NON DESTRUCTIVE EVALUATION OF DEFECTS AND EFFICIENCY OF STRUCTURES

DIAGNOSIS OF HISTORICAL BUILDINGS AND MONUMENTS USING NDT

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UGR

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Chapter 1

Introduction

1.1 Scope of Work

A full understanding of how the building is servicing its occupants is important for all facility managers to know. Occupant interviews regarding active leaks, where drafts are detected, etc. is valuable information to have during a building evaluation. Maintenance reports will provide useful information regarding where the building has been repaired and where the problem areas still exist. This information helps the investigator better understand the condition of the building and determine the areas that need to be more closely reviewed. On these areas some testing procedures is required.

There are many different types of testing that can be used during the investigation to suit a particular building's needs. These testing categories include:

- Non-Destructive Testing (NDT)
- Destructive Testing
- Laboratory Testing

In this work, the NDT were deeply studied, in chapter 2 one can find a brief description of some well-known tests. Cases of historical buildings were NDT were used as testing procedures are mentioned in chapter 3.

1.2 The importance of NDT

Ancient monuments and historic buildings are the precious sign of our past, they are non-replaceable fragments of our cultural heritage and their future depends on our attitudes and actions. For this reason we must study ancient buildings to understand their conditions, their problems, but also their values and meanings. A great aid to achieve this result can derive from the wide and complex technological and scientific field of the non-destructive techniques, which are today available for the analysis of architecture.

Their importance comes from that there are non-invasive techniques. This type of testing causes little or no damage or interference to the building envelope. Also they can be helpful in finding hidden charecteristics (internal voids, flaws and characteristics of the wall section) which can not be known otherwise than through destructive tests, and DT are not a solution allowed in the case of historical buildings!!

Sampling of masonry specimens is a costly operation, which also can lead to misunderestanding when the operation is not carried in an appropiate way. When an overall knowledge of the wall is needed NDT can be very useful.

Chapter 2

Non destructive techniques

2.1 Some of NDT

2.1.1 Acoustic Emission (AE)

Is a non-destructive testing method allowing to detect in real time growing defects. Many damaging processes can be in the scope of the technique such as crack propagation, delimitation, corrosion of reinforced bars, ... The AE signature of each phenomenon under interest can be characterized in order to discriminate genuine AE from noise but moreover to identify the damaging process and to evaluate the severity of the damage for the integrity of the structure.

To provide a good diagnosis, the analysis of AE signals with statistic tools and pattern recognition processing is often necessary to understand genuine AE and eliminate unwanted phenomenon effects.

Intrinsic mechanical properties of concrete give rise high signal to noise emission when damage propagates. The high attenuation coefficient of elastic wave in concrete material was a limitation to apply AE on a large civil structure, the development of specific AE sensors has contributed to overcome this difficulty and nowadays AE can be applied on full scale structures.

In real time a minimum diagnosis is available: AE monitoring detects the occurring of growing damage versus the loading level, displays the trend of its AE activity and locates it. From a practical view of point, AE can be applied during proof test in order to investigate the fitness for service or repair validation, during service to detect a problem of fatigue or corrosion. In more severe cases, AE continuous monitoring helps to take the decision to maintain a damage structure in service.

AE has been known and clearly described for over 50 years and its use in monitoring and testing has steadily increased for a number of reasons. Advances in electronic equipment, followed by the almost exponential grow in computing power in recent decades aided the scientists to correlate AE signals with fracture mechanics and damage characterization. Furthermore, the enhanced power and speed of acquisition system allows a multitude of features to be extracted from the acoustic emission hits allowing a detailed signature of different types of damage to be identified and stored in a data base.

AE will always be an experience based technology. In order to understand the AE signals you receive from the material in real structures it is important to be able to correlate the data to experiences where the damage process has been studied in greater depth. These advances coupled with the associated cost reductions have allowed a vast increase in applications. All large scale industrial applications in aerospace and petrochemical industry have been due to a thorough understand of the relationships between AE and damage growth. Its this knowledge that allows AE to be used as a non-invasive monitoring tool identifying different types of damage using sensors mounted on the external surface to asses the structure.

The AE phenomenom

AE is an elastic energy that is spontaneously released by materials when they undergo micro deformation. These stress waves radiate from defects or damaged areas through

the structure as material-borne sound. The stress waves can be detected as wave forms at the surface of the material. Each waveform holds information about the initial source. One of the greatest strengths of AE is that it is capable of locating the position of active defects.

Numerous physical phenomena can give rise to detectable AE hits such as: Plastic train, dislocations movement, slip, grain boundary sliding, twinning, fracture, crack growth, decohesion of inclusions ...., Liquefaction, solidification, and solid phase transformations, Specific phenomena as crystallization, setting of cement, inflating, Initiation and propagation of cracks (under static mechanical or thermal stresses, fatigue cycling ...), hydrogen embrittlement, Localized corrosion of metallic structures (stress corrosion cracking, pitting, crevice corrosion ...), damage propagation of composite materials and concrete (matrix micro-cracking, delimitation, breakage of interface, rupture of fiber ...), Internal friction (interface concrete/fiber, concrete/reinforced bar...), impact of particles... turbulent flows (leaks).

Some advantages and limitations are very specific of this non destructive technique:

Limitations :

- Structure should be stressed or in service.
- AE sensor has to be held in contact with the structure with coupling medium.
- Sensitive only on active defect.
- Non reversible (Kaiser effect).
- Gives no information of defect geometry (size).

Advantages:

- High sensitivity on lots of material as concrete, metals or composite material.
- Sensitive only on active defect.
- Detection of hidden defects on large and complex structures.
- Not sensitive to defect orientation.
- Orientation, opening mode and location of crack can be processed (moment tensor analysis).
- Non reversible (Kaiser effect): basis of periodic examination.
- Real time detection and location (real time alarm).
- Remote control continuous monitoring possible.

2.1.2 Radar

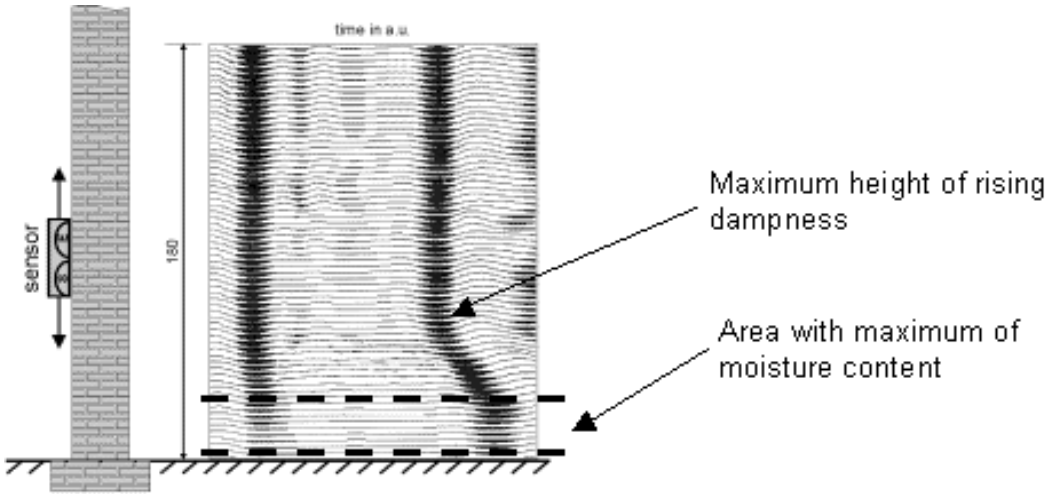
Radar is based on the transmission of short electromagnetic impulses by an antenna at frequencies between 300 MHz and 2.5 GHz. These impulses are reflected at interfaces with changing dielectric properties of the materials. Also the propagation velocity depends on the dielectric properties. Since moisture 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.

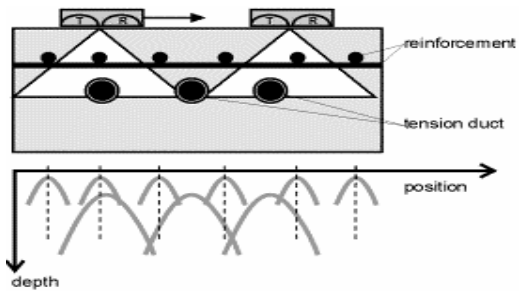
For the investigation of brickwork or concrete radar can be applied to the following topics:

- Determination of the dimension from structural members (e.g. wall or slab thickness).

- Investigation of the inner structure of multi-layer systems, detection of delamination, cavities, defects, metallic or wooden fixtures (anchors, clips), construction unit joints.
- Quality control after crack or joint injection.
- Determination of the moisture distribution.
- Detection and localisation of the reinforcement and tendons ducts.



Radar testing with visualisation of rising moisture in brick work.



Schematic presentation of the localization of reinforcement and tendon ducts in a concrete slab.

2.1.3 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. 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 raypaths 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.

2.1.4 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 pseudosections 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 pseudosections. 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.

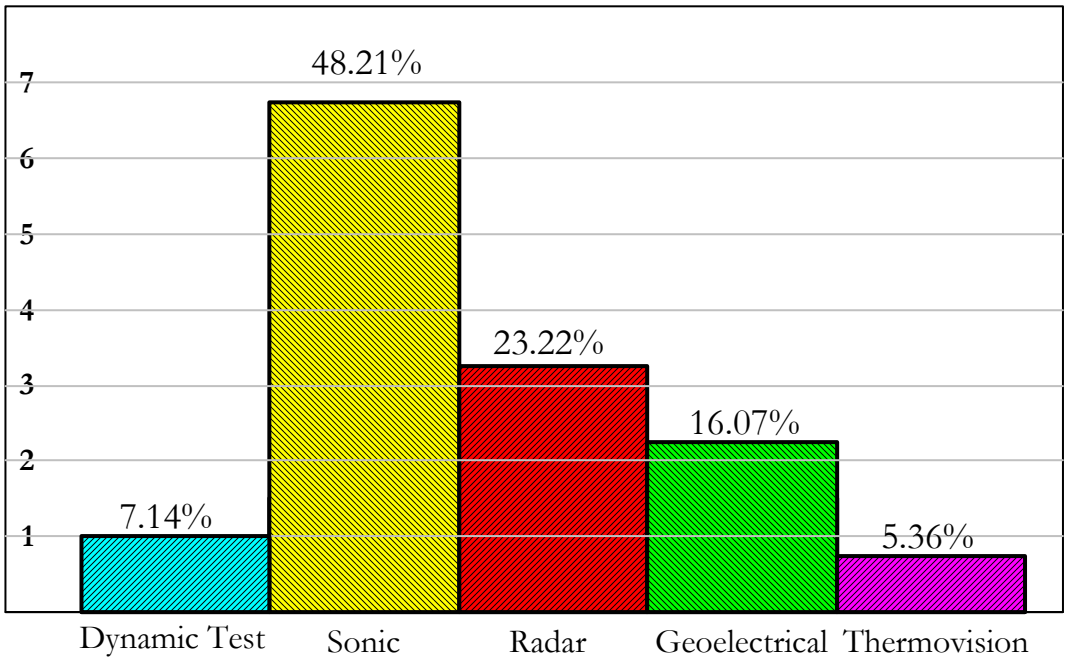
2.1.5 Impulse thermography

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.
A relatively new approach of IT is the pulse phase thermography (PPT). 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.

2.2 Statistics

In this work 14 cases were studied, each case used one or more NDT, if its required to make a summary of the percentage of the tests most used one can get the following chart.
One can notice that the sonic and radar tests are the most applied ones, detailed information of the reasons of preferring one method to another could be found in chapter 3.



Chapter 3

Historical Cases

CASE 1
Cloister of the Gerona's Cathedral, Spain

Introduction

The construction of the Cathedral started on the 11th century, it's a live example of different architectural styles since the first known Romanesque building that was consecrated in 1038. It offers four architectural styles: Romanesque, Gothic, Renaissance and Baroque, this mix of styles is difficult to be found in similar buildings and is what enlighten it (Fig 1).

The cloister (Fig 2), built during 11th and 12th centuries, represents fully the spirit of the Romanesque era. It is conserved entirely, despite the fact that some double columns and capitals display signs of erosion which affects the limestone rock, sculptured to create a series of Biblical representations, that form a valuable part of the Catalan Romanesque period.

The Gothic nave, which is the widest in the world and measures 22.98 meters, is at the same time, the widest of any style, excepting that of St. Peter's in Rome (which measures 25 meters).

Fig 1: Cathedral of Girona

Summary

In this case an overview of the use of a method based on dynamic identification for the detection and characterization of damage in 24 stone columns located in the XI-century cloister of Girona Cathedral in Spain. The columns were dynamically evaluated 14 times for different load levels. 48 dynamic tests (2 per column) were also developed *in-situ* to monitor the columns.

No significant variation between the result obtained in the two tests carried out each column was observed. Dissipation of the impact energy took place in about 0.3 seconds. Basically, one mode was always satisfactory clear and in some cases the second mode was also detected.

The information of this case is obtained from reference [1]

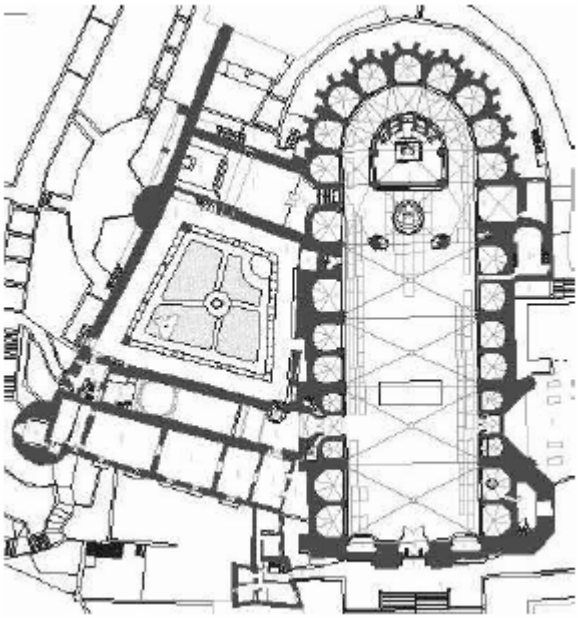


Fig 2: Overview of the Cathedral and Cloister

The generation of impulsive force was caused through a 10- pound hammer applied at mid span of every column with a single impact. A dynamic transducer consisting of a ceramic accelerometer was attached in horizontal direction (Fig 3).
A clear pattern was observed on the time-response diagram of every column. Very *clean* time responses were extracted. A typical example of those plots is presented in figure 4.

Results

After obtaining the first natural frequency for every column, a clear trend can be observed. Columns next to one of the corners of the cloister present higher frequencies and columns close to midway present lower frequencies. As can be observed in figure 3, columns are displayed by pairs, and the frequencies of two twin columns were always the same.

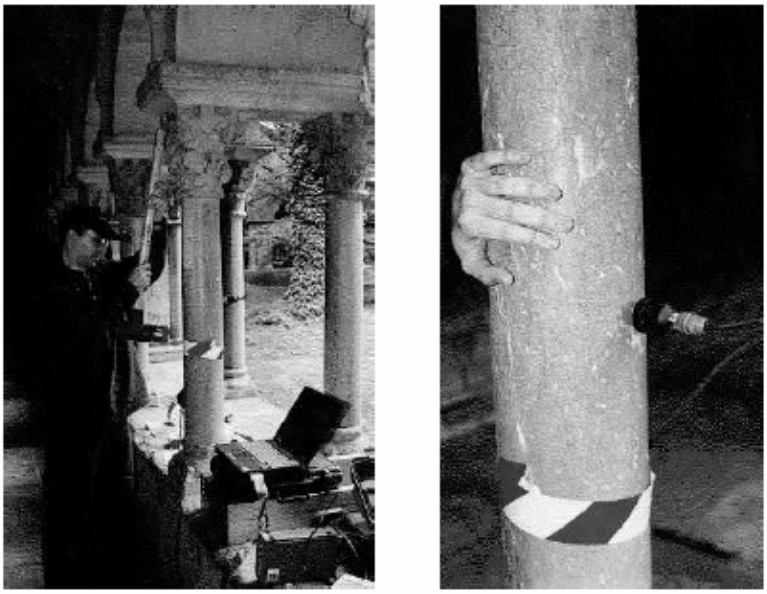


Fig 3: Acquisition system (left) and accelerometer attached on a column (right)

This proves that variation in frequencies is mostly due to location than material or geometrical parameters. Data acquisition was developed using a routine of Lab view code, on an interval of one second, and acquiring at a frequency of 30,000 Hz.

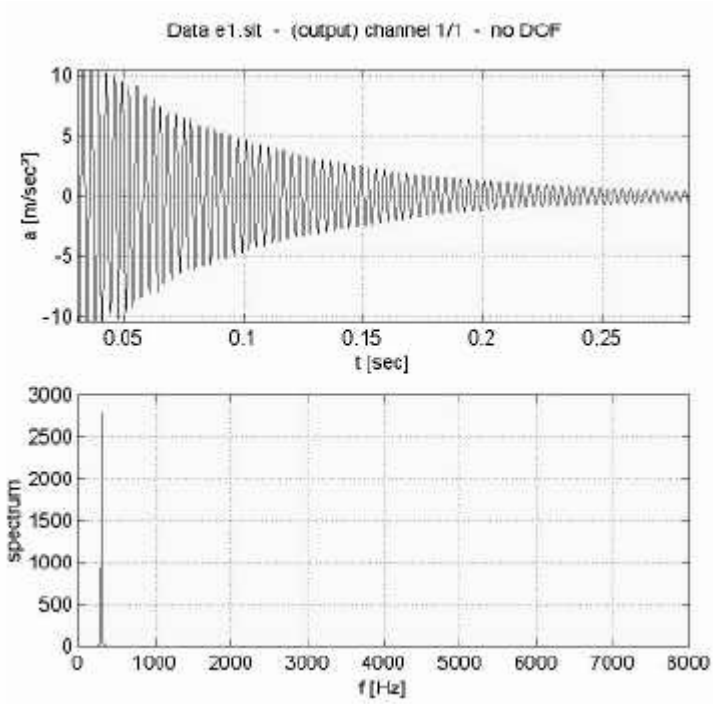


Fig 4: Typical time-response of a column (above) and FFT diagram (below).

CASE 2
The 'Acueducto' of Segovia, Spain

Fig 5 : Aqueduct of Segovia

The object of the repair work is to improve the structural safety and overall structural behavior. Also to prevent the falling of small pieces of granite and to delay the fitness process of the blocks.
One of the restoration procedures involved the use on NDT, in this case the measure of the sonic velocity in 19,460 visible blocks. The ultrasonic velocities helped to measure the degree of compatibility and deterioration of granite, and this will permit the check its functionality.

The information of this case is obtained from reference [2]

CASE 3
Cathedral of the Blessed Sacrament, New Zealand

Introduction

The Catholic Cathedral of the Blessed Sacrament is located in the southeast quadrant of central Christchurch, New Zealand. Construction of the Cathedral began in 1901, and the Cathedral was opened in February 1905. The Cathedral is 64 m long and 32 m wide, and the main dome is 41 m high (Fig 6). The sediments underlying the Cathedral site are recent (Holocene) stream and swamp mud and peat underlain by inter bedded gravels and marine silts. Such sediments are susceptible to enhanced shaking and liquefaction during an earthquake. Christchurch is located in a seismically active area , near many active faults, and thus the Cathedral may be at risk if a seismic event occurs. Therefore, a program was initiated to bring the seismic strengthening of the Cathedral up to modern building safety standards.

Fig 6: The Catholic Cathedral of the Blessed Sacrament is located in south central Christchurch, New Zealand, which is underlain by soft sediments.

Summary

Before the repair work could begin, questions regarding the nature and extent of the foundations of the Cathedral needed to be solved. From its beginning, cracks appeared due to settling of the Cathedral, and rising damp was and is apparent in some of the support pillars, suggesting that the foundations are shallow and limited in extent. Historical research yields little direct information on the Cathedral foundations. A number of test pits and cone penetrometer tests (CPTs) were done outside the Cathedral, and indicated that it was in a zone of high liquefaction potential. However, test pits and CPTs are (1) invasive, (2) costly, and (3) point samples, and did not cover the target. Therefore, a suite of near surface geophysical surveys were carried out, particularly ground penetrating radar (GPR).

The pE 100-survey lines covered the floor of the nave of the Cathedral (Fig 7). The spacing between transmitting and receiving antennas was fixed at 0.56 m. The survey lines were spaced every 1.1 m, in order to accommodate the spacing and dimensions of the support pillars. Readings were acquired every 5 cm along each survey line. The surveys were acquired in two orientations, because reflections can originate from features that are oriented parallel and perpendicular to the survey lines. The two data sets were then combined to yield a more complete response. In addition, the radar antennas were stepped out from a central survey point, a common mid-point (CMP) survey, at selected locations in the cathedral in order to determine the radar velocity as a

The information of this case is obtained from reference [3]

function of depth and to isolate the above ground features that may cause reflections of radar waves through the air.

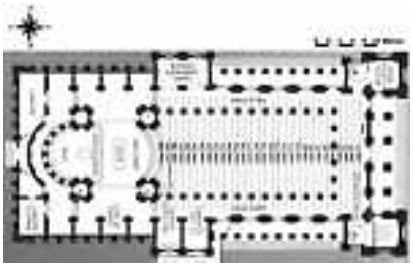


Fig 7: Layout of the GPR survey lines across the nave of the Cathedral. Two antenna orientations were used to obtain reflections from the two dominant orientations.

Once the profiles were collected, the data are corrected for "wow" - the saturation of the receiving antenna with time - and are migrated. Migration is a process that collapses subsurface diffractions - i.e. scattering from discrete features - and which places dipping features in their correct positions. Basic seismic and radar propagation theory is based initially on horizontal layering; dipping features are steeper than they appear in the raw profiles. Finally, the closely-spaced profiles are collected together to form a three-dimensional (3D) data cube, which can be "sliced" in different orientations, including at specific times which are equivalent to different depths once corrected for the radar propagation velocity.

Analyses of CMP's (Fig 8) and subsurface diffractions in the radar profiles yielded subsurface velocities ranging from 50 to 80 m/μs, values that are characteristic of saturated soils. Concrete, in contrast, has radar velocities of the order of 120 to 140 m/μs. The velocity results, coupled with the radar cross-section profiles, suggest that the cathedral foundations consist of, at best, compacted soils.

The combination of the CMP velocities and the lack of an extensive reflective feature at depth beneath the central main part of the Cathedral suggest that there is no solid foundation to the Cathedral. This is supported by qualitative observations within the Cathedral: rising damp in the pillars; cracks in the walls, especially on the mezzanine level, which have continued to appear throughout the life of the Cathedral; the shaking felt in the Cathedral due to heavy traffic on nearby roads.

Complementary cone-penetrometer tests (CPT's) and GPR profiles and CMP's were acquired outside the Cathedral. The CPT and GPR results correlated well, confirming previous studies in the area and previously identified sediment types. The agreement between the two approaches provides greater confidence in the GPR results inside the Cathedral.

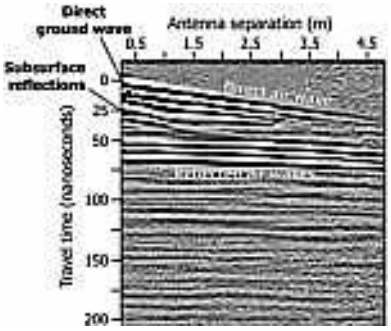


Fig 8:Example of a common midpoint (CMP) record, showing the direct air wave, direct ground wave and reflection events from the ceiling and walls .

The information of this case is obtained from reference [3]

CASE 4
The case of some Sicilian Churches, Italy

- *S. Nicolò l'Arena in Catania*
- *The Cathedral of Noto*
- *SS. Crocifisso Church*

Introduction

The three cases reported were chosen because the structures present similarities in geometry, technique of construction or materials and damage. The three Churches, S. Nicolò l'Arena, Noto's Cathedral and SS. Crocifisso in Noto were all built after the earthquake, which hit Sicily in 1693 and were damaged by the 1990 earthquake.
Furthermore the two last churches were nearly contemporarily built with the same type of stones and with similar mortars. Apparently the stones used for S. Nicolò were stronger being from volcanic origin.
The three buildings showed after the 1990 earthquake similar damages mainly on vaults, domes and arches. No or very low damages were visible on the pillars which were covered with plaster at least 20 or more years before.
After the collapse of the Cathedral of Noto, it was clear that plaster could hide dangerous crack pattern due to long term behavior of the material and present since long time.

S. Nicolò l'Arena in Catania

It's one of the most impressive in Catania (Fig 9). The knowledge about the year of construction and the evolution of the church through historic documents is not so easy. Its construction started probably following the Etna volcano eruption of 1660.
After the 1990 earthquake, the structural elements of the Church of S. Nicolò l'Arena in Catania, as the dome and the vaults were damaged and the appearance of vertical cracks on the original pillars were detected. It is not clear whether those cracks were already visible and were simply propagating during the earthquake.
An extensive investigation program (including sonic, radar, flat jack, coring, boroscopy, etc.) has been planned to design the preservation and restoration actions.

Sonic tomography is a powerful method to obtain information on the conditions of a structural element through the interpretation of velocity and attenuation maps. In general, the velocity distribution is an indication of the elastic properties of the element. The attenuation distribution is related to the non-elastic behavior of the material and so the presence and importance of fractures. The masonry texture appears characterized by two different topologies: solid stonework built by large and regular blocks and filled with rubble masonry made with rather strong mortar.
Highly inhomogeneous stone masonry surrounded by a cover more than 300 mm thick, made with tile fragments, stone and rather weak mortar, locally called "incoccio" often two topologies are present in the same structural element. Apparently the second was used as a repair technique.

The information of this case is obtained from reference [4]

To recognize the presence and the localization of the two different masonries, sonic tomography was extensively applied. They show the velocity distribution of the elastic waves generated by an instrumented hammer in the sonic frequency band. The obtained results are very interesting and basically consistent with the external observations of the pillars and the extracted cores.

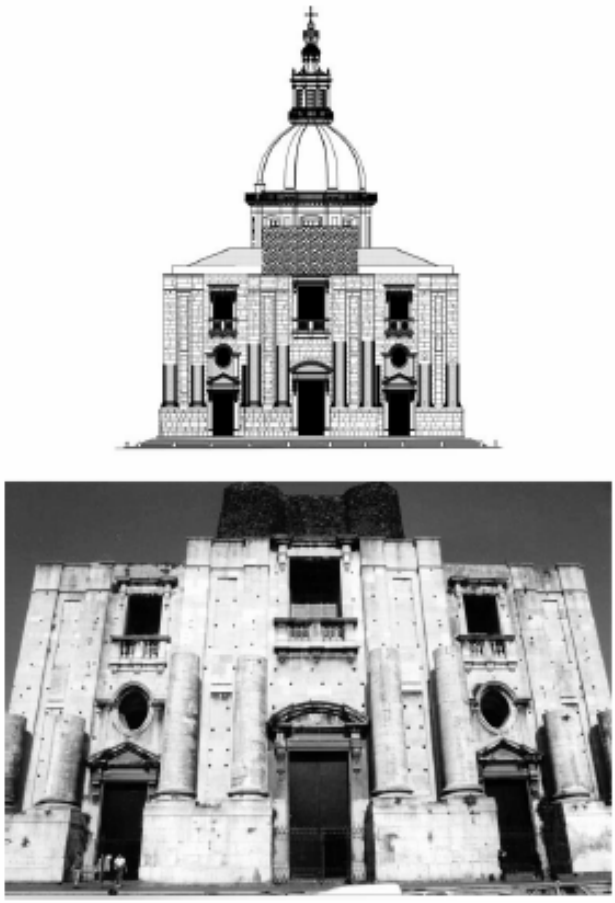


Fig 9: S. Nicolò l'Arena Church

In figure 10 the sequence of the horizontal tomographies of pillar 2 are represented.
A typical distribution of the velocity on the pillars 1 and 2 shows average velocities relatively high at the base and at the top of the pillars and much lower velocities in the middle. This situation is very clear in the vertical tomography of both pillars even if the vertical sections have a lower density of ray.

The low velocities that have been found in the pillars 1 and 2 and the fact that these pillars show a dangerous crack pattern (Fig. 11) confirm the need of urgent preservation actions.

From coring of the pillars it was also clear that the internal mortar is very weak. The other pillars that have been investigated generally present much higher velocities indicating a less alarming state of conservation.

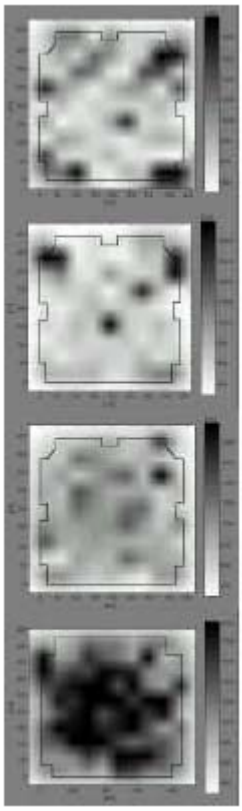


Fig 10: horizontal tomographies of pillar 2 at 7.6, 4.9, 3.8, and 1.8m.

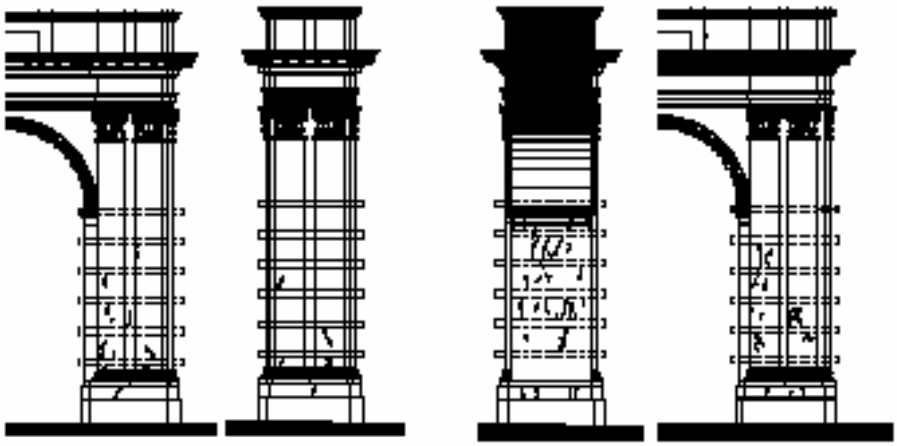


Fig 11: Crack pattern of pillars 1 and 2 consequently

The Cathedral of Noto

Sonic tests and other diagnostic techniques were applied on the remaining walls and pillars of the Cathedral (Fig 12 and 13). In fact, the right main pillars and most of the dome of the Cathedral collapsed in 1996.

Sonic tests were used to control the effect of grout injection used as a possible technique for repair of the damaged masonry.

The information of this case is obtained from reference [4]

Fig 12: view of the entrance of the Cathedral after the removal of the ruins.

Fig 13: detail of a pillar section.

The sonic pulse velocity tests were carried out on the left-hand side pillars and on remains of the collapsed pillars, as well. It is well known that ultrasonic frequencies can not be used on rubble walls due to the high attenuation caused by joints, voids and homogenates. Nevertheless, being travertine and calcarenite so different the ultrasonic velocities measured in laboratory on single blocks were very useful.
Measurements were taken at different heights (Fig. 14). It was impossible to position equal levels for all the pillars due to the presence of safety scaffolding. Low velocity values were systematically recorded in all the tested pillars of the Cathedral from 1.00-1.50 m.

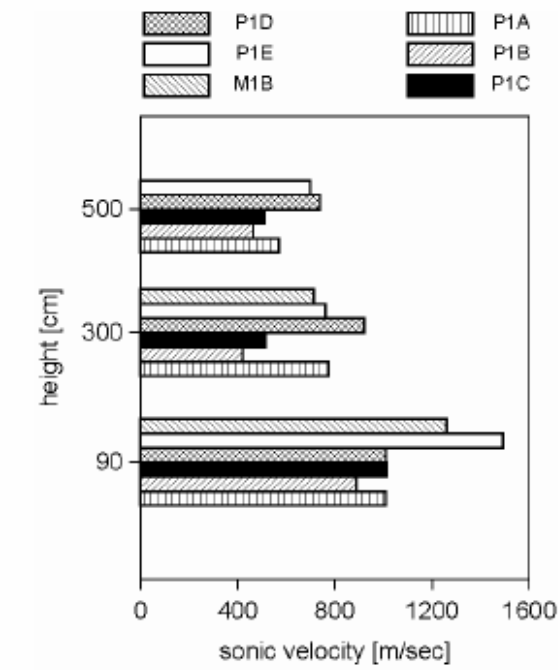


Fig 14: Vertical distribution of the sonic velocity measured on pillars and walls

The pillar P1B, the most investigated, shows the lowest value of the sonic velocities recorded at each level compared to the other P1 pillars. The pillar state is in fact characterized by a very serious damage, as described by the crack pattern of figure 15. The survey of the crack pattern was possible only after the removal of the plaster. Large vertical cracks had been filled with gypsum and lime mortar during the restoration carried out in the sixties. From figure 14 it can be seen that the lowest velocities were measure around 3.00 m, where the crack pattern shows a very high damage. This is also confirmed by figure 16.

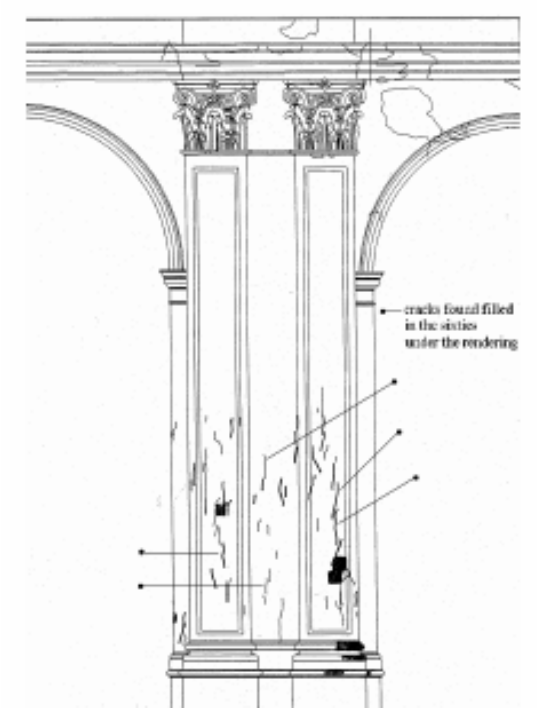


Fig 15: Prospect of left pillar P1B and survey of the crack pattern.

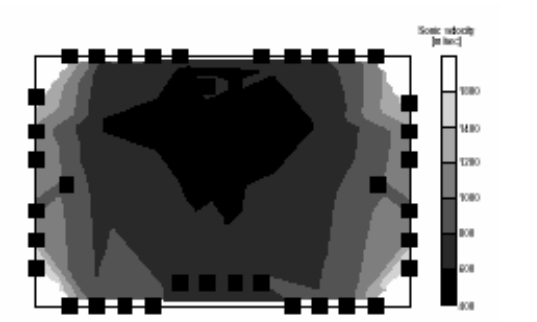


Fig 16: Sonic velocity distribution in the section of pillar P1A at 90 cm.

The masonry behavior was observed both during the injections and after 28 days. After this time, the collapsed pillars PA and PC were dismantled to observe the grout penetration and diffusion.
The sonic tests were carried out 28 days after the injection. A general increase of the sonic velocity was observed, as a consequence of the injection. Pillar PC. (Fig. 17) shows consistent increases. It is interesting to observe that in some points the velocity values

The information of this case is obtained from reference [4]

are similar to the ones initially acquired. This effect is easily explained because the section was not all injected, but only in one part.

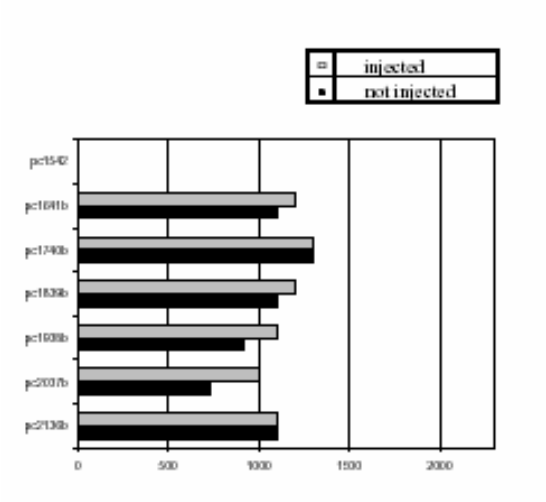


Fig 17: Results of the sonic tests carried out on the pillar PC at 25 cm before and after the injection.

The results explain the distribution of sonic velocities, which are lower in the internal part of the pillar. In the case of the Noto Cathedral it was possible to find that the crack pattern survey, the flat-jack tests and the sonic tests defined very well the masonry characteristics. The sonic tests were able to reveal the presence of the travertine in the upper part of the pillars.

SS. Crocifisso Church

The Church was damage by the 1990 earthquake, especially in the transept and lateral naves, domes and in the vaults, which were then supported by provisional structures. The pillars, apparently, did not show any damage. During the on-site investigation, the plaster was locally removed, revealing an alarming state of damage due to compressive stresses.

Sonic tests were carried out in order to detect the characteristics of the pillars. Figure 18 shows typical sonic test results. The sonic velocities are higher in coincidence with the external stone leaves and lower in coincidence to the rubble material.

The lower average velocities concerns the pillar called D, characterised by the worst crack pattern situation, as well. It is also possible to notice that in the case of highly cracked external leaf the velocity becomes much lower.

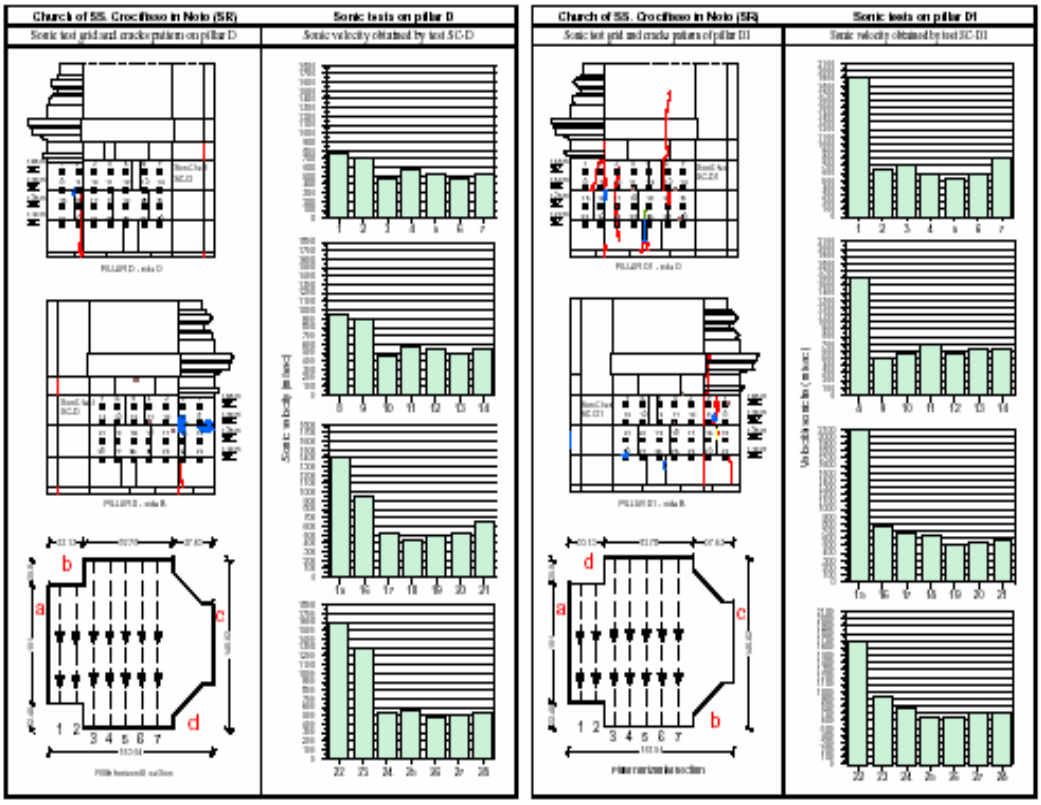


Fig 18: Results of sonic tests applied to the pillars D and D1.

CASE 5
The Cathedral (Duomo) of Lucca, Italy

Some tests were performed to obtain geoelectrical tomographies across masonry.. Different methods can be used. The "transparency" tomographies use an experimental disposition of the electrodes corresponding to the "cross-hole tomography" in the subsoil: in this case two series of electrodes are fixed along two profiles on the opposite faces of a masonry structure.

Another technique 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 four electrodes at a time with one of the typical arrays used in geoelectrics. By connecting the electrodes in different combinations, a good number of measurements are obtained (typically several hundreds). Multi-electrode (24, 48 or more) automatic switching geo-resistivity-meters are necessary. 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 geo-electrical tomography. This is sometimes referred as the impedance tomography.

The main difficulty to perform geo-electrical measurements on walls is due to the very high contact resistance at the electrodes. First of all, the instruments must have very high input impedance. A good electrical contact with the masonry is necessary, without making too invasive operations. Several kinds of special mini-electrodes can be used. In this test an IRIS SYSCAL SWITCH 48-electrode instrument (whose input impedance is 10 MΩ) was used.

The experiments were carried on the damaged section of the transept of the Cathedral, on the same damaged wall where the seismic tomographies were made.

As the external stone face of the wall is very compact and the contact resistivities should be too high, it was decided to perform an impedance tomography from inside only. The internal face, in fact, is a mixed bricks-stone wall, with thicker mortar joints, and it looked more suitable for this experiment.

Twenty-four small metal electrodes were used in the same small holes made for the seismic receivers: they had been bored, when possible, in bricks or in the junction and not in the stones. A conductive gel was injected in the holes to ensure a good contact with the wall material. The input impedance was measured at all the electrode couples: it was in the order of 5-10 kΩ, compatible with the instrument input impedance. The Pole-Dipole and the Dipole-Dipole electrode arrays were used. The apparent resistivity pseudo-sections were quantitatively inverted to obtain two electrical tomographies of the wall. The results are shown in figure 19. The presence of low-resistivity zones put in evidence the damage due to the water infiltration. The general trend of these anomalies is rather similar to the distribution of the low-velocity areas in the seismic tomographies.

The information of this case is obtained from reference [5]

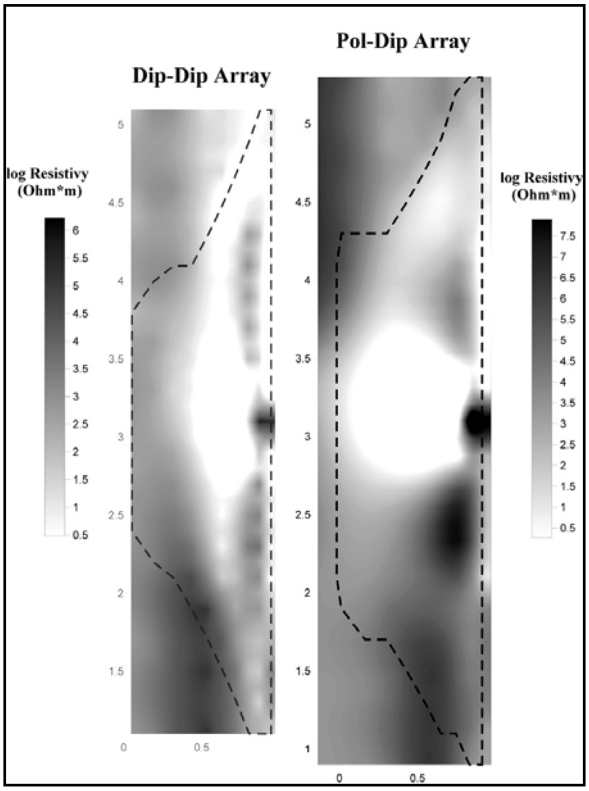


Fig. 19: Two geo-electrical tomographies across the same section of the seismic tomographies. The internal conductive zones put in evidence the water infiltration in the damaged areas.

The information of this case is obtained from reference [5]

CASE 6
The Walls of Vicopisano (a small town near Pisa), Italy

An investigation on the external face of the walls of Vicopisano, a small town near Pisa was made. The middle-age stone walls were reinforced, in the XV century, by several towers and more complex gates. The walls are about 6.5 m high and about 0.9 m thick.

Two tests were made with the electrodes fixed along a horizontal profile on the external face (impedance tomography) in correspondence of a niche on the other side. The result is shown in figure 20. Note that the Pole-Dipole array is axymmetrical: so the irregularity due to the niche on the backside of the wall is deformed, but the localization of the depth of the cavity is quite good.

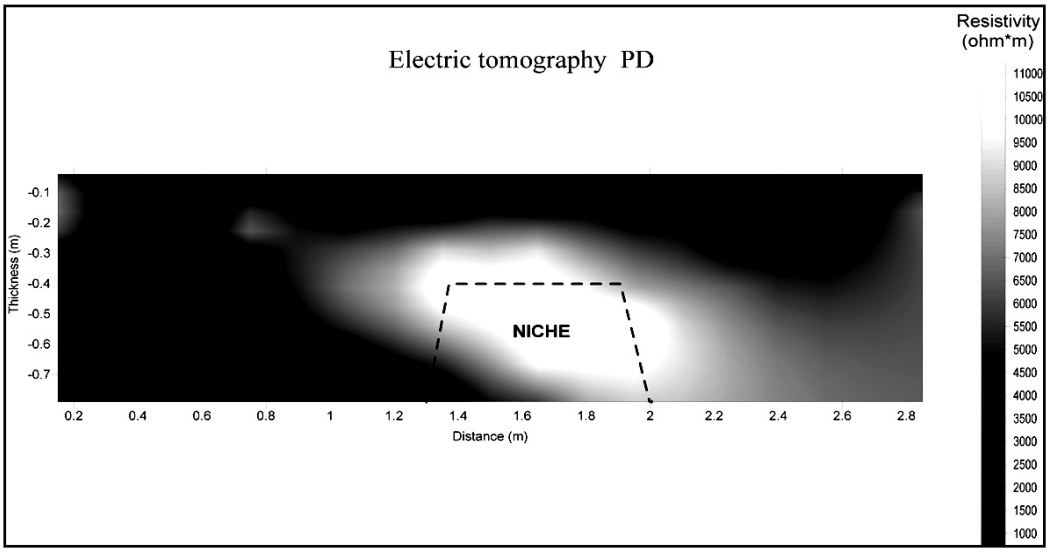


Fig 20: A resistive anomaly is well visible: it corresponds to a niche on the other face.

Both of the geoelectrical tomographies were carried on the ground near the same wall that helped to estimate the depth of the foundations (Fig 21). The first one was obtained with a profile 0.5 m from the wall; the second one, not to be disturbed by it, was made more than 5 m away from the way; the third figure was obtained by subtracting, point by point, the "undisturbed" values from the first one.

The depth of the foundations can be estimated to about 2-2.5 m. The presence of subsurface irregularities is quite clear.

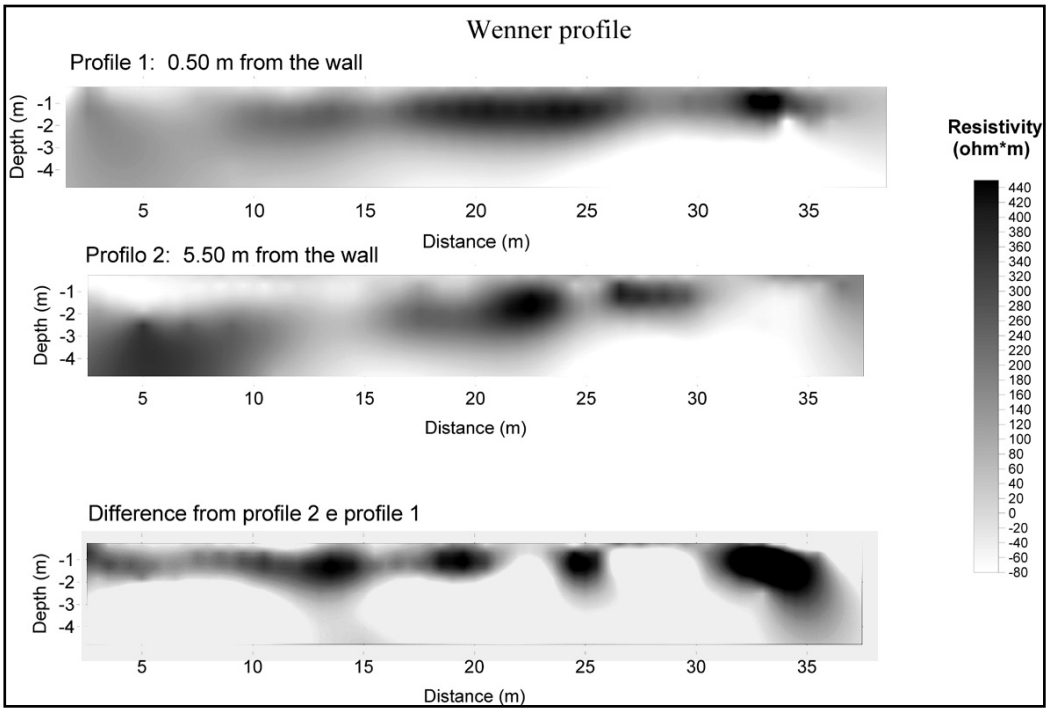


Fig 21: Geoelectrical tomographies performed on the ground near the wall of Vicopisano allow to evaluate the depth of the foundation (2-2.5 m).

CASE 7
Historic Town Walls of CITTADELLA, Italy

Introduction

The impressive town walls that surround the historic center of Cittadella in the northeastern part of Italy were built in 1220. They have a diameter of about 450 meters and a length of about 1.5 km (Fig 22). Their height varies between 13 and 14 meters and the transversal section is 220 cm thick. Two external leaves made of alternate layers of pebbles and thick mortar joints constitute the section. Four gatehouses split the town walls into as many quadrants. The four gatehouses plus twenty eight towers, built at inter axis of about 40 m, divide the town walls, along their extension, into thirty two sectors.

Fig 22: Arial view of Cittadella from southeast side

The repairs of the town walls started in 1994 and were divided into four main phases, one for each quadrant of the wall. And advanced damage state characterized by structural deficiencies, partial collapse of walls and decay of the masonry structures was detected. The most critical conditions characterized by an increasing out of plumb, high level of stresses and the presence of vertical and horizontal cracks, was detected on the north eastern quadrant. The causes of damage were investigated and some repairs were made up to ensure structural safety.

Description of damage

The periodical monitoring with simple procedures of the north eastern quadrant revealed an increasing flow plumb towards the outside of the town walls. In the most critical area it reached to 3.5º, i.e. about 80 cm of horizontal displacement on a height between 13-14m. The survey of the walls showed the presence of both horizontal cracks

that could facilitate the penetration of rain and the growth of vegetation and vertical ones along the height of the walls.
The superficial foundations reaching to only 40cm below the ground level and the presence of an embankment on the internal side of the walls, having a height of 3.6m from the external ground level, were the main causes of the out of plumb.

The repair aimed to improve the structural safety and the overall structural behavior of the walls, and the contribution involved strengthen a portion of the town walls between the northern and the eastern gatehouses. Both local repairs such as grout injections and partial rebuilding and global reinforcing measures such as the construction of supporting struts were carried out. NDT (sonic and tomographies) were carried out before and after the injections. So NDT in this case were used to evaluate the effectiveness of grout injections.

The injection of grouts was carried out on the lower portion of the walls and to the towers up to a height of about 3.5m (Fig 23). A natural hydraulic lime based grout characterized by low water soluble salts content was used.

Fig 23: Supporting struts and reinforcement of the tower foundations (left), local rebuilding of a crack.

Sonic tests and tomographies on the walls

Direct sonic tests on a 6x6 grid (60x30 cm) of acquisition points and a vertical tomography were performed before and after injections to evaluate their effectiveness. Bore hole coring and endoscopies were also carried out to crosscheck the results of sonic tests and verify the actual penetration of the grout inside the walls. The mean sound velocity on the direct tests before the injection was about 950m/sec value that corresponds to bad condition masonry (v<1000 m/sec). After injection the velocities increased up to 90% and their mean value was 1300 m/sec. These values considering also the large thickness of the wall and the great number of joints crossed by sonic waves reveal fair good condition of masonry.

The values of sonic velocities on the vertical tomography before injection were between 690 and 1030 m/sec (Fig 24). After injection, all the velocities increased and their mean value was equal to 1110 m/sec. The highest value of velocity was equal to 1390 m/sec. The mean increase of velocity was of 35% on the section, this show that the grout injections were effective in consolidating properly the masonry wall. The highest increase in sonic velocities were generally localized in areas previously

characterized by lower values, thus reveal an effect of homogenization of the wall section operated by the injection.

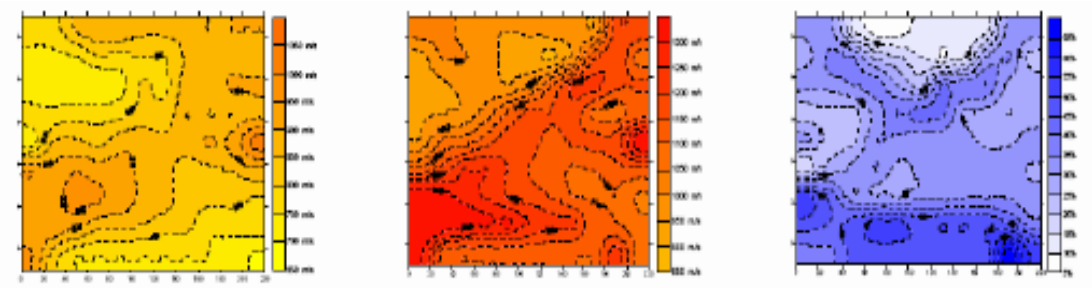


Fig 24: Results of the vertical sonic tomography: original conditions (left): after grout injection (middle): percentage increase of sonic velocities (right).

The quantity of injected grout was estimated and the leakages of grout from injection holes and from cracks were detected. After carrying out the sonic tests and tomographies, it was possible to relate the highest increase in sonic velocity to the highest quantity of injected grout. Where this relationship was not clear the differences in velocities could be related to the detected propagation of the grout inside the wall. (Fig 25).

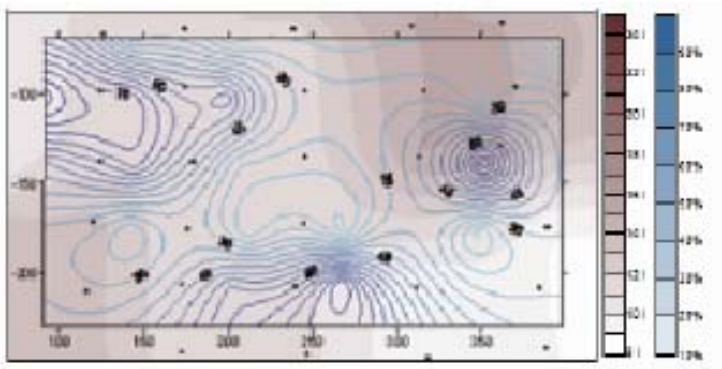


Fig 25: Quantity of injected grout (brown) and increase of sonic velocity in direct tests (blue).

CASE 8
St Giustina Church (Padua), Italy

Introduction

The church is the example of several historic transformations that passed through centuries from the Roman era until now (Fig. 26). The current construction which was inaugurated on 1608 still unfinished. The façade was subjected to several studies to complete it. It faces the main square of Padua, which is the one of the largest squares surrounded by water in Europe.

Summary

The façade walls are composed externally by a layer of clay bricks, showing diffused deterioration phenomena on materials; erosion of bricks and mortar and concentrated cracks, mainly located in the left portion, some minor cracks are also visible at the interior of the church, on the correspondent plaster.

Series of investigation techniques were planned on different areas of the façade. In particular sonic tomography was executed in the most cracked zone (Fig 27), on five horizontal sections crossing a long vertical one (for a total superficial area of 100*400 cm, Fig 28). Also four horizontal sections at the base of the nave (2 sections 225 cm long, at left and right of the main entrance) and the two aisles (for 125 cm), in uncracked zones were studied. The thickness of the wall was about 295 cm in the nave and 163 to 175 cm for the left and right aisle, respectively.

Fig 26: View of the St. Giustina church in 'Prato Della Valle' square, Padua

Fig 27:Crack pattern detected on the main wall of the façade

Direct comparison of the maps of velocities, which were detected on the vertical and horizontal sections for the cracked zone, is given in figure 29. The central zone in the vertical section is characterized by the minimum value (around 620 m/s), confirmed also from the horizontal tomographies (values from 380 to 600 m/s). The lowest values were found along the three medium sections, were cracks are mainly concentrated.

The information of this case is obtained from reference [8]

Fig 28: Test grid configuration for sonic tomography in the higher portion of the wall.

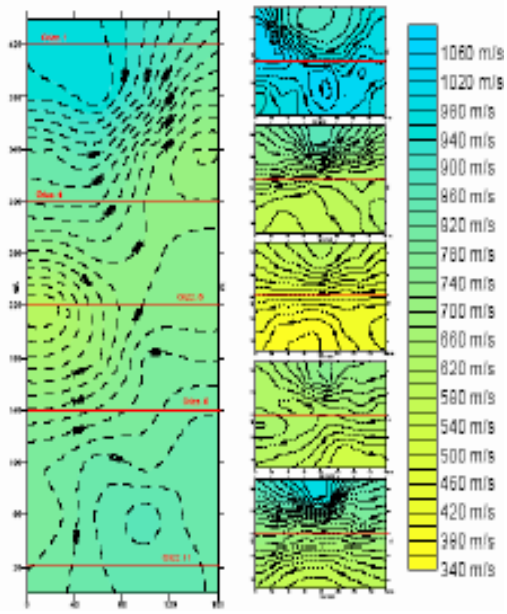


Fig 29: Sonic tomography results on the cracked zone.

Results of the flat jack tests together with the morpholic and compositional information (by sonic tomography and corings), allowed to calibrate a FE model able to show even in the elastic field, the main stress and stain distributions on the masonry see figure 30.

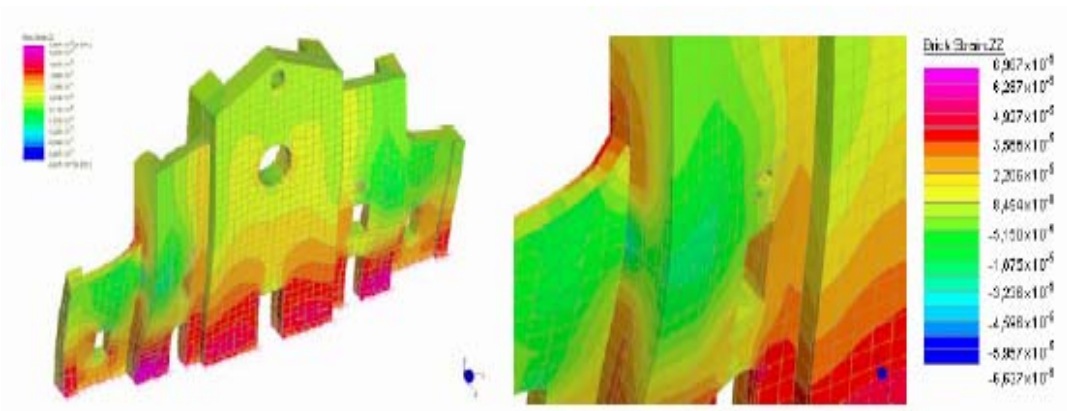


Fig 30: FE model of the St. Giustina façade: horizontal deformations from linear elastic analysis (general view and detail of the left aisle in correspondence to the cracked zone).

The information of this case is obtained from reference [8]

CASE 9
St Maria del Carmine Church (Padua), Italy

Summary

The static behavior of the Carmine Church façade in Padua was analyzed in 2001 before carrying up some conservation works. Up to 10m of height the façade of the church is made of the original 14th century masonry wall. This portion that is 95 cm thick, is made of a mixed masonry, with layers of bricks and stones linked together with irregular mortar joints. The external surface of the wall is characterized by the presence of some loose elements and of relevant vertical cracks.

A sonic test was carried out in the lower part of the façade at about 6 m of height. The area crossing one of the main vertical cracks was investigated. Direct sonic tests were carried out on a 6x7 grid (20x25 cm) of transmitting / receiving points as well as two horizontal and two vertical tomographies.

The sonic pulse velocity measured during the test varied between 1000 and 2000 m/s, these values were lower on the column near the crack (the velocity was between 1200 to 1400 m/s while on other portions 1400 to 1700 m/s values were detected). Tomographies showed the same trend of velocities, confirming the results obtained from direct tests. These results could be related to the presence of many irregularities and loose elements in the lower part of the tested area.

Moreover, and due to the possible deepening of the crack in the thickness, the sonic velocities are layered parallel to its direction of propagation. In the upper horizontal section for example, the values of the velocity vary from 1800 m/s at about 90 cm from the crack to about 1100 m/s in correspondence of the crack (Fig 31).

The results show in general that the average conditions of the wall are fair good according to the main classifications available on literature. In particular, the clear and strong decrease of velocity in the wall sections and in the areas of the wall sections close to the crack. The FE model (Fig 32) calibrated on the inspection and flat jack results allowed the detect of the main stress strain distributions.

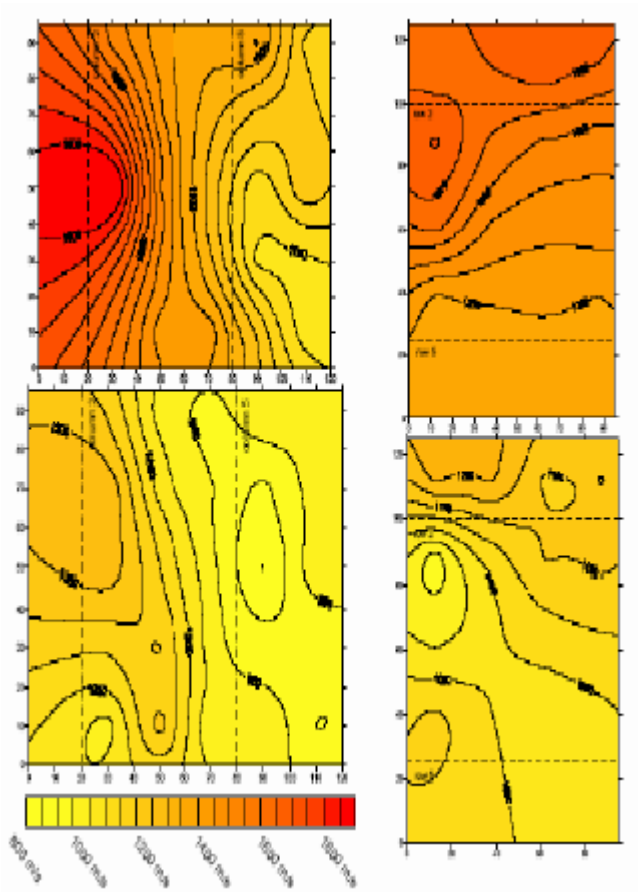


Fig 31: Results of the sonic horizontal tomography; upper left and lower left and vertical tomography at 80 cm (upper right) and at 20 cm (lower right).

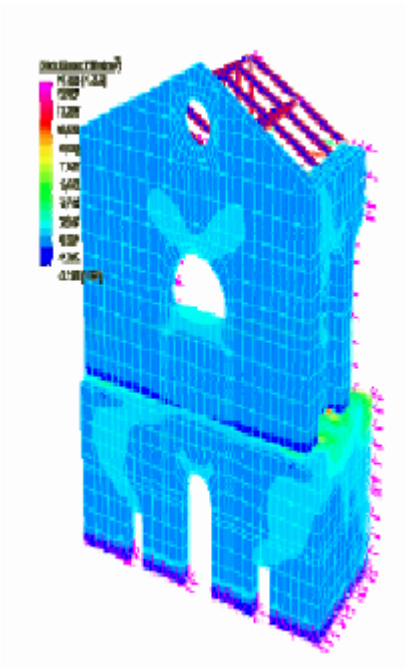


Fig 32: FE modeling of the façade of the church showing that the principal tensile stresses are concentrated in the effective cracked zone.

The information of this case is obtained from reference [9]

CASE 10
Bell Tower in Cremona, Italy

Introduction

The Bell Tower, called 'Torrazzo' by the Cremona citizens, is adjacent to the Cathedral (Fig 33), the date of its construction is not exactly known and may be either in the 8th or in the 13th century.
The tower, probably the tallest Medieval tower in Europe, is 112 m high. Its structure consists of a square plan part up to 70 m and a framed structure called 'Ghirlandina' with an octagonal plan and topped by a spire, from 70 to 112 m. The staircase from the ground to the Ghirlandina level was built within the thickness of the walls (approximately 3.3 m). The staircase also allows the access to some internal rooms.

Along the staircase which is covered with a barrel vault, the thickness of the external wall is about 1 m while the thickness of the internal wall ranges from 0.7 to 1 m, the span of the staircase being from 1.3–1.6 m.

Fig 33: Picture of the Bell Tower of Cremona (Torrazo)

Summary

Several signs of damage such as cracks crossing the wall, and surface deterioration appearing on the tower walls, suggested the need to carry out a laboratory and on site investigation to check the safety of the tower.
The investigation used among other techniques, the sonic pulse velocity and georadar investigations to detect the existence of an external masonry leaf which was suspected

of being detached from the rest of the wall, and therefore there was a wary of a possible dangerous local failure.

The geometrical instrumented survey allowed the building of a 3D model of the tower; the surveyed crack pattern was carefully reported on the geometrical survey. Vertical cracks are present on all sides of the tower and extended from the top of the base up to the top of the square part. Furthermore, the Ghirlandina showed the most important cracks on the supports and on the brick columns. Also, the internal part of the tower along the staircase and inside the internal rooms showed a diffuse crack pattern and some cracks extending through the walls. The presence of the detachment of the external leaf was noticed on several parts of the tower. Cores from boreholes and video camera internal observation also showed this phenomenon (Fig. 34). Due to the large thickness of the tower's external walls it was necessary to match the results of local tests (such as boroscopy and flat jack) to ND tests (radar), which could be more easily applied and extended to whole parts of the tower sides.

Three main problems concerning the safety of the tower itself can be highlighted:

(a) The upper part of the tower, just under the Ghirlandina, was badly cracked on each side and also showing detachments of the external leaf of the wall as in the lower part. To understand the extent of this detachment, which seemed to be very large on each side of the tower, it was decided to carry out a ND investigation; georadar was chosen as the most appropriate and easy to use technique.
(b) The observation of the external bearing walls and of the internal complex arched structure supporting the Ghirlandina led to the hypothesis that is behind figure 34.
(c) The influence of the stiffness of the concrete frame supporting the bells and built in the 1960s on the overall behaviour of the structure was not very clear; furthermore the detailed geometry of this frame was unknown.

Fig. 34: local inspection of the external leaf detachment

During the restoration works, there was an opportunity of using a mobile platform mounted on the west side of the tower. So it was possible to collect 18 radar profiles running parallel to the platform for the whole width of the tower between a height of 53 and 58 m from the ground at a separation of 25 cm from one to another.
Another 24 profiles were carried out at a height between 61 and 66 m at a separation of 46 cm between them (Fig. 35).

Fig. 35: High frequency radar survey on the mobile platform mounted on the west side of the tower.

These two areas were selected for intense radar investigations on the basis of some preliminary visual inspections and sonic tests that indicated that these areas were the most critical on the west side of the tower. Some previous coring made through the wall from the inner part showed clearly the external leaf detachment on the opposite end of the wall. The radar experiments were carried out using a very high frequency antenna (1.6 GHz) produced by IDS.

The radar unit was regularly triggered along the profiles by using an odometric wheel.. The radar profiles were pre-processed in 2D mode and then assembled in two 3D volumes, which were then submitted, to a 3D processing procedure. The resulting data volume was explored according to planes parallel to the external surface.
At a depth from the external surface of the wall corresponding to the thickness of one brick (about 12 cm) appears an image, as the one reported in figure 36.

The color map is associated with the intensity of the radar energy back scattered by the void space behind the external leaf. Thus, red color areas indicate areas with serious detachment problems while blue areas are expected to be safe. The images were overlapped to the AutoCAD images with the crack pattern to facilitate the correlation of the detachment with the stress state apparently affecting this side of the tower.

Actually, the radar results are consistent with the expert expectations since the lower part in figure 36 was more affected than the upper one by cracks and deformations of the external surface induced by the stress state. This deformation trend is the main reason of the detachment problem affecting this area.

A coincidence can be observed between the most critical detached areas and the crack pattern: most of the red areas are located in the center of the tower, below the multi-colored window (with four lights), where the most important cracks were observed (Fig. 37). Some local inspections, removing one of the external bricks, were also used to validate the results.

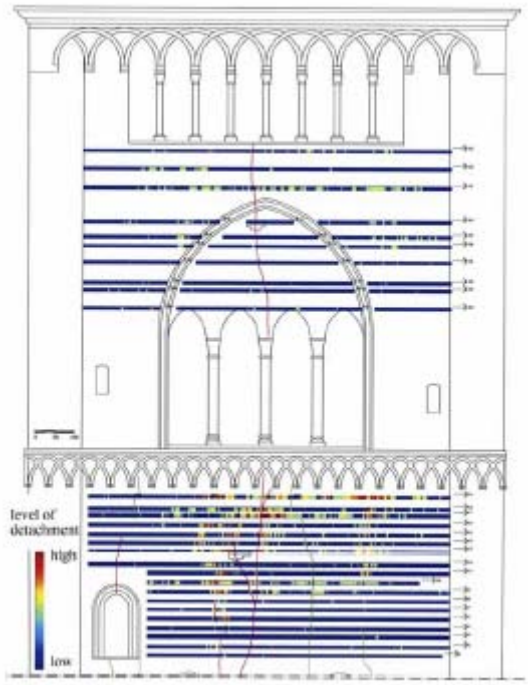


Fig. 36: Detection of the areas affected by the detachment problem. The color map is associated with the intensity of the detachment phenomenon.

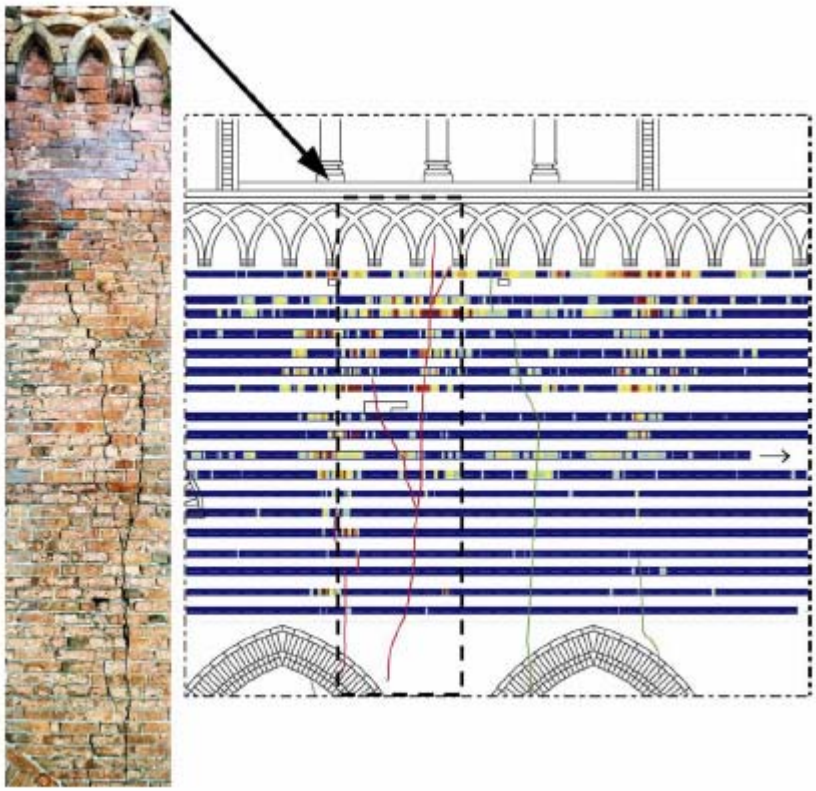


Fig. 37: Coincidence can be observed between the most critical areas of detachment and the crack pattern.

The results obtained from this work demonstrate that the choice of the radar method was appropriate for the addressed problems.

A high frequency and light antenna is very appropriate for these applications where a very limited penetration is needed, but where a high resolution is essential. Thus, a 1.6 GHz antenna as the one experimented here is a good choice. Unfortunately, the dimension and the shape of the antenna base were not facilitating the antenna movement on the brick masonry surface that was rather rough. As a result, the most deteriorated areas of the wall surface were investigated with a discontinuous movement of the antenna.

In these critical areas the odometric wheel was also suffering contact problems producing a position inaccuracy in the order of several centimeters. This experience indicates that an antenna bottom with a more appropriate shape, e.g. with smooth corners shaped like the sledge elements, might be more appropriate to investigate a rough masonry surface.

CASE 11
Villa Litta Modignani, (Milan) Italy

Introduction

The Villa Litta Modignani (Fig. 38) is one of the most interesting examples of a noble country palace in the Milan area. The Villa was built starting from 1687 until the beginning of the 18th century on the ruins of a previous noble building of the 14th century. It has three levels and a double porch at the main entrance. The most representative rooms of the building were paced in the central U-shaped part. The lateral parts of the Villa have lower height but only the western one was connected to the central part, being occupied by service activities.
The Villa, such as many historic building, shows a great variety of problems and unknown structural details. The study of these characteristics can be very important to correctly evaluate the building state of conservation and to plan an intervention even of simple maintenance.

Fig 38: Villa Litta Modignani

Summary

Morphology of the Vaults
The investigations were carried out with two main proposes:

- To find the presence and position of hidden tie rods in the porch cross vaults.
- To detect if the vaults in one of the library hall were true or false vaults.

The knowledge of the presence and the exact location of tie rods is a very important factor for the future design for conservation and re-use. Both radar and thermo vision were applied to solve the problem without using any scaffolding. Thermo vision was used for inspection of the vault surface from the porch area and for inspection of the wall above the columns. Radar was used to investigate the vaults from top to bottom with profiles executed on the floor of the library hall above the vaults.

Figure 39 shows an example of the images produced by thermo vision observing the wall above the columns. A vertical rod connecting the two plates is clearly detected. Figure 40 shows again the result after the application of a gradient filter to improve the contrast.

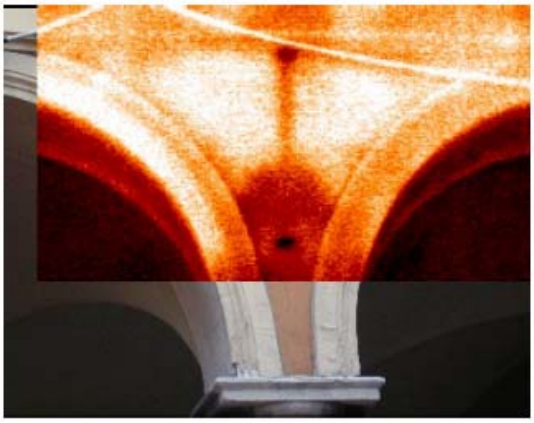


Fig. 39: Thermo vision applied to detect a vertical rod behind the plaster.

Fig. 40: data of figure 39 after the application of a gradient filter to enhance the target.

This example demonstrates that thermo vision is very effective to detect near surface rods. The method produces a very quick inspection also from the point of view of the data elaboration. Furthermore, the test equipment does not have any direct contact with the wall surface. This is a great advantage when we deal with large surfaces, non-easy access position or non-smooth or irregular surfaces and shapes. The scaffoldings are then not necessary with is a remarkable economical benefit. The limit of thermo vision is connected to the penetration depth, usually limited to a few centimeters.

Detection of voids

Radar was successfully used to detect chimney flues in the internal walls of the building. In fact, voids are a quite favorable target for radar thanks to the large permittivity contrast between masonry and air.

Villa Litta, as many other ancient buildings, had rain water pipes inside the wall section, often replaced in second times by external ones. If one internally rainwater pipes is corroded and cracked, the leaking of water inside the masonry can produce a decay concentration (Fig 41).

Fig. 41: Thermo vision applied to detect a vertical rod behind the plaster.

The information of this case is obtained from reference [11]

Thermo vision is also an interesting method for mapping the voids in the external walls belonging to abandoned rainwater pipes. With this method it was possible to detect some of these elements also where the plaster is not showing any evidence of decay (Fig 42).

Fig. 42: example of thermo vision result showing an abandoned rainwater pipe hidden by the plaster on the right side of the new external element.

Material and construction techniques of some columns

Two types of columns were investigated at Villa Litta; stone (granite) columns of the porch and two columns in an internal room subjected to modification in the fitness.
The granite columns were subjected to ultrasonic tests to find eventual defects, flaws or cracks. The results showed that the columns are very sound and therefore they don't need any repair, also they do not show signs of surface deterioration.
The two internal columns were covered with a plaster called 'marmorino' made of gypsum, lime and finished with a special treatment in order to simulate a marble column. To understand the internal structure, the columns were studied using the radar method and the results indicate that they consist of a reinforced concrete core covered by a layer of 'marmorino' of about 5 cm in thickness.

Figure 43 demonstrates the conclusion. The radar test was performed vertically by moving the 1GHz antenna from to bottom on one side of the column. The data was processed by removing the background signal. This enhances the diffractions produced by the metal rings distributed in the column as indicated in figure 43. Since the column diameter is not constant the antenna is not oriented horizontally and for this reason the metal rings seem not horizontally aligned. Actually, this is an expected artifact produced by the antenna orientation and the correct interpretation of the diffractions consists of horizontal metal rings.

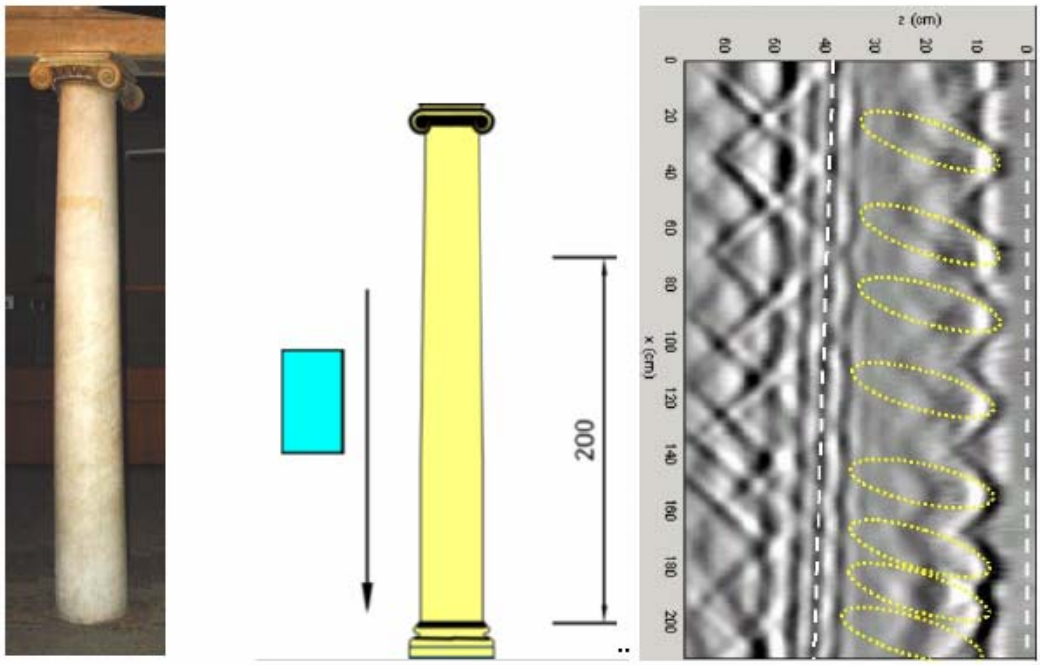


Fig. 43: Detail of an indoor column (left), radar profile executed with a 1GHz antenna running vertically from top to bottom. As the diameter of the column increases as the antenna moves down so the opposite side reflection is not parallel to the profile surface (white dashed line) and the diffractions produced by the metal rings (yellow dashed circles) are not horizontally aligned.

The information of this case is obtained from reference [11]

CASE 12
Civic Tower in Vicenza, Italy

Introduction

The Civic Tower of Vicenza is a slender structure with a base section of 6.2x6.5 m and a height of about 82 m. The tower ends with an octagonal tip, a lantern and a small dome. The thickness of the masonry walls vary from about 250 cm at the base to 140 cm at the level of the octagonal tip (about 47 m), whereas this one has walls of about 75 to 80 cm thick. The West side of the structure leans against the Municipality building for its first 18 m. Figure 43 shows a view of the Tower and the adjacent Palladian Basilica.

The Tower construction, by the Bissari family, started in 1174 and ended with the raising of the first belfry, at about 47 m of height. In 1311 the walls of the first belfry were filled (the arches of the original belfry can be still seen in the masonry texture). And the tower was raised till the first upper section, at a height of 57 m. The new belfry, therefore, is exactly on the top of the previous one. The belfry is standing on four masonry pillars (Fig 44). The pillars have a polygonal pseudo-squared section, with sides of about 150 cm in length. Four multi-colored windows with two lights and with small columns complete the belfry. All these elements are made of Vicenza Stone and were put in place only in 1444-46 and subsequently restored in 1921.

In 1347 a strong earthquake struck Vicenza, but the town chronicles do not report of significant damage of the tower. In the first half of the 15th Century (1444-46) the octagonal tip and the top were added above the belfry, and the tower reached its current height of 82 m.

Fig 43: The Civic Tower of Vicenza and the Palladian Basilica

The information of this case is obtained from reference [12]

Fig 44: View of the masonry pillars of the belfry

Damage Description

The damage state is characterized by the presence of localized deep cracks and diffused micro-cracks and a deterioration phenomena was detected. The main deep large cracks had a vertical and sub-vertical trend. Many of them were located near the tower corners and had caused the detachment between orthogonal walls and the partial collapse of the masonry edges (Figure 45.a).

Evidence of complete or partial detachment of the external leaf and of local buckling of the masonry was found also in some areas of the façades (Figure 45.b) and thin vertical cracks was interpreted as evidence of a probable creep phenomenon, developed under heavy dead loads.

This behavior, with time can cause a continuous damage of the masonry until its sudden collapse. Finally, local deterioration of the materials related the poor quality of the masonry texture was found (Figure 45.c).

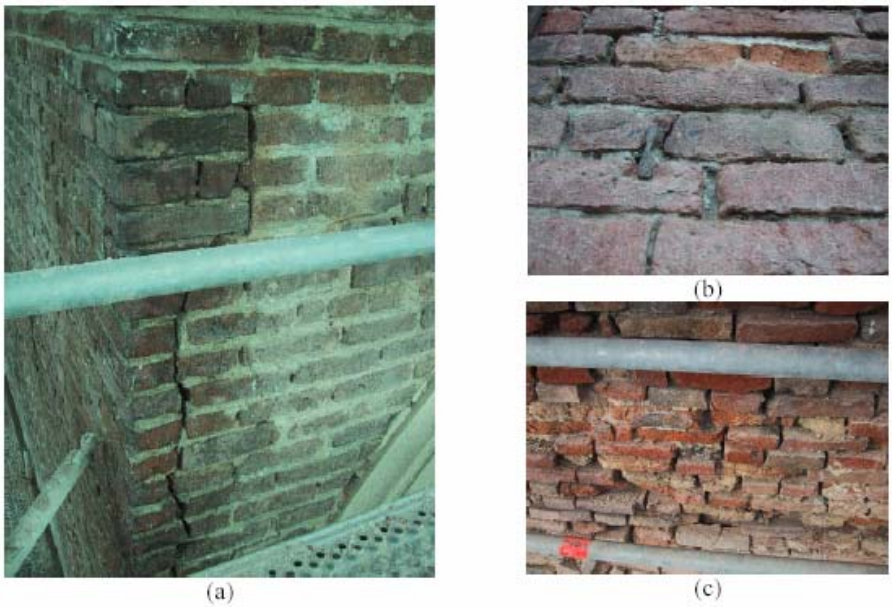


Fig 45: Vertical crack at a corner (a), deterioration of the external leaf of the masonry walls (b) and effect of the harshness of the texture (c).

The information of this case is obtained from reference [12]

Summary

In order to improve the safety conditions of the tower, a series of repair and build up techniques were planned, aimed to strengthen the masonry walls and enhancing the global behavior. One of the interventions consisted of grout injection at the base of the tower and on the belfry pillars.

Two horizontal tomographies of the pillars at a height of 1.40 and 3.05 m and two vertical one were carried out before and after the grout injection. Figure 46 shows the scheme of a horizontal section tested by NDT.

The horizontal tomography that was carried out before the injections at the height of 3.05 m, showed the lowest values of sonic velocities (600 to 750 m/s) in correspondence of the masonry triangular filling prisms.

This demonstrates that this portion was completely disconnected from the main body of the pillar. The remaining part of the pillar was characterized by values of sonic velocities between 1400-1600 m/s (Figure 47.a). After the injection, the mean increase in sonic velocity was about 30% (Figure 47.b and c), this means that a variation in consistency of the masonry occurred.

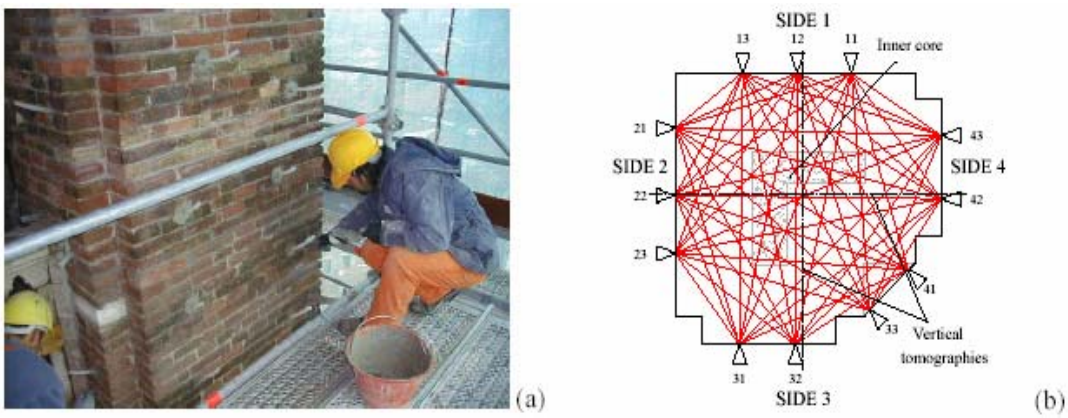


Fig 46: View of the grout injection intervention (a);
plan of a pillar with the scheme of a horizontal tomography (b)

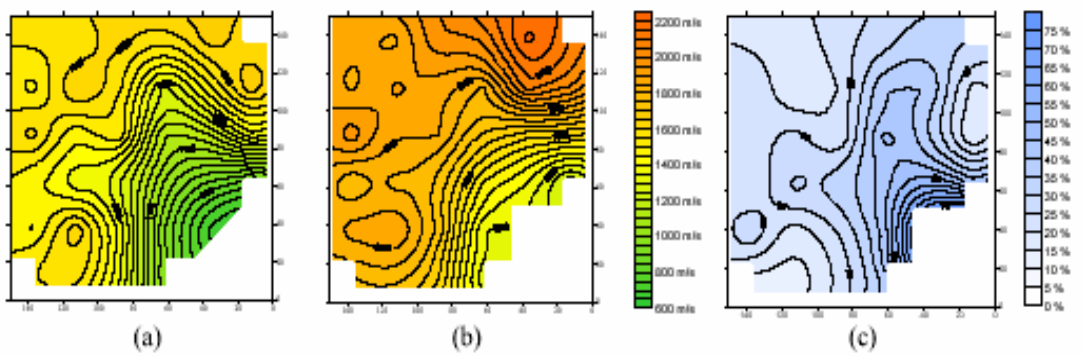


Fig 47: Horizontal tomography at 3.05 m: before injections (a); after injections (b);
percentage increase of sonic velocity (c)

During the repairs, the prismatic filling elements were removed. Therefore, in the post-injection condition, the section was characterized by a higher "apparent" increase of sonic velocity, localized in the corner of the section.

And the highest increase in sonic pulse velocity measured on the horizontal section at 1.40 m of height (Fig 48.a and b) was detected exactly in the portion of

masonry that received the highest quantity of grout (Figure 48.c). Vertical tomographies mainly confirmed the results obtained on the horizontal sections.

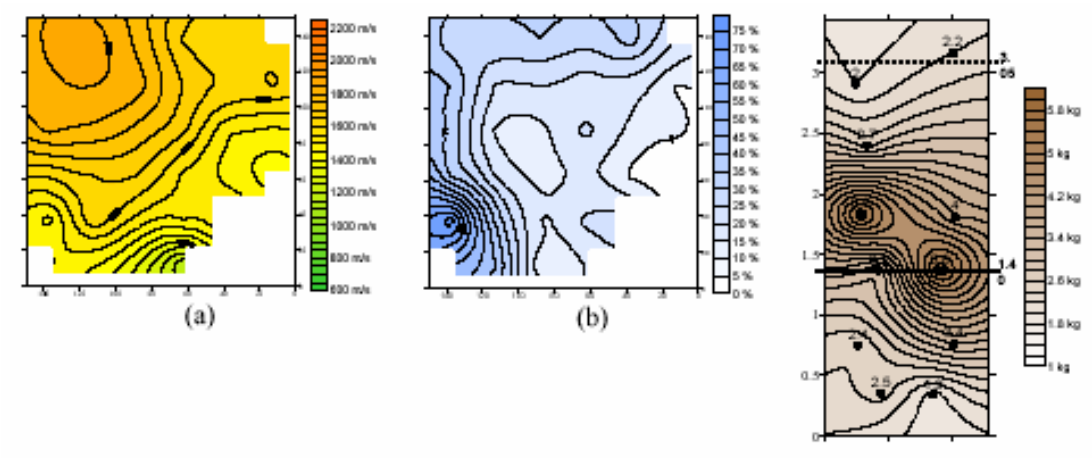


Fig 48: Horizontal tomography at 1.40 m before injection (a),
percentage increase of sonic velocity after injection (b),
quantity of injected grout on side 2 of the pillar (c).

Conclusions

Preliminary non-destructive (ND) or minor destructive (MD) tests allowed to clarify the main causes affecting the structure and to diagnose the particular deficiencies in the different constructive elements and materials composing the tower.

The masonry structure was characterized by a diffuse damage condition and by very high local compressive stresses that were dangerously reducing the safety level. Besides the global reinforcing measures, specific repair and strengthening intervention were designed and executed with particular attention on the choice of the most compatible materials and techniques, in order to improve the structural performances of the tower and assure a suitable durability.

Due to the high risk of brittle collapse mechanisms that may happen to the masonry, especially under high compressive load conditions, the bed joints reinforcement technique was applied, together with injections and limited rebuilding in different portions. The use of sonic tomography in the injected zones (in particular in the belfry) confirmed their validity in qualifying the masonry sections and evaluating the real effectiveness of the intervention.

CASE 13
Pisece Castle, Slovenia

Introduction

The pisece castle in Slovenia (Fig 49) was built in the first half of the 13th century as defense fortification against the Hungarian danger by the archbishop of Salzburg. The oldest parts belonging to this building phase are the Romanic tower, the peripheral walls and the Romanic chapel. It belonged to the knights of Pisece until the 14th century.
In the 1595 the castle was sold to Inocent Moscon, and his heirs were owners of the castle until the end of the Second World War, when it became property of the state. Since the 1998 the castle stands empty. Important interventions were introduced in the 16th century with the addition of the wide circular tower in the south west side. Successively, other architectural details were built, such as the small tower over the chapel in the baroque time and the neoromanic and neogothic decorations in 1867.

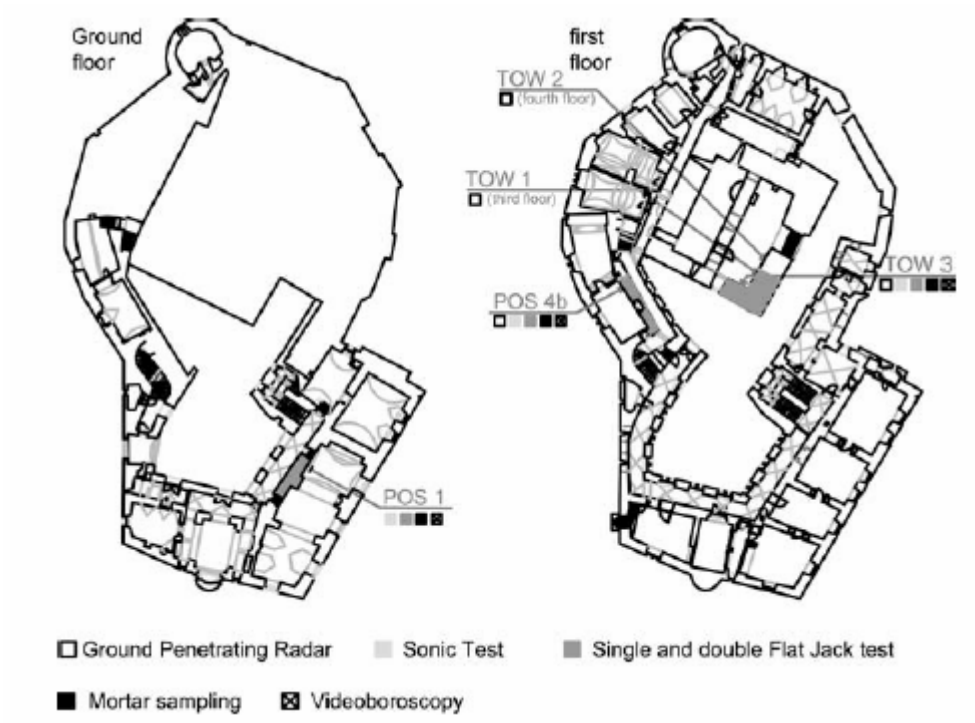


Fig 49: Plan of the castle.

Summary

Testing area: POS1

In this position the consistency of the wall section was unknown. The results of a flat jack test show how in some cases preliminary application of sonic tests and radar is useful to control eventual irregularities like the presence of chimney flues or other voids. The unknown masonry morphology affected the results. Sonic tests, in fact, revealed the presence of a cavity behind the tested area. This is very clear considering the low sonic velocity measured (Fig 50).

The videoboroscopy inspection shown in figure 51 confirms this observation, revealing the presence of a real fireplace. The superficial brick masonry texture appears irregular (Fig 52).

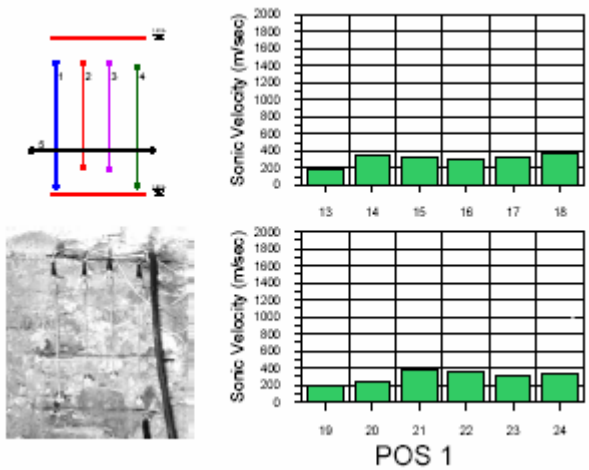


Fig 50: Sonic test results

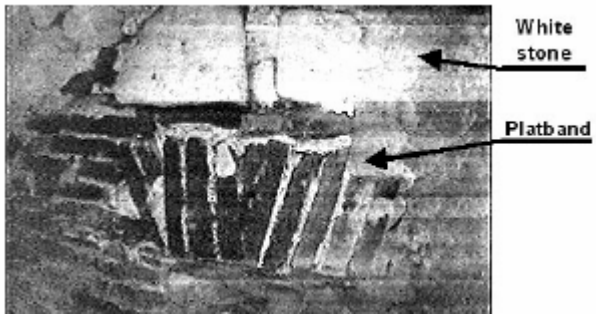


Fig 51: Videoboroscopy of the masonry in the position POS1

Fig 52: Detail of the masonry in the position POS1

Testing area: POS4

The wall of the tested area POS4 appeared very inhomogeneous with signs of past interventions, the first inspection was made by radar profiles (Figs. 53 and 54) that clearly showed a position were the signal could not pass through the wall section although the thickness is not particularly large (about 90cm). Profile and time acquisitions were carried out with 1 GHz and 500 MHz antennas. The time acquisitions were performed in positions 5 to 10 placing a metal shield on the backside of the wall

during the second half of the experiment. Moving from left to right positions, the shield reflection is absent in positions 5, 6 and 7, then it appears as a week signal in position 8 and finally as a good signal (positions 9 and 10).

To show this transition, the radar data collected at positions 8, 9 and 10 are plotted in figure 53 (right). Where the radar signal could penetrate, an average velocity of 11cm/ns was measured which is rather common value for a stone masonry.

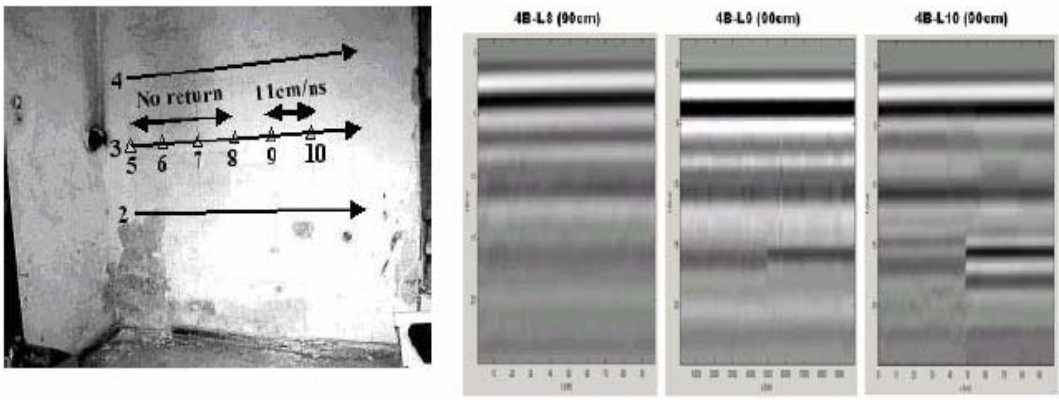


Fig 53: Geometry of the radar survey (left) and time radar data (right) acquired at positions 8, 9 and 10. A metal shield was placed on the backside of the wall during the second half of the experiment to enhance the backside reflection.

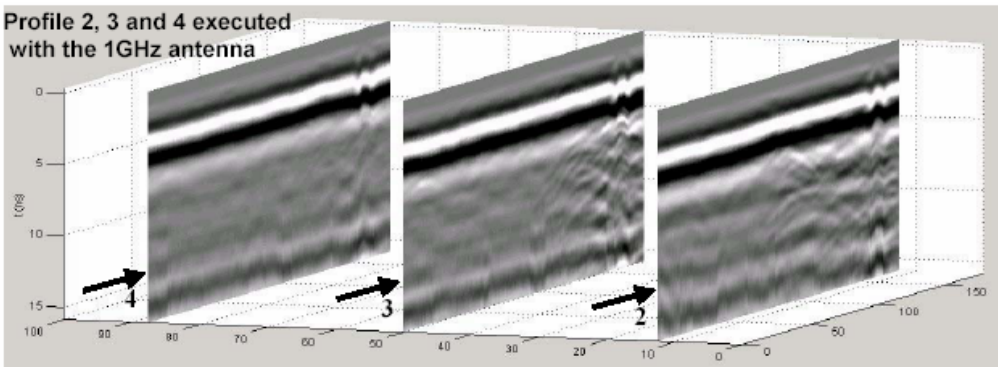


Fig 54: results of the radar test along the profile 2, 3, 4 of Fig. 53 (right)

Figure 55 below shows the sonic velocity map compared to the non-return area revealed by the radar test. The area where the radar was enable to reach the backside of the wall is associated with low sonic velocities. This indicates the presence of a void or a deteriorated masonry that results in a poor elastic response for the sonic test and in a high absorption effect for the radar test. The profiles acquired by high frequency radar (Fig 54) confirm a low penetration on the left side where no reflections and/or diffractions appear after the background signal.

The information of this case is obtained from reference [13]

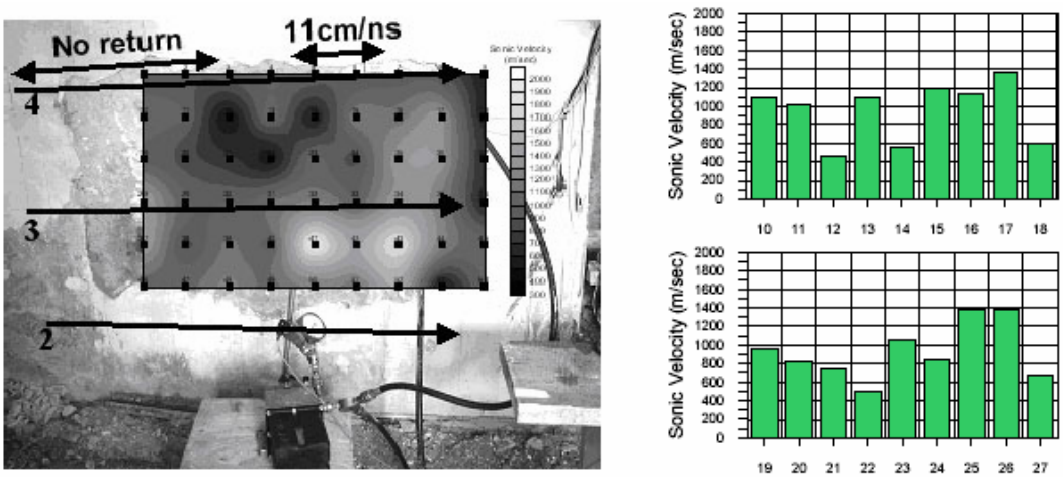


Fig 55: Results of the sonic test in the position POS4 (right).

Testing area: TOW1, TOW2 and TOW3

Positions TOW1, TOW2 and TOW3 are part of the tower structure that seems to be made by regular stone blocks. It was expected that this masonry typology should provide different and better results compared to the others walls. However the tower is highly affected by deep and major cracks, also at the higher floors (Fig 56).

Thus, an accurate crack pattern survey was carried out on every side of the tower. At the highest levels (third and fourth floors) radar tests were executed with medium and high frequency antennas to explore the morphology of the walls. In spite of the huge thickness of the wall (2.3 m at the third floor and 2 m at the fourth one), even the 1 GHz antenna could penetrate through the whole section and could show the signal reflected by the backside.

Average velocities of 12cm/ns and 11cm/ns were measured at positions TOW1 and TOW2 respectively. From these values and from the horizontal profiles executed at these levels, as shown in figure 57, it can be excluded the presence of voids or slow material inside the wall section.

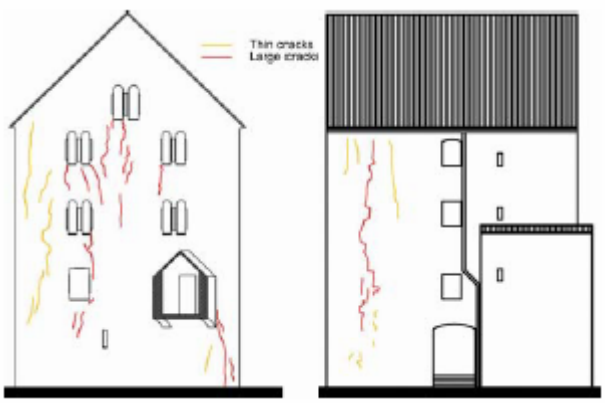


Fig 56: Crack pattern survey of the Tower in the south and east side.

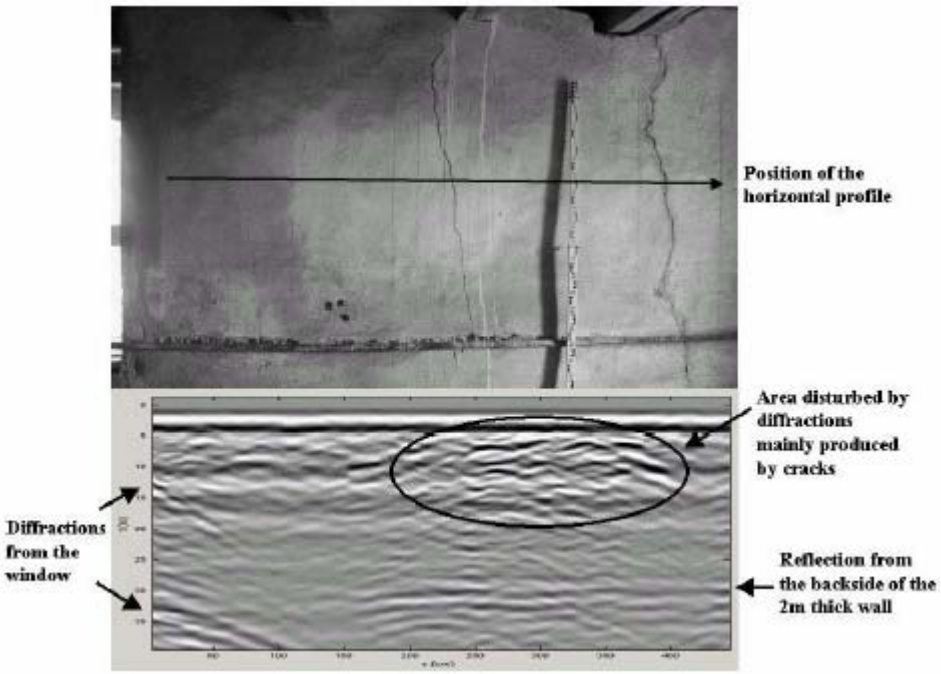


Fig. 57: Position of one of the horizontal profiles collected at the fourth floor of the tower (TOW1). The independent radar section is shown below. Some diffraction from main cracks and the reflection from the backside can be observed. The diffractions at the left side are lateral artifacts produced by the window at the left of the profile.

The information of this case is obtained from reference [13]

CASE 14
The Altes Museum, Berlin (Germany)

Introduction

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 58 shows a view from the Lustgarten. The building was designed with an atrium containing pillars relevant 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.

Investigations have to be performed to assure structural integrity and to provide a basis for a sustainable and considerable conversion of the building. With radar, geoelectric, microseismic, sonics, impulse-thermography and flat-jack, in this study different testing problems have been solved.

Fig 58: Altes Museum in Berlin-Mitte.

Summary

Structure columns in the entrance hall

Investigation 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. 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.

a) 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 59 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.

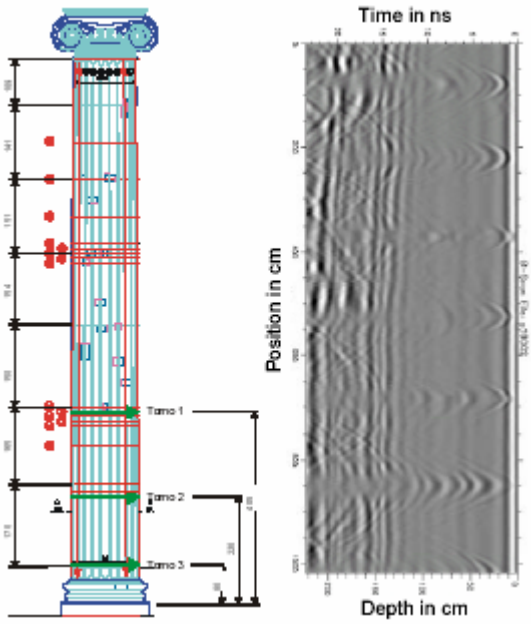


Fig 59. Investigated column (left) and radargram of a vertical trace (right) recorded along the total height of the column with the 900 MHz antenna. The hyperbolas are related to the joints between the drums.

b) 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 (Fig 60). 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 60, 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.

The information of this case is obtained from reference [14]

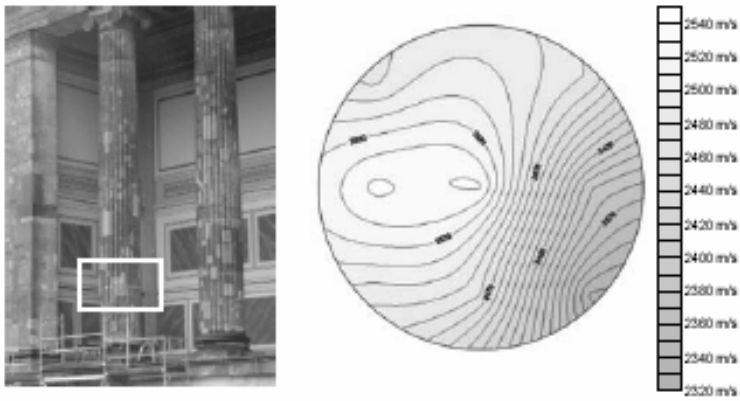


Fig 60: Investigated column (left), tomographic reconstruction of the section (right).

Plaster detachments at 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 sand stone 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.

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 2000W avoiding temperatures at the surface higher than 50ºC.
The infrared camera is an Inframetrics 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.

To access all the 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 61, right after 5 min of heating.

From comparisons with results obtained from 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.

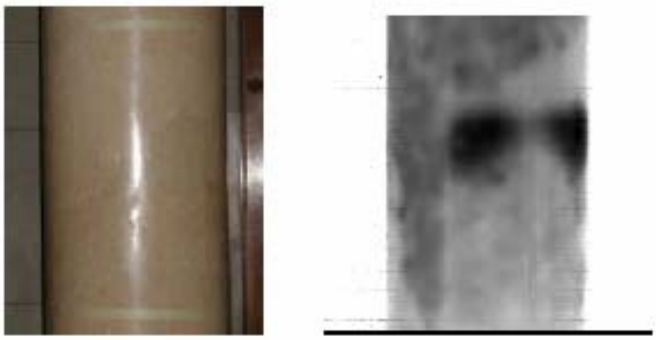


Fig 61. Photo (left) and phase image (right) of the same area of the column after a heating of 5 min. The delaminations appear in the phase image as dark areas.

Properties of a carrying wall in the cellar

Investigation of the structure and moisture content of an inner carrying wall in the cellar (Fig 62). 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 misture.

a) Sonics

Direct sonic tests were carried out on two positions of the load bearing wall in the cellar (P1 and P2). In correspondence to the flat-jack tests, the tests were carried out on a 6x8 grid (six rows and eight columns, 15 cm x 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 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 63.

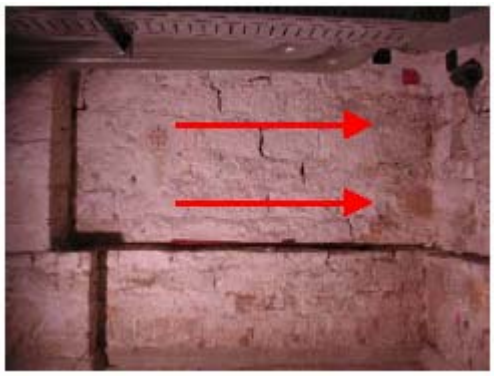


Fig 62: Part of the investigated inner carrying wall in the cellar showing a large crack. The arrows mark the position of the radar traces for tomography.

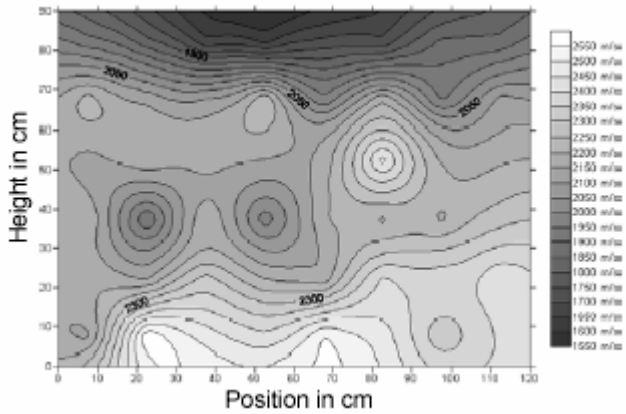


Fig 63: Sonic velocity distribution as obtained from direct tests at position P1.

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. This trend was observed 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 64.

The values of sonic velocities are typical of masonry in fair good condition . 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 .

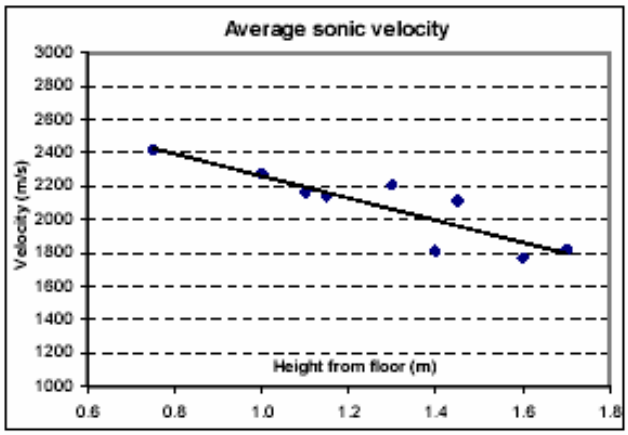


Fig 64: Sonic velocity measured in direct tests on test area P1 and P2 versus height from floor.

b) <u>Geoelectric</u>

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) . In figure 65, 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.

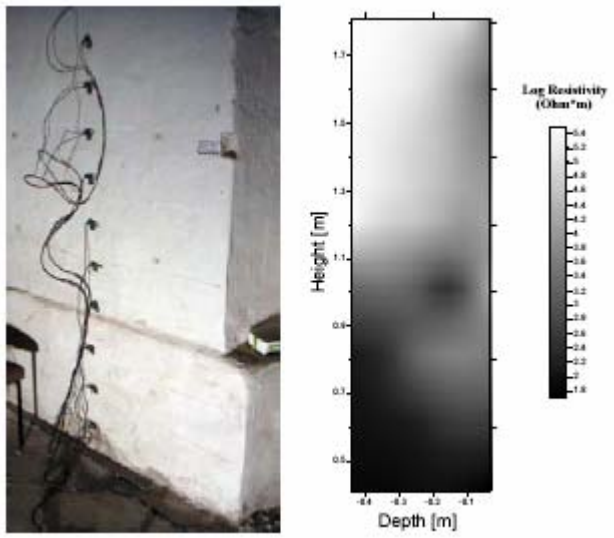


Figure 65. Left: Electrode array for geoelectrical measurements. Right: Reconstructed electrical resistivity distribution in the wall calculated from geoelectrical measurements (T2).

Other Worldwide CASES

In the following historical monuments NDT were used as a complimentary procedure to detect defects and/or to check the efficiency of a repair procedure that the investigation phase recommended.

The SPHINX, EGYPT

The Great Sphinx, carved out of limestone of the Eocene Mokattam Formation, standing sixty-six feet (twenty meters) high and 240 feet (seventy-three meters) long, sits on the edge of the Giza Plateau (just west of Cairo, Egypt), east of the three great pyramids. Most Egyptologists currently attribute the carving of the Great Sphinx to King Chafre (Chephren) of the Old Kingdom's Fourth Dynasty, in approximately 2500 B.C. by various chronologies. In addition the so-called Sphinx Temple (situated directly in front of the Great Sphinx) and Valley Temple (on the Sphinx's right side) are also generally attributed to Khafre.

As presently viewed, the Great Sphinx presents the image of a leonine body bearing a human head in a names head-dress.

Nineteen refraction profiles, two reflection profiles and a refraction tomography data-set were collected on the Giza Plateau during April 1991. The seismic work performed around the base of the Sphinx consisted of hitting a sledgehammer on a steel plate, thus generating energy waves that entered the rock, traveled into the subsurface, and reflected and refracted off of subsurface features. In the Sphinx enclosure, refraction profiles gave us information on the subsurface weathering of the rock. In addition, we located various voids, cavities and other subsurface features (the subject of a paper currently being prepared by Dobecki and me). For instance, the apparent thinner weathering around stations 150 to 160 feet (forty-five to forty-nine meters) on seismic line S2, taken along the south flank of the Sphinx, may not be real; it is probably due to induced resonance caused by a subsurface void.

The information of this case is obtained from reference [15]

The STATUE of LIBERTY, USA

Despite inexorable problems of aging, the Statue of Liberty's generally sound condition by the 1980s was a testament to the genius of her creators, sculptor Frederic Auguste Bartholdi and engineer Alexandre-Gustave Eiffel. However, a century of corrosion, weathering, pollution, and almost two million sightseers a year had taken their toll and a major restoration became essential.

The massive 1986 restoration was undertaken by a team of architects, historians, engineers, and labourers who toiled for two and half years to shore up the statue.

Inside the Statue, American craftsmen turned their attention to the 1,800 iron armature bars that formed the vast interior strap work that supports the Statue's copper skin. The armature was part of Eiffel's innovative structural design, which allows the skin to expand or contract with changes in temperature or with shifts in the wind. Through galvanic or electrolytic corrosion, some iron bars had eroded to as little as a third of their original thickness. Workers had to replace 10,000 linear feet of armature weighing a total of 35,000 pounds, along with 30,000 copper rivets. The job took 18 workers 12 months to complete, since maintaining the structural integrity of the Statue meant that they could only remove and copy a maximum of 12 bars in any given 24-hour period.
Using the original armatures as templates, workers fashioned exact duplicates from non-corrosive stainless steel with a forming press, hammers, and acetylene torches. They heated the shaped bars to 1,950°F for five minutes, then cooled them by water quenching to reduce brittleness. Finally, they inserted Teflon insulating strips to prevent the iron from touching the statue's copper skin. All together, workers replaced all but ten armature bars in the right foot, which remain in place as examples of the original puddled iron structure.

The information of this case is obtained from reference [15]

PARTHENON, GREECE

The principal challenge in restoring the Parthenon was undoing the effects of earlier accidents, natural disasters, and poor restoration, not to mention millennia worth of punishment from rain, pollution, wind, and visitors.

The most damaging accident at the Parthenon occurred in 1687, when the Turks used the structure as an ammunition dump. During a Venetian bombardment of the Turkish-held Acropolis, a powder magazine in the building blew up, destroying its centre. More damage occurred in the wake of a 1981 earthquake. Previous restoration has wrought its own damage as well. Workers had to bring down 300 or so stones, for instance, that previous restorers had repositioned at random on the lateral walls in 1842-44. They will soon reconstruct the lateral walls using authentic stones.

The most recent restoration at the Parthenon, still underway, is thorough and historically accurate. This new effort has as its aim the conservation of the structure and surfaces, maximum protection for the sculptures, correction of the position of previously restored stones, and additional restoration of certain parts, mostly using fallen stones preserved in situ.

For the treatment of marble, workers have used both the varied tools of traditional marble sculpture and modern electrical tools. The latter include two electrical cranes, lifting devices, a pantograph for marble cutting, and metal scaffolding. All told, they brought down ancient marbles weighing in total approximately 300 tons for conservation before repositioning them in their original places. They have used titanium to reinforce broken stones and have designed clamps in such a way that, in the case of excessive stress, the clamps break before the marble

The information of this case is obtained from reference [15]

The METROPOLITAN Cathedral, MEXICO

Construction of the Metropolitan Cathedral started in the second third of the 16th century. It was built on the ruins of the pre Hispanic city. In order to be able to understand the nature of the soil on which it was built, one has to imagine the configuration of the land after thirty years of moving construction materials over the area. It is known that the construction of the city of Tenochtitlan required a great deal of preparatory work in the area of the islands, and required large loads of earth for the construction of the terraces and other buildings. This gives an idea of the underlying strata in the area, it is possible that under that, there are ravines and gullies of different depths that cause the different thickness of different points of the subsoil.
In other words the cathedral is sinking and this process continues to this day.

The general objectives of the cathedral restoration is to restore the geometry of 40% of the sunken areas, this is equivalent to the sinking experienced 60 years ago.

The information of this case is obtained from reference [15]

Chapter 4

Remarks

- From the examples that we have seen it can be concluded that NDT proved their efficiency. In all the cases the results were compared with results obtained from MDT as flat jack tests and as one can see they reached to the same conclusions. Although that, it's rare or uncommon to find a repair project of historical buildings that depends totally on NDT. This may be due to difficulty in transform the signs of the NDT apparatuses to data that can be understood.

- NDT are getting big support in most of the developed countries, new techniques are found developing the old ones, 3D data can now be obtained, and the calibration becomes more and more easy.

- The examples chosen for this study show that NDT techniques are more widely used in Europe, taking into account that the USA hasn't an old history heritage. Unfortunately, it was difficult to find information or contact persons from Asia and Africa regarding the methods that they use in the diagnosis of their historical buildings that are the oldest of the human history. Little information about the conditions of the oriental heritage in known or published.

- Among the European campaign supporting the use of NDT, ONSITEFORMASONRY is the widest and most important. It is the result of the collaboration of several European countries that had tested several historical buildings in different countries. They developed new techniques based on old ones and will present a software which has been further developed for tomographic reconstruction called "Tomopoli", this program still under development and it's not on the market yet.

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