



# Dix années d'eikologie : bilan et perspectives

Equipe « Eikologie » du 

# Vous avez dit eikologie ?

Eikologie :

du grec eikôn [εἰκῶν] « image » et lógos [λόγος] « discours rationnel sur » soit un néologisme désignant la science de (et avec) l'image

Eikologie à l'Institut Farman :

tous les labos utilisent/traitent des images

Eikologie au LMT :

Images pour la mécanique des matériaux et des structures (photomécanique)

# Farman F-68BN4 Goliath (1937)



# Défis actuels

Faire des calculs pour

**concevoir, prévoir, certifier**

- résultats corrects
- résultats fiables
- (très) rapidement

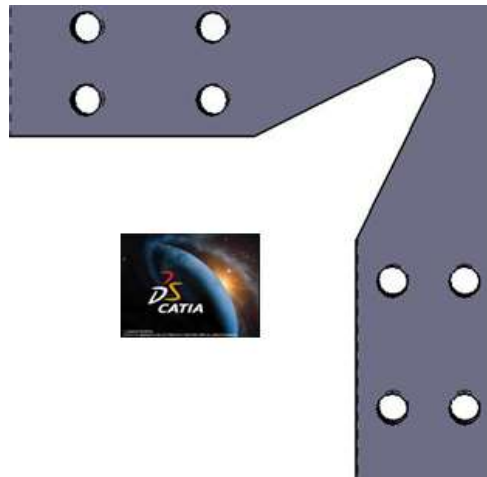
⇒ De l'empirisme à des modèles robustes\*

⇒ Sciences de l'ingénierie basées sur la simulation\*\*

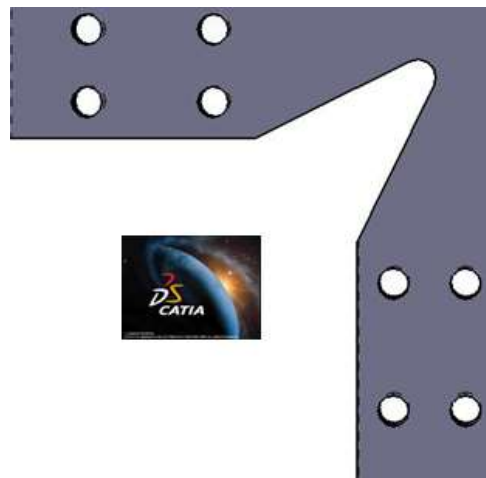
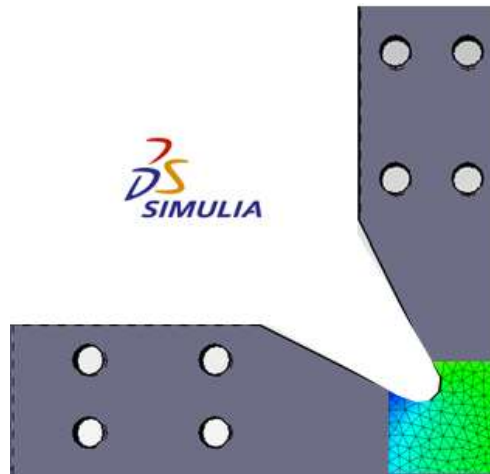
\*[Walraven *et al.*, 2011, *Struct. Concrete* 12(3) 139-147]

\*\*[Oden *et al.*, 2006, *Simulation-Based Engineering Sciences*. Final report, NSF]

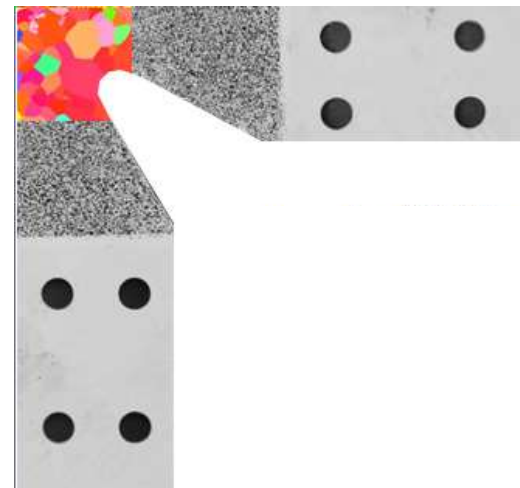
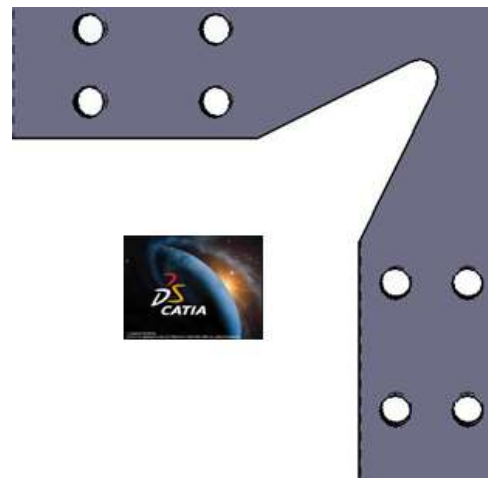
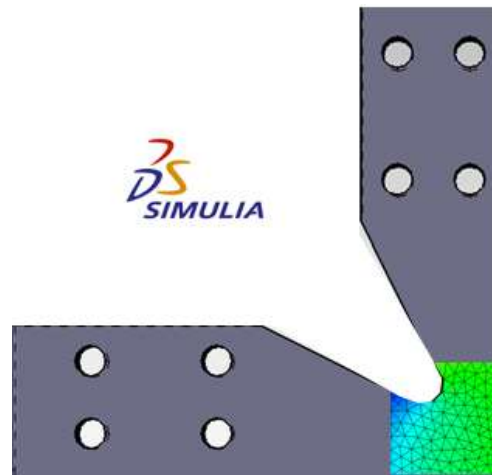
# Modèle CAO



# Modèle EF

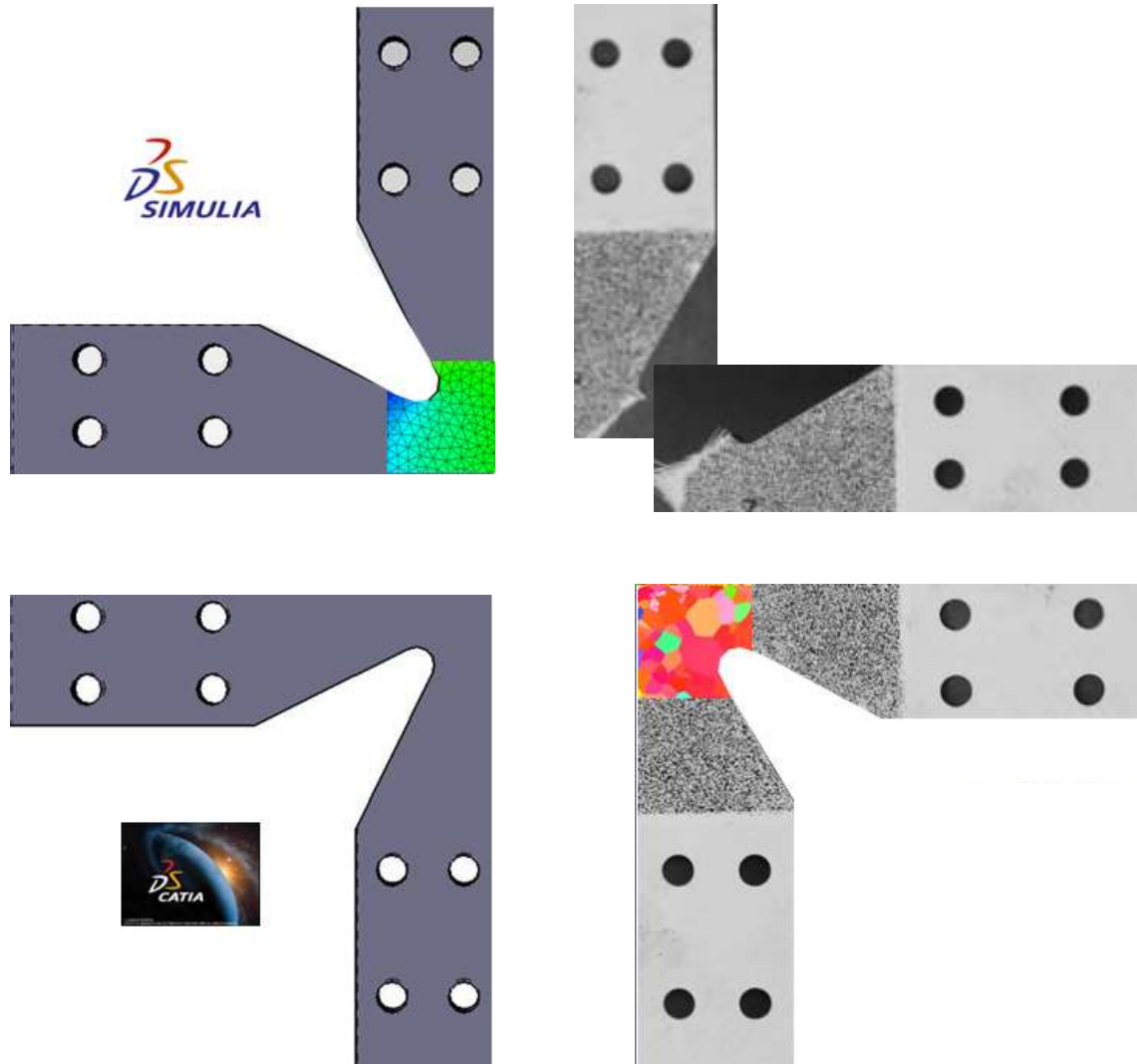


# Information de microstructure



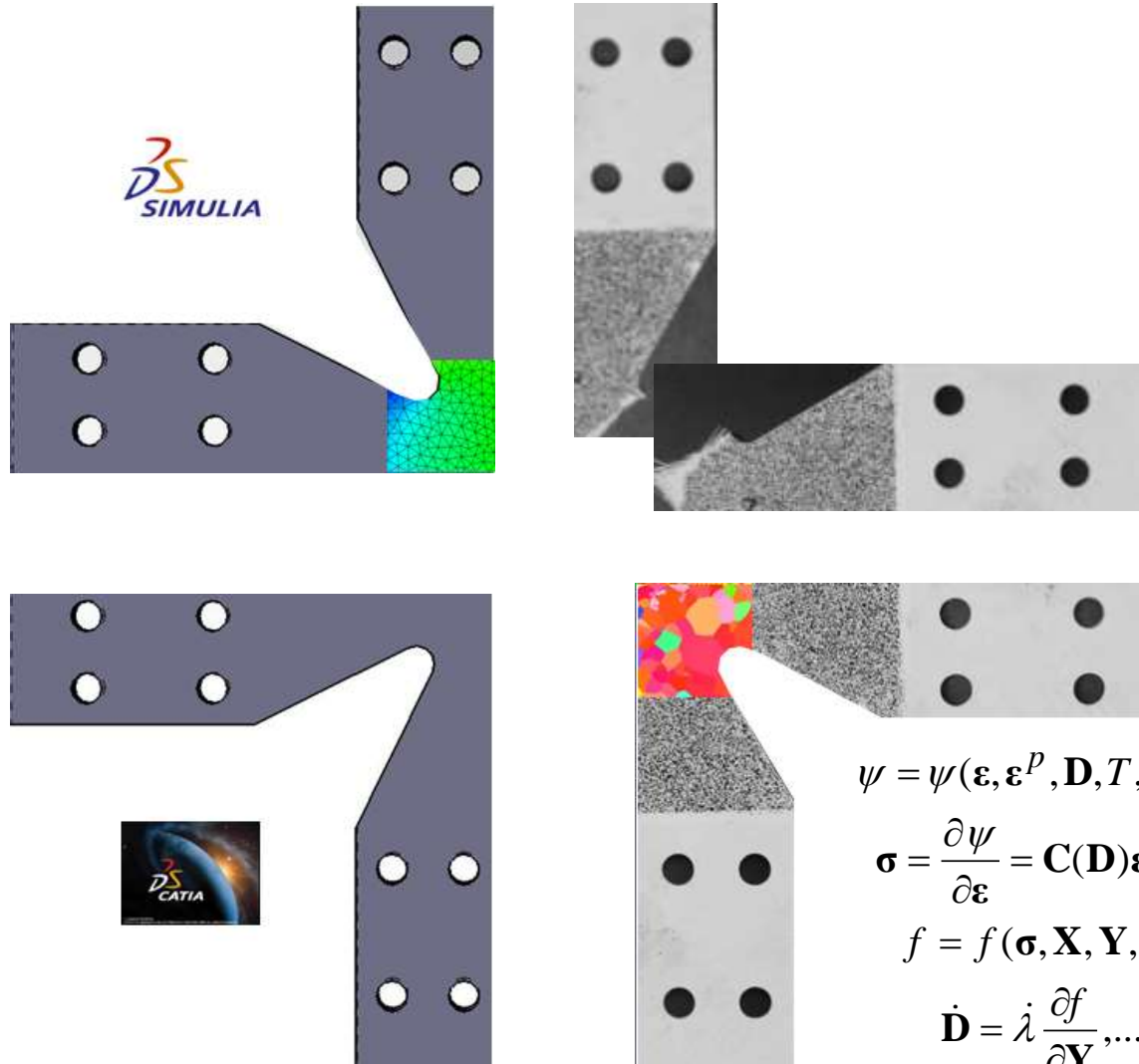


# Suivi d'essais





# Lois de comportement



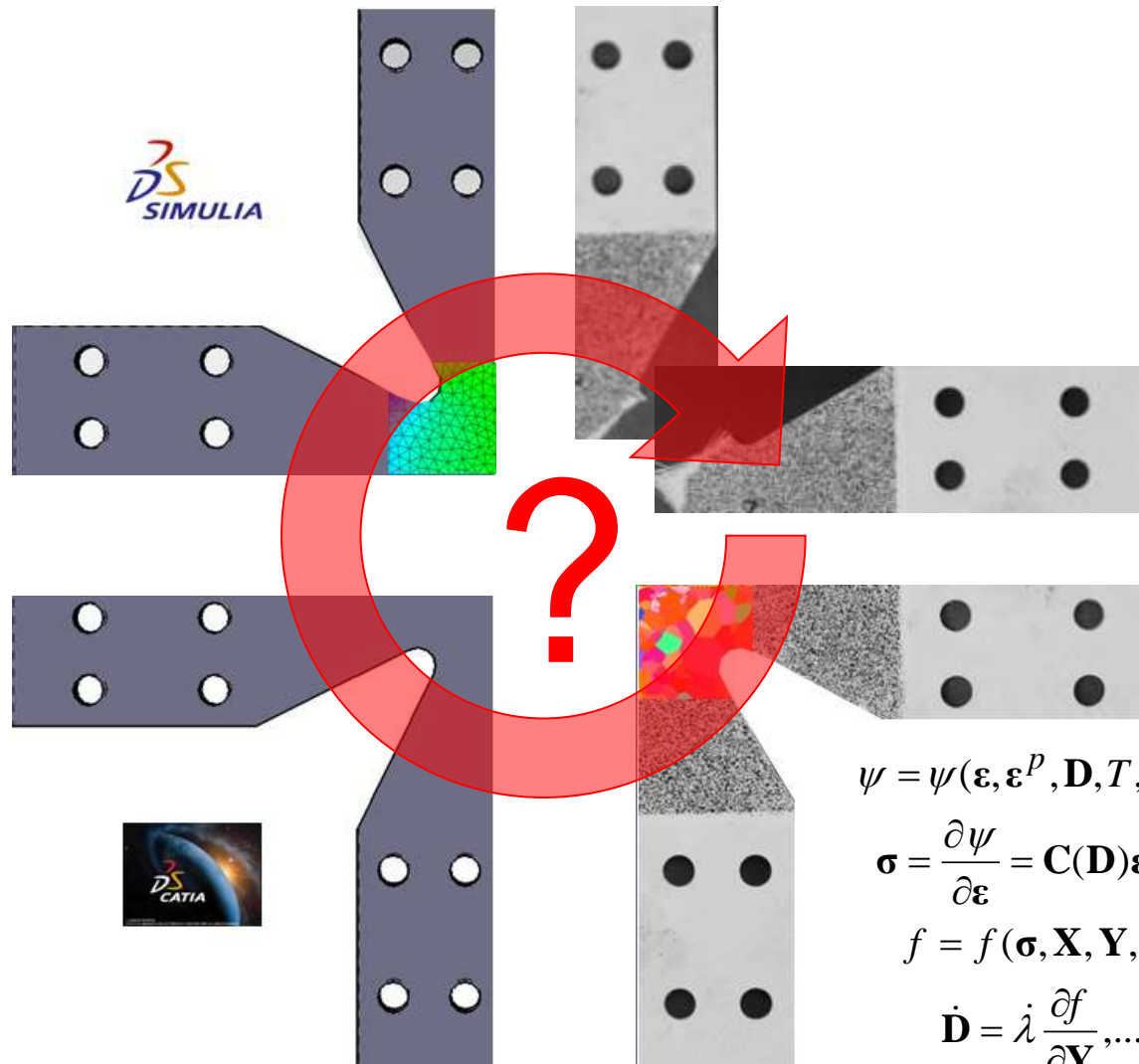
$$\psi = \psi(\boldsymbol{\varepsilon}, \boldsymbol{\varepsilon}^p, \mathbf{D}, T, x, \dots)$$

$$\boldsymbol{\sigma} = \frac{\partial \psi}{\partial \boldsymbol{\varepsilon}} = \mathbf{C}(\mathbf{D}) \boldsymbol{\varepsilon}^e, \dots$$

$$f = f(\boldsymbol{\sigma}, \mathbf{X}, \mathbf{Y}, \dots)$$

$$\dot{\mathbf{D}} = \lambda \frac{\partial f}{\partial \mathbf{Y}}, \dots$$

# Dialogue(s) essais / calculs



$$\psi = \psi(\boldsymbol{\varepsilon}, \boldsymbol{\varepsilon}^p, \mathbf{D}, T, x, \dots)$$

$$\boldsymbol{\sigma} = \frac{\partial \psi}{\partial \boldsymbol{\varepsilon}} = \mathbf{C}(\mathbf{D}) \boldsymbol{\varepsilon}^e, \dots$$

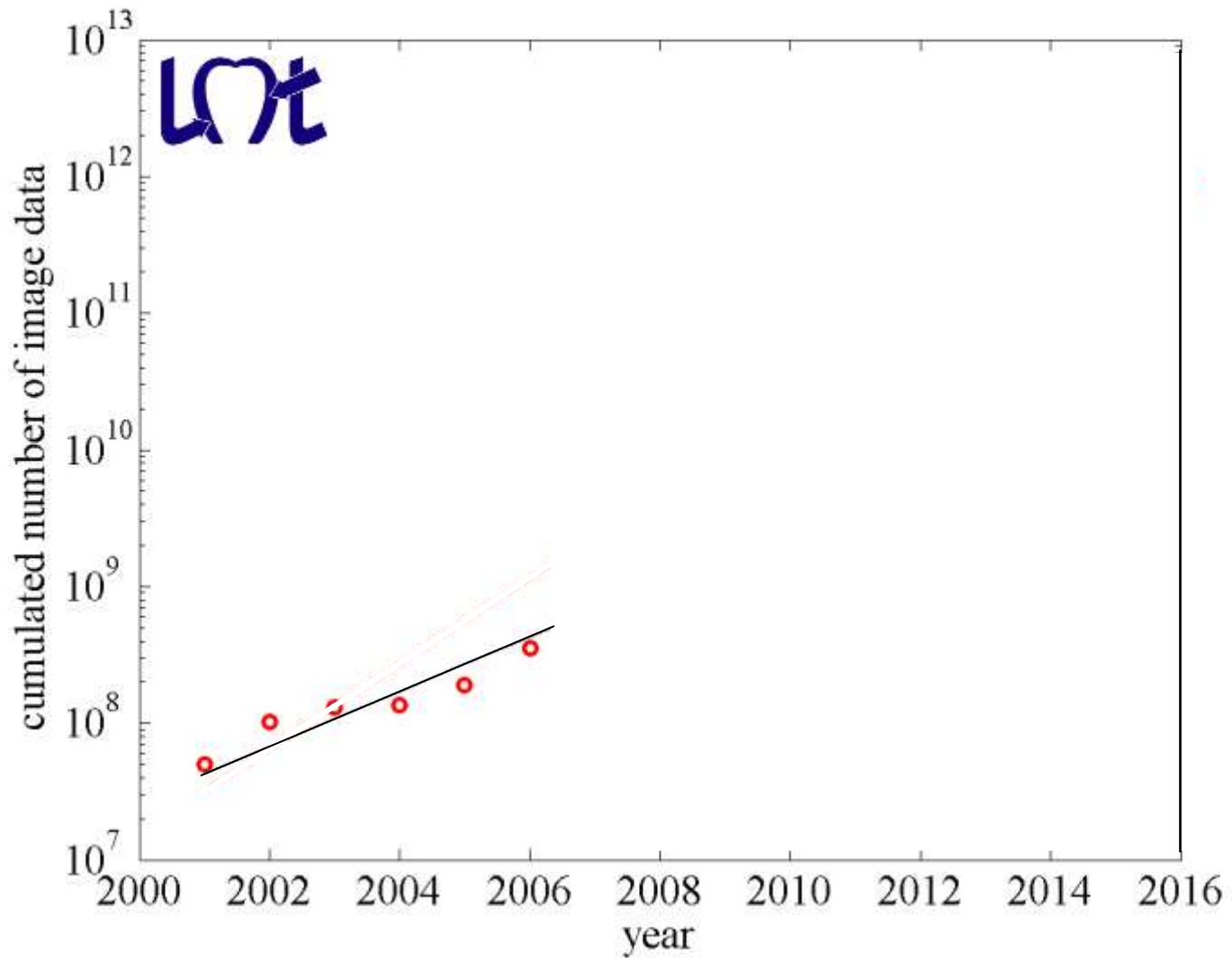
$$f = f(\boldsymbol{\sigma}, \mathbf{X}, \mathbf{Y}, \dots)$$

$$\dot{\mathbf{D}} = \lambda \frac{\partial f}{\partial \mathbf{Y}}, \dots$$

# Et les images dans tout ça ?

- Chaque pixel (voxel) est un capteur pas très précis mais il y en a beaucoup !
- Ordre de grandeur
  - Essai élémentaire : 2-200 Gbytes
  - Essai in situ (tomographie) :  $\approx 1$  Tbyte
- Utilisation des images :
  - Mesure de formes 3D
  - Mesure de champs de déplacements 2D/3D
  - Mesure de paramètres mécaniques
  - Validation des simulations numériques

# En 2007



# Corrélation d'images

Mesure du flot optique

$$I_0(\mathbf{x}) \cong I_t(\mathbf{x} + \mathbf{u}(\mathbf{x}))$$

Approches locales

$$\eta_c^2(\mathbf{u}) = \sum_{\text{ZOI}} [I_0(\mathbf{x}) - I_t(\mathbf{x} + \mathbf{u})]^2$$

$$(I_0 * I_t)(\mathbf{u}) = \sum_{\text{ZOI}} I_0(\mathbf{x}) I_t(\mathbf{x} + \mathbf{u})$$

Mécanique des fluides : PIV

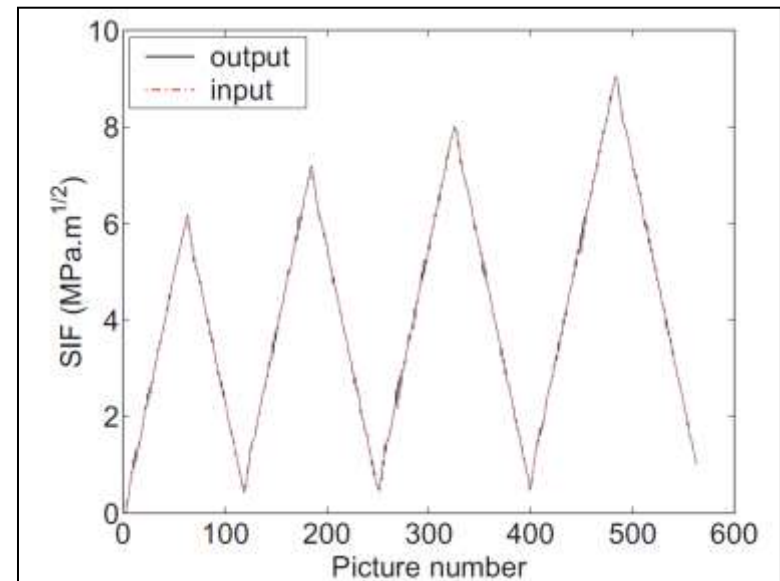
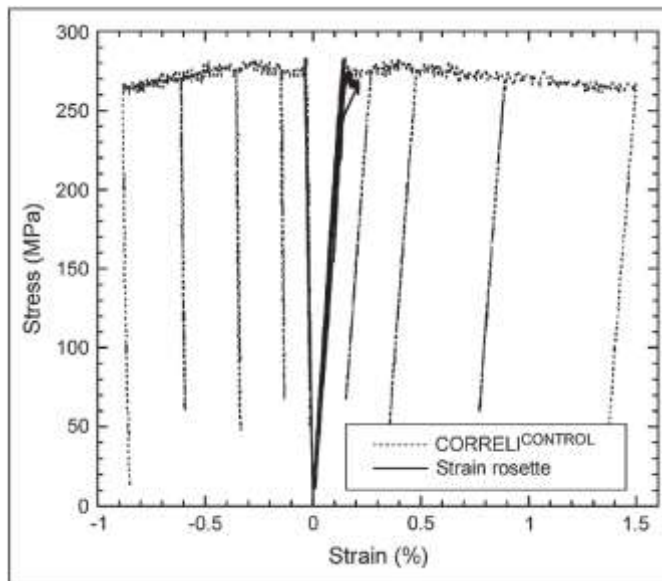
[Barker *et al.*, 1977 ; Grousson *et al.*, 1977 ; Dudderar and Simpkins, 1977]

Mécanique des solides : DIC

[Kanade *et al.*, 1981 ; Burt *et al.*, 1982 ; Sutton *et al.*, 1983]

# Pilotage d'essais mécaniques

- Quantité d'intérêt cinématique\*
- Quantité d'intérêt mécanique\*\*

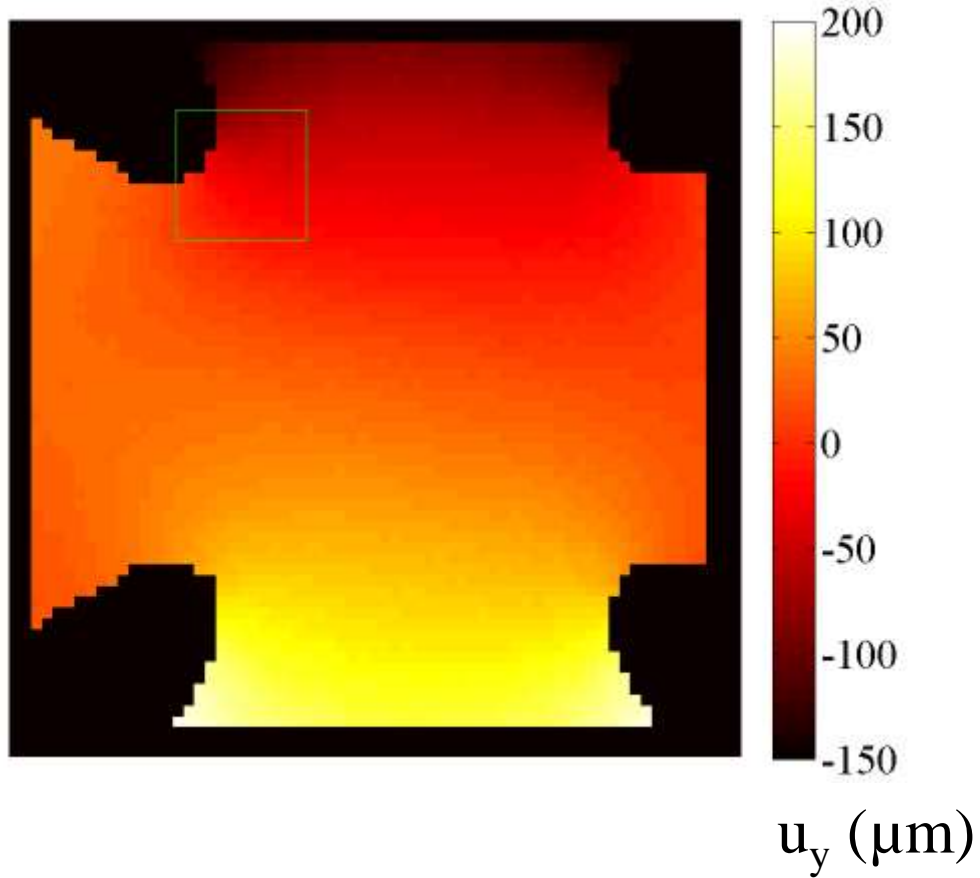


\*[Fayolle *et al.*, 2007, *Exp. Tech.* 31(3) pp. 57-63]

\*\*[Fayolle *et al.*, 2014, *Exp. Mech.* 54(2) pp. 305-314]

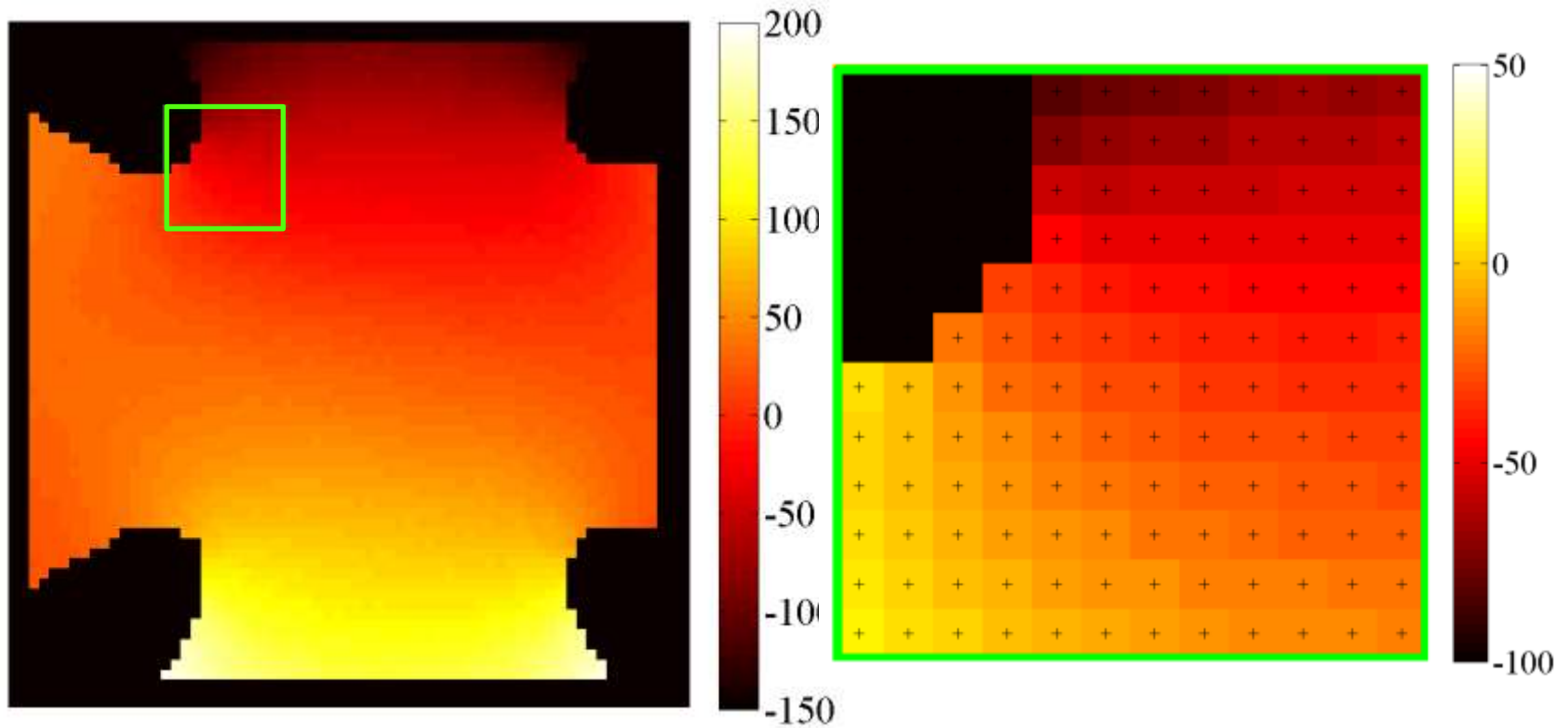


# Approche locale





# Approche locale



$u_y$  ( $\mu\text{m}$ )

→ Nuages de points

# Premières régularisations

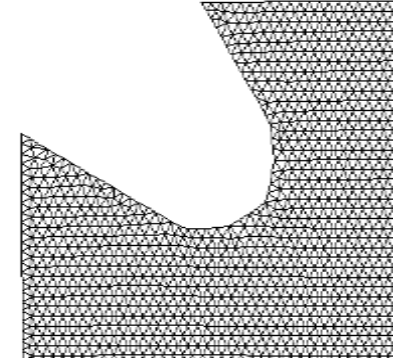
Mesure du flot optique

$$I_0(\mathbf{x}) \cong I_t(\mathbf{x} + \mathbf{u}(\mathbf{x}))$$

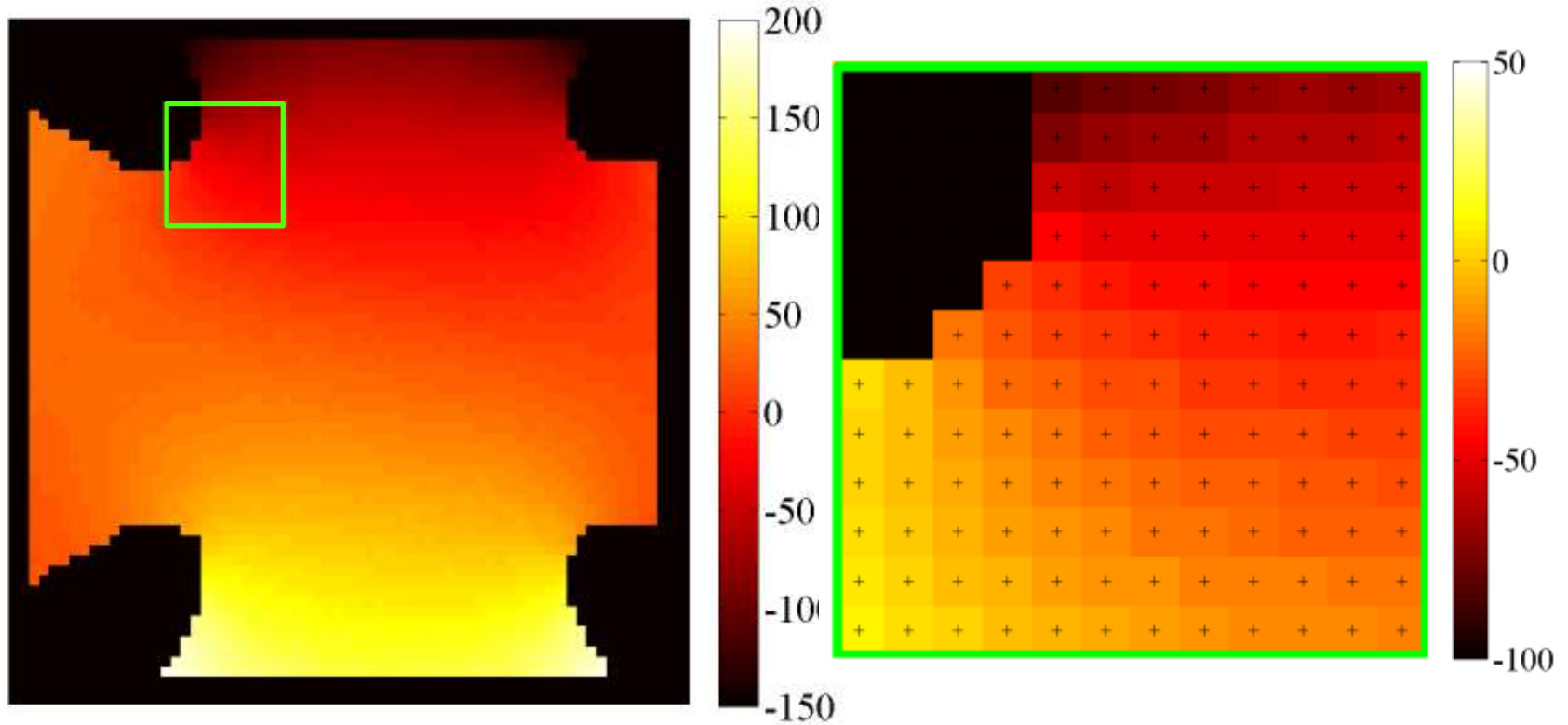
Approches globales (base EF\*)

$$\mathbf{u}_m(\mathbf{x}) = \sum_i a_i \mathbf{N}_i(\mathbf{x})$$

$$\eta_c^2(\{\mathbf{a}\}) = \sum_{\text{ROI}} [I_0(\mathbf{x}) - I_t(\mathbf{x} + \mathbf{u}_m(\mathbf{x}))]^2$$



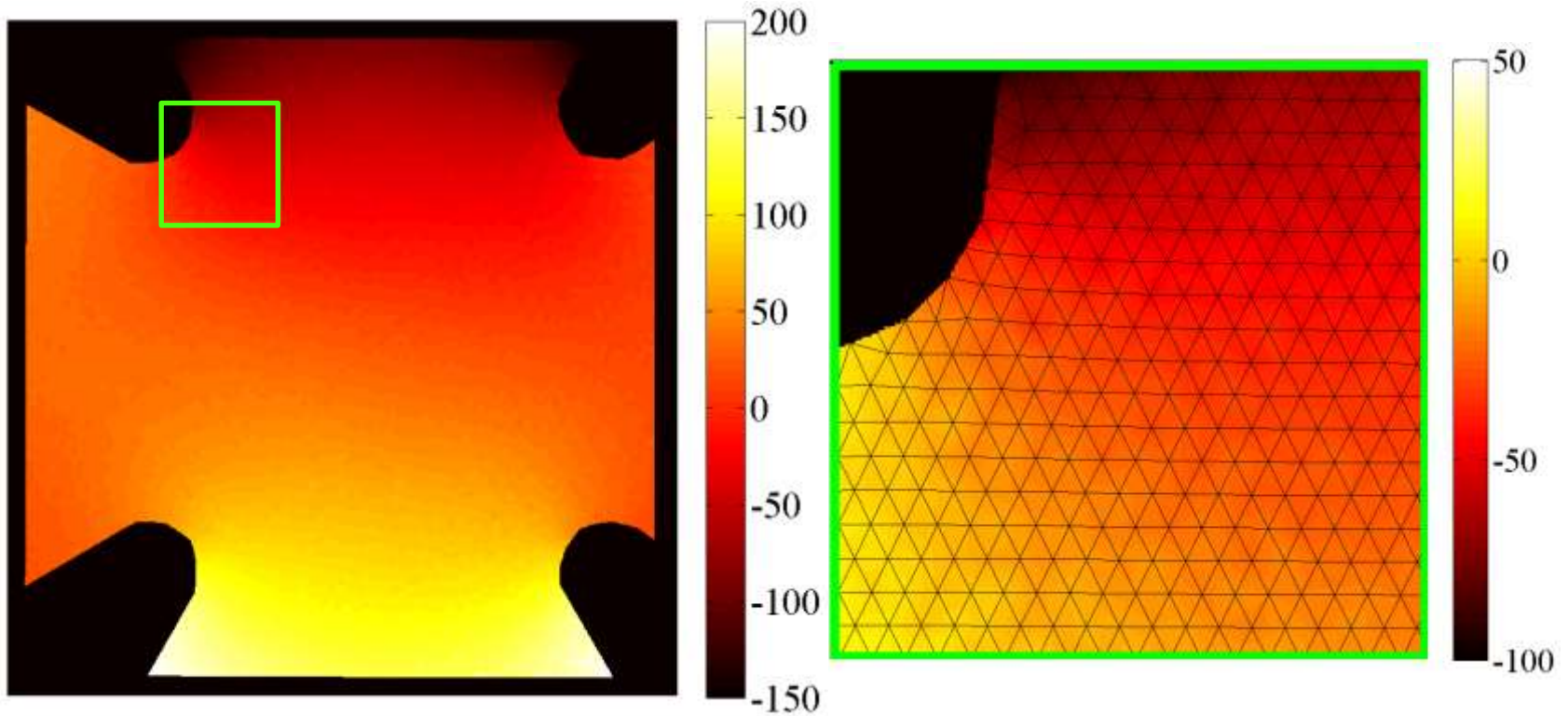
# Approche locale



$u_y$  ( $\mu\text{m}$ )

→ Nuages de points

# Approche globale



$u_y$  ( $\mu\text{m}$ )

→ **Champs denses et continus**

# Régularisation mécanique

- Conservation de la brillance

$$\eta_c^2(\{\mathbf{a}\}) = \sum_{\text{ROI}} [I_0(\mathbf{x}) - I_t(\mathbf{x} + \mathbf{u}_m(\mathbf{x}))]^2$$

- Equilibre interne

$$\eta_{EQ}^2(\{\mathbf{a}\}) = \{\mathbf{a}\}^t [\mathbf{K}]^t [\mathbf{K}] \{\mathbf{a}\}$$

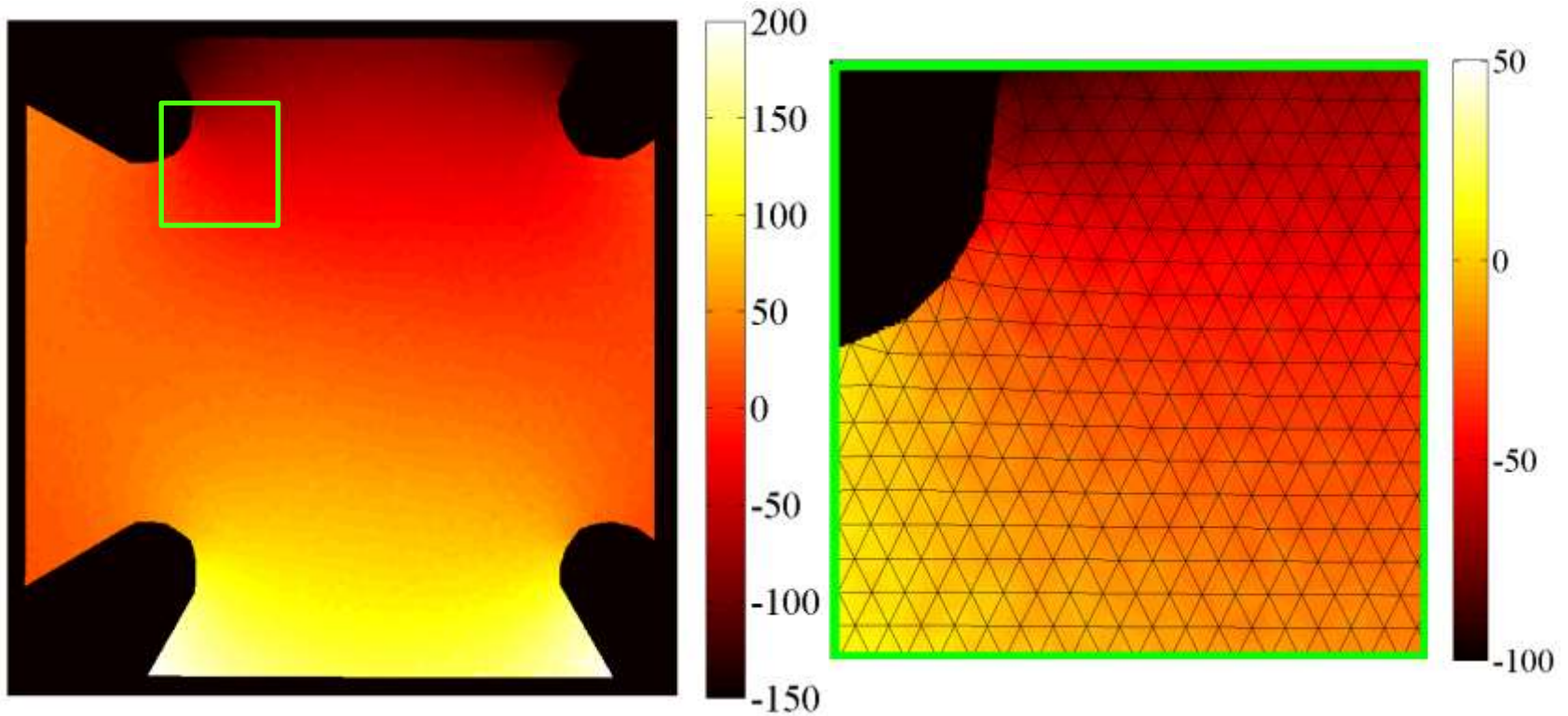
- Gestion des frontières

$$\eta_{EP}^2(\{\mathbf{a}\}) = \{\mathbf{a}\}^t [\mathbf{L}]^t [\mathbf{L}] \{\mathbf{a}\}$$

$$\eta_{tot}^2(\{\mathbf{a}\}) = \eta_c^2(\{\mathbf{a}\}) + w_{EQ} \eta_{EQ}^2(\{\mathbf{a}\}) + w_{EP} \eta_{EP}^2(\{\mathbf{a}\})$$



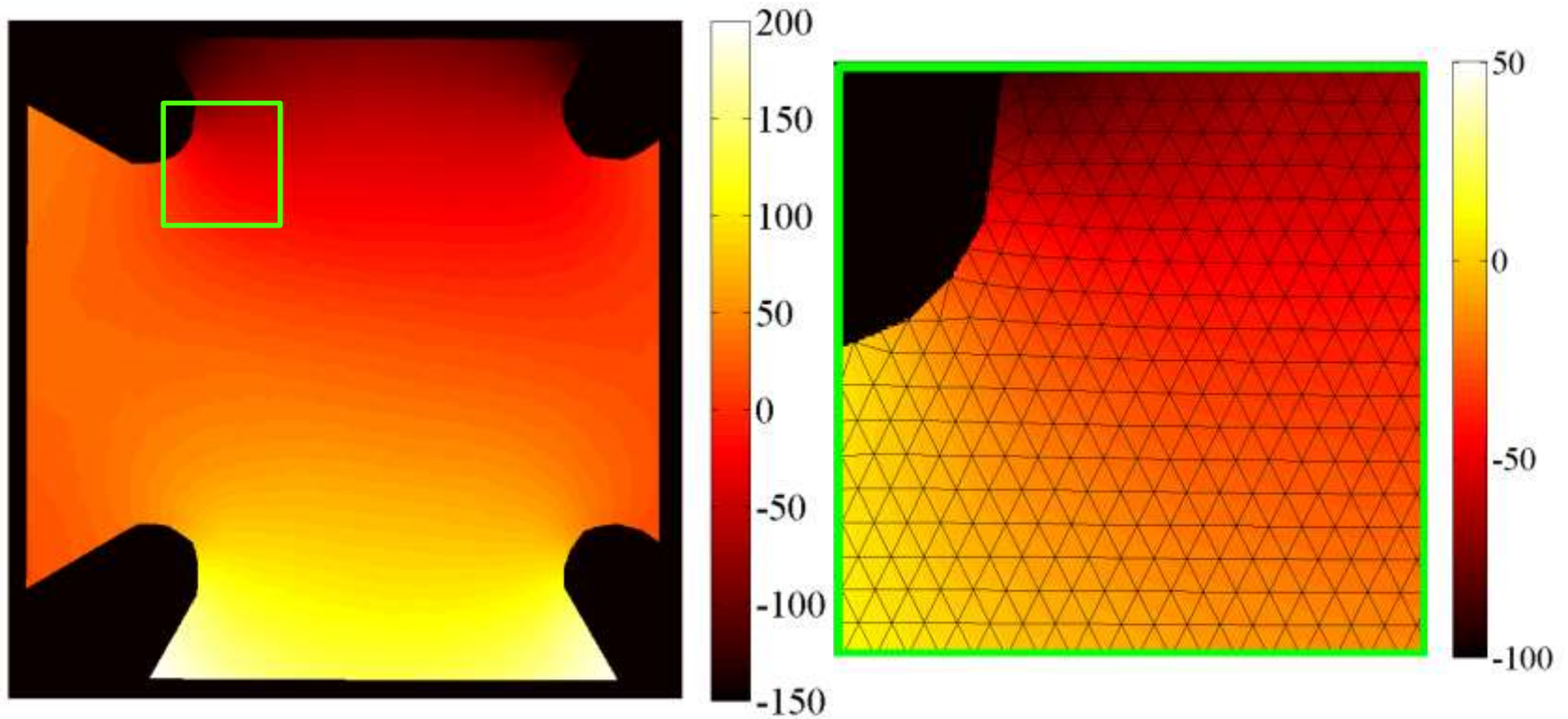
# Approche globale



$u_y$  ( $\mu\text{m}$ )

→ **Champs denses et continus**

# Approche régularisée (filtre mécanique)

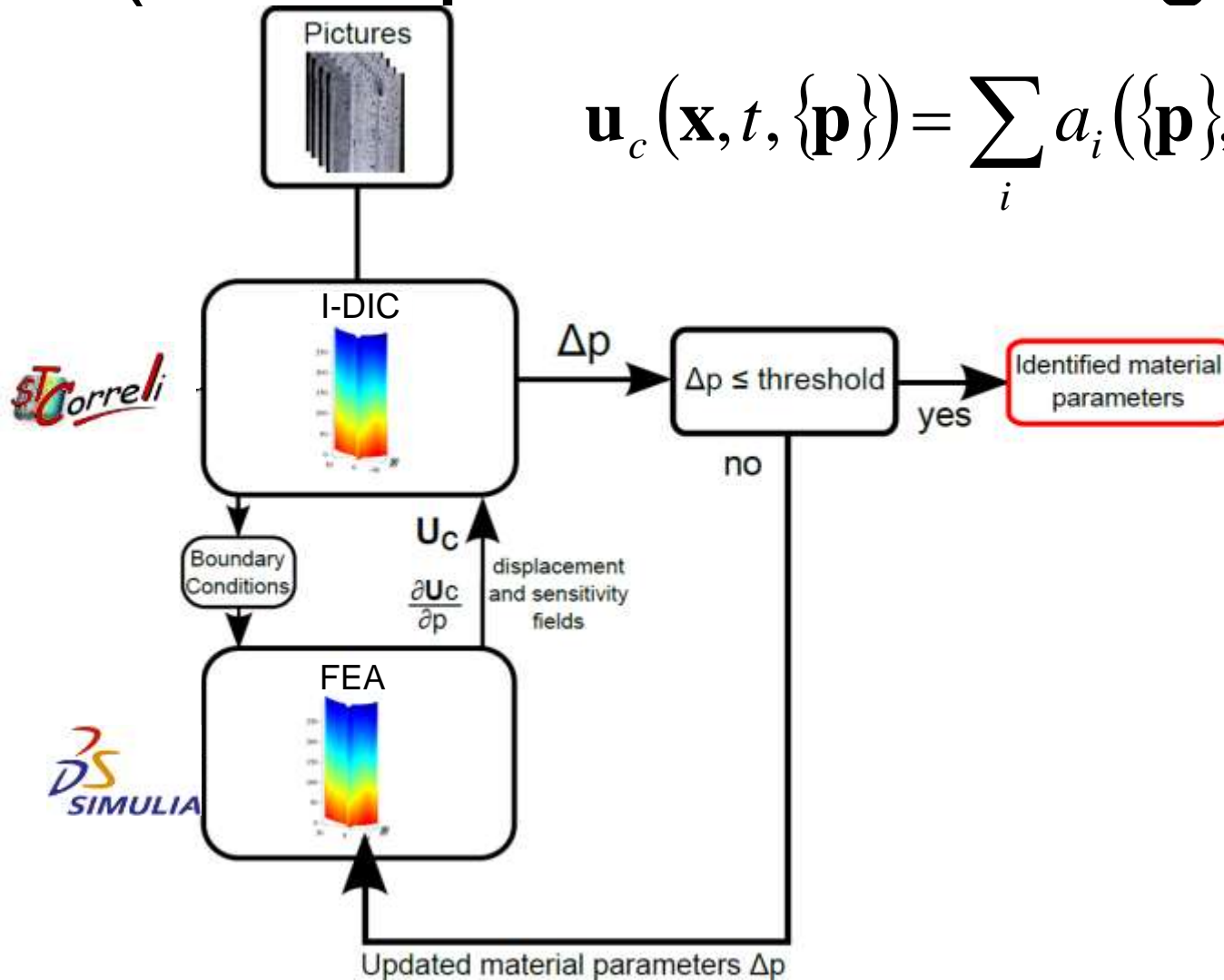


$u_y$  ( $\mu\text{m}$ )

→ **Champs denses, continus et filtrés**



# Approches intégrées (« compressed sensing »)

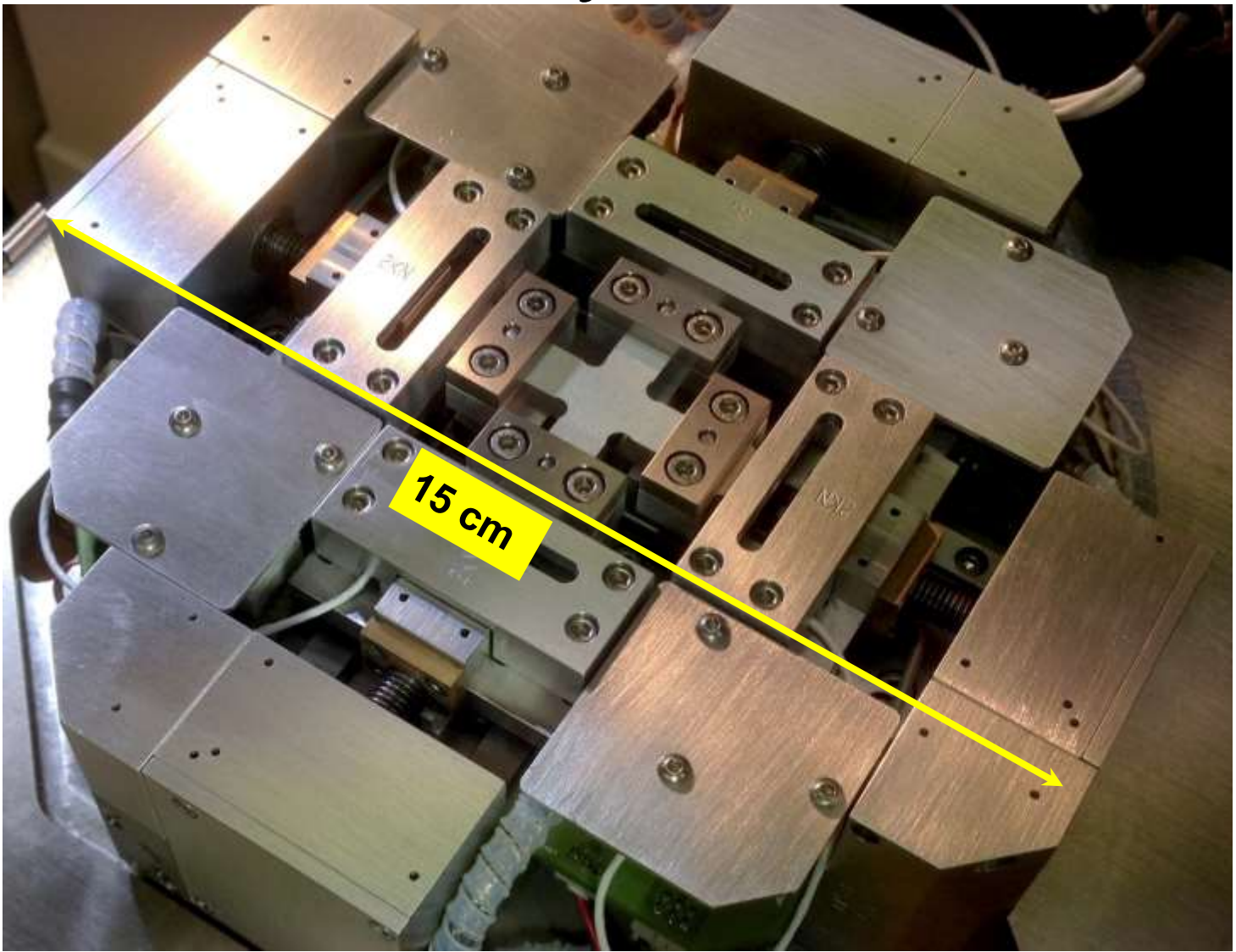


$$\mathbf{u}_c(\mathbf{x}, t, \{\mathbf{p}\}) = \sum_i a_i(\{\mathbf{p}\}, t) \mathbf{N}_i(\mathbf{x})$$

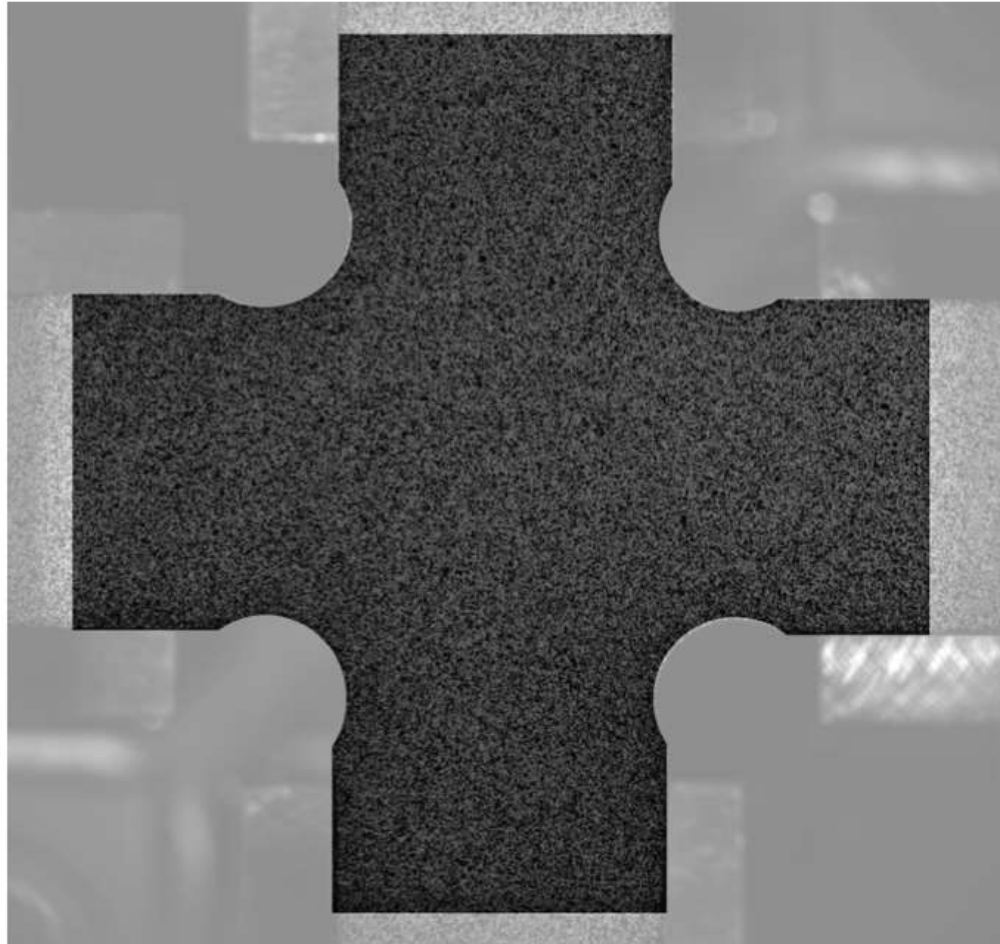
[Leclerc *et al.*, 2009, in *LNCS* 5496 pp. 161-171]

[Mathieu *et al.*, 2015, *Exp. Mech.* 55(1) pp. 105-119]

# Essai biaxial sur acier inoxydable

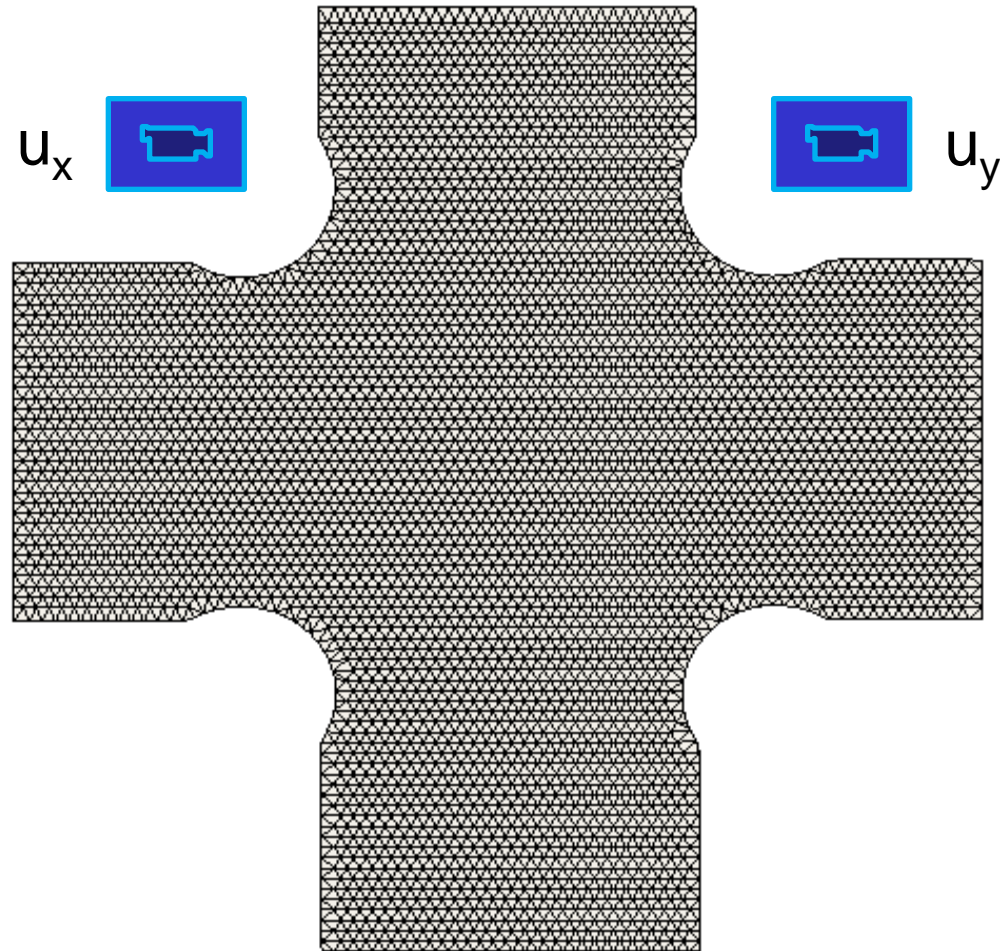


# Géométrie optimisée





# Corrélation d'images intégrée

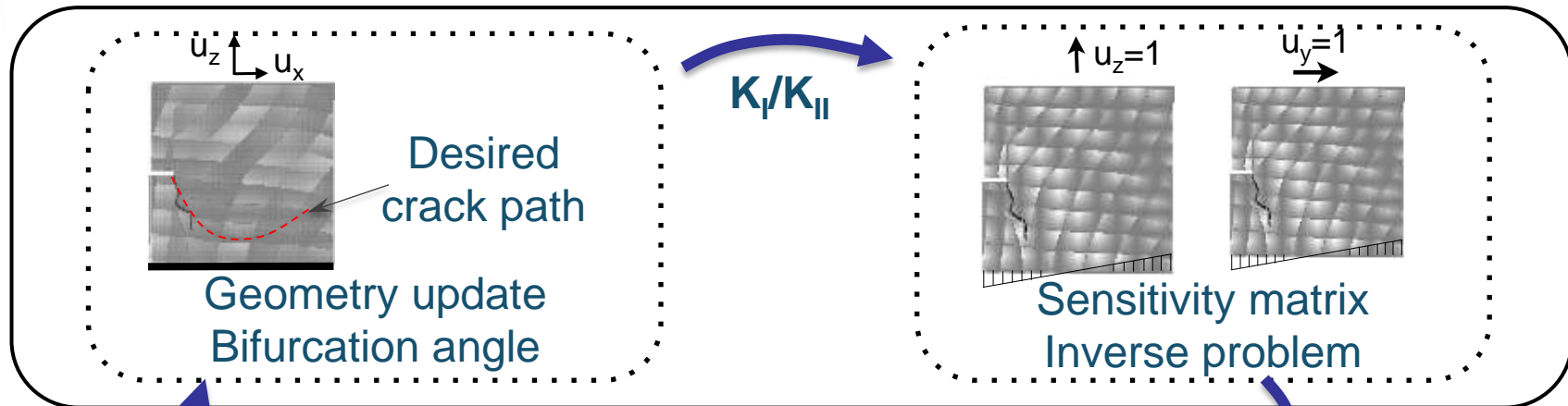


# Hexapode



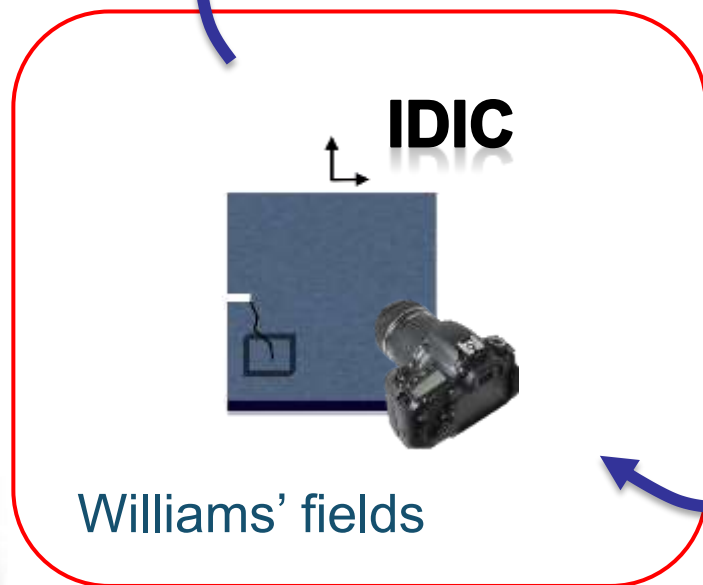
# Essais hybrides

Control - LEFM



Crack tip

$U_z/U_y$



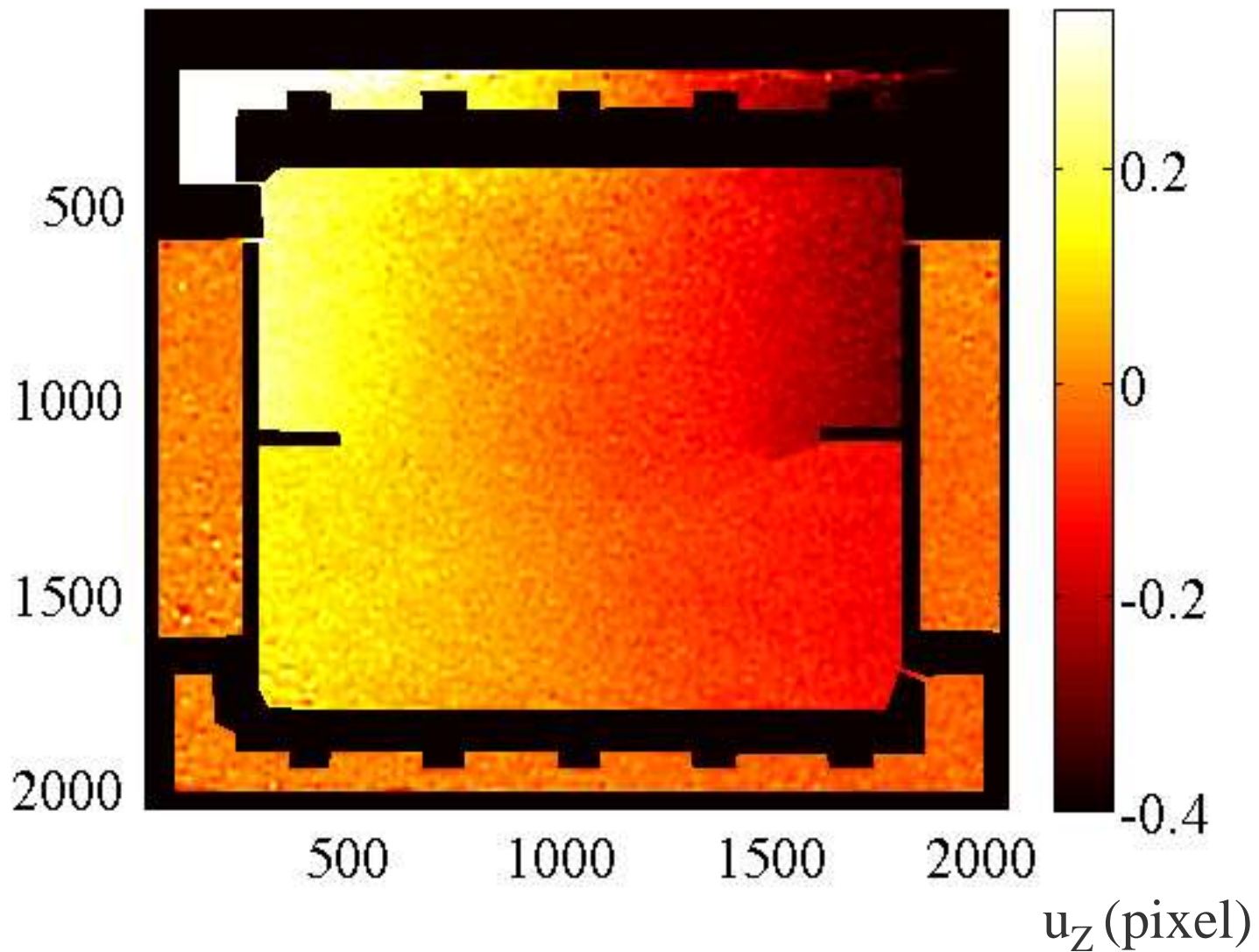
**Measurement**



**Mechanical loading**

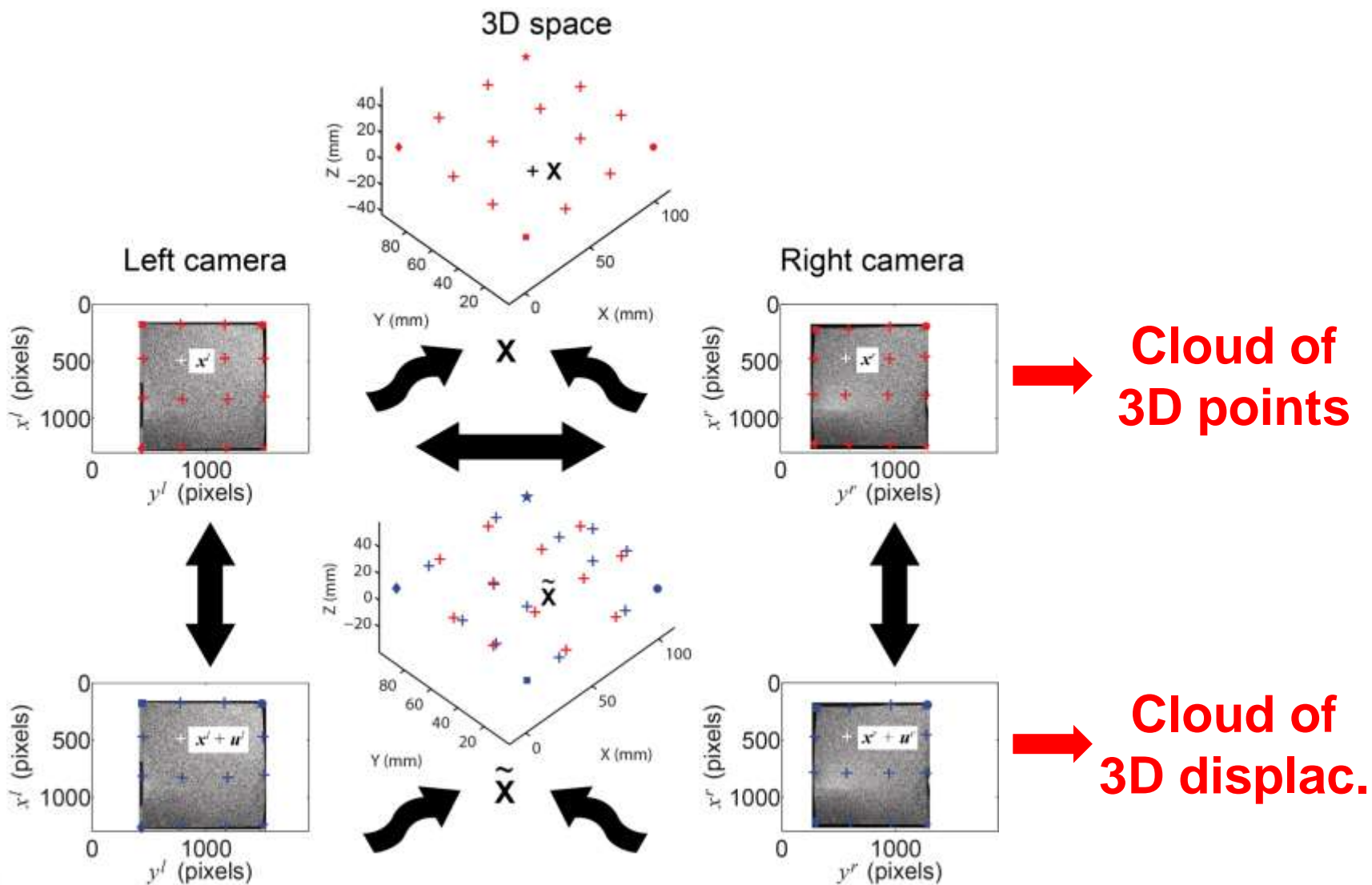


# Essai hybride



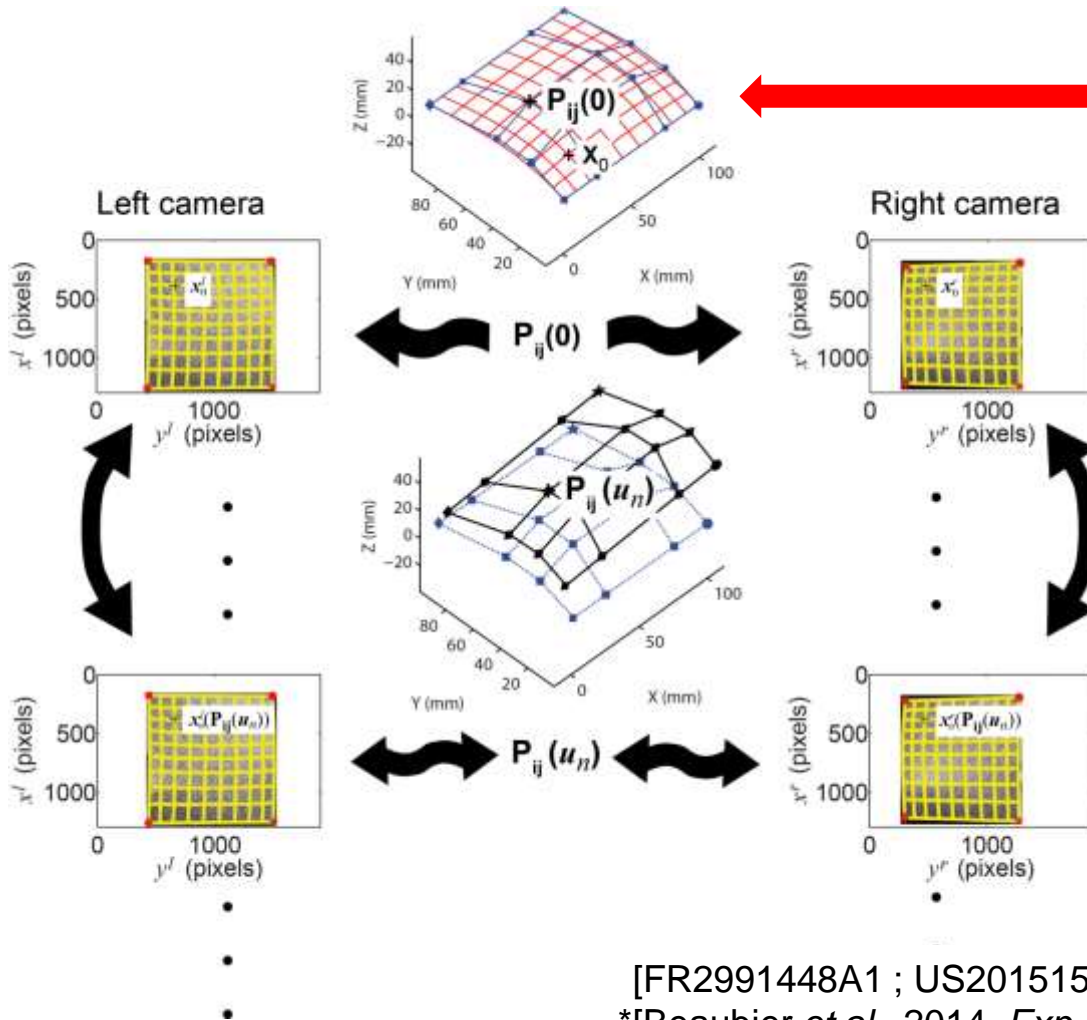


# Stéréocorrélation en 2007



# Approche globale de stéréocorrélation

**3D surface  
(e.g. NURBS\*, EF\*\*)**



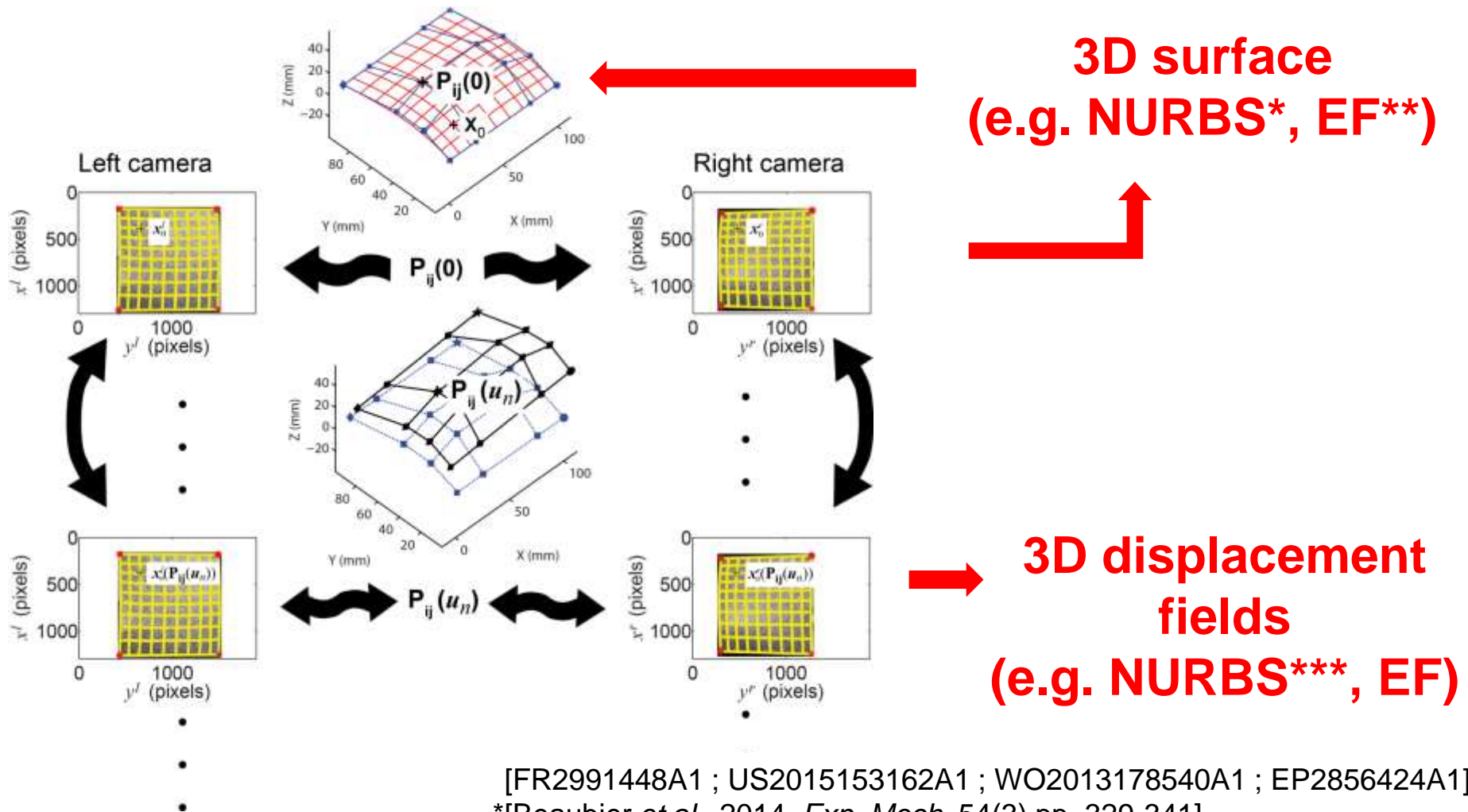
[FR2991448A1 ; US2015153162A1 ; WO2013178540A1 ; EP2856424A1]

\*[Beaubier *et al.*, 2014, *Exp. Mech.* 54(3) pp. 329-341]

\*\*[Dubreuil *et al.*, 2016, *Exp. Mech.* 56(7) pp. 1231-1242]

\*\*\*[Dufour *et al.*, 2015 *Exp. Mech.* 55(9) pp. 1657-1668]

# Approche globale de stéréocorrélation



[FR2991448A1 ; US2015153162A1 ; WO2013178540A1 ; EP2856424A1]

\*[Beaubier *et al.*, 2014, *Exp. Mech.* 54(3) pp. 329-341]

\*\*[Dubreuil *et al.*, 2016, *Exp. Mech.* 56(7) pp. 1231-1242]

\*\*\*[Dufour *et al.*, 2015 *Exp. Mech.* 55(9) pp. 1657-1668]



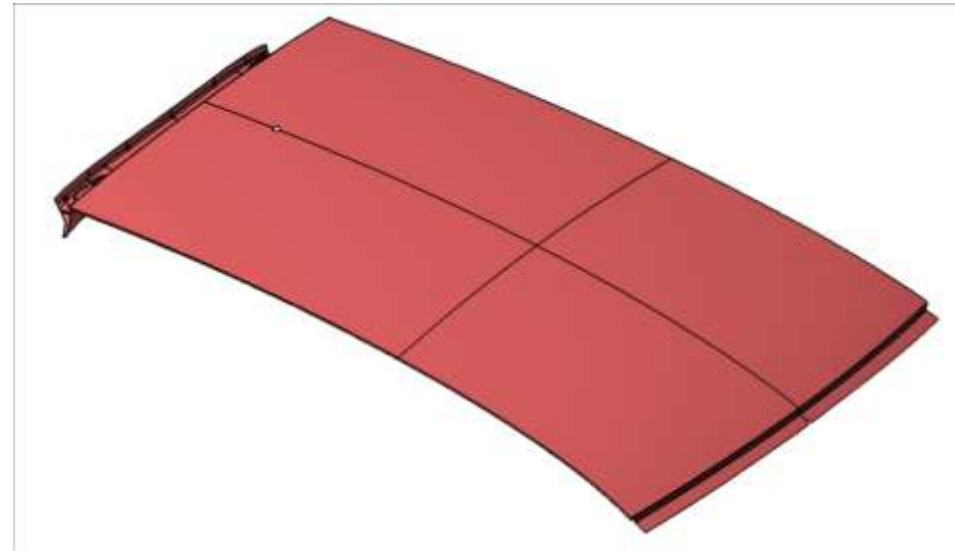
# Farman A6 (1921-32)



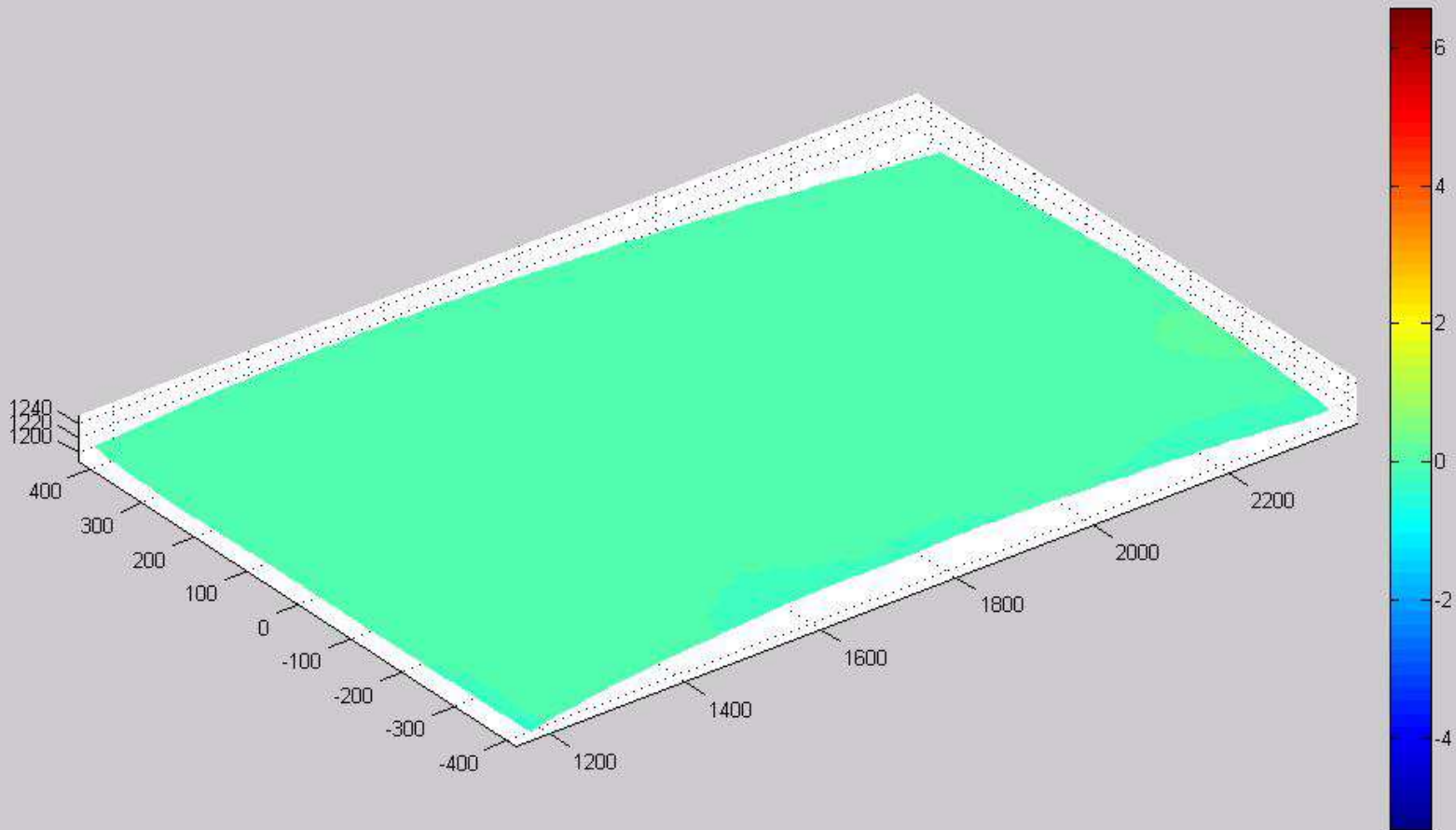
# Soudo-brasage de toit automobile



Modèle CAO



# Champ de déplacement normal (mm)



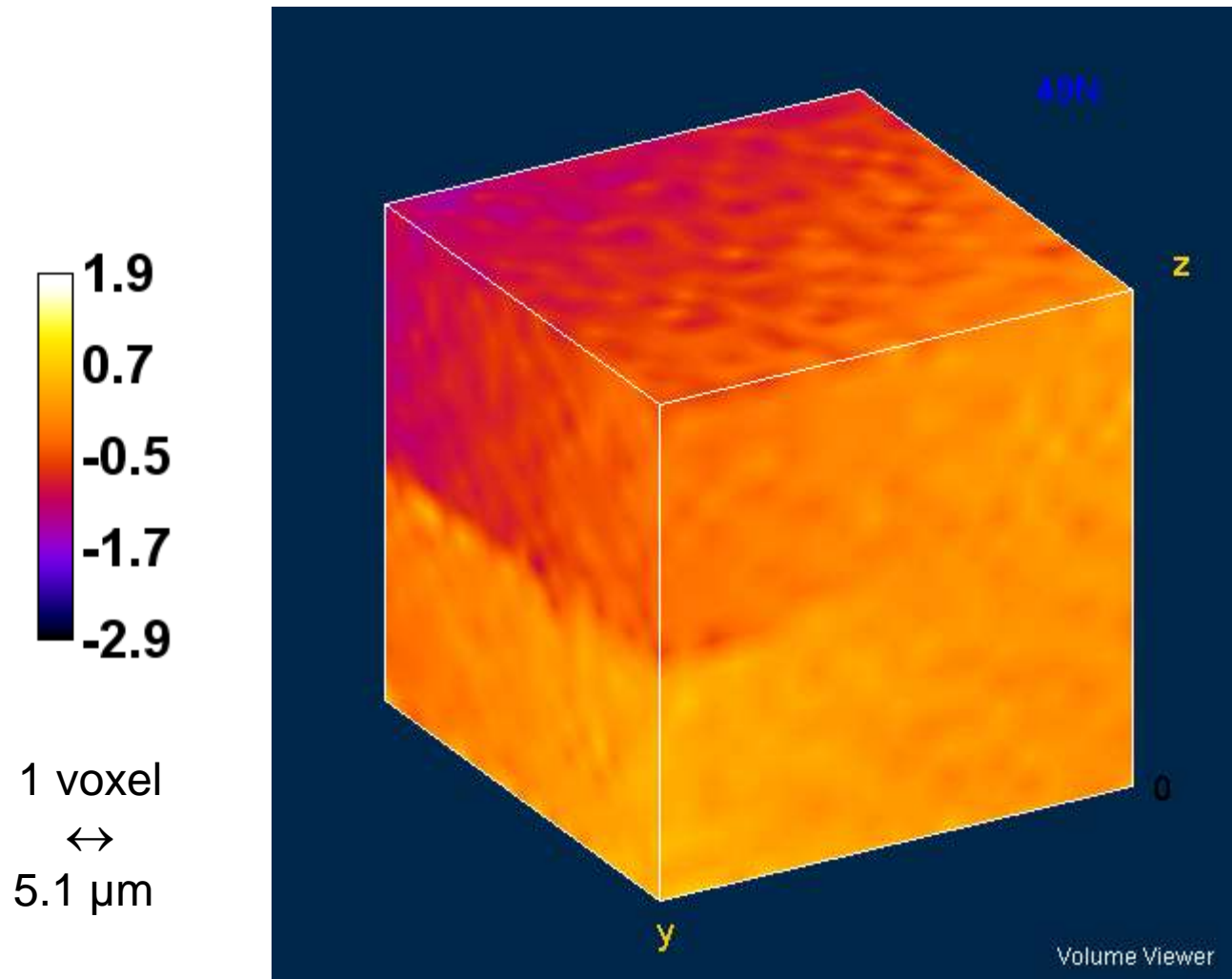


# 2012 : tomographe au LMT





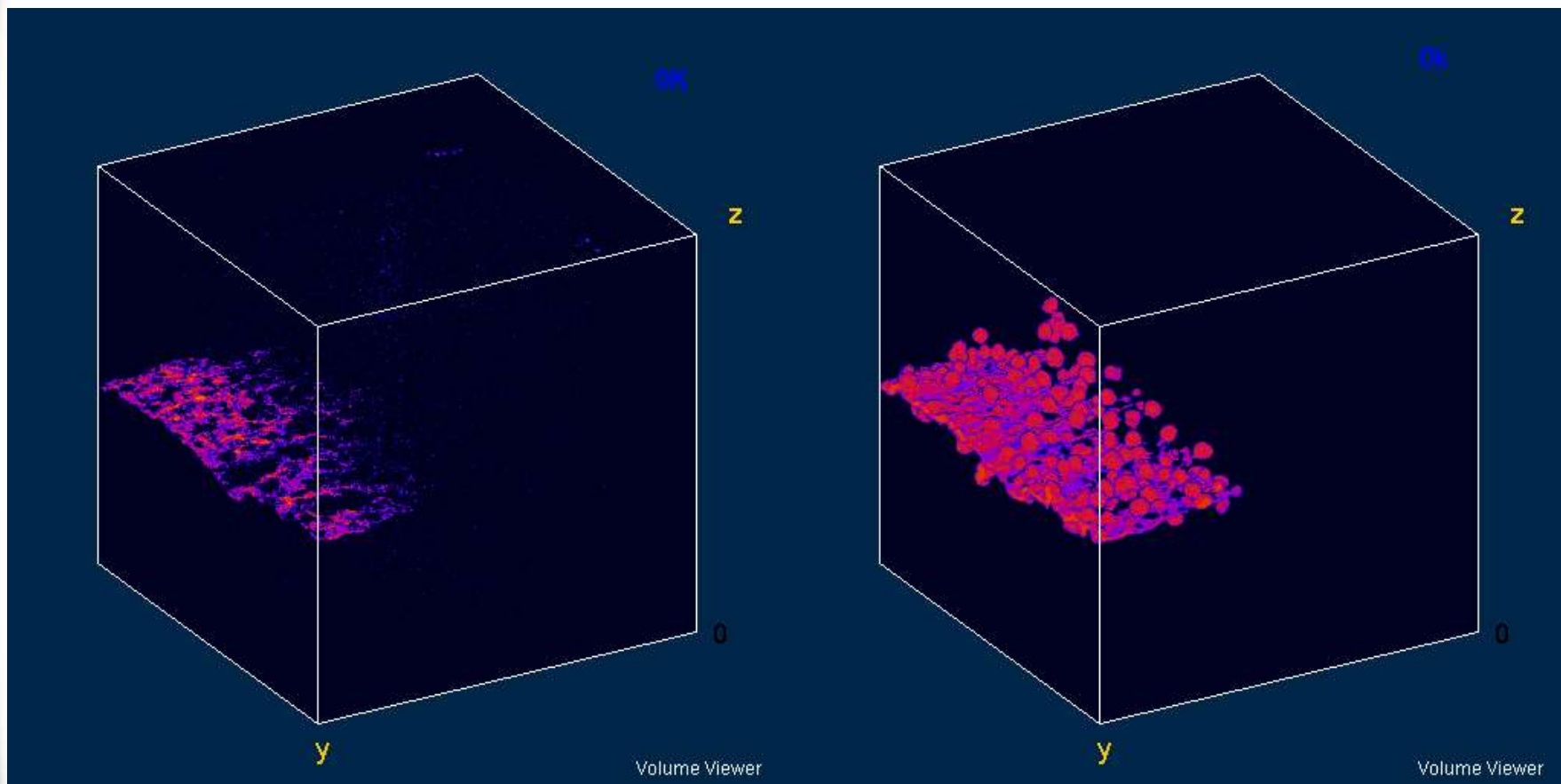
# Fissure de fatigue



[Roux *et al.*, 2008, *Comp. Part A* 39 pp. 1253-1265]

[Limodin *et al.*, 2009, *Acta Mat.* 57 pp. 4090-4101]

# Imager la fissure ?

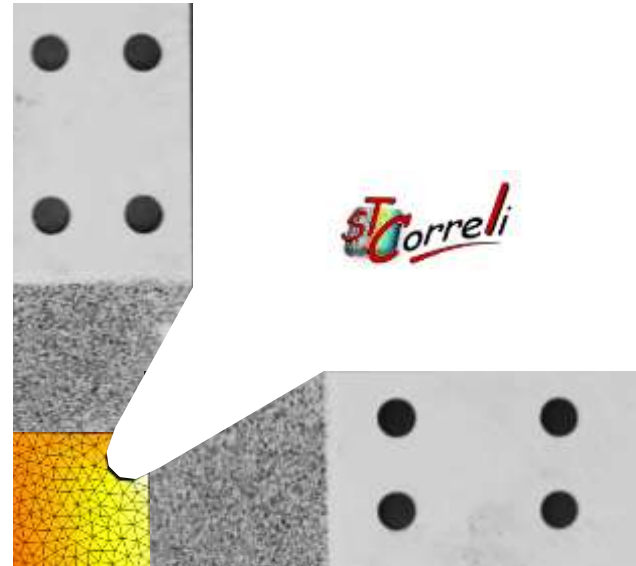


Résidus de corrélation

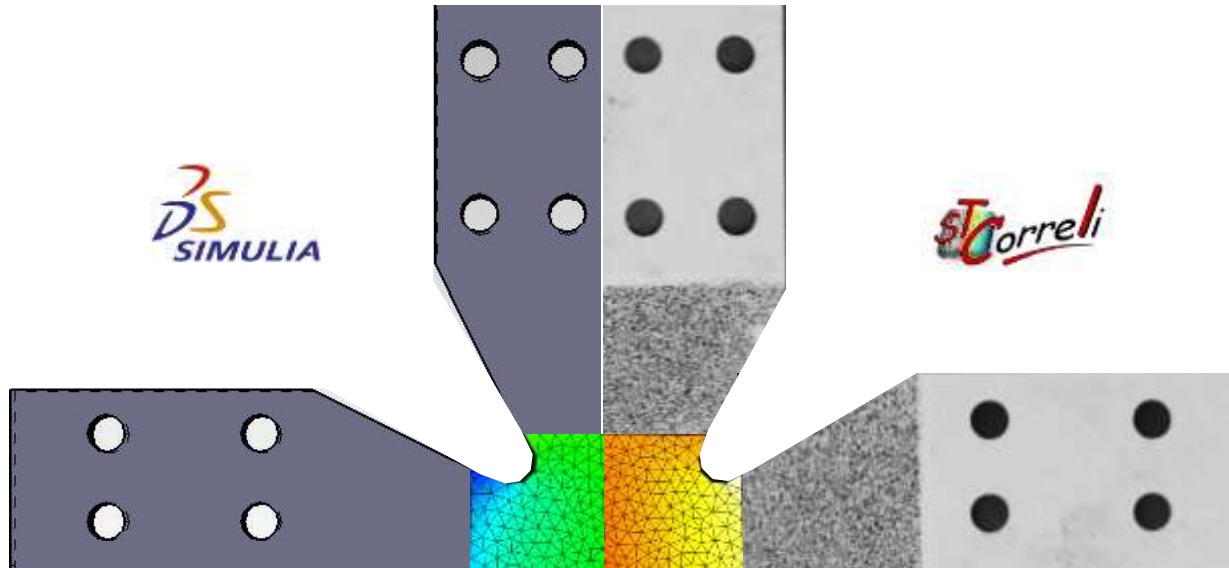
Image seuillée

$$\rho(\mathbf{x}) = |I_0(\mathbf{x}) - I_t(\mathbf{x} + \mathbf{u}_m(\mathbf{x}))|$$

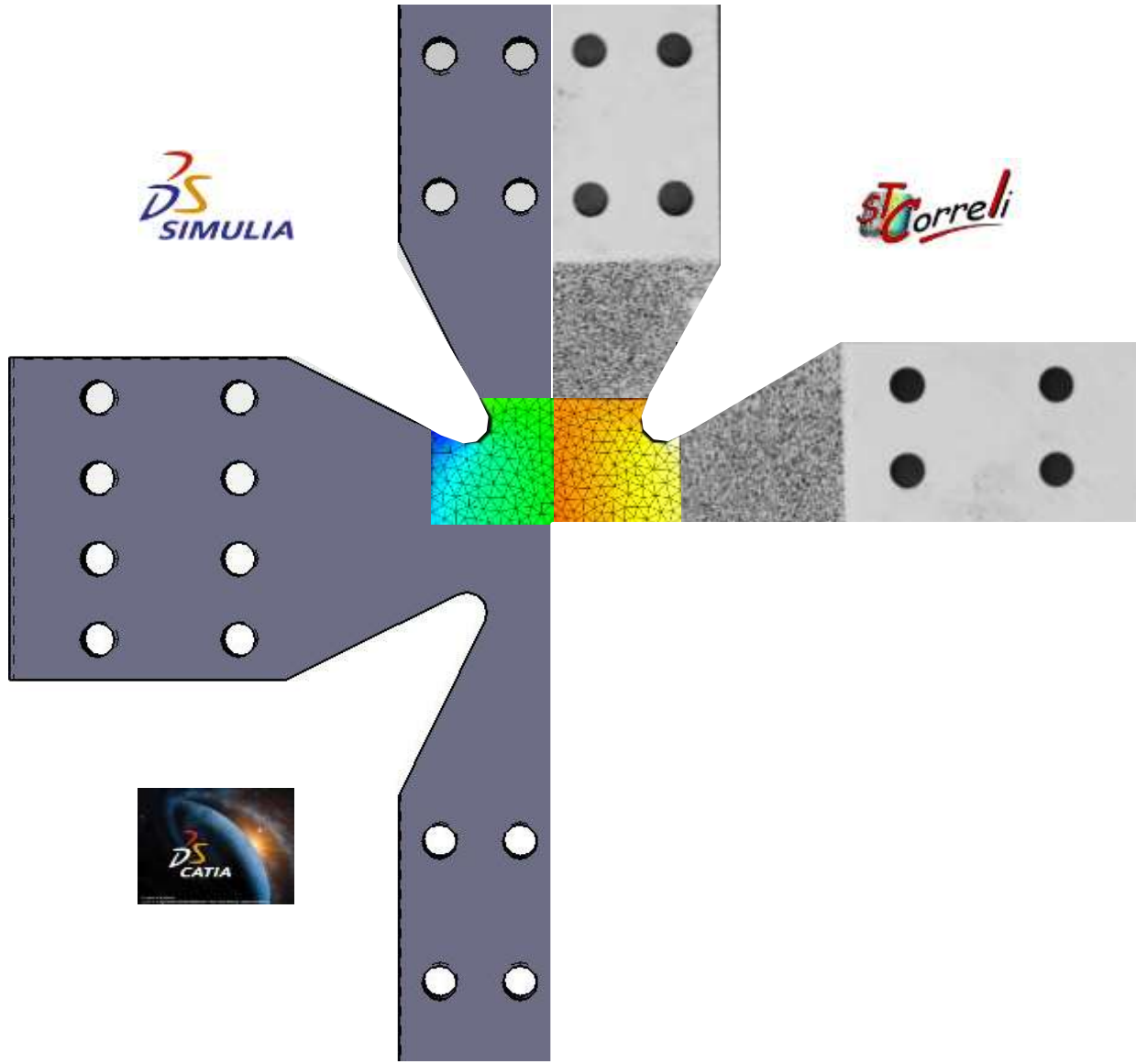
# Conclusions



# Conclusions

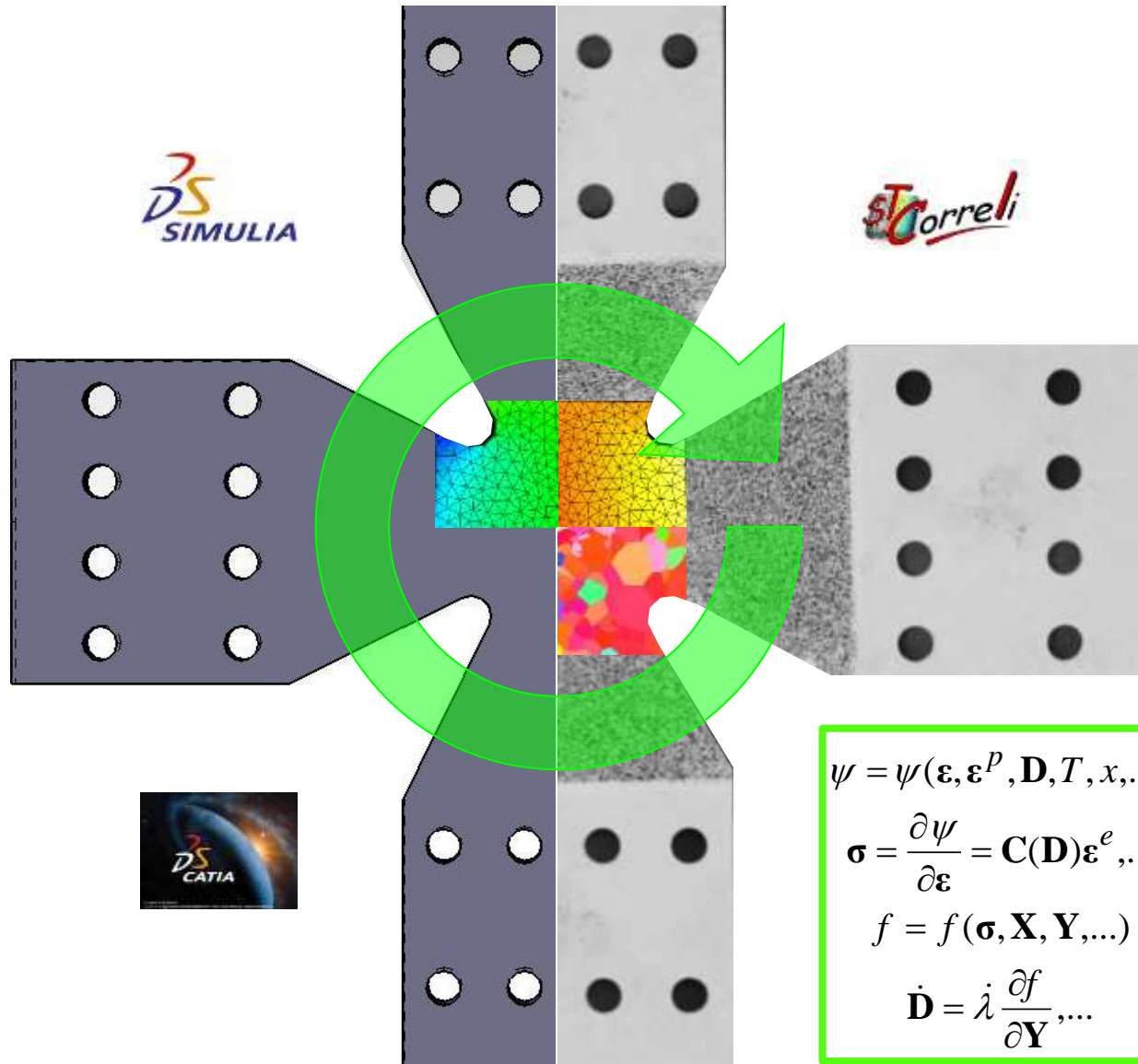


# Conclusions





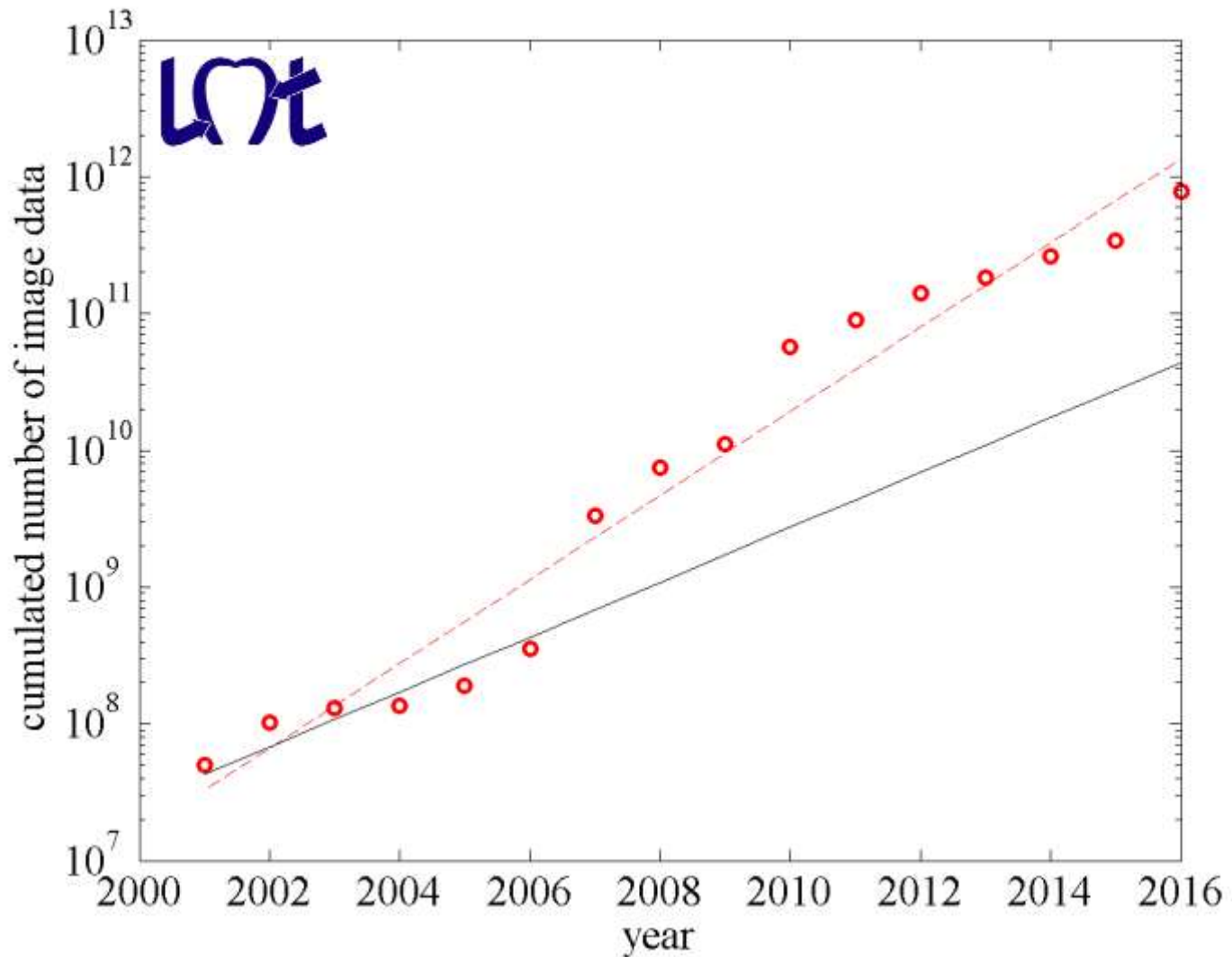
# Conclusions



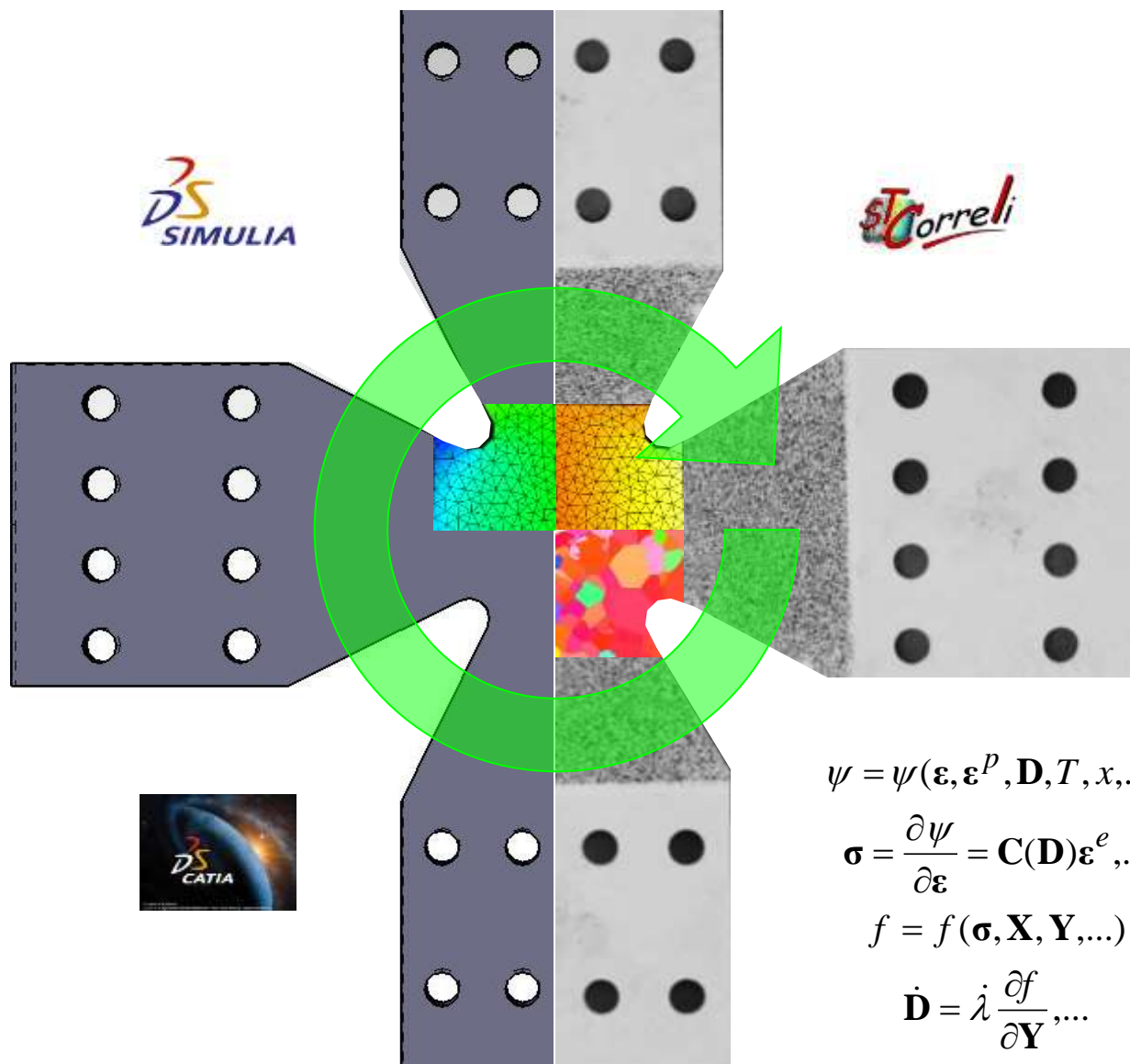
# Perspectives

- De nombreuses opportunités pour répondre aux (nombreux) défis actuels (mesure, pilotage, identification)
- Une seule mécanique (expérimentale et numérique)
- Explosion des données\*

# Extraction des données pertinentes ?



# Approches « temps réel »




$$\psi = \psi(\boldsymbol{\varepsilon}, \boldsymbol{\varepsilon}^p, \mathbf{D}, T, x, \dots)$$

$$\boldsymbol{\sigma} = \frac{\partial \psi}{\partial \boldsymbol{\varepsilon}} = \mathbf{C}(\mathbf{D}) \boldsymbol{\varepsilon}^e, \dots$$

$$f = f(\boldsymbol{\sigma}, \mathbf{X}, \mathbf{Y}, \dots)$$

$$\dot{\mathbf{D}} = \lambda \frac{\partial f}{\partial \mathbf{Y}}, \dots$$

# Perspectives

- De nombreuses opportunités pour répondre aux (nombreux) défis de la simulation numérique moderne
- Une seule mécanique (expérimentale et numérique)
- Explosion des données
- Transfert  EikoSim
- Normalisation (ASD-STAN, EN ?, ISO ?)
- Enseignement (L3, M, D)





**Merci de  
votre  
attention !**