Detection and Characterisation of Safety Relevant Detachments of Façade Elements Using a Combination of Active Thermography and Optical Scanning Methods

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Abstract
In this contribution, the development and application of optical and thermographic methods for the non-destructive evaluation of delaminations, cracks and further substructures in connection with bulging is presented. Since delaminated façade elements show geometric as well as thermal anomalies, surface geometry and defects beneath the surface were investigated. As methods, stereo photogrammetry, a tracking based method for tactile recording of geometric 3D data and active thermography were used. Two case studies were assessed with a combination of these methods: the plaster scratches at the Magdeburg Cathedral and a mural painting in Cobbelsdorf, both located in Germany. While the plaster scratches have been investigated by artificial heating with an infrared radiator, the rural painting was tested by analysing the temperature increase due to solar heating.

Keywords: Active thermography, stereo photogrammetry, tracking sensor, historic plaster, masonry, delamination, crack;

1. Introduction

The preservation of historic plaster and façade elements is reasonable due to economic, material technological and conservation related criteria. In several cases, plaster is not only protecting the masonry but is also carrying paintings or other image information. At ceilings and higher walls, safety aspects have to be considered, which means that the falling down of larger particles and pieces has to be avoided. Only a careful and systematic assessment of damages like cracks, loss of material, detachments and loose material as well as the monitoring of changes enables the application of preservation measures in due time. In the field of building redevelopment, the conservation of plaster is rather more the exception than the rule. Accordingly, a non-destructive condition monitoring including the assessment of large plaster surfaces is, unlike in the field of natural stone, rather unusual. There are relevant publications for the rehabilitation practice of plaster, which are also considering diagnostic aspects. But these focus generally 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]. Also for the detection of cracks and their dynamics, there are already established measurement methods available (e. g. crack monitors, fibre optic systems, 3D laser scanning, laser extensometer or potentiometric systems) [4].

Very often, plaster detachments can be recognized as geometric changes of the surface due to bulges, delaminations and/or cracks. Below the surface, material deterioration occurs. For
detecting these geometric changes, different optical methods which are recording the 3D geometry can be applied. In several cases, plaster delamination as well as delamination of ceramic façade elements cannot be visualized from the outside and are therefore associated with particular risk related to the safety of the building. For detecting these hidden defects, active thermography is very well suited. Therefore, a combination of active thermography with tactile and contactless deformation measurements is appropriate, innovative and efficient for the evaluation and assessment of damage and detachment of plaster and façade elements. Below two case studies of these combinations are presented: the plaster scratches at Magdeburg Cathedral and a mural painting in Cobbelsdorf.

2. Experimentals

2.1 Stereo Photogrammetry

For the visualization of specific surface topologies such as the plaster scratches in Magdeburg, a stereo photogrammetry system was used. Unlike scanning methods (e.g. laser scanner), the advantage is that only two synchronous images are required for each measurement field and that a high spatial resolution (one 3D value per pixel in the ideal case) is reached. Here, a field size of 17 x 17 cm was selected at a distance of 40 cm with a system shown in figure 1 a. But also larger areas with less resolution can be recorded with a system like in figure 1 b. 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. The measurement method itself is tolerant with respect to distance variations or minor deviations from the grid, so it can also be carried out from a scaffold. The analysis of the data is carried out in the laboratory and includes the calculation of 3D data for one measuring field, the determination of the actual positional relationship of the individual measurement fields to each other using the overlapping areas, and the transfer of the point data of the entire examined area into a triangular mesh.

![Figure 1. Measurement systems used for stereo photogrammetry. a) System consisting of two AVT Pike grey level cameras (2056 x 2062 pixels), mounted at a fixed distance on a slide. b) System for recording larger areas from a larger distance.](image)

2.2 Tactile 3D Crack Mapping

For the 3D crack mapping a simple test rod was used, which is moved manually along the crack while its position and orientation is detected in the room by an optical tracking system.
The usual application of this system is the recording of human movement for motion capture applications. For the 3D crack mapping measurement a spatial resolution in the millimeter range is required. Investigations revealed that a tracking precision of individual markers (infrared reflective balls) is possible with an accuracy of ± 0.5 mm. In order to achieve this resolution, on-site calibration of the camera system is necessary. The system consists of an infrared tracking system, a rod with markers and custom software, which was developed specifically for the purpose of convenient data recording directly at the object. The recording of data can be controlled either for individual discrete points or continuously. Using corresponding points in 2D images and the recorded data points, the recorded crack can be projected into the 2D image for further analyses. For the investigations at the mural painting in Cobbelsdorf presented below, a tracking system consisting of six cameras as shown in figure 2 was used.

2.3 Active Thermography

Active thermography is based on an active heating of the structure to be examined with a suitable heat source (also with solar radiation) and of recording the surface temperature during heating and/or cooling with an infrared (IR) camera [4]. The heating process is generating a non-stationary heat transport, which is influenced by structural or material inhomogeneities. If these inhomogeneities are not too deep, these can be detected at the surface by analyzing the temperature distribution as a function of space and time. Plaster delaminations or voids usually appear as warmer areas, as these are reducing the heat transfer, which is therefore accumulated at the surface.

For testing the suitability of the method for the detection of plaster delaminations, seven test specimens have been constructed. Among these, two are described in more detail. These consist of concrete panels with a size of 50 × 50 × 5 cm³, which were plastered by a single layer of lime plaster with thicknesses of 1 and 2 cm, respectively. In both concrete panels (Pk2 and Pk3), different artificial delaminations were included consisting of three voids filled with sand (sizes: 10 × 10 cm², 5 × 5 cm² and 2 × 2 cm²), three pieces of parchment paper with holes inside (sizes: 10 × 10 cm², 5 × 5 cm² and 2 × 2 cm²), and three areas where Cyclododecan was sprayed dot wise (sizes: 10 × 10 cm², 5 × 5 cm² and 2 × 2 cm²). At the backside of the voids filled with sand, holes were drilled. Thus, the sand was removed after plastering. Experimental investigations with active thermography were performed by heating the samples with an IR radiator with an input power of 2.4 kW for about 5 min. After heating, the cooling down was observed with an IR camera consisting of a microbolometer detector.
with a size of 640 x 480 pixels and an NETD of 50 mK. Data were recorded for 15 min with a frame rate of 2 Hz. In the following, additional to selected thermograms, also phase images analysed according to pulse-phase thermography are shown [5].

Figure 3. Results of the investigations of Pk2 (1 cm Plaster) and Pk3 (2 cm plaster) with active thermography. a, d) thermograms and phase images of both test specimen showing each the optimum contrast of the artificial defects. b) Temperature differences of the sand voids having different sizes in Pk2. c) Temperature differences of the paper voids having different sizes in Pk2. e) Temperature differences of the sand voids having different sizes in Pk3. t = 0 s corresponds to the end of the heating period.

Figure 3 a and d show the thermograms and phase images of test specimens Pk2 and Pk3, respectively. For both, the voids formerly filled with sand show the highest thermal and phase differences. Much lower differences were found at the paper and Cyclododecan defects. The temperature differences of the three sand voids related to undisturbed material as a function of time are shown for both test specimens in figure 3 b and e. The zero on the time scale corresponds to that time where the IR radiator was switched off. Here it becomes obvious that the temperature differences measured at Pk2 with 1 cm plaster are much higher than for Pk3.
with 2 cm plaster. Also the time, where the maxima of the temperature differences occurs, is shifting to later times with increasing plaster thickness. Figure 3 c shows the temperature differences of the delaminations simulated by the parchment paper for Pk2. Here, the temperature differences are much lower than for the sand voids, which could be explained by the lower height of the artificial delamination.

3. Case Studies

3.1 Plaster Scratches at the Magdeburg Cathedral

One of the most important artworks 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 restoration 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 (up to now). 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 the stereo photogrammetry system for visualizing of the plaster scratches and active thermography for locating and characterizing plaster delaminations.

Figure 4 shows two photographs of one part with a size of about 1 x 0.6 m² of the central picture of the plaster scratches presenting one of the two wives of Otto I. One photo was taken in 2012 before restoration (a), the other one just after laser cleaning, while a small part was still left uncleansed, in 2014 (b). Results of experimental investigations at this part concerning the location of voids as well as the visualization of the plaster scratches are shown below.

Figure 4. Photo of the upper left quadrant of the central picture of the plaster scratches showing Adelheid, the second wife of Otto I. a) Photo before the restoration in 2011. b) Photo after the restoration and laser cleaning in August 2013, a small area was still not cleaned.

3.2 Rural Painting in Cobbelsdorf

The rural painting made by Erich Enge in 1970/71 and shown in figure 5 a 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 x 18 m. Now the ownership belongs to the Flämingland Touristik und Freizeit GmbH Cobbelsdorf. The House of Culture is a former hall for the storage of fertilizers, and consists of a pillar structure, where
the roof rests on. The spaces between the pillars are walled with hollow blocks from GDR production. Figure 5 b shows the interior view of the wall which carries the painting.

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. These damages were accompanied by fine cracks in several plaster areas especially along the joints of the masonry, which in turn led to losses of paint layer. 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.

4. Experimental investigations and results

4.1 Plaster Scratches at the Magdeburg Cathedral

At the central picture, measurements with active thermography were carried out in April 2012 and October 2014. At these times a scaffold was available, so that the measurement areas could be heated with the infrared radiator as described above for the laboratory investigations of the test specimens. Figures 6 a and b show the thermograms of the left upper quadrant of the central picture recorded in 2012 before and in 2014 after laser cleaning. The mean temperature in the thermograms is slightly higher in 2012, probably due to an enhanced absorption of IR radiation of the darker contaminated surface. In both thermograms certain areas could be identified which are more than 6 K warmer than its surroundings. These areas might be related to delaminations or voids. Temperature difference curves above three different positions P1 to P3 marked in the thermograms and related to cooler homogeneous areas are shown in figure 6 b and d. These temperature difference curves are similar to those observed for the sand voids in test specimen Pk2 in figure 3 b, although in the case of the plaster scratches, the maximum temperature difference is less. Therefore, the warmer areas in the plaster scratches might be related to delaminations, which have a less height as those in Pk2. It is expected that the plaster layer thickness of about 1 cm is similar.
Figure 6. Results of thermographic investigations at the top left quadrant of the central picture of the plaster scratches recorded directly after 5 min of heating with an IR radiator. a, c) Thermograms recorded in April 2012 and October 2014, respectively. b, d) Temperature difference curves of the data recorded in 2012 and 2014, respectively. P1 to P3 are related to different positions shown in the thermograms.

Figure 7. Comparison of results of photogrammetric 3D data and active thermography of the top left quadrant of the central painting. a) Mapping of the height of the plaster scratches. The values are related to mm. b) Thermogram of the same area recorded in 2012 after 5 min heating (same as figure 6 a). Both images are superimposed to the 3D data representing the plaster scratches.

The central picture was also investigated with stereo photogrammetry as described above. For a visualisation of an elevation mapping of the plaster scratches, a mean reference plane was included and the differences of all 3D data to this reference plane were calculated. The results are shown in figure 7 a. Positive values are corresponding to bulging out of plane and are
shown in red. Negative values show depressions and indentations and are visualized in blue. This elevation mapping was superimposed with the 3D of the plaster scratches. Figure 7b displays the thermogram of the same image section which was recorded in 2012 directly after heating. Warmer areas are shown in red. The warmer area in the middle part of the image can be directly correlated to bulging, thus these are voids. The warmer area in the top right of the thermogram cannot be related to a bulging. Therefore, the possible delamination in this area did not lead to bulging of the plaster.

4.2 Rural Painting in Cobbelsdorf

The thermographic investigations at the rural painting in Cobbelsdorf were performed at one day in September 2014 and at one day in April 2015. The measurements of the temperature distributions occurred during solar heating. The wall is orientated south-west, thus at both days, 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 (Huxeflux PU11). These data are shown together with the mean wall temperature for both days in figure 8a and c. During the day in September 2014 (figure 8a), the heat flux was varying strongly due to moving clouds, and the maximum heat flux of 800 W/m$^2$ was recorded at 01:40 p.m. The wall temperature was directly following the solar power density with temperature maxima of about 28°C. In April (figure 8c), no clouds appeared and the solar heating was homogeneously increasing over time. The small eruptions of the measured solar power density are due to shadowing of the sensor by passing pedestrians. With the beginning of the measurements, the heat flux started at 600 W/m$^2$ and increased and saturated to 1000 W/m$^2$, when the sun radiated perpendicular to the wall surface. According to this radiation, the wall temperature was increasing linearly from 16.5 to 33°C.

From each of these two measurement days with different types of solar radiations, a thermogram was selected from the sequence at 01:56 p.m. and is shown in figure 8b and d. From both thermograms, 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 in April 2015, the temperature rise of the warmer areas was much higher as in September 2014 due to the continuous heating. Secondly, in the thermogram recorded in April 2015, thermal features related to the different colours of the painting and thus to different emissivities are much stronger than in the one recorded in September 2015. As in September the thermogram was taken during a minimum of solar radiation, the influence of direct reflections due to emissivity contrasts at the surface is mainly suppressed. In both thermograms, 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 in figure 8b, while only one pillar is visible in figure 8d. 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. These inhomogeneities appear much clearer in the thermogram in September, as fewer distortions due to inhomogeneous emissivities appear. Additionally to these signatures, also features related to joints and bricks are visible.

At the bottom of the left pillar, the cracks at both sides of the pillar were recorded with the tactile sensor. The results are shown in figure 9a. Most of these cracks can also be seen in the thermograms in figures 9b and c, which were recorded at different times. Both thermograms together contain similar information as the tracked data. But in the tracked data, already the 3D information is contained (not shown here). The next step now is the fusion of all data sets.
Figure 8. Results of thermographic investigations during solar heating of the mural painting in Cobbelsdorf.
a, c) Solar power density and wall temperature during the measurements in September 2014 and April 2015. b, d) Thermograms recorded at 01:56 p.m. in September 2014 and April 2015, respectively.

Figure 9. Comparison of 3D data recorded with the crack tracking method (a) and with two thermograms, which have been taken at different times during solar heating (b, c). d) Alignment of a photo with the recorded crack data and the thermogram from c).
5. Conclusion

In this paper, two case studies have been presented concerning the locations of plaster delaminations and of cracks and structures below the plaster. For the investigations of plaster delaminations, the plaster scratches at the Magdeburg Cathedral were heated actively with an IR radiator. During cooling down, thermograms were recorded which clearly show warmer areas. From a comparison to temperature difference curves of the test specimens with known defects, these warmer areas could be related to delaminations. Some of these delaminations coincide with bulging detected with the stereo photogrammetry system.

Cracks and structures below plaster were detected during solar heating of the mural painting in Cobbelsdorf. Here, two measurement campaigns at two different days clearly show that moving clouds in alternation to direct solar radiation is much better suited to detect inhomogeneities of the structure as a continuous direct solar radiation. In addition to active thermography, cracks could be detected with higher spatial accuracy using the tactile tracking sensor.

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