Technische Universität Braunschweig

GRK 2075

Damage evaluation and measurement via correlation techniques

(*Schadensbewertung und Messung mit Korrelationstechniken*)

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université PARIS-SACLAY

LMT

cnrs dépasser les frontières

Damage / Fracture

Challenges

- Need for reliable kinematic fields
- Robust and validated models

Outline

- Evaluation of damage via DIC and DVC
- Design of discriminating experiments (e.g., concrete)
- Summary and perspectives

Damage / Fracture

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- Summary and perspectives

Digital Image Correlation

Measurement of optical flow

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

Local approach

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

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

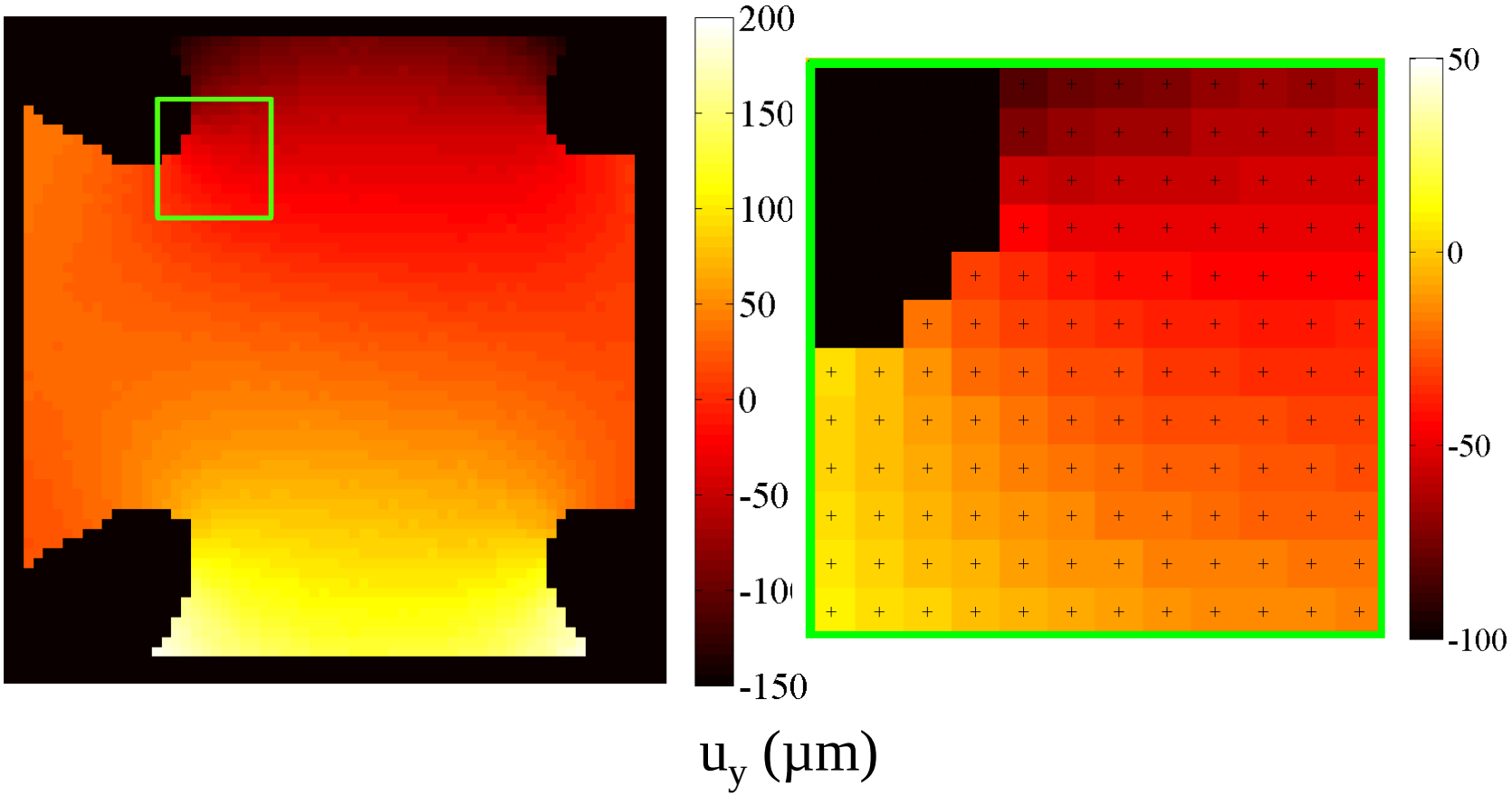
Fluid mechanics : PIV

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

Solid mechanics : DIC

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

Local Approach



→ **Cloud of points**

Standard Practice in Commercial Codes

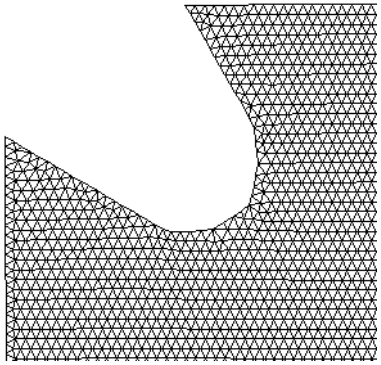
GOM

GOM headquarters in Braunschweig

Founded in 1990

Global Approach

Measurement of optical flow



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

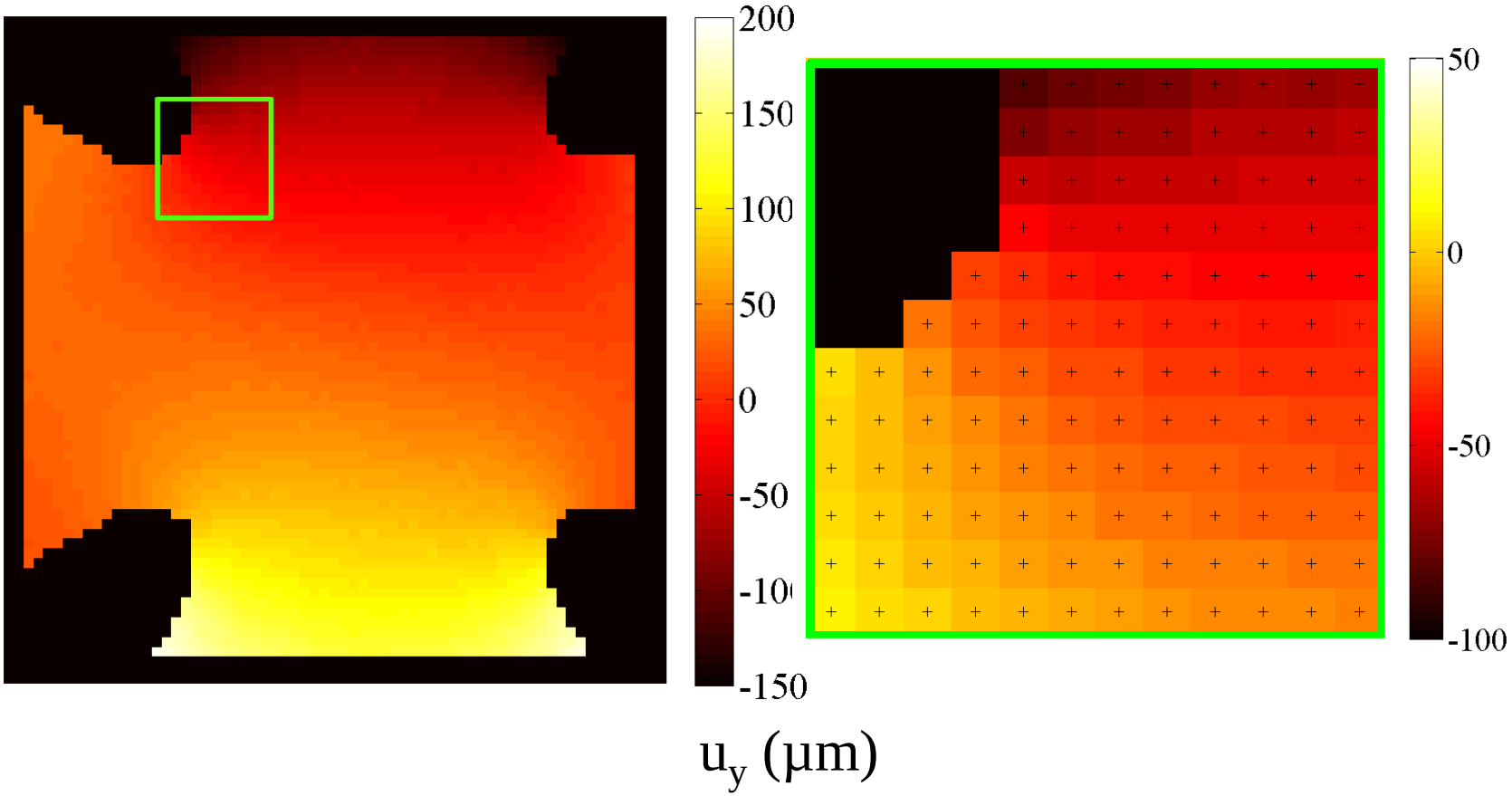
Global approach (FE bases*)

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

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

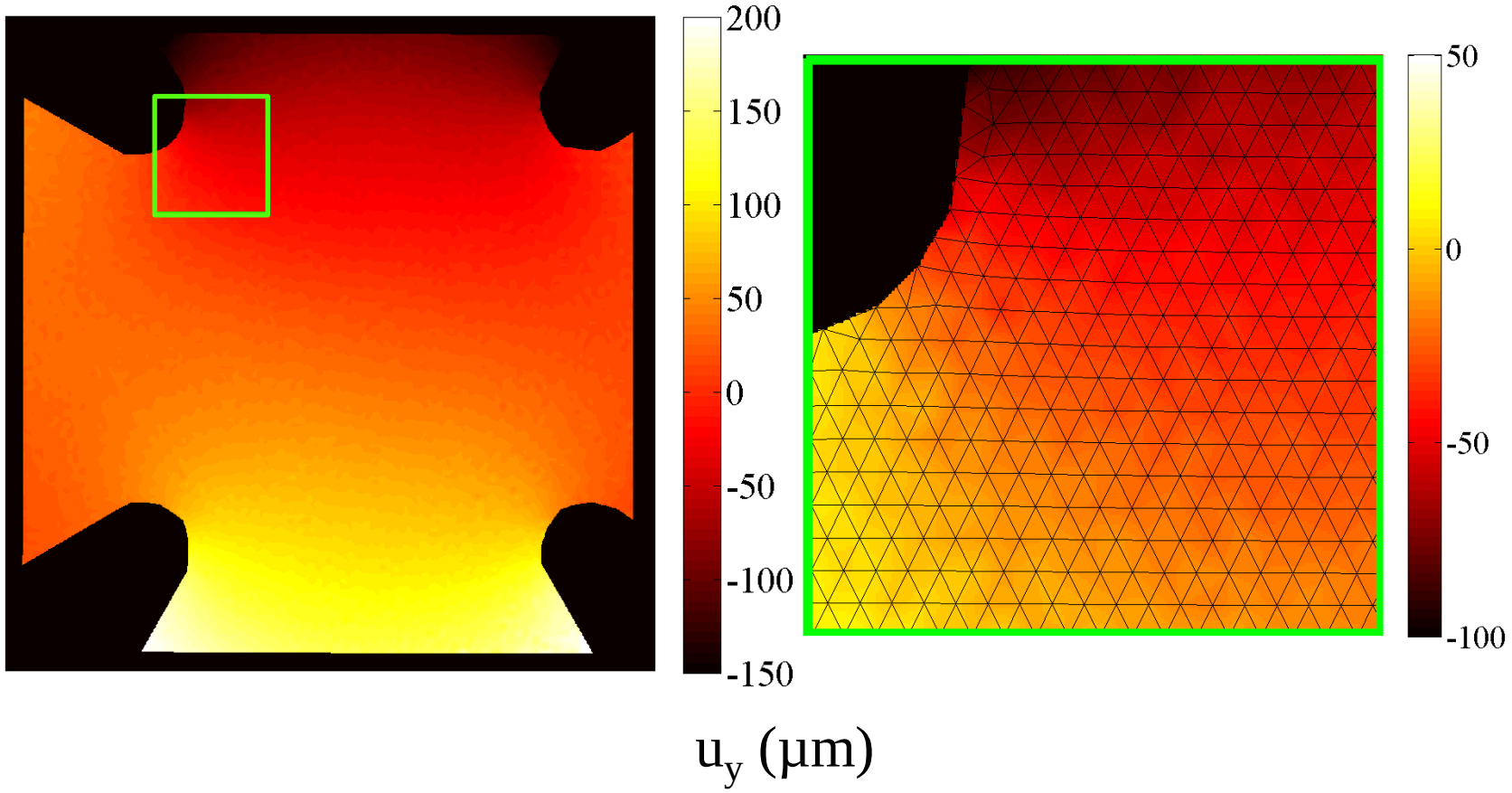
*[Besnard *et al.*, 2006, *Exp. Mech.* 46 pp. 789-803]

Local Approach



→ **Cloud of points**

Global Approach



→ **Dense and continuous field**

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

Mechanical Regularization

- Gray level conservation

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

- Internal equilibrium

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

- Boundary regularization

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

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

[Réthoré *et al.*, 2009, *Europ. J. Comput. Mech.* 18 pp. 285-306]
[Tomičević *et al.*, 2013, *J. Strain Anal.* 48 pp. 330-343]

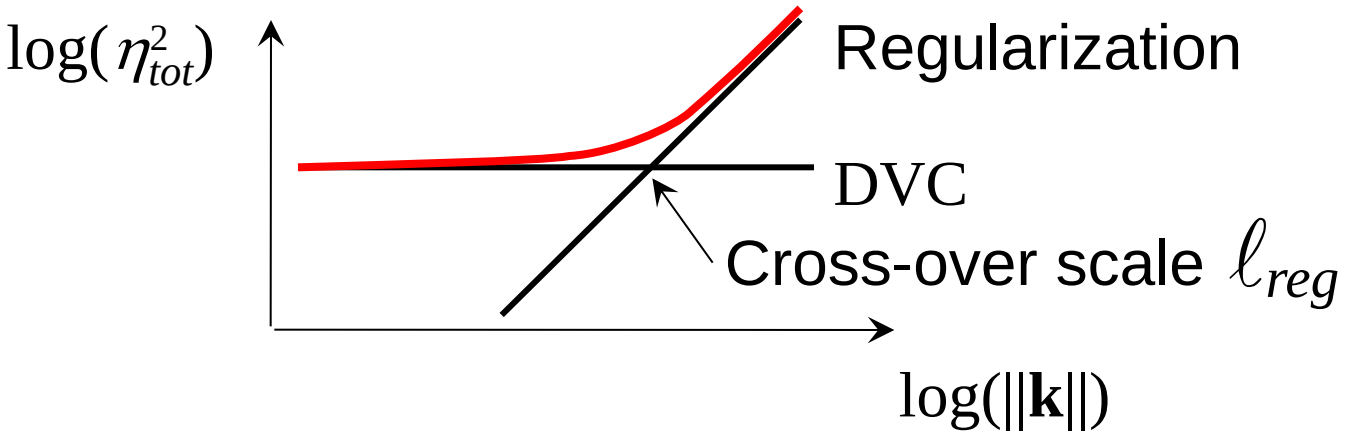
New Length Scale(s)

- Choice: plane wave for $\mathbf{v}(\mathbf{x}) = \mathbf{v}_0 e^{i\mathbf{k}\cdot\mathbf{x}}$

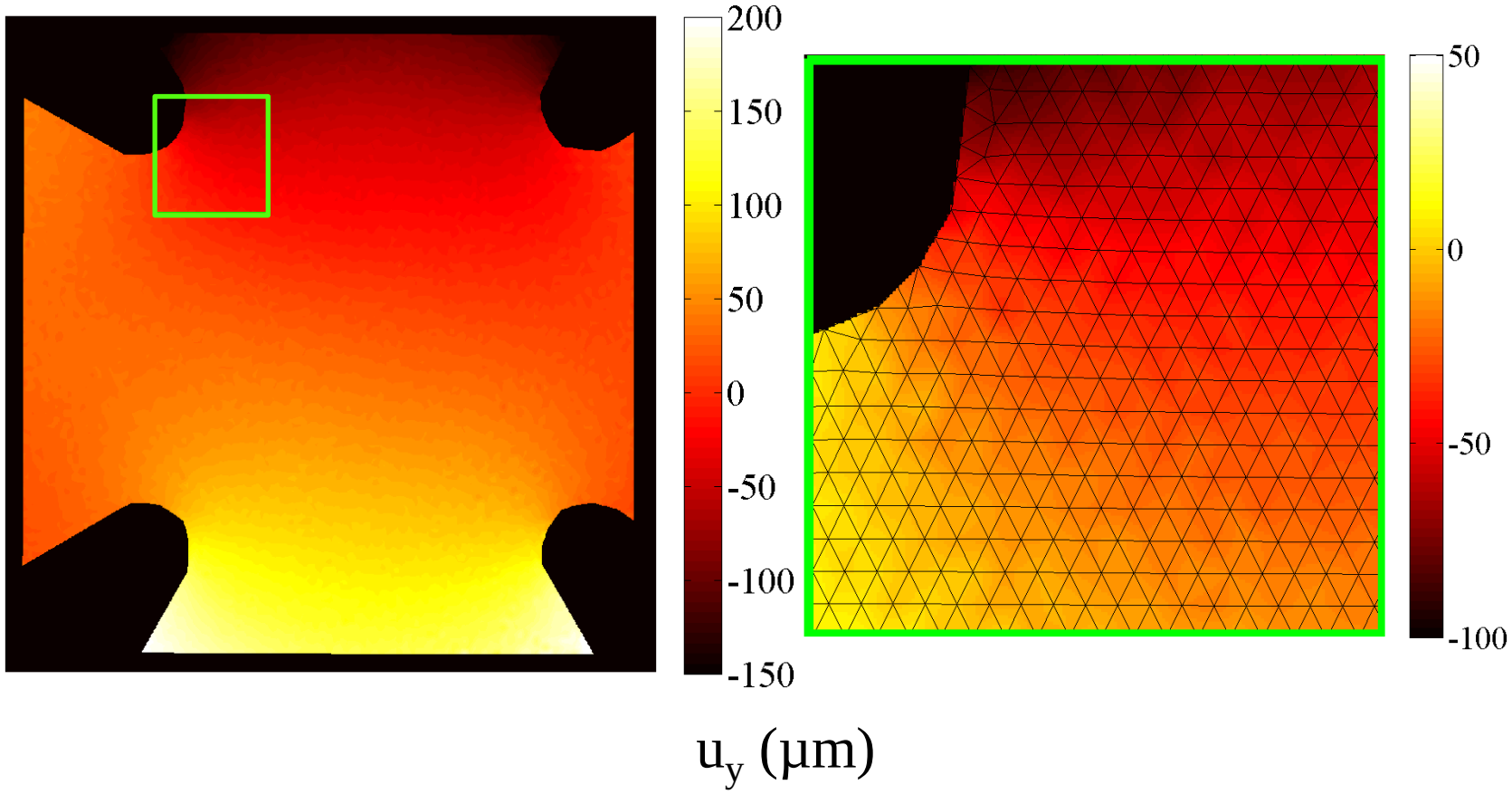
$$\eta_c^2(\mathbf{v}) \propto \|\mathbf{k}\|^0$$

$$\eta_{EG}^2(\mathbf{v}) \propto \|\mathbf{k}\|^4 \quad \text{and} \quad \eta_{EP}^2(\mathbf{v}) \propto \|\mathbf{k}\|^4$$

- Weights w_{reg} proportional to ℓ_{reg}^4



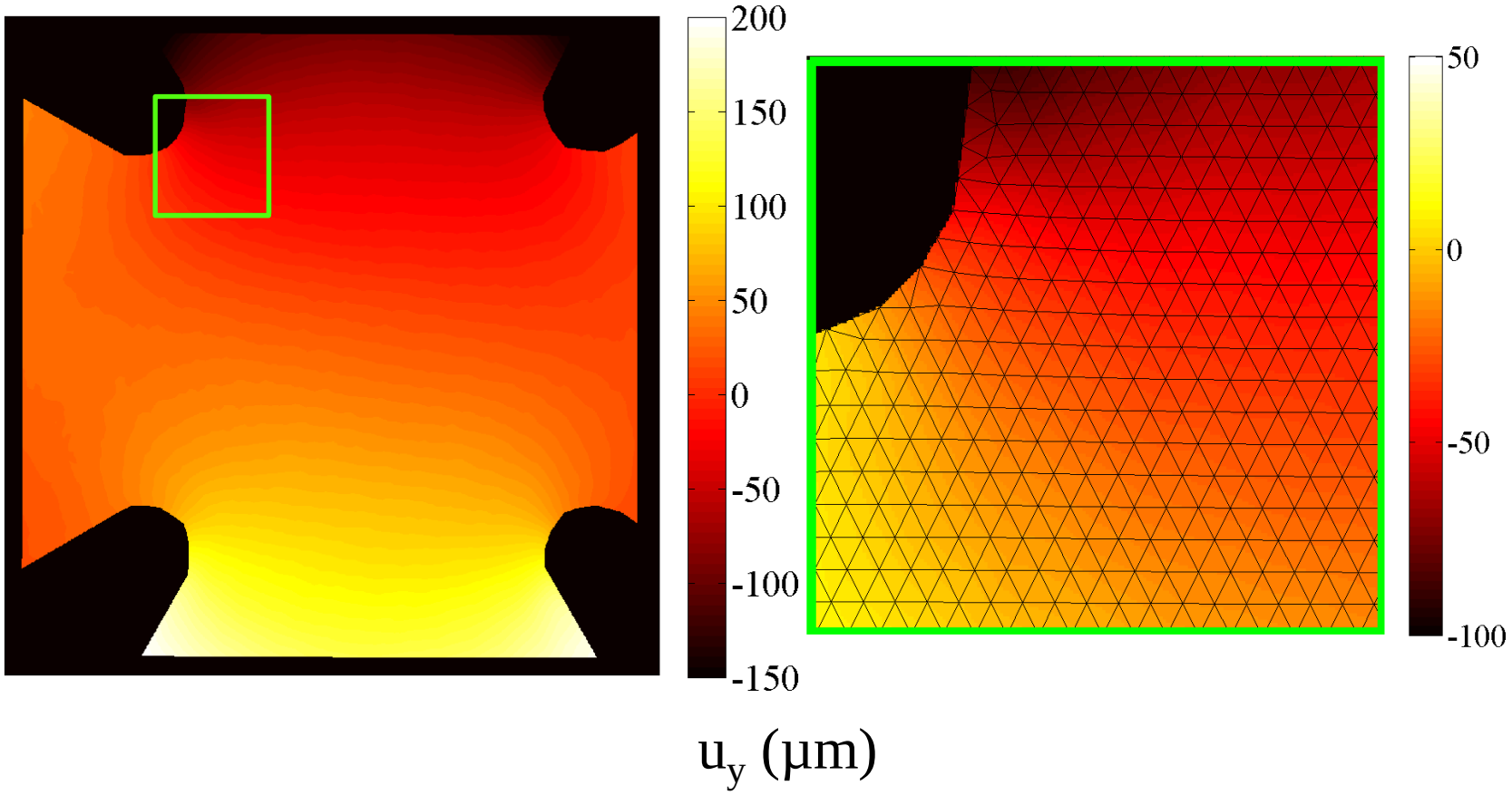
Global Approach



→ **Dense and continuous field**

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

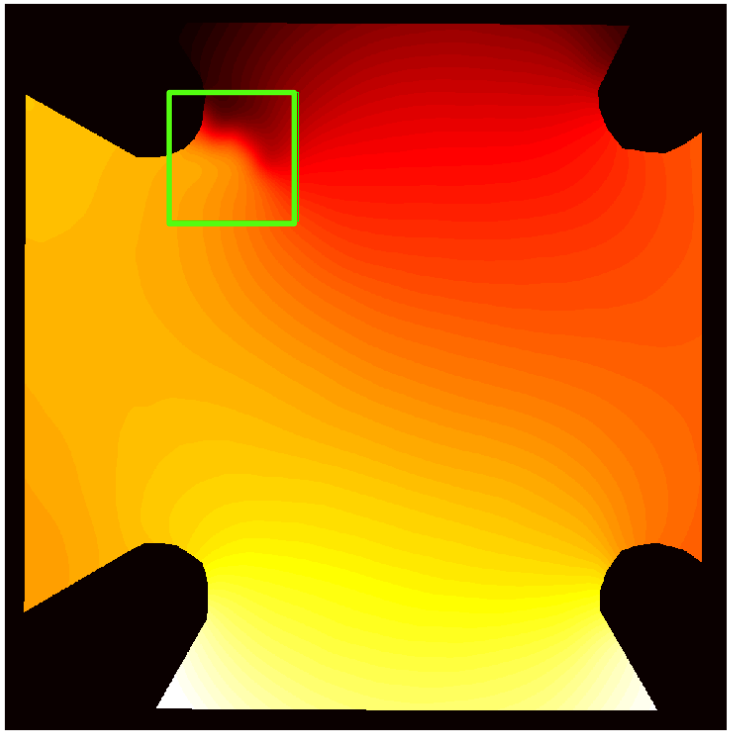
Reguralized Approach (mechanical filter)

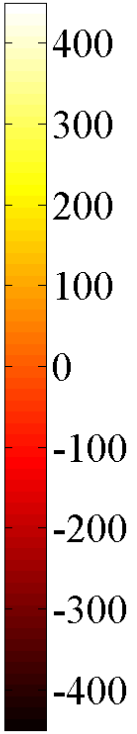


→ **Dense, continuous and filtered field**

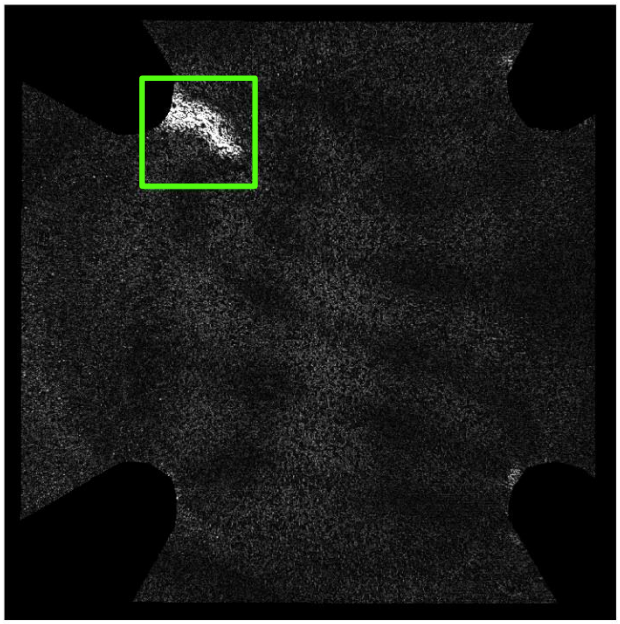
Cracks?

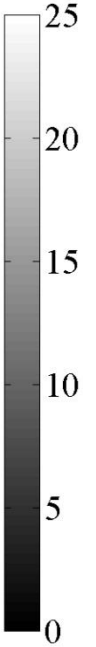
Reguralized Approach (w/ Crack)





u_y (μm)

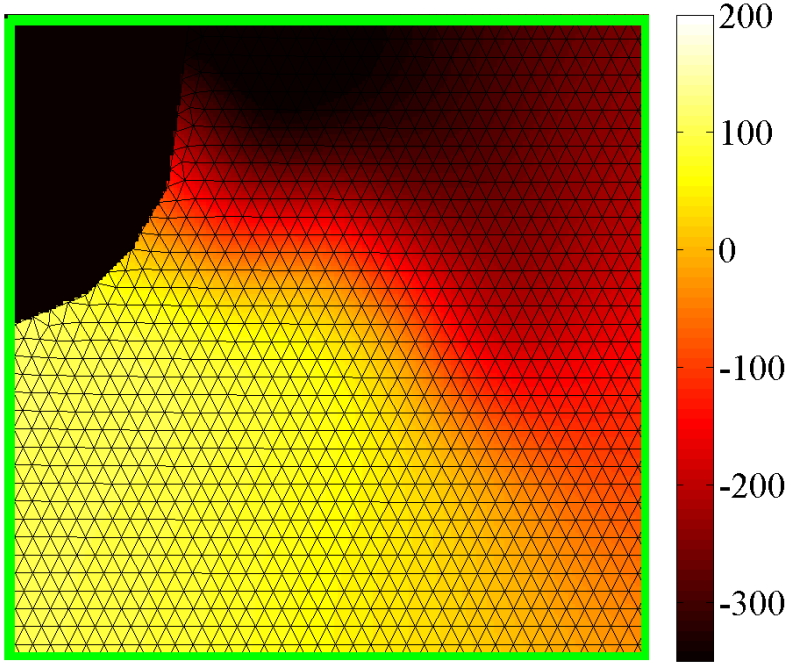




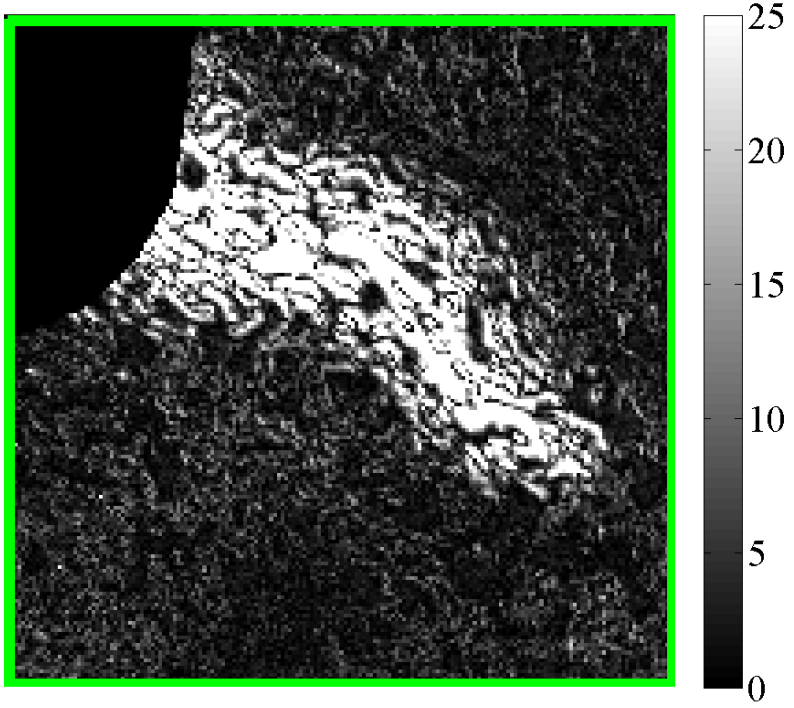
ρ

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

Reguralized Approach (w/ Crack)



u_y (μm)



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

Mechanical Regularization w/ Damage

- Gray level conservation

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

- Internal equilibrium

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

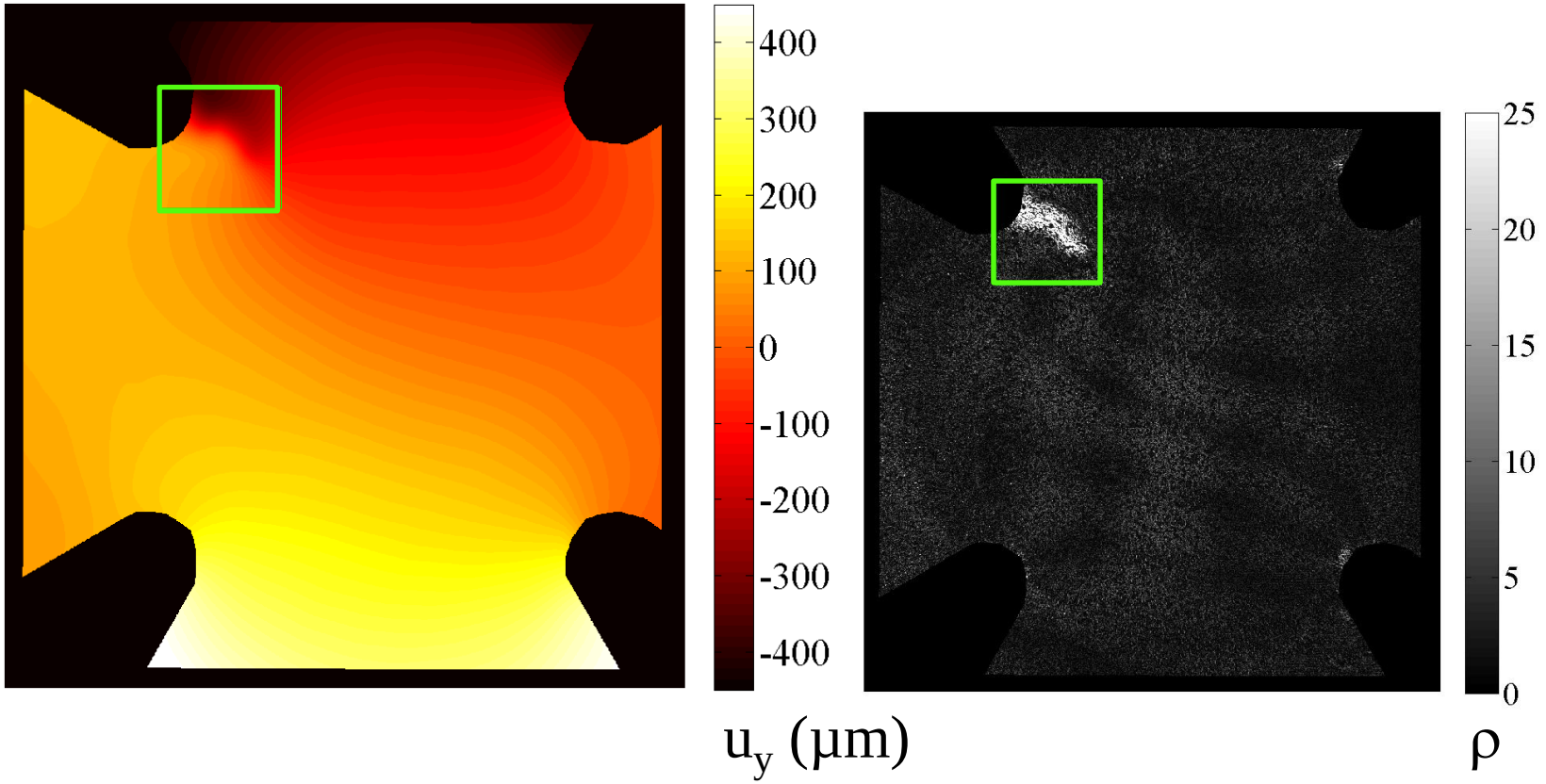
- with

$$[\tilde{\mathbf{K}}^e] = [\mathbf{K}^e](1 - D^e) \qquad D^e = D_\infty \left(1 - \exp\left(- \frac{\langle \varepsilon_1^e \rangle}{\varepsilon_0} \right)^m \right)$$

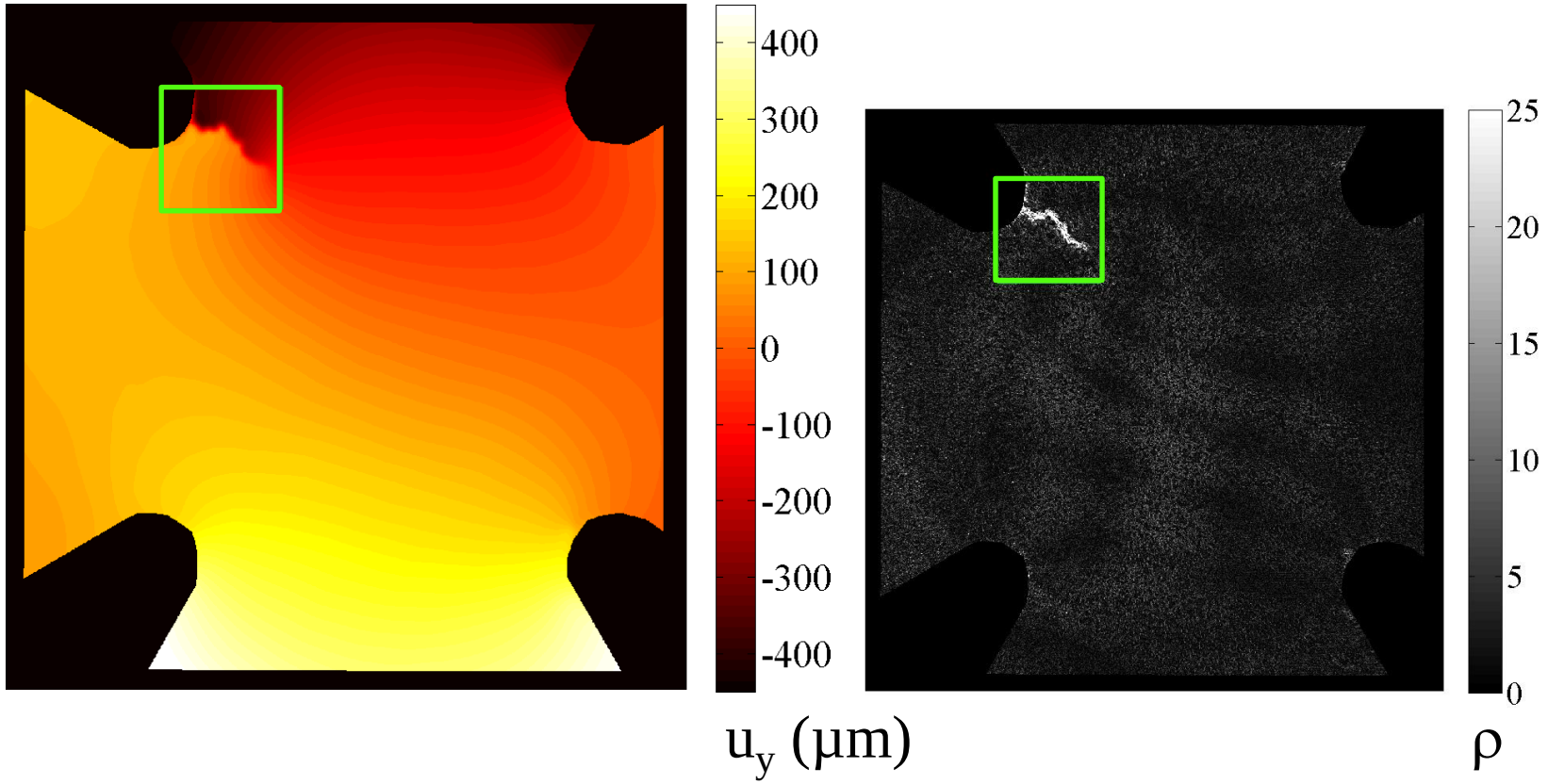
$$\eta_{tot}^2(\{\mathbf{a}\}) = \eta_c^2(\{\mathbf{a}\}) + w_{EQ}\eta_{EQ}^2(\{\mathbf{a}\}) + w_{EP}\eta_{EP}^2(\{\mathbf{a}\})$$

*[HF *et al.*, 2015, *Int. J. Fracture* 191(1-2) pp. 77-105]

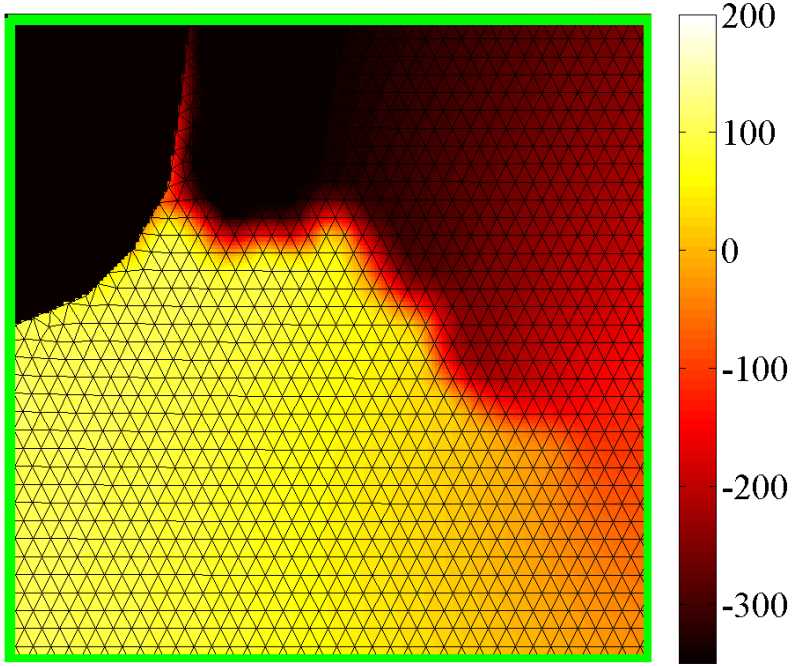
Reguralized Approach (w/ Crack)



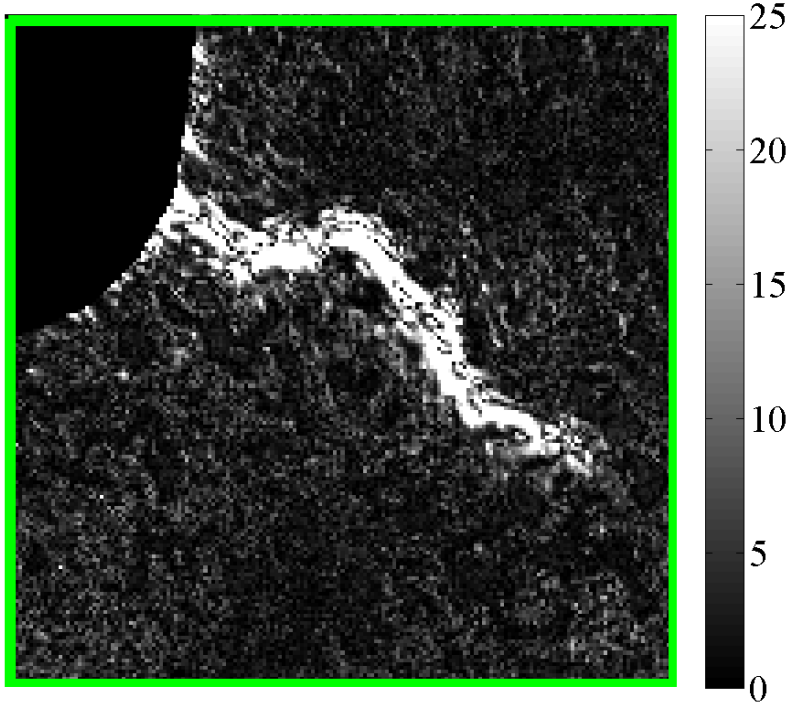
Reguralized Approach w/ Damage



Reguralized Approach w/ Damage

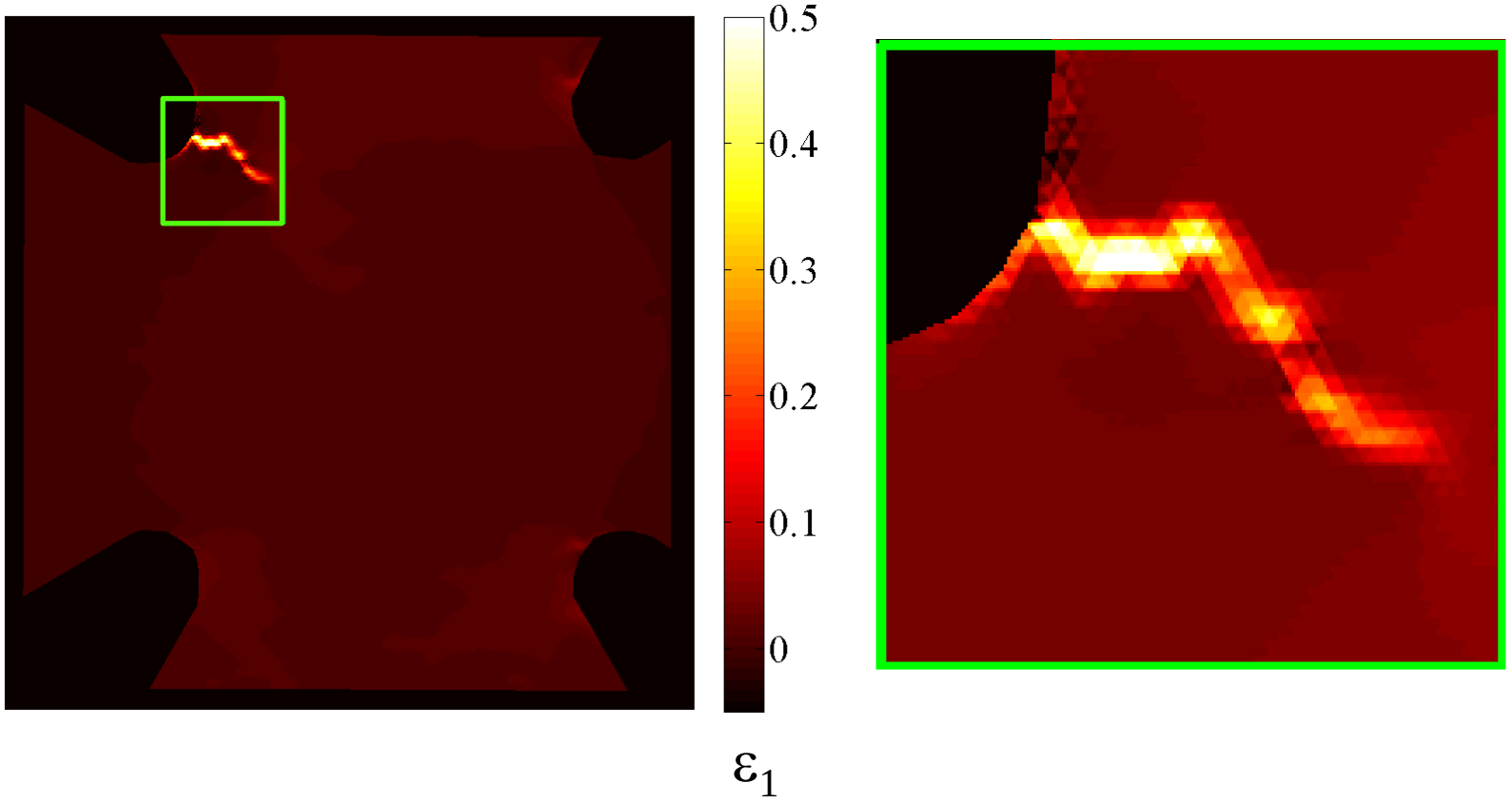


u_y (μm)



ρ

Reguralized Approach w/ Damage



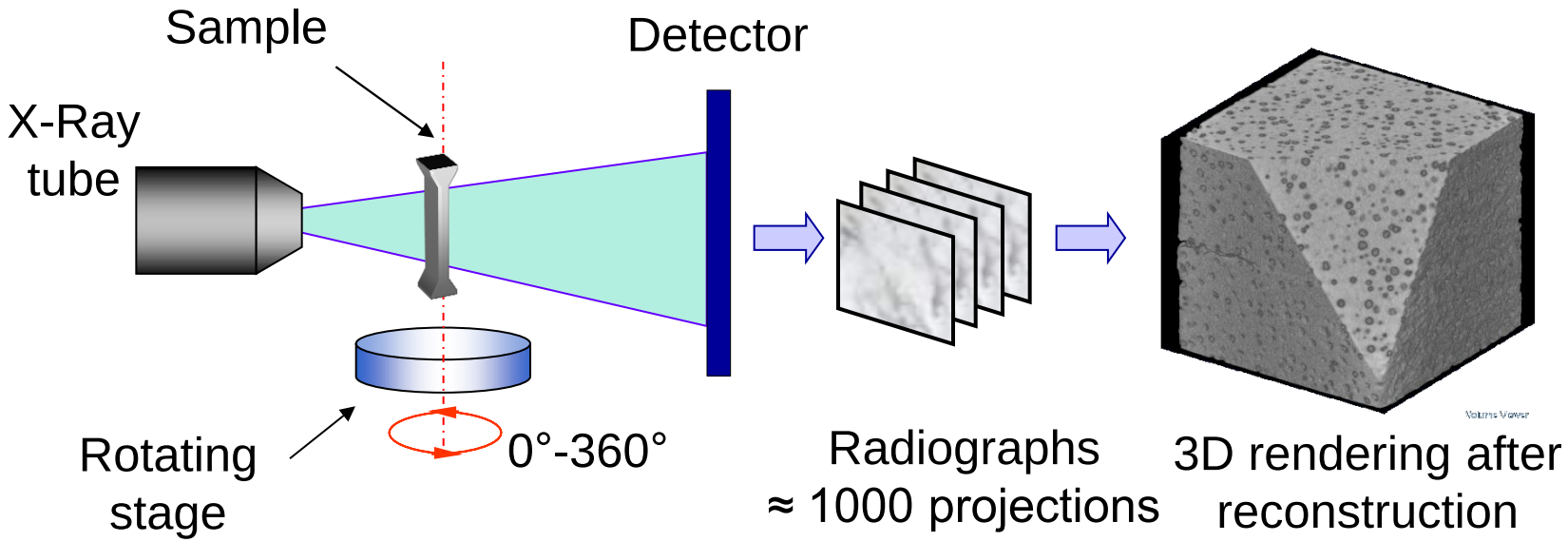
Cracks in 3D?

X-Ray Imaging

3rd generation synchrotron facilities

Lab tomograph

X-Ray Computed Tomography



Digital **Volume** Correlation

Local approach*

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

Global approach**

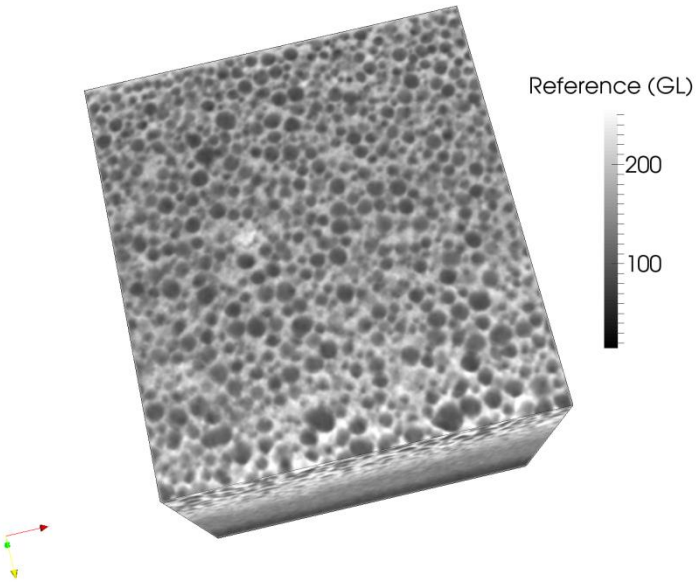
$$\eta_c^2(\{\mathbf{a}\}) = \sum_{\mathbf{ROI}} \left[I_0(\mathbf{x}) - I_t(\mathbf{x}+\mathbf{u}_m(\mathbf{x})) \right]^2$$

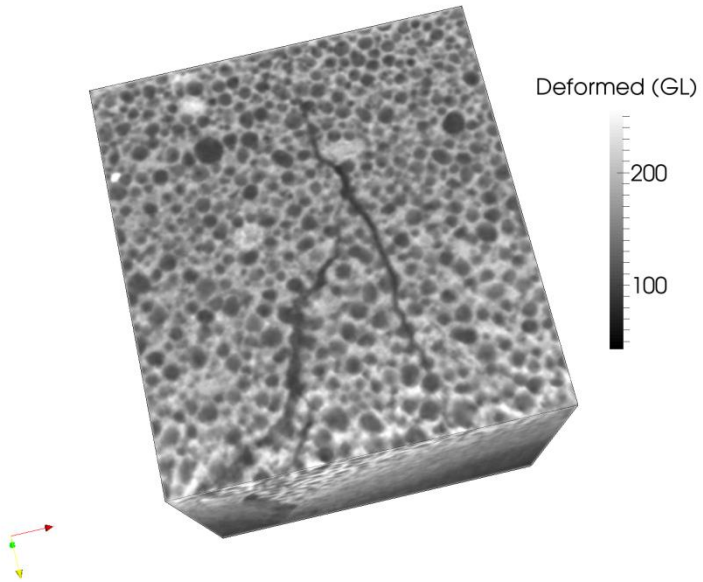
Regularized approach***

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

*[Bay *et al.*, 1999, *Exp. Mech*. 39(3) pp. 217-226]
**[Roux *et al.*, 2008 *Compos. Part A* 39(8) 1253-1265]
***[Leclerc *et al.*, 2011, *Exp. Mech.* 51(4) pp. 479-490]

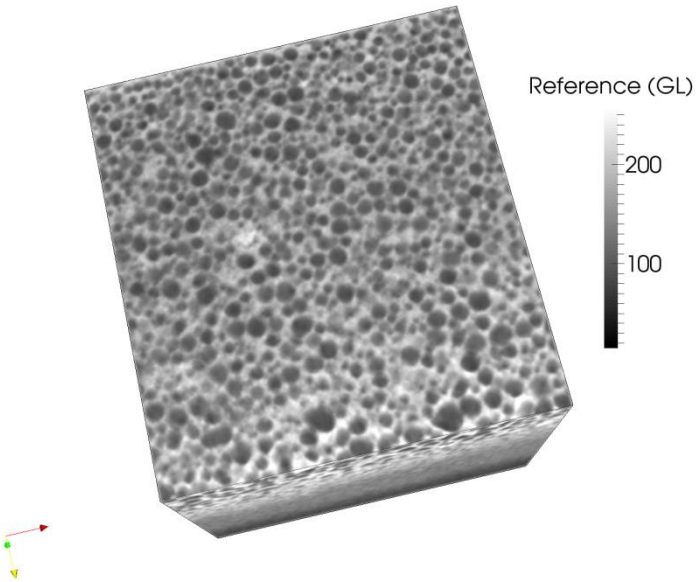
3-Point Flexural Test on Plaster

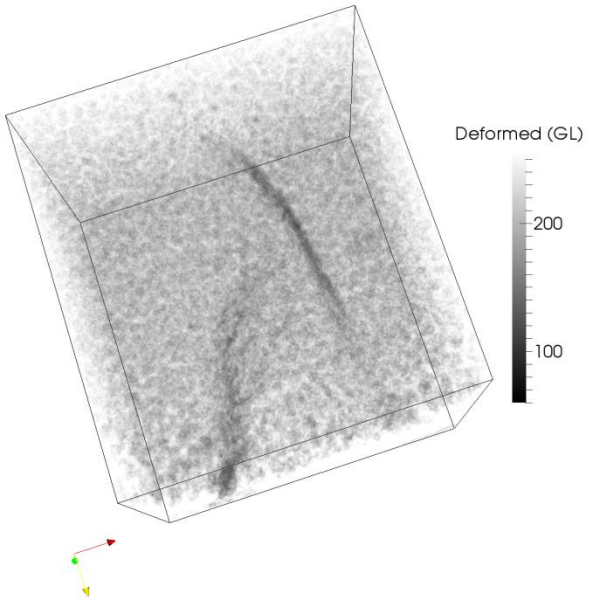




1 voxel ↔ 25 µm

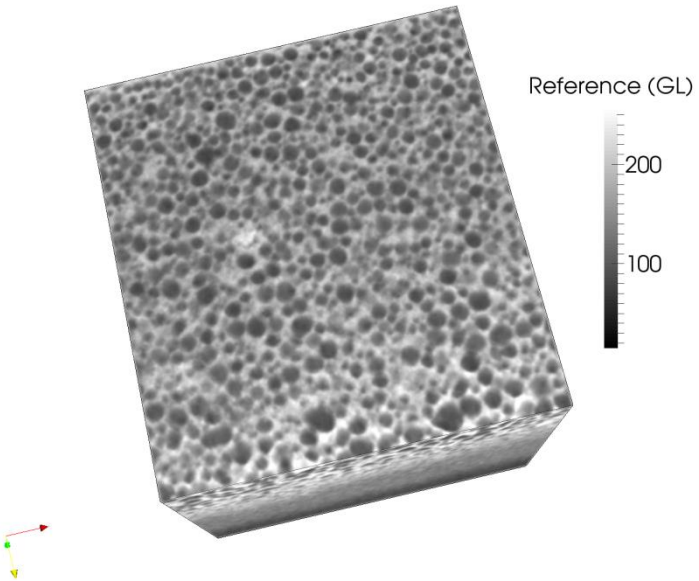
3-Point Flexural Test on Plaster

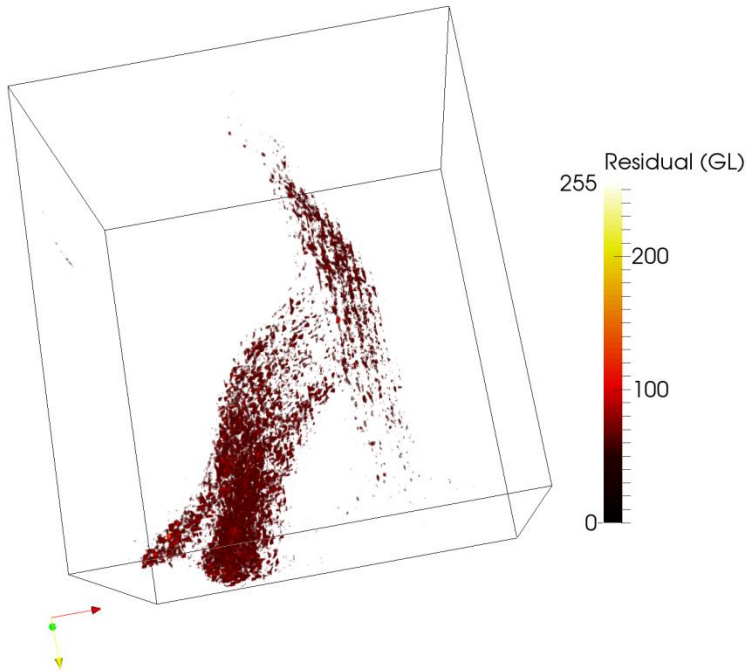




Crack visualization?

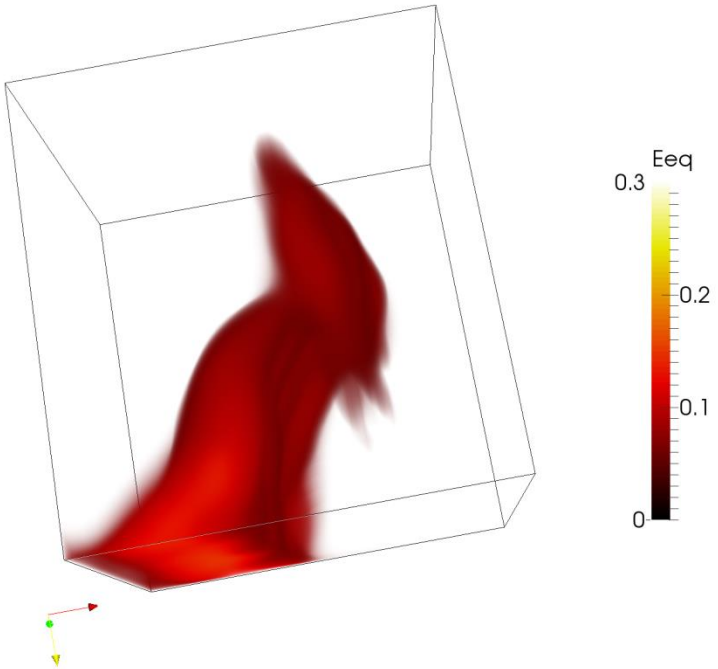
3-Point Flexural Test on Plaster





Maximum principal strains?
Elastic strains ?

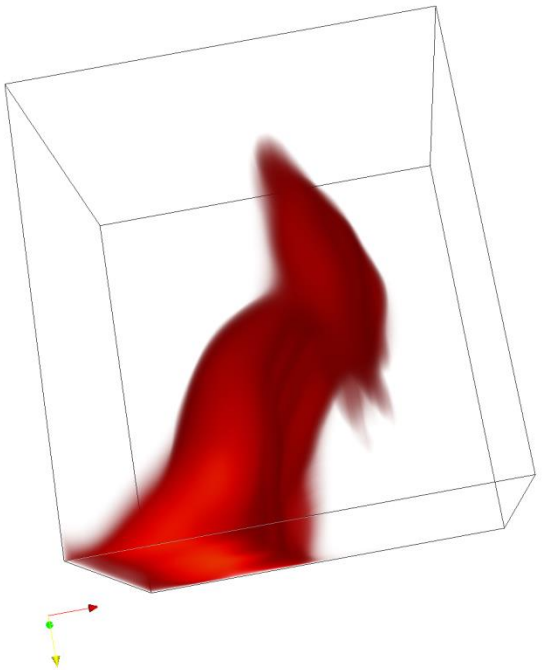
Quantified Cracking

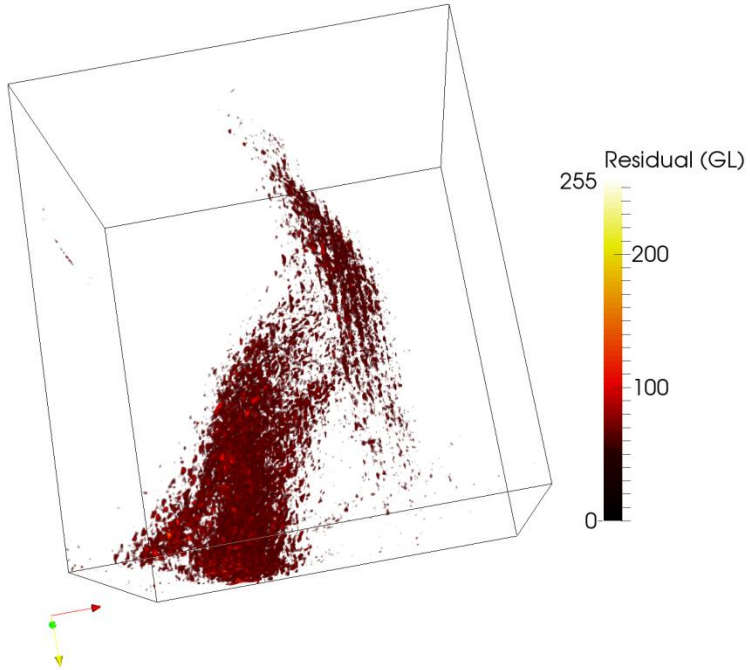


$$\ell = 8\,\text{voxels}$$

$$\ell_m = \ell_b = 60\,\text{voxels}$$

Quantified Cracking





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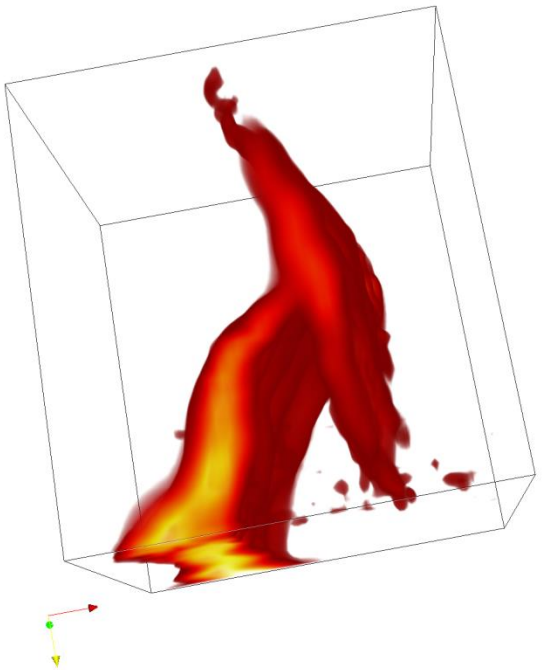
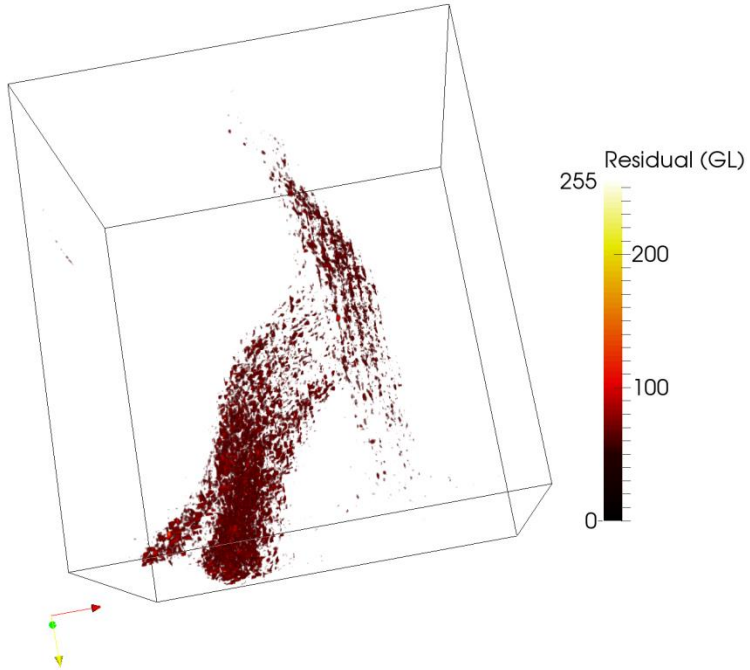
$$\ell_m = \ell_b = 60\,\text{voxels}$$

Quantified Cracking



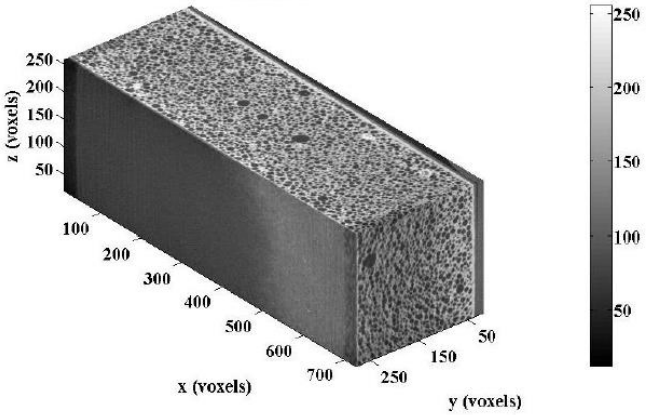


$$\ell = 8 \,\text{voxels}$$

$$\ell_m = 4\ell_b = 60 \,\text{voxels}$$

w/ damage

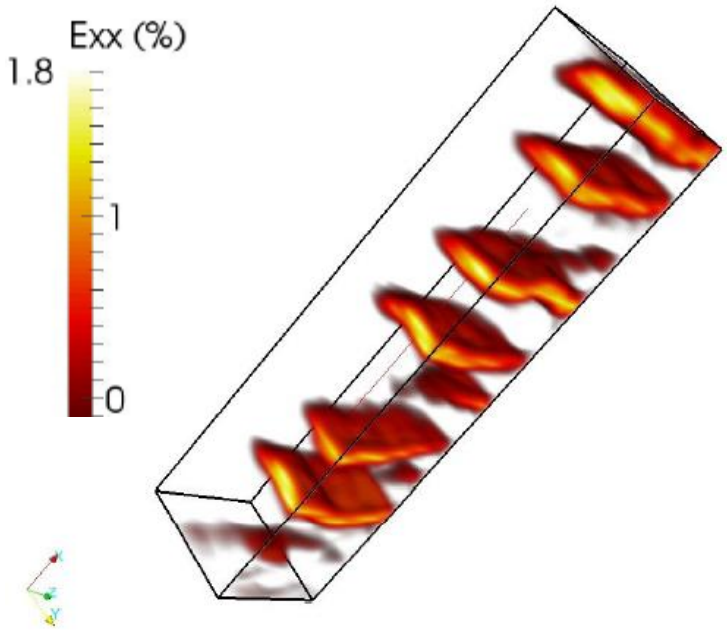
Multiple Cracking?



1 voxel $\leftrightarrow$ 50 µm

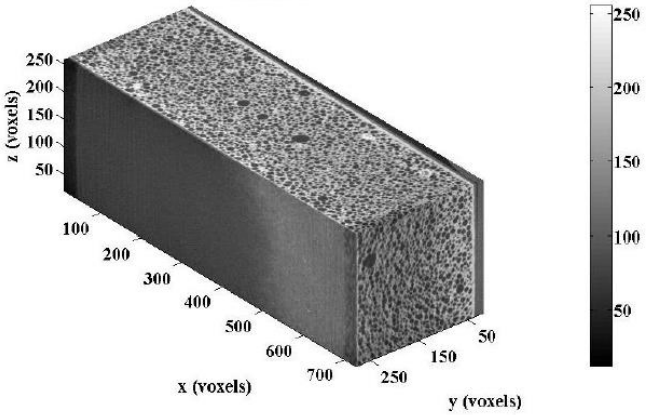
ℓ = 12 voxels

$\ell_m = \ell_b$ = 30 voxels



[Bouterf, 2014, *PhD thesis*, ENS Cachan]

Multiple Cracking



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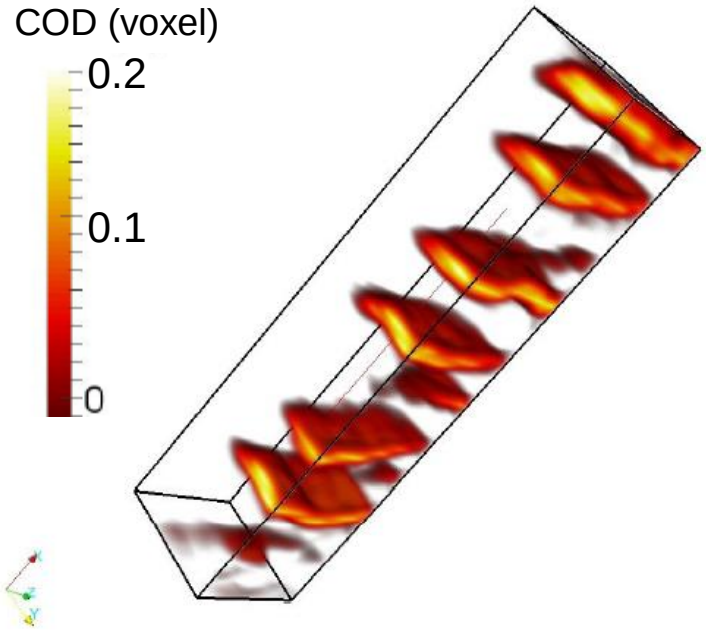
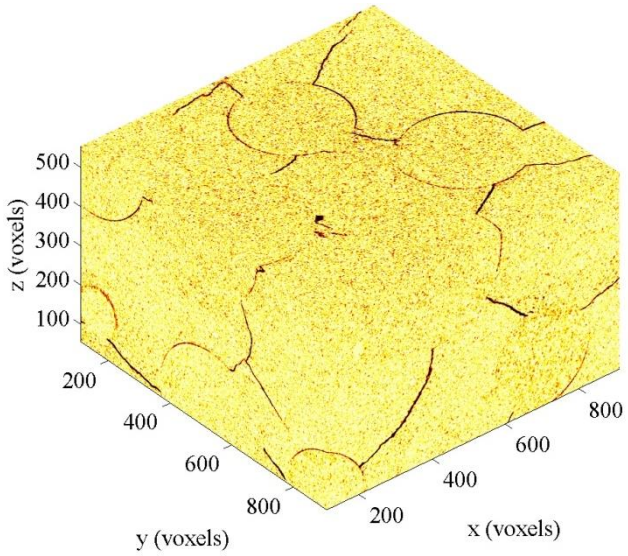


[Bouterf, 2014, *PhD thesis*, ENS Cachan]

Interim Summary

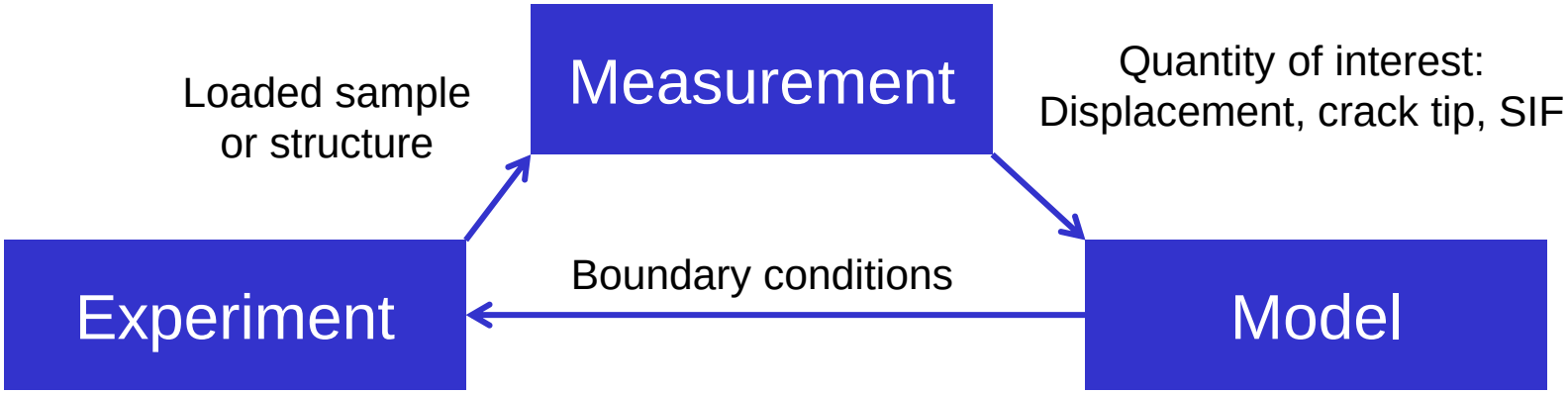
- 2D & 3D imaging:
  very powerful (qualitative) tool!
- DIC and DVC:
  quantitative tools
- Damage quantification in
  brittle materials

Outlook



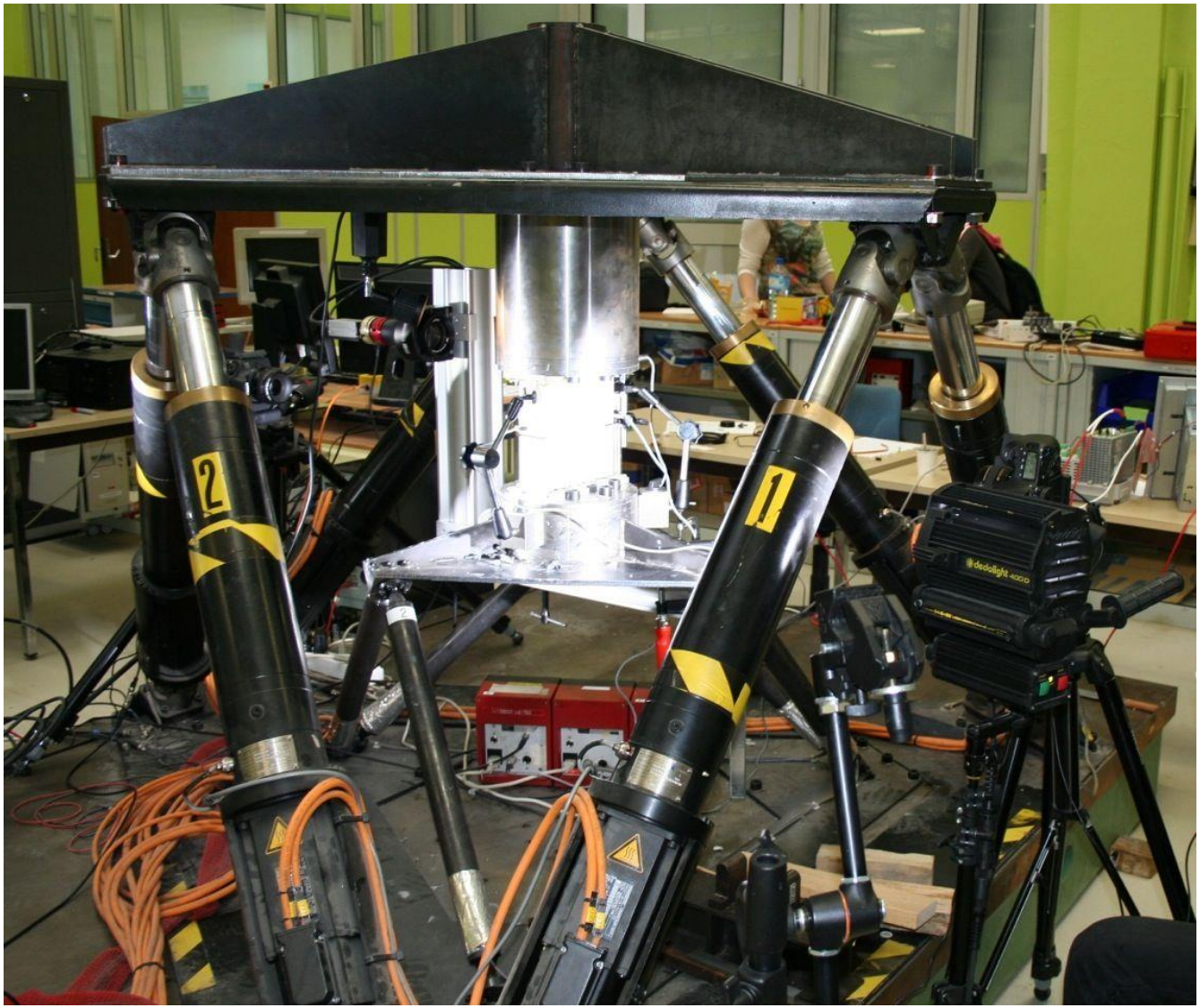
- 3D imaging:
  - big data
  - 4D extensions
- DVC:
  - big and fast calculations
  - multiscale analyses
  - robust when localization or damage set in
- Quantitative assessments of damage
- Model identification and validation

‘Smart Testing’ with DIC

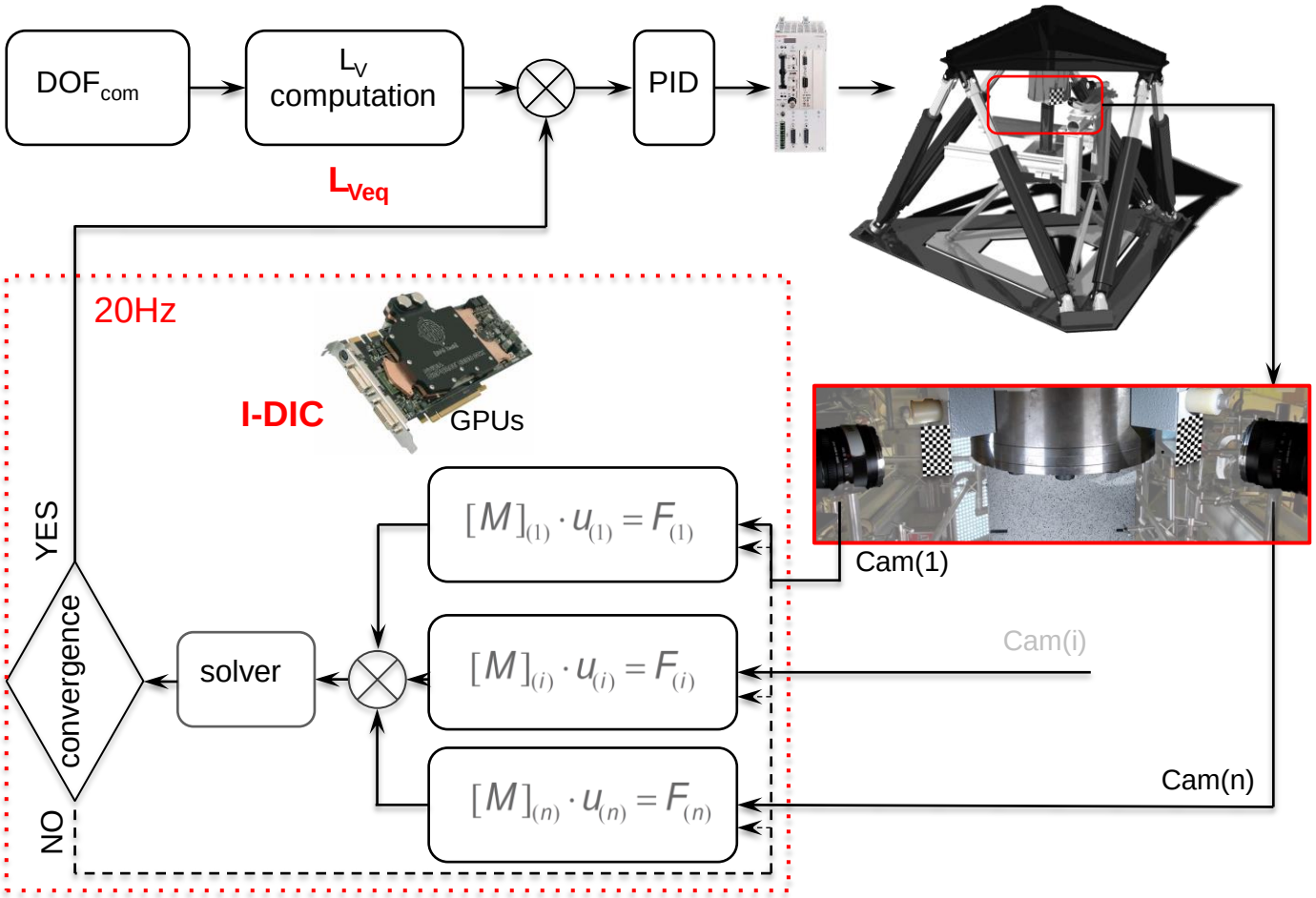


- Hexapod kinematics
- Crack path:
  - manual control (interactive procedure)
  - real time (hybrid procedure)

Hexapod



DIC-Controlled Hexapod

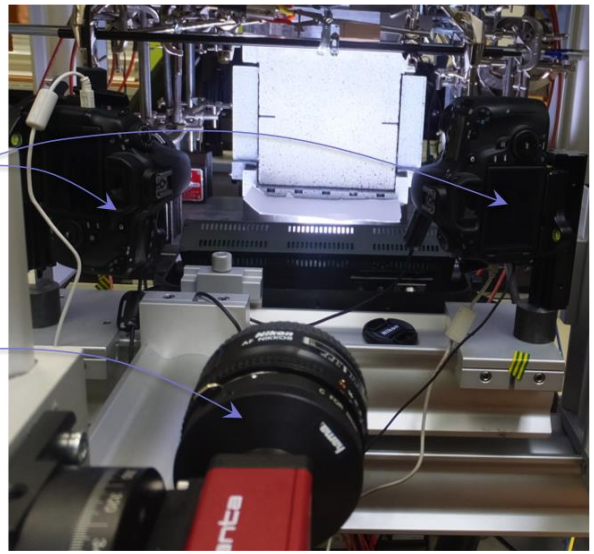


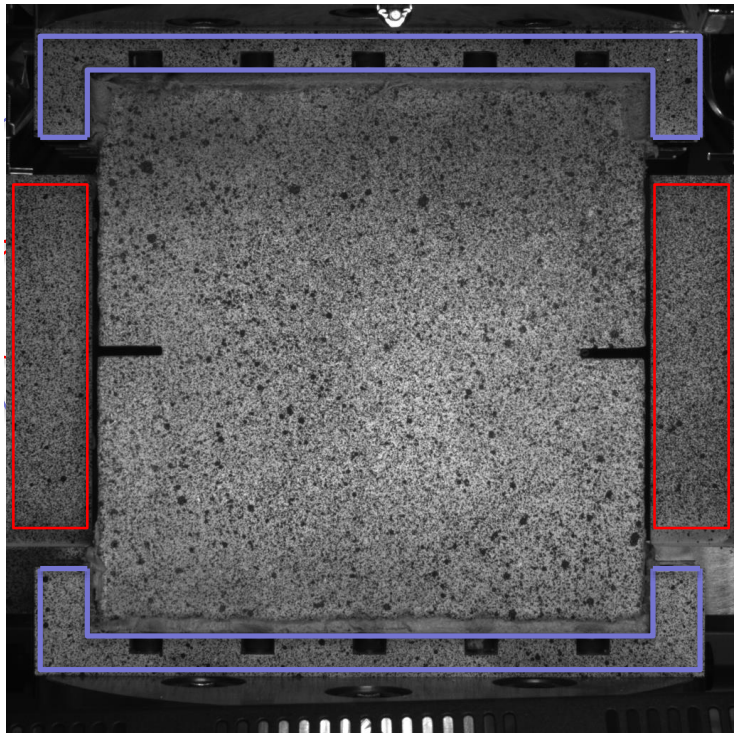
[Le Flohic *et al.*, 2014, *Exp. Mech*. 54(5) 817-828]

DIC All Over The Place…

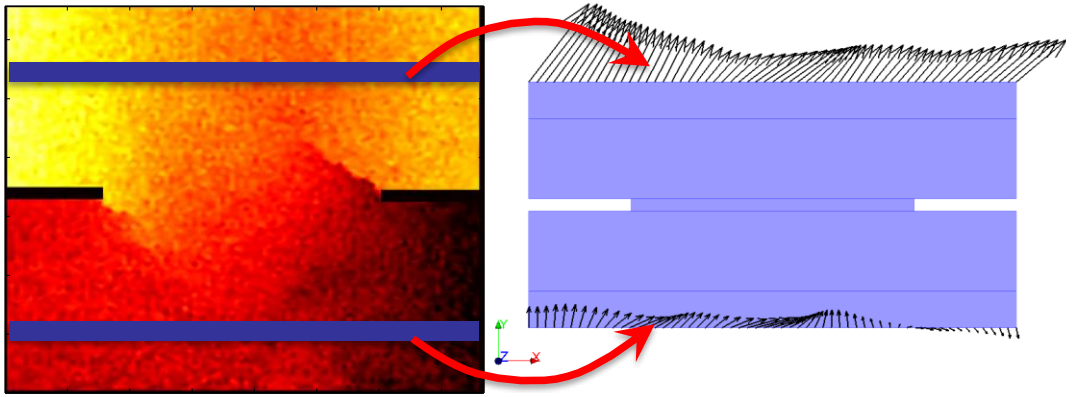
Stereo DIC

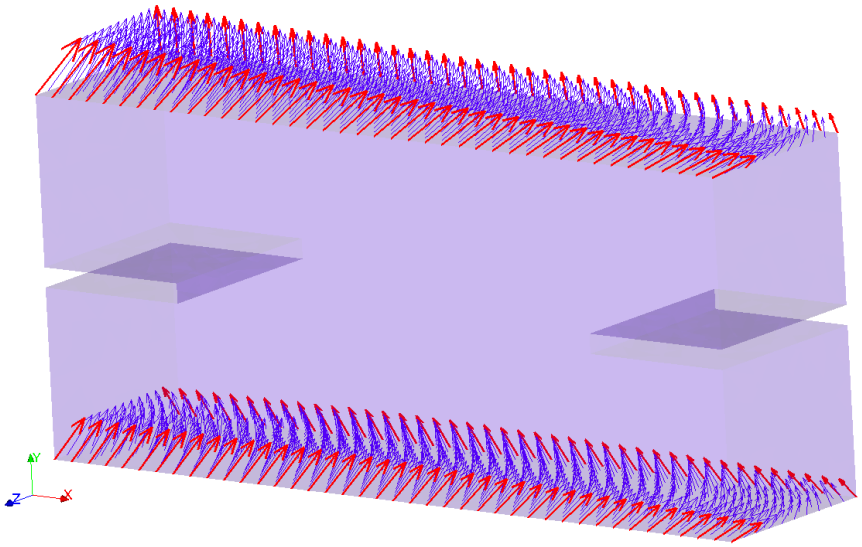
2D DIC





3D Simulations Driven by Measured BCs

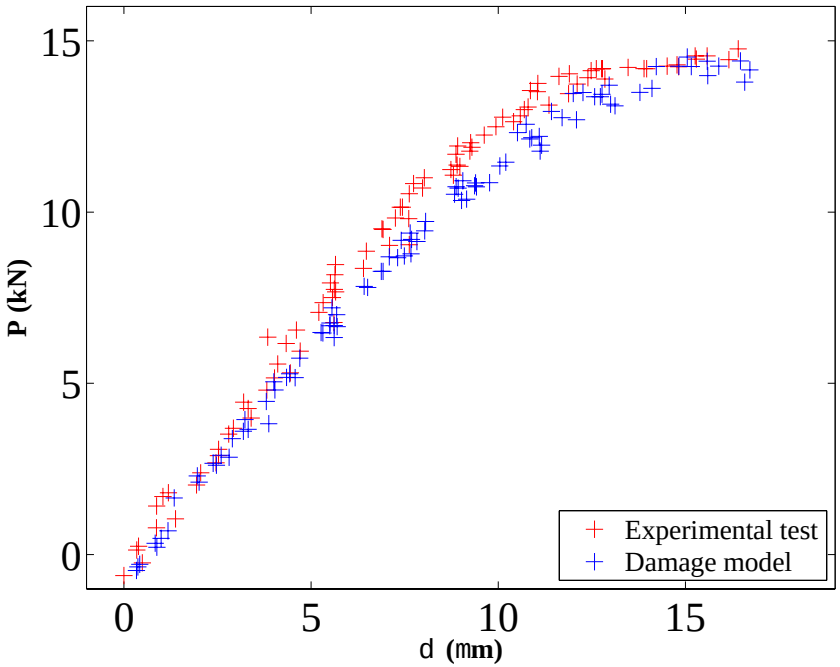




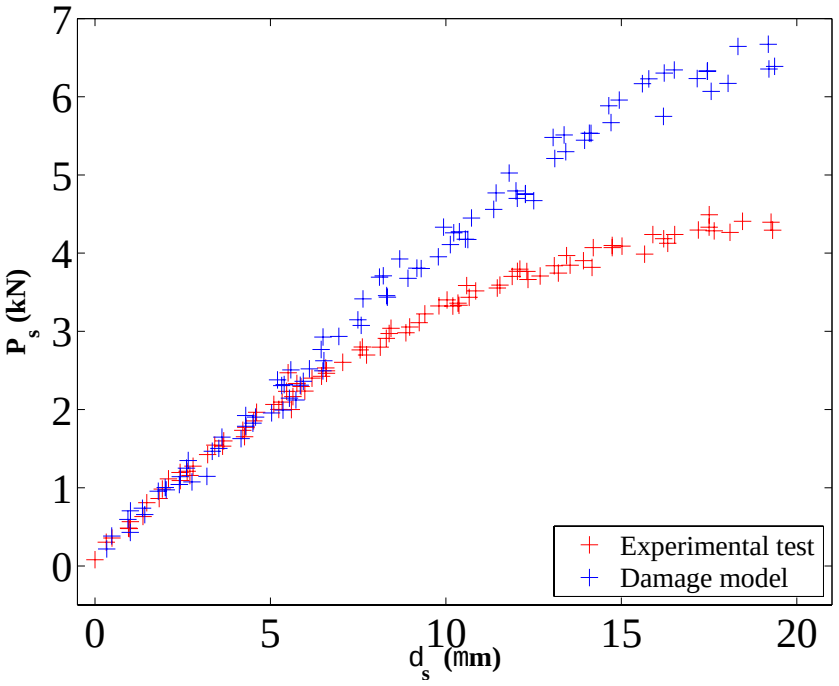
[Carpiuc *et al.*, 2017, *Cem. Concr. Res.* 100 pp. 329-340]

Macroscopic Validation?

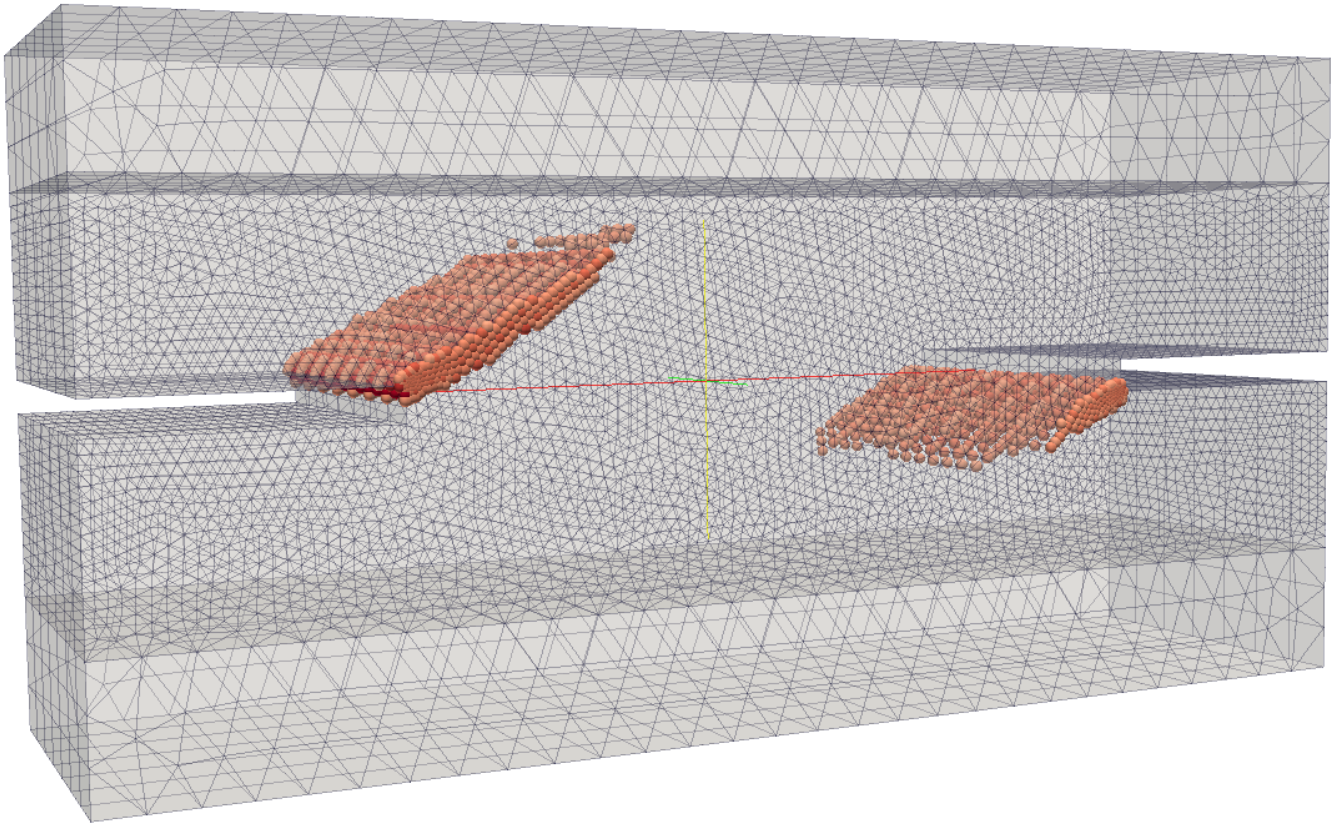
Longitudinal Response



Transverse Response

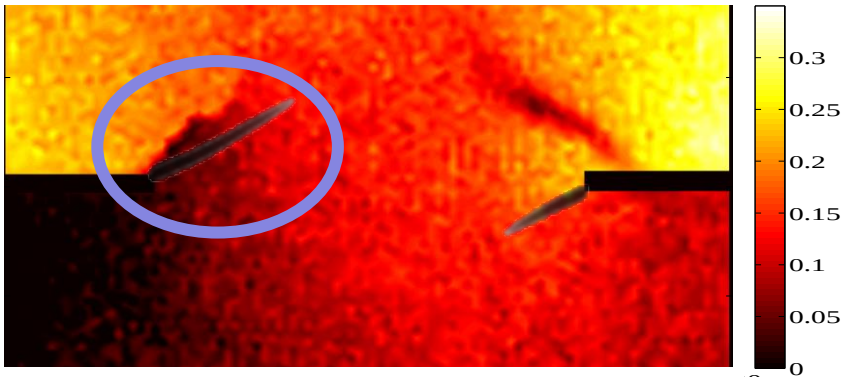


Nonlocal Damage Model

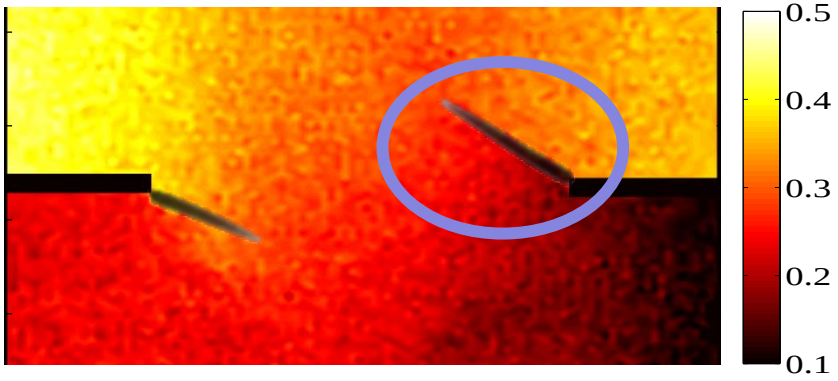


Cracking Pattern

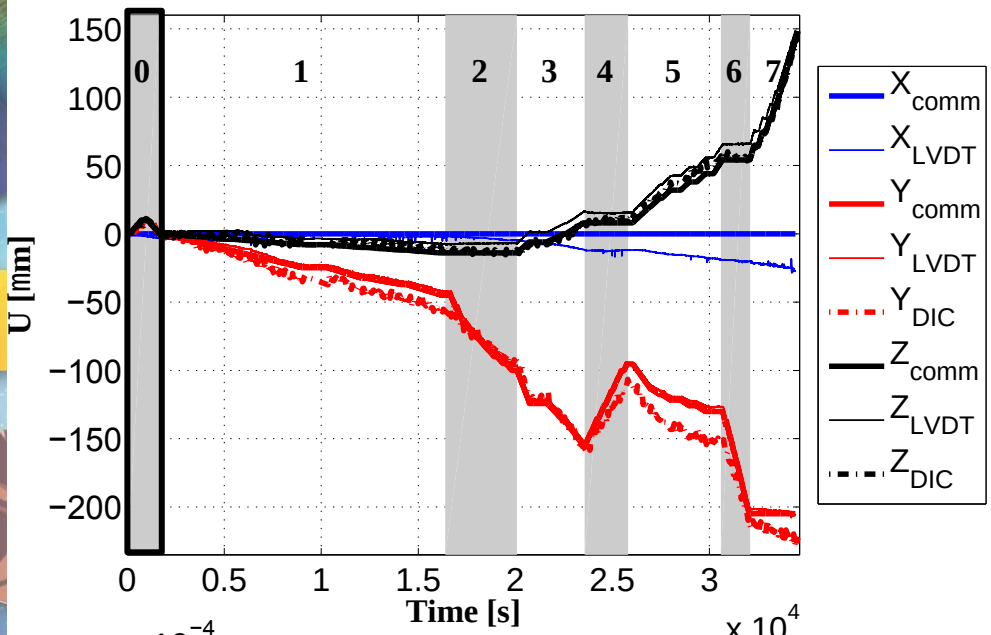
Back Face

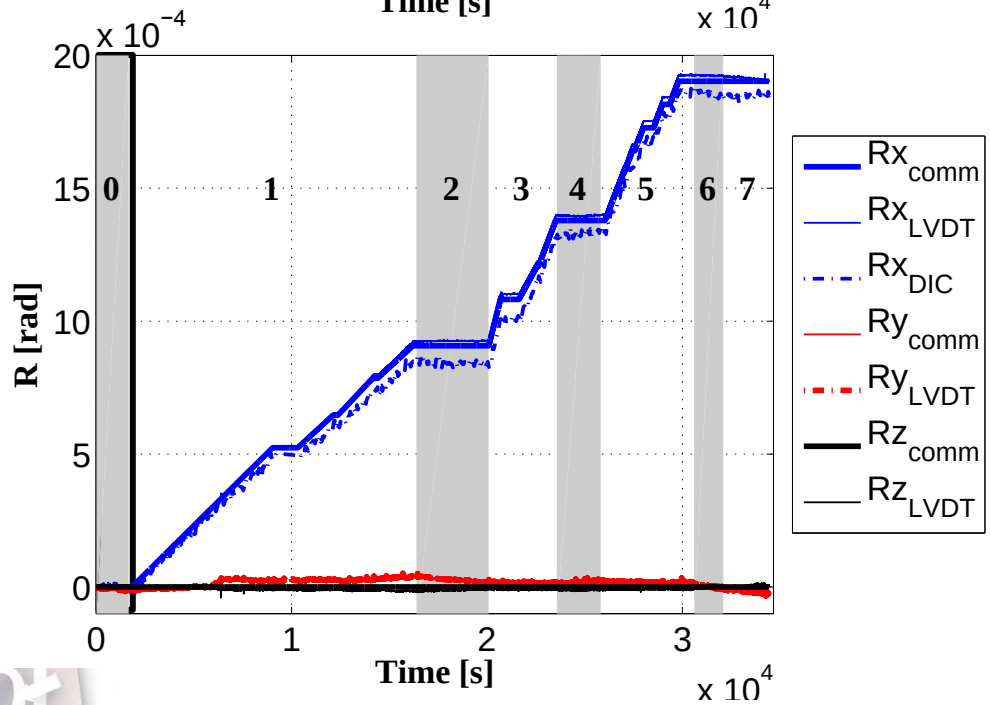


Front Face



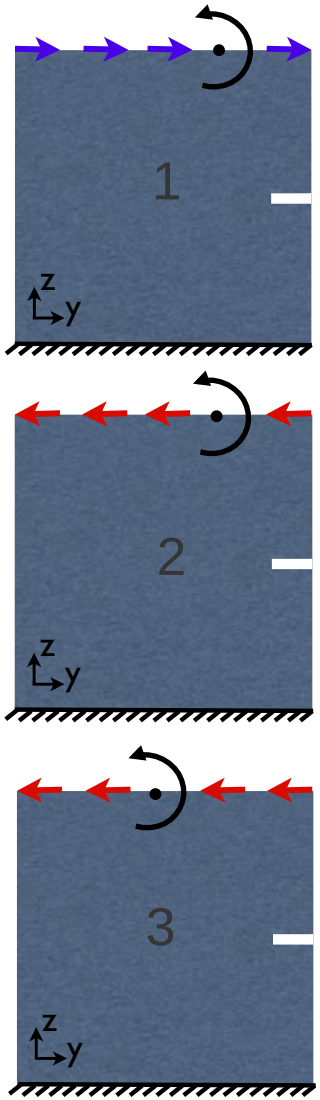
Interactive Test





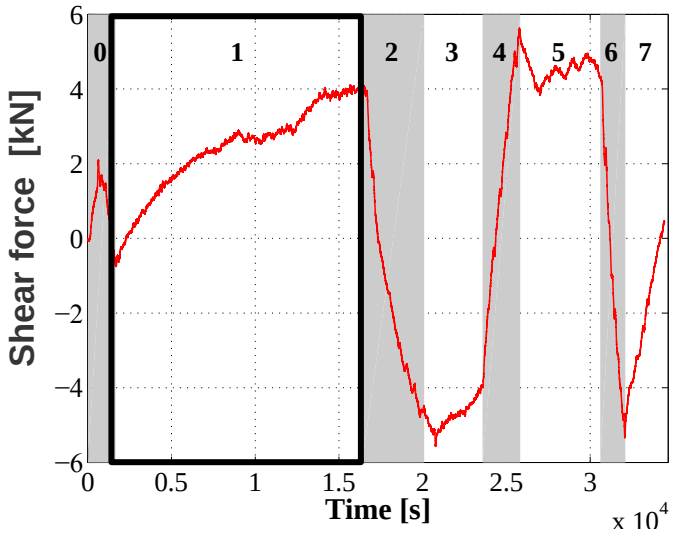
Loading steps:

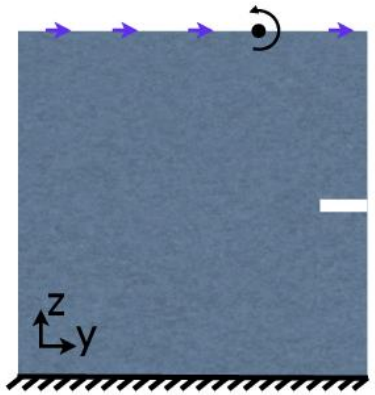
0. Elastic load-unload
1. Rotation & shear +
2. Shear –
3. Rotation
4. Shear +
5. Rotation
6. Shear –
7. Traction

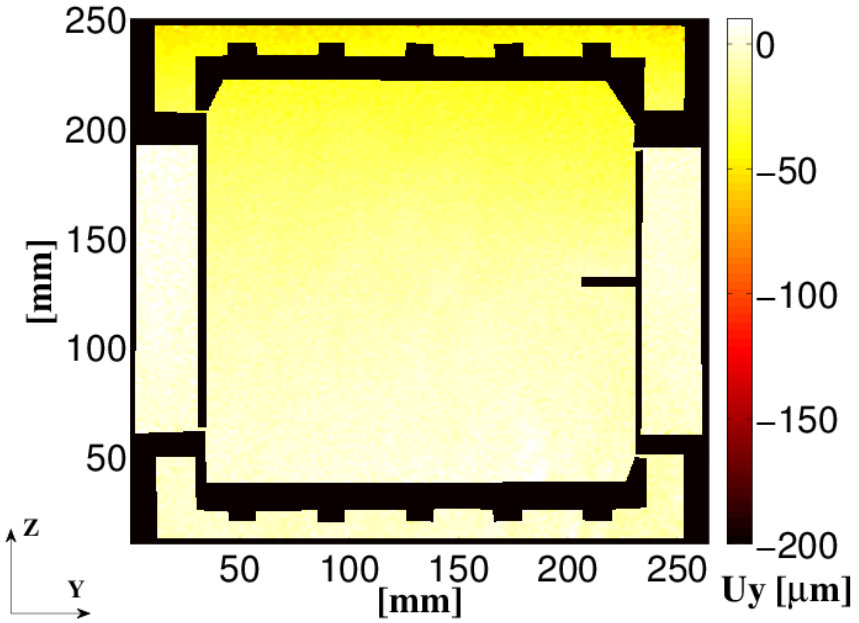


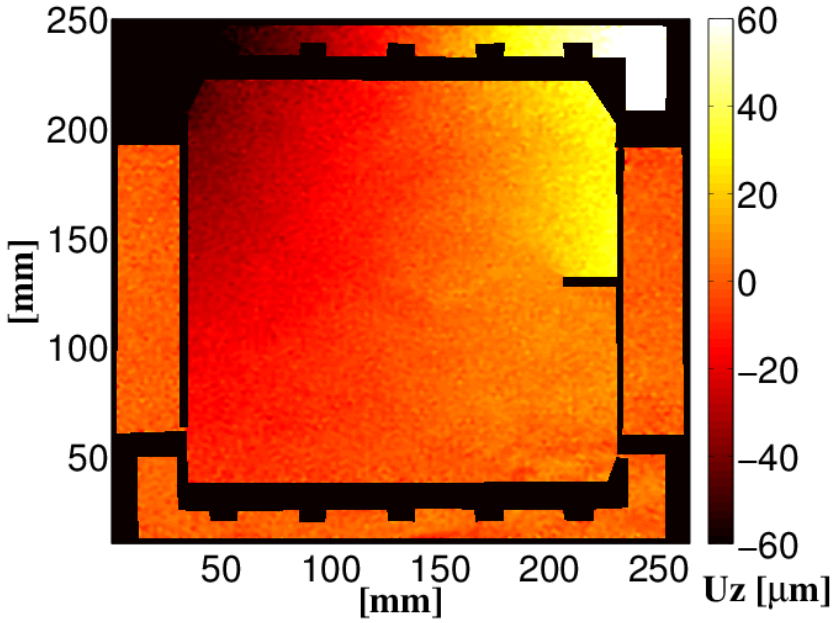
[Carpiuc *et al.*, 2017, *Eng. Fract. Mech.* 176 pp. 1-22]

Rotation + Shear

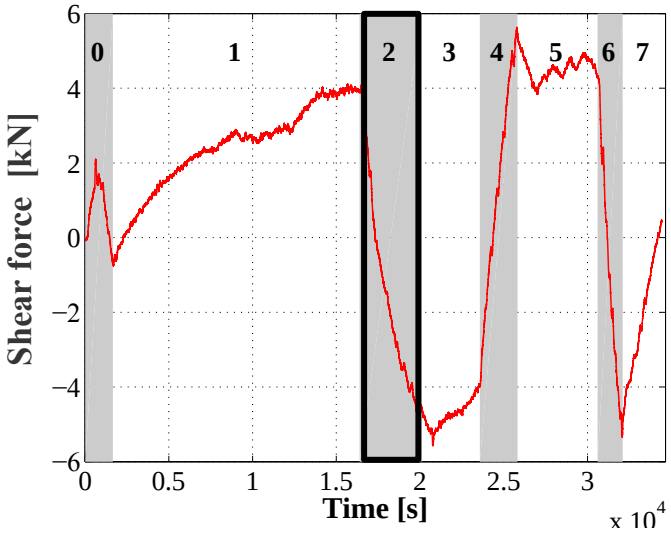


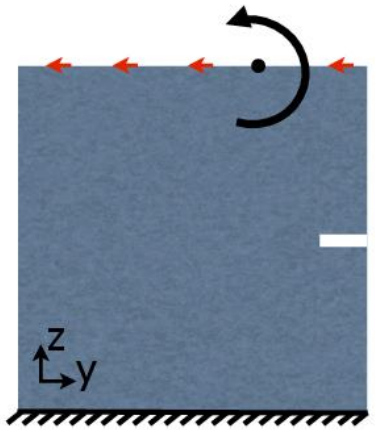


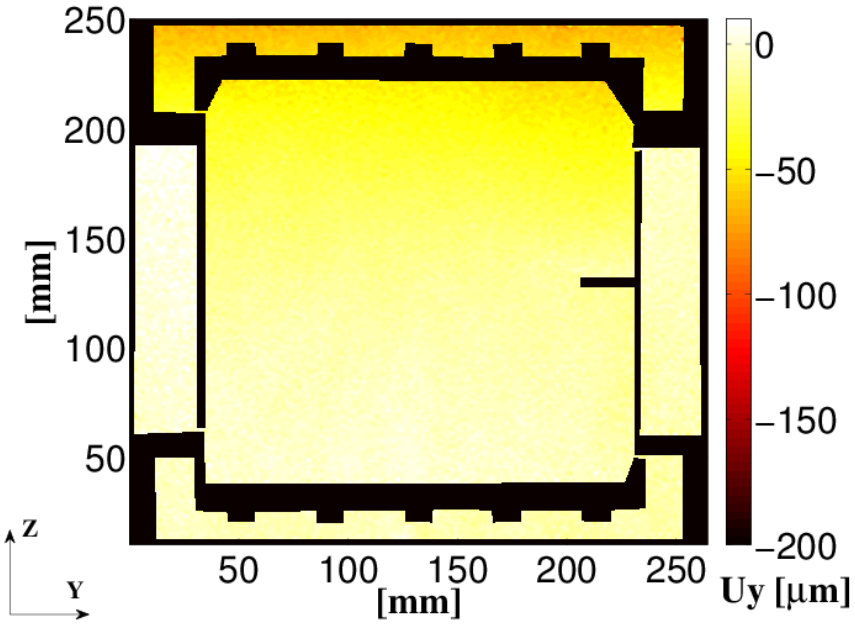


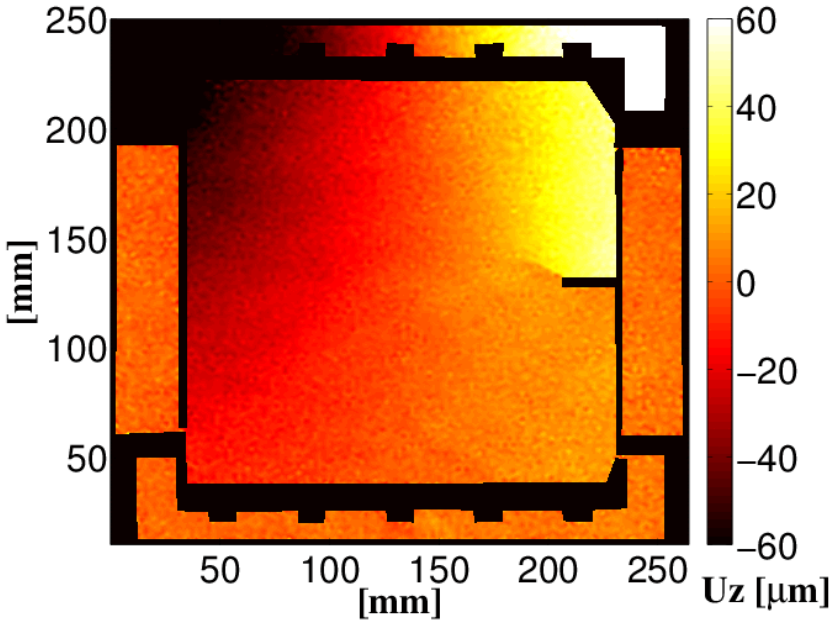


Shear

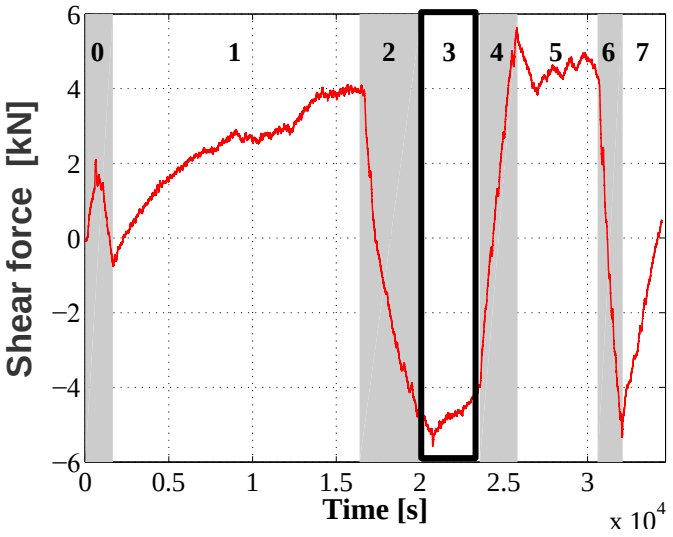


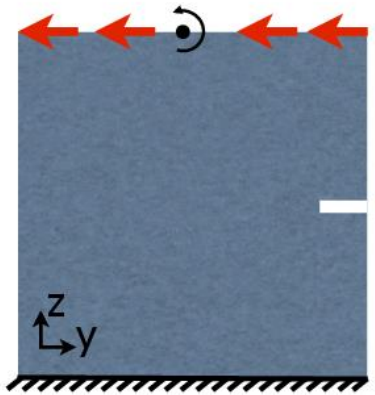


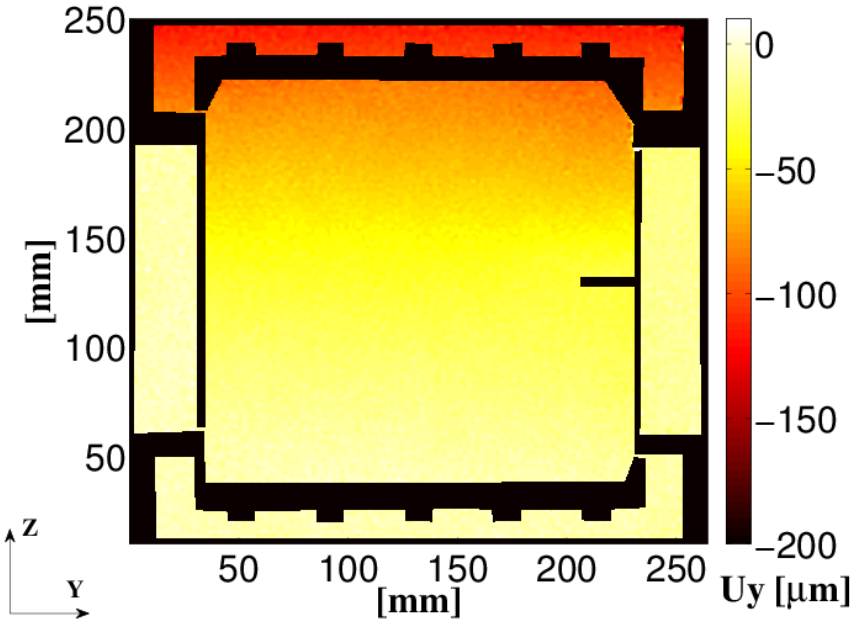


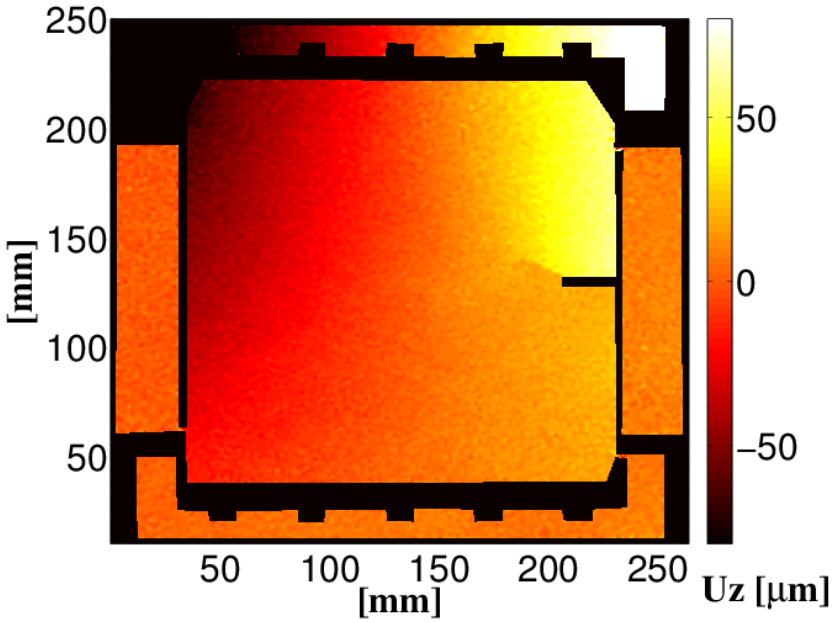


Rotation

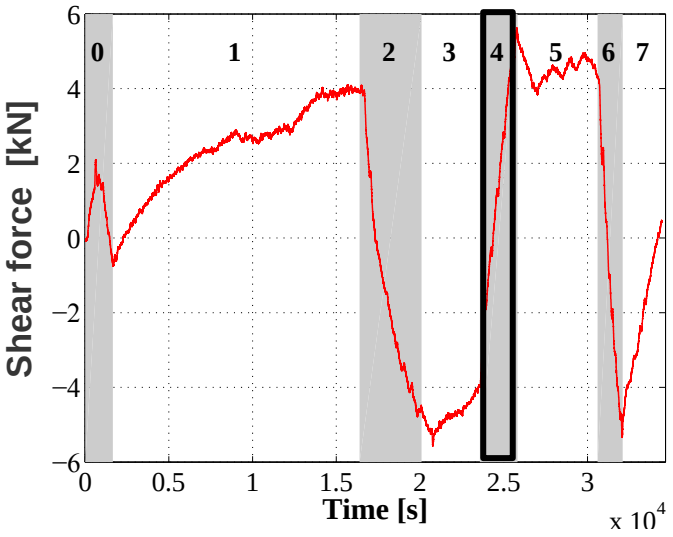


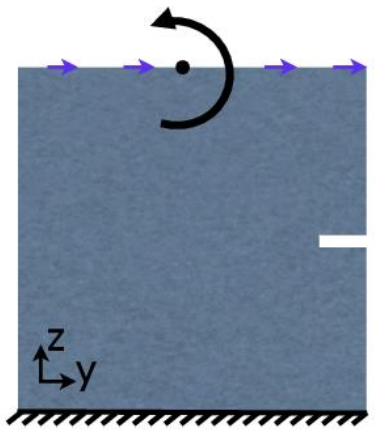


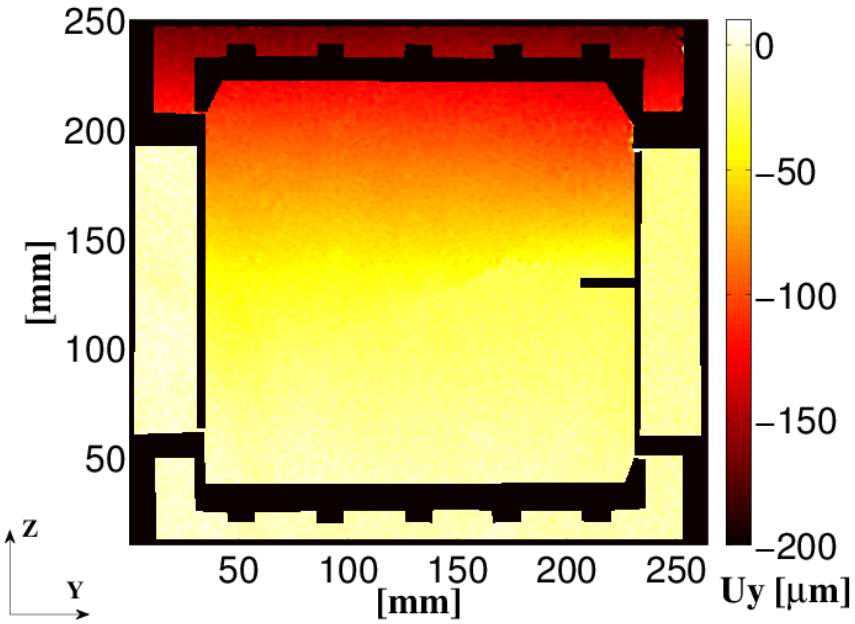


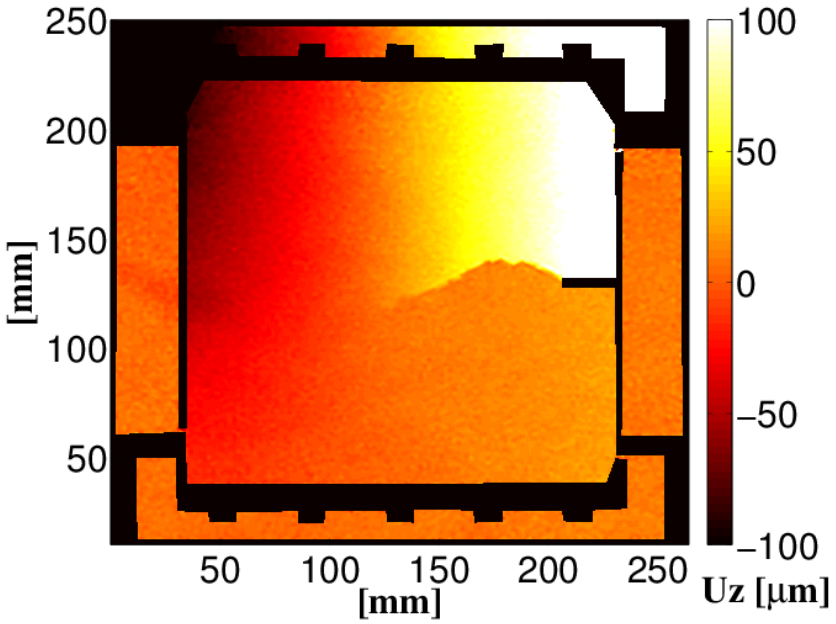


Shear

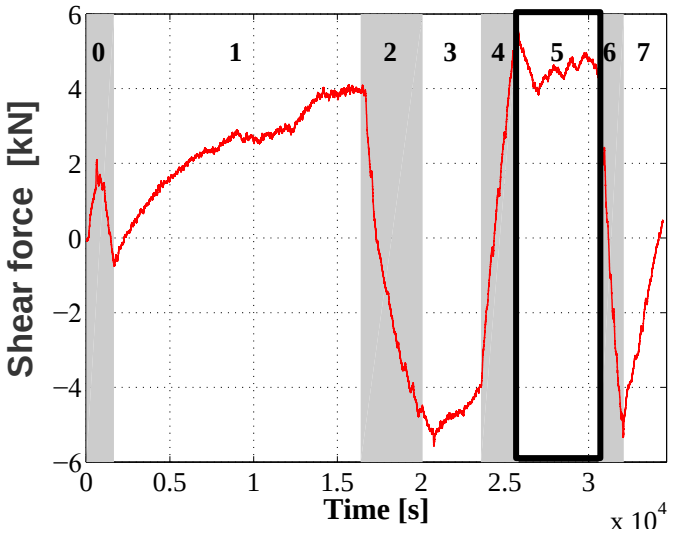


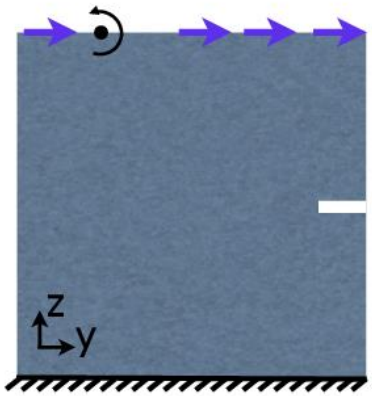


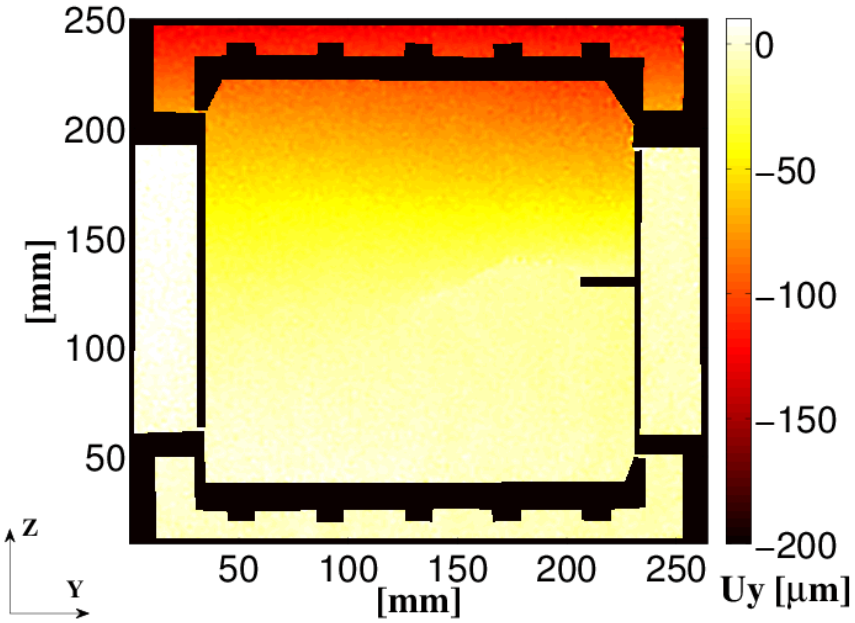


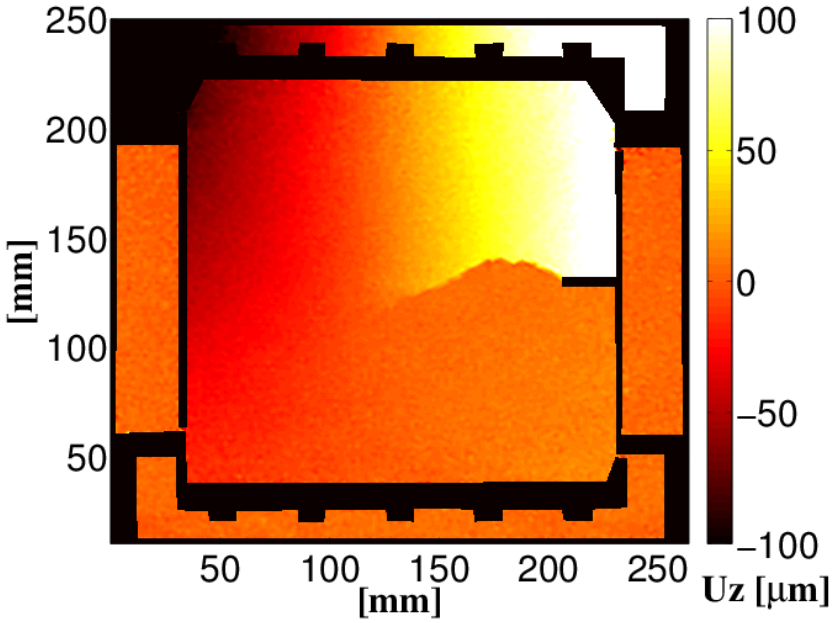


Rotation

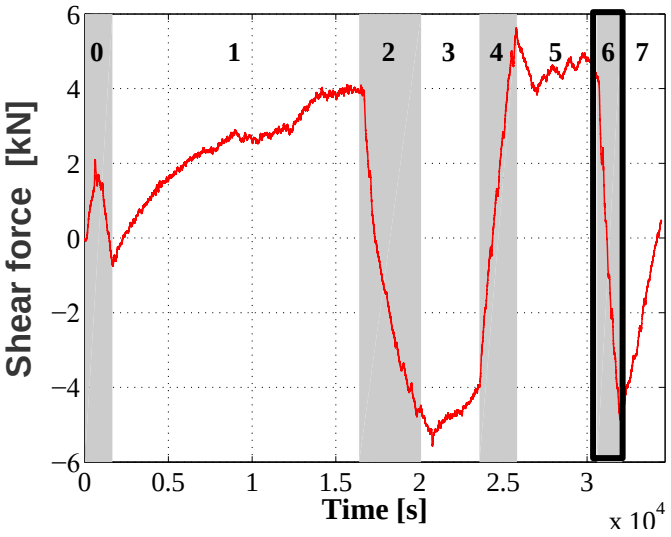


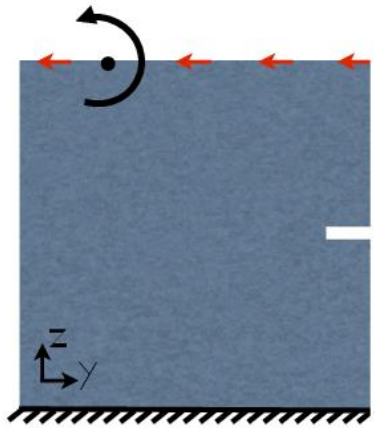


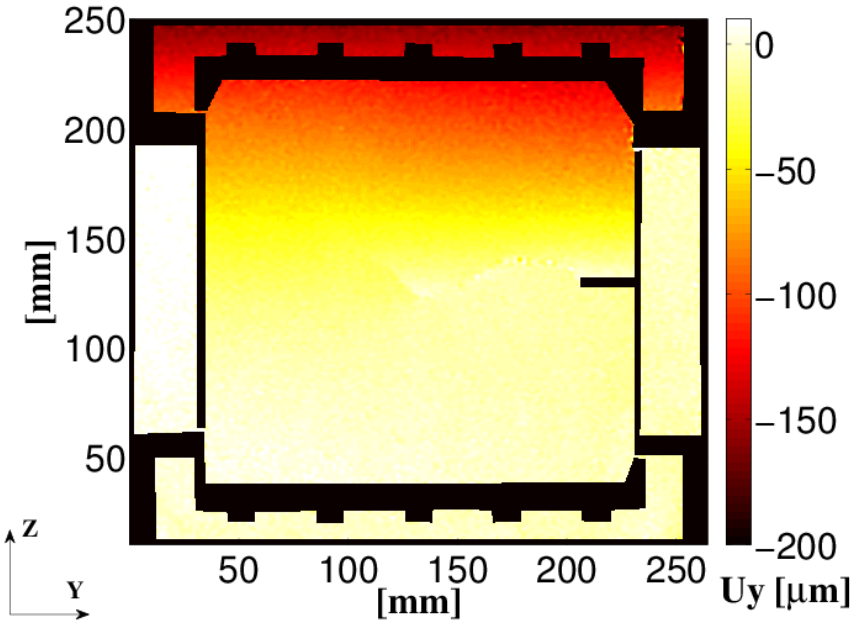


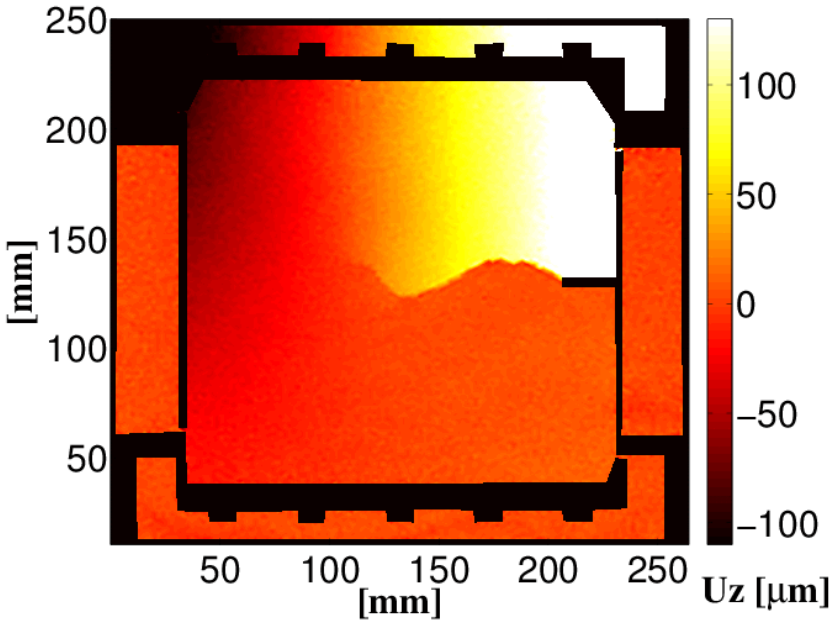


Shear

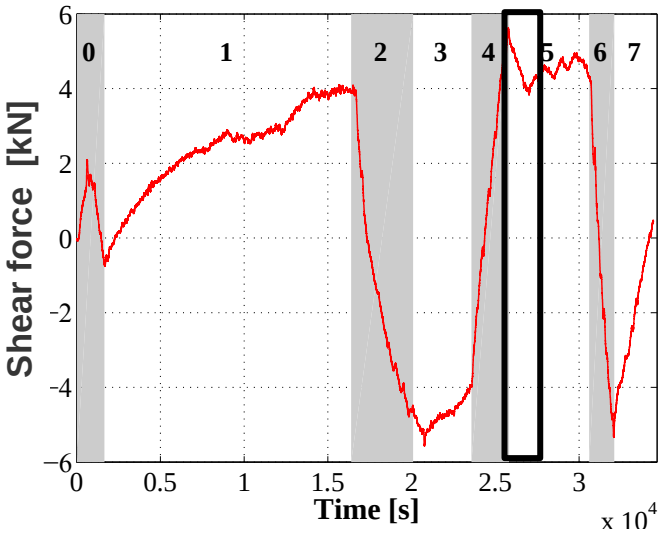


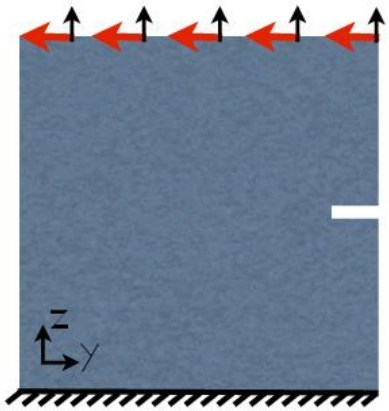


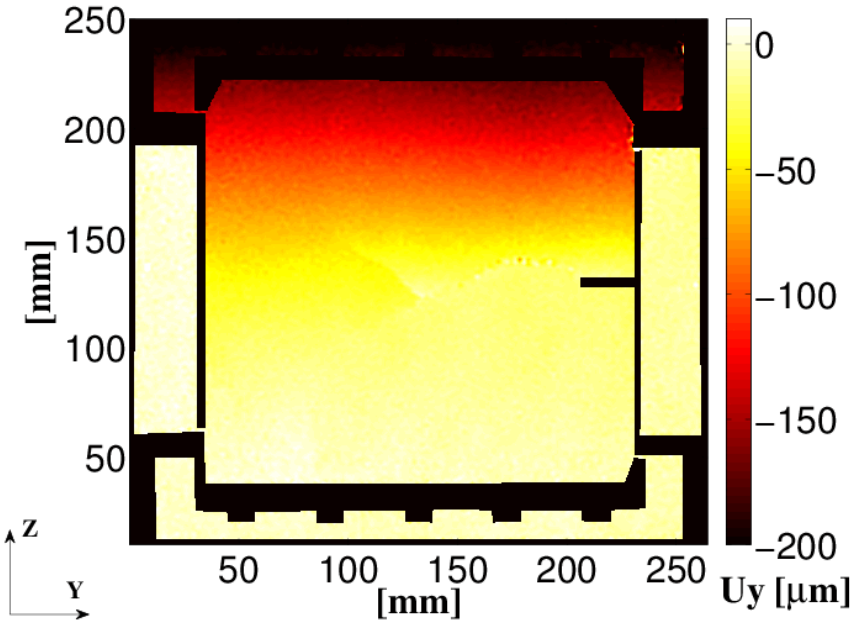


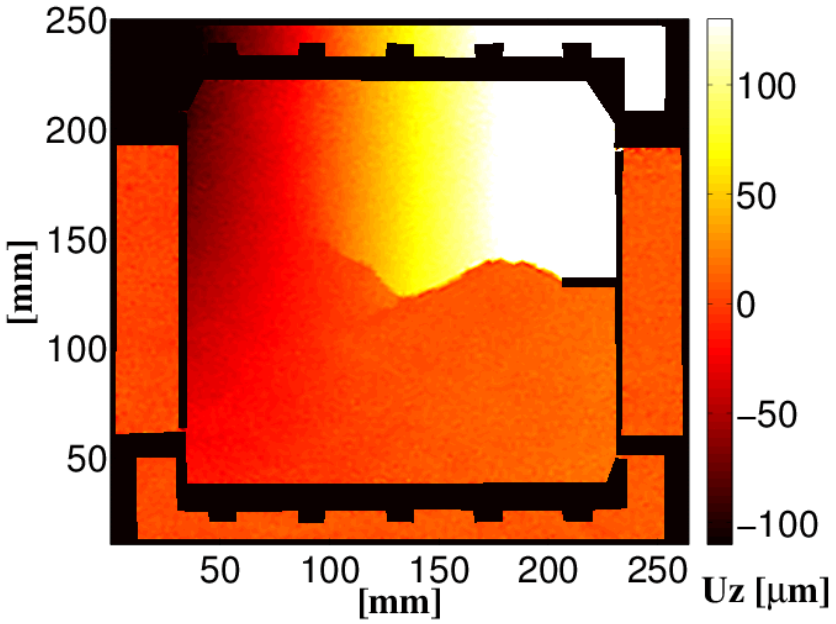


Tension



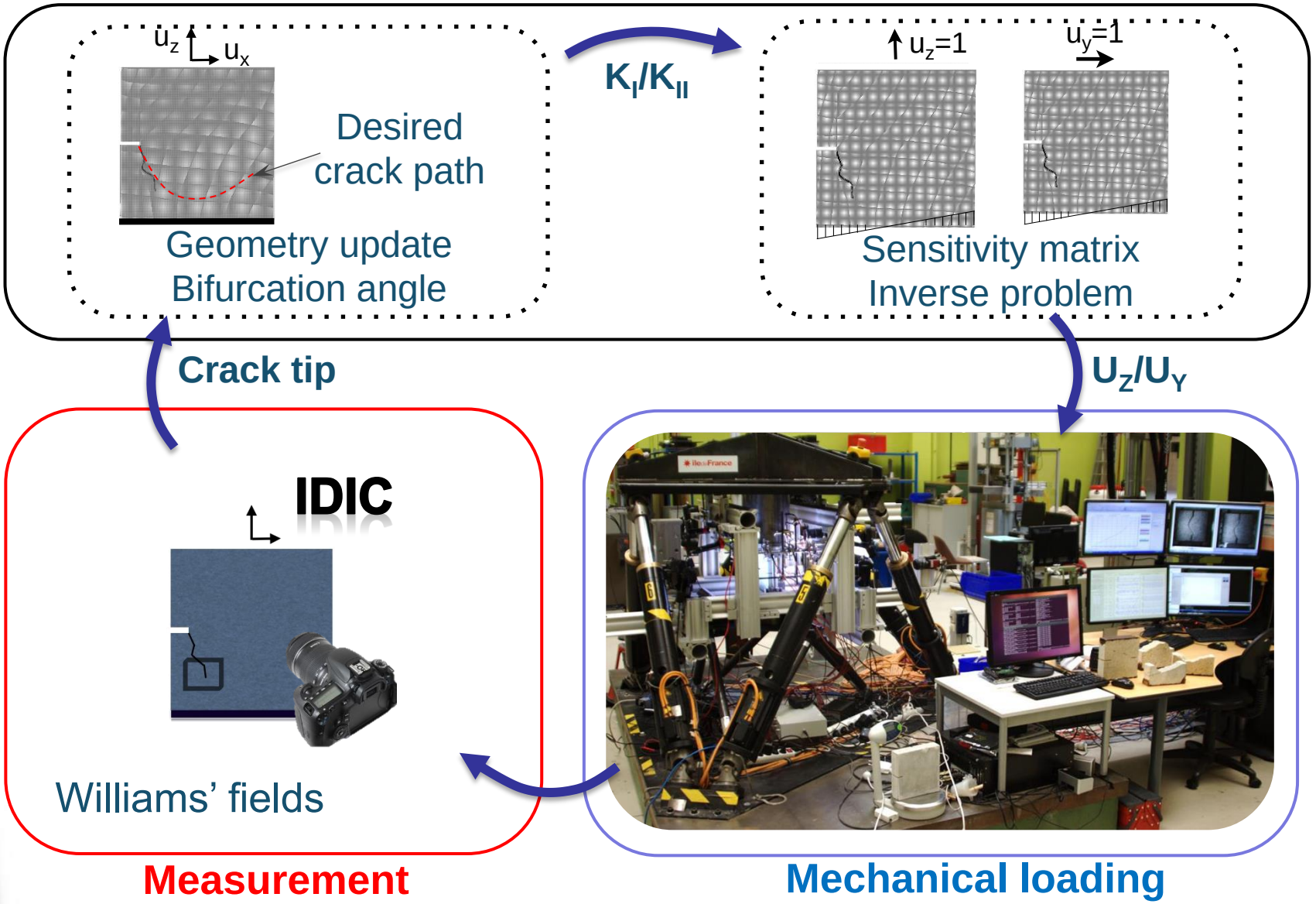




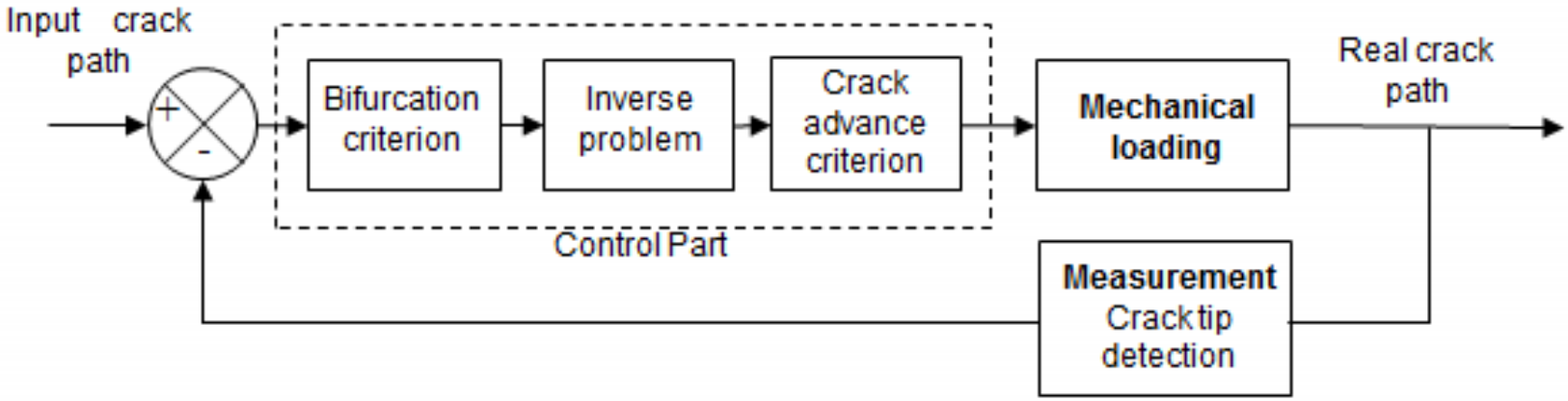


Hybrid Test

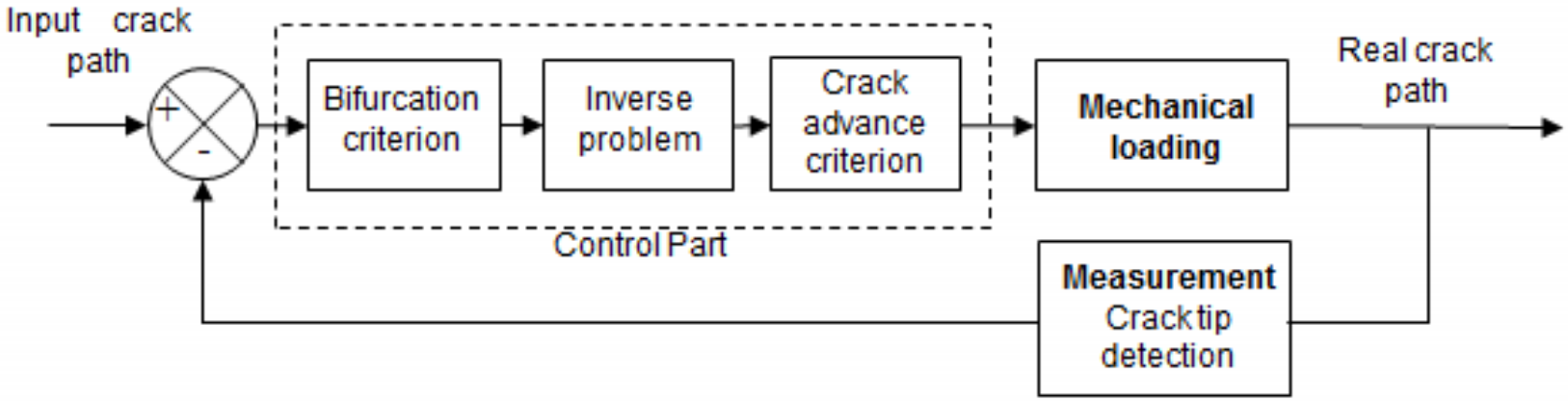
Control - LEFM

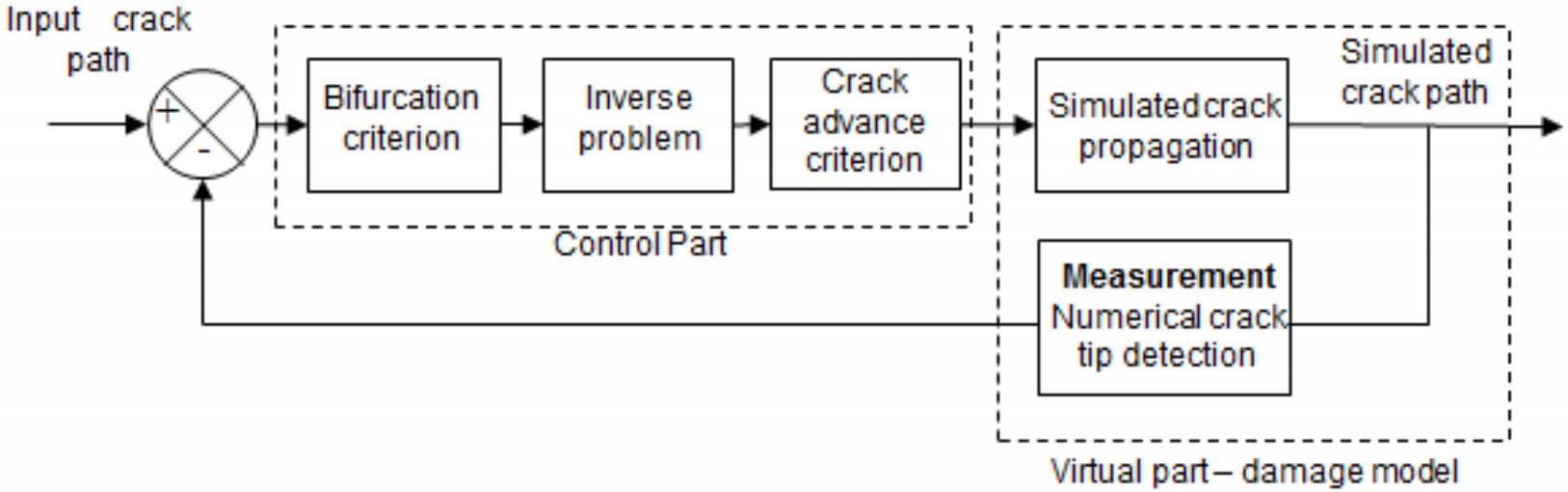


Hybrid Test


Input crack path
+
-
Bifurcation criterion
Inverse problem
Crack advance criterion
Control Part
Mechanical loading
Real crack path
Measurement
Crack tip detection

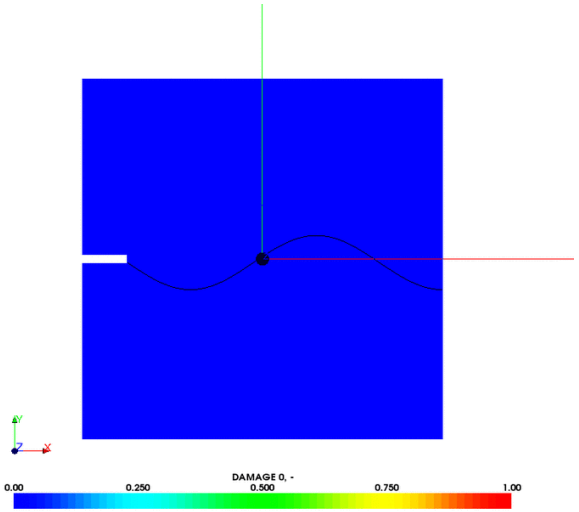
Virtual Hybrid Test*

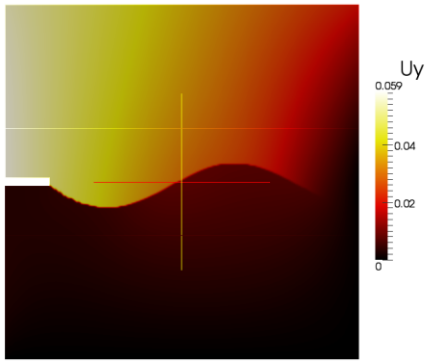


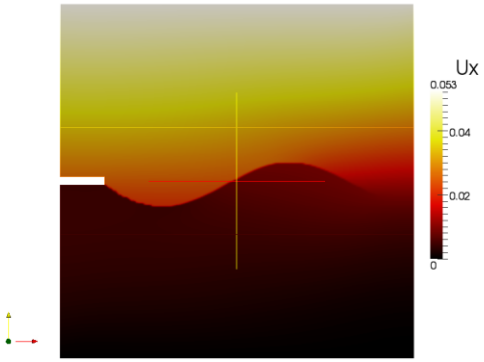


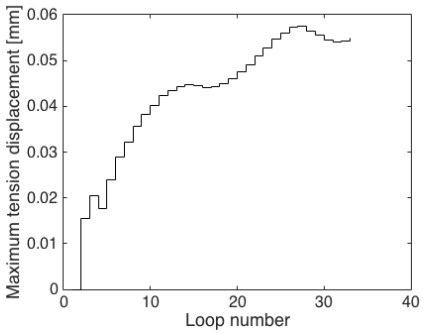
*[Jailin *et al.*, 2017, *J. Mech. Phys. Solids* 102 pp. 239-256]

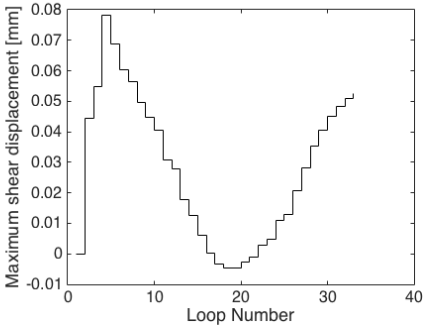
Virtual Hybrid Test



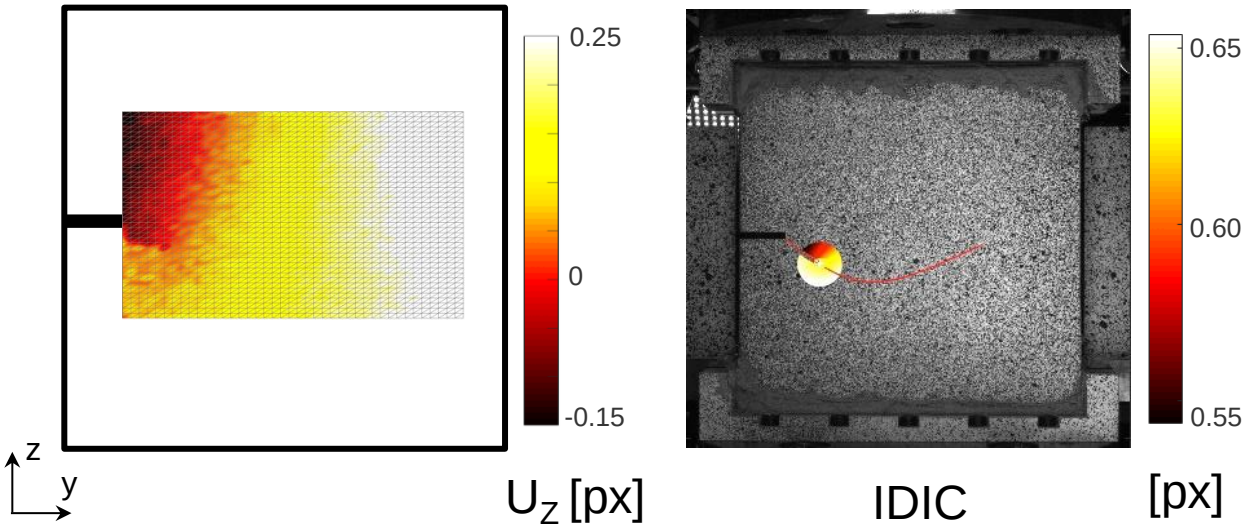








Hybrid Test

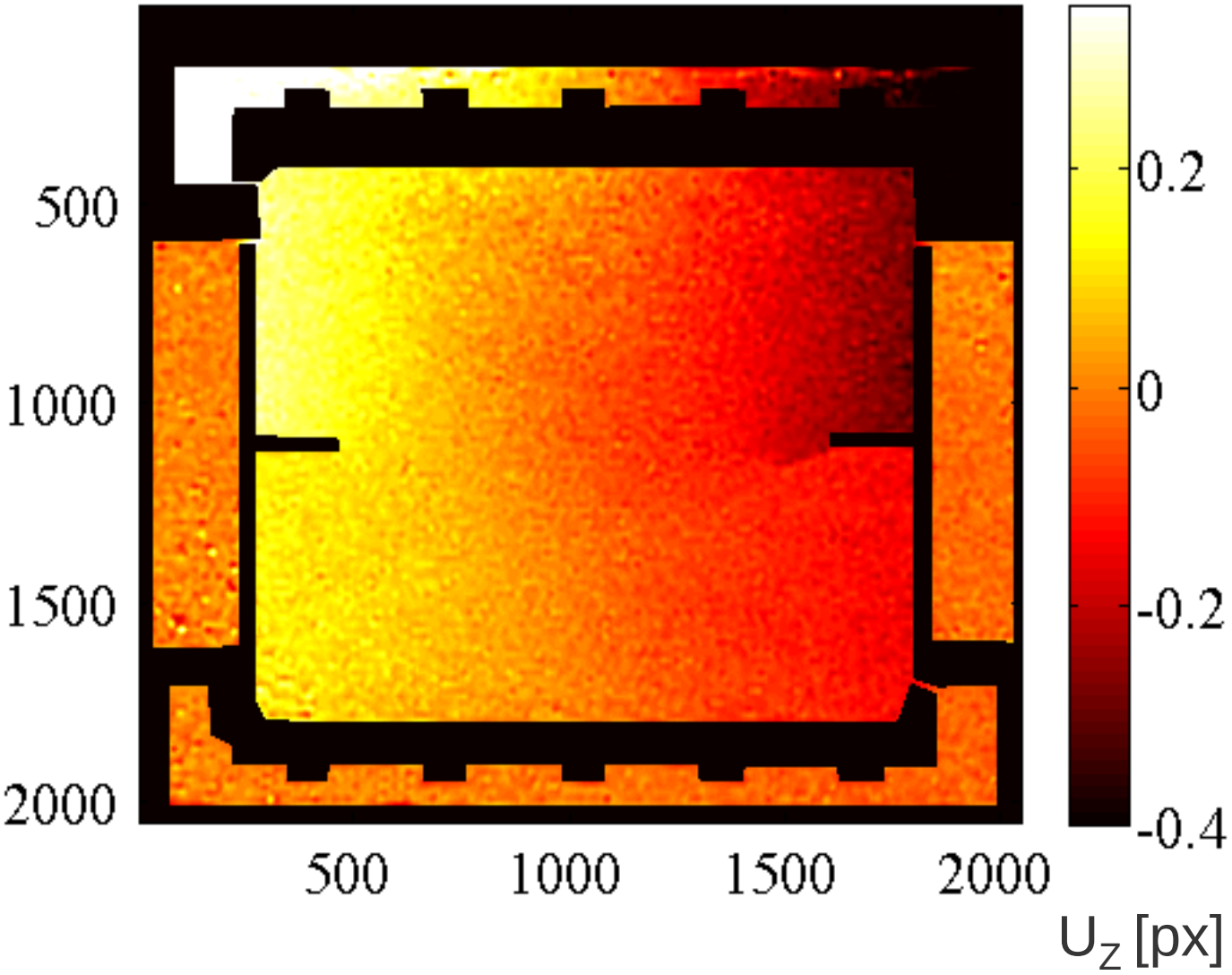


Crack tip detection

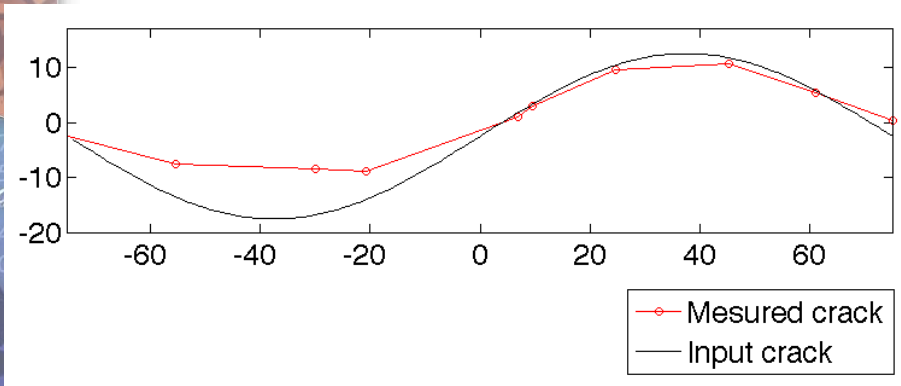
- IDIC: Williams [1957] fields (LEFM)
  [Roux et al., 2006] for straight cracks
  [Réthoré, 2015] for curved cracks

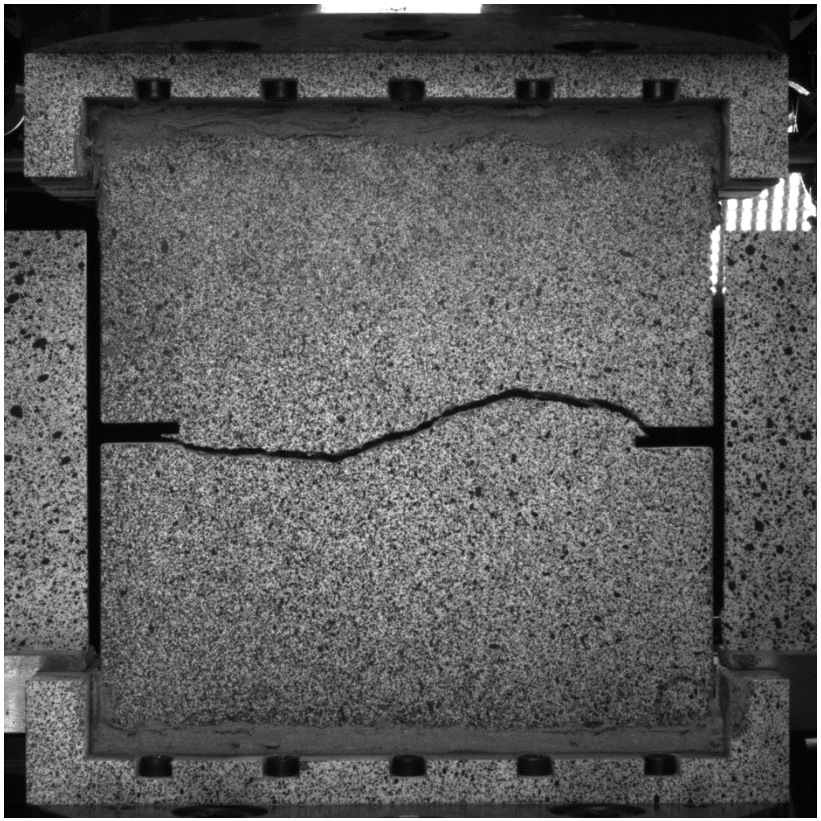
[Carpiuc, 2015, *PhD thesis* ENS Cachan]

Hybrid Test



Hybrid Test





Summary

- Evaluation of damage in brittle materials via **DIC** and **DVC**

- Design of discriminating experiments (e.g., concrete)
  → **DIC**
  → **benchmark**
  → **DIC-driven tests**
  → **optimized tests**

Vielen Dank für Ihre Aufmerksamkeit!