Darmstädter Massivbau

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

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June 18, Darmstadt - Germany

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

- **Anamnesis:**
  - Description and documentation of building, context (environment)
  - Description of building history and context
  - Documentation (of surveys)
  - Building survey, state of conservation, state of structural decay,
    structural investigation, using: visual inspection, NDT, ...

- **Analysis:**
  - Structural analysis model (idealized)

- **Diagnosis:**
  - Assessment of structural integrity and its load-bearing capacity
  - Monitoring as part of the diagnosis

- **Therapy:**
  - Plan and choices for (non-)intervention
  - Motivation of choices, with attention towards durability of the solution.
  - 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 occurring;

• 3D lasercanning:
  – 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)
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.
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 stress 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

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Successive stress increase steps (in % of compressive strength $f_c$)</th>
<th>Days to failure after last stress increase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(0)</td>
<td>(1)</td>
</tr>
<tr>
<td>28</td>
<td>50 $\rightarrow$ 60 %</td>
<td>60 $\rightarrow$ 65 %</td>
</tr>
<tr>
<td>30</td>
<td>-</td>
<td>85 $\rightarrow$ 87 %</td>
</tr>
</tbody>
</table>
## AE during creep tests – test results

### Table: Successive stress increase steps

<table>
<thead>
<tr>
<th>Specimen</th>
<th>(0)</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>Days to failure after last stress increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>50 → 60 %</td>
<td>60 → 65 %</td>
<td>65 → 70 %</td>
<td>70 → 75 %</td>
<td>8 days</td>
</tr>
<tr>
<td>30</td>
<td>85 → 87 %</td>
<td>87 → 90 %</td>
<td>90 → 93 %</td>
<td></td>
<td>5 days</td>
</tr>
</tbody>
</table>
## AE during creep tests – test results

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<td>8 days</td>
</tr>
<tr>
<td>30</td>
<td>$(0)$ - $(1) 85 \rightarrow 87 %$ $(2) 87 \rightarrow 90 %$ $(3) 90 \rightarrow 93 %$</td>
<td>5 days</td>
</tr>
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<td>(0) - (1) $85 \rightarrow 87%$ (2) $87 \rightarrow 90%$ (3) $90 \rightarrow 93%$</td>
<td>5 days</td>
</tr>
</tbody>
</table>
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 within the framework of the creep modeling - extensive research program has almost finalized.

2 further challenges:

• **Monitoring for real case studies** – attempts have been made (church tower at Zichem, Castle Ter Leenen at Geetbets and apartment building in Recife, Brazil)
  
  • measurement period: sufficiently long: to clearly assess the event rate;
  
  • Repetiveness of measurement campaigns to serve as an appropriate monitoring technique and to assess the damage evolution (or increase in event rate) on the long term.

• With additional laboratory experiments, the monitoring results are being extended from giving good **qualitative information towards quantification of the damage accumulation**. This will also enhance 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-transparent sample based on the attenuation of X-rays.

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

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

\[ \kappa = \frac{\sigma_h}{\sigma_v} \]

<table>
<thead>
<tr>
<th>Stress state</th>
<th>Uni-axial</th>
<th>Triaxial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Behavior</td>
<td>brittle</td>
<td>Elasto-plastic</td>
</tr>
<tr>
<td>Failure mode</td>
<td>Shear bands</td>
<td>Pore collapse</td>
</tr>
</tbody>
</table>
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) \((E_m < E_b)\).

<table>
<thead>
<tr>
<th>Mechanical property</th>
<th>brick</th>
<th>Hybrid mortar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength: (f_c) ([N/mm^2])</td>
<td>8.86 (0.89)</td>
<td>10.88 (0.15)</td>
</tr>
<tr>
<td>Bending tensile strength: (f_t) ([N/mm^2])</td>
<td>/</td>
<td>3.19 (0.09)</td>
</tr>
<tr>
<td>Direct tensile tests: (f_{ty}) ([N/mm^2])</td>
<td>0.30(0.10)*</td>
<td></td>
</tr>
<tr>
<td>Young’s Modulus: (E) ([N/mm^2])</td>
<td>1700(400)*</td>
<td>11200 (160)</td>
</tr>
</tbody>
</table>
### Preparation of test samples

<table>
<thead>
<tr>
<th>Accessory device</th>
<th>Step 1: brick bottom layer</th>
<th>Step 2: hybrid mortar layer</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Accessory device" /></td>
<td><img src="image2" alt="Step 1: brick bottom layer" /></td>
<td><img src="image3" alt="Step 2: hybrid mortar layer" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 3: parallel brick top layer</th>
<th>Step 4: sample before core drilling</th>
<th>Test sample – d=29mm – h=48 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image4" alt="Step 3: parallel brick top layer" /></td>
<td><img src="image5" alt="Step 4: sample before core drilling" /></td>
<td><img src="image6" alt="Test sample – d=29mm – h=48 mm" /></td>
</tr>
</tbody>
</table>
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

stress [MPa]

0  1  2  3  4  5  6  7

0  50  100  150  200  250
time [min]
Crack development - hybrid mortar

stress [MPa]

strain [mm/mm]

28mm
Crack development - hybrid mortar

- Stress [MPa]
- Strain [mm/mm]

Graph showing the stress-strain relationship for hybrid mortar, with images indicating crack development at different stress levels.
Crack development - hybrid mortar

stress [MPa]

strain [mm/mm]
Crack development - hybrid mortar

stress [MPa]

strain [mm/mm]

0.0E+00 2.0E-03 4.0E-03 6.0E-03 8.0E-03 1.0E-02 1.2E-02 1.4E-02 1.6E-02
Conclusions and further research

- Lateral displacements for brick > mortar ($E_m > E_b$)
  - lateral compression in brick;
  - tensile stresses in mortar – exceeding $f_t$ –
- crack occurrence at initial deficiencies within the material (to be confirmed)
- Spatial resolution: 31$\mu$m – 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

Meshed model

Slices
Grid projection

Autocad export

Text files for Calipous

Leica HDS3000 Laser scanner

Point cloud processing: cyclone, rapidform

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**: $\alpha_g > 1$
  – Symmetry of both cross-ribs clearly visible
  – **Horizontal reaction forces at abutments** – design of new tie-rods replacing temporarily tie-rods placed after removal of flying-butresses

<table>
<thead>
<tr>
<th></th>
<th>Vertical reaction forces V [kN]</th>
<th>Minimum thrust $H_{\text{min}}$ [kN]</th>
<th>Maximum thrust $H_{\text{max}}$ [kN]</th>
<th>Geometrical factor of safety $\alpha_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Diagonal AB</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load case 1</td>
<td>28.9</td>
<td>32.9</td>
<td>1.52</td>
<td></td>
</tr>
<tr>
<td>Load case 2</td>
<td>28.6</td>
<td>32.4</td>
<td>1.38</td>
<td></td>
</tr>
<tr>
<td><strong>Diagonal CD</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load case 1</td>
<td>26.9</td>
<td>29.3</td>
<td>1.28</td>
<td></td>
</tr>
<tr>
<td>Load case 2</td>
<td>26.6</td>
<td>28.9</td>
<td>1.65</td>
<td></td>
</tr>
</tbody>
</table>

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 measurement

Based on: ASTM E837-95

\[ Gage 1 (e_1) \]
\[ Gage 2 (e_2) \]
\[ Gage 3 (e_3) \]

\[ s_{\text{max}} \]
\[ s_{\text{min}} \]

\[ \beta \]

135°
Hole Drilling Technique – on site stress measurement
Sint-Jacobscurch
Hole Drilling Technique – on site stress measurement

\[
\begin{align*}
\sigma_{\text{max}} &= \frac{\varepsilon_1 + \varepsilon_3 - \sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2}}{A} \\
\sigma_{\text{min}} &= \frac{\varepsilon_1 + \varepsilon_3 + \sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2}}{A} \\
\end{align*}
\]

\[
\begin{align*}
B &= -4 \left( \frac{1}{2E} \right) b \\
A &= -4 \left( \frac{1+v}{2E} \right) a \\
\beta &= \frac{1}{2} \arctan \left( \frac{\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2}{\varepsilon_3 - \varepsilon_1} \right)
\end{align*}
\]
Hole Drilling Technique – on site stress measurement

Material properties (test in lab from available stones):
- E=15700 MPa
- ν= 0.2

Geometrical properties [ASTM E837-95 ]:
- a= 0.2
- b= 0.5

\[
\begin{align*}
\sigma_{max} &= \frac{\varepsilon_1 + \varepsilon_3 - \sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2}}{A - \frac{B}{1 + \frac{1}{2E}}} \\
\sigma_{min} &= \frac{\varepsilon_1 + \varepsilon_3 + \sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2}}{A + \frac{B}{1 + \frac{1}{2E}}} \\
\beta &= \frac{1}{2} \arctan \left( \frac{\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2}{\varepsilon_3 - \varepsilon_1} \right)
\end{align*}
\]
Hole Drilling Technique – on site stress measurement

Strains recorded versus time: Pier of central nave

Drilling of the hole
Hole Drilling Technique – on site stress measurement

Final strains recorded

Pier 1 of central nave

Pier 2 at crossing
Hole Drilling Technique — on site stress measurement

Since 3 strain gauges are required ⇒ redundancy in the system. Theoretically 8 combinations available:

- Combination 1: $C_0 (\varepsilon_1)$, $C_2 (\varepsilon_3)$ and $C_5 (\varepsilon_2)$;
- Combination 2: $C_1 (\varepsilon_1)$, $C_3 (\varepsilon_3)$ and $C_6 (\varepsilon_2)$;
- Combination 3: $C_2 (\varepsilon_1)$, $C_4 (\varepsilon_3)$ and $C_7 (\varepsilon_2)$;
- Combination 4: $C_3 (\varepsilon_1)$, $C_5 (\varepsilon_3)$ and $C_0 (\varepsilon_2)$;
- Combination 5: $C_4 (\varepsilon_1)$, $C_6 (\varepsilon_3)$ and $C_1 (\varepsilon_2)$;
- Combination 6: $C_5 (\varepsilon_1)$, $C_7 (\varepsilon_3)$ and $C_2 (\varepsilon_2)$;
- Combination 7: $C_6 (\varepsilon_1)$, $C_0 (\varepsilon_3)$ and $C_3 (\varepsilon_2)$;
- Combination 8: $C_7 (\varepsilon_1)$, $C_1 (\varepsilon_3)$ and $C_4 (\varepsilon_2)$. 
Hole Drilling Technique – on site stress measurement

Sint-Jacobschurch

\[ s_{\text{min}} = -2.45 \text{ MPa} \]

\[ s_{\text{max}} = 0 \text{ MPa} \]

\[ s_{\text{vert}} = -2.3 \text{ MPa} \]

\[ 14^\circ \]

\[ s_{\text{min}} = -1.8 \text{ MPa} \]

\[ s_{\text{vert}} = -1.7 \text{ MPa} \]

\[ 10^\circ \]

\[ s_{\text{max}} = -0.4 \text{ MPa} \]

Pier 1

Pier 2
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)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>symbol</th>
<th>Unit</th>
<th>Pier 1</th>
<th>Pier 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical force</td>
<td>$F_V$</td>
<td>kN</td>
<td>1160</td>
<td>1945</td>
</tr>
<tr>
<td>Cross-section</td>
<td>$A$</td>
<td>m²</td>
<td>0.541</td>
<td>1.69</td>
</tr>
<tr>
<td>Average value of vertical stress</td>
<td>$\sigma_{V,num}$</td>
<td>[N/mm²]</td>
<td>2.14</td>
<td>1.15</td>
</tr>
<tr>
<td>Stress gradient</td>
<td>$\Delta\sigma_{V,num}$</td>
<td>[N/mm²]</td>
<td>0</td>
<td>0.22</td>
</tr>
<tr>
<td>Stress level at measuring point</td>
<td>$\sigma_{Vtot,num}$</td>
<td>[N/mm²]</td>
<td>2.14</td>
<td>1.37</td>
</tr>
<tr>
<td><strong>Experimental value</strong></td>
<td>$\sigma_{V,exp}$</td>
<td>[N/mm²]</td>
<td>2.24 (Comb.3)</td>
<td>1.50 (Comb.1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.40 (Comb.7)</td>
<td>1.90 (Comb.5)</td>
</tr>
</tbody>
</table>
Hole Drilling Technique — on site stress measurement

Pier 1:
• Stress levels (experimental: 2.24-2.40 MPa – 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 stress measurement, also for natural stone masonry.