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An assessment of a micromechanical damage model for porous solids exhibiting tension–compression asymmetry

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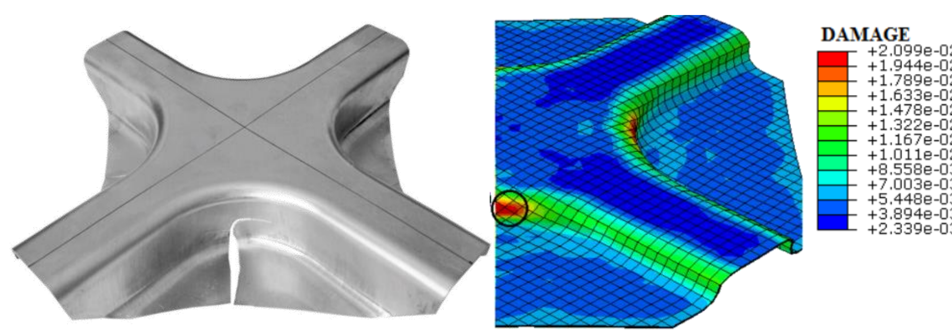
Introduction

- Introduction of new materials with high <u>strength-to-weight ratio</u>:
  - Reduction of the overall mass of the structures;
    - Meet the ever-stringent standards on passenger safety and gas emissions.
  - Reduction of **ductility** ⇨ <u>Lower ability to undergo plastic deformation</u>.

- Success of the forming operation ⇨ Ability to <u>predict</u> the occurrence of forming defects, viz. **ductile fracture**

- Development of reliable numerical tools to describe the internal <u>damaging</u> and failure of ductile materials.

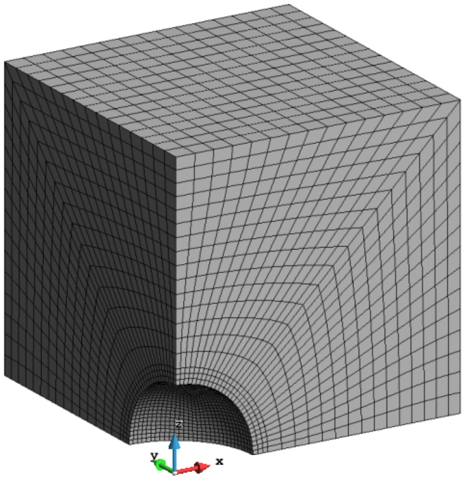


(Amaral, R. *et al.*, 2016)

Objectives

- Assess the response of the **CPB06 porous model** regarding the damage evolution and mechanical response of porous solids exhibiting tension-compression asymmetry (SD effects).

- The predictive capability of the model is evaluated comparing the performed numerical tests with analogous results on unit cell studies.
  - Numerical simulations on a single finite element:
    - Axisymmetric stress states;
    - Isotropic form of the damage model;
    - ↳ Simulations performed with DD3IMP in-house FE solver.



3D unit cell model (Alves and Cazacu, 2015)

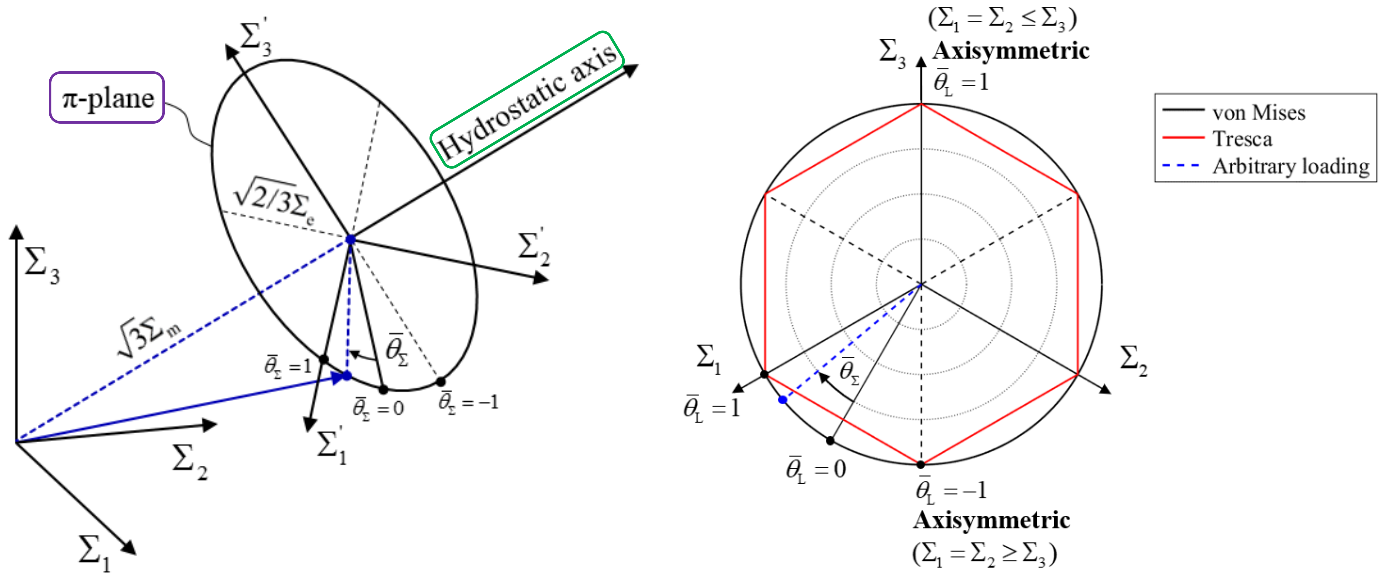
Description of the stress state

- In ductile fracture mechanics, the stress state is usually described by **two adimensional parameters**, relating the I_1^Σ, J_2^Σ and J_3^Σ stress invariants:
  - Stress triaxiality:

$$T_\Sigma = \frac{1}{3}\frac{I_1^\Sigma}{\sqrt{3J_2^\Sigma}} = \frac{\Sigma_m}{\Sigma_e}, \qquad (1)$$

  - Lode parameter:

$$\bar{\theta}_\Sigma = \frac{2}{\pi}\arcsin\left(\xi_\Sigma\right), \text{ with } \xi_\Sigma = \frac{3\sqrt{3}}{2}\frac{J_3^\Sigma}{\left(J_2^\Sigma\right)^{3/2}}. \qquad (2)$$



CPB06 Porous Model

- Quadratic and **isotropic** form of the CPB06 yield criterion (Cazacu, Plunkett and Barlat, 2006):

$$\varphi\left(\boldsymbol{\Sigma}', k, a, \sigma_{\mathrm{T}}\right) = \tilde{\Sigma}_{\mathrm{e}} - \sigma_{\mathrm{T}} = 0, \tag{3}$$

with

$$\tilde{\Sigma}_{\mathrm{e}} = m\left[\sum_{i=1}^{3}\left(\left|\Sigma_i'\right| - k\Sigma_i'\right)^2\right]^{\frac{1}{2}}; \quad \text{and} \quad m = \sqrt{\frac{9}{2\left(3k^2 - 2k + 3\right)}}. \tag{4}$$

  - Parameter k quantifies the tension-compression asymmetry (**SD effects**).

- Cazacu and Stewart (2009) derived the following isotropic plastic potential for porous aggregates containing randomly distributed spherical voids:

$$\varphi\left(\boldsymbol{\Sigma}', k, \sigma_{\mathrm{T}}, f\right) = \left(\frac{\tilde{\Sigma}_{\mathrm{e}}}{\sigma_{\mathrm{T}}}\right)^2 + 2q_1 f \cosh\left(z_{\mathrm{s}} \frac{3q_2\Sigma_{\mathrm{m}}}{2\sigma_{\mathrm{T}}}\right) - q_3 f^2 - 1 = 0, \tag{5}$$

with

$$z_{\mathrm{s}} = \begin{cases} 1 & \text{if } \Sigma_{\mathrm{m}} < 0; \\ \left(\dfrac{\sigma_{\mathrm{T}}}{\sigma_{\mathrm{C}}}\right) = \sqrt{\dfrac{3k^2 + 2k + 3}{3k^2 - 2k + 3}} & \text{if } \Sigma_{\mathrm{m}} \geq 0, \end{cases} \tag{6}$$

  - Internal damage variable is the void volume fraction (or **porosity**), f.

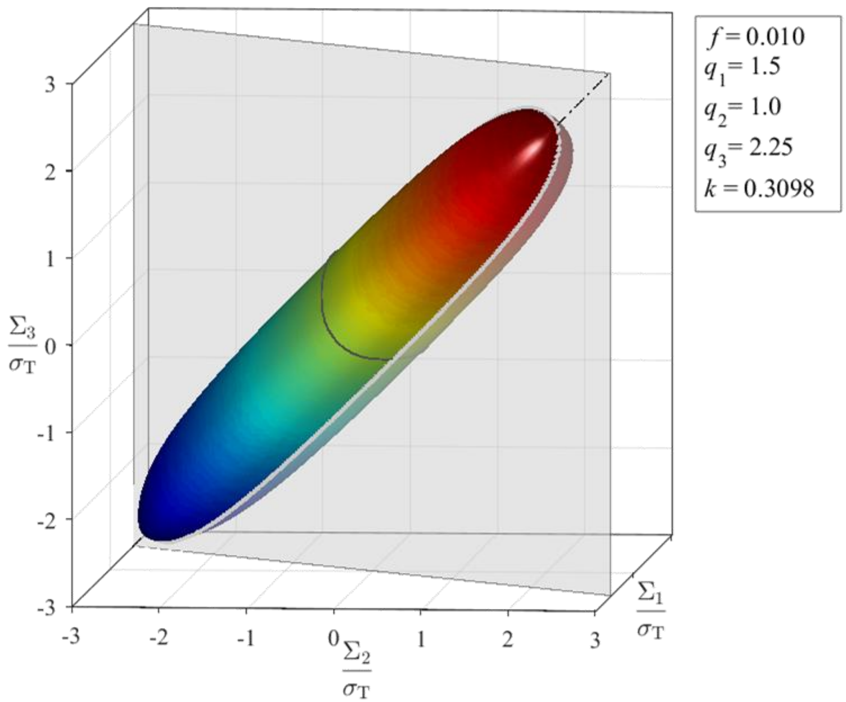
SD Effects and Materials

- The tension-compression asymmetry is more pronounced in metals with hexagonal closed packed (HPC) structure:
  - α-titanium, magnesium, zirconium, etc;
- Materials with cubic structure can also exhibit some SD effects, e.g.:
  - High strength steels (HSS), molybdenum and aluminium alloys, etc;

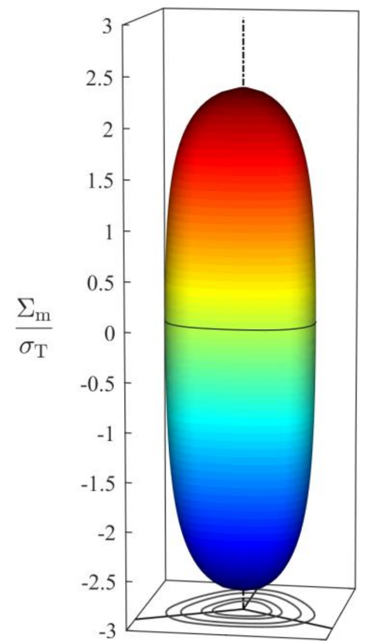
- The study is conducted for **three** virtual materials exhibiting different SD effects (in agreement with Hosford and Allen, 1973):
  - $k = 0$ ($\sigma_T / \sigma_C = 1$), which corresponds to a von Mises material;
  - $k = 0.3098$ ($\sigma_T / \sigma_C = 1.21$), corresponding to a fully-dense isotropic BCC material;
  - $k = -0.3098$ ($\sigma_T / \sigma_C = 0.83$), corresponding to a fully-dense isotropic FCC material.

CPB06 Porous Model

- **Three-dimensional** representation of the yield surfaces.
  - Material with $k > 0$ *and* $f > 0$ (i.e. in the presence of voids/damage).



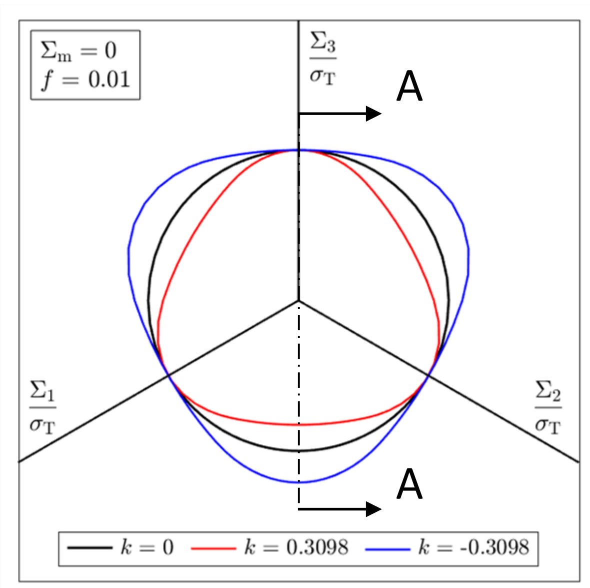
(a) Principal stress system $(\Sigma_1, \Sigma_2, \Sigma_3)$. Definition of the **axisymmetric plane** $(\Sigma_1 = \Sigma_2)$.



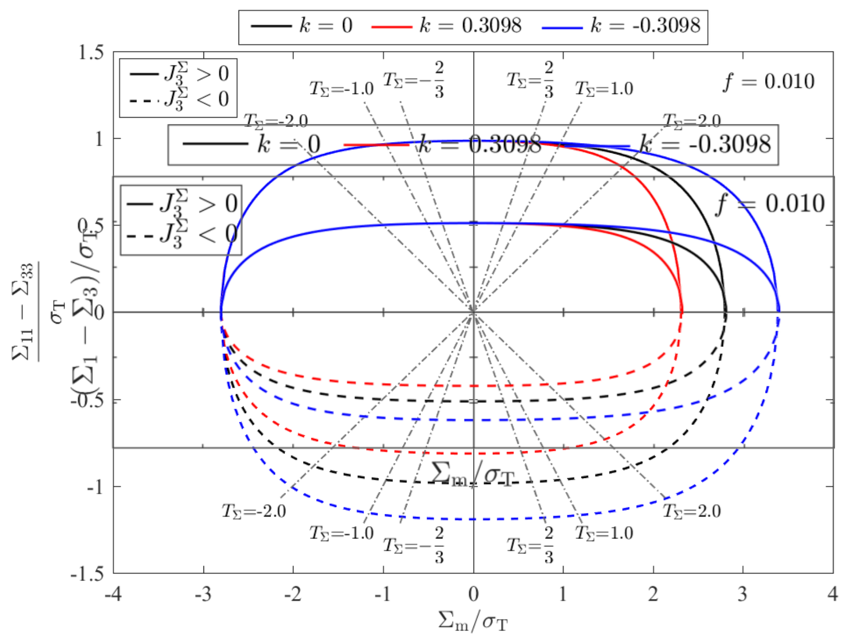
(b) Cylindrical coordinate system: z-axis normal to the π-plane.

CPB06 Porous Model

- **Two-dimensional** representation of the yield surfaces.
  - Three materials (different k – values);
  - The straight lines through the origin contain all the points that verify a given Σ_m / Σ_e ratio, i.e. same **stress triaxiality**.



(a) Projections on the ***π*-plane**;



(b) Projections on the **axisymmetric plane**: $\Sigma_1 = \Sigma_2$.

Evaluation of the response of the CPB06 Porous model using elementary numerical tests

a) Numerical model;

b) Numerical results:

- Axisymmetric tensile loadings (effect of J_3^{Σ});
- Discussion

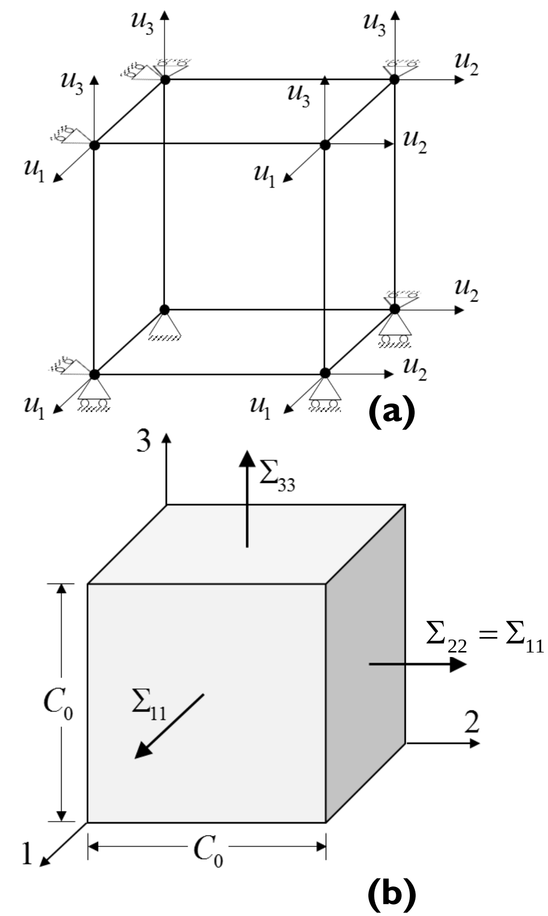
Numerical model

- Single tri-linear hexahedral **finite element**:
  - Initial cubic geometry with width C_0;
  - Symmetric boundary conditions applied;
- **Tensile axisymmetric loading** applied such that:

$$\boldsymbol{\Sigma} = \Sigma_{11}\left(\mathbf{e}_1 \otimes \mathbf{e}_1 + \mathbf{e}_2 \otimes \mathbf{e}_2\right) + \Sigma_{33}\left(\mathbf{e}_3 \otimes \mathbf{e}_3\right), \quad \text{with} \quad \rho = \frac{\Sigma_{33}}{\Sigma_{11}}, \tag{7}$$

  - Applied macroscopic stress is updated in order to maintain a constant stress triaxiality;
- Isotropic hardening according to **Swift's Law**:

$$\sigma_\mathrm{T} = K\left(\varepsilon_0 + \bar{\varepsilon}^\mathrm{p}_\mathrm{M}\right)^n, \quad \text{with} \quad \varepsilon_0 = \left(\frac{\sigma^\mathrm{T}_0}{K}\right)^{1/n}, \tag{8}$$



(a) Elastic and plastic properties;

E [GPa]	ν	K/σ^T_0	n
200	0.33	2.2	0.1

(b) CBP06 Porous damage parameters.

q_1	q_2	q_3	f_0	f_c
1.5	1.0	2.25	0.01	0.10

Numerical results

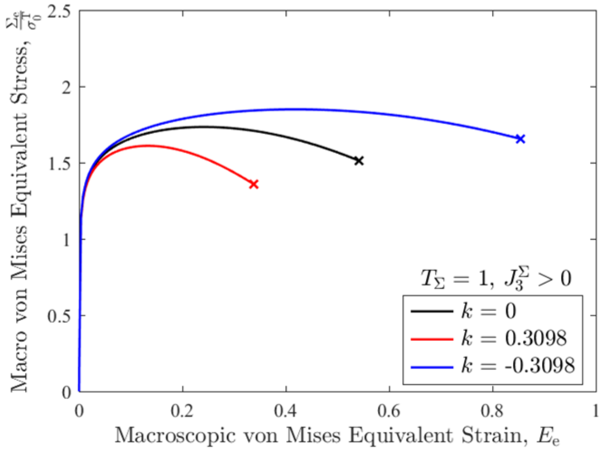
- <u>Axisymmetric tensile loadings</u> with a **constant** triaxiality ratio, distinguished by the sign of J_3^{Σ}:

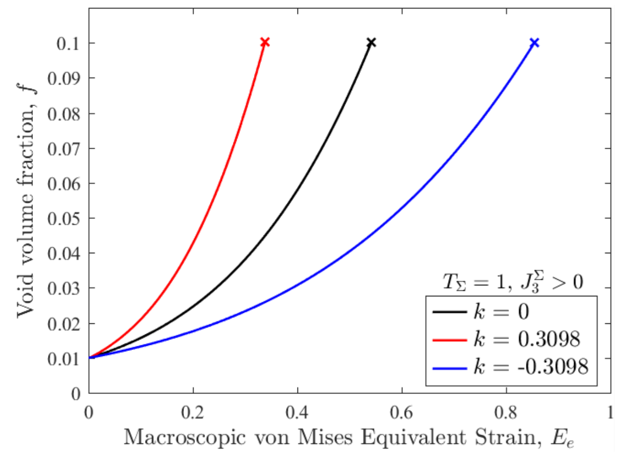
(a)

$\rho = (\Sigma_{33} / \Sigma_{11}) = 2.5;$

$T_{\Sigma} = 1;$

$J_3^{\Sigma} > 0;$



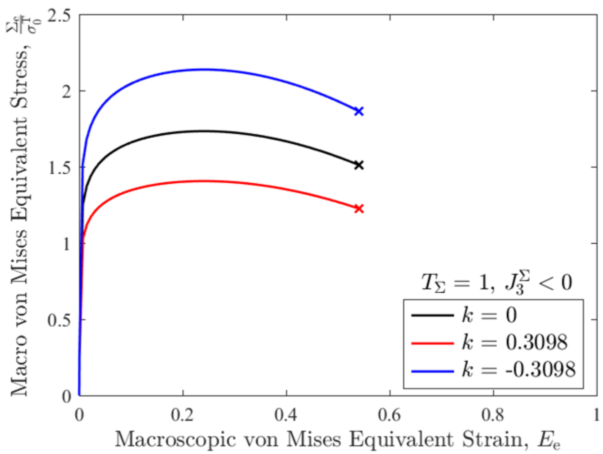


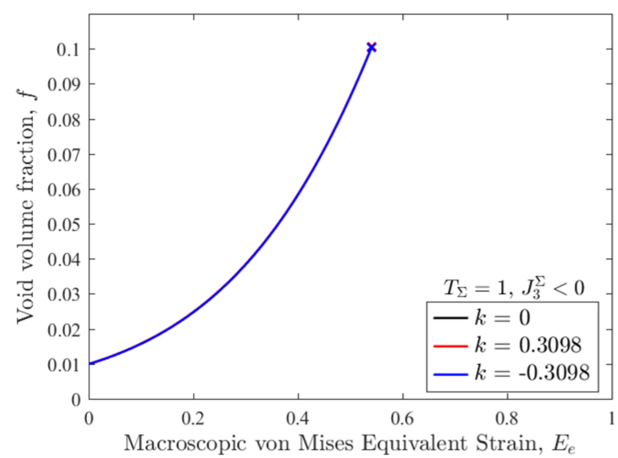
(b)

$\rho = (\Sigma_{33} / \Sigma_{11}) = 0.25;$

$T_{\Sigma} = 1;$

$J_3^{\Sigma} < 0.$





Discussion

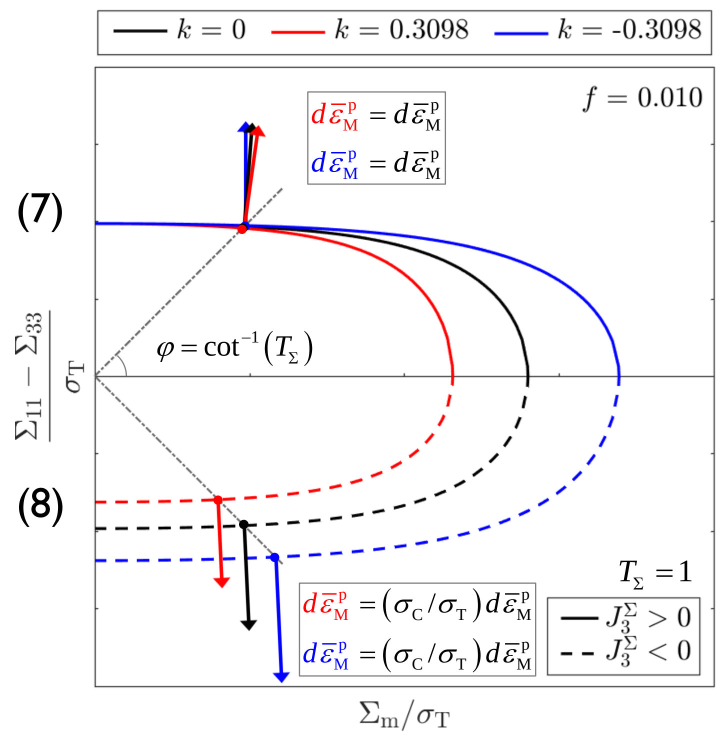
- Yield loci on the 4th quadrant of the axisymmetric projections ($J_3^\Sigma < 0$) are **homothetic transformations** of the von Mises reference curve ($k = 0$):
  - The **normal** to the surface at the intersection point with a given stress triaxiality is independent of SD effects;
  - ↳ The direction of the matrix plastic strain increment, $\bar{\varepsilon}^{\mathrm{p}}_{\mathrm{M}}$, is independent of the SD effects.
- Damage evolution law for $J_3^\Sigma > 0$:

$$\dot{f}_{\text{growth}} = (1-f)D^{\mathrm{p}}_{kk} = (1-f)\dot{\lambda}\left(\frac{\sigma_{\mathrm{T}}}{\sigma_{\mathrm{C}}}\frac{3q_1q_2 f}{\sigma_{\mathrm{T}}}\right)\sinh\left(\frac{3}{2}q_2\frac{\sigma_{\mathrm{T}}}{\sigma_{\mathrm{C}}}\frac{\tilde{\Sigma}_{\mathrm{e}}}{\sigma_{\mathrm{T}}}T_\Sigma\right), \quad (7)$$

- Damage evolution law for $J_3^\Sigma < 0$:

$$\dot{f}_{\text{growth}} = (1-f)D^{\mathrm{p}}_{kk} = (1-f)\dot{\lambda}\left(\frac{\sigma_{\mathrm{T}}}{\sigma_{\mathrm{C}}}\frac{3q_1q_2 f}{\sigma_{\mathrm{T}}}\right)\sinh\left(\frac{3}{2}q_2\frac{\tilde{\Sigma}_{\mathrm{e}}}{\sigma_{\mathrm{T}}}T_\Sigma\right), \quad (8)$$

Plastic multiplier, λ implicitly **eliminates** the SD effects, i.e. the $\sigma_{\mathrm{T}}/\sigma_{\mathrm{C}}$ scaling ratio



Conclusions

- The numerical simulations for axisymmetric tensile loadings showed that:

$J_3^\Sigma > 0$	• The model distinguishes the role of the T-C asymmetry in the damage evolution; • As in the micromechanical studies, different ductilities are predicted depending on the displayed SD effects.
$J_3^\Sigma < 0$	• The model does not distinguish different damage evolutions according to the displayed SD effects; • The softening regime and ductility of the materials are independent of the SD effects, which disagrees with the results in the same micromechanical studies (e.g. Alves and Cazacu, 2015).

- In **future work**:
  - Study of the combined effect of the T-C asymmetry *and* **anisotropy** on the damage evolution (Cazacu and Stewart, 2011);
  - Depart from the current preliminary/conceptual analysis into more **practical** and real-world **applications** (simulation of standard mechanical tests and sheet metal forming operations).

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Thank you

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