Strategies for the assessment of historic masonry structures

L. Binda, C. Maierhofer

Abstract

Historic buildings and centers, an important part of our cultural heritage, need to be preserved. In order to reach this goal, a deeper knowledge is needed. The main objective of an EC project involving 15 partners is the development and improvement of methodologies for the evaluation of structural and material properties. These methodologies are based on non-destructive (NDT) and minor destructive (MDT) testing methods that are adapted and optimized to assess selected damages and testing problems. The achieved results of the project are outlined.

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1. Introduction

Historic buildings, no matter whether they are famous monuments, so-called “minor” architecture, or even the vernacular, represent an important part of our cultural heritage. The patrimony that is the living memory of a country’s history and development must be preserved as much as possible as an historic document of our past. Unfortunately, wars, dramatic events (e.g., earthquakes, floods, slides, and fires), abandonment, and lack of maintenance are constant menaces to the immense patrimony in every country of the world.

Much experience in the restoration and rehabilitation of damaged masonry buildings has been accumulated in Europe, as in other countries, over the past fifty years. In some cases, reconstructions of destroyed monuments and historic centers were the consequence of wars (e.g., the reconstruction of the center of Warsaw). In others, restorations were carried out after a long period of misuse and lack of maintenance following the Second World War. During these decades, major earthquakes have occurred in most Mediterranean countries, destroying monuments and dwellings and leading to the demolition of badly damaged constructions or to quick reconstructions of dwellings and villages that were wrongly considered as minor patrimony on which invasive intervention could have been made.

In the last decades, the term “restoration” has often been substituted by the term “conservation”, meaning that the historic buildings should first be preserved as much as possible; this preservation need has also been extended to minor architecture, considering the historic centre as a monument on its own.

Also, in the case of damages due to earthquakes or other calamities, the word "adequate" (meaning the possibility of invasive interventions in order to reach the safety coefficients adopted for new buildings) was substituted by the words "improve by minor repair and strengthening." This policy was assumed when failures of some repair and strengthening techniques were seen after additional earthquakes.

Prevention and rehabilitation can be successfully accomplished only if a diagnosis of the state of damage of the building has been formulated. Therefore, it is clear that knowledge of the building construction should be deep in order to understand the role of all its features and details, the characteristics of the materials, and of the structure and its eventual evolution in time. Besides the damage controls and investigation before the intervention, the effectiveness of the repair techniques should be controlled during and after the repair work as well. The investigation also may require the long-term monitoring of the structure.

The diagnosis should result from an experimental investigation on site and in the laboratory that aims to define the characteristics of the materials and of the structure itself from the structural analysis based on appropriate mathematical models. The on site investigation must be as non-destructive as possible and provide information with a high level of precision. The work carried out within the frame of an EC Contract (ONSITEFORMASONRY) is presented here, which will be the basic work for a new RILEM TC on the assessment of masonry structures.

2. Design for Investigation and Diagnosis

Historic masonry buildings, whatever use is made of them at present or in the future, have to show structural stability. From the point of view of the risk for human life, they may belong to several categories as isolated buildings, buildings in an urban area, or buildings open to the public or open to large assembles of people (e.g., cathedrals, theatres, etc.). For each of these categories a certain amount of risk, as for new buildings, has to be accepted.

An appropriate and rational use of the structural analysis can help in defining the eventual state of danger and in forecasting the future behavior of the structure after repair. To this aim, the definition of the mechanical properties of the materials, the implementation of constitutive laws for decayed materials and of methods of analysis for damaged structures, and the improvement of reliable criteria are needed.

In the case of historic buildings, appropriate constitutive laws for materials are implemented with great difficulty due to the inhomogeneity of the masonry structures. Masonry is a composite material obtained with complicated techniques of construction (e.g., single leaf, multiple leaf walls) and can be modeled with great difficulties. Furthermore, the classes of buildings mentioned above usually correspond to different typologies and to different behaviors of the structure: a) isolated buildings, b) buildings in a row, c) complex buildings, d) towers, e) palaces, f) churches, and g) arenas. The modeling of these structures can be very complex. In fact, when the structure is a complex one, only linear elastic models are easily usable. Non-linear models or limit state design complex models are difficult to apply, as noted above, because the needed constitutive laws for the material are seldom available.

Furthermore, when the complexity of the structure is given by its evolution over the centuries from a simple typology to a more and more complex volume (Figure 1) [1], modeling has to take into account all the vulnerabilities accumulated during the subsequent transformations.

The same difficulties can be found in choosing the techniques for repair and strengthening. Without a doubt, many of the incompatibilities and mistakes made in the recent past, due to lack of knowledge, could have been avoided if a better investigation of the materials, of the structure, of the existing damages, and of their causes would have been carried out.

The designer, who is in charge of the selection of the available techniques and procedures, and of the technically and economically most correct method to define the

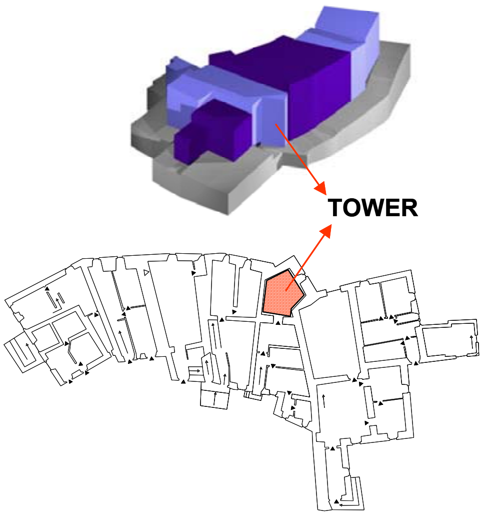


Figure 1 A complex building in an Umbria village and its evolution

state of preservation or damage of the structure, faces several difficulties.

Figure 2 shows, as an example, which information is available from in-situ and laboratory surveys and how it can constitute the input data for the structural analysis. When the design of the survey is available, the conclusions from the experimental and numerical investigation will diagnose the real state of the structure.

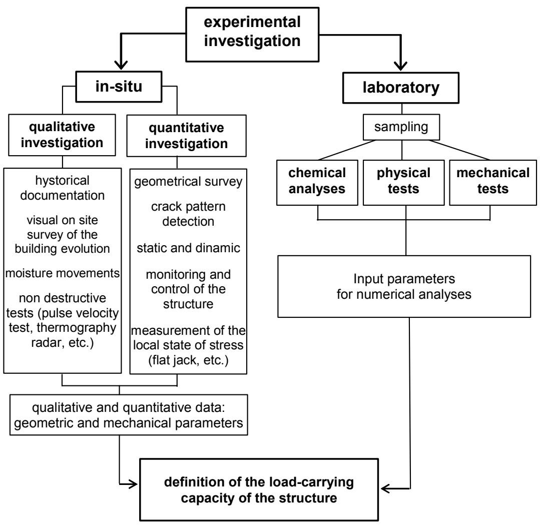


Figure 2 Finalization of the experimental survey to the structural analysis

The designer should remember that every investigation has its cost; it is evident that every single operation must be carefully designed and optimized to obtain the desired results. Therefore, different levels of detail in the investigation should be considered also as a function of the available resources

3. Procedures for Investigation

The careful preparation of the investigation together with a precise description of the problem is a basic condition of every successful NDT (non-destructive techniques) and MDT (minor destructive techniques) application. It is necessary to take into account all available information and documentations about the object of investigation [2].

Knowing the task of the investigation as accurately as possible is necessary to get reasonable and reliable results. Therefore, it is essential that the main elements of information about the building are available and evaluated before NDT or MDT investigations are started. The information includes all data, which is based on inspection: the verbal, photographic, and graphic documentation, description of the building or structure (allowance and detailed mapping of the building), climate measurement reports, and descriptions and mappings of damages. The evaluation of all kinds of archival materials concerning the building and the region (e.g., information about prior earthquakes or floods) is required. In addition, documents concerning geological, hydrological, and biological conditions should be taken in account. An accurate evaluation of all available older material concerning the building has to be done in order to limit the technical complexity and the cost of more extensive researches. In each case, there are four questions to be answered in order to select the adequate investigation technique and to develop a fitting investigation strategy:

- What information is needed?
- With what accuracy?
- What is the method to fulfill the needs?
- Which decision should be made, depending on the test results?

Exact geometrical, crack pattern, and damage surveys of the building in a large scale are needed for every NDT and MDT application to determine the investigation area and to document the measuring traces and the results of the measurements. This is necessary to make measurements repeatable and interpretable. It makes sense to check the requirements of all involved experts in the beginning of the building project in order to avoid mapping mistakes.

Moisture inside the masonry structure may influence the NDT measurements. Some methods (e.g., radar and other microwave techniques) do not work properly or with limited performance if there is moisture inside the structure. On the other hand, these and other methods are suitable to measure the distribution and concentration of the moisture inside the construction. Therefore, again, the question determines the standard of the investigation and the required information.

4. Where is the Application of NDT and MDT Methods Recommended?

The respect for the answers of the previous questions avoids invasive interventions on historical structures as far as possible. Building fabric of high cultural value and protected buildings should not suffer destruction. For this reason, NDT should be generally preferred and an iterative approach is recommended [3]. In any case, the first step is the acquisition of all available data concerning the building and its history. Archival studies do not need any intervention in the historic building fabric. In the same way, mathematical methodologies like structural modeling can be characterized as non-destructive techniques even if they are based on material characteristics, which are gained from MDT (e. g., flatjack) and minor invasive investigations (e.g., core extraction).

NDT is a very good way to do a first survey of the possibilities of planned future interventions or changes to the architecture. Some of the investigative techniques provide clues to hidden voids or joints between parts of the building, which originate from different building periods. Others are useful to find out characteristic data for structural assessment. NDT can be used to detect hidden elements of the construction as metal anchors or beams or elements consisting of materials with different properties. Also, in cases of a very weak structure when even the smallest interventions are risky, as is often the situation after earthquakes or explosions, NDT is a suitable means for investigation.

NDT also offers possibilities for quality assurance after the intervention. For example, remaining voids, present after the performance of injections, can be satisfactorily shown.

On the other hand, NDT offers possibilities to identify more or less delicate and worthwhile areas of constructions if taking samples cannot be avoided (e.g., to mark out salts inside the building material). If, for example, a thermography indicates areas of repair, the samples for salt analyses could be taken first in these areas.

In any case, it is necessary to measure costs and benefits. NDT and MDT are not necessarily more expensive than common methodologies of investigation. It has to be decided in individual cases which technique should be applied. The advantages and disadvantages and the costs have to be taken into account. So, in any case the cost for reconstructions following even small interventions should be considered.

The ONSITEFORMASONRY project (On-site investigation techniques for the structural evaluation of historic masonry buildings) developed within the EC Contract Project EVK4-2001-00091 that involved ten partners from different countries (Germany, Czech Republic, Italy, Slovenia, Spain, and Sweden) to respond to all the previous questions and to produce guidelines for the professionals who face the investigative and diagnosis problems.

The work carried out within the project and the results are briefly described in the following pages with the aim of justifying the request of a new RILEM TC on the assessment of masonry structures.

Some of the following phases developed within the project are described in the next sections:

- Identification of typical damages and testing problems of historic masonry

- Development and optimization of non-destructive testing (NDT) and minor destructive testing (MDT) systems for on-site building diagnosis
- Design and construction of test specimen for testing and calibration of technologies
- Development and optimization of structural models
- Laboratory and on-site testing and validation of measurement systems and structural models
- Ten case-studies, distributed throughout Europe, have been carried out, describing measurement campaigns with various testing problems and applications of combined NDT and MDT systems

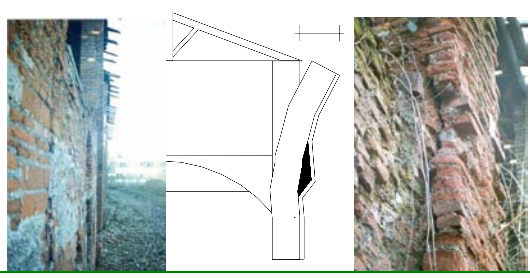
5. Damage Catalog

To achieve a wide base of knowledge for the investigations ONSITEFORMASONRY was aiming at, a first essential step was to determine which types of damages typically affect historic masonry.

All partners contributed to this state of the art project by providing their case studies of former or ongoing investigations concerning historic masonry. These include the characterization of the structural element, a description of the damage, and the building materials, the probable origin of the damage and a significant picture, completed by a proposition of applicable NDT methods and relevant measurement parameters. While collecting the case studies, it became apparent rather quickly that the term Damage Catalogue would need to be extended, since many investigations dealt with questions about the recognition of structures (one- or multiple-leaf walls, thickness of walls, presence of voids, etc.), which is a major aspect in restoration and preservation of monuments and historic buildings and which is as important as the survey of damages [4].

The collection of case studies is now called *Standard Damage Catalogue and List of Structural Typologies and Related Requirements* and comprises currently more than 100 examples. An example of damage description is given in Table 1.

Table 1 Damage description of cracks from the *Standard Damage Catalogue and List of Structural Typologies and Related Requirements*

DAMAGE: Vertical cracks on the middle part of a brick masonry built in column causing detachment of a layer.
Structural element*: Solid masonry built in column.
Description: Vertical cracks are evident on separating the external part of the column.
Origin(s): Due to excessive horizontal and vertical loads on top of the column which at first cause rotation of the upper part of the column at the upper floor. The lack of protection caused the rain to go through the column. Salt crystallisation and frost-defrost action caused the loss of material and the detachment (expulsion) of a thick layer of the external part of the built in column.

Measurement Parameters: depth, width and length of the crack over time; geometrical dimension of the pier, masonry composition, deformation, out of plan and inclination of the pier; state of stress; strength., acting loads, radar reflections
Applicable Non Destructive Techniques: geometrical and photographic survey, sonic tests, radar

The documents developed under the supervision of the Spanish partner Geotecnica Y Cimientos S. A. represents thus far more than just a collection of damages. It is a comprehensive classification of problems, questions, and damages related to historic masonry.

The crucial point of the overview is the definition of structural typologies and the classification of damages together with a compilation of measurement parameters needed for their characterization. The structural typologies comprise among others a systematic structuring of:

- Construction typologies (buildings, bridges, etc)
- Structural elements (arch, vault, wall, dome, etc.)
- Singularities of masonry structures (number of leafs, construction technology, history)
- Masonry cross sections (types of wall cross sections)

For an all-embracing assessment of the structures, the chemical, physical, and mechanical properties of the components have to be determined. The measurement parameters necessary for characterization (e.g., mineralogical composition, mechanical properties, dynamical properties, dimension, morphology, etc.) have been compiled and described in detail.

The damages typical for historic masonry have been divided into two main groups:

1. Damages due to material deterioration, including:
   - Moisture and related damages
   - Erosion and other damages due to wind and air pollution
2. Damages due to mechanical effects on the structure, including:
   - Static direct actions (increase and decrease of loads, traffic)
   - Static indirect actions (differential settlements, thermal deformation, etc.)
   - Combination of static direct and indirect actions
   - Dynamic and exceptional actions (earthquake, explosion, etc.)

The *Standard Damage Catalogue and List of Structural Typologies and Related Requirements* offers the user the opportunity to make a first estimation of the extent, the cause, and the kind of damages, and indicates which of the available investigation methods can be used for an evaluation. Relevant measurement parameters are described in detail. Additionally the Catalogue visualizes representative types of damages and thus helps to identify problems occurring in historic masonry.

6. Methodologies and Technical Achievements

6.1 Methodologies

The combination of several NDT and MDT methods like ultrasonics, impact-echo, sonics, microseismic, radar and flatjack can provide more reliability for interpretation of results and for the detection of irregularities like voids, cracks, presence of moisture and/or salt, etc. If a void is detected by more than one method, the presence of this irregularity can be regarded with a higher level of reliability. Furthermore, it can help to clarify the morphology of the structure investigated, in order to give information about the presence of weakened areas and about the state of stress in masonry structures. ONSITEFORMASONRY evaluates the methodologies of various system combinations related to different testing problems.

The main field of application of each method and the developments and optimizations performed during the project are summarized in Table 2.

Table 2 Methods developed, optimized, and applied in ONSITEFORMASONRY

Method	Field of application	Development and modification
Radar (impulse-echo and tomography) [5, 6]	Geometry, internal structure (voids, de-laminations), moisture content and distribution, salt distribution using different frequencies, location of inclusions (metal targets, wood)	Optimization and application for tomographic measurements, tomographic data analysis; Development of a new light high frequency radar antenna consisting of separable transmitting and receiving elements, enabling tomography with enhanced resolution; Development of the positioning system for 3D acquisition
Microseismic [7]	Geometry, internal structure (voids, de-laminations)	Improvements of transmitter and receivers to obtain a higher frequency band of the signal and a better signal/noise ratio; Development of tools for positioning transmitter and receivers to speed up the measurements; A specially modified seismograph should help to obtain quickly a very sharp time-picking
Impact-echo (reflection and trans-mission) [8]	Geometry, thickness of first leaf, internal structure (voids, de-laminations)	Development of automated data acquisition at masonry in reflection and transmission; Selection of optimum sensor and detector; Development of software for tomographic data analysis
Sonics (direct and indirect) [9, 10]	Geometry, internal structure (voids, de-laminations), density variations, estimate of elastic modules, weak areas	Optimization to reduce acquisition and elaboration times, especially for tomography; New devices (low cost transducers and controlled wave sources) for multi-channel sonic tomography; Extension of the software for tomographic reconstruction by including the attenuation analysis with the frequency downshift method
Ultrasonics (impulse-echo and tomography) [11]	Geometry, thickness of first leaf, internal structure (voids, delaminations)	Selection of optimized pulse form and frequency range depending on material and masonry structure; Application of array technique for tomography

6.2 Test Specimens

The strategies for an evaluation of historic masonry, which were developed in the project, had undergone comprehensive tests before they could be incorporated in guidelines or recommendations. Previous experiences with measurements on real masonry have shown that very often unexpected difficulties occur because of the distinctive non-homogeneity of many masonry structures. A first step was therefore the construction of a masonry specimen, which features a diversity of properties (e.g., material, thickness, presence of voids), and represents several aspects or characteristics of real historic masonry. These specimens were used to perform measurements under specific conditions.

A large masonry wall simulating various situations found in historic walls has been constructed at BAM in close cooperation with Luther Memorial Foundation in Saxony-Anhalt (Wittenberg, Germany), Institute for Diagnostic and Conservation at Monuments in Saxony und Saxony-Anhalt e. V. (Halle, Germany) and Institute for Applied Science in Civil Engineering (IaFB), (Berlin, Germany). This wall called “Obelix” features a diversity of typical materials, structures, and non homogeneities (e. g., brick and stone, multiple leave structure, voids, wooden pile, metallic beam, metallic anchors) and thus represents several aspects of real historic masonry (see Figure 3). This specimen with the dimensions 7 m x 3 m x 1.5 m has been planned and constructed in consideration of traditional manufacturing techniques, partly by using historic materials from demolished buildings. It represents a large variety of problems and characteristics of real historic masonry (e.g., mixed masonry, multiple-leafed walls, hidden inclusions, cracks, voids, etc.). Each of the characteristics or properties of this Historic Masonry Specimen, which has been erected by a very experienced building company specialized in the restoration of cultural heritage buildings, is known in detail. This specimen is, in a way, the link between usual masonry specimens and real historic masonry buildings and will make the validation and calibration of the investigation techniques possible. It enables investigations under more or less defined conditions. The detailed documentation compiled during construction permits a reliable interpretation of the recorded experimental data.

In Figure 4, a radargram of a horizontal trace along the test specimen is displayed. Layers as well as some voids could be clearly detected. This wall was used by all the partners to calibrate some NDT procedures.

Figure 3a Historic Masonry Specimen “Obelix” at BAM

Figure 3b Simulation of voids

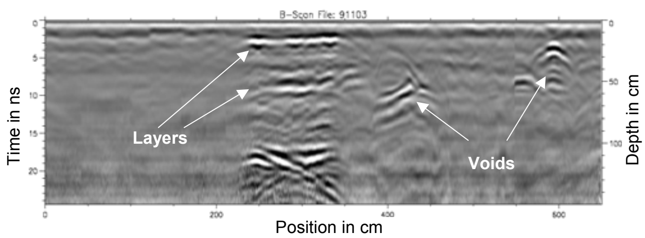


Figure 4 Radargram of a horizontal trace along the historic test specimen recorded with the 900 MHz antenna

6.3 Development and Calibration of NDT and MDT Technologies (Including Software, Hardware and Results of Calibration)

The most important productions of the contract are briefly described in the following [2].

Small sample testing device Small samples from masonry materials, namely from all kinds of brick and stones, are taken as drilled cores. It is useful to have an opportunity to test the core specimens directly on site, because it helps i) to select the sampling places, ii) to minimize the number of samples and iii) to test the specimens conditioned similarly to the situation in masonry ("fresh" specimens).

Therefore, a portable testing frame has been designed and a first prototype has been produced, (Figure 5). It enables testing of not only core samples, but also mortar samples, even though the first prototype has not been intentionally designed as a universal device. It is expected to be developed in this respect [12].

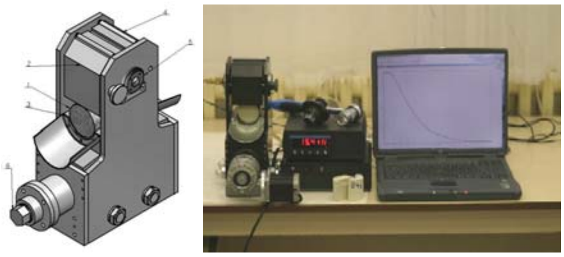


Figure 5 Portable testing set with the portable testing device with stepper engine and laptop with software for data acquirement and analysis

Positioning system for fast radar data acquisition The development of a positioning system was dedicated for tomographic and 3D high-resolution echo techniques. The available system overcomes the pitfalls of existing systems, (e.g., price, complexity, reliability, and speed) and integrates the acquisition of sensor co-ordinates with the acquisition of radar data so that every radar scan can be exactly positioned in the subsequent analysis process. The system consists of hardware and software both integrated with the radar system and its data acquisition process. The positioning system has an open interface that enables it to be used by other systems, provided they are computerized and can be reprogrammed. The system is easy to set up, and is transportable and configurable for both tomographic and echo mode.

The final prototype of the positioning system for a radar antenna is based upon the principle of a retractable string and an angular encoder. A photograph of the prototype and the principle of operation is shown in Figure 6. The prototype was studied by MALA (Sweden).

Together with the positioning sensor, new data acquisition software was developed that enables the user to set up measurement geometry, perform data acquisition, and, at the same time, monitor the antenna position. This is done in a graphical way and includes quality control measures to ensure that enough accurate data has been acquired at the site.

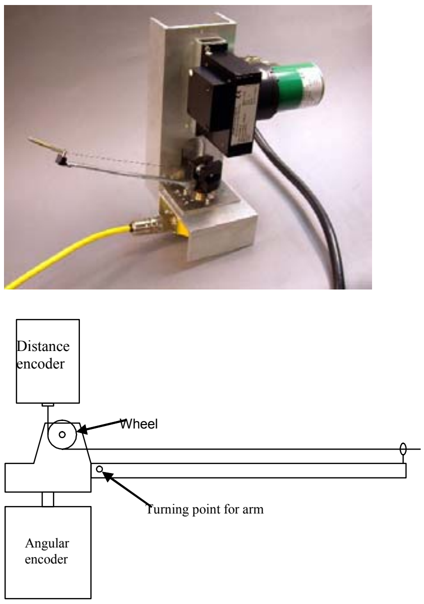


Figure 6 The prototype positioning sensor and the principle of the positioning sensor

New high frequency radar antenna The radar method is based on the transmission and reflection of short electromagnetic impulses, which are emitted by a high frequency antenna. These impulses are reflected at interfaces of materials with different dielectric properties, thus inhomogeneities like voids and metals can be detected. During the project, a new high-frequency antenna with a center frequency exceeding 1.6 GHz in air was developed. The antenna was designed as a lightweight unit (weight less than 500g), separated from the electronic unit and the battery.

The main targets were defined as: a) Improved amplitude and time stability, b) flexible cable length between control unit and antenna electronics, c) decreased weight, d) separable receiver and transmitter antennas.

All these goals were met during the development work.

The radar system consists of two separated antennas individually connected to an electronic unit with electrical cables. These cables are complex, built up with coaxial and normal electric cables as well as shielding. The receiver antenna includes antenna flares, preamplifier, sampler head, and DC/DC converters. Each time a trigger is fed to the receiver antenna, an analog value representing the voltage between the antenna terminals is put on hold on an electrical line feeding the A/D-converter inside the electronic unit.

The electronic unit includes an A/D-converter, driver stages for the trigger signals to the antennas, high voltage for the transmitter step generator, DC/DC converters, and optical-electrical conversion circuitry.

3D tests in reflection configuration. Among others, 3D tests were performed at the Obelix specimen (test specimen 2B, description see above) with the new antenna and the positioning system. The data were collected on a 2 cm x 2 cm grid by moving the antenna in vertical polarization along horizontal profiles. Figure 7 presents the results by showing two sections parallel to the wall surface that intersect a metallic anchor and a void at the respective depths. The geometry and the position of both targets are correctly imaged.

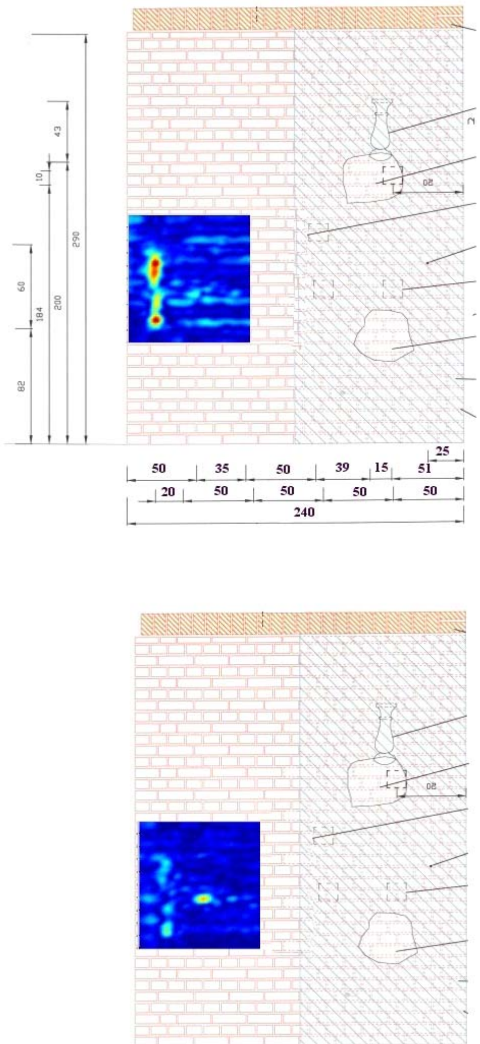


Figure 7 An example of radar data measured with the new antenna on the historic test specimen Obelix. Above, location of a metallic anchor. Below, location of a small void with a diameter of 10 cm.

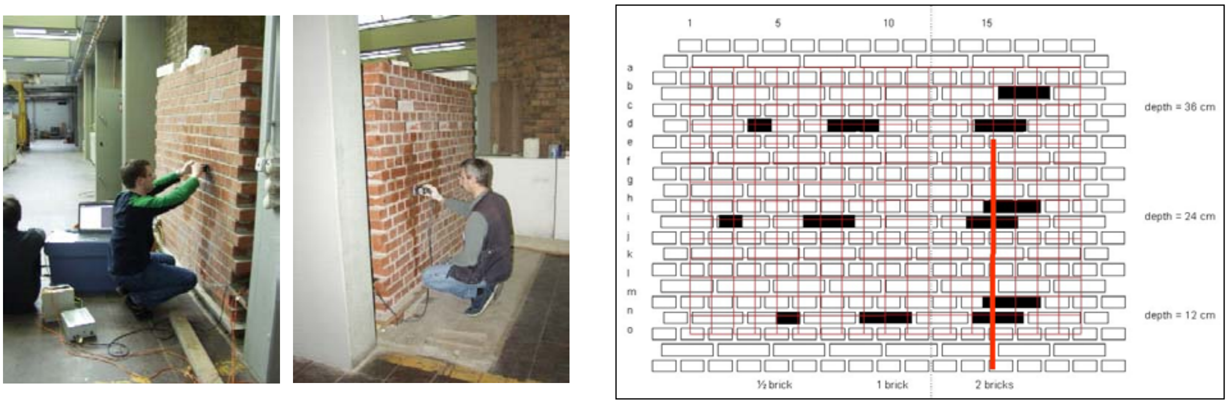


Figure 8 Pictures of specimen 2A during the tomographic acquisition. Left, the TX side, with the TX element moved top-down on a vertical profile. TX position is monitored by the new positioning system. Middle, the RX side with the RX element moved systematically at the end of each TX profile. Right, Position of the tomographic section on the 2A construction scheme. The tomographic section intersects two void anomalies

Tomographic tests. An example of a tomographic test that was performed on the specimen 2B (masonry wall with voids) is shown in Figure 8. Two operators are working on opposite sides of the wall with separate antenna elements. The RX element (receiver antenna) is kept in a fixed position while the TX element (transmitter antenna) is moved top-down repeating the same vertical line for each receiver position. 49 receiver positions, 2.5 cm spaced, were defined on a vertical distance of 120 cm. The position of the experiment with respect to the specimen targets is shown in Figure 8. The tomographic section is expected to intersect two void anomalies [6].

The data were processed by POLIMI with the TOMOPOLI [13] software, also developed in the project. The result from travel time tomography, i.e., the velocity map is shown in Figure 9. Two clearly visible anomalies are detected, corresponding with the positions of the voids. The velocity of the wave propagation is much higher (> 24 cm/ns), around the position of the voids as it is in the brick masonry (13-15 cm/ns). The resolution of the tomographic reconstruction is encouraging.

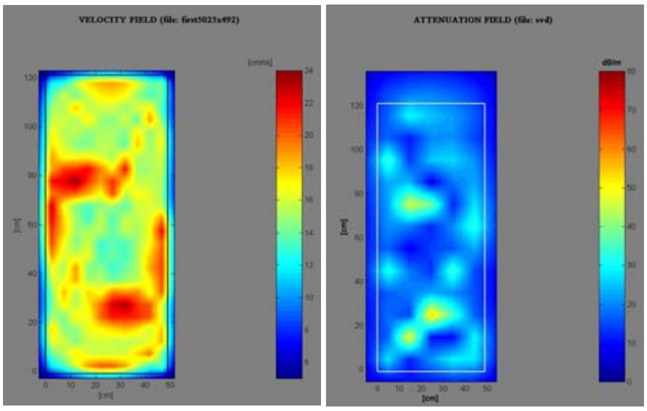


Figure 9 Left, velocity map resulting from the travel time tomography. Right, attenuation map resulting from the application of the frequency downshift method

Geoelectric: new sensors The classical geophysical survey methodologies were developed to explore the subsoil with different kinds of physical measurements performed at the soil surface. However, the use of several high-resolution geoelectrical tools proved to be very effective in the non-destructive testing of masonry structures. In general, the main problem is connected with miniaturization of the instrumental arrays. An interesting aspect of these methodologies is the capability of pointing out hidden anomalies: layering or leafs, cavities, variations of the materials, defects. The use of micro-geophysical techniques offers many advantages compared with "classical" techniques from different points of view: velocity of execution, non-pervasiveness, and cost.

The geoelectrical survey methods give information about the sub-surface based on the different conductivities of the materials. The current is injected through couples of point electrodes and the induced potentials are measured at other electrodes. Direct or very low frequency currents are used. The main difficulty to transfer these methods to the masonry structure is the very high resistance of the masonry surfaces. To improve the performing time and to extend the field of use of this method, a new tool has been developed [14]. The HeP_El_01 prototype is a two-piece flexible wooden bar with articulated connections. Each one has six specially built metallic contact electrodes with spring mounting at 15 cm interval spacing (Figure 10). The tool must, with very light pressure, lean against the surface of the wall. It was tested the first time during the measurement campaign at the Wartburg.

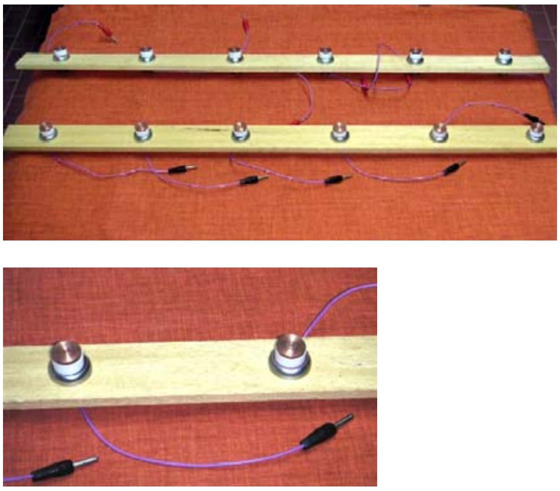
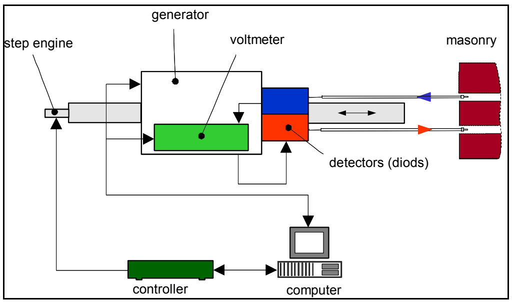


Figure 10 The HeP_El_01 prototype with mini electrodes

Microwave borehole method: Depth resolved moisture distribution. To obtain information about the moisture distribution along the cross section of the wall the microwave borehole system was developed at BAM (prior to the project) and was calibrated during the project. Here the absorption of continuous microwaves between boreholes is measured. This method requires two thin boreholes with a diameter of 12 mm and a distance of about 50 mm. As the method requires small boreholes, it is regarded as only quasi non-destructive. The method can be used in boreholes up to a depth of 2 m. By moving the antennas stepwise along the boreholes, depth resolved profiles can be recorded. Figure 11 shows a schematic presentation of the system and the system set-up for on-site measurements [5].



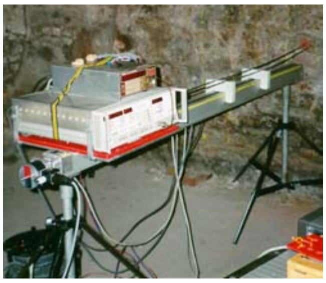


Figure 11 Microwave borehole system for on-site applications

The real and imaginary parts of the complex permittivity were calculated from the absorption of continuous microwaves between the two antennas at each antenna position. Since the absorption depends on the frequency of the continuous microwaves, measurements at different frequencies, between 6 and 10.4 GHz, were performed to select the optimum dynamic range.

Impact-echo: Automatic measurements with a 2D scanner. With impact-echo, a mechanical point impact is used to generate an acoustic impulse, which propagates into the material. Multiple reflections of low frequency waves between the external surface and internal reflectors (delaminations and defects) are used to measure transient resonance frequencies in time domain and to evaluate structural integrity in frequency domain.

Systematic investigations with different impact-echo system components have shown that the Olson equipment and a matching sensor has the best-suited frequency range, sufficient sensitivity, and the best tuning between detector and impactor. The Olsen system uses a half sphere as an impactor, which can be activated automatically. It is a commercially available impact-echo system for testing masonry (excluding scanner, acquisition, and visualization software for 3D automatic measurements).

The tests on different test objects as well as on-site gave valuable hints for the modification of the scanning system to enable automatic measurements on different surfaces as shown in Figure 12. With the developed scanning system for masonry, it is possible to scan lines and areas automatically. Parallel to the development of the scanner, the data acquisition software and data visualization software has been completed [5].

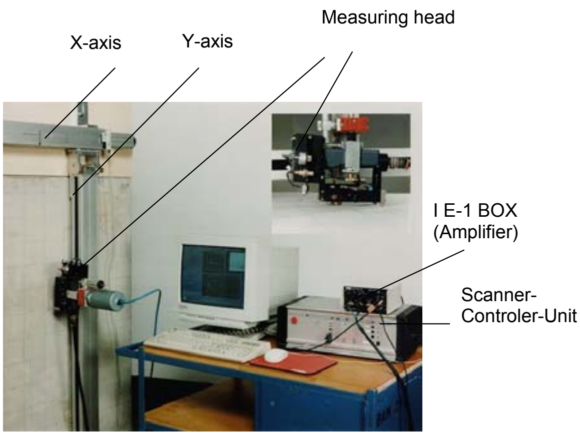


Figure 12 Impact-echo system with scanner

Sonics: Calibration. The sonic pulse velocity method is used to measure the transit time of sonic pulses (stress waves) in masonry structures for frequencies between 20 and 20,000 Hz. This transit time and the calculated sonic pulse velocity result in basic information about the quality and consistency of the masonry element under investigation. The velocity is influenced by the composition of the masonry as well as by the presence of inhomogeneities, voids, and deteriorated areas. The propagation of a stress wave through a solid depends upon the density and elastic properties of the given material for pulses traveling through elastic, isotropic, homogeneous media. Some works show that a certain relationship can be found between the sonic pulse velocity and the modulus of elasticity of the masonry. However, this relationship varies according to the given masonry typology and texture, and must be stressed that the statistical database for rough estimations of elastic properties from velocity values is still in a very experimental phase. Therefore, the sonic pulse velocity method can be usefully applied for the qualitative evaluation of masonry structures and for the quantitative control of the effectiveness of repair intervention such as injections.

The successful application of sonic tests to any of these problems depends on the appropriate application of the method but unfavorable conditions also exist where the application to some of these problems might fail. Sonic pulses, which consist of stress waves, do not generally have problems with signal penetration or attenuation. The execution of the tests is thus generally successful.

Within the Contract, the Politecnico (POLIMI) and the University of Padua (UNIPD) did calibrate the sonic tests on site and in the laboratory.

Ultrasonics: Tomography and impulse-echo applications. The main aim of the development of an ultrasonic prototype was to investigate historic masonry with ultrasonic tomography. This equipment should enable the user to localize voids and delaminations in masonry elements, when they are accessible from at least two sides. A second aim was to adapt ultrasonic echo techniques for masonry in order to localize delaminations and to determine crack depths [16].

Single and double flatjack. The objective of the flatjack test is to obtain the local state of stress in compression of a masonry element that works under vertical stress. The method is based on stress release. The general procedure of this test consists of restoring the vertical displacement caused by a horizontal slot made in a loaded masonry. The distance between three or four points fixed across the slot is measured by gages before and after cutting. The device used to restore the displacement is a flatjack; oil is pumped in the jack until the distance between the gage points is restored to the initial situation. In order to obtain the local state of stress, the restoring pressure must be corrected taking into account two coefficients that depend on the mechanical characteristics of the flatjack, calibrated in the laboratory, and on the relation between the geometry of the slot and the shape of the flatjack.

Two types of jacks were used by Politecnico of Milan (Polimi) and Geotecnical y Cimientos S.A. (Grecia). The test procedure used by POLIMI was performed according to ASTM [17] test taking into account four measurement points and cutting in the mortar joint [18].

GEOCISA´s single flatjack tests follow a developed procedure based on ASTM, but with modifying some testing conditions for more fast and user-friendly equipment.

The main differences of the flatjack tests performed by GEOCISA compared to those performed by POLIMI are due to the smaller dimensions of slot and flatjack used. The slot was made with a diamond circular saw and the cutting was guided to ensure a horizontal plane using a platform fixed to the wall. With this procedure, the flatjack fits perfectly in the shape of the slot cut with the circular saw and, accordingly, the coefficient depending on the relation between the geometry of both elements (slot and jack) is equal to 1 in all GEOCISA’s tests.

6.4. Structural Models

The analysis of historical masonry constructions is a demanding and complex task. This is primarily because only limited resources are usually allocated for the study of the mechanical behavior of masonry. Furthermore, even though sophisticated numerical models are available and some previous in-situ or laboratory tests were made, numerous difficulties in using existing tools and knowledge still exist. Usually, the silent aspects are:

- Geometry data is missing
- Morphology of the wall is missing
- Characterization of the mechanical properties is difficult
- Large variability of mechanical properties due to workmanship and the use of natural materials in historic masonry
- Significant changes in the core and constitution of structural elements, associated with long construction periods as well as the presence of some retrofitting work can make the assessment difficult
- Existing damage in the structure is unknown
- Regulations and codes are not applicable

Several methods and computational tools are available for the assessment of the mechanical behavior of historical constructions. The methods resort to different theories or approaches, resulting in different levels of complexity (from simple graphical methods and hand calculations to complex mathematical formulations and large systems of non-linear equations), different availability for the practitioner (from readily available in any consulting engineering office to scarcely available in a few research oriented institutions and large consulting offices), and, of course, different costs. It should also be expected that results of different approaches might be also different, but this is not a sufficient reason to prefer one method to the other. In fact, a more complex analysis tool does not necessarily provide better results than a basic and simple tool.

In general, the methods for the evaluation of the load bearing capacity of masonry structure and its elements are complementary and the selection of one of them depends on many factors, such as the required accuracy, measured parameters, the typology of the structural element, type of action, morphology of the masonry, etc.

6.5. Integration of NDT, MDT, and DT Techniques in Structural Modeling

The structural geometry, the crack pattern survey and monitoring, and the local slightly destructive and non-destructive test results should be concretely used to choose the appropriate analytical model for the detection of the safety of the structure and its load carrying capacity. With this information, it will be clear that a choice has to be made among all the available models, taking into account the typology of the structure and of the masonry.

This previous description of available techniques and procedures illustrates the difficulty the designer has to face, who must select the technically and economically correct method to define the state of preservation or damage of the structure to be restored. When the results of the survey are previously available, then conclusions from the experimental and numerical investigation will bring the real state of the structure to the diagnosis. Table 3 shows the possibilities when dealing with structural analysis, from the elastic to the inelastic or limit analysis, provided that one can obtain enough information from the experimental survey; nevertheless, appropriate constitutive laws for the masonry materials are still not well developed.

The aim is to assess the load carrying capacity of existing buildings, and hence to determine a safety factor, which can assure an acceptable performance for the function assigned to the building. This function is frequently different from the original one for which the building was designed, due to a modification of the loads (e.g., stone-or brick masonry bridges under modern traffic) or of the destination (e.g., a convent transformed into a university building). Therefore, a safety coefficient should be calculated taking into account all the possible seismic loads. It is clear that the safety coefficient of these structures cannot be calculated as easily as in the case of contemporary concrete, steel, or even masonry structures due to all the uncertainty concerning the material, the construction technology of the walls, the geometry, etc.

The following questions have to be answered once the experimental data has been collected on-site and in laboratory:

- Which mathematical models should be adopted to calculate the state of stress and strain in a masonry structure?
- Knowing that the structure was not designed according to the contemporary analytical methods but to simple geometrical or static rules, would it be better to assume simple engineering models or sophisticated models?
- Do we really know the constitutive laws of any type of masonry, since they differ so much from one to another (e.g., solid brick and stone masonry from multiple leaf walls or rubble walls)?
- What is the role played by the elastic model and how reliable is it for an existing old masonry structure?
- How reliable are non-elastic or limit analysis models implemented for other materials?
- How can we take into account the long-term behavior of a masonry structure and the synergetic effect of loads and environment?

7. Selection of Cultural Heritage Sites

A selection of pilot sites has been made considering material (regular brick and stone masonry, masonry made with irregular stone), typology (single and multiple leaf walls, columns, etc.), deterioration mechanisms, or environmental condition.

The following table indicates the ten case studies and their problems.

Table 3 List of chosen sites and of their problems

 **Altes Museum, Berlin, Germany**	**Testing Problem(s):** Investigation of structure, plaster delaminations at columns, construction of the floor, state of stress basement wall, moisture	 **Pallazzo Bottagisio, Verona, Italy**	**Testing Problem(s):** Typology of leafs, detachment of leafs, voids, state of stress and mechanical properties
Applied methods: Radar, impact-echo, ultrasound, sonics, microseismics, geoelectrics, thermography, videoscopy, microwave-borehole-method, hole-drilling, flat-jack, structural modeling		**Applied methods:** Single and double flat-jack, sonic tests, videoboroscopy, microseismic	
 **Wartburg, Eisenach, Germany**	**Testing Problem(s):** Structure of a wall (detection of a hidden former entrance), plaster delaminations, moisture	 **Villa Litta, Italy**	**Testing Problem(s):** Localisation of timber beams and metal ties, localisation of voids
Applied methods: Radar, radar- tomography, thermography, microseismics, geoelectrics		**Applied methods:** Radar, thermography	
 **Pisece Castle, Slovenia**	**Testing Problem(s):** Investigation of structure, state of stress, moisture, detachment of leafs, cracks	 **Avio Castle, Italy**	**Testing Problem(s):** Typology of leafs, delamination of frescoes, crack survey, state of stress, moisture
Applied methods: Radar, ultrasound, flat-jack, crack-survey, microseismics, geoelectrics		**Applied methods:** Single and double flat-jack, sonic tests, radar, videoboroscopy, sonic tomography, microseismic	
 **Veltrusy Castle, Czech Republic**	**Testing Problem(s):** Investigation of structure, moisture	 **Church of Toro, Zamora, Spain**	**Testing Problem(s):** State of stress, cracks
Applied methods: Radar, radar-tomography, microwave-borehole-method, microseismics, endoscopy, moisture determination		**Applied methods:** Hole-drilling, flatjack	
 **San Alessandro, Lucca, Italy**	**Testing Problem(s):** Thickness of the outer leafs of the walls, filling between the leafs, foundation	 **Church of Turegano, Segovia, Spain**	**Testing Problem(s):** State of stress, cracks
Applied methods: Radar, ultrasonics, geoelectrics		**Applied methods:** Hole-drilling, flatjack	

8. Guidelines and Recommendations

For the dissemination of knowledge gained from the project, different types of guidelines and recommendations were worked out [2]:

- Guidelines for the use of the developed technologies (technical guidelines)
- Guidelines for structural modeling of the assessment of the load bearing capacity of the masonry structures
- Recommendations for end users about strategies of building assessment and diagnosis

From the on-site measurement campaigns a lot of knowledge was transferred between the partners. In particular, the comparison of results from different methods applied to the same structure contributed to the evaluation of the range of application, of reliability, and of the limits of each testing method as well as of the combinations of methods. Several new ideas have been generated related to data acquisition, analysis, visualization, and interpretation. Therefore, it is planned to implement the project achievements into future standards and regulations about the maintenance and assessment of masonry buildings.

8.1 Technical Guidelines

This collection of guidelines includes several NDT (and MDT) techniques, which have proved to be applicable to historic masonry structures with good results.

Each of the guidelines describes the application of the technique and the handling of the equipment. It is made for the user as well as for the operator of the method and provides necessary information and decision criteria for the planned application of the method on historic masonry buildings. For each method, a short summary of the technical basic principles is given.

In this first issue of the guidelines, nine methods are listed:

- Geoelectric tomography
- Hole drilling
- Impact-echo
- Microseismic
- Radar
- Active thermography
- Ultrasonic methods
- Flatjack
- Sonic pulse velocity test

In the future, it is planned to extend the collection and to include further techniques, which are suitable for the investigation of historic buildings and which have already been tested under real conditions on-site and not only in the laboratory.

The structure of all these guidelines is very similar, although it can vary for different methods according to the needs. The main chapters are equal for each of the methods, but due to the complexity of the techniques sometimes, it was reasonable to change the structure slightly:

- Introduction
- Basic principles
- Application to masonry investigations
- Requirements
- Investigation design
- Acquisitions
- Measurement
- Analysis
- Final report

The nine methods, for which the Technical Guidelines are already available, have been selected because they have proven to be the most useful techniques for a large number of applications. Nevertheless, it is important to consider also other methods or combinations of methods. In particular, the parallel application of different techniques often leads to better results than relying only on one testing method.

8.2 Guidelines for Structural Modeling

The analysis of historical masonry constructions is a demanding and complex task. This is primarily because only limited resources are usually allocated for the study of the mechanical behavior of masonry. Furthermore, even though sophisticated numerical models are available and some previous in-situ or laboratory tests were made, there might still exist numerous difficulties in using existing tools and knowledge.

The strategies for an evaluation of historic masonry, which were developed in the project, have to undergo comprehensive tests before they can be incorporated into guidelines or recommendations. Previous experiences with measurements on real masonry have shown that very often unexpected difficulties occur because of the distinctive inhomogeneity of many stonework or mixed-technology structures.

Therefore, in the frame of this project it was attempted to apply numerical models on selected parts of historic buildings and to compare the performance results, which were gained with conventional testing methods (e.g. flatjack).

For the performance of on-site calibrations and testing of methodologies, a preliminary selection of pilot sites has been made considering material (regular brick and stone masonry, masonry made with irregular stone), typology (single and multiple leaf walls, columns, etc.), deterioration mechanisms, or environmental conditions.

The chosen sites (e.g. Wartburg, Altes Museum / Germany, Pisece Castle / Slovenia, Veltrusy Castle / Czech Republic, Avio Castle in Trentino, San Alessandro in Lucca, Palazzo Bottagisio in Verona / Italy, Church at Turegano Castle in Segovia and Church at Toro in Zamora/Spain) allowed the evaluation of the reliability of the results through the comparison with a priori information and/or with coring or other destructive investigations. The assessment of the pilot sites also includes structural modeling based on the measured parameters.

8.2 Recommendations for End Users

The project results and achievements are summarized comprehensively in the document *Guidelines and Recommendations for the End User*. It was written to help the end user to understand the general strategies of investigation and assessment in order to achieve a good cooperation with the responsible workgroups (architects, civil engineers, diagnostics organizations, archaeologists, etc.).

Non-destructive (NDT) and minor-destructive testing methods (MDT) are tools of investigation, which can be applied without any or with only small interventions in the object to be examined. These techniques can give hints to irregularities within the historic masonry structure, which is often inhomogeneous. Irregularities may derive from differences in material or microstructure, from voids or delaminations, cracks, salt or moisture, or differences in loading. Starting at the surface of the object NDT and MDT offer possibilities to border problem areas, to detect structural differences, and to amend the reliability of statistic evidence relative to or in addition to selective material extractions and investigations.

Depending on the particular question and methodology NDT and MDT techniques are useful to get a first survey of large areas at the beginning of building or restoration projects on structures with defects or damages. It is then possible to investigate surfaces and parts of protected historic constructions or areas, which are difficult to access, with higher precision. These techniques can also be applied for long-term observations (monitoring) or used as quality assurance after repair interventions and during historical building research. Generally NDT and MDT applications are part of the global investigation of the building. They do not replace other investigation techniques completely but in the case of historic monuments, NDT should be preferred to traditional tests on extracted samples when both types of techniques can solve the problem.

9. Conclusions

The preservation of historic buildings is of great importance in order to maintain our cultural heritage.

The knowledge of the state of damage, of feature, and the details of these buildings can be found through on site non-destructive and laboratory investigations. Towards this aim, procedures and techniques for diagnostic investigation have to be implemented and calibrated. Through the EC Contract ONSITEFORMASONRY, several investigation techniques were studied, calibrated, and applied to chosen sites with different building typologies.

Guidelines and recommendations for users were prepared for the appropriate use of investigation and modeling. A transfer at the international level of the accumulated knowledge is now required through the establishment of a proposed new RILEM TC.

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