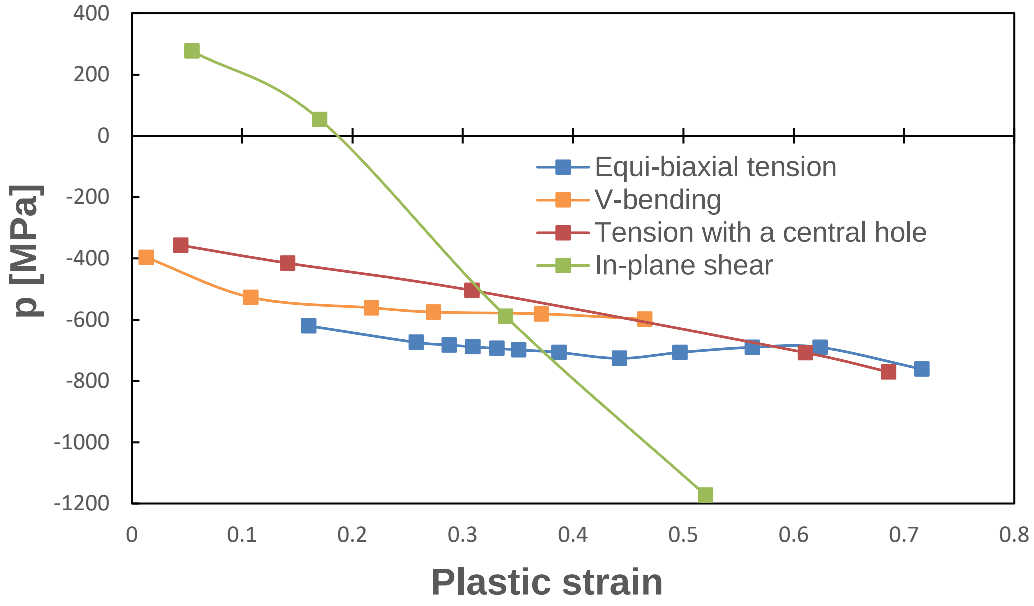
Tension with a central hole

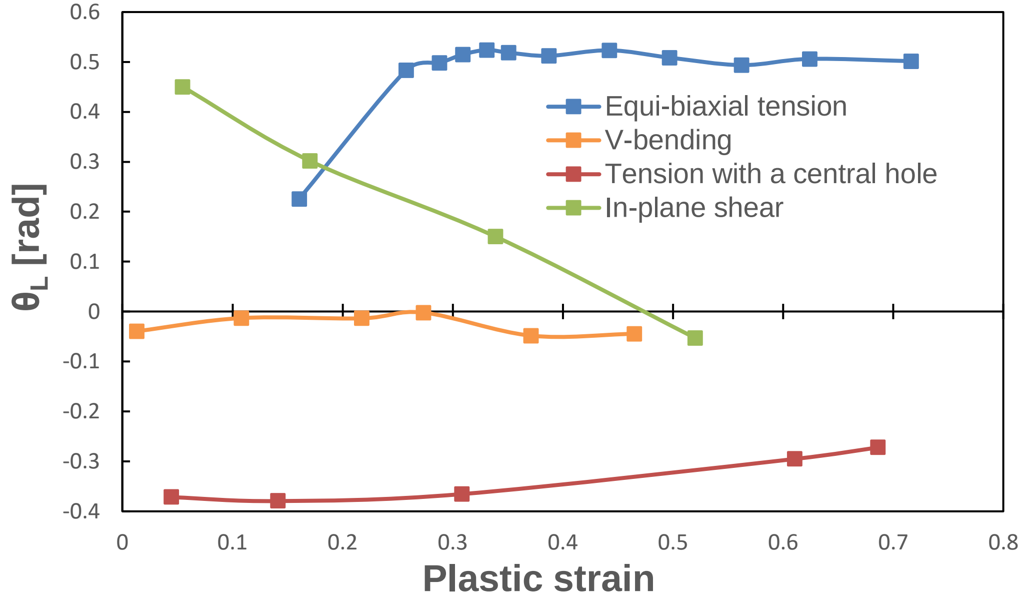


In-plane shear

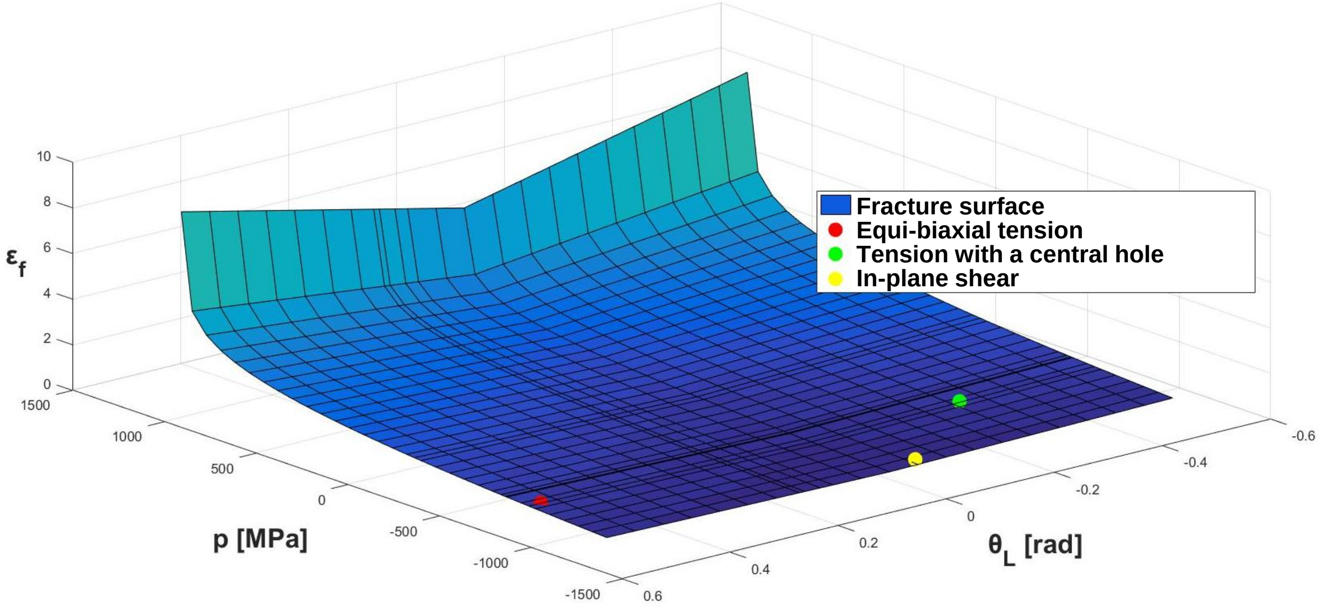


Numerical results: Xue-Wierzbicki's damage model





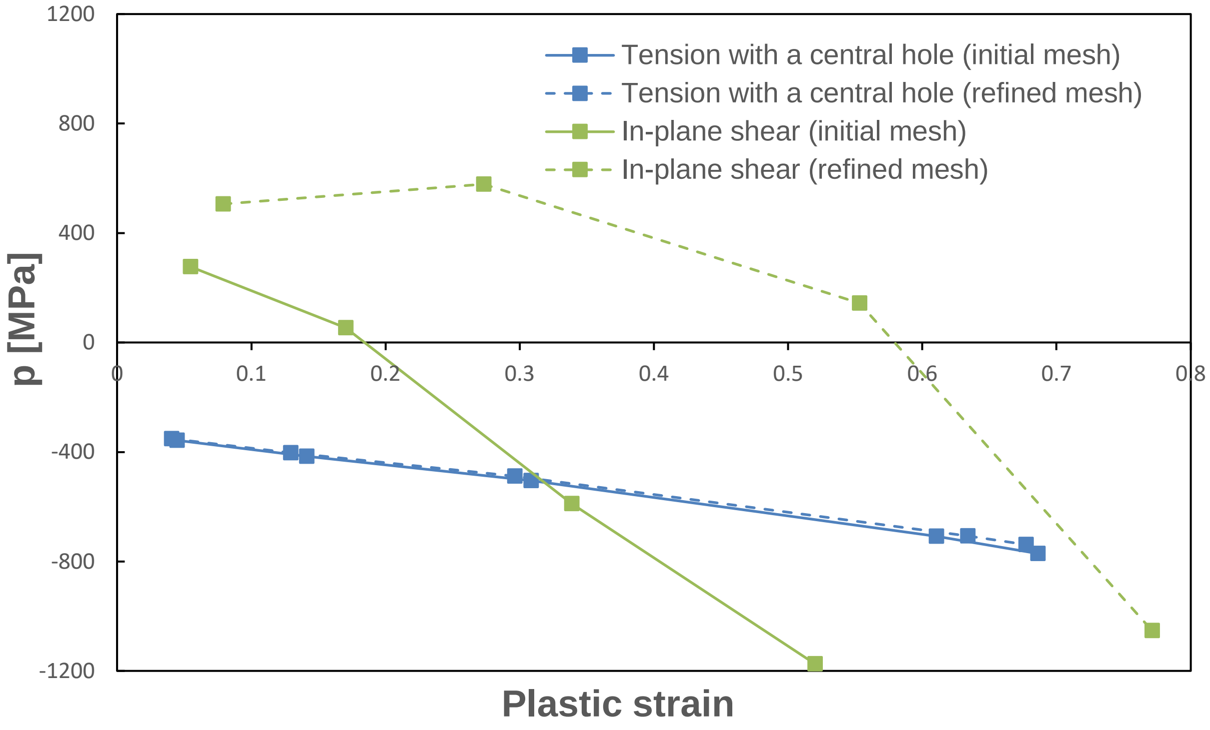
Numerical results vs calibration

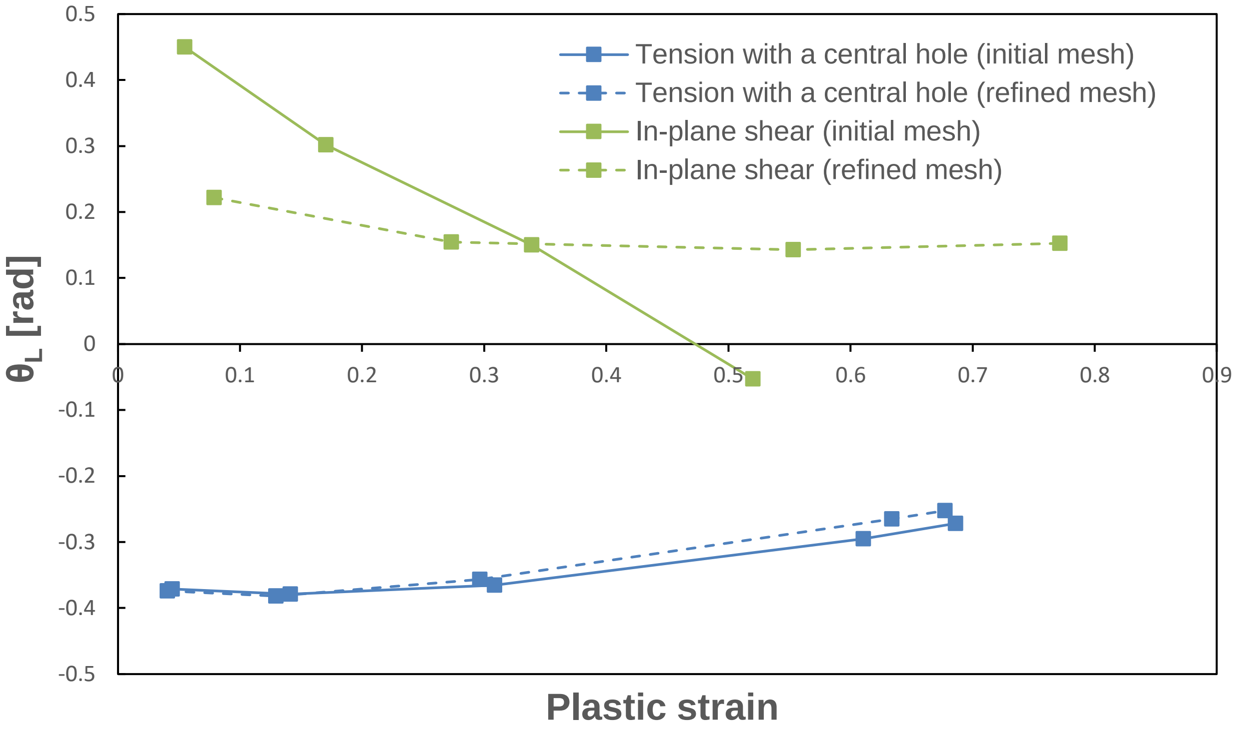


	$\bar{\varepsilon}_f$	$\bar{\varepsilon}_f$ surface	Relative error [%]
Equi-biaxial tension	0,7238	0,7092	2,059
Tension with a central hole	0,6860	0,5971	14,889
In-plane shear	0,5200	0,3603	44,324

- Fracture was not predicted for the V-bending test

Xue-Wierzbicki's damage model





	p [MPa]	θ_L [rad]	$\bar{\varepsilon}_f$	$\bar{\varepsilon}_f$ surface	Relative error [%]
Tension with a central hole	-738,703	-0,25266	0,67734	0,60227	12,465
In-plane shear	-1052,297	0,152461	0,77134	0,43567	77,047

Conclusions

- Globally, simulations performed with Bao-Wierzbicki's model predicted fracture strain values closer to the calibration function
- None of these damage models predicted the occurrence of fracture for the V-bending test
- The more constant the evolution of the stress triaxiality, hydrostatic pressure and Lode angle is with respect to the plastic strain the smaller the error in estimating the fracture strain
- It is always necessary to use a numerical-experimental approach to evaluate the evolution of the variables that characterize the stress state
- The spatial discretization of the numerical models should be selected carefully, once it can influence significantly the error committed in the evaluation of the fracture strain

Acknowledgements

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Thank you for your attention!