Application of active thermography to the detection of safety relevant defects in civil engineering structures

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Introduction

During the last ten years, advanced non-destructive testing (NDT) methods like radar, ultrasonic and sonic methods have become available for the assessment of existing structures in civil engineering[1,2]. These technologies are mainly suited for the detection and characterization of inhomogeneities at depths between 5 and 100 cm. In the near surface region within the first 10 cm, there is still a deficiency of information as many safety relevant cases of damage originate from defects close to the surface. E. g. voids and honeycombing among the top layer of reinforcement in concrete structures, delaminations of CFRP laminates used for subsequent strengthening of concrete and masonry structures, delaminations of protective coating systems as well as surface and subsurface cracks can be characterized with active thermography as will be shown in this contribution.

The main innovation of active thermography related to standard testing methods is a faster, non-destructive, image-guided and reliable detection of defects and inhomogeneities close to the surface of a variety of building structures[3,4]. In contrary to the well known passive investigations of the quality of thermal insulation of building envelopes, this method is based on active heating by using either an internal or external heating source for a distinct time interval. Due to the resulting temperature differences, a non-stationary heat transfer is induced. Structural elements, inhomogeneities of material properties, voids and delaminations can be detected in the thermal images (thermograms) recorded with an infrared (IR) camera, if thermal properties are different related to the surrounding material. The difference between temperature distribution and change as a function of time above non-defect regions and inhomogeneities includes information about the defect parameters like depth, lateral size and type of material. Sophisticated data analysis of temporal temperature data in time and frequency domain (e. g. pulse-phase-thermography) affords the detection of flaws in concrete structures, masonry and multi-layered systems with high reliability[5]. The combination of experimental data and numerical simulation enables the selection of optimum measurement parameters as well as quantitative information from experimental results[6].

Theoretical background

Active thermography is based on a non-stationary heat transfer, i. e. the temperature changes as a function of time. Derived from the first law of thermodynamics by Fourier, this process of heat conduction can be described by the general equation of three-dimensional heat transfer in anisotropic media:

$$\frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda_z \frac{\partial T}{\partial z}\right)+w(x,y,z)=\rho\, c\,\frac{\partial T}{\partial t} \qquad \text{Eq. 1}$$

with

$T(x,y,z,t)$:	temperature as a function of direction and time
λ_x, λ_y, λ_z:	thermal conductivity in different directions
ρ:	density
c:	specific heat capacity
$w(x,y,z)$:	internal heat sources, here w = 0

Thermal conductivity λ, density ρ and specific heat capacity *c* can be combined to two different terms being specific for each material. The thermal **diffusivity** α describes how fast temperature differences are compensated in a material:

$$\alpha = \frac{\lambda}{\rho \cdot c} \qquad \text{Eq. 2}$$

The unit of the diffusivity is [$\frac{m^2}{s}$].

The thermal **effusivity *e*** is a measure of how much heat is exchanged at the interface between two different materials:

$$e = \sqrt{\lambda \cdot \rho \cdot c} \qquad \text{Eq. 3}$$

The unit of the effusivity is [$Ws^{0.5} K^{-1} m^{-2}$].

The heat transfer can be described by the propagation of thermal waves[7]. In this model, the reflectivity of thermal waves (harmonic heating process with wavelike temperature field) at interfaces is determined by the differences of the effusivities of the adjacent materials. For the one-dimensional case, the **reflection coefficient *R*** of a plane thermal wave for transmission from medium 1 to medium 2 is equal to:

$$R_{12} = \frac{e_1 - e_2}{e_1 + e_2} = \frac{\sqrt{\rho_1 c_1 \lambda_1} - \sqrt{\rho_2 c_2 \lambda_2}}{\sqrt{\rho_1 c_1 \lambda_1} + \sqrt{\rho_2 c_2 \lambda_2}} \qquad \text{Eq. 4}$$

Thus, for a successful detection of inhomogeneities, there must be a sufficient difference between the thermal properties of medium 1 and 2. The larger the difference of the effusivities of the two media, the higher the detectivity of the inhomogeneities is. E. g. the reflection coefficient at the interface concrete/air is about 100%, while the reflection coefficient of concrete/steel is about – 24%.

Thermal waves are strongly damped. The thermal **diffusion length *l*** represents the depth at which the amplitude of the thermal wave (temperature) is reduced to e^{-1} of its value at the surface:

$$l = \sqrt{\frac{2\alpha}{\omega}} \qquad \text{Eq. 5}$$

ω is the angular frequency of the thermal wave.

In the case of impulse heating instead of harmonic heating, eqs. 4 and 5 can only be used as a rough estimation.

Experimentals

For active thermography, a thermal pulse is applied to a surface causing a non-stationary heat flow. During the cooling-down process, the emitted thermal radiation is observed with an IR camera as a function of time. Data is transferred to a computer unit for further post processing, e.g. via thermal contrast images, transients and fit functions. The main intention of impulse-thermography is the detection of defects.

For the application in civil engineering, different kinds of heating units including radiant and fan heaters, flash and halogen lamps can be applied. The heating procedure is usually done dynamically by moving the heating source computer controlled or manually to obtain a nearly homogeneous initial temperature distribution. For the location of injection faults inside tendon ducts, the pre-stressing steel can also be heated electrically[4].

With an IR camera, the thermal radiation emitted by the object under test is detected. The intensity of the radiation strongly depends on the temperature, but also on the emissivity which can have any value between 0 and 1 and is equal to 1 for a blackbody. The emissivity of real bodies depends on material, surface roughness, contaminations at the surface, temperature,

wavelength, polarization and the angle of the radiation related to the surface normal. For each body, the directed spectral emissivity is equal to the directed spectral absorptivity (Kirchhoff's law). Usually, IR cameras are only sensitive for a defined wavelength interval. Therefore, the wavelength dependency of the emissivity has to be considered. Typical data for different building materials can be found in[8]. Particularly in the long wavelength range, several building materials have a high and constant emissivity between 0.8 and 1. Therefore, these materials are well suited for thermographic investigations.
For the applications described below, the experimental set-up included a thermal radiator, an IR camera and a computer system that enables digital data recording in real time. The thermal heating unit consisted of up to three IR radiators having a power of 2400 W each. The radiators were mounted in a linear array and were moved perpendicular to this array at a fixed distance to the surface of about 15 cm. Also manual heating was performed. A commercial IR camera (Inframetrics SC1000, 256x256 pixels sensitive in a wavelength range of 3-5 µm) was used. Depending on the testing problem, the heating time was between 15 s and 15 min and the observation time was between 15 and 120 min using a frame rate of 2 up to 10 Hz.

Data analysis
For qualitative data analysis, thermograms of experimental data recorded at different time intervals after heating were selected. The grey values of the images were scaled to minimum and maximum temperature in each image. Shallow defects have maximum thermal contrast after short cooling-down time while deeper defects appear later.

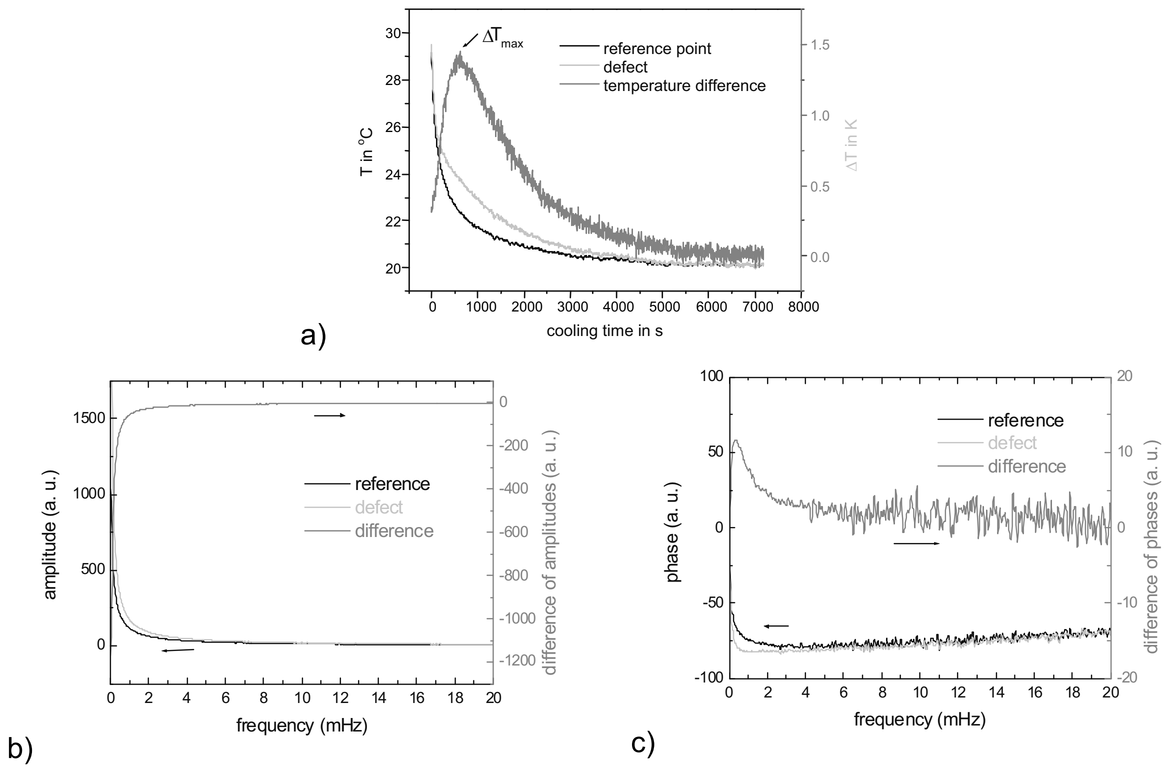


Figure 1: a) Transient curve above reference and defect area and difference curve and the related b) amplitude spectra and c) phase spectra.

For quantitative analysis, transient curves (surface temperature as a function of time for each pixel *(i,j)*) of areas above defects and above homogeneous bulk material were compared and difference curves were calculated as shown in figure 1 (a). These difference curves usually have a maximum ΔT_{max} at a distinct time t_{max} that depends on the depth and size of the defects, on the heating time and on the thermal properties of bulk and defect materials.
Pulse-phase-thermography (PPT) is based on the analysis of the above-mentioned transient curves in frequency domain[5,9]. Each pixel *(i,j)* of a series of thermal images describing the

cooling down behavior after heating is analyzed by application of the Fourier Transformation. One obtains amplitude and phase images for different frequencies.
Amplitude images show the internal structure of a specimen up to a maximum available depth depending on the frequency (low pass filter behavior). Phase images show the internal structure within a certain depth range depending on the frequency (band pass filter behavior). Therefore, phase images are less influenced by surface infrared and optical characteristics and are less sensitive to non-uniform heating than thermal images and amplitude images.
In figure 1 (b) and (c), the amplitude and phase spectra processed from the transient curves in figure 1 (a) are displayed, respectively. In our experiment the heating pulse is represented as a square pulse, which can be described as superposition of different frequencies with varying amplitudes. The maximum frequency is determined by the acquisition rate, the minimum frequency is limited by the recording time. In practice only the first images at low frequencies are of interest, since most of the energy is concentrated here. Higher frequencies exhibit a higher noise level.

Areas of application

Detection of voids and honeycombing in concrete
Systematic investigations concerning the localization of voids and honeycombing in concrete test elements by considering the influence of moisture, varying reinforcement and different material and surface properties are described in detail in[10].
In the following, results are presented concerning the applications of active thermography for the location of voids and honeycombing in industrial pre-casted concrete beams of an underground car park. After the assembly of the beams, visual inspection, impact tests, and destructive openings have shown a large amount of voids and honeycombing due to bad compaction of concrete around the reinforcement bars (see figure 2 (a)). Partly, these areas were refilled, but there were several voids left. For a comprehensive registration of all voids, active thermography was applied after a detailed pilot survey and optimization of the method. Two infrared radiators were used for heating for 15 min of an area of 1 m^2. The cooling down behavior was observed for 1 h. Afterwards, a PPT data analysis was performed. In figure 2 (b), an amplitude image calculated at a frequency of 2.77×10^{-4} Hz is displayed. Here, the voids are clearly visible as light areas. Additionally, some rebars (dark lines) and six reinforcing bar spacers (light dots) can be recognized. For the area-wide investigation of all beams, the measurement time was optimized by recording of single thermograms at maximum temperature contrast (t_{max})[11].

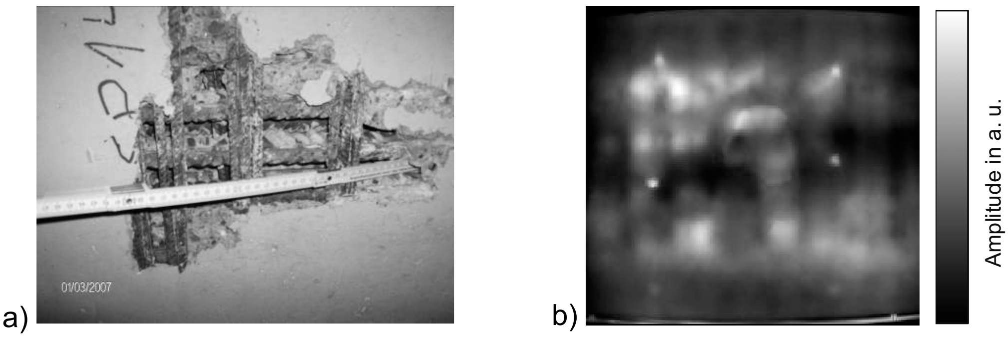


Figure 2: a) Honeycombing and voids close to the surface of a reinforced concrete beam.
b) Amplitude image calculated at a frequency of 2.77×10^{-4} Hz after 15 min of heating.

Detection of CFRP delaminations
Adhesive bond defects between carbon fiber reinforced plastic (CFRP) laminates and concrete can be easily detected by short active heating of 15 s with IR radiators as shown in figure 3. Also flashlights can be applied[12].

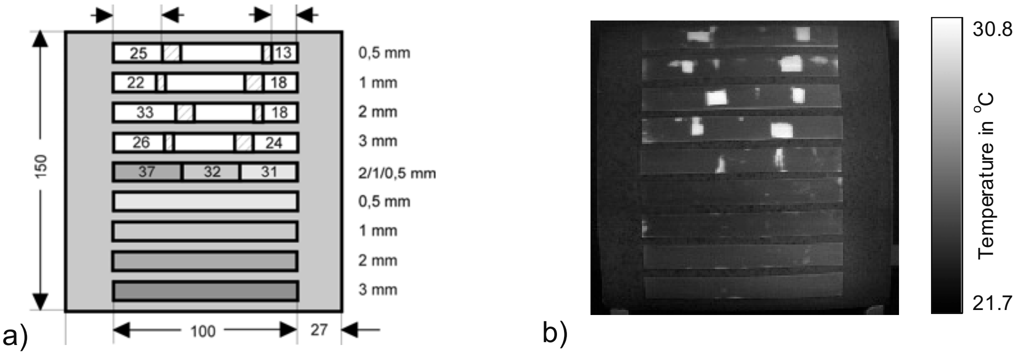


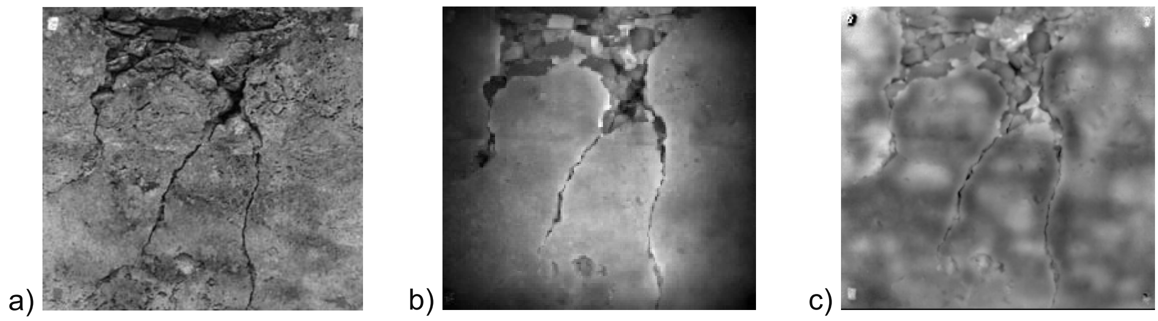
Figure 3: a) Test specimen with carbon fiber reinforced plastic laminates which have no contact at the shaded areas (nominal glue thickness is written on the right side). b) Thermogram directly recorded after a heating time of 15 s using an infrared radiator.

Location of cracks

The case study presented herein encompasses experimental work carried out at the Church of St. John the Baptist at the Carthusian monastery at Žiče, Slovenia, which was built in 1160. One of the positions investigated was located at the wall at the centre of the apses of the chapel. The wall is mainly covered with plaster and shows some large cracks and missing bricks. The testing problem was the location of plaster delaminations, the visualization of the covered masonry structure, the correlation between cracks and masonry structure and the location of possible further cracks.

This area was heated for about 10 min with two IR radiators. The size of the heated area was 1.14 x 1.08 m^2. After switching off the heating source, the surface temperature was observed during cooling down with the IR camera with a frame rate of 5 Hz for about 45 min.

In figure 4, a photo (a), a thermogram directly recorded after switching off the heating source (b), and a phase image gathered with PPT (c) are displayed. In the thermogram (b), the cracks and the structure around the cracks are well resolved. The phase image (c) shows light and dark areas, which might be related to single stones (light) and joints (dark). It can be noticed that the position of the cracks in mainly inside the joints, between the bricks.



a) Photo | b) Thermogram, 0 s cooling down, 20.9°C to 48.4°C | c) Phase image at 4.88x10^{-4} Hz

Figure 4: a) Photo, b) thermogram and c) phase image for the visualization of cracks.

Conclusion and Outlook

The case studies presented above clearly show that active thermography is very well suited for the location and quantification of safety relevant defects in building structures. Currently, the method is still not applied regularly for on-site testing. Most investigations were carried out in the laboratory. However, the measurement equipment including radiator, infrared camera and computer can be applied at the building site without major modifications. The main requirement is the accessibility of the surface of the structure under investigation. A direct contact to the surface is not required. A limit of the maximum surface temperature should be set for avoiding any damage due to heating. Active thermography can be applied for quality assurance during construction and after reconstruction and repair as well as for regular and exceptional building assessment.

References

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