Measuring in-plane displacement and strain fields with the grid method. A feasibility study on superconducting magnet

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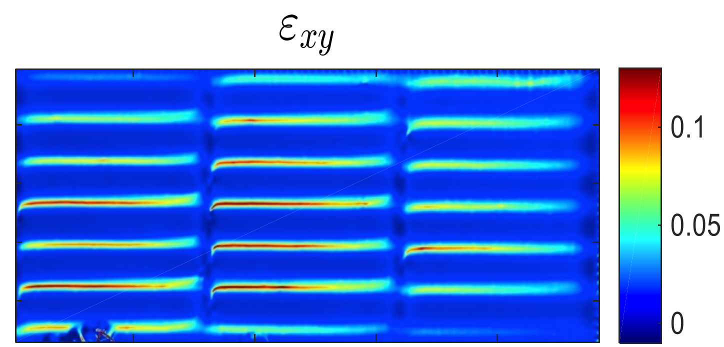

Paris, October 11th, 2018

Objective:

- measuring displacement and strain fields on a superconducting magnet specimen subjected to a mechanical loading
- applying a suitable full-field measurement technique: the grid method
- are the heterogeneities due to the heterogeneous nature of the material observable?

Outline:

1- Basics on the grid method
2- Preparation of the specimen
3- How to extract displacement/strain fields from the images?
4- Results
5- Conclusion

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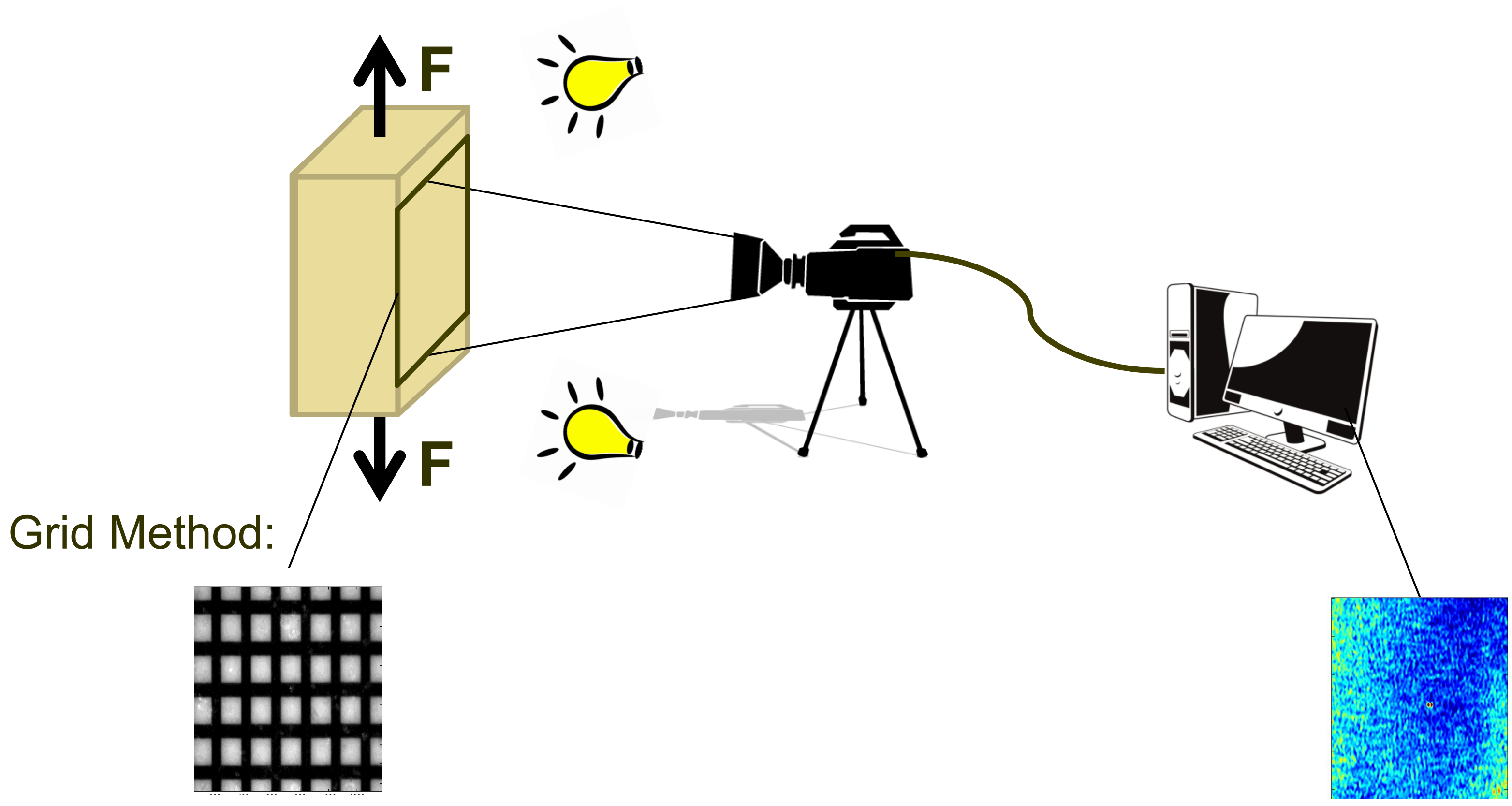
1- Grid bonded/engraved/transferred on the specimen

2- Image of the grid captured by a camera before and after loading

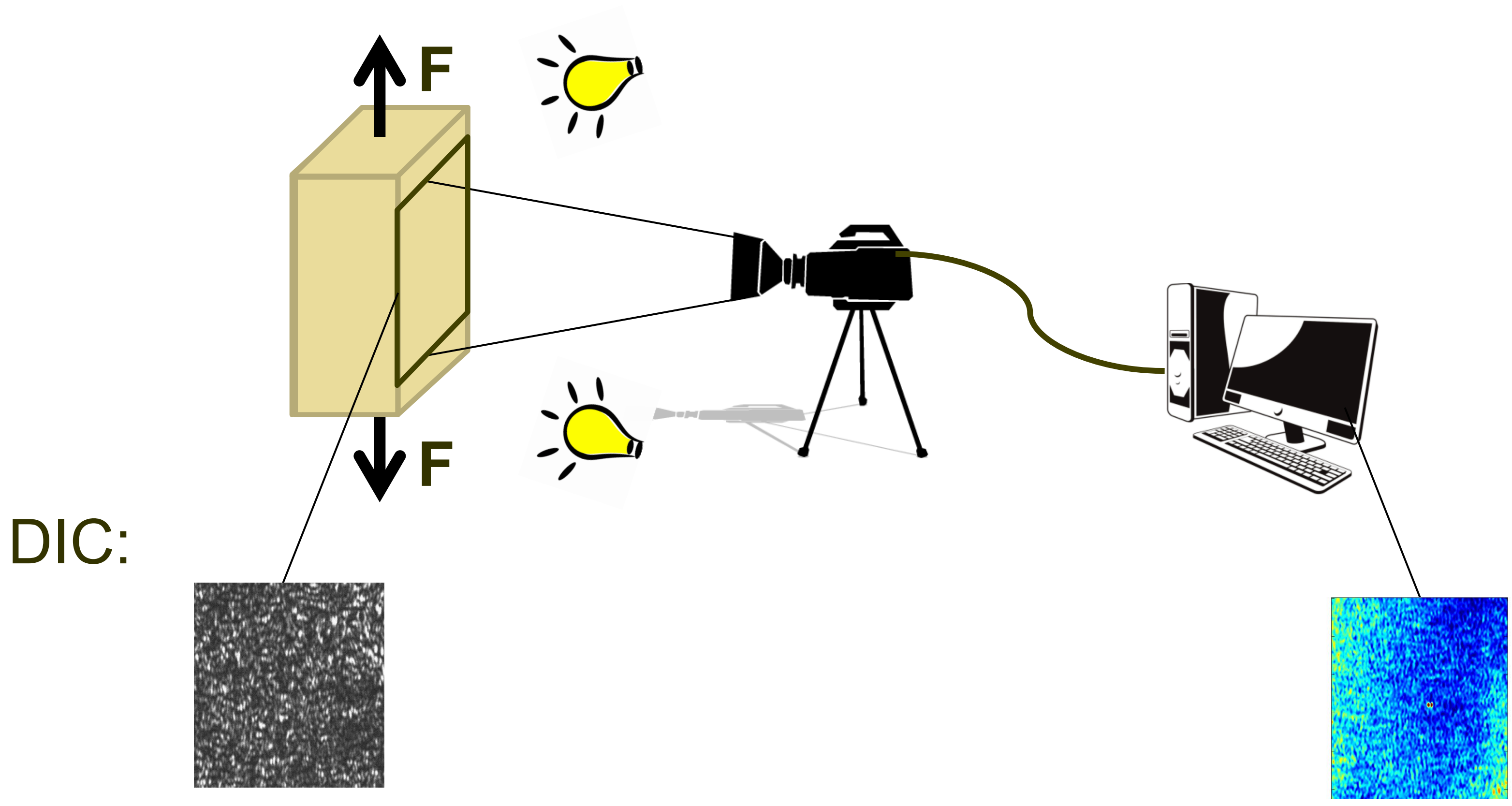
3- Displacement and strain fields deduced by processing these images



1- Speckle deposited on the specimen

2- Image of the speckled pattern captured by a camera before and after loading

3- Displacement and strain fields deduced by processing these images



- a priori knowledge on the pattern with grid → better compromise between noise level and spatial resolution with grids than with speckles [1]

- price to pay: depositing a regular marking

[1] M. Grédiac, F. Sur, B. Blaysat, *Experimental Mechanics*, 57(3): 871-903, 2017

Outline

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Step 1:

- cutting the specimen in a superconducting magnet
- polishing the surface of the specimen

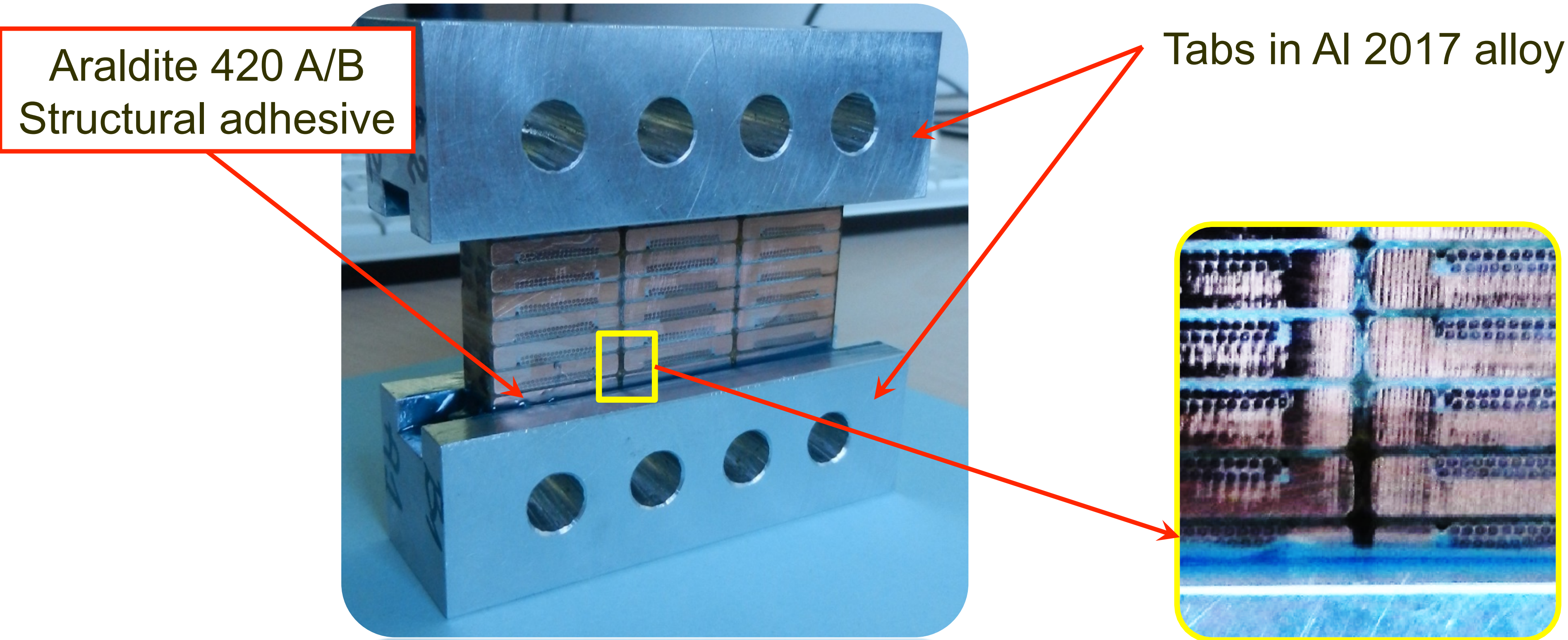
Specimen:

- selected and thoroughly polished and prepared by François NUNIO, CEA Paris-Saclay, France
- cable from JLab magnet for CLS12 torus magnet

dimensions: 60x35x10 mm^3

Step 2:

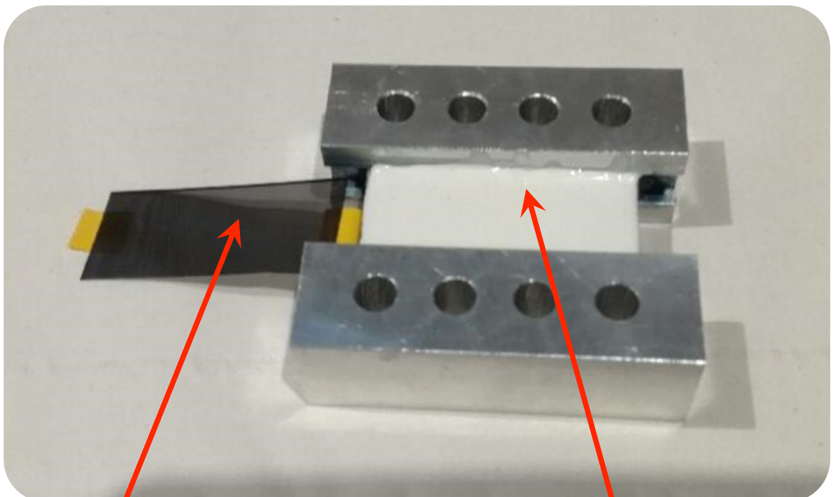
- bonding tabs onto the specimen, suitable for an ARCAN fixture



- special attention while machining the tabs to ensure the symmetry of the resulting specimen
- adjusting the thickness of the glue (200 mm) with slip gauges
- polymerisation: 5 hours, 80°C

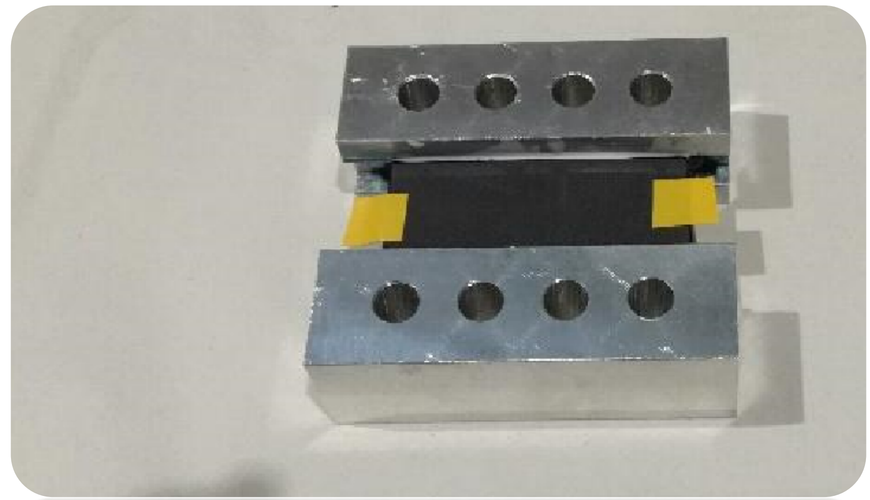
Step 3:

- transferring a 2D grid onto the specimen



2D grid printed onto a polymeric sheet pitch: 0.2 mm

adhesive for transferring the grid (ink only)

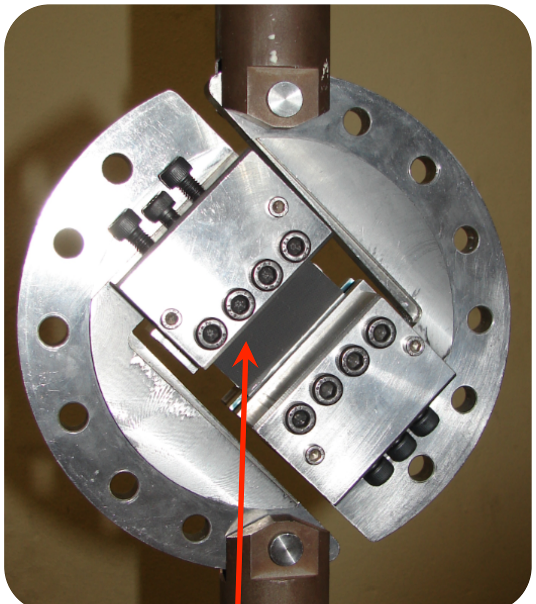


polymerisation + peeling off the polymeric sheet

- grid printed on the polymeric sheet with a high-resolution photoplotter (64,000 dpi)
- white epoxy adhesive to ensure a good visual contrast with black inck

Step 4:

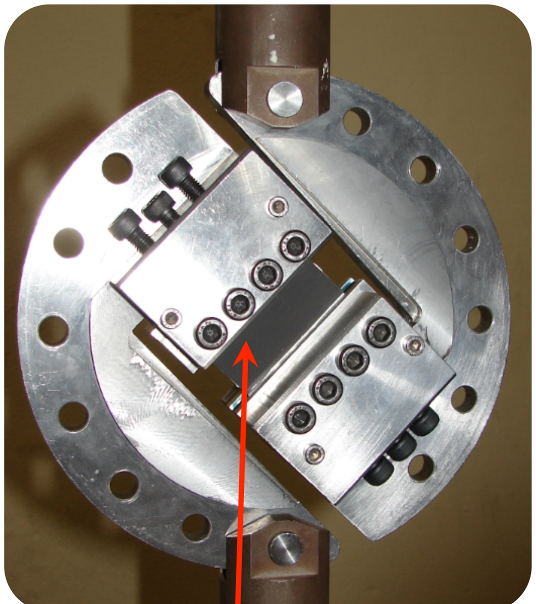
- mounting the specimen in an Arcan fixture + testing it



Arcan fixture + specimen

Step 4:

- mounting the specimen in an Arcan fixture + testing it



Arcan fixture + specimen

force cell

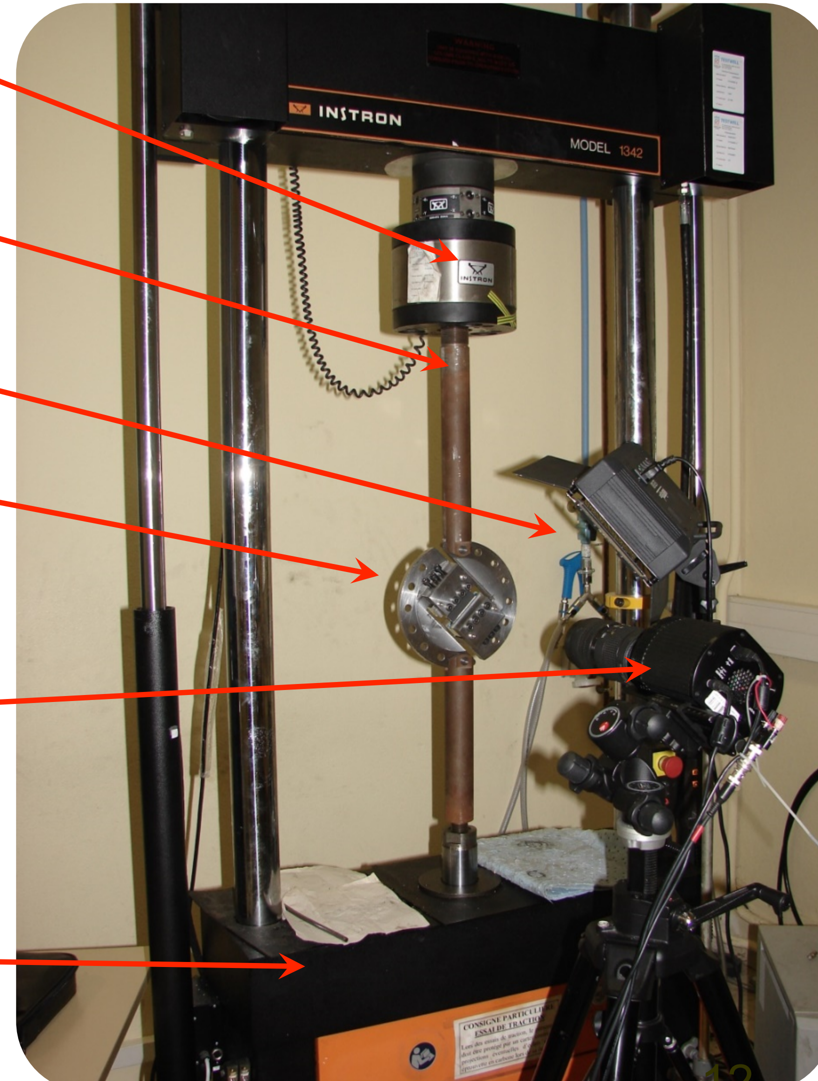
pièces d’interfaces

Lighting system

Arcan fixture

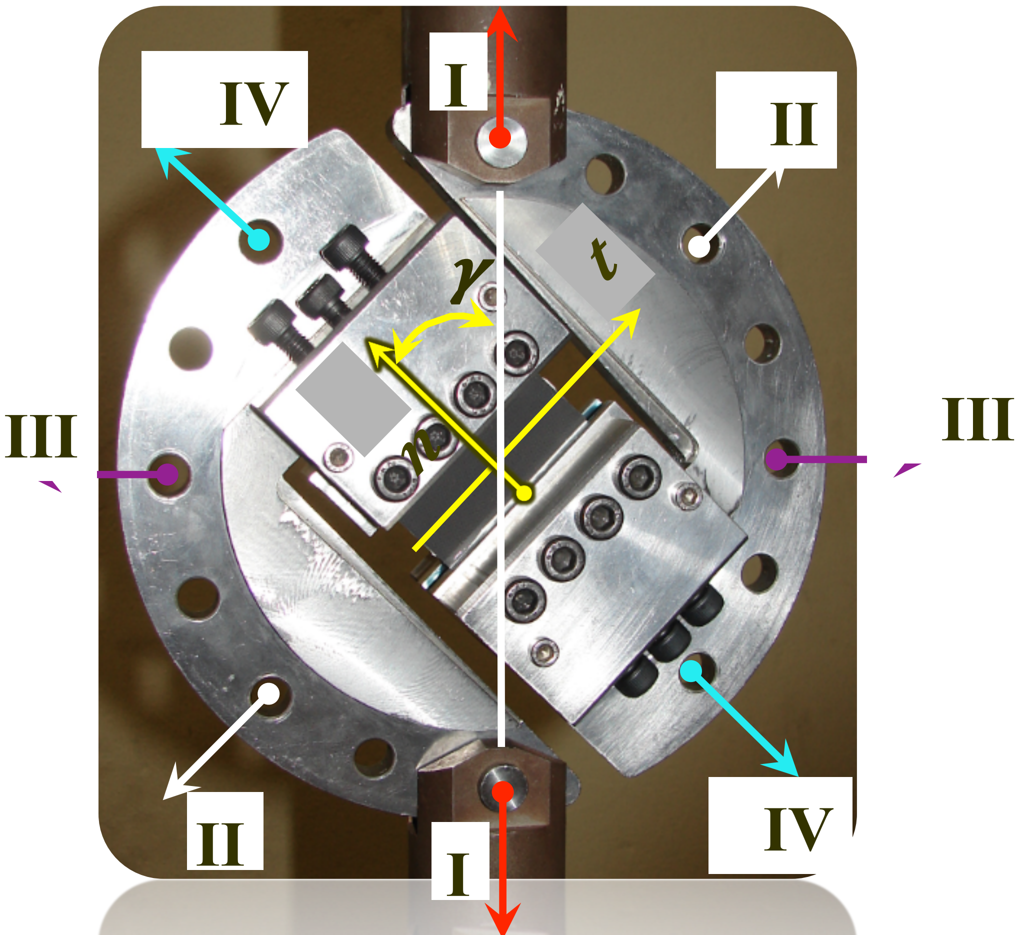
Retiga 6000 CCD BW 14-bit camera 2758 x2208 pixels

Hydraulic INSTRONTensile machine Fmax=100kN

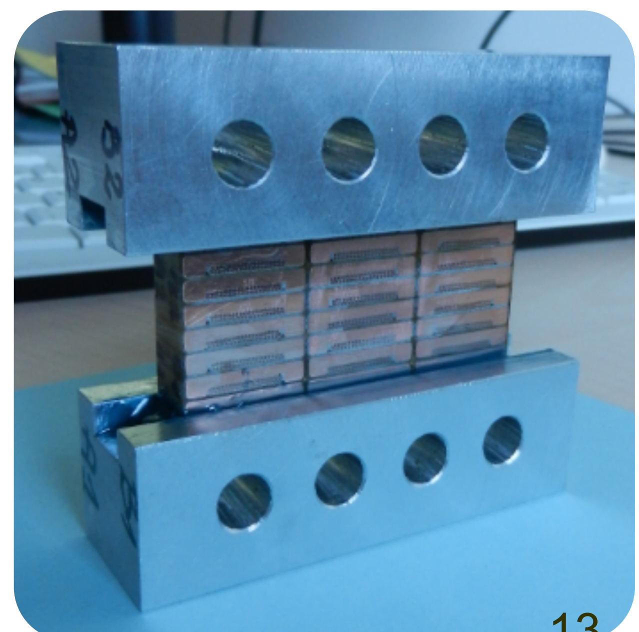


Various (potential) 2D loading configurations with the Arcan fixture

I-I → **compression + shear**
II-II → shear
III-III → tensile load + shear
IV-IV → **tensile load**

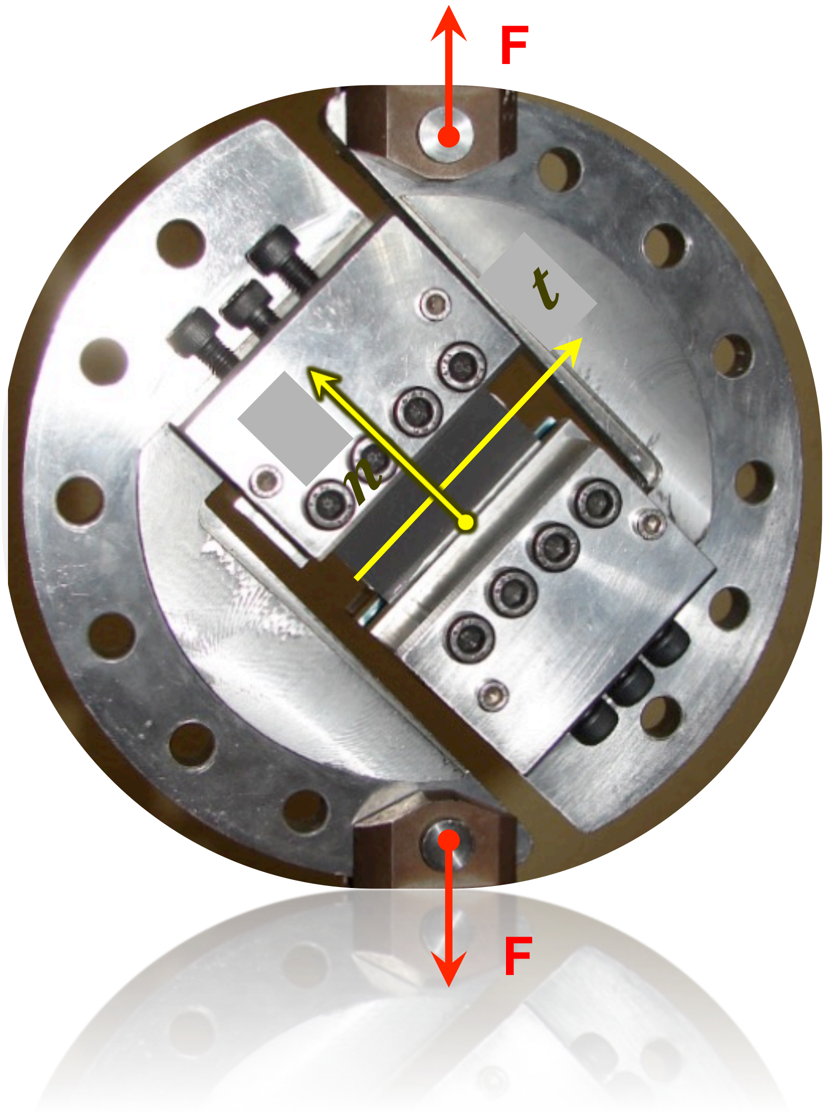


specimen

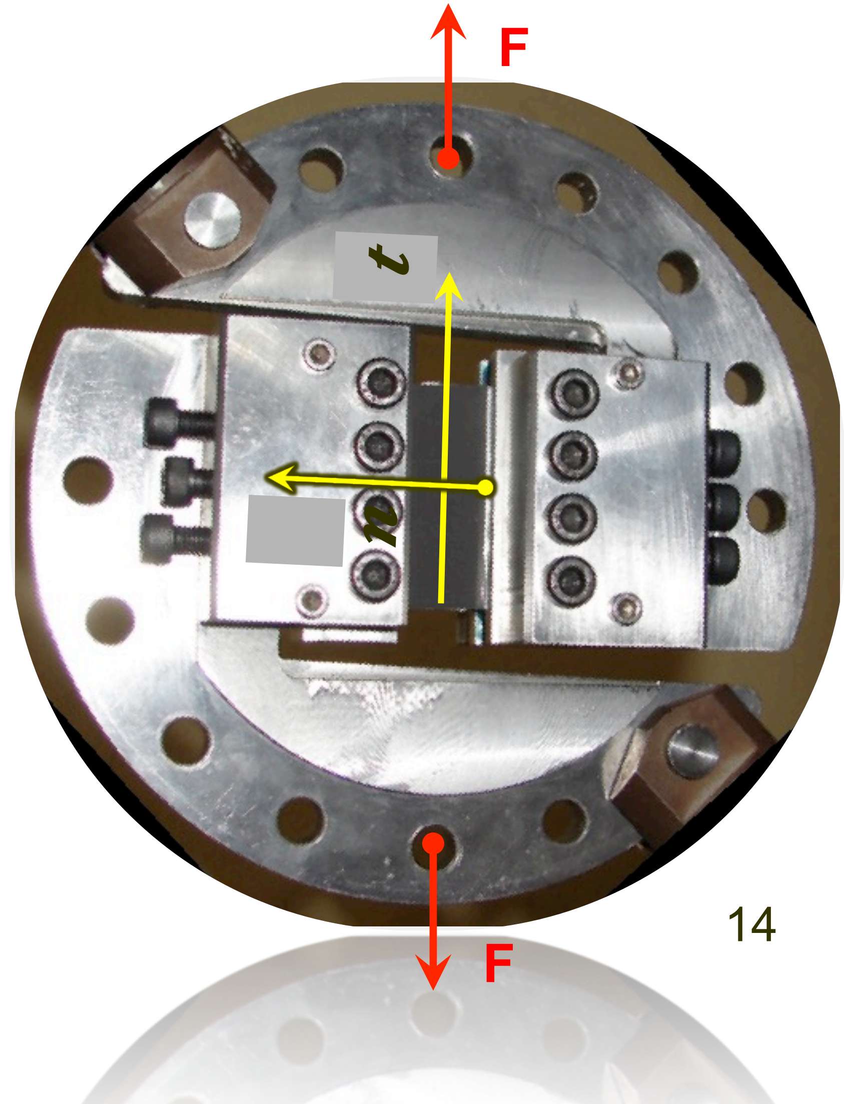


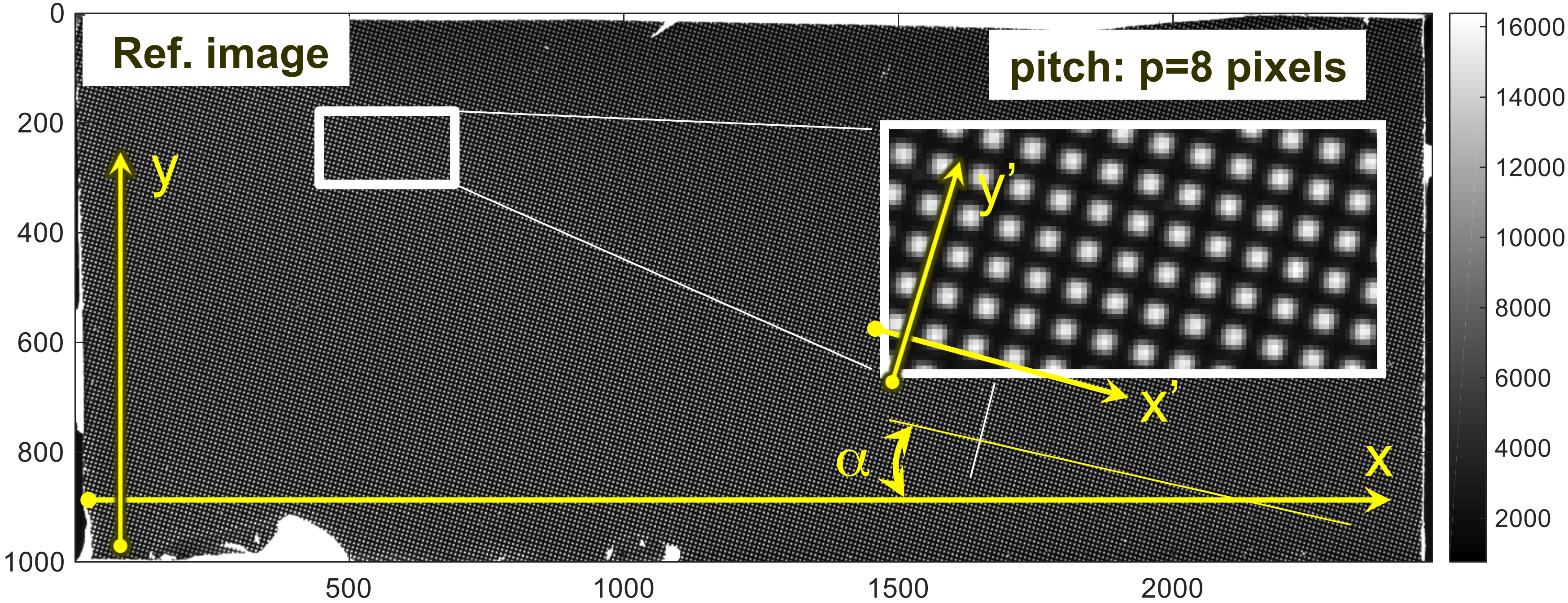
Tested configurations

A: compression + shear



B: shear




Ref. image
pitch: p=8 pixels
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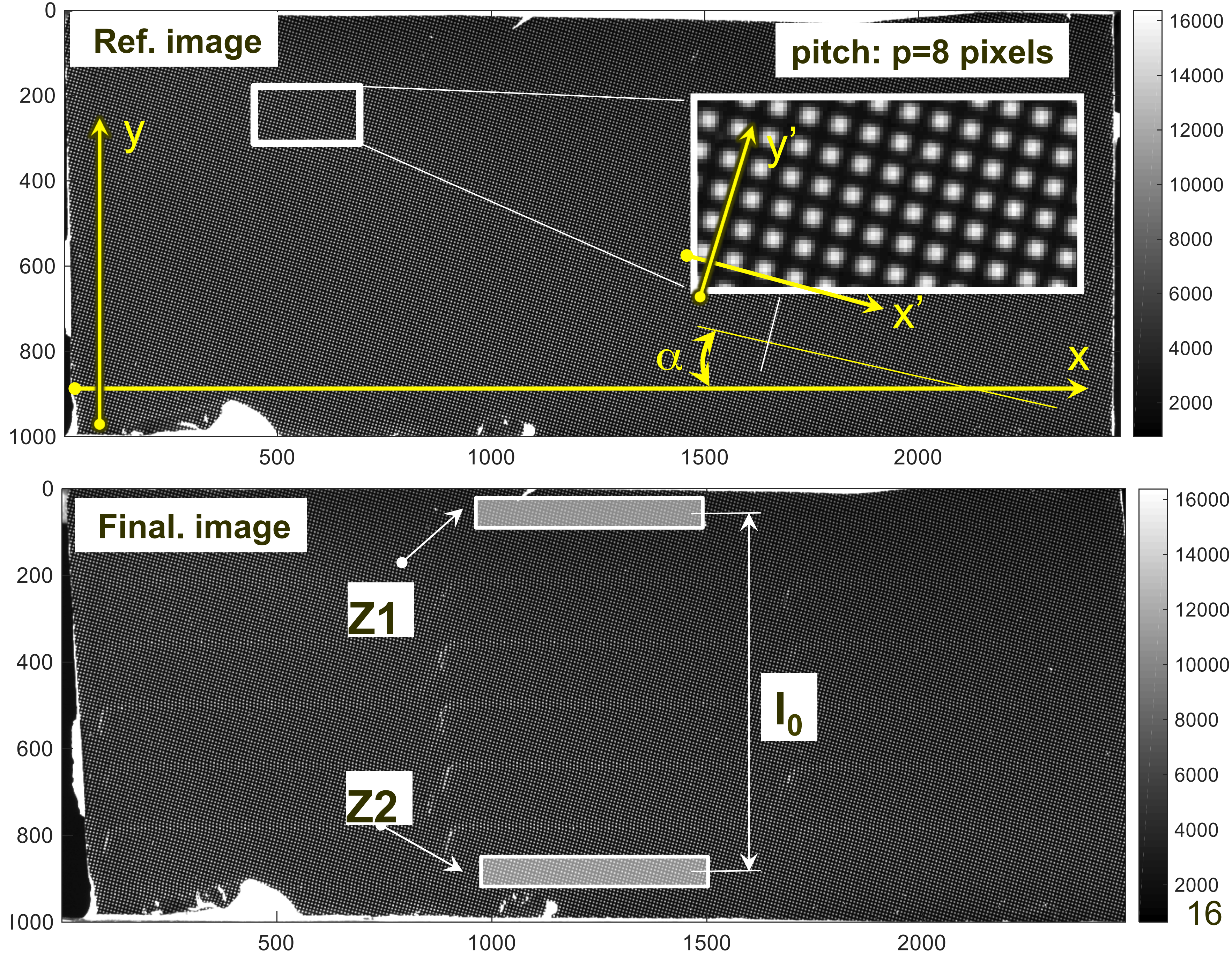
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6000
4000
2000

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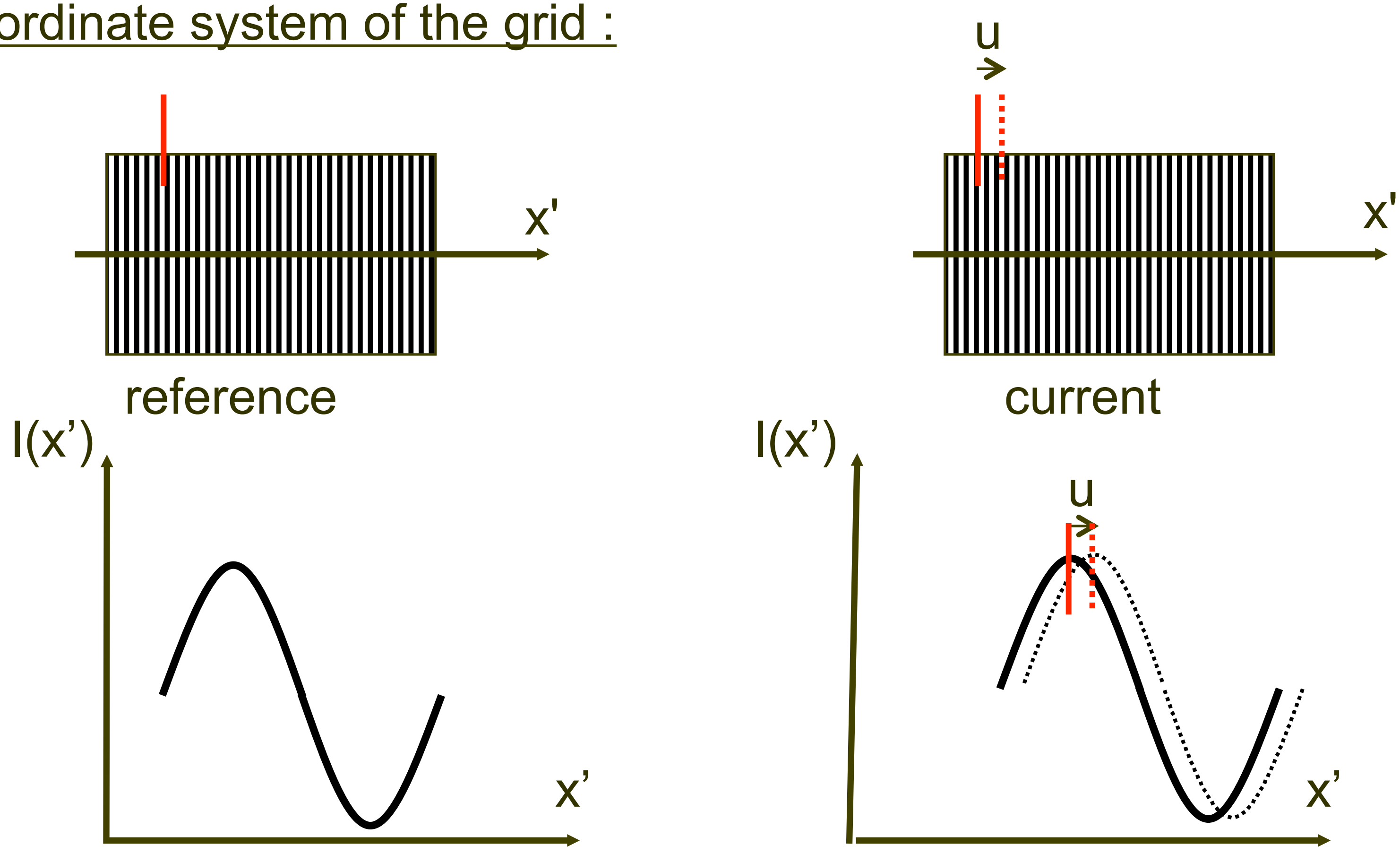
Link between displacement and phase [1] :

in the coordinate system of the grid :



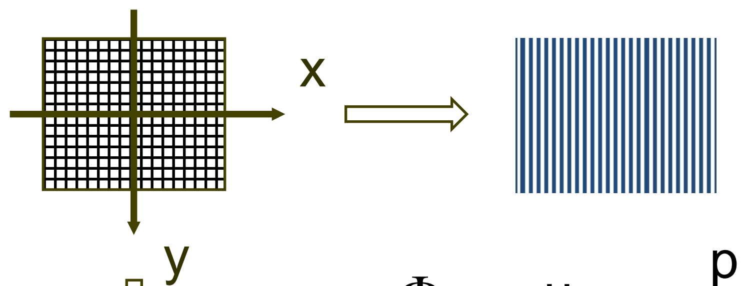
Displacement proportional to the change in phase

$$\rightarrow \quad u = -\frac{p}{2\pi}\left(\Phi_{current} - \Phi_{reference}\right) = -\frac{p}{2\pi}\Delta\Phi$$

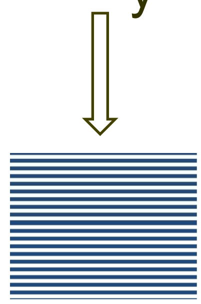
[1] Y. Surrel, **Topics in Applied Physics**, 2000

Case of 2D-grids:

2D grids → 2 displacements u_x and u_y



$$\Phi_x \rightarrow u_x = -\frac{p}{2\pi}\Delta\Phi_x$$



$$\Phi_y \rightarrow u_y = -\frac{p}{2\pi}\Delta\Phi_y$$

Extracting the phases from the images

- by using a Fourier-based method such as:
  - the Geometric Phase Analysis [1] (the whole spectrum)
  - the windowed Geometric Phase Analysis [2] (windows in the spectrum)
  - the Localized Spectrum Analysis, LSA [3] (points in the spectrum)

- LSA:

$$\widehat{s}(x,y,f,0,\alpha)=\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\underline{s(u,v)}\,\underline{g(x-u,y-v)}\,e^{-2i\pi fu(cos\alpha+fvsin\alpha)}dudv$$

with:

1. $s(u,v)$: signal = matrix of gray levels
2. $g(x\text{-}u,y\text{-}v)$: Gaussian window

[1] M. J. Hytch, E. Snoeck, R. Kilaas, Ultramicroscopy, 74:131-146, 1998
[2] X. Dai, H. Xie, H. Wang, Optics and Laser Technology, 58(6):119-127, 2014
[3] M. Grédiac, F. Sur, B. Blaysat, Strain, 52(3):205--243, 2016

Extracting the phases from the images

- by using a Fourier-based method such as:
  - the Geometric Phase Analysis [1] (the whole spectrum)
  - the windowed Geometric Phase Analysis [2] (windows in the spectrum)
  - the Localized Spectrum Analysis, LSA [3] (points in the spectrum)

- LSA:

$$\widehat{s}(x,y,f,0,\alpha) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \underline{s(u,v)}\,\underline{g(x-u,y-v)}\,e^{-2i\pi f u(cos\alpha + f v sin\alpha)} du dv$$

with:

1. *s(u,v)*: signal = matrix of gray levels
2. *g(x-u,y-v)*: Gaussian window

- $\widehat{s}(x,y,f,0,\alpha)$ and $\widehat{s}(x,y,0,f,\alpha)$: two complex numbers for each image

→ 2 arguments → 2 phases for each image → 2 displacement components

[1] M. J. Hytch, E. Snoeck, R. Kilaas, Ultramicroscopy, 74:131-146, 1998
[2] X. Dai, H. Xie, H. Wang, Optics and Laser Technology, 58(6):119-127, 2014
[3] M. Grédiac, F. Sur, B. Blaysat, Strain, 52(3):205--243, 2016

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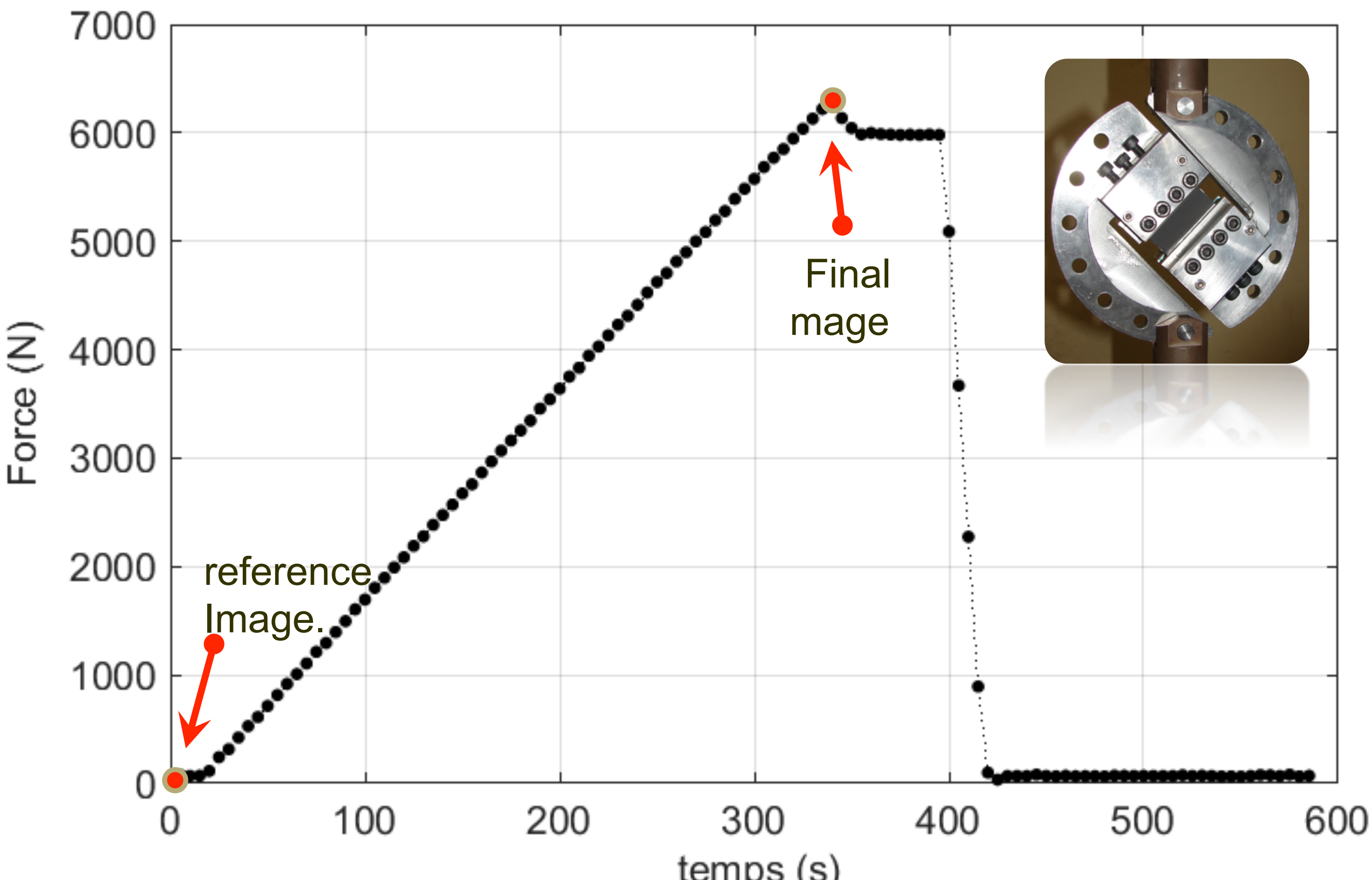
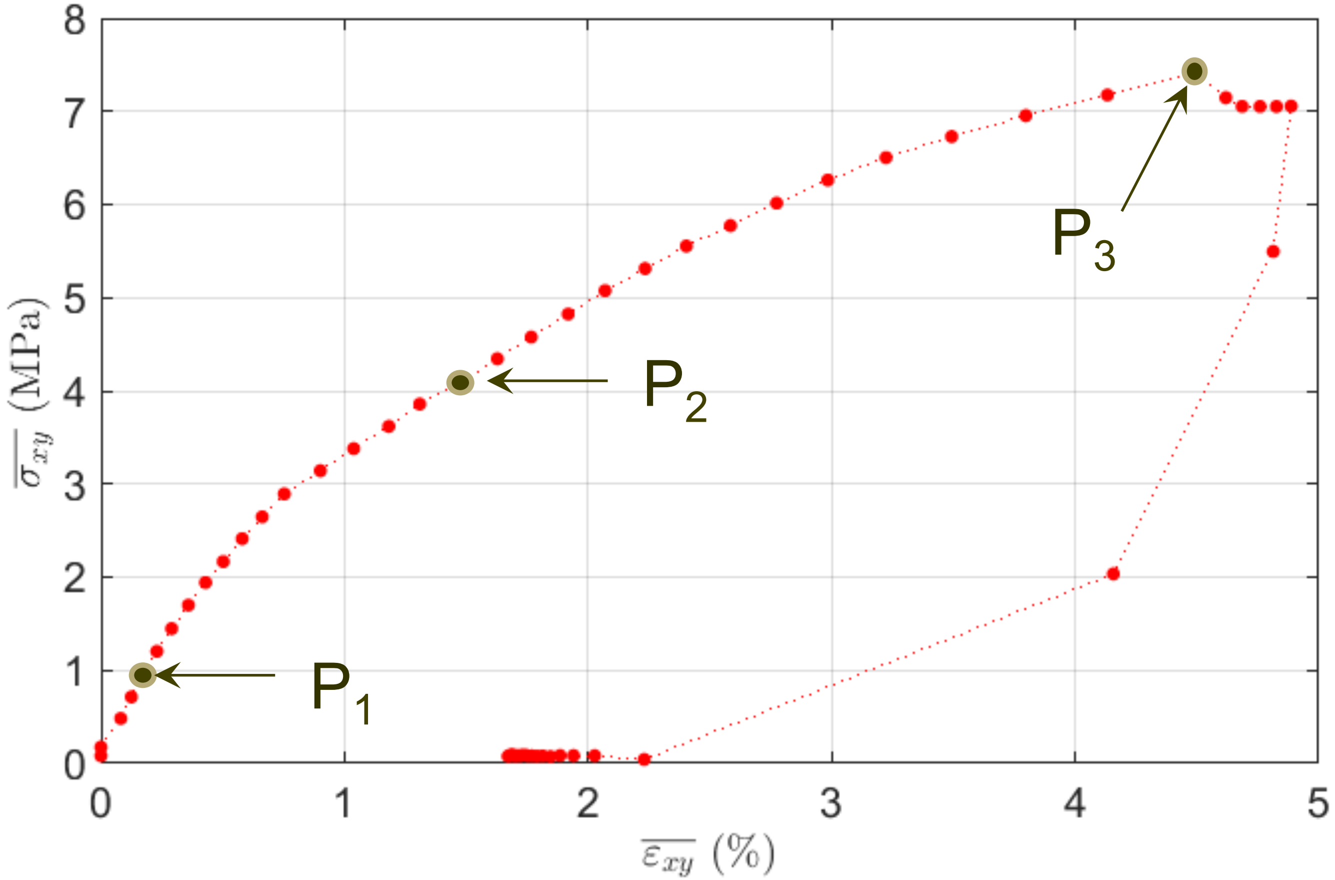
Test A: compression + shear
- force-driven: 0,02 kN/s, Fmax=6,3 kN (...)
- frequency: 2 images/s



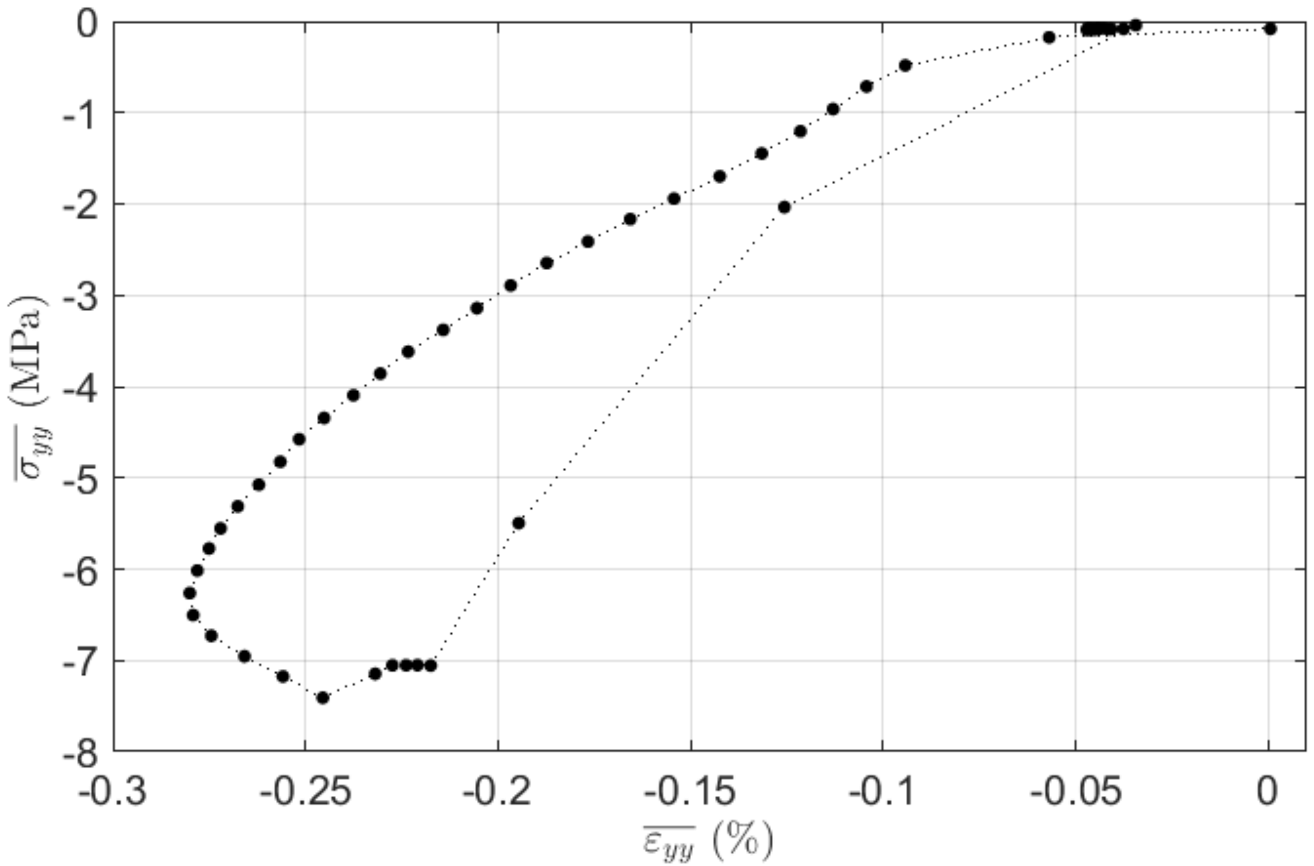
mean stress $\overline{\sigma_{xy}}$ vs. mean strain $\overline{\varepsilon_{xy}}$

$$\overline{\sigma_{xy}} = \frac{F}{S} \times \frac{\sqrt{2}}{2} \qquad \overline{\varepsilon_{xy}} = \frac{\overline{u_x}(Z_1) - \overline{u_x}(Z_2)}{distance(Z_1, Z_2)}$$

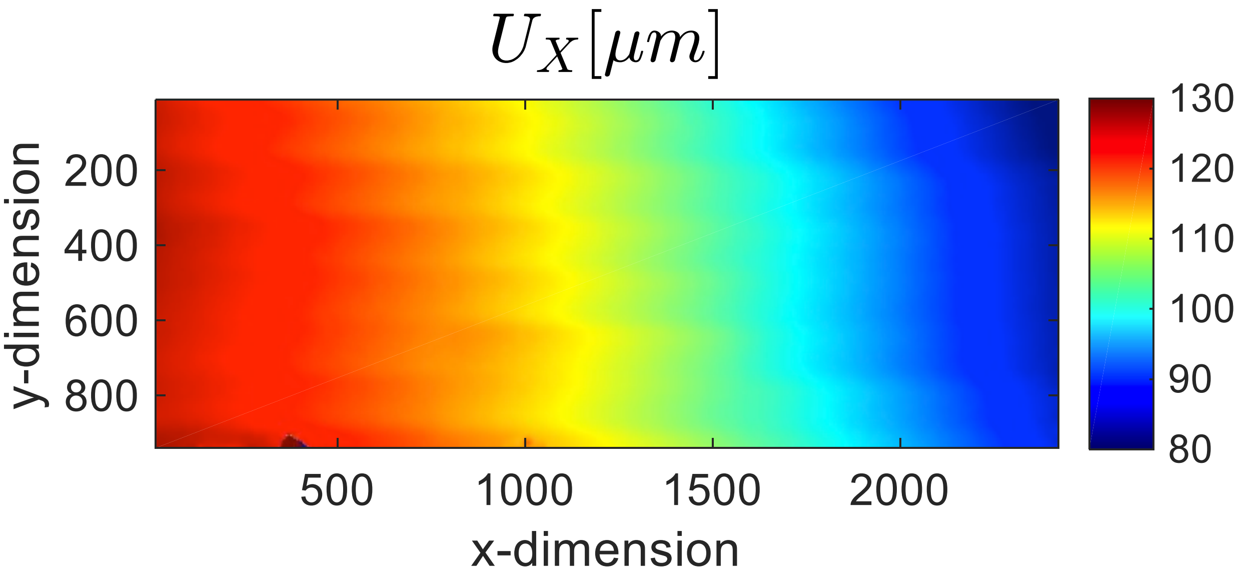


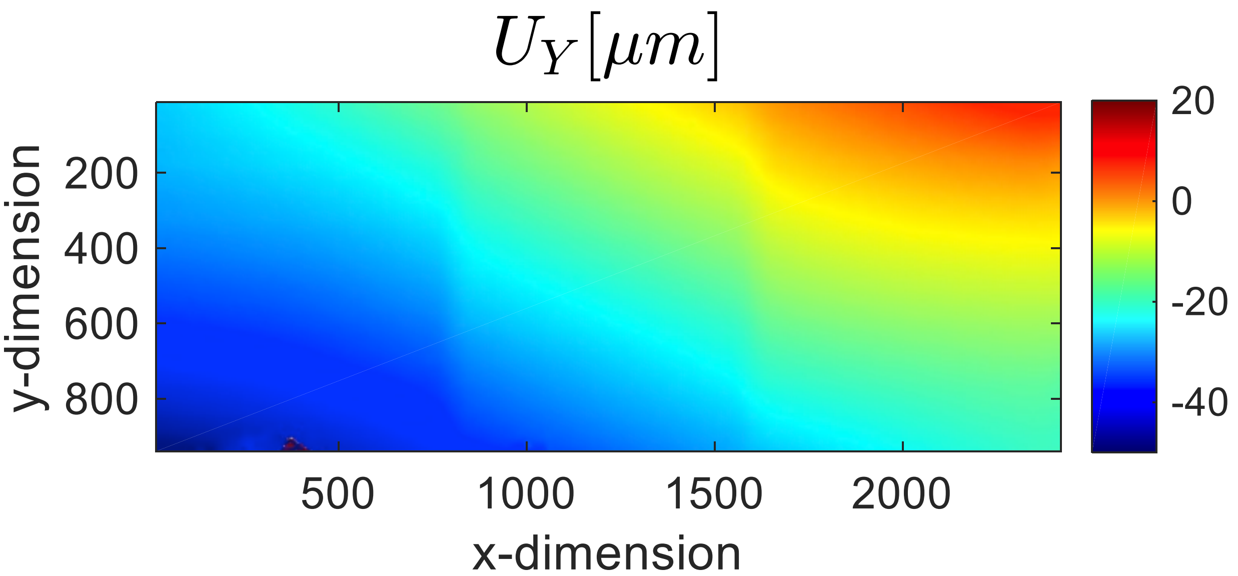
mean stress $\overline{\sigma_{yy}}$ vs. mean strain $\overline{\varepsilon_{yy}}$

$$\overline{\sigma_{yy}} = \frac{F}{S} \times \frac{\sqrt{2}}{2} \qquad \overline{\varepsilon_{yy}} = \frac{\overline{u_y}(Z_1) - \overline{u_y}(Z_2)}{distance(Z_1, Z_2)}$$

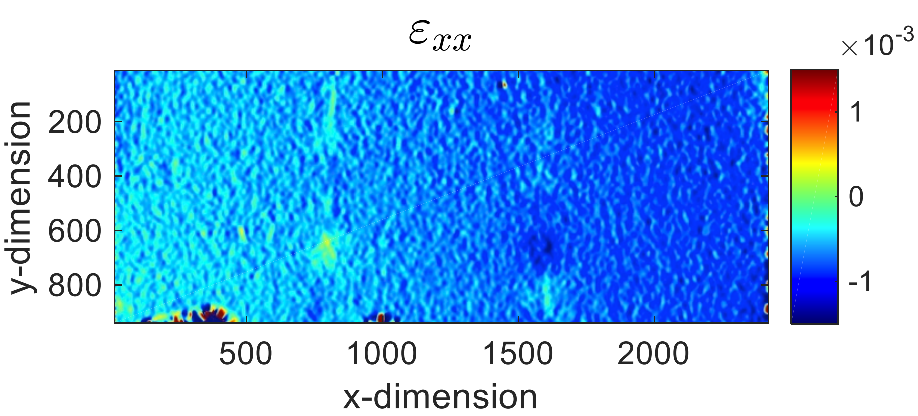


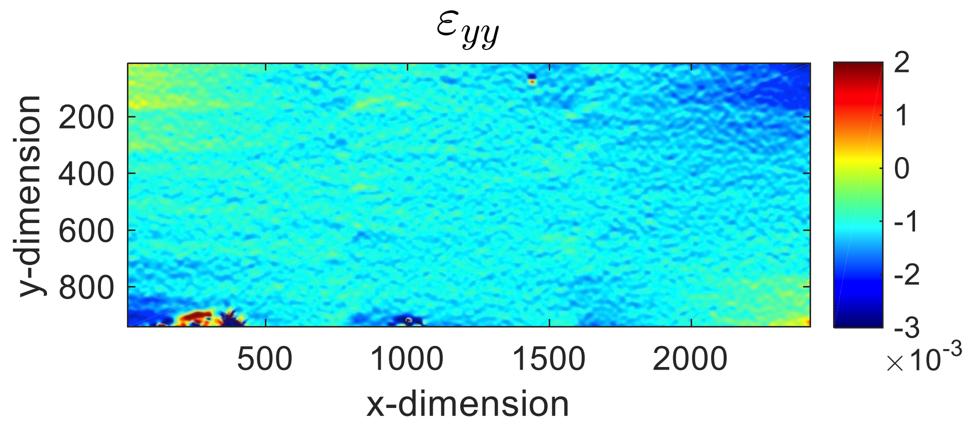
Displacement maps at Point P_1

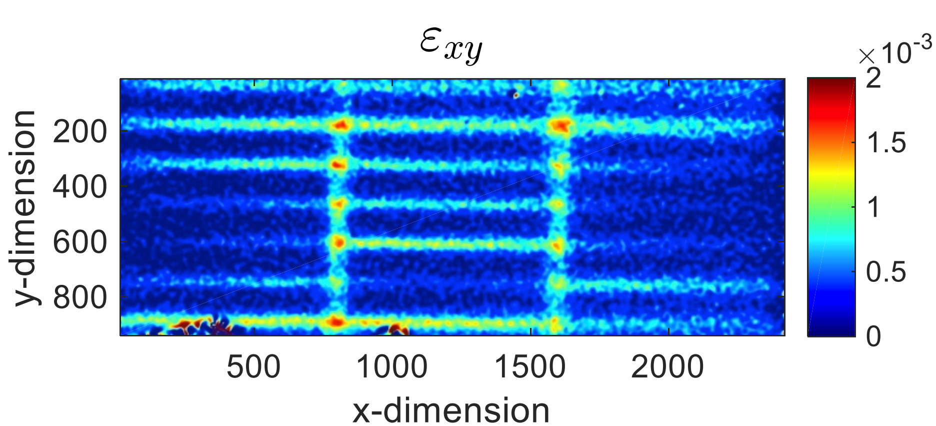


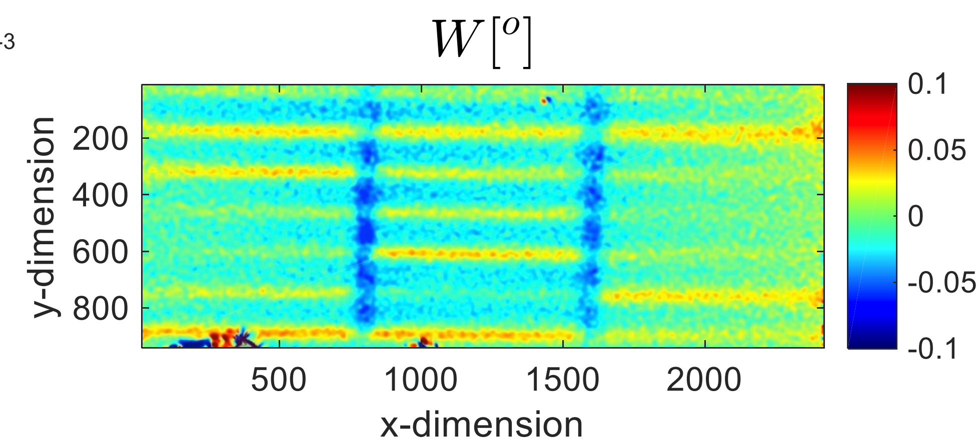


Strain and rotation maps at Point P_1

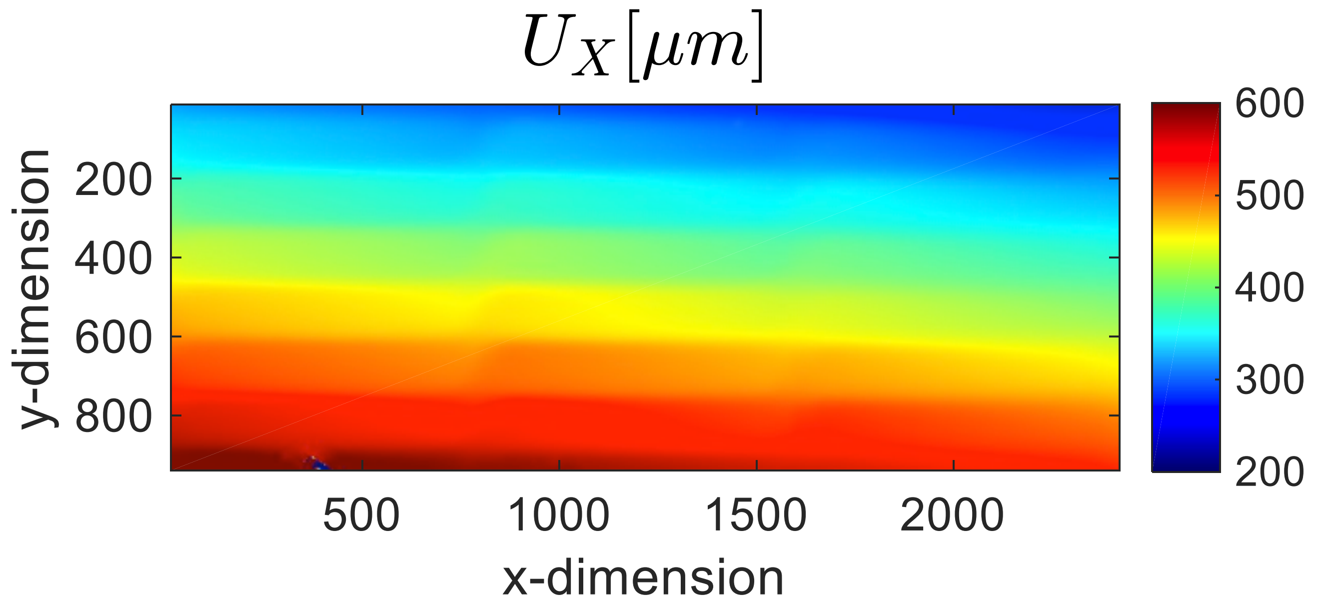


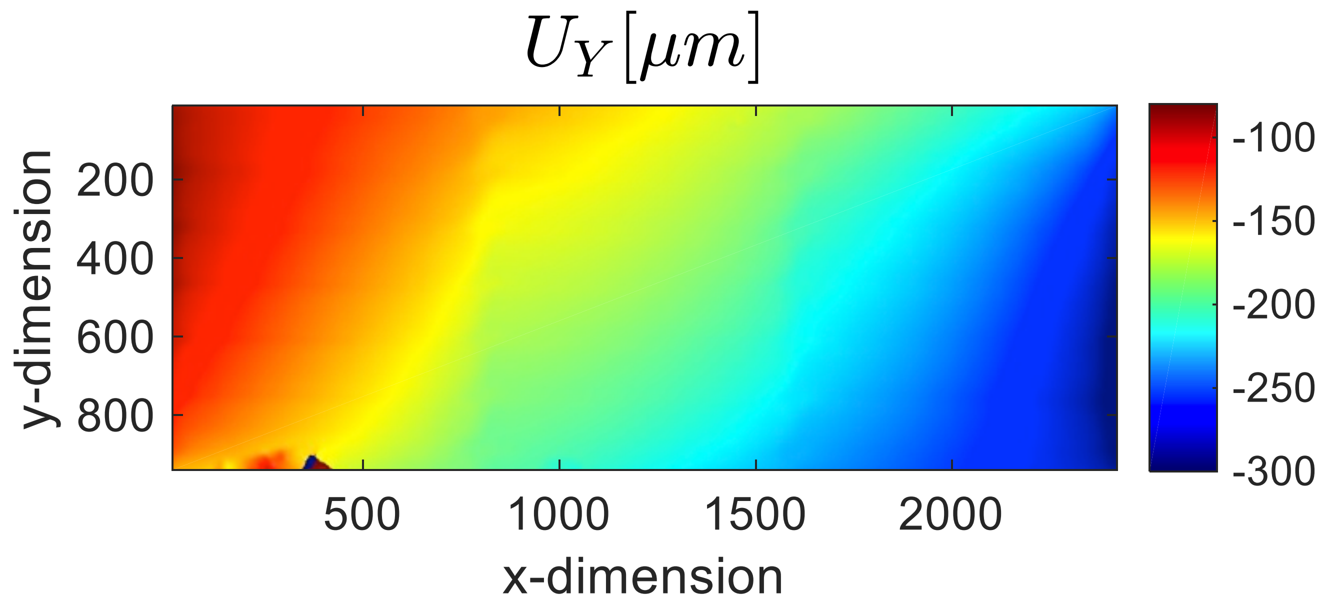




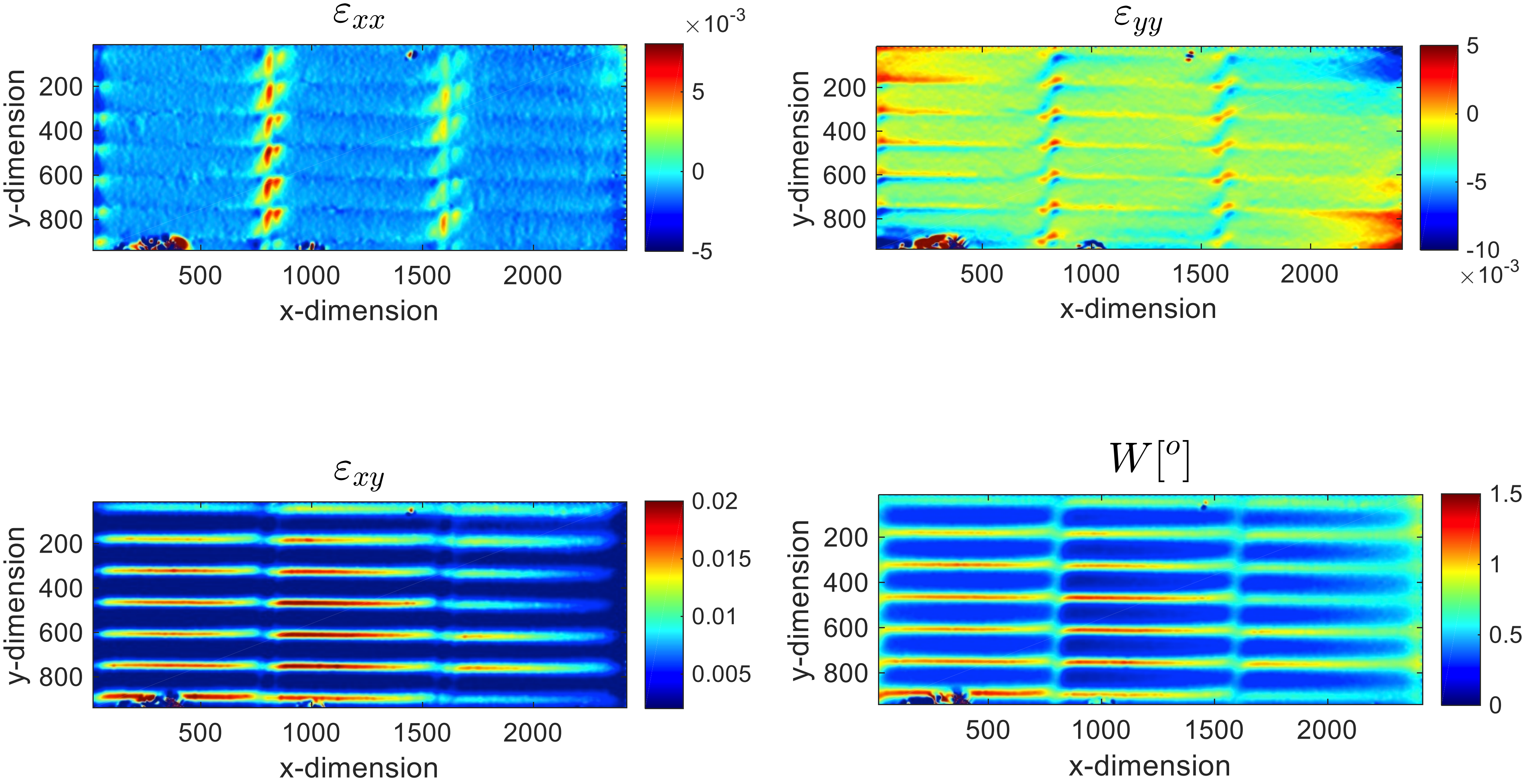


Displacement maps at Points P_2

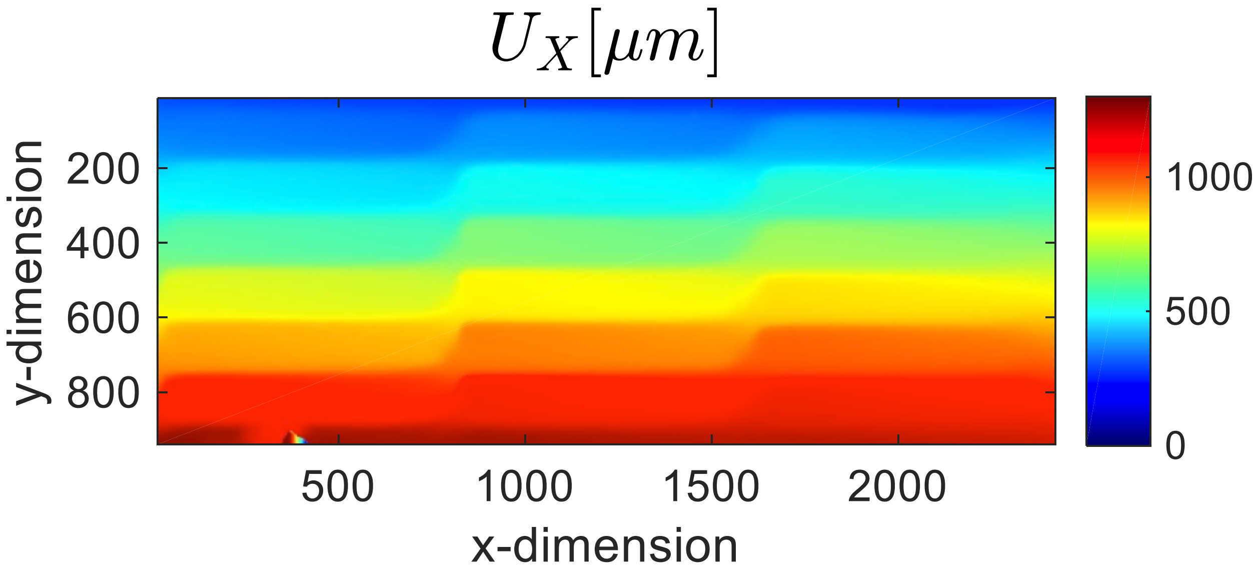


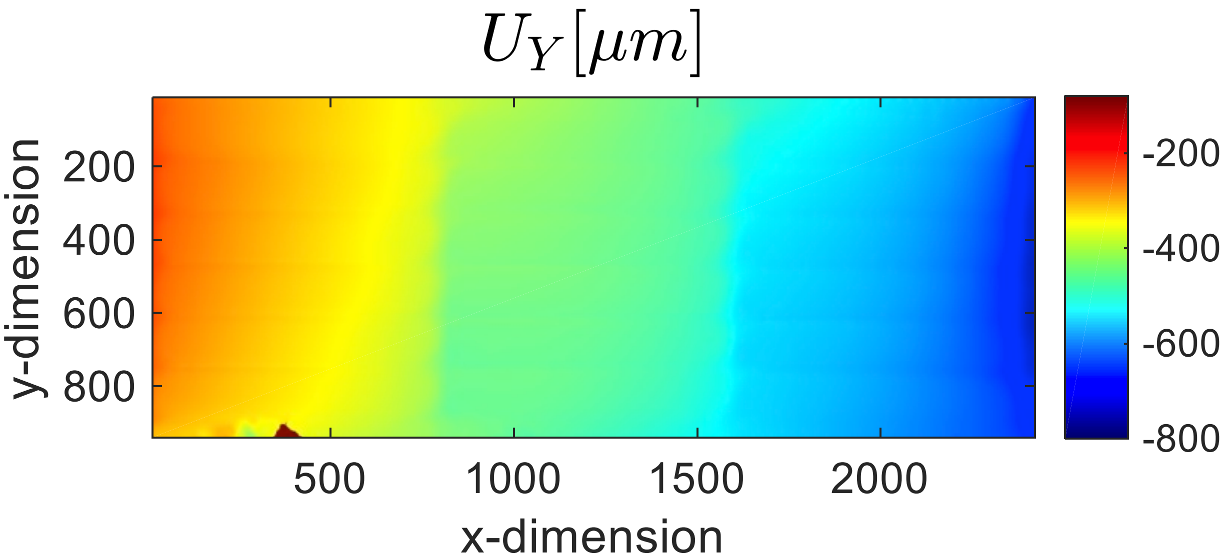


Strain and rotation maps at Point P_2

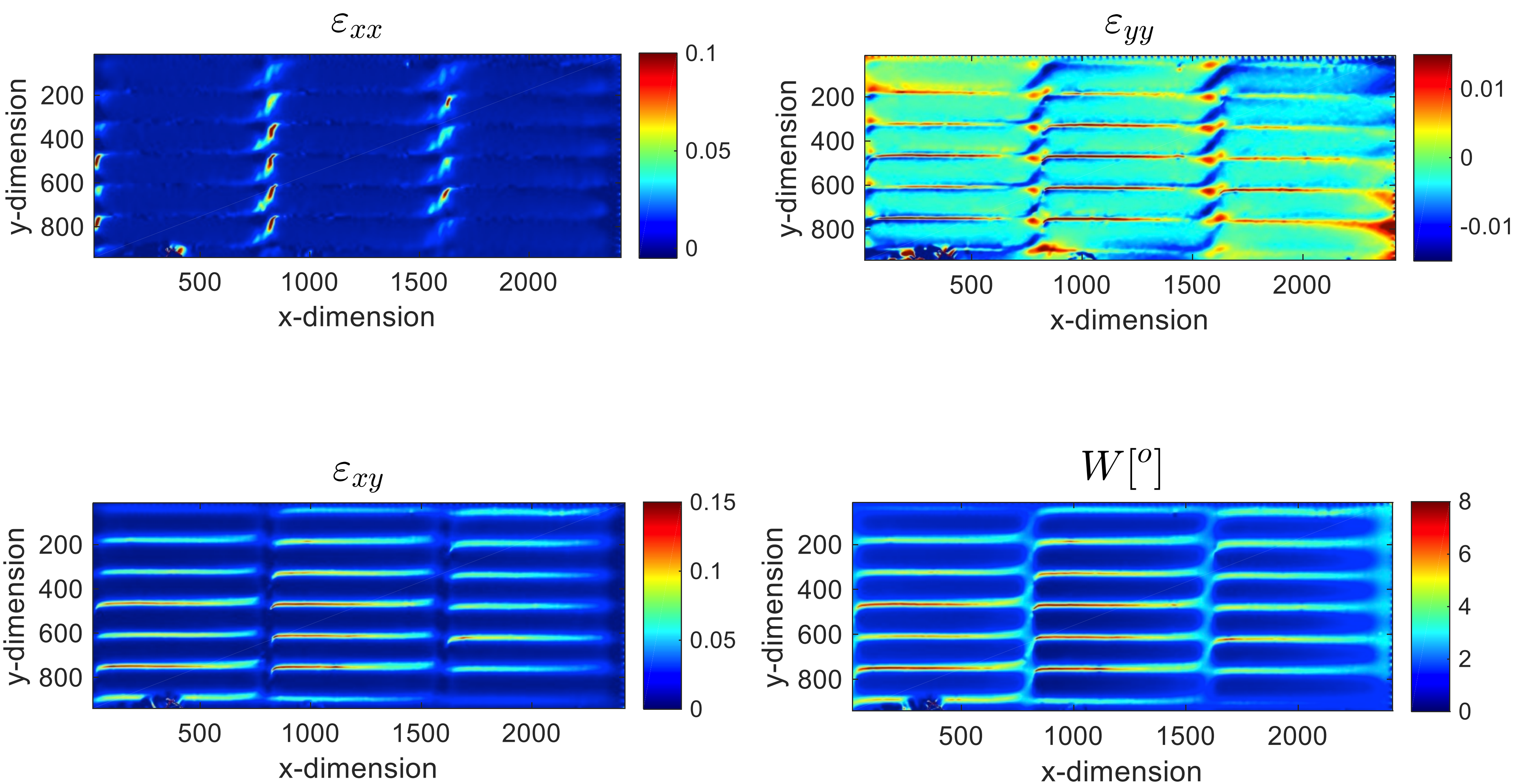


Displacement maps at Points P_3



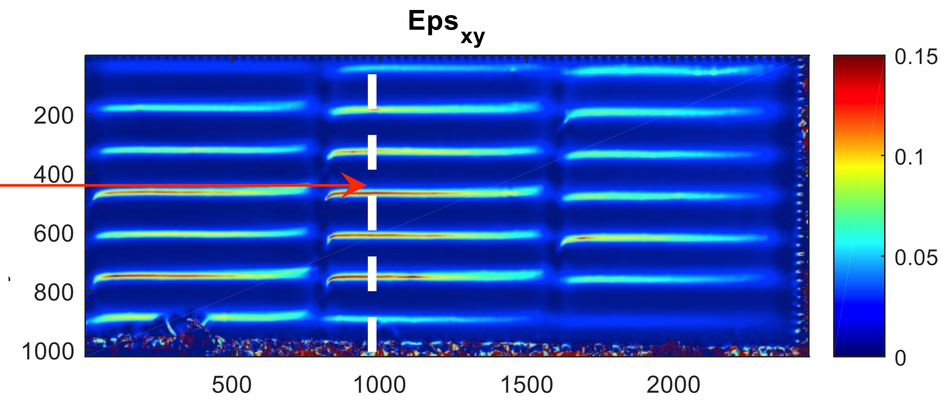


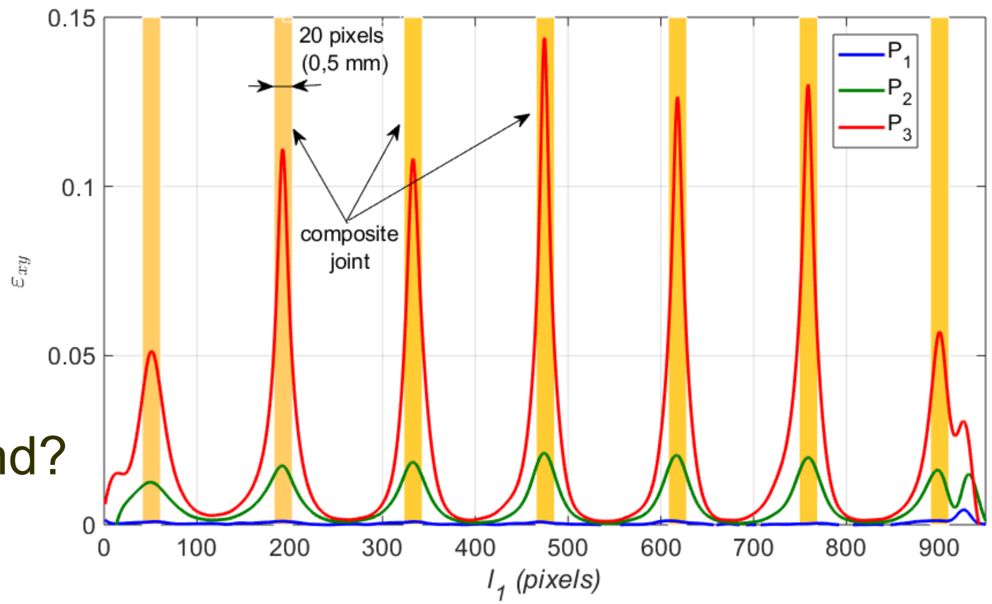
Strain and rotation maps at Point P_3



Strain field: cross-section of the ε_{xy} map for various loading amplitudes

Cross-section along this line





Remarks:

- peaks ↗ as the load ↗
- smooth distribution…

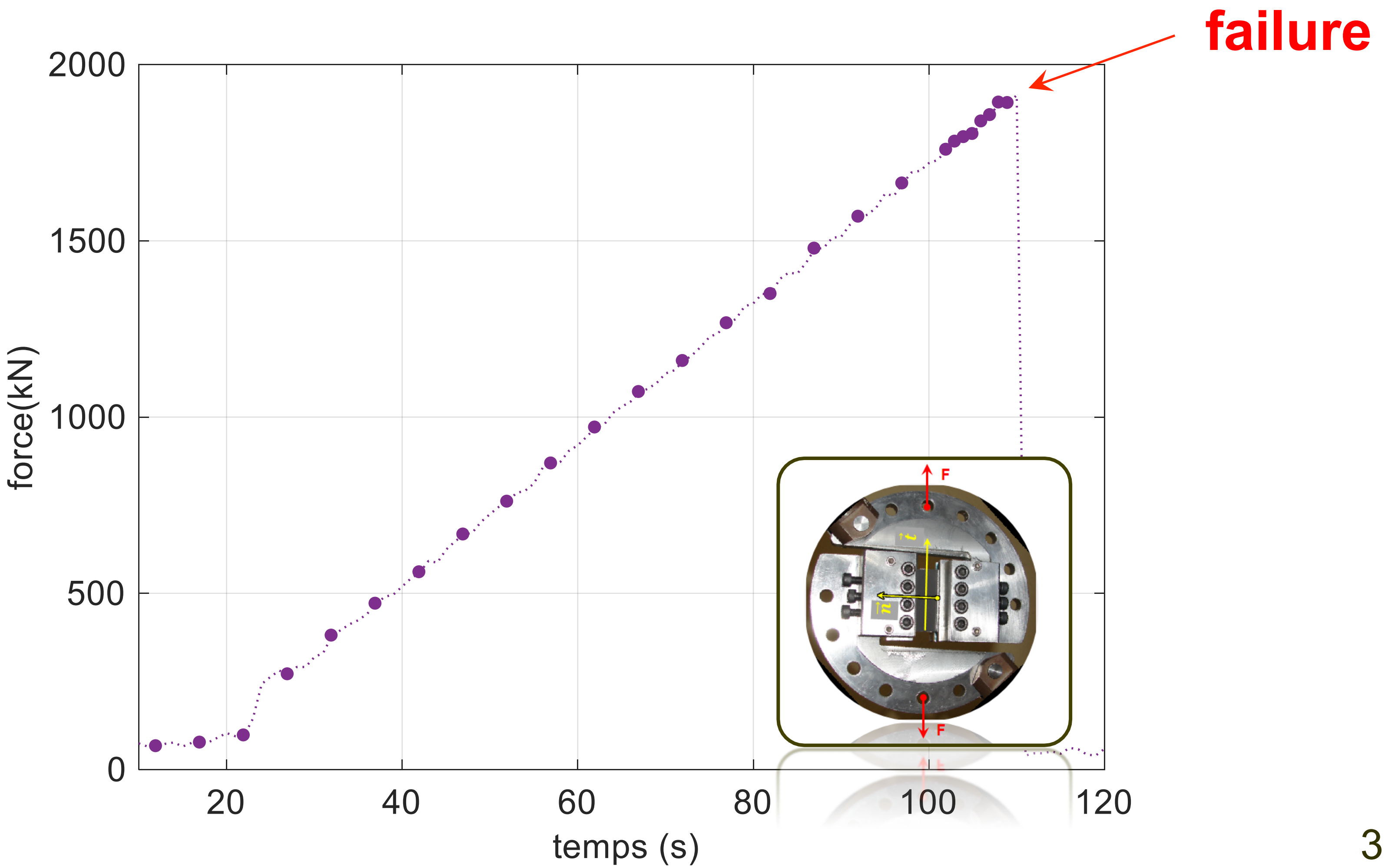
… but blur = systematic error

- actual value within these narrow band?
- systematic error removed up to a certain frequency [1]

[1] M. Grédiac, B. Blaysat, F. Sur, *Experimental Mechanics*, in revision, 2018

Test B: shear

- force driven 0,02 kN/s, Fmax=**1,9** kN
- frequency: 2 images/s
- lighting issues → noiser strain maps



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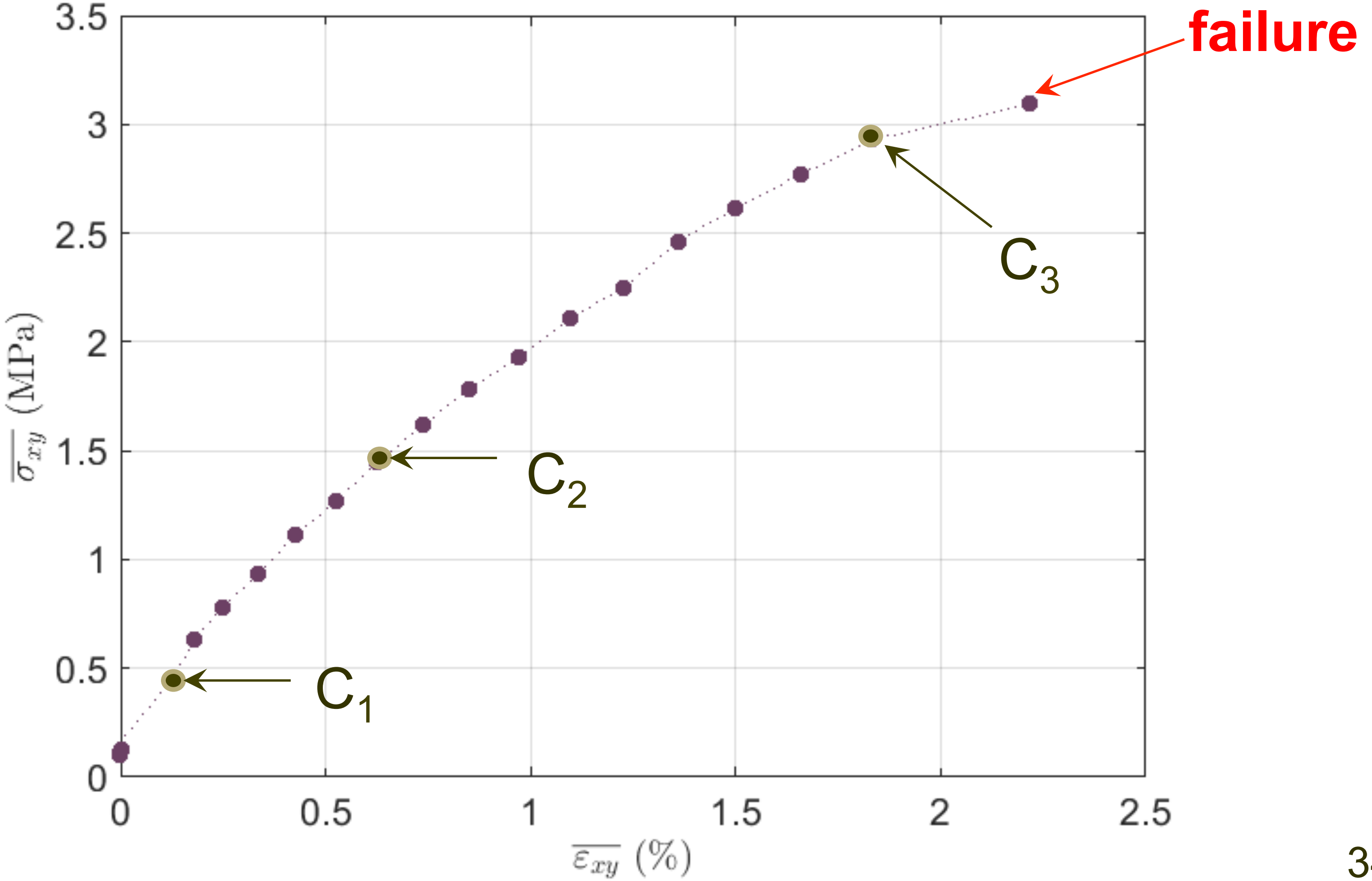
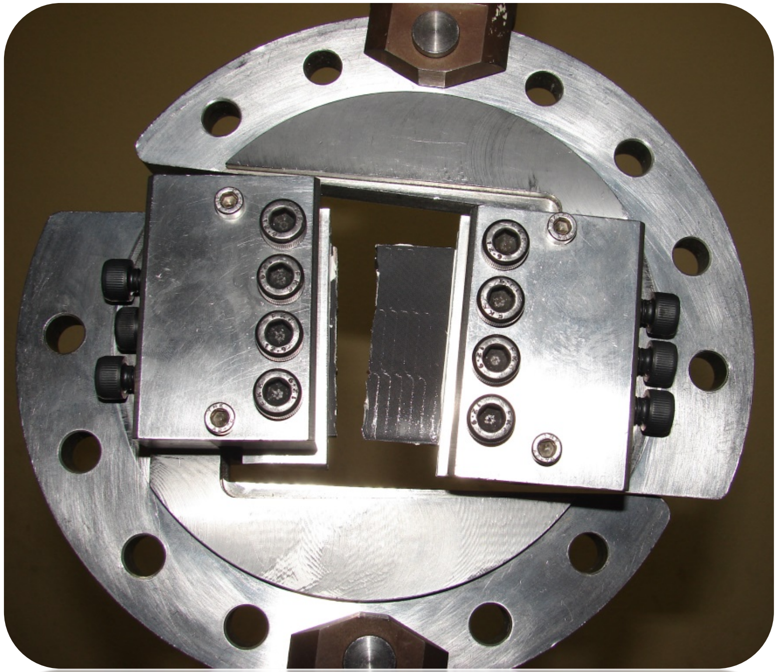
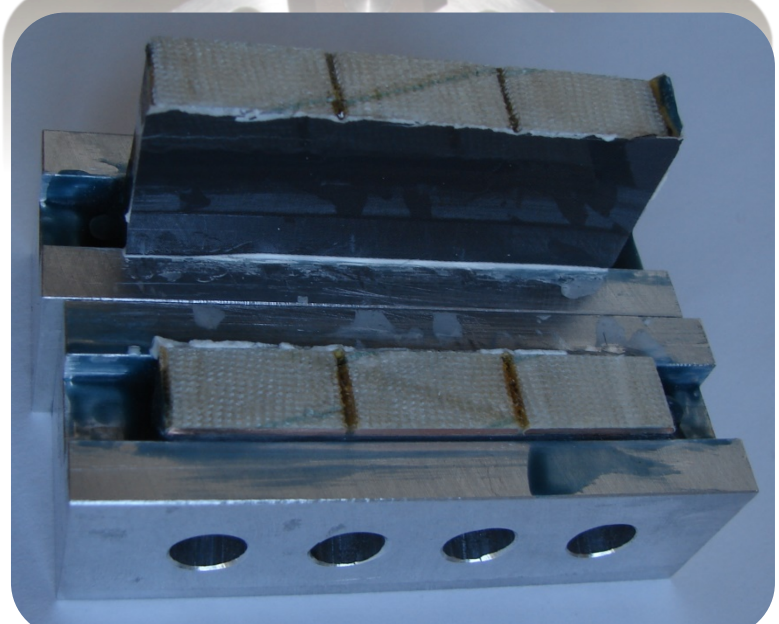
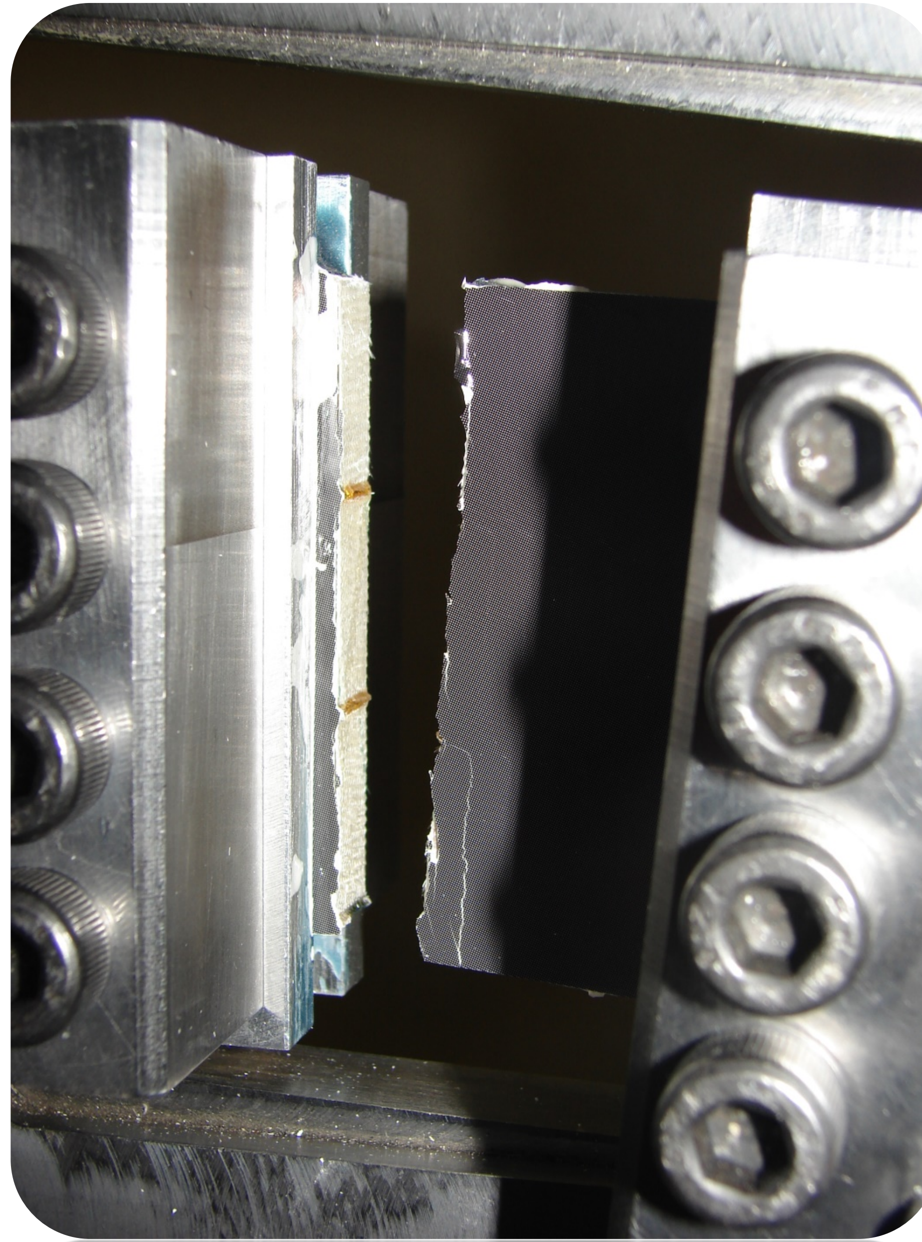
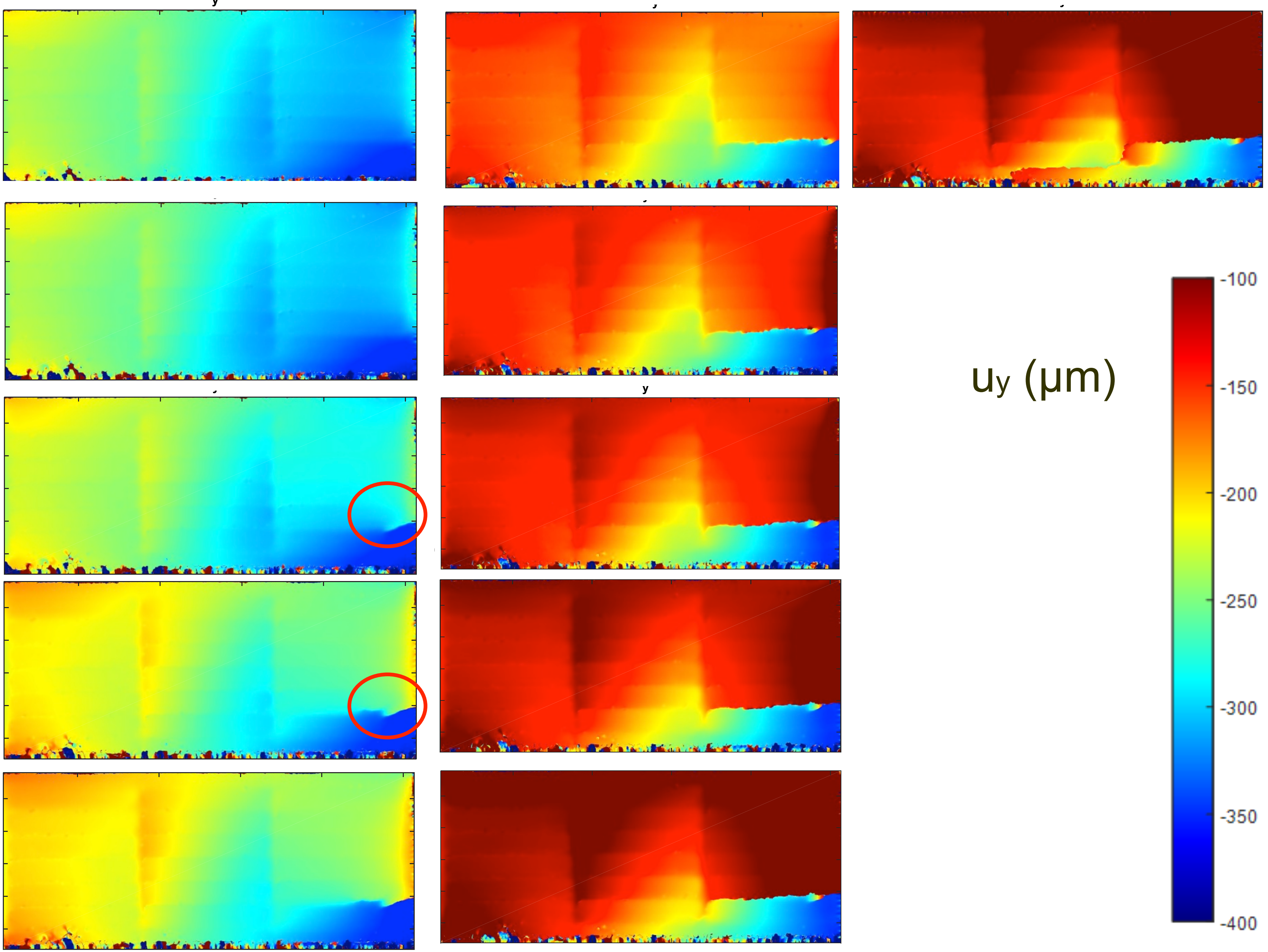








Crack initiation + propagation



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Conclusion:

- feasibility study, in-plane displacement/strain measurement with the grid method

- strong heterogeneities in the strain field due to the heterogeneous nature of the materials

- crack detection (appearance + propagation) in the displacement field

Conclusion:

- feasibility study, in-plane displacement/strain measurement with the grid method
- strong heterogeneities in the strain field due to the heterogeneous nature of the materials
- crack detection (appearance + propagation) in the displacement field
- information potentially valuable for the design of superconducting magnets

Conclusion:

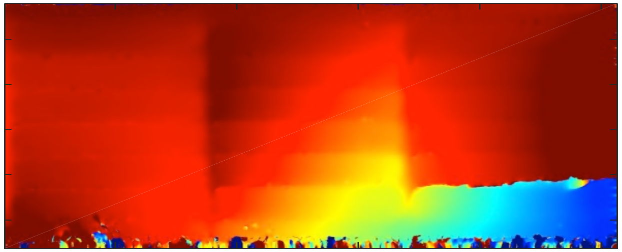
- feasibility study, in-plane displacement/strain measurement with the grid method
- strong heterogeneities in the strain field due to the heterogeneous nature of the materials
- crack detection (appearance + propagation) in the displacement field
- information potentially valuable for the design of superconducting magnets
- qualitative or quantitative measurement? → two recent improvements:

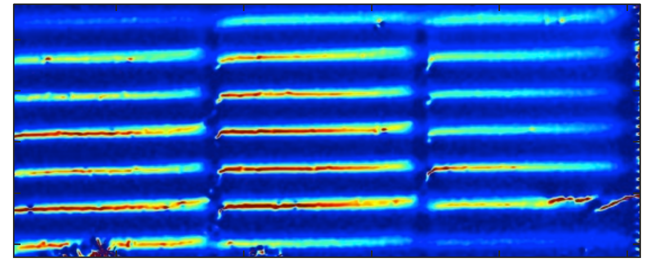
1- decreasing the noise level in the map → optimizing the pattern

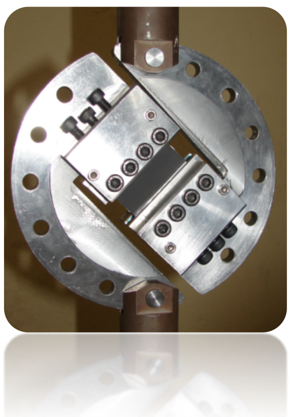
2D grids → checkerboards [1]

2- strain maps blurred because of convolution → systematic error → deconvolution algorithm suitable for strain maps [2]

[1] M. Grédiac, B. Blaysat, F. Sur, *Experimental Mechanics*, in press, 2018
[2] M. Grédiac, B. Blaysat, F. Sur, *Experimental Mechanics*, in revision, 2018

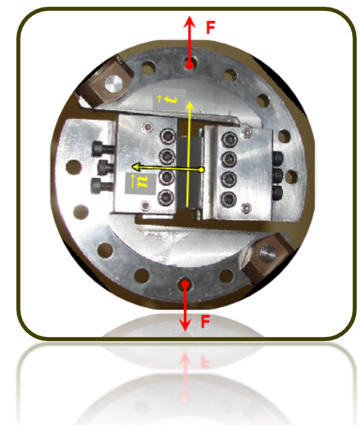


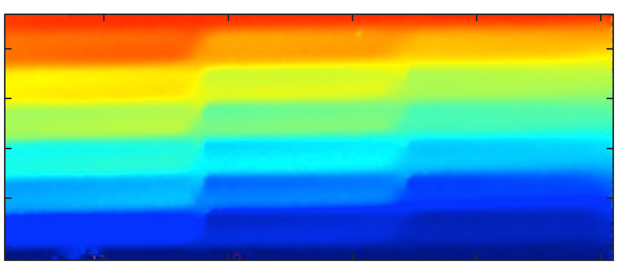


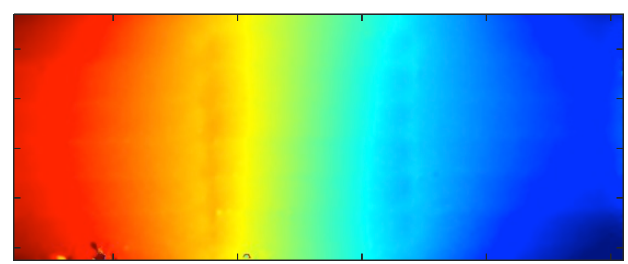


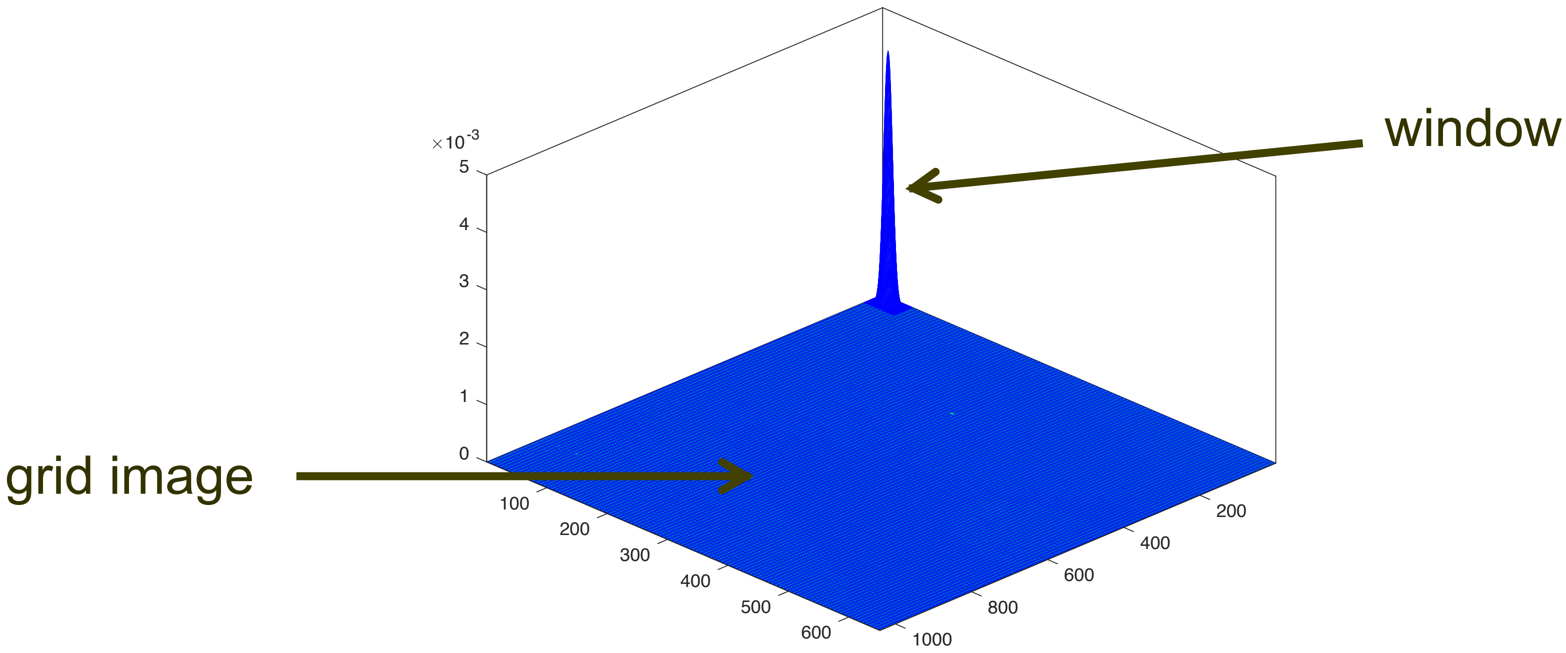
Thank you for your attention

Any questions?








window
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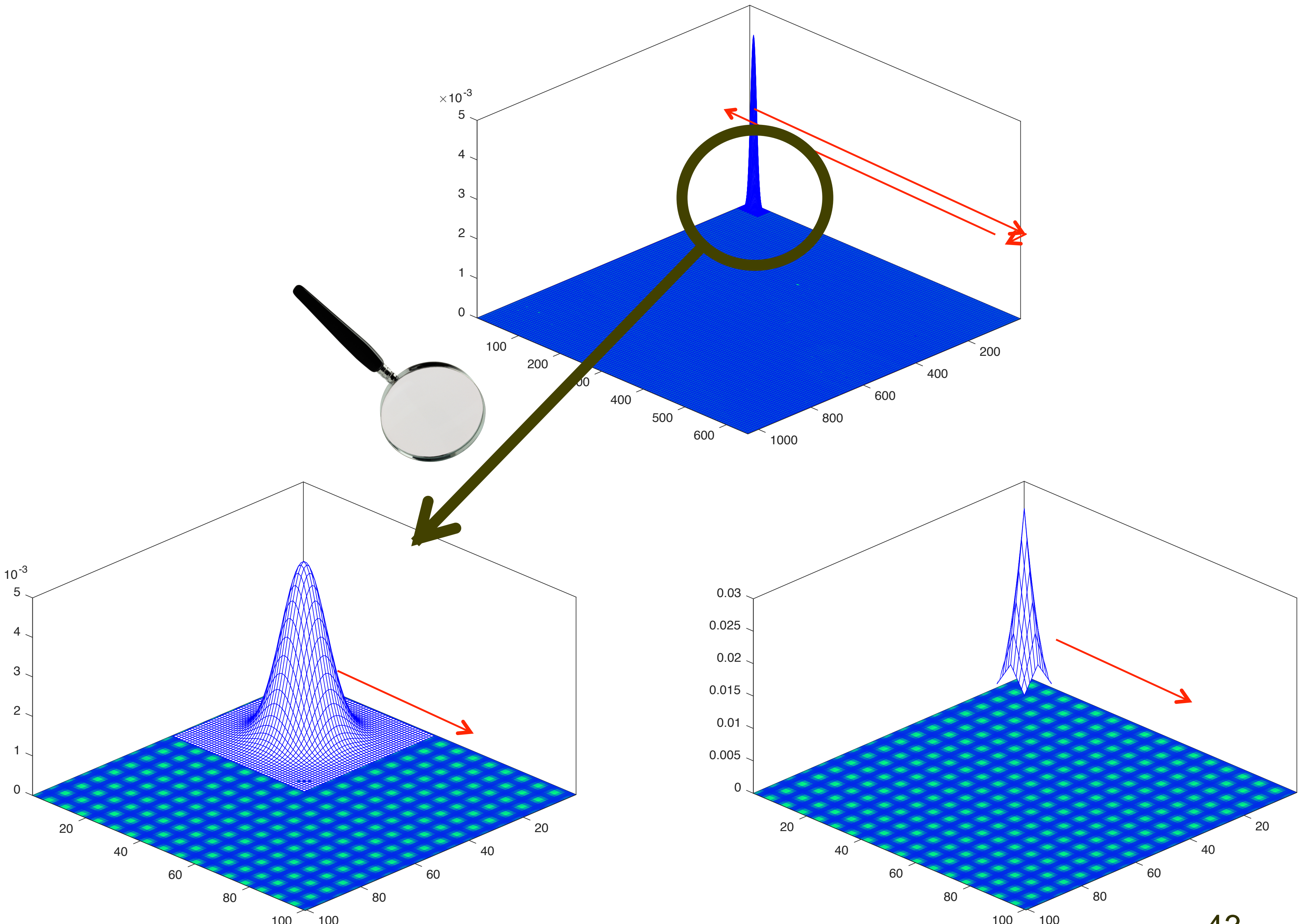
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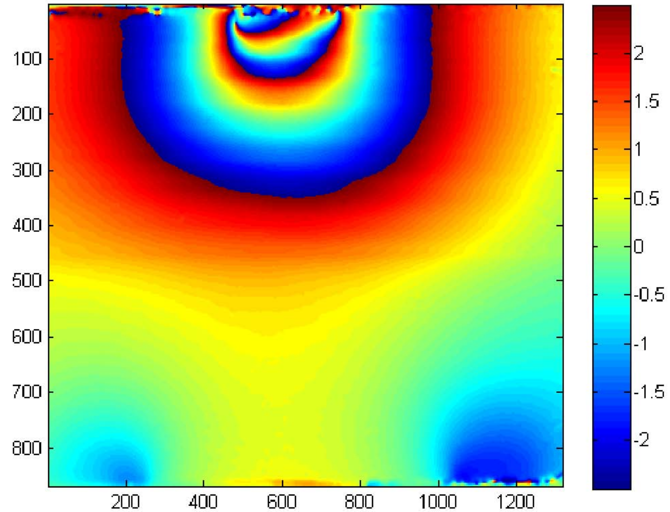
2
1
0
20
40
60
80
100
20
40
60
80
100
0.03
0.025
0.02
0.015
0.01
0.005
0
20
40
60
80
100
20
40
60
80
100

Phase unwrapping:

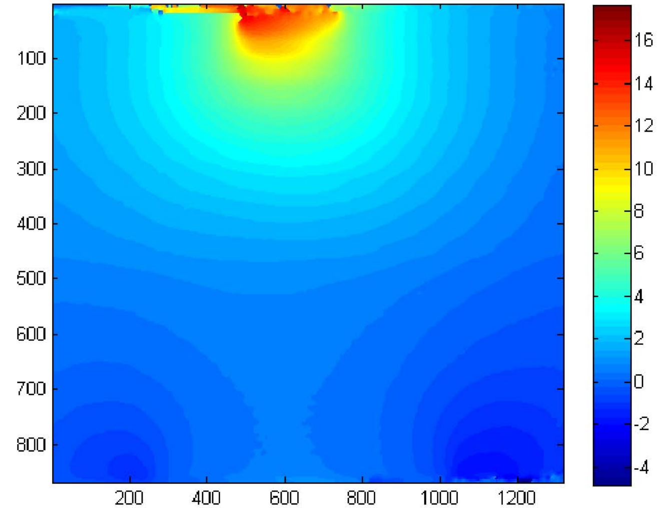
- argument of a complex number → 2π phase jumps in phase maps if the amplitude of the phase > 2π

- map of « wrapped » phases → phase maps must be « unwrapped » [1]

- example



before unwrapping



after unwrapping

[1] Huntley J. M., **Applied Optics**,1989

- $\widehat{s}(x, y, 0, f, \alpha)$ and $\widehat{s}(x, y, f, 0, \alpha)$: two complex numbers for each image $\rightarrow$ 2 arguments $\rightarrow$ 2 phases for each image $\rightarrow$ 2 displacement components

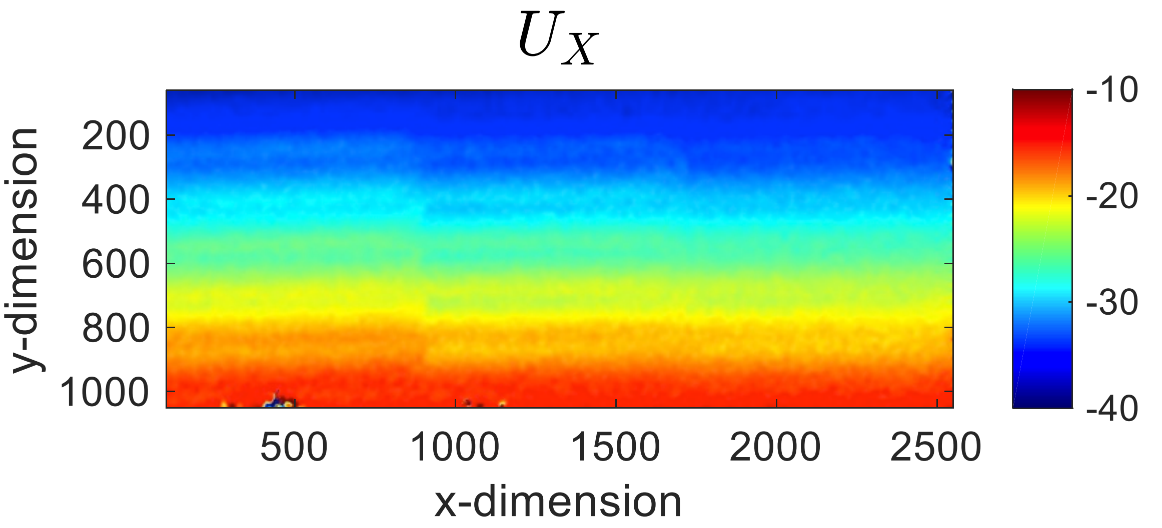
$$\left|\begin{array}{l} u_x(x,y) = -\dfrac{p}{2\pi}\Delta\Phi_x \\ u_y(x,y) = -\dfrac{p}{2\pi}\Delta\Phi_y \end{array}\right.$$

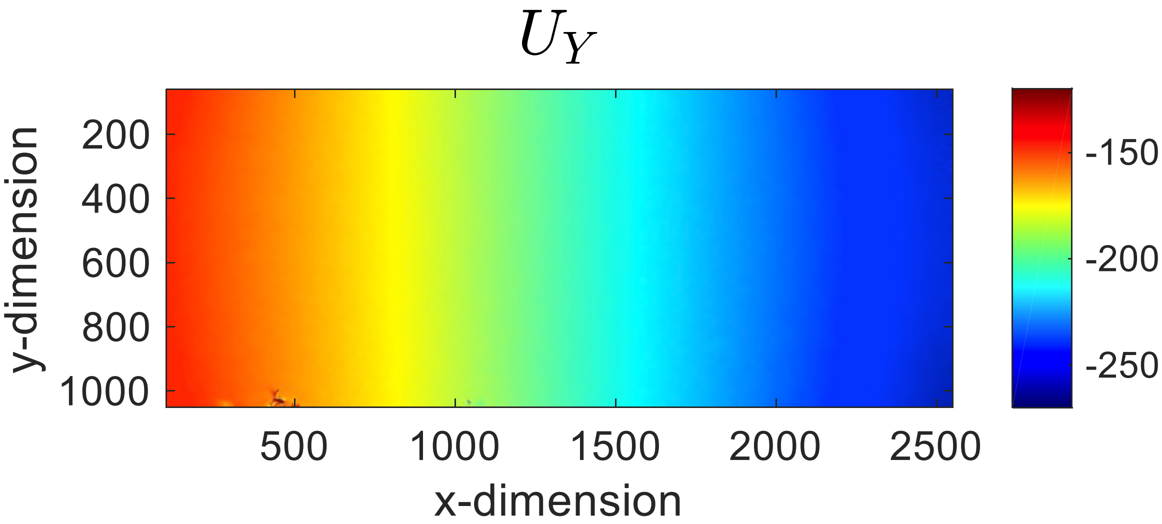
- fixed-point algorithm to find the displacement:

$$\left|\begin{array}{l} u_x(x,y) = -\dfrac{p}{2\pi}\left[\Phi_x^{cur}(x + u_x(x,y), y + u_y(x,y)) - \Phi_x^{ref}(x,y)\right] \\ u_y(x,y) = -\dfrac{p}{2\pi}\left[\Phi_y^{cur}(x + u_x(x,y), y + u_y(x,y)) - \Phi_y^{ref}(x,y)\right] \end{array}\right.$$

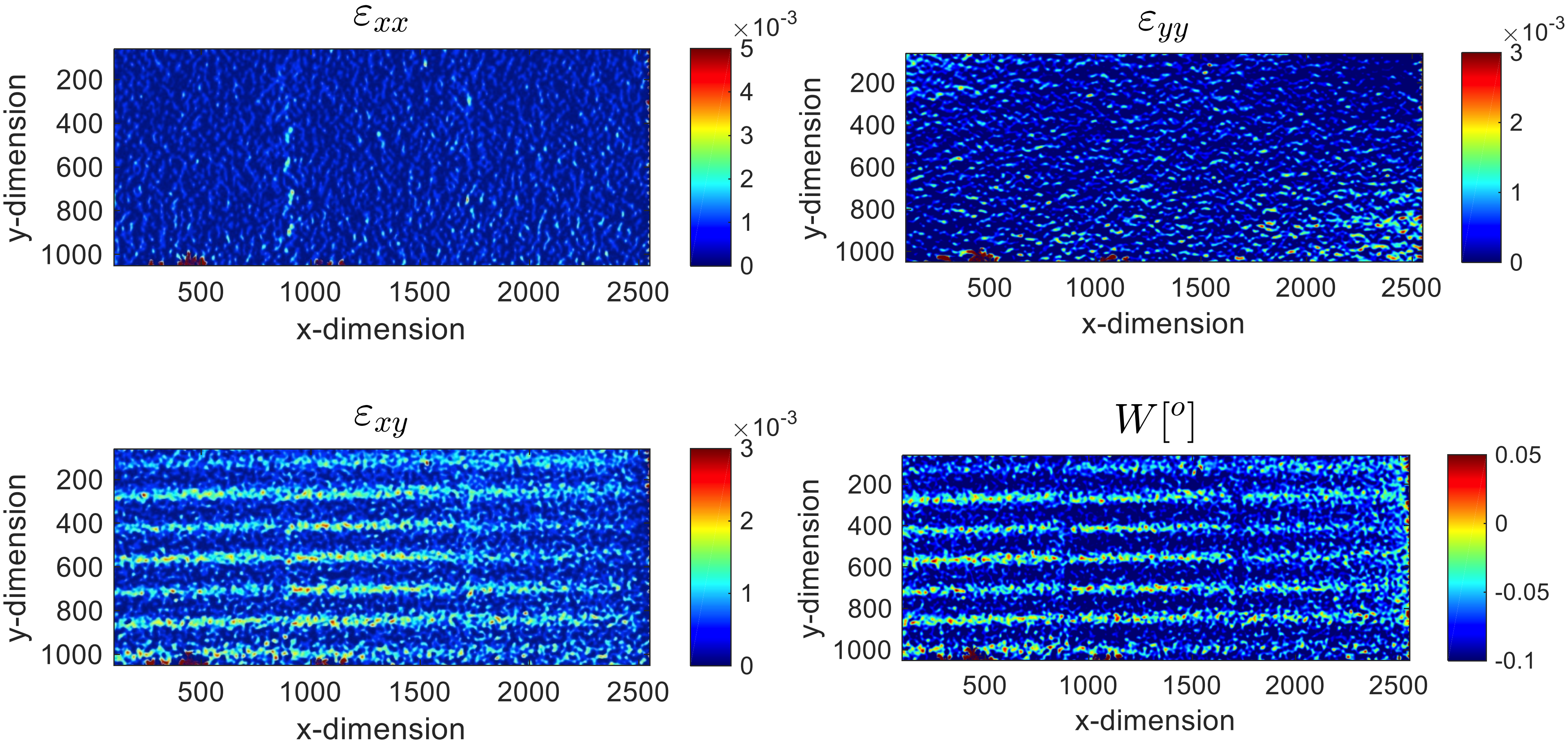
- with small strains, one iteration to reach convergence

Displacement field at Point C_1

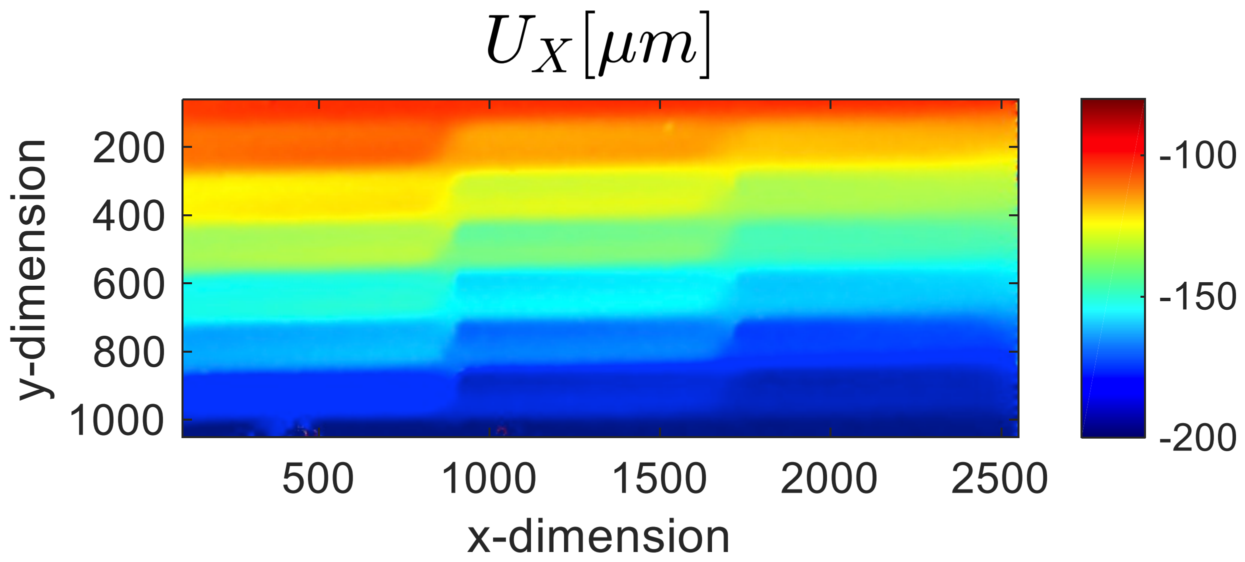


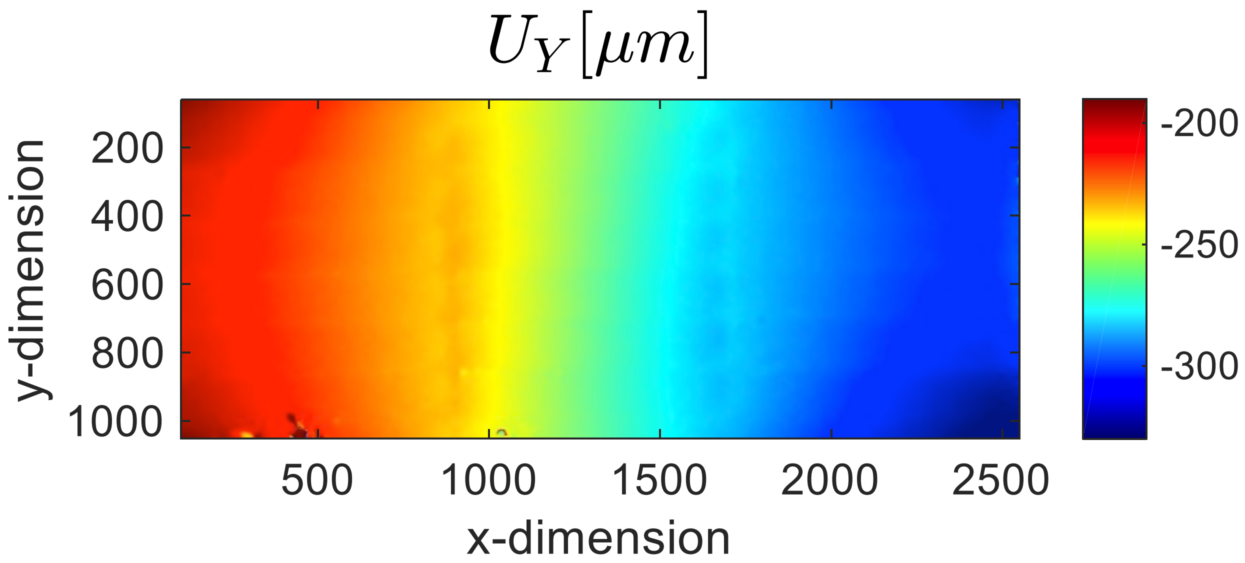


Strain + rotation fields at Point C_1

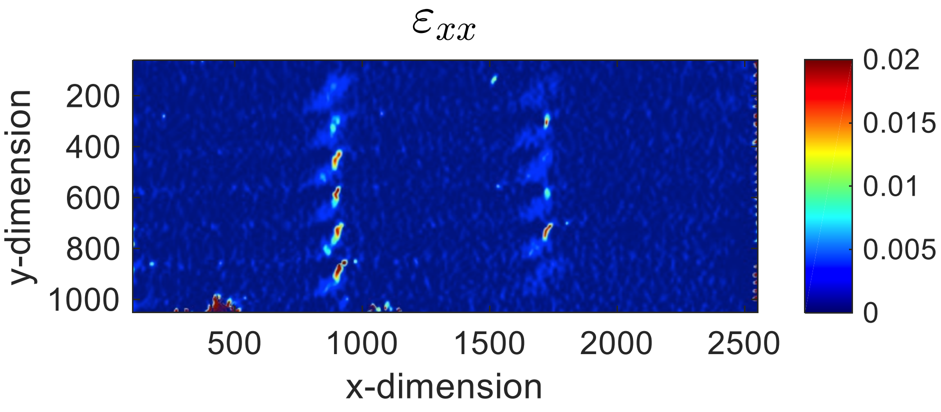


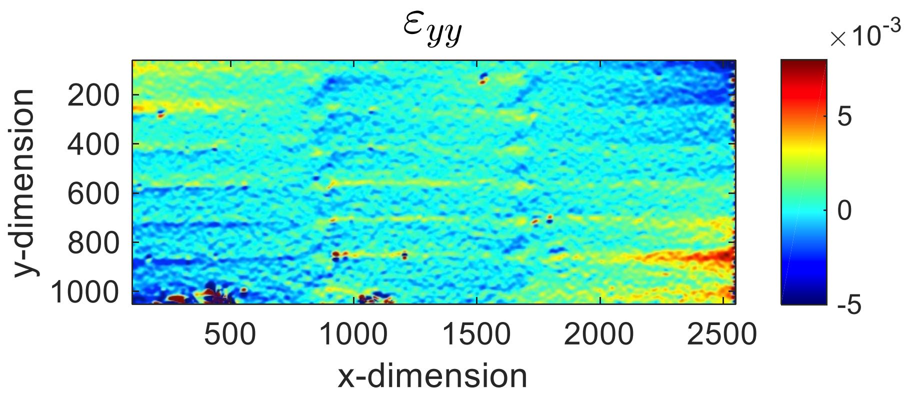
Displacement field at Point C_2

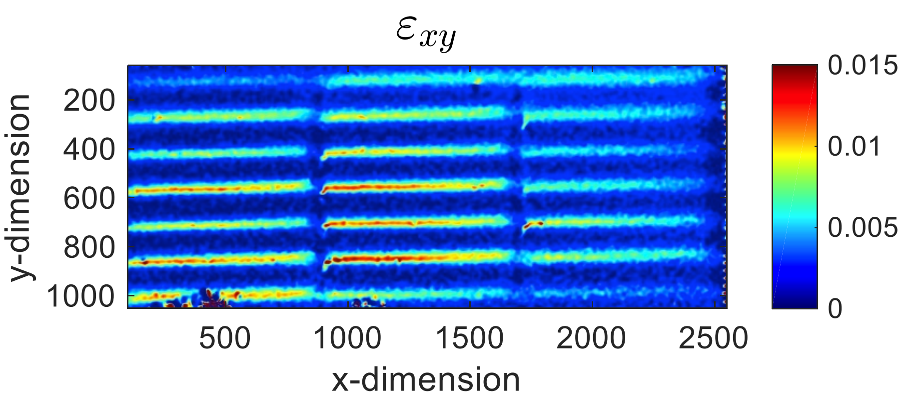


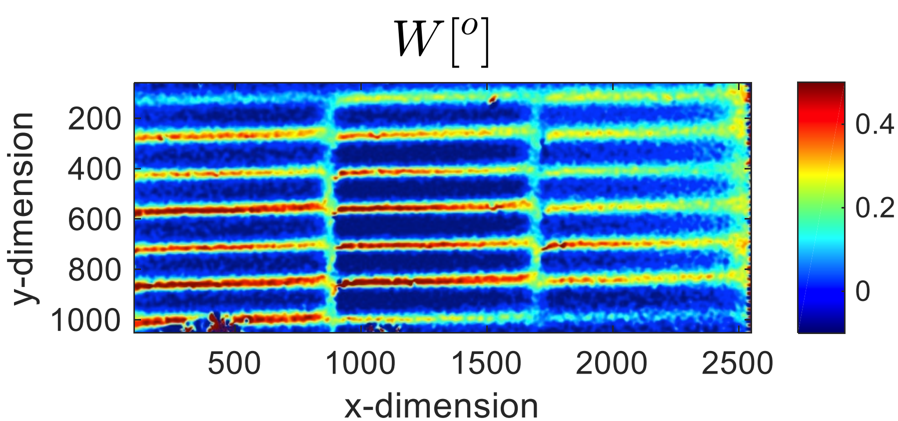


Strain + rotation fields at Point C_2

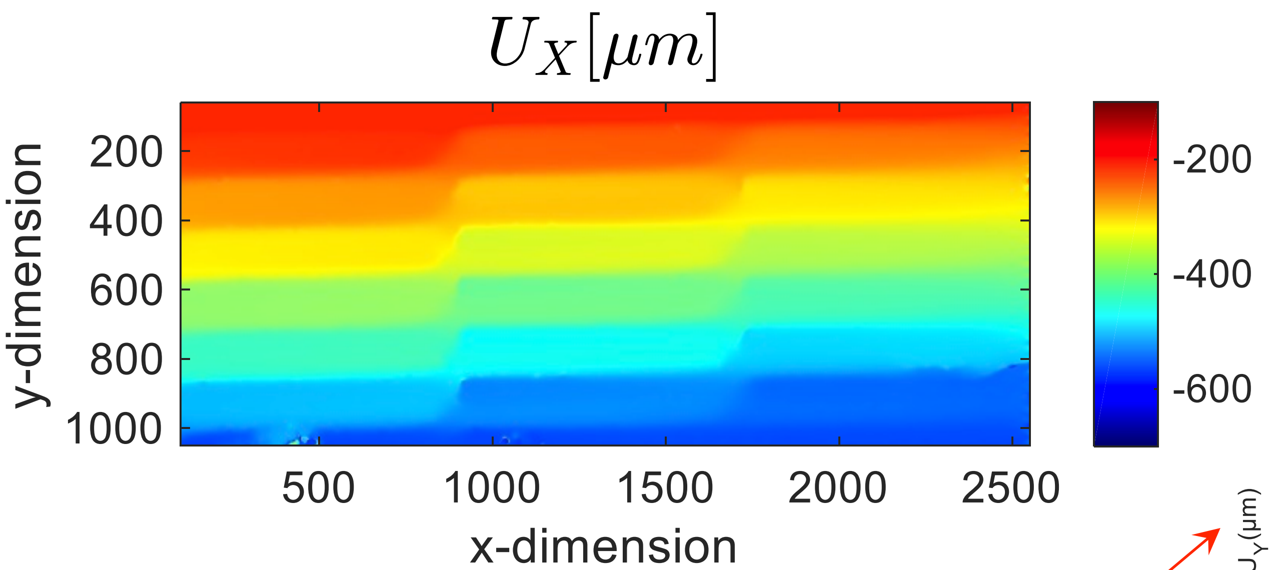


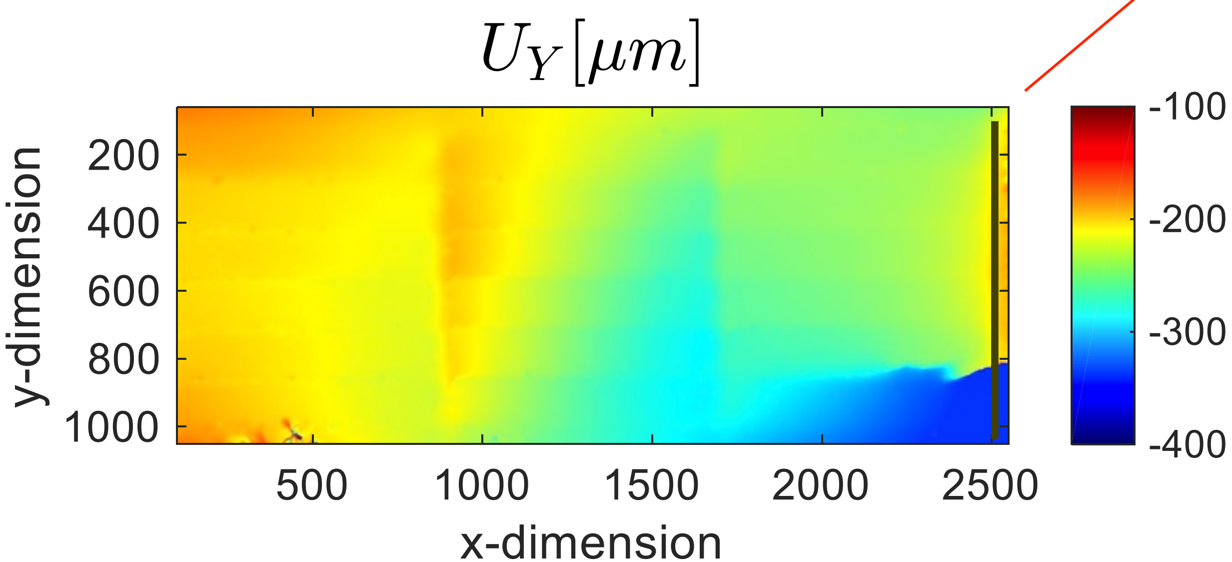


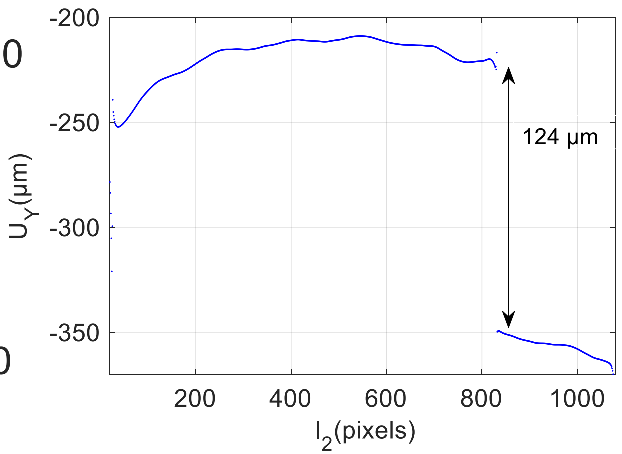




Displacement field at Point C_3







Strain + rotation fields at Point C_3