Adaption of Pulsed Phase Thermography for the Quantitative NDT-CE

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„Non-destructive Damage Assessment and Environmental Measurement Methods “

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Division VIII.2

Non-destructive Damage Assessment and Environmental Measurement Methods

Electromagnetic Methods for the Assessment of Structures; Development and Validation

Acoustic Methods for Testing Building Structures

Non-destructive Environmental Measurement Methods

Combination and Automation of Non-destructive Testing of Buildings
Overview

Introduction
Applications
Quantitative Approach
Conclusions
Outlook
Applications of passive thermography at BAM

- Detection of heat leacages
- Detection and control of wall and floor heatings
- Moisture detection
- Control of electric installations
Principles

Restriction to passive thermography

Existing temperature gradient, limited applications

Development of active thermography - methods

Pulsed thermography (Time Domain - TD)
Lock-in thermography (Frequency Domain - FD)
Pulsed phase thermography (FD)
Step heating thermography
Square pulse thermography (TD / FD)
Alternative stimulation in active thermography

Pulsed heating  Step heating  Square pulse heating  Periodic heating
PT→PPT  TRIR  SPT (TD) → SPT (FD)  LT

Problems of applying thermography in CE

- Relative low thermal conductivities of used materials
- Large dimensions of most building structures
- Changing environmental conditions
- Inhomogeneous surface structures

Flexibele equipment and high energetic heat pulses with long heating and recording times (PT→SPT in time domain)

Increasing signal-to-noise ratio of the phase images, quantitative solution with phase and amplitude data (PPT→SPT in frequency domain)
Introduction

PT / SPT time domain

Lock-in-Thermography

\[ A: \text{Amplitude} \]
\[ \omega: \text{Frequency} \]
\[ \phi: \text{Phase} \]

PPT / SPT frequency domain

Time domain

Frequency domain

[Maldague(modified)]
Typical problems for active thermography in civil engineering

• Localisation of voids in concrete structures
• Localisation of delaminations of layered structures (e.g. tiles or carbon reinforced laminates on concrete)
• Localisation of plaster delaminations on concrete and brickwork
• Localisation of voids and delaminations behind tiles
• Localisation of enhanced moisture in the surface near region
Introduction

Quantiative approaches

PT / SPT - time domain → FT → PPT / SPT - frequency domain

Transients and temperature-time-difference-curve of the cooling down process

Phase-frequency-difference-curve after FT of the transients
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Structure- and humidity investigations in Civil Engineering by means of impulse thermography, part 1 (TD) and part 2 (FD) (2001 to 2005)
   in collaboration with the Technical University of Berlin (TUB)
   Supported by the Deutsche Forschungsgemeinschaft

On-site investigation techniques for the structural evaluation of historic masonry buildings (2001 to 2004)
   in collaboration with thirteen international partners
   Supported by the fifth supporting programme of the EC

SUSTAINABLE BRIDGES
   in collaboration with thirty international partners
   Supported by the sixth framework programme of the EC

and many small and big investigations and case studies…
Actice Thermography at BAM, VIII.2

- Development of equipment for manual and automated application on the building site
- Application to concrete and historic masonry structures
- Development of software tools for time and frequency related data analysis and defect quantification (e.g. SPT in frequency domain)
- Numerical simulation of heat transport based on Finite Differences and Finite Elements
- Close cooperation to TU Berlin (Prof. Hilemeier)
ActiceThermography at BAM, VIII.2 and TUB

- Localisation of voids in concrete structures (DFG)
- Localisation of enhanced moisture in the surface near region (DFG)
- Localisation of poorly grouted regions in tendon ducts (TUB-DFG)
- Localisation of plaster delaminations on concrete (DFG) and brickwork (EU)
- Localisation of delaminations of layered structures (e.g. carbon reinforced laminates or tiles on concrete - DFG / EU)
Applications

Measuring equipment

Laboratory investigations
- monitor
- infrared camera
- computer
- Infrared radiator
- specimen

On-site investigations

Heating units
- Infrared radiator
- Fan heater
- Halogen lamps
- Flashlights
- Sun

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Set-up of the thermography scanner

Scanner with flash lights and IR camera
Applications

Location of a former door behind plaster at Wartburg Castle, Eisenach

- Wartburg Castle is situated on a mountain above Eisenach
- Eldest residential building of a mediaeval castle in Germany
- Built between 1156 and 1172
- Part of the World Heritage
- Martin Luther stayed here in 1521 translating the New Testament into German
Cross section of the Palas showing cellar, ground floor and first floor
Measurement positions at the Landgrafenzimmer
Location of a former door behind plaster at Wartburg Castle, Eisenach

Heating of the surface:
Manually, area size: 1 m², fan heater, 5 min

Observation of cooling down:
Area size 1 m², 15 min, 2 Hz
SC1000, 3.4 to 5 µm

Data analysis:
SPT
Location of a former door behind plaster at Wartburg Castle, Eisenach

Foto of area

Phase image at $2.46 \times 10^{-4}$ Hz: Structure of masonry with bricks and joints can be resolved in detail
Location of connecting elements (metal and wooden nails) and possible delaminations of inlays in the New Palais, Potsdam

- Constructed from 1763 to 1769 by Friedrich II. of Prussia
- Late baroque summer residence and guest house for the royal families
- Home of the last German Emperor Wilhelm II. and his family from 1889 to 1918
- Restoration of the wooden parquet floors
New Palais, Potsdam

Heating of the surface:
Manually, areas: 1 m²
fan heater, 5 min

Observation of cooling down:
Area height 1 m, 15 min, 0.5 Hz
SC1000, 3.4 to 5 mm

Data analysis:
SPT
Applications

New Palais, Potsdam

Photo

Themogram

Phase image

0 s

2.22 x 10^-3 Hz
Investigation of masonry walls and ceilings
Location of voids below a floor paved by natural stone

Heating of the surface:
Manually, area size: 1 m radiator, 3 min

Observation of cooling down:
Area size 1 m, 15 min, 2 Hz SC1000, 3.4 to 5 mm

Superpositioning of an equalised digital photo and the related equalised thermogram
Location of asphalt delaminations on a concrete bridge heated up by sun radiation

Heating of the surface:
Sun radiation, 23rd of June 2006, 10 a.m.

Observation of cooling down:
Shadowing of an area of 1 m², 15 min, 2 Hz
Location of damages at CFRP strengthened systems

Damages:
• Insufficient application
• Aging effects due to heavy loads and environmental influences
• Further impacts

>> delaminations and deteriorations

Photograph: STO
PT on CFRP-strengthened Composites

Concrete block specimen with designed defects

Concrete block specimen with CFRP-stripes

Polystyrene patches

Foam rubber patches
Applications

Thermograms and temperature evolution

**Infrared radiators**
Power: 3 x 2400 W  
Area: 1.5 x 1.5 m²  
Heating time: 1 min  
Observation time after heating: 5 min  
Recorded 66 s after heating

**Halogen lamps**
Power: 2 x 650 W  
Area: ~625 cm², defect: 50 cm²  
Heating time: 3 s  
Observation time after heating: 5 min  
Recorded 76 s after heating

**Flashlights**
Power: 2 x 1500 W  
Area: ~625 cm², defect: 50 cm²  
Heating time: 7 flashes during 60s  
Observation time after heating: 2 min  
Recorded 40 s after heating
Set-up of 2 test beams, 0.3 m x 0.5 m x 5.2 m, CFRP-Application: STO

Lamellae: STO BPE: 100 x 1,4 mm

Elasticity: ≤ 1,2 %

Tension strength: ≥ 2500 N/mm²
Set-up of the thermography scanner

Heating of the surface:
Automatically flash lights (1500 W each)
area size: 30 cm x 30 cm
7 flashes each area

Observation of cooling down:
Area size: 30 cm x 30 cm
5 min, 10 Hz
SC1000, 3.4 to 5 µm

Data analysis:
PPT
Set-up of the thermography scanner

Scanner with flash lights and IR camera
Applications

Load test: Test set up

5200 mm

1100 mm
Preloading

5200 mm

1100 mm

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Applications

Unloading

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5200 mm

1100 mm
Load test with repeated thermographic evaluation
Applications

Beam Loading

289.5 kN: Debonding of CFRP-Plates

After Failure: < 150 kN

→ Load limit without strengthening

Preloading ~ 90 kN

Weight of the beam

Load kN

Deflection in the middle mm

Load kN

0 10 20 30 40 50 60

0 50 100 150 200 250 300
Phase images at critical areas during loading

Frequency: $3.33 \times 10^{-3}$ Hz
Total delamination after unloading

Finally failed cross section
~ ca. 1/3 l at 285 / 292 kN
Applications

Increase of debonding between adhesive and concrete

Failure of concrete caused by the returning wave
Overview

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Quantitative Approach

Concrete specimen A with voids

<table>
<thead>
<tr>
<th>Number of defect</th>
<th>Intended concrete cover</th>
<th>Radar result on concrete cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8 cm</td>
<td>9.2 ± 1.5 cm</td>
</tr>
<tr>
<td>2</td>
<td>6 cm</td>
<td>7.6 ± 1.5 cm</td>
</tr>
<tr>
<td>3</td>
<td>4 cm</td>
<td>± 0.0 cm</td>
</tr>
<tr>
<td>4</td>
<td>2 cm</td>
<td>± 0.0 cm</td>
</tr>
<tr>
<td>5</td>
<td>2 cm</td>
<td>3.0 ± 1.0 cm</td>
</tr>
<tr>
<td>6</td>
<td>4 cm</td>
<td>4.3 ± 1.0 cm</td>
</tr>
<tr>
<td>7</td>
<td>6 cm</td>
<td>3.5 ± 1.0 cm</td>
</tr>
<tr>
<td>8</td>
<td>8 cm</td>
<td>4.3 ± 1.0 cm</td>
</tr>
</tbody>
</table>
Quantitative Approach

Concrete specimen with A voids

20 * 20 * 10 cm³

10 * 10 * 10 cm³

plan view

15 min heating

2 h cooling down
Temperature time curves and difference curve of the cooling down process
Time of maximum temperature difference depending on heating time

- Void no 1, d = 9.2 cm
- Void no 2, d = 7.6 cm
- Void no 3, d = 0.0 - 1.0 cm
- Void no 4, d = 0.0 - 1.0 cm

Heating time in s

Time of maximum temperature difference in s
Quantitative approaches

Transients and temperature-time-difference-curve of the cooling down process

Phase-frequency-difference-curve after FT of the transients
Quantitative PPT in NDT of thin-layered structures and pulse-heating

Relationship between depth of a defect and blind frequency $f_b$ in literature [1]:

$$z = C_1 \cdot \sqrt{\frac{\alpha}{\pi \cdot f_b}}$$

where:
- $z$ ... Depth of a defect in [m]
- $f_b$ ... Blind frequency in [Hz]
- $\alpha$ ... Thermal diffusivity [m$^2$/s]
- $C_1$ ... Correlation factor

and for bad sampled data:

$$z = C_1' \cdot \varphi_{\text{min}} \cdot \sqrt{\frac{\alpha}{\pi \cdot f_b'}}$$

where:
- $z$ ... Depth of a defect in [m]
- $f_b'$ ... Blind frequency in [Hz]
- $C_1'$ ... Regression coefficient
- $\varphi_{\text{min}}$... Phase at the detection threshold in [rad]

Quantitative Approach

Phase contrast curves

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Phase-contrast-curves for void 2 concrete specimen B for different heating times
Quantitative Approach

New quantitative approach for PPT in NDT-CE

Relationship between depth of a defect and the frequency of the maximum phase contrast $f_{ch}$:

$$z = f\left(\frac{\alpha}{f_{ch}}\right) = k_c \cdot \sqrt{\frac{\alpha}{f_{ch}}}$$

- $z$ ... Depth of a defect in [m]
- $f_{ch}$ ... Characteristic frequency in [Hz]
- $\alpha$ ... Thermal diffusivity [m²/s]
- $k_c$ ... Correction factor

Calculated depths for specimen A with 30 min of heating and fitted $f_{ch}$ (depths between 3 and 8 cm), $k_c=1$ and $\alpha = 8.75 \times 10^{-7}$ m²/s.
Quantitative Approach

Figure 1: Phase correlation results for the polystyrene voids of specimens A and B for 30 (left) and 15 min (right up) of heating with an IR-radiator.

Figure 2: Phase correlation results for the polystyrene voids of specimens A and B for 10 (left) and 5 min (right) of heating with an IR-radiator.
Amplitude contrast curves

Quantitative Approach

15 min

frequency in Hz

$\Delta A$

$\Delta A_{V1}$

$\Delta A_{V2}$

$\Delta A_{V5}$

$\Delta A_{V6}$

$\Delta A_{V7}$

$\Delta A_{V8}$
Amplitude and Phase in comparison

<table>
<thead>
<tr>
<th>Specimen A</th>
<th>$f_{ch}$ in Hz x 10^{-4}</th>
<th>Equation 1 without $k_c$ in cm</th>
<th>Radar result on concrete cover in cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30 min</td>
<td>15 min</td>
<td>10 min</td>
</tr>
<tr>
<td>Void / $t_h$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V1 / Phase Amplitude</td>
<td>1.46</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td>V2 / Phase Amplitude</td>
<td>1.46</td>
<td>1.46</td>
<td>1.46</td>
</tr>
<tr>
<td>V5 / Phase Amplitude</td>
<td>7.81</td>
<td>5.86</td>
<td>9.28</td>
</tr>
<tr>
<td>V6 / Phase Amplitude</td>
<td>3.42</td>
<td>3.42</td>
<td>2.44</td>
</tr>
<tr>
<td>V7 / Phase Amplitude</td>
<td>6.35</td>
<td>4.39</td>
<td>5.37</td>
</tr>
<tr>
<td>V8 / Phase Amplitude</td>
<td>3.42</td>
<td>2.93</td>
<td>2.44</td>
</tr>
</tbody>
</table>

Overview of the parameters for quantitative SPT in frequency domain for heating times $t_h$ of 30, 15, 10 and 5 min and with estimated $\alpha = 8.75 \times 10^{-7}$ m²/s for concrete, the values in () were gained by using fit-functions.
Many other examples approve, also for laminated specimens with thicknesses between 1 to 2 cm
Altes Museum, Berlin, Germany

- Eldest museum building of Berlin
- Built by Karl Friedrich Schinkel between 1823 to 1829
- World Heritage
- Regular limestone and brick masonry
- Dimension: 86.79 m * 53.52 m
- Partly destroyed by bombs and fire during WW II.
- Reconstruction in the 1960ies
- General rebuilding planned for 2008
Position 4: Columns in the rotunda

- Localisation of debonding between sandstone/mortar or mortar/stucco marble
  - Mortar: 2 to 3 cm
  - Stucco marble: 3 to 6 mm, cracks
Quantitative Approach

Location of plaster delaminations at columns in the rotunda of the Altes Museum, Berlin

Heating of the surface:
Manually, area height: 1 m fan heater, 5 min

Observation of cooling down:
Area height 1 m, 15 min, 2 Hz SC1000, 3.4 to 5 mm

Data analysis:
SPT
Quantitative Approach

Location of plaster delaminations at columns in the rotunda of the Altes Museum, Berlin

Temperature range: 20 to 30°C

5.56 x 10^{-4} Hz
Application for in-situ investigations, case study Altes Museum in Berlin

\[
Z = \sqrt{\frac{\alpha f_{ch}}{111 \times 10^{-3}}} \times 10^{0.7} \approx 2.3 \text{ cm}
\]
Comparison with simulations (specimen B, void 2, 15 min heating, FT)

\[ Z = \sqrt{\frac{\alpha_f}{c_h}} = \sqrt{\frac{8.75 \times 10^{-7}}{2.93 \times 10^{-4}}} \times 100 = 5.47 \text{ cm} \approx 6.00 \text{ cm} \]

Maul, BAM VIII.2
Overview

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Conclusions

- SPT in frequency domain is a suitable enhancement for qualitative and quantitative measurements in CE with a wide span of applications

- The new inverse approach for quantitative thermography via characteristic frequency $f_{ch}$ is very useful for the estimation of defects depth between 1 to 10 cm

- Advantage of the phase in qualitative measurements
  - Influence of inhomogeneous surface structures or heating is reduced
  - It displays deeper voids with higher contrast

- Advantage of the amplitude in quantitative measurements
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What next?

- Further going analysis of experimental and numerical time sequences of thermograms with square pulse thermography (SPT) in frequency domain, parameter studies and validation
- Systematic investigations on the localisation and the shape of inhomogeneities
- Comparison of numerical simulations and experimental data
- Quality system for the repair and strengthening of bridges with carbon fibre, reinforced polymers (CFRP) by means of IT (Sustainable Bridges)
- Optimized and automated scanning system for tests with IT by using flashlights will be set-up and applied as a prototype for on-site tests at bridges
Thanks for your attention!

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