Berliner Beiträge zur Archäometrie	Band 21	Seite 23-32	2008

Condition Assessment of Ancient Architectural Monuments in the Pergamon Museum – The Combined Application of NDT-Methods for Structural Investigations

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Abstract

In this paper the possibilities of the combined application of nondestructive testing (NDT) methods for structural investigation of ancient architectural monuments is presented using the example of the columnar portal of the holy hall at the market gate of Priene in the Pergamon Museum, Berlin. Due to missing documentation and in the context of a structural condition assessment, it was necessary to determine the rear anchorage of the entablature and to verify the structural bond between the artificial stone and the original material in the architrave of the monument. The combined use of radar and videoscopy proved very efficient in conjunction with the determination of the type and position of the metal components of the rear anchorage of the entablature. The structural investigation of the architrave was accomplished by radar and radiography. The radar method was utilized to determine the overall position of the metal special fittings. Additional investigations by radiography using a new generation of digital imaging plates in the region between original marble and artificial stone showed an air gap, which was not visible from the outside. Furthermore, it was observed that two dowels from the marble reach into this gap, but are bent upwards and have therefore no static function. This led to the important conclusion that the load bearing capacity of the architrave and thus of the whole entablature is established exclusively by a continuous metal girder with a T-shaped profile.

1 Introduction

Beginning in 1875 the Berlin museums carried out several excavation campaigns near the Turkish coast, mainly in Pergamon, Priene and Magnesia, which lasted until the beginning of the 20th century. To exhibit the excavated objects in an appropriate environment, a new museum building in Berlin was planned and opened in 1930 as the Pergamon Museum. From the beginning the museum was designed to feature the full sized architectural objects. However, in recent years many defects of the museum building were recorded and repair was deemed necessary. Since many of the records documenting the objects in the museum were missing, or destroyed as a result of World War II, it was decided to carry out an assessment of the materials and condition of the objects before undertaking any intervention.

The investigation focused on a reconstructed portion of the holy hall at the market gate of Priene. This acted as a pilot study to prove the suitability of NDT-methods for this type of construction. The main task focused on the entablature, which is primarily reconstructed in reinforced artificial stone (Fig. 1).

The only original material in the architrave is one large marble block, complemented by artificial stone. The structural bond between the original material and the artificial stone was initially unknown, and the construction method for anchoring the cantilevered sima to the wall behind was unclear.

Since both data are necessary to reconfirm the structural stability of the monument, it was necessary to apply non-destructive inspection techniques in order to solve the following investigative problems:

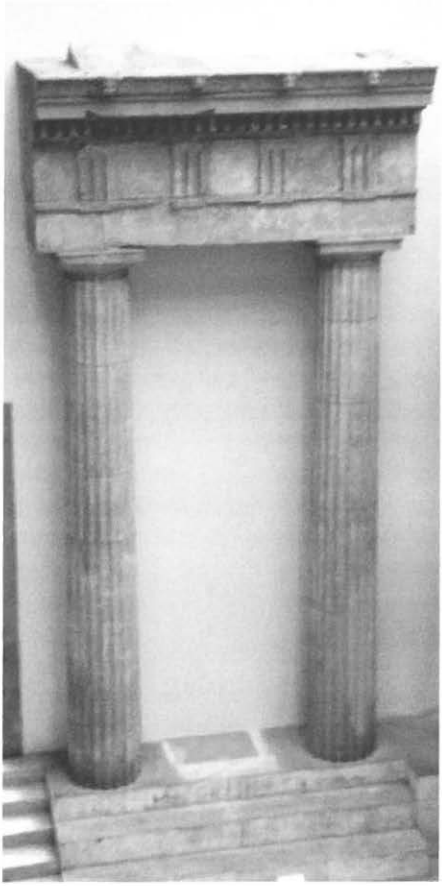


Figure 1. View of the columnar portal of the holy hall of the market gate of Priene.

- Determination of the type of rear anchorage of the heavily cantilevered cornice.
- Verification of the type of structural bonding between the artificial stone and the original marble in the architrave.

2 Investigative concept

To solve the investigative problems the non-destructive testing techniques represented in Figure 2 were applied.

2.1 Radar method

The radar method applied to both investigative problems enabled a first and fast global survey of the relevant parts of the building. It was successfully utilized for detection of metal reinforcements in the entablature. The measurement principle is based on the reflection of short electromagnetic impulses at material boundary layers with

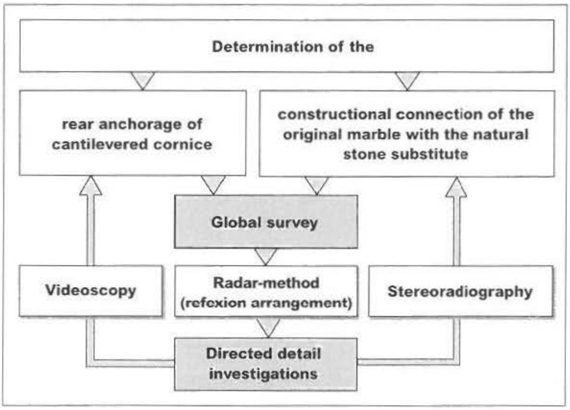
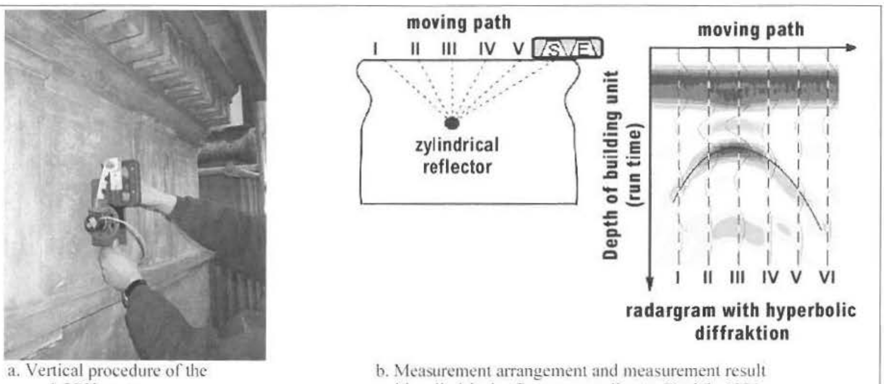


Figure 2. Investigative concept.

strongly different dielectric characteristics, as found in this case at the interface between marble/artificial stone and the steel reinforcements.

The measuring setup consisted of an integrated pair of 1.5 GHz antennas (including transmitter and receiver). The setup was chosen considering the thickness of the construction parts, the very low moisture content of the material, accessibility from three sides and the required high local resolution. For the actual measurement the antennas were guided by hand along a measuring grid on the surface of the specific parts. The results were then represented as radargrams, which coincided with the vertical and horizontal lines of the surface grid (Fig. 3a). In such a radargram the intensity of the reflected signals was represented over the moving path of the antenna versus the depth of the construction part (Fig. 3b). A cylindrical reflector (e.g. a round steel bar) appears, due to the opening angle of the antenna, as a hyperbolically shaped diffraction in the radargram.

The information of the radargrams can be substantially impaired because of superposition of many reflections, due to various inhomogeneities in the structural elements (e.g. cavities, change of material such as marble/ artificial stone, special metal reinforcements). According to experience, every now and then clear statements can not be made by using radar as a structural investigation method exclusively (DGZfP 2001). It is therefore recommended to amend the information gathered by radar by employing other non-destructive testing methods.



a. Vertical procedure of the 1.5GHz antenna

b. Measurement arrangement and measurement result with cylindrical reflector according to Daniels 1996

Figure 3. Measurement principle and practical application of the radar method in reflection arrangement.

2.2 Videoscopy

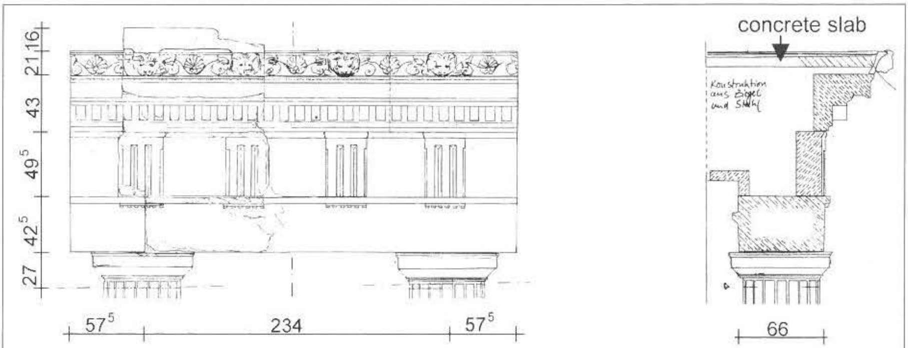
Interconnected cavities and voids behind the tryglyph frieze, the dentil course and the gaison allowed the use of videoscopy for analyzing the rear anchorage of the sima (Fig. 4).

The cavities were accessed by drilling a small hole into the concrete slab covering the entablature. Figure 5 provides a visual impression of the videoscopic observation on site.

2.3 Stereo radiography

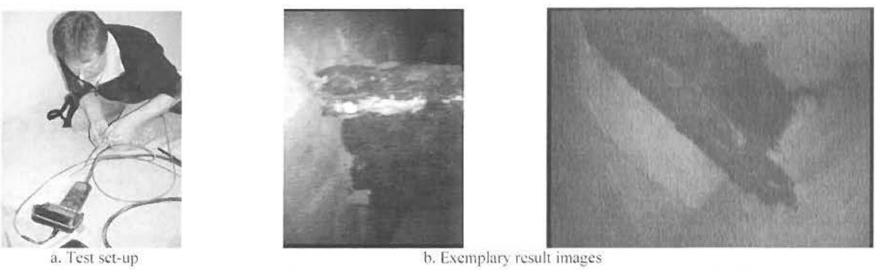
The analysis of the marble / artificial stone interface delivered an initial overall picture concerning the position of steel reinforcements in the architrave. In addition to radar, stereo radiography was applied in order to acquire detailed information about the exact position, dimension and shape of these reinforcements.

The technique of radiography is based on the attenuation (absorption) of ionizing radiation by differences in material density and the thickness of a construction element. Two radiographic images from different positions are needed (Fig. 6a). The reconstruction of the position and size of the metal parts is realized by a graphic or



a. Front view b. Cross section

Figure 4. Detail design of the entablature of the columnar portal.



a. Test set-up b. Exemplary result images

Figure 5. Realization of the videoscopical observation of the anchorage at the cantilevered sima.

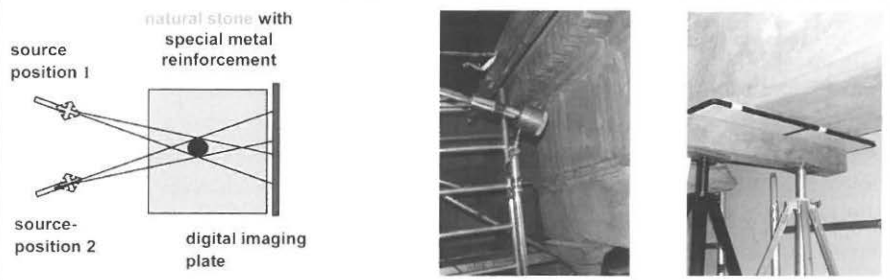
computer aided back projection technique. Figures 6b and 6c show a typical arrangement of the radiographic method.

Considering the material thickness, a γ-emitter, the radio nuclide Co-60 with an activity of 35 Ci, was used as a primary radiation source. The detector system consisted of digital imaging plates (Ewert et al. 1996) with a lead-tin intermediate filter for the reduction of the contrast reducing scatter radiation. The exposure time is comparable to a fluorescent screen film system and amounted up to 2.5 h depending on the wall thickness.

3 Results and their evaluation

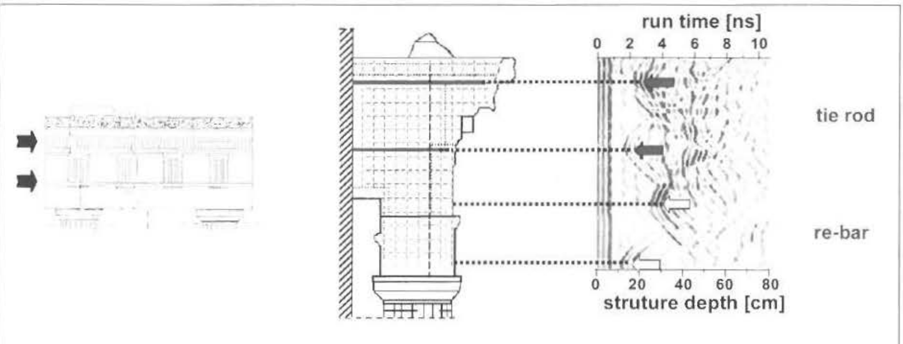
3.1 Rear anchorage of the cantilevered cornice

Figure 7 shows an example of a radargram, obtained by moving the radar antenna along a vertical line of the measuring grid on the side elevation of the entablature. The two upper diffractions were caused by horizontal running tie rods and the lower by horizontal running reinforcing bars.



a. Principle sketch according to DGZfP 1990 | b. Positioning of the radiation source (Co-60) | c. Computed radiography technique (CRT)

Figure 6. Measurement principle and practical application of the stereo radiography



a. Investigated side of the entablature | b. Side view of the entablature with measurement grid | c. Radargram of a vertical measurement line

Figure 7. Selected results of the radar investigations with a 1.5 GHz-antenna pair.

The videoscopy permitted an exact verification of the cross sectional shape of all tie rods. Altogether steel profiles with L- and U-shapes as well as flat steel bars were used. (Fig. 8).

3.2 Structural bonding of the original marble in the architrave

Figure 9 illustrates an exemplary radargram with two different diffractions. The radargram has been measured by moving the antenna along a vertical line of the grid applied to the front of the entablature. The upper diffraction suggests a large surface parallel reflector (back wall of the frieze plate) and the lower a geometrically clearly smaller reflector (metal reinforcing bar). Since all the radargrams along the vertical grid lines on the front of the entablature differ only slightly from each other (with the exception of the boundary region), it can be concluded that the metal profile must run continuously through the architrave. This is also confirmed by the radargrams from the underside of the architrave (Fig. 10). Here metal dowels can be recognized in the area between original marble and artificial stone. However, their exact position, shape and dimensions cannot be determined by radar only. The same applies to the shape

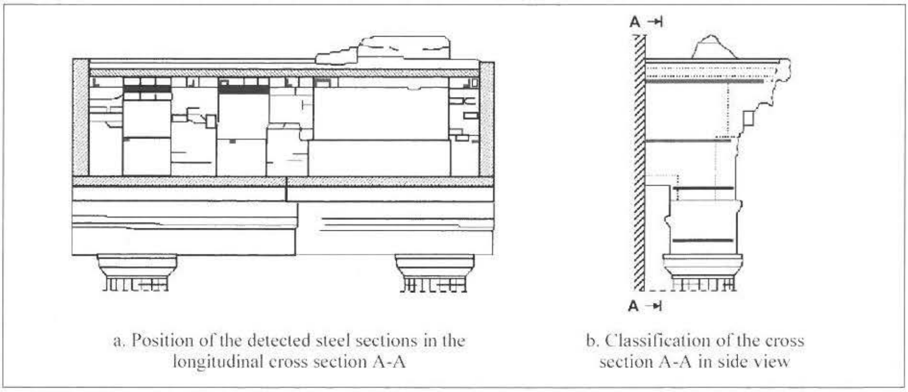


Figure 8. Result of the videoscopic investigations.

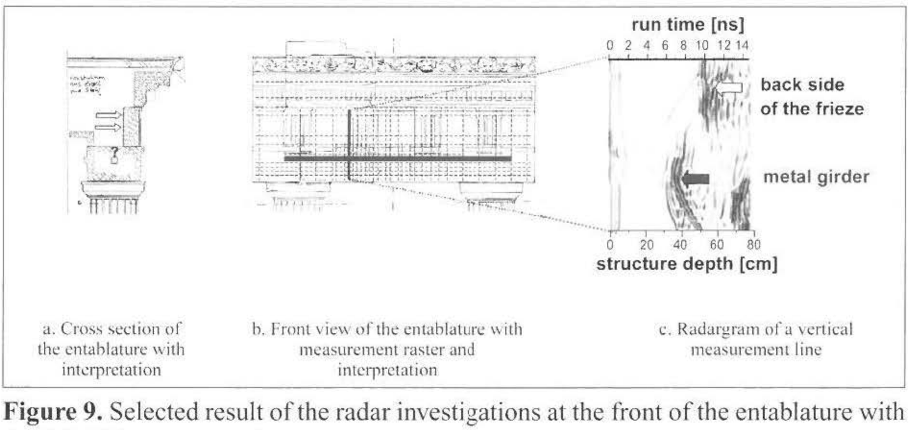


Figure 9. Selected result of the radar investigations at the front of the entablature with the 1.5 GHz-antenna pair.

and dimensions of the continuous metal girders in the architrave. The results from stereo radiography of selected areas provided more in depth information concerning these issues.

These are described by the examples provided by Figures 11 and 12. In the grayscale images bright areas indicate high material density and/or greater thickness of a structural element. Dark areas represent the opposite. The grayscale image of Figure 11, which was obtained by the external arrangement of the radiation source, illustrates the presence of a gap between the original marble and the artificial stone. In addition, parts of the metal bars and girder passing through the architrave could clearly be recognized. It was evident that the dowels extended only into the original marble and not into the artificial stone. This led to the important conclusion that the dowels do not tie the marble to the artificial stone.

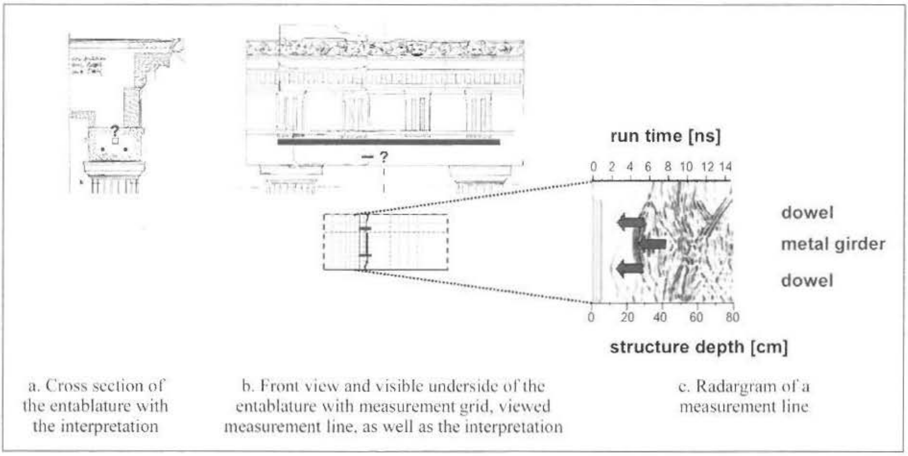


Figure 10. Selected result of the radar investigations at the underside of the architrave with the 1.5 GHz antenna pair.

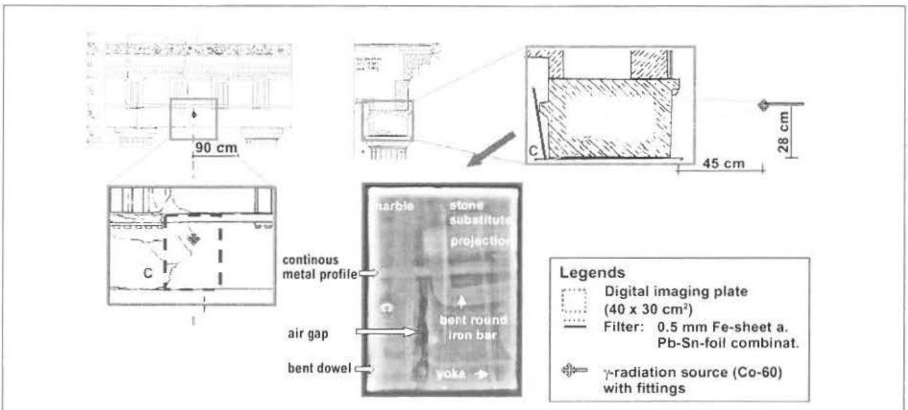


Figure 11. Result of the radiography on a selected measurement point with external positioning of the radiation source.

The grayscale image of Figure 12 was acquired by positioning the radiation source in the entablature internally. It shows the exact position and shape of the dowel in the interface of marble and artificial stone: the dowels are embedded into the marble with mortar and are bent outward, not locking into the artificial stone. The geometry of the measurement arrangement and the resulting radiograms also allowed for detection of a T-shaped profile for the girder, which runs through the architrave.

Figure 13 shows in summary the exact spatial position of all non-destructively determined reinforcements in the architrave with their shapes and dimensions.

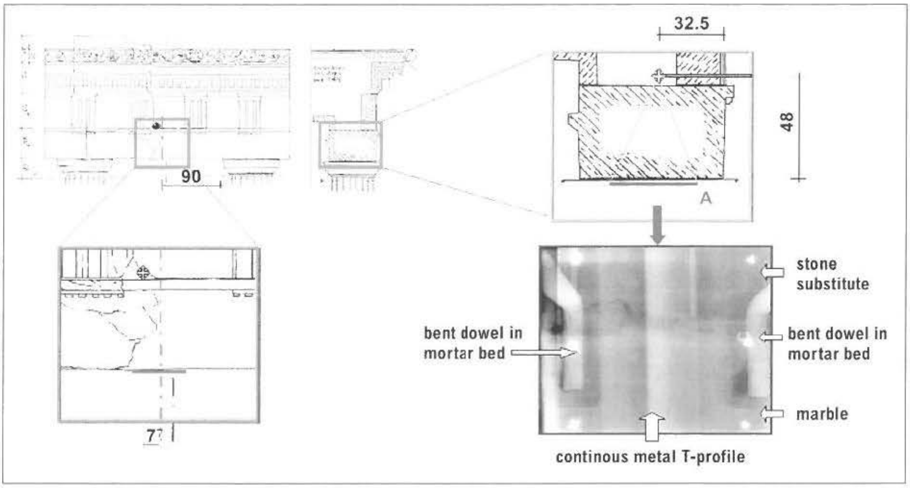


Figure 12. Result of the radiography on a selected measurement point with internal positioning of the radiation source.

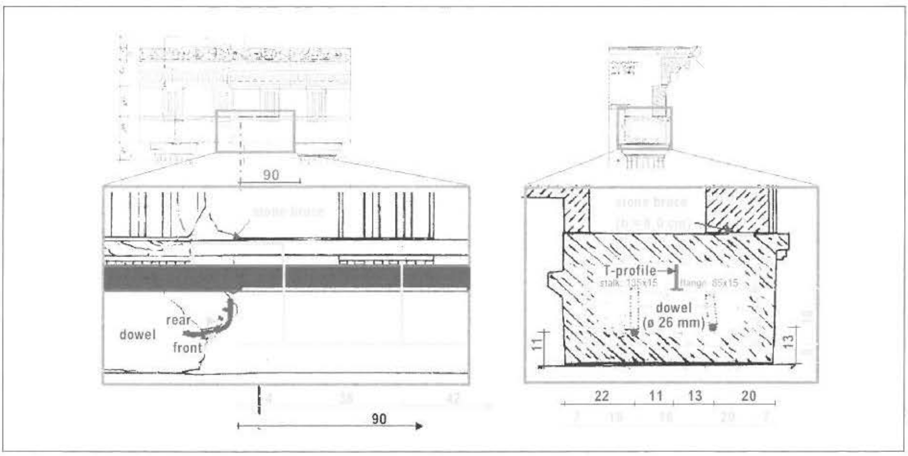


Figure 13. Reconstructed position of all metal reinforcement in the architrave as a summary of the application of non-destructive testing methods.

4 Conclusions and Summary

Both, the type of rear anchorage of the heavily cantilevered sima and the nature of the mechanical bonding between the artificial stone and the original marble in the architrave, could be determined in detail by the combined application of different non-destructive testing methods. The following test methodology worked satisfactorily in practice:

1 Preliminary global investigation by radar
2 Purposeful in depth analysis, depending on the investigative problem, by:
   - Videoscopy (In the case study: type of the rear anchorage of the cantilevered sima).
   - Radiography (In the case study: mechanical bonding between artificial stone / original marble in the architrave).

The following useful information for the structural integrity of the monument could be communicated to the structural engineer:

- Type and position of the steel sections for the rear anchorage of the sima.
- Confirmation of the load bearing capacity of the architrave, which is established primarily by a continuous T-shaped steel girder (dimensions were determined).
- The presence of an air gap in the architrave at the interface of marble and artificial stone.
- No actual connection between the original marble and the artificial stone, since the dowels protruding from the marble were bent upwards into the gap.

5 Acknowledgement

We express our thanks to the ARGE Pfanner at the Pergamon Museum for the interesting task assignment, and to the Federal Office for Building and Regional Planning for the financial support of the study. Furthermore we would like to thank the colleagues of the ‚Non-destructive Testing and Characterization', ‚Radiographic Methods' and ‚Building Materials' divisions at the Federal Institute for Materials Research and Testing (BAM) for the effort expended and participation during nightly measurement sessions and Gabi Patitz from the Engineering Office for Building Diagnostics, Damage Analysis and Structural Design (IGP). Last but not least we want to thank Mary Hardy from the Getty Conservation Institute in Los Angeles, for proof reading the manuscript.

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