Monitoring historical structures, from their past to their future
Eva Coisson; Federica Ottoni
University of Parma, Dept. of Civil Engineering, of Environment, Territory and Architecture, Parma, Italy

1. Introduction
The aim of this paper is to inspect the role of structural monitoring in the knowledge and also in the conservation process of the built historical heritage, bearing in mind that knowledge and conservation should always go hand in hand. One of the most interesting, and in some ways innovative, contents in the recent Directive on the seismic protection of cultural heritage is certainly the role ascribed, in the evaluation of seismic risk, to the observation of the buildings and to their control, and thus to their “monitoring.” Indeed, the Directive defines the “regular monitoring of construction” as “a practice highly desirable because it is the main instrument for the conscious conservation”. Moreover, it adds that “in some cases, when the possible collapse mechanism is well understood and safety thresholds can be reliably defined, monitoring can constitute a valid alternative to strengthening interventions”[DPCM, 2011, 15, 19].

On the other hand, the same concept was expressed, at the end of the 80s, by the Commission Ballardini-Gavarini, which emphasized as “from this data series [monitoring] can derive an indication on the building global behavior, considering the phenomena that have taken place over time as a direct experimentation, at a real scale, very indicative and conclusive” [Ballardini, Gavarini, 1989, 16]. Indeed, monitoring is not only a matter of understanding what has happened in the past: it can also assume an active role in the conservation of historical buildings. A methodology of “slow” experimental investigation is particularly suitable for the historic buildings, as it allows to calibrate a reliable model of the structure, which is not only able to understand better its “normal” behaviour but also to simulate responses to various accidental events (earthquakes, wind, temperature variations and changes in structural constraints). This procedure allows a constant evaluation of the cracks and damages and the ability to run short and long term forecasts and simulations on the behavior of the monument, also assessing the actual effectiveness (or possible recalibration) of interventions, which are proposed or even put in practice. Indeed, monitoring is based on the most reliable “model” available to date of the real structural behavior: the real response of the building and its deep observation.

2. So many “monitorings” to achieve knowledge
The monitoring systems are the basic instruments for the achievement of a complete and reliable knowledge of historical heritage. Indeed, these systems are able to grasp the actions that disturb the buildings: thermal changes, wind, earthquakes, changes in level, changes in groundwater. They can also provide alarms if certain thresholds are exceeded. However, they have to be conceived and designed not only as means of warning - a very limited use - but as
instruments of scientific knowledge of the mechanical behavior of an artifact. Moreover, they must be designed to measure not only the deformations and instabilities, but also the underlying external causes (temperature, wind, dynamic actions, ground settlements, etc.).

But structural monitoring is not only a matter of instruments: it would be more correct to talk about "monitorings", in plural, as the possible complementary approaches in this field are numerous, with different purposes, instruments and time-domains.

In short, there are different "types" of possible monitorings, which for simplicity can be summarized in the following broad categories:

• the historical monitoring;
• the instrumental monitoring for the understanding of the physiological behavior of the structure, essentially useful to the calibration process of interpretative models;
• the instrumental monitoring for the control of structure reactions to singular events (the one that in the Directive is evoked as possible "alternative intervention");
• and, finally, the “control monitoring” of the proposed (and implemented) intervention.

In all these meanings, monitoring is crucial in the preservation of cultural heritage, not only as a means of “damage control” but as a fundamental instrument of knowledge [Ottoni, 2012, 60].

2.1. Historical monitoring

Usually monitoring is dealt with only considering instrumental, modern monitoring, aimed at the comprehension of the present structural behavior of a building and, in some cases, to the calibration of numerical models, which, in turn, can be used for risk assessment and/or to define possible interventions. Indeed, this type of monitoring only opens a very small window on a centuries-long experiment [Roca, 2004, 63-73], if we consider that the data that can be obtained, although very useful do define the present evolution speed, are very partial and do not give any information on the much longer period which goes from the construction to the present condition of the examined monument.

To inspect this period, often full of modifications, traumas and deformations, the so-called “historical monitoring” is needed. This method consists on one side of a specific research on historical documents and on the other side on a strict attendance of the monument to check the signs that history has left. This allows to reconstruct the evolution of the disorders in time, from the construction to present times, without any instrument. The historical monitoring is fundamental to understand the present static conditions of the building, as it is usually deeply influenced by past events, and it is also important in order to insert the modern instrumental monitoring in a more complete frame.

First of all, a careful study of the historical archives has to be carried out. The identification of the traumatic events suffered during centuries (earthquakes, fires, wars, etc.), of the building reaction (collapses and damages) and the dating of consequent restoration works, together with any repair or strengthening intervention is extremely important, as well as the knowledge of any
historical “spy” or historical measurements. The next step is to enter into the monument and “read” the information it conceals. The deformation of a decorative element, the measurement of a crack on a fresco, the different levels of a pavement or the out of plumb of the walls, become as many historical evidences of the path followed by the structure since its construction.

The obtained series of data can be completed by the data registered by the modern monitoring system; a global graph of the building behavior from the past to date can then be derived (Fig.1). The results of damage observation, in fact, can be misunderstood if they are not correctly inserted into the long period behavior of the monument: indeed, in the monument stability assessment, the alarm aroused by a recent crack is quite different from the danger represented by an ancient crack.

Since the 80s, Roberto Di Stefano had pointed out that “The study of the static behavior of structures [is] always historical investigation” [R. Di Stefano, 1981, 76-77]. The information that a careful and focused historical analysis can provide on the static (and seismic) behavior of historical monuments are in fact many and provide, to those who can read and interpret them, the results of a unique “experiment” in real scale.

For structural experts, this historical approach is not so obvious, but it becomes crucial in the process of validation and interpretation of the model chosen to calculate the ancient structure safety, by measuring its “similarity” to reality.

Conversely, the historical study must be careful to pick the aspects related to structural implications, which are often overlooked.

Numerous examples can be cited to demonstrate the fundamental role of this approach in the definition of the stability condition of a historic building: one of all, exceptional for extent of damage and for the amount of information collected over the centuries, is Santa Maria del Fiore in Florence. Thanks to historical analysis, in the above described meaning, the cracks insisting on the great dome were fully included in their secular evolution [Blasi, Ottoni, 2012]. Whatever the measure observed in relation to the damage of the structure, the “historical monitoring” not only follows the evolution of the damage but notes the behavior of the structures and, more, investigates the reasons for the collapse, paving the way for an interpretative model of the building essentially derived from its own history. Therefore, it results clear that in such a process of progressive understanding of the behavior of the building, the modern systems of instrumental monitoring can be considered only as the last and most recent update of this story.

2.2. Structural monitoring and model validation

The application of instrumental monitoring systems for high-precision motion control of abnormalities in the structures is a well known method to civil engineering, which commonly monitors the great infrastructures (dams, for example) with particularly advanced measuring systems, given the obvious and disastrous consequences that their movement, or worse collapse, would have for the general safety.
However, in this case, the purpose of monitoring is to check that the reality actually resembles to the numerical model used to design it: this similarity is in fact the first guarantee of safety for modern structures. For historic structures, instead, it is the opposite: the problem is to better calibrate the model to reliably interpret reality and therefore to be able to make realistic predictions of ancient structures behavior. The purpose of monitoring is therefore specular and, in some ways, diametrically opposed. Thus, in the field of ancient structures, static and dynamic monitorings can be used as calibrating methods for the interpretative model chosen to understand and simulate the behavior, by comparing some structural parameters “registered” by instruments with the model’s results.

Indeed, after decades of experience, the scholars had finally to admit that numerical modeling procedures, which can provide with good accuracy the behavior of structures made of homogeneous and isotropic materials, are not yet capable to fully describe, with an acceptable precision, the seismic response of historical buildings. By contrast, the empirical procedures, traditionally defined as approximate, allow to understand the behaviors and risks of ancient buildings better than the so-called scientific methods.

In step with this, when a huge amount of data are available, the statistical analysis becomes a tool to analyze the phenomena, to identify the interrelations between all the components of the system and thus to verify the possible causations - both direct and indirect. Defining a statistical-dynamical model, which fully exploits the measurements obtained through the monitoring system, allows to prepare numerical models able to make predictions on the performance of cracks depending on the possible external actions and, consequently, to calibrate a reliable pattern of behavior of the structure.

2.3. Damage evolution and alarm

Given the long duration of plastic phenomena involving masonry structures (like creep), it’s clear that also monitoring systems must be designed in order to operate for enough time. In general, short time-monitoring is not very useful: in some cases, it can even provide misleading claims. Some years (or better, decades) can be considered as a significant time-span for the monuments monitoring systems, thus they need to be designed for the same duration. They must be seen as means of knowledge which has to be bequeathed to future generations, allowing them to introduce, if necessary, structural improvements on the monuments, to control them in the future and to verify the past interventions. Most of the time, instrumental monitoring can then simply serve to control an evolution of the damage which can be more or less known and risky. Therefore, the installation can follow a sudden alarm, like the onsetting of new cracks or obvious deformities, or, conversely, can constitute the first intervention for monument safety. In this process, it’s crucial to distinguish the quantities to be monitored: the more meaningful ones for the stability of a structure. Once the measures to control are identified, the problem is the management of the monitoring data. In the so-called “qualitative monitoring”, the measurement of the single parameters can be reset and restarted at any time. The comparison is therefore between initial and final measurements, for
Fig.1 - Evolution of the main crack amplitude in web n.4, Santa Maria del Fiore dome from the construction to date.

Fig.2 - The numerical model to interpret the complex interaction between the Ghirlandina tower and the Modena Cathedral was calibrated also thanks to the monitoring data.

Fig.3 - When the damage mechanism is well understood, even very small, single point instruments can allow to control with precision the evolution of cracks and to check the reaction of the building in case of singular events (in this case: earthquakes).
varying time intervals depending on the importance of each recorded data. This process requires not only a previous clear identification of the expected behavior of the structure, which can only come from a deep knowledge of the past movements and of the characteristic parameters of the structure but also, consequently, a critical classification of the detected parameters (crack widths, temperature variations, inclination, levels, etc.). What is clear is then the need, in the design of a monitoring, to organize the information acquired, or rather, their classification in terms of relevance. This classification needs to be assessed in relation to the peculiar history of damage and deformation of the monument. Ultimately, the monitoring system must be designed not only to be complete and exhaustive, but especially targeted, and therefore a minimum, like every intervention.

2.4. Intervention control or “observational method”
When historical buildings are not subjected to immediate hazards, we can normally work slowly, making minor changes and controlling them for a long time. Especially for monuments, it is highly desirable to detect in time the effectiveness of restoration and strengthening interventions before making them definitive. The proposed method is far different from the usual one: very frequently, some extensive, costly and irreversible interventions have actually reacted negatively in the long time period, or against earthquakes.
Indeed, recalling the interpretation of a historical building as a non-replicable experiment, in real time and dimension scale, we can gather from this experiment precious information also on the behavior of its strengthening interventions, to be read by means of an appropriate monitoring [Ottoni, 2012, pp.63-91]. First of all, as ratified explicitly by the recent Italian seismic law (DPCM, 2011), the structural monitoring can be an alternative to the direct intervention. This strategy can be adopted only when the structural problem has been clearly identified and some safety thresholds have been defined, but in these cases the minimum intervention criterion is fully guaranteed. Moreover, monitoring can also have an important role in controlling the interventions, verifying their efficiency and in some cases calibrating their application. More, it can be a real guide for the intervention, since it reliably records - better than any forecasting model (which the monitoring contributes significantly to build and calibrate) - the results of the designed interventions on the building itself, measuring experimentally their effectiveness and even correcting possible errors. In the case of the Tower of Pisa, for example, monitoring has contributed significantly to the definition and to the implementation, in the 90s, of the inter-
ventions necessary to ensure its stability and conservation. In that case, the monitoring not only has allowed to fully understand the causes of the inclination, but also to perform, consequently, a consistent intervention: the underexcavation of soil from beneath the foundations, whose effects on the tower's inclination was continuously controlled and guided by the monitoring system. The experience of the tower of Pisa is particularly significant because it highlights another aspect of monitoring, already known in the geotechnical field, which seems particularly appropriate also in the restoration and conservation process of historic buildings, where no reliable tools are present, until now, to predict the real behavior of structures: the “observational method”. This method consists in defining the characteristics of the system, through a prediction model, and to define a series of scenarios, analyzed in relation to the possible interventions. This step allows to define which variables have to be controlled, which thresholds have to be defined, or rather the limits within which to proceed with the intervention. The interpretative forecasting model is then "adjusted" on the basis of the observations made during the implementation of the interventions, guiding the operations on the basis of the measured response. What we get at the end of the process can be defined “dynamic design”. This allows the adoption of appropriate and suitably calibrated corrections to the intervention in case of ineffectiveness (or worse, damage).

In this way, monitoring becomes an essential part of the design, modified in process. Sometimes it happens that an intervention and a case study becomes not merely an example from which to learn but a kind of experiment to the truth, fully recovering the concept of empiricism of the ancients. That’s what happened with the intervention of strengthening through an encircling system of tie rods in the hexagonal dome of Santa Maria del Quartiere, in Parma. The period of measurement after the intervention is too short to testify its effectiveness on the global, long term crack width trend. Nevertheless, it’s interesting to stress that in this case the measurements have allowed to register the effects of post-tensioning operations on the cracks (Fig. 4). Moreover, this intervention does not seem to prevent the natural dome behavior in response to temperature variations (its “breath”) which are evident even after the insertion of the tie rods, but it has already demonstrated to be active against seismic actions. Further elaboration of monitoring data will give the final evidence of the efficacy of this intervention, providing fundamental information to reevaluate it during time, starting, at the ancient manner, from empiricism and from damage evolution observation [Ottoni, F., Coisson, E., 2012].

The reference is clearly to the well-studied and more complex Brunelleschi’s dome of Santa Maria del Fiore, in Florence, and to its imposing monitoring system, whose comparative analysis provided, in a continuous cross-reference between the two structures, the confirmation of a mechanism and maybe also of the strengthening solution. In conclusion, the small cupola of Parma can constitute a monitored experiment, in scale, for the great Brunelleschi’s cupola, allowing to assess with certainty the effects in the long run, confirming the validation and forecast model prepared on the basis of the observation in a “test site”.

708
3. Conclusions
The described frame shows that it’s not completely correct to think the instrumental monitoring as a sort of “alarm system” to signal an imminent threat, but rather as a tool to achieve a better understanding of the monument and to define the possible interventions. Starting from the identification of an initial situation, monitoring allows to determine with sufficient accuracy the movements of the structure and the evolution of its instability, particularly important in evaluating the effectiveness of structural interventions. The crucial importance of monitoring also in the operative phase is even more clear in the cases in which the intervention does not derive directly from the numerical model of interpretation but it is rather addressed, and if necessary correct, by the instrumental evidence. The underlying idea is that only by understanding the “error”, the modern architect-engineer can approach the historic structures in order to understand their evolution and only measuring this error and its variations he/she will be able to assess its present stability condition and to control the effectiveness of any intervention.
This, in the end, is not very different from what the ancients did, while studying new construction methods by observing the past.

References