

## **Active thermography for the characterization of surfaces and interfaces of historic masonry structures**

Christiane MAIERHOFER, Mathias ROELLIG

*Federal Institute for Materials Research and Testing (BAM), Berlin, Germany,*  
[christiane.maierhofer@bam.de](mailto:christiane.maierhofer@bam.de)

### **Abstract**

Influences from environment are inducing structural damage, modification of materials and agglomeration of pollutants, salt and microorganisms which first become visible at outer or inner surfaces of historic buildings. Non-destructive testing methods and especially active thermography are well suited for assessing and monitoring the condition and modification of facades. Active thermography methods with a selective heating of the surface enable structural and material investigations from one side of building elements up to a depth of about 10 cm. In this paper, results of case studies will be presented concerning the detection of subsurface defects and moisture.

### **Résumé**

Les influences de l'environnement conduisent à des dommages structurels, la modification du matériel et à l'agglomération de polluants, sels et micro-organismes qui deviennent d'abord visibles aux surfaces extérieures ou intérieures de bâtiments historiques. Les méthodes d'essai non-destructives et surtout la thermographie active conviennent bien pour évaluer et contrôler l'état et la modification de façades. Les méthodes de thermographie active avec un chauffage sélectif de la surface permettent des investigations structurelles et matérielles d'un côté des éléments construits jusqu'à une profondeur d'environ 10 centimètres. Dans ce papier, les résultats d'études de cas qui sont présentés concernent la détection de défauts souterrains et de l'humidité.

### **Keywords**

Pulse-phase-thermography, infrared radiation, heating, delamination, plaster

### **1 Introduction**

Influences from the environment such as sun, wind, rain and pollution as well as changes in temperature first have an impact on the surface of building structures before the whole structure is affected. In most cases, structural damage, modification of materials and agglomeration of pollutants, salt and microorganisms first become visible at outer or inner surfaces. Thus, the facade of buildings as an interface between environment and building gives a lot of information concerning the actual condition of a building and the influence of environment and usage of the building.

Non-destructive testing (NDT) and minor destructive testing (MDT) methods are well suited for assessing and monitoring the condition and modification of facades. Optical properties can be determined by spectral resolved acquisition of single data and images at surfaces in various spectral ranges from ultraviolet to infrared (IR) regions. A good overview of different methods is given in [1]. With these methods, information is gained about pigments, color, soiling, moisture, salt and biological contamination. The results of a multi-spectral analysis especially in the near infrared (NIR) can serve as a basis for damage

mapping and are delivering quantitative results on the damaged area and about the nature of the damage. In [2] a multi-spectral laser-scanner system was set up using four semiconductor laser diodes working at different wavelengths. From the difference in reflectivity, information about the surface condition and surface damage are gained. Geometric information about surface geometry, topology and roughness is gained via 3D-laserscanners and digital photogrammetry [1].

But all these techniques give only information in the very near surface region. For the detection of delaminations, the investigation of masonry structures behind plaster and the location of moisture at interfaces, active thermography has proven to be a suitable NDT method. Active IR thermography methods with a selective heating of the surface under investigation enable structural and moisture investigations from one side of building elements up to a depth of about 10 cm [3]. Therefore, also hidden structures can be detected. But thermography measurements suffer from an interference of various effects at the same time, namely temperature, reflections, moisture, flow of air around the object and different material characteristics like emissivity, density, thermal conductivity and heat capacity [4]. Therefore, techniques will be introduced to give better separation of these effects by combining complementary measurements based on passive and active thermography. Here, different heat sources based on convection and radiation have been applied. Advanced signal and image processing tools have been developed for enhancing the contrast of images.

In this paper, results of case studies will be presented concerning the limits and resolutions of the applications for the investigation of cracks, location of delaminations between plaster and masonry, determination of hidden structures like form of stones or bricks and thickness of joints and location of moisture

## **2 Theoretical background of active thermography**

Impulse-thermography is an active approach for a quantitative thermal scanning of the surface of various structures and elements. It has been established as a fast and reliable tool in many areas of NDT [5]. It is well known for material testing in several branches of industry for the detection of defects and delaminations. In recent years several investigations have been carried out for applying active thermography in civil engineering.

Impulse-thermography functions as follows: A thermal pulse is applied to a surface causing a non-stationary heat flow. The propagation of the heat into the body depends on material properties like thermal conductivity, heat capacity and density of the inspected specimen. If there are inhomogeneities in the near surface region of the structural element this will result in measurable temperature differences in the local area of the surface. During the cooling-down process the emitted thermal radiation is observed with an IR camera. Data are stored and 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.

A further approach of impulse-thermography is pulse-phase-thermography (PPT) [6]. It combines the method of data acquisition of impulse-thermography with the approach of frequency analysis also used in lock-in thermography. The stored data received during impulse-thermography are analyzed in the frequency domain via Fast Fourier Transformation of the transient curve of each pixel in a series of thermal contrast images. Defects lead to changes in amplitude or phase of the corresponding images. The main advantage of PPT is the information included in the phase images, which are reported to be less influenced by surface IR and optical characteristics. That also means less sensitivity to non-uniform heating compared with the thermal contrast images of impulse-thermography.

### 3 Experimentals

For actively heating the surface of structures to be investigated, different kinds of heating units including radiant and fan heaters, flash and halogen lamps can be applied. One experimental set-up for the performance of impulse-thermography measurements consists of a thermal radiator, an IR camera and a computer system that enables digital data recording in real time. The thermal heating unit contains of up to three IR radiators having a power of 2400 W each. The heating procedure is usually done dynamically by moving the radiators under computer control to obtain the best possible homogeneous heating. Therefore, radiators are mounted in a linear array and are moved vertically to this array and parallel to the surface at a distance of about 15 cm. Also manual heating can be performed as shown in Fig. 1, left

A commercial IR camera (Inframetrics SC1000, 256x256 pixels sensitive in a wavelength range of 3-5  $\mu\text{m}$ ) and a computer system, which enables digital data recording in real time, were used. Typically, the heating time is varied between 5 and 30 min and the observation time after heating is between 15 and 120 min using a frame rate of 2 up to 10 Hz.



*Figure 1. Left: Manual heating of the surface with an infrared radiator. Right: Recording of surface temperature with an infrared camera during cooling down.*

### 4 Investigation of interfaces between plaster and masonry

The case study presented herein encompass experimental work carried out at the Church of St. John the Baptist at the Carthusian monastery at Žižce, Slovenia, which was built in 1160 AD by Carthusian monks as one of the first such monastery to be built outside Romanic area in German and Slavic lands. One of the landmarks of the monastery is Church of St. John the Baptist which through its history passed several phases of reconstruction works. Within this project, non-destructive on-site investigations were carried out with impulse-thermography.

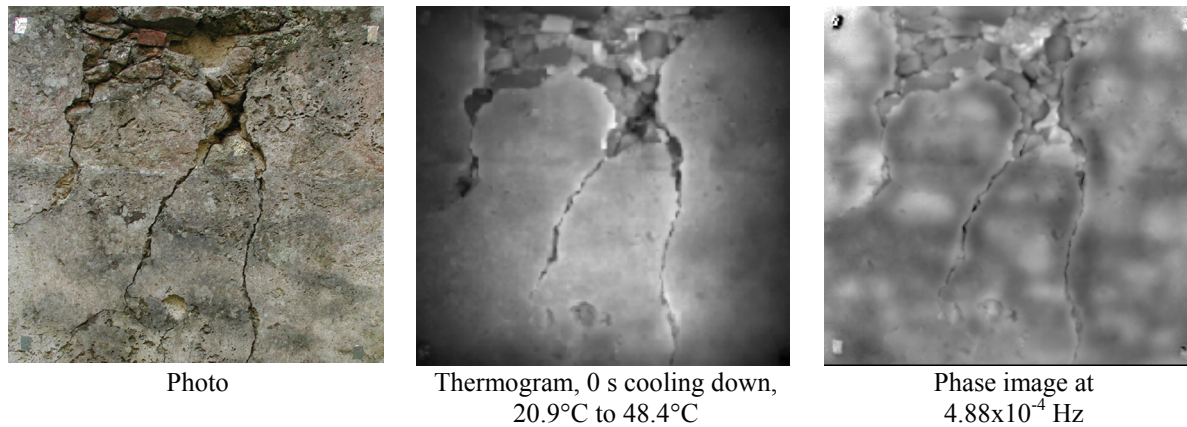
#### 4.1 Location of masonry structure below plaster for crack detection

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<sup>2</sup>. 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 Fig. 2, a photo (left), a thermogram directly recorded after switching off the heating source (middle), and a phase image gathered with PPT (right) are displayed. In the thermogram (middle), the cracks and the structure around the cracks are well resolved. The

phase image (right) 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 is mainly inside the joints, between the bricks.



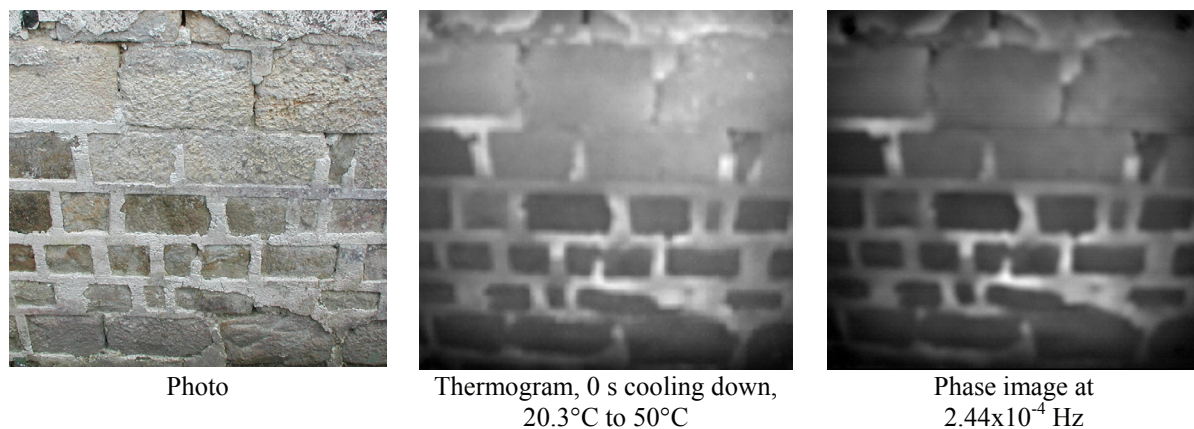
*Figure 2. Results of impulse-thermography.*

#### **4.2 Investigation of the structure of mortar filling of joints**

The second position is located at the north wall of the church, in the bottom part of the outer wall close to an entrance. In front of the wall, there is a narrow ditch, thus the IR camera was located at higher position and was tilted down to record the thermograms as shown in Fig. 1. This wall consists of regular stones. The joints between the stones were filled with plaster and were covered at the surface with broad plaster stripes (pointing mortar). The testing problem was to analyze if the thickness of these plaster stripes is equal along the investigated area and if there are any delaminations.

This area was heated for about 10 min with the IR radiator. The size of the heated area was  $1.08 \times 1.38 \text{ m}^2$ . The surface temperature during cooling down was observed with the IR camera with a frame rate of 5 Hz for about 45 min.

In Fig. 3, one thermogram of the investigated area and one phase image analyzed with PPT are displayed. In the thermogram directly recorded after switching off the heating source (middle), some of the joints appear to be very warm while others have lower temperature. In the phase image (right), possible debonding/delaminations (or not completely filled joints) can be seen as white areas.



*Figure 3. Results of impulse-thermography.*

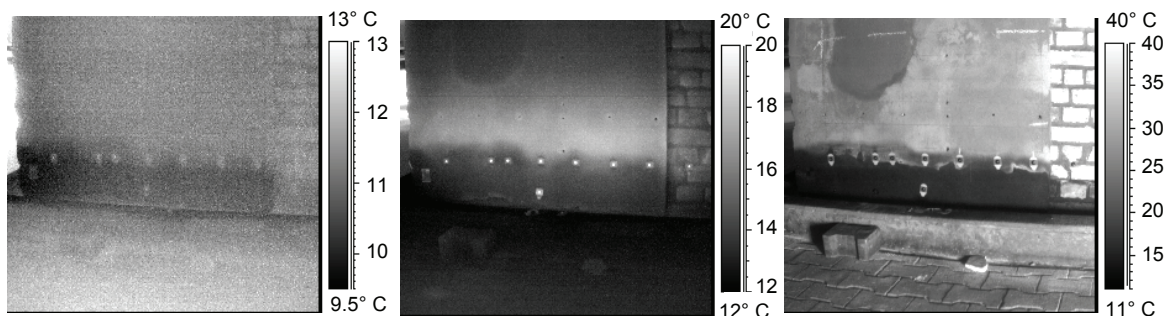
## 5 Location of moisture near the surface

With passive and active thermography, measurements have been performed at a large test specimen consisting of different historic masonry structures for recording of rising moisture. This test specimen with a size of  $7 \times 3 \times 1.5 \text{ m}^3$  was erected at the exterior area of BAM in course of the European Research project ONSITEFORMASONRY [7]. Partly, the test specimen was covered with lime mortar. Before the measurements, the specimen was soaked for four days while the water level was covering the first layer of bricks. After this time, the visible water line had a height of 12 to 15 cm, while the height was higher at the area with plaster. During the measurements, the environment temperature was between 10 and 15°C and the relative humidity was about 60 %.

First, thermograms were recorded without additional radiation or heating. One thermogram for an area with plaster is displayed in Fig. 4, left. Here, the temperature scale is related to an emissivity of 1, therefore measured temperature values might be different from real ones. The moist area appears about 0.5 to 1 K cooler than the dry part. This can be related to cooling of the surface due to moisture evaporation, but also to a different reflectivity of the environmental radiation. The border between dry and moist area is lower than in the related photos.

In a second step, the lower part of the wall up to a height of 50 cm was heated for about 5 min with a fan heater (2000 W). After switching off the heater, the cooling down behavior was recorded with the IR camera. A thermogram recorded directly at the beginning of cooling down is shown in Fig. 4, middle. Again, the lower moist part appears cooler with an enhanced contrast to Fig. 4, left. Due to the different thermal properties of the moist material, the thermal diffusivity increases and the heat is transported faster into the structure. This is consistent with numerical simulations [8]. Now the border between moist and dry areas appears at the same height as in the photos.

After cooling down of the specimen, in a third step thermograms were recorded during illuminating the surface with an IR radiator. Although the radiator was positioned in a distance of more than 2 m and a direct warming up of the specimen did not occur, the reflected radiation was much higher than the emitted radiation from the test specimen. Such a thermogram with reflected radiation is shown in Fig. 4, right. Here, the moist area appears much cooler with a temperature difference of about 20 K, which means that less radiation is reflected than from the dry area. At the border between dry and moist area, two moisture lines and thus a transition zone can be observed: The lower line corresponds to the height of the moisture line detected in Fig. 4, left, while the upper line corresponds to that one observed in the photo.



**Figure 4.** Investigation of rising moisture at a test specimen made of historic masonry.  
Left: Thermogram recorded at the surface (passive). Middle: Thermogram recorded after heating. Right: Thermogram with additional infrared radiation.

By comparing the results obtained with passive and active thermography, it can be concluded that the thermograms recorded with additional IR radiation gives the images with the highest contrast for the detection of rising moisture at the surface.

## 6 Conclusions

The presented case studies clearly show that impulse-thermography can be applied for the investigation of cracks, delaminations and masonry structure behind plaster. Active and passive thermography measurements were applied for covering of capillary moisture rise in historic masonry structures. Recording thermal images with additional IR radiation gives the best contrast for the detection of rising moisture at the surface. Here, it is assumed that also information is obtained about the penetration depth of moisture at the surface. For the future, further applications and influences will be studied and quantitative data will be gained by combining experimental and numerical data.

## Acknowledgements

The test specimen Obelix was constructed in the frame in the FP5 European research project ONSITEFORMASONRY. The work at the Carthusian Monastery was financed in the frame of the European program CULTURE 2000 under Action 3 – European Heritage Laboratory (2005-2006).

## References

1. Tiano, P., Pardini, C. (eds.) (2008) "In situ monitoring of Monumental surfaces", Proceedings of the International Workshop SMW08, 27-29 October 2008, Florence, Italy
2. Wehr, A., Hemmleb, M., Maierhofer, Ch. (2006) "Multi-spectral Laser Scanning for Inspection of Building Surfaces - state of the art and future concepts", in : Proceedings of VAST 2006 : Virtual reality, archeology and cultural heritage, 30 October – 4 November 2006, Cyprus
3. Maierhofer, Ch., Arndt, R., Röllig, M., Rieck, C., Walther, A., Scheel, H., Hillemeier, B. (2006) "Application of impulse thermography for non-destructive assessment of concrete structures", *Cement & Concrete Composites*, Vol. 28, pp. 393-401.
4. Maierhofer, Ch., Arndt, R., Röllig, M. (2007) "Influence of concrete properties on the detection of voids with impulse-thermography", *Infrared Physics & Technology* Vol. 49, Issue 3, pp. 213-217.
5. Maldague, X. P. V. (1993) "Non-destructive evaluation of materials by infrared thermography", Springer-Verlag, London.
6. Ibarra-Castanedo, C. and Maldague, X. P. V. (2005) "Pulsed phase thermography review", *Quantitative Infrared Thermography Journal*, Vol. 1, pp. 47-70.
7. Maierhofer, Ch., Köpp, Ch., Binda, L., Zanzi, L., Santiago, J. R., Knupfer, B., Johansson, B., Modena, C., da Porto, F., Marchisio, M., Gravina, F., Falci, M., Galvez Ruiz, J. C., Tomazevic, M., Bosiljkov, V., Hennen, Ch. (2006) "Project Report EUR 21696 EN - Onsiteformasonry project - On-site investigation techniques for the structural evaluation of historic masonry buildings", European Commission, Luxembourg: Office for Official Publications of the European Communities, Brussels , 141 pages
8. Maierhofer, Ch., Brink, A., Röllig, M., Wiggenhauser, H. (2005) "Quantitative impulse-thermography as NDT method in civil engineering - Experimental results and numerical simulations", *Construction in Building Materials*, Vol. 19, Issue 10, pp. 731-737.