MECAMAT

GT « PHYSIQUE ET MECANIQUE DE L'ENDOMMAGEMENT ET DE LA RUPTURE »

Vers une identification locale de modèles de zone cohésive utilisant la corrélation d'images numériques

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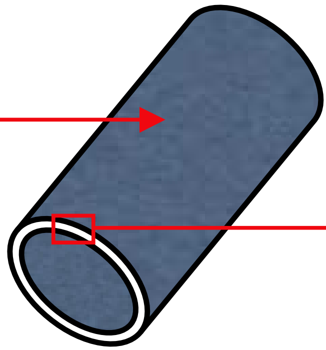
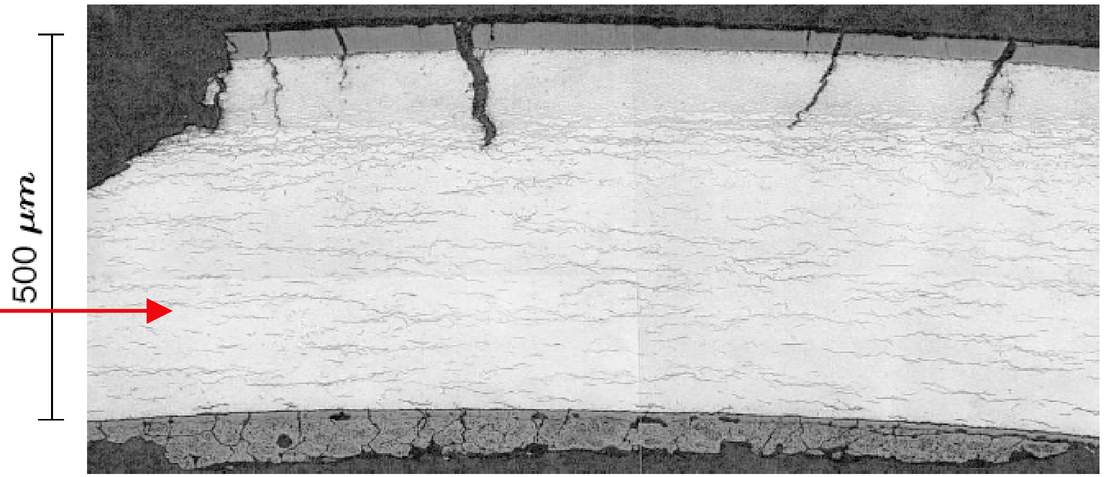
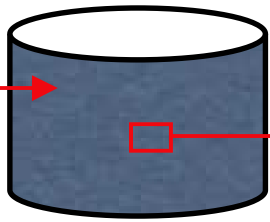
Nuclear safety applications

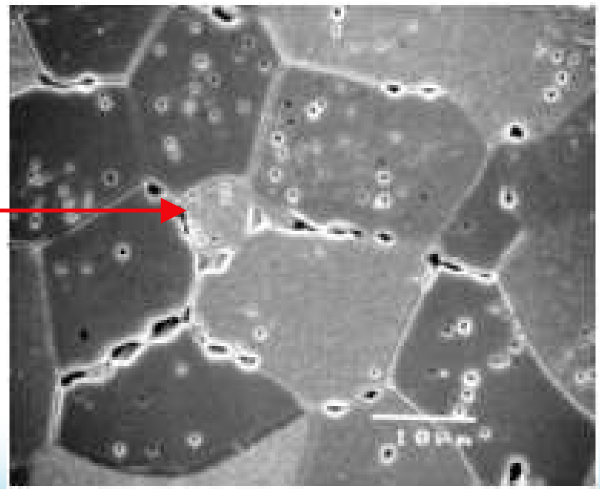
Tube: two-phase composite, multi-layered, functionally graded





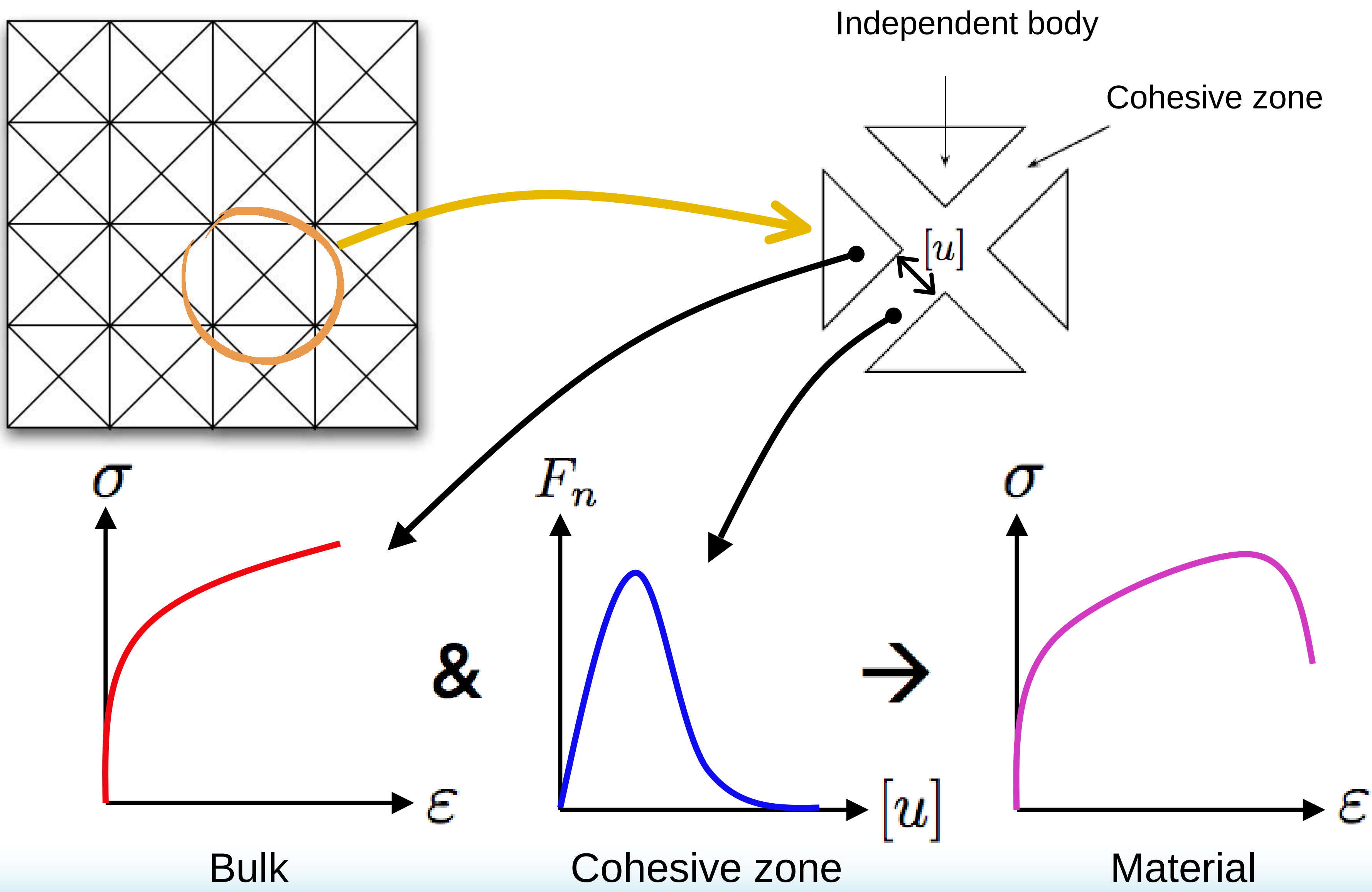
Nuclear fuel: porous medium under pressure



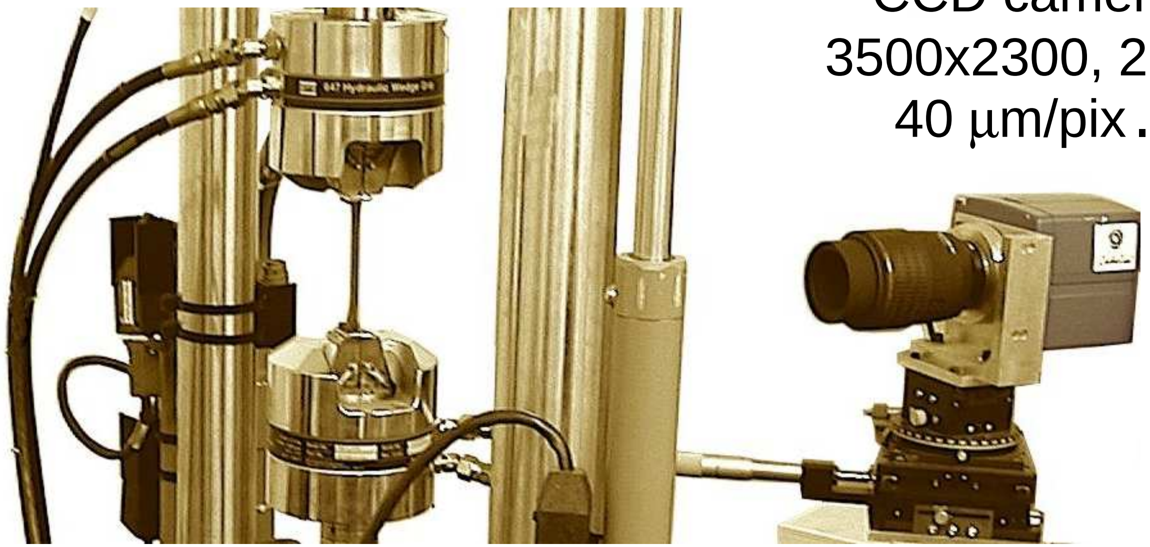


L = 4 m, ∅ = 10 cm,
$R_e - R_i$ = 500 µm

Cohesive zone approach



Experimental setup and tests



CCD camera
3500x2300, 2 Hz
40 µm/pix.

Uniaxial testing machine

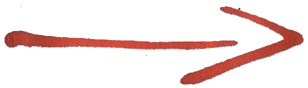
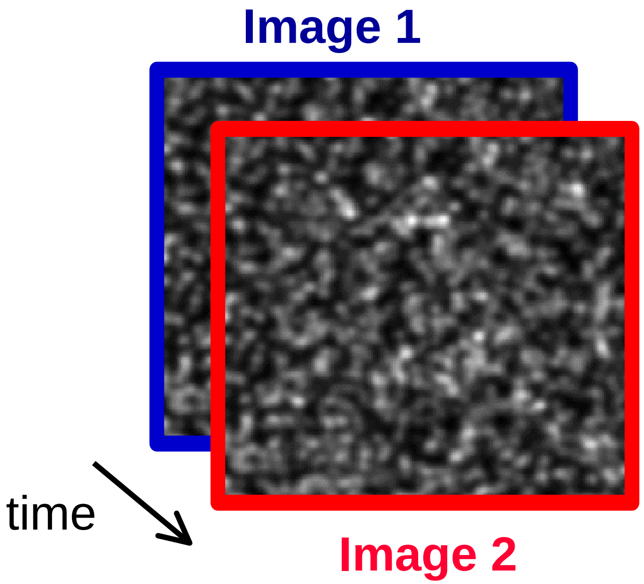


Image processing (Kelkins)

Digital image correlation

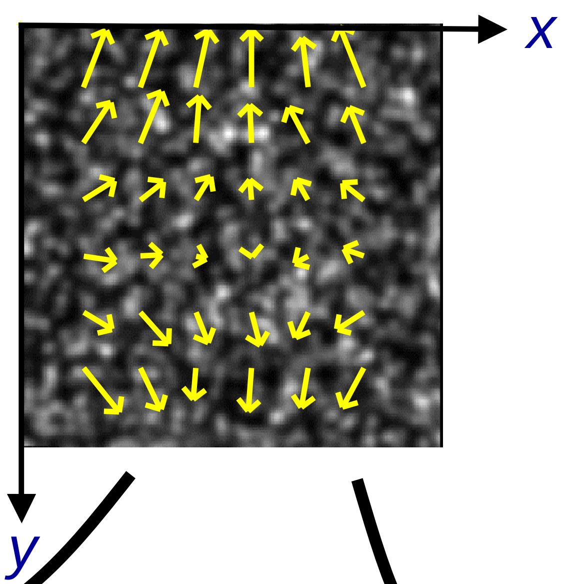
[Wattrisse *et al.* (2001)
Eur. J. Mech. A/Solids

Digital speckle images



Correlation

Displacement field



$$F_{iK} = \frac{\partial x_i}{\partial X_K}$$

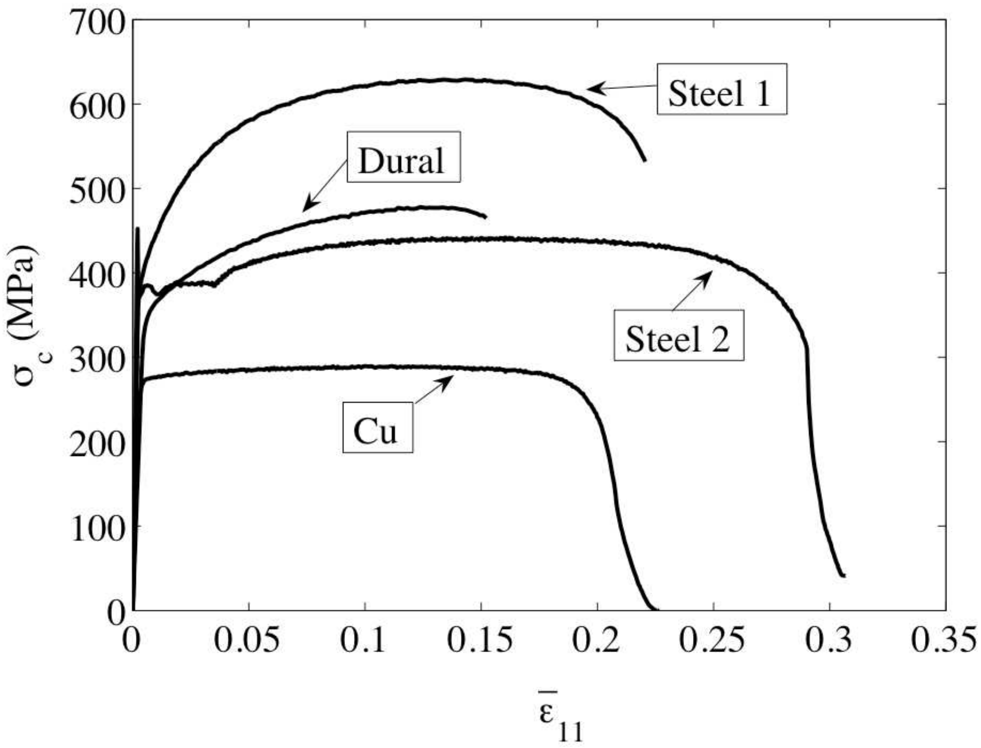
Space or time derivation

$$\gamma_i = \frac{D^2 x_i}{Dt^2}$$

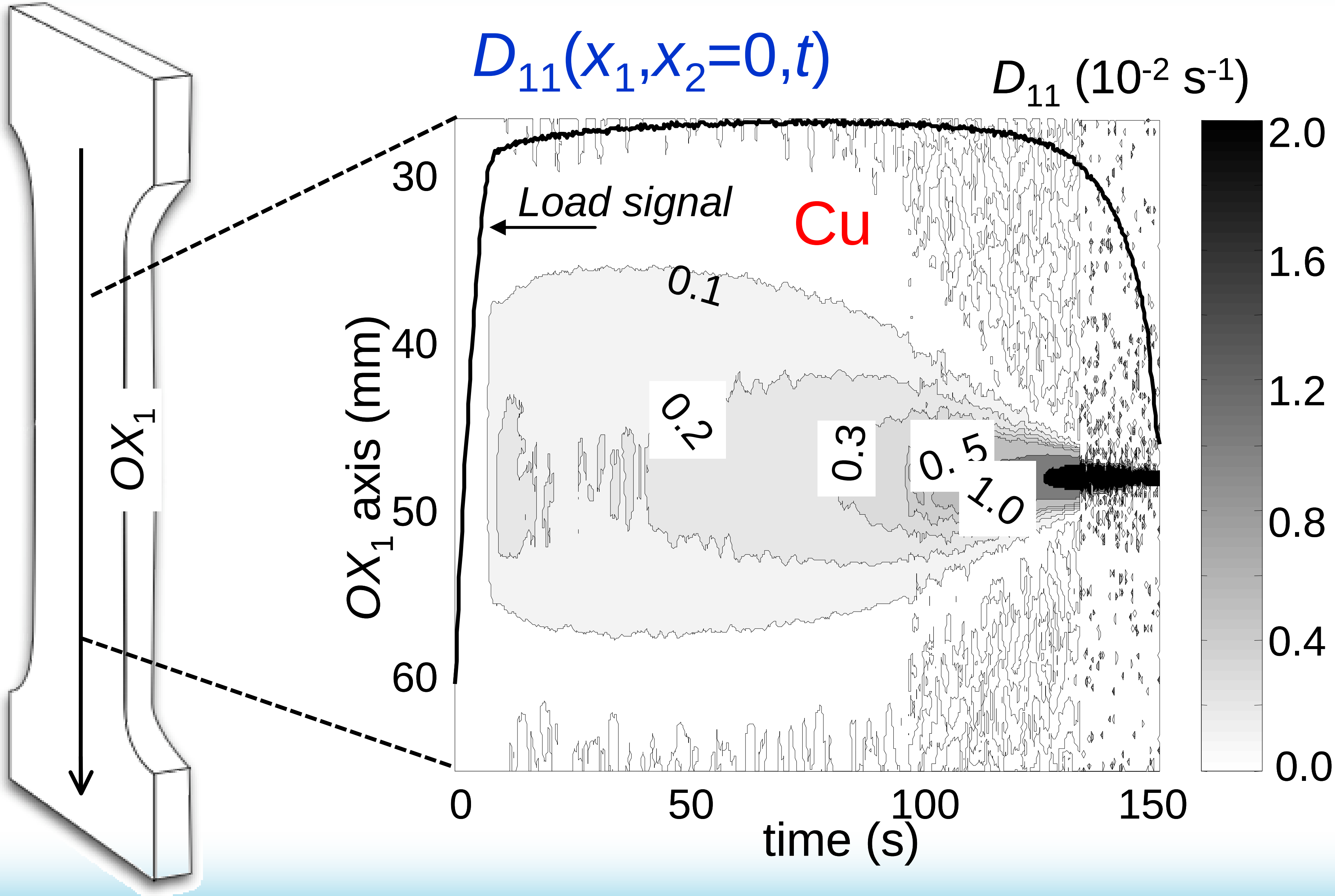
$\{X_K\}$ Lagrangian, $\{x_i\}$ Eulerian coordinates

Materials

Steel 1 Steel 2 Dural Cu

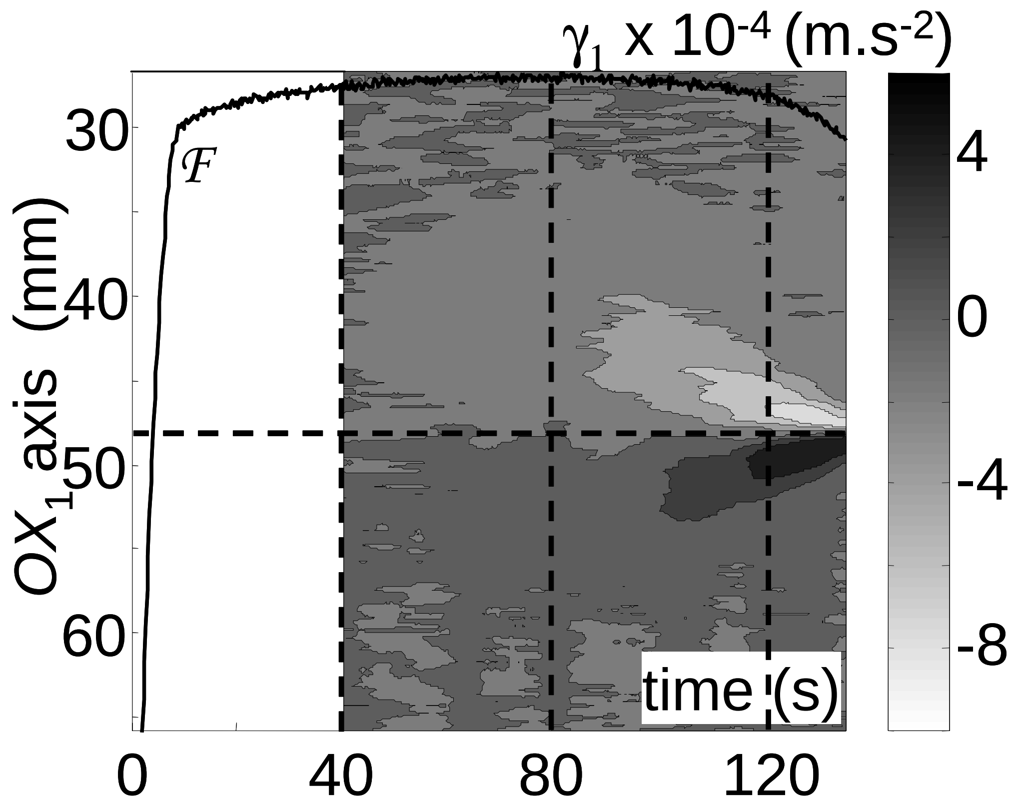


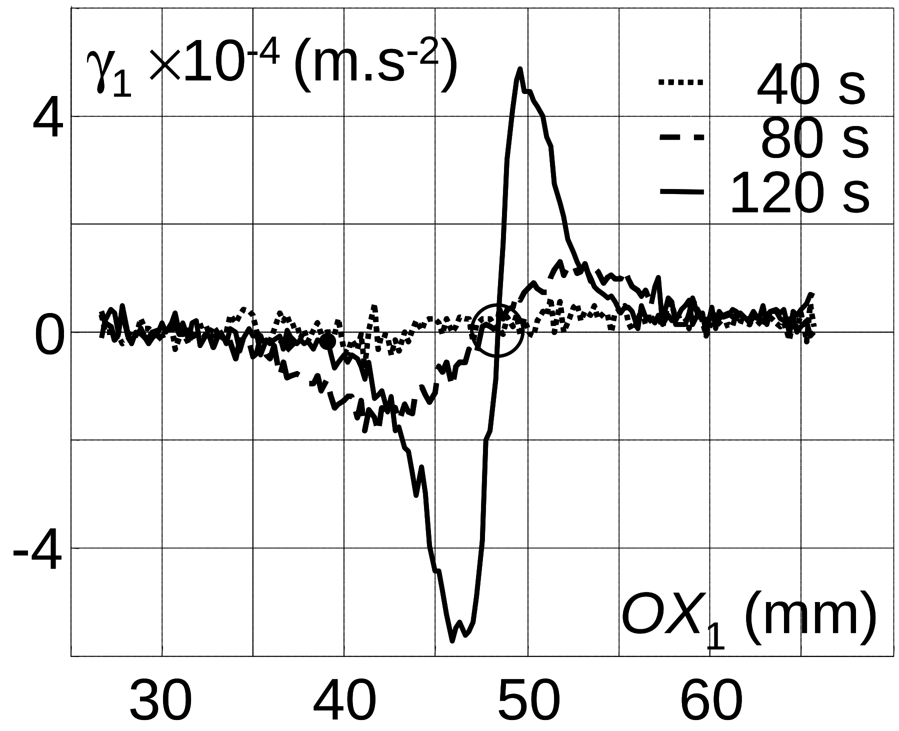
Longitudinal strain rate distribution



Distribution of longitudinal acceleration

Cu



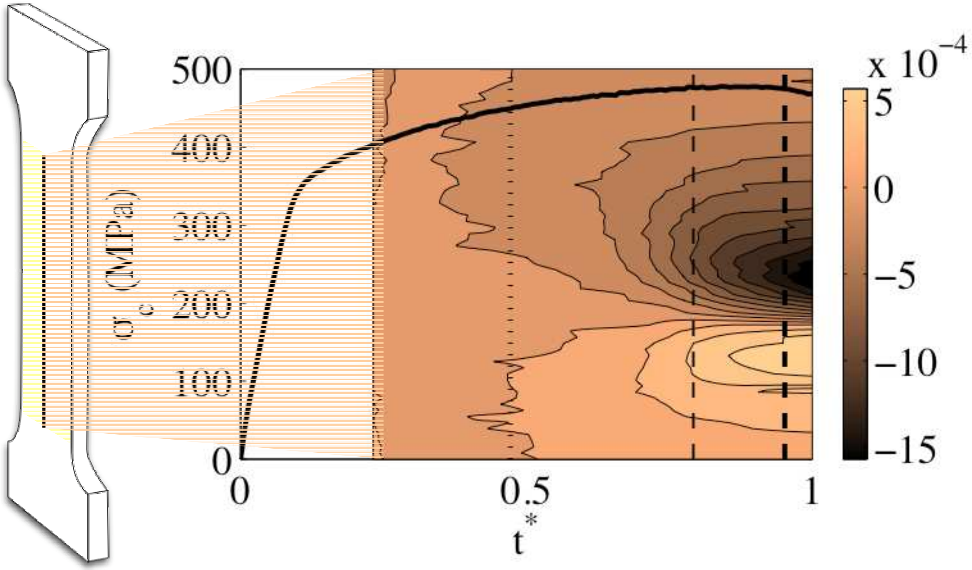


Low acceleration (≈ 10^{-3} m.s-2); quasi-static process

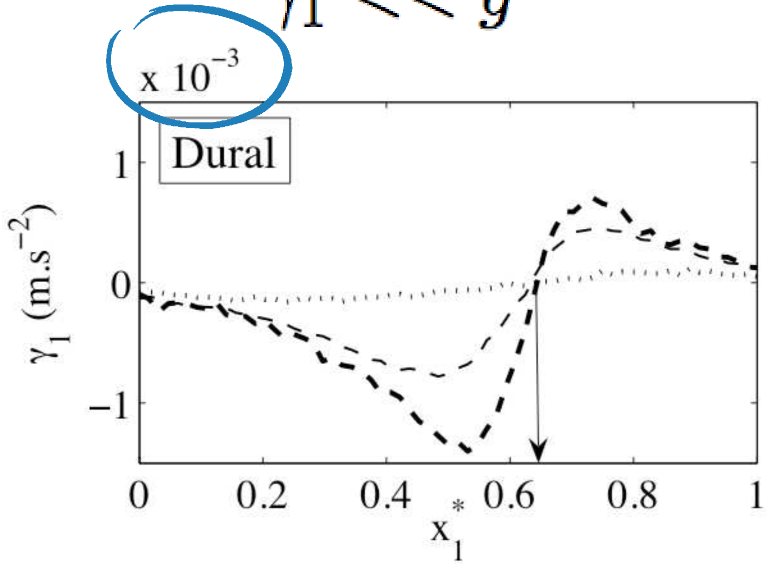
Crack cross section characterized by a zero acceleration with a change of sign.

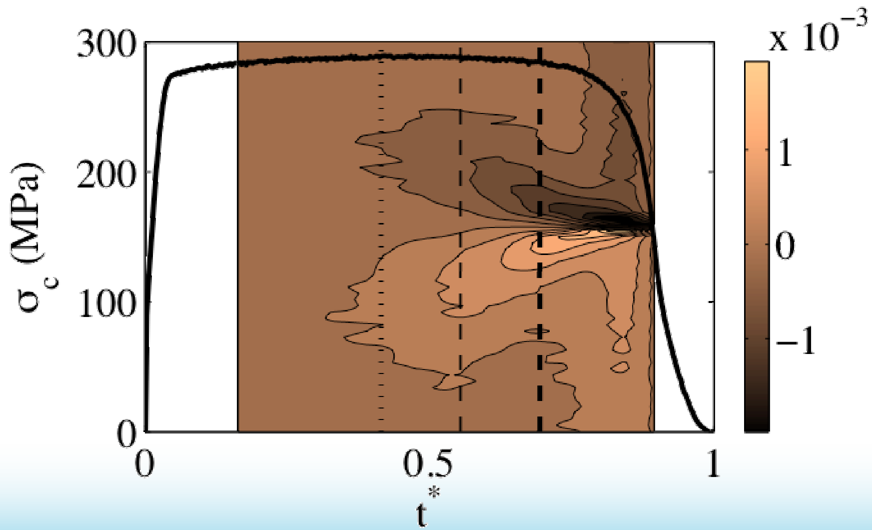
Possibility of tracking the most damaged zone without generating artificial stress concentration

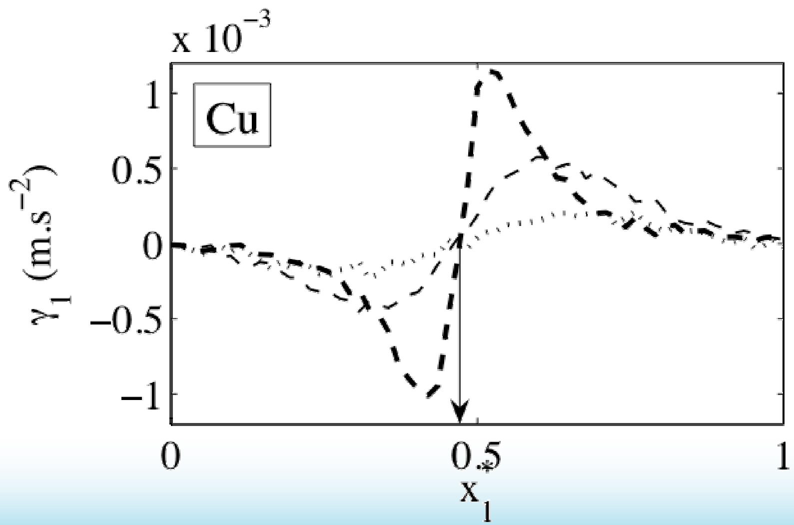
Localization : an early, gradual mechanism



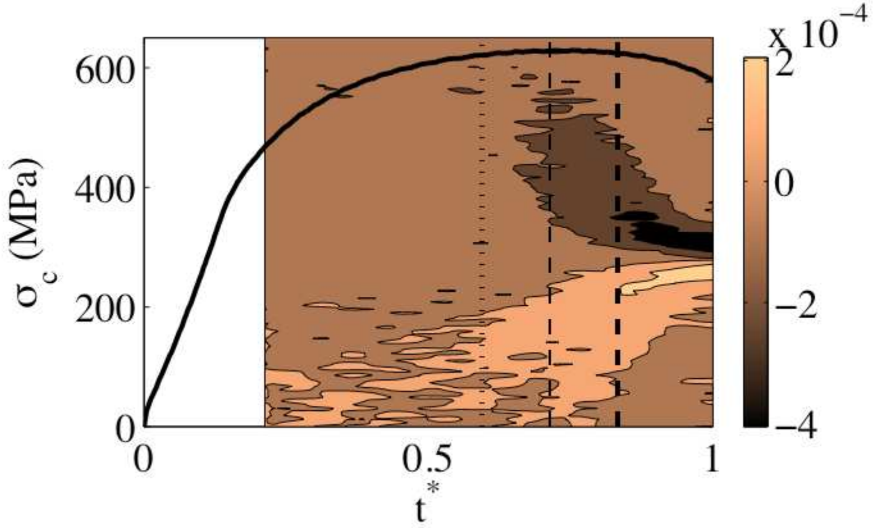
$\gamma_1 << g$

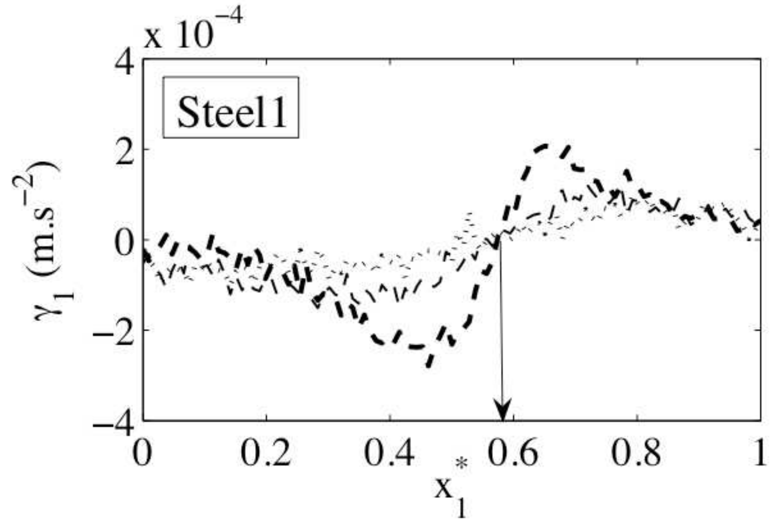


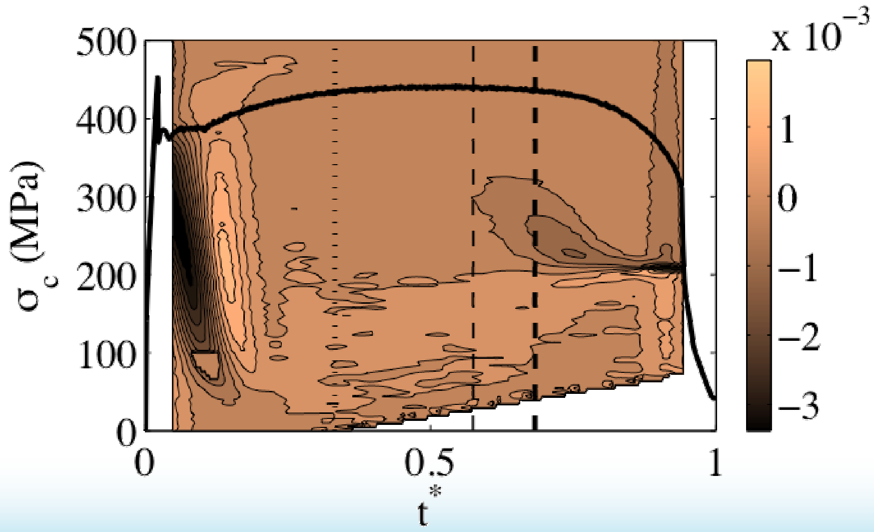


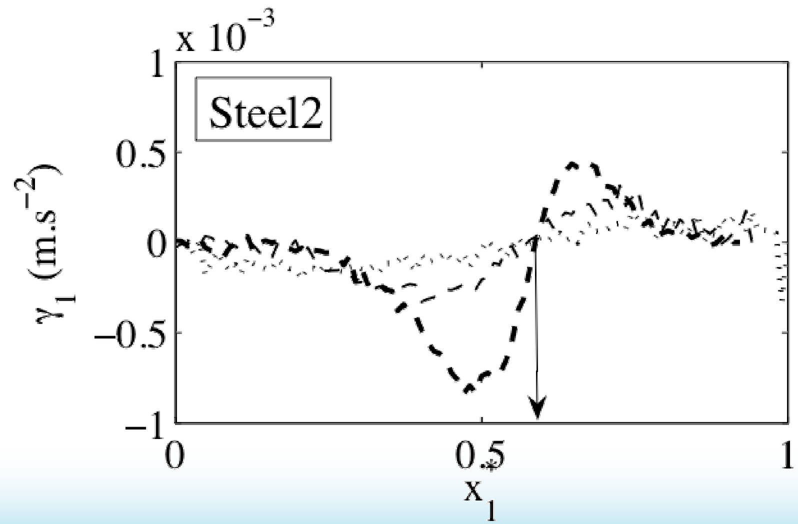


Localization : an early, gradual mechanism



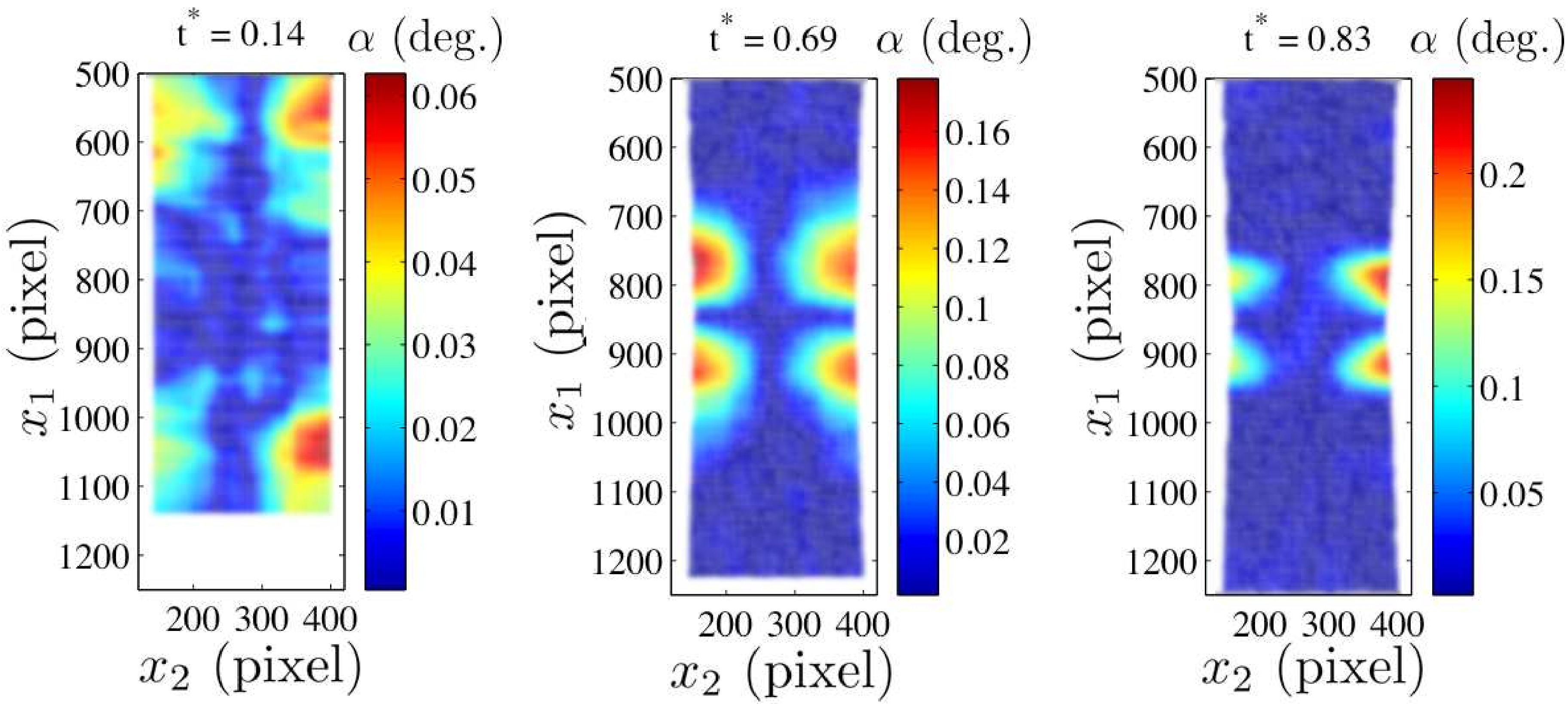






Strain field analysis

$$F = R\,U \qquad R = \begin{pmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



Distribution of rotation at 3 different times for Cu specimens

Main results of the kinematical full-field analysis

- Low rotation ($\alpha < 5\times 10^{-3}$ (rad.))

- Low shear strain ($|\varepsilon_{12}| < 10^{-2} \times \varepsilon_{11}$)

- x_1, x_2 and x_3 remain the principal axes of strain

Not far from a non homogeneous tensile test

- Local construction of tensile stress-strain diagrams

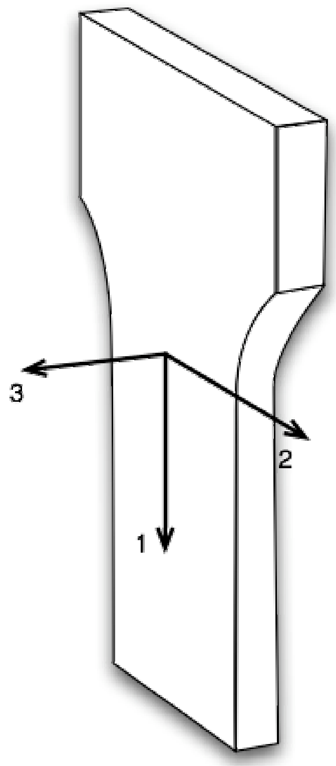
- Early localization of the most damageable cross-section

Analysis of the damage development within a 1D context

Volume variation & damage

Pure elastoplastic transformation → Isochoric !

Volume variation = porosity induced by microvoids or microcracks



$$\frac{\mathrm{d}v}{\mathrm{d}V} = e^{\mathrm{tr}\,\varepsilon} = e^{\varepsilon_{11}+\varepsilon_{22}+\varepsilon_{33}}$$

$$\bar{\varepsilon}_{22} = \bar{\varepsilon}_{33}$$

Use of coordinate-measuring machine

[Wattrisse *et al.*, 2001, Exp. Mech.]

Relative volume variation $= \frac{\mathrm{d}v}{\mathrm{d}V} - 1 = e^{\varepsilon_{11}+2\varepsilon_{22}} - 1 = \frac{\mathrm{d}v_{\mathrm{v}}}{\mathrm{d}V}$

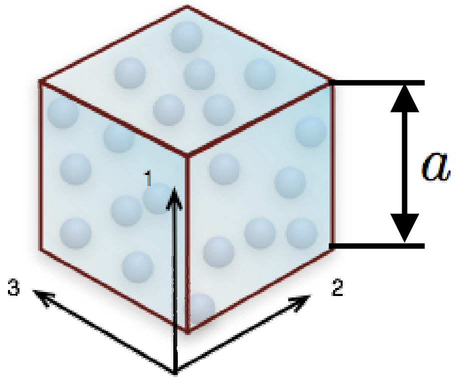
Damage field estimate

$$D = \frac{\mathrm{d}s_v}{\mathrm{d}S}$$

A scalar variable to describe

isotropic damage

[Lemaitre, A course on damage mechanics]



ASSUMPTIONS for microvoids:

(i) Uniformly distributed within a volume element
(ii) Same initial spherical shape
(iii) Same isotropic growth kinetics

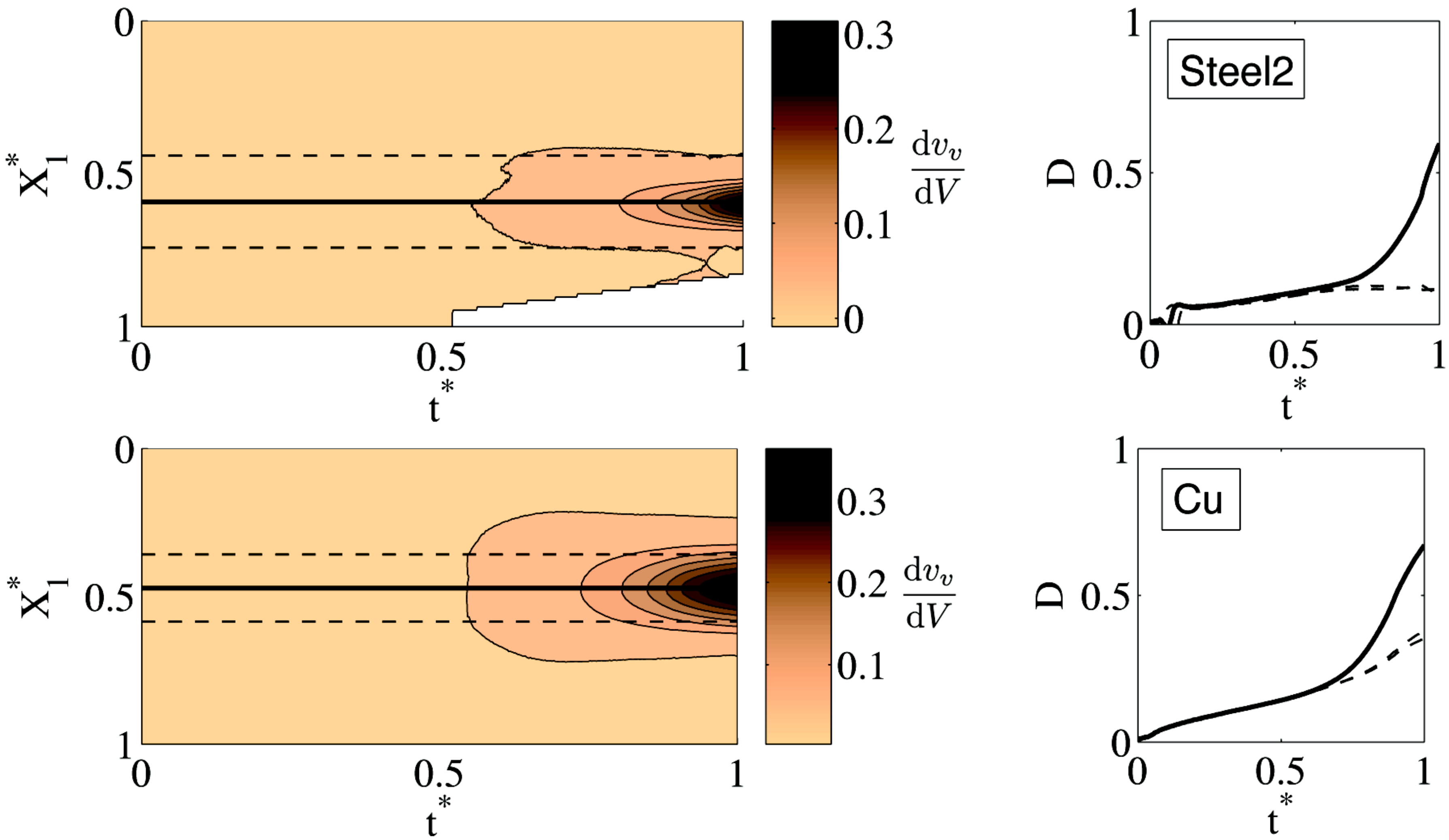
$$\frac{\mathrm{d}v_\mathrm{v}}{\mathrm{d}V} = \frac{4}{3}\pi(a\eta)^3$$

$$D = \pi(a\eta)^2$$

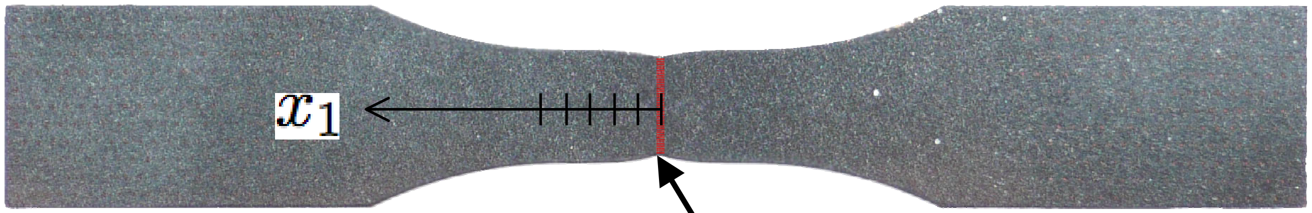
$$\rightarrow D = (3/4)^{\frac{2}{3}}\pi^{\frac{2}{3}}\left(\frac{\mathrm{d}v_\mathrm{v}}{\mathrm{d}V}\right)^{\frac{2}{3}}$$

η : Density of microvoids per unit length

Void fraction & damage : results

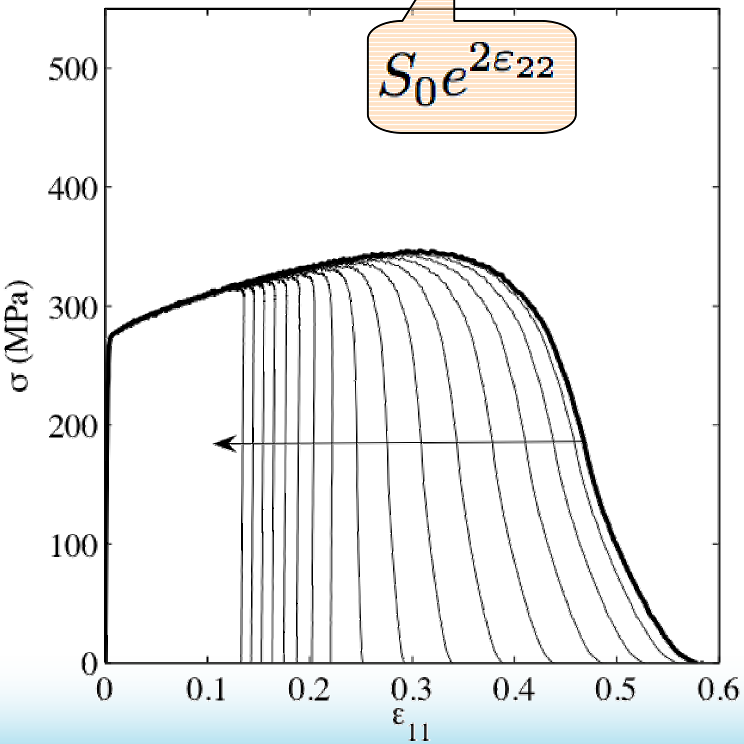


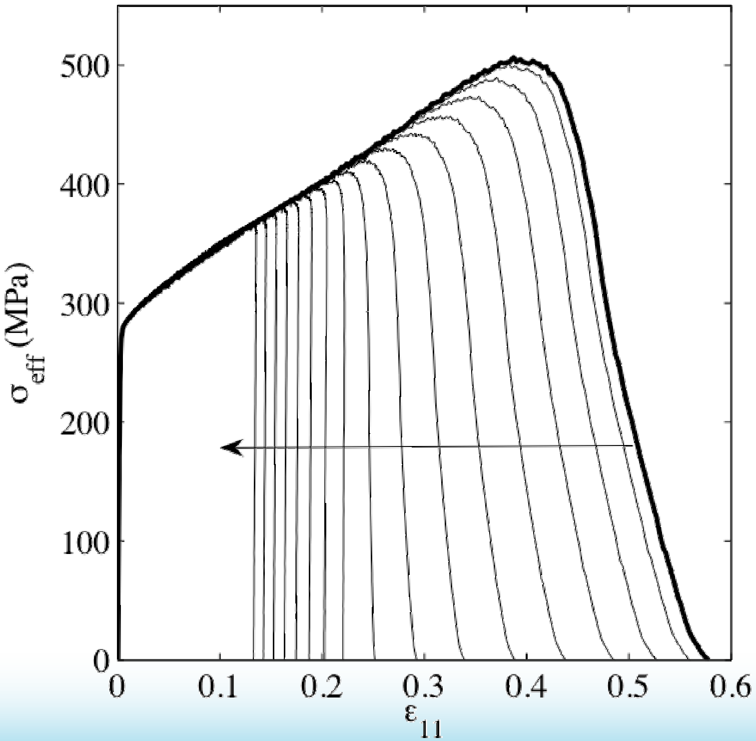
Local stress-strain responses



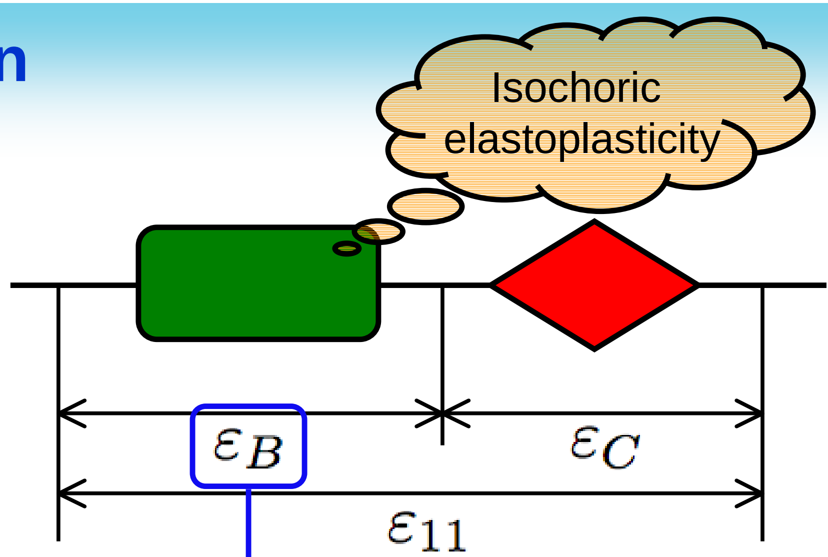
$$\sigma(x_1,t) = \frac{F(t)}{S(x_1,t)} \qquad \sigma_{\text{eff}}(x_1,t) = \frac{\sigma(x_1,t)}{1-D(x_1,t)}$$

$S_0 e^{2\varepsilon_{22}}$





Towards a CZM identification



Explicit separation of damage effects

$$\varepsilon_C = \varepsilon_{11} - \varepsilon_B$$

$$F = \sigma_{\text{eff}} S_{\text{eff}} = \sigma_{\text{inc}} S_{\text{inc}}$$

$S_0 e^{-\varepsilon_{11}}$

$S_0 e^{2\varepsilon_{22}}$

$$\varepsilon_{11} = \frac{\sigma_{\text{eff}}}{E} + \varepsilon_p = \frac{\sigma_{\text{inc}}}{E} + \varepsilon_p^\star + \varepsilon_C$$

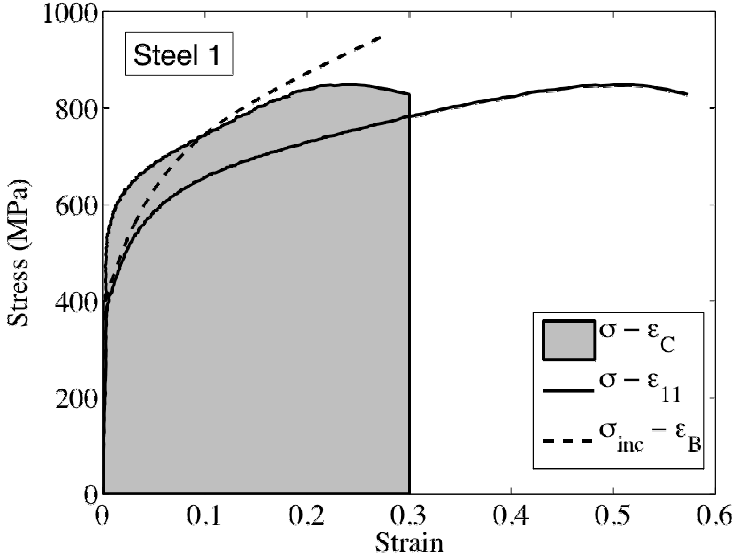
Principle of strain equivalence

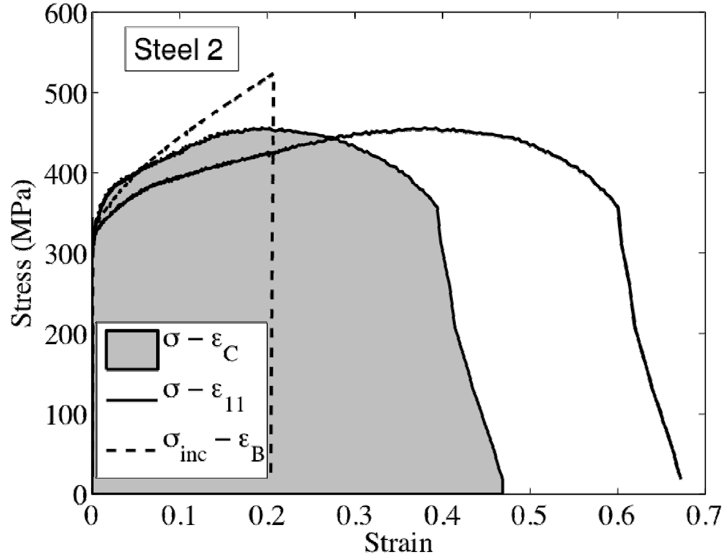
Assumption: same hardening function *H*

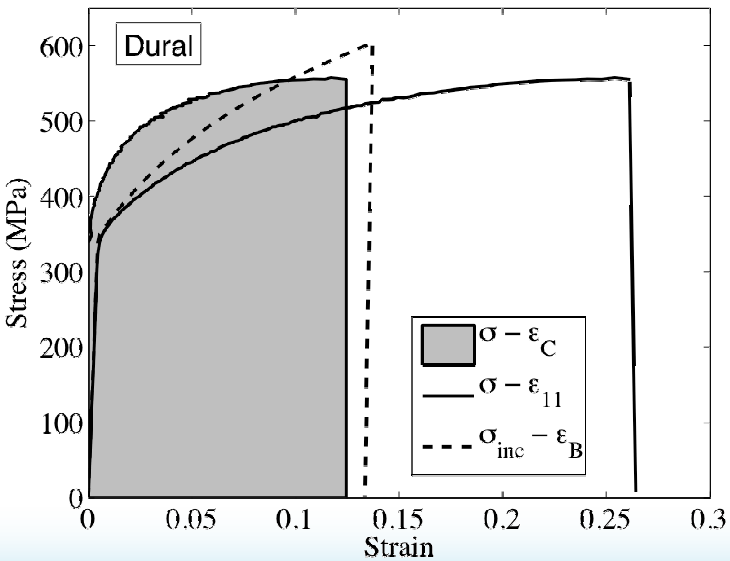
$$\sigma_{\text{eff}} = \sigma_Y + H(\varepsilon_p) \longrightarrow H(\varepsilon_p^\star) - (\sigma_{\text{inc}} - \sigma_Y) = 0$$

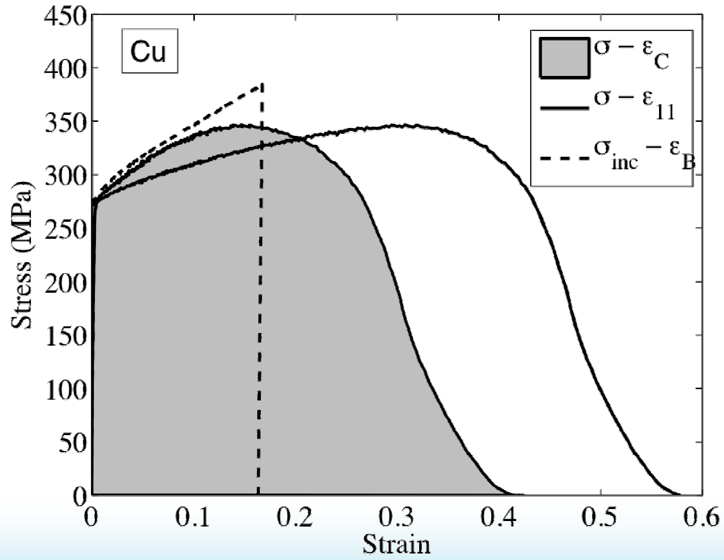
$$\varepsilon_C = \varepsilon_{11} - \frac{\sigma_{\text{inc}}}{E} - H^{-1}(\sigma_{\text{inc}} - \sigma_Y)$$

Identified CZ responses









Discussion

- Analysis of acceleration profiles: convenient to track the localization zone
- DIC: useful to estimate µvoid proportions (if transverse isotropy)
- Identified responses of CZ: similarities with usual CZM of the literature
- Physical interpretation of CZ ‘interface’ law and ‘displacement jump’
- Voids modeling, internal length, ...

Pending work (Shuang’s thesis / sup. by Ym + Bw)

- Mechanical standpoint : tangential response of CZM
- Thermomechanical standpoint : use of dissipation
- Numerical validations (material vs. structure effects)
- Ductile to brittle materials (high speed testing)