Structural evaluation of historic walls and columns in the Altes Museum in Berlin using non-destructive testing methods

C. Maierhofer, M. Hamann, C. Hennen, B. Knupfer, M. Marchisio, F. da Porto, L. Binda & L. Zanzi

Federal Institute for Materials Research and Testing (BAM), Berlin, Germany
Institute for Applied Science in Civil Engineering (laFB), Berlin, Germany
Stiftung Luthergedenkstätten in Sachsen-Anhalt, Lutherstadt Wittenberg, Germany
GEOClSA, Research and Development, Madrid, Spain
University of Pisa, Dept. of Civil Engineering, Pisa, Italy
University of Padova, Dept. of Construction and Transport, Padova, Italy
Politecnico di Milano, Dept. of Structural Engineering, Milano, Italy

ABSTRACT: The methodologies developed in ONSITEFORMASONRY were applied to assess the structure and material properties of selected structural elements in the Altes Museum in Berlin-Mitte. Since at all times the Altes Museum was of great concern in the archival studies, a lot of information exist about former destruction and restoration which support the interpretation of data recorded with the different testing methods.

1 INTRODUCTION

Analysing the damages and other problems affecting historical constructions for their structural evaluation, methodologies based on the application of non-destructive (NDT) and minor destructive (MDT) testing methods have been designed during the ONSITEFORMASONRY-project according to the type of damage or problem, the construction typology, the level of assessment and the environmental conditions. These methodologies are being applied on real cases like the Altes Museum in Berlin for their validation.

The Altes Museum (old museum) in the city centre of Berlin was designed by Karl Friedrich Schinkel and was built between 1823 und 1830 on the Lustgarten. Figure 1 shows a view from the Lustgarten. The building was designed with an atrium containing pillars and a central cupola related to the Roman Pantheon and having antique temples as an archetype. It represents the eldest exhibition hall in Berlin. During the Second World War parts of the Altes Museum burned down, and it was rebuilt in 1966.

In 1999, the planning stage started for a broad reconstruction in the frame of a master plan concerning the whole Museumsinsel (museum island) taking into account contemporary requirements for a museum building. Extensive investigations have to be performed to assure structural integrity and to provide a basis for a sustainable and considerable conversion of the building.

At all times the Altes Museum was of great concern. Thus archival studies of the Technical University of Berlin provided a lot of information about the structure. These studies are of fundamental interest for ongoing NDT and MDT in the frame of the European Research Project ONSITEFORMASONRY.

With radar, geoelectric, microseismic, sonics, impulse-thermography and flat-jack, different testing problems have been solved which are described in more detail below.

2 OBJECTIVES

The Altes Museum has been chosen as pilot site because several questions are also typical for other historic structures in general. In the frame of reconstruction, testing problems mainly occur related to
the inner structure of different structural elements like columns, floors, ceilings and walls. In this paper, the following objectives have been analysed (see also Figure 2):

- Investigation of the inner structure of the outside columns in the entrance hall of the museum. Here, the outer column located at the west part of the entrance hall was selected for solving the following questions: How are the single drums connected to each other? Is it possible to locate the different materials used for restoration at the cylindrical shell? A scaffold was raised for performing measurements along the whole length. Radar and ultrasonic investigations in reflection as well as in tomographic mode had been planned.

- Localisation of plaster delaminations at the columns in the rotunda. These columns belong to the original asset from 1830. The columns consist of massive sandstone which is covered with lime plaster having a thickness of 2 to 3 cm. This plaster is the carrying layer for the visible stucco marble layer of 3 to 6 mm. The sandstone core is massive and it is expected that it consists of single drums. The whole surface of the columns is covered with a net of small cracks. The cracks are very thin, but few of these have a width of up to 2 mm. By knocking on the surface, different types of delaminations can be accessed: Delaminations of the stucco marble layer, delaminations of the plaster and a combination of both. One column (no 14) had been selected for investigations with impulse-thermography to locate and quantify these delaminations.

- Investigation of the structure and moisture content of an inner carrying wall in the cellar. The foundation of the Altes Museum is based on wooden piles, which have been positioned in a dense grid. The top of these piles is covered with wooden frame constructions. These are the basis for the foundation consisting of natural lime stone. The walls constructed on this basement are made of bricks. Only parts of the building have a cellar. The level of the ground water is at 31 mNN (normal level), while the floor of the cellar is at approx. 31.71 mNN.

Therefore, at least the basement consisting of natural stone is exposed to moisture. The inner carrying wall which was selected for the investigations is accessible from both sides, one side is covered with mortar. From the floor up to a height of 70 cm, the wall consists of a pedestal made of lime stone. Above the pedestal, there is still stonework made of lime stone up to a total height of 2.0 m. The connection to the ceiling was closed by two to three layers of brickwork. At both sides of the wall, there are wall porches which are connected to the wall. At the side without mortar, the wall shows a crack with widths from 0.5 to 3 cm at the area close to the outer wall. The crack follows the steps of the joints from the lower edge of the ceiling down to the floor. For the investigation of the inner structure, for the determination of the moisture distribution and for analysing the load measurements, investigations had been performed at this wall with radar, geoelectric, microseismic, sonic tests and flat-jack.

- Structural investigation of the sandstone ring. Figure 3 shows the assumption of the architects regarding the existence of a stone ring embedded inside the brick masonry structure supporting the dome. The objective of the investigations was to validate this assumption and to derive as many information as possible regarding the morphology of the ring. Thus, radar measurements had been carried out in reflection mode.

3 METHODOLOGIES

3.1 Radar

Radar is based on the transmission of short electromagnetic impulses by an antenna at frequencies between 300 MHz and 2.5 GHz (Daniels, 1996). These impulses are reflected at interfaces with changing dielectric properties of the materials. Also the propagation velocity depends on the dielectric properties. Since moisture is influencing this parameter, radar can also be applied to detect an enhanced moisture content.
and to determine the moisture distribution. With radar, reflection measurements from one surface as well as tomographic measurements from both sides are usually performed to obtain information about the internal structure of the structural element under investigation (Maierhofer et al., 2000; Colla et al., 2000; Maierhofer et al., 1998).

3.2 Sonics

Sonic tests consist in transmitting stress waves within the frequency range of acoustic waves (20 Hz to 20 kHz), generated by an instrumented hammer, and in measuring their travel time by means of accelerometers. For given masonry typologies it is possible to find a relationship between the sonic velocity and the elastic properties of masonry (Riva et al., 1997).

In general, sonic tests can be applied to get qualitative information on the morphology, consistency and state of conservation of masonry (Berra et al., 1992; Abbaneo et al., 1996). Besides direct and indirect tests, carried out through the thickness or on the same side of the wall, also sonic tomographies can be performed. In that case, the measures of sonic pulse velocity are combined along different ray-paths on a cross section of masonry, and are subsequently processed in order to define mean values of velocity on each portion of the wall section itself (Valle et al., 1998; da Porto et al., 2003).

3.3 Geoelectric

The geoelectrical tomography is the reconstruction of the distribution of the electrical resistivities in the body of a structure obtained by current injections across many different couples of electrodes.

Two different methods can be used: transparency tomographies or inverted pseudo-sections when only one side of the structure is accessible.

The transparency tomographies use an experimental disposition of the electrodes corresponding to the cross-hole tomography in the subsoil: in this case 2 series of electrodes are fixed along 2 profiles on the opposite faces of a masonry structure. The electrodes are connected in different combinations, performing a high number of measurements (typically several hundreds). The cross-section covered by the ray paths is ideally divided into a number of cells (pixels). Their resistivity is computed by means of complex iterative routines. The numerical output (resistivity of each cell) must be converted into an image of the distribution of the velocities in the cross-section to render it usable.

Another technique, the inverted pseudo-section, uses only one profile with many electrodes on one face of the structure. Measurements are made with the technique of the so-called resistivity pseudo-sections by connecting 4 electrodes at a time with one of the typical arrays used in geoelectrics. A high number of measurements (several hundreds) is performed. The measured data, namely the apparent resistivities, can be directly plotted versus some kind of pseudo-depths to build the so called pseudo-sections. These are purely qualitative images.

By means of a complex inversion process, the distribution of true resistivities versus true depth can be obtained, that is, another kind of geoelectrical tomography. This is sometimes referred as the impedance tomography.

In both cases multi-electrode (24, 48 or more) automatic switching geo-resistivity-meters are necessary. Very high quality instruments are required. A particular care must be taken to ensure a good electric contact of the electrodes with the surface of the wall (Marchisio et al., 2000; Cosentino et al., 1998; Marchisio et al., 2002).

3.4 Impulse-thermography

Impulse-thermography (IT) is an active approach for a quantitative thermal scanning of the surface of various structures and elements. A thermal pulse is applied to a surface causing a non stationary heat flow. During the cooling-down process the emitted thermal radiation is observed with an infrared camera. The propagation of the heat into the body depends on material properties like thermal conductivity, heat capacity and density of the inspected object. 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 (Maierhofer et al., 2002).

A relatively new approach of IT is the pulse phase thermography (PPT) (Vavilov et al., 1998; Maldague et al., 1996; Maldague, 2001). The stored data received during the IT is analysed in the frequency domain via Fast Fourier Transformation of the transient curve of each pixel in a series of thermal contrast images. This leads to changes in amplitude or phase of the corresponding images. The main advantage of PPT lies in the phase images, which are reported to be less influenced by surface infrared and optical characteristics. That also means less sensitivity to non-uniform heating compared with the thermal contrast images of IT (Maldague, 2001).

3.5 Single and double flat-jack

The objective of the flat-jack test is to obtain the local state of stress in compression of a masonry element that works under vertical stress. The method is based on stress release.

The general procedure of this test consists on restoring the vertical displacement caused by a horizontal slot made in a loaded masonry. The distance between three or four points fixed across the slot is measured by gages before and after cutting. The device used to restore the displacement is a flat-jack; oil is pumped
in the jack until the distance between the gage points is restored to the initial situation.

In order to obtain the local state of stress, the restoring pressure has to be corrected taking into account two coefficients that depend on the mechanical characteristic of the flat-jack, calibrated in laboratory, and on the relation between the geometry of the slot and the shape of the flat-jack.

A double flat-jack test is carried out by two flat-jacks inserted in two parallel slots at a convenient distance and pumping oil into both so that a compression test is performed. In fact, the two jacks delimit a masonry sample of appreciable size to which a uni-axial compression stress can be applied. Measurement bases for removable strain-gauge or LVDTs on the sample face provide information on vertical and lateral displacements. Several unloading and re-loading cycles can be performed at increasing stress levels in order to determine the deformability modulus, an important parameter in the masonry classification (Binda et al., 2004). It is interesting to compare these last results to the stress level measure in order to verify the actual state of the masonry in relation with its potentialities (Binda et al., 1999).

4 RESULTS

4.1 Structure of columns in the entrance hall

4.1.1 Radar

For getting an overview four evenly distributed traces in direction of the longitudinal axis (vertical) of the selected column were recorded with the 900 MHz antenna along the whole height (10.2 m). A measuring wheel mounted to the antenna performed measurement triggering and recording of the path. Figure 4 shows one of these radargrams. Clear signals related to the surface and to the backside reflection can be detected. The travel time of the backside echo increases when going from top to bottom corresponding to an increase of the diameter of the column. Close to the surface reflection, hyperbolas occur representing the reflection of the joints between the different drums. Due to the high intensity of these reflections, it is assumed that these joints contain plumb layers that were used as a non-seizing compound for the alignment of the column drums.

For detailed investigations on the joints between the drums, horizontal traces at different areas close and far from the joints were recorded. The measurements were performed radial along the surface of the column with the 1.5 GHz antenna. One of these radargrams below a joint is shown in the bottom of Figure 5. Due to the cannelures the backside reflections appears in a wave-like shape. Noticeable reflections can be detected at a depth between 70 and 75 cm. The position and intensity of this reflection is changing with the angular position of the antenna around the column (trace of antenna: 360°). The reflections at opposite antenna positions (180°) are similar. From this reflection profile it can be concluded, that in the middle of the drum below the joint, a rectangular hole exists (with a length of ca. 7 to 10 cm and a width of 2 to 3 cm) which was used for
mounting, see figure 5, top. This hole was only located at the top of each drum and was presumably used for mounting and alignment of the drums. There were no hints to metal compounds as pins between the drums, only this lead dies.

It was also possible to locate the restored areas, but the thickness of the replaced structures could not be resolved.

4.1.2 Sonics

On the same column, also a sonic tomography was carried out in order to check the distribution of different materials. A horizontal section, 1.10 m high from the level of the entrance floor and 0.10 m above the lower ashlar, was chosen for the sonic tomography (Figure 6, left and tomo 3 in Figure 4, left). A very simple acquisition grid with six points located on the outer perimeter of the column was chosen to carry out the tests. Three measurements per point have been recorded and they were subsequently processed with software purposely developed in Visual Basic 6 and based on the theoretical non rectilinear propagation of elastic waves. The investigated section was divided into nine large square pixels.

The tomographic reconstruction gave uniform values of velocity in the section, with velocities included between 2330 and 2540 m/s (about 8% scatter, Figure 6, right). The lowest values of velocities were actually located around an area restored with a pigmented mortar after the bombing that damaged the columns.

No other differences were found in the column composition, such as the presence of large inner core, etc. It has to be noted that a higher number of transmitting/receiving points, in order to have the cross section more densely investigated, would have improved the accuracy of the obtained results. The sonic tomography allowed detecting areas built with different materials (macroscopic phenomena consistent with the tested cross section dimension) but its resolution is too low, also in terms of wavelength, to detect the position of small iron fasteners or minor irregularities.

Figure 6. Investigated column (left), tomographic reconstruction of the section (right).

Figure 7. Photo (left) and phase image (right) of the same area of the column after a heating of 5 min. The delaminations appear in the phase image as dark areas.

4.2 Plaster detachments at columns in the rotunda

4.2.1 Impulse-thermography

The experimental set-up consists of a thermal heating unit, an infrared camera and a computer system, which enables digital data recording in real time. For the heating of the surface of the columns a conventional electric fan heater has been used with a heating power of 2000 W avoiding temperatures at the surface higher than 50°C. The infrared camera is an Infraometrics SC1000 with a PtSi-focal plane array detector with a resolution of 256 vs. 256 pixels. It detects the emitted radiation in a wavelength range from 3 to 5 μm. For accessing all parts of the column, a lift was used. Large areas with delaminations appear in the lower parts of the column as demonstrated in the dark parts of the phase image in Figure 7 right after 5 min of heating. From comparisons with results obtained at test specimens with different mortar thickness in the laboratory, it is assumed that these delaminations belong to the stone/mortar interface. But this assumption was not proved with destructive tests.

4.3 Properties of a carrying wall in the cellar

For the investigation of the structural and material parameters of the inner carrying wall in the cellar (plan view in Figure 8, part of the wall with a large crack is shown in Figure 9), several tomographic and indirect and direct transmission investigations had been performed with sonics, microseisminics, geoelectric and radar. Flat-jacks had been applied at four positions as shown in Figure 8.

4.3.1 Sonics

Direct sonic tests were carried out on two positions of the load bearing wall in the cellar (P1 and P2 in Figure 8). In correspondence to the flat-jack tests, the tests were carried out on a 6 × 8 grid (six rows and eight columns, 15 cm × 15 cm) of transmitting/receiving points, for a total of 48 points. The thickness of the wall was 1.71 m. A single measurement per point has been
Figure 8. Part from the plan view of the cellar showing the cross-section of the investigated inner wall and the different measurement positions. P1, P2: Direct sonic tests. R1 to R5: Microseismic profiles. T1 to T5: Geoelectric profiles. BAM1, BAM2: Radar tomography profiles. AMJ1S to AMJ3S: Single flat-jack by Polimi. AMJ2D: Double flat-jack by Polimi. FJ01 to FJ04: Single flat-jack by Geocisa.

Figure 9. Part of the investigated inner carrying wall in the cellar showing a large crack. The arrows mark the position of the radar traces for tomography.

Figure 10. Sonic velocity distribution as obtained from direct tests at position P1.

Figure 11. Sonic velocity measured in direct tests on test area P1 and P2 versus height from floor.

4.3.2 Microseisms

Seismic velocity profiles were performed on the basement wall of the cellar in five positions (R1 to R5 in Figure 8).

Some examples of seismic velocity profiles are shown in Figure 12.

The figures show the so-called dromochrones, that is the arrival times for a single shot plotted versus the distances from the shot point. The slope of the straight parts of the dromochrones are the reciprocal of the propagation velocity of the micro-seismic waves.

also in other tested area in the cellar. The mean values of direct sonic measurements taken at different heights on the cellar wall are shown by Figure 11.

The values of sonic velocities are typical of masonry in fair good/good condition (Berra et al, 1992; Forde et al, 1985). With similar thickness, multi-leaf stone masonry walls with internal filling with poor mechanical properties, internal voids and detachment of the external layers, in bad conservation condition, usually give lower values of velocity (Riva et al, 1997).

recorded. The velocities ranged between 1600 and 2600 m/s, with a high scatter (38%), about 1000 m/s. The results of position P1 are presented in Figure 10.

The mean value is 2150 m/s. The upper part of the tested area presented lower velocities and the lower part of the tested area was characterised by higher values. This might be related to higher moisture content in the bottom of the wall, considering that the presence of moisture results in apparent increases of sonic velocity (Riva et al, 1998). This trend was observed
The velocities of the elastic (or seismic) waves in a homogeneous body depend on the elastic properties of the body and on its density.

The propagation velocity of the pressure (longitudinal) waves, $V_p$, is given by:

$$V_p = \sqrt{\frac{\lambda + 2\mu}{\delta}} = \sqrt{\frac{E(1-\nu)}{\delta(1+\nu)(1-2\nu)}}$$

while the propagation velocity of the shear (transversal) waves, $V_s$, is given by:

$$V_s = \sqrt{\frac{\mu}{\delta}} = \sqrt{\frac{E}{\delta}} \cdot \frac{1}{2(1+\nu)}$$

where $\lambda$ and $\mu$ are the constants of Lamé; $E$ is the Young modulus; $\nu$ is the modulus of Poisson; $\delta$ is the density.

The elastic moduli can be derived from the velocities and density. These elastic moduli are referred as **dynamic elastic moduli** as they refer to very small stress and deformations, while the static values are measured with much higher values.

If both $V_p$ and $V_s$ are known, the Poisson ratio can be computed:

$$\frac{V_p}{V_s} = \frac{2(1-\nu)}{1-2\nu}$$

All the velocity profiles are well consistent. Velocity values are high (from 2400 to 2800 m/s). These values correspond to dynamic elastic moduli values of 80000–110000 DaN/cm² (Gucci et al, 1997; Marchisio et al, 2002).

Figure 12. Velocity profiles recorded with microseisms.

Figure 13. Left: Electrode array for geoelectrical measurements. Right: Reconstructed electrical resistivity distribution in the wall calculated from geoelectrical measurements (T2).

4.3.3 **Geoelectric**

Electrical tomographies were performed on the basement wall of the cellar at five positions. There are 4 vertical electrical tomographies (from T1 to T4) and 1 horizontal electrical tomography (T5) (Figure 8).

In Figure 13, the geoelectric measurements at T2 are shown together with the reconstructed tomogram. In the lower part, the material is relatively more conductive. Probably this is due both to change of material and presence of moisture.

4.3.4 **Radar**

Radar measurements in transmission mode were performed along the two traces marked in Figure 9 using two 900 MHz antennas (BAM1 and BAM2 in Figure 8). The transmitting antenna was placed at the wall in a fixed position, while the receiving antenna was moved along the measuring trace on the opposite side of the wall from left to right with constant velocity. The next measurement was carried out with the sending antenna shifted of about 10 cm. The measurement was then completed in a similar way (shifting of transmitter after each trace) with a total of 15 sending positions.

The data were reconstructed by TOMOPOLI (Valle et al, 1998). The respective velocity distributions are shown in Figure 14. The velocities in the lower tomogram are lower than in the top tomogram which might be related to a higher moisture content in the bottom of the wall. In both tomograms, two areas with higher velocity can be recognised being perpendicular to the $x$-axis and parallel to the $z$-axis. The position of these areas can be correlated to the position of the crack as shown in Figure 9. In the area of the crack, there might be several voids which have a higher penetration velocity for electromagnetic waves.
Figure 14. Reconstructed horizontal velocity distribution along the cross section of the basement wall. Top: Profile along the top trace (BAM1). Bottom: Profile along the bottom trace (BAM2). The values are in $10^{-1}$ m/ns.

4.3.5 Flat-jack

Polimi and Geocisa carried out several single flat-jack tests localised at 4 positions at the inner carrying wall and at the outside wall as shown in Figure 8.

The test procedure used by Polimi was performed according ASTM test (ASTM, 1999) (AMJ1S, AMJ2S, AMJ2D, AMJ3S) taking into account 4 measurement points and cutting in the mortar joint.

Geocisa single flat-jack tests (FJ01 to FJ04) follows an own developed procedure also based on ASTM, but modifying some testing conditions for a faster and friendly use equipment: at each position, three gage points are placed centred in the future slot as the flat-jack has smaller dimensions and the cut is performed in the stone assuring good contact conditions between the flat-jack and the masonry (stone). To guarantee a correct measure the surface of the wall is arranged and points are fixed with a rigid adhesive. The initial distance between gage points is the reference measure to achieve the test. The control of the gage displacement was done with a mechanical extensometer with an accuracy of 0.001 mm. The slot was made with a diamond circular saw (radius 115 mm), the cutting was guided to ensure a horizontal plane using a platform fixed to the wall (see Figure 15).

The flat-jacks used in both procedures have circular shapes. In the first case, the size was $350 \, \text{mm} \times 250 \, \text{mm} \times 4 \, \text{mm}$, with a calibration factor of 0.88 and a geometrical factor of 0.93. In the second procedure, the length of this flat-jack is 211 mm, the depth is 70 mm and it is 3 mm thick. The calibration constant was determined at laboratory and the value obtained is 0.5. The geometrical factor is 1.0 because the prepared slot has the same shape as the flat-jack.

After cutting the slot the distance between gage points was measured, obtaining a closing movement. The flat-jack was introduced into the slot as shown in Figure 15, increasing gradually the internal pressure while the distance between gage points is controlled until the distance is restored to the reference measure.

The use of a flat-jack of smaller dimensions allows the testing of elements of smaller dimensions as columns.

Figure 16 shows the results of the single flat-jack test carried out by Polimi. The recovery of the slot displacements was reached in all the measuring points, almost at the same stress.

A double flat-jack test (AMJ2D) was carried out by Polimi at the inner carrying wall as shown on figure 8 according to ASTM (ASTM).

The results are summarised in Table 1.

The stress–strain diagram of the double flat-jack test AMJ2D (not shown here) demonstrates the good
Figure 16. Results of the flat-jack tests carried out according ASTM (AMJ2S).

Figure 17. Cross-sections of the 3D radar data showing two main reflections at about 45 and 80 cm.

5 CONCLUSIONS AND OUTLOOK

5.1 Structure of columns in the entrance hall

With radar, the joints between the drums could be located very easily. The high intensity of these reflections could be related to possible plumb layers between the joints as non-seizing compound. Related to the connections between the single drums, metal compounds like pins could be most probably excluded. At the top of each column, a rectangular hole is expected which was used for mounting and alignment of the drums.

With radar reflection as well as with sonic tomography, the repaired areas could be located. But it was not possible to determine the depth of these structures. The uniform values of sonic velocities vary between 2330 and 2540 m/s. The lowest areas of velocity were located around a repaired area.

5.2 Plaster detachments at columns in the rotunda

With impulse-thermography, it was possible to detect delaminations which are most probably related to the stone/mortar interface. But this assumption was not proved with destructive tests. Also, it is planned to compare the experimental results with numerical simulations.

5.3 Properties of a carrying wall in the cellar

The main objectives of the multifaceted investigations of the carrying wall in the cellar were the analysis of the inner structure and the moisture content. As NDT and MDT methods radar, sonics, microseisms, geoelectric and single and double flat-jack have been combined.

Related to the internal structure, the sonic investigations resulted in acoustic velocities between 1600 and 2600 m/s with a mean value of 2150 m/s. With microseisms, velocities between 2400 and 2800 m/s were

characteristics of the masonry in terms of compressive strength and elastic properties.

4.4 Stone ring reinforcement in the dome

The radar experiment was planned in a position of a corridor where the supposed stone ring should be quite close to the internal wall (Figure 3).

4.4.1 3D radar

For a more reliable interpretation of the radar images, the experiment was executed in 3D mode by collecting a number of dense parallel profiles on an area of about 80 cm x 80 cm. The data were processed with a 3D software obtaining a 3D data volume that confirms the existence of the stone ring (Figure 17). The two reflections observed at about 45 and 80 cm were respectively interpreted as the reflection from the stone ring and from the interface separating the first and the second stone layer of the structure. A hole was also drilled in the position where the stone ring should be closer to the corridor wall and a sandstone block was actually found behind a 50 cm brick wall.

<table>
<thead>
<tr>
<th>Position</th>
<th>Single flat-jack AMJxS</th>
<th>Local state of stress (N/mm²)</th>
<th>Single flat-jack FJx</th>
<th>Local state of stress (N/mm²)</th>
<th>Double flat-jack AMJ2D</th>
<th>Young modulus (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.13</td>
<td>1.50</td>
<td></td>
<td></td>
<td></td>
<td>33900</td>
</tr>
<tr>
<td>2</td>
<td>0.96</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.79</td>
<td>0.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>–</td>
<td>0.7</td>
<td></td>
<td></td>
<td></td>
<td>–</td>
</tr>
</tbody>
</table>
obtained. These values are typical for fair good/good condition of masonry. But it should be regarded that these are mean values over the whole cross section, thus only an averaged parameter is given. At the bottom of the wall, the sonic as well as the microseismic investigations give higher velocities in comparison to the results at the top. This might be explained by a higher load and/or by a higher moisture content.

The radar tomograms appear homogeneous, some readings could be related to the crack at this area. The radargrams recorded in reflection configuration and not presented here showed a more or less inhomogeneous structure related to stones having different size and inhomogeneous joints.

The single flat-jack tests show mainly the same stress at all positions. The stress strain diagram of the double flat-jack investigation demonstrate good characteristics of masonry related to compressive strength and elastic properties. A load set of the museum by a simple engineering method gave significant differences to the stress results of the single flat-jack tests. The local determination of the elastic modulus by double flat-jack gave comparatively high values (33000 N/mm²). An additional investigation by endoscopy has shown differences in the masonry conditions over the depth. Due to the high measured values of the elastic modulus in the outside part of the wall and the results of endoscopy it is to assume a concentrated load distribution over the wall section.

A simplified 3D linear elastic FE model of the west wing of the museum is under development. On the bases of the NDT tests carried out, it is possible to make some assumptions for a more reliable modeling of the structure. The model can be calibrated on the bases of the flat-jack tests results. It will be thus possible to simulate the behavior of the structure and simulate the presence of possible interventions.

Information about the moisture situation could be gained from geoelectric and radar measurements. The results of the geoelectric measurements give a higher conductivity at the bottom of the wall. This is consistent with the horizontal radar tomograms, which showed lower velocities in the lower part. Both readings can be correlated to a higher moisture content at the bottom of the wall. At the height of the lower radar tomogram, small cores (12 mm in diameter) were extracted and the moisture content was determined by weighting. At depth between 0 and 30 cm, a moisture content from 0 to 2 Vol% (moisture content relatively to the total volume) was determined. This increases up to 10 Vol% at depth deeper than 30 cm.

5.4 Structural investigation of the sandstone ring

With 3D radar, the sandstone ring was investigated in horizontal direction from the outside of the dome on an area of about 80 cm × 80 cm. It was possible to observe reflections at depth between 45 and 80 cm, which could be related to the reflection from the stone ring and from an interface separating the first and second stone layer. Videoscopic investigations of a borehole in this area should the beginning of the sandstone at a depth of about 50 cm (behind a 50 cm thick brick wall).

ACKNOWLEDGEMENTS

This work was funded by the European Commission under the 5th Framework Program.

For the assistance in preparation of the measurement campaigns we thank Mrs. Röver (Technical University, Berlin) and Mrs. Rüger (German Federal Office for Architecture, Berlin).

REFERENCES


Colla, C., Maierhofer, Ch. (2000): Investigation of historic masonry via radar reflection and tomography. Proc. on 8th Intern. Conf. on Ground Penetrating Radar, Gold Coast, Australia, CDROM.


