1. Conservation of the architectural heritage: structural, seismic and geotechnical aspects

In this first chapter the main issues involved in the seismic protection and analysis of the architectural heritage are introduced. In particular, the most relevant national and international codes such as the ISCARSAH guidelines or the Directive PCM 2011 are reviewed. Successively, the so called "path of knowledge" as recently introduced by the Italian national standards is explained and analysed. Furthermore, the various types of analysis which concur to increase the level of knowledge of a structure are introduced and briefly discussed, with particular emphasis on masonry structures.

The importance of attaining an adequate level of knowledge in historic structures is better evidenced in the last section, where the intimate relations between safety and knowledge levels are examined. Then, the solutions proposed by guidelines and building codes are presented.

1.1 Structural engineering and architectural heritage: national and international deontological guidelines

1.1.1 International and deontological guidelines

The difficulty, or even lack, of communication between architects and engineers has always been one of the main obstacles in the analysis and conservation of the architectural heritage. During the 14th General Assembly of ICOMOS (International Council on Monuments and Sites) in the 2003, a fundamental document was produced and approved. In fact the ISCARSAH guidelines [1] states that the conservation, reinforcement and restoration of the architectural heritage require a multidisciplinary approach. A typical example of interdisciplinary approach is the interaction that has to occur between historical research and structural diagnosis: historical research can discover particular phenomena involving structural behaviour whilst historical questions may be answered by considering the global or local structural behaviour.

The guidelines define the restoration of heritage structures using a peculiar metaphor: the structural rehabilitation of heritage structures can be seen as the cure of a sick person, hence "the heritage structures require anamnesis, diagnosis, therapy and controls, corresponding respectively to the searches for significant data and information, individuation of the causes of damage and decay, choice of the remedial measures and control of the efficiency of the interventions".

In this framework, the guidelines combine the various approaches involved in the structural conservation. This combination of approaches, both qualitative and quantitative, has been quite difficult due to the different philosophies at the base of traditional and innovative techniques. Moreover, the guidelines introduce the concept of holistic approach for the evaluation of a building, considering the building as a whole entity and not a union of individual elements.

The guidelines distinguish clearly between the data acquisition, as the phase of information gathering and investigation of the structure, the study of the structural behaviour, as intermediate stage, and the two latter phases of diagnosis and safety evaluation.

The data acquisition is particularly important in historic buildings, in fact a correct assessment of the structural problems cannot be achieved if there is lack of information about the structure. The guidelines specify that the "knowledge of the structure" can be reached with the following steps:

- definition, description and understanding of the building's historic and cultural significance;
- a description of the original building materials and construction techniques;
- historical research covering the entire life of the structure including both changes to its form and any previous structural interventions;
- description of the structure in its present state including identification of damage, decay and possible progressive phenomena, using appropriate types of test;
- description of the actions involved, structural behaviour and types of materials.

What is also important to point out is that all these actions can be carried out at different levels of detail, therefore this study must be cost efficient (proportional to the importance of the structure and the level of knowledge desired).

It is also noteworthy that the restoration of the structure must not be an end in itself but a means to an end, which is the building as whole. Therefore, no action should be undertaken without having discerned between benefit and harm to the architectural heritage (except in the case where urgent interventions are required) and having demonstrated that they are indispensable.

For what concerns "innovative" methods and materials the guidelines establish that their use has to be weighed up with "traditional" ones. In particular the compatibility with existing material and long-term impacts has to be established, in order to avoid side-effects.

Moreover, the monitoring of existing structures assumes an important role in the preservation of the architectural heritage. In fact, as it is clearly said in the guidelines: "the best therapy is preventive maintenance" that can only be achieved via monitoring of the structure. Monitoring is necessary not only in the case of a progressive phenomenon occurring but also during a "step-by-step procedure of structural renovation".

Accordingly, Ian Hume [2] states that the principles of structural conservation of historic structures can be summarised in five main points:

- *Conserve as found.* Structures should ideally be conserved as they are found. They should not be taken back to the condition that it is supposed they might have been in at some period in their history; neither should they be 'improved' without good cause. Part of the value of a historic structure is that it contains a record of the changes that have taken place during its history.

- *Minimal intervention*. In many instances it is, of course, necessary to make changes either because of excessive decay or distortion resulting in a threat to the structural stability or because changes are necessary to ensure that the structure has a viable future. Whenever changes are made, these should be kept to a minimum. Tried and tested techniques are preferable to new methods that may have an unforeseen detrimental effect on the structure at some time in the future.
- *Like-for-like repairs*. If repairs are to be made, the ideal is that they are made using the same materials as are found in the original construction. Ideally a timber beam should be repaired with timber and a brick wall with a similar type of brick. However, there are times when to do this would cause a great loss of fabric and consequent loss of detail and history.
- *Repairs should be reversible*. If repairs have to be made, these should be designed and carried out with subsequent removal in mind. Ideally, it should be possible to remove repairs from a structure, should it later prove possible to make better repairs or should, for some reason, the repairs become redundant. Of all the principles of conservation, this is the most difficult to achieve. Indeed, in many cases it will not be possible to make sensibly reversible repairs.
- *Repairs should be sympathetic*. Repairs need to be in character with the structure. If it is decided to use modern materials for the repair then it is good if the design fits the general style of the original structure. Occasionally repairs that are plainly modern in design are needed, but these can still be designed to sit happily with the original fabric.

Bernard Feilden [3] defines what the standard of ethics and recommendations should be in any conservation work:

The condition of the building must be recorded before any intervention.

- Historic evidence must not be destroyed, falsified or removed.
- Any intervention must be the minimum necessary.
- Any intervention must be governed by unswerving respect for the aesthetic, historical and physical integrity of cultural property.
- All methods and materials used during treatment must be fully documented.

Moreover, all the interventions proposed for a historic building should be reversible or repeatable, if technically possible or at least must not prejudice a future intervention whenever this may become necessary. Moreover, the interventions must allow the maximum amount of original material to be retained, must be harmonious in colour, tone, texture, form and scale, and if additions are necessary and unavoidable should be less noticeable than original material but, at the same time, should be identifiable. Nonetheless, Feilden adds that the problems which arise from historic buildings are often unique and have to be solved from first principles on a trial-and-error basis. Feilden continues stating that architectural conservation does not share all the goals of artistic conservation. In fact, the architectural fabric has to function as a structure, resisting dead and live loadings, and must provide a suitable internal environment as well as be protected against certain hazards (i.e. fire, earthquake, vandalism).

According to Claudio Modena [4] structural repair of a historic build has to be "cautious" and that the "cautiousness" principle must lead the whole process of the conservation of historic architectural heritage buildings. In fact, a considerable number of restorations failed due to inappropriate applications of modern technologies: these technologies may also perform well from a technical point of view but they can alter the cultural value of the restored building. From the designer's point of view, the principle of "cautiousness" entails two fundamental rules: firstly, avoiding unnecessary interventions (i.e. intervene as less as possible) and secondly, choosing intervention technologies that alter as less as possible the chemical, physical and mechanical properties of existing materials and structures (i.e. "compatible technologies") and that can be easily removed and replaced in any circumstances. Furthermore, usual safety and reliability concepts may become inadequate when immaterial values are involved, such in the case of human life or historic and artistic assets.

1.1.2 The Italian scene

In the Italian scene one the first operative documents which has explicitly addressed the problem of architectural heritage buildings in seismic regions was a regulation of the Italian Ministry of Cultural Heritage, sometimes referred to as "Documento Ballardini" [5]. This document established some general criteria and provided a classification of different types of interventions on historic buildings in seismic areas. The document has also presented an outline of what the interaction among different disciplines has to be in order to attain an adequate depth of the analysis of the building.

Another important contribution to the seismic protection of cultural heritage is represented by the Italian Legislative Decree "Codice dei Beni Culturali e del Paesaggio" [6]. Article 29 of this law, in fact, explicitly mentions the seismic protection requirements of cultural heritage and states seismic upgrade as a part of the restoration intervention. Furthermore, the code binds the government and the local authorities to provide for the safety and the conservation of historic buildings owned by them (Article 30).

As a matter of facts, recent seismic regulations for cultural heritage structures, (such as the Directive PCM and successive guidelines [7,8] in Italy) introduce and encourage the attainment of an appropriate "level of knowledge" which can be obtained solely through extensive tests and investigations. The level of knowledge must be appropriate for the type of analysis that the designer is carrying out. For instance, the Directive distinguishes between three different "levels of evaluation" for the analysis methods: LV1, LV2 and LV3. Whilst the lower level (LV1) is applied in the case of seismic assessment at territorial or urban scale on the entire protected architectural heritage, LV2 is applied when the building necessitate of local interventions. The latter level (LV3), and therefore most detailed, is required to be achieved in the case of intervention that modify the structural behaviour of the building or in the case that a seismic assessment of the building is required.

In detail, when dealing with a historic building, this must be done in several steps including: (a) identification of the structure; (b) geometric data gathering; (c) historical analysis; (d) survey of the materials and their state of preservation; (e) mechanical characterisation of the materials; (f) soil and foundation analysis; (g) monitoring. As for geometric survey, nowadays sophisticated and accurate techniques are available, including laser scanner, interferometry, thermography etc. Needless to say, the acquisition of knowledge meets with the difficulties normally associated with the assessment of existing structures that have to be preserved [9].

1.2 The path of knowledge: historic, geometric, structural and geotechnical aspects

Historical constructions show a large variety of building technologies, employed materials, stylistic canons and "rules of art" which change both in time and space. Most of them are monumental masterpieces, unique examples of their type whose characteristics impede a general classification and represent particular sources of weakness and vulnerability. Therefore, the analysis of a historic structure is not a trivial matter and it requires precise guidelines. As previously mentioned, Directive PCM 2008 [7] has introduced , conformingly to ISCARSAH guidelines, the so-called "path of knowledge": a serious of standardised actions and aspects which have to interact in order to achieve the desired level of knowledge of the building.

When dealing with historic building, even the identification of the structure is often a difficult task. In fact the first step introduced by the Directive is the distinction between the structure considered and the block where it may be inserted; this can be achieved via a preliminary survey of the building, the analysis of the elevations and the in plane and in elevation layout of the building.

The acquisition of knowledge must continue with the analysis of the functional evolution of the edifice. In this case a historic analysis is essential. In this way it is possible to gather information and understand the motivations related to the structural changes at which the building underwent. The analysis of the functional evolution may prove to be useful also in the design of the interventions, in order to set an intended use of the building compatible with its history.

1.2.1 Geometric data gathering

The knowledge of the structural geometry of a building derives from a geometric survey of the structure. Several survey techniques can be employed simultaneously, using the best fitted for each task. Among the principal survey techniques it is worth mentioning:

- Photogrammetry: it is the practice of determining the geometric properties of objects from photographic images. The photogrammetric process is safe; failures of draughtsmanship in photogrammetry can be recovered by reference to the photographic originals and there is always an option to use 3D output. Photogrammetry is a relatively high-cost process but the cost and other disadvantages are often outweighed by consistency, precision and reliability.
- Total station theodolite: it is an electronic theodolite integrated with an electronic distance meter to read slope distances from the instrument to a particular point. The measure can be really precise and it can appear to reduce costs in

comparison with photogrammetry, but it requires skilled operation and a surveyor who is aware of the data-selection demands of the project.
- 3D Laser scanner (LIDAR): it is an optical remote sensing technology that can measure the distance to target by illuminating the target using pulses from a laser. Laser scanners can capture huge numbers of precise points at great speed. The points are undifferentiated and rarely make a useful contribution to historic building survey practice unless a 3D model is specifically required.

As matter of facts, the geometric survey of the building often is conducted using the rule of thumb for geometric surveys finalised to structural assessments. In detail, it must refer to both the global geometry of the building and to all the constructive elements. The survey must also detect the connection with adjacent buildings which can prove to be relevant for what concerns the seismic behaviour of the structure. When dealing with masonry structures in particular, the structural elements to be analysed are vaults, floors, roofs (typology and truss), stairs and a special attention must be given to the localisation of niches, cavities, flues, closed openings and the foundation typology. In the case of models intended for seismic assessment the impost of horizontal retains, of arches and of vaults requires particular attention. It must also be pointed out that geometric models obtained from survey activities for mechanical representation of a structure should not be too detailed. In fact, mechanical models are computational intensive; therefore the geometric model must avoid adding useless data to the solution of the mechanical problem (such as non-structural elements or architectural details). In order to achieve this point, indirect measurement techniques, such as ground probing radar or thermography, may prove to be useful.

Moreover, a typical aspect regarding the geometric survey for structural assessment is the map cracking of the structure. The cracks must be classified in terms of geometry (extent, width) and the type of kinematic mechanism (detachment, rotation, sliding or out-of-plane displacement). In the case in point, historical maps of cracking can be particularly useful in order to carry out the anamnesis and to monitor the evolution of cracks in the time. Deformations are to be taken in account to: off plumbs, lowerings or bulges.

1.2.2 History of the structures

The collection of documental information is the first step. The history of a building will have to be unravelled and research may have to be made into site conditions and the building technology of the period or periods of construction. All other relevant historic and archival evidence should be found, digested and recorded, but there is a danger (especially with inexperienced persons) of doing too much research and analysis, treating it as an end in itself and thereby delaying decisions and necessary action [3]. In order to understand a building, one must know the story of its phased construction and the whole history of the ground upon which it stands, and have a record of any external environmental changes. Obtaining this information is not always simple. Archaeologically, ground levels tend to rise steadily as the dust and rubbish of generations build up.

The second step is the direct analysis of the building. In fact, the building methods, the materials used, the general style, the artistic composition, proportions and aesthetics principles give an approximate dating for many buildings. For instance, the tooling and cutting techniques are a rough indication of the date of masonry. Stamp marks may be found on tiles and bricks. Occasionally, documentation may be concealed within the walls or foundations.

As previously mentioned, historic analysis can prove to be very helpful in the case of buildings that underwent turbulent construction process or successive modifications. The technical construction history must highlight the succession of the realisation of different part of the fabric, in order to identify potential discontinuity or non-homogeneity zones. In fact, when dealing with ancient structures it is not rare to encounter buildings that have been under construction for centuries, this leading to very different construction techniques and qualities of material. Furthermore, historic analysis of seismic, accidental and other traumatic events may allow realising a predictive structural model concerning that particular phenomenon.

Finally, historic analysis can prove to be really useful in the case in which a particular traumatic event occurred during the lifetime of the building. In fact, in such a case, a qualitative behaviour model can be deduced from the response of the building to that particular event. As a matter of fact, a historic building may be seen as a full-scale experimental model [10], and the structural engineer must be able to read through the historic data and to interpret the building response.

1.2.3 Survey of constructive materials and state of conservation

The survey of constructive materials consists of the identification and classification of all materials used in the structure and building details. For instance, in the case of a masonry building, one has to pay attention to the quality and typology of masonry texture, including various geometric, assembly and mechanical characteristics of the component.

Typically, in the survey of constructive materials most of the state of conservation the information is hidden and often not even accessible with traditional techniques [11]. In fact historic buildings frequently exhibit elements with great artistic value such in the case of decorations, frescoes or plasters. Therefore non-invasive/non-destructive or indirect techniques are preferable for historic buildings. Among the most the following instruments and techniques are worth to be mentioned:

- Endoscope: it is an optical instrument (traditional or optical fibre) which allows visioning the internal condition of the masonry (presence of cavities and/or cracks, conservation state, stratigraphy). An opening of few millimetres is required to use the instrument.
- Sonic tomography: tomographic imaging is a computational technique which utilises an iterative method for processing data collected on the external surface in order to reproduce the internal structure of an object. The standard result from sonic tomography is a map of the velocity distribution on a plane section of the structure under investigation. The input to the method consists of the travel times taken by the elastic wave to cross the structure along several directions, which uniformly cover the section under investigation. The section of the masonry is marked by a mesh grid whose dimension is related to the expected resolution and to the distance between two subsequent transmission or receiving

points [12]. The calculation is carried out under the assumption that, in a non-uniform velocity field, sonic impulses do not necessarily propagate along straight lines but can follow curved lines according to Snell's law.

- Thermograph: it allows the survey of hidden structures (close openings or similar), of the map cracking of the structure and the monitoring, during the intervention phase, of the strengthening material.
- Cover meter: while it usually employed to locate rebars in concrete structures, it may be useful in the localisation of metallic elements such as metal hoops and bracings.
- Chemical analysis: useful for distinguish the chemical composition of mortars, grout and structural materials. Among the others, are worth to mention the X-ray scattering (which allows to identify the crystalline substance composing a material), the porosimetric analysis of the materials and, finally, the study of the material using the optical or electron microscope (allows determining the microstratigraphy and the granular interlock).

The survey of building details entails particular attention because of the influence which those details assume in the overall seismic behaviour of the structure. Hence, for what concerns building details one should carefully check the following aspects:

- The quality of the connection between vertical walls.
- The quality of the connection between vertical walls and horizontal elements (roofs, vaults…) and the presence of edge beams or other connection devices.
- Structurally efficient lintels over openings.
- Structurally efficient elements used to suppress thrust (buttresses or similar).
- Masonry typology (one layer, multiple layers, with or without transversal retains) and its constructive characteristics (brickwork, dry set masonry, regular, irregular …).

1.2.4 Mechanical characterisation of the materials

In addition to the previously mentioned type of analysis, aimed at classifying and detecting constructive materials and details, a mechanical characterisation of materials in a complete structural analysis is required.

In addition to visual inspections, a series of typical non-destructive and weakly-destructive tests are usually required [13,14]. In this context it is worth mentioning:

- Dynamic testing: the dynamic test of structures consists of examining the behaviour of the building under the effect of usual dynamic action such as wind, traffic or micro-earthquakes. A set of sensors is dislocated along the structure (usually accelerometers) in appropriate, sensible, locations. In this way the dynamic parameters of the structure are detected, such as frequencies, modal shapes and damping ratios. Dynamic testing is the only form of test which allows detecting the global response of the structure. This type of tests are easily applicable for structural health monitoring (see section §1.2.6).
- Schmidt hammer: it is a rather simple mechanical instrument, with a steel head. The hammer measures the rebound of a spring loaded mass impacting against the surface of the sample. Its rebound is dependent on the hardness of the

material and is measured by the test equipment. By reference to the conversion chart, the rebound value can be used to determine the compressive strength.

- Ultrasonic testing: in ultrasonic testing, very short ultrasonic pulse-waves with centre frequencies ranging from 0.1-15 MHz and occasionally up to 50 MHz are launched into materials to detect internal flaws or to characterise materials. The technique is also commonly used to determine the thickness of the test object. Ultrasonic testing is usually performed on steel structures, albeit it can be used with masonry, concrete or wood structures (though with less resolution).
- Penetration tests: there are several types of penetrometers available to characterise both mortars and bricks, see for instance [15]. Normally, the test consists in measuring the energy spent to create a hole with standard dimensions. The perforation energy is directly related with compressive strength of the material through standardised tables.

For what concerns the weakly-destructive tests, we can find:

- Flat-jack testing: it is a weakly-destructive way to evaluate the stress condition of in-situ masonry. Mortar joints are cut out and preloaded. Two methods of testing are utilised: measurement across one cut to evaluate acting stress and between two cuts to evaluate deformation or modulus of elasticity of the masonry wall. Before cutting the wall, original dimensions are taken between gage points. After data for both tests are obtained, the cuts are repointed with mortar.
- Pull-out tests: weakly-destructive tests. A steel bar is inserted in the masonry, and extracting the bar from the masonry it is possible to correlate the dimensions of the hole created and the force needed to extract the bar with the shear modulus.
- Shove tests: it is aimed to find the in-plane horizontal sliding resistance along a mortar bed. Usually the test consists in removing some bricks and placing a jack on one brick. Then, measuring the horizontal force and the displacement it is possible to determine the shear resistance of the mortar.

The last family of tests is the one of destructive tests. In this case part of the structure has to be locally demolished in order to collect undisturbed samples and in contrast with the other tests they are usually carried out in laboratory. There are three principal destructive tests that are performed on historic masonry:

- Compressive strength test.
- Shear strength test.
- Diagonal compressive test.

These tests are carried out on a masonry panel, and they allow determining the mechanical parameters related to the ultimate behaviour of the masonry [16]. Usually these tests are not suggested due to their invasive nature. In fact, they are often seen as a last resource only in the case that all the other tests produced results not completely reliable. Compatibly with conservation requirements, destructive tests should be conducted on more than one sample, due to the high uncertainties presents in the masonry.

1.2.5 Soil and foundation analysis

The first fundamental step in the soil and foundation analysis is the realisation of the stratigraphy and the classification of the terrains underneath the structure [17,18]. This can be done as follows:

- Undisturbed core samples.
- Standard Penetration Tests (SPT): The test uses a thick-walled sample tube, with standard dimensions. This is driven into the ground at the bottom of a borehole by blows from a slide standard hammer. The sample tube is driven 150 mm into the ground and then the number of blows needed for the tube to penetrate each 150 mm is recorded. The blow count provides an indication of the density of the ground, and it is used in many empirical geotechnical engineering formulae.

Moreover, it is fundamental to monitor (for at least one year) the level of the underground water table by means of an adequate net of piezometers.

As far as the mechanical characterisation of the soil is concerned, there are several type of tests available:

- Triaxial shear tests: it is a method for determining the shear strength of different type of soils. These tests are carried out in laboratory, and there are several variations, such as: consolidated drained, consolidated undrained, unconsolidated undrained. In a consolidated drained test the sample is consolidated and sheared in compression with drainage. The rate of axial deformation is kept constant, i.e. is strain controlled. In a consolidated undrained test the sample is not allowed to drain. The shear characteristics are measured under undrained conditions and the sample is assumed to be fully consolidated under the stresses applied that should be similar to the field conditions. In an unconsolidated undrained test the sample is not allowed to drain. The sample is compressed at a constant rate (strain-controlled).
- Downhole test: it is a method which determines soil stiffness properties by analysing direct compressional and shear waves along a borehole down to about 30 m. The aim of the downhole testing is to derive elastic rock properties such as Poisson's ratio or Young's modulus. Shear waves have to be generated at surface. A shear wave source (sledge hammer hit sidewise) is used at surface and a coupled receiver system is moved in the borehole. Travel times of the seismic waves are analysed and seismic velocity is calculated. Shear wave velocity can be transformed to soil stiffness. The measurements can be performed below and above the groundwater table [19].
- Crosshole test: the setup of the test is similar to downhole test. In this case there are two parallel boreholes and the source of shear waves moves along one of the two bores. Travel time of the seismic waves allows for a better characterisation of the soil dynamic parameters [19].
- Seismic refraction of shear horizontal waves (SH): The seismic refraction method is based on the measurement of the travel time of seismic waves refracted at the interfaces between subsurface layers of different velocity. Seismic energy is provided by a source ('shot') located on the surface. Energy radiates out from the shot point, either travelling directly through the upper layer (direct arrivals), or travelling down to and then laterally along higher velocity layers (refracted arrivals) before returning to the surface. This energy is detected on surface using a linear array of geophones. Observation of the travel-times of the refracted signals provides information on the depth profile of the refractor [19].

- Multichannel analysis of surface waves (MASW): similar to the previous, MASW is a seismic exploration method evaluating ground stiffness in 1-D, 2-D, and 3-D formats for various types of geotechnical engineering projects. The active MASW test needs a longitudinal receiver array with vertical oriented receivers and a constant spacing. A vertical impact source is required for excitation. Receivers can be geophones with low natural frequencies or accelerometers. If the receivers are assembled to a landstreamer, a huge amount of shot points can be measured in a short time. Small projects can be tackled with planted sensors. At least 12 receivers are necessary [19].

In the specific case of the dynamic characterisation of the soils, the phenomenon of the soil liquefaction assumes great importance. Again, SPT can be used to characterise the soils together with:

- Cone Penetration Tests: it is a standardised test similar to the SPT. The test method consists of pushing an instrumented cone, with the tip facing down, into the ground at a controlled rate (usually 2 cm/s). The resolution of the CPT in delineating stratigraphic layers is related to the size of the cone tip, with typical cone tips having a cross-sectional area of either 10 or 15 cm², corresponding to diameters of 3.6 and 4.4 cm.

For what concerns the foundation substrates one can use traditional techniques such inspection pits, trenches or probing. Also for this aim one can use geophysics techniques such as:

- Sonic tomography (see section §1.2.3)
- Electrical resistivity tomography: is a technique for imaging sub-surface structures from electrical measurements made at the surface, or by electrodes in one or more boreholes.
- Thermal tomography: thermal tomography is accomplished by analysing the surface temperature evolution of a component to be inspected following an initial thermal stimulation. Such stimulation can be achieved by applying pulse heating with duration ranging from a few milliseconds for high-conductivity materials to a few seconds for low-conductivity materials.

1.2.6 Structural health monitoring

Historical structures are inevitably subjected to ageing effects and require expensive maintenance acts and surveillance against accidental events in order to preserve them. A monitoring system has the purpose of recording the variations of some significant parameters such as crack openings, tilting, deformations, thermal variations, etc. Monitoring systems are used in different situations, among which: the recording of evolving phenomena such as soil settlements (the data allows to detect trend values, if the phenomenon is cyclic…), the control of the improvement in the behaviour of a structure under repair (or the appearance of undesired stresses or deformations), the control of the behaviour of the structures when there are work in progress in the neighbourhoods (diggings, realisation of tunnels, drillings).

In addition to traditional methods for structural monitoring, in the last three decades new experimental procedures have been developed in order to provide widespread and accurate information about the structural performance and integrity. Farrar and

Worden [20] define structural health monitoring (SHM) as a process which involves the periodic monitoring of a structure through measurements, the extraction of features symptomatic to the phenomena under investigation and their statistical analysis to determine the actual state of the system. A diagnostic monitoring system is therefore the result of the integration of several sensors, devices and auxiliary tools, like:

- a measurement system
- an acquisition system
- a data processing system
- a communication/warning system
- an identification/modelling system
- a decision making system.

Even if it is based on innovative measuring, analysing, modelling and communication techniques, SHM shares the same goals of traditional methods. In fact, the diagnostic monitoring can be considered as an extension of the well-established investigation practices since it integrates these novel technologies in a unique smart system. SHM tries to overcome the limitations of traditional visual inspections.

The traditional survey methods are affected by a large series of technical drawbacks. Visual inspections are generally performed with a periodicity too spaced in time which risks affecting their predictive nature. Moreover, they are neither exhaustive, because they do not allow to identify hidden defects or the invisible effects of an on-going damage process, nor objective, because the estimation is related to the subjective judgement of an expert who can be fallible. More specific and accurate non-destructive testing (NDT) techniques are carried out off-line and usually only after the damage has been located. This means that in the meanwhile an excessive level of deterioration could have been reached. Nevertheless, non-destructive estimations are performed in a local manner and so can provide useful information referred to a limited portion of the structure.

Modern diagnostic monitoring systems were born with the prerogative to overcome these limitations providing an exhaustive depiction of the structural health state and easing the plan of maintenance and restoring interventions. Among NDT techniques which can be easily implemented for online monitoring, we can cite:

- Vibration-based damage assessment: modal properties have been successfully used for the damage identification in real existing structures. Many issues require further investigation and still represent challenges that have to be undertaken. A new philosophy must be pursued, which is aware of the importance of a reasoned design of the monitoring system. It must integrate a sensors network which is capable of operating a continuous surveillance and providing reliable analyses based on different information sources [21]. The environmental and operating conditions variability must be taken into account too.
- Acoustic emissions: among the various non-destructive techniques, acoustic emission monitoring is arguably based on the simplest physical concepts, but is one of the most difficult techniques to practically implement. A formal definition of acoustic emission is often given as "the release of transient elastic waves produced by a rapid redistribution of stress in a material." The application of acoustic emission to non-destructive testing of materials typically takes place

between 100 kHz and 1 MHz, using tools specifically designed to work in the ultrasonic regime.
- Geometric control: techniques such as laser scanner or photogrammetry easily allows for online monitoring of the geometry of the building. Local control can be performed on particularly sensible points (such as strain gauges for crack openings or wall tilting) with ad hoc sensors.

When designing a SHM system, it is necessary to perform preventively an accurate analysis of the structural behaviour, in order to monitor the most expressive and sensitive parameters.

1.3 Safety assessment of the architectural heritage

Before undergoing any consideration on the structural safety of historic structures it is useful to point out something that may sounds obvious: old structures were not “designed” as we intend nowadays, but they were built using some “rule-of-the-thumb” such as geometric proportions, verbally handed down rules often guarded as secrets by builder guilds during the middle age. These rules developed by trial and error (e.g. several of the great medieval cathedral suffered failure before determining safe rules) and were modified through the centuries, and some of which were even incorporated in the first building codes and survived until the mid of twentieth century [22]. The more, due to higher risk acceptance, safety levels implicitly used when conceiving historic structures were considerably lower. Therefore, it is straightforward that historic buildings will or will not (mostly will not) achieve the level of safety required by modern building codes for those type of structures.

This said, peculiarities of safety assessment of historic structures may be classed into different categories, e.g.:

- needs to adapt structural safety requirements to conservation requirements (choice of the safety levels);
- needs to adapt structural the safety assessment to the maintenance strategy and to the temporal horizon of the intervention (choice of the nominal life of the intervention);
- geometrical and topological complexity (modelling requirements);
- mechanical response (mechanical and constitutive models).

1.3.1 Evolution of the safety levels

Concerning the structural safety assessment, in modern codes uncertainties in materials and actions are usually covered by safety factors that lead to the assumed safety level. This approach is viable as far as generalised costs are deemed to be acceptable to the community. In the case of architectural heritage buildings this approach would be inappropriate, because it could require very intrusive rehabilitation works, whose costs are of a cultural nature and cannot be generalised.

After these considerations, it is desirable to use a more flexible approach when dealing with historic buildings safety assessment in order to both guarantee safety for the users and reduce the intervention to the minimum possible. Therefore, in historic buildings, lower safety levels than in new buildings may be sometimes justified, because it is possible to diminish the risks related to the use of the building by restricting the access in some area of the building, or because of continuous or periodic monitoring programs etc. Anyway, the most important consideration regarding safety, probably, is that the usual partial factors used for new buildings, which take in account uncertainties related to strength of materials, can be greatly reduced if a the level of knowledge on the building justify that. Codes such as the Directive [7] in Italy explicitly introduces a "confidence factor" which is conventionally applied to the material strength side, though it actually is intended to cover also model uncertainties. In this case the greater is the level of knowledge the lower is the value of the "confidence factor".

1.3.2 Nominal life

With respect to common buildings or dwellings, monumental buildings are often seat of activities which requires very long design life. For instance, one may think about churches: most of them have been in service for centuries. In the case of an intervention on a cultural heritage building the designer has to choose the appropriate nominal life in order to determine the partial safety coefficients to apply. As previously stated, the nominal life of the building can be very long but this condition cannot be always satisfied. In fact, in order to achieve very long service life it is possible that massive interventions on the building are required. Cultural heritage buildings are so peculiar that one may also decide to do not intervene or to do only slight interventions that allow achieving a design life of few decades. The idea is preserving the structure for a few decades, while waiting for less invasive technologies. Future technologies are in fact expected to guarantee longer design life for the building without being too much intrusive.

1.3.3 Modelling

The structural assessment of heritage buildings, as defined by the CIB (Conseil International du Bâtiment) commission W023 [23], is the evaluation of the collected data related to the safety of the building, with the objective of deciding whether its structural safety is sufficient, or not. It is an essential phase of an intervention of rehabilitation, because it is when it is decided if measures are necessary and to what extent. Structural engineers, when assessing the reliability of an existing structure, must take into account various important facts that may affect their calculations: the physical presence and condition of the building; it is there, it has performed its functions for so many years, it may show such and such signs of 'fair wear and tear' and it may or may not show signs of past or present structural distress. If the calculations show that the building should have fallen down and the building still stands, obviously the calculations or the assumptions at their base are wrong. Nonetheless, especially when dealing with structures in seismically active areas, phenomena such as damage accumulation must be taken in account. When dealing with historic structures modelling one has to keep in mind few basilar concepts:

- The structural system may turn out to be quite complex, for instance several unorthodox but perfectly effective load-carrying assemblies may provide multiple load paths. Therefore, the structural engineer has to be ready to account more sophisticated model (e.g. non-linear models) in order to do not neglect an important part of the structural resistance.

- The structural members are there and their dimensions can, in principle, all be verified (although there may be difficulties in practice) and the actual strengths of the materials, in situ, are there and can, in principle, be tested. In fact, as already mentioned, the link between safety and knowledge indexes is tight.
- Lack of knowledge about the events to which the building has been subjected in the past.

Modelling, in particular, constitutes an important focus of this thesis. For instance, techniques such as structural modal analysis together with model updating are becoming nowadays the standard tools used to characterise the global dynamic behaviour of the structure. Several notable examples of structural modal analysis on churches with oval domes are analysed in chapter 4. Furthermore, as it has been stressed previously, the structural behaviour of architectural heritage buildings may be particularly complex, therefore complex non-linear models may prove to be useful in the framework of seismic assessment and retrofitting. A review of the principal non-linear and dynamic models suitable for masonries will be made in chapter 6, introducing also a new developed hysteretic degrading model for multi-degree of freedom systems allowing for pinching effect. Also the non-linear identification problem will be deeply analysed with a review of the principal non-linear identification algorithm with particular emphasis on instantaneous and on-line methods. Finally, the case of an experimental model of a masonry arch bridge will be analysed, showing how with simple dynamic tests (i.e. shaker tests) weak non-linear behaviours are helpful in the characterisation of non-linear models of the global structure.

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