

Characterisation of Historic Façades using Active Thermography with Solar Heating and Optical Methods

Christiane MAIERHOFER¹, Mathias RÖLLIG¹, Henrik STEINFURTH¹, Sven AUGUSTIN¹, Rüdiger MECKE², Michael SCHILLER², Alexa KERNCHEN², Uwe KALISCH³, Jeannine MEINHARDT³, Christiane HENNEN³, Ernst Thomas GROLL⁴, Torsten ARNOLD⁵

¹ BAM Bundesanstalt für Materialforschung und -prüfung, Berlin, Germany
 ² Fraunhofer Institut für Fabrikbetrieb und -automatisierung IFF, Magdeburg, Germany
 ³ Institut für Diagnostik und Konservierung an Denkmalen in Sachsen und Sachsen-Anhalt

e. V. (IDK), Halle, Germany

⁴ Restorer, Magdeburg, Germany

⁵ Landesamt für Denkmalpflege und Archäologie Sachsen-Anhalt Landesmuseum für Vorgeschichte, Halle/Saale, Germany

Contact e-mail: christiane.maierhofer@bam.de

Abstract. Active thermography is well suited for the detection of delaminations and cracks in façade elements like plaster and tiles. Not only artificial heating but also solar heating can be used if the adjustment of the façade and the weather conditions are suitable. Optical methods like laser scanners, photogrammetric methods and crack tracking sensors are providing geometrical 3D data which can be used for a 3D mapping of thermograms and for providing data with higher geometrical resolution. Thus, by the combination and fusion of these data, a comprehensive mapping and monitoring of damages of façade systems is possible.

1. Introduction

In historic structures, plaster and façade elements like tiles or natural stone are not only protecting the walls behind but are also carrying paintings or other image information. Therefore, the preservation of these objects of cultural value is reasonable. At ceilings and higher walls, also safety aspects have to be considered, which means that the falling down of larger particles and pieces has to be avoided. Therefore, delaminations, voids and cracks have to be detected as early as possible for initiating preservation measures and thus avoiding larger damages.

Up to now, most relevant publications for the rehabilitation practice of plaster, considering diagnostic aspects, generally focus on local damage assessments in terms of salt and moisture analysis or of small-scale delaminations, which are mainly detected by percussion test [1, 2, 3]. Established measurement methods are already available for the detection of cracks and their dynamics (e. g. crack monitors, fibre optic systems, 3D laser



scanning, laser extensometer or potentiometric systems) [4], but again only local information is provided.

For locating cracks and especially delaminations, it is shown that active thermography using solar heating is a very efficient method, as larger areas could be investigated at once. If the façade can be viewed optically and has such an orientation that it can be heated by the sun, no scaffolding or installation of further access technology is required. Sequences of thermal images can be recorded with an infrared camera before, during and after solar heating from the ground. Depending on the generated non-stationary heat flux, delaminations can be detected by thermal contrasts in relation to undisturbed areas or by further data analysis in time and frequency domain [5, 6].

Façade elements with cracks and delaminations do not only show thermal anomalies, but also deviations from the geometry, like bulging of plaster and presence and widening of cracks. Therefore, active thermography measurements have been combined with data from a laser scanner, a stereo photogrammetric sensor and a tactile sensor which enables 3D data recording of crack position and depth. For active thermography, data fusion requires a geometrical calibration of the infrared camera with the appropriate focus position. For stereo photogrammetry, the influence of surface properties on measurement accuracy was assessed and the concatenation of several single measurement areas was optimised [7, 8].

In this contribution different combinations of the methods will be presented in three case studies, all located in Germany:

- Detection of inhomogeneities behind tile pictures at a prefabricated concrete building in Halle
- Location of girders and cracks at a mural painting in Cobbelsdorf
- Detection of delaminations behind plaster scratches at the west façade of the adjoining cloister of the Magdeburg Cathedral

2. Description of case studies

2.1 Tile pictures at a prefabricated concrete building in Halle

At the prefabricated concrete building in Halle-Neustadt, Germany and former GDR, which was constructed in 1968, two tile pictures by Josè Renau representing *The Forces of Nature and Technique Dominated by the Human Being* were mounted at the front of the staircases. Each of these pictures has a size of $37 \times 7 \text{ m}^2$ and consists of 232 rows, each row with 46 tiles. Each tile has a size of $15 \times 15 \times 0.9 \text{ cm}^3$. The carriers of the pictures are prefabricated concrete plates. The tiles were stuck by using the thin mortar bed technique. The joints were filled with a sealing for avoiding ingress of water.

In 2006, a restoration concept was developed and a detailed mapping of the damages was performed. Due to defects in the roof and at the boundaries of the pictures, water could penetrate resulting in frost damages and efflorescence originating from the materials of the carrier. Cracks appeared as well as damages of the glaze. Loss of tiles and detached tiles were located. At staircase 2, damaged areas of the tiles were thus supported by nets for avoiding a falling down of tiles. Active thermography investigations were planned in 2014 for an update of the damage mapping.

2.2 Mural painting in Cobbelsdorf

The mural painting made by Erich Enge in 1970/71 belongs to a former House of Culture of the former agricultural production cooperative (LPG) Lenin in Cobbelsdorf. It represents

The Industrialized Agriculture and has a size of $11 \times 18 \text{ m}^2$. Now the ownership belongs to the Flämingland Touristik und Freizeit GmbH Cobbelsdorf. The House of Culture is a former hall for the storage of fertilizer, and consists of a pillar structure, where the roof rests on. The spaces between the pillars are walled with hollow blocks from GDR production.

The wall was covered with a thin cementitious plaster of varying thickness. For a better stability, a brick wire was used as carrier. The painting was based on silicate 68, an industrial wall painting from GDR production. A comprehensive conservation and restoration campaign was carried out in October/November 2006. Inside the masonry structures, four large cracks with widths up to 4 cm and depths up to 12 cm were found, which were running continuously from the roof down to the basement along the joints between the pillars and the masonry and its surroundings. These cracks have induced irreversible shifts inside wall and plaster. Several plaster slices were loose and parts of the plaster were hollow. The extensive conservation of the plaster with large delaminations was one essential measure of the restoration. The injection of the voids was performed using mortar which was binded with an acrylic dispersion. For the future, the restorer indicated that movements of the construction might induce further cracks.

2.3 Plaster scratches at the Magdeburg Cathedral

One of the most important artwork of the Magdeburg Cathedral are the plaster scratches on the west façade of the cloister from the 13th century. In the central picture Emperor Otto I and his two wives, Editha and Adelheid, are shown. From the plaster surface only fragmentary original areas have been preserved. Most of the individual plaster surfaces are repairs or new plaster from various restorations or repair phases. The much smaller part is original plaster, which only exists as islands between the various patches. Restoration work has been performed from 2011 to 2015. Beside plaster consolidation, the surface of the plaster scratches has been cleaned using laser ablation. This work has been accompanied by non-destructive investigations using a laser scanner, the stereo photogrammetry system for visualizing of the plaster scratches and active thermography for locating and characterizing plaster delaminations.

3. Experimental set-up used for the investigations at the case studies

Investigations with active thermography were performed using a microbolometer IRcamera with a detector size of 640 x 480 pixels and an IR-camera with a cooled MCT detector with a detector size of 640 x 512 pixels. For artificial heating, an infrared radiator with a power of 2.4 kW was moved along the surface for achieving a homogeneous heating. For natural heating, solar radiation was exploited. During the experiments, the solar power density was measured with a heat flux sensor.

The measurements with the Laser scanner were realized with a commercial system enabling a resolution of distance of up to 0.1 mm, having a beam diameter of 3.5 mm at 1 m distance and a beam divergence of < 0.3 mrad. The maximum measurement rate was 1×10^6 pixels/s.

For stereo photogrammetry, a stereo system with two video cameras having each a resolution of 2056 x 2056 pixels was used. Two synchronous images were taken at a distance of 40 cm covering an area of about $17 \times 17 \text{ cm}^2$. The entire area to be examined was divided like a chessboard into individual measuring fields. These single fields are overlapping each other, which is necessary to assemble all individual fields into one data set of the entire examined area.

For the 3D crack mapping, a simple test rod with markers (here: three infrared reflective balls) was used, which was moved manually along the crack while its position and orientation in the 3D space is detected by an optical tracking system. Investigations revealed that a tracking precision of individual markers is possible with an accuracy of \pm 0.5 mm. In order to achieve this accuracy, on-site calibration of the camera system is necessary [4, 7].

4. Results at case studies

4.1 Tile pictures at the prefabricated concrete building in Halle

Measurements at the tile pictures were performed in May and August 2015. While in May the highest temperature was about 21°C and the sun was partially hided by clouds, in August the maximum temperature was about 35°C and the sky was clear. The IR-camera was positioned at distances of 50 to 61 m to the building façade. Due to the high reflectivity of the tiles, mostly difference thermograms were analysed, which were calculated from thermograms with time intervals of up to 600 s. Essential damage could only be detected at staircase 2, thus only those data are discussed below.

Fig. 1 shows a collection of photos, damage mapping and selected difference thermograms of three stacked sections of staircase 2. From comparison, the following observations could be summarized:

- In the photos, the fixed nets used for protecting the tiles against falling down could be recognized easily.
- In the top part, the tiles in the top left corner with salt efflorescence and with damage of glaze could be detected as warmer (lighter) areas. Few of the warm single spots could be related to missing tiles, which are not registered in the damage mapping.
- In the middle part, the areas which are marked as total loss in the damage mapping are appearing as warm (light) areas in the thermograms.
- In the bottom part, especially the area with the large net is appearing relatively warm, which could be explained by detachment of the tiles protected by the net. But it has to be considered that all areas with a net are appearing slightly warmer.

4.2 Mural painting in Cobbelsdorf

The thermographic investigations at the mural painting in Cobbelsdorf were performed at one day in September 2014 and at one day in April 2015. In the following, only the results recorded in 2014 are shown in figure 2. The wall is orientated south-west, thus direct sun radiation to the wall started at about 11.00 a. m. and ended with sun-set approx. at 08.00 p. m. During both days, the solar power density was recorded with a heat flux sensor. These data are shown for September 2014 together with the mean wall temperature in figure 2.b. Here, the heat flux was varying strongly due to moving clouds, and the maximum heat flux of 800 W/m² was recorded at 01.40 p. m. The wall temperature was directly following the solar power density with temperature maxima of about 28°C.

A thermogram was selected from the sequence at 01.56 p. m. directly after the maximum radiation and is shown in figure 2.d. From this thermogram, the temperature distribution recorded directly at the beginning of the measurement was subtracted. Thus, only temperature changes due to solar heating from the beginning of the measurements are shown. First of all, it can be noticed that some of the thermal structures are related to the

drawing in the picture and thus to different degrees of emissivity at the surface. Below the roof, thermal features related to cracks can be detected. In the middle of the wall, two vertical bars related to the pillars can be seen. These structures appear colder, which might be related on the one hand to a view directly into the cracks, where the structure is cooler, and on the other hand to a higher thermal diffusivity due to the underlying metallic pillars.



Fig. 1. Sections of the tile picture of staircase 2, selected from top to bottom. The left row shows the photos of the sections, the middle row the results of damage mapping (source: Fa. Wandwerk, Berlin) and the right row selected difference thermograms.

Additionally to these signatures, also features related to joints and bricks are visible. In addition to the thermogram, two phase images calculated by pulse phase thermography from the recorded thermal sequence are displayed in figure 2.e and f. Figure 2.e shows the 2^{nd} phase image of the sequence, thus it is belonging to lower frequencies of the temporal behaviour of the surface temperature. Here, the two steel pillars could be clearly detected as darker areas. In figure 2.f, phase image no. 10 is shown, thus it is belonging to a higher frequency. Cracks below the roof and at the edges of the vertical pillars are visible.

In the bottom left corner of the wall, cracks were recorded with the 3D crack tracking system. Figure 2.c shows a data fusion of these 3D crack data, a photo and a thermogram of this area. The thermogram was recorded from a closer distance. Markers stuck to the wall were used as reference points in order to find correspondences in the different data domains. Although the crack could already be detected well in the thermogram, the crack tracking sensor enabled a more detailed 3D recording of the crack position with both higher accuracy and resolution.



Fig. 2. Results of investigations at the mural painting in Cobbelsdorf. a) Set-up of the IR-camera in front of the painting. b) Solar power density and wall temperature during the measurements on 2014-09-09. c) Fusion of 3D data of the cracks, photo and thermograms of a section of the painting (bottom left corner).

d) Difference thermogram recorded at 01.56 p.m. on 2014-09-09. The values of the grey scale are given in K.
e) Phase image no. 2 of the whole sequence. The values of the grey scale are given in rad. f) Phase image no. 10 of the whole sequence. The values of the grey scale are given in rad.

4.3 Plaster scratches at the Magdeburg Cathedral

The central picture of the plaster scratches at the Magdeburg Cathedral was investigated with active thermography, with the laser scanner and with the photogrammetric stereo sensor. For active thermography, the picture was separated into four overlapping sections, each with a size of about 1 m^2 . These areas were heated with the infrared radiator for about 5 min, which resulted to a temperature increase between 8 and 16 K.



Fig. 3. Results of investigations of the central picture of the plaster scratches. a) Combined 3D data recorded with the photogrammetric stereo sensor (grey: 2012-07-24, yellow: 2014-09-12). b) 3D mapping of the recorded thermograms after 5 min heating with an infrared radiator.

The whole area of the plaster scratches was investigated with a laser scanner. Here, for an area of about 9 x 3 m^2 the scanning was performed within 20 min. A spatial resolution of a few mm was obtained.

With the photogrammetric stereo sensor system, the central picture was first recorded in 2012. This area was enhanced in 2014, thus an area with a total size of $2.3 \times 2.1 \text{ m}^2$ was captured and is shown in figure 3.a. For the recording of the whole area, in total 12 h were needed. Thus, the 3D data acquisition and recording took much longer for the stereo sensor in comparison to the laser scanner, but a significant higher spatial resolution of sub millimetres was gained.

The 3D data recorded with the laser scanner and the four thermograms taken directly after the heating were fused. For both methods, six corresponding point pairs were selected, which was repeated for each thermogram. The resulting image is shown in figure 3.b. In this thermogram of the whole central picture, first of all the structure of the underlying masonry becomes visible. Lighter and thus warmer areas are hints to joints between the single bricks and stones, while these areas with much higher temperatures are an indication for plaster delaminations.

5. Summary and Conclusion

Active thermography (among others, exploitation of solar heating), a crack tracking method (adaption of the system to various on-site situations, improvement of accuracy and operability) and stereo photogrammetry (a rail system for faster data recording) were further developed with success. Tools for fusing different 2D and 3D experimental data are enabling both objective comparison and interpretation of measurement results as well as support a quantitative monitoring of damages (e. g. cracks, delaminations, voids) of façade systems. Selected examples for the application of these methods considering three case studies are presented in this paper.

Acknowledgements

These investigations were performed within the research project Acquisition and Evaluation of Safety Relevant Delamination Processes of Plaster and Façade Elements Using Non-destructive Testing Methods. This project was funded within the frame of the research initiative ZukunftBau by the Federal Institute for Research on Building, Urban Affairs and Spatial Development (SF-SWD – 10.08.18.7-13.42).

References

[1] H Kollmann, 'Sanierungspraxis Putz. Von der Diagnose bis zur Ausführung', 2010, Praxis kompakt 4, C. Maurer

[2] T Dettmering and H Kollmann, 'Putze in Bausanierung und Denkmalpflege', 2012, DIN e. V.

[3] M Patzner, 'Ursachen von Putzschäden', In: Die Mappe, Nr. 5, 2012, S. 32-37

[4] C Maierhofer, R Krankenhagen, P Myrach, M Röllig, R Mecke, M Schiller, T Seidl, U Kalisch, C

Hennen, J Meinhardt, H Kersten and E T Groll, 'Entwicklung eines Verfahrens zur zeitaufgelösten 3D-

Kartierung von Verformungen und Schäden an Bauwerken und Bauteilen⁺, Abschlussbericht 2014, 193 S., Fraunhofer IRB Verlag, ISBN 978-3-8167-9145-4

https://www.baufachinformation.de/forschungsbericht/240758

[5] C Maierhofer, R Arndt, M Röllig, C Rieck, A Walther, H Scheel and B Hillemeier, 'Application of impulse thermography for non-destructive assessment of concrete structures', Cement & Concrete Composites, 2006, Vol. 28, pp. 393-401

[6] C Maierhofer, M Röllig, H Steinfurth, J Meinhardt, T Arnold, Untersuchung sicherheitsrelevanter Ablösungen von Fassadenelementen mit aktiver Thermografie. Bautechnik Vol. 92(10), 2015, 677-682

[7] C Maierhofer, M Röllig, H Steinfurth, S Augustin, R Mecke, M Schiller, A Kernchen, U Kalisch, J

Meinhardt, C Hennen, E T Groll, T Arnold, "Erfassung und Bewertung von sicherheitsrelevanten Ablösungsprozessen bei Putzen und Fassadenelementen mit zerstörungsfreien Mess- und Prüfverfahren." Abschlussbericht 2016, Fraunhofer IRB Verlag, in print

[8] C Maierhofer, M Röllig, H Steinfurth, R Krankenhagen, R Mecke, M Schiller, A Kernchen, U Kalisch, J Meinhardt, C Hennen, E T Groll, T Arnold, Detection and Characterisation of Safety Relevant Detachments of Façade Elements Using a Combination of Active Thermography and Optical Scanning Methods. Proc. Of International Symposium Non-Destructive Testing in Civil Engineering (NDT-CE), http://www.ndt.net/search/link.php?id=18393&file=article/ndtce2015/papers/202_maierhofer_christiane.pdf