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Guidelines for reliable seismic analysis and knowledge based assessment of buildings

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COORDINATOR: Università di Padova (Italy)

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Small or medium scale focused research project

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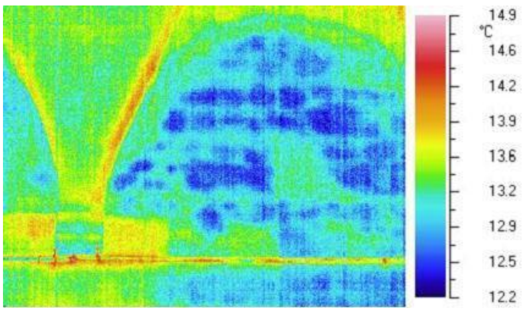

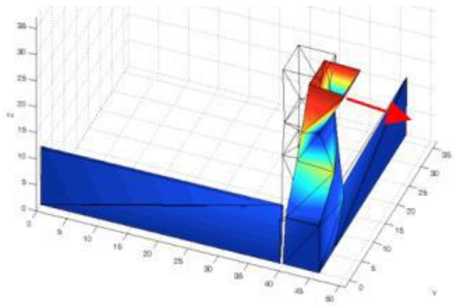

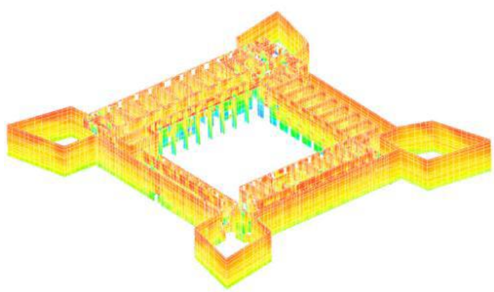

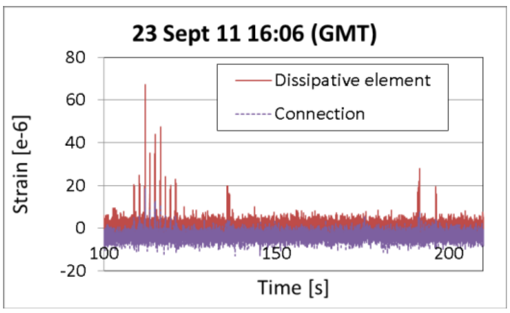

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1 INTRODUCTION

1.1 DESCRIPTION AND OBJECTIVES OF THE WORK PACKAGE

The exploitation of NIKER results covers both the use of exploitable knowledge and exploitable measures and products. Exploitable knowledge brings mainly non-commercial benefits for project participants and beyond the partnership (e.g. cultural heritage institutions, owners, RTD performers). By means of guidelines prepared in WP10, disseminated as described previously in other deliverables, the internal processes are improved for authorities in charge of CH maintenance. In such a way, cultural institutions and owners of cultural heritage can integrate the technologies and methodologies developed into their project and will be able to carry them out more effectively and more efficiently. The WP10 is subdivided into:

WP10.1: Guidelines for specific problems. These guidelines outline the main results obtained in WP3; WP4; WP5; WP6, WP7 and WP8 and are intended for designers and users of the technologies. Therefore, the entire work carried out into the project will be substantially simplified for the needs of the end-users and designers, by providing simple design rules, design formulations and design charts.

WP10.2: Guidelines for integrated methodologies. These guidelines summarize the main results obtained in WP7; WP8 and WP9 and are mainly oriented to designers or bodies responsible of the management and maintenance of the structures. They will contain the description of the new integrated knowledge based approaches for the protection the CH from earthquake-induced risks emerging from the project.

The main objectives of WP10 can be summarised as follows:

- Produce guidelines for the direct end-users of the developed technologies and tools (designers, architects, engineers, construction companies, bodies responsible of building maintenance, etc), with practical information on design of interventions, execution of techniques, assessment tools, monitoring procedures;
- Produce guidelines for production and installation of advanced instrumented dissipative devices;
- Produce guidelines for owners and end-users of the developed technologies and tools (public entities, bodies responsible of building maintenance, authorities, etc), with description of step-by-step integrated methodology for effective protection of cultural heritage;
- Spread awareness and establish reliable, effective, compatible, integrated approaches for the protection of cultural heritage from earthquake-induced risks.

The outcome of Workpackage 10 is presented in 5 deliverables, covering the aspects listed above.

1.2 SUMMARY AND OBJECTIVES OF THE DELIVERABLE

The guidelines for reliable seismic analysis and knowledge based assessment of buildings (D10.4) focus on seismic analysis and assessment (intended as entire process to assess a building, from inspections to monitoring). They summarize the results of WP8, WP9 and WP3. The development of procedures for knowledge-based assessment and for sequential application of intervention involves the use of analytical/numerical tools for seismic analysis and of monitoring to carry out knowledge based assessment of buildings.

2 KNOWLEDGE-BASED ASSESSMENT PROCEDURE

2.1 GENERAL REMARKS

The knowledge-based approach aims at achieving a reliable seismic assessment and an implementation of minimal, but efficient, upgrading solutions. The intervention solutions must be therefore determined and developed based on the evidence obtained through an integrated methodology (see D10.5 for details) which takes advantage of historical research, inspection and monitoring in addition to structural analysis.

The general process, to be more specifically tailored for each type of problem, should normally comprehend the following steps:

(1) Documentary research and inspection

First, a detailed documentary research is to be carried out on the history of the building and possible previous alterations or restorations. Also, a comprehensive inspection, including NDT technologies and other more direct methods, is to be carried out to sufficiently characterize the geometry, the morphology (including the internal composition of structural members), the connections, damage and deformations, past alterations and past repair or strengthening operations. Inspection comprises visual inspection, different NDT and MDT and in-situ or laboratory tests (chemical, physical or mechanical) oriented to identify the material composition, existing alterations, working stress levels, material properties, soil foundation properties and damage distribution, among other aspects.

(2) Preparation of structural models and first analyses

This information gathered is used for the preparation of the numerical models' input data and a preliminary structural analysis of the behaviour of the building can be performed to also support the next step.

(3) Lay out of monitoring

The information provided by the inspection works is used for the design of the monitoring as well. As mentioned, an initial structural analysis may assist in taking decisions on the type of monitoring to be implemented (type, accuracy and range of sensors, number of measurements and critical locations). Simulation using a numerical model can help lay out adequate and truly informative monitoring, for instance by casting light on the most significant variables to be measured, the expectable ranges of variation (which are meaningful for selecting the type of sensors) or the best location for the sensors.

(4) Monitoring for the diagnosis phase

Monitoring, including possible dynamic identification tests, is installed, checked and maintained active during the investigation phase. The technologies used for inspection and monitoring should be adequately calibrated previously to their exploitation.

The use of a numerical model, even if not yet fully calibrated, may help interpret the monitoring results through the comparison of numerical and experimental results. For this purpose, and for the later model calibration and validation, it is essential to not only characterize the structural response but also the main actions that may be affecting the structure during the period monitored. Wind (force and direction), temperature, humidity and accelerations caused by micro-tremors may be included among the effects which act on the structure and generate meaningful measurements.

(5) Model updating and validation

Once available, the monitoring results (comprising either or both static and dynamic monitoring) can be used to carry out model updating and validation. In particular, modal matching based on dynamic monitoring results can be used to update the model. The model can be as well validated or upgraded using results from inspection by comparing the numerical predictions (on cracking, deformation, work stresses, etc.) with real observations on the present condition of the structure.

(6) Seismic assessment

Once the model is sufficiently updated and validated, it is used for seismic assessment. Different approaches, such as capacity spectrum method combined with kinematic limit analysis or pushover analysis, or non-linear dynamic analysis in the time domain, can be used for this purpose. In the case of large and complex models, pushover analysis appears as the more feasible approach due to the excessive computational demands required by other more sophisticate methods such as analysis in the time-domain.

In any case, the conclusions on the performance of the building should be not only based on the structural analysis, but also on other evidence of a more empirical nature, such as the investigation of the past performance (historical approach) the results of monitoring and the comparison with similar buildings (comparative approach).

The evidence so far gathered and, particularly, the quantitative seismic assessment carried out will permit conclusions on the seismic performance of the building and the need for possible upgrading or strengthening operations. As mentioned, this assessment should consider as well the available information on the past-performance of the building and, particularly, possible available evidence on the response and damage experienced by the building in the occasion of historical earthquakes.

In addition to characterize the seismic capacity of the building, seismic assessment also allows to identify the seismic upgrading and general intervention needs.

(7) Design of intervention

Once the upgrading needs are determined, an adequate intervention solution can be designed complying with the aforementioned definition of minimal intervention. For that purpose, a number of alternative solutions have to be envisaged, based on different strengthening technologies and approaches, all of them satisfying the targeted seismic capacity (or general reliability level). The minimal solution will be the one better complying with the conservation principles and hence causing the minimum alteration on the cultural value of the material and structure. Looking to the possibility of future interventions, the removability of the proposed solution has to be taken into account.

(8) Evaluation and control of the upgraded structure

The adequate performance of the strengthened structure must be assessed during the entire design period by means of inspection and monitoring plans defined in the intervention project. The need for maintenance and possible corrective actions must also be considered in the project. The proposed approach for the post-intervened structure distinguishes between two different phases, as explained below, corresponding to evaluation and verification phases. These are characterized by different objectives, different duration and a different monitoring intensity.

2.2 IMPACT ON INTERVENTION SELECTION

In the perspective of an optimal intervention, the different requirements of technical and theoretical nature can be efficiently met only when comprehensive and extensive knowledge is obtained. This efficiency translates into more durable and compatible interventions which postulates in some cases relevant time saving and reduction of costs.

The application of knowledge based assessment procedures to cultural heritage buildings can contribute, in a fundamental way, to help identifying the most compatible and least impacting strengthening intervention thus avoiding the execution of unnecessary actions to heritage.

Monitoring strategies, as explained in section 3, can strongly affect the selection of the intervention by supplying necessary information, gathered in situ. Monitoring may be profitably used to control the response of a historic masonry building by experimental measurement of the parameters related to the global structural behaviour. More specifically monitoring strategies may be used as to postpone or limit the execution of strengthening interventions, for assessing precautionary strengthening for the increase of seismic capacity, for studying the vulnerability of structures and evaluating the need for seismic improvement, for studying of vulnerability of buildings damaged by earthquake and design of provisional strengthening measures, for assessing repair and seismic strengthening (improvement of seismic behavior) of structures severely damaged by earthquake and for validating their effectiveness of adopted strengthening solutions.

Modelling can have a huge influence on intervention selection. Following the modelling and interpretation of the structural behaviour, models are often used as numerical laboratories to simulate the application of the different interventions possibilities and to assess their influence in the behaviour of the structures to be strengthened. For each candidate intervention, advantages can be identified and possible harm can be minimized or even avoided.

The use of modelling allows identifying the best candidate interventions and it allows further optimization of the selected intervention by carrying out parametric analysis on selected intervention solutions. However, reasonable judgment has to be put in the analysis of results, as the degree of simplification introduced in modelling, both for the structure and for the intervention, needs to be also considered. Experienced users are typically required at this level (Lourenço, 2002).

Finally, it has to be highlighted that numerical results need always to be validated against in situ observations and measurements (ex: cracking patterns, results from dynamic identification tests, etc.). In this sense, inspection and monitoring provide modelling tasks with essential information.

The following sections are intended to provide a set of guidelines on the use of inspection, monitoring and modelling techniques in the frame of the general methodology proposed for the analysis and seismic upgrading of heritage structures. Relevant techniques together with their application, essential methodological aspects, advantages and limitations are presented.

3 INSPECTION AND MONITORING

Inspection and monitoring techniques applied during NIKER are categorized into the following categories:

Punctual or periodical inspection refers to non-destructive technologies (NDTs) that can be used to inspect structures before or after the intervention and that, when used in a repeated or periodical way, can be used as monitoring strategy.

Static monitoring includes techniques oriented to the long-term measurement of environmental or structural variables by means of sensors fixed to the structure.

Dynamic identification refers to techniques aimed at characterizing the dynamic properties of the structure under forced or (most frequently) ambient vibration. When used in a repeated or periodical way, it also offers a possible monitoring strategy.

Dynamic monitoring encompasses solutions for the repeated, episodic or continuous measurement of the dynamic response of the structure according to a given programme.

Early warning monitoring refers to techniques specifically oriented to the early detection of anomalous responses requiring decisions or rapid actions.

It must be noted that information on the technical specifications of the technologies and devices to be utilized was already given in deliverable D9.2, along with considerations on the previous calibration, innovative aspects and advantages with respect to other conventional technologies. The present document, based on the experience attained during the development of the project NIKER, focuses on the methodological aspects to be considered in their real application to CH buildings.

3.1 PUNCTUAL OR PERIODICAL INSPECTION

Monitoring does not necessarily involve fixed installation of recording systems. Instead, it may be also attained by applying, in a repeated or periodical way, non-destructive inspection technologies (NDT). The repeated application of this type of techniques may contribute to the identification of variations in the response of the structure caused by increasing damage. The effect of possible interventions such as deep repointing or injections may be also evaluated by applying convenient inspection techniques before and after the intervention.

Four different NDTs usable for the purpose of periodical inspection, namely sonic pulse velocity, radar technique, thermovision and crack measurement are considered and discussed below. There is in fact abundant scientific and technical literature on these techniques. Therefore, the information herein included is oriented to offer some additional guidance for their application to the inspection and monitoring of cultural heritage structures.

3.1.1 Sonic pulse velocity

<u>Purpose</u>

Sonic pulse velocity test is based on the generation of sonic impulses at the surface of a structural member. The input signals are generated by a hammer, often instrumented, while the transmitted pulse is received by an accelerometer positioned on the masonry surface. The velocity of propagation of sonic waves is strongly influenced by the density and the connections between the elements (stone, brick, and mortar) of the masonry members.

Application

- Evaluate the homogeneity and compactness of the section of masonry members. Identify internal homogeneities (as the presence of inner rubble masonry fillings).
- Identify differences in composition among different masonry members.

- Obtain indications on the damaged or altered condition of masonry members. In particular, obtain indications on the presence of cracking or large discontinuities. In some cases, evaluate the depth of existing cracking.
- Contribute to investigate the possibility and efficiency of injection as repair or seismic improvement solution.

Methodological considerations

The application of the sonic test requires previous information about the masonry construction type. In situ investigations (such as radar technique and boroscopy) are to be performed complementarily with the aim of identifying the construction features of masonry members.

In some cases, sonic test allows the detection of major cracks affecting walls or pillars, along with their depth in the thickness, as a clear decrease of the speed of the sonic waves in the affected portion of the section. Combining the acquisitions on the pillar’s faces it is possible to define and analyze the mapping of speeds in the investigated section, whose value is indicated by different colors. The obtained average speeds distribution can identify the areas of the section where the main crack is located.

3.1.2 Radar technique

Purpose

The radar technique is based on the use of a radar system consisting of a central unit and various antennas by means of which electromagnetic signals are emitted across the material under investigation. The antenna is moved along a straight line on the surface of the examined material or element. When the signal meets an interface (be it a void or a discontinuity within the material or a different material), part of the emitted radiation is reflected and recorded by the central unit and part of it travels deeper into the material. The distribution of reflection intensity may be utilized to identify heterogeneities caused by voids, heterogeneities (changes in material) or insertions.

Application

Systematic radar measurements assisted and confirmed by boroscopy observation, can be utilized to identify the thickness of the exterior leaves of masonry members.

The radar technique can contribute to the investigation of the possibility of grouting (in combination with other inspection technologies).

Methodological considerations

As masonry is a multi-phase discontinuous material, its dielectrical constant needs to be somehow estimated. Therefore, and in order to calibrate the technique, trial measurements have to be performed in areas where the geometry of the stones is known (for instance in unplastered corners of the walls).

Additionally to trial measurements, a number of so-called “static tests” have to be carried out before applying the technique. During a static test, the antenna is held firm in a position, whereas a metallic object is moved (by hand) on the other side of the wall. The reflection of the metallic object is very strong and easy to recognize, The image captured on the screen of the radar central unit is altered by the instantaneous presence of the metallic object in the area under observation. The depth of masonry at which the reflection is detected is equal to the thickness of the wall. The static test is applied in positions where the thickness of the wall is known. Thus, using adequate equations, the dielectric constant of masonry can be estimated.

In the case of heterogeneous or irregular masonries, it may not be easy to detect accurately the thickness of big stones as their reflections may be confused with the reflections of the smaller adjacent stones. The results are also of more limited reliability in the case of stones having a small height or length as the information obtained gets confused with the information of the adjacent stones. Internal discontinuities of the stones, or the form of the stones, in the case of non-orthogonal ones or with the edges not perfectly parallel, may also produce inaccurate results.

As is well known, also the presence of humidity may alter or remove the reliability of radar measurements. In real masonry structures, and in some cases, the information provided by radar technique may be unreliable because of the small dimensions of the outer face of some stones (that lead to several deflections) or because of the presence of humidity in some regions of the monument (either close to the pavement or in the regions most affected by the rainwater). Another problem may be caused, also in heterogeneous masonries, by multiple reflections within the thickness of masonry not allowing for the total thickness up to the exterior leaf to be accurately identified.

Often, radar technique by itself does not provide conclusive information on the internal nature of a masonry member (as a wall or a pier), not allowing to determine if a member consists of a typical three-leaf masonry (including two exterior leaves and a core of loose filling material) or a rather “solid” masonry with a rubble core of limited amount of big voids. However, this issue is of paramount importance to assess the current mechanical properties of masonry, to judge whether masonry is injectable or not and to design the proper grout, in case masonry is injectable. In general, radar will have to be combined with a limited use of boroscopy and possible core drilling in order to confirm or calibrate the radar results. Moreover, further investigation may be needed in order to check the percentage of voids in the inner core and judge about the possibility of the applicability and the efficiency of grouting.

However, radar can be largely useful to analyze and map the distribution of the identified masonry morphologies, and masonry qualities, in the entire structure.

3.1.3 Thermovision

<u>Purpose</u>

The surface of the structure to be investigated is heated by using a radiation source. After switching off the heating source, or when the surface stops to be directly lighted, the cooling down behaviour is recorded in real time with an infrared (IR) camera. While observing the temporal changes of the surface temperature distribution with the infrared camera, near surface discontinuities will be detected if they give rise to measurable temperature differences on the surface. Thermovision can be useful to evaluate the external layers of hidden surfaces in building structures, as well as to detect inhomogeneites.

<u>Application</u>

Thermovision is a powerful technique allowing a wide range of applications. These include the following ones:

- Measurement of near surface discontinuities.
- Detection of inhomogeneities.
- Inspection of the external layers of hidden surfaces in buildings.
- Identification of constructive systems and cracking hidden by renderings or coatings
- Investigation of decorative elements regarding presence of moisture and bonding to substract
- Investigation of the bonding condition of tiles glued to the intrados of vaults or on wall surfaces
- Assessment of the efficiency of superficial strengthening techniques such as FRP bonded at paraments

3.1.4 Crack monitoring

Purpose

Crack monitoring consists of the monitoring of the cracks on a large region of the building by means of digital crack meters. Using the proposed arrangement, measurements can be carried out punctually, to obtain a single measurement of crack distribution at a given moment; continuously, to study the variation of cracks over a long period of time; and periodically, to characterize seasonal or long time variations in crack distribution.

Application

- Assess the level of connection between parts partially separated by cracks.
- Assess the influence of major damage on the response of the building
- Assess the effect of possible repair and strengthening solutions by comparing crack opening trends before and after the intervention.
- Study of the influence of environmental parameters (temperature and humidity) in the case of buildings sensitive to them, as in particular (but not only) earthen structures.
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Methodological considerations

Crack inspection and measurement offers an inexpensive and efficient periodical monitoring solution which, in the case of strong economic or technical constraints, may provide by itself valuable information on the response of the building.

3.2 DYNAMIC IDENTIFICATION

The dynamic identification (DI) tests are able to give information on the global dynamic behavior of the building, including information on natural frequencies, damping and modal shapes. Dynamic identification tests are of special importance for the updating and validation of structural models. The results are directly related to the physical and structural parameters of the structure, such as the geometry (distribution of masses), the stiffness and the boundary conditions. Once updated, models can be used more reliably to assess the current behavior of the building and to predict the response of the structure in case of exceptional events, such as earthquakes.

Dynamic identification can be exploited for monitoring purposes if used in a repeated or periodical way. In particular, it may be used to evaluate the efficiency of possible interventions influencing on the stiffness or mass of the structure. Two different types of dynamic inspection technologies are here considered:

Dynamic identification (conventional). The dynamic monitoring system is used to measure, record and also transfer the records of the velocity parameters of some selected points using high sensitivity piezoelectric accelerometers.

Dynamic inspection by radar interferometry. The system is composed of an engineering microwave interferometer and a sensor module consisting of radar which can generate, transmit and receive electromagnetic signals. These signals can be processed to determine the deflection measurements.

3.2.1 Dynamic identification (conventional)

Purpose

The dynamic identification tests are able to give information on the global dynamic behaviour of the building, including information on natural frequencies, damping and modal shapes. Dynamic identification tests are of special importance for the updating and validation of structural models. The results are directly related to the physical and structural parameters of the structure, such as the geometry (distribution of masses), the stiffness and the boundary conditions. Once updated, models can be used more reliably to assess the current behaviour of the building and to predict the response of the structure in case of exceptional events, such as earthquakes. Dynamic Identification can be carried out by means of accelerometers, by combining different accelerometers setups, or by radar interferometer. Methodological issues regarding both techniques are discussed below.

Application

Dynamic identification is of large importance as part of the activities allowing knowledge based seismic assessment of heritage buildings. It can be applied to the following aims:

- Obtain information on the global dynamic behaviour of the building, including natural frequencies, modal shapes and damping.
- Identification of weak structural features
- By comparison with the output of modal analyses, carry out model updating and validation of the numerical model using the technique of “modal matching”.
- Assess the level of connection between different parts. In particular, assess the level of connection between parts partially separated by cracks.
- Assess the influence of major damage on the response of the building
- Assess the effect of possible repair and strengthening solutions by comparing the dynamic parameters before and after the intervention.
- Allow monitoring before (diagnosis phase) and after the intervention (post-intervention control phase) by repeating periodically the dynamic tests and comparing the results. Some

significant changes in the response of the building may be detected through the variation of the dynamic properties.

- Study of the influence of environmental parameters (temperature and humidity) in the case of buildings sensitive to them, as in particular (but not only) earthen structures.

Methodological considerations

DI by means of accelerometer setups

A successful application of dynamic identification requires a clear understanding of some the possibilities and limitations of the technique along with some methodological requirements.

In large historical structures, and due to the difficulty of sufficiently excite the structure by means of artificial means, dynamic identification will normally have to rely in the measurement of the effect of ambient vibrations due to wind, traffic and noise due to microtremors. Hence, output only identification techniques (Operational Modal Analysis) are normally used.

The use of only input identification will normally only permit the measurement of low amplitude vibrations. The dynamic properties of the structure (frequencies, modal shapes, damping) derived from these low amplitude recordings may not be sufficiently significant of the actual properties developed by the structure during a larger motion such as the one produced by a true earthquake. The properties derived for low amplitude motion should be only understood as representing the behaviour of the structure in its present initial condition. They will normally represent the response of the structure for low amplitude motion and before the effect of possible larger motions able to generate additional damage. If used to calibrate a model, these properties should only be considered to update the model in its initial condition. The numerical tool should then be able to simulate the effect or larger amplitude motion (including possible damage) and its influence on the variation of the dynamic properties.

In the case of bell towers, the swinging of the bells can be utilized to excite the structure. In these cases, it is recommenced to measure the response in two different series, corresponding to (1) ambient excitation (wind and possible micro-tremors) and (2) bell swinging. It has been noticed that the bell swinging may produce a far larger vibration (10-30 times) level compared with ambient excitations. However, the resulting dynamic response may be biased by the position of the bells and the swinging frequency.

The well-known rule of thumb according to which the length of the time windows to be acquired should be at least 1000 times the period of the structure's fundamental mode can be considered to decide on the acquisition intervals needed. Taking into account typical periods for masonry structures and towers, long acquisition periods, of about 900s or even 3600s, may be needed. A dense sample rate of about 100 to 200 Hz may be needed to provide good waveform definition.

The features of the dynamic tests must be carefully planned based on detailed inspection and preliminary structural analysis. In particular, structural analysis will assist in taking decisions on the best sensor locations and different setups. The sensors should be located at points providing meaningful information of the overall structural response. Non-structural members, or structural members with a predominant local response (such floor slabs) should be avoided.

The number of sensors is often limited by both technical and budgetary limitations. Because of it, the adequate characterization of a structure will normally require the repetition of the test for a number of test setups covering a sufficient number of acquisition points. An absolute minimum number of 2 sensors is needed, with one sensor in a fixed position during all the different setups to allow correlation. However, a larger number of sensors is recommended in order to avoid a large number of test setups and allow for a more detailed correlation. Tests on masonry towers and buildings are frequently done using many accelerometers (for example, 9 triaxial or 30 uniaxial ones) combined according to a few setups.

The investigations carried out in some of the case studies have shown a significant variation of the natural frequencies with the environmental parameters, and particularly with the temperature. Variations up to 10% of the value of the natural frequencies have been measured. This variation is in the order of magnitude of the corrections applied on the numerical frequencies when model updating is performed. Therefore, when dynamic identification is used for modal calibration, it is important to investigate the range of variation of the frequencies with the temperature. It is suggested to carry out model updating for a range of values comprising at least the maximum, the minimum and the average values. This can be done by repeating the model identification at least two times corresponding to the cooler and the warmer periods of the year.

As part of the dynamic test, the response of the foundation soil has to be accurately characterized by placing some of the sensors at the base of the structure. It is necessary to take into account that the resulting structural vibration may be significantly influenced by the soil characteristics and soil-structure effects.

Accurately characterizing the modal shapes of the structure may be difficult in the case of complex buildings or buildings connected to other buildings (as often occurs in historical urban centres). In these cases, the possibility of using dynamic identification for model calibration may be strongly compromised by limitations related to the quality and sufficiency of the information obtained through the test.

When carrying out the dynamic tests, it is important to consider the possible influence of auxiliary structures such as shoring, centerings or scaffoldings, as they may significantly influence on the resulting measurements. Their possible influence must be considered, in particular, in structures having been stabilized in the aftermath of an earthquake. Moreover, the installation or removal of scaffoldings and accessory elements can in some cases modify the environmental conditions.

In the case of the extrados of vaults in churches and buildings, for every measured point and whenever possible, the roof tiles should be removed and the sensors placed directly on the top of the vault (extrados) to avoid any possible noise contamination from the roof structure. .

The elaboration of the measured data and the modal matching procedure must be carried out using an adequate algorithms (normally a dedicated software) allowing and objective measure of disagreements or errors. Using several methods (rather than a single one) is recommended. For modal parameter extraction, the recommended methods are the FDD (Frequency Domain Decomposition), the EFDD (Enhanced Frequency Domain Decomposition), SSI (Stochastic subspace identification and pLSCF (poly-reference Least Squares Complex Frequency-domain).

In order to compare the mode shapes identified using different methods and different test data, the Modal Assurance Criterion (MAC, Allemang & Brown 1983) can be considered.

DI by radar interferometry

In radar interferometry, the sensor module is a coherent radar (i.e. a radar preserving the phase information of the received signal) generating, transmitting and receiving the electromagnetic signals to be processed in order to provide the deflection measurements. The equipment radiates at a central frequency of 16.75 GHz so that the radar is classified as Ku-band, according to the standard radar-frequency letter-band nomenclature from IEEE Standard 521-1984. The sensor unit, weighing 12 kg, is installed on a tripod equipped with a rotating head, allowing the sensor to be orientated in the desired direction. In addition, two horn antennas are placed on the sensor module for transmission and reception of the electromagnetic waves. The sensor, including the antennas, has a moderate weight and is installed on a tripod equipped with a rotating head, so that it can be aligned in any desired direction.

The technique is a non-contact measurement device of displacement that can be in principle applied for any purpose and scale of measurement provided that the direction of the displacement is known. Nevertheless, in restricted spaces, indoor interferences and wall reflection can affect the reliability of the measurements.

The advantage is related to the distance of survey, avoiding long installation time and cable length of conventional sensors, or when the access is difficult. The technique can be applied to quickly verify the structure overall behavior before and after an intervention evaluating possible stiffness changes.

3.3 STATIC MONITORING SYSTEMS

The second group of techniques selected involves the measurement of different variables, both environmental and structural, across a long period of time according to some predefined time interval. Two different complementary technologies are selected, corresponding continuous static monitoring by means of a variety of sensors applied on the surfaces of the structure, and non-contact thermographic monitoring by means of a thermographic camera fixed in the structure.

3.3.1 Continuous static monitoring

Purpose

Continuous static monitoring consists on the measurement of the gradual variation of wide variety of variables, either environmental (temperature, humidity, wind parameters) or structural (crack openings, displacements, deformations, work stresses...) by means of a number of specific sensors applied at critical locations on the structural surfaces. The information yield by the different sensors is collected centrally to be sent to a remote computer or storage system.

Application

Static monitoring is of large application to the study of historical buildings. In the context of the methodologies proposed within the NIKER project, static monitoring can contribute to the following purposes:

- Better understanding the structural behavior of a complex construction
- Continuously assessing the structural conditions (Structural Health Monitoring, SHM)
- Detecting damage at an early stage
- Evaluating quantitatively the progression of the damage pattern
- Carrying out model updating and validation of the numerical model by subjecting the model to known actions (thermal variations, wind) and comparing the result with the monitoring measurements.
- Assessing the effect of possible repair and strengthening solutions by comparing the recorded parameters (displacements, deflections, crack openings) before and after the intervention

- Study of the influence of environmental parameters (temperature and humidity) in the case of buildings sensitive to them, as in particular earthen structures.
- Assisting in the design of effective and urgent interventions if unsafe variations (such as displacement patterns) are recorded.
- If used during the execution of interventions, provide warning procedures contributing to the safety of the personnel involved.
- Evaluating the effectiveness of used strengthening techniques.
- Carrying out verification and long term control within a long-term maintenance programme after the intervention.

Methodological considerations

For obvious reasons, type and location of the sensors and auxiliary devices has to be studied in order to minimize the visual impact in the interior. Modern systems use wireless connections to save all the otherwise needed large length of cable and to reduce the aesthetical impact.

The monitoring systems are long term installations with continuum data records able to provide a recognition of the seasonal (and sometimes, also daily) variation of the environmental and structural parameters. The minimum monitored period should be of a year in order to complete a full yearly cycle, but longer periods (spanning to 4 or even more years) are necessary if the monitoring is intended to detect possible irreversible deformation components due to active damaging processes.

It is important that static monitoring records both the environmental actions (as temperature and humidity, wind speed and orientation) along with the response of the structure (displacements, rotations, crack openings, strains). This double recording is necessary for the correct interpretation of the response of the structure. It is also necessary to carry out model updating based on the static monitoring results, which requires the use of the actions as input to then predict the corresponding numerical response.

The assessment of the structural condition can be carried out by evaluating the opening or reclosing of the main cracks, controlling the inclination of piers and walls and monitoring the deformation of strengthening devices such as steel ties. The system may provide valuable information on the progression or stability of the assessed damage pattern with reference to the already carried out stabilisation actions and the foreseen strengthening interventions. These readings are constantly related to environmental parameters (temperature and relative humidity). The evaluation of the measured quantities, and in particular their changes over time, gives a strong indication in assessing the structural behaviour of the building.

Static monitoring is normally used in combination with dynamic identification or dynamic monitoring. In this context, static monitoring contributes to a better interpretation of the dynamic results by providing information on the evolution of the structural conditions and the variation of the climatic environmental actions.

Static monitoring can be defined according to very different configurations regarding the amount of sensors and parameters measured. It can also encompass very different technological sophistication levels. Generally, equipment of low to moderate cost can be considered in cases of budgetary constraints. A static monitoring system, for instance, may be limited to the periodical measurement of crack width variation to understand if there is any propagation in the crack and observe how the crack behaves with temperature. For instance, monthly processing of the data may give a solid understanding of the behaviour and may act as an early warning criterion for kind unexpected increase in the cracks. In the case of important buildings, or when the budged constraints allow for it, monitoring may include not only the measurement or crack widths, but also measurements of distances (such as the opening or closing of arches and vaults) and rotations (as wall or façades out-of-plumb variation).

The measurement of forces, stresses or strains in strengthening devices (such as ties) by means of strain gauges or cell loads is of particular interest as a way to verify the correct working and efficiency of these devices. This type monitoring, along with the measurements on the original structure itself, is of critical importance during the execution of the strengthening and should be also utilized after the intervention as part of the verification and control procedures to be carried out in the long term (during the maintenance period).

3.3.2 Thermographic monitoring

Purpose

Thermographic continuous monitoring consists of the measurement of the temperature on a large region of a historical building by means of a fixed thermographic camera with large storage capacity. Thermographic monitoring is used to measure infrared radiation during a certain period of time and to display the resulting temperature distributions as a collection of images, corresponding to different time intervals, converted to a visible chromatic scale.

Application

The main application is in the study of the influence of the temperature in the static or dynamic response of the building. In particular, thermographic monitoring allows a detailed analysis of the influence of temperature changes on the natural frequencies of the building.

Thermographic monitoring allows for a very detailed analysis of the influence of the interior surface temperature of different member types (vaults, walls, piers) on the static and dynamic response of the building and, particularly, on the variation of the natural frequencies.

This type of detailed investigation will not be normally necessary in practical studies aimed to seismic assessment. The application of this type of technology seems better found on detailed investigations aimed at gaining a deep scientific understanding on the behavior of historical masonry structures. Moreover, it has been found that the inner surface temperature may not be so relevant, or at least may be equally relevant as the exterior environmental one.

3.4 DYNAMIC MONITORING SYSTEMS

Dynamic monitoring systems consists of fixed systems, with sensors permanently active, allowing highly dense measurements adequate for the characterization of the dynamic response of the building. In the case of large historical buildings, the systems adopted perform normally dynamic monitoring via environmental vibration measurements. Dynamic monitoring systems are intended to measure the dynamic effects on buildings caused by environmental vibrations as well as microtremors, earthquake and wind. In the case of bell towers, dynamic monitoring may as well capture the effects caused by the bell swinging.

Dynamic monitoring techniques are normally regarded as a complement to punctual or periodical dynamic inspection. Dynamic monitoring aims to capture meaningful vibrational episodes caused by earthquakes, microtermors or wind. The main aim is in recording larger oscillation amplitudes than those due than normal ambient effects. The amplitude of measurements recorded by dynamic monitoring may be expected to be several orders of magnitude larger than those normally acquired by dynamic inspection.

Due to technical and budgetary reasons, dynamic monitoring is normally carried out using a limited number of sensors. Therefore, a detailed characterization of modal shapes is normally carried out by means of dynamic inspection, using a larger number of sensors, while dynamic monitoring is oriented to confirm the results of dynamic inspection for larger amplitude vibration or to detect nonlinear effects (dependency of dynamic response with amplitude) and changes possibly related with damage in the structure.

Three different systems are considered depending on the activation regime of the recording devices. The different systems may require very different equipment regarding sophistication and cost.

Dynamic monitoring with threshold. The recording devices are automatically activated when the amplitude caused by the excitation (as an earthquake a strong with episode) surpasses some predefined threshold. Only the strong motion experience during meaningful episodes is captured.

Periodical dynamic monitoring. The recording devices works constantly, capturing a sufficiently dense input, during some given intervals activated a periodic way according to a predefined programme.

Continuous dynamic monitoring. The system records continuously the vibrations experienced by the building. Meaningful episodes involving earthquakes, micro-tremors or wind are extracted a posteriori using the information provided by seismic stations or parallel static monitoring.

3.4.1 Dynamic monitoring with threshold

<u>Purpose</u>

Dynamic monitoring with threshold will be normally applicable to measure the dynamic response in buildings located in seismic prone locations, where sufficiently important micro-tremors or moderate earthquakes (or even important earthquakes) may be expected during the monitored period, producing neat signals able to trigger the sensors.

<u>Application</u>

This type of monitoring is useful for the following aims:

- Obtain information on the global dynamic behaviour of the building during the occurrence of moderate seismic events. This characterization will normally require the use of punctual ambient dynamic identification in a complementary way.
- Capture the dynamic response in the occasion of possible seismic events
- Carry out model updating and validation of the numerical model using the technique of “modal matching”.
- Assess the influence of major damage on the response of the building (if a sufficiently large number of sensors is utilized).

- Evaluate quantitatively the progression of the damage pattern.
- Assess the effect of possible repair and strengthening solutions by comparing the dynamic parameters before and after the intervention.
- If used during the execution of interventions, provide warning procedures contributing to the safety of the personnel involved.
- Carry out verification and long term control within a long-term maintenance programme after the intervention.

Methodological considerations

The current practices of structural health condition are based mainly on visual inspection or condition surveys. At present, however, software and hardware developments have made dynamic monitoring possible. However, it is important to adequately select the information that needed for structural health monitoring and for the damage analysis.

For economic and technical reasons, dynamic monitoring will normally be carried out by installing permanently a limited number of sensors in the building. Typically, two or three triaxial accelerometers are used for this purpose. However, it is advisable to use systems allowing for the later inclusion of additional sensors. Alternatively, the systems may be equipped with devices for remote data transmission to a central server.

Dynamic monitoring should be always accompanied with static monitoring to measure the variation of climatic environmental actions (temperature and humidity), crack opening and other relevant structural parameter. Temperature influences in fact largely both the static and dynamic monitoring output, and a good characterization of its variation and distribution within the structure is necessary for a correct interpretation and post-processing of both results. A previous inspection with detailed damage survey is also important.

The sensors may be connected by a network allowing a common trigger and time programmed records. In most of the current technologies the data are stored locally by means of recorder devices connected by cable to the accelerometers. A first recorder is set as the master one and enables the synchronization and updating the internal clock of the slave recorders. When the information is stored locally, the storage capacity may significantly limit the monitoring period or may require frequent visits to download the acquired information.

In case of complex structures it would be desirable to use a larger number of measuring points. However, the cost of traditional wire-based monitoring systems is driven by the number of sensors, where the sensors are essentially electrical. In addition, installation time and installation costs limit the scale of deployment of such systems. From experience, the installation time of a structural monitoring system for bridges and buildings can consume over 75% of the total testing time, and the installation labour costs can approach well over 25% of the total system cost. These installation time and device costs can be greatly reduced with the implementation of Micro Electric Mechanical Systems (MEMS) based sensors integrated in Wireless Sensors Networks (WSN).

The sensors must be placed in suitable positions in relation to the mode shapes of the structure. In fact, and given the limited number of sensors normally utilized for dynamic monitoring, their location becomes critical for a successful monitoring. Previous numerical analyses and dynamic identification should be carried out to assist in the selection of the sensor locations. Whenever possible, at least one sensor should be located at the base of the structure to record the ground acceleration and allow the evaluation of the dynamic amplification of the structure. The type and location of the sensors and cables must be carefully chosen also to minimize the visual impact in the interior of the church.

During an event that exceeds the established level, the recording system should be able to store the data several seconds before and after the violation. Hence, it is ensured that the registration does not lose important data on the event.

The continuous monitoring of the climatic environmental parameters (temperature and humidity) is also necessary in parallel to the dynamic monitoring.

Dynamic monitoring permits dynamic identification using input-output techniques (records during the earthquake of base accelerations as input and response of the structure in various positions as output). Thus it is possible to use the earthquake records into a full-scale force vibration testing, to analyze the dynamic behavior of the structure during a significant dynamic event and evaluate the possible correlation between modal parameters (natural frequencies and mode shapes) and level or intensity of the vibrations.

The dynamic characteristics of masonry structures may be dependent on the amplitude of the excitation and, in some cases, it is of interest to study the variance of resonant frequencies to different excitation levels. The processing of the dynamic monitoring data may reveal that some modes (as for instance the bending modes) may be much more frequently identified than others (as the torsion ones) probably as a consequence of the low level of ambient actions.

During earthquakes (even if of moderate intensity) the dynamic response of masonry structures can change significantly due to both the higher energy transmitted to the structure during the event (and higher vibration level) compared to ambient vibrations and the non-linear behavior that characterize such structures even under moderate seismic actions. In some cases, a clear decrement of the frequencies of the structure can be noticed during the earthquake. If these frequency decrements are recorded only during the main shock, and the frequency values return to their original value afterwards, the result can be understood as a possible indication that the earthquake did not induce permanent and significant structural damage to the structure. In turn, the damping ratios can significantly increase during an earthquake. The recorded values of damping during the earthquakes confirm that masonry structure like this presents high damping and a marked non-linear behavior appreciable either for rather low displacements.

A system of this kind may also be utilized for early warning purposes by setting some lower values of the natural frequencies to signal the need for possible actions. The trespassing of defined limit values of some parameters may provide information on damage occurrence and may alert about a worsening of the structural condition of the building. However, the choosing the threshold values may pose some difficulties and has to be accurately investigated and verified. The use of dynamic monitoring as early warning system is further discussed in section 3.5.1.

3.4.2 Periodical dynamic monitoring

Purpose

Periodical dynamic monitoring consists of the periodical activation of an implemented monitoring system for a fixed interval of time. Both the periodicity of the activation and the duration of the monitoring are fixed and programmed in advance. The duration of the monitoring can vary from minutes to several days.

Application

Periodical dynamic monitoring is normally utilized in combination with dynamic monitoring with threshold activation. In addition to record meaningful vibrational episodes (threshold activation), the system is also programmed to periodically record ambient vibration to capture additional information more oriented to the study of the influence of the environmental climatic parameters and the possible variation of the dynamic parameters due to damage processes.

This type of monitoring, which can be utilized for a detailed assessment of the variation of dynamic parameters in the building, can be applied, in particular, for the following purposes

- Study the influence of environmental climatic effects on the dynamic parameters
- Evaluate quantitatively the progression of the damage pattern in the building.
- Detect the need for urgent interventions if unsafe displacement patterns are recorded.
- Evaluate the effectiveness of implemented strengthening techniques.

Methodological considerations

Periodical monitoring is normally combined with dynamic monitoring with threshold. A single system can be utilized to combine a long-term acquisition on regular intervals oriented to identification in different environmental conditions (seasonal cycle), and short-term acquisition which is done automatically when the vibrations exceed the trigger (significant event).

The programming of the periodical dynamic monitoring may encompass very different frequencies and periods depending of its specific objectives. A possible programme may include the following operations:

- Activation of the recording devices for low acceleration levels, allowing measurement when a micro tremor occurs on the site (monitoring with threshold)
- Activation of the recordings every month for an interval of 10 minutes in order to detect frequency shifts. This allows to separate the influence of environmental conditions and to compare the consecutive dynamic responses before and after the occurrence of significant events.
- Seasonal activation consisting of 10 minute records every hour and during one complete day. These measurements can be carried out to observe the influence of environmental conditions in the dynamic response of the church.

This type of monitoring can be utilized to analyse the influence of environmental parameters over the dynamic response of the building. The cyclic evolution of the natural frequencies over each day-time or the annual seasons is often observable in masonry historical structure. This cyclic variation is likely to be related to temperature and, to lower extent, to humidity cycles. Observing the plots of the external temperatures versus the resonant frequencies, it can be observed that the oscillation in time of natural frequencies is in-phase with the external temperature of the masonry. Normally, natural frequencies increase as the temperature increases. This behaviour can be explained through the closure of superficial and deep cracks induced by the thermal expansion of materials; furthermore, the stone interlocking of irregular stonework masonry conceivably tends to increase as the temperature increases.

3.4.3 Continuous dynamic monitoring

Purpose

Continuous dynamic monitoring with extraction is oriented to measure the dynamic response in buildings located in moderate to low seismic locations. Highly dense information on the motion of the building is constantly recorded during a sufficiently long period of time that may involve several months of years. The effect of far epicenter earthquakes or local moderate tremors (or significant wind episodes) is extracted from the stored information a posteriori based on information obtained by nearby seismic stations. This approach may be utilized in moderate seismic locations where no sufficiently important local micro-tremors or moderate earthquakes may be expected during the monitored period. In these cases, relying on a threshold to activate the recorders may lead to spurious measurements. Instead, the information is permanently and the meaningful information is extracted after the occurrence of meaningful events. The continuously recorded information may be also utilized to study the influence of the environmental parameters (temperature, humidity) over the dynamic response (as the frequency values) and for post-intervention control in the long term.

Application

- Obtain information on the global dynamic behaviour of the building, including natural frequencies, modal shapes and damping.
- By comparison with the output of modal analyses, carry out model updating and validation of the numerical model using the technique of “modal matching”. Normally, this application will require punctual dynamic identification as a complementary technique.

- Assess the effect of possible repair and strengthening solutions by comparing the dynamic parameters before and after the intervention.
- Allow monitoring before (diagnosis phase) and after the intervention (post-intervention control phase). Some significant changes in the response of the building may be detected through the variation of the dynamic properties.
- Study of the influence of environmental parameters (temperature and humidity) in the case of buildings sensitive to them, as in particular (but not only) earthen structures.
- Carry out verification and long term control within a long-term maintenance programme after the intervention.

Methodological considerations

In the case of dynamic continuous monitoring the information sampled is continuously stored in a large-storage capacity system. The user can later extract any meaningful vibration intervals corresponding to possible wind episodes or seismic tremors. Noise can as well be processed across very long periods to analyze the possible influence of environmental parameters (in particular, temperature) on the dynamic response of the building. The continuous dynamic monitoring system is utilized to continuously measure, record and also wirelessly transfer the records of the acceleration of some selected points using tri-axial accelerometers. The system includes an analog-digital converter (digitizer), data acquisition system, a GPS antenna and an internet router. The GPS antenna is utilized to discipline the acquisition system to global time, thus allowing the correlation of the measured information with seismograms obtained at near seismic stations.

3.5 EARLY WARNING SYSTEMS

Early warning systems consist of networks of sensors that provide real-time measurements and allow for the assessment of a number of seismic parameters that can be used for risk-management procedures. Sensors send an alarm in case of events that activate any of the trigger thresholds set for the system; as these systems are meant for quick response, no data processing regarding the seismic event in general is carried out.

At the state of the art, early warning systems still face challenges such as the level of accuracy of the seismic estimates, which influences the difficult balance between false alarms and missed alarms, and the velocity of transmission of the seismic signal and of the system signal. Despite these unresolved issues, early warning systems have a high potential in terms of safety of human lives and reduction of damage to structures.

In principle, the previously described static and dynamic monitoring systems can be used, to some extent, for early warning purposes thanks to their potential ability to detect processes connected to damage in the structure.

The possible application of dynamic monitoring is discussed below into some more detail.

3.5.1 Dynamic monitoring as early warning system

Site-specific early warning systems rely on the accurate knowledge of the structural behaviour of the building that risk-reduction strategies aim to protect. For an appropriate early warning strategy, it is necessary to know how the building will respond to different levels of seismic excitation and what the meaningful parameters to assess the risk and the performance levels are. Given that the dynamic behaviour of historic buildings is not normally well known, it is usual to implement a monitoring system to study the dynamic behaviour along with the conservation state of the building and its response to different-level intensity vibrations. Monitoring will provide the information needed to set the threshold levels of the early warning system.

For this purpose, it is suggested to distinguish among several phases.

The first phase is the collection of all the possible data of the structure and the performance of a global dynamic modal test and a numerical model analysis for static and dynamic calibration. In particular, dynamic identification or dynamic monitoring need to be performed in order to obtain a detailed characterization of the dynamic response of the building. This provides a first understanding of the structural behaviour and health condition at an initial moment.

In a second phase, the health monitoring can be performed with a limited number of sensors (e.g. a pair of reference accelerometers in combination with static monitoring devices). Data should be stored periodically and the monitoring system should be able to send immediate alarms. The presence of damage may be observed by the global modal parameters.

In the third phase, if an alarm is triggered, a full-scale dynamic survey with more sensors and measuring points may be performed. In this phase, the health condition of the structure is studied with more detail. Damage identification methods can be applied to the structure after filtering the environmental and loading effects. The aim of the dynamic methods is to confirm and locate the (possible) damage in a global way.

In the last phase, a local approach with complementary non-destructive tests can be performed to locally classify and assess the damage. This can be realized with sonic tests or radar tests, depending on the access conditions and the type of damage sought. This local approach can give a better identification of damage.

During the third phase it is important to establish confident intervals (triggers levels) for the monitored structural parameters, as well as to filter the environment effects. Auto Regressive eXogenous (ARX) models can be used to model the structural response. It can include regressive data in order to simulate the thermal inertia of structures. The model needs to be calibrated with, at least, one year of monitoring period. Static and or dynamic response can be used. After model calibration, the observed values by the monitoring system can be compared with the predicted ones based on the ARX models. The prediction with the ARX models is carried out by using only the environmental effects, like temperature, humidity etc. With defined trigger levels, the method may help detect outliers and the damage occurrence. It can used to define and apply early warnings for the structure.

3.5.2 Specific early warning devices

An innovative device specifically oriented to early warning has been developed within the NIKER project research activities. The device proposed consists of an instrumented anchor connected to a dissipative device. The anchor is used to restore the connection between horizontal (vaults, roofs) and vertical (walls) structural members. The measures allowed by the system provide indication on the evolution of damage while also recording acceleration values. The system includes a set of sensors that measure the relative displacements at various points along the length of the anchor, the acceleration, and other environmental parameters. A data acquisition system with embedded software stores the data in hourly blocs and creates files containing the summary statics of the various parameters over a chosen interval of time.

Specific information on the dissipative device and its applications is provided in deliverable D10.2.

3.6 AUTOMATIC DATA PROCESSING SYSTEMS

Given the large amount of data to be processed in the management and processing of monitoring campaigns, and the need to set an adequate programming of the data acquisition, structural health monitoring should normally be carried out with the help of automatic procedures. These procedures can assist in treating, managing and processing data acquired by static and dynamic monitoring systems.

Ideally, as in the case of the system utilized in some of the case studies considered within the project NIKER, these procedures should allow for the controlling of the static conditions of the building and the correlation of the result of the sensors with the variation of the environmental parameters in real time. The procedures may afford the calculation of the Power Spectral density functions and the identification of the dynamic parameters by the Peak Picking method.

In the methods developed within the NIKER project the processing of each data file includes the following tasks: (a) creation of a database with the original data (in compact format) for later developments; (b) preliminary pre-processing (i.e. de-trending, automatic recognition and extraction of the time series associated to the input signal); (c) statistical data analysis; (d) pre-processing (low-pass filtering and decimation) of the data containing the response to micro-tremors and wind only, and creation of a second database with essential data records.

3.7 CRITICAL REVIEW OF MONITORING

3.7.1 Feasibility of methods

Knowledge-based methodologies for seismic assessment require a deep understanding of the real condition and performance of the structure. This understanding should be acquired by activating and integrating different approaches or activities, including historical research, detailed inspection, monitoring and structural analysis. Monitoring is, in fact, an essential part of the proposed approaches for seismic assessment and should be considered in all studies on architectural heritage oriented to the design and verification of optimal seismic upgrading interventions.

Monitoring systems should be carefully designed to fulfill the aim of contributing with useful information for seismic assessment, and should allow for a successful integration with the other mentioned approaches. Specifically, the monitoring systems should be designed so as to render useful information for model updating and validation. In turn, this calls for reliable information on the dynamic response of the building.

The monitoring categories described in section 2 comprise a wide variety of approaches characterized by different applicability and potential, but also by very different costs and technical demands. The type of system and devices to be applied to each specific case must be very carefully chosen taking into account the objectives of the study and the nature of the problem, but also the importance of the building and the possible budged and technical constraints. For obvious reasons, the technical and economical effort allocated to monitoring must be in proportion with the type and amount of information actually needed and the resources available. For the same reasons, also the monitoring period must be carefully decided. In this sense, the different monitoring categories allow for a variety of possible solutions adapted to very different problems and constraints.

Continuous static and dynamic monitoring is considered appropriate, if not necessary, for important and vulnerable monuments. Compared to periodical or repeated monitoring, continuous monitoring shows crucial advantages. Firstly, continuous monitoring permits the study of the influence of environmental climatic actions (mostly temperature and humidity) on the response of the structure; secondly, a permanent monitoring allows for the possible capture of the effect of earthquakes or significant wind episodes, whose occurrence is not predictable. For this purpose, the dynamic information may be stored permanently, to be later extracted, or the recording may be triggered by the surpassing of some predefined threshold values; thirdly, continuous monitoring can be utilized as early-warning system through the possibility of triggering alarm signals when some security threshold limits are surpassed. Both static and dynamic monitoring can be utilized for this aim. Specific early warning devices can be implemented in adequate locations of historical buildings.

However, continuous dynamic monitoring has some limitations. The main drawbacks of dynamic continuous monitoring are found in the need for large storage capacity systems and also in the need for relying in external information (external seismic stations or complementary static wind monitoring) to devise the episodes to extract from the entire recording. This may produce time-consuming signal extraction and processing. These drawbacks limit the usability of continuous dynamic monitoring to very important historical structures, with meaningful problems, or to scientific researches oriented to produce more general conclusions on the seismic performance of similar historical buildings. A more conventional threshold-triggered system, where the recording is only activated during salient vibrational episodes, will normally be less expensive than a truly continuous monitoring and will suffice for a majority of cases.

When using dynamic monitoring (be it continuous, threshold-triggered or periodical) only a small number of sensors can be normally utilized because of the need to limit the cost of the equipment. In many cases, the number of sensors fixed to the building is hardly sufficient for a detailed characterization of the modal shapes. Conversely, the information yielded by punctual dynamic identification, by means of a larger number of sensors, is often more exhaustive and permits a more detailed restitution of the modal shapes. Because of it dynamic monitoring will generally need to be combined with punctual dynamic monitoring, the latter being carried out with a sufficiently large number of sensors.

As mentioned, monitoring does not necessarily involve sophisticated or expensive systems permanently fixed to the structure. In cases affected by technical or economic constraints, or in cases of minor architectural heritage (for which a significant economic effort may not be justified), monitoring can be achieved by the periodical or repeated application of inspection techniques. In its more essential configuration, monitoring may only involve periodic visual inspection with crack opening measurement. Nevertheless, when the concept of periodical monitoring is used, the repeated application of dynamic inspection is considered important for the purpose of assessing the evolution of the structure (for instance, after earthquakes), to study the improvement produced by possible seismic upgrading and to allow for experimental results for the calibration of numerical models. In fact, some of the studies carried out within the NIKER project have shown that punctual dynamic inspection, even for very low amplitude ambient vibration, may deliver reliable information on the dynamic properties of the building (as specifically the natural frequencies) in full agreement with that obtainable by means of dynamic monitoring during the occurrence of micro-tremors.

3.7.2 Effectiveness of application in real cases

As seen in D9.4 monitoring strategies applied to real cases consent to increase the knowledge about behavioural characteristics of monuments in the perspective of a more appropriate control of foreseen or existing interventions. The lesson learnt from practical experience can be summarized into several contexts in which monitoring proves to be effective:

- Increase the knowledge on the structural behavior using Structural Health Monitoring (SHM) o postpone or limit alternative to the execution of strengthening interventions.

In this case structural health monitoring allows avoiding hasty strengthening intervention by increasing of knowledge on the structural behavior. Monitoring strategies in fact permit, as in the *Arena of Verona* case, by setting adequate safety thresholds to successfully keep the building under control and contextually postpone the execution of possible interventions unless a worsening of the structural conditions is recorded. Indeed the evaluation of the controlled quantities, and in particular the study of their changes over time, outline useful indications in the definition of the structural behaviour and in the determination of the presence or occurrence of damage's phenomena.

- Precautionary strengthening for the increase of seismic capacity.

Monitoring activities prove to be successful in evidencing whether the seismic capacity of a structure is insufficient or not and in defining precautionary strengthening solutions based on step-by-step approaches. Monitoring strategies applied to *Jerónimos Monastery* and the *Minarets in Bosnia-Herzegovina*, both still in progress, underline the possiblity for dynamic monitoring to confirm and locate the (possible) damage in a global way.

- Study of vulnerability of structures and evaluation of the need for seismic improvement.

Monitoring systems allow evaluating the seismic capacity of the building, particularly if located in moderate or low seismic places, which may show potential vulnerability under future earthquakes due to the absence of specific seismic resistant structural features. The main aim is to permit the calibration and validation of numerical models later utilized for seismic assessment.

In the *Ras Cherratine Medersa* case, where the dynamic characterization has only relied on dynamic identification (punctual), some difficulties are found in the upgrading of the model due to the complex dynamic response of the building which is connected to other surrounding ones within an urban texture.

The use of a long term dynamic monitoring, as in the case of *Mallorca Cathedral*, has provided a better understanding of its dynamic behaviour compared to that obtained by means of punctual dynamic identification (dynamic test). In particular, the continuous dynamic monitoring has permitted the capture of larger amplitude vibration (several orders of magnitude larger than in the dynamic test) during the occurrence of seismic tremors or strong wind episodes. In the *Ambel Preceptory* case dynamic parameters assessed during monitoring activities allowed calibrating and adjusting the structural numerical model. Furthermore monitoring has proved essential for evaluating the influence of existing damage on the strength of the building. Instead of both dynamic and static monitoring, the study of the building has been performed by combining true static monitoring (with permanent sensors) with periodic dynamic inspection. The latter was preferred to continuous dynamic monitoring due to its significantly lesser costs.

Economic constraints prevented true dynamic monitoring to be applied also in the *Hagia Sophia Museum in Trabzon* case. The dynamic characterization of the building has relied on an accurate dynamic identification carried in a punctual dynamic test. In this case monitoring is aimed to facilitate the identification of the state and progression of the main structural crack. It will also serve as an early warning system that will provide a base for any further inspection.

- Study of vulnerability of buildings damaged by earthquake and design of provisional measures.

Monitoring allows to analyze the response of the damaged building and to design provisional stabilization to control or stop further damage, including possible partial collapses activated by the earthquake. Monitoring strategies applied before and after the execution of the stabilization technique provide essential information on the response of the damaged building, controlling and validating the efficiency of the applied solution.

In post-seismic scenarios the application of monitoring systems to damaged cultural heritage buildings has proven to be a sound tool to control the structural conditions of the monuments and to assist the designers in taking decisions on stabilization or repair interventions. For example in the case of the *Civic Tower in l'Aquila* monitoring helps recording displacements, increments of strain and ongoing damage phenomena and concluding that damage pattern induced by the earthquake is stable.

If a vast amount of buildings is seriously damaged and the time schedule for the interventions is difficult to be a priori planned, a low cost distributed monitoring can provide evidence of the need for urgent actions on selected monuments. These actions may be necessary because of the worsening of their structural conditions. In some cases, the only necessary action may consist of continuous survey of the damage pattern (and assessing that it keeps compatible with an acceptable stability level). When, after an earthquake, the design of definitive interventions is postponed due to the need for further investigation or the need for time for developing adequate solutions, the role of monitoring becomes fundamental. The presence of the monitoring system is useful in evaluating possible changes in the structural conditions of the building and also for the continued assessment of the provisional interventions undertaken.

In the *Church of San Silvestro* case monitoring becomes fundamental as a way to survey the stability of the damaged structure and the adequate performance of the provisory interventions. Indeed the monitoring system has been very useful to evaluate possible changes in the structural condition from both static and dynamic points of view.

- Repair and seismic strengthening (improvement of seismic behavior) of structures severely damaged by earthquake.

After the application of provisory stabilization measures in structures severely damaged by earthquake, there is need to design a more definitive solution oriented to repair and sufficiently improve the future seismic response. The application of step-by-step procedures based on monitoring is of large interest to limit the amount of strengthening provided to the structure. The *Church of S. Biagio and Oratory of S. Giuseppe* and the *Church of San Marco* cases, in fact, prove the advantage of monitoring activities in determining the behaviour of damage induced by the earthquake and confirming the effectiveness of the adopted provisional interventions. In the *Spanish Fortress* case monitoring and inspection results are used for the creation of the model and for the intervention proposal. During the intervention works, the activities of inspection, static and dynamic monitoring should be continuously active. This will allow a controlled gradual intervention avoiding unpredicted structural behaviour and for assessing the effectiveness of the applied techniques. After the end of the intervention works the inspection and monitoring should be continued for identifying if the post-intervention behaviour is in accordance with the predictions. The intervention works will be considered finalised only after the verification of the effectiveness by the monitoring systems, guaranteeing that the structure meets the desired seismic capacity demand.

- Validation of effectiveness of adopted strengthening solutions by using monitoring

Monitoring allows validating the effectiveness of already existing strengthening solutions. In *Casignorio Stone Tomb* case, for example, the monitoring strategy allows the detection of possible variations in the assessed structural functioning with the passing of time and to have a record of the dynamic behaviour of the stone tomb during severe events.

4 MODELLING

Structural models must contemplate and simulate all the aspects that influence the structural response, including the geometry and morphology of the building (structural form, internal composition, connections between the structural elements, between others relevant aspects), the material properties, the external actions (mechanical, physical, chemical…), existing alterations and damage (cracks, constructional mistakes, disconnections, crushing, leanings, etc) and the interaction between the structure with the soil (except in the cases where it is judged to be irrelevant) (Roca, 2009) . The structural model of a masonry building can focus on the individual components of masonry, units and mortar, or in the material as a composite.

Several different approaches for modeling masonry structures can be performed depending on the level of accuracy, complexity of the structure, availability of input data, use of the results and simplicity desired. Depending on the structure to be studied and what kind of analysis will be performed, the model can be more or less complex. Indeed, a more complex model requires a thorough knowledge of the building and its materials, and requires more time for performing the analysis and to evaluate the results. So, for each building the analyst must choose the best option: the one that combines the simplest model for the level of accuracy desired.

Another important issue is the constitutive law to be adopted. In large finite element models, the most expensive task is the generation of the mesh itself, which might make months of work. Considering the current computational resources, structural analysis using simple non-linear constitutive models that require few experimental data are perfectly feasible. As an example, assuming that a linear analysis can be carried out in half a day and that a non-linear analysis can be performed in half a week, the difference of cost between linear and non-linear analysis is not significant. The really costly task is the preparation of the mesh. Therefore, even a simple non-linear analysis based in a simple non-linear model should be preferable to a linear analysis. It is worth to note that simple linear elastic analyses are not able to simulate fundamental features of masonry as its low tensile strength.

The next two sections outline the most common modeling strategies available. The first section is entirely dedicated to the macro-modeling approach which, during the research activities in NIKER, has been extensively adopted; the second section summarizes, for the sake of completeness of information for the reader, other methods available for the analysis of heritage structures.

4.1 FEM BASED APPROACHES – MACROMODELLING

Purpose

Continuum finite element modeling is a powerful tool for understanding the behavior and damage of complex heritage constructions. This approach allows assessing the global system behavior making it suitable for the study of large-scale constructions instead of structural details. Thus, the major advantage of this advanced modeling strategy is that it allows the study of a construction as a global interaction between all his structural elements with good accuracy.

Application

This technique of modeling is very useful, especially when the structural analysis requires a complete and accurate 3D model. Indeed, the equivalent material models have proven to be able to assess and understand the global behavior of the structure without the number of parameters and the computing effort needed in the micro-model. However, to generate the model, to carried out the analysis and to interpret the results, specialized engineers and extensive data information about the material are required.

As in micro-modeling, this approach requires much effort in terms of time and computations. When a three-dimensional 3D modeling approach is needed for the study of a construction, a very high number of degrees of freedom are mobilized due to the large size of these structures. A fully 3D model is usually very time-consuming concerning the geometric discretization and the preparation of the model with the introduction of the appropriate constitutive laws, the performance of the analysis and at last the processing of the results.

The usual approach to the modeling of complex historic buildings is by the application of different type of elements, as beam, plate or shell elements to represent columns, piers, arches and vaults, typically assuming the hypothesis of homogeneous material behavior (Lourenço, 2002). When one dimension of a structural component is very large with respect to the others, the structural elements can often be simulated as beam, plate or shell elements. Otherwise, volume elements are adopted.

Methodological considerations

Finite element modeling based on the macro-modeling approach has been extensively used within the numerical activities of NIKER, in WP4 (vertical elements), WP5 (horizontal elements), WP8 (parametric modeling) and WP9 (case studies). In the framework of WP8, continuum finite element models were used in the non-linear modeling of walls, floors, trusses, entire multi-story buildings and churches, under both static and dynamic loading. The results obtained from the several users have shown that this approach presents a very good relation between material parameters required for the analysis, computational time, scope of application, and accuracy and usefulness of the results. Two additional advantages in favor of this approach are related to the availability and reliability of different wide-spread continuum FEM-based softwares and basic experience from almost all the professionals dealing with structural analysis.

The most relevant results to be analyzed are related to the crack pattern (tensile strains), stress level (stresses), displacement capacity (displacements), dissipated energy (plastic strains) and failure mode (displacements).

4.2 OTHER METHODS

The use of other modelling techniques can be justified in many situations. For some structural components, a very detailed knowledge of the structural behaviour might be required. On the contrary, in some practical-oriented problems, the reduction of computational costs and/or the available experimental data imposes the use of modelling approaches simpler than continuous FEM-based techniques.

4.2.1 Simplified modelling: use of rigid and deformable macroelements

The most advantage of the macro-element modelling is that it allows performing reliable linear or non-linear seismic analyses of wide masonry structures with a simple mesh discretization and a limited number of degrees of freedom. Within the macro-modelling approach, the structure is divided into blocks with a considerable size and each block represents a large portion of undamaged, or little damaged masonry. This approach does not provide a detailed mesh, the discretization is very simplified, resulting in a global model with a reduced number of degrees of freedom. The macro-model is an assembling of blocks attempting to represent the mechanical behaviour of the structure. Macro-models are applicable when the structure is composed of solid walls where stresses along the block area can be regarded essentially as uniform.

Consequently the analysis of these kinds of model is relatively short in time and can be performed in a common computer technology. This strategy is basically practice-oriented due to the reduced time required to generate the model and performing the analysis, the reduced computational efforts as well as a user-friendly mesh generation. Indeed, and as demonstrated by the presented examples, macro-element modelling approach leads to satisfactory analysis results without heavy computational efforts. The main problem of this approach is that the results strongly depend on model geometry. In other words, the final results are always conditioned by the initial input. Depending the results substantially on the model geometry adopted, experienced users are required. Concluding, macro-modelling is a very easy to use technique and quite simple to interpret in spite of some detail is lost. On that account, despite the fact that it might be a less accurate methodology, macro-modelling is a very expeditious option. This type of modelling approach represents a very valuable approach when a compromise between accuracy and efficiency is needed.

4.2.2 Simplified modelling: kinematic analysis of single rigid blocks

A very simplified approach for the analysis of existing masonry buildings in seismic areas concerns the application of single or combined kinematics models involving the equilibrium of structural rigid blocks, or macro-elements [Bernardini et al. 1988 and 1990, Giuffrè 1993, Doglioni 1994]. Such method is particularly addressed to existing masonry buildings, when they do not satisfy the general conditions required for the application of global analysis procedures, based on the “box” behaviour of the structure (lack of well-connected walls and floors and inadequate stiffness of horizontal diaphragms). In this case, the ultimate capacity of the building depends on the stability of its macro-elements, that is of portions of the structure bounded by the potential damage pattern (cracks, borders of poor connections, etc.) which can behave as a whole, following a kinematics mechanism. Macro-elements are defined by single or combined structural components (walls, floors and roof), considering their mutual bond and restraints (e.g. the presence of ties or ring beams), the constructive deficiencies and the characteristics of the constitutive materials.

The first crucial step is a detailed in-situ survey of the buildings under study, including the historic evolution of the structures, their repair and strengthening connected to different damage conditions, for the identification of macro-elements and possible collapse mechanisms. The practitioners are helped as, the systematic collection and analysis of damage data deriving from post-earthquake surveys, brought to the creation of abacuses of the typical damages occurring in different construction typologies (buildings, churches, clustered buildings). This led to the systematization of the mechanical models able to describe the specific behaviour by kinematics models, both for in-plane and out-of-plane mechanisms. Kinematics models provide a collapse coefficient c=a/g (where a is the ground acceleration and g the gravity acceleration), which represents the masses multiplier able to activate the mechanisms and subsequently lead the element to failure. The collapse is thus due to a loss of equilibrium of the structural portions involved in the kinematic mechanism, rather than to state of stress exceeding the material ultimate capacity. It is also possible to proceed with a non-linear analysis, and generate a capacity curve of the mechanisms yielding to the displacement capacity of the element. This type of analysis, that is roughly simplified, is a local analysis but, when systematically carried out on the entire set of macro-elements constituting the structure, it represents a sort of global analysis for buildings where poor structural details prevent a global behavior to develop.

4.2.3 Discrete elements method

Discrete element method represents masonry as discontinuous, performing separately the mechanical behaviour of the units, joints and interface (interaction between units and joints). Implied in this approach is the aim of modelling strongly nonlinear behaviour, including joint sliding and total separation, which may involve large relative movements between the units, with the consequent changes in structural geometry and connectivity. Thus, discrete element models allow the assumption that blocks (units) are rigid and the system deformability is concentrated in the joints. However, nowadays it is also possible discrete element models include deformable block formulations. Furthermore, discrete element models are designed to allow full separation between blocks, and most of them permit the analysis to continue for large displacements (Lemos, 2007). Summarizing, discrete element method is a modelling approach that can be successful used for the assessment of seismic vulnerability of masonry buildings due to the blocky nature of this type of buildings. The main advantages that make this method very suitable for masonry structures are

- A more appropriate representation of masonry in relation to its discontinuous nature by a system of blocks (rigid or deformable). With this modelling approach the collapse mechanism is governed by the joints, what really happen in masonry buildings when subjected to horizontal actions.
- Ability to simulate progressive failure associated with crack propagation; the capability of simulating large displacements/rotations between blocks, including sliding, the opening cracks and the complete detachment of the blocks (Azevedo and Sincraian, 2000; Azevedo et al., 2000).
- Contact points are updated automatically as block motion occurs (Azevedo and Sincraian, 2000; Groza and Pop).
- The problem of interlocking is overcome by automatically rounding the corners (Azevedo and Sincraian, 2000).
- Excellent visualization of the sequential collapse mechanism.

Concerning the disadvantages, the principal limitation of this strategy of modelling is the high computational effort necessary for running this analysis due to the huge number of particles. So, discrete elements method is computationally intensive and therefore limits both the length of a simulation as the number of particles, as a result the duration of a virtual simulation is limited by computational power. An alternative to reduce the computation time is to treat the material as a continuum and joint discrete and finite element approaches (as mentioned above).

4.2.4 FEM based approaches - micro modelling

Micro-modelling is a technique that encloses all the constituents of masonry with the detailed characterization of their mechanical properties and simulates the interaction between them. This strategy of modelling simulates with better accuracy the behaviour of all the constituents materials of masonry structures, when the mechanical characteristics are known with some detail. So, this is a precise and rigorous analysis tool particularly suitable for small structures. Micro-modelling is also able to give a better understanding about the local behaviour of masonry structures. Although all these advantages, the implementation of this type of modelling is quite laborious. Indeed, a micro-model can have many degrees of freedom due to the huge detail that this kind of modelling requires, which makes this strategy high computational effort. To reduce this time and computational effort, and as referred before, some simplification techniques can be applied. For instance, the application of homogenization could eliminate this disadvantage: the continuum model can have the accuracy of the micro one by using constitutive laws that simulates with good accordance the behaviour of masonry. So, when large real structures have to be studied a different approach is needed. It can be used continuum or macro elements, these approaches are explored in the next chapters.

4.2.5 Fibre elements

This modelling technique consists on the development of an equivalent system of beam elements in order to model the entire structure. Thus, after the structure is discretized into rectilinear beams, each beam is subdivided into longitudinal fibres, whose stress-strain behaviour is defined according to the material properties that can be easily obtained through experiments. This approach stands out not only by the low required computational time and efforts analysis but also by simplicity of the non-linear material models. Hence, this approach offers a good compromise between simplicity and accuracy: a simple numerical model (discretized into beams) which takes into account the backfill and considering the interaction between normal force and bending moment in the non-linear behaviour (Felice, 2009). Using the fiber beam model, non-linear dynamics analysis, which is very complex and time and computational consuming as stated before, can be easily performed, obtaining accurate results.

4.3 CRITICAL REVIEW OF MODELLING

4.3.1 Feasibility of methods

There are several difficulties inherent to the process of modelling cultural heritage structures due to the huge variations of masonry, which complicates the correct characterization of its mechanical properties. Indeed, all modelling strategies require a comprehensive description of the mechanical behaviour of the material and all the numerical modelling strategies reviewed above have advantages and shortcomings. Nevertheless some general recommendations for the construction of a numerical model can be given:

- The key issue is preferring simplicity over complexity, the geometric idealization should be kept as simple as possible, as long as it can be considered adequate for the problem being analysed.
- Adopt a modelling technique that can be validated and assessed.
- Model structural parts and details instead of complete structures.
- Use full-structure three-dimensional models only if necessary; they are usually very time consuming with respect to preparation of the model, to perform the calculations and to analyse the results.
- Avoid using shell elements in areas important for the global behaviour of the structure. The large thickness of the structural elements may yield a poor approximation of the actual state of stress.
- Avoid making linear elastic calculations for historic structures.

4.3.2 Effectiveness of application in real cases

A large number of the case studies were submitted to numerical modelling aiming at understanding the structural behaviour and at explaining the damage processes as well as the major causes associated to it. This process can only take place if in situ observations and data are available to be used in the calibration of the numerical models. This intrinsic need makes inspection and monitoring as key aspects in the analysis of cultural heritage buildings.

Furthermore, modelling was extensively used to test the effectiveness of possible strengthening interventions. In some of the case studies (e.g. the church of Monastery of Jeronimos), several strengthening solutions were consecutively tested and apparently good interventions proposals proved to be inefficient in solving the structural problems identified.

Finally, reasonable judgment of the results is required, as the degree of idealization introduced in modelling has to be critically assessed. Experienced analysts are required at this level.

5 CONCLUSIONS

The knowledge-based approach aims at achieving a reliable seismic assessment and an implementation of minimal, but efficient, upgrading solutions. Such assessment is based on an integrated methodology (described in D10.5) which takes advantage of historical research, inspection and monitoring in addition to structural analysis.

Inspection and monitoring techniques applied during NIKER are categorized into the following categories:

Punctual or periodical inspection refers to non-destructive technologies (NDTs) that can be used to inspect structures before or after the intervention and that, when used in a repeated or periodical way, can be used as monitoring strategy.

Static monitoring includes techniques oriented to the long-term measurement of environmental or structural variables by means of sensors fixed to the structure.

Dynamic identification refers to techniques aimed at characterizing the dynamic properties of the structure under forced or (most frequently) ambient vibration. When used in a repeated or periodical way, it also offers a possible monitoring strategy.

Dynamic monitoring encompasses solutions for the repeated, episodic or continuous measurement of the dynamic response of the structure according to a given programme.

Early warning monitoring refers to techniques specifically oriented to the early detection of anomalous responses requiring decisions or rapid actions.

The structural model of a masonry building can focus on the individual components of masonry, units and mortar, or in the material as a composite. Several different approaches for modeling masonry structures can be performed depending on the level of accuracy, complexity of the structure, availability of input data, use of the results and simplicity desired. The choice of one modelling technique instead of another depends on: the available financial resources; the level of experience of the engineer; the availability of input data; the level of accuracy required; the aim of the study and at last the analysis method to be applied. Cost and the need for experienced users seem straightforward issues (Lourenço, 2002).

The availability of input data is another key issue in the choice of the modelling strategy to use. It should be underlined that the modeling technique applied to most of case studies is macro-modelling.

Techniques used in NIKER include: macro-modelling, simplified modelling by macro elements, discrete elements method, micro modelling and fibre elements.

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