



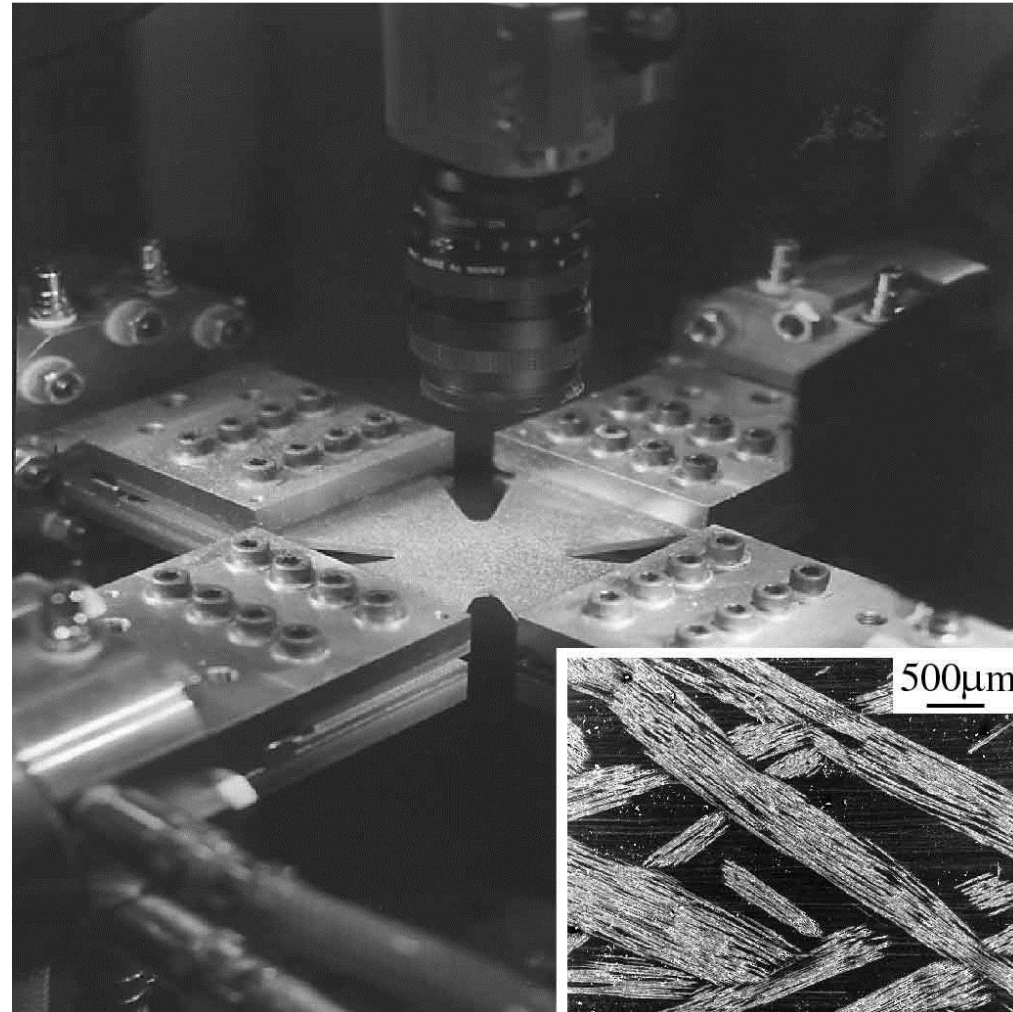
Un film de F. Hild, H. Leclerc & S. Roux

La Mécanique en images : mieux que du cinéma ?

Avec B. Beaubier, S. Calloch, J.E. Dufour, K. Lavernhe
J.Y. Buffière, A. Gravouil, N. Limodin, J. Rannou, J. Réthoré

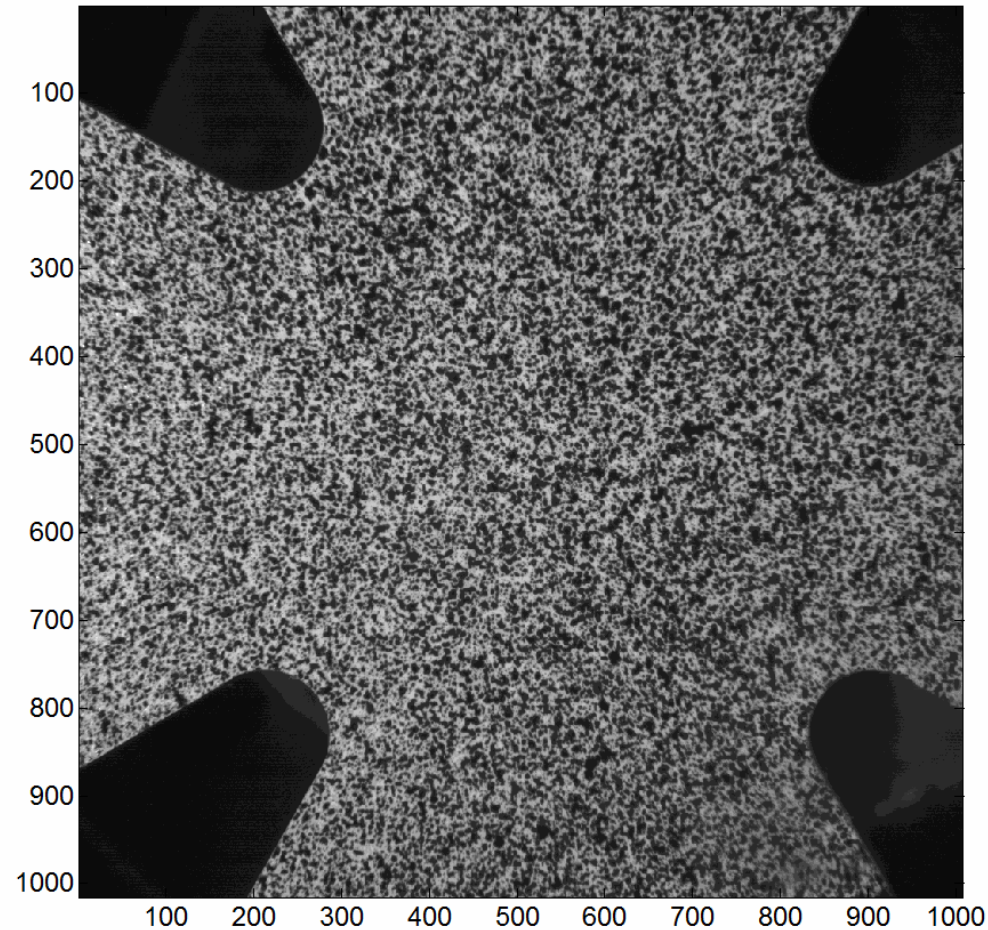
INTRODUCTION : LA MECANIQUE FAIT SON **CINEMA**

Essai biaxial sur composite bas coût



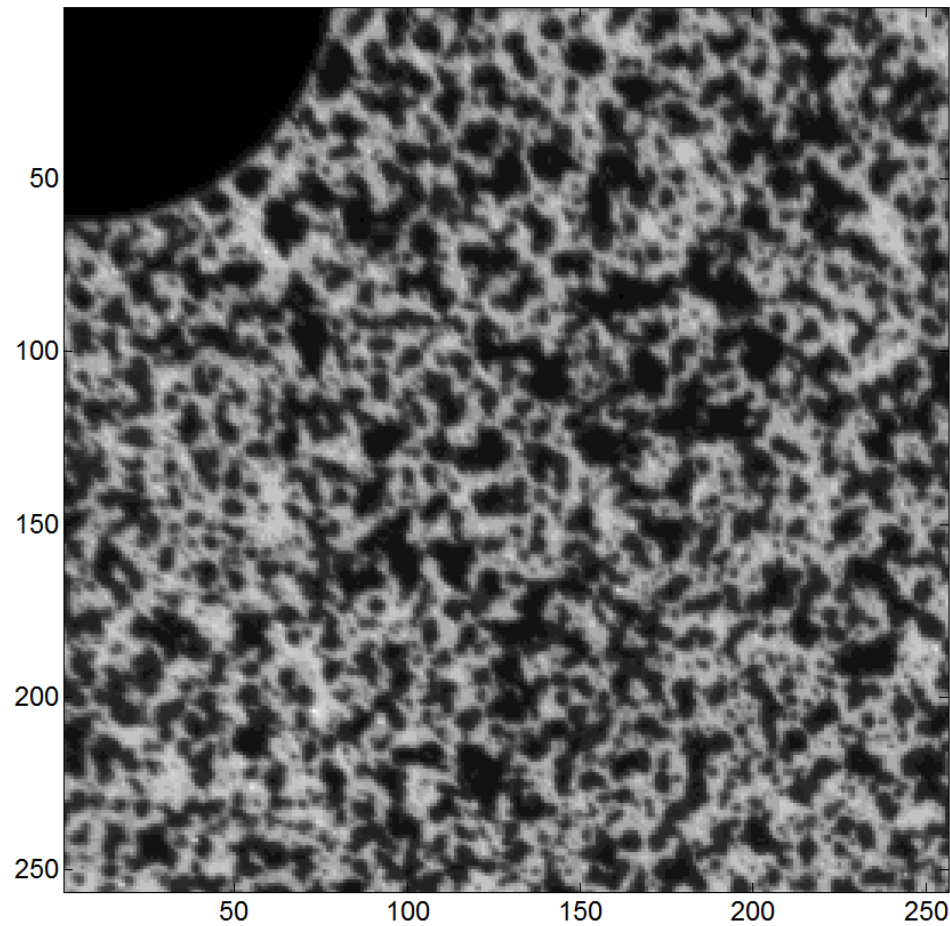
Données brutes : film de l'essai

Picture #: 0



Zoom du film de l'essai

Picture #: 0



Corrélation d'images numériques (CIN)

- Images (niveau de gris)

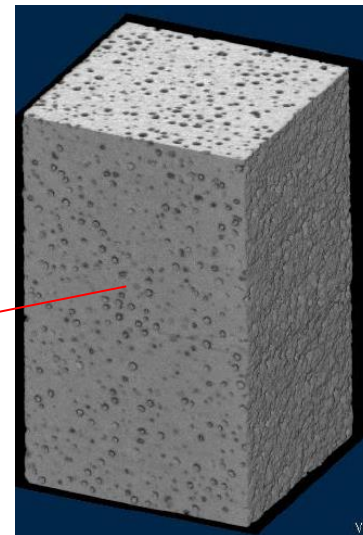
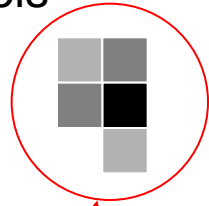
$$f(\underline{x}) \quad g(\underline{x})$$

- Conservation des niveaux de gris

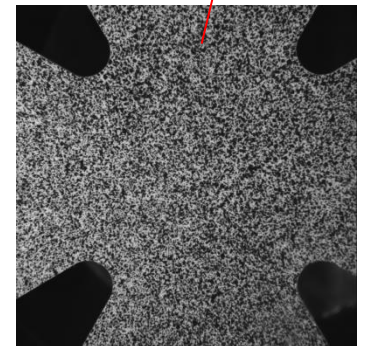
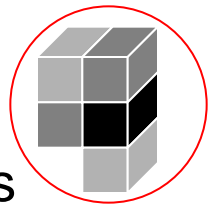
$$f(\underline{x}) \cong g(\underline{x} + \underline{u}(\underline{x}))$$

- Mesurer $\underline{u}(\underline{x})$?

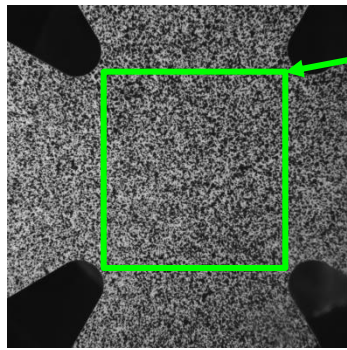
pixels



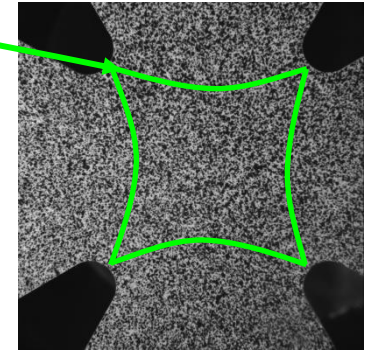
voxels



Corrélation d'images numériques



Deux images f et g



$$f(\underline{x}) = g(\underline{x} + \underline{u}(\underline{x})) + n(\underline{x})$$

Minimisation de l'écart quadratique moyen

$$\Phi^2(\underline{u}) = \int [f(\underline{x}) - g(\underline{x} + \underline{u}(\underline{x}))]^2 d\underline{x}$$

RE

Champ de déplacement mesuré

$$\underline{u}(\underline{x}) = \sum a_i \underline{\varphi}_i(\underline{x})$$

Corrélation d'images numériques

Décomposition spatiale du champ de déplacement

$$\underline{u}(\underline{x}) = \sum_i a_i \underline{\varphi}_i(\underline{x})$$

Minimisation équivalente à

$$\left[\int_{\text{ROI}} (\underline{\nabla} f(\underline{x}) \cdot \underline{\varphi}_i(\underline{x})) (\underline{\nabla} f(\underline{x}) \cdot \underline{\varphi}_j(\underline{x})) d\underline{x} \right] \delta a_j(t) =$$

$$= \int_{\text{ROI}} [f(\underline{x}) - g(\underline{x} + a_i \underline{\varphi}_i(\underline{x}))] (\underline{\nabla} f(\underline{x}) \cdot \underline{\varphi}_i(\underline{x})) d\underline{x}$$

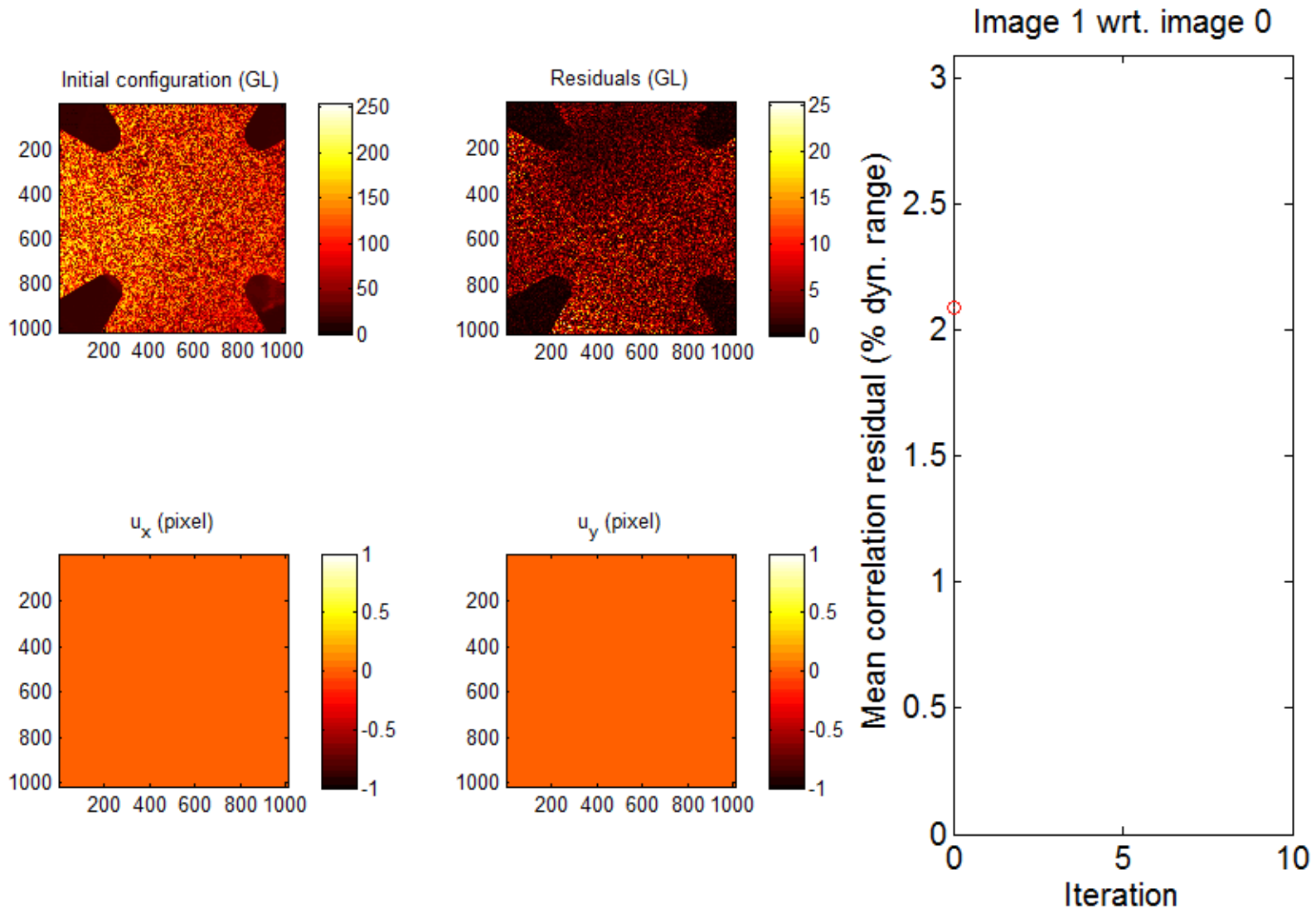
Systèmes **linéaires***

$$M_{ij} \delta a_j(t) = b_i(t)$$

*[Wagne *et al.*, 2002, *Eur. Phys. J. AP* 17 pp. 247-252]

[Besnard *et al.*, 2006, *Exp. Mech.* 46 pp. 789-803]

Champ de déplacement mesuré



CINEMA: Corrélation d'Images Numériques Et Méthode d'écart A l'équilibre !

Méthode d'écart à l'équilibre

- Comportement : élasticité linéaire

$$\underline{\underline{\sigma}} = \mathbf{C}(\underline{x}) : \underline{\underline{\varepsilon}}$$

- Equilibre (admissibilité statique)

$$\operatorname{div}(\underline{\underline{\sigma}}) + \underline{f} = \underline{0} \quad \text{dans } \Omega$$

$$\underline{\underline{\sigma}} \cdot \underline{n} - \underline{t} = \underline{0} \quad \text{sur } \partial\Omega_t \cup \partial\Omega_T$$

- Compatibilité (admissibilité cinématique)

$$\underline{\underline{\varepsilon}} = (\underline{\nabla} \otimes \underline{u})_s$$

Méthode d'écart à l'équilibre

Fonctionnelle d'écart à l'équilibre

$$R_{EG}(\mathbf{C}) = \int_{\Omega} \left\| \operatorname{div}(\mathbf{C} : \underline{\nabla} \otimes \underline{u}) + \underline{f} \right\|^2 d\underline{x}$$

Méthode d'écart à l'équilibre

Fonctionnelle d'écart à l'équilibre

$$R_{EG}(\mathbf{C}) = \int_{\Omega} \left\| \operatorname{div}(\mathbf{C} : \underline{\nabla} \otimes \underline{u}) + \underline{f} \right\|^2 d\underline{x}$$

Version discrétisée (EF)

$$R_{EG}(\mathbf{C}) = \left\| [\mathbf{K}(\mathbf{C})]\{u\} - \{f\} \right\|^2$$

mesuré

généralement
connu

Régularisation (loi d'endommagement)

Fonctionnelle d'écart à l'équilibre

$$R_{EG}(D) = \sum_i \left(f_i^{res} \right)^2 = \sum_i \left(\sum_e L_{ie} (1 - D_e) \right)^2$$

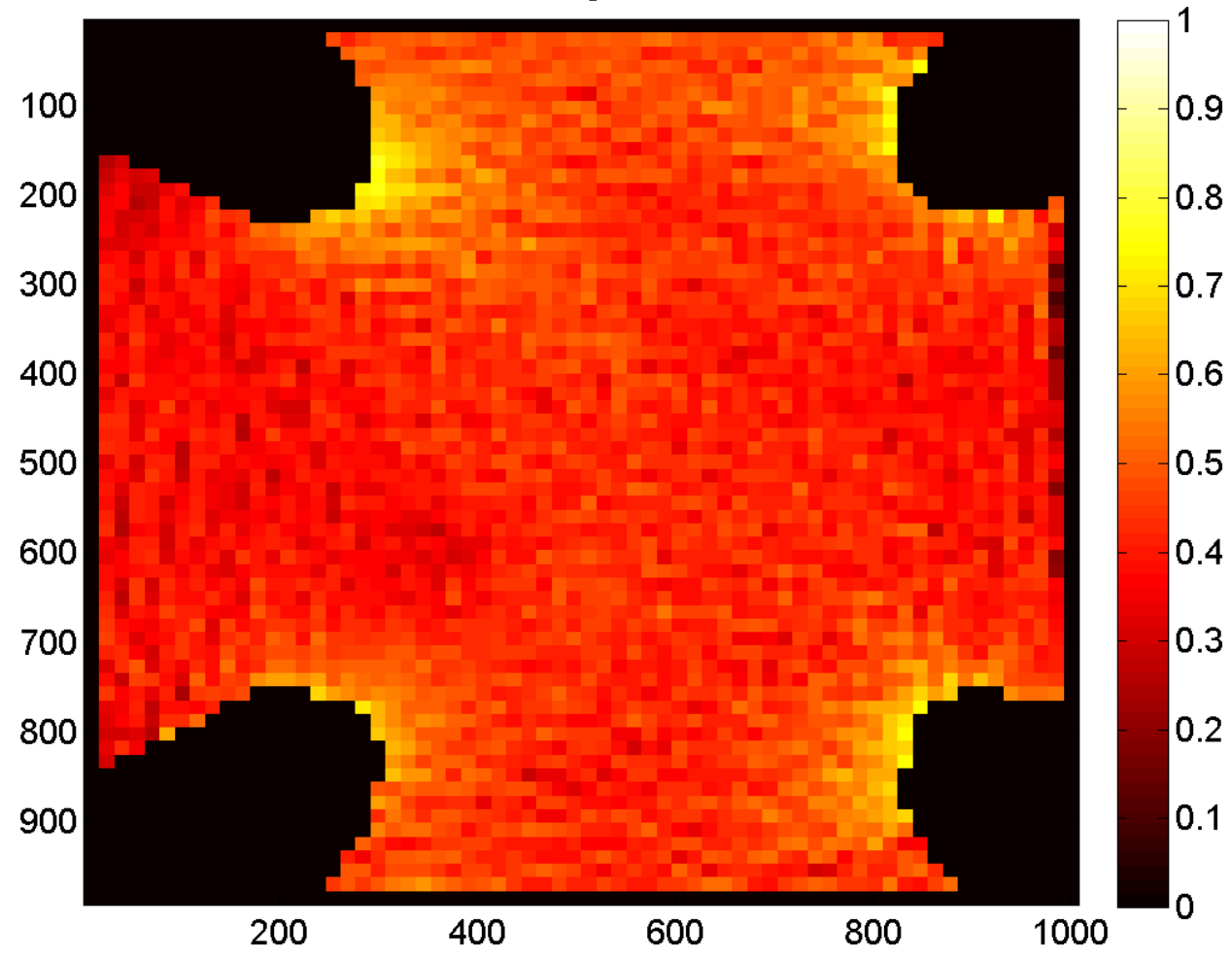
Loi d'endommagement

$$D = \sum_k c_k \varphi_k (\hat{\varepsilon}_{eq}) \quad \text{avec} \quad \hat{\varepsilon}_{eq}(t) = \max_{0 \leq \tau \leq t} [\varepsilon_{eq}(\tau)]$$

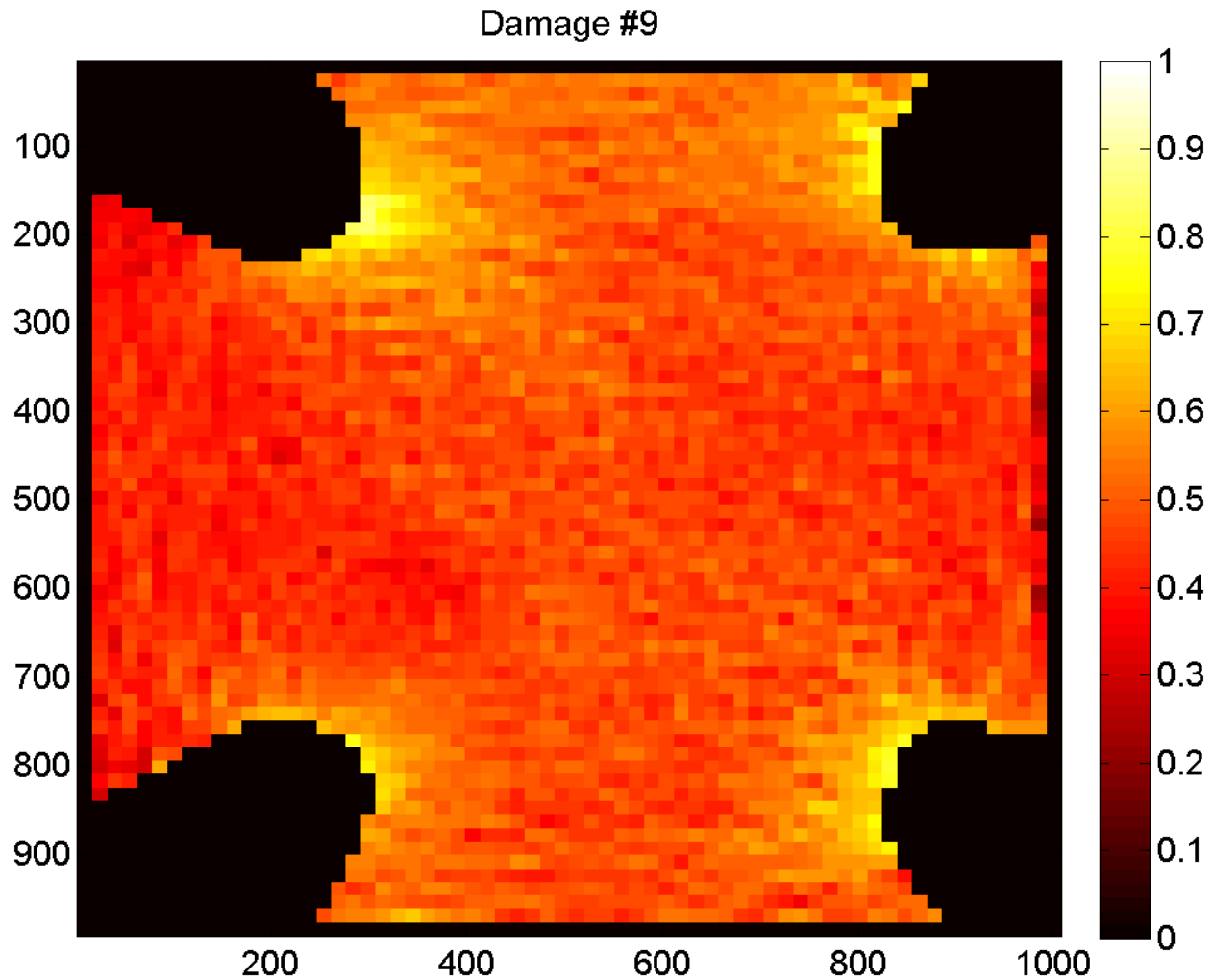
$$R_{REG}(\{c\}) = \sum_i \left(u_i^{meas} - \sum_k c_k w_k [\hat{\varepsilon}_{eq}^i] \right)^2$$

Champ d'endommagement

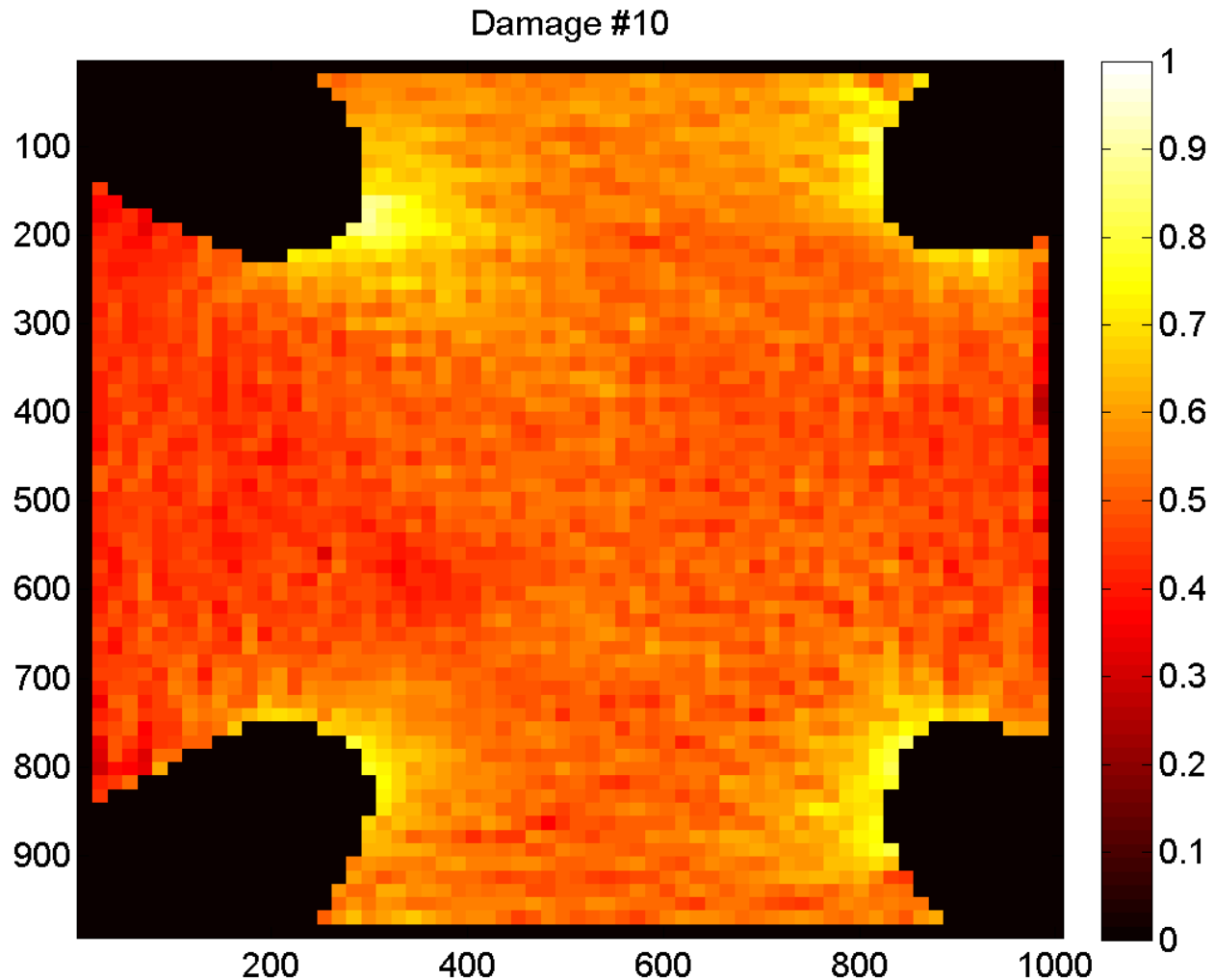
Damage #8



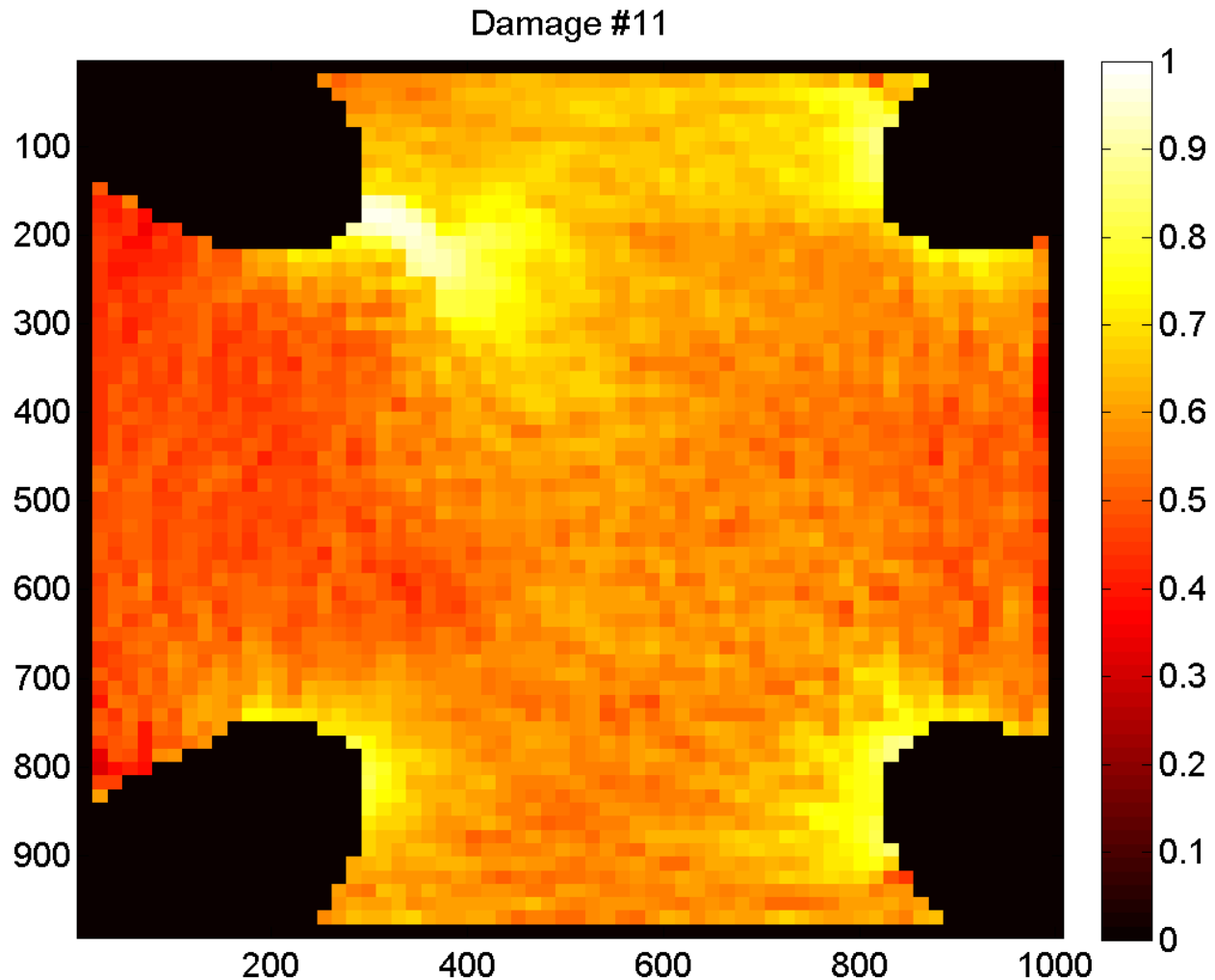
Champ d'endommagement



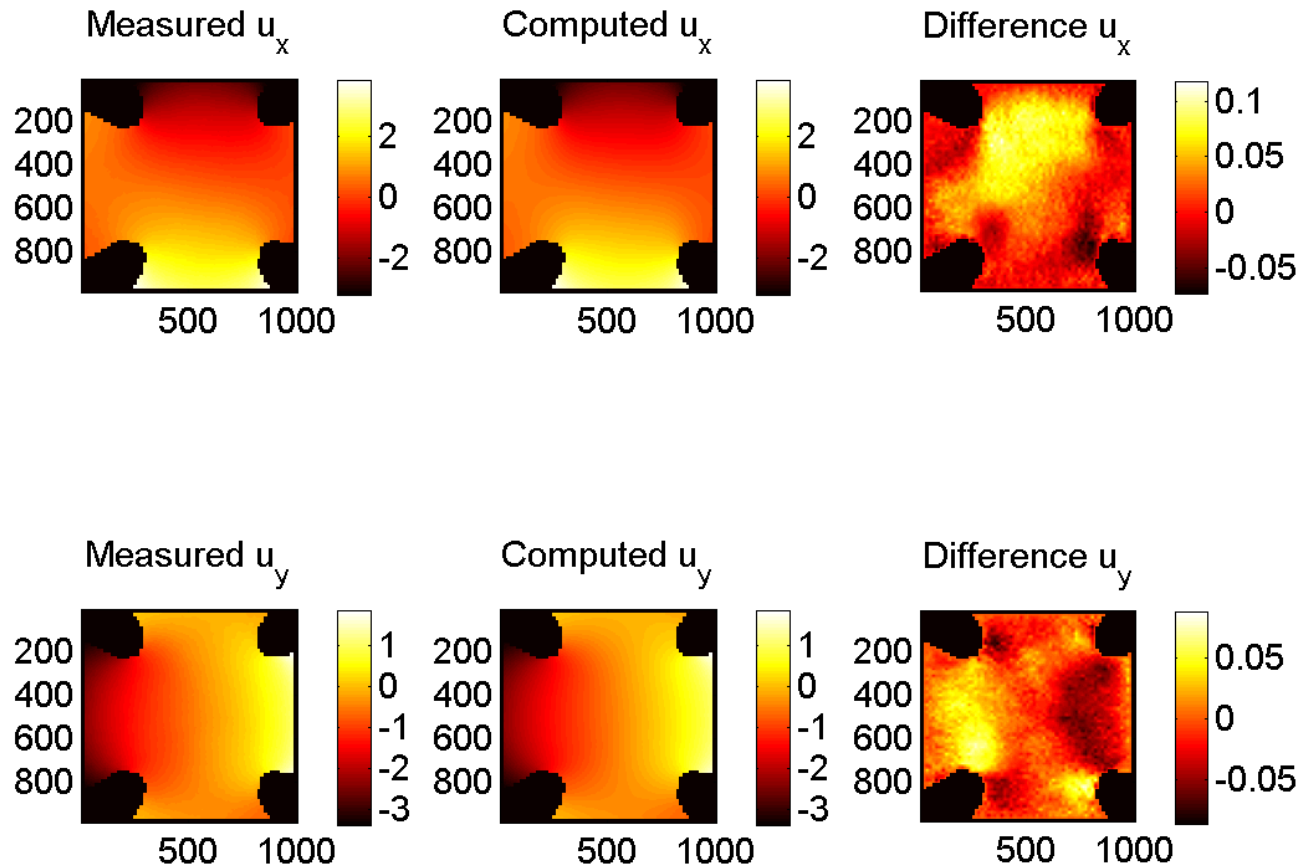
Champ d'endommagement



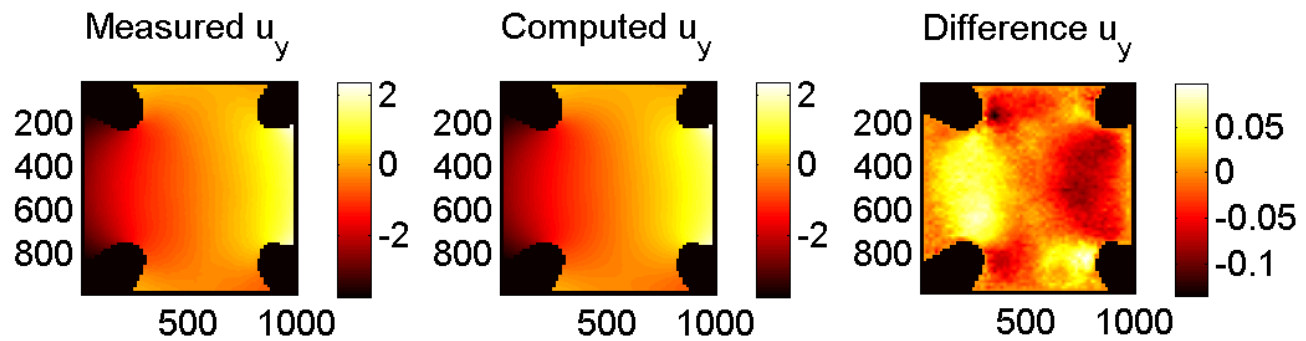
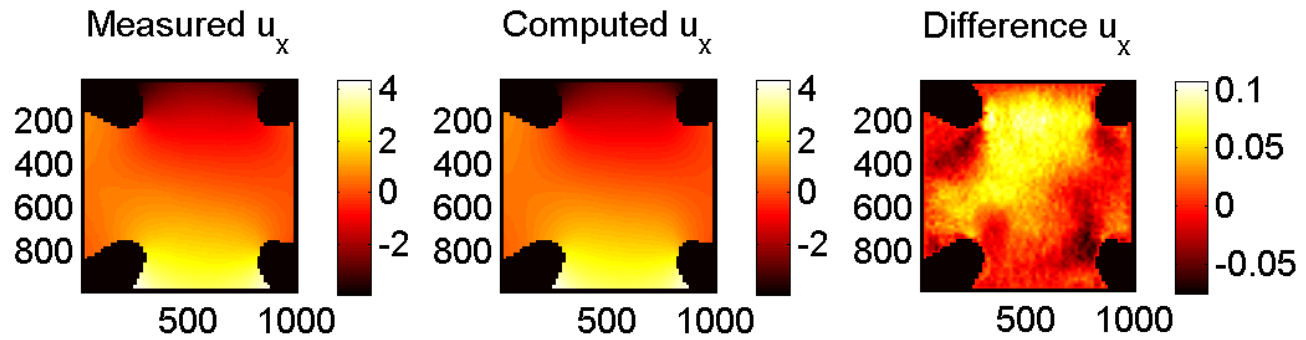
Champ d'endommagement



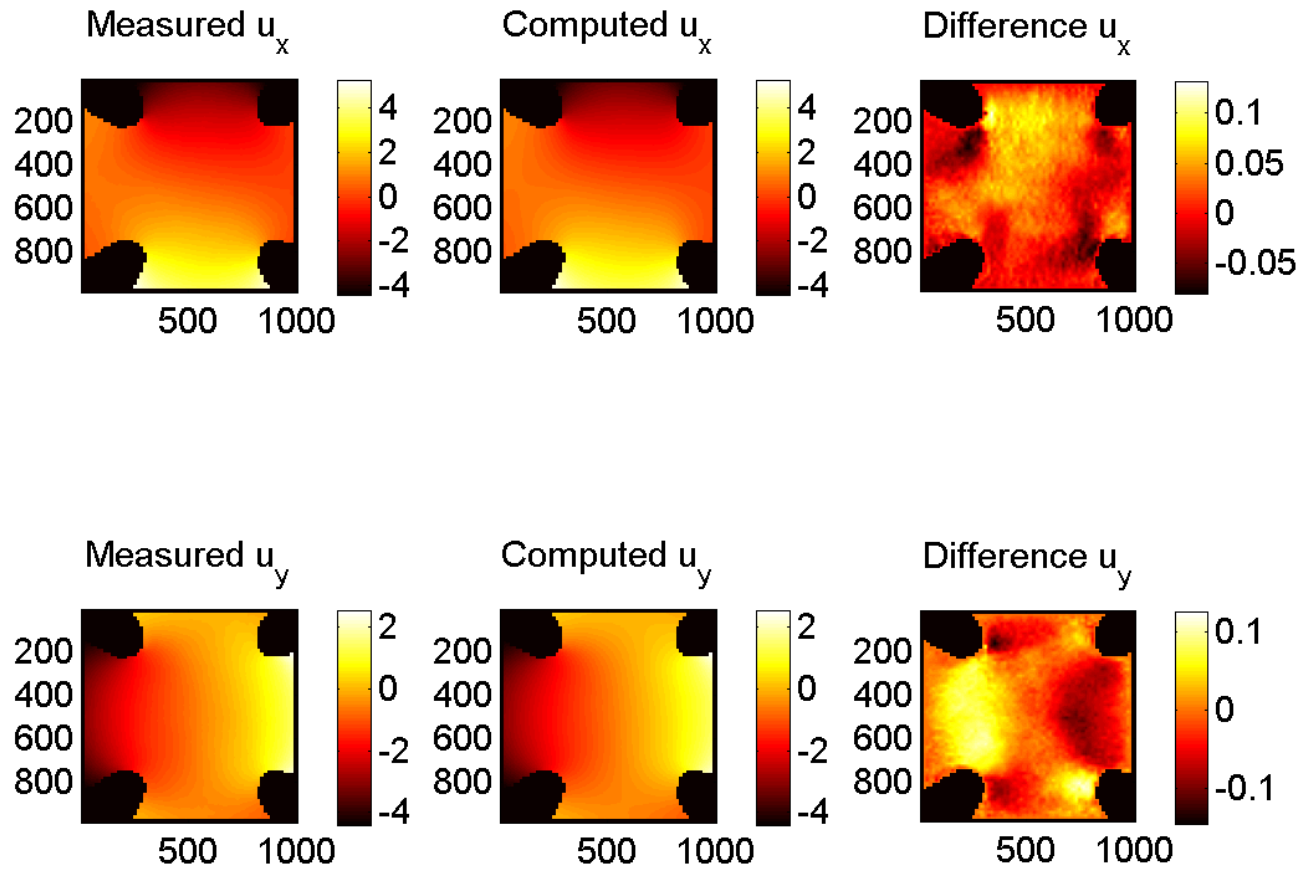
Validation



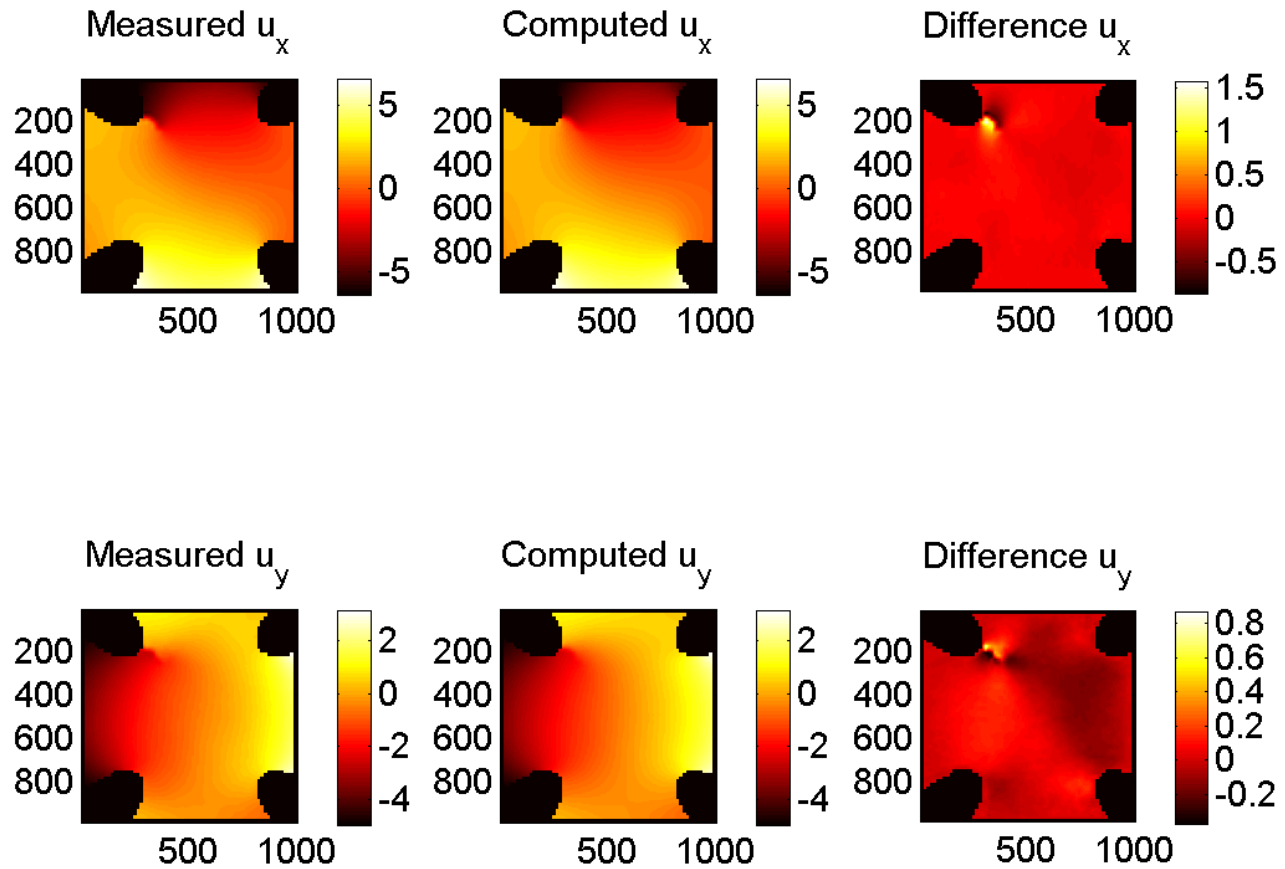
Validation



Validation



Validation



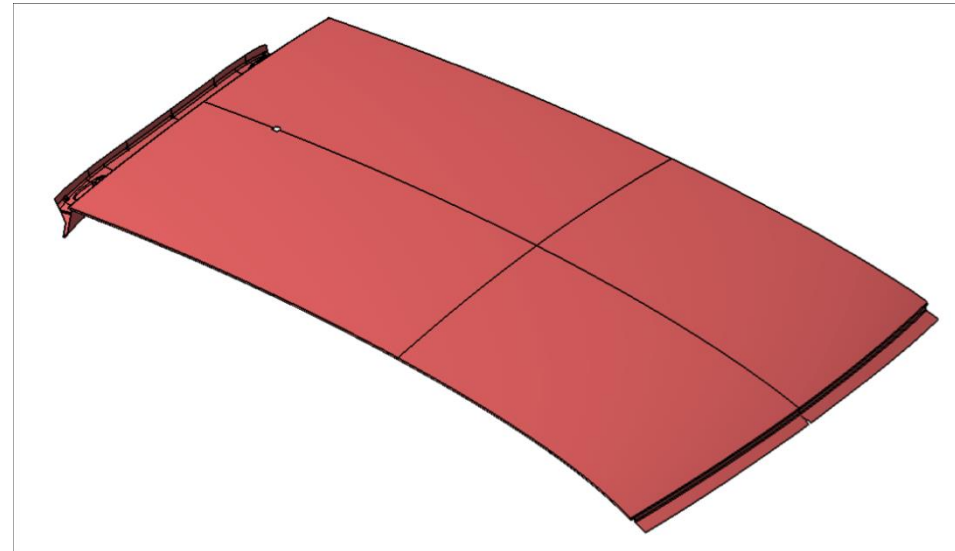


DANS L'INDUSTRIE : CINEMA 3D

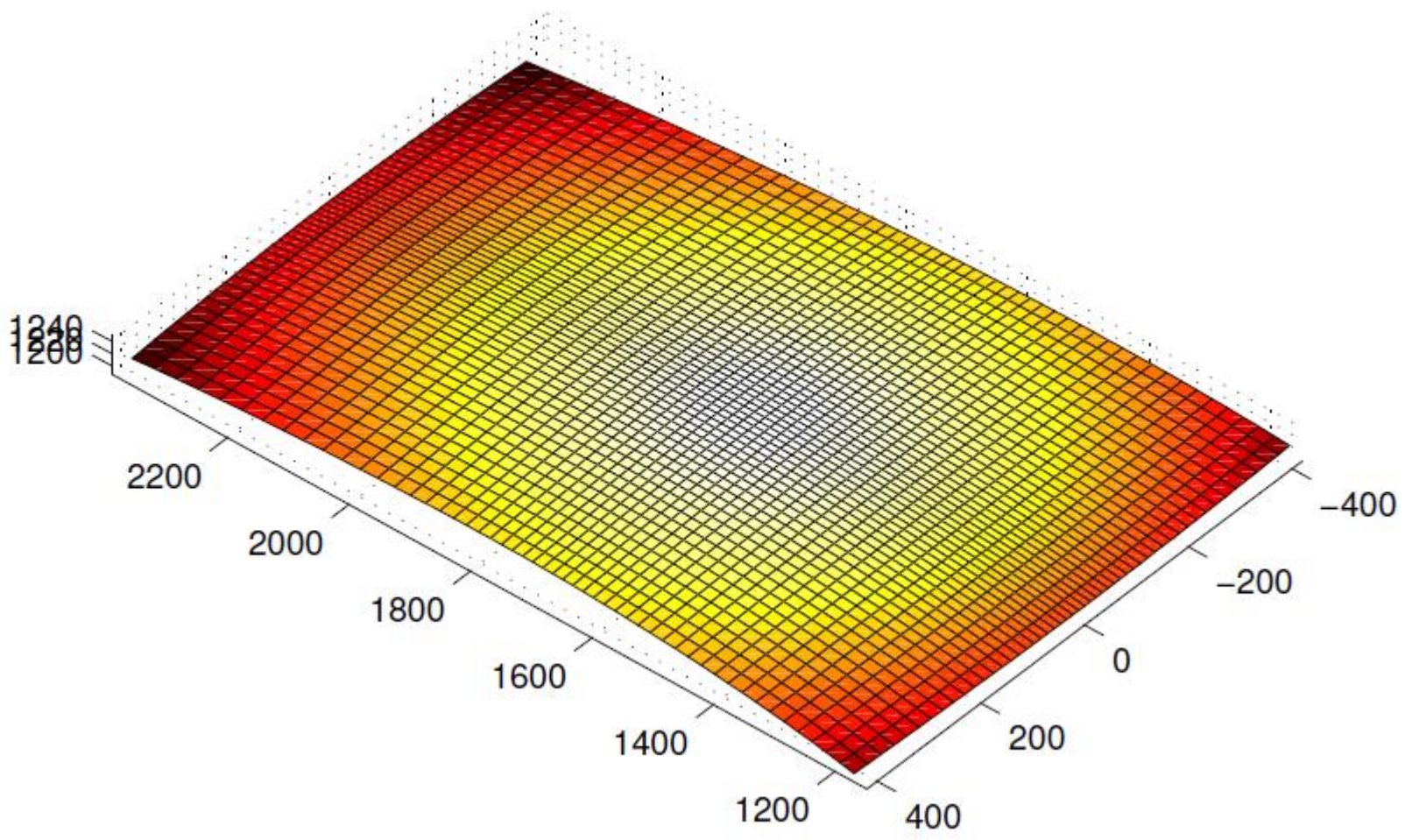
Soudo-brasage d'un pavillon automobile



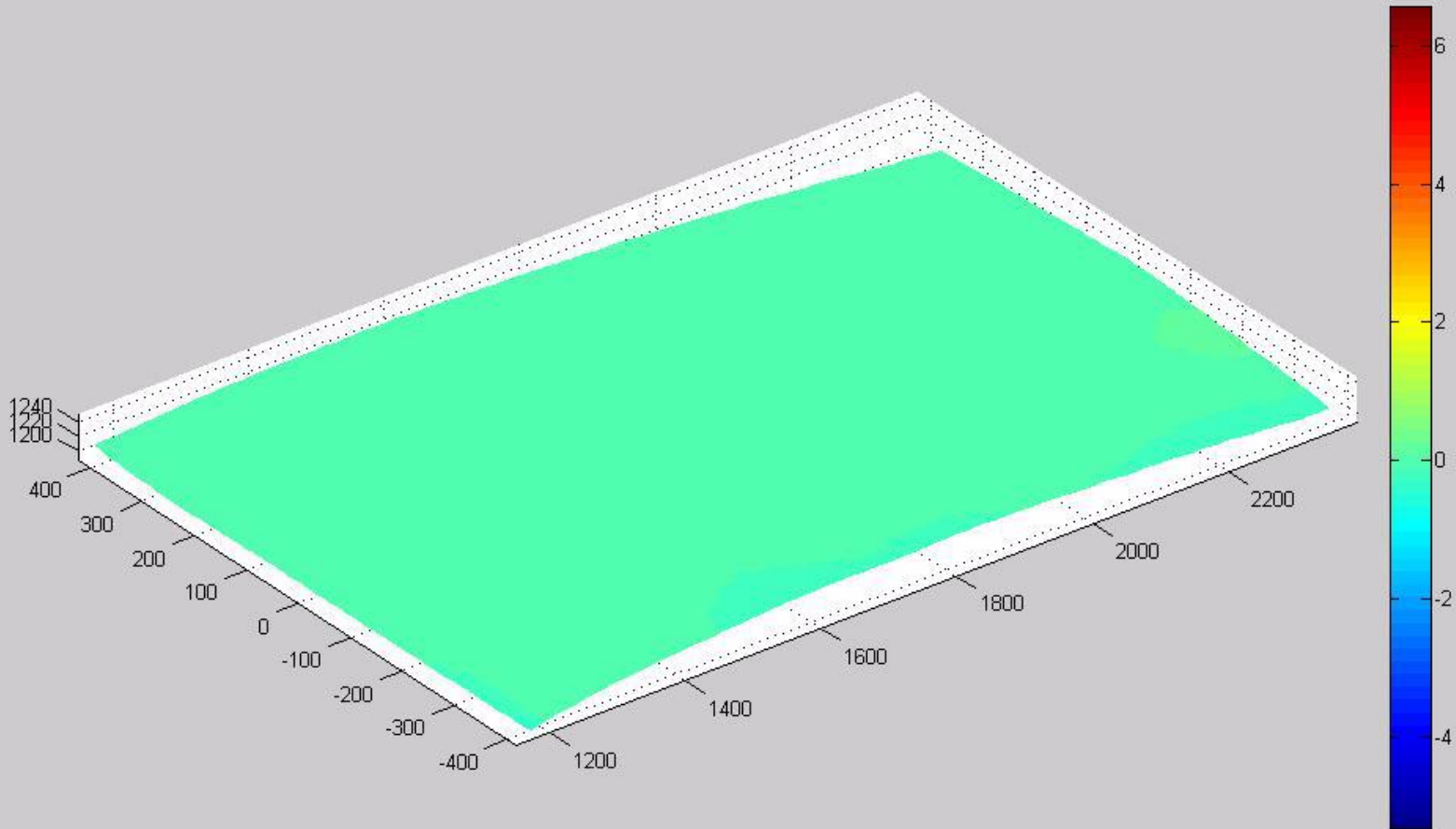
Modèle CAO de la surface observée



Forme 3D mesurée



Déplacements normaux (mm)



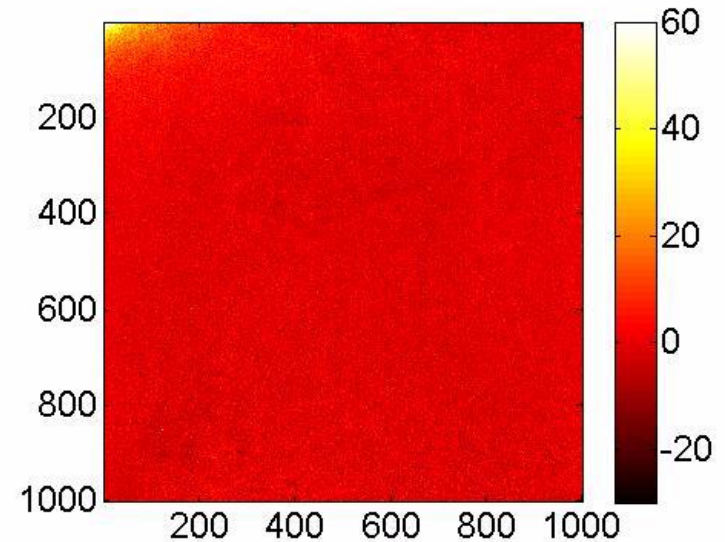
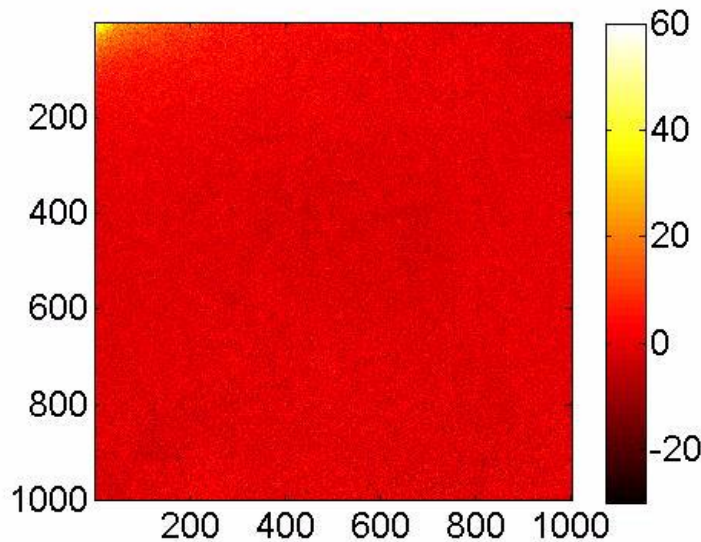
Résidus de corrélation (NdG)

Caméra gauche

$$I_n^l(\underline{x}^l + \underline{u}^l(u, v, \mathbf{P}_{ij}(\mathbf{u}_n))) - I_0^l(\underline{x}^l)$$

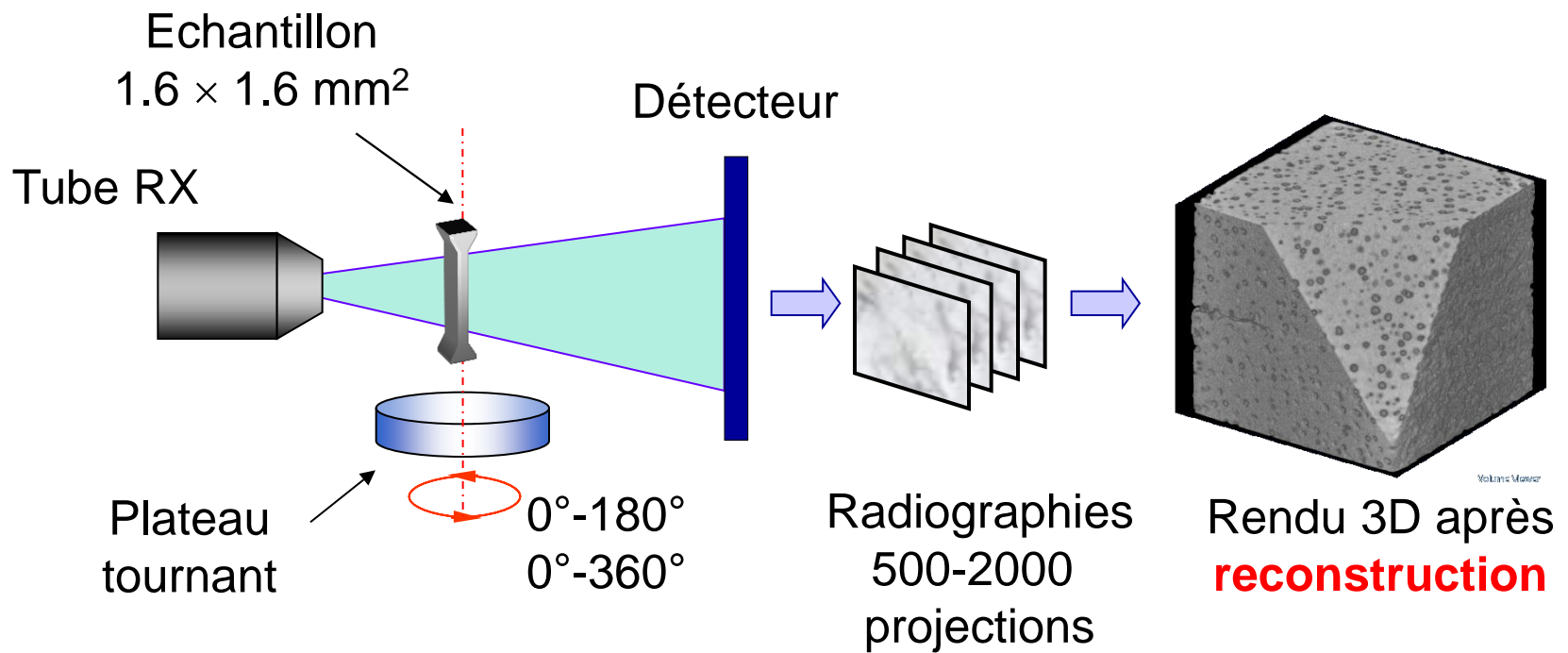
Caméra droite

$$I_n^r(\underline{x}^r + \underline{u}^r(u, v, \mathbf{P}_{ij}(\mathbf{u}_n))) - I_0^r(\underline{x}^r)$$

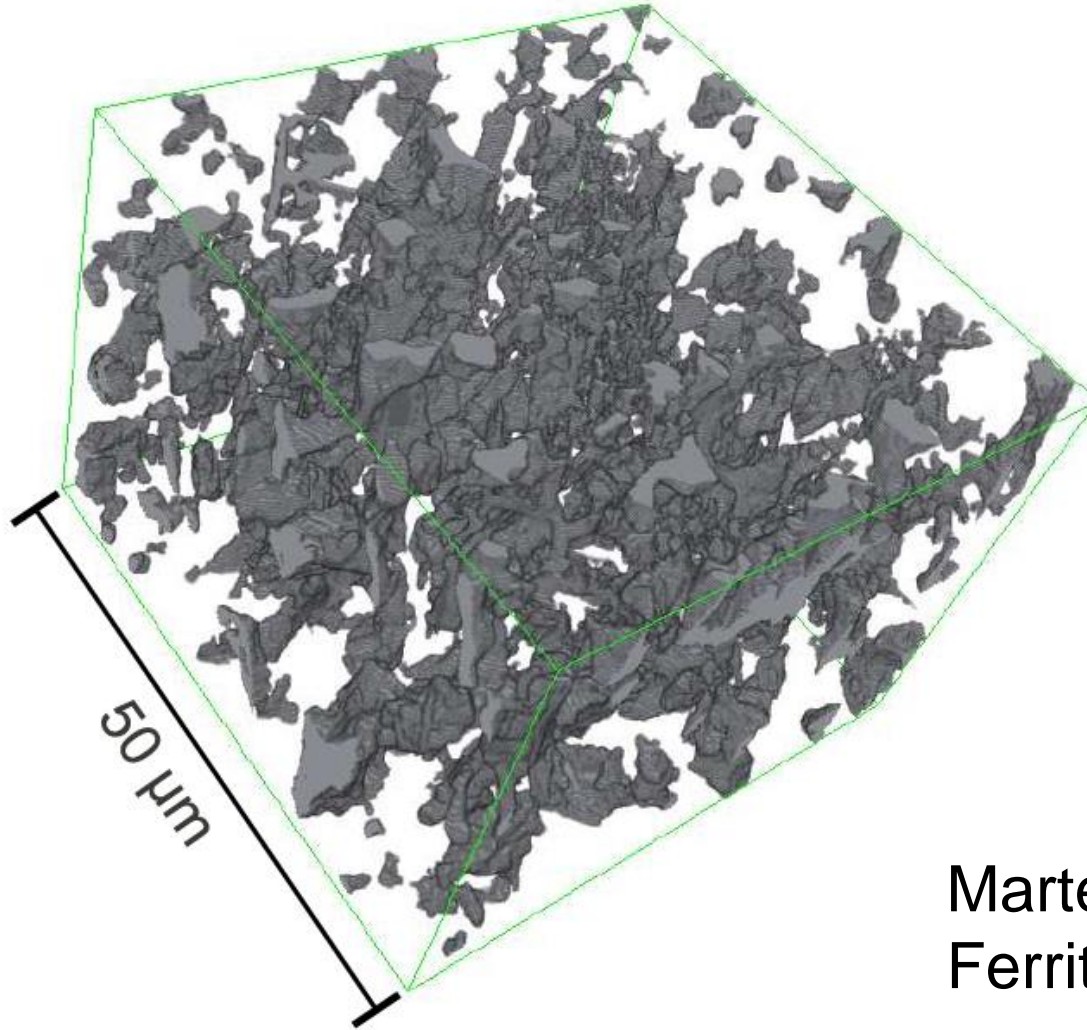


**CINEMA 3D :
L'ESSENTIEL EST INVISIBLE
POUR LES YEUX...**

Tomographie

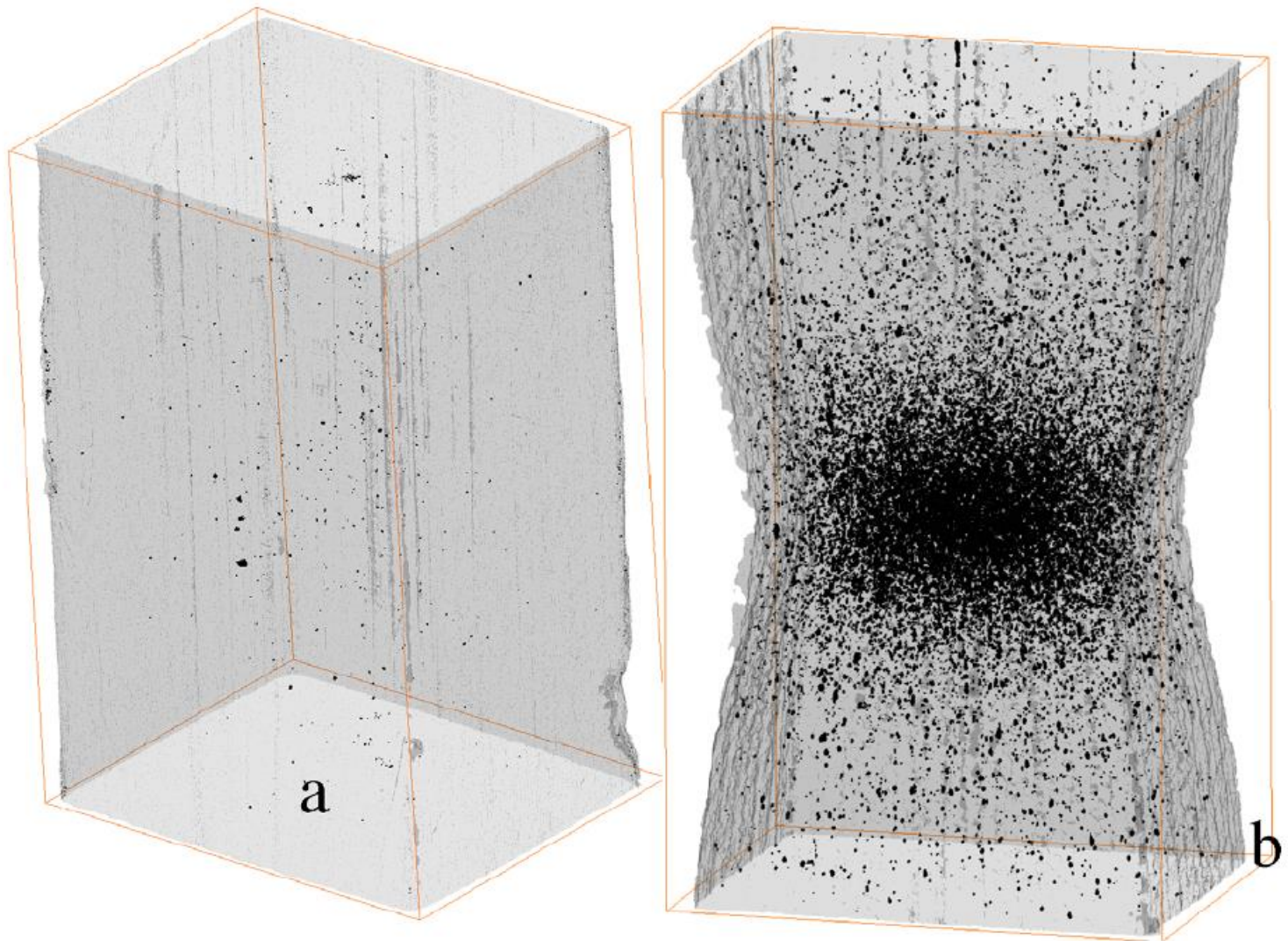


Acier DP 11

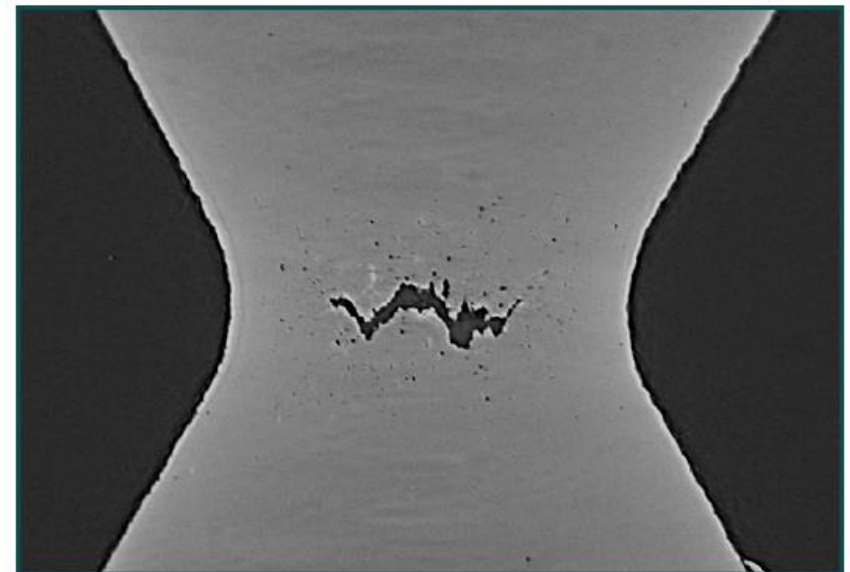
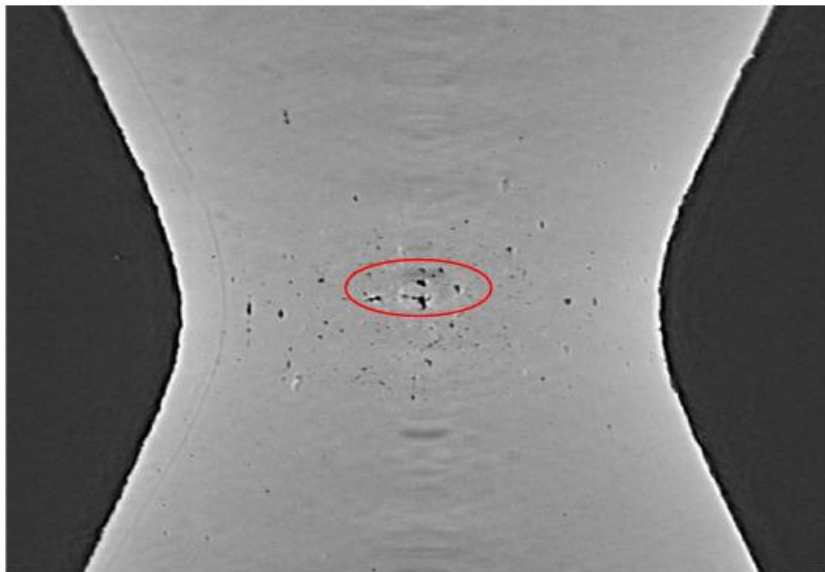


Martensite : grise
Ferrite : transparente

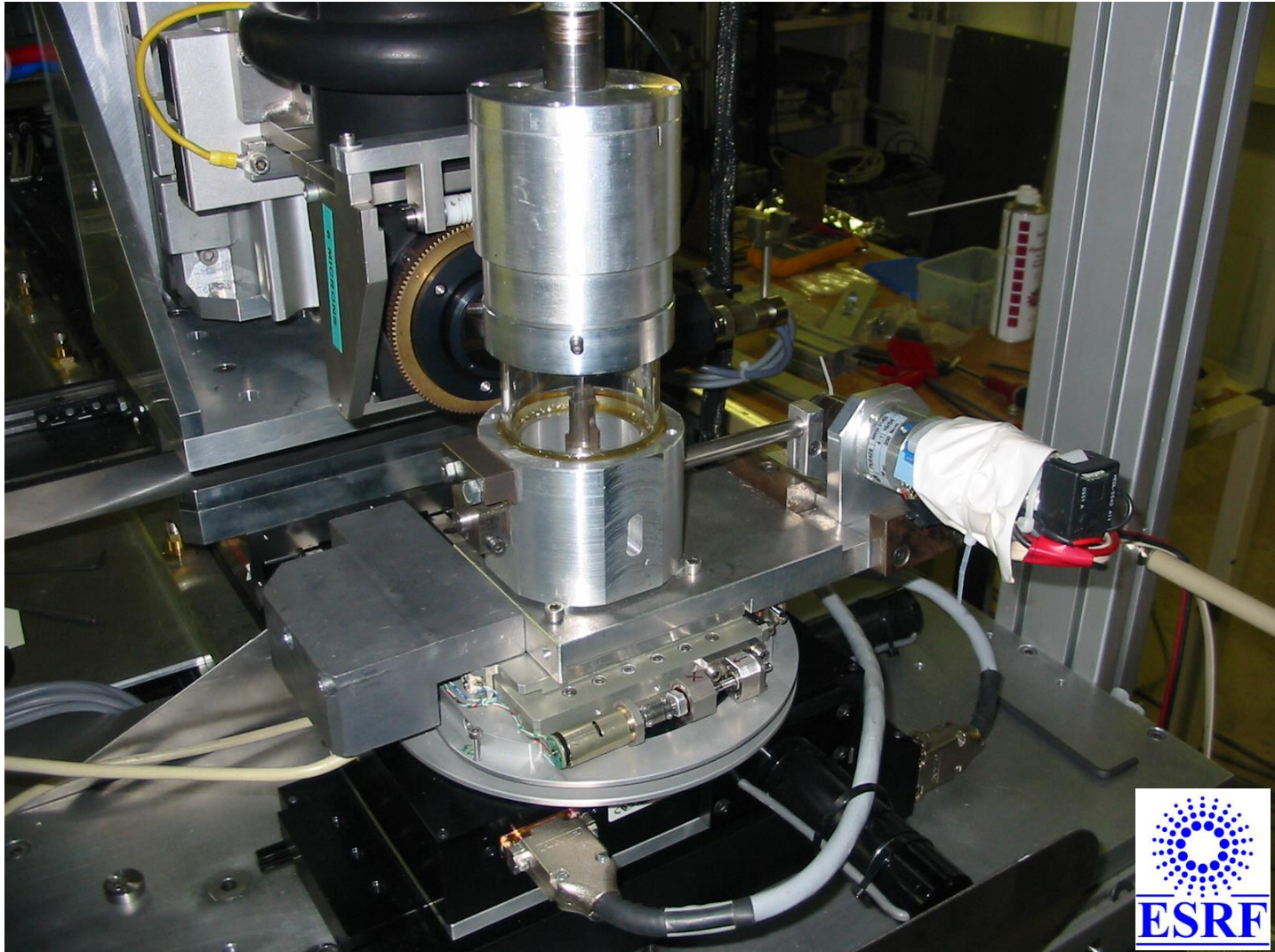
Endommagement ductile : germination / croissance



Endommagement ductile : croissance / coalescence

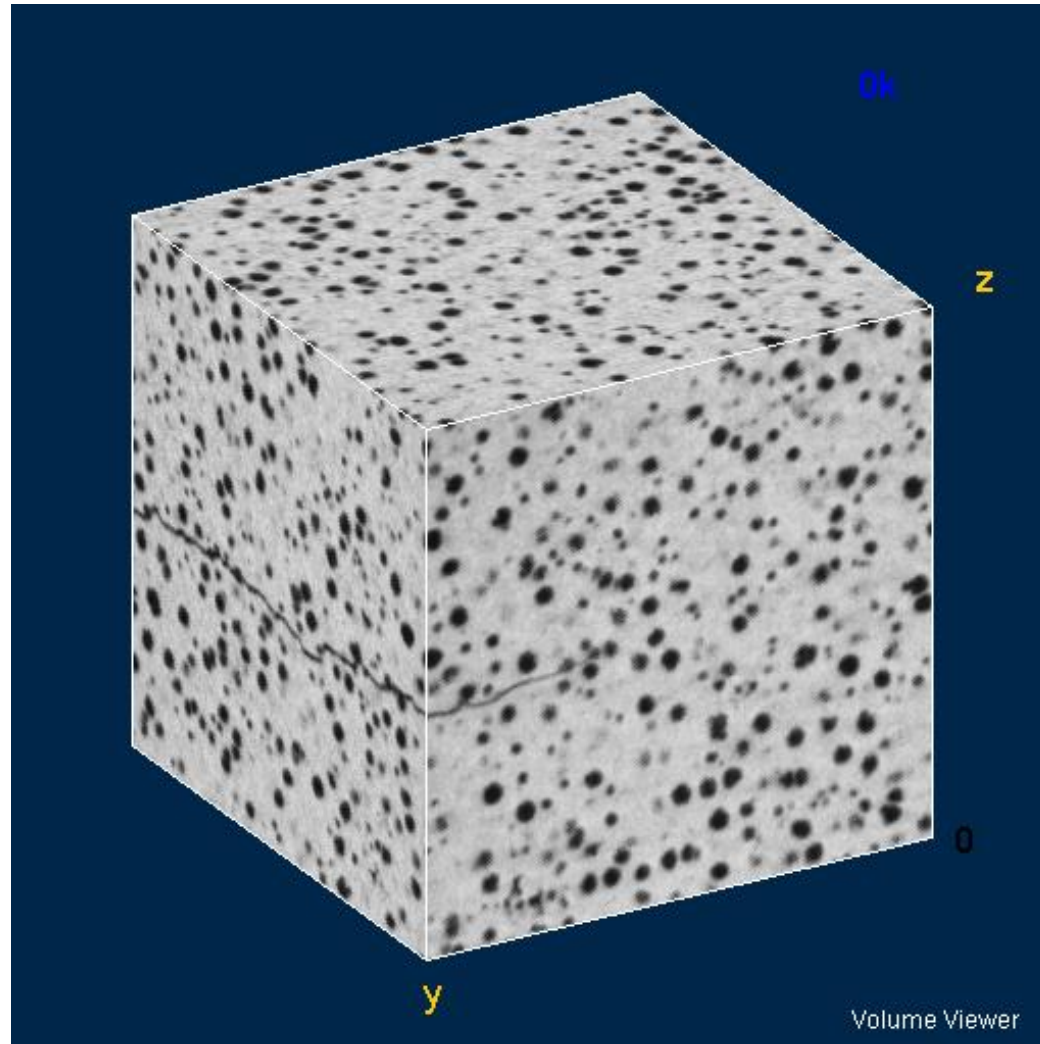


Essai de fatigue *in situ**



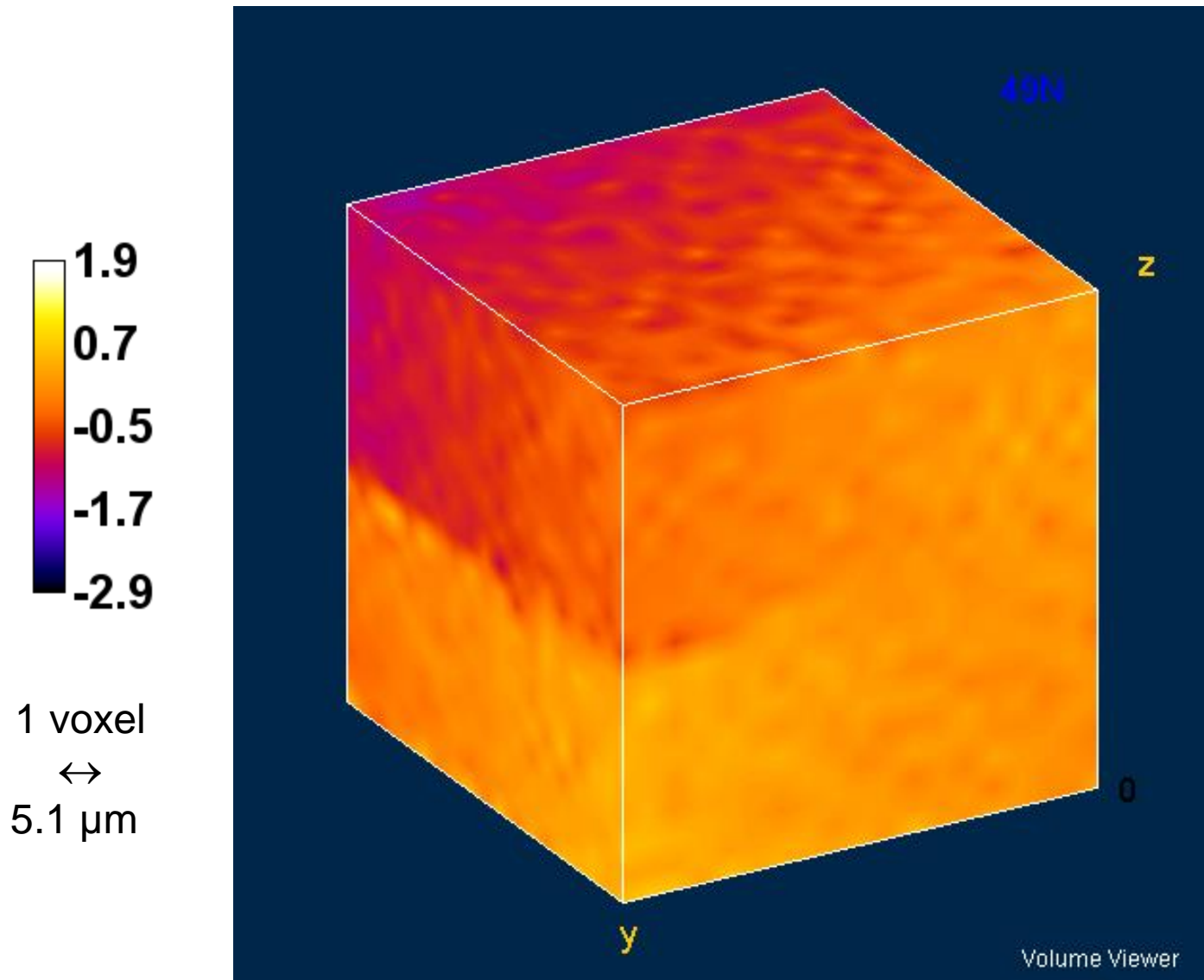
*[Ludwig et al., 2003, *Acta Mater.* 51 pp. 585-598]

Volume imagé (FGS)

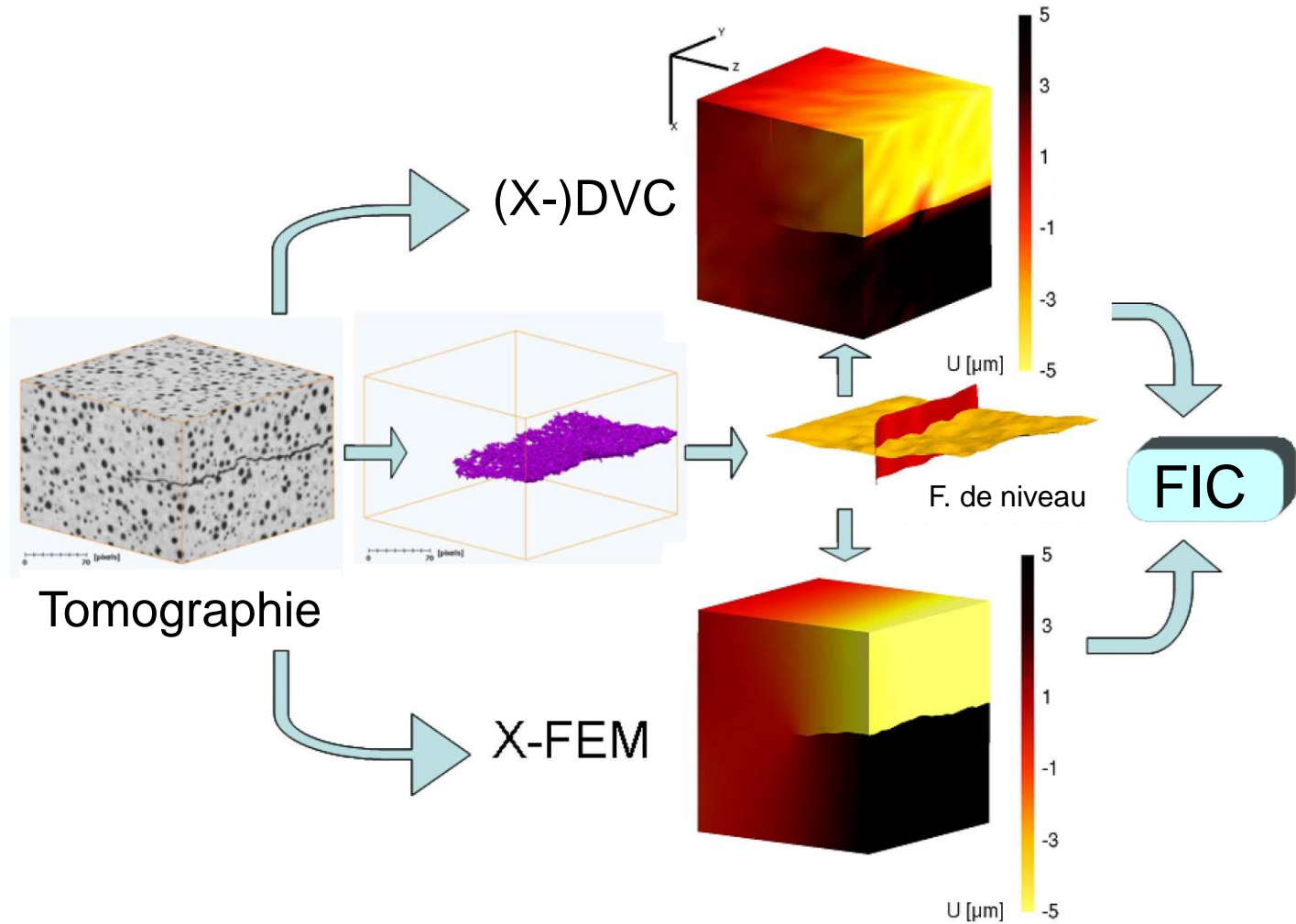


1 voxel \leftrightarrow 5.1 μm

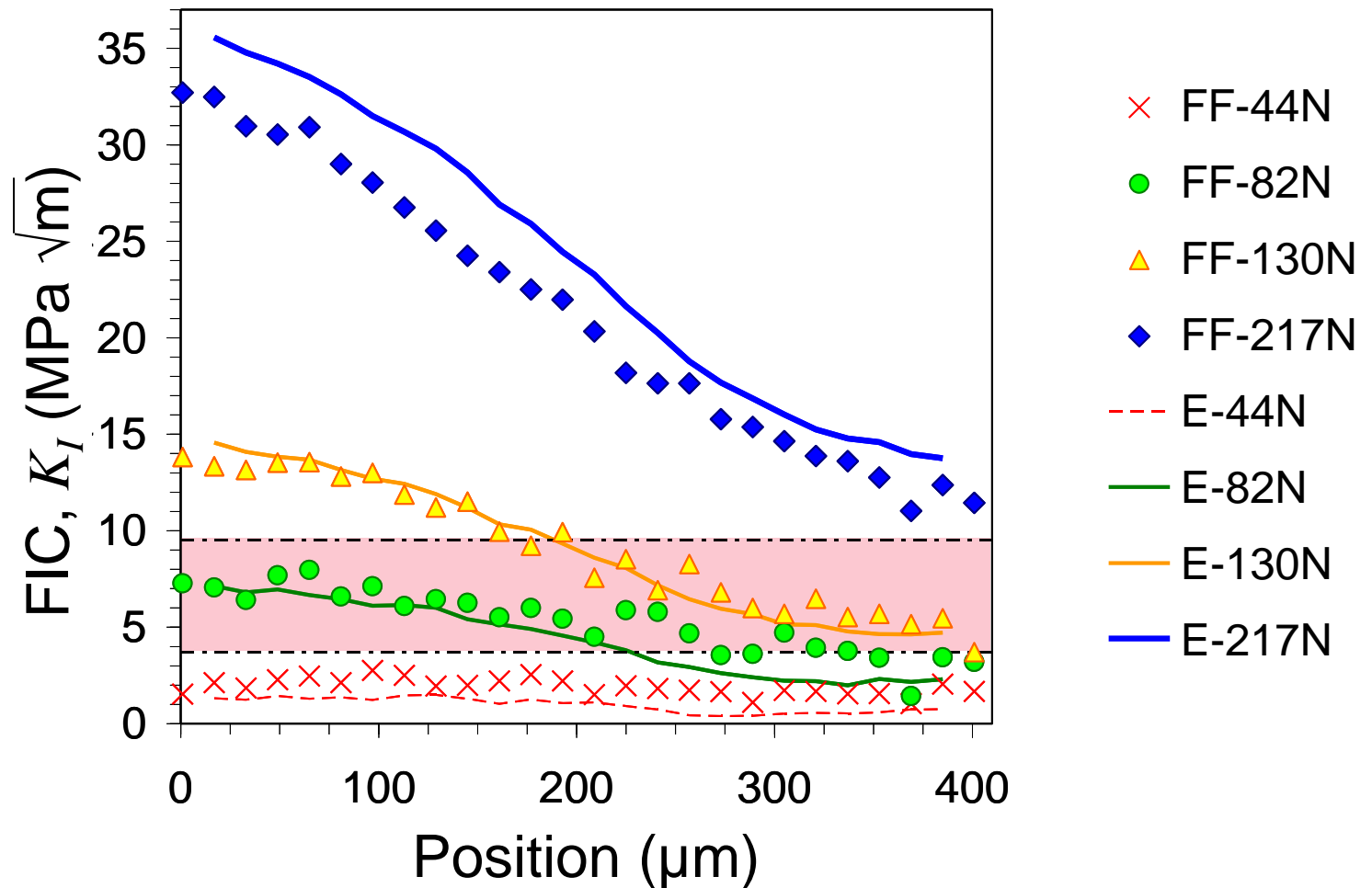
Déplacement normal (49 kcycles)



Validation d'un calcul 3D



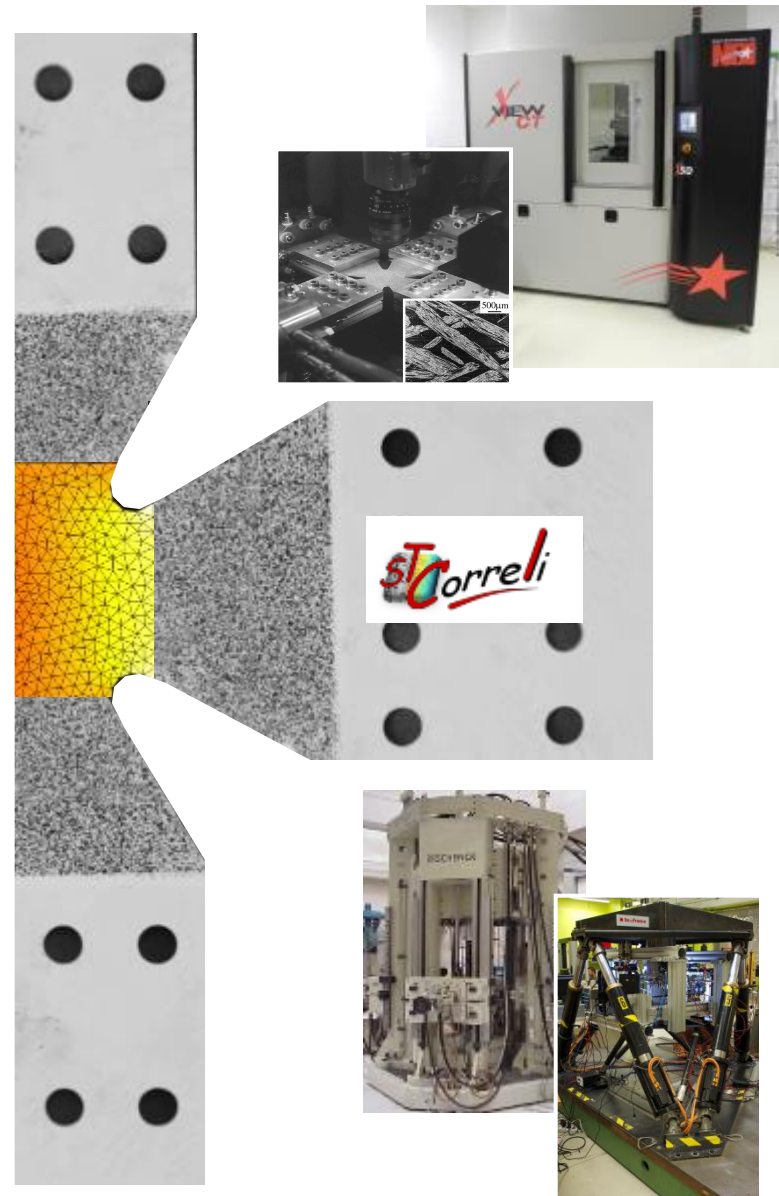
Profils de FIC



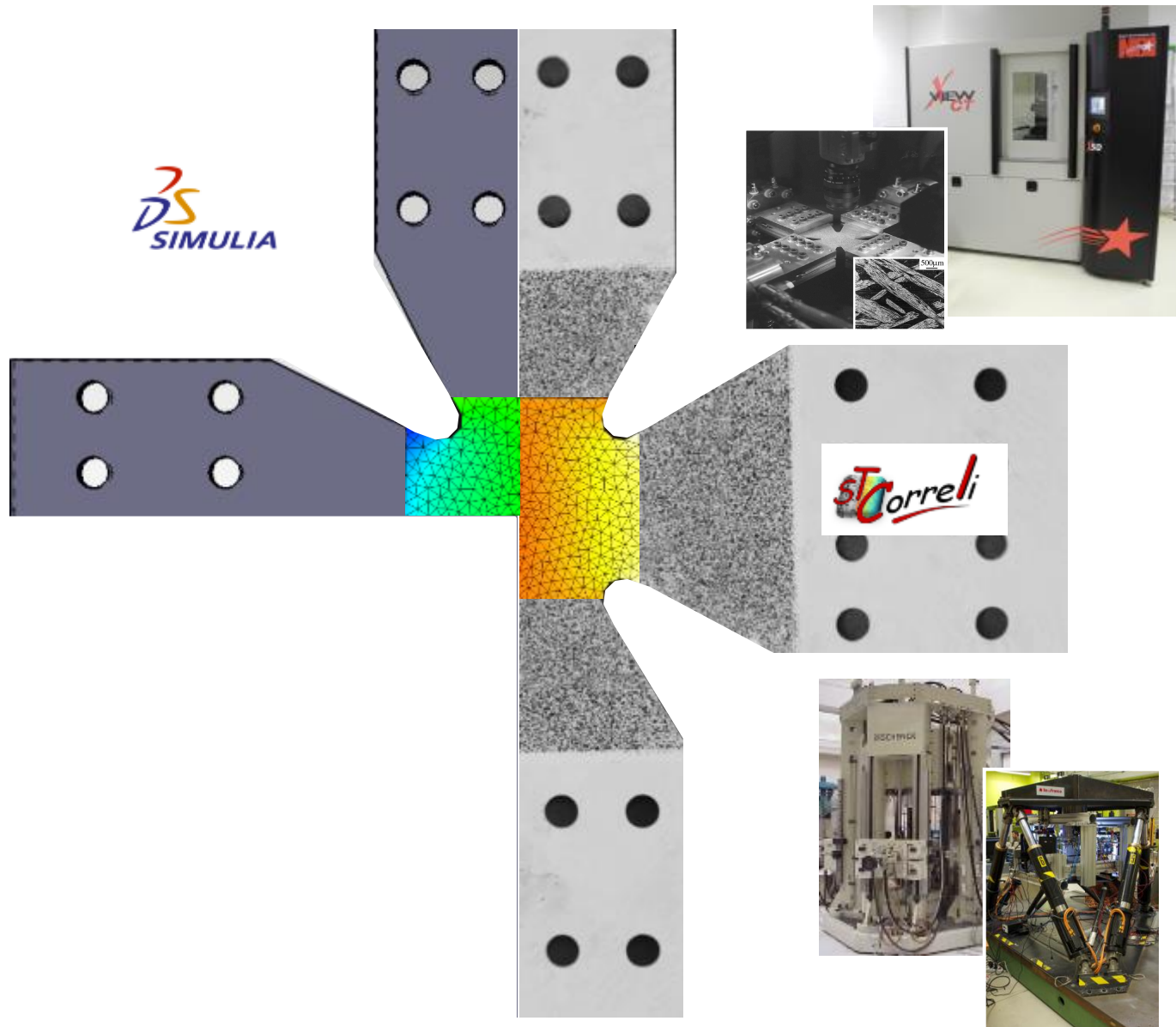


CONCLUSIONS ET PERSPECTIVES : MIEUX QUE DU CINEMA ?

Dialogues CAO / essais / mesures / calculs EF



Dialogues CAO / essais / mesures / calculs EF



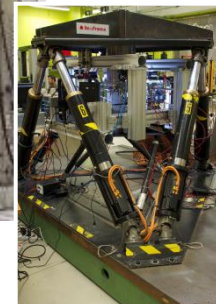
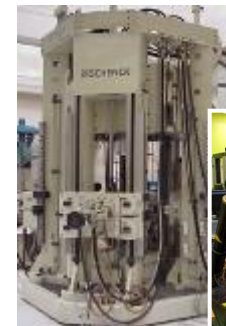
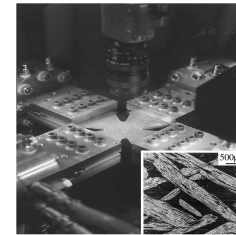
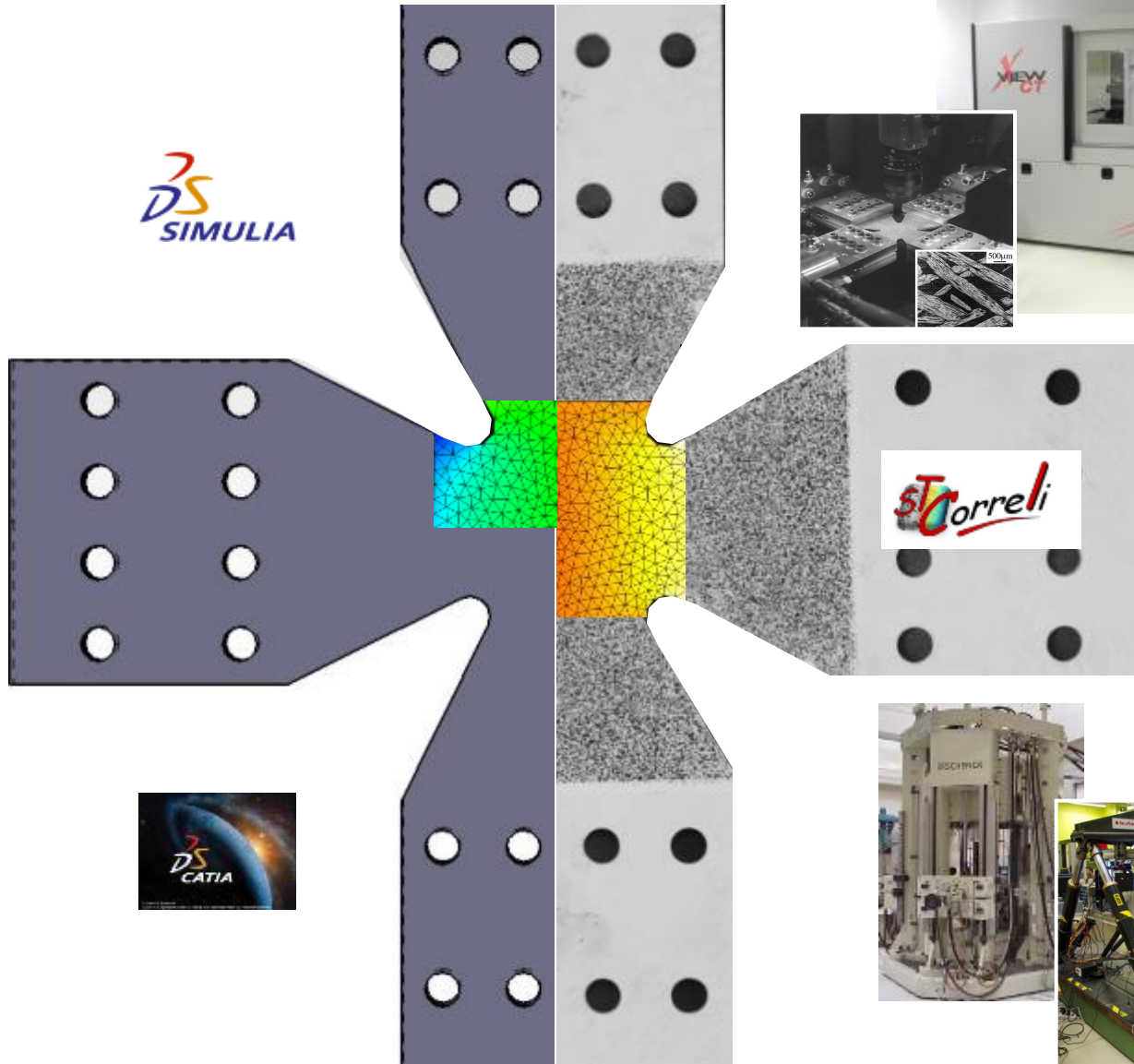
Dialogues CAO / essais / mesures / calculs EF



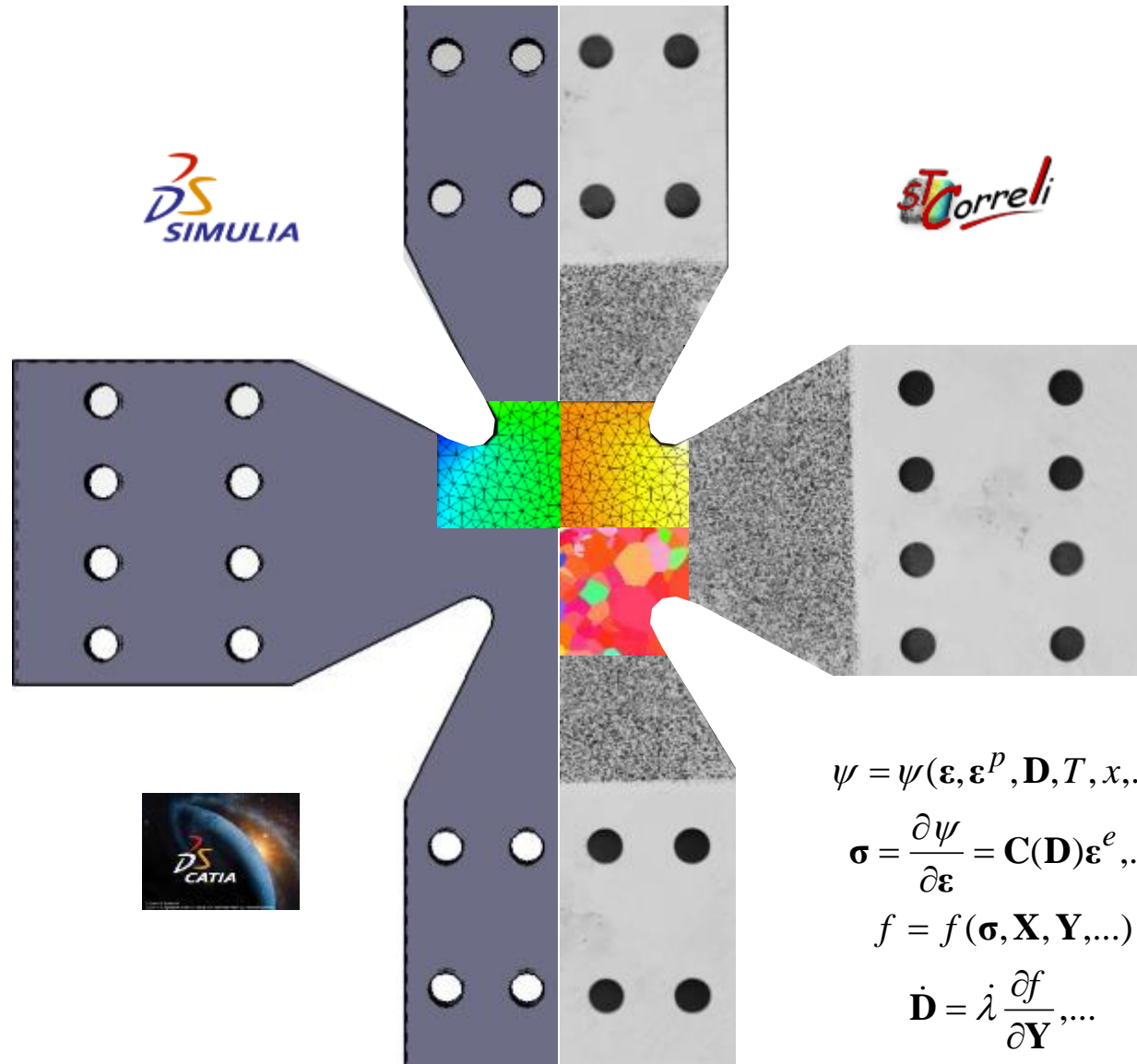
A central composite image illustrating the workflow from design to testing. On the left is a grey CAD model of a mechanical part with four circular holes. To its right is a vertical cross-section of the part, showing a yellow finite element analysis (FEA) mesh in the center. Further right is a photograph of a physical part with a 'STCorreli' logo. Surrounding these are several smaller images: a top-right photo of a 'VIEW 3D' coordinate measuring machine (CMM); a middle-right photo of a 'SCHENCK' universal testing machine; and a bottom-right photo of a robotic assembly line. A small '500µm' scale bar is visible in one of the inset images.



Dialogues CAO / essais / mesures / calculs EF



Modèles identifiés et validés



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

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

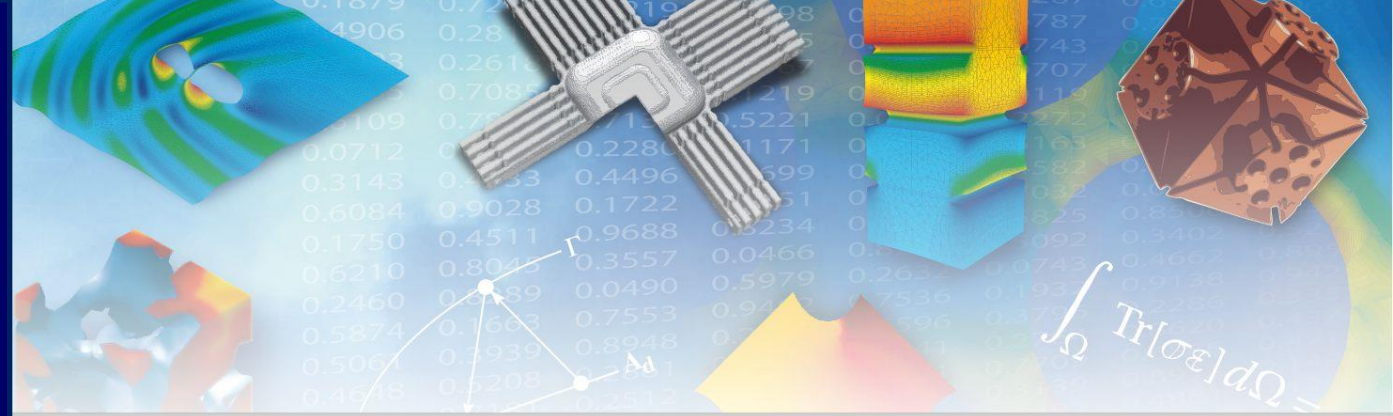
$$f = f(\boldsymbol{\sigma}, \mathbf{X}, \mathbf{Y}, \dots)$$

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



CINEMA :

Corrélation d'**I**mages **N**umériques
En **M**écanique **A**ppliquée



FIN