Darmstädter Massivbau

Material research and monitoring related to consolidation and strengthening of existing historic masonry structures

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http://www.kuleuven.be/bwk/materials

Preservation Process

- **Anamnesis**:
  - Description and documentation of building, context (environment)
  - Description of buildi
  - Documentation (of s
  - Building survey, sta
    structural investigat
    DT, …
- **Analysis**:
  - Structural analysis r
- **Diagnosis**:
  - Assessment of struc
  - Monitoring as part of the diagnosis
- **Therapy**:
  - Plan and choices for (non-)intervention
  - Motivation of choices, with attention towards durability of the solutio
  - Execution, including control on site during execution
- **Control**:
  - Maintenance plan
  - Monitoring

Acoustic-Emission

Micro-focus X-ray CT – brick mortar interaction during collapse

3D laserscanning

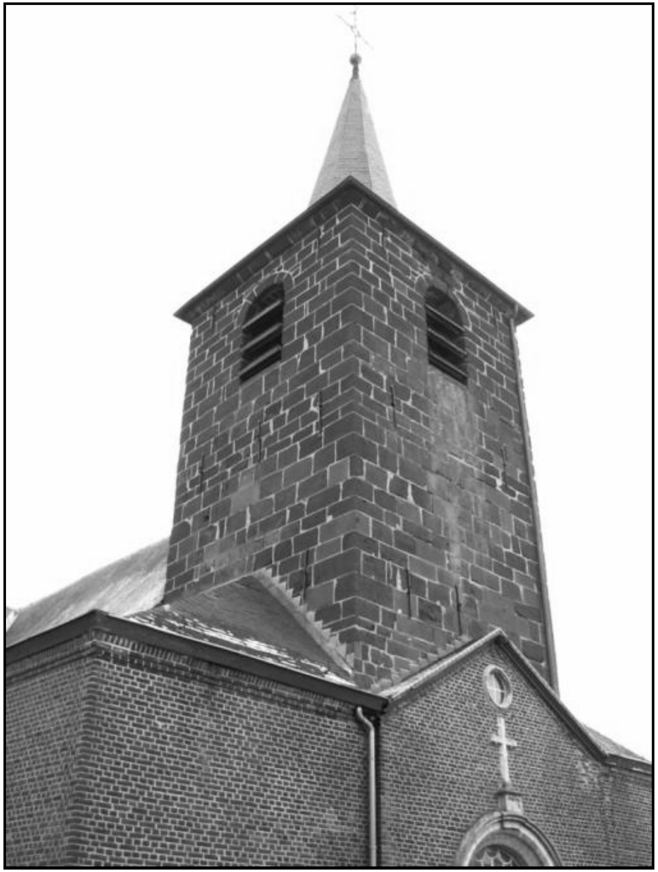
Hole Drilling Technique

Objective – masonry integrity

Enhance the understanding of structural behavior of masonry – look for possibilities of techniques used in adjacent research fields:

- Acoustic-emission:
  - NDT – fatigue testing of steel and composite materials;
  - On site application – mainly reinforced concrete structures
  - Extension towards damage assessment for masonry structures – quantify damage occurrence and propagation
- Micro-focus X-ray Computed Tomography:
  - Combined test-setup: µf-X-ray CT + compressive test
  - Developed for synthetic building materials
  - Focus on full 3-D visualisation of evolution of masonry subject to compressive loading and failure mechanisms occuring;
- 3D laserscanning:
  - Piping;
  - Accurate geometrical data and their influence on structural stability;
- Hole Drilling technique:
  - Residual stresses in steel;
  - On site stress measurements

Acoustic Emission – assessment of damage accumulation in masonry under persistent loading



Bell tower of the Sint-Willibrordus Church at Meldert, Belgium
(14th (church) – 17th (tower) century

(collapse: 07/07/2006)

Acoustic Emission – assessment of damage accumulation in masonry under persistent loading

Bell tower of the Sint-Willibrordus Church at Meldert, Belgium

(collapse: 07/07/2006)

Problem definition: long-term stability of masonry

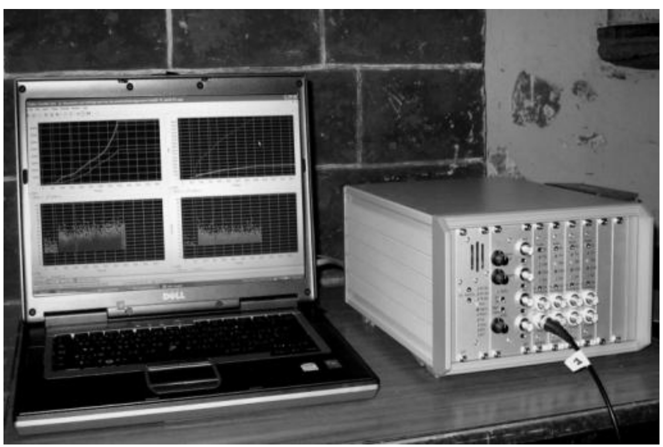
- New models and techniques are necessary in order to assess the long-term structural safety of masonry structures.
- Preferably, this is combined with (several) non-destructive techniques for on-site assessment, to acquire accurate and sufficient information on the damage (accumulation) within a structure

Therefore, research efforts are concentrated on (**PhD research Els Verstrynge**):

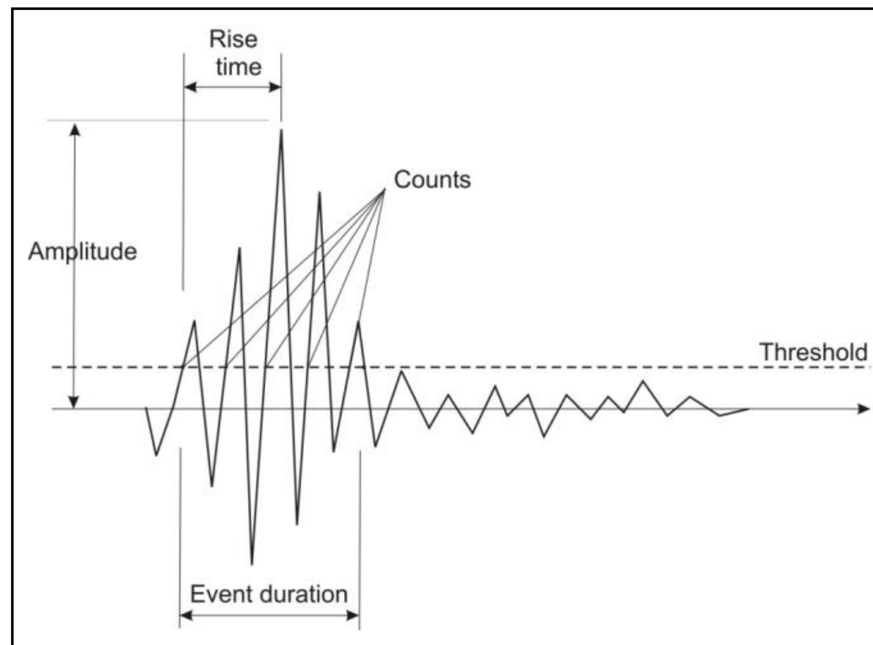
- Theoretical research: prediction of the live span with theoretical models, based on experimentally obtained parameters;
- Experimental research on the long-term behaviour of historical masonry;
- **Non-destructive techniques to assess the damage accumulation, such as the acoustic emission technique (AE)**

Consequently, adequate preventive measures can be taken.

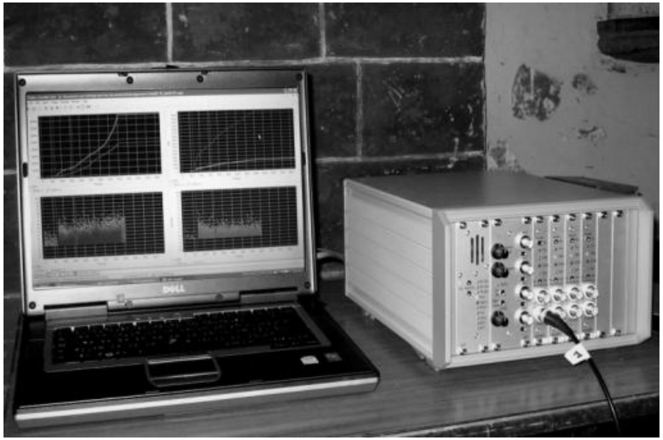
Acoustic Emission Measurements (AE)



- “listening” to the appearance of cracks
- detection of high-frequent energy waves (250-700 kHz)
- possible “online-monitoring” of damage-accumulation in masonry

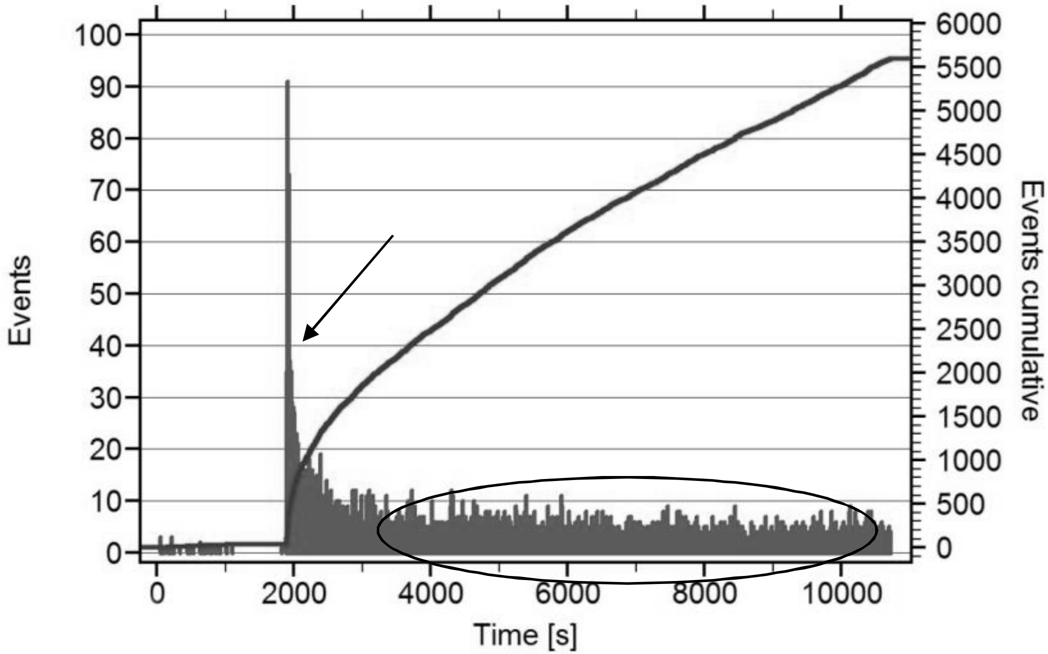


Acoustic Emission Measurements (AE)



- Two sensors / specimen
- Preamplifier: 34 dB gain
- Threshold level: 34 dB
- AE system from Vallen Systeme, type AMS-3 (2 channel) and AMSY-5 (4 channel).
- Simultaneous monitoring of two specimens

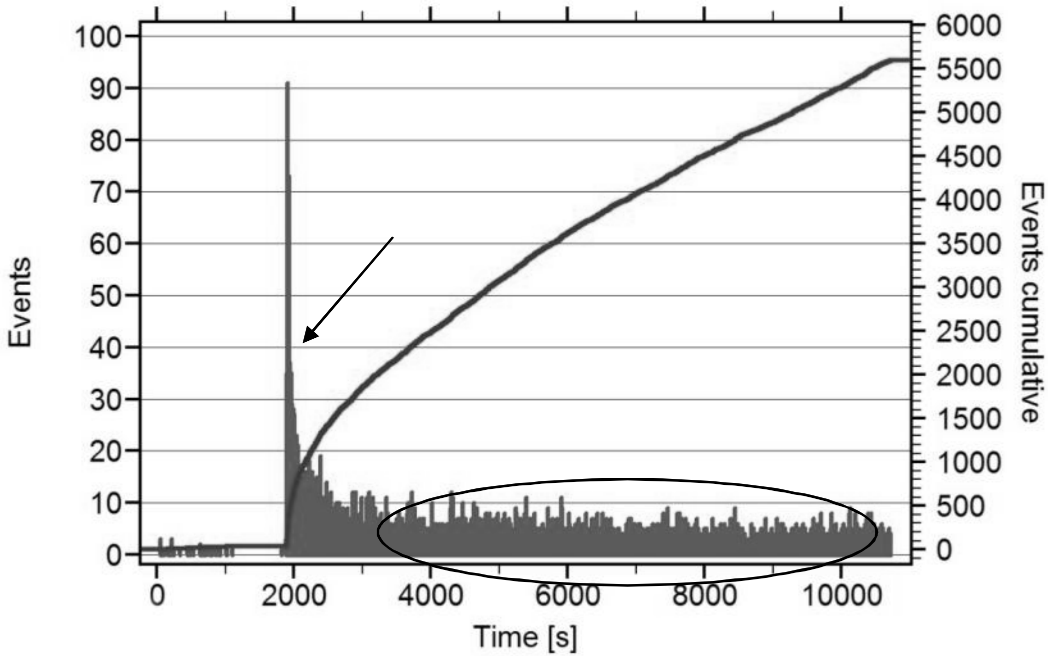
AE during creep tests



Stress increase 85→ 90% of f_c,

persistent damage increase: premonition of failure 10-20 hours after stress increase.

AE during creep tests



Stress increase 85→ 90% of f_c,

persistent damage increase: premonition of failure 10-20 hours after stress increase.

AE during creep tests – test program

- A longer monitoring period is required
- The data have to be analyzed “on-line”, during the measurement

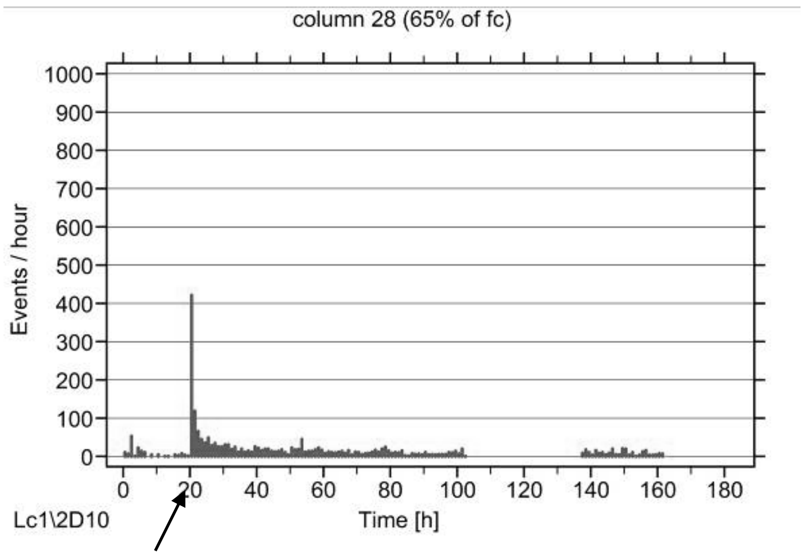
AE monitoring before, during and about a week after the small stres increase steps, in order to capture the different phenomena:

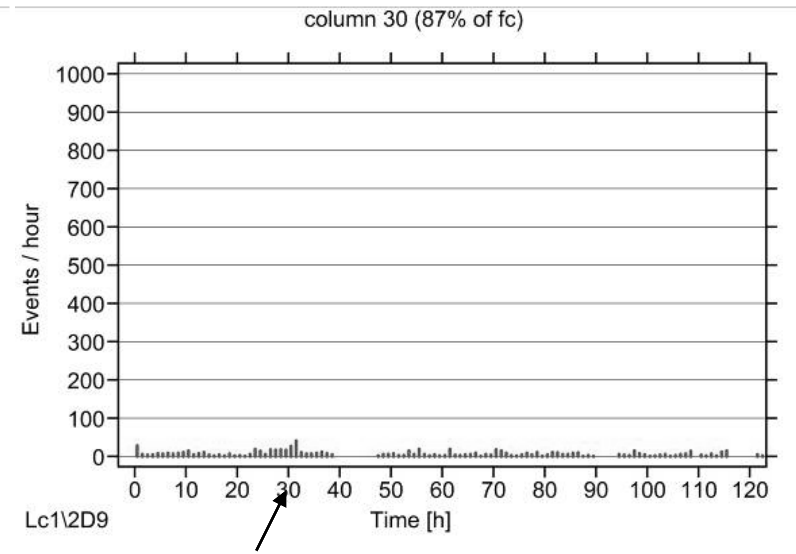
- The elastic deformation during stress increase;
- The dissipation of the AE events after the stress increase;
- The AE-events emission level during a constant stress interval;
- The accelerated damage-accumulation during the tertiary creep phase.

AE during creep tests – test program

Specimen	Successive stress increase steps (in % of compressive strength f_c)				Days to failure after last stress increase
	(0)	(1)	(2)	(3)	
28	50 → 60 %	60 → 65 %	65 → 70 %	70 → 75 %	8 days
30	-	85 → 87 %	87 → 90 %	90 → 93 %	5 days

AE during creep tests – test results





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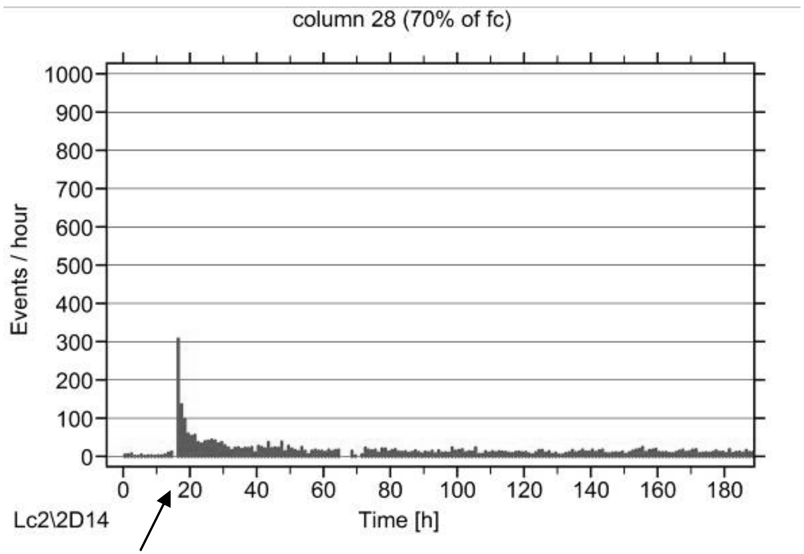

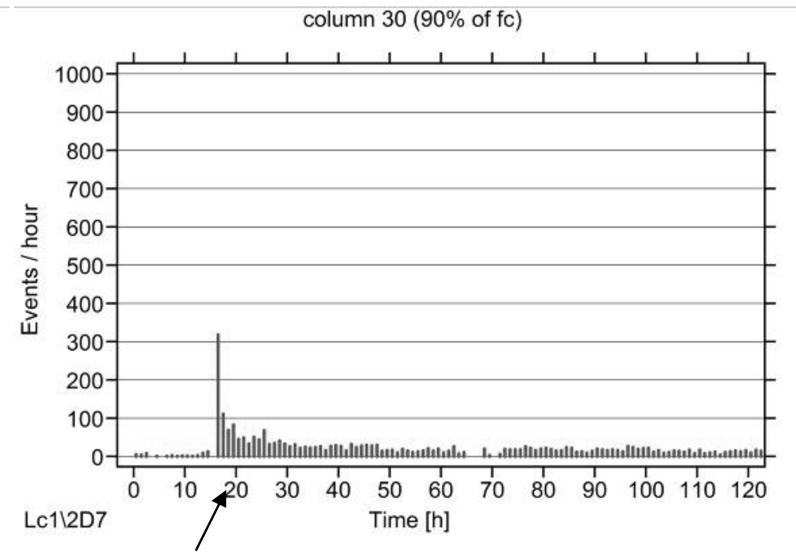

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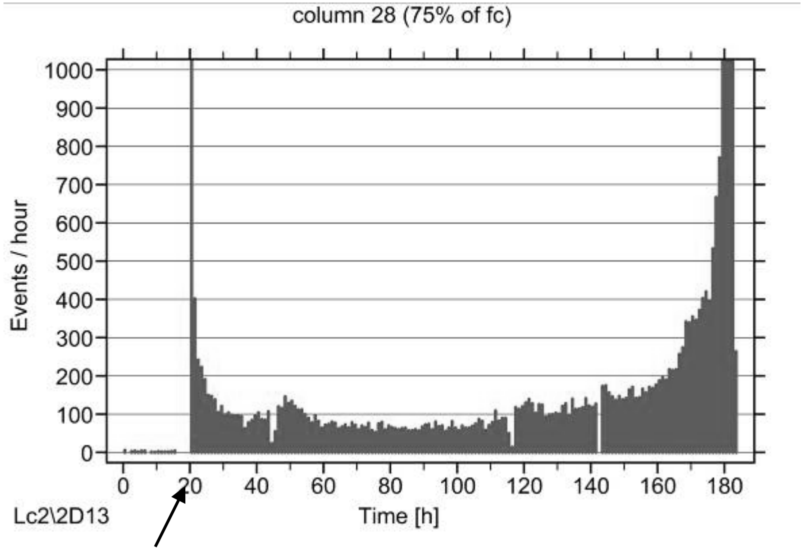

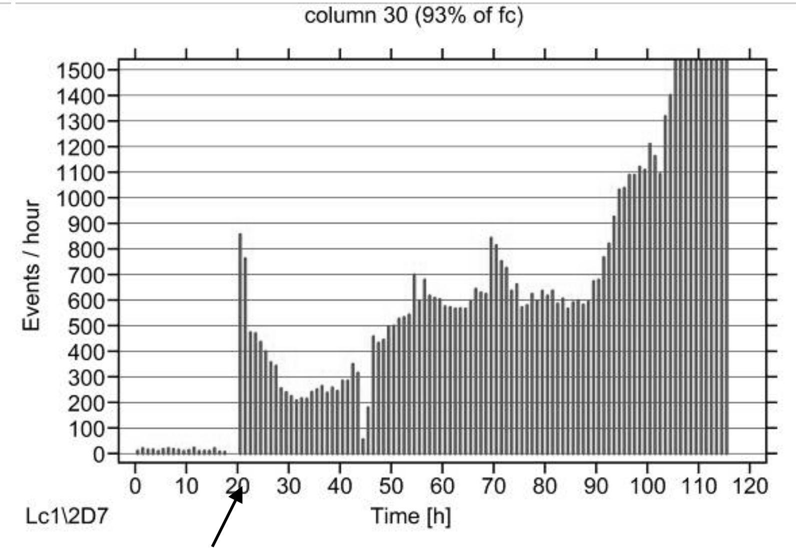

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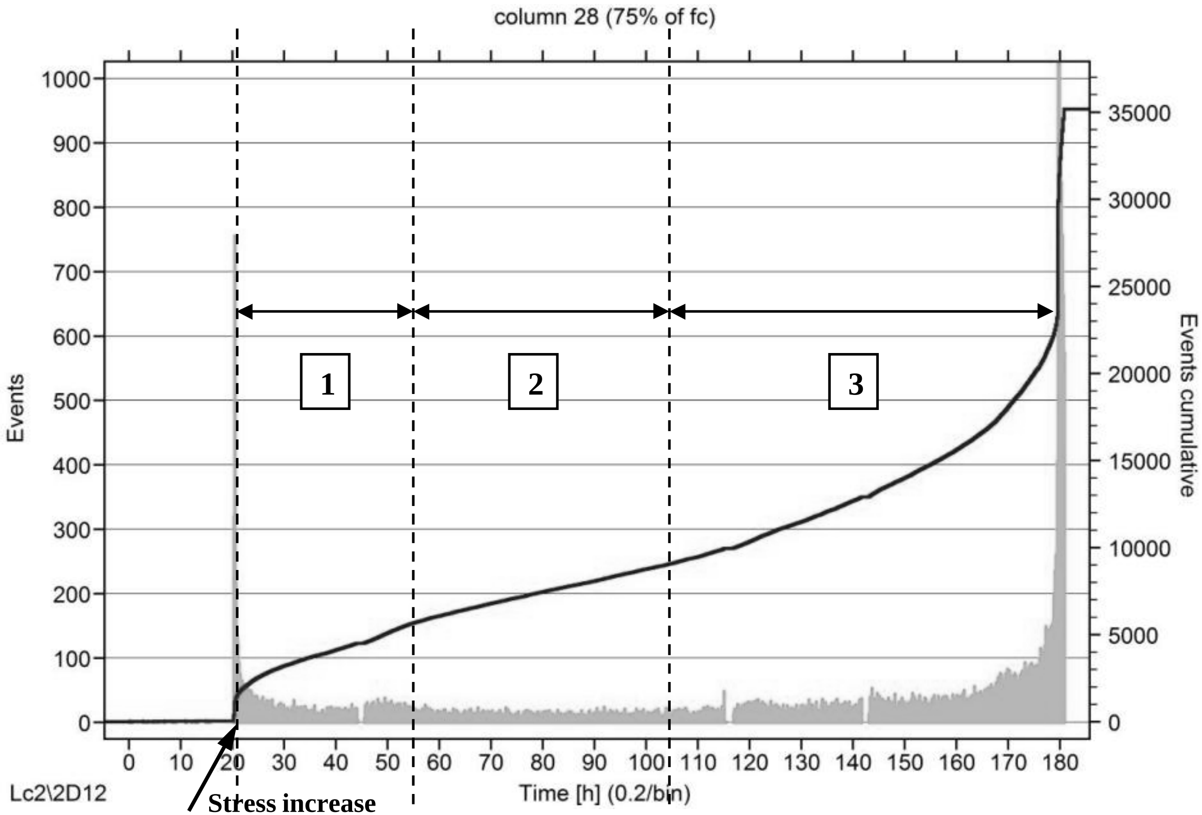


3 phases can be distinguished, comparable with a creep curve:

1. **Decreasing damage rate**
2. **Constant slope**
3. **Increasing damage rate**

AE - further aims

PhD research (Els Verstrynge), assess the damage evolution withi the framework of the creep modeling - extensive research prograr has almost finalized.

2 further challenges:

•**Monitoring for real case studies** – attempts have been mad (church tower at Zichem, Castle Ter Leenen at Geetbets and appartme building in Recife, Brazil)

- •measurement period: sufficiently long: to clearly assess th event rate;
- •Repetiveness of measurement campaigns to serve as a appropriate monitoring technique and to assess the damag evolution (or increase in event rate) on the long term.

•With additional laboratory experiments, the monitoring results ar being extended from giving good **qualitative information toward quantification of the damage accumulation**. This will also enhanc the possibilities of on-site monitoring

Micro-focus X-ray Computed Tomography – brick-mortar interaction

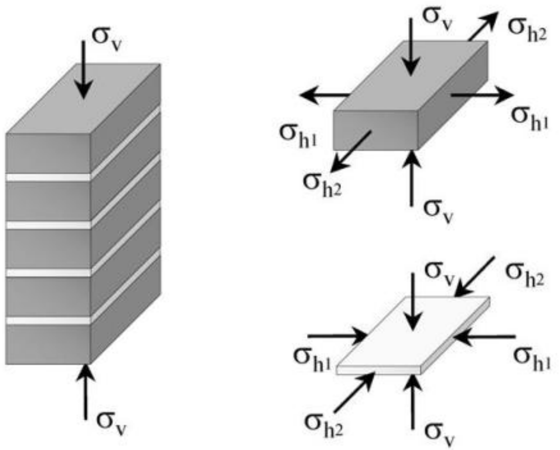
Computed Tomography: NDT building up cross-sections of a non-transparant sample based on the attenuation of X-rays.

3D visualization: subsequent cross-sections are stacked on top of th other

Aim: visualizing internal structure of mortar, brick and interface durin compressive failure:

$$k = \frac{s_h}{s_v}$$

	? = 0,25	? = 0,25
Stress state	**Uni-axial**	**Triaxial**
behavior	**brittle**	**Elasto-plastic**
Failure mode	**Shear bands**	**Pore collapse**

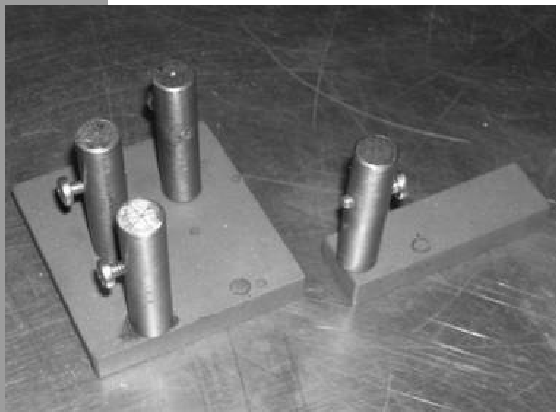


Test campaign

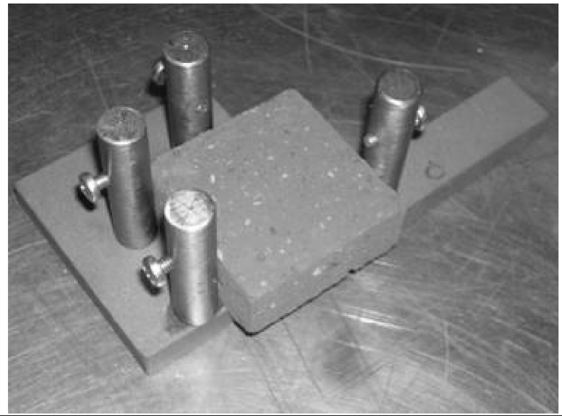
- 1 type of brick – low strength;
- Different mortars having different mechanical properties:
  - **Hybrid mortar (lime and cement) ($E_m>E_b$)**;
  - Cement mortar ($E_m>E_b$);
  - Hydraulic lime mortar ($E_m<E_b$);
  - Air hardening lime mortar (carbonated) ($E_m<E_b$);
  - Air hardening lime mortar (non-carbonated) ($E_m<E_b$).

Mechanical property	brick	Hybrid mortar
Compressive strength: f_c [N/mm²]	8.86 (0.89)	10.88 (0.15)
Bending tensile strength: f_t [N/mm²]	/	3.19 (0.09)
Direct tensile tests: $f_{t,y}$ [N/mm²]	0.30(0.10)*	/
Young's Modulus: E [N/mm²]	1700(400)*	11200 (160)

Preparation of test samples



Accessory device

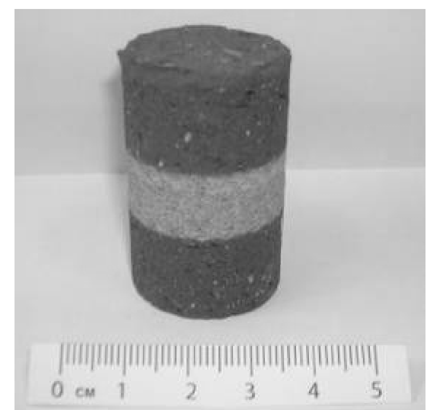


Step 1: brick bottom layer

Step 2: hybrid mortar layer

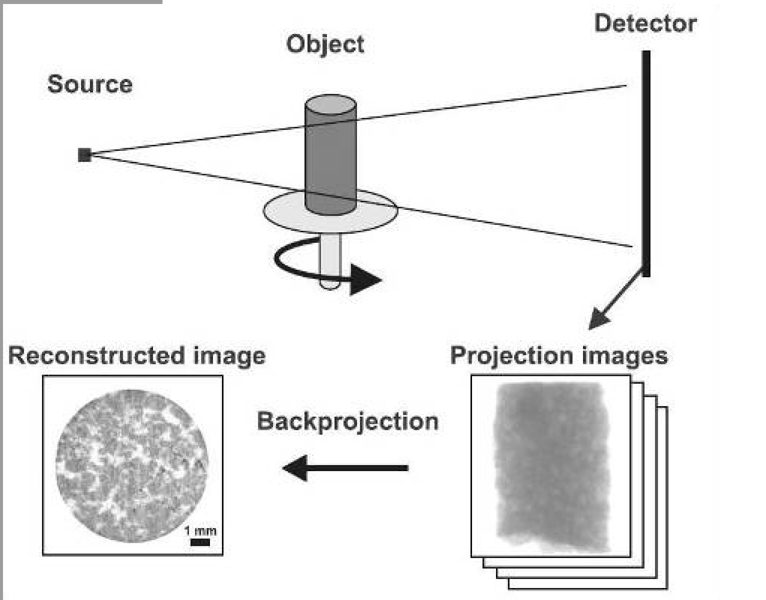
Step 3: parallel brick top layer

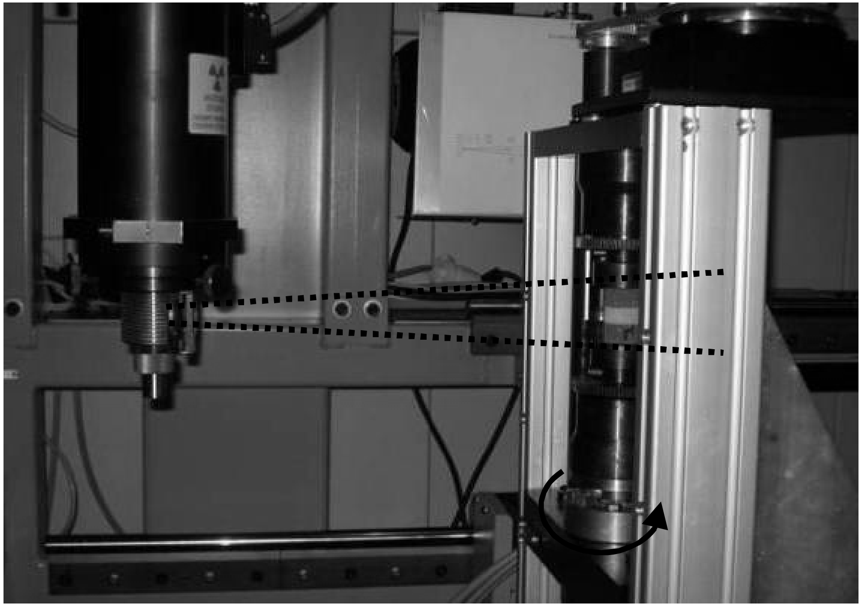
Step 4: sample before core drilling



Test sample – d=29mm – h=48 mm

Micro-focus CT - test setup

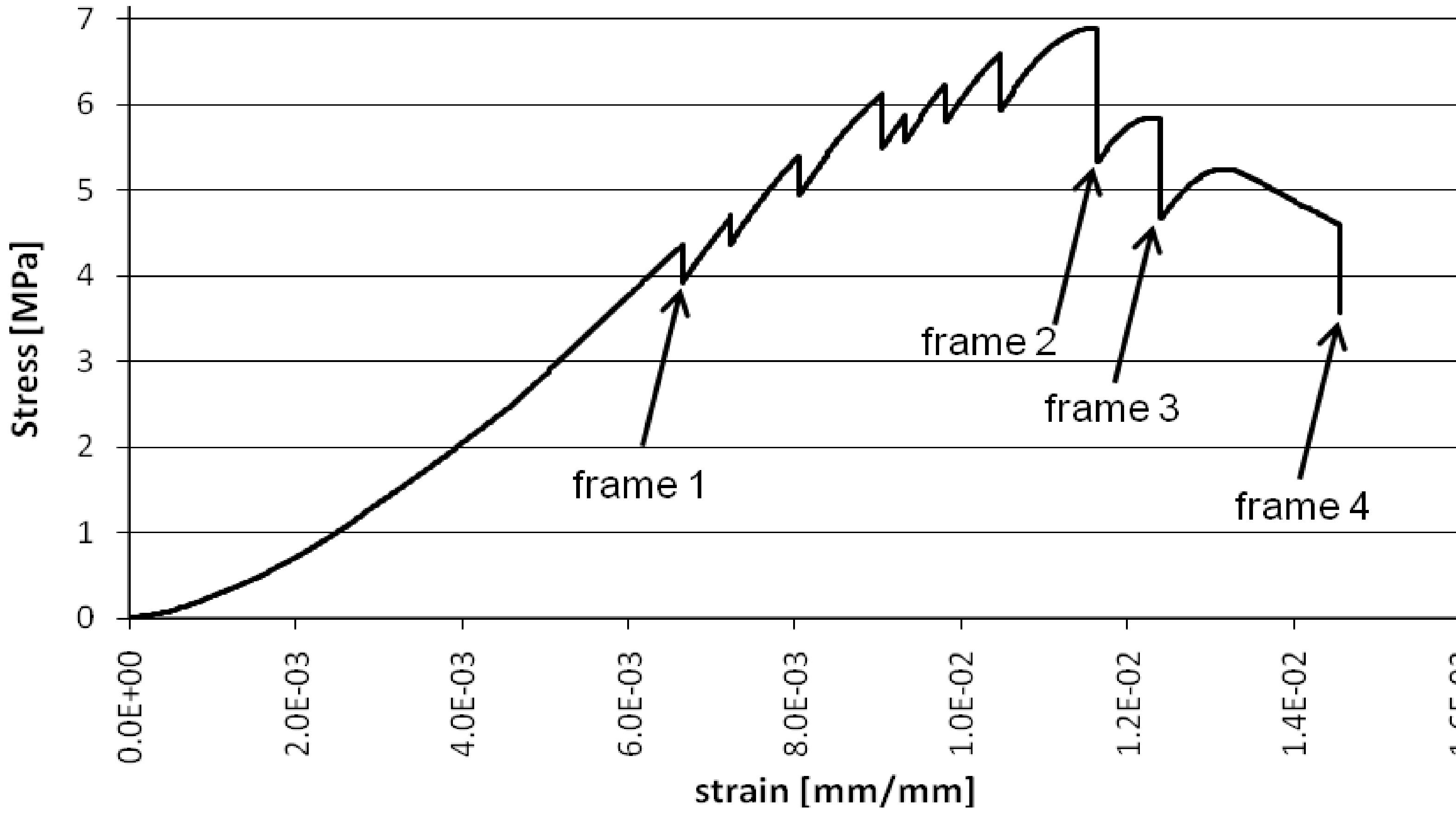




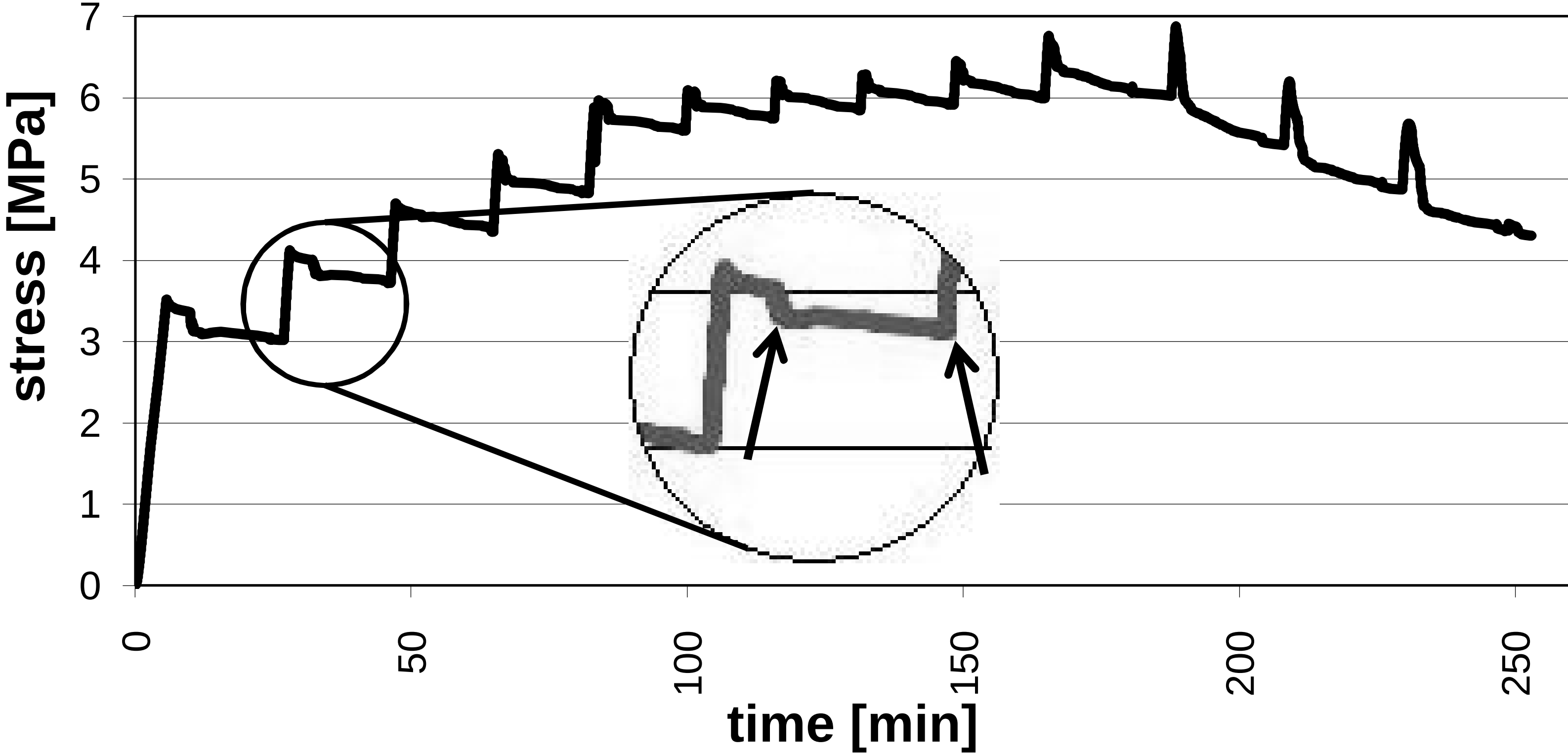
- **X-ray source**: HOMX161 (Philips); electric potential in between 5 and 160 kV, maximum current of 3,2 mA. Cross-section of focal point within 5 and 200 µm;
- The sample holder has a **rotation with a minimum increment of 0.5 degrees**;
- Detection system: phosphorus screen, light amplifier, optical lens and a CCD camera. The CCD camera is an Adimec MX12P. The resolution of the images equals **1024 x 1024 pixels**. Gray-scale contains 12 bits and the **image rating has a maximum of 25 images/s**.

Results on hybrid mortar

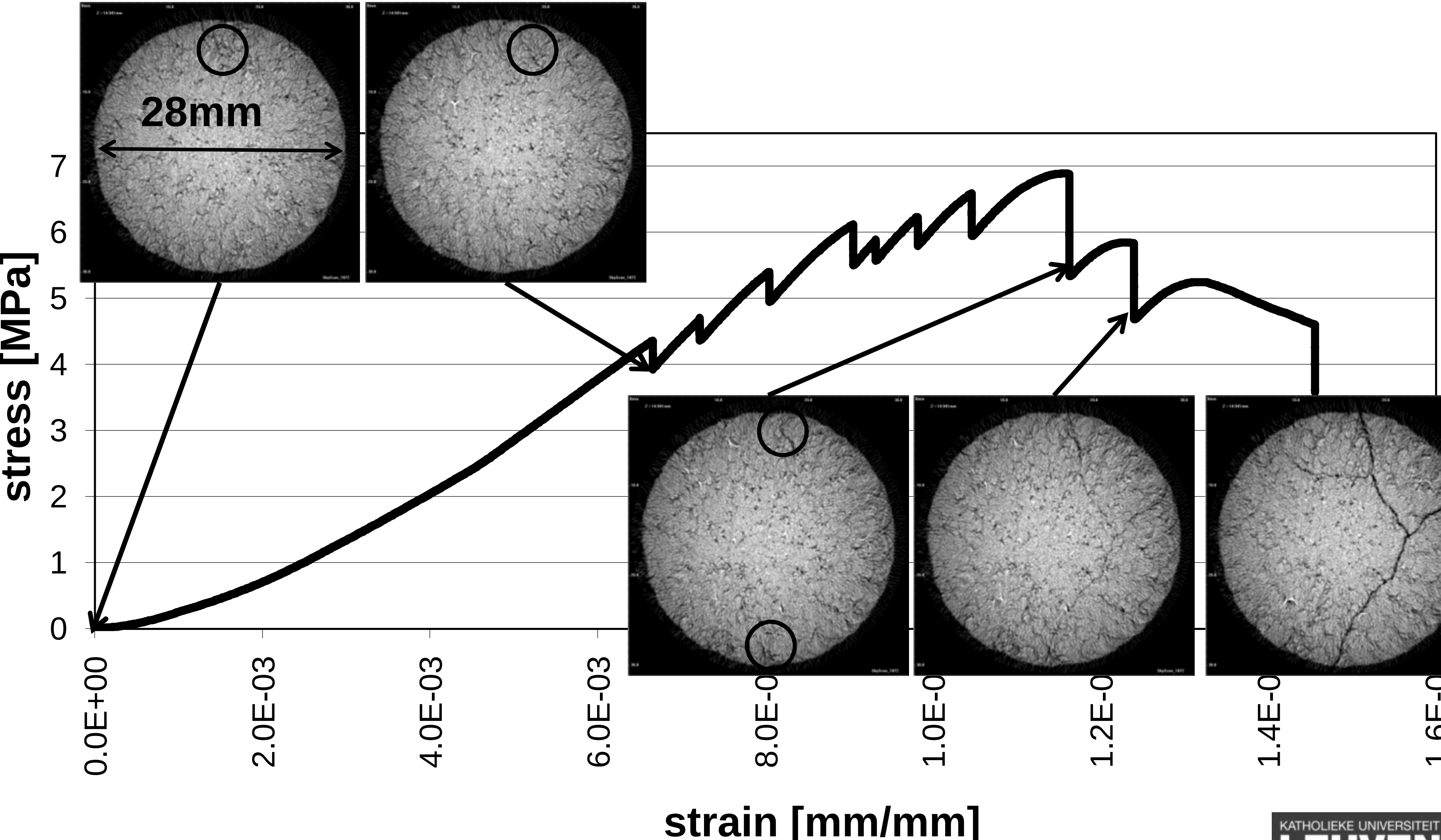
- Micro-focus CT-scanning + compressive test
- Scanning at each load step



Scanning after relaxation



Crack development - hybrid mortar



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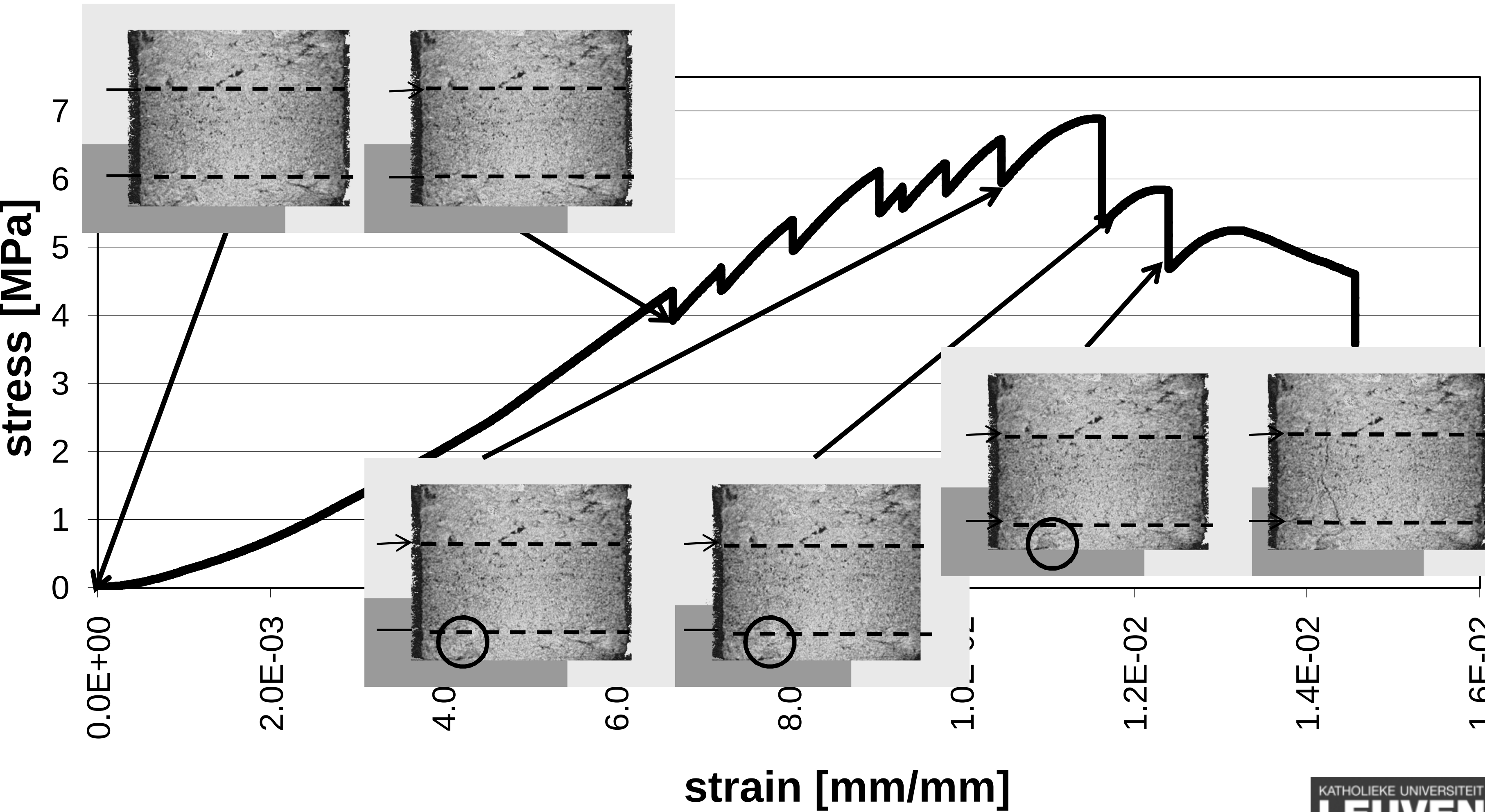

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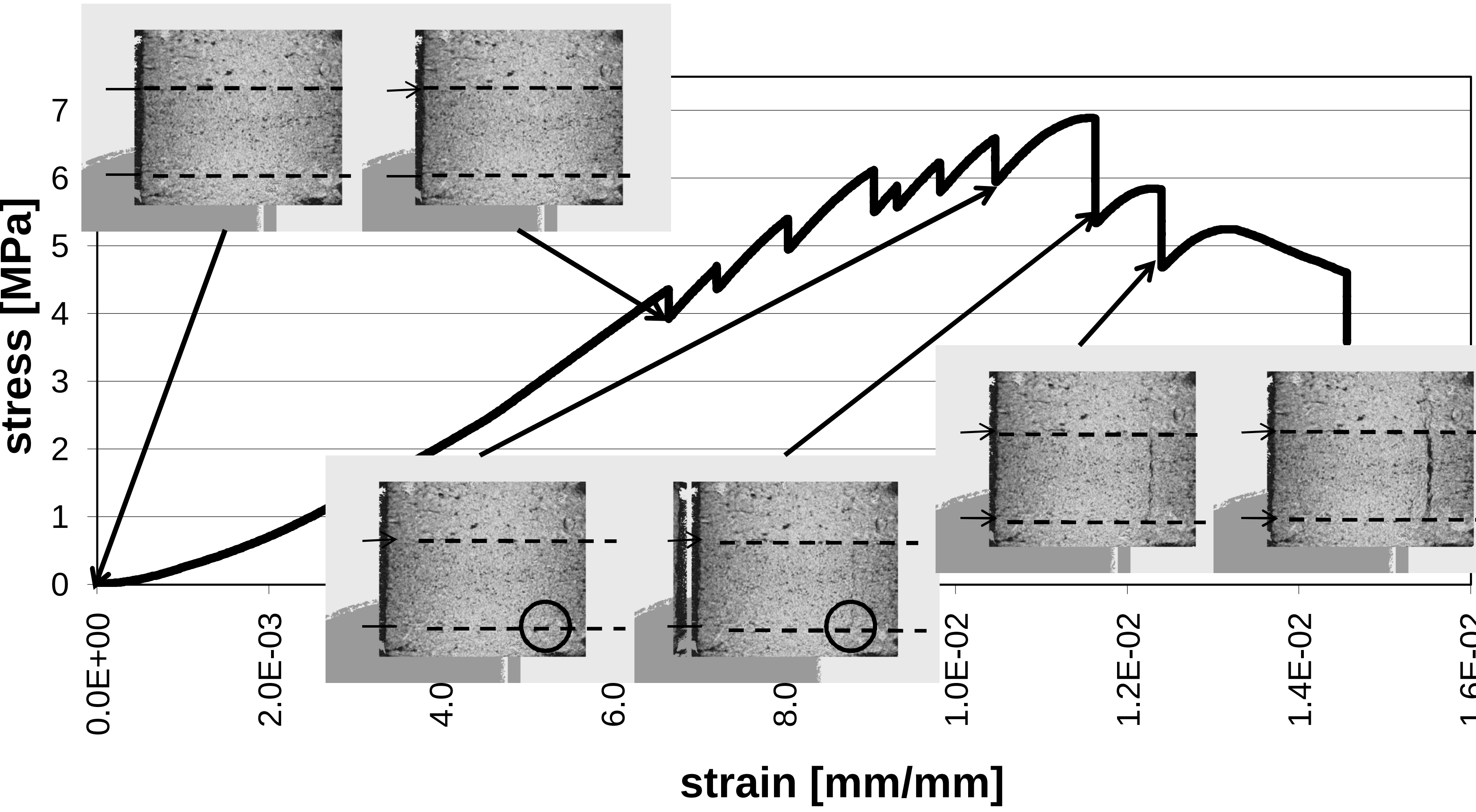

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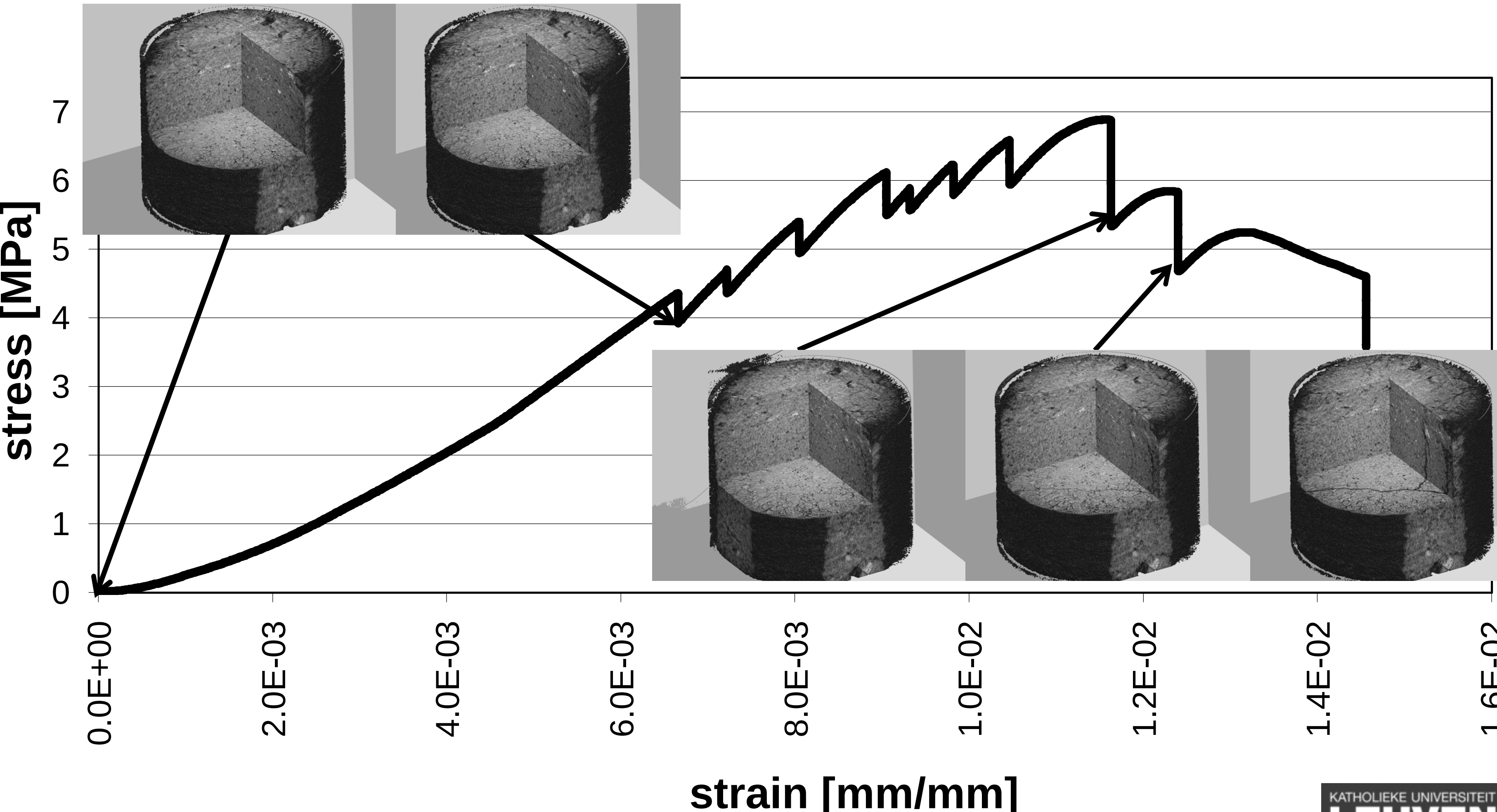


Conclusions and further research

- Lateral displacements for brick > mortar ($E_m > E_b$)

$\rightarrow$ lateral compression in brick;

$\rightarrow$ tensile stresses in mortar – exceeding f_t –

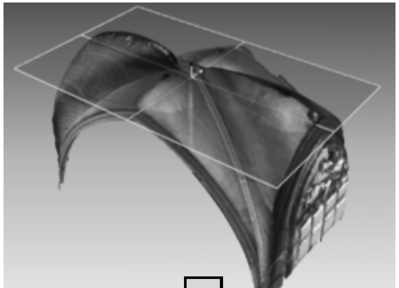
- crack occurrence at initial deficiencies within the material (to be confirmed)
- Spatial resolution: 31μm – occurrence of crack tip not directly visible within the images

Further research:

- Gray-scale comparison at different load steps
- Comparative tests – 2D – cross-sections at rate of 25 images/s (without relaxation – disturbing the measurements).

3D-laserscanning– supporting structural assessment

leshed
nodel



lices
Grid
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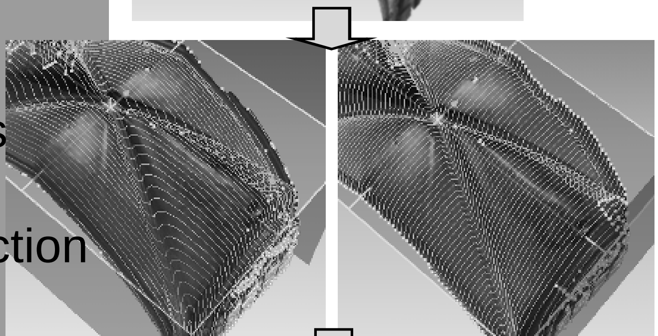

utocad
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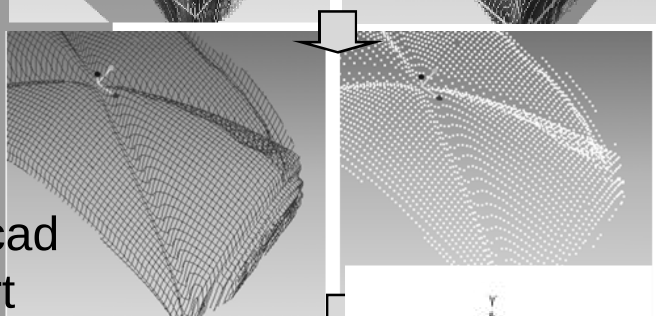

ext files
or
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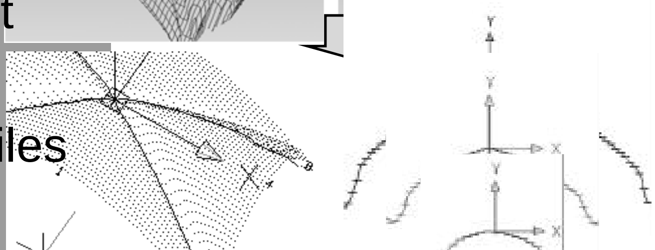
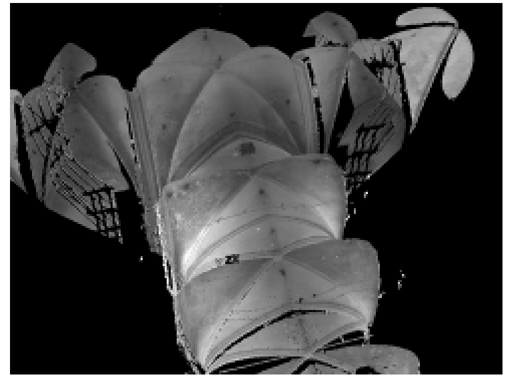
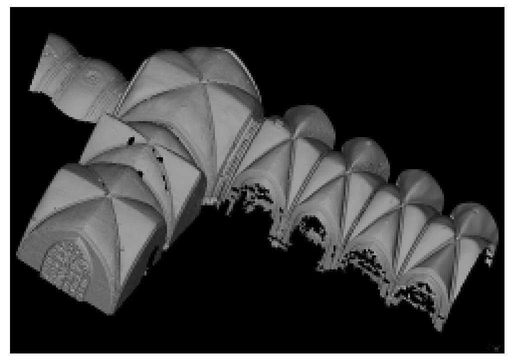
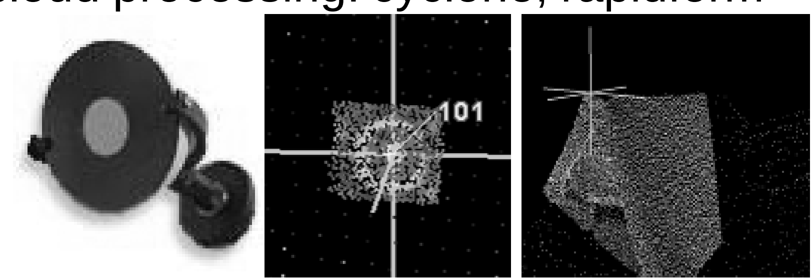






Point cloud processing: cyclone, rapidform

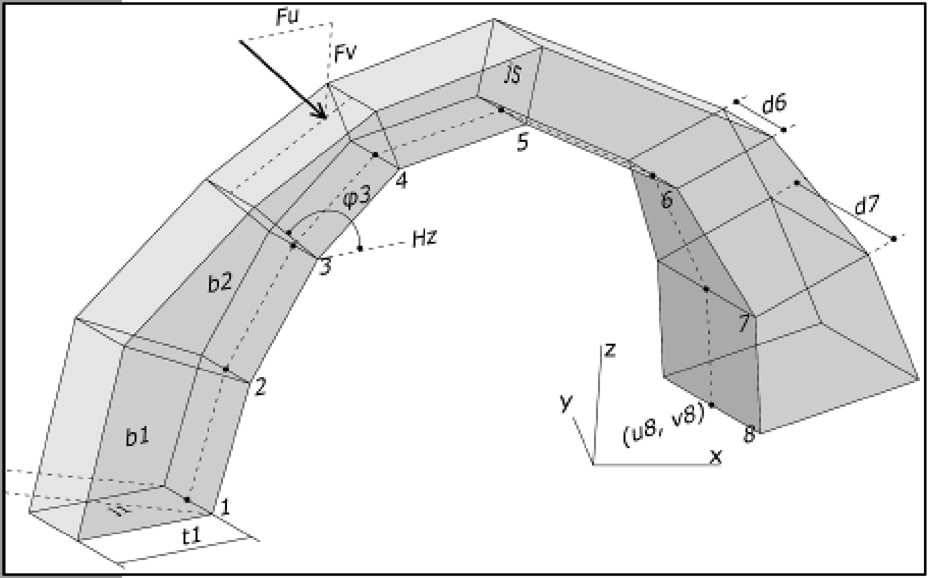
Leica HDS3000 Lase
scanner

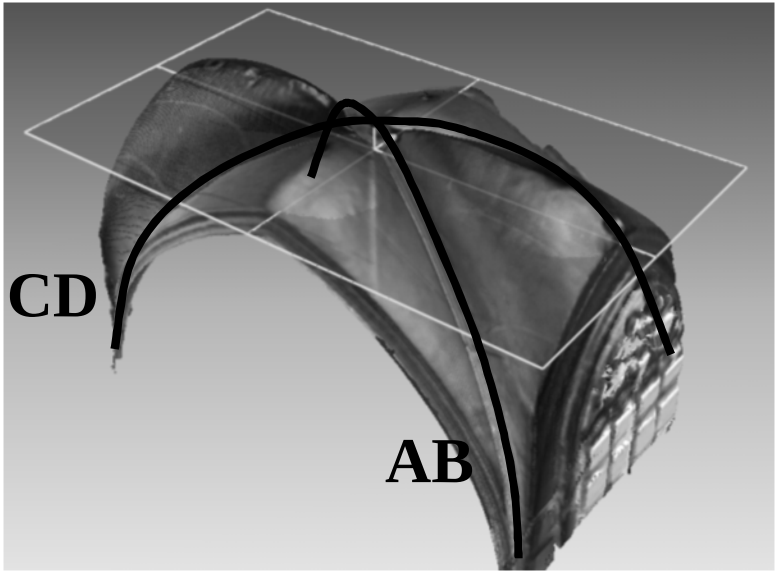


Targets for optimal registration

3D-laserscanning – supporting structural assessment

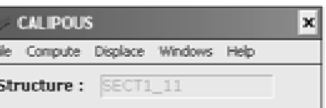
- Calipous Limit Analysis: computer program
  - Analyses the stability of arches of complex geometry
  - Subjected to external loads or movement of abutments
- Calculates:
  - Thrustline passing through 3 given points;
  - Extreme (minimum and maximum) thrustlines;
  - Average (minimizing sum of squares of excentricities) thrustlines.

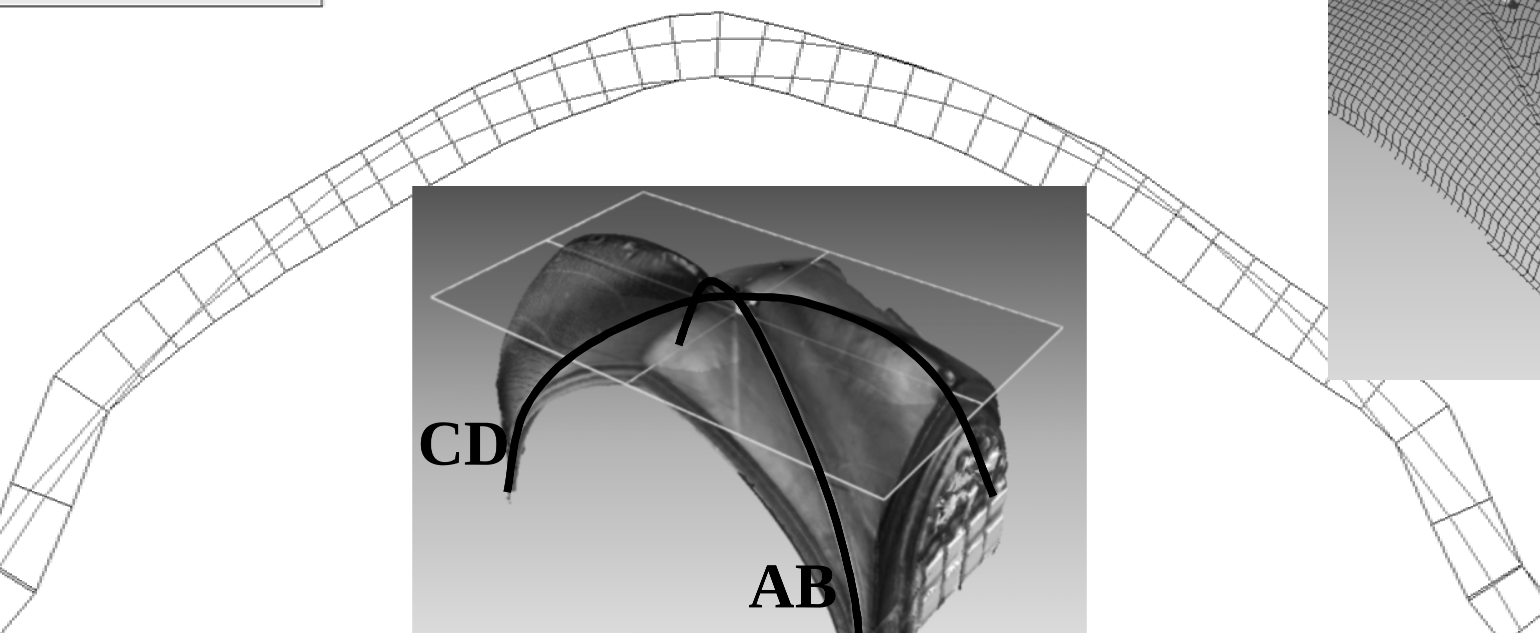


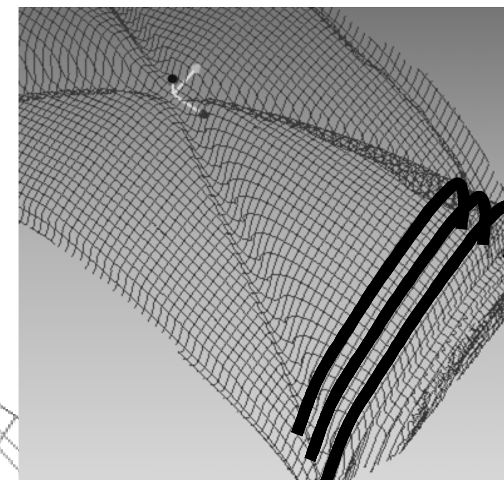


3D-laserscanning – supporting structural assessment

- Results for the vault of the main nave of the Sint-jacobs church
  - Assumptions:
    - Load accounted for: proper weight solely
    - Main structural elements: cross-ribs
    - Intermediate shell transfer their loads towards the main ribs
    - The shell is split up in small sections – each section working as an independent arch







3D-laserscanning – supporting structural assessment

- Result – practical use:
  - Resulting geometrical **factor of safety:** a_g **>1**
  - Symmetry of both cross-ribes clearly visible
  - **Horizontal reaction forces at abutments** – design of new tie rods replacing temporarily tie-rods placed after removal of flying-buttresses

	Vertical reaction forces V [kN]	Horizontal reaction forces		
		Minimum thrust H_{min} [kN]	Maximum thrust H_{max} [kN]	Geometrical factor of safety α_g
		Diagonal AB		
Load case 1	97.	28.9	32.9	1.52
Load case 2		28.6	32.4	1.38
		Diagonal CD		
Load case 1	103	26.9	29.3	1.28
Load case 2		26.6	28.9	1.65

Legend: Load case 1 and 2 represent the loading obtained from the minimum and maximum thrust from the shell sections that transfer their loading towards the ribs

3D-laserscanning – supporting structural assessment

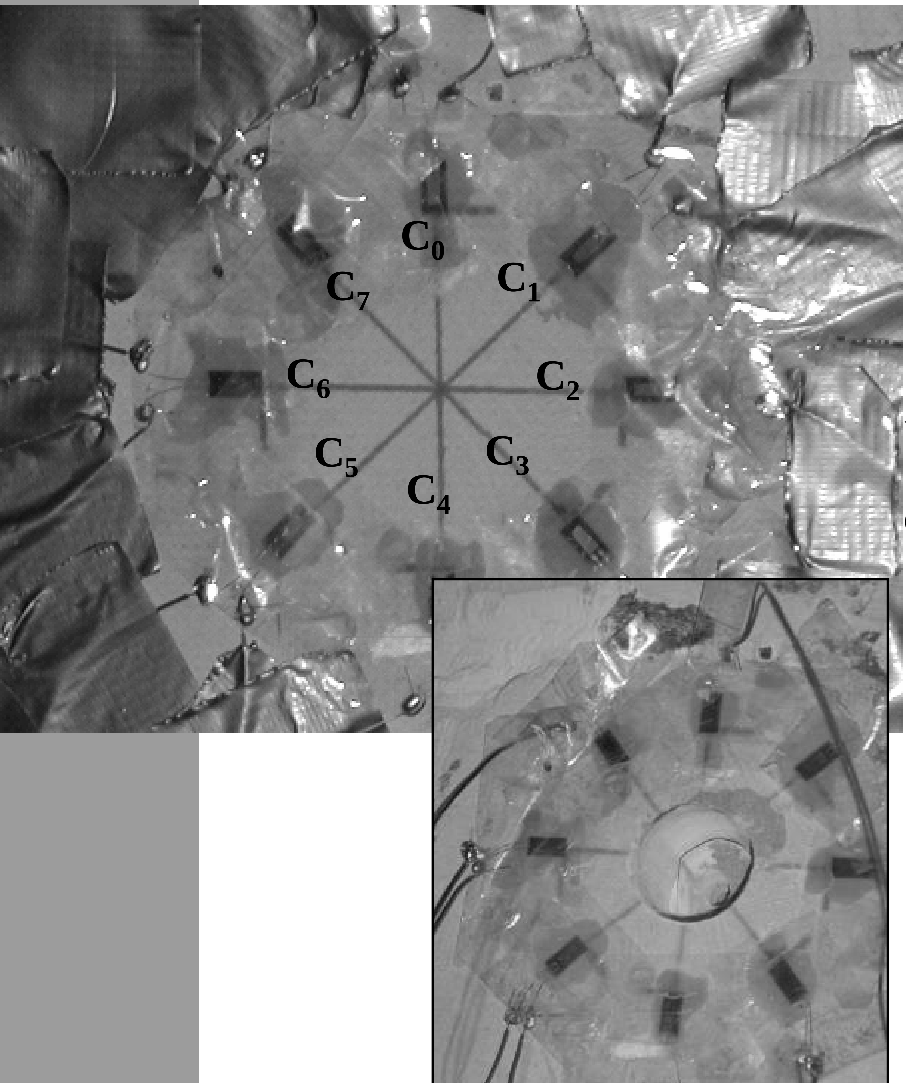
3D-laserscanning – 3D-reconstitution;

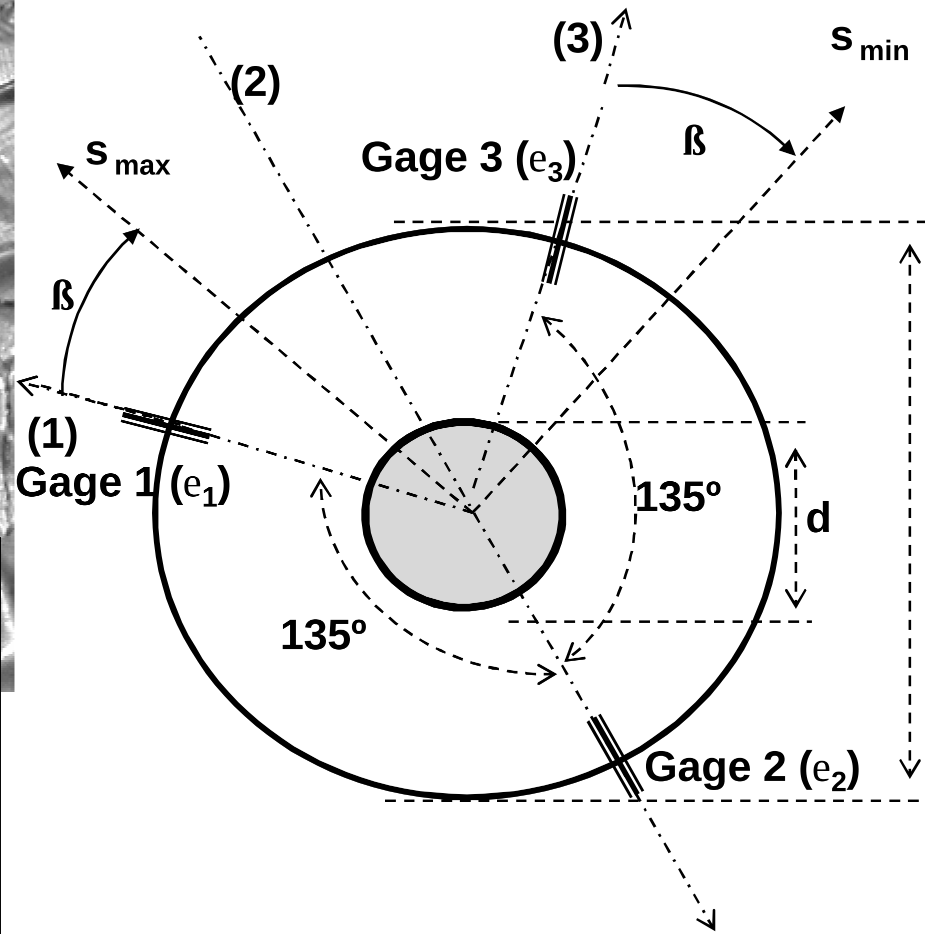
- Partial Collapse - 01/06/2006 of external wall and some vaults
- Residential tower (donjon), 13th century.
- owner: Flemish Government;

Maegdentoren te Zichem (B)

Hole Drilling Technique – on site stress measuremen

Based on: ASTM E837-95

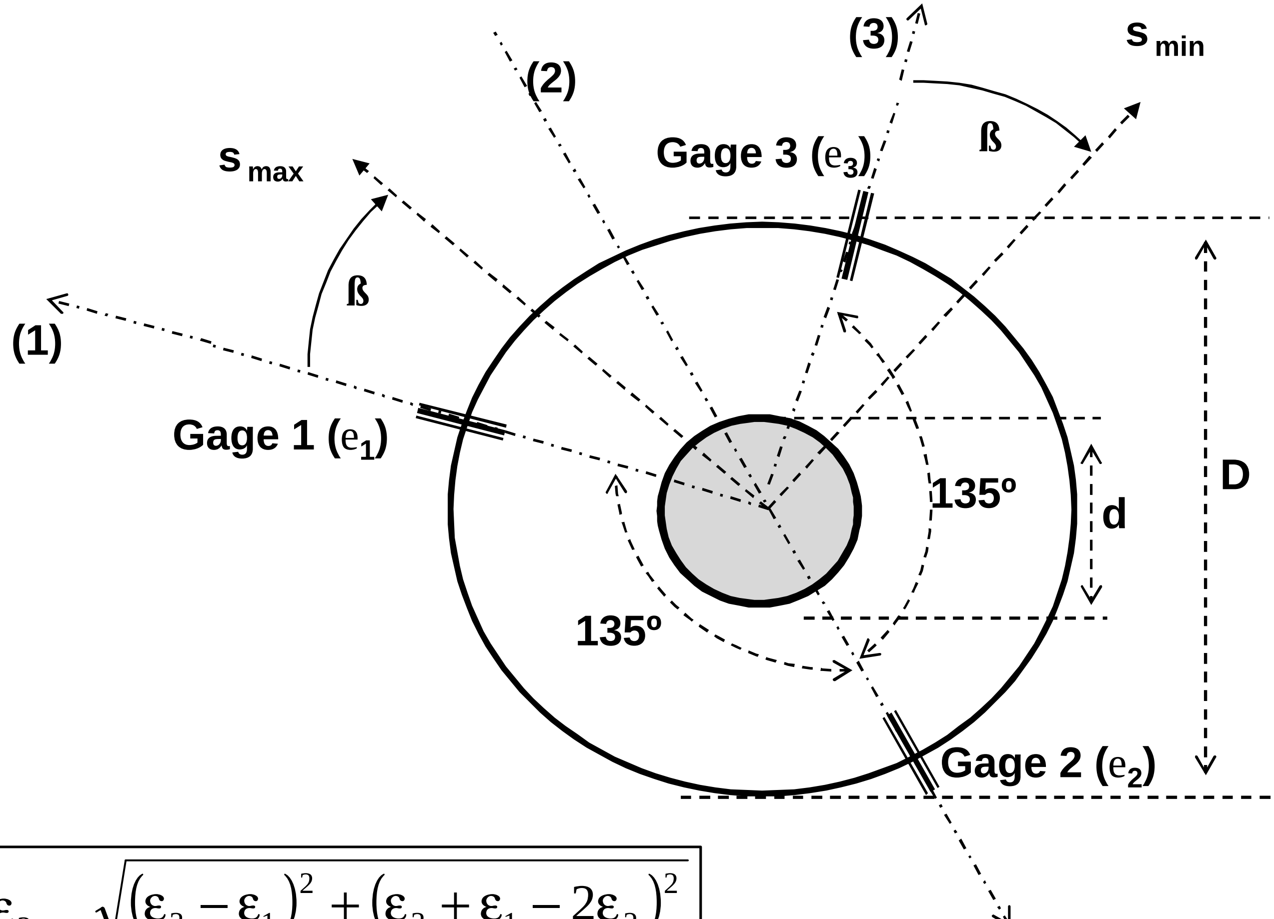




Hole Drilling Technique – on site stress measuremen

Sint-Jacobschurch

Hole Drilling Technique – on site stress measuremen



$$\sigma_{max} = \frac{\varepsilon_1 + \varepsilon_3}{A} - \frac{\sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2}}{B}$$

$$\sigma_{min} = \frac{\varepsilon_1 + \varepsilon_3}{A} + \frac{\sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2}}{B}$$

$$A = -4\left(\frac{1+\nu}{2E}\right.$$

$$B = -4\left(\frac{1}{2E}\right)b$$

$$\beta = \frac{1}{2} arctan\left(\frac{\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2}{\varepsilon_3 - \varepsilon_1}\right.$$

Hole Drilling Technique – on site stress measuremen

Material properties (test in lab from available stones):

- E=15700 MPa
- ν= 0.2

$$A = -4\left(\frac{1+\nu}{2E}\right)a$$

$$B = -4\left(\frac{1}{2E}\right)b$$

Geometrical properties [ASTM E837-95]:

- a= 0.2
- b= 0.5

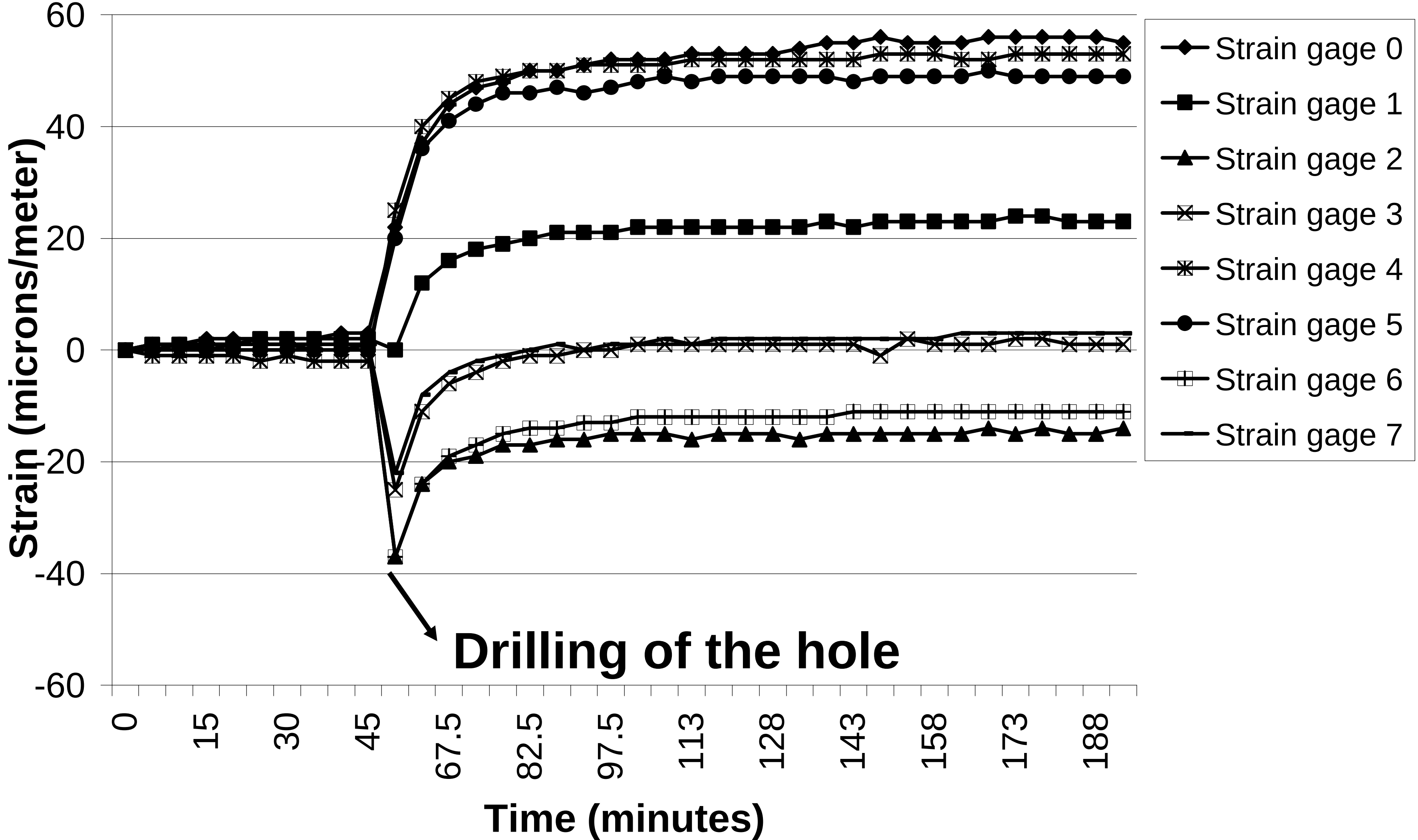
$$\sigma_{max} = \frac{\varepsilon_1 + \varepsilon_3}{A} - \frac{\sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2}}{B}$$

$$\sigma_{min} = \frac{\varepsilon_1 + \varepsilon_3}{A} + \frac{\sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2}}{B}$$

$$\beta = \frac{1}{2} arctan\left(\frac{\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2}{\varepsilon_3 - \varepsilon_1}\right)$$

Hole Drilling Technique – on site stress measuremen

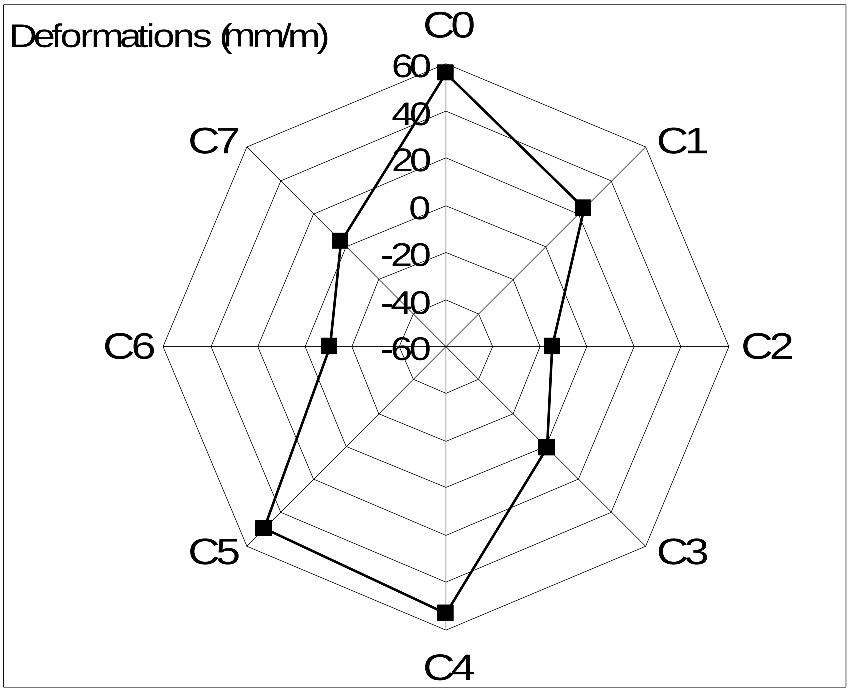
Strains recorded versus time: Pier of central nave



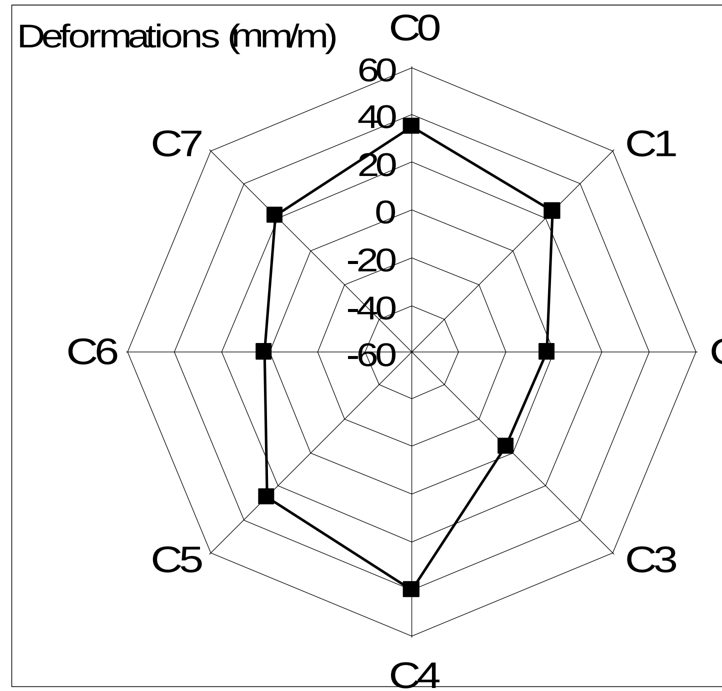
Hole Drilling Technique – on site stress measuremen

Final strains recorded

Pier 1 of central nave



Pier 2 at crossing



Hole Drilling Technique – on site stress measuremen

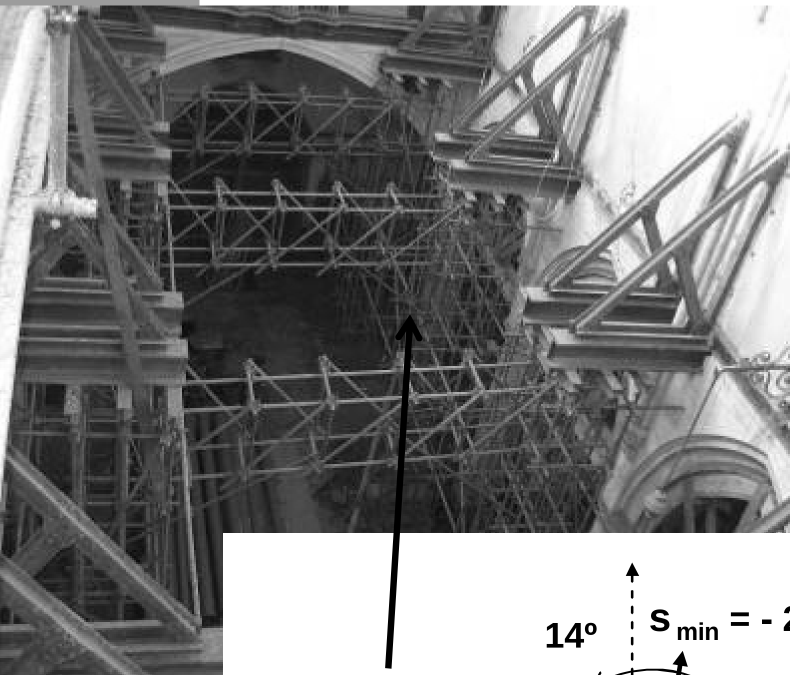
Since 3 strain gauges are required ⇒ redundancy in the system.

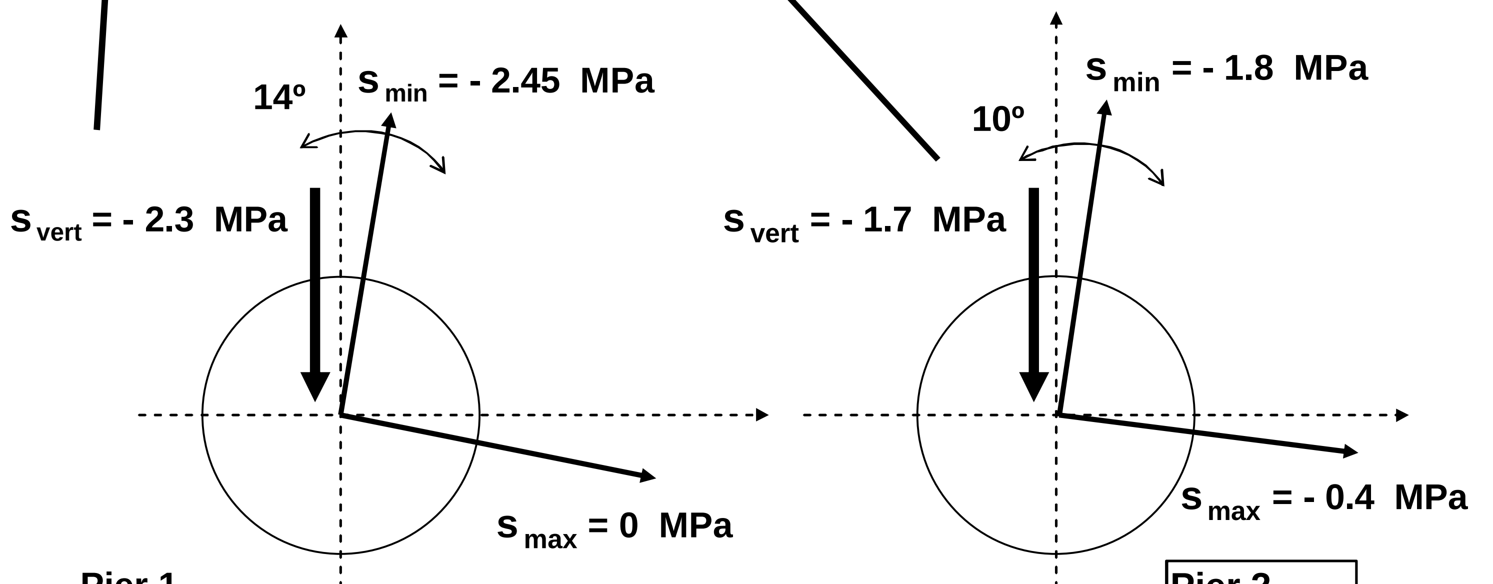
Theorectically 8 combinations available:

- Combination 1: C_0 (ε_1), C_2 (ε_3) and C_5 (ε_2);
- Combination 2: C_1 (ε_1), C_3 (ε_3) and C_6 (ε_2);
- Combination 3: C_2 (ε_1), C_4 (ε_3) and C_7 (ε_2);
- Combination 4: C_3 (ε_1), C_5 (ε_3) and C_0 (ε_2);
- Combination 5: C_4 (ε_1), C_6 (ε_3) and C_1 (ε_2);
- Combination 6: C_5 (ε_1), C_7 (ε_3) and C_2 (ε_2);
- Combination 7: C_6 (ε_1), C_0 (ε_3) and C_3 (ε_2);
- Combination 8: C_7 (ε_1), C_1 (ε_3) and C_4 (ε_2).

Hole Drilling Technique – on site stress measuremen

Sintt-Jacobschurch





Hole Drilling Technique – on site stress measurement

Stress analysis:

- vertical forces caused by dead weight of of the structure
- Horizontal forces caused by thrustline of arches (crossing)

Quantity	symbol	Unit	Pier 1	Pier 2
Vertical force	F_V	kN	1160	1945
Cross-section	A	m²	0.541	1.69
Average value of vertical stress Stress gradient Stress level at measuring point	$s_{V,num}$ $Ds_{V,num}$ $s_{Vtot,num}$	[N/mm²] [N/mm²] [N/mm²]	2.14 0 **2.14**	1.15 0.22 **1.37**
Experimental value (Hole Drilling Technique)	$s_{V,exp}$	[N/mm²]	**2.24 (Comb.3)** **2.40 (Comb.7)**	**1.50 (Comb.1)** **1.90 (Comb.5)**

Hole Drilling Technique – on site stress measuremen

Pier 1:

- Stress levels (experimental: 2.24-2.40MPa– numerical: 2.14 MPa are in line;
- Loading of column of pier central nave: nearly vertical;
- !! Portion of vertical loading deviated to steel tube shoring: negligible (present for almost 40 years).

Pier 2:

- Experimental stress level (1.37 MPa) underestimates numerical value (1.50-1.90 MPa);
- Loading of column of pier crossing: horizontal component (arches of arcades of main nave nave and transept);
- !! Again: Portion of vertical loading deviated to steel tube shoring: small/negligible (present for almost 40 years);

Conclusions

Consolidation, repair or strengthening of masonry: multidisciplinary.

→ correct consolidation measures to be taken, such as grouting, requires fundamental insight within the failure modes occurring and within the actual state of damage of the structure.

→ Benefit is taken from expertise gathered within neighboring research fields:

- **Acoustic Emission** proved to be a very useful tool for damage assessment during short and long term testing of masonry.
- The first results visualizing the crack evolution within masonry, obtained by **Micro-focus X-ray Computed Tomography**, are promising.
- Accurate geometry has an important impact on consolidation measures: **3D-laser scanning** point cloud provides a huge number of 3D data – easy on site applicable;
- **Hole drilling techniques** proves to be adequate for on site stres measurement, also for natural stone masonry.