



## Uncertainty Quantification in Digital Image Correlation

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UNIVERSITY OF  
**Southampton**

# Propagation of DIC uncertainties in material identification and FE model validation

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# Introduction – 1/4

## ■ Uncertainty quantification

Well-understood

Under-explored

- Random error due to camera noise
- Interpolation and noise bias

Wang, Y. Q., Sutton, M. A., Reu, P. L., & Miller, T. J., *SEM Annual Conference and Exposition on Experimental and Applied Mechanics 2009*.

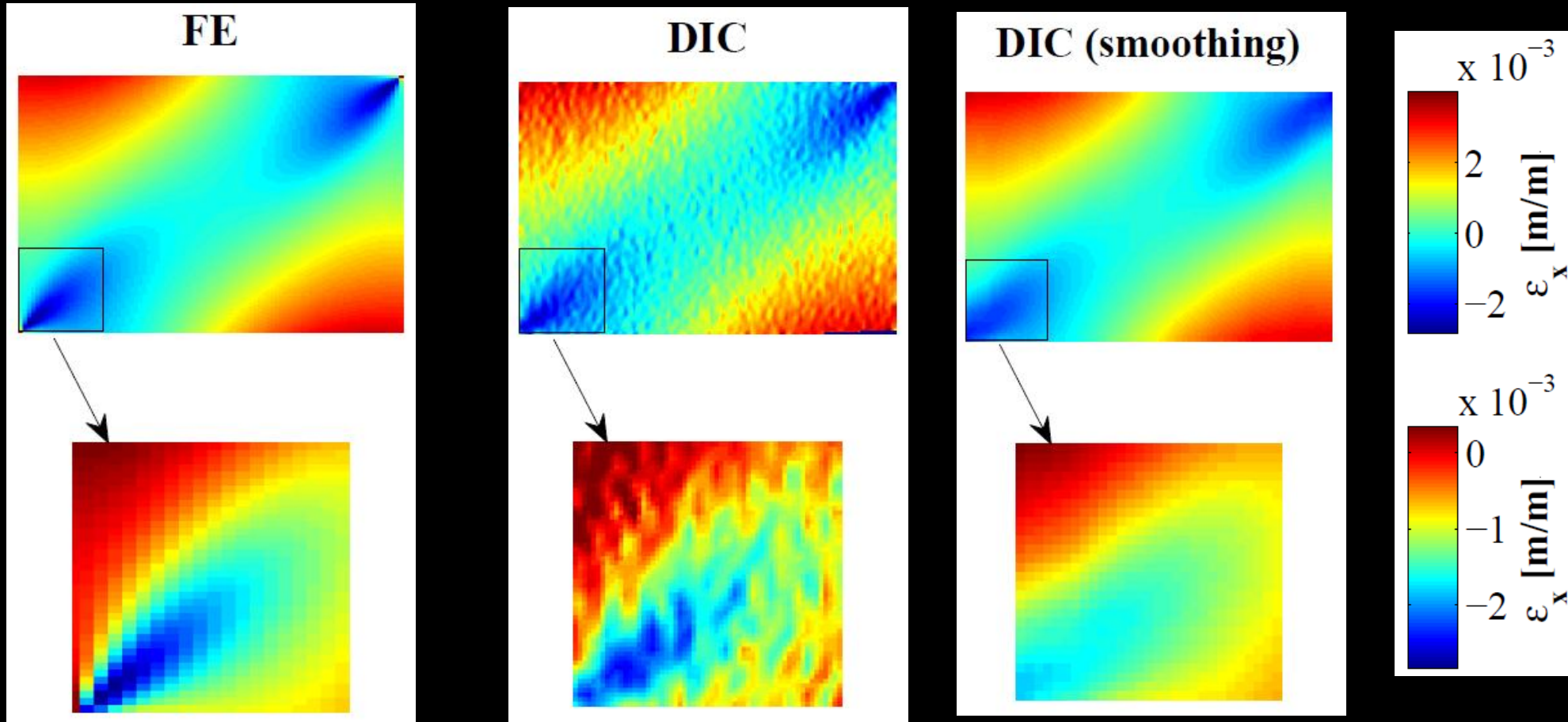
- Reconstruction error

# Introduction – 2/4

- Finite element model: convergence
  - Refine mesh until solution does not change
- DIC: impossible to refine mesh!
  - Except by changing
    - The camera
    - The field of view
- Is the DIC measurement ‘converged’?

# Introduction - 3/4

- DIC as a low pass filter (no noise here)

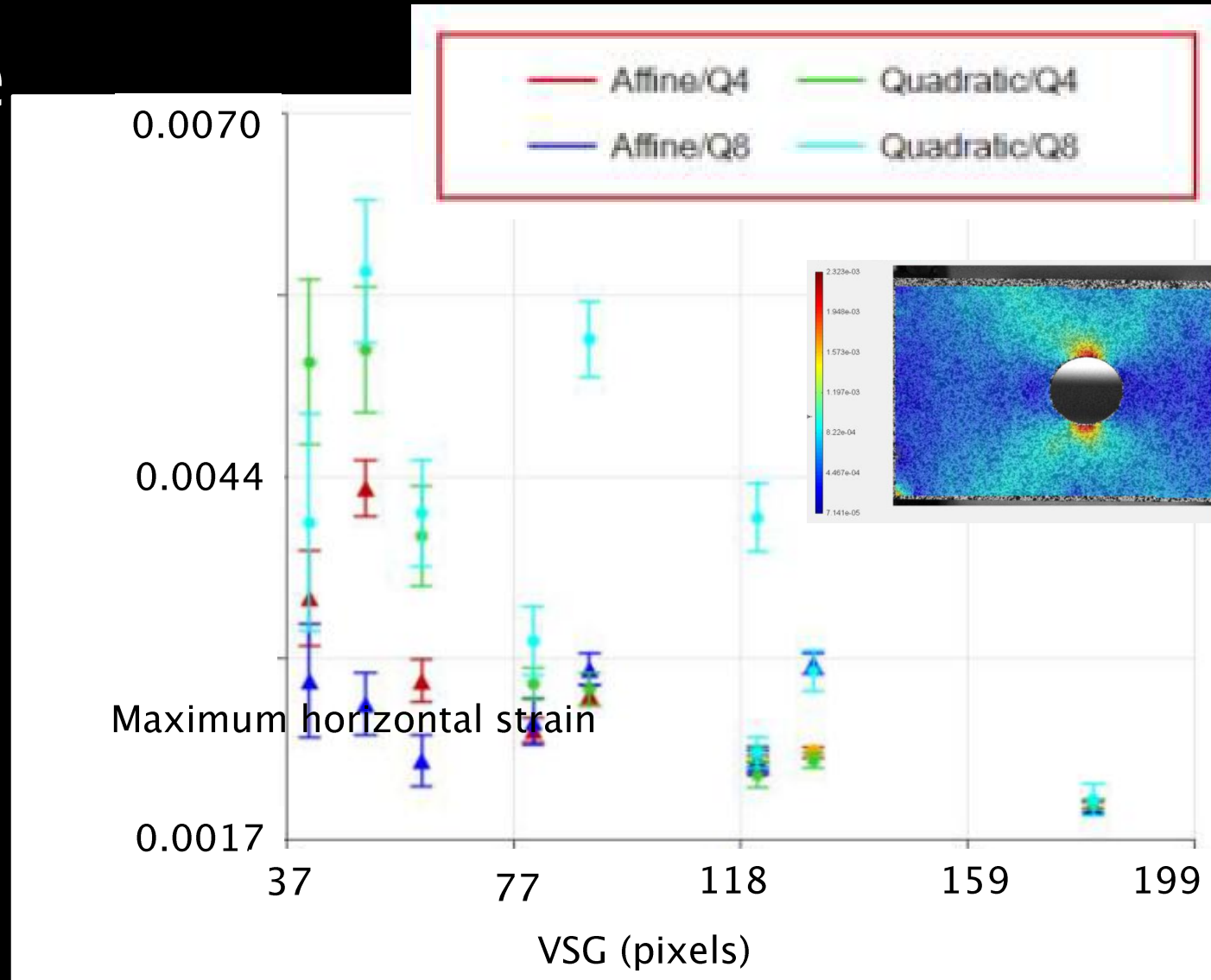


Rossi M., Lava P., Pierron F., Debruyne D., Sasso M. Strain, 2015.

VSG: 141 pixels

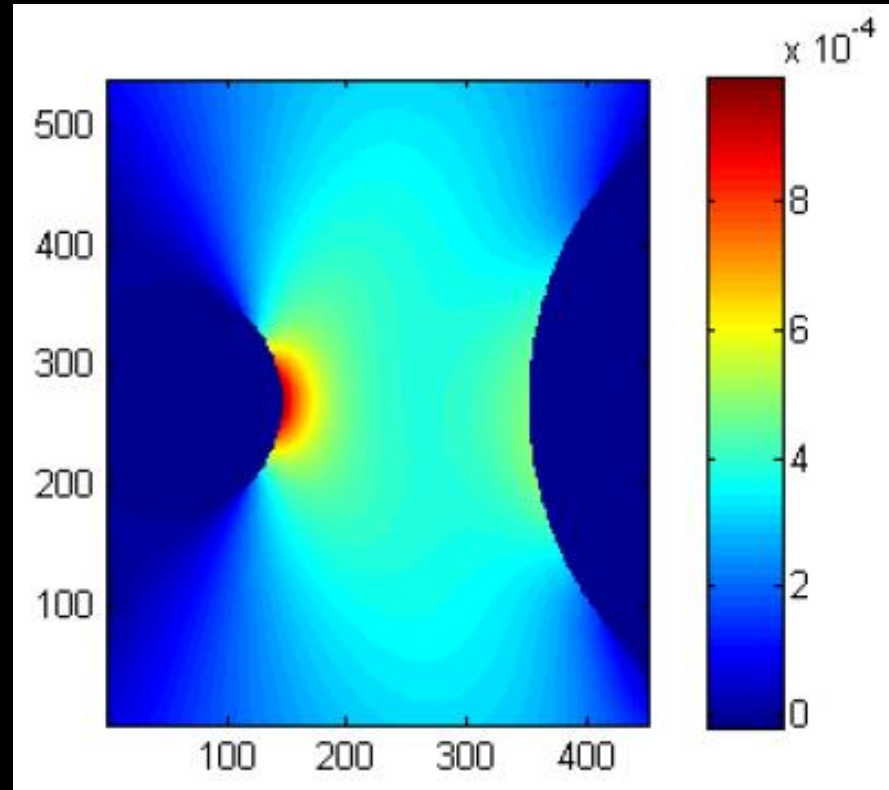
# Introduction - 4/4

## Example

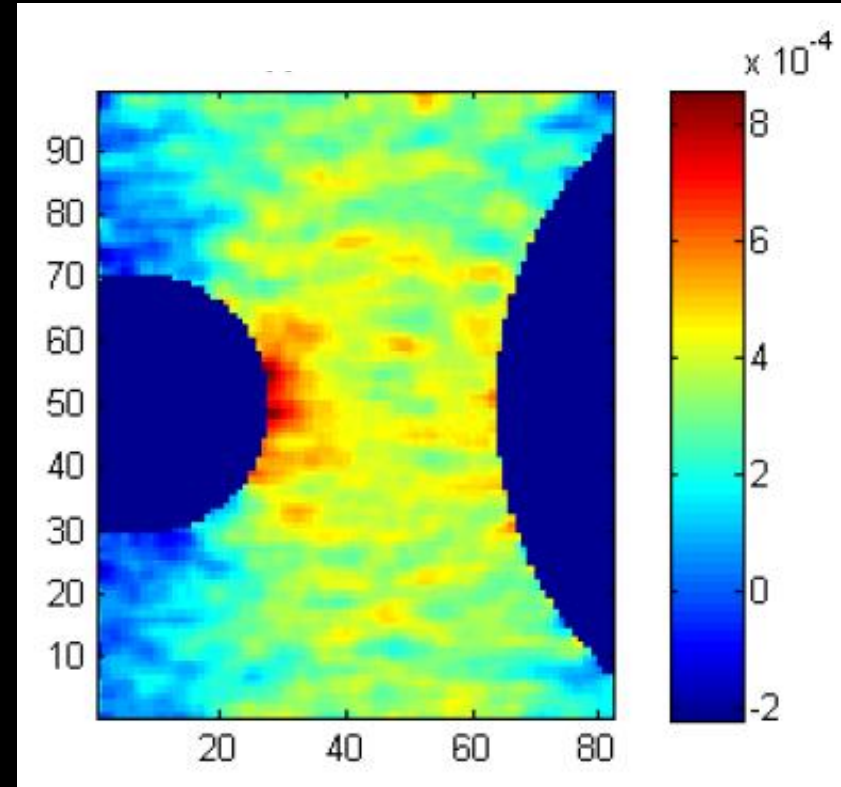


# FE model validation

# Direct comparison - 1/6



FE strain

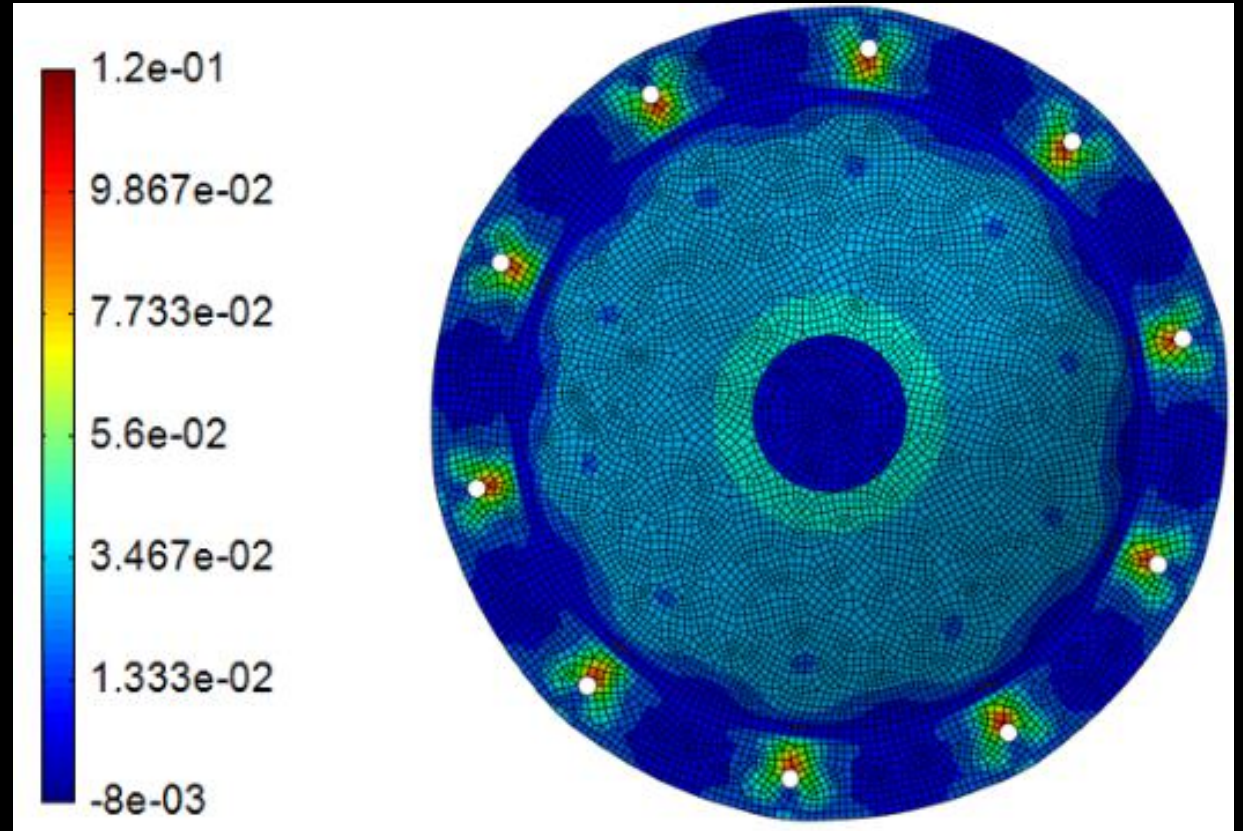
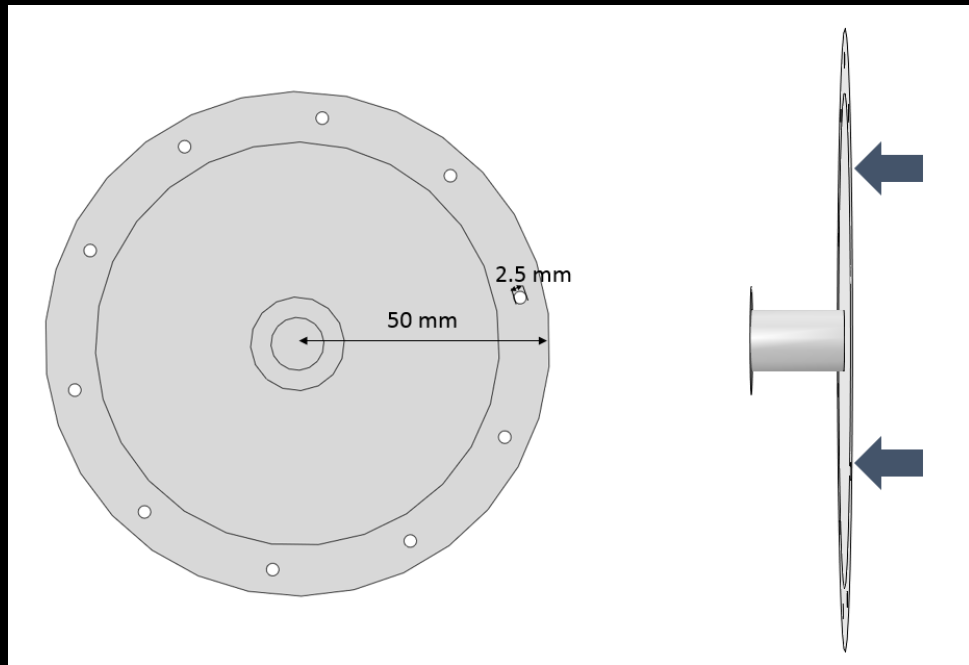


DIC

Model validated??

# Direct comparison - 2/6

- FE model of a flange under pressure



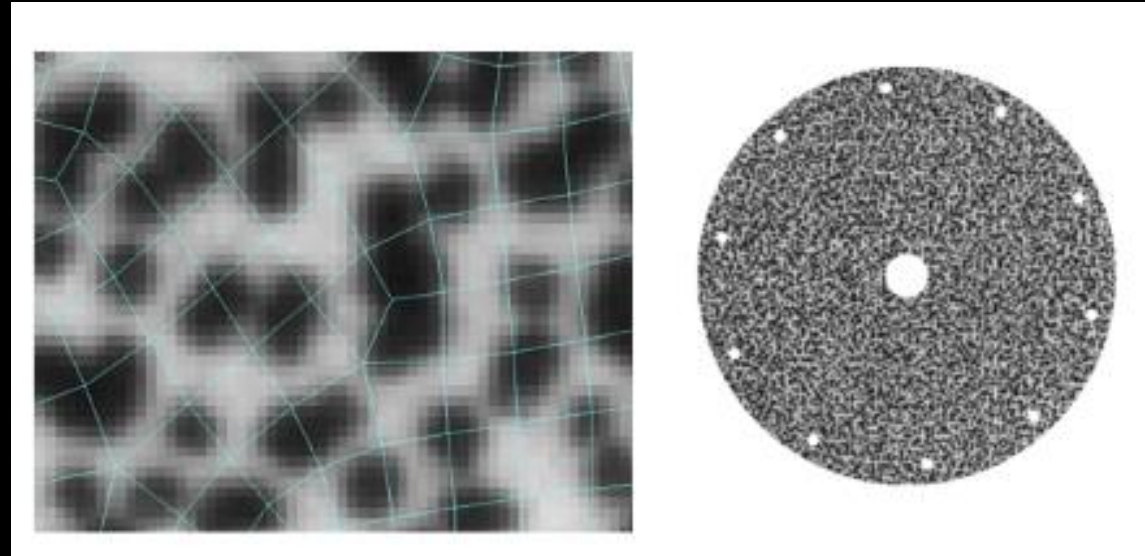
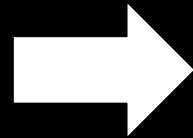
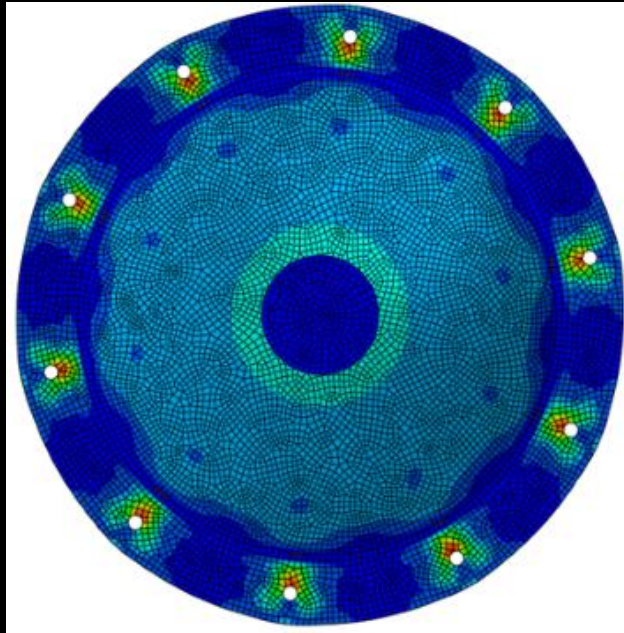
Pierron, Lava, Wittewrongel,  
in preparation, 2017

E1 principal strain (Log. Euler Almansi)



# Direct comparison – 3/6

- FE generated DIC measurement
  - Stereo-DIC simulator (Balcaen et al., Exp. Mech., 2017)

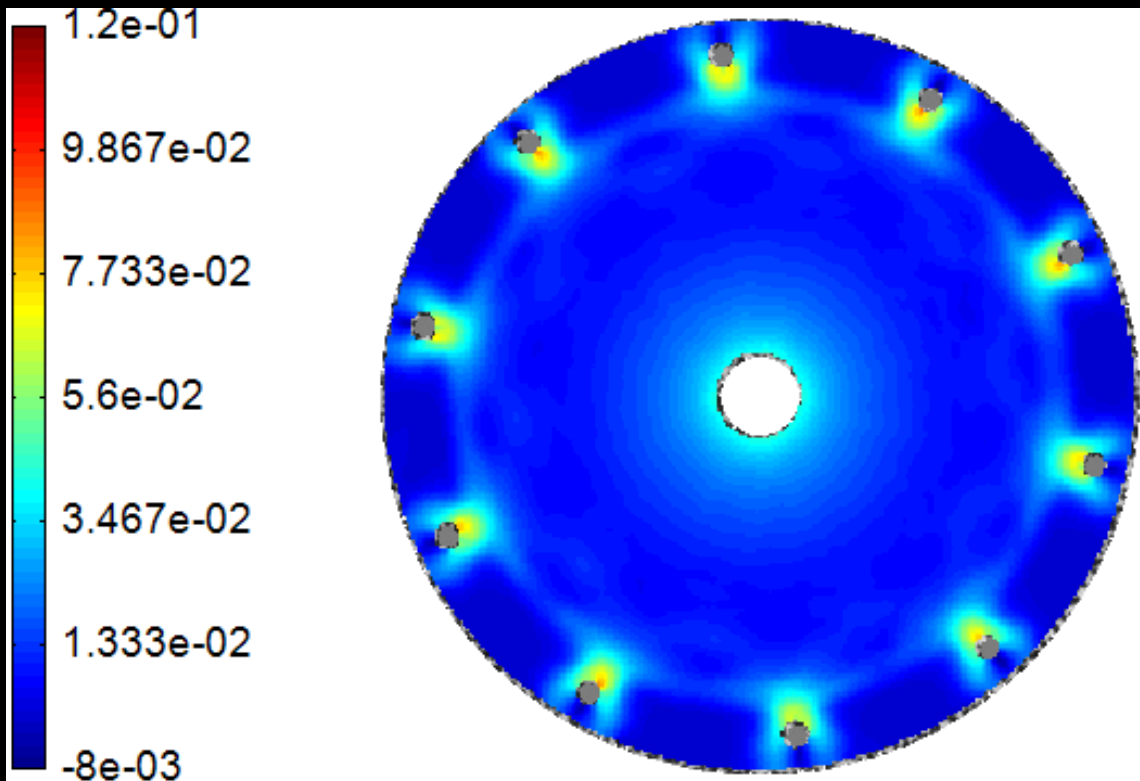


MatchID FE-DIC module

- Simulated DIC data encoding FE model EXACTLY

# Direct comparison – 4/6

## ■ DIC ‘measurement’

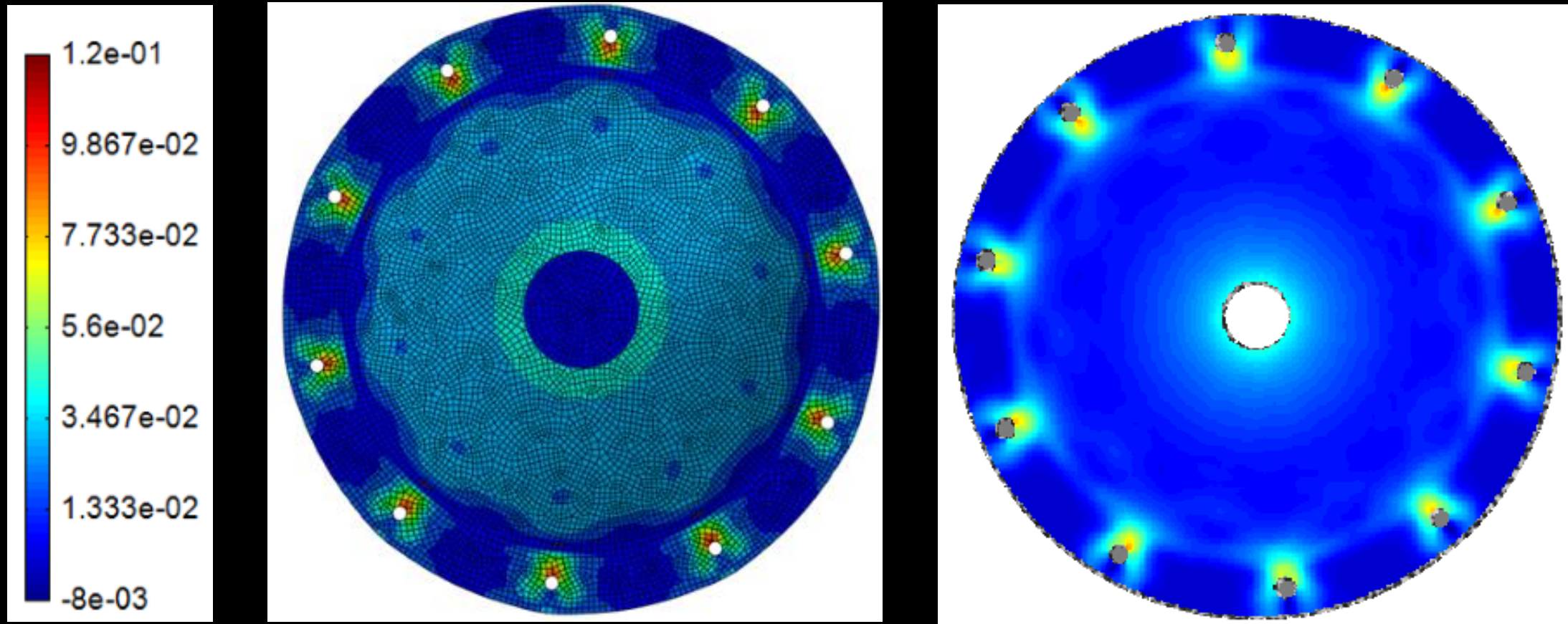


Technique	Stereo DIC
Noise (% of dynamic range)	0.5
Prefiltering	Gaussian 5 pixels kernel
Subset	21
Step	3
Correlation Criterion	ZNSSD
Shape Function	Affine
Interpolation Function	Bicubic splines
Evaluated data points	48618
Displacement resolution	
In-plane	$6.10^{-4}$ pixels
Out-of-plane	$4.10^{-3}$ pixels
Strain smoothing method	Polynomial bilinear
Strain convention	Log. Euler-Almansi
Strain window	9 data points
VSG	45 pixels
Strain resolution	$253 \mu m/m$

# Direct comparison – 5/6

- ‘Visual comparisons’

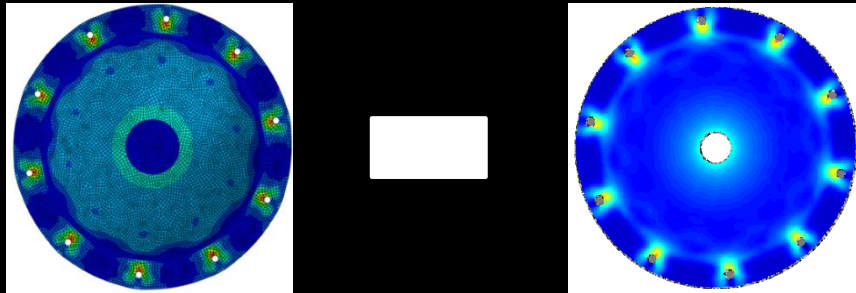
- Differences though EXACT model is encoded



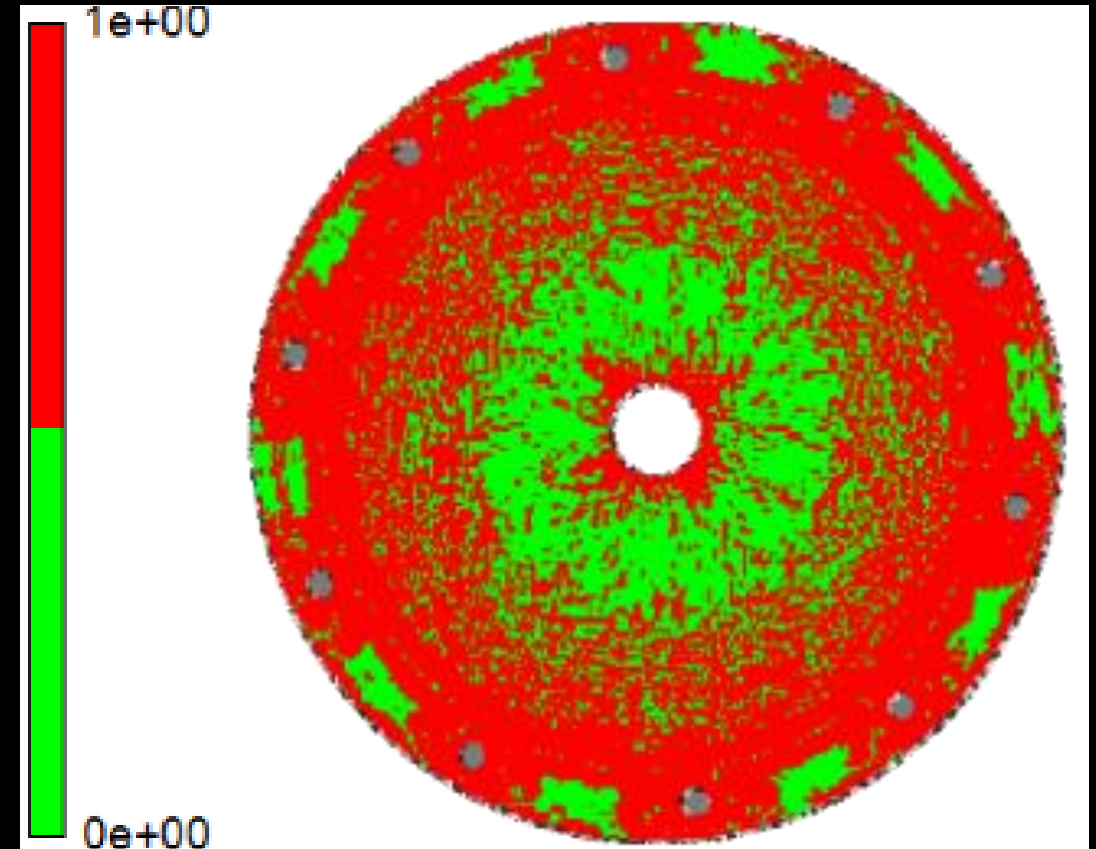
# Direct comparison – 6/6

## ■ Validation map

- FE – DIC map

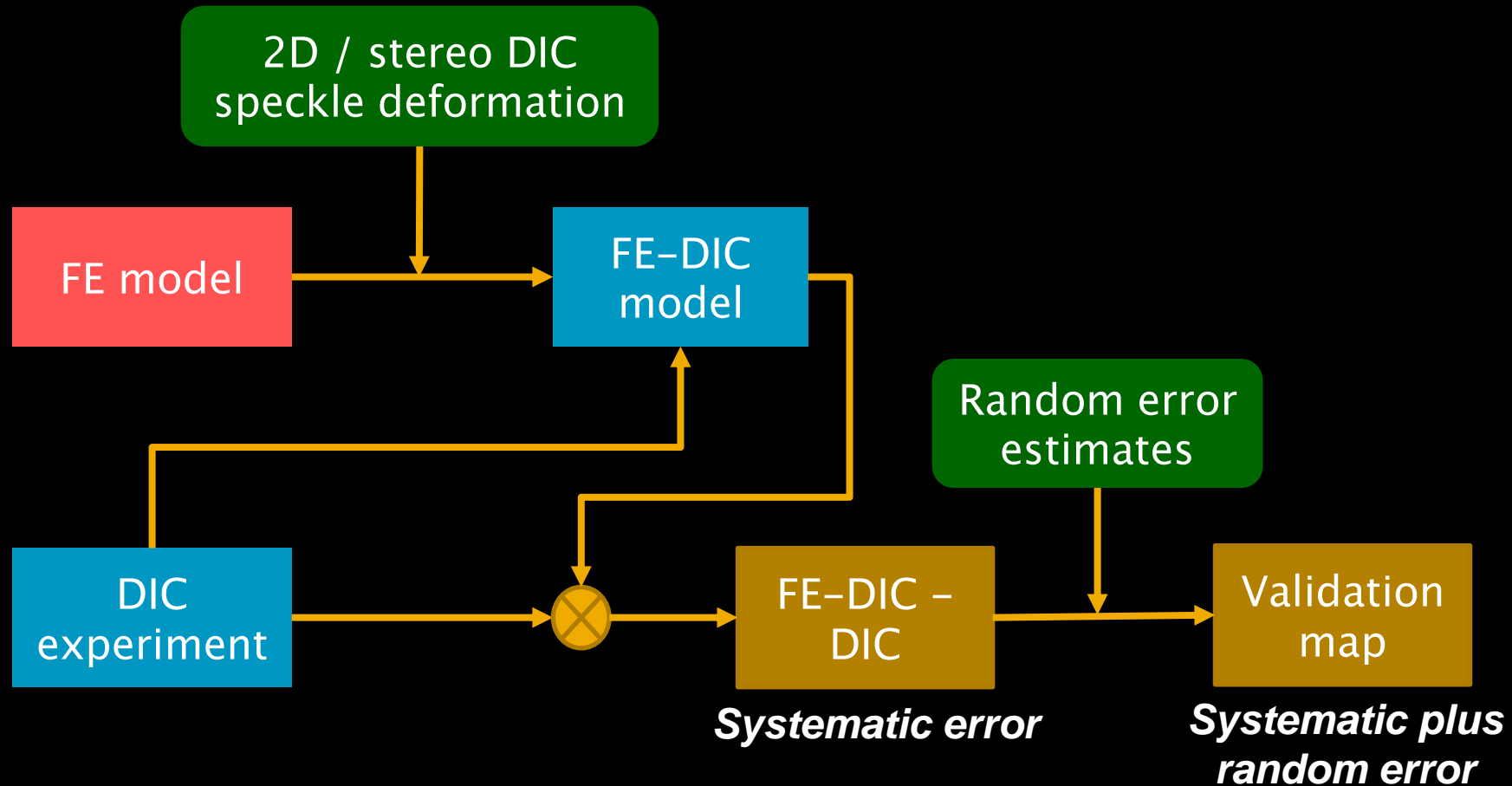


- Uncertainty from stationary or rigid body images
- FE – DIC larger than 3x uncertainty: red, otherwise green



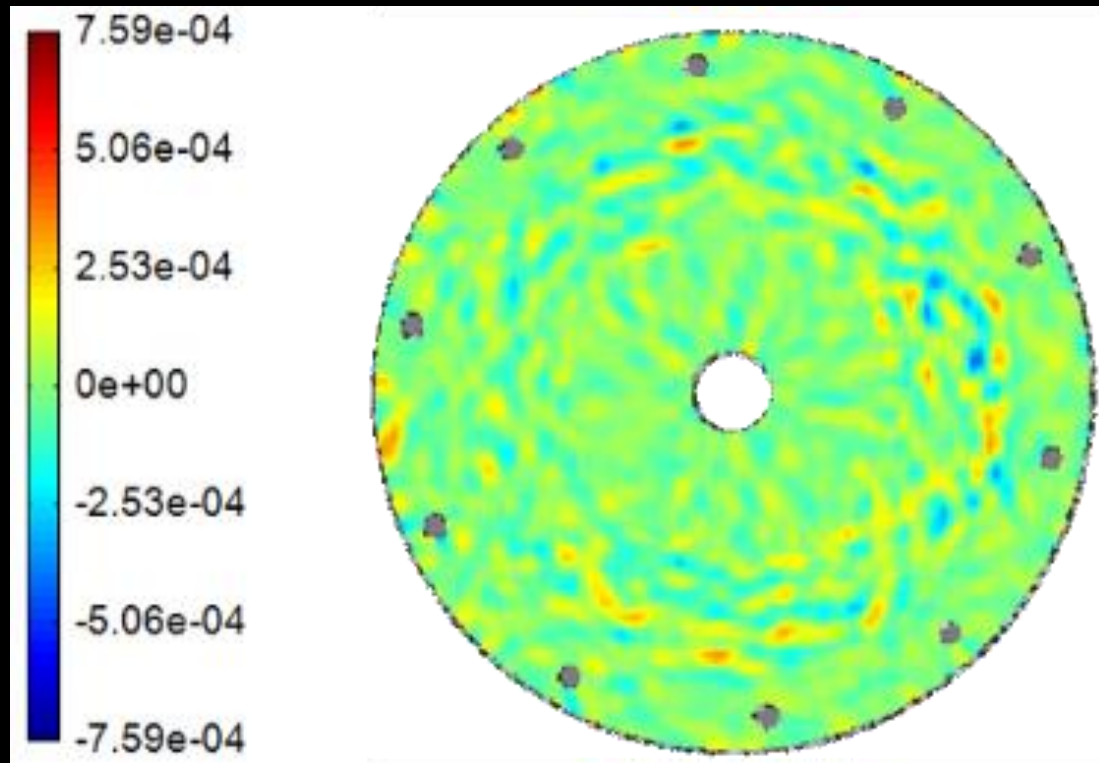
**FALSE NEGATIVE!**

# Model validation process

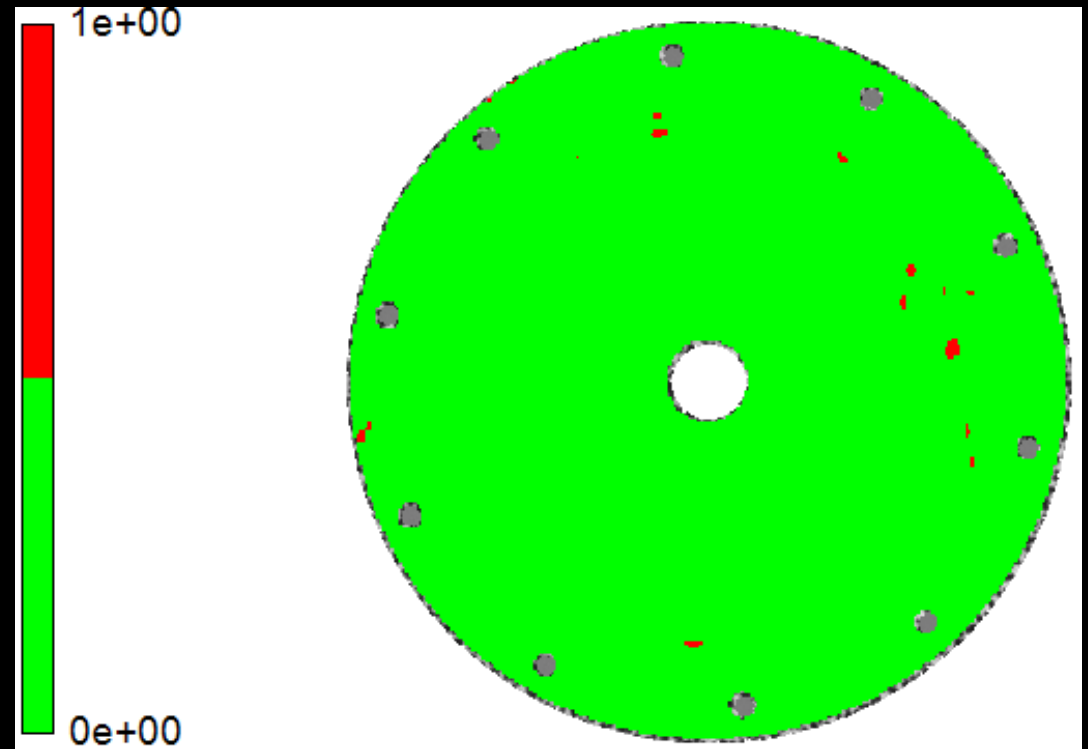


# FE vs FE-DIC

- Error map of strain and validation map
  - Here, the data only differs by a different copy of noise



FE-DIC - DIC

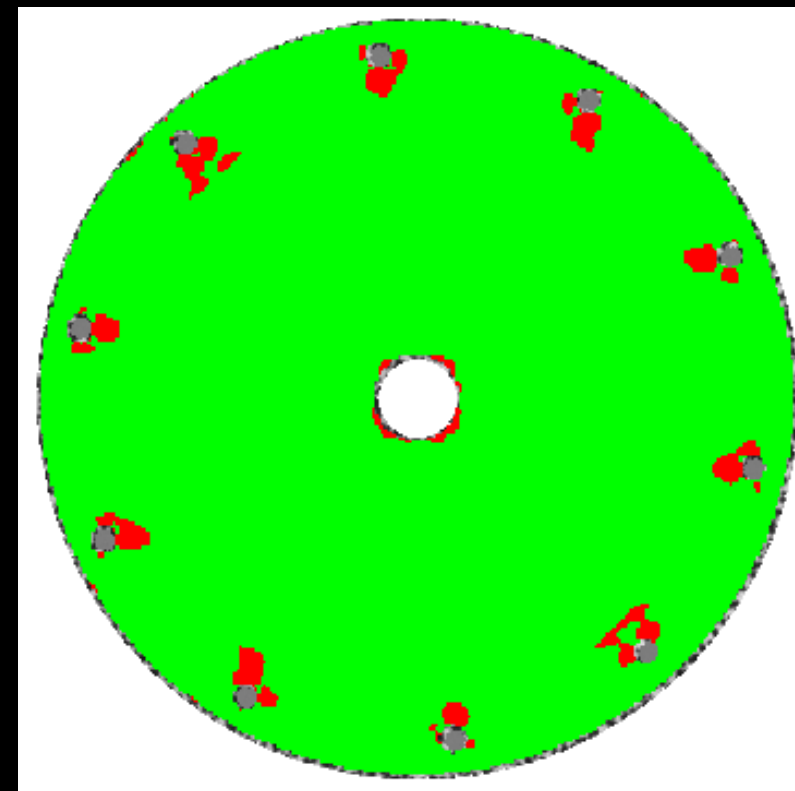
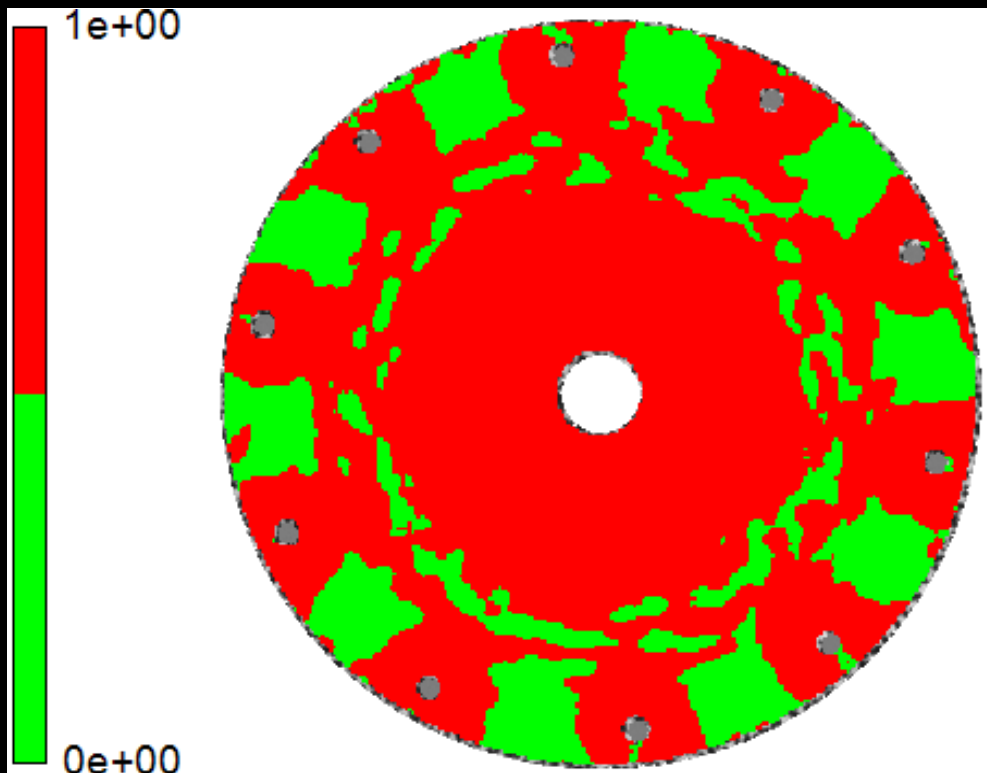


Validation map

# Model error

- Yield stress 450 MPa in FE model
  - vs 500 MPa in DIC ‘measurements’

FALSE POSITIVE!



FE-DIC – DIC validation map

VSG 93, direct FE vs DIC

# Material identification



# Material identification

- New opportunities from full-field measurements
  - More complex tests (statically indeterminate)
  - More information from the tests
    - Reduce the number of tests
  - Heterogeneous materials
    - Mapping the properties (welds etc.)
- Different tools
  - Finite Element Model Updating (and I-DIC)
  - Virtual Fields Method (VFM)

# UQ on parameters – 1/3

- Error on strain not directly relevant
  - Material identification is regularizing
- Identification simulator

FE model of test

FE-DIC model of test

Material parameters

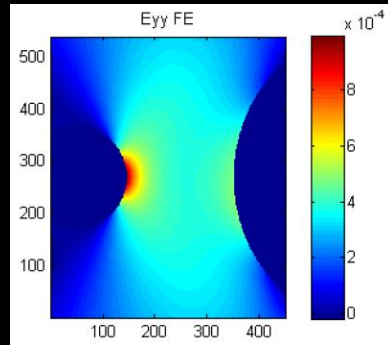
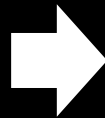
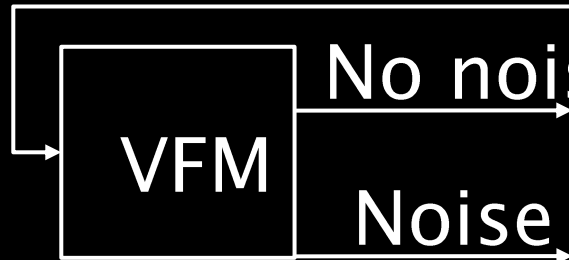
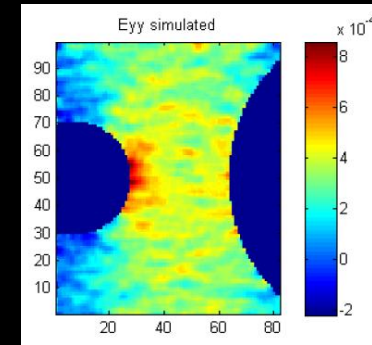
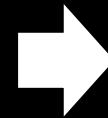


Image deformation



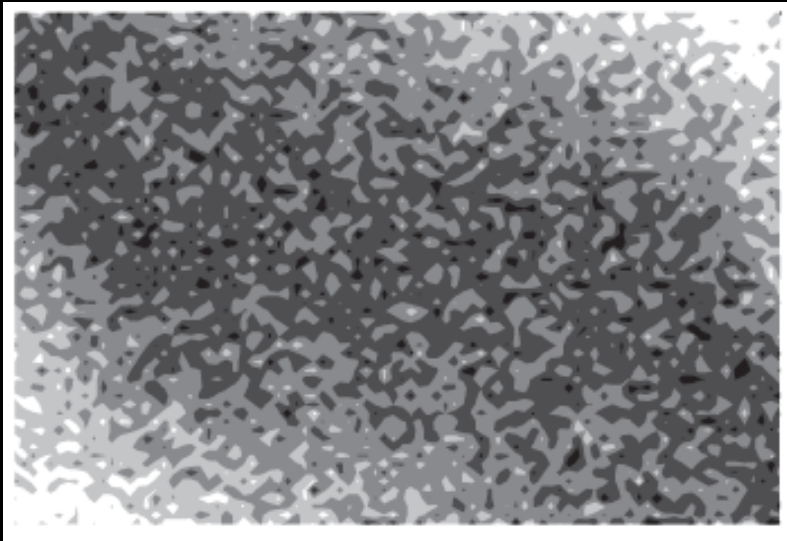
Bias

Distribution of identified parameters

➔ Variance

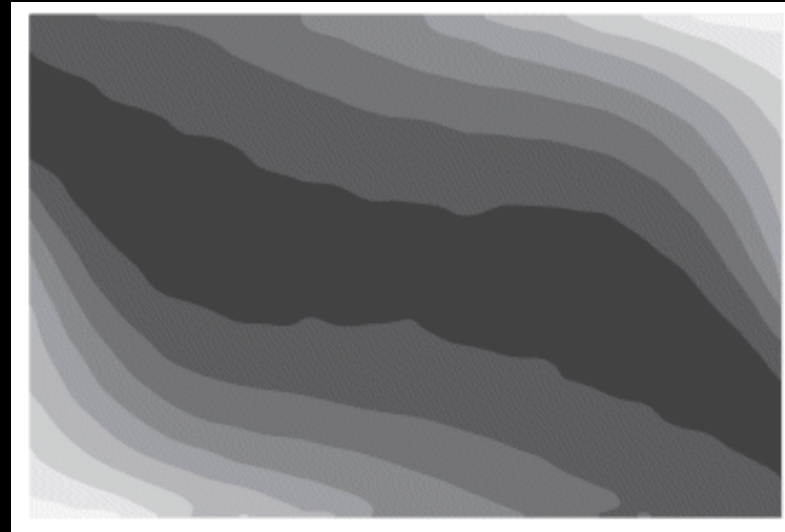
# UQ on parameters – 2/3

- Shear strain maps obtained by image deformation plus different levels of smoothing

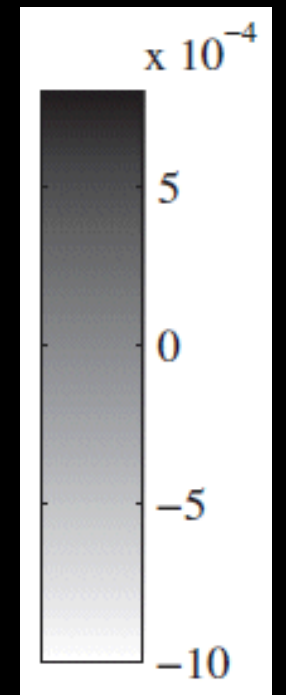


VSG=10 pixels  
(no smoothing)

Best ?



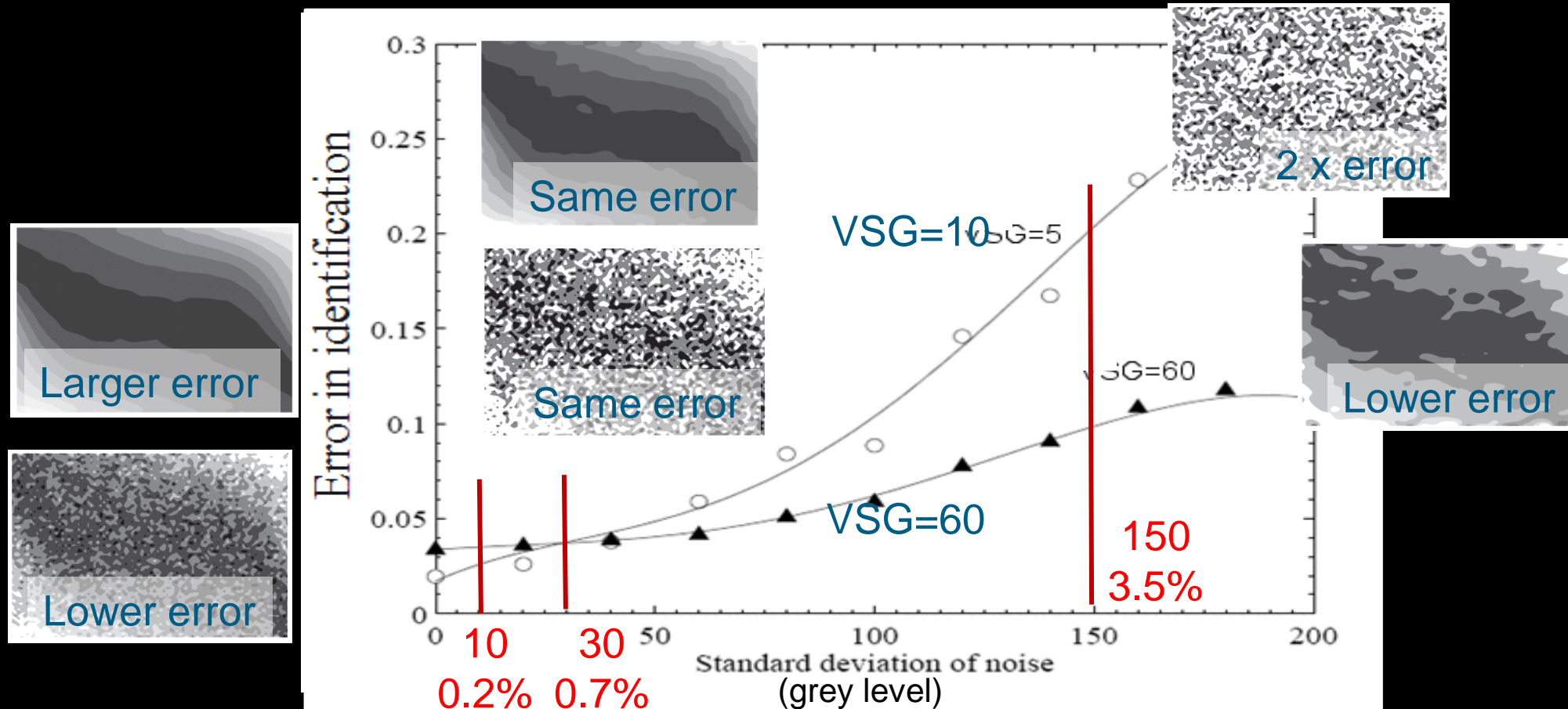
VSG=60 pixels  
(local polynomial)



Rossi, M., & Pierron, F. (2012). *International Journal of Solids and Structures*, 49(3-4), 420-435.

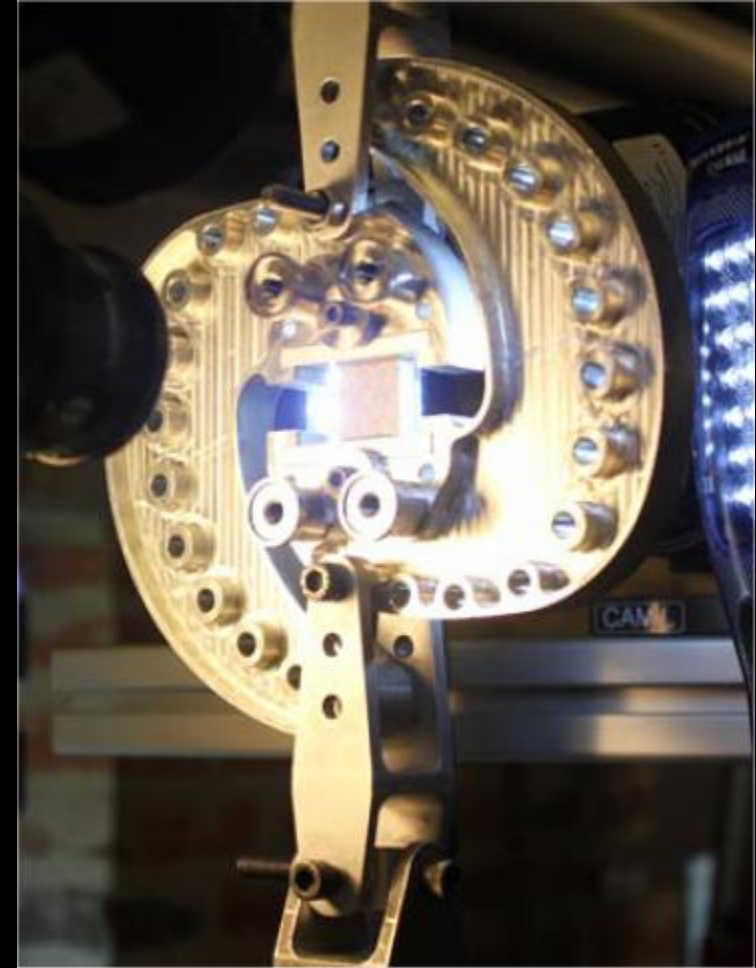
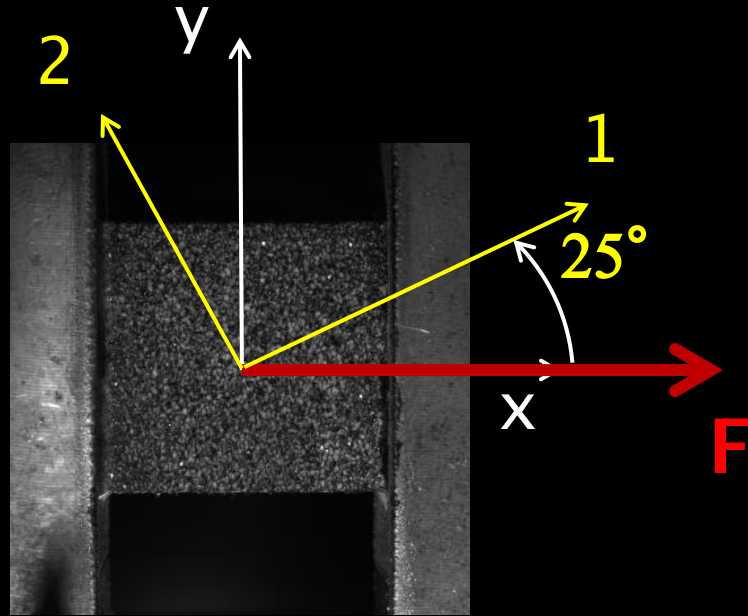
# UQ on parameters – 3/3

- Reference stiffness components are known, can build error function (RMS error)



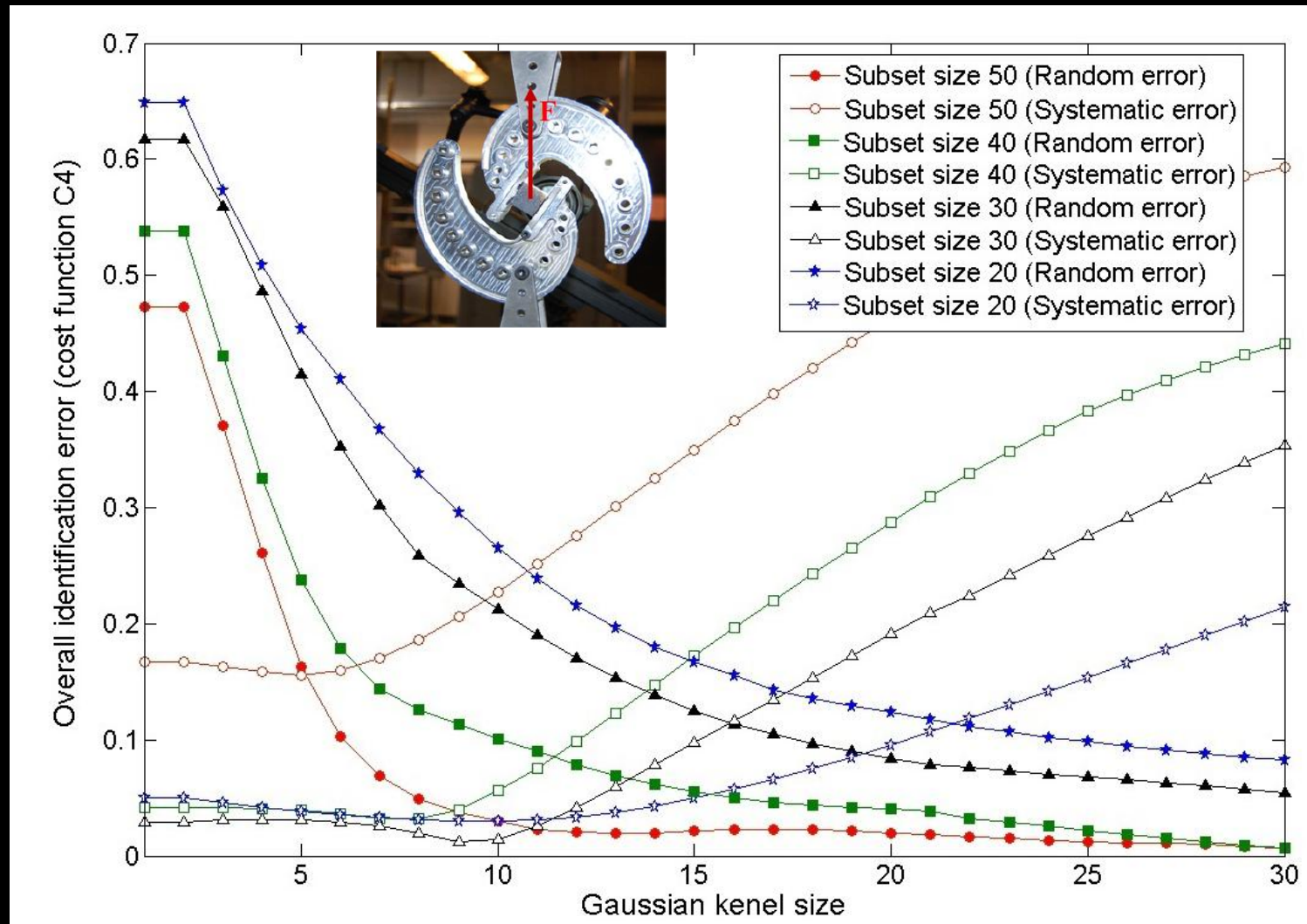
# Experimental validation - 1/4

- PU foam, orthotropic, Arcan fixture
- Two back-to-back cameras
- 20 repetitions



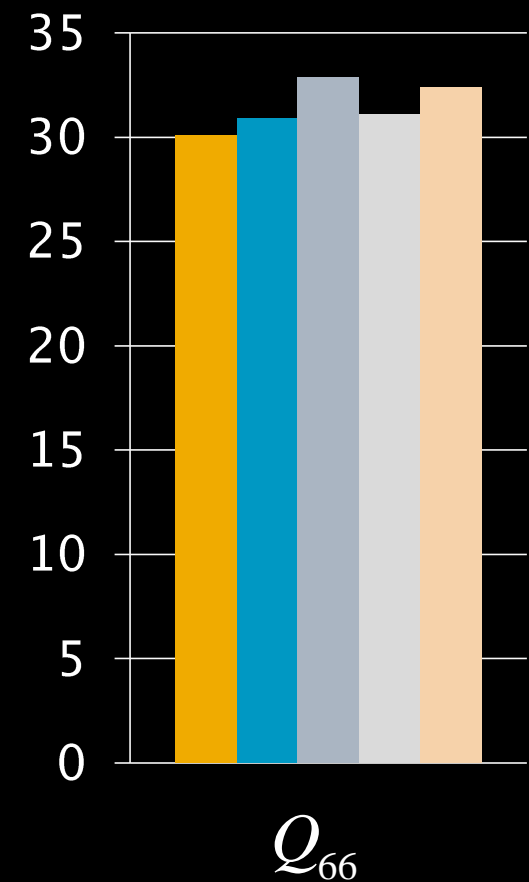
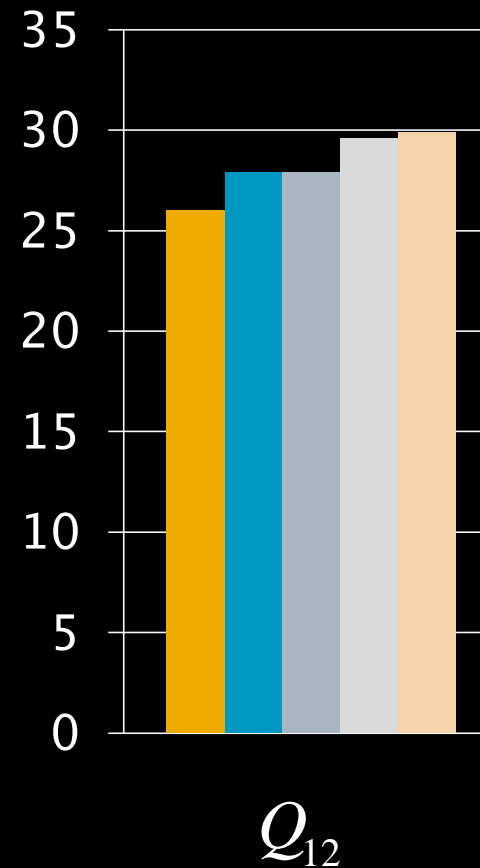
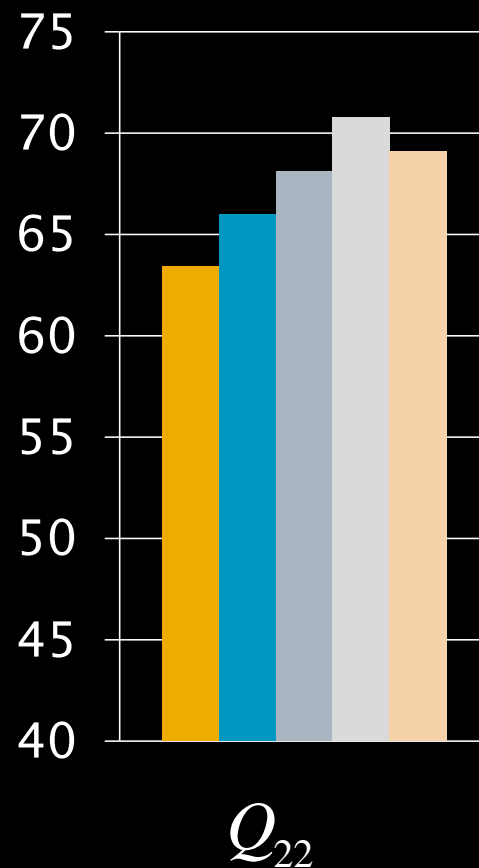
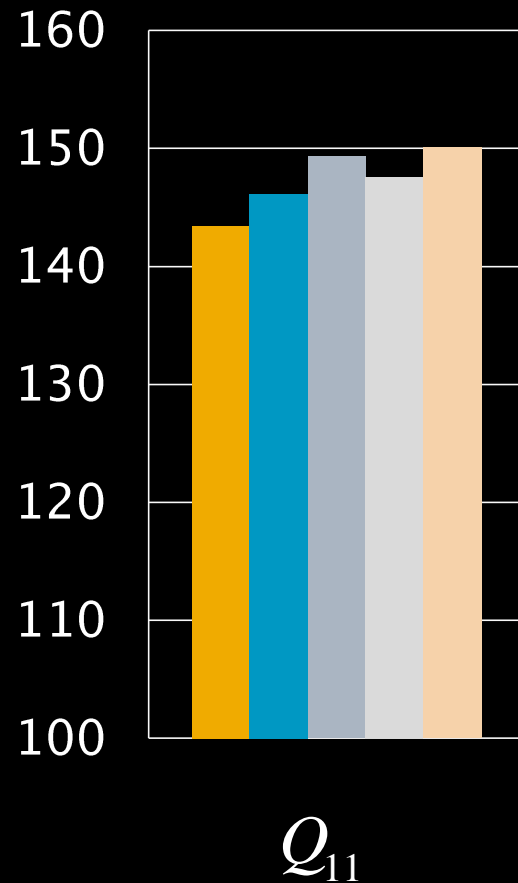
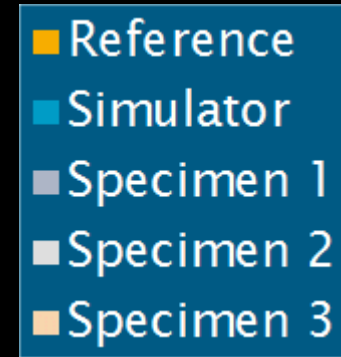
Wang P., Pierron F., Rossi M., Lava P., Thomsen O.T., Strain, 2016.

# Random vs reconstruction error



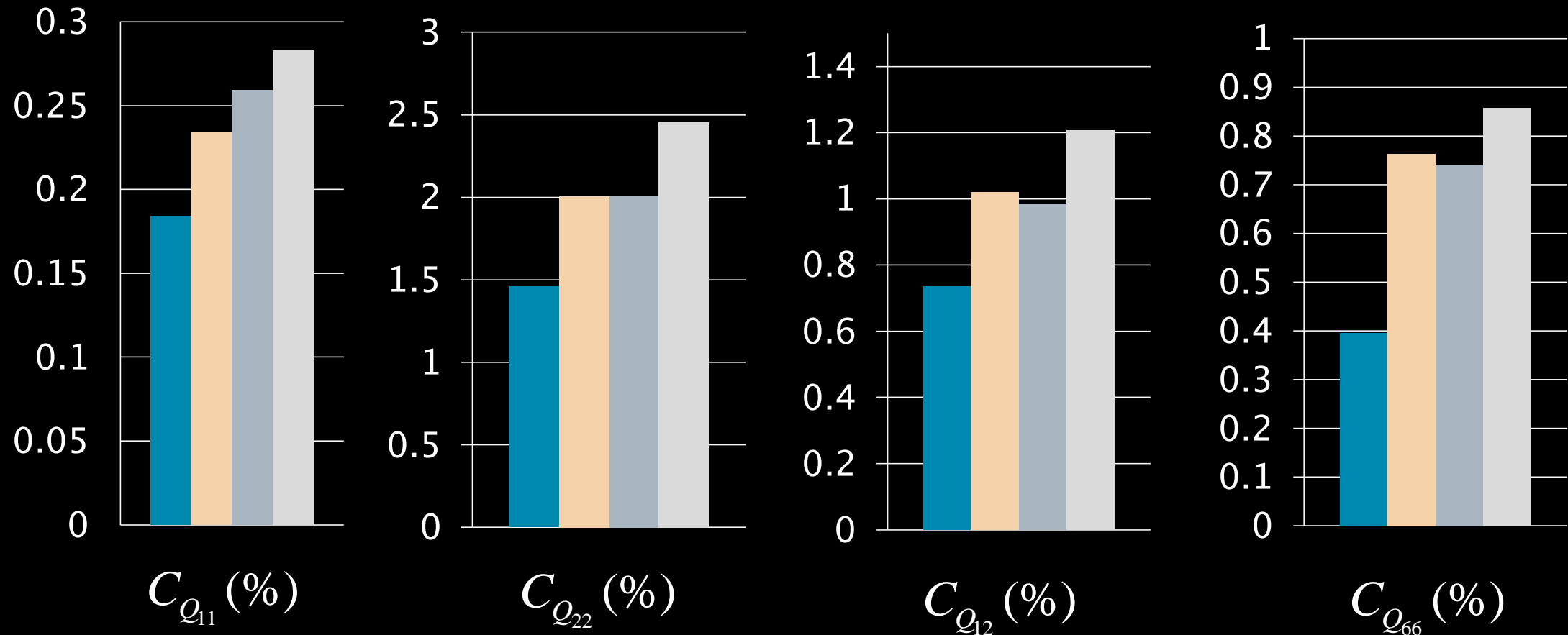
# Experimental validation - 2/4

- Mean, average over 20 repetitions (results in MPa)



# Experimental validation - 3/4

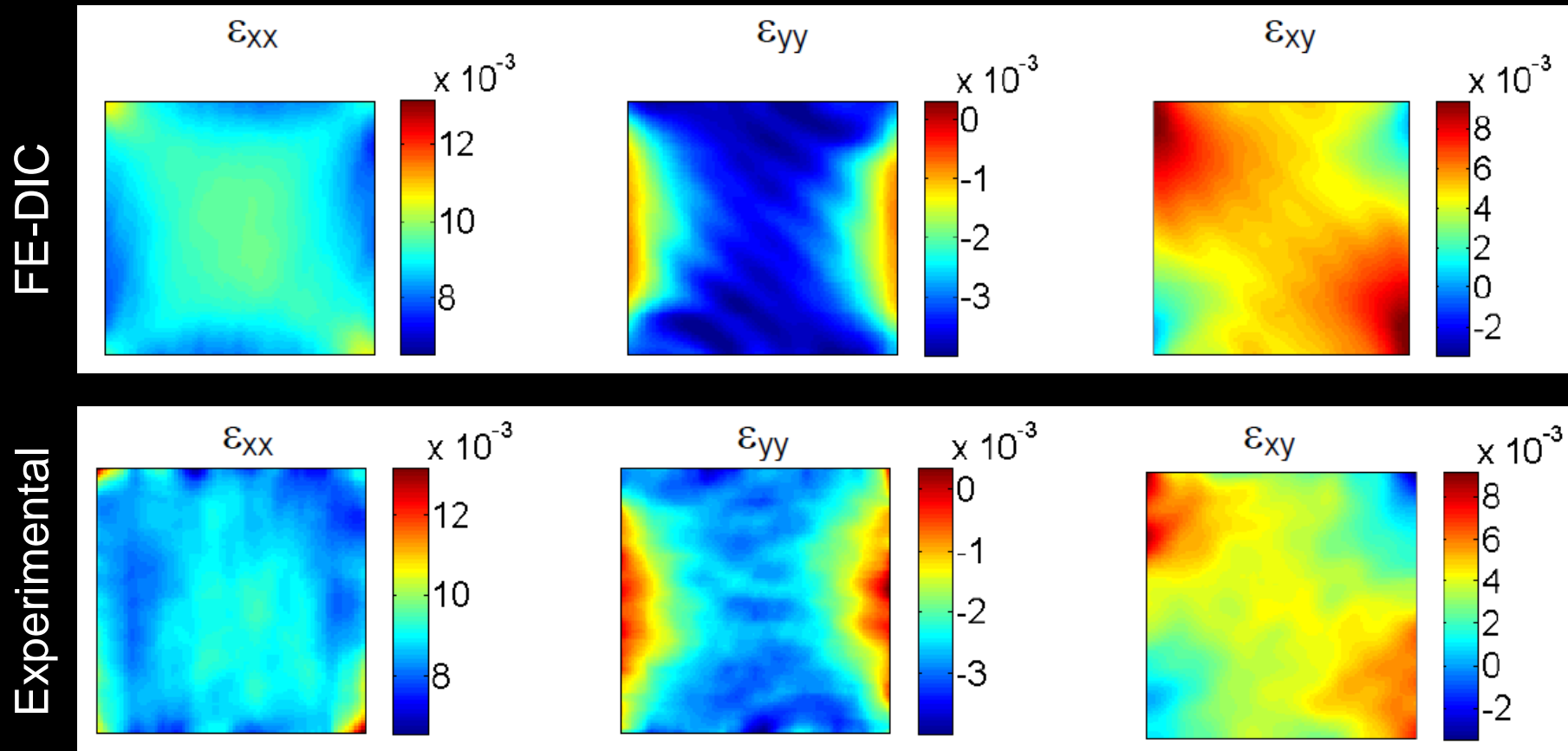
- Coefficients of variation, average over 20 repetitions (results in MPa)





# Experimental validation - 4/4

- How realistic is this 'simulator'

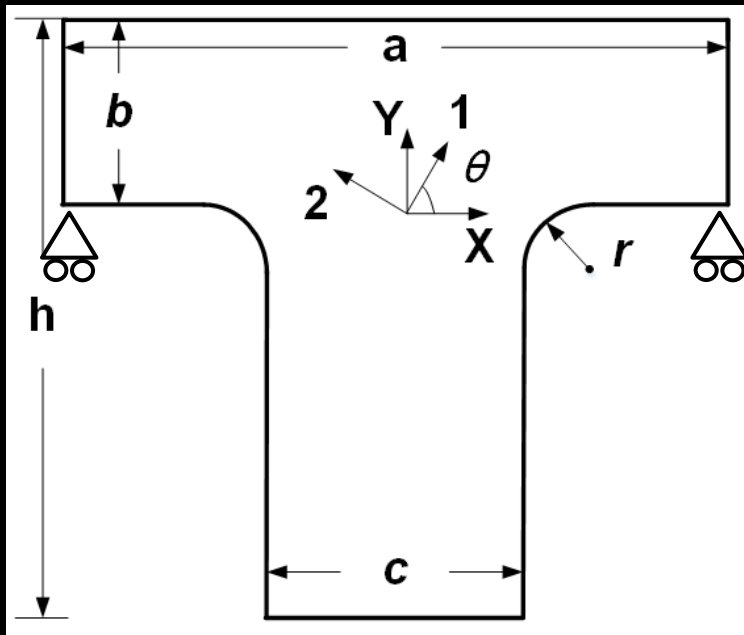


Wang P., Pierron F., Rossi M., Lava P., Thomsen O.T., Strain, 2016.

# Opportunity - 1/2

## Optimal test design

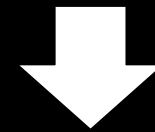
- 4 orthotropic stiffnesses from single test



Variables:

- Geometry
- Fibre angle
- DIC parameters

Genetic algorithm



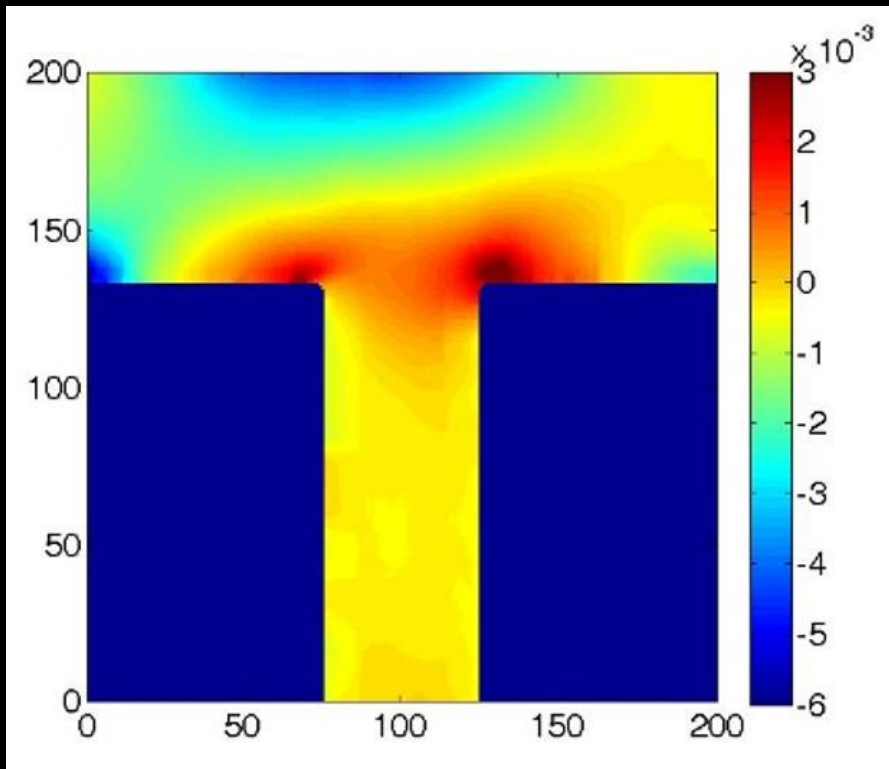
Min. total error

Variable	$b$	$c$	$r$	$\theta$	Subset	Step	Shape function	Strain window	Total error
Optimal value	42	24	6	27	36	1	Quadratic	8	0.0182

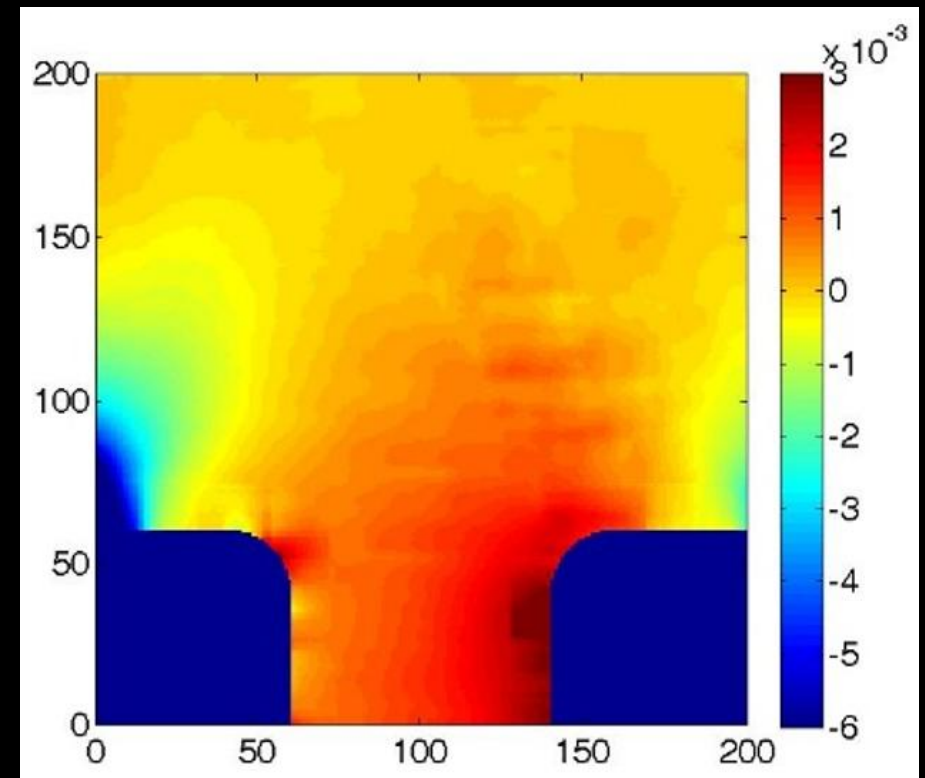
Gu X., Pierron F., unpublished, 2016

# Opportunity – 2/2

- Good vs bad design
  - Spatial resolution essential!



Bad



Good

# Summary

- DIC uncertainty
  - DIC convergence impaired by camera resolution
  - Importance of shape function
- FE model validation
  - FE data through DIC filter
- Parameter identification
  - Full UQ possible on parameters
  - Powerful tool for test design

# Future work

- Experimental exploration of FE validation module
  - MatchID and industrial partners
- DIC standardization?
  - I do not believe in it (see strain gauges)!
  - Users need TRAINING! (DIC course in Ghent, July 2017)
  - Standard TESTS based on DIC
- Need for new test designs