CHAPTER 6

Monitoring of long-term damage in long-span masonry constructions

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6.1 Introduction

Monitoring is a key activity in the study of ancient structures, providing reliable insight into its present condition and the significance and progress of damage. Monitoring can contribute to identifying and evaluating existing damage and help determine which active physical phenomena are involved in its generation. However, which monitoring procedures and strategies are to be considered depends highly on the type of processes experienced by the structure. Four different phenomena – large deformation, tensile damage, compressive damage and large-scale fragmentation – are considered and discussed with regard to monitoring possibilities for measuring and characterizing them. Not only the structural effects (rotations, displacements, crack openings, etc.), but also the actions experienced by the construction (wind, earthquake, thermal cycles, soil settlements, etc.) are to be measured together over a sufficiently long period comprising several years. The use of a detailed numerical model may, in most cases, allow accurate physical and quantitative interpretation of the information obtained.

6.2 Monitoring and long-term damage

Large deformation and damage are observed in almost all ancient masonry constructions. Structures – and particularly masonry structures – are not fully inert
and static objects, but living entities which experience active processes throughout their entire life span. Such processes, related to construction effects, material decay, environmental actions and extraordinary actions (such as earthquakes) manifest in deformation and damage which develop in the long term.

Monitoring can provide a certain degree of insight into the condition of the structure and the possible presence of active processes associated with incremental damage. However, the results of a monitoring programme are only fully comprehensible when analysed in the light of the historical nature of the construction or, in other words, when its results are interpreted as an evidence of processes which act and evolve over a deep-time or historical scale.

Monitoring can be understood as the attempt to open a small window in the domain of time, over a response that develops over centuries or millennia. The challenge, thus, is to develop possible hypotheses or conclusions on the condition of the structure and the phenomena acting upon it, based on just a small, almost infinitesimal, patch or picture of the variation of the structural response in the time domain (Fig. 6.1).

Deformation and damage develop as a superimposition of different phenomena, some of which act persistently, some cyclically or periodically, others occurring only on isolated occasions. The effects of these different actions result in the final response of the structure. Obtaining realistic conclusions through a monitoring programme requires the ability to unravel the registered information into its different components, so that they can be related to different actions or phenomena. In particular, the information obtained can include an assortment of reversible (cyclic) components mixed with the long-term accumulation of irreversible components. Obtaining meaningful hints related to long-term damage requires the ability to

Figure 6.1: Monitoring as a window over historical time.
distinguish the unidirectional, accumulative trends from the totality of data registered during the monitored period (Fig. 6.2).

Characterizing long-term damage is a challenging task due to the slowness of the processes involved and the fact that they may be masked by more apparent, short-term variations caused by present environmental actions. Both the viability of characterizing long-term damage by monitoring and the possible strategies that can be used to attain it are discussed in the following paragraphs.

6.3 Role of monitoring in the study of ancient constructions

Monitoring provides quantitative information on the response of the structure across a short, recent period of time. Monitoring may specifically allow recognition of incremental processes over a term reasonable for engineering purposes, and thus provide information useful for the study and restoration of ancient constructions.

Both structural analysis and monitoring deal with quantities and thus allow direct comparison. Monitoring results can be used in combination with a numerical model, provided that not only the parameters associated with the response (deformations, displacements, rotations, vibrations, etc.) are measured, but also those characterizing actions (environmental thermal effects, ground motion, etc.).

The role of monitoring in the study of an ancient construction is better understood in the light of the application of scientific methodology based on a multidisciplinary approach. Experts involved in the study of historical structures of the architectural heritage base their research on a combined set of activities, including historical investigation, inspection and structural modelling. Monitoring constitutes
Learning from Failure

a fourth complementary activity intimately related to the rest (Fig. 6.3); used alongside the other activities, monitoring contributes to the successful application of the scientific method in the study of ancient constructions.

Applying the scientific method first requires adopting a set of hypotheses and, second, the use of available empirical evidence to prove them. Some of the activities mentioned (specifically, structural modelling) are related to the first stage of the process, namely, the adoption of hypotheses. The structural model is the receptacle of the hypotheses on the physical and mechanical nature of the construction. History, inspection and monitoring are activities intended to provide the empirical evidence needed to validate these hypotheses or to correct or improve them to a satisfactory extent.

More specifically, monitoring produces quantitative measurements which allow comparison to the numerical predictions of the structural model. System identification can be undertaken to adjust the material properties or morphological features of the model. An updated or calibrated model, with enhanced predictive capacity, is thus obtained.

6.4 Monitoring: methodology and requirements

6.4.1 Technology

Nowadays a variety of sensors and associated equipment is available for measuring structural movements (including absolute or relative displacements, rotations, settlements or accelerations) and environmental parameters such as internal or external temperatures, humidity or wind force and direction. Electronic devices and sophisticated digitizers provide reliable automatic data collection systems and fast and remote recovery of large amounts of data.

Figure 6.3: Activities involved in the study of an ancient construction and their role in the application of the scientific method. The structural model is the receptacle of the hypothesis to be validated by the empirical evidence provided by historical research, inspection and monitoring.
Removable mechanical extensometers or electrical crack gauges are commonly used to measure relative movements between crack surfaces. Not only is it the opening of cracks which is meaningful; attention must also be paid to the relative movements tangent to the crack faces; three different extensometers, placed perpendicularly, can be used to measure possible movements between crack faces.

Absolute horizontal movements of vertical members can be registered by means of direct pendulums with measuring systems based on telecoordinometers. Relative horizontal movements can be measured more inexpensively and easily by means of long-base extensometers. Rotations of either vertical or horizontal elements can be measured by fixed or removable clinometers.

Differential settlements can be measured by levemetric vessels where the level of the liquid is registered by an electrical transducer. Settlement gauges and piezometers are used to analyse the deformation of the soil foundation in relation to the water table variations.

Air temperature and the temperature gradient across the wall thickness can be measured by thermal-gauges fitted inside small diameter boreholes drilled in the walls.

A monitoring programme must be laid-out in accordance with a precise definition of its objectives and scope. The design of a monitoring system must bear in mind conditions related to the environment (protection, accessibility, etc.), the necessary accuracy (of instruments and also of the entire system), system reliability (possibility of self-diagnosis, redundancy, etc.), flexibility (easy substitution and recalibration of sensors) and the maintenance needs [1].

More information of the technological alternatives and their application to specific studies can be found in [1–4].

6.4.2 Distinction between dynamic and static monitoring

The monitoring system must be adequately designed to satisfy its intended purpose. Rather than universal, all-purpose systems, more specialized systems aimed at specific targets may be more efficient and also less expensive.

In particular, a distinction can be made between static monitoring, aimed at the continuous measurement of gradual, slow-varying parameters over a long period, and dynamic monitoring, aimed at the intensive measurement of sudden variations caused by isolated and short-lived actions (such as micro-tremors or hurricanes), over a brief interval of time (Fig. 6.4).

Static monitoring requires the regular measurement of small variations over lengthy periods comprising several years. In principle, there is no need to register measurements at a very high frequency. A few measurements per minute, or even per hour, may be enough to characterize the variations caused by daily climatic cycles or other periodical or gradual effects.

Dynamic monitoring is intended to characterize the dynamic or seismic response of the building. It can be carried out by means of dynamic tests measuring the motion of the building caused by forced or natural vibration.
Another possibility is to install a fixed system capable of self-activating and capturing the motion of the structure at every occurrence of a micro-tremor or any other significant vibration source above a certain threshold.

Dynamic monitoring requires the ability to capture a very dense amount of information during a very short interval. Thousands of readings per minute (for instance, 200 readings per second) may be needed to adequately characterize the oscillation of the structure caused by an external source of vibration, and to later carry out the signal processing leading to the determination of significant dynamic properties such as the shapes of the vibration modes, frequencies and damping. High sensitivity sensors are needed when measuring natural vibrations caused by traffic, wind or micro-tremors. Fixed dynamic monitoring may provide valuable information specifically related to the response of the structure during micro-tremors or even significant earthquakes. Long-term variations of damage are also better measured by means of a fixed system left active over a long period. Depending on the chosen threshold, a fixed dynamic system may require significant data storage capacity (or alternatively, frequent information transfer from data-loggers to other storage media). Meaningful information has been recorded using this type of systems for several ancient towers. In the case of the Torrazzo (civic tower) of Cremona, the monitoring system allowed the detection of wind-forced oscillations due to vortex shedding excitation [5].

The continuous capture of dynamic motion over long periods, covering several months or even years, is also possible thanks to more recent technological developments concerning dynamic data acquisition. Modern portable instruments, equipped with large storage capacity (tens or hundreds of Gb), allow the capture of continuous and dense information over long periods of time without having to
set up an activating threshold. This last possibility, used in the dynamic monitoring of Mallorca Cathedral (Section 6.7.1), is particularly useful when the amplitude of the seismic motion expectable in the short term is very low and similar in magnitude to the effects of wind or traffic; in these cases, it may be difficult or even impossible to set a threshold that would allow the specific capture of seismic motion. Linking the equipment to GPS time, by means of a GPS antenna, allows the information collected to be synchronized with seismic events registered at seismic stations. This specifically enables information related to meaningful seismic episodes to be extracted from the entire volume of data registered over a long period.

System identification on data recorded during low-intensity earthquakes has been successfully used to characterize the dynamic response and the effect of soil structure interaction in the case of Hagia Sophia in Istanbul [6]. Non-linear behaviour was identified even at very low response levels; this non-linearity can be related to existing damage and might become more evident for large intensities.

Dynamic monitoring provides the only way to experimentally measure parameters related to the global structural behaviour of the historical construction. However, its real contribution to a clear understanding of structural damage propagation is strongly limited due to several causes. The parameters related to the dynamic response of the structure behave always in the non-linear range (at least those of interest for damage detection) and are highly sensitive to the local or global material properties and the support conditions. Furthermore, the dynamic response of the structure may be highly influenced by the soil–structure interaction. No theoretical or numerical tools are yet available to simulate such effects in an accurate way, and thus to assist in the interpretation of the influence and variation of such parameters. However, dynamic monitoring can be very useful in carrying out model calibration or sensitivity analyses, especially when combined with complementary information on other experimentally measured ‘static’ parameters (local Young modulus, local stresses, via flat-jack measurements).

6.4.3 Requirements

Besides the technical challenges posed by the need to acquire information reliably, technicians also face the need to interpret results adequately. In order to ensure the correct interpretation of measurements, a series of requirements should be considered:

1. Before or while undertaking a monitoring programme, detailed characterization of the building is needed. Historical investigation and geometrical and morphological surveys are needed to allow correct interpretation of the monitoring output. Monitoring will normally be accompanied (or preceded) by characterization based on non-destructive or quasi non-destructive tests aimed at determining the internal morphology of the structural members and the mechanical properties of the materials. Damage patterns (particularly major cracks) must also be recognized and carefully documented. The foundation (soil and structure) must be
characterized carefully since it may significantly influence the motion and deformations to be monitored.

2. Specific and actually monitorable targets should be selected, adequately related to the physical phenomena to be identified or analysed. In particular, long-term damage will require the monitoring of effects such as crack opening and deformation. Characterizing different phenomena (soil settlements, deformations caused by thermal cycles, mechanical deformations caused by loads, etc.) requires specific monitoring strategies.

3. Actions affecting the construction are to be monitored in combination with its structural response. This normally requires monitoring of climatic environmental parameters (temperature and humidity), wind parameters (speed and direction), seismic ground motion and soil settlements, among others. The obvious aim is to correlate causes (actions) and effects (structural response). Furthermore, the varying effect on the structure of different actions can only be extracted accurately from the overall response if the actions themselves have been accurately measured and characterized.

4. Even if climatic actions are not the target they will have to be characterized, since their impact on the structure is normally very prominent and may alter or even mask deformations caused by other possible effects, such as those specifically linked to long-term damage. In this case, characterizing climatic actions is necessary in order to determine and cancel out the climatic component in the monitoring output. In order to characterize incremental, long-term processes, monitoring must be designed to allow a clear distinction between the reversible or cyclic components of the parameters measured, on the one hand, and their irreversible, cumulative components on the other.

5. An accurate numerical model must be available to interpret the results and correlate the causes identified (measurements related to actions) with their effects (deformations or displacements measured at different critical points of the building) in light of hypotheses on the configuration and condition of the structure. Characterizing the action in the time domain will later allow its numerical simulation and comparison between the numerical prediction and the actual response measured. An identification process can then be carried out by adequately modifying such hypotheses until a satisfactory coincidence is attained between the numerical predictions and the measurements.

6. Monitoring must be carried out over a period long enough to cover the entire duration of the cyclic actions at work; since annual variations in temperature must be considered in all cases, the minimum acceptable period is a complete year. Additional years will be of value to confirm the tendencies observed and appraise their possible long-term evolution. In fact, a period of four years is a more reasonable minimum, since it allows confirmation of tendencies and detection of anomalous, local (in time) measurements produced by extraordinary actions or alterations in the monitoring system itself.

7. In order to provide meaningful information with regard to the monitoring target, critical points of the structure must be selected. Prior numerical simulation may help determine the optimal configuration and location points. Normally, the
Long-term Damage in Long-Span Masonry Constructions

Most adequate points to install sensors will be those showing comparatively large or even maximum displacement.

8. The global nature of structural response must be taken into account while designing the monitoring strategy or when interpreting its results. Monitoring points should not be chosen individually or based on local considerations, but according to a strategy involving meaningful structural parts or even the entire structure.

9. Moreover, the monitoring system must be designed to allow redundant measurement of related effects, allowing results to be interpreted more consistently and soundly. For instance, displacements or rotations of a façade experiencing a gradual out-of-plumb can be measured in combination with related crack openings experienced at the junction of the façade with other walls.

6.5 Measuring damage and deformation related to historical or long-term processes

6.5.1 Monitoring and long-term damage

Long-term processes may cause damage to manifest in different ways. Some of the most significant structural disorders observed are (1) overall large deformations, (2) cracks in elements subject to tension, (3) cracking or crushing in elements subjected to compression and (4) large cracks causing separation between different structural components or significant portions of the building (fragmentation). The following paragraphs consider these types of disorders and how monitoring might contribute to their characterization.

6.5.2 Structural deformation

Large deformations affecting piers, buttresses and other structural components are commonly observed in ancient constructions (Fig. 6.5). In most buildings, deformation has been determined by many different actions occurring both during the construction process and the later historical life of the building. Numerical approaches may normally provide fair qualitative simulations of the deformed shape, but they fail at predicting, even roughly, the absolute values of deformations and displacements. In many cases, the real deformation is one or more orders of magnitude superior to those predicted by instantaneous or short-term numerical analysis; this is so even when non-linear material or geometrical effects, or even a conventional treatment of primary creep, are considered.

Important effects related to deformation can be ascribed to construction. On the one hand, construction of historical structures spanned large periods of time which, in turn, included lengthy stages during which the structure was subject to provisional support conditions; during these intermediate phases, the structure was forced to develop resisting mechanisms not entirely consistent with its final arrangement and design. Significant deformation could be expected during these phases, due to the
Learning from Failure

more deformable or mobile character of the incomplete substructures and provisional wooden, iron or masonry buttressing systems.

Even after structure completion, creep will tend to partially amplify the deformation acquired at intermediate construction phases, causing both a significant increase of deformation and possible stress redistributions, eventually leading to cracking due to internal deformation incompatibility.

Actions occurring after the construction process may have also contributed very significantly to the continuous increase of deformation. Extraordinary actions such as large earthquakes may produce important lesions and irreversible deformations. Low-intensity earthquakes or repeated occurrences of hurricane-force winds may act cumulatively to cause ever-increasing damage and deformation. The individual effect of daily or annual thermal cycles is minimal; however, a certain, irreversible increment of deformation may take place after each cycle, thus contributing to a significant increase in overall deformation over very long periods of time. It must be noted that the effects of cyclic actions do not dissipate with time, but may increase and accelerate as the construction becomes increasingly damaged.

Damage affecting the construction, which in normal circumstances always increases due both to the aforementioned and other possible causes, will, in turn, enlarge the sensitivity of the construction towards a variety of actions. This situation contributes to constantly increasing (never-mitigating) stiffness reduction and long-term deformation, or even to an acceleration of long-term deformation, which, in the worst cases, can lead to the collapse of the construction. Since gravity is the most persistent action, it is not strange that such constant increases of flexibility

Figure 6.5: Küçük Ayasofya Mosque in İstanbul. Example of large deformation of an ancient building. Condition of the real construction and predicted deformed shape (m) [7].
and deformation may manifest as a monotonic, non-asymptotic amplification of the initial deformed shape due to dead load. Generally speaking, all historical actions may contribute towards amplifying the initial dead load deformation to a lesser or greater extent. Owing to this, the progress of structure deformation must generally be registered, regardless of the type of damage or physical phenomenon to be characterized. However, the progress of overall deformation of the structure alone can hardly provide enough information to determine the cause or phenomenon generating the progress of damage. Other possible parameters or effects (such as crack opening) must also be measured simultaneously for identification of the involved phenomenon to be more conclusive.

6.5.3 Tensile damage in arches and vaults

Tensile damage in arches and vaults will manifest in cracking and deformation. As is well known, the tensile strength of masonry is almost negligible, meaning that a certain amount of cracking may easily develop in members subject to tension effects or eccentric loading. In fact, masonry may initially show significant tensile strength. The presence of a certain amount of tensile strength may help understand the stability for a limited period of time of some intermediate construction configurations. However, tensile strength is easily lost in the medium or the long term due to a variety of effects (settlements, vibrations, deformation cycles, etc.) causing micro-cracking or cracking in the mortar and the stone and the separation of both along their interface. Viable ancient buildings were designed in such a way that equilibrium did not require any tensile strength at their final construction configuration.

This type of cracking, which is not normally too meaningful, is not necessarily linked to long-term damaging processes caused by the decay of the material itself. Severe tensile effects – such as severe cracks or large deformation – are likely to be caused by other indirect effects appearing at the buttressing elements or at the foundation. For instance, differential soil settlements, or the decay of the material in piers, buttresses or footings, may produce a loss in the capacity of such elements to properly counter-balance the thrust of arches or vaults, which in turn will experience cracks and openings between voussoirs associated with plastic hinges (Fig. 6.6). Monitoring these cracks, however, will be of use for characterizing the mobility of the structure and the overall progress of damage. Due to the perceptible deformation of the elements and measurable opening of the cracks, this type of effects can be easily monitored.

6.5.4 Damage of compressed members

The authors have observed frequent vertical cracking in the piers of long-span buildings. Vertical cracks and related lesions in piers are particularly frequent in Gothic cathedrals and churches. In many cases, severe cracking, spalling or material bursting has appeared in spite of the moderate average compressive stress caused by gravity load (Fig. 6.7a).
As is well known, cracks parallel to the direction of applied compression may appear in materials such as concrete or stone, even for stresses significantly lower than the compressive strength. In tests performed at the Laboratory of Structural Technology of the Universitat Politècnica de Catalunya on specimens made of stacked sandstone blocks with 1 cm mortar joints [8], longitudinal cracks appeared for an applied stress ranging from 30 to 60% of the compression strength of the specimen. As expected, specimens made of larger units showed a greater tendency to crack under moderate compression. The lowest ratios between cracking stresses and compression strength (30%) were obtained for specimens made of large blocks (40 × 20 × 20 cm), while the largest ratios (60%) were obtained for specimens with the smallest units (20 × 10 × 10 cm, placed horizontally in both cases).

In order to understand the actual existing damage, long-term phenomena leading to progressive deterioration during historical periods must be accounted for. As observed apropos of the study of recent collapses [9, 10], the long-term effect of creep under constant stress may induce significant, cumulative damage in rock-like materials. As mentioned by Binda et al., damage accumulation (eventually leading to collapse) may occur for stress values significantly lower than the normal strength obtained by standard monotonic compression tests. The same authors found that such phenomena could start at 40–50% of normal strength value. Actions other than dead load may also contribute to long-term damage and couple synergistically with the effect of creep.

As previously mentioned, the construction process (and the construction techniques used) may induce mid-term or long-term effects. Aspects such as the construction sequence, the duration of the construction, or the use and removal of scaffoldings and other auxiliary elements, may influence the later behaviour of the overall building and even cause deferred lesions or other structural disorders.
A specific aspect could be the use of small wooden wedges as a device to keep stone units in position while the mortar had not yet hardened, which in some cases (for instance, in Mallorca Cathedral, Spain) produced high stress concentrations leading to a deterioration of the external face of the stone (Fig. 6.8a) and causing cracks. Past human actions may be very significant in causing additional damage. In some cases, large operations undertaken during the life of the construction for purposes unrelated to the structure may cause significant alterations in the geometry of the piers or other structural members (such as the ‘thinning’ of piers in Tarazona Cathedral, Spain, to make space for a wooden choir, Fig. 6.7b); in other

Figure 6.7: Deterioration of piers in Tarazona Cathedral, Spain. (a) Longitudinal cracks and bursting of compressed material at the springing of diagonal arches (b) Artificial thinning of piers. (c) Coupled mechanical and chemical deterioration.
Learning from Failure

cases, small, apparently inoffensive actions, may reveal to be potentially damaging after some time (such as the insertion of iron or wooden devices in compressed members for ornamental or liturgical purposes, Fig. 6.8b). On the other hand, lack of maintenance or inadequate historical repairs may also contribute to an accelerated deterioration of the building. Initially minor construction or material defects – such as the loss of a portion of mortar, in Fig. 6.8c – may cause cracks to initiate in zones subjected to significant compression.

The repeated occurrence of extraordinary actions, such as earthquakes or hurricane-force winds, even if moderate in intensity, also contributes with irreversible,
cumulative effects. Such actions may cause dramatic increases in the eccentricity of the applied vertical forces at the base of the piers; in turn, this will cause additional vertical cracking or other effects associated with increased maximum compression stresses.

Stone or mortar decay due to chemical attack (as observed at the base of the piers of Tarazona Cathedral, Fig. 6.7c), may couple synergistically with mechanical effects related to sustained compression forces and thus cause accelerated deterioration.

Cracks in piers or compressed members may be also caused when large blocks accommodate to deformation or irregularities in mortar joints. In this case, such cracks are not necessarily related to actual long-term and cumulative damaging processes. Normally, this type of crack will affect individual blocks and will not propagate causing long discontinuities along the height of the member. Monitoring will allow distinguishing between an already stabilized effect, caused by this type of accommodation, or a more severe, destabilized phenomenon compromising the safety of the construction.

Conversely, a truly concerning effect is the development of separated wedges in compressed zones, which in turn produce a reduction of the available resisting section of the members (Fig. 6.8d). This effect usually starts in less-confined parts, in the corners of a rectangular or polygonal pier for example.

Measuring variations due to long-term damage in compressed members is intrinsically difficult, due to the very small magnitude of associated movements or crack openings. In fact, such movements may be far smaller than those caused by climatic actions, and thus remain masked. Measuring this type of damage may require very long monitoring periods (much longer than the 4-year minimum previously mentioned) and highly sensitive equipment. A sufficiently long monitoring period may be the only possibility of telling them apart from the entire measurements. Furthermore, certain forms of damage (such as cracks and material losses) may develop suddenly, with almost no previous indication, making anticipated symptomatic detection through monitoring very difficult.

6.5.5 Fragmentation

Another common type of damage, not necessarily related to long-term decay, consists of the division (or fragmentation) of the structure into large structural parts or substructures. Similarly, division owing to large cracks affecting the entire contact between structural members or parts of large members is not uncommon in historical constructions. The cause for this type of response can be found in different phenomena (soil settlements, thermal contraction or dilation, construction effects, etc.). In many cases, the safety of the structure is barely affected because the resulting structural parts are self-stable.

Soil settlements are a very frequent cause for fragmentation. They can induce the generation of new cracks, enlargement of existing ones or opening of construction joints. The process may stabilize whenever the divided structure becomes cinematically compatible with the settlements.
Similar effects may be caused by cyclic winter contractions of the structure. In this case cracks or separation planes act as a contraction joint. In Mallorca Cathedral, wide discontinuities can be observed between some of the transverse arches and the vaults of the nave (Fig. 6.9a). Unlike soil settlements, which tend to mitigate with time as the soil consolidates, thermal cycles act continuously and may cause indefinite cumulative damage.

Cracks or separation planes, acting as expansion or settlement joints, may easily develop starting at weak planes generated during construction itself. In some ancient buildings, construction joints were finished by interlocking stone units without filling the joints with mortar (Fig. 6.9b).

6.6 Structural modelling and monitoring

Structural modelling is of extreme interest to enhancing the possibilities and understanding provided by monitoring. In fact, monitoring fulfills its overall potential when used in combination with a model of the structural response. Structural analysis is useful both when designing a monitoring system and when later interpreting the information collected.

On the one hand, a prior structural analysis may contribute to better define significant aspects of the monitoring system. 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.

On the other hand, and more importantly, a numerical model will help interpret monitoring results by comparing them with the predictions of a numerical analysis. This comparison may allow, among other aspects, a more quantitative (or absolute) understanding of the variations measured by sensors. For this purpose, it is essential, as mentioned in Section 6.4.3, not only to characterize the structural response but also the main actions that have affected 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 have acted on the structure and generated meaningful measurements. The numerical model can be used to produce a prediction of the response of the structure when subjected to one or more of the actions measured. Comparison with the response actually measured will provide criteria for identifying some of the structural or material properties (in particular, stiffness of materials or structural members) and for improved calibration of the model.

In the case of studies addressing long-term phenomena (such as long-term damage), the numerical model needs to have special capabilities in order to allow the simulation of historical processes. Ideally, the numerical model should be capable of simulating most of the present or historical actions that have affected the construction; it should also allow sequential analysis in order to simulate the construction process and the possible structural alterations or repairs that followed. Specific constitutive equations for long-term creep of masonry or stone-like materials, such as the one proposed by Papa and Taliercio [9], are of utmost importance for the purpose here referred. As shown in other chapters of the present book, significant efforts are presently being made for the experimental characterization and numerical modelling of long-term creep-induced damage.

6.7 Case studies

6.7.1 Dynamic monitoring of Mallorca Cathedral

The main space of Mallorca Cathedral, built between 1350 and 1601, consists of a three-nave building, 77 m long and 35 m wide, comprising seven bays with central and lateral vaults spanning 19.9 m and 8.75 m respectively (Fig. 6.10). The height of the central vaults at crown reaches 44 m. The central vaults are sustained on octagonal piers with circumscribed diameters of 1.6 and 1.7 m. The remarkable slenderness of the piers, rising up 22.7 m to the springings of the lateral vaults, contributes towards generating the impression of an immense, diaphanous inner space. The construction has reached our days in a satisfactory state of conservation. However, some structural disorders can be observed, including (1) significant deformations affecting the piers; (2) vertical cracks at the base of some of the piers, sometimes forming surface wedges partially expelled from the core of the
Learning from Failure

pier (Fig. 6.8d); (3) wide cracks developed throughout the contact lines between transverse arches and vaults (Fig. 6.9a) and (4) significant deformations affecting the flying arches.

A detail of the structure, intended to determine the causes and significance of the mentioned lesions and to provide criteria for its future conservation, is now being carried out. The study, funded by the Spanish Ministry of Culture, includes historical research, detailed geometric surveillance, non-destructive testing and structural analysis. Mallorca Cathedral is also one of the case studies considered for the EU–India cooperation project for improving the Seismic Resistance of Cultural Buildings (contract ALA/95/23/2003/077-122) funded by the EC. As part of the activities envisaged within this last project, a monitoring system aimed at characterizing dynamic response has been also implemented.

The system consists of a 24-bit resolution dynamic acquisitor connected to two triaxial accelerometers, one of which has been installed on top of a vault of the central nave. The acquisitor’s clock is disciplined to GPS time by means of a GPS antenna (Fig. 6.11). Among the different strategies mentioned in Section 6.4.2, continuous dynamic measurement has been preferred to allow the capture of low-intensity oscillations. The system, with a sensitivity of $10^{-6}$g, allows continuous acquisition at 100 sps and 600-plus days of storage. Meaningful seismic episodes are detected thanks to information provided by the nearest seismological station, ETO 8 in Mallorca. Information corresponding to any interval measured in GPS

Figure 6.10: Interior of Mallorca Cathedral.
time can be then easily extracted from the entire data. The system was installed during April 2005.

Preliminary results, which provide some hints as to the dynamic response of the structure, are already available. The effect of the Northern Chile earthquake of 13 June 2005, produced measurable effects on the building. Figure 6.12 shows the variation of accelerations in the time domain and the resulting spectral distribution for two different time intervals (windows) retrieved, for both the ETO 8 seismic station in Mallorca and the accelerometer placed above one of the cathedral vaults. Note that, due to the great distance from the epicentre, the building was mostly subjected to low-frequency oscillations. In spite of this, the building experienced a certain excitation and its fundamental vibration mode can be clearly distinguished in the peak corresponding to 1.68 Hz in the spectral diagrams. Both windows produced similar results. The acceleration referred is that produced in the longitudinal direction of the building, which showed the largest amplitude due to the fragmentation caused by the cracks between transverse arches and vaults (Fig. 6.9a).

The mentioned frequency matches the measure previously obtained by means of a dynamic test carried out at the level of the vaults, in April 2005, during which traffic and wind vibrations were measured. In turn, another dynamic test, based on Nakamura’s (or H/V relationship) technique [11] and executed at the ground surface, yielded a soil natural frequency of 2.0 Hz. The corresponding peak can also be recognized in Fig. 6.12d (right). It must be noted that the building is founded over strata composed of quaternary sediments to a depth of about 80 m over the bed rock and that certain concern exists over the possible dynamic amplification effects that could be caused by such strata.

The analysis of additional information generated in the occasion of future earthquakes may provide larger and more accurate information on the dynamic response of the building. This information will be used, among other purposes, to calibrate a detailed numerical model of the building.
Figure 6.12: Effect of a long-distance earthquake on Mallorca Cathedral: (a) accelerogram captured in nearby seismic station and (b) at the vaults of the structure; (c) corresponding spectral diagrams and (d) transference functions. Left and right: windows corresponding to two different time intervals.
6.7.2 S. Maria Assunta Cathedral, Reggio Emilia, Italy

The S. Maria Assunta Cathedral in Reggio Emilia, Italy, is one of the most important religious buildings of the city. Built on a previous Roman construction around 857 AD, it underwent several style remodellings during the thirteenth, fifteenth, sixteenth and seventeenth centuries. The Cathedral presents a Latin cross plan with three naves and transept; the crypt is placed below the presbytery. The building ends in three semicircular apses, the central longer than the two lateral ones (Figs 6.13 and 6.14).

A static monitoring system was positioned to evaluate a settlement phenomenon affecting one of the pillars sustaining the massive cupola at the crossing between the main nave and the transept. Such settlement, bringing visible deformations on the horizontal structures connected to the pillar (see Fig. 6.15), is a ‘historical’ phenomenon, in the sense that it was noticed since long time, but it seemed to worsen in the last period, so it was decided to control its possible evolution.

Figure 6.13: View of the Cathedral’s façade.
The acquisition system is composed of 10 long base cable extensometers, 13 electric extensometers, 2 multi-base extensometers equipped with 3 measurement bases each, 2 measurement panels equipped with switch and thermometer (Fig. 6.16). The acquisition is semi-automatic, meaning that the system is able to store the data in the panels’ memory, and at determined time intervals it is necessary to recover the data on-site.

Figure 6.14: Plan, longitudinal and transverse cross-section.

Figure 6.15: Slope in the access steps to the aisle apse due to the sinking of the pillar, indication of the affected pillar.
The system was implemented in a way to have redundant information, from the measurement obtained at specific reference points. In fact, the settlement of the pillar brings deformations also on the surrounding structural elements and determines visible crack patterns, evidently related to the observed phenomenon. Aiming at defining further settlements of the pillar, the different types of extensometers positioned are able to detect the relative displacements of the vertical structures, to measure variations in the openings on the main fissures, to evaluate the settlements of the foundations of the crypt’s pillars with respect to fixed points of the underlying soil, at the depths of 5, 10 and 15 m. The temperature, fundamental parameter for the comprehension of seasonal non-monotone behaviours, is also monitored.

A year and a half have passed since the system has been active, hence at least the seasonal effects can be appreciated. Figure 6.17 shows the crack mouths relative displacements, plotted versus the observation date. From the visualized data,
it is possible to notice that the seasonal effect is fully visible (contraction when the temperature is higher), and that the relative displacements are contained within narrow variations (the tenth part of a millimetre/half mm). There still are some sensors that indicate some trends that are not directly related to the temperature; longer observation periods are needed in order to define if such singular relative displacement tendencies are of importance for the studied phenomenon.

### 6.7.3 Vitoria Cathedral

The Cathedral of Santa Maria, also known as the Old Cathedral or Vitoria’s Cathedral, is located on the highest part of the city of Vitoria. The construction of this interesting monument of Gothic Style began in the thirteenth century and finished in the fifteenth. The building, declared Historic-Artistic Monument, has the form of a pronounced Latin cross with three naves in the main hall space and a head wall with ambulatory and radial chapels (Fig. 6.18). Throughout its life, many interventions have taken place in the monument in order to solve different structural problems. The first intervention happened just a few years after the construction was finished. The last intervention stands among the major ones carried out through the ages and took place in 1967. Twenty-six years after that, the temple had to be closed to the general public owing to the appearance of worrying signs of ancient structural problems reactivating.

Figure 6.17: Crack mouth opening, extensometers EL1 . . . EL13.
At that time, people in charge of the conservation of the Cathedral opted decisively for embarking on a long study towards the integral understanding of the building before starting new structural interventions. They conceived the Cathedral Refurbishment Programme as a living project open to the public. The restoration of Vitoria Cathedral has deserved the Europa Nostra 2002 Prize, the highest award given by the European Union for the conservation and enhancement of the city’s cultural heritage.

The structural studies have demonstrated that the important historical deformations of the cathedral are due to insufficient capacity of the piers to adequately resist the thrust of the vaults. The original structure had no flying arches and all the buttressing capacity depended on the piers.

The monitoring of the Cathedral is one of the most important activities in the process of the study and restoration of the structure. In the beginning it provided knowledge on the structural behaviour and its stability, and nowadays it allows detecting states of risk during the restoration works. Likewise, monitoring is used to gauge the repercussion of the consolidation actions on the whole structure.
The monitoring began in November 1992 and, at the moment, is intended to continue indefinitely. Since 1998, the Labein Technological Centre is responsible for it. In order to improve monitoring, the equipment installed was complemented in 1999 with new sensors.

The monitoring equipment consists of temperature and relative humidity sensors (5), crackmeters (16), clinometers (6), extensometers (load cells and chains, 10) and convergence meters (9). Sensors are located in strategic points to detect the largest and more significant movements. Readings of all sensors are taken automatically every twelve hours and once in a week a computer collects all the data.

![Graph](https://example.com/graph.png)

**Figure 6.19:** (a) Fluctuation of temperature and (b) movements registered in extensometers from 16 March 2000.
readings by telephone from the headquarters of Labein. During special periods experiencing important operations, such as movements of the strengthening structures in the main nave of the temple, readings of all the sensors and the interpretation are done daily.

The control carried out to date has given very useful information about the evolution of the movements and damage manifested in the structure. The active movements have been perfectly identified, and it is well known that these movements are cyclical in time and related with the changes of temperature and humidity (Fig. 6.19). The main active movement detected is the opening of the central nave and the transept caused by the expansion of the materials of the vaults as a result of the rise in temperature.

The evolution of movements obtained at the same time of two consecutive years shows that the structure seems to be now stable. However, certain changes measured during three years since 2002 indicate that the monitoring system is detecting the effect of the present use of the Cathedral and associated infrastructures, as well as the consolidation works that are being carried out.

6.8 Conclusions

In the framework of a global study of an ancient structure, monitoring contributes with quantitative information related to the current response of the structure subjected to a combination of ordinary actions (dead load, thermal environmental actions, micro-tremors, wind, traffic, etc.). This information may provide significant evidence as to the type and progression of damage affecting the structure. However, characterizing long-term damage by means of monitoring is a challenging task that requires specific strategies involving lengthy observation periods.

Most damage manifestations – including large deformation, cracking under tension or compression and crushing or bursting under compression – are caused by the combined effect of a variety of physical processes, comprising the long-term creep of the materials, cyclic environmental actions or repeated extraordinary actions. They are also influenced by historical facts related to construction, utilization and maintenance. The measurements obtained (crack openings, displacements, accelerations, etc.) will include all these effects bundled into a single response; interpreting the results requires the mixed responses to be broken down into cyclic and reversible processes and monotonic (or cumulative) ones. A further step consists of breaking measurements into the components associated with different effects acting on the structure (wind, temperature, earthquakes, traffic, etc.). The latter specifically requires monitoring of the actions themselves by means of appropriate equipment (thermometers, hygrometers, anemometers, seismometers, etc.).

Accurate numerical simulations of structural response, by means of detailed structural models, are also needed, both for the results to be interpreted and for reliable conclusions to be reached regarding the condition of the building and the actions or processes contributing to its decay or damage.
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