Création d'un benchmark de fissuration du béton en mode mixte

CARPIUC Benchmark

Crack Advance, Reorientation, Propagation and Initiation Under Complex loadings

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AUSSOIS 2019

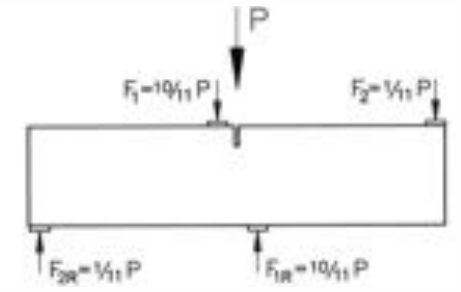
Outline

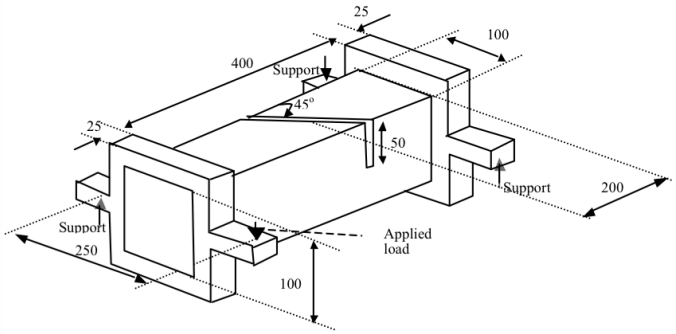
- **Motivation**
- **Experimental protocol**
  - Principle
  - Technical settings
  - Loading paths
- **Experimental campaign results**
  - N-M-like tests
  - CARPIUC tests
- **Spreading the data**
- **Summary & perspectives**

Which tests exist ?

Very few experimental test results for:

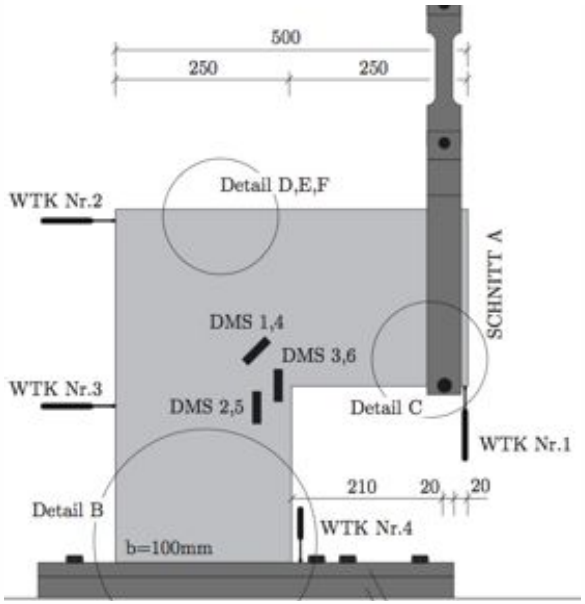
- **middle-scale specimen**
- **mixed mode crack propagation**
- **quasi-fragile materials**





Main works on concrete:

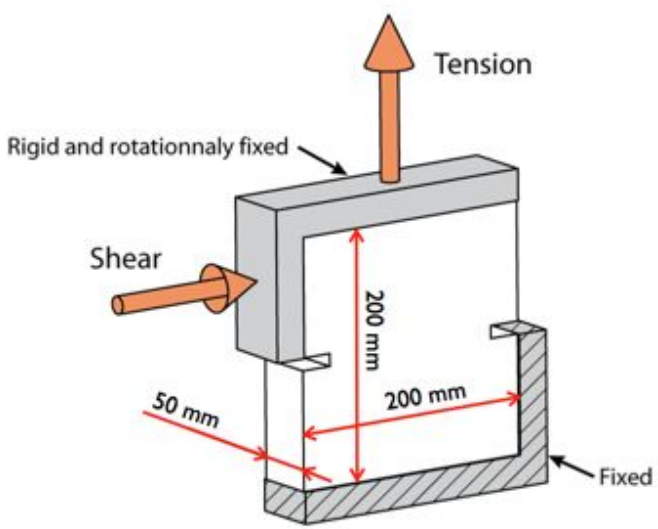
- **1982 Arrea & Ingraffea**
- **1992 Nooru-Mohamed**
- **1996 Brokenshire**
- **2001 Winkler**



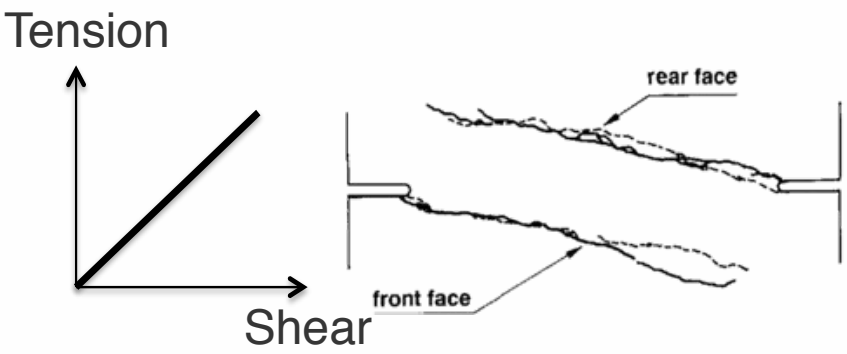
The Nooru-Mohamed test

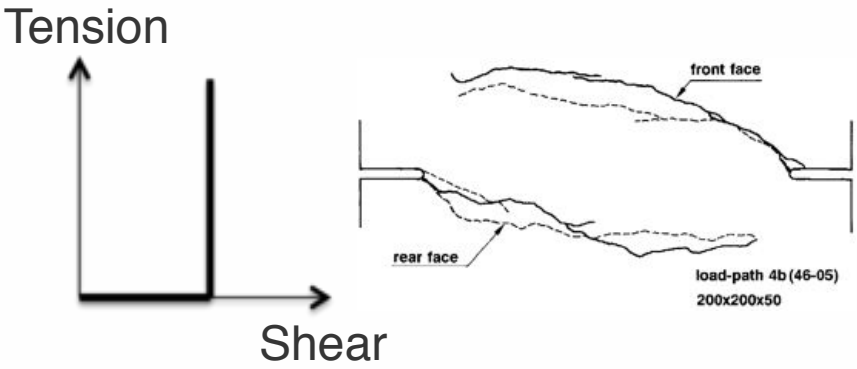
Largest test campaign: [Nooru-Mohamed, 1992]

Principle:



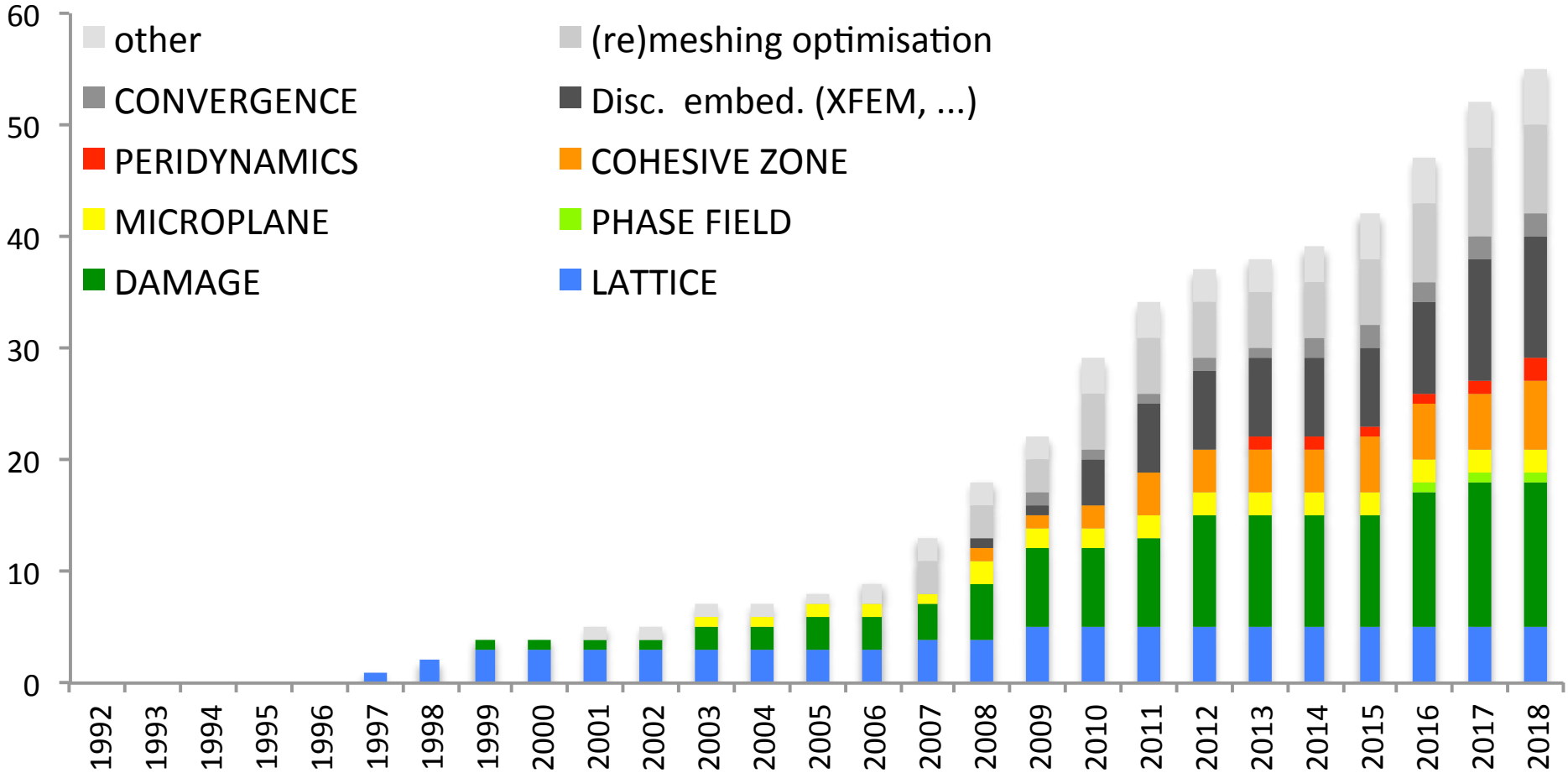
Results:





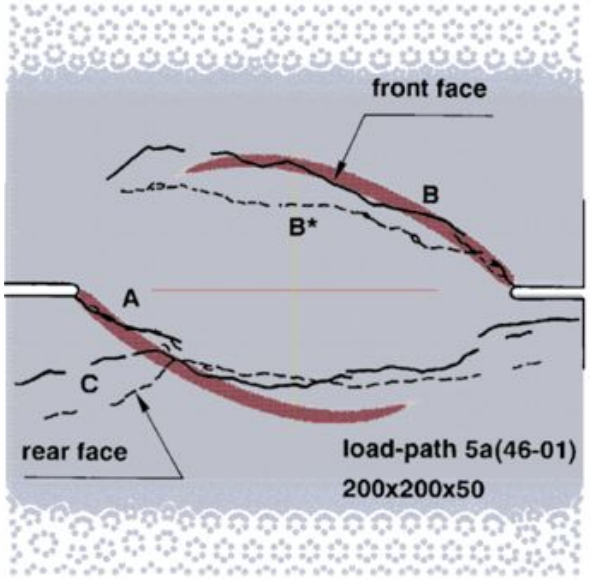
An `unofficial' benchmark

Articles using N-M for validation : both theoretical and numerical



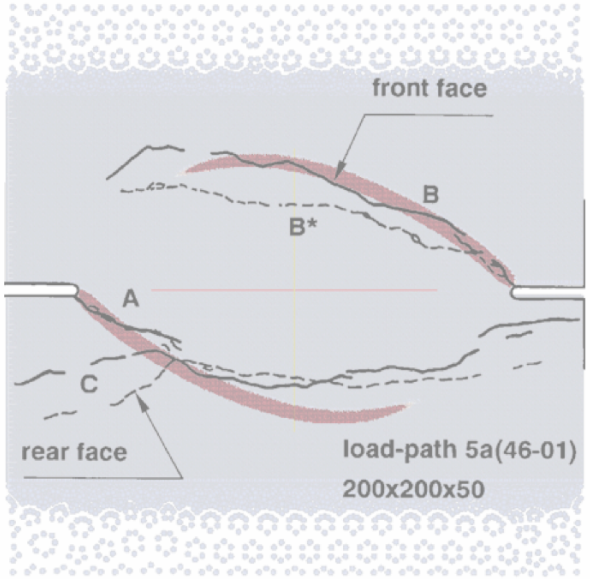
Why so much interest ?

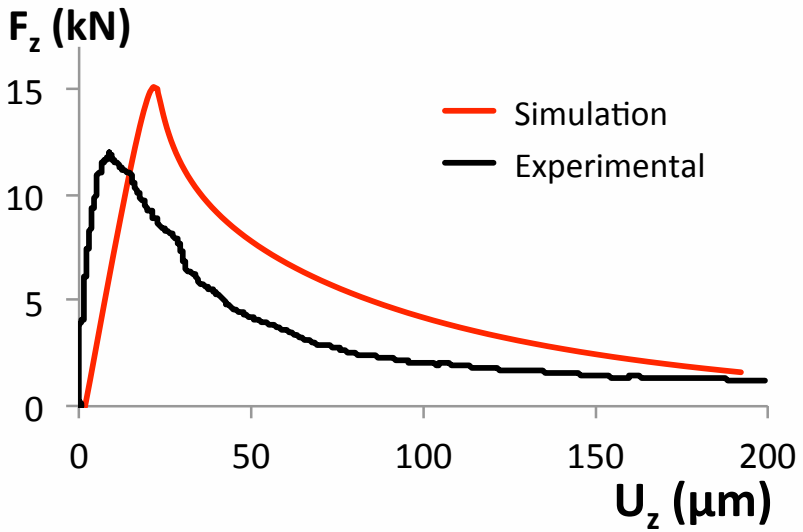
- **Many advantages**
  - Mixed I-II
  - Non-trivial crack patterns
  - Stable crack propagation
  - Important database:
    - Different concrete formulations
    - Different sizes of specimens
    - Different loading histories



`Great … but'

- **Many advantages**
  - Mixed I-II
  - Non-trivial crack patterns
  - Stable crack propagation
  - Important database:
    - Different concrete formulations
    - Different sizes of specimens
    - Different loading histories
- **Some important drawbacks**
  - Inconsistent force-displ. curves
  - Unavailable data:
    - Crack propagation
    - Material parameters
    - Measured boundary conditions





Motivation of the new test campaign

- **Many advantages => main goals**
  - Mixed I-II
  - Non-trivial crack patterns
  - Stable crack propagation
  - Important database:
    - ~~Different concrete formulations~~
    - ~~Different sizes of specimens~~
    - Different loading histories
- **Some important drawbacks => special attention to**
  - ~~Inconsistent force-displ. curves~~ => 3D loadcell
  - ~~Unavailable data:~~
    - ~~Crack propagation~~ => full-field kinematic measurements
    - ~~Material parameters~~ => standard tests
    - ~~Measured boundary conditions~~ => 3D BC measurements
    - ensures a LONG stable propagation

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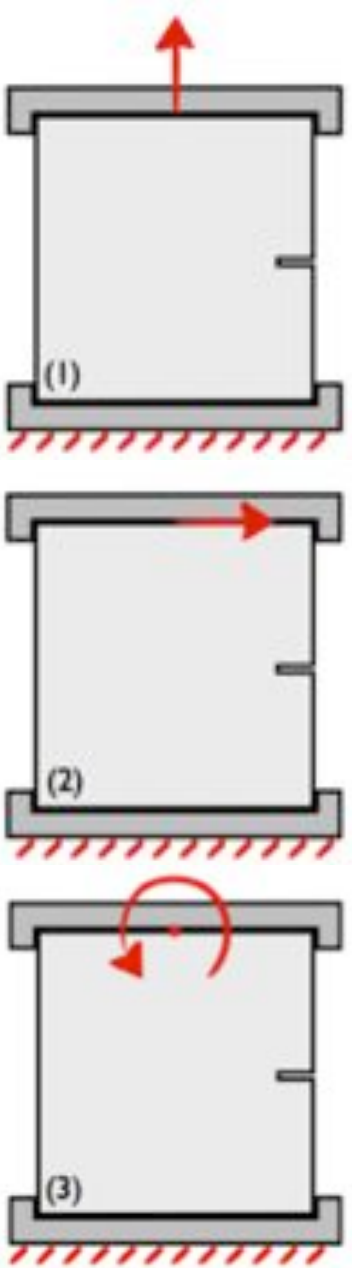
Loading principle



Global tension: crack opening (= Nooru-Mohamed)

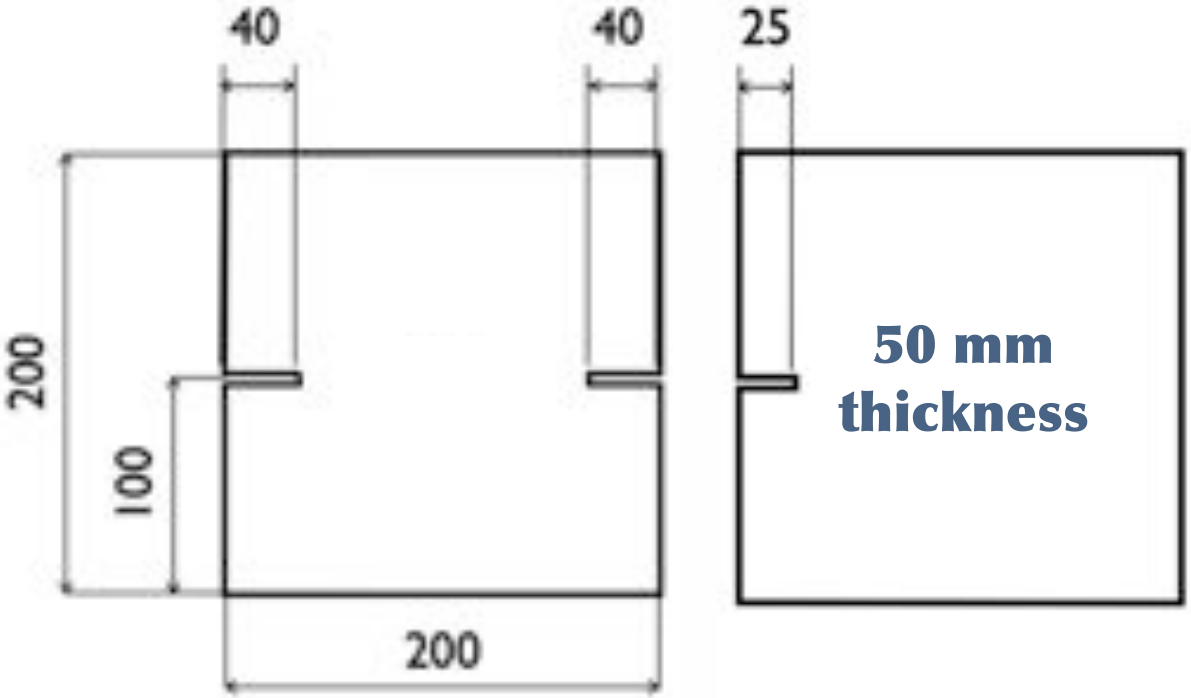
Global shear: crack orientation (= Nooru-Mohamed)

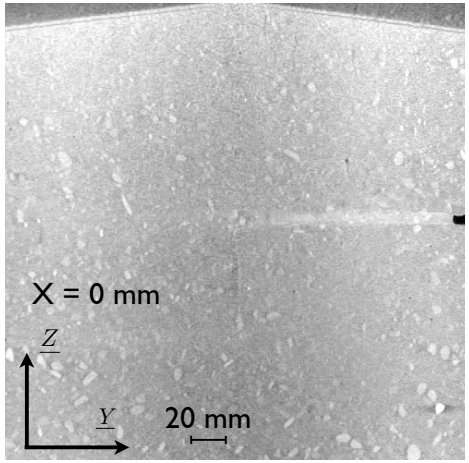
Global rotation: crack stabilisation (≠ Nooru-Mohamed)

Specimens: shape, size and material

VERCORS Mortar, not concrete !

Effective water [kg/m3]	Cement [kg/m3]	Sand 0/4 [kg/m3]	Plasticizer [kg/m3]
319	611	1235	5.25





slice of a tomographic image

Specimens: material parameters

3-point bending tests
on 40x40x160 specimens
(196-1 NF-EN standard)

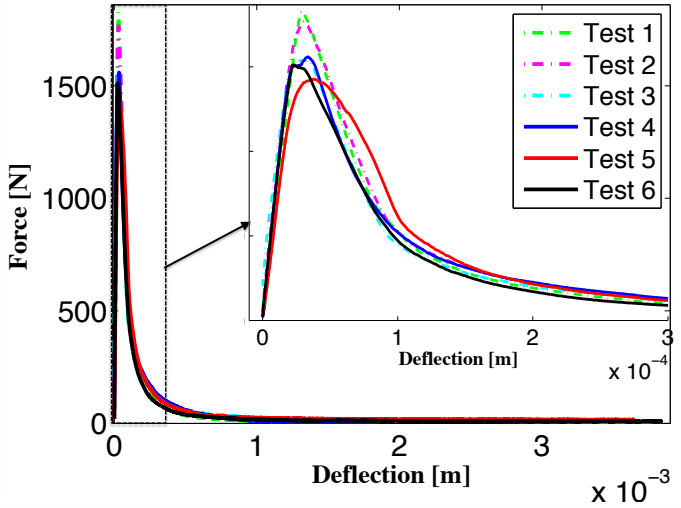
	Test 1	Test 2	Test 3	Test 4	Test 5
Load rate	50 N/s	50 N/s	50 N/s	0.5 N/s	0.5 N/s
E [GPa]	17.6	16.4	17.75	20.03	20.04
Mean [GPa]	17.25 ± 0.74			20.035 ± 0.005	

	Test 1	Test 2	Test 3	Test 4	Test 5
Load rate	50 N/s	50 N/s	50 N/s	0.5 N/s	0.5 N/s
F_t [MPa]	4.125	3.275	3.894	3.823	4.33
Mean [MPa]	3.8 ± 0.4			4.1 ± 0.4	

Compression tests
on broken specimens
at 2400+/-200 N/s
(196-1 NF-EN standard)

	Test 1	Test 2	Test 3	Test 4	Test 5
F_c [MPa]	80.31	77.19	76.88	83.59	81.72
Mean [MPa]			79.94±2.9		

3-point bending tests
on 70x70x280 specimens
(RILEM 1985 standard)



$$G_f = \frac{(W_0 + mg\delta_0)}{A_{lig}} = 114.6 \pm 18.8 \text{ N/m}.$$

Loading: 6 DOF testing machine

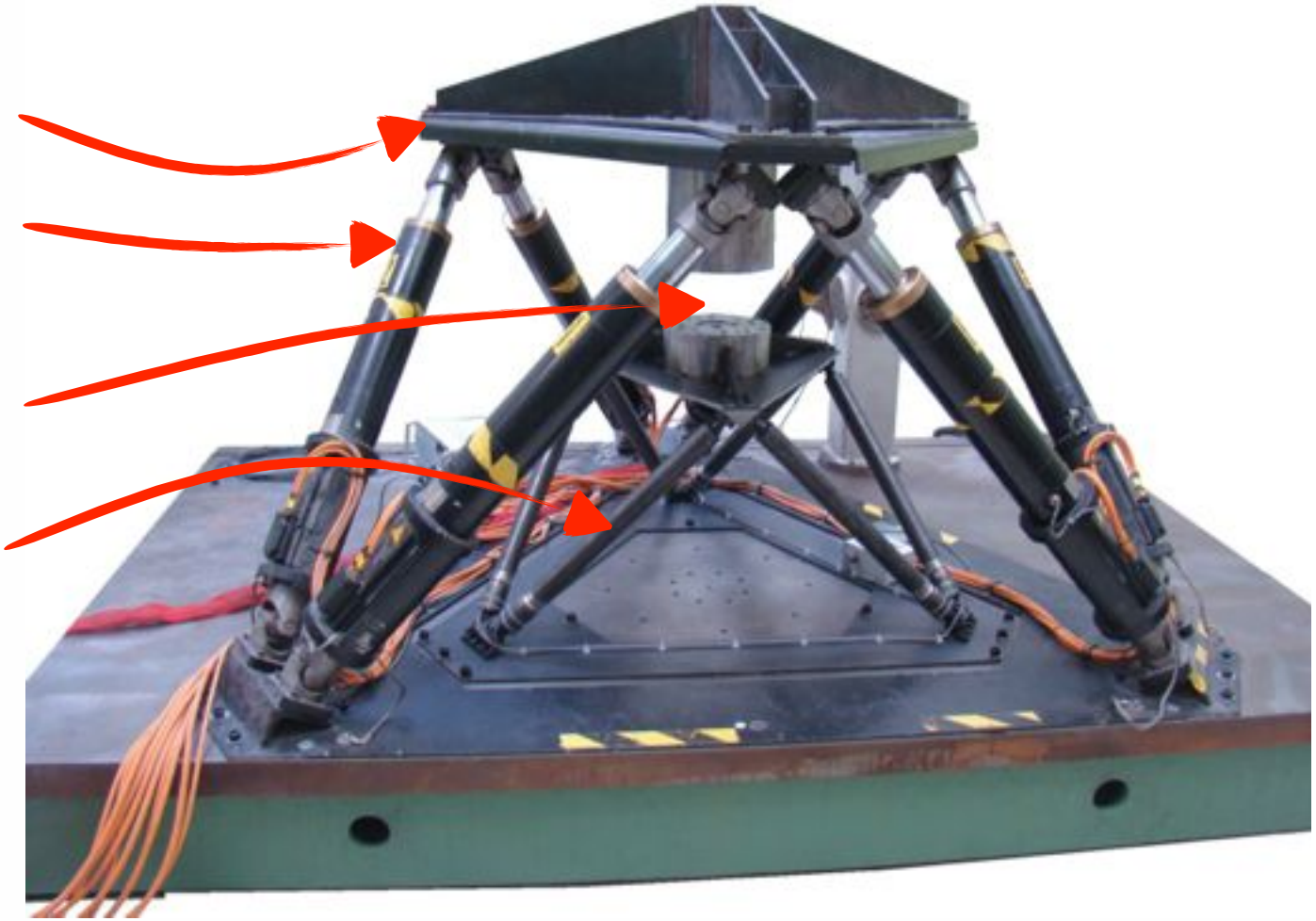
Loading: 6 DOF testing machine

Mobile Platform

Electrical jack

Specimen space

6 DOF Load cell



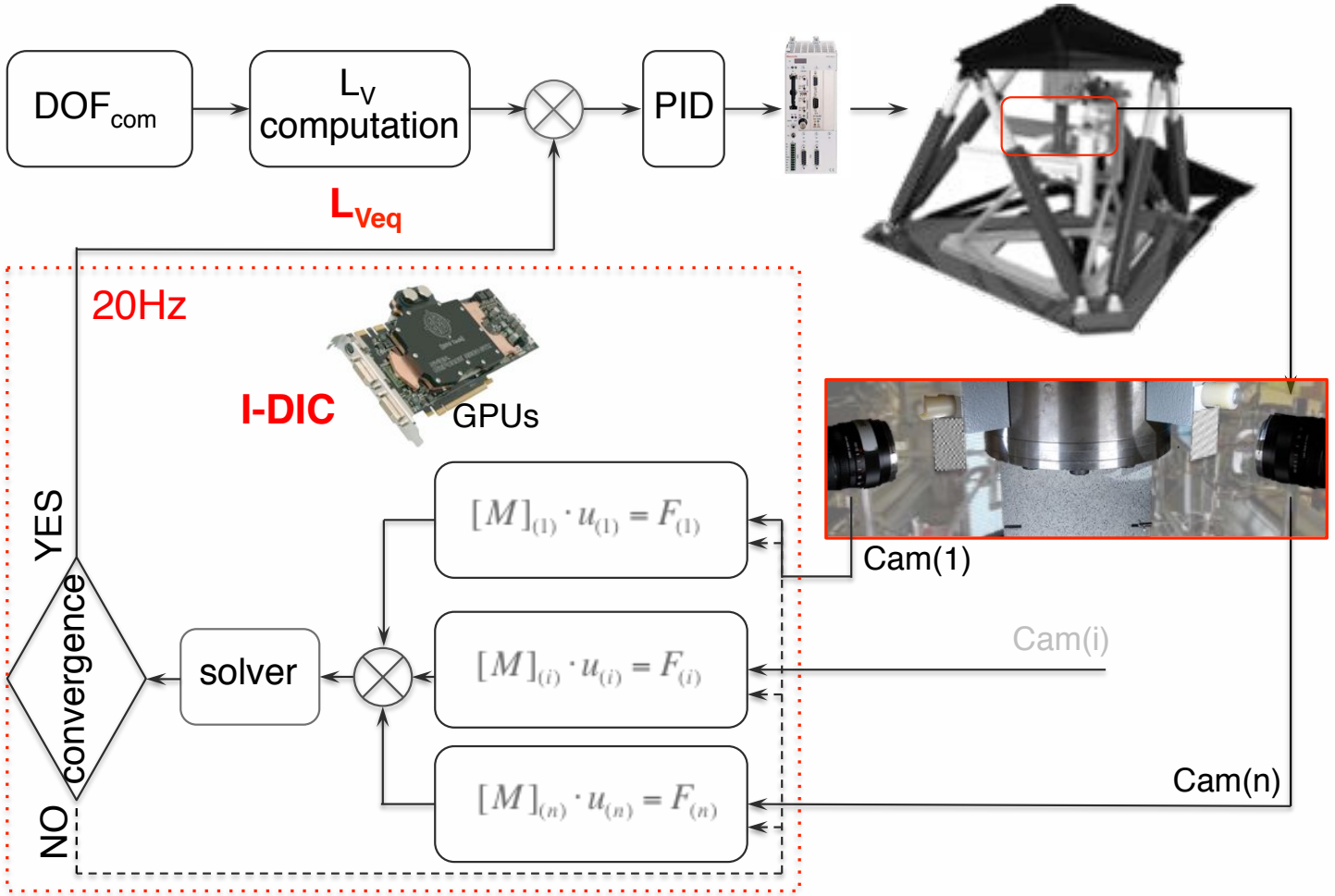
Force capacity ~ 120 kN
Torq. capacity ~ 70 kN.m

Displ. range ~ 500 [3] mm
Rot. range ~ 45° [3]

Force uncertainty: ~80 N et ~20 N.m

control loop sampling: 4 ms

Loading: DIC-based control loop

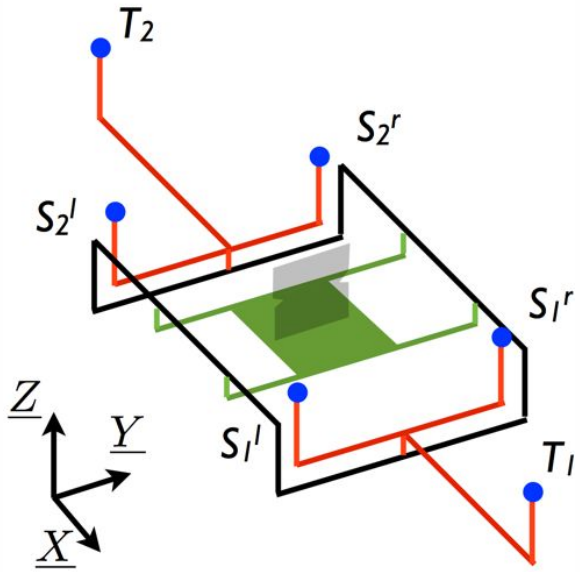


- **3 CCD cameras @ 20 Hz**
- **Complete computation time (GPU +CPU) < 50 ms**
- **Actuator displacement uncertainty < 1 µm**
- **Machine displacement uncertainty ~ 1 µm**

[LeFlohic et al. 2014]

Camera setup

- DIC : 2 cameras @ 0.2 Hz
  - T_1
  - T_2
- Stereo DIC : 4 DSLR cameras @ 0.2 Hz
  - S_1^l & S_1^r
  - S_2^l & S_2^r
  - (T_1, T_2)

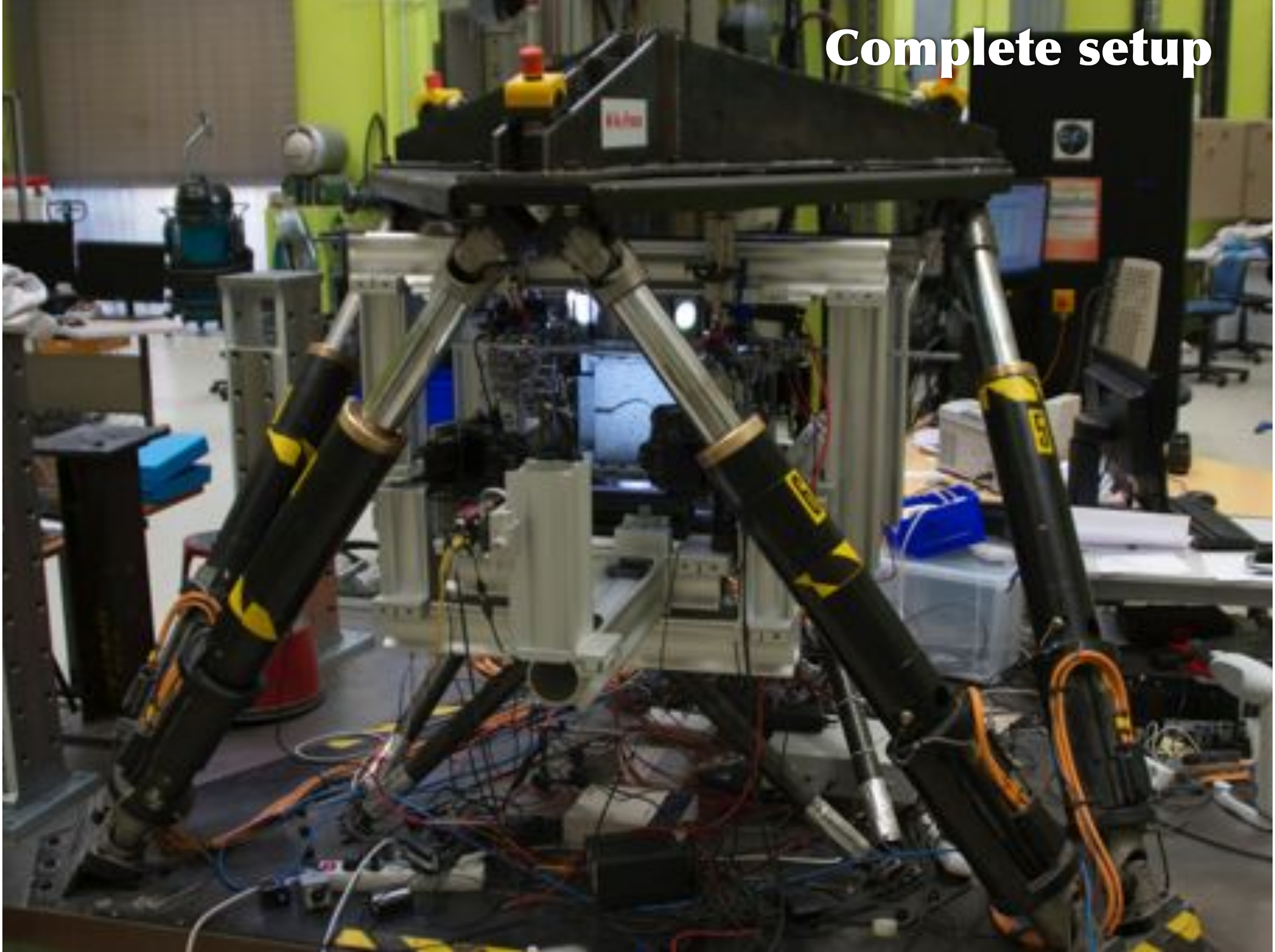


- Possible measurement :
  - full field 2D on each face [Tomicevic et al., 2013]
  - full field 2.5D on each face [Beaubier et al., 2014]
  - relative RBM of the plates

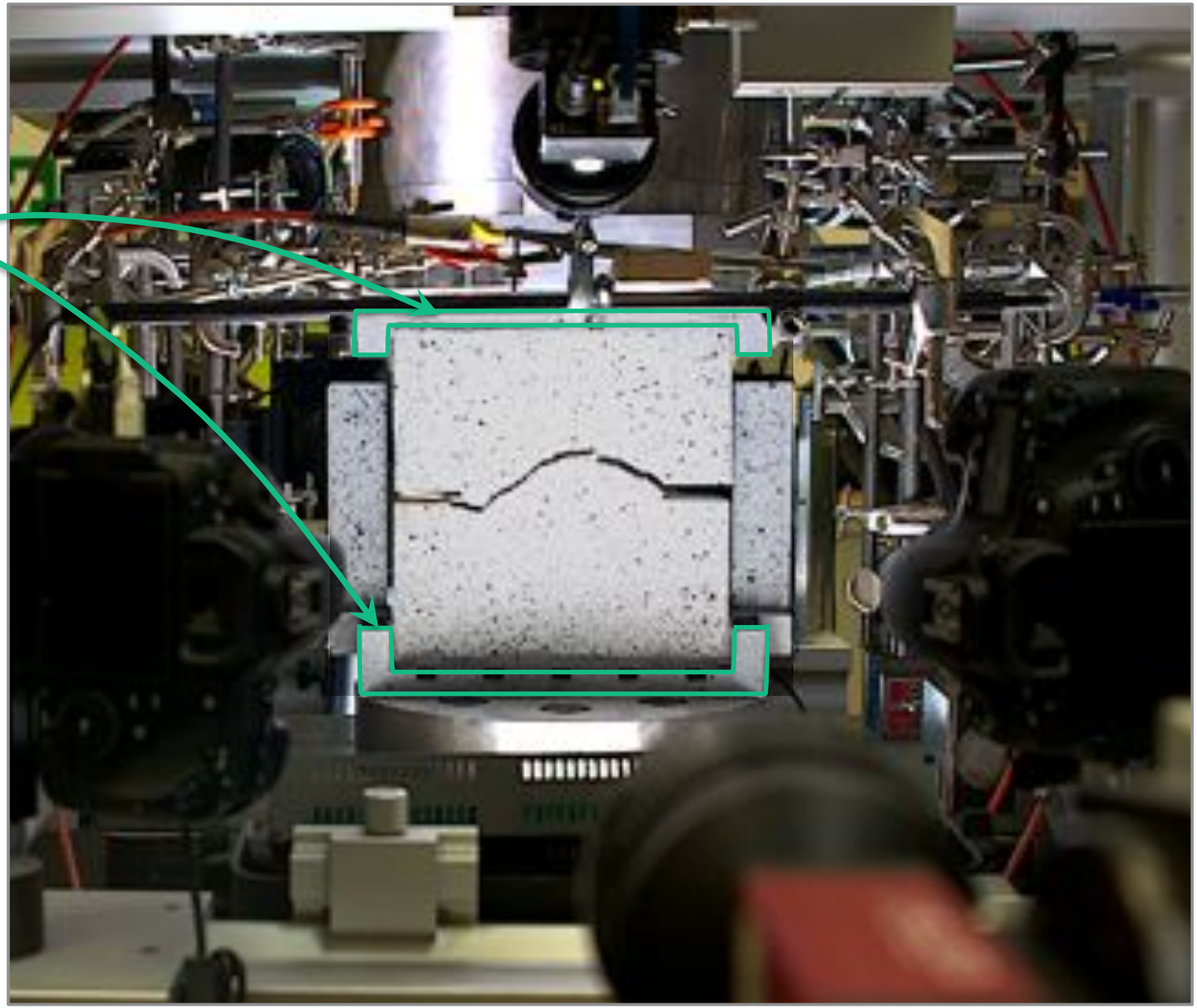
2D DIC		
uncertainty	(µm)	(pix)
along Y	2.4	0.018
along Z	1.3	0.010

Relative RBM		
uncertainty	Trans (µm)	Rot (10
along X	0.07	0.4
along Y	0.68	7.7
along Z	1.77	1.1

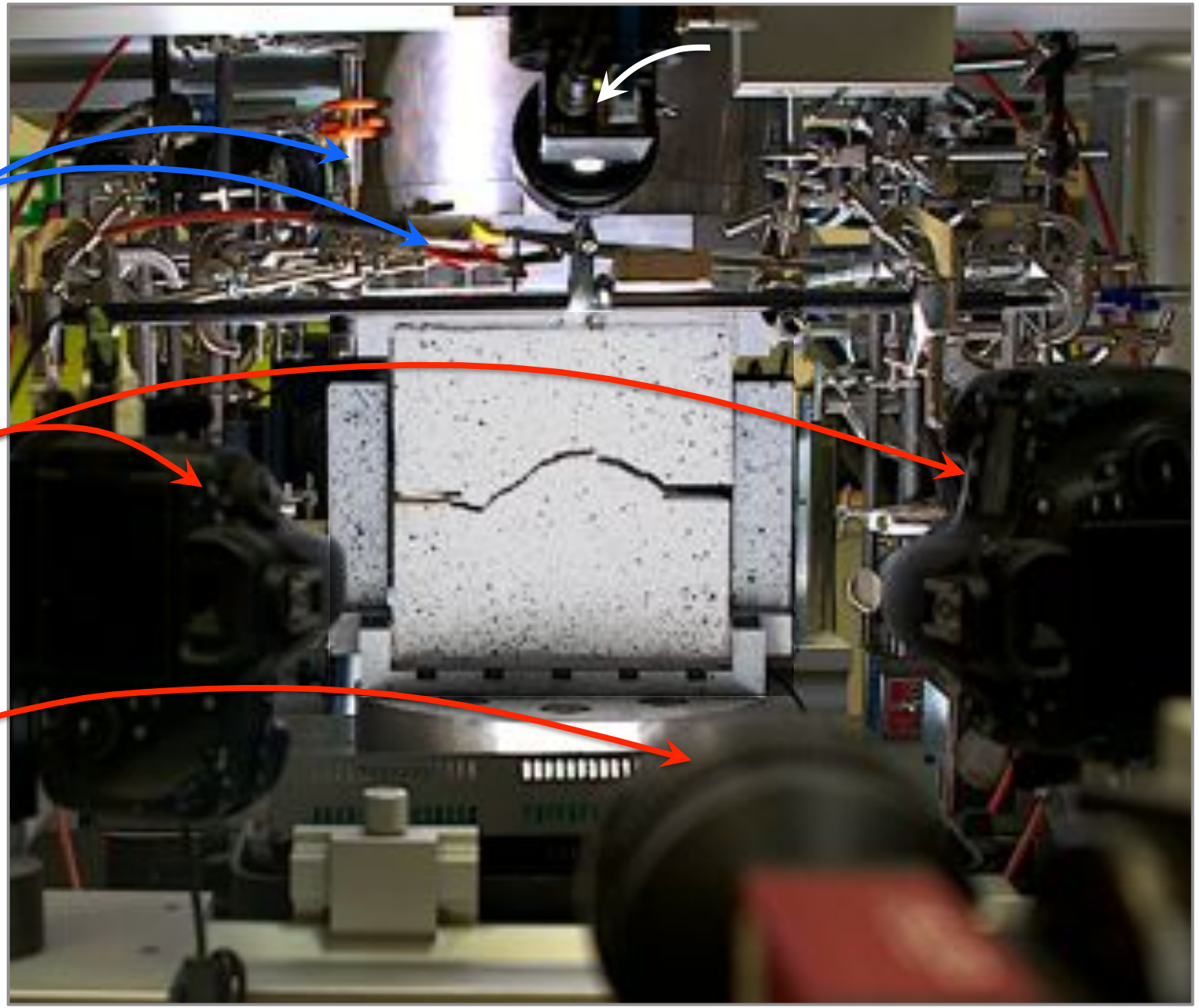
Complete setup



Complete setup



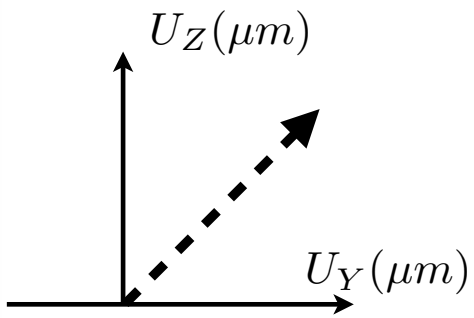
Complete setup



Choosing tests

- **N-M-like tests (limited to displacement control)**
  - Validate machine/protocol
  - Confirm (force/displacement measurement)
  - Enrich (full-field measurement)

prop.



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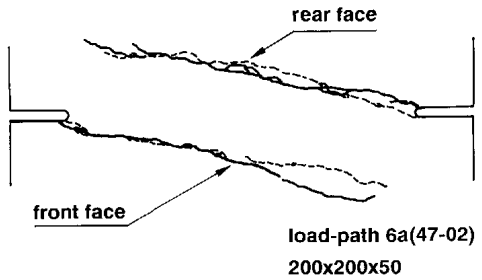
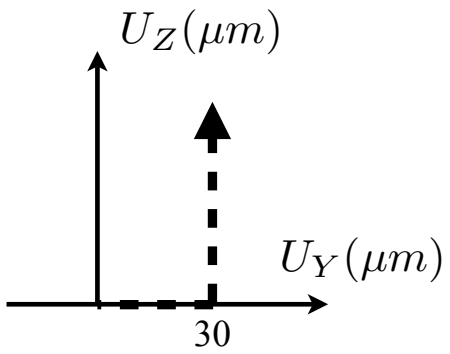
6a N-M tests (displ. control)



n-prop.



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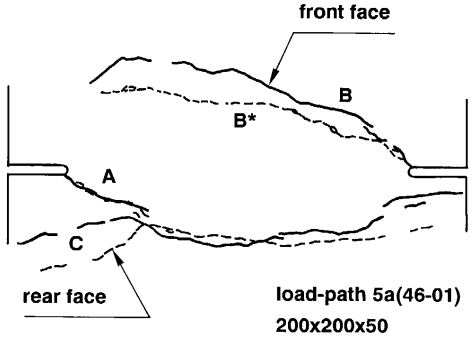
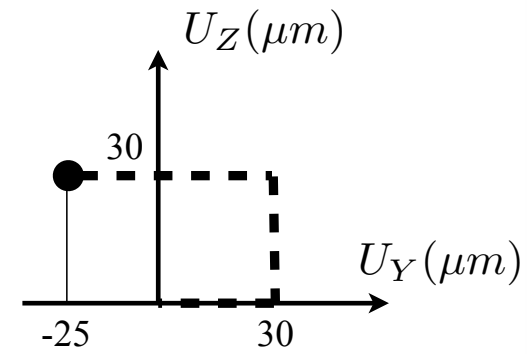
5 N-M tests (displ.+force control)





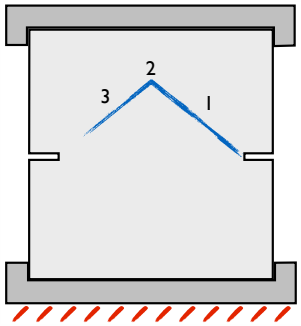
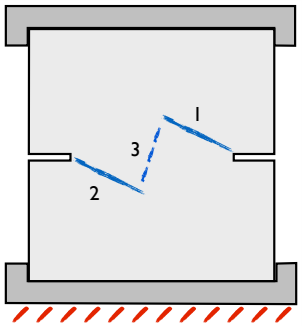
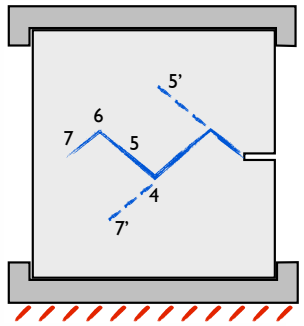
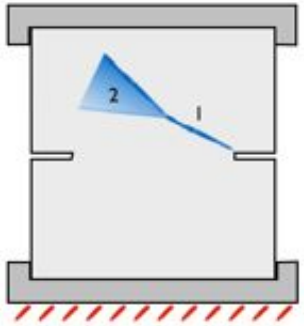
no equivalent

Choosing tests

- **« CARPIUC » tests**
  - Prove testing machine interest: in-plane & out-of-plane DOF are relevant
  - Prove testing protocol : stable mode I-II propagation
  - Build rich database
    - stable propagation
    - multiple initiation
    - réorientation
    - branching
    - linking

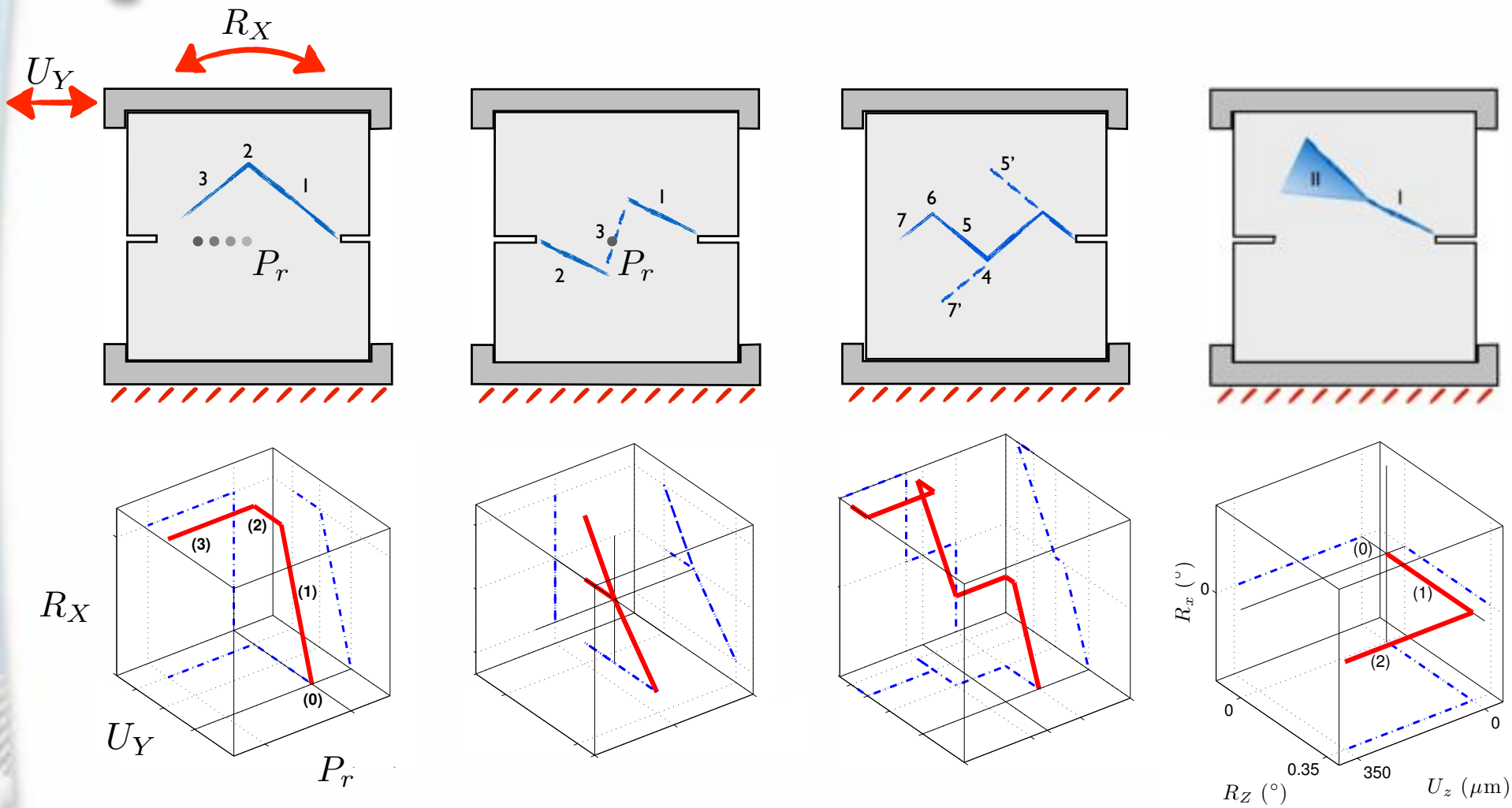
Choosing tests

« CARPIUC » tests : goals

			Test			
			1	2	3	4
						
Features	I-II	stable	+++	++	+++	+
		reorientation	++	?	+++	
		branching			+++	
		multiple ini.		+++		?
		linking		+++		
	III					+++

Choosing tests

« CARPIUC » tests : how ?



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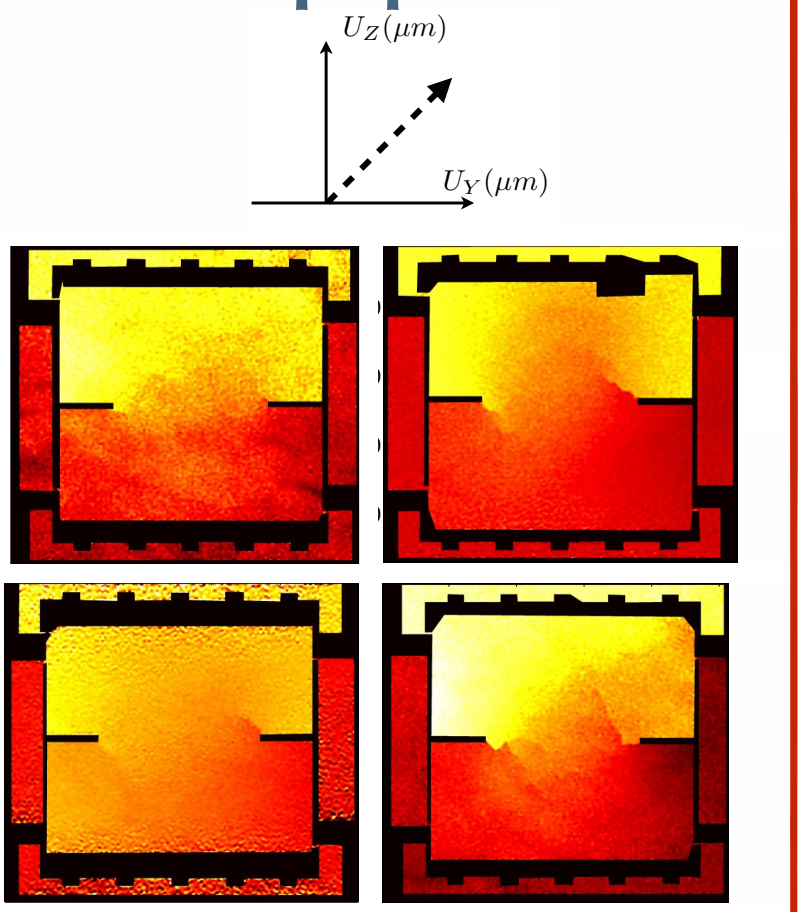
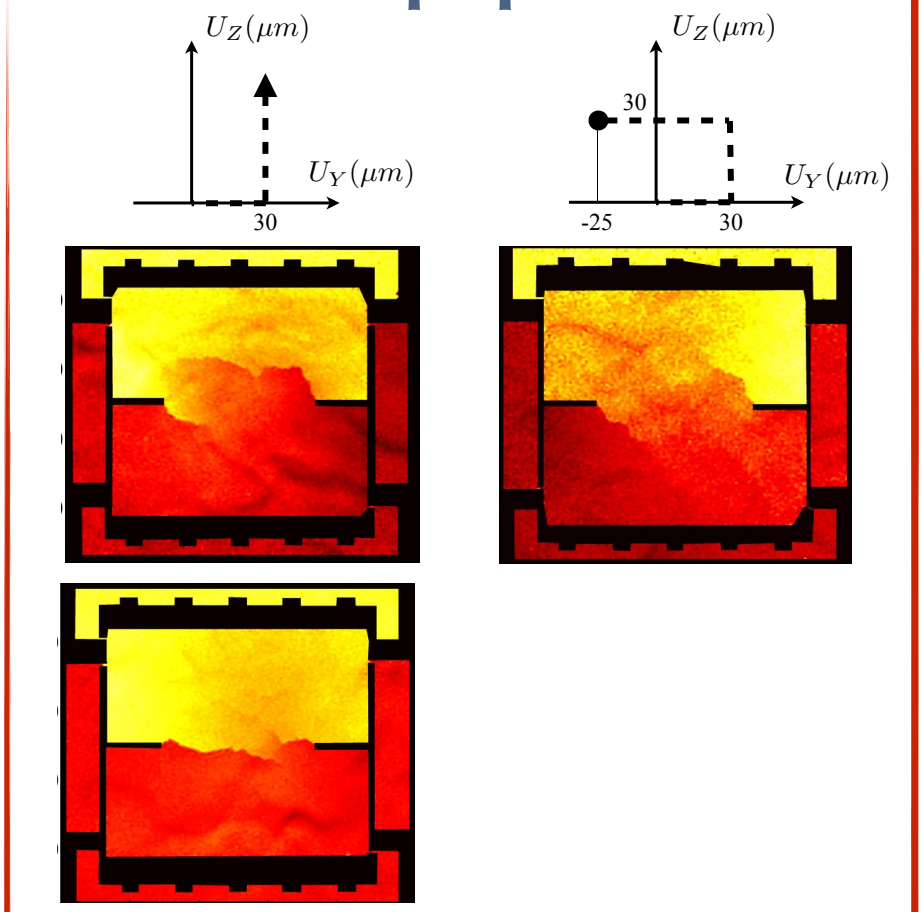
N-M-like tests results in a nutshell

prop.



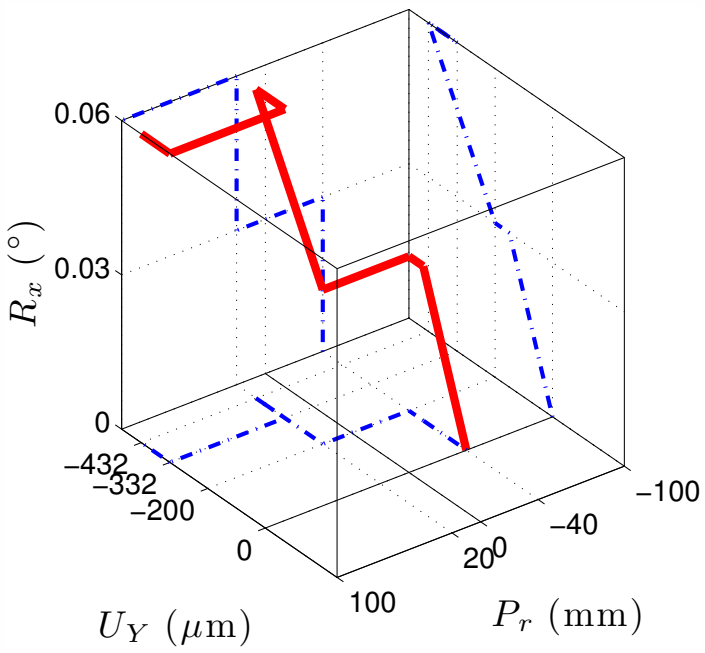
n-prop.

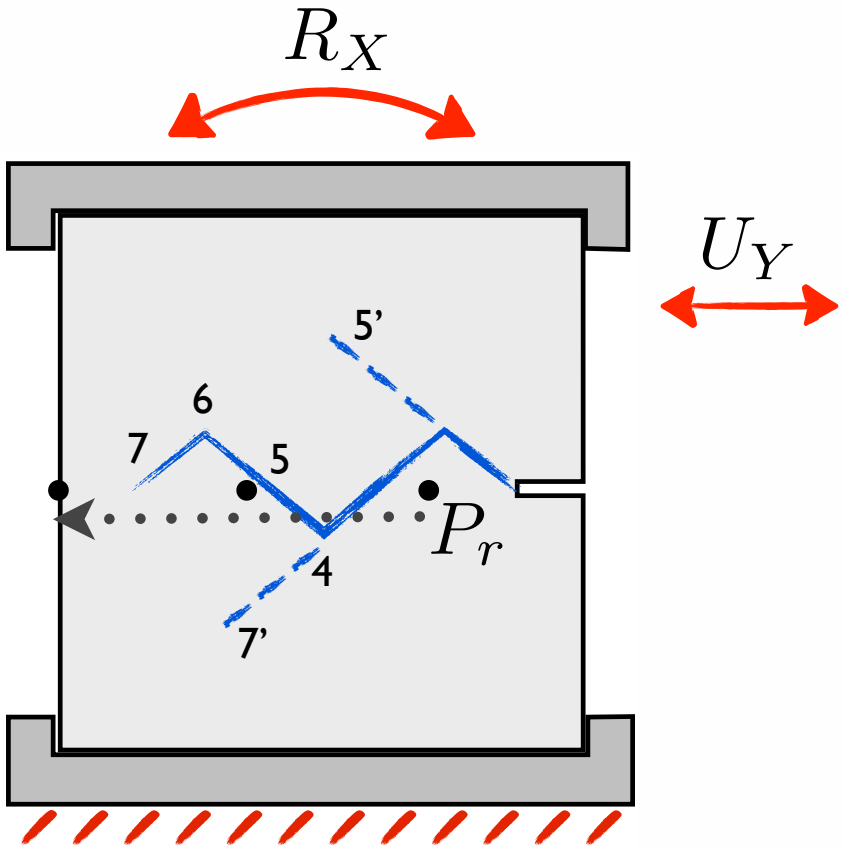


- **Very early unstable propagation**
- **Surface crack ≠ bulk crack**
  - Surface cracks differ for the same loading
  - Surface cracks ≠ final cracks
  - Apparent ligament ≠ stiffness decrease

Test 3 : Expected crack path

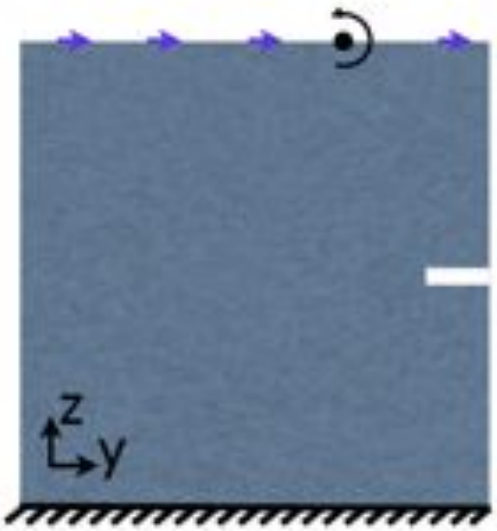
- Several reorientations
- Possible branching

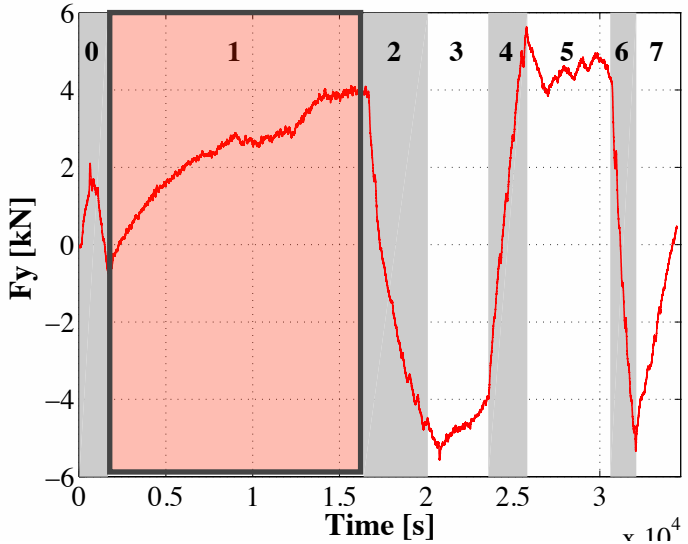


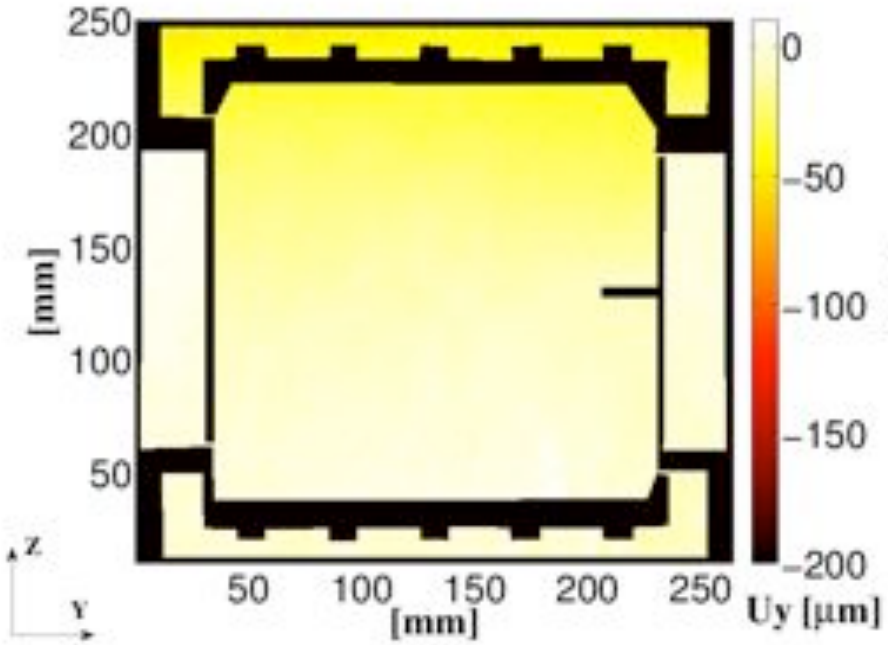


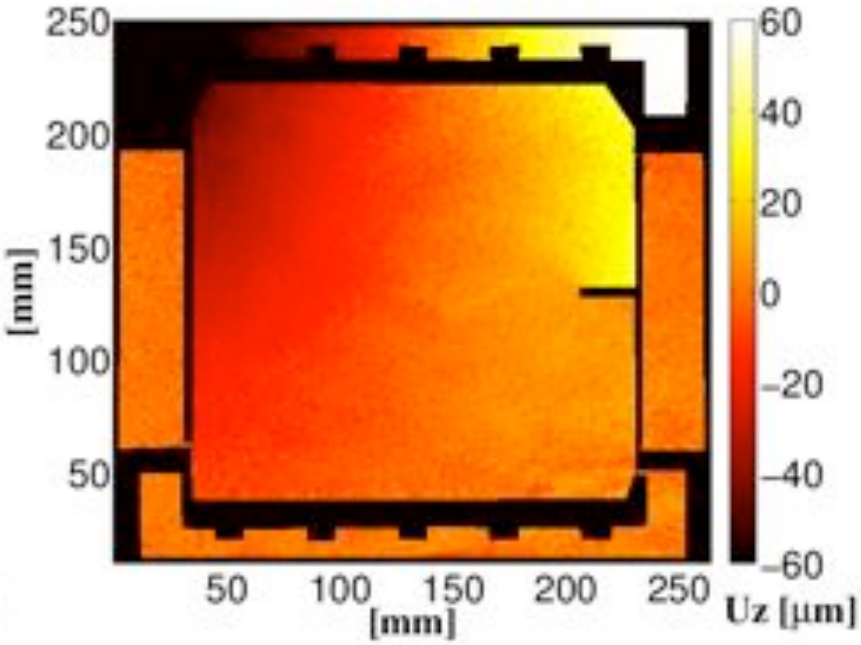
CARPIUC test 3: force and crack evolution

Step 1



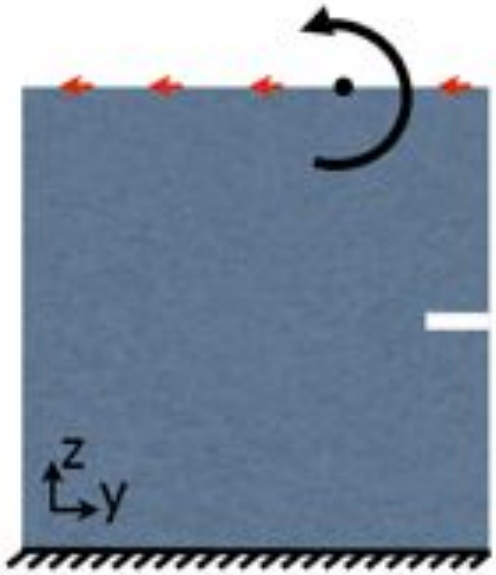


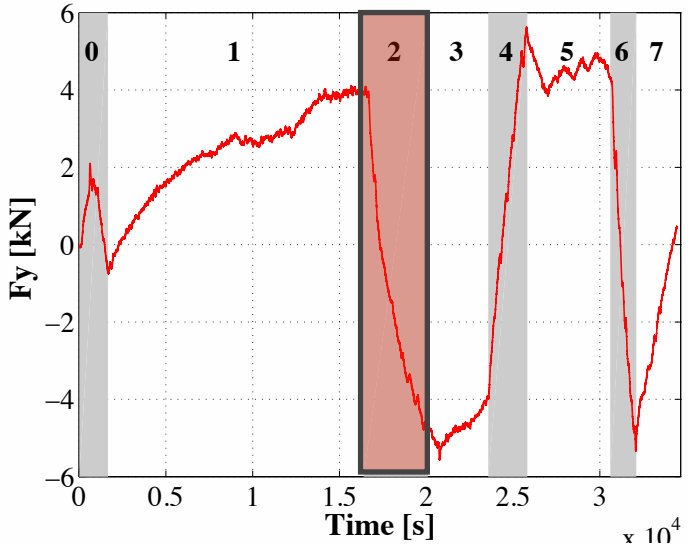


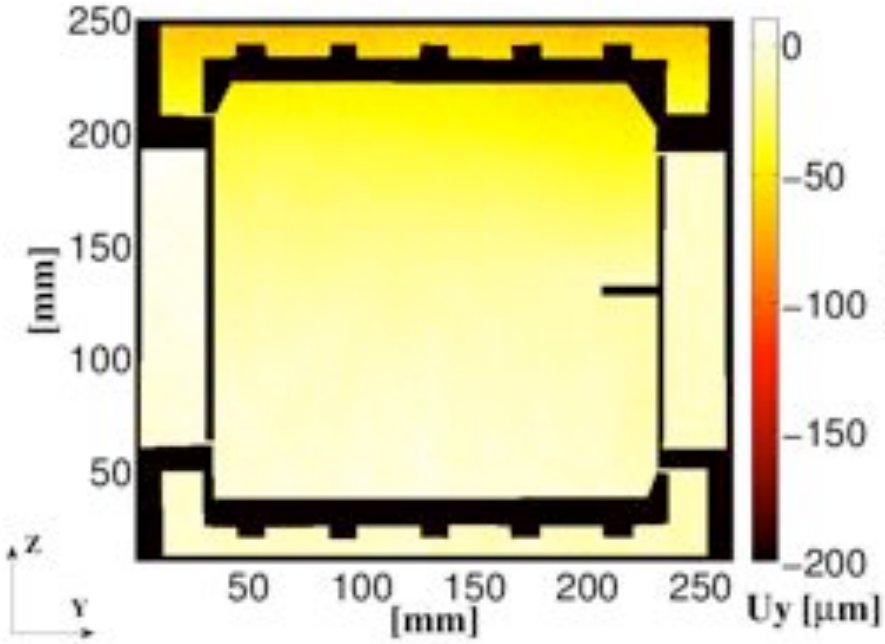


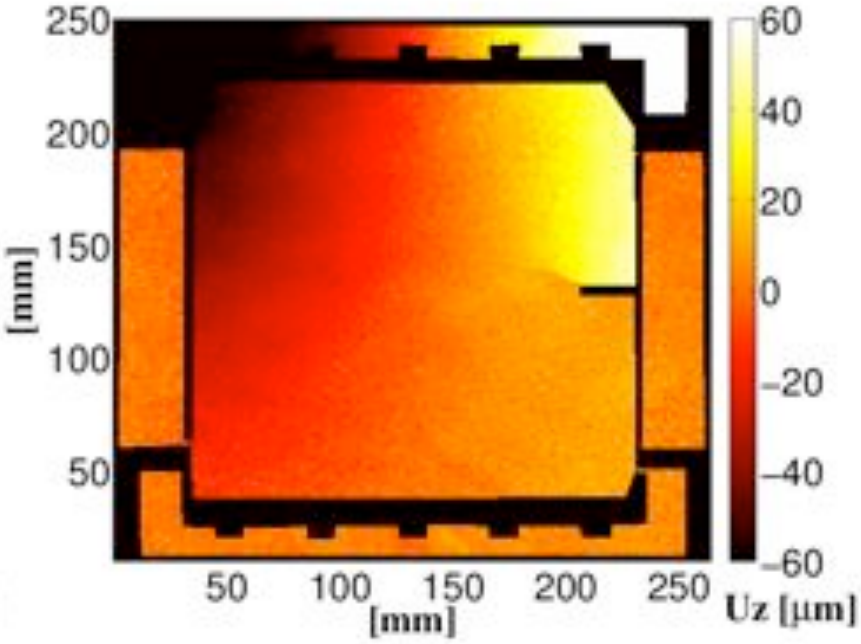
CARPIUC test 3: force and crack evolution

Step 2



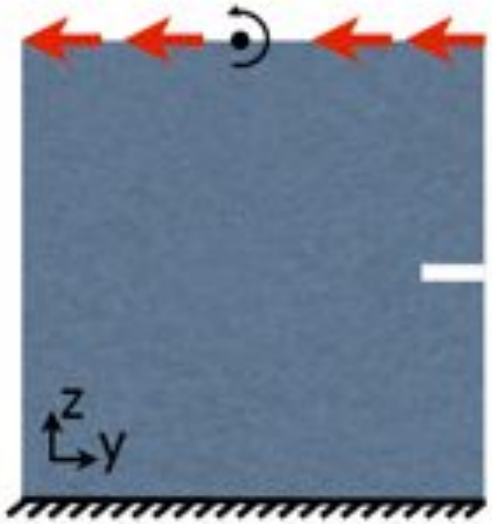


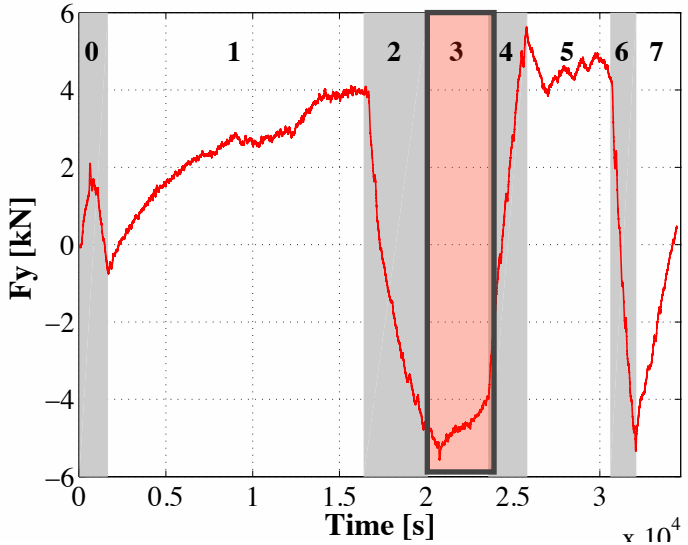


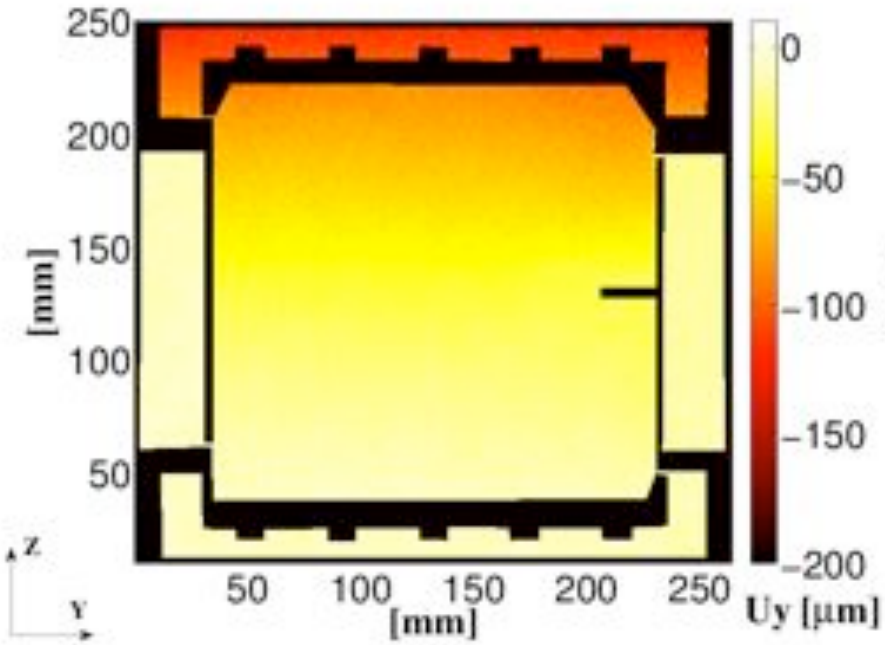


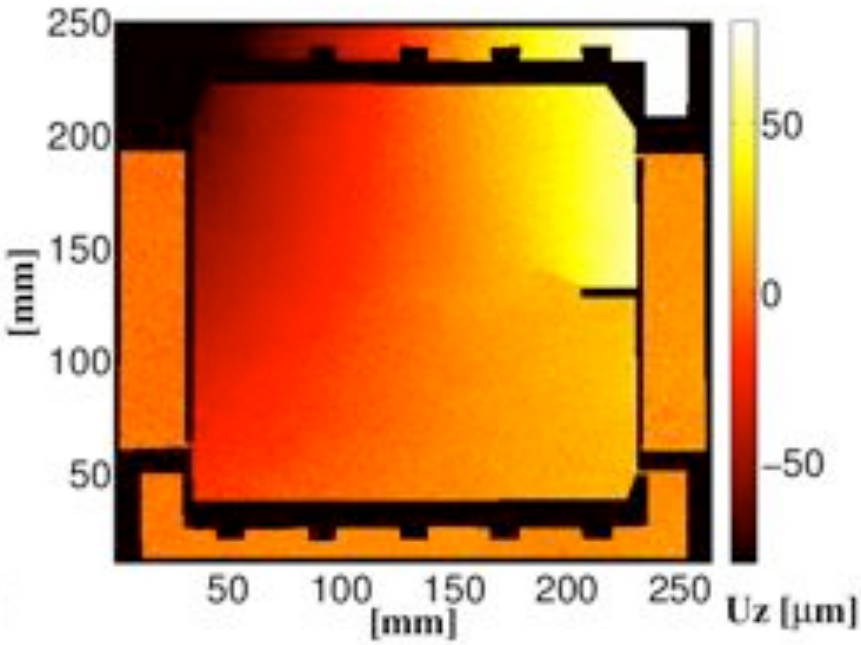
CARPIUC test 3: force and crack evolution

Step 3



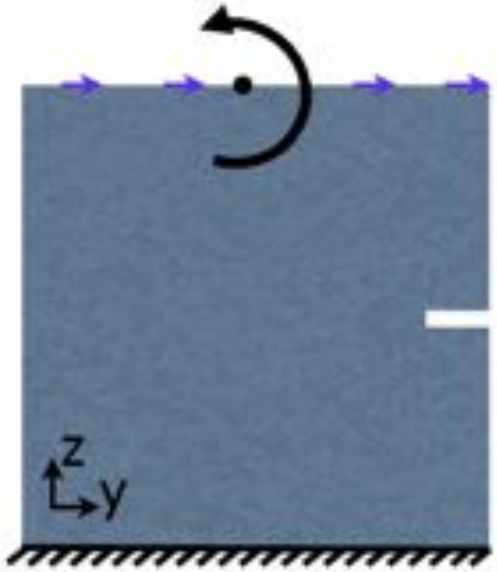


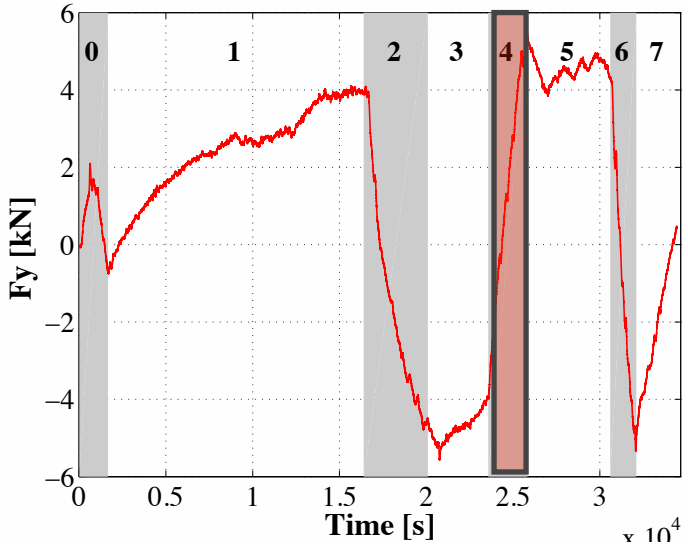


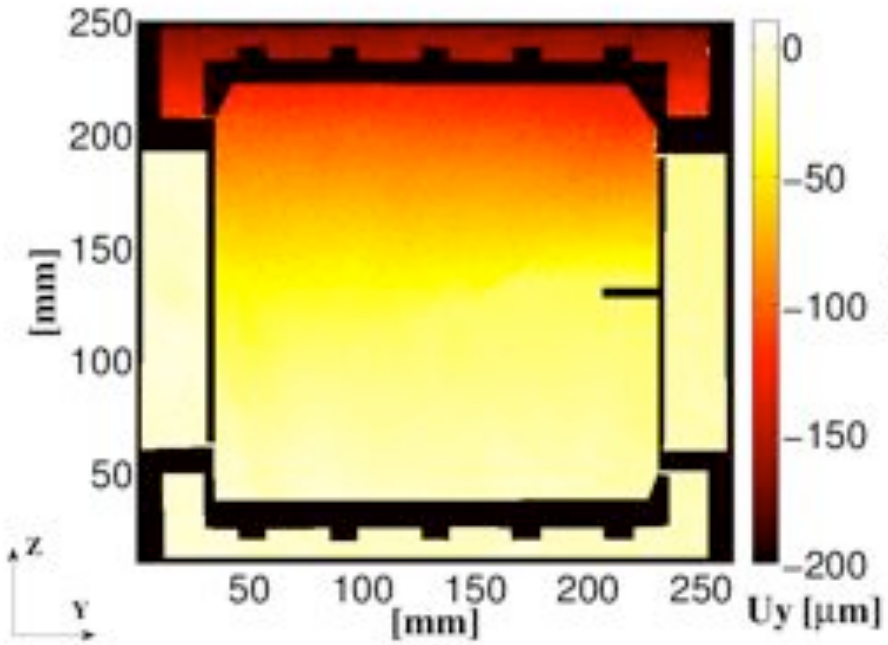


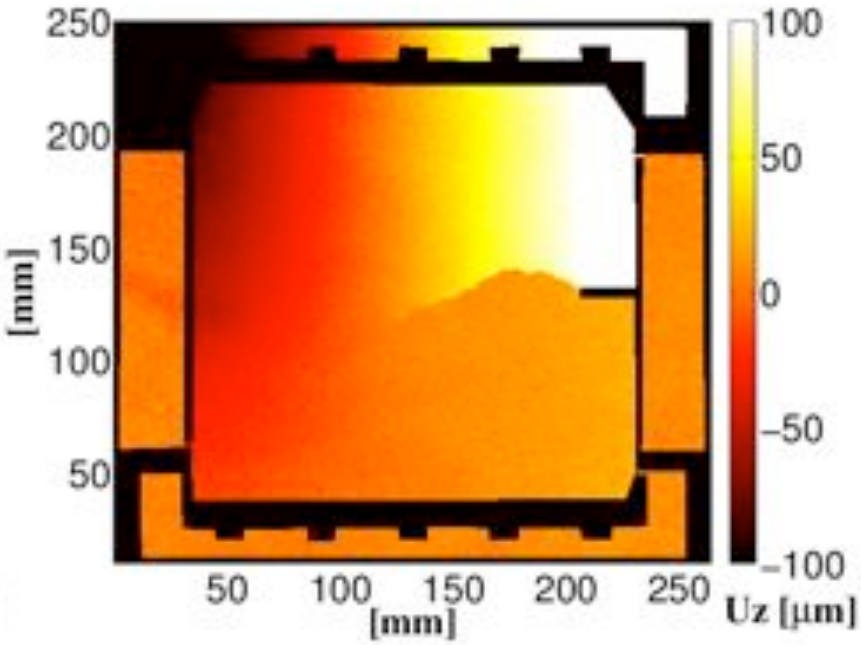
CARPIUC test 3: force and crack evolution

Step 4



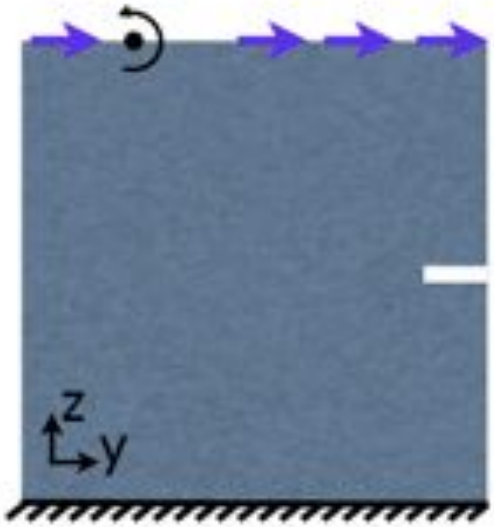


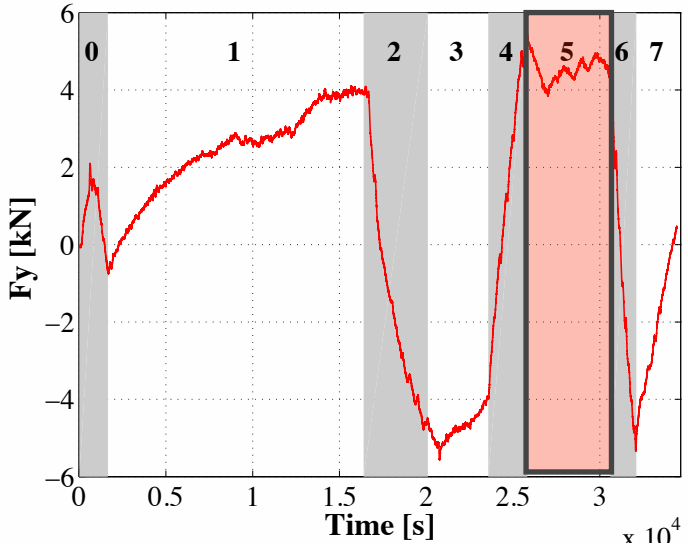


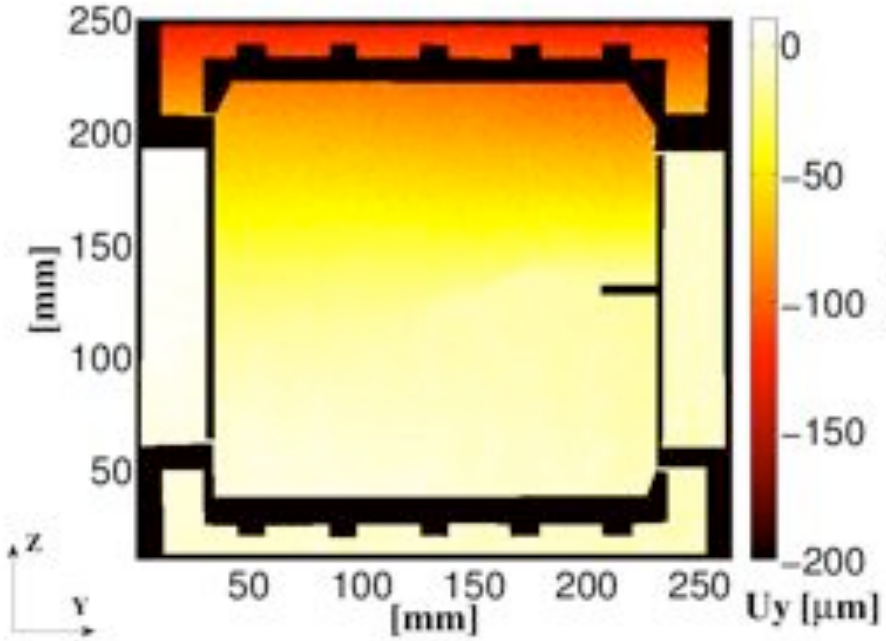


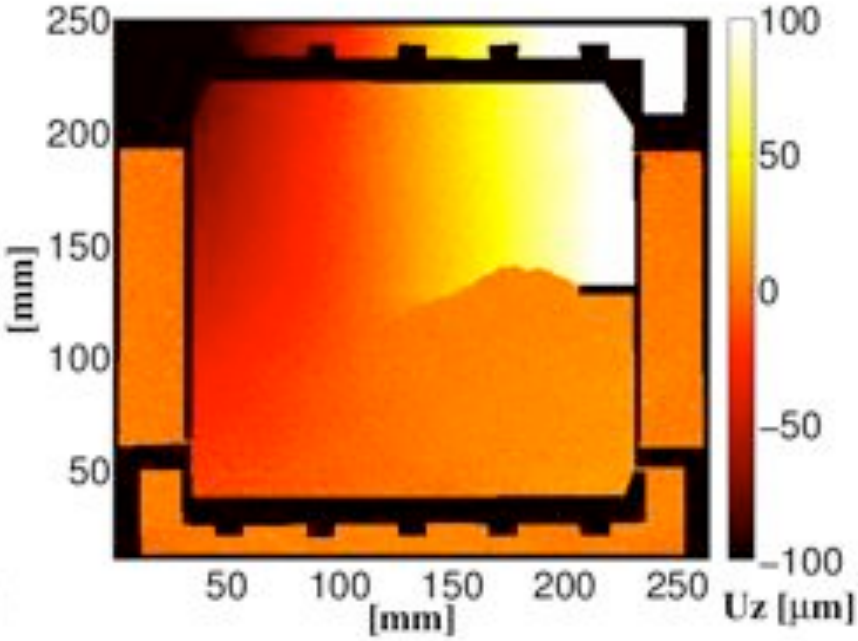
CARPIUC test 3: force and crack evolution

Step 5



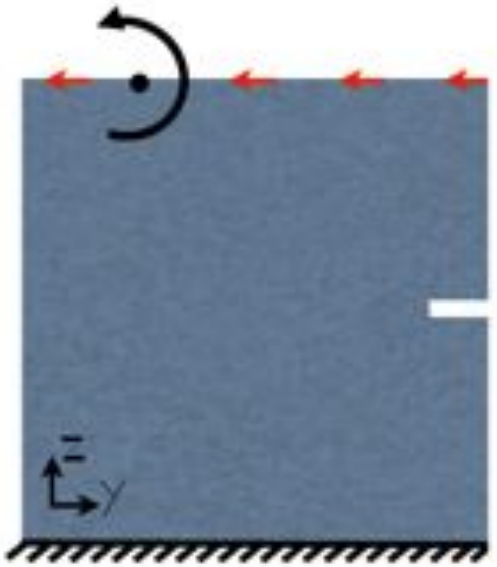


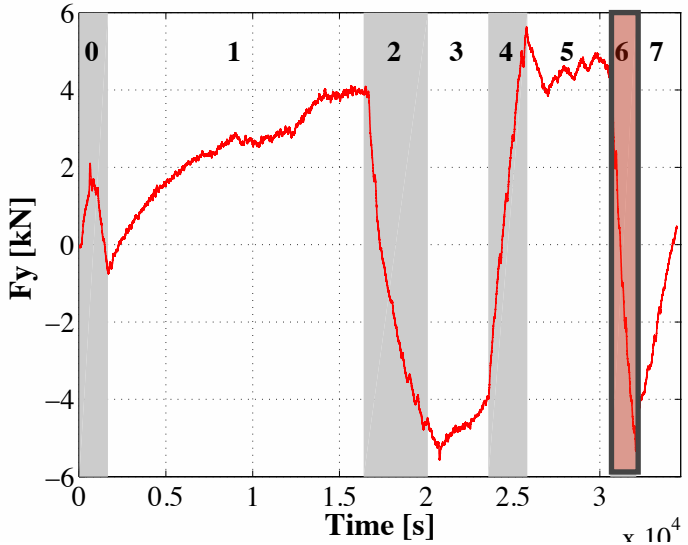


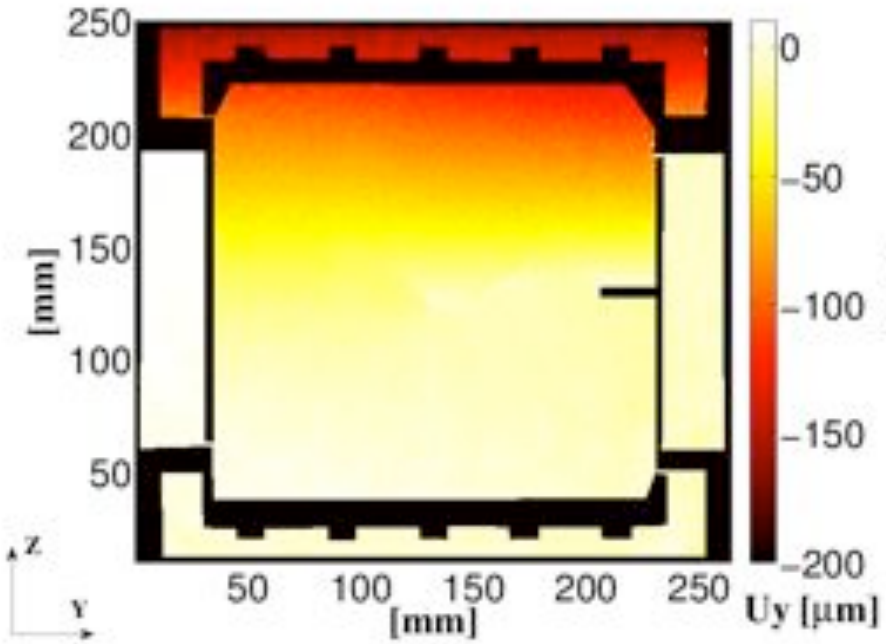


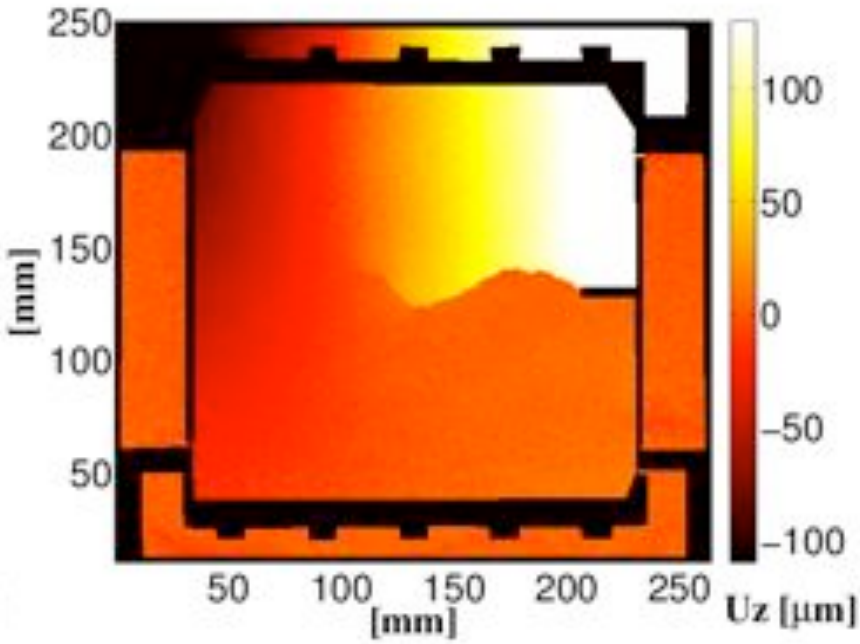
CARPIUC test 3: force and crack evolution

Step 6



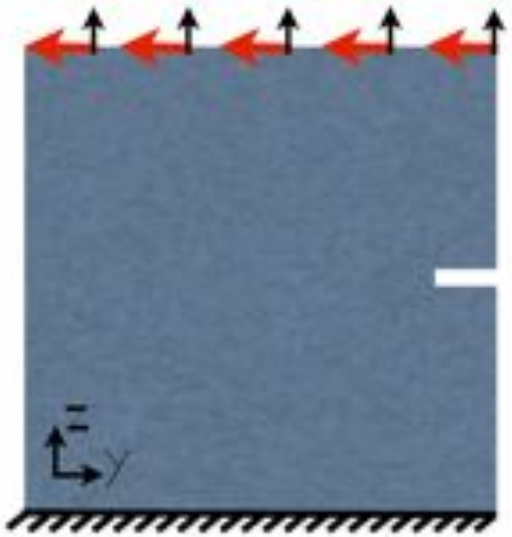


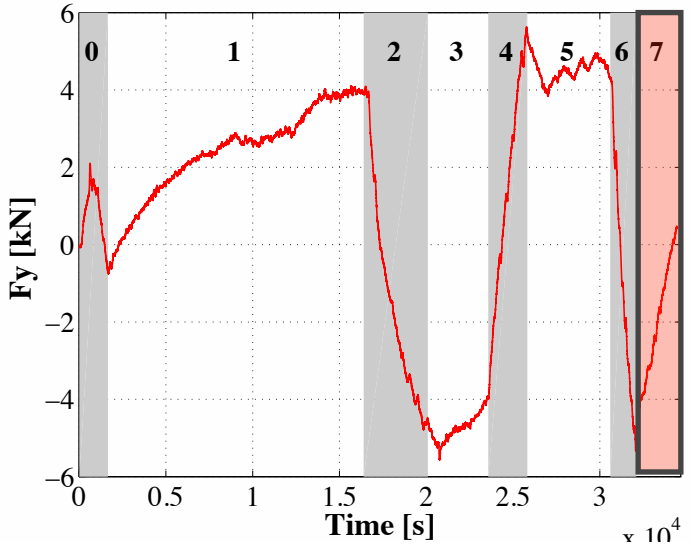


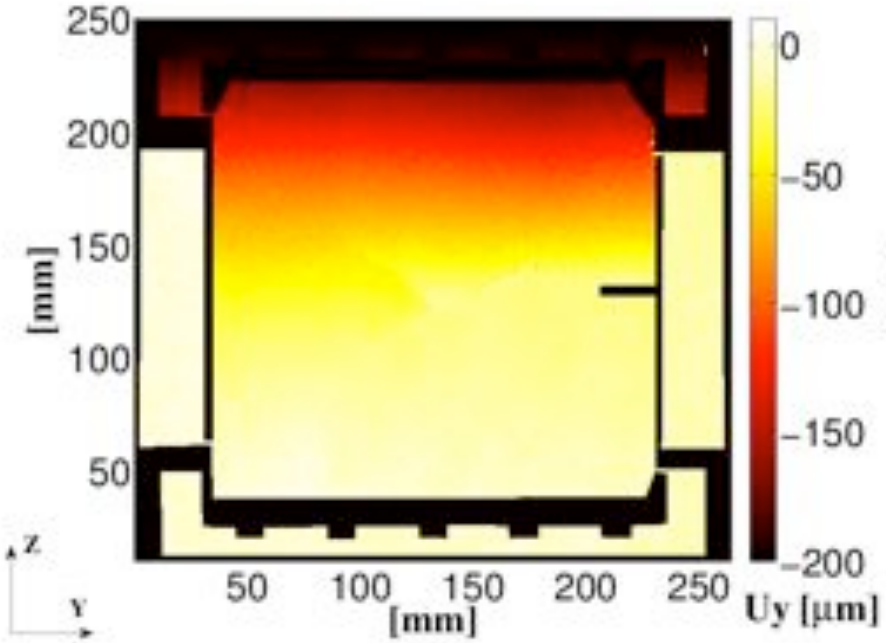


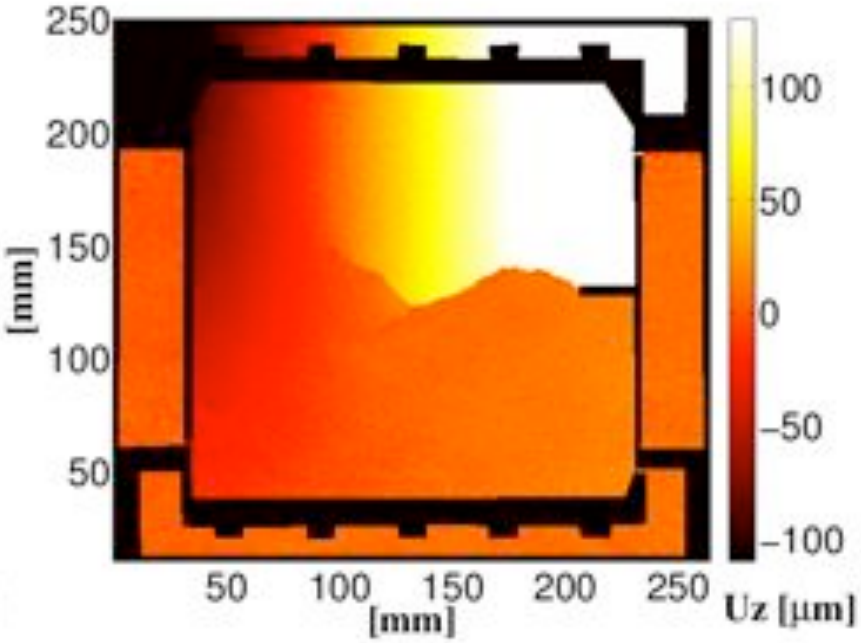
CARPIUC test 3: force and crack evolution

Step 7

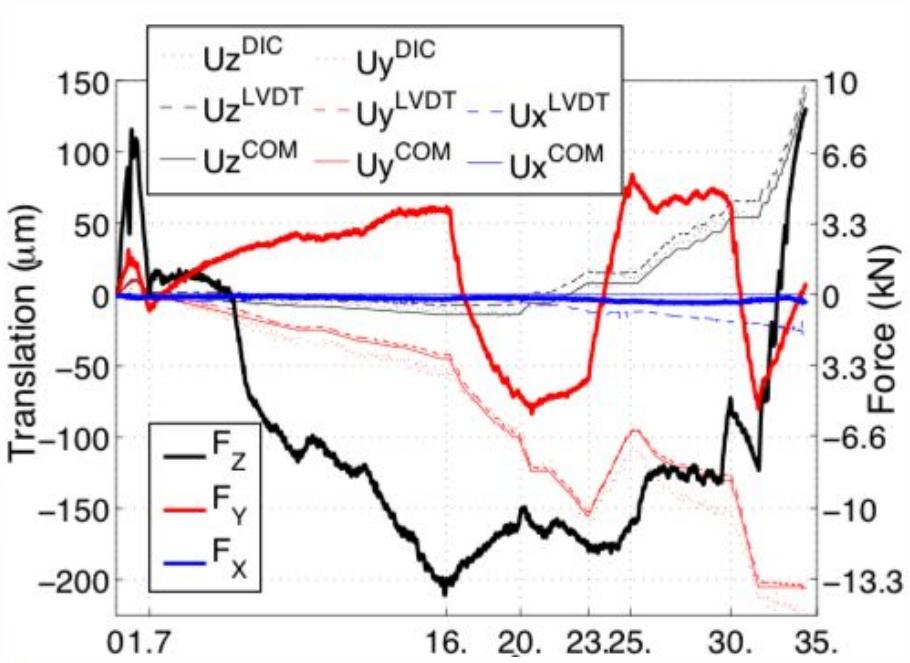


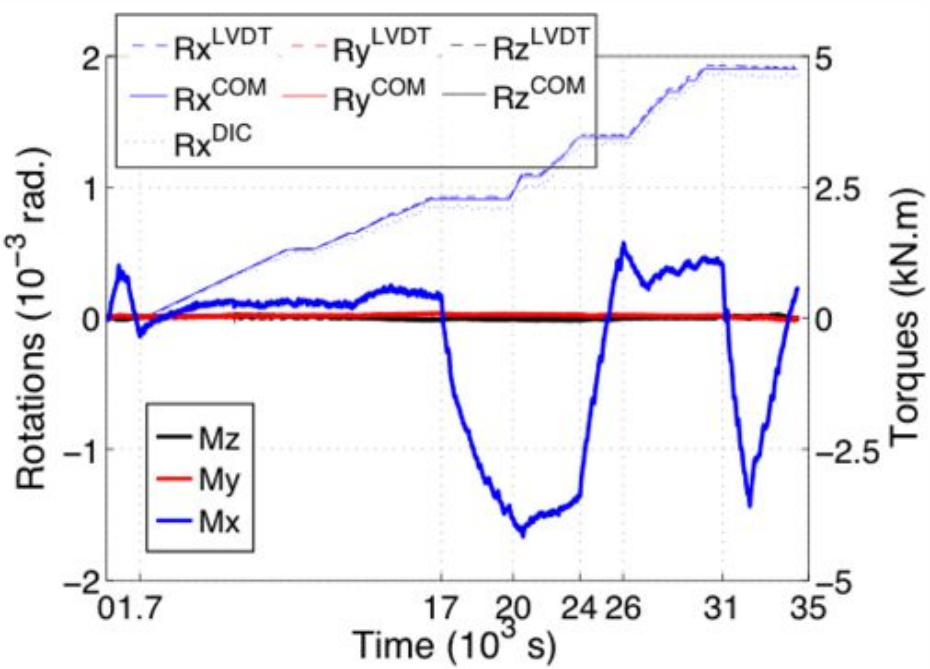






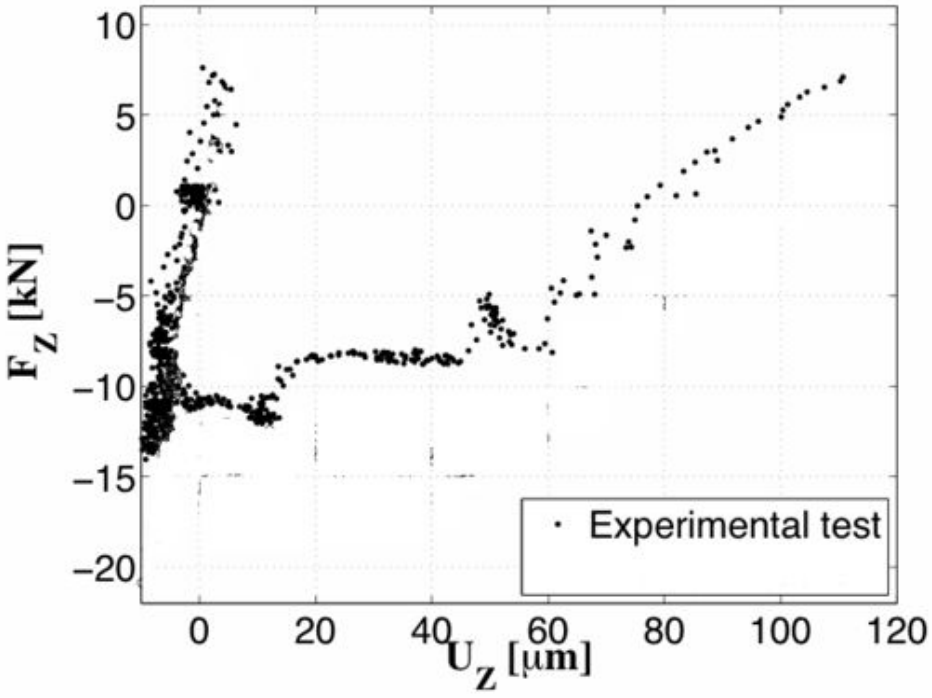
CARPIUC test 3: force & displ.

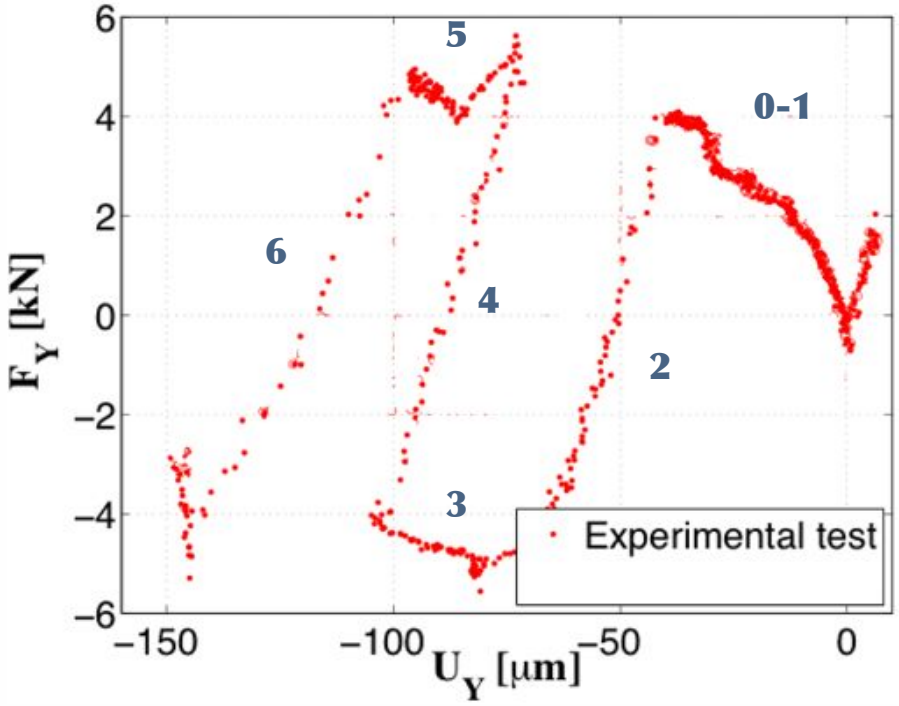




(Test duration ~ 9h30)

CARPIUC test 3: force vs displ.



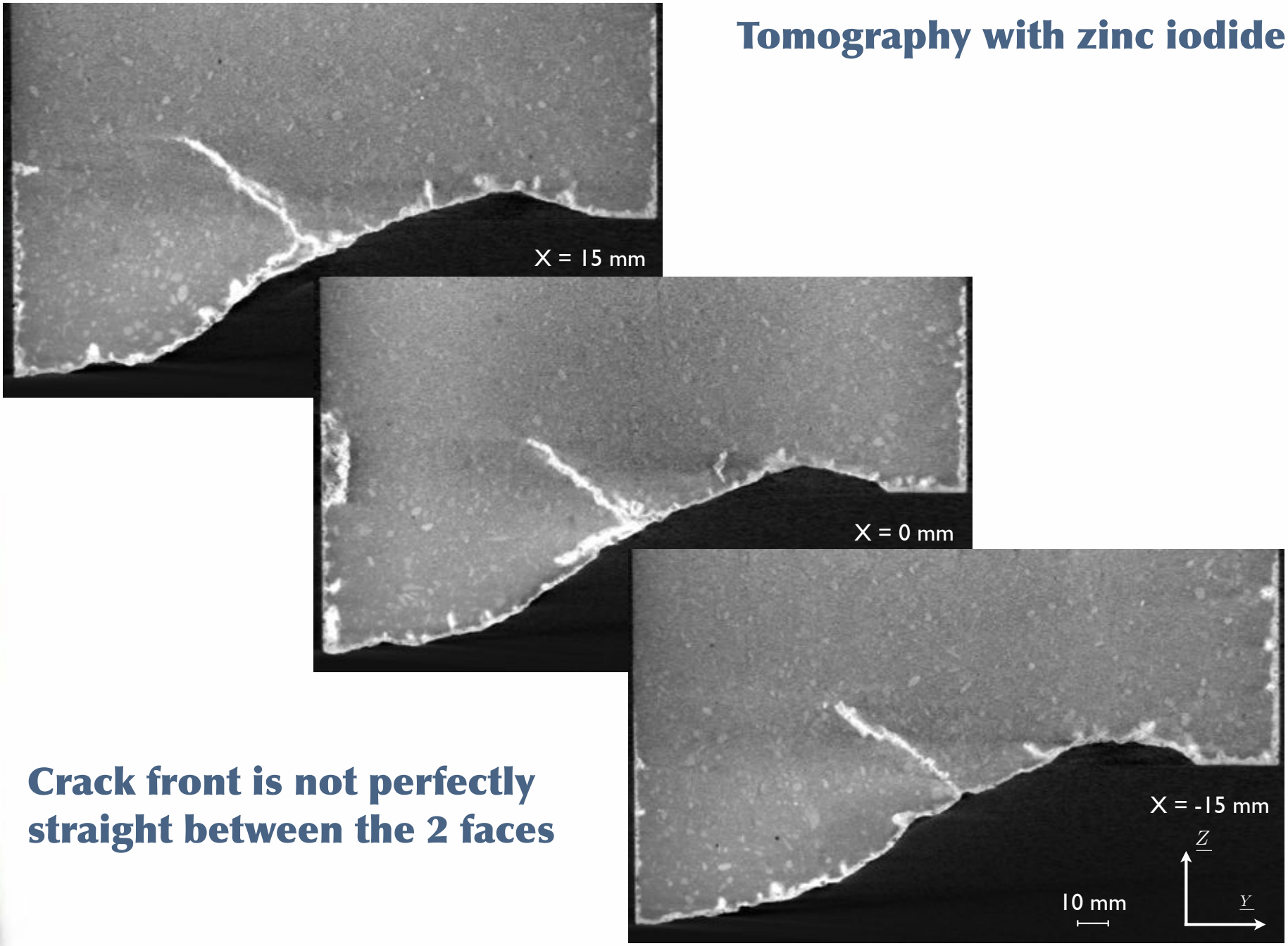


Force-displacement curves:

- **loss of stiffness**
- **crack closure**

CARPIUC tests 3: final state

Tomography with zinc iodide



Crack front is not perfectly straight between the 2 faces

CARPIUC test 3: data

Raw:

- **Force: 25.2 Mb**
- **LVDT: 25 Mb**
- **Images from 2 front cameras: 0.1Tb**
- **Images from 4 sides cameras: >1 Tb**

Processed:

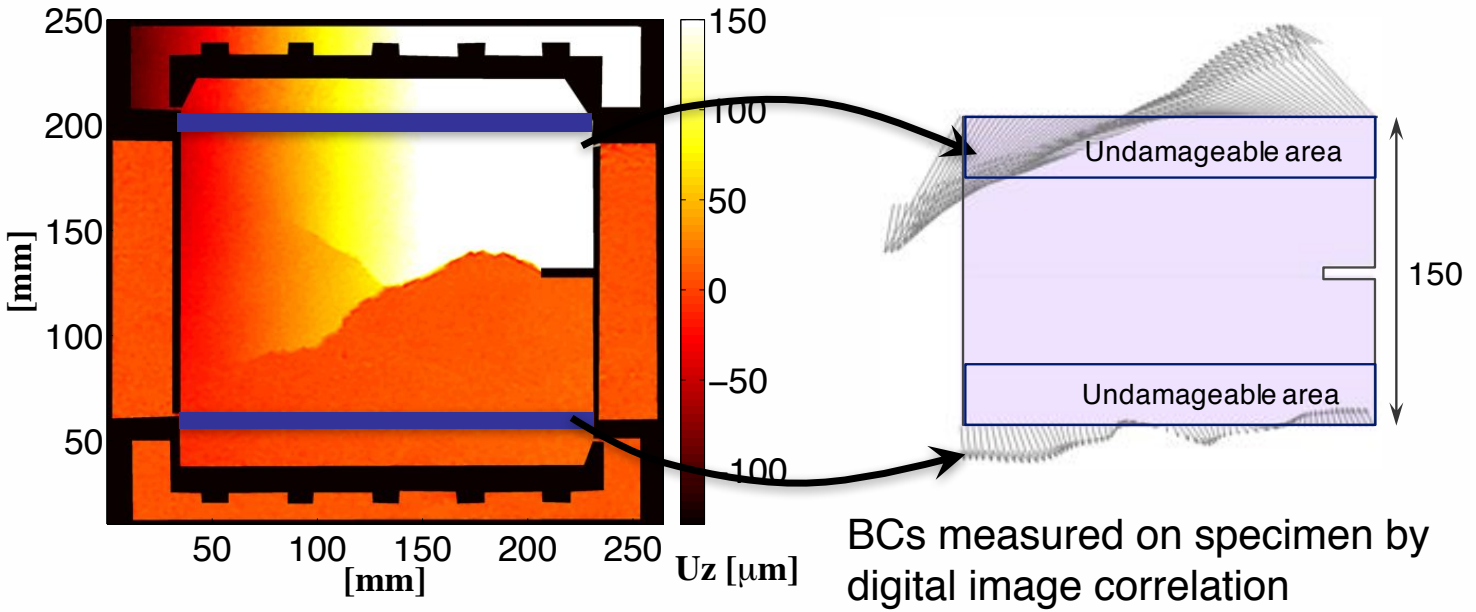
- **Mono DIC: 1 Tb**
- **Stereo DIC: not fully processed**
- **Boundary condition from DIC: 6.8 Mb**

Outline

- **Motivation**
- **Experimental protocol**
  - Principle
  - Technical settings
  - Loading paths
- **Experimental campaign results**
  - N-M-like tests
  - CARPIUC tests
- **Spreading the data**
- **Summary & perspectives**

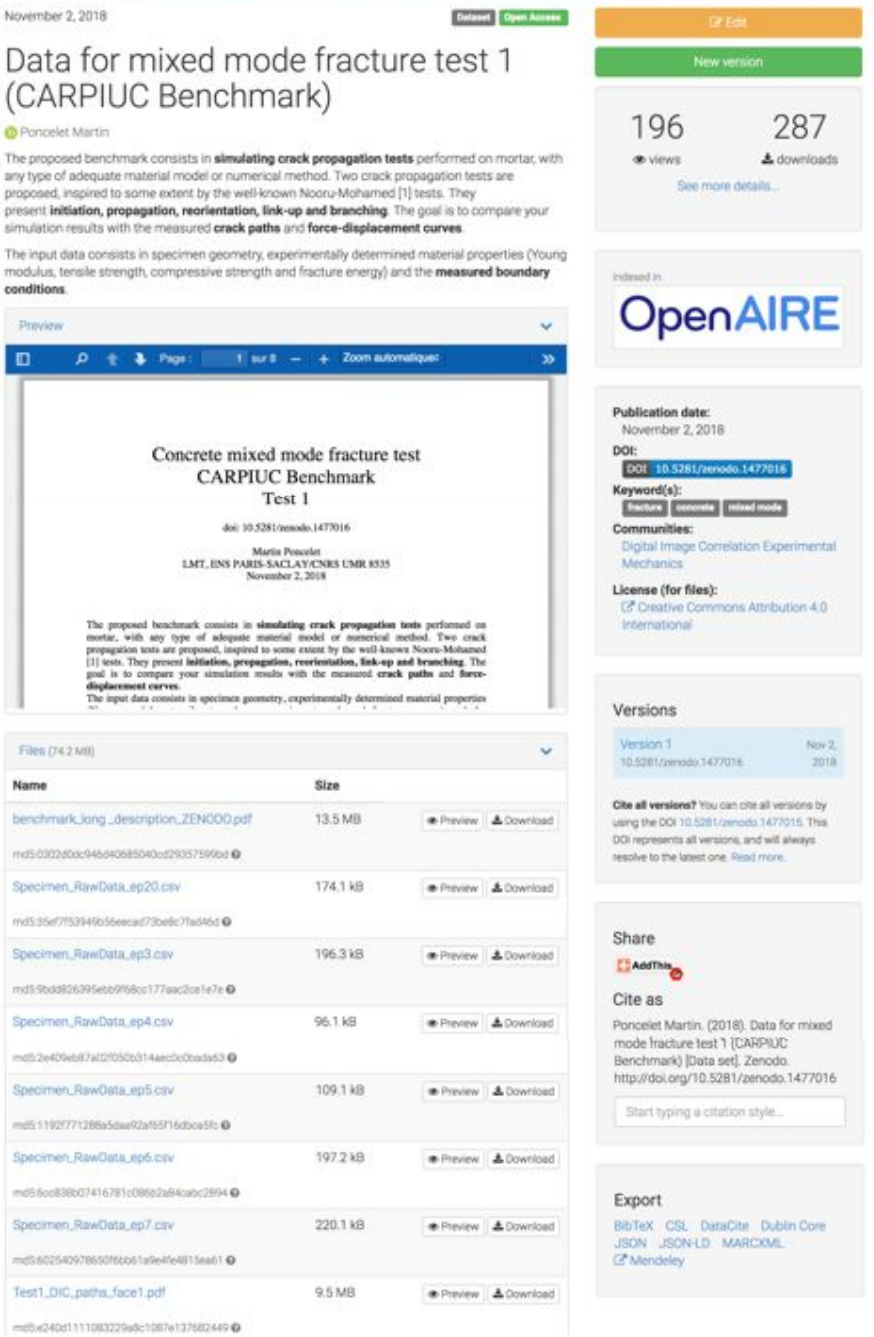
Benchmark principle

- **Available data for test simulation:**
  - Specimen geometry
  - Standard material parameters
  - F-d curves for Gf identification
  - Boundary conditions temporal evolution
- **Available data for checking results:**
  - Force & torque temporal evolution
  - Displacement fields at some specific time steps



BCs measured on specimen by digital image correlation

Online database



- **DOI: identification and citation**
- **Flexible licensing:**
  - **Closed**
  - **Restricted**
  - **Embargoed**
  - **Open**  
- **Safe: CERN's LHC cloud infract.**

zenodo.org/record/1477016

References

Initial work:

- Carpiuc-Prisacari A. *Innovative tests for characterizing mixed-mode fracture of concrete: from pre-defined to interactive and hybrid tests*, PhD Thesis, 2015

Benchmark summary:

- Carpiuc A., Poncelet M., Réthoré J., Roux S., *CARPIUC benchmark overview: crack advance, reorientation, propagation and initiation under complex loadings,* Adv. Mod. and Sim. in Eng. Sc., 2018, 5(1)

Testing machine:

- Le Flohic J., Parpoil V., Bouissou S., Poncelet M., Leclerc H., *IA 3D Displacement Control by Digital Image Correlation for the Multiaxial Testing of Materials with a Stewart Platforms*, Exp. Mech., 2014, 54, 817–828

Tests results:

- Carpiuc-Prisacari A., Poncelet M., Kazymyrenko K., Leclerc H., Hild F. *A complex mixed-mode crack propagation test performed with a 6-axis testing machine and full-field measurements*. Eng. Fract. Mech. 2017 176, 1-22.
- Carpiuc-Prisacari A. Jailin C., Poncelet M., Kazymyrenko K., Leclerc H., Hild F., *A series of mixed-mode crack propagation tests performed on concrete specimens with a 6 axes testing machine and full-field measurements. Part I : predefined loading tests,* in preparation
- Carpiuc-Prisacari A. Jailin C., Poncelet M., Kazymyrenko K., Leclerc H., Hild F., *A series of mixed-mode crack propagation tests performed on concrete specimens with a 6 axes testing machine and full-field measurements. Part II : interactive loading tests,* in preparation

Boundary condition choice:

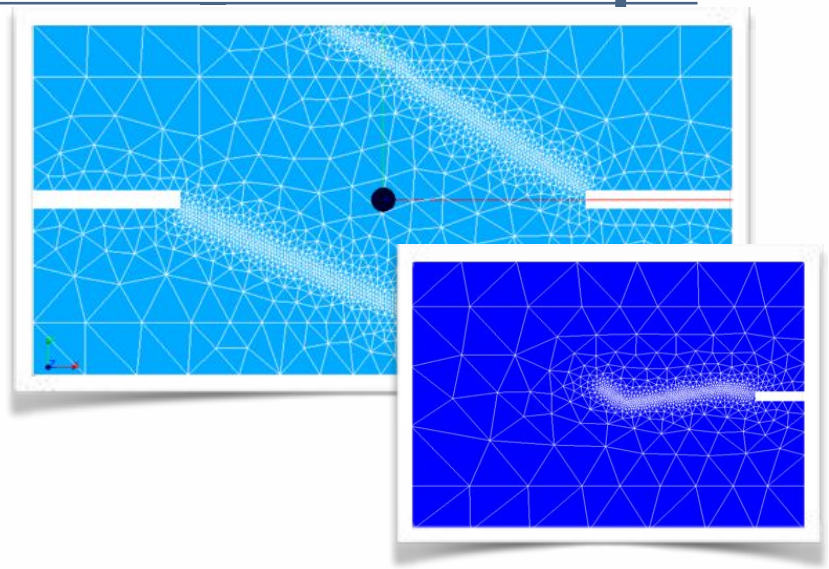
- Carpiuc-Prisacari A., Poncelet M., Kazymyrenko K., Hild F., Leclerc H. *Comparison between experimental and numerical results of mixed-mode crack propagation in concrete: Influence of boundary conditions choice*. Cem. & Con. Res. 2017, 100, 329-340

Simulations:

- Wu T., Carpiuc-Prisacari A., Poncelet M., De Lorenzis L., *Phase-field simulation of interactive mixed-mode fracture tests on cement mortar with full-field displacement boundary conditions* Eng. Fract. Mech., 2017, 182, 658-688
- Oliver-Leblond C., *Discontinuous crack growth and toughening mechanisms in concrete: A numerical study based on the beam-particle approach,* Engineering Fracture Mechanics, 2019, 207 (15), 1-22

Additional facts

- **Code_Aster test-case**
  - **SSNP168**
    Endommagement d'éprouvettes béton de type Nooru-Mohamed
  - **For damage model validation**
  - **Proposed optimized 2D meshes**
  - **www.code-aster.org/V2/doc/default/fr/man_v/v6/v6.03.168.pdf**

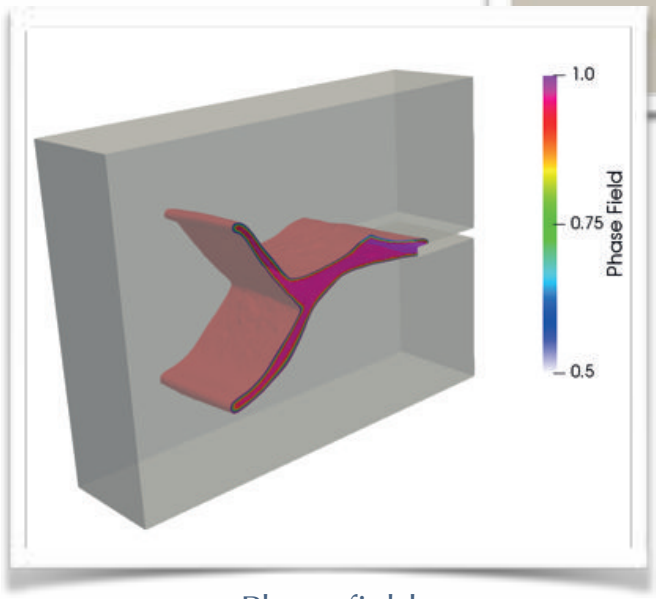


- **Physical database ;)**
  - **Samples are still available**
    - **4x416**
    - **7x7x28**
    - **16x32**
  - **Kept in PH-balanced water, room temperature**
  - **Ask if needed**

CFRAC17 & CFRAC19 benchmark summary

- **2017:**
  - 7 teams (2 international)
  - 6 different approaches:
    - Beam-particle
    - Cohesive zone
    - Microplane
    - Phase field
    - Non-local damage
    - Thick Level Set
- **2019 (up to now)**
  - 1 Phase field (1 team)
  - 1st deadline : tomorrow

Beam-particule



Phase-field

- **Keypoints:**
  - Different values of fracture energy were used to match !
  - Simulated Force-Displacement curves roughly agreed
  - Crack propagation simulation is not difficult, but other phenomenon are
  - Imposing full-field BC is difficult for some codes

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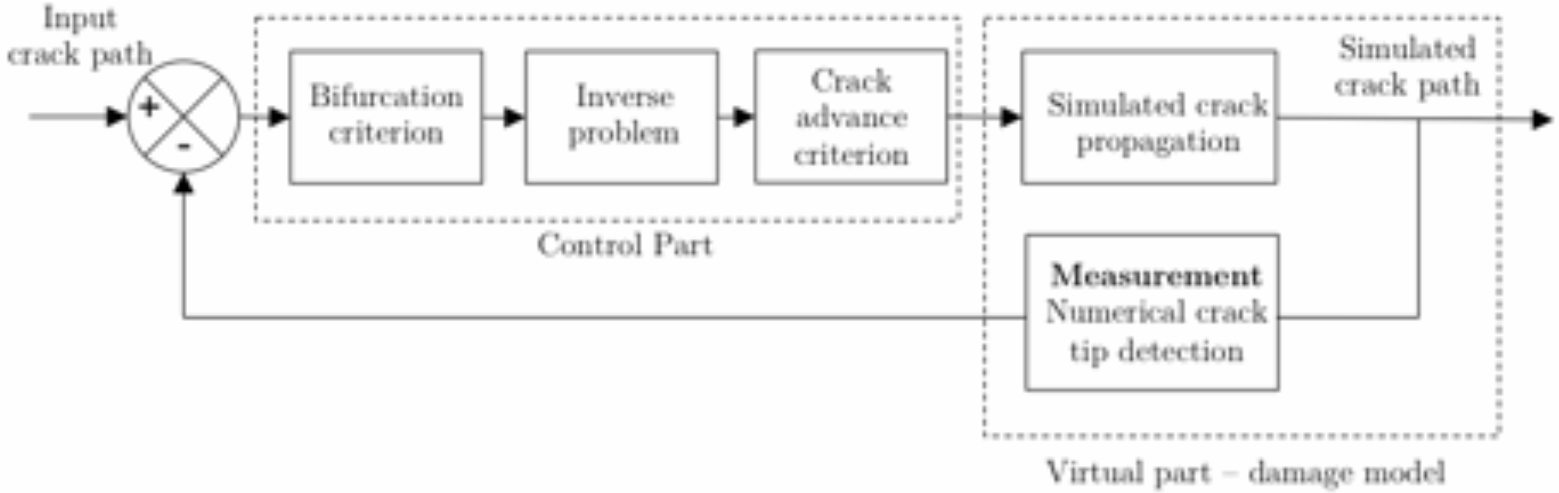
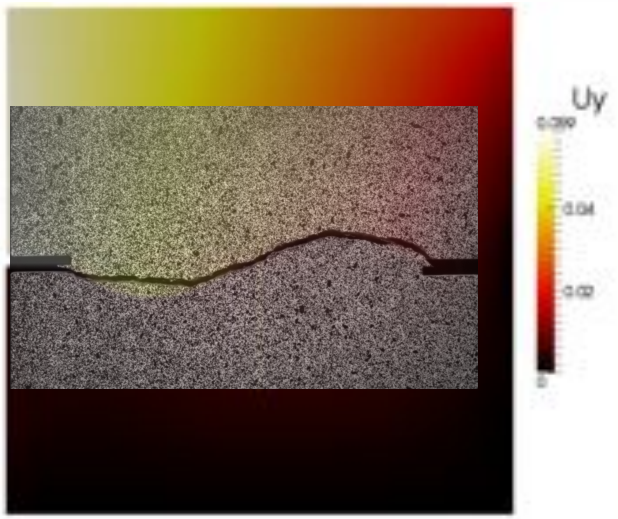
Summary

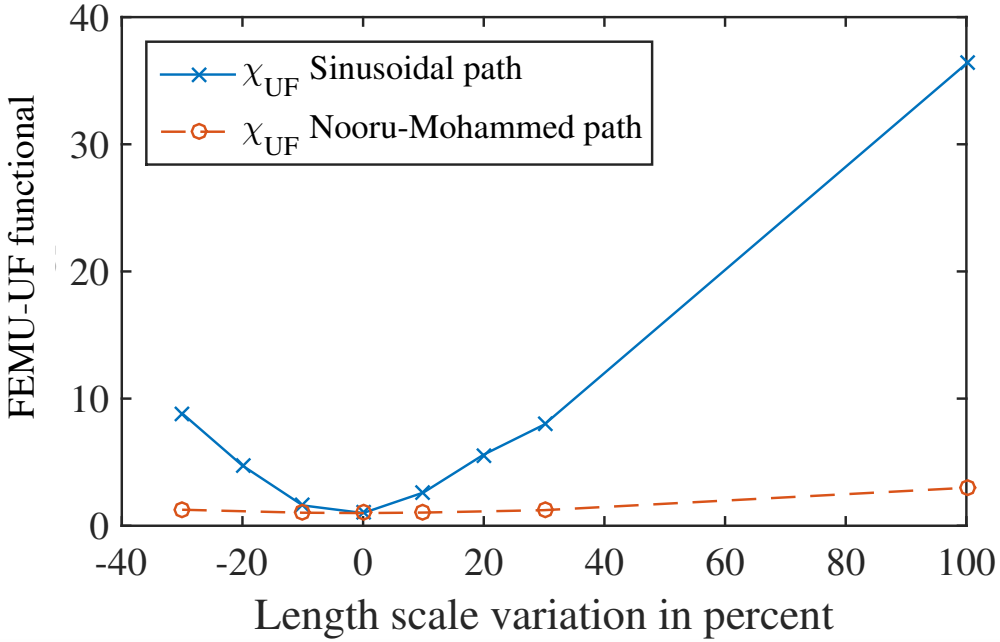
- **Long term work (2008-2019) from machine design to simulations**
- **Based on a simple idea: « just » improving a well-known test**
- **A lukewarm validation of Nooru-Mohamed results**
- **CARPIUC test validation interest:**
  - Restricted material type
  - Stupid for propagation simulation
  - Rich for other phenomena:
    - reorientation
    - branching
    - link-up
- **Large communication**
  - Articles
  - Benchmark sessions
  - Downloadable data
  - Several teams already challenged !

Perspectives: toward hybrid testing

Hydrid testing with real and virtual specimen to have sensitive tests







[C. JAILIN et al. Virtual hybrid test control of sinuous crack. JMPS 102, 239-256 2017]

Acknowledgments

- **Students**
  - S. Bouissou, V. Parpoil, J. Le Flohic — Hexapod develop.
  - C. Jailin — Hybrid test
  - A. Carpiuc-Prisacari — +/- everything ;)
- **Colleagues**
  - H. Leclerc — Coding support (GPU …)
  - K. Kazymyrenko — Num. Sim. (D), industr. partner
  - F. Hild, S. Roux — DIC support
  - J. Réthoré — Benchmark co-chairman
  - B. Smaniotto — X tomography
  - O. Rateau, B. Raka — Test support
  - T. Wu, L. De Lorenzis, C. Oliver-Leblond — Num. Sim (Ph.Field, Lattice)
- **Institutions/Company/Organisation**
  - EdF R&D — CIFRE PhD
  - Ile-de-France — Hexapod electronics funding
  - CFRAC — Benchmark support