Investigating historic masonry structures at different depths with active thermography

by Ch. Maierhofer*, R. Krankenhagen*, M. Röllig*, J. Schlichting*, M. Schiller**, Th. Seidl**, R. Mecke**, U. Kalisch***, Ch. Hennen*** and J. Meinhardt***

**BAM Federal Institute for Materials Research and Testing, Berlin, Germany, christiane.maierhofer@bam.de;*
Mail: Unter den Eichen 87, 12205 Berlin, Germany; Phone: +49 30 8104 1441, Fax: +49 30 8104 1845
***IFF Fraunhofer Institute for Factory Operation and Automation, Magdeburg, Germany*
****IDK Institute for Diagnosis and Conservation on Monuments in Saxony and Saxony-Anhalt, Halle, Germany*

Abstract

As shown recently, the quantification of damages in historic masonry structures is possible by using active thermography. In this paper, a case study is presented concerning systematic studies of the determination of damage depth and size by using different approaches of active thermography. Various heating sources as well as impulse and periodic heating will be compared. A combination with geometrical 3D data recorded with a laser scanning system (light section methods) demonstrates the complementarities of both methods. Reproducible investigations in regular time intervals for structural monitoring are possible.

1. Introduction

Active thermography enables structural investigations of building elements considering a large amount of different testing problems. As advanced non-destructive testing (NDT) methods like radar, ultrasonic and sonic methods are mainly suited for the detection and characterization of inhomogeneities deeper than 5 to 10 cm [1], active thermography closes the gap for testing the near surface region to a depth of 10 cm [2]. Many classes of damage originate from defects which are close to the surface, e. g. delaminations of plaster, surface and subsurface cracks, voids, spalling, soiling, moisture, efflorescence and microbiological attack. Therefore, active thermography is very well suited for applications in this area. By using various heating sources and impulse and periodic heating at different frequencies (lock-in thermography), depth resolved investigations can be realized.

For monitoring structural modification and damage, repeated investigations are needed in regular time intervals, e. g. once or a few times a year. As for each measurement campaign the heating sources and IR camera have to be remounted, the recorded data are not totally reproducible which makes data analysis and interpretation difficult. Allocation of the thermal images to the detailed geometrical positions will solve this problem. Additionally, the combination of infrared images with geometric 3D data enables the discrimination between external geometrical effects due to material properties and internal faults.Therefore, the geometry of the investigated areas has to be digitized with a 3D laser scanner. With the light section method a very precise determination of position is possible. Arbitrary surfaces can be surveyed with an accuracy of about 0.1 mm [3, 4]. 2D photos can be concatenated [5]. The disadvantages are the complexity of the experimental set-up as well as the data analysis. In the presented work, the light section method using a laser scanner and robotic pivot arm for recording the geometry, topology of the surface, and geometric alterations (e.g. cracks, bulging, deformations) was combined with active thermography.

For recording of congruent mappings of the object under investigation, first the internal deviation of the infrared (IR) cameras have been corrected (intrinsic camera calibration). This calibration reveals that uncorrected thermograms show considerable distortions up to 5 % at the boundaries, which cannot be neglected for datafusion. For facilitating the fusion to the 3D data, parallel to the capturing of thermograms digital photos are taken from the measured object. For this, IR camera and digital camera were both mounted into a common frame structure enabling a reproducible relative position.

Both methods have been applied to several historic buildings, compiling experimental data. In the following, repeated investigations for monitoring of a sandstone column (dome of Magdeburg) are presented.

2. Active Thermography

2.1 Principle of active thermography

The active approach of thermography investigation of historic masonry structures implies a direct heating. Common heating techniques are usually operating directly like step impulse (long impulse) and periodic heating (lock-in technique for data analysis) [6]. The optimal heat source should generate a homogeneous heat flow without any delay along the whole surface area of the structure under investigation. In reality, these conditions can only be approximated. Heating sources can be classified related to the three different heat transport processes: radiation, convection, and conduction. In several cases, radiation sources like flash lights, halogen lamps, and IR radiators have proven to be the most suitable sources by being fast and efficient and generating a homogeneous and moderate temperature increase at the surfaces of historical building materials. For uneven and/or inhomogeneous surfaces with varying emissivities and jutties, convective sources by using fan heaters should be applied [2, 7].

For periodic heating (also known as lock-in thermography), the surface temperature is modulated with a step function or a sinus, e. g. by using halogen lamps. Thus, the surface background temperature is increasing. The generated thermal waves are reflected at interfaces, where the thermal effusivity is changing abruptly. These reflections superimpose with the incident thermal waves and generate a temperature field at the surface. Intensity and phase of the temperature field vary with position and time and depend on depth and material properties of the reflector. This temperature field is recorded as a sequence of thermograms by the IR camera. Afterwards, the sequences, which are correlated to the frequency of the heat source, can be analyzed by Fast Fourier Transformation (FFT) [8].

For quantitative analysis of data gained by impulse heating, pulse-phase-thermography (PPT) can be applied [9, 10]. It combines the method of data acquisition of impulse-thermography with the approach of frequency analysis used in lock-in thermography described above. The stored data received during impulse heating and cooling down (mainly during cooling down) are analyzed in the frequency domain via FFT of the transient curves. The maximum frequency is determined by the acquisition rate, the minimum frequency is limited by the recording time. In practice, only the first amplitude and phase images at low frequencies are of interest, since most of the energy is concentrated here. Higher frequencies exhibit a higher noise level. For this procedure, no pre-knowledge about the position of defects is required.

In the case study presented below, a microbolometer IR camera (Variocam hr from Infratec) with a maximum frame rate of 50 Hz and an array size of 640 x 480 pixels was used. The objectives can be changed and either a wide angle, standard or telephoto objective can be mounted. As heating sources, two halogen lamps with a power of 500 W each were applied.

2.2 Calibration of camera parameters

As the thermograms only include 2D information in medium geometric resolution, the spatial allocation of the data on objects with complicated surfaces is difficult. This becomes particularly clear with the admission of single details of a sculpture and with the comparison of data, which were recorded at different times and from different perspectives. The transformation of the 2D thermograms into the 3D space solves these problems partially. The mapping of the 3D object space onto the 2D image level of the camera is described by a camera model, mostly delineated as a central projection. For this transformation, extrinsic and intrinsic camera parameters are required.

The *intrinsic camera parameters* are modelling the optical imaging process. In the ideal case of the central projection the focal length of the objective would be sufficient. But in reality, undesirable changes occur due to optical distortion of the objective. Therefore, further intrinsic parameters are describing these deviations using several functional models. For the determination of these intrinsic parameters, there exist effective methods based on photogrammetry. These methods analyse images of geometrically well known pass points. In the following, the „Camera calibration toolbox for Matlab“ from Jean-Yves Bouguet is used, which can be downloaded from http://www.vision.caltech.edu/bouguetj/calib_doc/. Here, a checkered pattern is employed as a pass point field. The software package contains suitable routines which support an automated pass point search in a selected image section. For applying the software tool to IR cameras, a pattern which delivers a sufficient contrast in the delicacy area of the camera is needed. A circuit board coated with tin and having different sizes has turned out to be well suited. The measured thermal contrast results from a superposition of two effects: different thermal radiation due to the various emissivities of tin and circuit board material and different reflection behavior of both materials for the diffuse reflections from the environment. For a reliable determination of the camera parameters, the pass point field must be recorded under four different angles in four different orientations. This procedure has to be performed several times with variable distances corresponding to different focus settings. The ascertained camera parameters permit a correction of the image. These parameters show that the largest aberration to be corrected is a radial-symmetrical divergence of the theoretical ideal form of the lens which entails a so-called barrel-shaped distortion of the original image. Repeated measurements after changing the camera objective revealed that the mechanical position of the objectives is not necessarily reproducible. This led to striking changes of the ascertained calibration parameters. Hence, for on-site measurements the user must fix the objectives with special care to guarantee the validity of the calibration parameters.

The *extrinsic camera parameters* describe the spatial position and orientation of the camera in relation to the object. For the determination of the extrinsic parameters, the intrinsic parameters have to be known. Then, the extrinsic parameters can be determined in two different ways: The triangle model requires a minimum of four points in order to obtain the projection center and the view angle of the camera. If possible, ten or more points should be considered to improve the accuracy of measurement. For the application of the model, the 3D and corresponding 2D points have to be picked manually in the geometrical 3D model as well as in the thermogram. The calculations can be performed using functions from the OpenCV library. If it is not possible to locate enough features (especially in the thermogram), an additional visual camera is required which has to be calibrated, too. This camera has to be mounted in a fixed connection to the IR camera. For each position, data have to be recorded with both cameras simultaneously.

A common frame for both cameras has to fulfil the following conditions: form-stability, absolute reproducible relative positions for both cameras, simple assembly and disassembly of both cameras, and operability of both cameras at fixed position. The frame shown in figure 1 is a practical solution: It consists of firmly screwed aluminium structure-profiles. The fixation of both cameras occurs in each case with a screw from below. This screw is positioned inside a precise borehole. In addition, for every camera a stop position is realized by a pin. As a result, the position of every camera is fixed unambiguously. For recording of similar image sections, an objective with short focal distance length is used for the visual camera. Then, the visual image contains the whole image of the IR camera as a section.

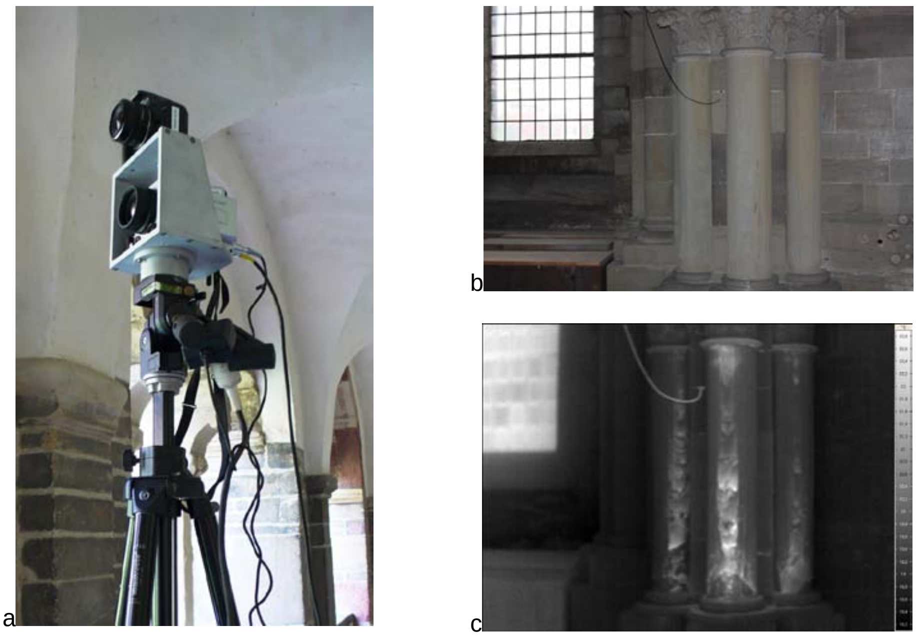


Fig. 1. *a: Frame for CCD camera and IR camera for the determination of extrinsic calibration parameters; b: Photo; c: Thermogram from sandstone column described below.*

3. Optical Methods

For the capture of the surface geometry of building surfaces and sculptures, a measuring system with two essential properties is necessary: The system should be suitable for a mobile application on the objects to be examined; and the data recording must be contactless. For the case studies described in the following, a light-section sensor developed at Fraunhofer IFF which is fastened to a measuring arm is used. The sensor consists of a camera and a line laser. By applying integrated hardware-based image processing, the measuring system can detect up to 100 contour lines per second, with 1536 3D points each. Larger and complicated freeform surfaces can be covered. It is designed for flexible applications and can be used directly on the objects to be examined.

Using this equipment a 3D point cloud is generated representing a spatially dense and detailed image of the object surface. The accuracy of the 3D measuring points is about ±0.1mm. To achieve a smooth and complete reproduction, a geometric surface model is generated: Single 3D points are connected with each other using triangles. During this procedure measurement errors as well as redundant data are filtered. Such a triangle model is the support for the visual representation and subsequent processing of the measuring data. If suitable, the number of the triangles can be reduced, e. g. for distinct application cases.

For fusing the data recorded with the laser scanner and active thermography, in a first step, the measurement position of the IR camera in relation to the object is determined. Afterwards, every 3D measuring point is assigned to the view ray that projects this point on the camera sensor chip. So, every point in a thermogram can be assigned to one or more 3D points on the surface of the investigated object. The method which describes the transformation of a 2D image onto a 3D model is known as texture mapping. A suitable mapping procedure should fulfill the following conditions:

- The images must be transformed with accurate fitting onto the 3D model

- A superpositioning of different images must be possible
- The ratio of data resolution (high for the 3D model, low for the 2D image) has to be considered
- No perspective distortions

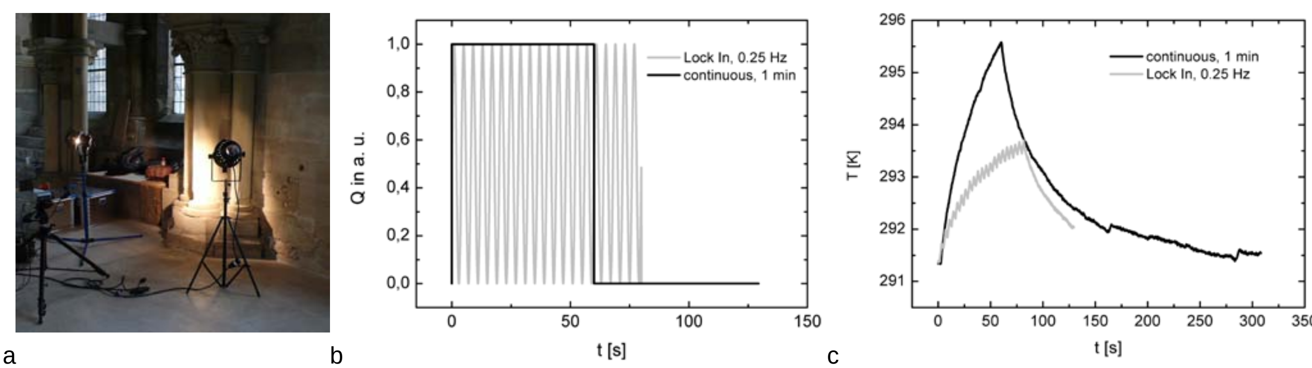
In the applied procedure, from each point of the triangle model a ray is sent to the center of the camera. The color value of this point is given by the 2D image, but is also influenced by the angle between the surface normal of the 3D point and the view direction of the camera. The mathematical basics are described in [11], while the applied mapping procedure is explained in [12]. The color values are stored in the different points of the triangle model. For visualization of the fused data, the color values are interpolated along the triangle. As the 3D model has a very high resolution, a continuous texture mapping is possible.

4. Case Studies

The Protestant Cathedral Saint Mauritius and Saint Katharina in Magdeburg, Germany, is a Gothic monumental building with rich equipment. It was constructed from early 13th to the early 16th century and is the second largest cathedral in Germany after the Cologne Cathedral. The Bishop's corridor, constructed after 1232, is unusually wide and high [13]. Big windows correspond to the wide gothic vaults of the choir. Columns made of lower triassic sandstone run around the octagon pillars. Several of these columns show large amounts of sand spreading and spalling due to environmental influences. One of the columns (see figures 2a and 3a) has been an object of further research and thus has been selected for investigation with active thermography and 3D laser scanner.

4.1 Active thermography

The heating has been performed with impulse duration of 60 s as well as periodically with different frequencies of 0.25, 0.10 and 0.05 Hz for 10 to 20 periods by using two halogen lamps. During and after heating, the thermal images have been recorded with a frame rate of up to 50 Hz with the above mentioned IR system. The distance of the two halogen lamps to the object surface was always 1.2 m, while the distance of the camera to the surface was 1.8 m. The standard objective with a field of view of 30°x23° was mounted. The set-up of the equipment in front of the column is shown in figure 2a. In figure 2b, the heat flow as a function of time for impulse heating and for periodic heating with a frequency of 0.25 Hz and 20 periods is shown (step-function). In figure 2c, the related average surface temperature as a function of time is displayed. With 60 s impulse heating, an average maximum temperature rise of about 4 K was obtained while with periodic heating (on and off) for 80 s, only about half of the average temperature rise (2 K) was measured.



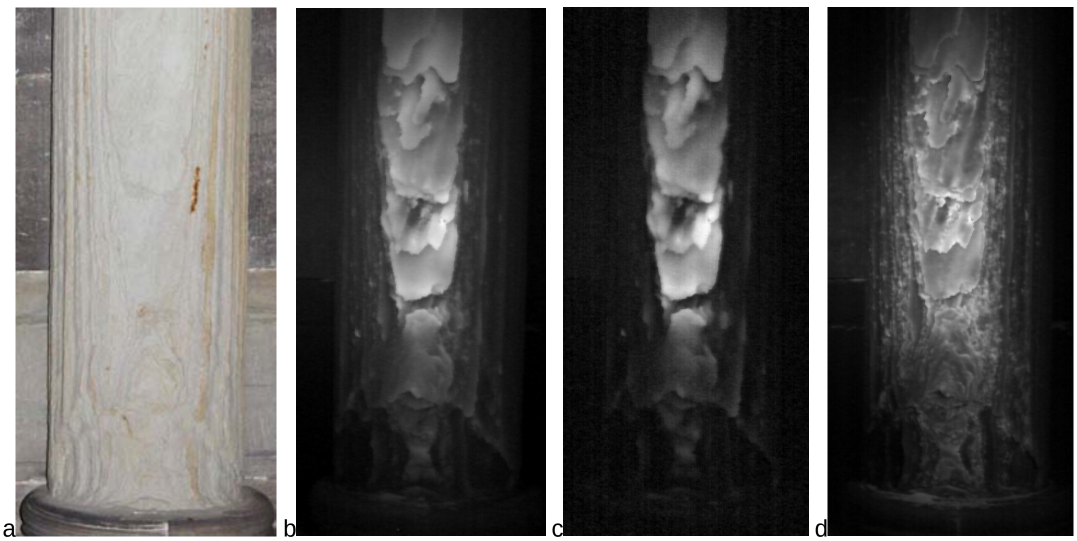
a b c

Fig. 2. *a: Illuminated (heated) bottom part of a sandstone column; b: Heat flow as a function of time for impulse heating for 1 min (black curve) and periodic heating with a frequency of 0.25 Hz; c: Average temperature at the middle of the column as a function of time during and after heating.*

In figure 3b, a thermogram recorded just after 60 s impulse heating is shown. Warm and cold areas clearly indicate the structure of different layers. Warmer areas are belonging to delaminations. Figure 3c shows the amplitude image calculated from the cooling down after impulse heating at a corresponding frequency of 0.02 Hz (PPT). In figure 3d, the amplitude image calculated from lock-in thermography with 0.05 Hz is shown. In the latter, the best contrast of the different layers is obtained while in the thermogram (and also in the amplitude image from the cooling down sequence) the warmer areas clearly mark the delaminated areas. By using figures 3b (or 3c) and 3d together a clear characterization of the structural condition close to the surface is possible. From the applied objective and the known distance of the camera, a spatial resolution of 1.5 mm per pixel is calculated.

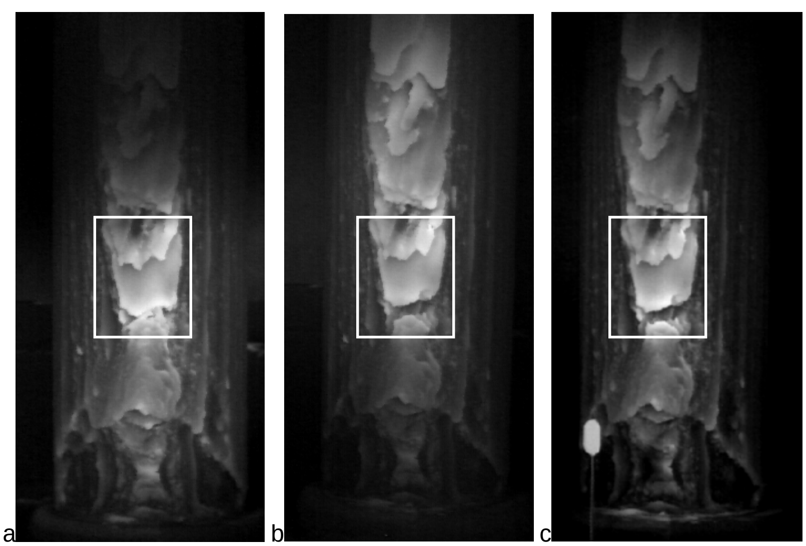
The first measurement campaign was performed in June 2009 and was repeated in November 2009 and March 2010. The related thermograms recorded just after heating are shown in figure 4. The environmental parameters, the temperature of the surface before heating, and the maximum temperature rise during heating are summarized in table 1. Although the illumination with the halogen lamps could not be reproduced in an optimal way as shown in the thermograms in figure 4, and although the initial surface temperatures were different (maximum in June 2009, minimum in March 2010 after a cold winter), it is shown in table 1 that the maximum temperature rise was more or less similar for all campaigns (from 5.9 to 7.0 K).

By comparing the temperature distributions in the thermograms in figure 4, it becomes obvious that some significant loss of material occurred between June and November 2009 (see rectangular in figures 4a and 4b). And it is also obvious that this loss occurred at the position with the highest temperature (delamitation) in figure 4a. Comparing figures 4b and 4c, only very small areas with additional loss of material can be detected, but again at the positions with the highest temperatures. Therefore, high temperatures reveal the positions where delaminations are present and where further loss of material is expected.



a b c d

Fig. 3. *Bottom part of a sandstone column with spalling in June 2009. a: Photo; b: Thermogram, directly recorded after a heating time of 60 s with two halogen lamps (10.6 to 18.0 K from black to white). c: Amplitude image at 0.02 Hz calculated by pulse-phase thermography after 60 s heating; d: Amplitude image calculated from lock-in thermography at 0.05 Hz.*



a b c

Fig. 4. *Thermograms directly recorded after a heating time of 60 s with two halogen lamps at different seasons; a: June 2009 (18.0 to 23.3°C from black to white); b: November 2009 (10.6 to 18.0°C from black to white); c: March 2010 (9.4 to 14.4°C from black to white). The white rectangle marks the area with considerable loss of material.*

Table 1. *Environmental parameters at the column and maximum temperature rise at the investigated area after 1 min of heating with two halogen lamps.*

Date	10.6.2009	17.11.2009	31.3.2010
Air temperature in °C	19.0	13.5	10.0
Air humidity in %	60	62	72
Surface temperature in °C (measured with contact thermometer)	17.3	11.0	8.5
Maximum temperature rise during heating in K	5.9	7.0	5.9

4.2 3D laser scanner and datafusion

With the laser scanner, 171 mill. data points were recorded during the measurement campaign in June 2009. The whole surface was divided into 7 subareas, which were digitized one after the other. For this procedure, a total time of about 5 h was needed. These points were networked and the resulting net (3D model) consists of about 15 mill. triangles with a resolution of about 0.5 mm. In figure 5a, the recorded surface geometry of the bottom part of the column is visualized. In this area, the joints behind the column can be used as pass points between the 2D- and 3D data, which can be used to determine the position of the IR camera (extrinsic camera calibration parameters). These extrinsic parameters and the equalized thermal image (here: amplitude image recorded with a frequency of 0.05 Hz) have been imported into the visualization tool. The resulting datafusion is shown in figure 5b. Here, a detailed positioning of the thermal image in relation to the 3D model is possible. The geometric borders as well as the thermal signature are corresponding to each other very well. A detailed determination of the position of further loss of material is possible as well as a quantification of the damaged area.

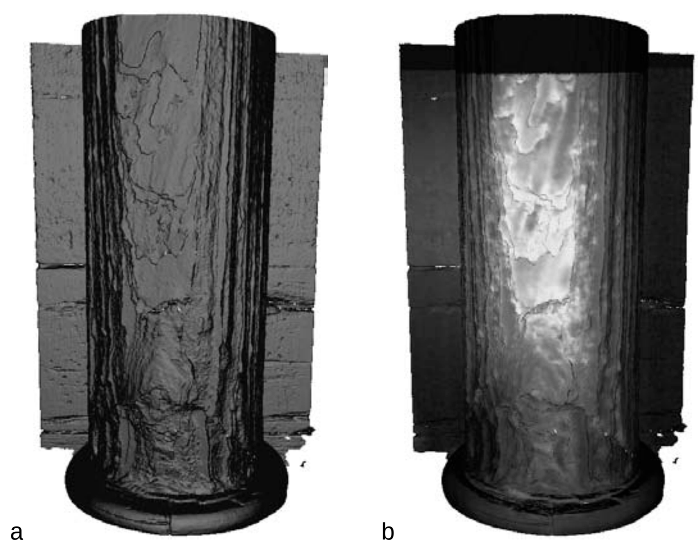


Fig. 5. *a: Visualized surface of the column recorded with the 3D laser scanner in June 2009. b: Data fusion of geometrical 3D data and amplitude image recorded in June 2009 with a frequency of 0.05 Hz.*

5. Summary and Outlook

The aim of the presented research was the development and qualification of an efficient strategy for early digital detection, spatial recording and quantification of damage at and close to the surface. Thus, structural changes can be observed for longer periods and appropriate measures and repair can be applied at an early stage. Beyond that the effectiveness and sustainability of protective measures can be analyzed.

With the help of the introduced approach and the developed software the thermograms can be visualized and analyzed three-dimensional for any complex object geometry. The combination of infrared images of unsteady thermal heat transfer processes with geometric 3D data enables the discrimination between external geometrical effects due to material properties and internal faults. Temporal changes can be observed with the demanded high local accuracy and damage can be recognized on time.

For the future, it is planned to introduce the visualization of temperature differences from different measurement campaigns. Further on, from the geometrical 3D model and the known position of the IR camera, the view angle of each surface point is known and enables the correction of angular dependent emissivities and thus temperature values. This is especially important for complex 3D structures like columns, sculptures, reliefs etc.

It is also possible to include further information from other non-destructive and minor destructive testing methods. This will enable a comprehensive damage assessment and monitoring which will support life time analysis and planning of interventions and restoration.

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