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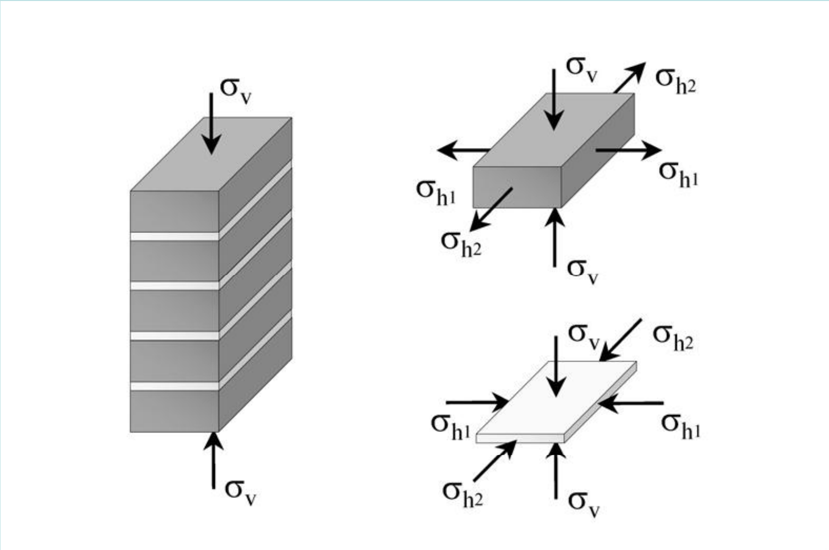
Observation of the failure mechanism of brick masonry doublets with cement and lime mortars by X-ray CT

R. Hendrickx, K. Bruyninckx, L. Schueremans, G. Kerckhofs, E. Verstrynge, M. Wevers, K. Van Balen

International Micro-CT symposium, KULeuven, 9th June 2009

Introduction – problem statement

- Brick masonry = layered composite of brick and mortar
- Strength and deformation characteristics different
- Existent research about effects in masonry on macro scale



Drawing: $E_b > E_m$ and $\nu_b \approx \nu_m$
after Hilsdorf (1969)

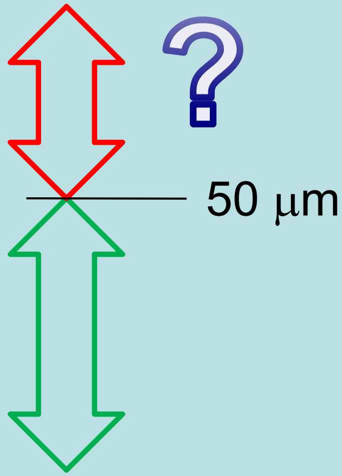
- On smaller scale (meso, micro), literature is available about mortar and ceramics, but NOT about masonry.

Goals and expected difficulties

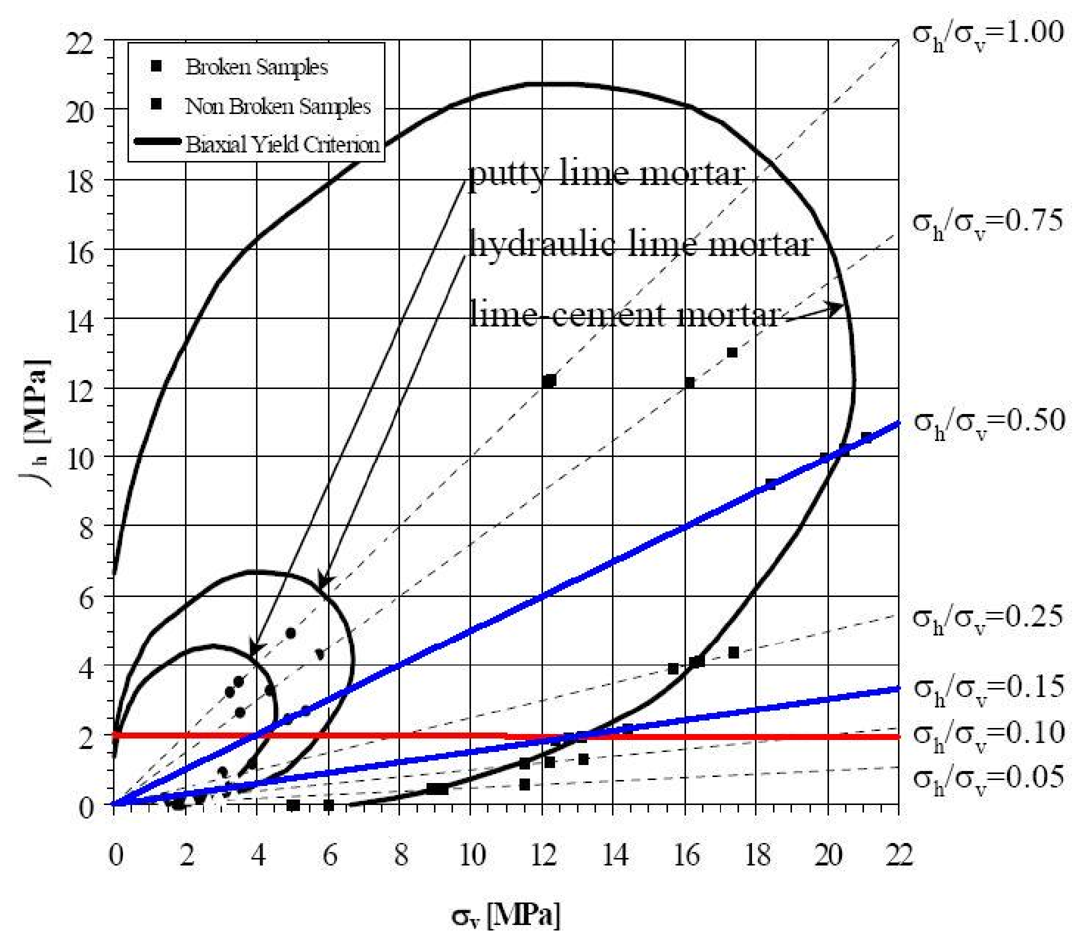
- Identify zone of origin of cracks, role of interface?
- Map the deformation before and during failure
- Observe and distinguish the types of failure mechanism for <u>different mortar types</u>

Difficulties: <u>multi-scale phenomena</u>:

Size	**Mortar**	**Brick**	**Observation**
10^{-9}m	gel pores		
10^{-6}m	capillary pores binder particles	porosity (monomodal)	
10^{-3}m	air bubbles sand grains		
10^{-1}m	constr. element	constr. element	



Preliminair research: masonry under compression



- Analysis Hayen (2003)
- Stress coefficient $\kappa=\sigma_{hor}/\sigma_{vert}$ in triaxial test
- $\kappa<0.25$: brittle failure, shear cracks
- $\kappa>0.25$: elasto-plastic, pore collapse, splitting of brick
- Tensile strength of brick: 2MPa

Preliminary hypothesis: strong mortars will cause brittle failure of masonry, weak mortars will have extended plastic deformation with pore collapse.

Methodology

- Concentrate on simple, empirical level of observation
- Elementary analysis of stresses and deformations
- Comparative qualitative analysis of the observed phenomena on meso and macro-scale

Observation masonry ⟺ Measured properties of brick

Measured properties of mortars

•lime hydrate mortar
•hydraulic lime mortar
•lime-cement mortar
•cement mortar

- Simple elastic calculation to estimate stress-levels in elastic region (simplified analytical, no numerical 3D calculations), to account for inhomogeneity

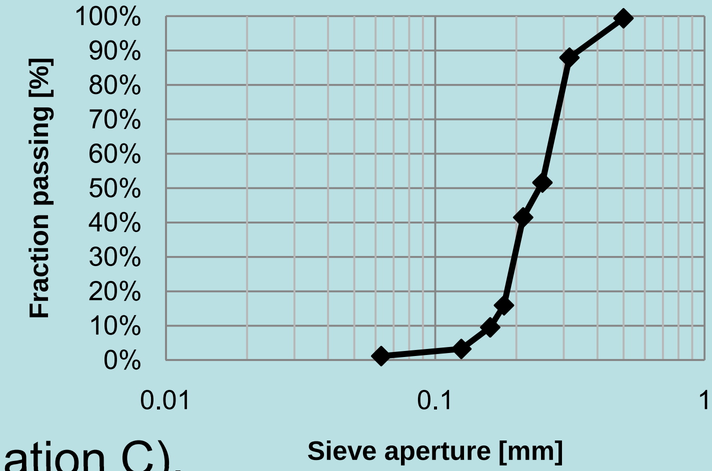
Materials: ceramic brick

- “Hand” moulded facing brick, nominal dimensions 19x9x5 cm³ (WxDxH) (type Wienerberger “Spaans rood”)
- Relatively low strength brick, often used in lab situations to be representative for historical masonry.
- High porosity and absorption, low bulk density.

	Mean	Stdev
Bulk density ρ [kg/m³]	1612	2
Open porosity [vol %]	28,06 %	0,48 %
Compressive strength (doublets) f [MPa]	8,86	0,89
Compressive strength (cylinders) f [MPa]	10,21	0,90
Static Young’s modulus E [MPa]	1095	157
Poisson ratio [-]	0,17	0,04
Dyn. Young’s modulus E [MPa]	3730	280
Bending tensile strength f_t [MPa]	3,12	0,47
Splitting tensile strength f_t [MPa]	0,88	0,23

Materials: mortars (5 different types)

		Sand [g]	Binder [g]	Water [g]
H+C	Lime-cement	2700,0	572,5	583,3
H	Cement	2700,0	666,9	604,9
H+C	Hydr. lime	2700,0	572,4	630,8
C	Lime hydrate	2700,0	342,9	620,6

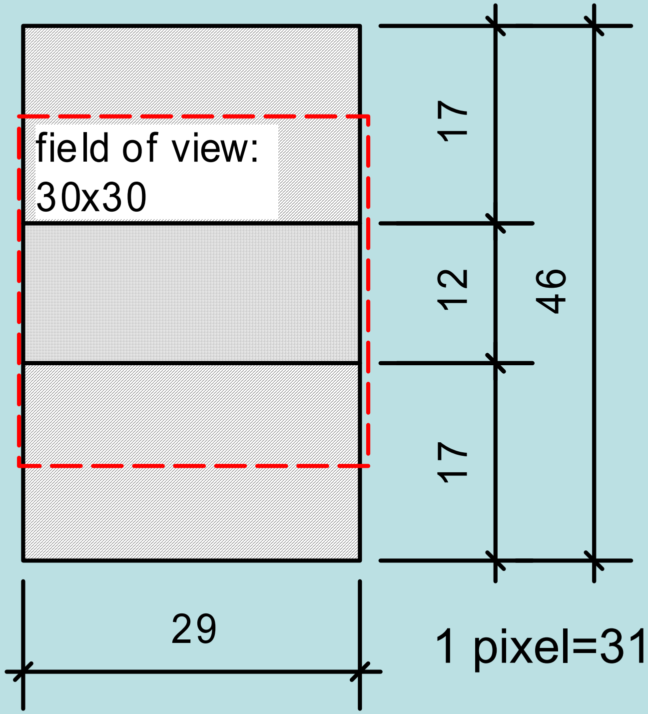


Binder harden due to hydraulic reaction (H) of carbonation C).
The lime hydrate mortars have been tested partly carbonated, and fully carbonated.
Carbonation was enhanced by curing in a CO_2 rich environment.

	Lime-cement	Cement	Hydr. lime	Lime, non carb	Lime, carb
Bulk density ρ [kg/m³]	1841	2016	1861	1722	1671
Dynamic Young's modulus E_{dyn} [MPa]	11182	21997	2573	5449	3244
Bending tensile f_t [MPa]	3,19	8,05	0,49	0,83	0,37
Compressive f [MPa]	10,88	29,48	1,37	2,22	0,81

Production of test specimens: high strength mortars

- $H_{max,press}$=50mm, t_{joint}=12mm, d_{core}=29mm, press: 30kN
- Importance of parallel and smooth top and bottom face.
- High strength mortar can be cored after assembly, low strength mortar can not.



faces made parallel by grinding

1 pixel=31µm

Production of test specimens: low strength mortars

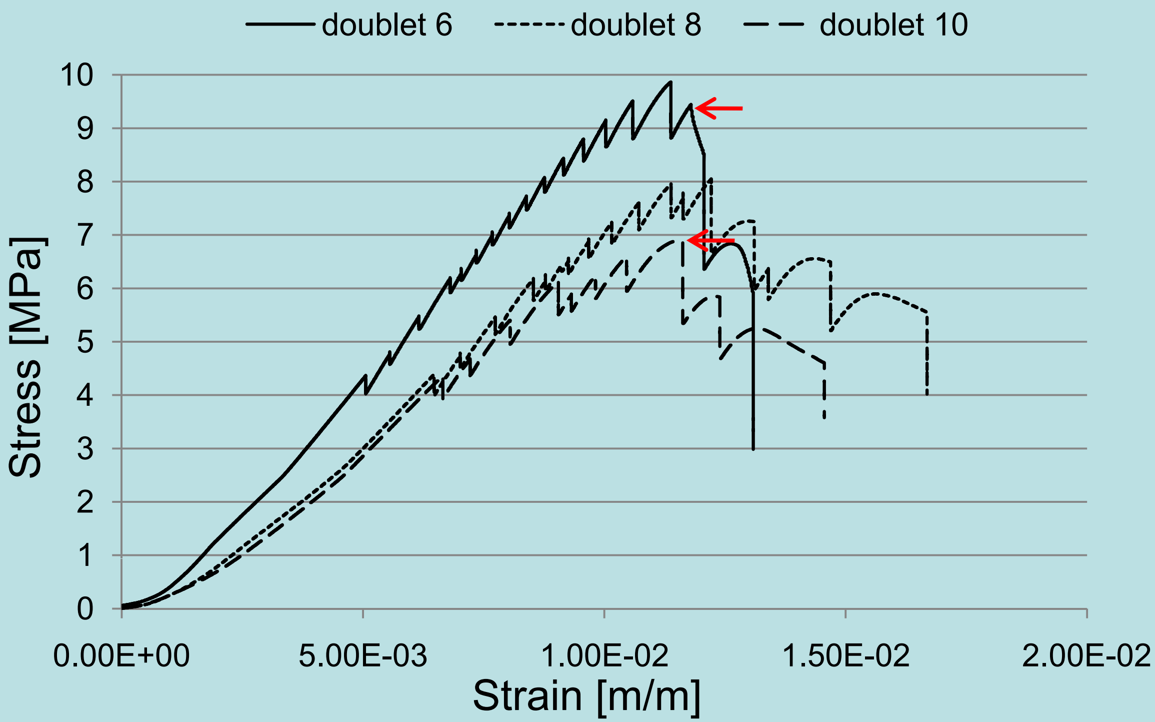
- Samples would break when drilled.
- Assemble cylindrical pieces, and add epoxy layer under press to make faces parallel.

capped with epoxy resin (problems with gypsum), leads to strong confinement

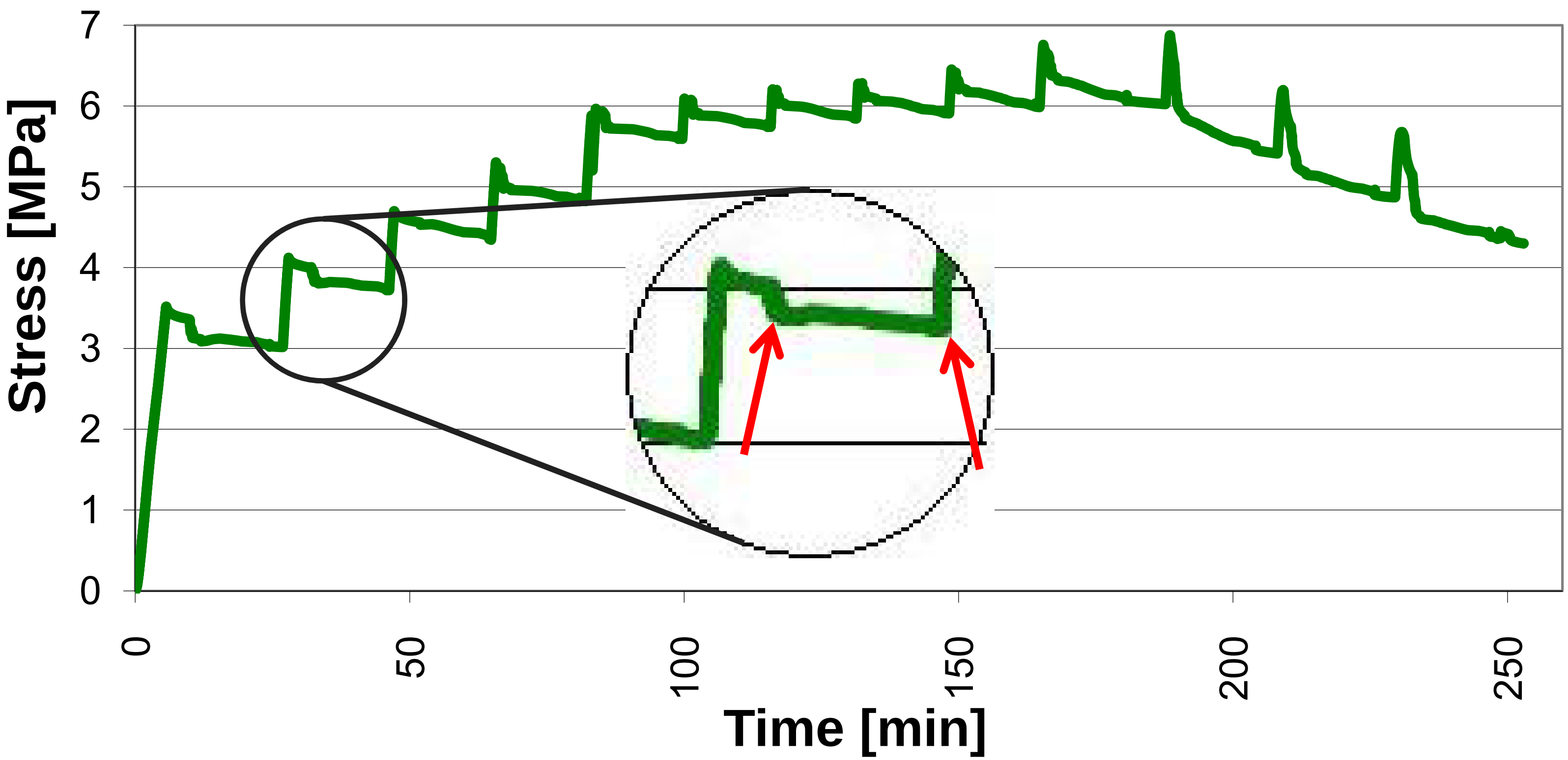
Testing procedure (age=28 days)

- Estimate compressive strength by pressing 3 specimens.
- Starting load, reference image.
- Stepwise displacement-controlled loading to 60% of estimated strength, then 70, 80, 90, 95,...
- After each step: allow relaxation for 2 min, turn sample 1 revolution, scan specimen.

Test parameters:
AEA Tomohawk
source: HOMX161
100keV, 0.35mA
A1 filter
10 img/1°
detector:1024*1024



Relaxation – time of scan



Results and data treatment

- Processing: raw data in *.rad files converted to *.tif, which served as input for reconstruction software.
- Output: horizontal sections and two vertical sections through symmetry planes, 3D renderings.
- Every type of mortar: 3 doublets (3*5=15 tests in total).

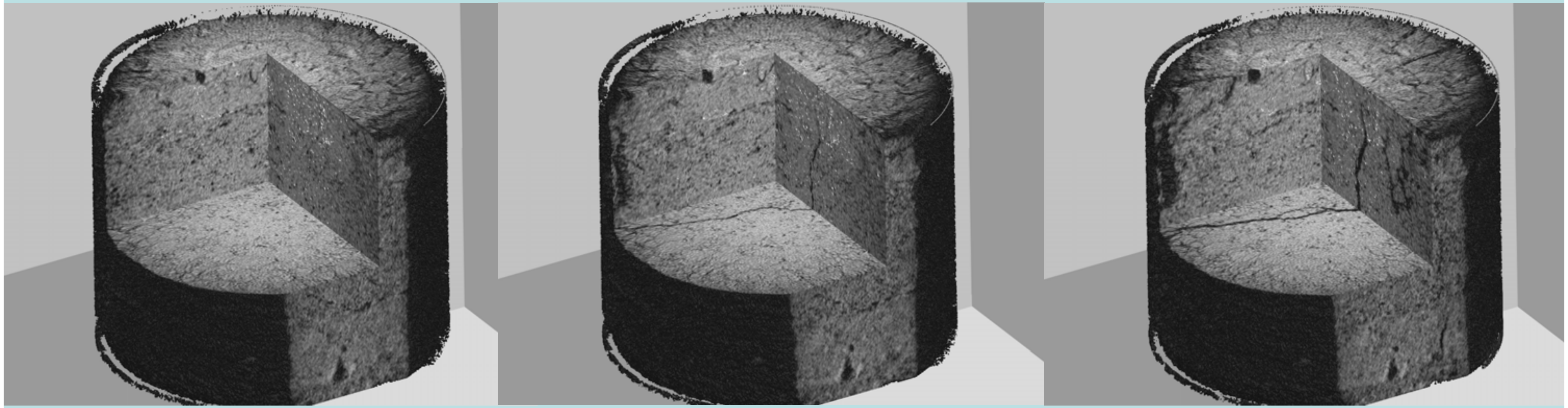
ANALYSIS:

- Renderings observed for crack propagation: image of first visible macro or meso-crack, versus image before.
- Measurements on vertical sections to estimate E.
- Horizontal sections calculated to differential images to estimate densification.

$f_{mortar} \approx f_{brick}$: lime-cement mortar

- Closest to homogeneous material.
- Mostly clear shear plane through mortar and brick.
- Crack develops over joint, tips in brick.
- Limited number of 3D renderings produced.

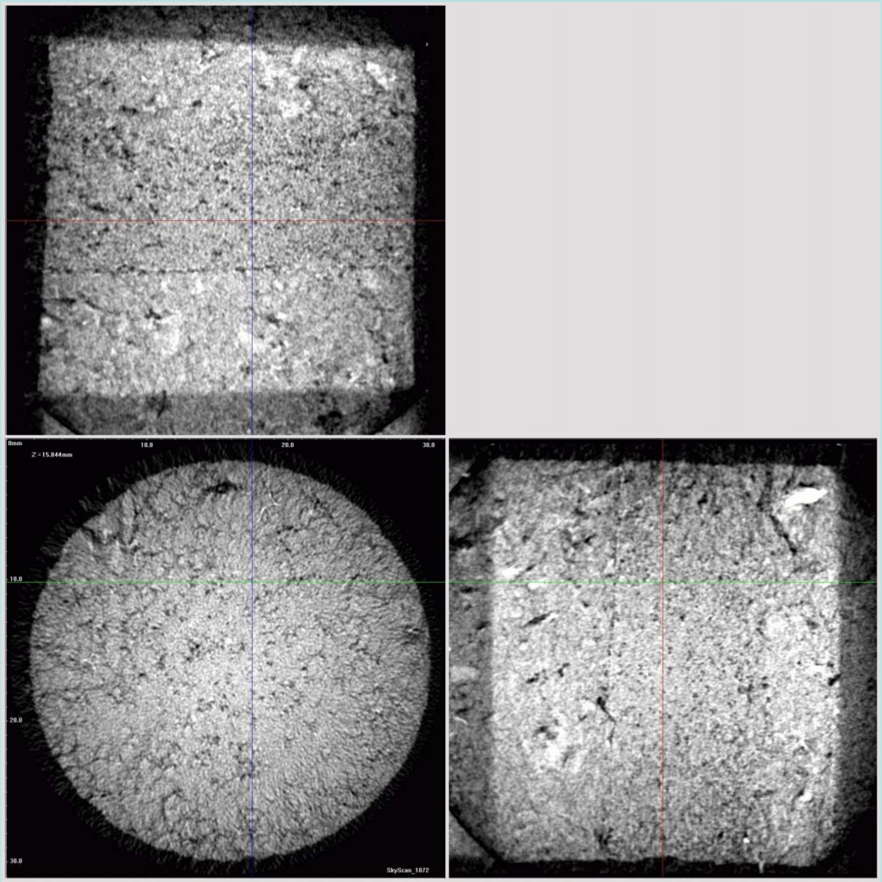
doublet 6



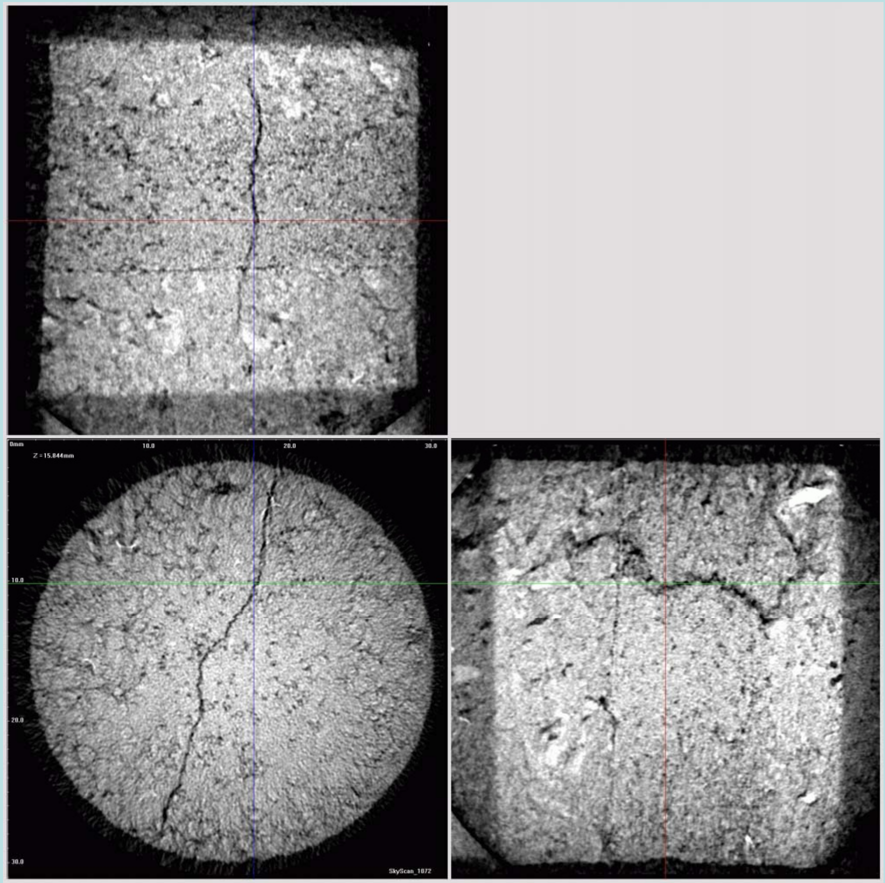
step 15 step 16 step 17

$f_{mortar} \approx f_{brick}$: lime-cement mortar

- The same load steps: horizontal and vertical sections.
- Lines indicate place of sections.



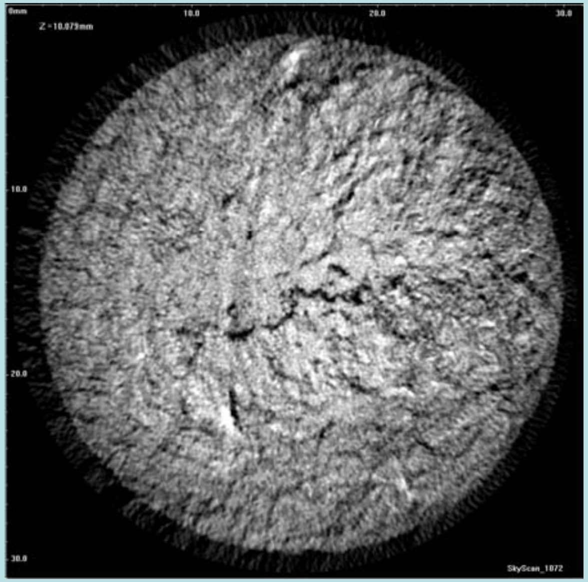
step 15



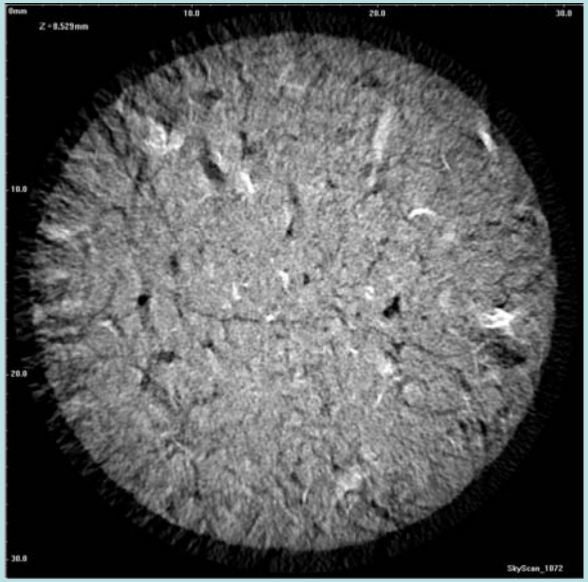
step 16

$f_{mortar} > f_{brick}$: cement mortar

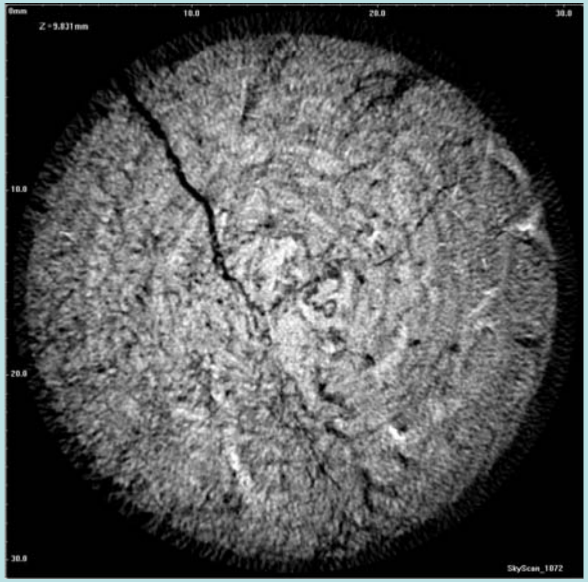
- Most damage visible in the brick.
- First signs of splitting crack near interface.
- After initiation, cracks develop over joint.
- Limited densification visible in mortar.



doublet 6
first visible crack near interface



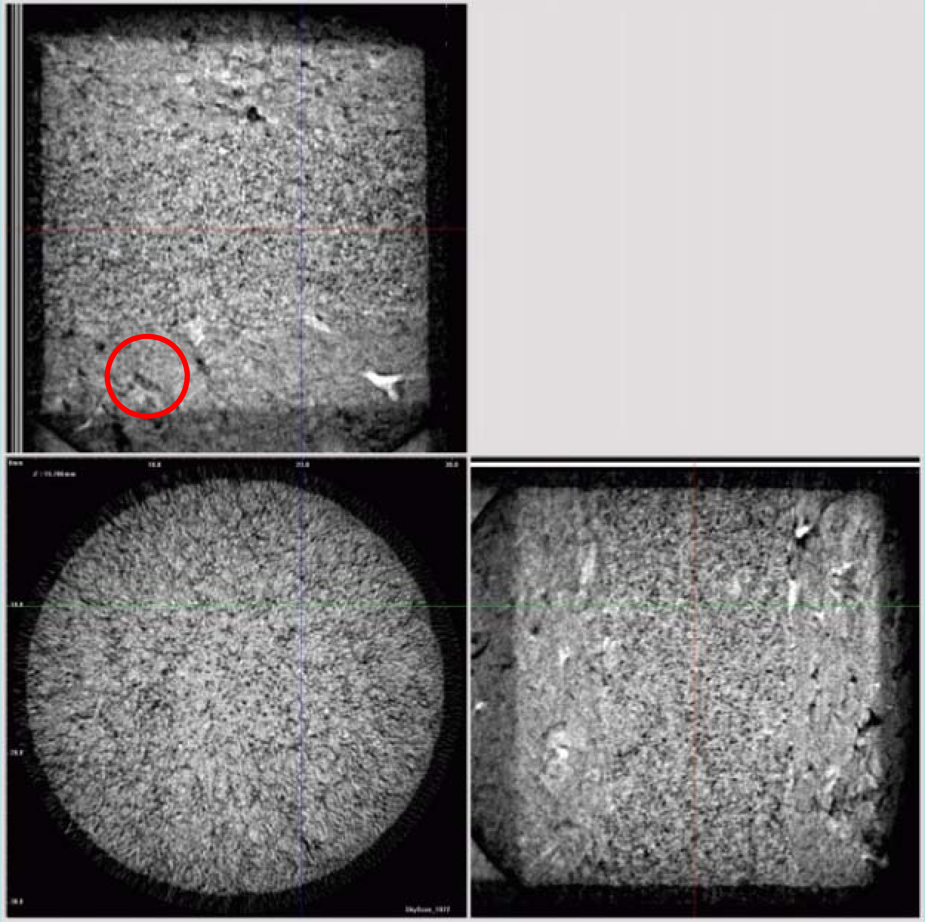
doublet 10
first visible crack in brick near interface

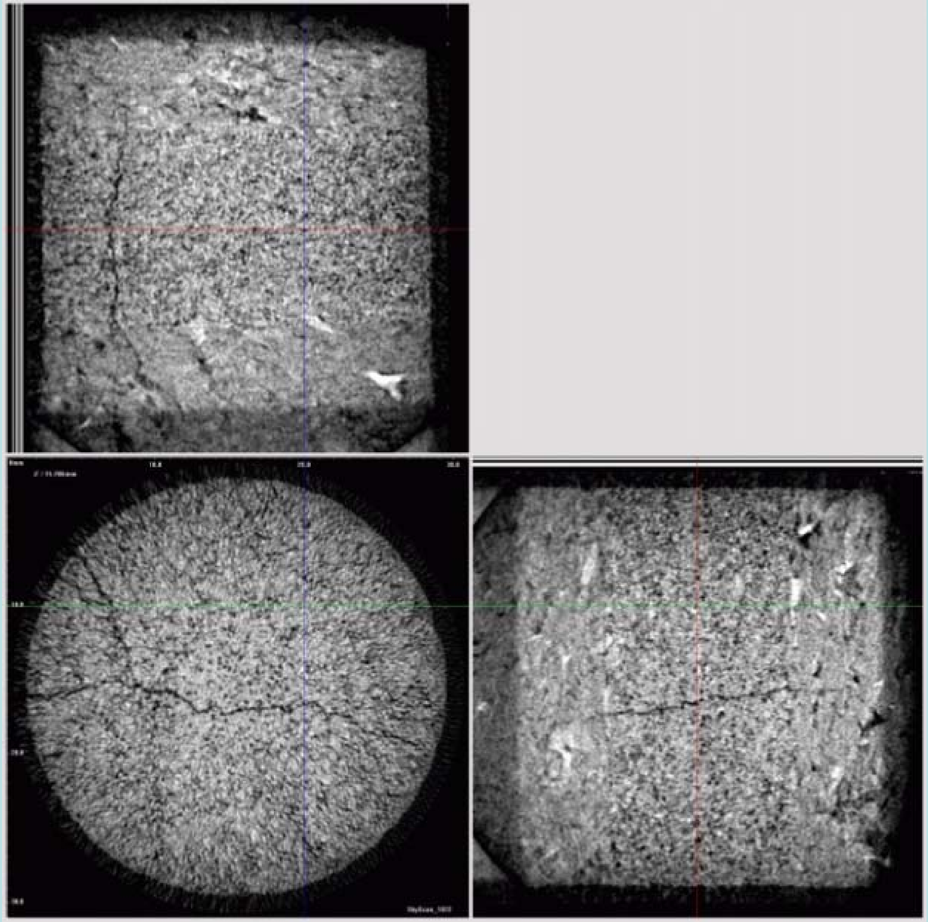


doublet 7
cracks interconnected upon failure

$f_{mortar} > f_{brick}$: cement mortar

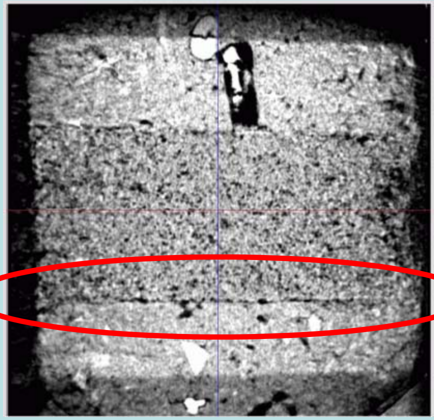
- First visible crack and subsequent image, doublet 10.





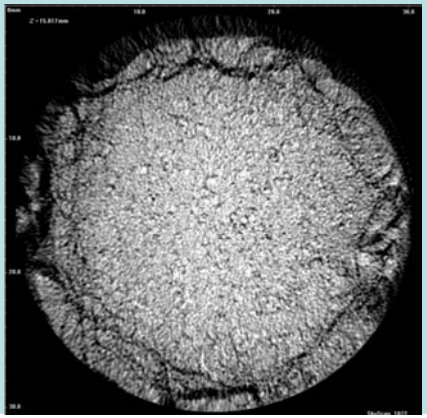
$f_{mortar} < f_{brick}$: lime mortars

- More “plastic” failure: large deformations in mortar.
- Sometimes defective bonding observed after test, especially for natural hydraulic lime.



Natural hydraulic lime mortar, doublet 5

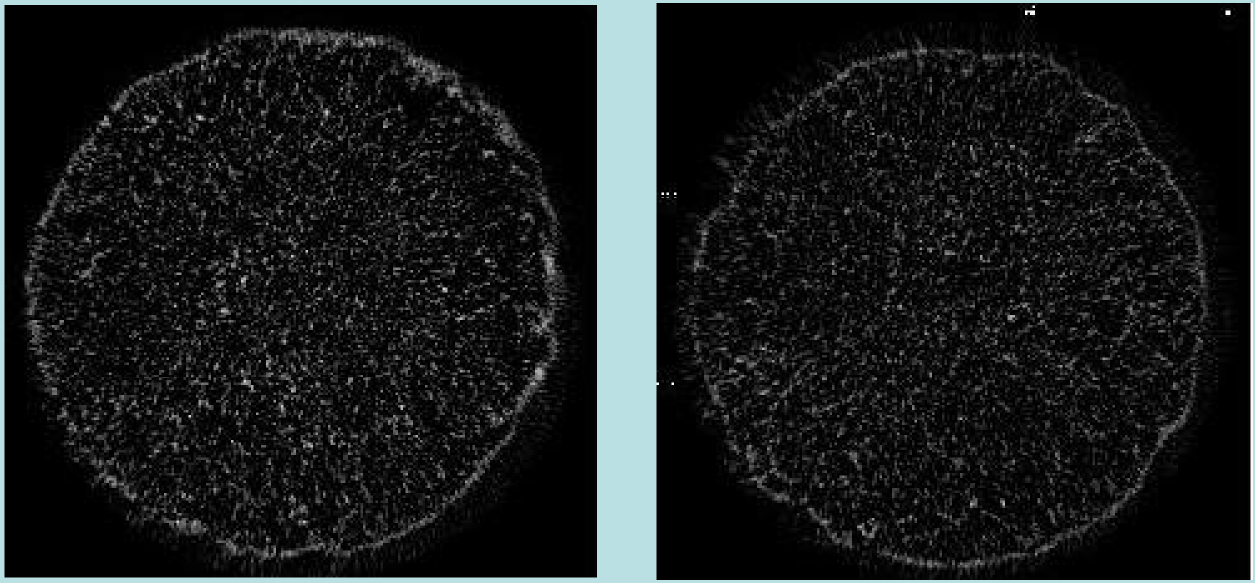
- Outer shell of the joint is being “squeezed” out.



Carbonated lime mortar, doublet 4

$f_{mortar} < f_{brick}$: lime mortars

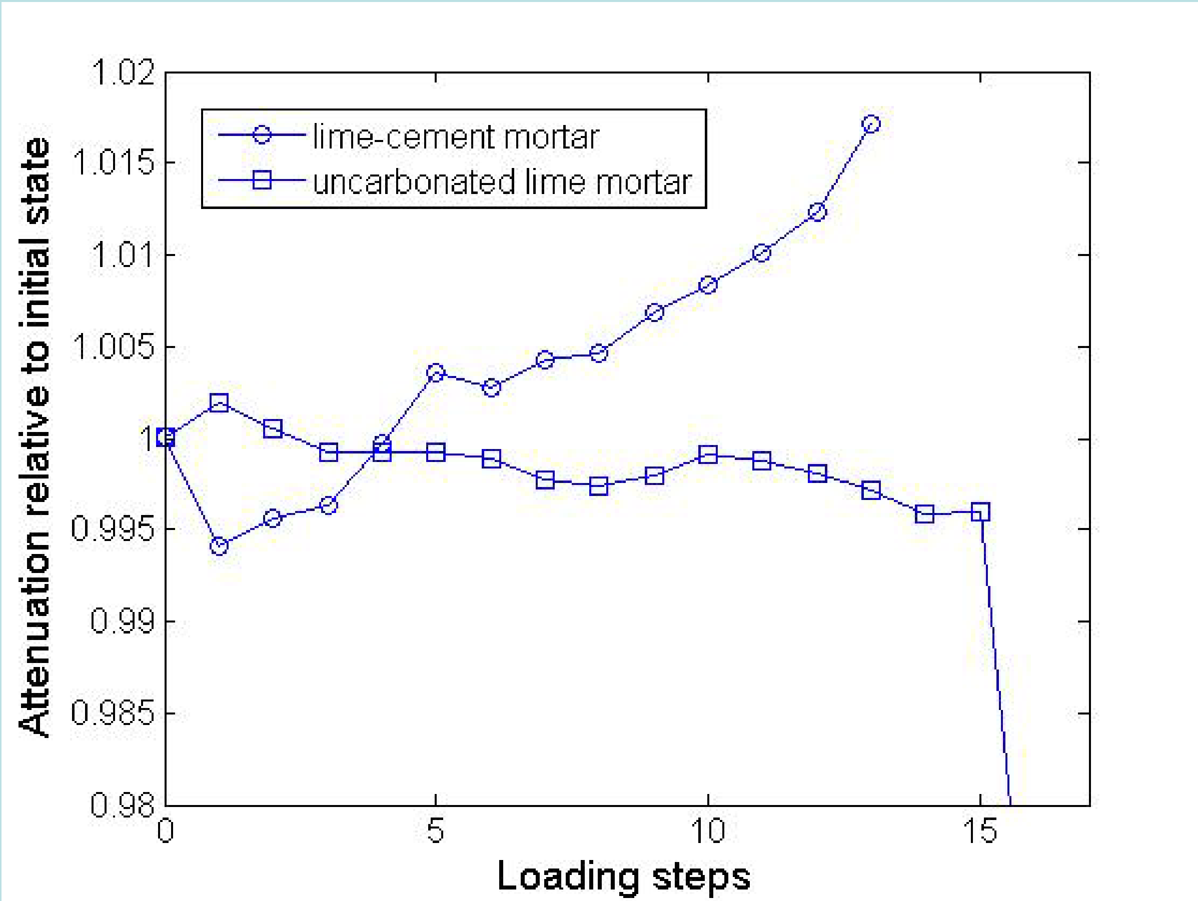
- Important densification visible in differential images of horizontal sections.



doublet 7 and 9, last image before visible cracking, difference with reference image (under pre-loading)

Differential attenuation: make compaction due to pore collapse visible?

Horizontal section through symmetry plane of mortar; grayscales of central zone



Lime-cement mortar, doublet 6

Uncarbonated lime mortar
doublet 4

Observations:
-More or less constant versus clear increase;
-Unclear during first steps;
-Scatter due to uncertain position of the plane.

Conclusions

- Technique is feasable and offers interesting possibilities for analysis.
- Crack initiation, which is a micro-scale phenomenon, can not be identified.
- Only meso and macro-cracks are visible, but their observation allows to discrimintate different mechanisms.
- Initial hypotheses about occurrence of pore collapse in low-strength mortars are confirmed.
- Calculation of Young’s modulus of mortar from the images is not successful (yet).
- Some important data (static Young’s modulus of mortars) is missing for in-depth stress analysis.

Suggested further research

- More numerical, quantitative treatment of data.
- Possibilities of strain mapping in 2D to be further investigated.
- Experimental determination of E_{mortar}.
- Options for FEM models, elastic-plastic, and/or DEM, considering the mortar as granular, to analyse elastic and plastic stress/strain behaviour.
- In the future?: adapted constitutive law for low-strength mortar including pore collapse mechanism?