Smart Monitoring of Historic Structures

SMOOHS

D2.1 Real Problems apparent at cultural heritage and monitoring demands and deficits

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COOPERATION

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1 Summary

This document provides information on real **material problems of museums and cultural heritage and structural problems** apparent at cultural heritage.

Monitoring demands and deficits in long-term investigation of damage grow are mentioned.

Long-term monitoring comprises:

- inspection of previous data,
- monitoring the real structure and
- modelling studies of the structure

Mechanical, physical and chemical properties of a certain material; physic-chemical-biological weathering reactions due to environmental parameters (temperature, relative humidity, air pollutants, wind, gases, light, etc.); events that promote vibrations (visitors traffic, transportation of works of art, vibrating machines, explosions, wind, earthquakes, etc.) as well as inadequate past treatments and lack of maintenance are example of factors that contribute to material deterioration. Damage can exhibit different signs, according to the construction material and maintenance conditions.

The different types of damage signs and their explanation based on construction material and external physical phenomena such as temperature, relative humidity and vibrations; the importance of monitoring those physical phenomena; the special demands that cultural heritage sites present regarding that monitoring are the main focus of this document.

2 Introduction

This document provides information on **material and structural** problems apparent at cultural heritage:

Monitoring **demands and deficits** for movable and immovable heritage were collected by WP2 (USTUTT, AURA; UNIBO; RRL; TBK; Riwaq; Pasc; Unizag; Eurac), which represent the end user point of view.

Chapter 3 regards the identification of material and structural problems affecting cultural heritage. Factors that contribute to the deterioration of movable and immovable heritage, as well as a detailed description of the deterioration signs/evidences in different types of materials (such as wood, stone, glass and metal) are listed and described in this chapter.

The importance of monitoring physical phenomena that generate damage is discussed in **chapter 4**, along with the monitoring demands in movable and immovable heritage, focusing in dynamic monitoring. Furthermore, long term weathering processes (such as structural deformation and fragmentation), their monitoring and the importance of a structural model are discussed.

Chapter 5 is dedicated to communication networks for monitoring systems. Wired and wireless models are compared, but special highlights are given to smart monitoring, that is, a monitoring system that adjusts to specific situations, as a cultural heritage monument might demand.

RRL sent a query to 23 institutions within the Prussian Cultural Heritage Foundation which represent the end user point of view. So far, among research institutes, libraries and museums, 10 museums answered the query, which is presented in Annex. Their results are discussed in **chapter 6** which provides a detailed and extended list of monitoring demands and deficits for movable and immovable heritage.

3 Identification and definition of real (material and structural) problems apparent at cultural heritage

In order to preserve historic structures and make them available for private and public use, it is more and more required to understand the deterioration processes mainly caused by their local and global environment.

To obtain more detailed information about the deterioration processes in certain cases continuous monitoring systems have been installed. The installed sensors are just weather or air pollution data acquisition systems and data analysis is performed just via basic models. The real influence of the environment to the structure or the structural material is often unaccounted for. That means that the health state of the structure and its structural resistance is just derived from environmental measurements and not calculated from environment **affected material parameters** monitored via sufficient sensors.

There are many factors that affect the deterioration rate. Especially the environmental conditions, e.g. air pollution and gases, wind, rain, humidity, temperature, frost, ambient light etc. are aspects that affect this rate. It has to be noted that for a holistic analysis of the deterioration processes the influence of the changing environment as well as of its effects on the material have to be considered.

3.1 Material problems in movable heritage

Factors that contribute to material deterioration

- Material properties (mechanical, physical, chemical)
- Physic-chemical-biological weathering reactions due to environmental parameters (temperature, relative humidity, air pollutants, wind, gases, light, etc.)
- Events that promote vibrations (visitor traffic, transportation of works of art, vibrating machines, explosions, wind, earthquakes, etc.)
- Inadequate past treatments and lack of maintenance

Examples of material problems found in objects from museums in response to their interaction with the environment [information collected by a query at the Prussian Cultural Heritage Foundation]

- **Polychrome surfaces**: crack opening due to volumetric changes in response to thermohygrometric variations, photo-oxidation due to light exposure, development of crack opening due to vibrations, chemical interaction with gases, dust accumulation
- **Wood**: crack opening due to volumetric changes in response to thermohygrometric variations, development of crack opening due to vibrations, loss of cohesion due to crystallisation/hydratation of soluble salts, attack by microorganisms and insects, chemical interaction with gases, dust accumulation
- **Natural stone**: crack opening due to volumetric changes in response to thermohygrometric variations, loss of cohesion due to crystallisation/hydratation of soluble salts and frost-defrost action, attack by microorganisms, development of crack opening due to vibrations, chemical interaction with gases, dust accumulation
- **Masonry wall as moveable heritage in museums**: crack opening due to volumetric changes in response to thermohygrometric variations, loss of cohesion due to crystallisation/hydratation of soluble salts and frost-defrost action, attack by microorganisms, development of crack opening due to vibrations, chemical interaction with gases, transport of

humidity, detachment of layers due to volumetric changes in response to thermohygrometric variations, dust accumulation

- **Textiles**: dust accumulation, attack by micro-organisms, chemical interaction with gases; photo-oxidation due to light exposure, volumetric changes in response to thermohygrometric variations
- **Paper and Photographic material**: chemical interaction with gases; photo-oxidation due to light exposure, volumetric changes in response to thermohygrometric variations, attack by micro-organisms
- **Glass**: chemical interaction with gases, volumetric changes in response to thermohygrometric variations, development of crack opening due to vibrations, loss of cohesion due to crystallisation/hydratation of soluble salts
- **Metal**: chemical interaction with gases, development of crack opening due to vibrations, loss of cohesion due to crystallisation/hydratation of soluble salts
- **Synthetic polymers**: chemical interaction with gases, attack by micro-organisms, photo-oxidation due to light exposure

3.2 Structural problems in immovable heritage

Factors that contribute to material deterioration

- Material properties (mechanical, physical, chemical)
- Physic-chemical-biological weathering reactions due to environmental parameters (temperature, relative humidity, air pollutants, wind, gases, light, etc.)
- Events that promote vibrations (visitor traffic, transportation of works of art, vibrating machines, explosions, wind, earthquakes, etc.)
- Inadequate past treatments and lack of maintenance

Examples of damages and deterioration in structural masonry elements

- Poor technique of construction of masonry, due to:
    - weak core structure (e.g. rubble masonry made with stones surrounded by **thick** mortar joints, where the mortar is **weak**)
    - Lack of connection between structural elements
    - Small height and thickness of stone blocs from the leaf if compared with the structural element dimensions (e.g. pillar)
    - No effective connection realised between stones of one structural with another structural element (e.g. stones of the pillar strips supporting arches with no connection to the internal masonry)
    - Walls and pillars without enough load carrying capacity for the weight of the structures above
    - Displacements and inclination of structural elements
    - Foundation settlements
- Weak construction materials as:
    - Mortars containing gypsum or soluble salts
    - Stones with low resistance to uniaxial compressive strength and high porosity

- Poor techniques of repair as:
    - Vertical cracks filled with poor repair mortars, which do not resist tensile stresses
- Use of the structure beyond its predicted time and beyond its predicted use:
    - incremental or extension of aperture elements, as doors or windows
    - additional charges
- Inadequate modifications to the original project:
    - removal of structural elements, as structural walls
    - removal or alteration of structures aligned with support structures, as arch joints, or dome joints
    - modification in the foundations
    - demolition of adjacent buildings
- Lack of maintenance and monitoring
- Physic-chemical-biological weathering reactions due to environmental parameters (temperature, relative humidity, air pollutants, wind)
- Events that promote vibrations (vibrations due to machines, explosions, wind, earthquakes, etc.)

Examples of damages and deterioration in structural timber elements

- Poor construction details in structural timber elements, due to:
    - Bad drainage of rainfalls from the outside elements: if elements cannot avoid direct exposure to rainfalls than they have to be well protected which is not case many times
    - Bad connection of timber elements to the foundation which causes capilar raising of the humidity and salts in timber elements
    - Use of too thin elements which are prone to deterioration
    - Errors of connecting too thin elements with steel connectors that are with rather big diameter which cause splitting of timber elements
    - No ventilation space for the timber beams on the supports and in the roofs which cause absorption of the humidity and rottening of the beams
    - No isolation on the contact points (places of the connectors and groups of connectors)
    - Not enough air exchanges in time period for spaces with greater humidity – baths, etc.
    - Lack of insolation materials which avoid condensation of water
    - Lack of protection caps (steel usually) on the exposed, frontal parts of elements
- Errors while building and repairing, as:
    - While repairing, building in and connecting the elements which has too big moisture content, or which are different botanical species or durability class and have different mechanical properties cause different swelling and shrinkage and additional stresses in elements
    - Gluing with incompatible glues which cannot activate their bearing capacity
    - Bad choice of connectors which can change statical scheme of structural element

    - Choosing FRP bands for repair elements from outside because they usually cannot activate enough
- Poor techniques of repair as:
    - Vertical cracks filled with poor repair mortars, which do not resist tensile stresses
- Use of the structure beyond its predicted time and beyond its predicted use:
    - incremental or extension of aperture elements, as doors or windows
    - additional charges
- Inadequate modifications to the original project:
    - removal of structural elements, as structural walls
    - removal or alteration of structures aligned with support structures
    - modification in the foundations
    - demolition of adjacent buildings
- Lack of maintenance and monitoring
- Physic-chemical-biological weathering reactions due to environmental parameters (temperature, relative humidity, air pollutants, wind)

4 Identification of monitoring demands

Monitoring

Monitoring can contribute to identifying and evaluating existing damage and help to determine which active physical phenomena are involved in its generation.

Weathering processes are due to:

- Construction effects
- Material decay
- Environmental actions
- Extraordinary actions (such as earthquakes)

Past human actions may be very significant in causing additional damage. Lack of maintenance or inadequate historical repairs may also contribute to an accelerated deterioration of the building.

Monitoring can provide a certain degree of insight into the condition of the object/structure and the possible presence of active weathering processes associated with incremental damage.

Deformation and damage develops as a superimposition of different phenomena, some of which act persistently, some cyclically or periodically, other occurring only on isolated actions.

Monitoring data can include an assortment of reversible (cyclic) components mixed with the long-term accumulation of irreversible components.

Monitoring demands

- Obtaining meaningful hints related to long-term damage requires the ability to distinguish the **unidirectional**, **accumulative trends** from the totally of data registered during the monitored period.
- Monitoring results can be used in combination with a numerical model, provided that not only the **parameters associated** with the **response** (deformations, displacements, rotations, vibrations, etc) are measured, but also the characterising **actions** (environmental thermal effects, ground motion, etc)
- A **multidisciplinary approach** is required (historical investigation, inspection – of present condition and monitoring campaigns - and material/structural modelling)

The above demands are necessary, so that the empirical evidence can validate the hypotheses set by the model.

Dynamic Monitoring

- Dynamic monitoring **demands** the ability to capture a very dense amount of information during a very short interval. Thousands of readings per minute may be needed to adequately characterise the oscillation of the structure caused by an external source of vibration, and to later carry out the signal processing leading to the significant dynamic properties such as the **shapes of the vibration modes, frequencies and damping**.
- Dynamic monitoring **provides** the only way to experimentally measure the parameters related to the **global structural behaviour** of the historical construction. However, its real contribution to a clear understanding of the structural damage propagation is strongly **limited** due to several causes. The parameters related to dynamic response of the structure behave always in the **non-linear range** (at least those of interest for damage detection) and are **highly sensitive** to the local or global material properties and the support conditions.

4.1 Monitoring requirements in movable heritage

- Movable heritage is always located either in rooms in buildings or in cases.
- Artefacts in rooms in buildings, especially in historical buildings are kept in best conditions, when it is possible, to use the building masses as a damping factor against heat and cold from outside.
- In addition to this a most efficient shading against external loads, very little internal load by light or what so ever (all kinds of technical installations), pure radiation heating systems in cold outer walls to avoid the "cold wall problems" with the negative consequences of mould due to condensation on cold walls and to avoid dust transports through a convective heating system on the artefacts and an air tight shell of the house to keep unfavourable climate conditions outside of the building will help to keep a best possible microclimate within limits, which have to be defined before depending of the kind of art, which is exposed, and should have reasonable ranges - let us say between 40% rel. humidity and 60% and the room temperature about 16°C up to 26°C, depending of the kind of exhibition and if it is a depot or an exhibition open to public.
- Most important mainly is a very, very slow changing of rel. humidity and temperature in the room with the movable heritage, according to outer changing of seasons.
- Mostly the keeping of artefacts in boxes what kind so ever, mostly help to keep a singular – hopefully better microclimate - in a room or building. Often "boxes" or showcases are used to provide a more specific micro climate wanted by persons, who loan the artefacts to the museum. But working with showcases must be done very carefully, because they can accelerate the ruin process, when for example the wrong lightning is installed in the "boxes" and by lighting them the internal heat of the lamps will press the existing air towards outside and in the evening, when switching off the lamps, the inside air gets cold and an artificial high air exchange rate can destroy the exposed artefacts.
- On the other hand, long term storage of books in wooden shelves or wardrobes help to keep a best possible micro climate for the books, as seen in the monastery of St. Gallen, with its collection of very old and famous books.
- When monitoring room climate, it is mostly important to have data in a way the user can react to it in a proper way. This means that the data should be generated automatically every month for example and printed out or given to the user regularly, so he has a chance to compare the data. Furthermore the data collecting system should give a warning to the user in a way, the user is informed, that something with temperature or rel. humidity has happened.
- Since this warning always comes too late and the damages have yet occurred, when temperature or rel. humidity exceeds given limits, a better solution would be, to have an "early warning system" which calculates in advance a possible exceedance of limits and will inform or warn the user.

4.2 Monitoring requirements in immovable heritage

- Before or while undertaking a monitoring programme, detailed characterisation of the building is needed. Historical investigation and geometrical and morphological surveys are needed to allow correct interpretation of the monitoring output. Monitoring will normally be accompanied by **characterisation based on non-destructive or quasi non-destructive testes** aimed at determining the internal morphology of the structural members and the mechanical properties of the materials. Damage patterns (particularly major cracks) must also be recognised and carefully documented.
- Specific and actually monitorable targets should be selected, adequately related to the physical, chemical or biological phenomena to the identified and analysed.
- Actions affecting the construction are to be monitored in combination with its structural response. This normally requires monitoring of climatic environmental parameters (temperature and humidity), wind parameters (speed and direction), seismic ground motion and soil settlements, and volumetric changes due to thermohygrometric variations, among others. The obvious aim is **to correlate causes (actions) with effects** (structural or material response).
- Even if climatic actions are not the target they will have to be characterised, since their impact on the structure is normally very prominent and may alter or even mask deformations caused by other possible effects. In this case, characterising climatic actions is necessary in order to determine and cancel out the climatic component in the monitoring output. In order to characterise incremental, long-term processes, monitoring must be designed to allow a clear distinction between the **reversible or cyclic components** of the parameters measured, on the one hand, and their **irreversible, cumulative components** on the other.
- Characterising the action in the time domain will later allow its numerical simulation and comparison between the numerical prediction and the actual response measured. An identification process can then be carried out by adequately modifying such hypotheses until a satisfactory coincidence is attained between the numerical predictions and the measurements.
- Monitoring must be carried out over a period long enough to cover the entire duration of the cyclic actions at work. Since annual variations in temperature must be considered in all cases, a suggested period is a complete year although this has to be adapted to each case study.
- In order to provide meaningful information with regard to the monitoring target, critical points of the structure or material must be selected. Prior numerical simulation may help determine the optimal configuration and location points.
- The global nature of the structural response must be taken into account while designing the monitoring strategy or when interpreting its results.
- The monitoring system must be designed to allow redundant measurement of related effects, allowing results to be interpreted more consistently and soundly. For instance, displacement or rotations of a façade experiencing a gradual out-of-plumb can be measured in combination with related crack openings experienced at the junction of the façade with other walls.
- An appropriate and rational use of the structural analysis can help in defining the eventual state of danger and forecasting the future behavior of the structure. To this aim, the definition of the mechanical properties of the materials, the implementation of constitutive laws for decayed materials and of methods of analysis for damaged structures and the improvement of reliability criteria are needed. Nevertheless, when the structure is a complex one, only linear elastic models are easily usable. Non-linear models or limit state design models are difficult to apply, also because the needed **constitutive laws for the material are seldom available**.

Monitoring long-term weathering processes

- **Structural deformation** - damage affecting the construction, will in normal circumstances always increases. Either due to previous stages in which the structure was subjected to provisional support conditions, or to actions occurring after the construction process finished. Both the aforementioned and other possible causes will in turn enlarge the sensitivity of the construction towards a variety of actions.
- **Tensile damage in arches and vaults** – tensile strength of masonry is almost negligible, meaning that a certain amount of cracking may easily develop in members subjected to tension effects or eccentric loading. This type of cracking, which is not normally too meaningful, is not necessarily linked to long-term damaging processes caused by decay of the material itself. Monitoring these cracks, however, will be of use for characterising the mobility of the structure and the overall progress of damage. Due to the perceptible deformation of the elements and measurable opening of the cracks, this type of effects can be easily monitored.
- **Damage of compressed members** – as it is well know, cracks parallel to the direction applied compression may appear in materials such as concrete or stone, even for stresses significantly lower than the compressive strength. As previously mentioned, the construction process (and the construction techniques used) may induce mid-term and long-term effects. Aspects such as the construction sequence, the duration of the construction, or the use and removal of scaffoldings and other auxiliary elements, may influence the later behaviour of the overall building and even cause deferred lesions or other structural disorders. The repeated occurrence of extraordinary actions, such as earthquakes or hurricane-force winds, even if moderate in intensity, also contributes with irreversible cumulative effects.
- **Fragmentation** – another type of damage consists on the division (or fragmentation) of the structure into large structural parts or substructures. Soil settlements are a very frequent cause for fragmentation. They can induce the generation of new cracks, enlargement of existing ones or opening of construction joints. The process may stabilise whenever the divided structure becomes cinematically compatible with the settlements. Similar effects may be caused by cyclic winter contractions of the structure. Cracks or separation planes, acting as expansion or settlement joints, may easily develop starting at weak planes generated during construction itself.
- **Structural modelling** - ideally, the numerical model should be capable of simulating most of the present or historical actions that have affected the construction; it should also allow sequential analysis in order to simulate the construction process and the possible structural alterations or repairs followed.

5 Communication networks

Wired communication network

Wired communication is defined as a physical link with wires between the central data acquisition and processing unit and the sensors. Today's most common implementation is the star-shaped topology network. Each sensor is connected to the central data acquisition and processing unit via a separate wire. Due to the large amount of wires involved, the risk of damage in such a network is high, in particular, for monitoring systems operating during retrofitting activities. An appropriate protection and marking of wires and instruction of the involved persons is essential for preventing wire damage and data loss.

Additionally, wiring represents an important element of the installation of a health monitoring system in terms of time and effort.

Wireless communication network

With respect to installation and operation, wireless health monitoring systems are less susceptible than wired systems against harsh environment. The particular disadvantage of these systems is that more than one central energy supply is required. The energy consumption of the individual sensors can be reduced significantly, if the connection of the sensors to the central processing unit is active only in case of a necessary data exchange. The triggering will be realized by a suitable impulse or rather a measuring signal. In other time periods, the measuring line will be in the "stand by" mode with minimal energy consumption.

Wireless communication media are:

- Electromagnetic waves in radio frequency and little power
- Acoustic carrier waves in massive metallic structures

Smart Monitoring

A smart and economical concept for performance or health monitoring is characterised by the following requirements:

- Applicability on structures with large sizes and on single component with small sizes
- Measurements of mechanical values as a result of static and dynamic loading, e.g. deformation, velocities, accelerations, strains etc.
- Storage of relevant data acquired at various measurement points
- Time-stability of the overall measurement chain
- Resistance against weather conditions
- Robustness
- Energetically self-sustaining and minimal energy consumption
- Easy handling

6 Resume of monitoring demands and deficit

6.1 Movable heritage

Based on a query prepared by the Prussian Cultural Heritage Foundation and contribution from the WP2 partners, information was collected from the end-user point of view, which can lead to future development of sensors for long-term monitoring:

- Monitoring climate data in rooms with movable heritage is a necessity
- Depending of the data which are necessary to know – temperature, rel. humidity, vibration, etc. – the preparation and the design of the data is very important and also the regularity, so that the user can realize immediately a wrong situation. All monitoring data should be combined with a signal, telling the user the exceedance of limits.
- Furthermore it is necessary to store the data in a place other people have a controlled access to the data in order to learn about the conditions in the room with the artifacts, when someone had changes a parameter of the housing services.
- Sensors should be minimally invasive in mounting and in installation (interchangeability, miniaturization, aesthetically appealing)
- Sensors of simple application (installation, data interpretation, calibration capability)
- Sensors should have a stable long term behavior
- More sensitive sensors for strain and crack opening, adapted to small objects, e.g.: wooden musical instruments
- Air velocity sensors that are sensitive to low speed air flow
- Lack of gas sensors, which are sensitive to low concentration gases and allow wireless automatic acquisition
- Sensors that can measure salt content in construction materials
- Sensors that can measure biological attack
- Sensors that can measure delaminations, detachments
- Sensors that can measure defects in construction materials
- Development of non-contact sensors for displacement measurements
- Development of wave velocity sensors with automatic acquisition
- Development of sensors for dust accumulation measurements
- Development of sensors that register vibrations of objects during transport and send warning when deterioration occurs
- Development of models that correlate the monitored weathering process with the weathering cause
- Simpler and user-friendly monitoring devices
- Measuring sensors that combine Temp., RH and LUX measurements and give warnings when fluctuations occurred
- Measuring sensors that combine colour coordinates and varnish crack opening in dependence of UV and LUX measurements
- Measuring sensors that combine Temp., RH and vibrations to be used during the transport of movable cultural heritage

- Software compatible with excel. Data loggers with USB port. and possibility of saving data in several computers
- A model show-case which construction materials do not emitt corrosive gases
- Calibration materials and easy calibration methods, that allow the end-user to control the precision of measurements
- Lack of sensors with warnings (e.g. if damaging factors increase) and recommendations for action
- Lack of sensors with built-in deterioration and material models
- Lack of sensors with built-in data pre-processing
- Lack of sensors with small smart wireless and robust sensors and sensor networks
- Lack of advanced models that take into account more precisely the real environment effects, predict deterioration rate and help interpreting the acquired data and their trends;
- Need of validation of quantity and quality of wireless sensors data in comparison with state of the art assessment methodologies of historic structures;
- Need of great implementation of the static and dynamic monitoring systems applied to different classes of structures and damage situations
- Need of calibration of appropriate mathematical models according to the masonry and building classification
- Need of reducing costs of Wireless Sensors Network (WSN) monitoring systems - by reducing sensors costs and reducing system installation and maintenance costs – with the aim of widening their use on historic structures, both monumental and minor architecture

6.2 Immovable heritage

6.2.1 Masonry structures

DEMAND
Evaluation of mechanical properties of masonry.

DEFICIT AND NEEDED DEVELOPMENT
Sonic tests are usually adopted for a preliminary evaluation of the homogeneity of the masonry. Local tests are used for strength estimation. The most commonly adopted methods are flat jack, tests on microcores, compressive tests on mortar specimens, surface hardness tests, shear tests on mortar joints. The values of sonic velocity allow estimating the elastic modulus.

Developments deals mainly with an improvement of the empirical relationships used to reliably transform the results of ND or MD (minor destructive) results in values of compressive strength. This requires specific experimental research.

DEMAND
Evaluation of morphology and internal structure of masonry structural elements.

DEFICIT AND NEEDED DEVELOPMENT
Sonic tests, radar, impact-echo and endoscopy are the most commonly used methods.

Sonic tests are very useful, but some deficit appears to affect both the data acquisition and the processing of results. The data acquisition, up to now, is based on hand testing. Automatic or semi-automatic systems are needed for pulse generation. The acquisition should be much more fast, in order to collect a great number of experimental values in a reasonable time. This would allow us to perform sonic tomography. Some tomography software are available, but there is a need of improvement to obtain images of sections immediately or in short time.

The Impact-echo method can give useful information to localize interface surfaces between different masonry layers. There is some lack of knowledge in this field, and more research is needed.

DEMAND

Analysis of cracks, defects, voids and damaged areas.

DEFICIT AND NEEDED DEVELOPMENT

As above, sonic tests, radar and endoscopy can be used. The above considerations are still valid.

The Impact-echo method can strongly improve the information, allowing to detect and localize voids, internal detachments and inclusions. The application of this method to masonry structural elements is a research topic still open and more knowledge in needed.

DEMAND

Monitoring of distances and absolute displacements.

DEFICIT AND NEEDED DEVELOPMENT

The measurement of distances and displacements is a frequent need in structural monitoring applications that deal with settlements, foundation problems and geological instabilities. Conventional displacement sensors require to be mounted on stable supports and placed in contact with the structure.

The need is to develop sensors that do not require contact and can be placed far from the structure.

Optical distance gauges are considered very attractive for such applications. Application of laser triangulation, Time-Of-Flight (TOF) laser, phase-shift measurement technique and interferometry based techniques are very promising and their application to monitoring of structural elements of the cultural heritage is to be encouraged.

DEMAND

Monitoring of local strain.

DEFICIT AND NEEDED DEVELOPMENT

Many conventional strain gauges are used to measure strain under static or dynamic loads. The most widely used are the electrical strain gauges. They are well known and reliable, but on the other hand they are affected by some negative factors, such as the creep and durability of the gauges and of the used adhesives. In addition the adhesive could be too invasive when used on very ancient and valuable masonry structures.

Needed developments should allow reducing invasivity and improving aesthetics, stability and durability. Low power consumption is another important requirement.

Electrical strain gauges can be used, but other attractive solutions are MEMS and fiber optic sensors.

MEMS strain sensors most commonly use the well known piezoelectric, piezoresistive or capacitive methods. Another approach is the use of resonant sensors.

The fiber optical sensors, such as fiber Bragg gratings or Fabry Pérot interferometers are embedded in optical fibers, so they are extremely miniaturized and non invasive. In addition they are insensitive to electromagnetical and radiofrequency fields, and to cable attenuation. Their application to structural monitoring is very promising, although some problems are still open, as the application and protection. If a bare fiber is used, very small amount of adhesive is used, and it can be easily removed at the end of monitoring.

DEMAND

Monitoring of inclination.

DEFICIT AND NEEDED DEVELOPMENT

Unlike displacement sensors, tilt gauges are in general absolute and self-referenced. They are usually directly put in contact with the element to be monitored.

For this reason the need in this field is limited to small and minimally invasive sensors. Several types of MEMS tilt sensors are available, and their application and improvement is to be encouraged.

DEMAND

Monitoring of relative displacements and crack opening.

DEFICIT AND NEEDED DEVELOPMENT

Electro-mechanical transducers as LVDT (Linear Variable Differential Transformer) and vibrating wire sensors are currently used. Fiber optic low coherence sensors are used too. All these types of sensors require to be fastened to the structure and are quite invasive.

There is a deficit in this field, because non contact sensors are not available. Very small electro-mechanical sensors should be developed.

An application that deserves to be improved deals with laser triangulation sensors. They are applied to one side of a crack, while a small target is fixed on the other side.

In order to strongly reduce the visual impact, bare fiber optical sensors can be used. They are fixed with small adhesive points on opposite sides of a crack, after prestressing them. The mean strain measured, multiplied for the distance between the contact points, provides a measure of the crack opening. This application is not currently adopted, and research is needed to improve it.

DEMAND

Monitoring of acceleration.

DEFICIT AND NEEDED DEVELOPMENT

The acceleration is currently monitored by piezoelectric accelerometers.

The needs are to use less invasive, low cost and non contact systems. The application of MEMS technology to accelerometers is a promising development.

The Laser vibrometry allows carrying out non contact vibration measurements by placing the system far from the structures and it allows scanning wide surfaces, but it allows only periodical survey and not continuous monitoring.

DEMAND

Cracking and damage grow.

DEFICIT AND NEEDED DEVELOPMENT

Monitoring of acoustic emission is a good way for detecting grow of cracks and other defects, and also to localize them.

The practical application of this method is affected by the need to use a large number of sensors, because their sensing capacity does not exceed limited distances.

Up to now no appropriate low cost MEMS sensors are commercially available for acoustic emission analysis. Research is needed to improve the performances in terms of bandwidth, sensitivity, signal-to-noise ratio and power consumption.

DEMAND

Monitoring of temperature and moisture.

DEFICIT AND NEEDED DEVELOPMENT

There are several temperature sensor technologies of wide commercial diffusion that directly interfaces to electronic-based systems. Most of them are low cost and non invasive.

In order to monitor the moisture diffusion in old masonry structures, there is the need of very small and low cost sensor that can be introduced in small holes drilled in masonry walls in order to assess the humidity profile along the wall thickness.

DEMAND

Monitoring of salt concentration in masonry.

DEFICIT AND NEEDED DEVELOPMENT

No commercial sensors are currently available.

New sensors are to be developed, which must be minimally invasive and easy to install.

6.2.2 Natural stone blocks and masonry

The assessment of the structural safety of historic natural stone masonry structures, the record of damages, material parameters and enhanced moisture is usually carried out by the designer performing manual optical inspections, laboratory tests on cored samples, drilling tests and mechanical tests on site and load carrying tests. But the internal structures of wall, columns, arches etc are often in homogeneous and differ significantly at various positions as, the elements being frequently built as multiple leaf masonry.

Without any volume inspection damages can increase and might suddenly cause complex consequences (e. g. spilling, large cracks, collapse), before they can be detected at the surface. Several methods have been developed and improved for monitoring and on-site diagnosis based on non-destructive (NDT) and minor destructive (MDT) approaches (like radar, ultrasonic, Sonics, flat-jack, strain gauges rooted on optical fibres etc).

The developed technologies collect very precisely data on the present situation of the building structures as well as of possible modifications, if regular inspection and/or monitoring is performed.

Diagnosis based on these data sets allows getting the following information:

Morphological characteristics

- Determination of the thickness of masonry structures
- Localisation of plaster delaminating
- Investigation of multi-leaf masonry, determination of the thickness of the leafs
- Localisation of metal parts, inclusions, voids and other in homogeneities
- Localisation of internal interfaces/change of materials
- Localisation of hidden crack patterns

Mechanical characteristics of masonry

- Investigation of the state of stress, compressive strength, elastic properties, correlation between mechanical parameters and NDT parameters (e.g. modulus of elasticity from flat-jacks and velocity from sonic tests)

Control of the repair intervention

- Control of the effectiveness of grout injection

Moisture

- Localisation of moisture, determination of moisture content, causes of damage

Although at present it is possible to solve many problems of historic masonry through application of NDT or MDT procedures, public awareness about these possibilities is very limited.

At time, only in very few cases these methodologies are applied on-site and contribute to the sustainable long-term maintenance of immoveable Cultural Heritage. This is due to the fact that these services are still too expensive and time consuming. Most of the NDT, MDT and monitoring techniques are not tested and calibrated for all materials applied in historic masonry constructions. Further on, the achieved results, the methods themselves and the possibilities for data processing and analysis are still not user friendly and not acceptable for the end-users. Another important topic is the lack of information about these possibilities. Therefore, at time there are only very few and only national located standards and recommendations, which describe the application of NDT and MDT methods in civil engineering.

The availability of information in Europe as well as worldwide must be improved considerably.

Different levels of investigation should generally be taken into account:

- theoretical studies, like the development of numerical models, describing the behaviour of masonry structures
- experimental laboratory research (calibration and validation of testing procedures, determination of material properties)
- archive study, building survey, recording of damages, evaluation of building conditions, monitoring
- on-site investigations at pilot sites
- parallel investigations with different approaches to find synergy effects

The range of application starts with simple masonry structures like single walls or pillars and can be exceeded up to larger building complexes. The latter requires the integration of technologies for building diagnostics and monitoring in the safeguarding and management process of Cultural Heritage buildings.

Recommendations

- Main problems in the structural and material assessment which can be solved with NDT, MDT and monitoring methods at time will be summarised.
- Comparison, combination and calibration of NDT, MDT and monitoring methods related to specific problems.
- Related to well described testing problems, which will also be simulated by masonry test specimens,
  Recommendations for the on-site application of combined NDT, MDT and monitoring techniques.
- Seminars and training courses
  For the spread of knowledge, the procedures for the efficient selection of the adequate testing methods and their combination as well as the correct on-site application will be described and demonstrated in seminars.
- These objectives will be reached by collaborative work of international working groups being involved in the development of NDT, MDT and monitoring techniques, in the application of these techniques, in the structural and material assessment of historic masonry structures, in building research as well as in building management.

6.2.3 Timber structural elements

DEMAND

Evaluation of mechanical properties of wood

Most common technique that is widely used is static bending testing. Measuring modulus of elasticity (*MOE*) of a member by static bending techniques is a foundation of Machine Stress Rating of timber. This simple measurement involves utilizing the load-deflection relationship of a simply supported beam loaded at its midspan. *MOE* can be computed directly by using equations derived from fundamental mechanics of materials to infer strength.

Transverse vibration techniques have considerable attention for NDT applications for timber. The analogy can be drawn between behaviour of vibrating beam and the vibration of a mass that is attached to a weightless spring and internal damping force. Solving Equation of transverse vibration, decay δ is a measure of internal friction and can be expressed in the form (for free vibrations). First frequency could be obtained as well as dynamic MOE.

DEFICIT AND NEEDED DEVELOPMENT

The results given by test has integral character and do not distinguish eventual local decrease of MOE, so it should be combined with scanner or X-ray testing of elements or similar techniques.

Since transverse vibration techniques significantly depend on boundary conditions, these techniques are usually used in laboratories more than in situ.

DEMAND

Timber elements damage and deviations identification

The simplest NDE technique is Visual inspection and it should be first step in assessing timber members in structure. Obvious damages can be easily identified, including external damage, decay, crushed fibers in bearing, creep, or presence of severe splits.

Today the smart image sensor enables several improvements in defect detection with respects to machine strength grading. A smart image sensor consists of a control for addressing and exposure time, a photo diode array, an A/D converter and a processor. When light strikes a wooden surface most of the light is reflected and some light is scattered within the wood. The amount of scattering is influenced by density of the material. Thus the light would scatter more in clear wood than it would in a knot due to a higher density.

DEFICIT AND NEEDED DEVELOPMENT

Visual inspection has definite limitations: variability stems from differences in visual acuity and training/experience of personnel, problems with access, knowledge is limited to the exterior surface of the wood.

DEMAND

Identification of decay in timber elements by observing that sound wood transmitted higher frequency components while decayed wood transmitted only low frequency components.

Determination of the modulus of elasticity (*MOE*) for structural members and estimation of various strength properties using statistical correlations

Speed-of-sound transmission and attenuation of induced stress waves in a material are frequently used as NDT parameters. Stress waves are generated from an impact on the surface of the material under investigation. The stress waves propagate at the speed of sound through the material and reflect from external surfaces, internal flaws, and boundaries between adjacent materials. The simplest method to utilizing stress waves is the time it takes for a stress wave to travel a specified distance. Monitoring the movement of a cross section near the end of such a bar in response to a propagating stress wave results in waveforms that consist of a series of equally spaced pulses whose magnitude decreases exponential with time.

Wave attenuation can be determined for the rate of decay of the amplitude of pulses using Equation for logarithmic decrement.

Since stress waves travel slower through decayed wood than sound wood, the localized condition of a member can be determine by measuring stress wave time at incremental locations along the member. Locations that exhibit longer stress wave times are locations of potential decay.

DEFICIT AND NEEDED DEVELOPMENT

If the stress wave is induced under any angle different parallel to wood grains, results are not enough accurate and they dissipate more if the is angle to the grains is bigger.

The method is not at all convenient for built in elements which have not free ends.

DEMAND

Estimation of timber element residual strength and quality

Ultrasonic inspection involves analysis of the characteristics of high frequency ($f > 20$ kHz) stress waves propagation through a material. Ultrasonic inspection techniques have been explored for detecting strength-reducing defects such as knots, slope of grain, and decay in wood members. However, most applications of ultrasonic inspections for wood members have focused on estimating product quality in a manufacturing environment but could be used also in-situ condition assessment of members in timber structures.

DEFICIT AND NEEDED DEVELOPMENT

Primary difficulties associated with ultrasonic inspection of wood members include effective ultrasonic coupling between the transducer and the wood surface, limitations on material dimensions for effective inspection due to the nature of wood. Since high frequency stress waves attenuate significantly over relatively short distance in wood (particularly for wave across the wood grain), ultrasonic detection of decay and other defects is primarily effective in relatively small regions of wood members. This limits the usefulness of ultrasonic field inspection for wood members with large cross sections in heavy timber structures.

DEMAND

Detect decay in timber elements and determine density.

Drilling resistance is classified as quasi-nondestructive because a small diameter (1.5mm – 3 mm) hole remains in the specimen after testing .Drill resistance devices operate under the premise that resistance to penetration is correlated with material density. Drill resistance is determined by measuring the power required to cut through the material. Plotting drill resistance versus drill tip depth results in a drill-resistance profile that can be used to evaluate the internal condition of timber member and identify locations of various stages of decay.

DEFICIT AND NEEDED DEVELOPMENT

Due to invasive nature of the drill resistance technique, and the fact that it provides a very localized measure of density and therefore this technique is best employed if used in conjunction with NDE methods that provides qualitative condition assessment (e.g., visual inspection) or regional condition assessment (e.g., stress wave or ultrasonic inspection). Drill resistance measurements could then be taken at the limited number of key locations.

DEMAND

Investigate condition of timber elements, localized wood density, wood degradation due to fungal attack.

Radiography typically involves positioning a radiographic energy source on one side of an object and a recording medium such as film on the other side. Radiation travels through the object and exposes the film. Local material density control how much radiation passes through the material resulting in two-dimensional picture of density variation in the object under inspection. A more advanced technique called computed tomography (CT) can be used to produce a three-dimensional representation of the internal structure of the object. The object is essentially radiographed at various orientations and then a computer is used to construct a three dimensional image. The condition of structural timber members has been investigated using radiographic techniques both in the laboratory and under field conditions. The condition of structural timber members has been investigated using radiographic techniques both in the laboratory and field conditions. Localized wood density has been accurately estimated by employing X-rays and gamma rays. Radiography has been used to investigate wood degradation due to fungal attack. The investigation revealed that density determined radiographically corresponded well to gravimetrically-determined density and decay.

DEFICIT AND NEEDED DEVELOPMENT

The equipment poses some problems for in situ inspection of timber members. Portability and member access are two major problems for field implementation, although devices have been developed that require access to only one side of the member and develop density measurements by employing Compton scattering rather then photoelectric absorption. These devices include a portable device that measures reflected gamma rays and one that employs gamma back-scattering to predict localized density in timber members.

DEFICIT AND NEEDED DEVELOPMENT

A variety of NDE techniques can be employed by inspector in order to determine the condition of aging timber elements. However advances are needed to improve the effectiveness of predicting timber strength and overall structural capacity from various NDE methods. The goal of this ongoing research is to develop a combination of techniques and AI techniques such as Neural Networks and FE modelling to provide more effective prediction of timber member condition and capacity.

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7 Annex: SMooHS query distributed to the Prussian Cultural Heritage Foundation by RRL

The RRL distributed a query to the Prussian Cultural Heritage Foundation (SPK) and the Museums of Berlin in order to collect information for this report, which follows bellow.

Since December 2008, the Rathgen-Forschungslabor is participating together with GD III Referat Technik in a 3-year EC project, which aims at the development of competitive tools to monitoring environmental and material parameters in the context of museums and monuments.

The aim is to follow and monitor the weathering progress in situ and non-destructively using modern methods and develop wireless and miniature sensor technologies. Besides data acquisition and evaluation, the project aims at developing warning and recommendation tools for the conservation of cultural heritage.

Possible sensors for monitoring may include:

- temperature
- rel. and abs. humidity
- air velocity
- strain and crack opening
- acoustic emission
- vibrations
- inclination of structures
- UV / VIS light
- chemical attack, corrosion
- Gases (VOC, Organic Acids, Oxygen)

We address the conservators in the SPK, the potential end users of these monitoring devices, with the following questions:

1. Which parameters do you monitor (are monitored in your collection) continuously?
2. Are the recorded data stored and evaluated, how, and by whom?
3. Which parameters did/do you measure discontinuously?
4. Which properties are in your opinion the most important to be measured and assessed? That property refers to which kind of objects and/or material (paper, stone, paintings, wood, metal, etc)?
5. Which monitoring tools (loggers, equipment) do you have available and handy in your collection?
    - a) for parameters
    - b) for change and damage?
6. What kind of change/damage do you intend to monitor and in which kind of objects/material?
7. What technical improvements do you think would be helpful in the monitoring and testing tools you work with?
8. What question/object would you suggest to be eventually studied within the EC-SMooHS project?