ON-SITE INVESTIGATION TECHNIQUES FOR THE STRUCTURAL EVALUATION OF HISTORIC MASONRY BUILDINGS ONSITEFORMASONRY

Recommendations for the end users

Onsiteformasonry Project
5th Framework Programme for Research, Technological Development and Demonstration
Energy, Environment and Sustainable Development – The City of Tomorrow and Cultural Heritage

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Onsiteformasonry Project

On-site investigation techniques for the structural evaluation of historic masonry buildings
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Content

1 Introduction

The document presented herein is devoted mainly to the final users of the ONSITEFORMASONRY project: owners of cultural properties and end users. It is written in simple way for better understanding of general strategies of investigation as well as for better communication and cooperation between involved workgroups (architects, civil engineers, diagnostics organisations, archaeologists etc.) involved in assessment of historical structures.
The document consists of following chapters:

- Description of the ONSITEFORMASONRY project (prepared by BAM)
- Basic principles of planning an investigation (prepared by SLG)
- Short description of the methods (prepared by POLIMI)
- Recommendations for different methods for different level of investigation (prepared by ZAG)
- Summary and short description of all deliverables from the project (prepared by RT).

1.1 "Diagnostic" Techniques used in Architectural Restoration

It is unnecessary to spend many words to underline the importance of monumental cultural heritage all over the world and especially in Europe. Europe owns, without any doubt, the most important and best-conserved quantity of monuments. Its towns are built around antique cores, which constitute a tangible representation of their common cultural identity. Conservation and maintenance of this heritage is not only a duty, but is an extraordinary opportunity. The restoration and maintenance of the antique monuments, built in most of the cases with masonry structures, needs a deep knowledge of their real constitution.
This knowledge is necessary, not only for a correct and economical design for restoration and conservation, but to assess the static conditions of the buildings and their capability to survive to the age and to natural catastrophic events. The diagnostics of the masonry structures (and especially the ones based on non destructive methods) may play, for the above-mentioned reasons, the same role of medical diagnostics in medicine. Unfortunately, there are many evident differences between the human body and the masonry structures, which did not allow a similar development of the diagnostic techniques in the two fields:

- All human bodies are very similar and well known in their anatomy: the masonry structures are very heterogeneous and their actual composition is generally unknown
- The human body is an easily handled subject from a diagnostic point of view: the contrary for the masonry structures
- The composition of the human body is favourable to the use of non-invasive methods: the composition of masonry is not, at least not with comparable resolution.

These difficulties negatively affected the development of NDT (Non Destructive Test) techniques and there is not a consistent market for the services related to them. The ONSITEFORMASONRY Project, funded by the European Union under the 'Environment and Sustainable Development Programme (1998-2002)' of the fifth framework programme, has tried to contribute to the filling of that gap. The project, started in 2001 and ended in 2004, has mainly pointed out integrated and structured methodologies for the assessment of historical masonry buildings based both on well-consolidated NDT (Non Destructive Test) methods and new ones.
"New" means that these methods have been improved or adapted to peculiar tasks, even if completely new techniques were not developed. The assumption was that the lack was not totally in the field of the techniques, but first of all in a standardised and integrated approach to their use. Nevertheless new pieces of hardware and software were developed, in any case with the adaptation of existing instrumentation.
The exploitation objectives of the project were in putting the bases for the development of the market of the diagnostics in the field of monumental restoration and conservation. This market is presently "evanescent" and is characterised by the following points:

- The diagnostics requires quite big investments in hardware, software and expertise
- The dimension of the market, not pushed by specific standards and not compelled by law requirements is only much less than 1% of the amount invested in restoration and conservation
- Consequently there is not an economic convenience for the private venture to operate specifically in this field and there are not specialised companies

- The diagnostics companies operate in different fields (geophysics, controls on concrete new buildings, etc) with a wide spectrum capability in the use of the instrumentation, but without a real know how in masonry

The know how in this specific field is therefore concentrated in Universities, Research Centres and other public Institutions, with a big advantage in terms of competence, but without booster effects on the market.

- On the other hand the lack of a massive private investment has a negative effect on the Research and Development of instrumentation which is specific for the masonry diagnostics
- The lack of effective, high confidence, high productivity and low cost instrumentation produces a negative effect on the demand with a clearly vicious circle.

The exploitation strategy of the ONSITEFORMASONRY project was to develop well tested and integrated methodologies based on already existing techniques (with slight adaptations and modifications) in order to create the exigency, in the wide world of the end users, to set compelling obligations in incorporating NDT activities in the preliminary phase of the restoration and conservation projects.

This obligation could increase the demand until a 3-4% of the total Restoration costs, easily financed by the return of the savings in terms of minor problems encountered during the works.

1.2 The role of the "end-user" in the project

"End-user", in the sense used during the project and in this document, has a double meaning:

- "Intermediate" end user: it may be the designer (engineer or architect) who needs the maximum of knowledge of the building to be restored in order to develop a good project without "surprises" during the works or a company or a group of professionals that intend to sell services in the market of diagnostics
- "Final end user": it is generally a public institution, which is the "owner" of the monument or is charged of its management or conservation. Owners are very often ecclesiastical subjects and sometimes public institutions, local or central governments, rarely private subjects or organisations. The managers are almost always public or, sometimes, private no-profit organisations.

From these points of view it is clear how the number of the potential end-users of the methods is very high and that the way to reach all of them is an intense dissemination activity. These actions, carried on during the project with about 140 "events" (articles, conferences, exhibitions, publications, courses, and so on), are continuing.

This CD represents all the outputs of the project, made available for end users for the over mentioned aims. You will find in it all the deliverables of the projects in a synthetic format or in the full one, at your choice. The CD allows the "navigation" and the possibility to download or print any of the documents or part of them. Particular emphasis is given to the document "Guidelines and Recommendations for End Users" (D11.3), which was produced by the Project Consortium at the very end of the activities, after three years. This document represents the ultimate result of the project with the aim of guiding End Users in the "jungle" of the methods and their combined use for the solution of specific problems. All the proposed solutions have been studied and tested in laboratory and field conditions.

The Guidelines contain, first of all, a short description of the project and of the deliverables, just to put them in the framework of the research activities. A very important chapter is the one, which deals with the planning of an investigation, pointing out all the basic principles for a correct approach to diagnostics in a restoration project.

Particular stress is given to the concept of the co-operation in a multi-disciplinary team, which is absolutely necessary for the success of any project, and particularly in this case. From this point of view, the approach of the medical intervention is the right one, with the differences above evidenced, where different specialists play their specific roles in the respect of the other ones, but there is one of them, which decides as leader of the group. In the case of the restoration project, the last decision is always of the designer, but he has the duty of knowing the general rules of the other disciplines and using their peculiarities. There is a collection of technical sheets of the main diagnostics methods, where particular emphasis is given to NDT techniques, with the purpose of giving a general survey about the available range of them.

The following and bigger chapter of the Recommendations tries to associate to the main problems encountered in a historic building at different levels of application, the right solutions in terms of diagnostic or assessment approach. For each combination of methods, advantages and disadvantages of them are depicted, in conjunction with their limits and resolution. It should be noted that this chapter does not pretend to be exhaustive and complete, but it represents, without any doubt a first and original approach to the standardisation of the diagnostic protocols. This standardisation is absolutely necessary to put order in the discipline of diagnostics and can be a good contribution for the stabilisation of the market of services.

1.3 Some final words about the language

For the problems underlined in the first part of this introduction, the results of diagnostics in the field of monumental masonry buildings are not always certitudes, even if they can be used normally with sufficient (and sometimes, extraordinary) utility when they are planned, processed and discussed in a multidisciplinary team of experts. The document which you are going to consult is prepared by scientists who are very fond of their work, have spent a lot of energy in it and they must express certitudes. They have created, in ultimate analysis, a model, which is, as any model is, a schematic and simplified representation of the reality. There is no other way for trying to understand a complex phenomenon. They used this language to communicate their results and they are very conscious that this is only the beginning. So read the document and particularly the Recommendations with these considerations well in mind: you will receive an important contribution to your work.

2 Description of the project

ONSITEFORMASONRY is a research project funded by the European Commission under the 5th Framework Programme 1998-2002 in the Thematic Programme: Energy, Environment and Sustainable Development and the Key Action: The City of Tomorrow and Cultural Heritage.

2.1 Objectives

The main objective of the project was the development and improvement of methodologies for the evaluation of the structure of historic masonry Cultural Heritages.
Buildings, structures and especially Cultural Heritages are major riches of any society, but their maintenance, repair and rehabilitation is very costly and time consuming. The quality of life in any urban environment is strongly affected by the safety and the functionality of its infrastructure. Moreover, in the old town centres, full of historical buildings, the problem of maintaining integral and functional the urban texture requires a continuous work of conservation and restoration. It is not infrequent to assist in some cases to such an activity lasting for centuries. Natural catastrophes like earthquakes or floods and human activities producing pollution and degradation complete the work of time. Any restriction in the access to public areas and any loss in the common heritage have a far-reaching effect to the life of the society, to tourism or public opinion, with unbelievable economical and cultural damages.
For effective restoration and conservation of historic buildings, a detailed assessment of the structural safety and physical damages of the masonry structure is required, which needs a deep knowledge of the actual internal constitution (geometries, materials, morphologies). As a matter of fact, generally, there is not sufficient documentation and the information has to be found in a case by case integration of historical and diagnostic information.
In the project ONSITEFORMASONRY methodologies have been developed for the evaluation of historic masonry, which help to enhance the cost/benefit ratio for investigation and diagnosis. They are based on the following achievements of the project:

- Typical masonry damages and the most frequent pathologies in each region have been compiled, identified and summarised in a catalogue of problems and damages.
- Current non-destructive (NDT) and minor-destructive (MDT) techniques have been improved / modified for better analysis, prediction and early prevention of environmental damages of Cultural Heritages (caused by ageing, microclimate, seismic and traffic vibrations and by dead load) to avoid higher costs in strengthening and repair intervention
- Strategies for effective integration of different techniques for the diagnosis have been developed, allowing more frequent assessment of Cultural Heritages with lower costs. The strategy for an effective and useful combination of different NDT and MDT methods was worked out considering the results of case studies and taking into account the experiences of the consortium members.
- A positioning system dedicated to tomographic and 3D high resolution echo techniques allows faster and more accurate performance of measurements
- Software packages for fast and automated data analysis and combined presentation are available
- Results and data of the NDT and MDT-testing were evaluated and used as input for structural analysis to evaluate the stress state on selected parts of the structure.
- NDT and MDT-methods have been verified and calibrated at laboratory specimen, which were specially designed to represent typical features of historic masonry.
- The developed strategies to assess historic masonry have been tested at Cultural Heritage buildings in extensive measuring campaigns with participation of engineers, scientist, historians, restorers, owners of the buildings and other interested parties.

2.2 Project partners

The consortium of the project included partners with complementary roles: equipment manufacturers (Mala Geoscience, Sweden), developers of NDT methodologies (BAM, Germany, Politecnico di Milano, Italy, University of Pisa, Italy), NDT and MDT users (BAM, Geotecnia y Cimientos S. A., Spain, University of Padua, Italy, Slovenian National Building and Civil Engineering Institute, Slovenia, University of Castilla La-Mancha, Spain, Institute for Research in Materials and Applications, Slovenia, Institute of Theoretical and Applied Mechanics of the Academy of Sciences of the Czech Republic, Czech), experts for structural models (University of Castilla La-Mancha, University of Padua) and owners of Cultural

Properties (Luther Memorial Foundation in Saxony-Anhalt, Germany, Regione Toscana, Italy, Regional Government of Castilla – La Mancha, Spain, Province of Verona, Italy).

2.3 Damage Catalogue

First it was necessary to get an overview about the problems, which have to be faced when dealing with historic masonry. The *Standard Damage Catalogue and List of Structural Typologies and Related Requirements* was set up at the beginning of the project and allows 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. It visualises typical types of damages and thus helps to identify problems occurring at historic masonry.
The crucial points of the overview are the definition of structural characteristics like construction typologies (buildings, bridges), structural elements (arch, vault, wall, dome, etc.) and the classification of damages (e. g. moisture and related damages, erosion and other damages due to wind and air pollution) together with a compilation of measurement parameters needed for their characterisation.

2.4 NDT / MDT methods

The selection of investigation methods depends on the accessibility of the object and its condition, on the problem to be solved and on many other factors, which only the experienced investigator can overlook.
The combination of several investigation techniques like ultrasonics, impact-echo, sonics, radar and some stress estimation methods like flat-jack and hole drilling can give more reliability for the interpretation of results and for the detection of irregularities like voids, cracks, presence of moisture and/or salt etc. For example if a void is detected by all three methods, the presence of this irregularity can be regarded with a high level of reliability. Furthermore, it can help to clarify the morphology of the structure investigated, to give information about the presence of weakened areas and about the state of stress in masonry structures. In ONSITEFORMASONRY, methodologies containing various system combinations related to different testing problems have been tested and evaluated. The limitations of the methods have been investigated deeply in order to help the user planning the strategies of application in a most reasonable and effective way.

2.5 Test specimen for calibration and validation

For the calibration and optimisation of the methodologies, several test specimens have been built. Among some wall-specimens under compressive load for the application of stress estimation methods, a large historic masonry wall has been constructed at BAM featuring a diversity of typical materials, structures and inhomogeneities and thus representing several aspects of real historic masonry. This specimen with the dimensions 7m x 3m x 1.5m has been planned and constructed in consideration of traditional manufacturing techniques, partly using historical materials from demolished buildings. It enables investigations under more or less defined conditions. The detailed documentation during construction permits a reliable interpretation of the recorded experimental data. The specimen can serve as a reference object for the validation of NDT-methods and is available for round robin tests.

2.6 Case studies and structural modelling

The strategies for an evaluation of historic masonry, which were developed in the project, have to undergo comprehensive tests, before they can be incorporated in guidelines or recommendations. Previous experiences with measurements at real masonry have shown that very often unexpected difficulties occur because of the distinctive inhomogeneity of many stonework or mixed technologies structures.
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 includes also structural modelling based on the measured parameters. This is the way of integrating the NDT techniques considered within the project focusing to the final aim of every end-user: to determine the actual state and the load carrying capacity by considering data obtained from NDT and MDT methods.

2.7 Guidelines and recommendations

The project results and achievements are summarised in comprehensive form 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 organisations, archaeologists, and so on).

3 General recommendations for end users

3.1 Basic principles of planning an NDT/MDT investigation

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 influence or differences of 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 namely 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-running observations (monitoring) or be used as quality-assurance after repair interventions and during historical building researches. Generally NDT and MDT applications are a 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.

The following general recommendations are based on the experiences gained in the research project ONSITEFORMASONRY, but also exceed the frame of the project and comply with general standards of preservation like the ICOMOS Charter "Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage" (quoted as ICOMOS principles) and the corresponding "ICOMOS Recommendations for the Analysis, Conservation and Structural Restoration of Architectural Heritage" (quoted as ICOMOS Guidelines).

The partners of ONSITEFORMASONRY recommend the ICOMOS documents and agree to the general task "to safeguard the cultural and historical value of the building as whole". In this frame "the evaluation of a building frequently requires a holistic approach" and a multi-disciplinary investigation strategy (ICOMOS Guidelines, 1).

3.2 Planning the investigation - Conditions precedent to NDT and MDT applications

The careful preparation of the investigation together with a precise verbalisation of the problem on the spot is the basic precondition of every successful global investigation and NDT and MDT application, too. It is necessary to take into account all available precognitions and documentations about the object of investigation. This can be said for every kind of diagnosis especially those which are connected with (small) interventions into the building fabric (for example archaeological interventions and restorer's cuts).

The question determines the choice of the adequate methodology and strategy as well as the possibilities of interpretation of the results of the investigation. Knowing the task of the investigation as accurate as possible is necessary to get reasonable and reliable results. Therefore it is essential that the main elements of stocktaking of the building are available and evaluated before NDT or MDT investigations are started. The stocktaking comprehends all data, which are based on inspection: the verbal, photographic and graphic documentation and description of the building or structure (allowance and detailed mapping of the building in terms of a *Raumbuch*), also climate measurement reports, descriptions and mappings of damages. The evaluation of all kinds of archive materials concerning the building and the region (e.g. information about former earthquakes or floods) is required. Also documents concerning geological, hydrological and biological conditions should be taken in account. All in all an accurate evaluation of all available older material concerning the building has to be done in order to limit the technical complexity and the costs of more extensive researches. The more precise the question is verbalised the lower the costs are. 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:

- Which information do I need?
- With what accuracy?
- Which is the method to fulfil my needs?

▪ Which decision will I take depending on the test results?

Exact drawings of the actual state of the building in a larger scale are needed for every NDT and MDT application to map changes and damages, 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. Especially in the case of questions concerning the structure of the building precise drawings are indispensable. Therefore it is often necessary to produce these drawings at first. It makes sense to check the requirements of all involved experts in the beginning of the building project in order to avoid mistakes of the mapping. If drawings prove to be insufficient in the course of the preparation of a building project, they have to be done once again in a larger scale or more detailed.

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

3.3 Where is the application of NDT and MDT methods recommended?

The respect for the achievements of the predecessors demands to avoid interventions into historical structures as far as possible. Building fabric of high cultural value and protected buildings should not be damaged under investigations. Existing older structures or colourings, which are actually not visible, should not be destroyed. For this reason NDT should be preferred generally and an iterative approach is recommended (ICOMOS Guidelines). In any case the first step is the acquisition of all available data concerning the building and its history. Archive studies do not need any intervention in the historic building fabric. In the same way mathematical methodologies like structural modelling can be characterised as non-destructive techniques even if they are based on material characteristics, which are gained from MDT (e. g. flat jack) and minor invasive investigations (e.g. core extraction).

NDT is a very good means to do a first survey of the possibilities of planned future interventions or changing of the architecture. If for example the use of the historic building requires a new entrance, a first investigation about the present state of the structures can partly be performed with NDT.

Figure 1. Luther House Wittenberg, Germany, Western gable: situation before and after erecting the new entrance building. The complete gable was investigated with radar in order to detect hidden voids and other irregularities.

Some of the investigation techniques which are described in chapter 4 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 mean high risks as it is the situation after earthquakes or explosion, NDT is a suitable means for investigation.
It is a matter of course that interventions soon after reconstruction have to be avoided. Therefore NDT offers possibilities for quality assurance. For example remaining voids, still present after the performance of injections, can be satisfactorily shown.
The application of some NDT or MDT methods allows moreover area-wide statements about masonry structures or characteristics of building materials. The results of such investigations differ from common spot tests like drilling cores, which are carried out to take samples.

Figure 2. Altes Museum Berlin, Radar (left) and flat jack tests.

Therefore NDT and MDT methods are helpful to find out the actual condition inside a historic construction. This is especially important if the actual allocation of load is required in order to avoid a treatment of the ancient building following the lines of modern architectural and structural rules (compare ICOMOS principles 2.8). Therefore ONSITEFORMASONRY examined the possibilities and limitations of structural modelling.
On the other hand NDT offers possibilities to identify more or less delicate and worthwhile areas of constructions if taking samples can not be avoided (e.g. to mark out salts inside the building material). If for example a thermography indicates areas of repair in the plastering samples for salt analyses could be taken first in these areas. On the one hand the former loss of plastering could be a damage in itself, caused by salts inside the masonry. On the other hand newly plastered areas cannot carry historical colourings or other valuable findings. The position of the borehole in these cases can be freely chosen. In order to determine the minimum number of boreholes it can be useful to find out first whether the structure of the masonry is in general more or less homogenous. If for example the radar investigation shows a homogenous structure the number of boreholes may be reduced. If it appears inhomogeneous the samples should represent different areas of the construction.

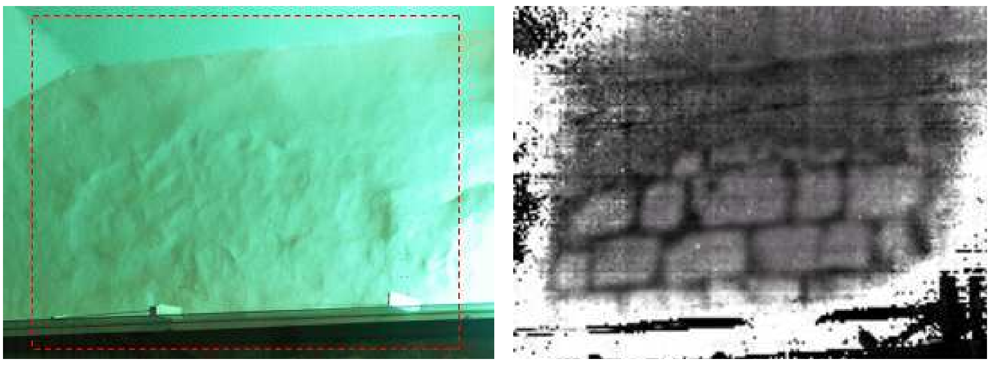


Figure 3. Wartburg Castle Eisenach, Germany, part of a wall where a walled-up former entrance could be detected using thermography.

A special field of application of NDT and MDT is the historical investigation. Contrary to archaeological surveys and restorer's cuts NDT does not need any intervention into the building fabric. NDT is therefore suitable as an exclusive methodology to answer historical questions or to provide the precondition for smaller "traditional" investigations.
In any case it is necessary to measure costs and benefit. 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 costs for reconstructions following even small interventions should be considered. Therefore it is emphatically recommended that the building owner and/or his architect should at first contact a Network of Expertise. This has to be an institution, which is working multidisciplinary, possesses a good overview about available NDT and MDT techniques and has wide experience in historical constructions. Such NDT Networks of Expertise should comprehend at least an architect and civil engineer familiar with historic buildings, an architectural historian and a NDT-expert. In the individual case this team should be supplemented by restorers, experts for building materials, experts for subsoil or building climate etc. This multidisciplinary team-work is the most effective way of preparing and applying NDT and MDT. "The tests should always be carried out by skilled persons able to gauge their reliability correctly" (ICOMOS Guidelines 2.4). The NDT network helps to find the investigator and to assess the strategy and the results of the tests.
Out of the panoply of different possibilities of NDT and MDT the adequate methodology has to be chosen, the singular steps of application have to be defined taking the special situation on site into account. The technical effort can often be reduced combining different tests, which means that the application of the testing methods has to be planned carefully and the tests have to be attuned to each other. Such effects of synergy can be achieved for example when boreholes, which are originally drilled for the extraction of material samples, are used again for videoscopies or endoscopies of the masonry structure. The combination of flat jack and structural modelling proved to be a suitable instrument to quantify the loads inside a historical structure (see Report on Case Study Altes Museum: Here, the flat-jack results hint to an enhanced load at the outer shell of the masonry basement walls in comparison to the more inhomogeneous interior of the wall). Radar in combination with active thermography is particularly suitable for investigating the structure close to the surface (active thermography) and at larger depths (up to 2 m and more), because in the radargram, reflection form structures close to the surface are superimposed by the direct surface reflection (see report on the Case Study Wartburg: The walled-up door could be detected with much more resolution with active thermography. The modified brick structure behind the plaster could be directly visualised with the infrared camera after heating the surface).
"Evaluation of the safety of the building should be based on both qualitative (as documentation, observation, etc.) and quantitative (as experimental, mathematical, etc.) methods that take into account the effect of the phenomena on structural behaviour" (ICOMOS Guidelines 4.1). In order to safeguard the historic structure it is often necessary to find out the actual structural behaviour to get the possibility to reduce inadequate safety factors. (ICOMOS Guidelines 4.1).

3.4 What are the capabilities of the different NDT and MDT methods? What are their limits?

Chapter 5 describes some typical problems to NDT and MDT which have been investigated in the frame of the ONSITEFORMASONRY project. Each methodology is briefly described in Chapter 4. There are also hints given to "traditional" investigation methods like visual inspection, ray of light or restorer's cuts, which could be used instead of NDT or in combination with it. The damage catalogue (see 2.3/6.3 and D3.3) specifies typical problems concerning historical masonry more detailed. The owner of the building or engineer may find here possible NDT and MDT methodologies for his own problem.
In many cases the combination of different methodologies leads to problem solving. The reports of the case studies present results from many different NDT and MDT applications (see reports on Case Studies - D10.2). Starting from the problem the strategy and the results of the individual investigation are documented. At the end of this chapter an address list of NDT-Networks of Expertise and NDT experts is also given.

3.5 The selection of the adequate investigation methodology

In order to find out the adequate NDT or MDT method in general one should emanate from the simplest method that is to be considered. First all available non-destructive methods should be pondered. Only if those methodologies seem not to be promising more complex ones should be taken in account. The exhaustive multidisciplinary discussion of the initial situation, of the results of inspections on site, of archive studies, and of the insights which are additionally gained by knocking or using ray of light may supersede more complex tests. Or they help to border the area of investigation as far as possible.

Different NDT and MDT methods offer different depths of penetration at different degrees of resolution. Until now there is no technique available, which interpenetrates masonry structures of more than 150 cm thickness with an adequate resolution and which can be applied with a justifiable effort.

3.6 Costs

The costs for each individual method of testing are summarized in D5.1 (see templates from D5.1) and estimate the range of prices within EU as they had been scheduled in September 2002. Quoted with the individual NDT or MDT method are the prices for 1 hour of work, the experience minimum of costs. Additional costs for scaffolds, transporting etc. have to be taken in account.

3.7 Preparing NDT and MDT applications

The flow chart shows the steps of NDT and MDT applications as part of a global investigation of a building: data collection and data analysis.

1. Preliminary Investigation

1.1. Preliminary inspection of the building/structure
1.2. Acquisition of the available documentation:
- drawings
- sketches
- surveys
- expert's reports
- climate reports
- etc.

1.3. Chronology of the building history:
- events which may have affected the structure and its foundations

1.4. Pictorial survey and photographical survey
1.5. Stocktaking of the building:
- verbal
- photographical documentation
- drawings

1.6. Organisation and management:
- address list
- special requirements of the owner/client and local authorities

2. Analysis and first interpretation of data

- Verbalisation of the existing problem(s) including previous hypothesis about their origins

3. Contact to NDT-Network

3.1. Verbalisation of the problem
3.2. Fixing the cost limit
3.3. Determining the time available for investigations
3.4. Meeting onsite
- Applicable NDT/MDT
- Results to be expected, costs, investigation time

3.5. Defining the scope of the investigation
- Specification of tasks
- Disposition of a working hypothesis

- Choice of the investigator

3.6. Plan for the next phase of detailed data collection

4. Detailed data collection

4.1. Detailed archive investigation:

- historic drawings and documents
- historic photographs
- archive materials and secondary literature to the history of the building and its use
- historic plannings and concepts, write-offs, contracts and accounts
- documents and records concerning particularly occurrences: fire, war, natural catastrophes

4.2. General structural assessment:

- static/dynamic actions
- exceptional actions (e.g. earthquakes)
- physio-chemical actions (weather, pollution, fire)
- biological actions (vegetation)
- materials
- structural elements

4.3. Detailed inspection:

- detailed mapping of the structure and the damages: crack pattern with identification of old and new cracks, deformations, out-of-plumbness, settlements

5. Analysis and Verbalisation of the problem(s):

Verbalisation of the problem(s) to be solved by testing.
For each problem the following questions should be previously answered by the investigation team:

- Which information do I need?
- With what accuracy?
- Which is the method to fulfil my needs?
- Which decision will I take depending on the results ?

NDT/MDT should be preferred to traditional tests on extracted samples when both types of techniques can solve the problem.
The Information looked for in documentation, inspection and tests should allow:

- To confirm or invalidate the previous hypothesis about the problem causes
- To know the data needed for the complete evaluation of the problem extension
- To estimate the importance of the problem, the possible consequences and the future evolution

6. Meeting onsite

- Definition of the allowed interventions
- Choice of NDT/MDT methods
- Fixing the order of investigations

7. NDT/MDT application

8. Analysis of the NDT/MDT results

- Revising the verbalisation of the problem
- Planning of additional NDT/MDT tests (if needed go to step 4)
- Controlling of the cost limit
- Are material extractions needed ? (If yes go to step 9.; if not go to step 10)

9. Selected material extractions and laboratory tests

- Selected material extractions (if necessary) in clear defined areas

10. Documentation of results

- Documentation of the investigation area, the NDT/MDT traces (drawings, photographs), the material extractions and the laboratory tests
- Interpretation of the individual results
- Merging the individual results

- Final tests report

11. Analysis of the general data

- Revising the verbalisation of the problem
- Planning of additional data collection (if needed go to step 3; if not, go to step 12)
- Controlling of the cost limit

12. Final report

- Documentation of the monument, the visual inspection and the tests (both on site
- NDT/MDT and laboratory tests)
- Interpretation of the individual results
- Merging the individual results
- Conclusions and proposals of intervention

3.8 Address list of NDT-Networks of Expertise and NDT experts

Please see Annex at the end of this document.

3 Description of the methods

In this chapter some of MDT and NDT methods are briefly described. Each method has been in short described in following structure:

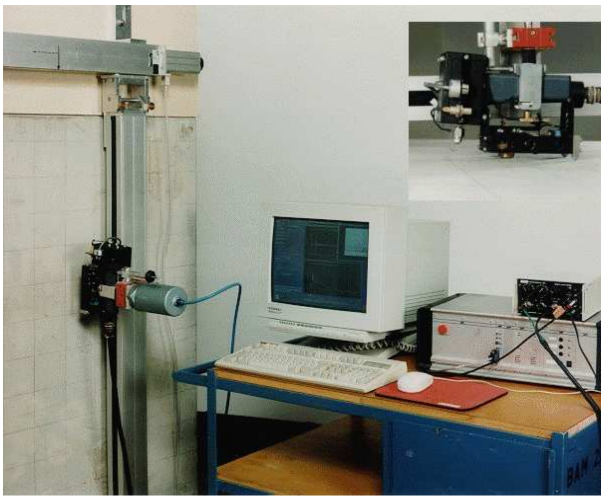
- Aim of test
- Theoretical background
- Picture or sketch
- Short description
- Code (recommendation references)
- Condition applicability

It should be noted that the aim of testing depending on the presented method has been previously defined by the responsible partner. Thus, the aim of testing depending on the method presented in this chapter does not automatically correspond to the recommendations given in the 5th Chapter of this document: Recommendations for different methods for different level of investigation. The recommendations from the 5th Chapter have been determined according to the testing results from the on-site campaigns carried out through this project.

4.1 *Impact-echo*

Aim of the test

- Determination of the thickness of walls and single leaves
- Detection of detachment of leaves
- Location of voids
- Location of deteriorated areas
- Quantification of cracks
- Correlation of sonic velocity to compressive strength (limited)



Theoretical background

In impact-echo a mechanical point impact is used to generate an acoustical impulse, which propagates into the concrete. Multiple reflections of low frequency waves between the external surface and internal reflectors (ducts, delaminations and defects) are used to measure transient resonance frequencies and to evaluate structural integrity.

Short description

Impact-echo is a wave propagation-based technique which uses frequency domain analysis for data interpretation. Frequency spectrum analysis is performed on the waveform obtained from a mechanical impact applied on the surface of the concrete element. By applying a point impact on the surface of the test object, a transient stress pulse is generated and propagates into the concrete as compressional, shear and surface waves. The compressional and shear waves, which travel through the material, are partly reflected by any internal interface or discontinuity such as reinforcements, ducts, defects, delaminations. These waves are almost totally reflected if the second material is air, such as in the presence of a void or at the external boundaries of the element under investigation. Therefore, the principle of Impact-echo testing is based on multiple reflections of an acoustical wave impulse between the surface and any internal reflector.

Code/recommendation references

- ASTM C 1383 – 98 Standard test method for measuring the p-wave speed and the thickness of concrete plates using the impact-echo method

Note

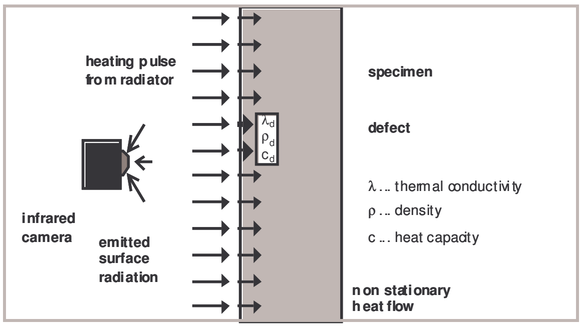
The values can not be generalised.

- Non-destructive
- On-site applicable
- Contact to surface required

4.2 *Active Thermography*

Aim of the test

- Localisation of voids and other irregularities in the near surface region (up to 10 cm)
- Localisation of plaster delaminations
- Investigation of the masonry structure behind plaster
- Detection of moisture in the near surface region



Theoretical background

A thermal pulse is applied to a surface causing a non-stationary heat flow. The propagation of the heat into the body depends on material properties like thermal conductivity, heat capacity and density of the inspected specimen. 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.

Short description

Impulse thermography (IT) and pulse-phase thermography (PPT) are active approaches for a quantitative thermal scanning of the surface of various structures and elements. The surface of the structure to be investigated is heated by using a radiation source. After switching off the heating source, the cooling down behaviour is recorded in real time with an infrared camera. While observing the temporal changes of the surface temperature distribution with the infrared

camera, near surface inhomogeneities will be detected if they give rise to measurable temperature differences on the surface.
The main approach of IT in analysing the thermal data is to interpret the function of surface temperature versus cooling time for selected areas with and without inhomogeneities. For solving the Inverse Problem, i. e. to get information about the thermal and geometrical properties of the detected defect from the difference curves, numerical simulations can be performed.
PPT is based on the application of the Fast Fourier Transformation (FFT) to all transient curves of each pixel. Thus, one obtains amplitude and phase images for all frequencies. Amplitude images show the internal structure of a specimen up to a maximum available depth depending on the frequency (low pass filter behaviour). Phase images show the internal structure within a certain depth range depending on the frequency (band pass filter behaviour).
Active methods have proven their usefulness for locating defects in the near surface region like voids and honeycombing in concrete and delaminations of tiles, plaster and glued carbon fibre reinforced laminates. Further developments and applications in civil engineering are using the sun as a natural heat source, e.g. for the inspections of bridge decks and of paving in general.

Code/recommendation references

- ASTM D4788-03 Standard Test Method for Detecting Delaminations in Bridge Decks Using Infrared Thermography

Note

The values can not be generalised.

- Non-destructive
- On-site applicable
- Contact to surface not required

4.3 *Ultrasonics (echo and through transmission)*

Aim of the test

- Determination of the thickness of walls and single leaves
- Location of voids having sizes in the order of the wavelength of the ultrasonic waves (20 to 100 mm) depending on frequency of the emitted pulses
- Characterisation of cracks (limited)
- Correlation of ultrasonic velocity to compressive strength (limited)

Theoretical background

The method is based on the transmission and/or reflection of ultrasonic waves generated by an ultrasonic transducer or transducer array. Longitudinal as well as transversal waves can be generated. The velocity of propagation depends on mechanical parameters of the structure, the reflection on the contrast of the acoustic impedances at the interface.

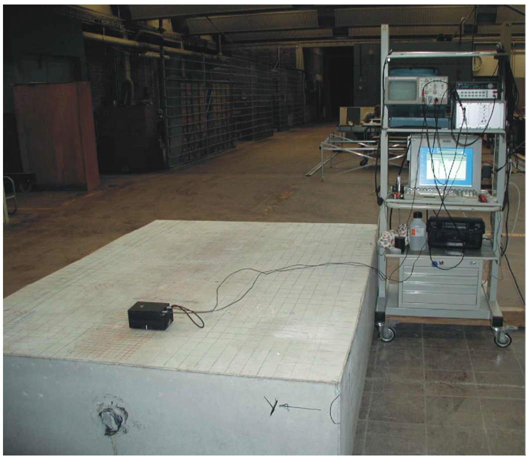
Short description

The principle of the ultrasonic echo technique with separated transmitter and receiver is based on the emission and reflection of impulses generated by a transducer. Inner voids in a specimen can be regarded as an interface between two different materials (brick/air) for the propagation of sound and lead to total reflectance of the ultrasound waves. The propagation time of the reflection echo is proportional to the depth of the reflector (assuming a constant velocity of propagation). For several test problems it is advantageous to use transducer arrays and/or to combine it with a 3D reconstruction calculation (3D-SAFT, Synthetic Aperture Focusing Technique).
For tomographic application the transit time has to be measured in different directions relative to the surface. The inner structure of the building element will influence this transit time. In order to measure the transit time most accurately, the first arriving point has to be detected.

Code/recommendation references

- Merkblatt für Ultraschall-Impuls-Verfahren zur Zerstörungsfreien Prüfung mineralischer Baustoffe und Bauteile (B4), Deutsche Gesellschaft für Zerstörungsfreie Prüfung e.V., Berlin (1999)
- ASTM C 597 – 83 (91) Standard test method for pulse velocity through concrete
- DIN EN 13296 Bestimmung der Ultraschallgeschwindigkeit (1998)





Note

The values can not be generalised.

- Destructive
- On-site applicable
- Contact to surface required with coupling agent
- Contact to surface required

4.4 Single Flat Jack Test

Aim of the test

- Determination of the state of stress acting in a masonry structure.

Def.: The flat jack is a steel pad which is to be inflated with oil until the slot is tied positively, i.e. the original situation is restored, the relative strength can be reconstructed.

Theoretical background

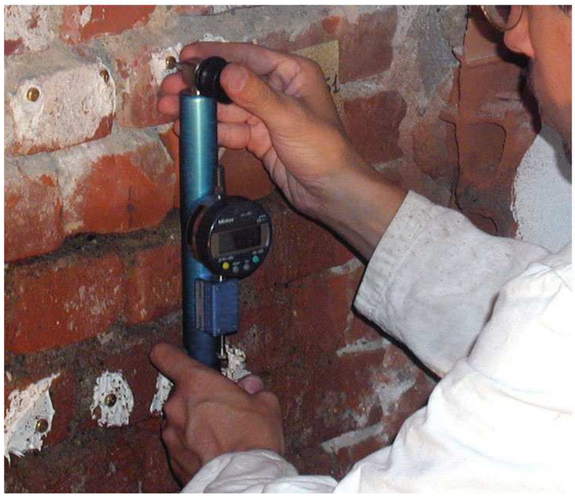
The determination of the state of stress is based on the stress relaxation caused by a cut perpendicular to the wall surface; the stress release is caused by a partial closing of the cut slot, i.e. the distance between the edges of the slot after the cutting is lower than before. A thin flat-jack is placed inside the slot and the pressure is gradually increased to restore the distance measured before the cut.

Short description

In a brick masonry, the cut can be easily made in the horizontal joints. For this type of masonry a rectangular flat-jack is used (120*240*8mm / 400*200*8 mm).
The cut can also be made by a steel disk, with a diamond cutting edge. The flat-jack has the same shape of the cut (350*250*4mm).
Potentiometric linear variable differential transducers or a mechanical meter are used with a sensitivity of about 0.001mm.







Code/recommendation references

- ASTM C 1196 (1991), Standard test method for in-situ compressive stress within solid unit masonry estimated using the flat-jack method, Philadelphia, ASTM.
- ASTM C 1197 (1991) - Standard test method for in-situ measurement of masonry deformability properties using the flat jack method Rilem Lum 90/2 Lum D.2 (1990) – In-situ stress based on the flat jack
- RILEM Lum 90/2 Lum D.2 (1990) – In-situ stress based on the flat jack RILEM Lum 90/2 Lum D3 (1990)- In-situ strength and elasticity tests based on the flat jack.

Note

The values can not be generalised.
- Minor destructive
- On-site applicable
- Contact to surface required

4.5 *Hole Drilling Method*

Aim of the test

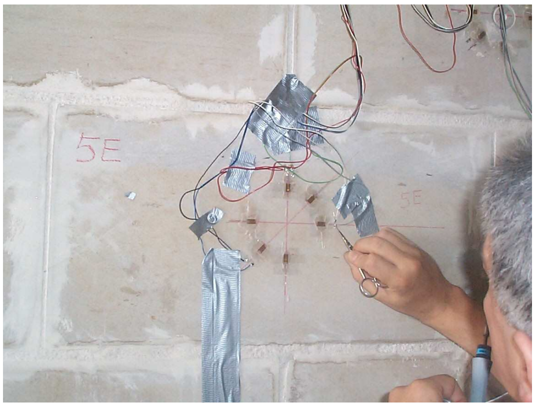
- Estimation of the stress field in the surface of stone masonry elements.

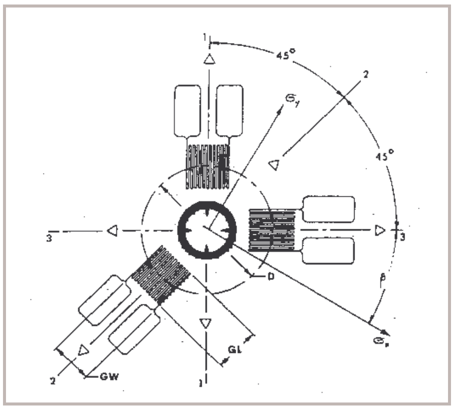
Theoretical background

The principal stresses are obtained from the effective strains corresponding to the stresses released by drilling a hole in the stone surface. Strains are recorded by three electrical resistance strain gages placed in a circumference around the hole.

Short description

A three strain gage scheme is placed in the selected point and strains are recorded during a certain period of time before drilling, in order to obtain a good "zero" reference reading. After drilling a hole at the geometric centre of the strain gages circumference, strains are measured again. The effective strains corresponding to the stresses released by drilling are the difference between the two strain readings (after and before drilling).
Principal stresses are obtained, from the effective strains Ei corresponding to the stresses released by drilling, and using two constants A and B, which depend on the material mechanical characteristics and on the geometry of the test.
A and B are determined experimentally using a calibration test in which a prismatic block sample is subjected to a uniform uni-axial compression stress. Tests are repeated twice, a first one before drilling a hole and the second one after drilling it.
The method is a generalization of the test regulated by ASTM E 837-95 for steel structures.





Code/recommendation references

- ASTM E 837-95, Standard test method for determining residual stresses by the Hole-drilling strain gage method".
- ASTM E 1237-93 (2003), Standard guide for installing bonded resistance strain gages.

Note

The values can not be generalised.
- Destructive
- On-site applicable
- Contact to surface required

4.6 *Double Flat Jack Test*

Aim of the test

- Determination of the deformability characteristics of a masonry.
- Study of the stress-strain behaviour of the masonry.

Theoretical background

Two parallel cuts are made in the masonry, at a distance of about 40 to 50 cm from each other. The two jacks delimit a masonry sample of appreciable size to which a uni-axial compression stress can be applied. Measurement bases for removable strain-gauge or LVDTs on the sample face provide information on vertical and lateral displacements. In this way a compression test is carried out on an undisturbed sample of large area. Several loading-unloading cycles may be performed at increasing stress levels in order to determine the deformability modulus of the masonry during loading and unloading phases.

Short description

In a brick masonry, the cut can be easily made in the horizontal joints. For this type of masonry a rectangular flat-jack is used (120*240*8mm) or rectangular flat jack (400*200*8 mm). The

cut can also be made by a steel disk, with a diamond cutting edge. The flat-jack has the same shape of the cut (350*250*4mm).
Potentiometric linear variable differential transducers or a mechanical meter are used with a sensitivity of about 0.001mm.
Measurement bases for LVDTs on the sample face provide information on vertical and lateral displacements. In this way a compression test is carried out on an undisturbed sample of large area. Several loading-unloading cycles may be performed at increasing stress levels in order to determine the deformability modulus of the masonry during loading and unloading phases.

Code/recommendation references

- ASTM C 1196 (1991), Standard test method for in-situ compressive stress within solid unit masonry estimated using the flat-jack method, Philadelphia, ASTM.
- ASTM C 1197 (1991) - Standard test method for in-situ measurement of masonry deformability properties using the flat jack methodRilem Lum 90/2 Lum D.2 (1990) – In-situ stress based on the flat jack
- RILEM Lum 90/2 Lum D.2 (1990) – In-situ stress based on the flat jack RILEM Lum 90/2 Lum D3 (1990)- In-situ strength and elasticity tests based on the flat jack.

Note

The values can not be generalised.

- Minor destructive
- On-site applicable
- Contact to surface required

4.7 *Pulse Sonic Test*

Aim of the test

- Qualification of the masonry morphology.

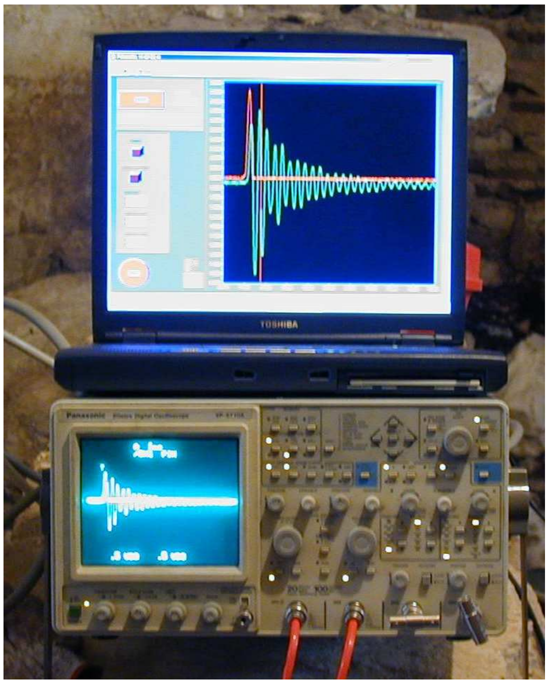
- Detection of the presence of voids and flaws and to find crack and damage patterns; control the effectiveness of repair by injection technique or where the changes of the physical characteristics of materials has occurred.

Theoretical background

The testing technique is based on the generation of elastic waves in the frequency range of sound (20 Hz-20 kHz), by means of mechanical impulses at a point of the structure. The pulse velocity is related in a homogeneous and isotropic solid to the modulus of elasticity and density. The relationship is independent of the frequency of the vibrations. In the case of masonry, due to its heterogeneity, the pulse velocity qualitatively represents the characteristic of the masonry.

Short description

A signal is generated by percussion with an instrumented hammer or by an electrodynamics or pneumatic device (transmitter) and is received by means of an accelerometer (receiver), which can be placed in various positions. The data processing consists in measuring the transit time between the transmitter and the receiver and in calculating the pulse velocity dividing the distance between the devices by the transit time. Signals are stored by a waveform analyser coupled with a computer for further processing. Three types of tests can be carried out: (1) direct (or through-wall) tests in which hammer and accelerometers are placed in line on opposite sides of the masonry element, (2) semi-direct tests in which hammer and accelerometers are placed at a certain angle to each other, and (3) indirect tests in which hammer and accelerometer are both located on the same face of the wall in a vertical or horizontal line. Generally a grid of acquisition points is investigated.



Code/recommendation references

- RILEM Recommendation TC 127-MS, “MS.D.1 Measurement of mechanical pulse velocity for masonry”, (published in Materials and Structures, Vol. 30, July 1997 pp. 463-466)
- NORMAL 22/86, “Misura in laboratorio e in sito della velocità apparente (o virtuale) di propagazione del suono (onde longitudinali) nel materiali porosi da costruzione
- ASTM C597-83 “Standard test method for pulse velocity through concrete”

Note

The values can not be generalised.

- Non-destructive

- On-site applicable
- Contact to surface required

4.8 *Geoelectrical Tomographies*

Aim of the test

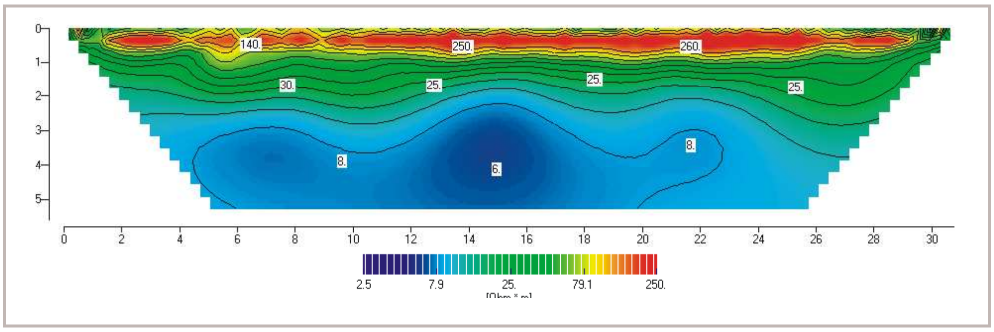
This technique allows to individuate the presence of anomalies of the resistivity of the masonry structures, due, for instance, to the presence of moisture or voids.

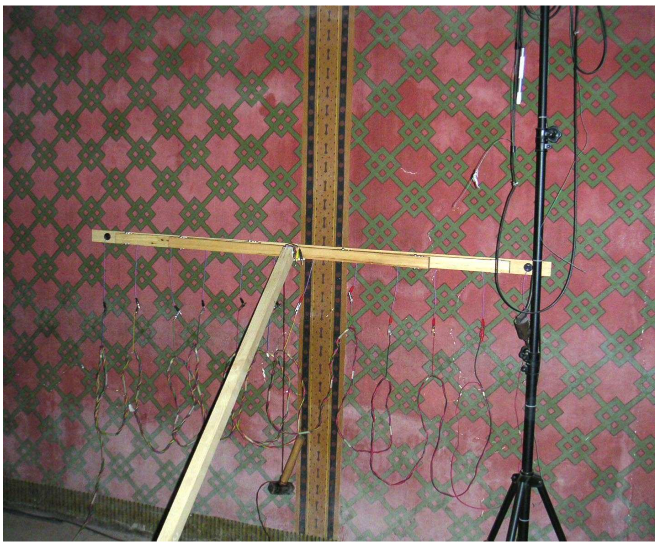
Theoretical background

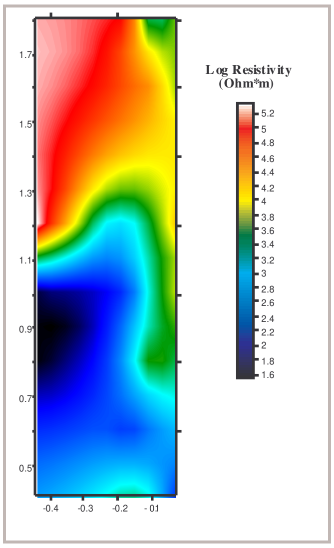
The testing technique is based on the generation of electrical current in two electrodes. An electrical field is generated and from other two electrodes, the electrical potential is measured. From this information it is possible to get the resistivity of the indagated area.

Short description

The measurements are made by means of a number of mini-electrodes (typically 24-48) placed along profiles at the surface of the wall. A multi-electrode Georesistivitymeter connects, in sequence, 4 electrodes at a time and measures the apparent resistivities. Different electrode arrays can be used: Wenner, Dipole-Dipole, Pole-Dipole, Pole-Pole, etc..By repeating the measurements with different electrode spacings, it is possible to build up a qualitative image of the apparent resisitvities under the profile, that is a "Pseudosection"..
By means of an inversion software, it is possible to obtain a quantitative image of the true resistivities under the surface, that is a Geo-electrical Tomography.
The main technical problem for this kind of measurements is due to the high contact resistances of the mini-electrodes on a masonry surface. It is necessary to use georesistivitymeters with very high input impedance (10 Mohm or more).







Code/recommendation references

- Ministère de l'Industrie Sous Direction Qualité-Normalisation, "Applied geophysics of practice", 1992

Note

The values can not be generalised.

- Non-destructive
- On-site applicable
- Contact to surface required

4.9 *Micro-Seismic Profiles*

Aim of the test

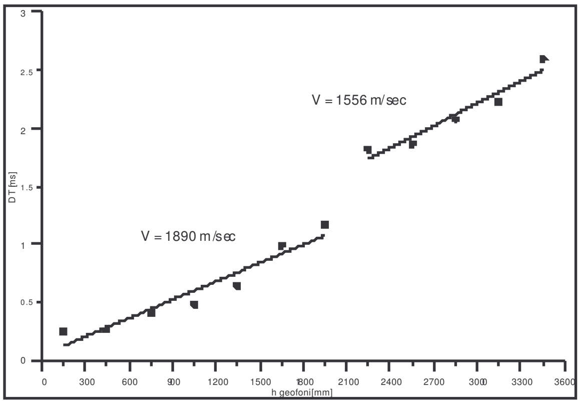
This technique allows to evaluate the sonic velocities along profiles at the surface of a masonry structure. It can be seen as a transposition of the Refraction Seismic method as a NDT on masonry.

Theoretical background

The testing technique is based on the generation of elastic waves by mechanical impulses at a point of the structure. The velocity of transmission qualitatively represents the characteristic of the masonry.

Short description

To measure the seismic velocities along profiles a number of transducers are fixed to the surface of the wall. Sonic waves by means of light sources at the ends of the profile. The travel times of the seismic waves from the source to each transducer are measured and plotted versus the distance from the source. These graphs are called dromochrones. The slopes of the straight segments of the dromochrones give the velocities of the seismic waves.



Code/recommendation references

- Ministère de l'Industrie Sous Direction Qualité-Normalisation, "APPLIED GEOPHYSICS OF PRACTICE", 1992

Note

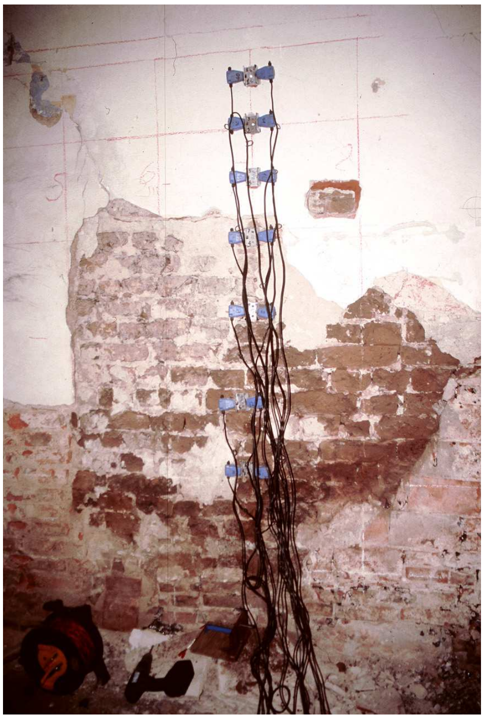
The values can not be generalised.

- Non-destructive
- On-site applicable
- Contact to surface required

4.10 *Micro-Seismic Profiles with Shear Waves*

Aim of the test

The simultaneous use of P-waves and S-waves technique can allow the discrimination of different type of "anomalies" in a wall.
The data obtained by this techniques give an important input for the static verification procedures, also if attention must be given to transfer the dynamic values of the elastic moduli to the static modelling.



Theoretical background

The testing technique is based on the generation of elastic waves by mechanical impulses at a point of the structure. The velocity of transmission qualitatively represents the characteristic of the masonry.

Short description

The method is a variant of the micro-seismic profiling: it is based on the propagation of the shear (or transversal) elastic waves (S-waves) instead of the pressure (or longitudinal) waves (P-waves).
The procedure is quite similar, but the excitation tool must produce S-waves (more precisely, SH-waves) and the sensors must be horizontal geophones.
There are two advantages in using s-waves: due to the smaller wavelength , it is possible to reach a higher resolution. As the velocity of the s-waves depends from the shear modulus, the simultaneous use of P- and S-waves allows a complete description of the elastic dynamic properties of the solid. The Poisson coefficient can be derived from the vs/vp ratio.

Code/recommendation references

- Ministère de l'Industrie Sous Direction Qualité-Normalisation, "APPLIED GEOPHYSICS OF PRACTICE", 1992

Note

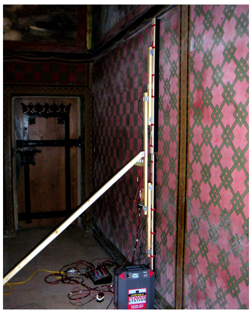
The values can not be generalised.

- Non-destructive
- On-site applicable
- Contact to surface required.

4.11 *Micro-Seismic Tomographies*

Aim of the test

The aim is to get an image of the ideal section (tomography) across the wall. This allows to point out eventual cavities, flaws or layerings in the structure, etc. But the most interesting fact is that the image shows the variations of the velocity, that depend mainly from the dynamic elastic moduli of the material.
The data obtained by this technique not only give a geometrical description of the masonry structure, but also an important input for the static verification procedures, also if attention must be given to transfer the dynamic values to the static modelling.



Theoretical background

The testing technique is based on the generation of elastic waves by mechanical impulses at a point of the structure. The velocity of transmission qualitatively represents the characteristic of the masonry or the presence of voids.

Short description

The method of sonic tomography is a small-scale variant of the cross-hole time-travel tomography used in geophysical high resolution investigations. Both sides of the masonry structure must be accessible. A series of receivers (small geophones) is positioned on one side of the wall and connected to a multi-channel seismograph. On the other side of the wall a series of pulses are generated by hitting the surface along a profile in correspondence to the receivers line. For every shot the arrivals to all the receivers are recorded. The source-receiver rays cover a section across the wall.
The interpretation consists in a tomographic reconstruction of the distribution of the sonic velocities across the section (which is divided in pixels). This velocity distribution is expressed, via graphi cal routines, in a grey-scale or in a colour scale.

Code/recommendation references

- Ministère de l'Industrie Sous Direction Qualité-Normalisation, "APPLIED GEOPHYSICS OF PRACTICE", 1992

Note

The values can not be generalised.
- Non-destructive
- On-site applicable
- Contact to surface required

4.12 *Shear-waves Micro Seismic Tomographies*

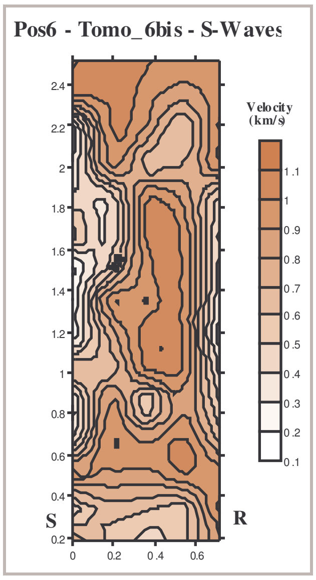
Aim of the test

The aim is to obtain a higher resolution in micro-seismic tomography. It is interesting also that it shows the variations of the shear-waves velocity, that depends from the dynamic shear modulus of the material.
The simultaneous use of P-waves and S-waves tomography can allow the discrimination of different type of "anomalies" in a wall. For instance, an air filled gap will have a quite different

aspect in P or S-wave tomographic images. The data obtained by these techniques not only give a geometrical description of the masonry structure, but also an important input for the static verification procedures, also if attention must be given to transfer the dynamic values to the static modelling.

Theoretical background

The testing technique is based on the generation of elastic waves by mechanical impulses at a point of the structure. The velocity of transmission qualitatively represents the characteristic of the masonry.



Short description

The method is a variant of the "sonic" tomography that is based on the propagation of the pressure (or longitudinal) elastic waves (P-waves). In this case the shear (or transversal) elastic waves (S-waves) are used. The procedure is quite similar, but the excitation tool must produce S-waves (more precisely, SH-waves) and the sensors must be horizontal geophones.
There are two advantages in using s-waves: due to the smaller wavelength , it is possible to reach a higher resolution, that is, smaller pixels in the tomographic reconstruction.
As the velocity of the s-waves depends from the shear modulus, the simultaneous use of P- and S-waves allows a complete description of the elastic dynamic properties of the solid. The Poisson coefficient can be derived from the vs/vp ratio.

Code/recommendation references

- Ministère de l'Industrie Sous Direction Qualité-Normalisation, "APPLIED GEOPHYSICS OF PRACTICE", 1992

Note

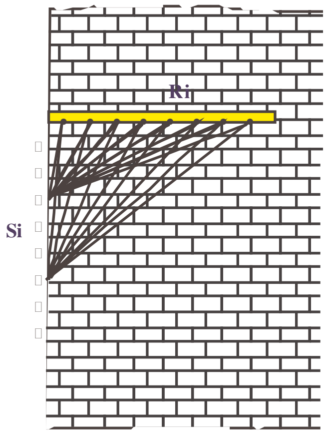
The values can not be generalised.
- Non-destructive
- On-site applicable
- Contact to surface required

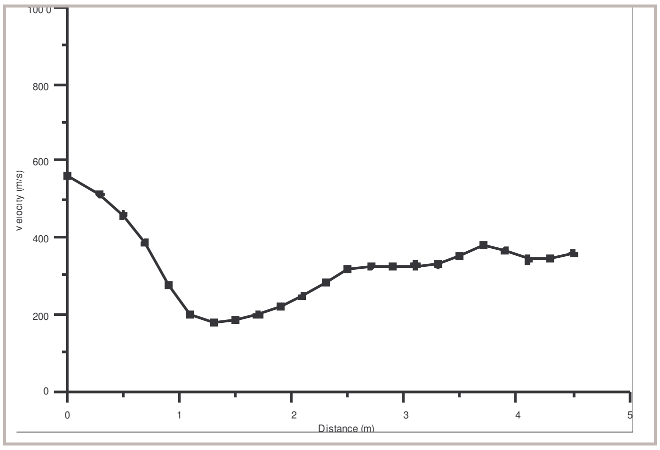
4.13 *TSS Profiles*

Aim of the test

The output of the method is a velocity profile along the depth of the hole. The resolution is very high, specially in detecting low velocity layers.

It can be used (if a borehole, typically 50-60 mm of diameter, is allowed) when the one of the surfaces of the wall is not practicable.





Theoretical background

The testing technique is based on the generation of elastic waves by mechanical impulses at a point of the structure. The velocity of transmission qualitatively represents the characteristic of the masonry or the presence of voids.

Short description

Another kind of seismic tomography is the so-called Tomographic Seismic Sounding, SST. In this case the transducers are in a hole drilled in the wall, while the energising points are along straight profiles at different distances from the hole. A triangular section is covered by the seismic rays. The data treatment uses algorithms similar to the 2D-tomography. The result is a velocity profile along the axis of the hole. This method gives the variations of velocities with the highest resolution.

Code/recommendation references

- Ministère de l'Industrie Sous Direction Qualité-Normalisation, "APPLIED GEOPHYSICS OF PRACTICE", 1992

Note

The values can not be generalised.
- Minor destructive
- On-site applicable
- Contact to surface required

5 Recommendations for different methods for different level of investigations

Recommendations for different methods for different level of investigations are based on:

- The results from WP4 – Methodology development for inspection
- The results from WP5 – Methodology development for assessment
- The results from WP7 – New data acquisition systems
- The results from WP8 – Integration
- The results from WP9 – Structural models and
- The results from WP10 – On-site Application and evaluation

The methodology used in individual cases consists of a set of already available methods as well as newly proposed NDT and MDT methodologies integrated in WP8 and WP10. Based on the results of case studies (200 test results at 10 different testing sites), and knowing which methods are required in the case of individual situations, the methodology is recommended to be used on the project related level.

The recommendations presented in this chapter are derived through join work and analysis of test results of all involved partners in the project. They represent the join results of all three involved groups in this project: experts, structural engineers and owners.

Depending on the problems to be solved the optimum combination of different methods are recommended following the analysis and limitations presented in the form of tables. For each type of problem the set of methods and their combinations are presented together with their limitations. Thus each table consists of:

- Applied technique
- Expected performance and resolution
- Limitation of the technique
- Diagnosis level
- Restriction of use
- Notes for recommendation

Following these tables and the results of on-site investigations, the final recommendations (REC), depending from the type of problem are stated at the end of each sub-chapter.

5.1 Evaluation of state of stress in compression and elastic properties

Class of the problems: Mechanical Evaluation of Masonry

Problem: Evaluation of state of stress in compression and elastic properties

Requirements:

- REQ(1): Evaluation of state of stress in compression
- REQ(2): Evaluation of elastic properties

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
Single flat jack	Evaluation of the local state of stress with a resolution of 0.1 N/mm² approximately.	The measurement is local and only related with jack dimension. In case of multiple leaves, the measurement is limited to the external leaves. The choice of the flat-jack dimensions and of the cut position should take into account the masonry texture dimensions and characteristics.	Any, provided the value of the stress is greater than the test resolution.	Restrictions being locally destructive. In the case of irregular stone wall the cut should preferably be carried out in the stones. Small flat jack tests are not applicable on low stresses stone masonry if the cut is carried out on stiff stone elements, as the measurable released strain is of 20 $\mu\varepsilon$ limited by the accuracy of the mechanical extensometer. The test does not give precise results on masonry subject to low stresses, even if this is already a precious information.	A previous control of the masonry by sonic test or other techniques is recommended. This would avoid carrying out the test in correspondence to unknown masonry defects or voids that could affect the reliability of the test. For a complete interpretation of test results, they should be compared to reference values obtained from more or less complex structural analysis (expected stresses) or material strength (for comparison of existing stresses).
Hole Drilling	Estimation of the stress field in the surface of stone elements with a resolution given by an accuracy of the strain gages of +/- 1 $\mu\varepsilon$.	The measurement is local and superficial (surface stress state). Masonry is considered as a isotropic material and the influence of the joint on the anisotropy is neglected. The thickness of the joints in comparison to the size of the units should be incomparable small.	Any, provided the value of the stress is greater than the test resolution.	Restrictions being locally destructive. The application is limited to regular stone masonry as the state of stress in irregular stone masonry is rather complex. It requires a calibration test performed on a stone block extracted from the structure understudy, to determine two calibration constants (A and B).	The results may represent very local state of stresses of the tested unit. For the complete interpretation of tests results, they should be compared to reference values obtained from more or less complex structural analysis (expected stresses) or material strength (for comparison of existing stresses). More research is needed before its recommendation.
Double Flat Jack	Evaluation of the local elastic modulus	The measurement is local being related to jack dimension. In case of multiple leaves, the measurement is limited to the external leaves. The dead load on top of the flat jack must equilibrate the induced state of stress.	Any, taking into account the limitation.	The test is partially destructive. In case of rubble stone masonry walls, the stones must be cut. The choice of the cut position is very important. The test cannot be carried out when stresses on masonry are very low due to lack of contrast. Eventually only low stresses can be inducted in order to calculate the modulus. In laboratory some problem might occur because of the non-	A preliminary control of the masonry by sonic test or other techniques is recommended. This would avoid to carry out the test in correspondence of unknown masonry defects or voids that could affect the reliability of the test. The main purpose of the method is its use in-situ, however the calibration coefficients have to be determined to obtain results comparable with standardised laboratory

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
				sufficient reaction of the testing frame or the use of unsuitable constraints. If double flat jacks are used to determine local elastic modulus (secant), it is necessary to multiply the modulus by a certain calibration coefficient. Its value depends on strength of mortar and height of masonry clamped between the two flat jacks. (Other influences come from the measurement itself and they are the geometry of flat jacks and the cut space for insertion of flat jacks.) In laboratory such coefficients are possible to obtain by calibration and comparative testing.	tests.
Sonic	Qualitative indication of the density properties of the different areas. The resolution depends on masonry texture and on the test points' grid, (20 cm is the minimum). A difference in sonic velocity cannot be directly related to the presence of different materials, only the fact that an inhomogeneity is present can be detected, not the nature of it.	The distribution of measurement points in the tomographic section has to be homogeneous.	Any.	Restrictions on frescos. The test can not give information concerning the elastic modulus or the strength of the masonry.	For this purpose, more research is needed before its recommendation.
Prismatic Sample Testing	Evaluation of the elastic properties and strength on (non-standardised) prismatic samples cut of bed mortar pieces taken from real buildings. The splitting test can be carried out, as well.	The properties are local and the method needs calibration for different materials. Peculiar attention should be directed to the sampling modality and quantity. The sampled material has to be enough to produce a prismatic sample. The test gives information on the elastic properties only of the single material. Up to now, reliable relationships between the behaviour of the masonry components and of wall are not available.	Any with bed joints thicker than 15 mm	Restrictions yield from the fact that the method is locally destructive. The sample is rarely allowed. The limitation lies in the sampling process. The stress decrease and the transportation phase often damage the sample itself.	The methodology of testing in bending provides reasonable correlation to standard test procedure. More research on small sample compression tests is needed before its recommendation.
Cubic and cylindrical sample testing	Evaluation of the elastic properties and strength on (non-standardised) cubic or cylindrical samples of building materials taken from real buildings.	The properties are local even they can be determined across the wall section in different places. The method needs calibration for different materials. Peculiar attention should be directed to the sampling modality and quantity. The cores	Brick, stone elements and the specimens of the size of single bricks or stone cylinders	Restrictions yield from the fact that the method is locally destructive. The sample is rarely possible. The stress decrease and the transportation phase often damage the sample itself.	Further research is needed i.e. testing of non-standard samples requires correlation coefficients with the standard tests for different types of natural stones or bricks.

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
		should be extracted in the direction of the load applied because the behaviour is not isotropic. The test gives information on the elastic properties only of the single material. Up to now, reliable relationships between the behaviour of the masonry components and of wall are not available.			
Sonic + double flat jack	Estimation of the distribution of the elastic properties in a large dimension wall. The local correlation of mechanical properties and sonic velocities allows calibrating the sonic test on the actual masonry typology. The sonic tests can be repeated on different areas of the wall. As results, an extensive sonic investigation can be performed on different areas of the wall, in order to evaluate the variation of mechanical parameters.	The area chosen for the local correlation has to be as much representative as possile of the actual masonry texture.	any	The calibration is partially destructive. The test does not give reliable results on low stress masonry.	Laboratory experimental research provides some interesting results, which have certain potential for practical application but more research is needed and it is not possible to recommend this methods for general application.
Vertical micro-seismic profiles	Evaluation dynamic elastic modulus E, for a “specimen” length of several meters	The masonry characteristics should be rather uniform in a vertical strip as long as the profile Rather wide range of the results.	Any, taking into account the limitation	Any. The new tools allow to work also on any delicate surface	More research is needed for the recommendation of this method.
Micro-seismic tomography	Qualitative evaluation of the distribution of dynamic elastic modulus E in the tomographic section.	The masonry structure must be accessible from both sides Sensitive to the moisture content so additional tests like coring and powder drilling are required for the correct interpretation of the results.	Any, taking into account the limitation. The obtainable resolution depends on the quality of the structure.	Any. The new tools allow to work also on any delicate surface. The results of the seismic tomography are to be considered carefully; a different pixel schematization may give different impression of the results..	More research is needed for the recommendation of this method.
TSS (velocity profilings in borehole)	From the high resolution velocity profile along the axis of the hole, it is possible to evaluate the dynamic elastic modulus E.	It is possible to obtain the velocities of the material around the hole, up to the depth of 80% of the hole	Any, taking into account the limitation.	Restriction of delicate surfaces (MDT)	For each borehole, different TSS should be performed changing the direction of the shoot profiles on the surface. More research is needed for the recommendation of this method.

Recommended procedure

Recommended procedures	Technique	Recommended by On-site investigation
REC(1): Evaluation of state of stress in compression:	Single flat jack	Pišece: the level stresess were similar to analytically and numerically calculated. Turégano: estimated stresses were high according to experience. But complementary information about material strength or structural analysis was lacking; accordingly results are qualitative values, not directly interpretable. Avio: size of flat jack is not big enough to generate a measurable strain release (combination of very rigid stone irregular masonry and very low existing stresses) Bottagisio: In the case of a highly heterogeneous masonry it has to be considered that the state of stress measured can be locally affected by the wall morphology and irregularity. The test position has to be carefully chosen.
REC(2): Evaluation of elastic properties	Double flat jack	Pišece, Avio, Altes Museum, Bottagisio

5.2 Control of the effectiveness of the grout injection

Class of the problems: Control of Intervention

Problem: Control of the effectiveness of the grout injection

Requirements:

…

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
Sonic	Indication of density before and after injection (from sonic velocity). Rough information on the modulus of elasticity if also flat jack tests are carried out The resolution depends on the masonry texture and on the grid (20 cm is the minimum).	-	Any	Restrictions on frescos. The test does not give information about the mechanical effectiveness of the injection but only concerning the grout diffusion.	The test should be carried out before and after the injection on the same measurements points. A direct visual inspection or coring is recommended in order to control the effectiveness of the injection. Local measurement by transmission is more effective than tomography.
Direct visual inspection by boroscopy or fiberscope or videocamera	Indication of internal material and layers composition by core drilling, by analysing the extracted material and inspecting the borehole with fiberscope or videocamera.	The test is locally destructive. For boroscope or fiberscope a hole of max 1 cm diameter may be sufficient. For video camera a hole must be at least 4 cm in diameter.	Any	Restriction being partially destructive. The evaluation is only local. Wet process of drilling may wash out weak lime mortar particles. Dust particles may easily cover the lenses of boroscope and fiberscope, thus the work with videocamera may be easier.	
Double Flat Jack	Evaluation of the local elastic modulus.	The measurement is local and only related with jack dimension. In case of multiple leaves, the measurement is limited to the external leaves. The dead load on top of the flat jack must equilibrate the induced state of stress.	Any, taking into account the limitation.	The test is partially destructive. In case of rubble stone masonry walls, the stones must be cut.	The test should be carried out before and after the injection.
Sonic transmission + direct visual inspection	indication of density before and after injection (from sonic velocity). The direct visual inspection controls the effectiveness of the injection.	The calibration is slightly destructive	any	Restrictions on frescos	The test should be carried out before and after the injection on the same measurements points. The direct visual inspection should be accurately designed, being partially destructive
Micro-seismic tomography	From the comparison of the tomographies performed before and after the injection, it is possible to evidence the effectiveness of the grounting. If the tomographies are performed both with P-waves and S-waves, it is possible to have some information of the effectiveness of the injection. The synergie of P-waves	The masonry structure must be accessible from both sides. Sensitive to the moisture content so additional tests like coring and powder drilling are required for the correct interpretation of the results.	Any	Any. The new tools allow to work also on any delicate surface. The results of the seismic tomography are to be considered carefully; a different pixel schematisation may give different impression of the results.	The measurement must be performed before and after the injection. More research is needed for the recommendation of this method.

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
	and S-waves tomography can be very useful.				

Recommended procedure

Recommended procedures	Technique	Recommended by On-site investigation
REC(3): Control of the effectiveness of the grout injection:	Sonic test + direct visual inspection	Recommended from previous experience. Note that laboratory investigation concerning the grout injectability on the sampled material should be always carried out

5.3 Presence of vegetation

Class of the problems: Morphological Information

Problem: Presence of vegetation

Requirements:

…

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
Well Logging	Local measurement of vegetation.		Any	The test is partially destructive.	
Video Camera	Qualitative information regarding the nature of vegetation and depth of roots.		Any		

Recommended procedure

Recommended procedures	Technique	Recommended by On-site investigation
REC(4): Detection of vegetation	Use of well logging to evaluate locally the presence of roots inside the wall.	Recommended from previous experience. Results are local.
REC(5): Detection of vegetation	Use of video camera to obtain more qualitative information about the extension of vegetation inside the wall.	Recommended from previous experience.

5.4 Evaluation of the masonry thickness (e.g. foundation, underground walls, vaults …)

Class of the problems: Morphological Information

Problem: Evaluation of the masonry thickness

Requirements:

…

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
Radar in Reflection	Indication of the wall thickness with a resolution of 5 cm (in reflection) depending on radar frequency and size of the masonry structure.	Possible failure when there is moisture or when there are no electrical property variations.		The moisture presence affects the test reliability. Multiple scattering from inhomogeneous materials could fail the test.	A calibration procedure and a direct control are recommended. A steel plate or any other material different from the masonry improves the detection.
Impact-echo	Determination of thickness of masonry walls Depth resolution : >1 cm	Maximum penetration depth: 0.60 m Minimum depth to be detected: 0.2 m Impactor and sensor need water resistant housings The presence of voids could affect the test. Thickness of the wall is limited, depends on the moisture content. Good results for regular brickwork (laboratory) and large homogeneous stonework (Lucca).		The test does not provide reliable results in presence of internal unknown defects.	A control or a calibration is needed because internal unknown defects (e.g. voids) could affect the tests meaningful. More research is needed before its recommendation.
Coring and direct visual inspection by boroscopy or fiberscope or videocamera.	Indication on the wall thickness by direct measurement.	The test is locally destructive.		The test is locally destructive. The test is local.	A complementary technique is recommended in order to control the extension of the result.
Radar + coring and direct visual inspection	indication of the wall thickness with a resolution of 5 cm (in reflection) depending on radar frequency and size of the masonry structure.	possible failure when there is moisture or when there are no electrical property variations.			The number and the position of the calibration area should be accurately chosen being locally destructive. Direct visual inspection is helpful for quantification of inclusions (size, material parameters).
Impact echo +direct visual inspection	Determination of thickness of masonry walls. Depth resolution : > 1 cm	Maximum penetration depth: 0.60m Minimum depth to be detected: 0.2 m Impactor and sensor need water resistant housings.			The number and the position of the calibration area should be accurately chosen being locally destructive.
Geoelectric tomography	Evaluation of the thickness of the masonry wall is possible but with low resolution. Evaluation of the depth of the foundation can be easily obtained by impedance tomography carried out on the soil very near the wall.	The investigation depth is connected with the length of the measurement profile.		Any. The new tools allow to work also on any delicate surface. The results of the seismic tomography are to be considered carefully; a different pixel schematization may give different impression of the results..	When working on walls to evaluate the thickness, impedance tomographies can be used when the situation was unfavourable for radar. More research is needed for the recommendation of this method.

Recommended procedure

Recommended procedures	Technique	Recommended by On-site investigation
REC(6): Evaluation of masonry thickness:	Radar in reflection	Pišece, Avio, Vila Litta, Altes Museum, Veltrusy, Wartburg, Lucca: The evaluation of masonry thickness by radar in reflection gained reasonable results which were confirmed by other direct measurements and drilling. A calibration procedure and a direct control are recommended.
	Radar + coring and direct visual inspection	Pišece, Avio, Vila Litta, Altes Museum, Veltrusy, Wartburg, Lucca: The evaluation of masonry thickness by radar in reflection gained reasonable results which were confirmed by other direct measurements and drilling.
REC(7): Evaluation of masonry thickness:	Coring and direct visual inspection by boroscopy or fiberscope or videocamera	Pišece, Altes Museum, Vila Litta, Veltrusy: Recommended by end-users.

5.5 Localisation of plaster detachments

Class of the problems: Morphological Information

Problem: Localisation of plaster detachments

Requirements:

…

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
Manual Percussion	Detection of delaminations between masonry and plaster. Resolution of spatial distribution of defects depends on the mesh of investigated points (typically 10 by 10 cm), defect size resolution very high – about 4 cm².	The measured area must be accessible by a technician (scaffolding). Point investigations. Low spatial resolution. Documentation by marking detached spots directly on the wall or sketches (when investigating masonry with wall paintings).	Any	Method might be limited on masonry with very delicate surfaces (precious or fragile paintings, frescoes or mosaic). The test is too qualitative.	Photography or video + PC is needed.
Natural percussion acoustic tracing	Detection of delaminations between masonry and plaster. Resolution of spatial distribution of defects along the investigated line is of order of the minimum size of a defect, in the perpendicular direction it depends on the distance of investigated lines (typically 10 cm), defect size resolution very high – about 4 cm².	The measured area must be accessible by a technician. Line investigations. Along the line a very good spatial resolution. Documentation by marking detached spots directly on the wall or sketches (when investigating masonry with wall paintings).	Any	No. Method might be limited on masonry with delicate surfaces (precious or fragile paintings, frescoes or mosaic). Photography or video + PC is needed.	The disadvantage of the necessity to be in contact with the investigated object remains. On the other hand, this approach is suitable namely in case of hard and polished surfaces, where the thermography usually fails.
Natural percussion automatic acoustic tracing	Detection of delaminations between masonry and plaster. Resolution of spatial distribution of defects along the investigated line is of order of the minimum size of a defect, in the perpendicular direction it depends on the distance of investigated lines (typically 10 cm), defect size resolution very high – about 1 cm².	The measured area must be accessible by a technician. Line investigations. Along the line a very good spatial resolution. A need of video, PC and special software for evaluation.	Any	Method might be limited on masonry with delicate surfaces (precious or fragile paintings, frescoes or mosaic). Photography or video + PC is needed.	The method is still under development and more research is needed. Automated acoustic tracing approach is a promising method. The main advantage of this method is seen in its low cost. Contemporary technology is still not sufficient for on-line automatic measurements and evaluation. However, this situation is going to change quickly and the method has a potential to be developed into a fully automated defect search. The disadvantage of the necessity to be in contact with the investigated object remains. On the other hand, this approach is suitable namely in case of hard and polished surfaces, where the thermography usually fails.
Laser Doppler interferometry	Detection of delaminations between masonry and plaster.	Dynamic excitation of the plaster layer must be ensured (mechanical or	Any	No. Dynamic excitation may cause propagation of defects and therefore	Detection of plaster detachment by means of surface velocity

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
	Spatial resolution excellent. Size resolution dependent on exciting frequencies, typically about 4 cm². It is quite time consuming and expensive procedure.	acoustical). For small defects high frequencies are needed. The measurement time is dependent on the quality of signal, frequency of movement and on the spatial resolution. The reading time is about one hour for scanning an area of about 10 000 points, i.e. a square of dimensions of 500 mm by 500 mm at resolution of 5 mm, or 1000 mm by 1000 mm at resolution of 10mm.		the method might not be accepted by the building owner.	measurements using laser Doppler interferometry and mechanical excitation of the wall is quite time consuming and expensive procedure.
Thermography	Detection of delaminations between masonry and plaster Estimation of the thickness of plaster in combination with numerical simulation The measurement depends namely on physical characteristics of the surface as well as of the substratum layers, on the surface qualities – namely reflectance and surface damages. The interpretation of results requires some experience and a detailed documentation of the measured surface quality, at the best by means of usual photography.	Surface should have uniform structure (roughness) Measurements outside require constant environmental conditions: The area measured should be windless and not directed to south or south-west. For exterior application the wind might complicate the measurements but might be also helpful (depending also from the thickness of the plaster).		The method is disturbed significantly by moisture content and this phenomenon should be further researched because it can bring about both the negative as well as positive effects. Not suitable for polished surfaces.	Direct visual inspection by boroscopy or videocamera or fiberscope should be use for verification (sufficient number of holes are needed for the verification). Manual percussion as additional method for verification is required. Perform the measurements early in the morning or late in the night. For exterior application, the winter time is more suitable.

Recommended procedure

Recommended procedures	Technique	Recommended by On-site investigation
REC(8): Localisation of plaster detachment:	Thermography	Altes Museum, Wartburg, the results should be verified by some other DT technique.

5.6 Presence of multiple leaves and measurement of the depth of each leaf

Class of the problems: Morphological Information

Problem: Presence of multiple leaves and measurement of the depth of each leaf

Requirements:

- REQ(1): Detection of the Presence of Multiple Leaves
- REQ(2): Measurement of the Depth of each Leaf

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
Radar in reflection or in tomographic mode	Indication on the presence and dimension of leaves with a resolution of 5 cm (in reflection) and a resolution from 10 to 40 cm (in tomography) depending on radar frequency and size of the masonry structure.	Possible failure when there is moisture or when there are no electrical property variations between the leaves Difficult in case of leaves made with the same materials.	Any	The moisture presence affects the test reliability. Multiple scattering from inhomogeneous materials could fail the test. Limits are given by very high moisture and salt contents as well as by very inhomogeneous structures.	A calibration procedure and a direct control are recommended The elaboration procedure should be very accurate. The use of a steel plate opposite the antenna is recommended in order to the wall thickness.
Sonic transmission or tomography	indication on the presence and dimension of leaves with a resolution from 20 to 70 cm depending on velocity and size of the masonry structure.	Possible failure when there are no elastic property variations between the leaves Not so accurate for smaller structural elements.	Any	Restrictions on delicate surfaces. The test by transmission can seldom recognise the presence of 2 leaves. The presence of a detachment could be supposed by low velocity that should be confirmed by other tests.	A calibration procedure and a direct control are recommended. Efficient when the external leaves are regular stones and the internal is weak rubble.
Direct visual inspection after local dismantling	Indication on the local presence and dimension of leaves		Any	The test is locally destructive (even if the removed material can be used for other analysis or replaced after reconstruction).	The number and the position of the inspection should be accurately chosen being locally destructive.
Impact-echo	Determination of the depth and thickness of the leaves. Depth resolution: > 1 cm	Maximum penetration depth: 0.60 m Minimum depth to be detected: 0.2 m Impactor and sensor need water resistant housings.	Any	The test does not provide reliable results in presence of internal unknown defects. Restriction on surfaces when contact not allowed. The test is meaningful only if the leaves are detached. Good results for regular brickwork (laboratory) and large homogeneous stonework (Lucca).	A control or a calibration is needed because internal unknown defects (e.g. voids) could affect the tests meaningful. More research is needed before its recommendation.
Ultrasonic impulse-echo and tomography	Determination of the depth and thickness of the leaves underneath templates (for positioning of the transducers, size of template: 0.2 m x 0.3 m). Depth resolution: 20 to 50 mm; spatial resolution parallel to the surface: 20 to 100 mm (both depending on the wavelength).	Air gaps between leafs lead to 100% reflection Max. penetration depth depending on side conditions and the materials. Minimum depth to be detected: 0.1 m. Depending on the wavelength and the material.	Any	Restriction on surfaces, if contamination with coupling agent and grinding of the surface is not allowed (some transducers). The penetration depth is very low in case of historic masonry. The test by transmission can seldom recognise the presence of first 2 leaves. Good results for regular	A preliminary control is strictly necessary. More research is needed before its recommendation.

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
				brickwork and large homogeneous stonework (Lucca).	
Radar + direct visual inspection	Indication on the presence and dimension of leaves with a resolution of 5 cm (in reflection) and a resolution from 10 to 40 cm (in tomography) depending on radar frequency and size of the masonry structure.	Possible failure when there is moisture or when there are no electrical property variations between the leaves. Only when the external leaf is regular stone and the thickness can be controlled by inspection or coring.	Any		The number and the position of the calibration area should be accurately chosen being locally destructive. The calibration should be accurately designed, being partially destructive.
Sonic trans./tomography +direct visual inspection	Indication on the presence and dimension of leaves with a resolution from 20 to 70cm depending on velocity and size of the masonry structure.	Possible failure when there are no elastic property variations between the leaves	Any	Restrictions on delicate surfaces. The test by transmission can seldom recognise the presence of 2 leaves.	The calibration should be accurately designed, being partially destructive
Impact echo + direct visual inspection	Determination of the depth and thickness of the leaves. Depth resolution: > 1cm	Maximum penetration depth: 0.60 m Minimum depth to be detected: 0.2 m Impactor and sensor need water resistant housings. Interpretation of the results.	Any	Restriction on surfaces when contact not allowed	The number and the position of the calibration area should be accurately chosen being locally destructive.
Ultrasonic impulse echo or tomography + direct visual inspection	Determination of the depth and thickness of the leaves underneath templates (for positioning of the transducers, size of template: 0.2 m x 0.3 m) Depth resolution: 20 to 50 mm; spatial resolution parallel to the surface: 20 to 100 mm (both depending on the wavelength).	Air gaps between leafs lead to 100% reflection Max. penetration depth depending on side conditions and the materials. Minimum depth to be detected: 0.1 m depending on the wavelength and the material.	any	Restriction on surfaces, if contamination with coupling agent and grinding of the surface is not allowed (some transducers) The penetration depth is very low in case of historic masonry. The test by transmission can seldom recognise the presence of 2 leaves.	The number and the position of the calibration area should be accurately chosen being locally destructive.
Micro-seismic tomography	indication on the presence and dimension of leaves with a resolution from 20 to 70cm depending on velocity and size of the masonry structure.	possible failure when there are no elastic property variations between the leaves Not so accurate for smaller structural elements. The masonry structure must be accessible from both sides. The synergie of P-waves and S-waves tomography can be vert useful. Sensitive to the moisture content so additional tests like coring and powder drilling are required for the correct interpretation of the results.	Any, taking into account the limitation. The obtainable resolution depends on the quality of the structure.	Any. The new tools allow to work also on any delicate surface. The results of the seismic tomography are to be considered carefully; a different pixel schematization may give different impression of the results.	More research is needed for the recommendation of this method.
TSS (velocity profilings in borehole)	It is possible to obtain the presence of multiple leaves by the variation of the velocity along the	It is possible to obtain the velocities of the material around the hole, up to the depth of 80% of the	Any, taking into account the limitation.	Restriction of delicate surfaces (MDT).	For each borehole, different TSS should be performed changing the direction of the shoot

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
	axis of the hole.	hole			profiles on the surface. More research is needed for the recommendation of this method.

Recommended procedure

Recommended procedures	Technique	Recommended by On-site investigation
REC(9): Presence of multiple leaves and measurement of the depth of each leaf	Radar in reflection or in tomographic mode	Altes Museum, Pišece, Avio, Villa Litta, Veltrusy, Wartburg, Lucca, see also restrictions and recommendations.
REC(10): Presence of multiple leaves and measurement of the depth of each leaf	Direct visual inspection after local dismantling	

5.7 Presence of inclusions (e.g. metal or wooden elements …)

Class of the problems: Morphological Information

Problem: Presence of inclusions

Requirements:

…

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
Thermovision	Mapping of the inclusions with a 2D resolution of 3 cm.	It gives only a near-surface information (a few cm deep), unless the inclusion is not a totally different material (e.g. steel). Surface should have uniform structure (roughness) Measurements outside require constant environmental conditions. The area measured should be windless and directed to south or south-west, if there is no artificial heat source. The method can not indicate the material of the inclusions.	Any	Restriction, when it is not possible to heat the surface (presence of frescos etc) or of a maximum surface temperature is given. The inclusion must be superficial.	A calibration procedure and a direct control are recommended. Active thermography is very well suited to investigate plaster and the structures behind up to a depth of max. 10 cm.
Radar	Mapping of the inclusions with a resolution of 5 cm (in reflection) and a resolution from 10 to 40 cm (in tomography) depending on radar frequency and size of the masonry structure.	Possible failure when penetration is precluded by moisture. The method can not indicate the material of the inclusions. Metal sheets lead to a 100% reflection of radar waves. Only in reflection mode.	Any	The moisture presence affects the test reliability. Multiple scattering from inhomogeneous materials could fail the test.	A calibration procedure and a direct control are recommended The elaboration procedure should be very accurate. Only when the inclusions are very different materials (e.g. steel, wood).
Pachometer	Mapping of the metal inclusions.	The method is useful only for the metal detection. The maximum penetration is about 15-20cm.	Any	no restrictions	A preliminary control is strictly necessary.
Radar + direct visual inspection	Mapping of the inclusions with a resolution of 5 cm (in reflection) and a resolution from 10 to 40 cm (in tomography) depending on radar frequency and size of the masonry structure The method can indicate the material of the inclusions and can be extended to wide portions of masonry after calibrating.	Possible failure when penetration is precluded by moisture. Metal sheets lead to a 100% reflection of radar waves. Only in reflection mode.	Any		The number and the position of the calibration area should be accurately chosen being locally destructive. The calibration should be accurately designed, being partially destructive.
Geoelectric tomography	Inclusion can be spotted if its size is big enough (bigger than 25-30 cm). The actual resolution depends from the quality and the homogeneity of the masonry	A high resistivity anomaly can be caused both by a cavity and a compact stone element.	Any	Any The results of the seismic tomography are to be considered carefully; a different pixel schematisation may give different impression of the results..	More research is needed for the recommendation of this method.

Recommended procedure

Recommended procedures	Technique	Recommended by On-site investigation
REC(11): Presence of inclusions (e.g. metal or wooden elements …)	Thermovision	Villa Litta, Wartburg, depth of investigation up to 10 cm.
REC(12): Presence of inclusions (e.g. metal or wooden elements …)	Radar	Altes Museum, Píšece, Avio, Villa Litta, Veltrusy, Wartburg, Lucca,

5.8 Masonry inhomogeneity (e.g. variation of masonry, texture, repair interventions …)

Class of the problems: Morphological Information

Problem Masonry inhomogeneity

Requirements:

…

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
Thermovision	Mapping of the inhomogeneity with a 2D resolution of 3 cm.	It gives only a near-surface information (a few cm deep). Surface should have uniform structure (roughness) Measurements outside require constant environmental conditions: The area measured should be windless and directed to south or south-west, if there is no artificial heat source.	Any	Restriction, when it is not possible to heat the surface (presence of frescos etc) or if a maximum surface temperature is given. The change must be superficial.	A calibration procedure and a direct control are recommended.
Radar	Mapping of the inhomogeneities with a resolution of 5 cm (in reflection) and a resolution from 10 to 40 cm (in tomography) depending on radar frequency and size of the masonry structure.	Possible failure when penetration is precluded by moisture or when there are no electrical property variations between masonry and inhomogeneity.	Any	The moisture presence affects the test reliability. Multiple scattering from inhomogeneous materials could fail the test.	A calibration procedure and a direct control are recommended The elaboration procedure should be very accurate. More research are needed before its recommendation.
Sonic	Mapping of the inhomogeneities with a lateral resolution of 10 cm (in transmission) and a resolution from 20 to 70 cm (in tomography) depending on sonic velocity and size of the masonry structure.	Possible failure when there are no elastic property variations between masonry and inhomogeneity.	Any	Restrictions on frescos	A calibration procedure and a direct control are recommended.
Micro-seismic tomography	Indication on the presence and dimension of the inhomogeneity with a resolution from 20 to 70cm depending on velocity and size of the masonry structure. The synergie of P-waves and S-waves tomography can be very useful.	Possible failure when there are no elastic property variations between the leaves The masonry structure must be accessible from both sides. Sensitive to the moisture content so additional tests like coring and powder drilling are required for the correct interpretation of the results.	Any, taking into account the limitation. The obtainable resolution depends on the quality of the structure	Any. The new tools allow to work also on any delicate surface. The results of the seismic tomography are to be considered carefully; a different pixel schematisation may give different impression of the results..	More research is needed for the recommendation of this method.
TSS (velocity profiling in borehole)	It is possible to get the inhomogeneity by the variation of the velocity along the axes of the hole.	It is possible to obtain the velocities of the material around the hole, up to the depth of 80% of the hole.	Any, taking into account the limitation.	Restriction of delicate surfaces (MDT).	More research is needed for the recommendation of this method.
Geoelectric tomography	The inhomogeneity can be spotted if its size is big enough (bigger than 25-30 cm). The actual resolution depends from the quality and the homogeneity of the masonry.	A resistivity anomaly can be caused both by a cavity and a compact stone element	any	Any The results of the geoelectric tomography are to be considered carefully; a different pixel schematisation may give different impression of the results.	More research is needed for the recommendation of this method.

Recommended procedure

Recommended procedures	Technique	Recommended by On-site investigation
REC(13): Masonry inhomogeneity (e.g. variation of masonry, texture, repair interventions …)	Thermovision	Villa Litta, Wartburg, depth of investigation up to 10 cm.

5.9 Presence of detached external leaves

Class of the problems: Morphological Information

Problem: Presence of detached external leaves

Requirements:

…

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
Radar in reflection	Mapping of detachment extension and depth.	The detachment must be sufficiently thick (more than 3mm).	Any	The moisture presence affects the test reliability. Multiple scattering from inhomogeneous materials could fail the test.	A calibration procedure and a direct control are recommended The elaboration procedure should be very accurate. More research is needed before its recommendation.
Single flat jack	Detection of the detachment by comparison of the local state of stress measured at different depths.	The test can not be extensively applied because of time and costs.	Any	Restrictions being locally destructive. Small flat jack tests are not effective on low stresses stone masonry if the cut is carried out on resistant stone blocks. The test does not give precise results on low stress masonry.	A previous control of the masonry by sonic test or other techniques is recommended. This would avoid to carry out the test in correspondence of unknown masonry defects that could affect the reliability of the test.
Direct visual inspection by boroscopy (fiberscope, videocamera, …)	indication on the local detachment.	The test is local.	Any	Restriction being partially destructive.	A complementary technique is recommended in order to control the extension of the result.
Impact-echo	Determination of the presence of detachments. Depth resolution : > 1cm	Maximum penetration depth: 0.60 m Minimum depth to be detected: 0.2 m Impactor and sensor need water resistant housings. The depth resolution of Impact-Echo is not high enough to detect detachment of plaster or thin leaves.	Any	Restriction on surfaces when contact not allowed. The test does not reliable results in presence of internal unknown defects.	A control or a calibration is needed because internal unknown defects (e.g. voids) could affect the tests meaningful. More research is needed before its recommendation.
Ultrasonic impulse-echo	Determination of the presence of detachments underneath templates (for positioning of the transducers, size of template: 0.2 m x 0.3 m) Depth resolution: 20 to 50 mm; spatial resolution parallel to the surface: 20 to 100 mm (both depending on the wavelength).	Air gaps between leafs lead to 100% reflection Max. penetration depth depending on side conditions and the materials. Minimum depth to be detected: 0.1 m depending on the wavelength and the material.	Any	Restriction on surfaces, if contamination with coupling agent and grinding of the surface is not allowed (some transducers) The penetration depth is very low in case of historic masonry. The test by transmission can seldom recognise the presence of 2 leaves.	A preliminary control is strictly necessary. More research is needed before its recommendation.
Radar in reflection + coring and direct visual inspection	Mapping of detachment extension and depth	The detachment must be sufficiently thick (more than 3mm)	Any	The calibration should be accurately designed, being partially destructive	The number and the position of the calibration area should be accurately chosen being locally destructive. The calibration should be accurately designed, being partially destructive.

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
Impact echo + direct visual inspection	Determination of the presence of the detachment. Depth resolution : >1 cm	Maximum penetration depth: 0.60 m Minimum depth to be detected: 0.2 m Impactor and sensor need water resistant housings.	Any	Restriction on surfaces when contact not allowed.	The number and the position of the calibration area should be accurately chosen being locally destructive.
Ultrasonic impulse echo + direct visual inspection	Determination of the presence of detachments underneath templates (for positioning of the transducers, size of template: 0.2 m x 0.3 m) Depth resolution: 20 to 50 mm; spatial resolution parallel to the surface: 20 to 100 mm (both depending on the wavelength).	Air gaps between leafs lead to 100% reflection Max. penetration depth depending on side conditions and the materials. Minimum depth to be detected: 0.1 m depending on the wavelength and the material.	Any	Restriction on surfaces, if contamination with coupling agent and grinding of the surface is not allowed (some transducers) The penetration depth is very low in case of historic masonry. The test by transmission can seldom recognise the presence of 2 leaves.	The number and the position of the calibration area should be accurately chosen being locally destructive.
TSS (velocity profilings in borehole)	It is possible to obtain the presence of detached external leaves by the variation of the velocity along the axes of the hole.	It is possible to obtain the velocities of the material around the hole, up to the depth of 80% of the hole. The detached external layer must have a minimum thickness of about 10 cm (not suitable for plaster detachments).	Any, taking into account the limitation.	Restriction of delicate surfaces (MDT)	More research is needed for the recommendation of this method.

Recommended procedure

Recommended procedures	Technique	Recommended by On-site investigation
REC(14): Presence of detached external leaves	Radar in reflection + coring and direct visual inspection	Altes Museum, Veltrusy, Wartburg, Lucca

5.10 Presence of voids or chimney flues

Class of the problems: Morphological Information

Problem: Presence of voids or chimney flues

Requirements:

…

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
Radar in reflection or in tomographic mode	Mapping of the voids with a resolution of 5 cm (in reflection) and a resolution from 10 to 40 cm (in tomography) depending on radar frequency and size of the masonry structure.	Possible failure when penetration is precluded by moisture. In reflection mode, the void signature might be confused with other type of inhomogeneity.	Any	The moisture presence affects the test reliability. Multiple scattering from inhomogeneous materials could fail the test in case of smaller voids.	A calibration procedure and a direct control are recommended. The elaboration procedure should be very accurate.
Sonic	Mapping of the void position with a resolution from 20 to 70 cm depending on sonic velocity and size of the masonry structure.	Sonic velocity in air is low so that sonic waves tend to bypass the voids. As a result the void must be sufficiently large (in the order of the tomographic resolution).	Any	Restrictions on frescos.	A calibration procedure and a direct control are recommended
Thermovision	Mapping of the void positions with a 2D resolution of 3 cm. The penetration of the method is up to 10cm, which is less than the normal width of brick unit.	It gives only a near-surface information (a few cm deep). Only voids and slots close to the surface can be detected: (diameter of void)/(depth) >1. Surface should have uniform structure (roughness) Measurements outside require constant environmental conditions: The area measured should be windless and directed to south or south-west, if there is no artificial heat source.	Any	Restriction, when it is not possible to heat the surface (presence of frescos etc) or of a maximum surface temperature is given. The void must be superficial.	
Impact-echo	Determination of the presence of voids . Depth resolution : >1 cm	Maximum penetration depth: 0.60 m Minimum depth to be detected: 0.2 m Impactor and sensor need water resistant housings.	Any	Restriction on surfaces when contact not allowed. The test does not reliable results in presence of internal unknown defects.	A control or a calibration is needed because internal unknown defects (e.g. voids) could affect the tests meaningful. More research is needed before its recommendation.
Ultrasonic impulse-echo or tomography	Mapping of the voids Depth resolution: 20 to 50 mm; spatial resolution parallel to the surface: 20 to 100 mm (both depending on the wavelength).	Large air voids and cavities lead to 100% reflection Max. penetration depth depending on side conditions and the materials. Minimum depth to be detected: 0.1 m depending on the wavelength and the material.	Any	Restriction on surfaces, if contamination with coupling agent and grinding of the surface is not allowed (some transducers) The penetration depth is very low in case of historic masonry.	A preliminary control is strictly necessary. More research is needed before its recommendation.
Direct visual inspection by boroscopy	Indication on the presence and localisation of voids	The test is local	Any	Restriction being partially destructive. The test is only local. Preliminary information is needed in order to choose the localisation of	A complementary technique is recommended in order to control the extension of the result.

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
				the boroscopy.	
Radar + direct visual inspection	Mapping of the voids with a resolution of 5 cm (in reflection) and a resolution from 10 to 40 cm (in tomography) depending on radar frequency and size of the masonry structure.	Possible failure when penetration is precluded by moisture. The calibration is partially destructive.	Any	The calibration should be accurately designed, being partially destructive.	The number and the position of the calibration area should be accurately chosen being locally destructive. The calibration should be accurately designed, being partially destructive.
Sonic + direct visual inspection	Mapping of the void position with a lateral resolution of 10 cm (in transmission) and a resolution from 20 to 70 cm (in tomography) depending on sonic velocity and size of the masonry structure.	The void must be sufficiently large (in the order of the tomographic resolution) The calibration is partially destructive.	Any	Restrictions on frescos. The calibration should be accurately designed, being partially destructive.	
Impact echo + direct visual inspection	Determination of the presence of voids . Depth resolution : >1 cm	Maximum penetration depth: 0.60 m Minimum depth to be detected: 0.2 m Impactor and sensor need water resistant housings.	Any	Restriction on surfaces when contact not allowed.	The number and the position of the calibration area should be accurately chosen being locally destructive.
Ultrasonic impulse echo or tomography+ direct visual inspection	Mapping of the voids Depth resolution: 20 to 50 mm; spatial resolution parallel to the surface: 20 to 100 mm (both depending on the wavelength).	Air voids and cavities lead to 100% reflection Max. penetration depth depending on side conditions and the materials. Minimum depth to be detected: 0.1 m depending on the wavelength and the material.		Restriction on surfaces, if contamination with coupling agent and grinding of the surface is not allowed (some transducers) The penetration depth is very low in case of historic masonry.	The number and the position of the calibration area should be accurately chosen being locally destructive.
Thermovision + direct visual inspection	Mapping of the void positions with a 2D resolution of 3 cm.	It gives only a near-surface information (a few cm deep). Only voids and slots close to the surface can be detected: (diameter of void)/(depth) >1. Surface should have uniform structure (roughness) Measurements outside require constant environmental conditions: The area measured should be windless and directed to south or south-west, if there is no artificial heat source.	Any	Restrictions on frescos if heating is necessary. The calibration should be accurately designed, being partially destructive The void must be superficial.	
Geoelectrical measurement	The void can be spotted if his size is big enough (bigger than 25-30 cm). The actual resolution depends from the quality and the homogeneity of the masonry.	A void gives the same anomaly of a very resistive material.	Any.	The calibration may be partially destructive.	A calibration procedure and a direct control are recommended. The survey (position and direction) should be accurately designed. The elaboration procedure should be very accurate.
Micro-seismic tomography	Indication on the presence and dimension of the void with a	The masonry structure must be accessible from both sides.	Any, taking into account the limitation. The obtainable resolution	Any. The new tools allow to work also on any delicate surface.	More research is needed for the recommendation of this method

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
	resolution from 20 to 70cm depending on velocity and size of the masonry structure. The synergie of P-waves and S-waves tomography can be very useful.	Sensitive to the moisture content so additional tests like coring and powder drilling are required for the correct interpretation of the results.	depends on the quality of the structure.	The results of the seismic tomography are to be considered carefully; a different pixel schematisation may give different impression of the results..	

Recommended procedure

Recommended procedures	Technique	Recommended by On-site investigation
REC(15): Location of voids or chimney flues	Radar in reflection + coring and direct visual inspection	Altes Museum, Veltrusy, Wartburg, Lucca, Pišece
REC(16): Location of voids or chimney flues	Sonic + direct visual inspection	Pišece, Avio, Bottagisio
REC(17): Location of voids or chimney flues	Direct visual inspection by boroscopy	

5.11 Presence of different materials (e.g. use of different construction materials in plastered walls)

Class of the problems: **Morphological Information**

Problem: Presence of different materials

Requirements:

…

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
Radar in reflection	Detection of the transition from different materials.	Possible failure when there are no electrical property variations between the different materials.	Any	The moisture presence affects the test reliability. Multiple scattering from inhomogeneous materials could fail the test in case of smaller voids.	A calibration procedure and a direct control are recommended The elaboration procedure should be very accurate. More research is needed before its recommendation.
Sonic	Detection of different materials from velocity variations.	Possible failure when there are no elastic property variations between the different materials. A difference in sonic velocity cannot be directly related to the presence of different materials, only the fact that an inhomogeneity is present can be detected, not the nature of it.	Any	Restrictions on frescos.	A calibration procedure and a direct control are recommended.
Thermovision	mapping of the different materials with a 2D resolution of 3cm.	It gives only a near-surface information (a few cm deep). Surface should have uniform structure (roughness) Measurements outside require constant environmental conditions: The area measured should be windless and directed to south or south-west, if there is no artificial heat source. The method can not indicate the material of the inclusions.	Any	Restriction, when it is not possible to heat the surface (presence of frescos etc) or of a maximum surface temperature is given. Heating can cause tension in the plaster and lead to delamination problems. The change must be superficial.	Succesfully applied in Vila Litta, Altes Museum and Wartburg.
Direct visual inspection after coring	Indication on the local materials.	The test is local.	Any	Restriction being partially destructive. The test is only local. Preliminary information is needed in order to choose the localisation of the boroscopy.	A complementary technique is recommended in order to control the extension of the result.
Radar + direct visual inspection	Detection of the different materials.	Possible failure when there are no electrical property variations between the different materials.	Any	The calibration should be accurately designed, being partially destructive.	The number and the position of the calibration area should be accurately chosen being locally destructive. The calibration should be accurately designed, being partially destructive.
Sonic by transmission + direct visual	Detection of the different materials.	Possible failure when there are no elastic property variations	Any	Restrictions on frescos.	The calibration should be accurately designed, being partially

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
inspection		between the different materials.			destructive.
Thermovision + direct visual inspection	Mapping of the different materials with a 2D resolution of 3cm.	It gives only a near-surface information (a few cm deep). Surface should have uniform structure (roughness) Measurements outside require constant environmental conditions: The area measured should be windless and directed to south or south-west, if there is no artificial heat source. The method can not indicate the material of the inclusions.	Any	Restrictions on frescos if heating is necessary. The calibration should be accurately designed, being partially destructive The change must be superficial.	
Micro-seismic tomography	Indication on the presence of different materials with a resolution from 20 to 70cm depending on velocity and size of the masonry structure. The synergie of P-waves and S-waves tomography can be very useful.	Possible failure when there are no elastic property variations between the materials. The masonry structure must be accessible from both sides. Sensitive to the moisture content so additional tests like coring and powder drilling are required for the correct interpretation of the results.	Any, taking into account the limitation. The obtainable resolution depends on the quality of the structure	Any. The new tools allow to work also on any delicate surface. The results of the seismic tomography are to be considered carefully; a different pixel schematisation may give different impression of the results..	More research is needed for the recommendation of this method.
Geoelectric tomography	The presence of different materials can be spotted if his size is big enough (bigger than 25-30cm). The actual resolution depends from the quality and the homogeneity of the masonry	Possible failure when there are no significant resistivity. Variations between the materials. Sensitive to the moisture content so additional tests like coring and powder drilling are required for the correct interpretation of the results.	Any	Any The results of the seismic tomography are to be considered carefully; a different pixel schematisation may give different impression of the results..	More research is needed for the recommendation of this method.
Micro-seismic profiles	The variation of velocity profile can be due to the presence of different materials	Favourable for "lateral" variations, that is material changes under the plaster.	Any, taking into account the limitation	Any. The new tools allow to work also on any delicate surface	More research is needed for the recommendation of this method.

Recommended procedure

Recommended procedures	Technique	Recommended by On-site investigation
REC(18): Presence of different materials (e.g. use of different construction materials in plastered walls)	Sonic test	Avio, Bottagisio, Pisece. A calibration procedure and a direct control are recommended.

5.12 Presence of an hidden crack pattern

Class of the problems: Morphological Information

Problem: Presence of an hidden crack pattern

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
Radar	Detection of main fractures by reflection; Mapping of areas affected by diffused cracks by reflection or by attenuation tomography with a resolution from 10 to 40 cm depending on radar frequency and size of the masonry structure.	Possible failure when penetration is precluded by moisture.	Any	The moisture presence affects the test reliability. Multiple scattering from inhomogeneous materials could fail the test. Effective only on the corners of very massive walls with homogenous structure and when the cracks are parallel to the antenna.	A calibration procedure and a direct control are recommended The survey (position and direction) should be accurately designed. The elaboration procedure should be very accurate. More research is needed before its recommendation.
Sonic	Mapping of areas affected by cracks by transmission or by travel time and attenuation tomography with a resolution from 20 to 70 cm depending on sonic velocity and size of the masonry structure.	Only for regular brick and stone masonry. Otherwise, the results may be only qualitative.	Any	Restrictions on frescos	A calibration procedure and a direct control are recommended. More research is needed before its recommendation.
Ultrasonic impulse-echo and/or tomography	Detection of fractures. Mapping of fractured areas. Depth resolution: 20 to 50 mm; spatial resolution parallel to the surface: 20 to 100 mm (both depending on the wavelength). Ultrasonic is more sensitive to cracks and much less sensitive to moisture and salt content.	Air voids and cavities lead to 100% reflection. Max. penetration depth depending on side conditions and the materials. Minimum depth to be detected: 0.1 m Depending on the wavelength and the material	Any	Restriction on surfaces, if contamination with coupling agent and grinding of the surface is not allowed (some transducers) The penetration depth is very low in case of historic masonry.	A preliminary control is strictly necessary
Ultrasonic (surface test)	Estimate of penetration depth of cracks orthogonal to the surface	Only applicable on single blocks because mortar joints produce high attenuation.	Any	Only for single blocks.	
Crack pattern survey (direct inspection)	Mapping of the surface crack pattern		Any	Restriction being partially destructive. The test is only local.	The technique is very efficient and indispensable. However, it is possible only after the plaster removal. A complementary technique is recommended in order to control the extension of the result.
Radar by reflection + crack pattern survey	Detection of main fractures and mapping of areas affected by diffused cracks by reflection	Possible failure when penetration is precluded by moisture.	Any	The calibration should be accurately designed, being partially destructive	The number and the position of the calibration area should be accurately chosen being locally destructive. The calibration should be accurately designed, being partially destructive.
Sonic transmission +	Mapping of areas affected by cracks by		Any	Restrictions on frescos	The calibration should be accurately designed,

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
crack pattern survey	transmission				being partially destructive. More research is needed before its recommendation.
Ultrasonic impulse echo + crack pattern survey	Detection of fractures. Mapping of fractured areas. Depth resolution: 20 to 50 mm; spatial resolution parallel to the surface: 20 to 100 mm (both depending on the wavelength)	Air voids and cavities lead to 100% reflection. Max. penetration depth depending on side conditions and the materials. Minimum depth to be detected: 0.1 m Depending on the wavelength and the material	Any	Restriction on surfaces, if contamination with coupling agent and grinding of the surface is not allowed (some transducers) The penetration depth is very low in case of historic masonry. It is applicable only on single blocks.	The number and the position of the calibration area should be accurately chosen being locally destructive.
Radar + ultrasonic impulse echo + crack pattern survey	Detection of fractures. Mapping of fractured areas. To detect areas behind larger metallic inclusions or shields / covers with Ultrasonic To detect areas behind larger voids with Radar Cracks: large cracks can be detected faster with Radar; smaller cracks can be detected more detailed with Ultrasonic	Possible failure for radar when penetration is precluded by moisture. Max. penetration depth depending on side conditions and the materials.	Any	Restriction on surfaces, if contamination with coupling agent and grinding of the surface is not allowed (some transducers)	The number and the position of the calibration area should be accurately chosen being locally destructive.
Crack pattern survey + ultrasonic	Mapping of the surface crack pattern and evaluation of main fracture penetration	Penetration can be estimated only on single blocks because mortar joints produce high attenuation.	Any	Only for single blocks.	The calibration should be accurately designed, being partially destructive.
Radar and thermography (+sonic)	Determination of possible distortions of a measured signal/response due to origin and distribution of cracks in masonry.	To be investigated	Any.	The moisture presence affects the radar test reliability and multiple scattering from inhomogeneous materials could fail the test. The thermovision is only superficial.	A calibration procedure and a direct control are recommended The survey (position and direction) should be accurately designed. The elaboration procedure should be very accurate.
Micro-seismic profiles	The jump of the domochrones is due to the presende of a crack	Easily detected crack patterns under mortars. Not for deeper areas.	Any	Any. The new tools allow to work also on any delicate surface	More research is needed for the recommendation of this method.
TSS (velocity profilings in borehole)	It is possible to obtain the presence hidden crack by the variation of the velocity along the axis of the hole. Resolution is very high.	It is possible to obtain the velocities of the material around the hole, up to the depth of 80% of the hole	Any, taking into account the limitation.	Restriction of delicate surfaces (MDT)	More research is needed for the recommendation of this method.

Recommended procedure

No recommended procedure for this type of problem.

5.13 Moisture detection, evaluation of the moisture and salt content, control of the effectiveness of dehumidification intervention

Class of the problems: Moisture

Problem: Moisture detection, evaluation of the moisture and salt content, control of the effectiveness of dehumidification intervention

Requirements:

- REQ(1): Detection of the Presence of Moisture
- REQ(2): Evaluation of the Moisture and Salt Content
- REQ(3): Control of the Effectiveness of Dehumidification Intervention

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
Thermovision	Qualitative indication of the 2D distribution of moisture with a resolution of 3 cm.	It gives only a 2D distribution of moisture on the explored surface. Uniform structure (roughness) Measurements outside require constant environmental conditions: The area measured should be windless and directed to south or south-west, if there is no artificial heat source.	Any	Restriction, when it is not possible to heat the surface (presence of frescos etc) or of a maximum surface temperature is given. Heating can cause tension in the plaster and lead to delamination problems.	
Radar	Qualitative indications of the 2D and 3D moisture distribution with a resolution from 10 to 50 cm. Measurement tolerance is too big.	High moisture and salt content reduce the penetration depth drastically.	Any	The test is only qualitative. Better on solid masonry.	With limited success applied in Pišece, Altes Museum, Wartburg, Avio and Veltrusy.
Powder drilling	Local measurement of moisture with a resolution in depth of 2 cm. Resolution for moisture content 1 to 3 Vol % The sampled material can be analysed in laboratory in order to recognise the type of salt and its content.	The friction of the drill bit causes thermal energy that might lead to a lower moisture content.	Any	The test is local and partially destructive Compact stones could be hit the driller and underestimate the moisture content.	
Borehole microwaves	Depth-resolved local and quantitative indication of the moisture content and distribution along the thickness of the wall Resolution for moisture content: 1 to 3 Vol% Depth resolution: 1 to 2 cm. The sampled material can be analysed in laboratory in order to recognise the type of salt and its content.	The test is partially destructive (requires two parallel boreholes, diameter 12 mm, distance 5 cm) Depends on the strength of the material, coring must be possible with low pressure without water cooling. Maximum depth: 2 m.	Any	Restriction in connection of destructive investigation methods (boreholes are required). Up to now there are not calibration laws between the dielectric properties and the moisture content.	More research is needed before its recommendation.
Moisture meter + Thermohygrometer + Powder drilling	Determination of the 3D distribution of the moisture content by punctual registration of the electric resistivity of the materials, that is	Indirect method to determine the moisture content by measuring the electric resistivity (function of the moisture content and every factor	Any	There are not precise and direct calibration laws between resistivity and each material, so that the moisture content must be verified in	

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
	function of the moisture content, in different points of the structure (on the surface and inside the structure). The resolution of the 3D moisture content distribution depends on the number and distribution of the moisture meters The method does not give information on the salt type and content.	that influences the electric conductivity of the materials (salts, composition,…)), only applicable if other parameters are invariable (generic information). No automated data acquisition.		laboratory by e.g. powder drilling technique. Thermohygrometer, that registers temperature, relative humidity, moisture content and dew in the air to determine the ambient conditions and its evolution, is necessary as supporting technique for the interpretation of data of moisture meters. If the material is very inhomogeneous, the interpretation of data is more difficult. Condensation of water inside the structure can disturb the measurements. The test is locally destructive, if the evaluation of the moisture content inside the masonry is requested, as it is necessary to bore a hole to insert a thermohygrometer inside the structure and close it hermetically.	
Thermo-hygrometer	Punctual or continuous registration (equipment with automated data acquisition) of temperature, relative humidity, moisture content and dew in the air in points distributed at different height and depth inside (on a bored hole) and outside (ambient) of the structure/structural element. It is a supporting technique for the interpretation of data of moisture meters. The tests does not give information on the salt type and content.	The resolution of the 3D distribution of the ambient conditions on the structure depends on the number of measurement points. Sometimes it is necessary to bore a hole to insert a thermohygrometer inside the structure and close it hermetically. Leaving it there for the time necessary to achieve the equilibrium with the ambient, a rough evaluation of the moisture content is possible.	Any	The test is locally destructive, if the evaluation of the moisture content inside the masonry is requested.	
Radar + Powder drilling	2D and 3D map of moisture content with a resolution from 5 to 40 cm depending on radar frequency and size of the masonry structure. Expected sensivity f radar to moisture content: 5 Vol%. The sampled material can be analysed in laboratory in order to recognise the type of salt	The friction of the drill bit causes thermal energy that might lead to a lower moisture content	Any	The calibration is partially destructive.	A calibration procedure and a direct control are recommended. The survey (position and direction) should be accurately designed. The elaboration procedure should be very accurate.

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
	and its content.				
Geoelectric tomography	Information of the presence of moisture in some volumes of the masonry by the tomographic section can be obtained.	Powder drilling method should be used for the verification of the data. The results are only qualitative.	Any.	Any. The new tools allow to work also on any delicate surface. The calibration is partially destructive.	A calibration procedure and a direct control are recommended. The survey (position and direction) should be accurately designed. The elaboration procedure should be very accurate.

Recommended procedure

Recommended procedures	Technique	Recommended by On-site investigation
REC(19): Moisture detection, evaluation of the moisture and salt content, control of the effectiveness of dehumidification intervention.	Powder drilling	Avio, Pisece, Altes Museum, Veltrusy: A sufficient number of tests should be evaluated.

5.14 Structural monitoring: origin and evolution of cracks

Class of the problems: Structural Monitoring

Problem: Structural monitoring: origin and evolution of cracks

Requirements:

- REQ (1): Inspection and Documentation of Visible Cracks
- REQ (2): Control of the Crack Pattern Evolution
- REQ (3): Support Activity to the Interpretation of the Origin of Cracks

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
Visual inspection and crack pattern survey	Quantitative values of the dimensions of cracks (width, length and possibly depth), their inclination and localisation in the structure/structural element.	Different according to type of structure or building.	Any	No	
Gypsum or glass strips	Short-term instability of crack movement. The evaluation is very rough and approximate.	No information about evolution in time course. Locally destructive for plaster layers. The evaluation is very rough and approximate Glass strips can be easily broken also due to severe temperature.	Any	Restrictions yield from the fact that the method is locally destructive for plasters. The evaluation is very rough and approximate. The progress of the structural damage could not be evaluated in time.	
Micrometric lens	Quantitative values of movement of masonry blocks separated by cracks in the course of time. Resolution of 0.05 mm.	Accessibility to the crack has to be given. No automated data acquisition (periodically inspections on-site). No automated data processing. The resolution could be not enough.	Any	Restriction in the case of frescoed surfaces. The resolution is very low. The progress of the structural damage could not be evaluated in time.	At least 1 year and half should be considered in order to take into account the thermal variation.
Mechanical extensometers	Quantitative values of movement of masonry blocks separated by cracks in the course of time. Resolution of 0.001 mm.	Accessibility to the crack has to be given. A need of access to the monitored place during the whole period of monitoring, regular inspection visits. No automated data acquisition (periodically inspections on-site). No automated data processing	Any	Restriction in the case of frescoed surfaces, where the permanent brass bases can not be glued. However, sometimes the importance of the structural problem can justify the insertion of the fixed element. They can be very small (ϕ 8-10 mm).	At least 1 year and half should be considered in order to take into account the thermal variation.
Electrical extensometer (LVDTs)	Quantitative values of movement of masonry blocks separated by cracks in the course of time. The resolution and the sensor sensibility can be variable, according to the monitored problem.	The sensors are very sensitive against instabilities. Accessibility to the crack has to be given while positioning the sensors, further automated data acquisition. No automated data processing.	Any	Restriction in the case of frescoed surfaces, where the permanent elements can not be glued. However, sometimes the importance of the structural problem can justify the insertion of the fixed element.	At least 1 year and half should be considered in order to take into account the thermal variation.
Electrical extensometers (LVDTs) connected to a PC	Quantitative values of movement of masonry blocks separated by cracks in the course of time.	Accessibility to the crack has to be given while positioning the sensors, further automated data acquisition including the	Any	Restriction in the case of frescoed surfaces, where the permanent elements can not be glued. However, sometimes the	At least 1 year and half should be considered in order to take into account the thermal variation. The managing and the

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
	The resolution and the sensor sensibility can be variable, according to the monitored problem. Automated data processing. The system is often very complex and to monitor several parts of the structure. It can be completed by further equipments, such as the one for the dynamic control of the structure, wind and/or environment measurement (vibration, temperature, humidity,…). In this last cases the measured quantitative values can be directly related to physical phenomena such as, temperature and relative humidity variations.	possibility of a online connection to the PC via internet. The sensors are very sensitive against instabilities. Electrical readings must be converted into required physical units by processing using calibration curves and temperature compensation functions. Special software has to be available.		importance of the structural problem can justify the insertion of the fixed element.	interpretation of the large amount of data needs specific resources.
Levelling	Quantitative values of differential settlements with a resolution of 0.05 mm.	Values that need an interpretation and need to be complemented by other techniques.	From single buildings to surrounding construction site.	no restrictions	
Tiltmeter	Quantitative values of out of plan deformations measured by an electrical transducer (high resolution).	Values that need an interpretation and need to be complemented by other techniques.	From structural elements to groups of buildings.	no restrictions	
Damage mechanism scenarios	Qualitative models of a most probable damage mechanism causing cracks.	Difficulty to assess contributions of different possible agents and actions. Up to now, reliable mechanical models are not available for all the materials and masonry typologies.	From structural elements to groups of buildings.	No	Needs a lot of experience of the investigator. Also require teamwork of structural engineer, architect and restaurateur.
Structural analysis model	Qualitative simulation of the state of stress of a structural element/structure.	The model needs several input data (geometrical, material, mechanical, environmental parameters) and theoretical assumptions and simplifications that could be limited in extent, incomplete or incorrect. Up to now, reliable mechanical models are not available for all the materials and masonry typologies.	From structural elements to groups of buildings	Information concerning the masonry characteristics and geometry are previously necessary.	For non-linear analysis it may require a numerous mechanical parameters. Even for the simple linear elastic analysis, a different scenarios of loading path should be evaluated before any final conclusions.
Single Flat Jack	Evaluation of the local state of stress with a resolution of 0.1 N/mm^2 approximately.	The measurement is local and only related with jack dimension. In case of multiple leaves, the measurement is limited to the external leaves. The choice of the flat-jack	Any, provided the value of the stress is greater than the test resolution.	Restrictions being locally destructive. In case of irregular stone wall the cut should preferably be carried out in the stones. Small flat jack tests are not applicable on low	A previous control of the masonry by sonic test or other techniques is recommended. This would avoid to carry out the test in correspondence to unknown masonry

Technique	Expected performances and resolution	Limitations of the technique	Diagnosis level	Restriction of use	Recommendation
		dimensions and of the cut position should take into account the masonry texture dimensions and characteristics.		stresses stone masonry if the cut is carried out on stiff stone elements, as the measurable released strain is of 20 $\mu\varepsilon$ limited by the accuracy of the mechanical extensometer. The test does not give precise results on masonry subject to low stresses, even if this is already a precious information.	defects or voids that could affect the reliability of the test.
Hole Drilling	Estimation of the stress field in the surface of stone elements with a resolution given by an accuracy of the strain gages of +/- 1 $\mu\varepsilon$.	The measurement is local and superficial (surface stress state). Masonry is considered as a isotropic material and the influence of the joint on the anisotropy is neglected. The thickness of the joints in comparison to the size of the units should be incomparable small.	Any, provided the value of the stress is greater than the test resolution.	Restrictions being locally destructive. The application is limited to regular stone masonry as the state of stress in irregular stone masonry is rather complex. It requires a calibration test performed on a stone block extracted from the structure under study, to determine two calibration constants (A and B).	The results may represent very local state of stresses of the tested unit. For the complete interpretation of tests results, they should be compared to reference values obtained from more or less complex structural analysis (expected stresses) or material strength (for comparison of existing stresses). More research is needed before its recommendation.

Recommended procedure

Recommended procedures	Technique	Recommended by On-site investigation
REC(21): Inspection and documentation of visible cracks	Crack pattern survey (direct inspection).	Recommended according to previous experience.
REC(22): Control of the crack pattern evolution	Use of gypsum or glass strips for (periodic) inspections of cracks to determine their evolution.	Recommended according to previous experience.
REC(23): Control of the crack pattern evolution	Use of micrometer lens (or mechanical extensometers or electrical extensometers – LVDT's) for (periodic) inspections of cracks to determine their evolution.	Recommended according to previous experience.
REC(24): Control of the crack pattern evolution	Use of electrical extensometers (LVDT's) connected to a PC for continual monitoring.	Recommended according to previous experience.
REC(25): Support activity to the interpretation of the origin of cracks	Levelling to verify differential settlements.	Recommended according to previous experience.
REC(26): Support activity to the interpretation of the origin of cracks	Tiltmeter to measure out of plan deformations.	Recommended according to previous experience.

7 Summary of all deliverables from the project

This paragraph deals with summary and short description of the deliverables, i.e. that complex of documents, data and physical objects which represent the practical and tangible output of the project.
The deliverables are organised following the subdivision of the project into tasks or work packages (WP): for every WP one or more deliverables are provided.
For a complete list of tasks and deliverables refer to the web site www.onsiteformasonry.bam.de.

WP1: Project Management

This task deals with organisation and follow up of the project.
The deliverables are all the reports necessary for the control of the correct development of the project by the EU Commission.
Also the web site and the official brochure of the project are official deliverables.

WP2: Dissemination and Exploitation

This task which consists with the promotion of the results to the end users of Cultural Heritage, to the small industries offering services of diagnostics and measurement and to the appropriate standardisation committees, as well as the identification and preparation of commercial opportunities has as principal deliverable the preparation and up dating of the "TIP" (Technological Implementation Plan) which is a standardised EU form in electronic format describing with numerical details all the actions and necessities for exploitation, the reports of the completed actions and the changes in the running actions.
As further output of this task there are also some divulgative documents related to the activities in the test sites and a memory on the cost/effectiveness relationships of the NDT techniques in the Restoration of Monumental Heritage context.
During the project all opportunities to promote the activities of the partners team were exploited, with participation at a lot of events, exhibitions, congresses, seminars and lessons, making presentations, writing articles and publications.
The complete list of the events and publications is available, annexed to the leaflet.

WP3: Requirements of users and performance specifications

This task defines with the maximum possible detail the inputs to the research and experimentation activities, starting from the most common needs of the end users and arriving to the definition of the theoretical requirements in terms of performance of the solutions, both for diagnostics and structural assessment. In the task also a definition of the state of the art in terms of techniques and methodologies was performed.
The deliverables are a set of specialist documents:

- a Standard Damage catalogue with the most common problems encountered in Historic Masonry;
- a list of the most common structural typologies;
- a classification of the different approaches for structural assessment;
- the complete system requirements specification for the project.

Especially the Damage Catalogue is an interesting tool for end users which need an overview of the problem/solution matrix for structural assessment.

WP4: Methodology development for inspection

This work package deals with the definition of the single techniques and the combination of complementary ones related to the requirements of WP3, with analysis of the expected performances, resolution and limitations. A definition of the on-site and laboratory procedures for evaluating the strategies (single techniques or combinations) is also defined.
The outputs of the task are principally:

- the definition of the strategies and the analysis of the expected performances, limitations and costs;

- specifications of laboratory specimens for the validation of the strategies in a controlled environment.

WP5: Methodology development for assessment

This task consists of the study and definition of the different levels of application for assessment, i.e. the different levels of application necessary for different needs of assessment: morphological information, moisture level detection, measurement of mechanical properties, diagnosis for small or complex buildings, assessment of seismic vulnerability, etc.
In this WP also the definition of the parameters needed for the assessment, with the possibility of integrated NDT and MDT methods to support these parameters is developed.
The deliverables are related to reports about the definition of parameters for assessment and on methodologies for optimal approach to structural and non-structural assessment, for different levels of application.

WP6: New data acquisition systems

This task produced the development of a general purpose positioning system dedicated to high resolution tomography and echo radar techniques, complete of the software and the necessary interfaces to the acquisition systems.
The deliverables consist of reports and specifications of the positioning system in order to use it on different acquisition systems and the hardware and software prototypes. Also an evaluation of the achieved accuracy, resolution and speed was provided.

WP7: NDT System modifications and optimisation

The task deals with modification to existing equipment in order to allow better resolution and penetration of echo and tomography configuration.
The techniques modify range from the radar to the ultrasound, passing through sonic equipment.
The deliverables of the task were:

- a new high frequency radar antenna suitable both for echo and tomography applications;
- a scanning impact-echo automated prototype (hardware and software);
- an ultrasound prototype for tomography;
- a new tool for quick positioning of sonic transducers for microseismic and sonic equipment;
- new sensors for sonic applications;
- software for integrated presentation of results coming from different techniques;
- report on calibration and testing results.

WP8: Integration

The aim of this task is to explore if and how it is possible that a multi-expert team can improve the interpretation through direct and quantitative comparison the results coming from different NDT techniques.

- In this task the following deliverables were provided:
- Software for 3D Echo Radar, Impact-Echo, sonic/radar tomography;
- Software for combined presentation of NDT and MDT methods;
- Laboratory specimens for calibration and validation;
- Report on calibration testing

WP9: Structural models

The task deals with the very complex matter of the numerical modelling of the masonry. During the project several models were proposed at different levels of computational difficulty in practical applications.
Also a correlation among data collected by MDT techniques (flat jacks and similar techniques), data given by NDT and mechanical properties measured in laboratory was performed.
Several activities of calibration and experimentation of models also in the test sites were tried.
The deliverables are the following reports:

- Experimental results of normal/shear fracture of brick masonry;
- experimental results of irregular masonry;

- normal/shear fracture model of brick masonry;
- mitigated model for irregular masonry.

WP10: Application and evaluation

The developed approaches to the assessment and the modified techniques were to be tested on the field.
This was the moment when the end users involved in the project had the possibility to propose practical problems, utilising also the results for their purposes.
After a long selection, a final list of 27 sites was proposed and in a large part of them where experimented the strategies and the methodologies developed.
The sites were representative of different typologies of buildings, building techniques and materials, in various conditions and presenting a variegated range of problems.
In every site a team composed by different partners worked utilising all their equipment, producing an impressive quantity of data.
The most of those data were processed and a lot of reports produced.
Among them the most significant are:

- the description of the pilot test sites and their open problems;
- the evaluation at the pilot sites;
- the implications for the evaluation guidelines to be developed at WP9 and WP11;
- the reports for the owners of the test sites.

The test sites were also an opportunity for dissemination activities, organising presentations, press conferences, visits and seminars everywhere and when possible (see also WP2).

WP11: Guidelines/Recommendations

This is the final output of the project giving all the guidelines for a correct structural assessment of Historic Masonry buildings to the end users. The principal deliverable is this very document you are reading.
In this WP was tried to council a necessary scientific methodological approach with a plane language, in order to stimulate end users, not always well prepared in terms of knowledge of the NDT, MDT diagnostic approaches to utilise them for an effective control and assessment of the building which they have in charge.

- The deliverables of this tasks are:
- Technical guidelines for an appropriate use of the suggested methods;
- Structural modelling for the assessment of the load bearing capacity of masonry;
- Recommendations for end users.

Annex: Address list of NDT-Networks of Expertise and NDT experts

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