Title: **APPLICATION OF SHM TECHNIQUES IN THE RESTORATION OF HISTORICAL BUILDINGS: THE ROYAL VILLA OF MONZA**

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## ABSTRACT

The paper describes the experience that is being carried out in the restoration of the Royal Villa of Monza, where the installation of a long-term and permanent instrumental monitoring system has been realized and put into operation in the last three years. The monitoring system, at the present stage, comprises three subsystems and includes SOFO fiber optic sensors as well as conventional sensors. The features and the architecture of the system, including hardware, software and integration are presented, together with the strategies for data analysis and interpretation.

## INTRODUCTION

Nowadays, structural health monitoring (SHM) is becoming an increasingly diffused tool for the management and in-service safety evaluation of different categories of structures. As concerning civil engineering applications, this is mainly true in the field of transportation infrastructure and lifeline critical facilities. These developments are also pushing an intensive research activity and the number of papers on the subject published worldwide in specialised journals and conference proceedings has dramatically increased in the last few years.

This paper is aimed at discussing a special topic within the framework of civil engineering applications, related to the role that SHM techniques can play in the preservation and rehabilitation of architectural heritage. The problem can be considered of a significant cultural and economical importance in several countries in Europe and worldwide, where old civilisation has left a significant number of monumental buildings and structures that must be protected against deterioration or submitted to a rehabilitation process in order to allow their reuse for public and private

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functions. Nonetheless, this topic has received very little attention in modern research on SHM techniques.

Internationally agreed standards for restoration (Chart of Venice – 1964, Chart of Krackow – 2000) require the rehabilitation process to be performed in full respect of the historical characteristics of a monument. This has led to establish the principle of reversibility, i.e. to require that any intervention should be conceived in such a way that the original conditions could be recovered theoretically at any time after the intervention has been performed. However, when the rehabilitation process involves the structural characteristics of a monumental building, safety requirements imposed by modern codes lead to strengthening techniques very often conflicting with the above principle. Consequently, we are forced to accept irreversible modifications of the original structure but, in this case, it is required that strengthening is performed at the minimal possible extent.

The mechanics of ancient structures is sometimes very difficult to analyse. Strength of aged materials is often unknown as well; distress phenomena may reveal unclear and structural geometry itself may be hidden by modifications of the building occurred after its construction. This has the consequence that conventional approaches to structural rehabilitation, based on structural surveys and diagnostic campaigns followed by design and construction, in an open-loop-like process, often result in oversize reinforcements and unnecessarily extend treatments.

The possibilities offered by modern sensing, data acquisition and data processing techniques introduce a substantially new approach, based on a feed-back-like process. Driven by the results of global and detailed surveys and investigations, a suitably designed monitoring system will improve effectiveness of the diagnostic process, reduce uncertainties in rehabilitation design, provide control over the execution phases and continuous evaluation of the in-service structural performance.

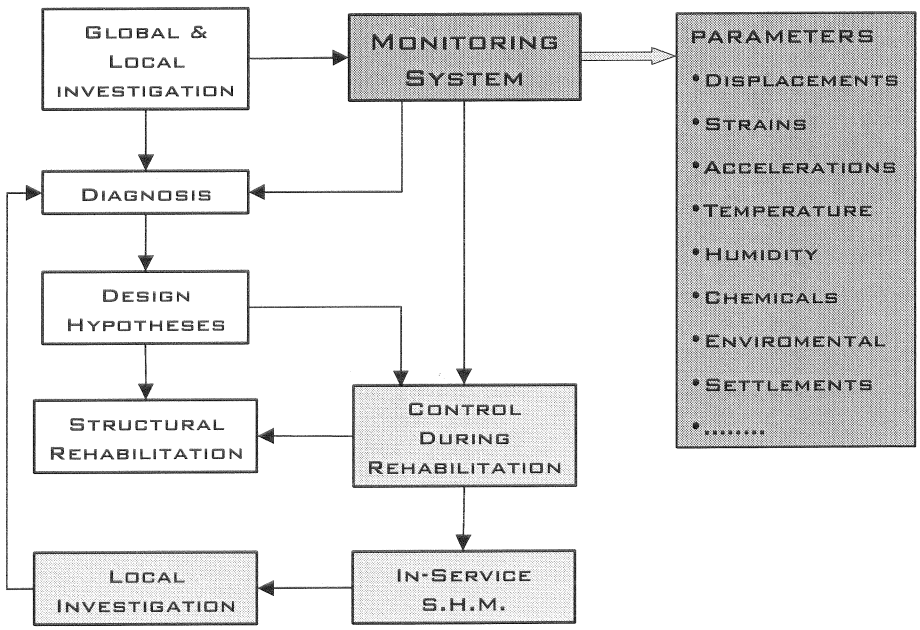


Figure 1. Flow-chart of a monitoring-based structural rehabilitation process

Processing and interpretation of the measured data over the entire life-cycle of the restored structure will provide the capability of verifying and eventually correcting the design hypotheses and design provisions, and of deploying corrective measures whenever the observed structural response indicates that damaging or deterioration of the structure is likely to reduce safety.

The overall process is logically depicted in Figure 1. The flow-chart indicates the main steps in the procedure and underlines the difference with respect to conventional approaches (white boxes). By this means the concept of reversibility may be substituted by the concept of graduality, i.e. by a maintenance-based management of the ancient structure according to which irreversible interventions are only performed when needed.

Of course, the selection of the interventions that may be performed during rehabilitation and the ones to be left over shall be very carefully conducted. However, going into deeper technical details on this subject is not the purpose of the present work. In the remaining part of the paper, a similar approach applied to the refurbishment of a part of a monumental residence, the Royal Villa of Monza, close to Milan in Italy, will be presented and discussed with special reference to the design and implementation of the monitoring system.

## DESCRIPTION OF THE STRUCTURAL FEATURES

The Villa Reale of Monza was originally built by architect Piermarini from 1777 to 1779 for the Austrian Empress Marie Therese and subsequently modified during the Napoleonic period and by the Italian King Umberto I. After the assassination of the King by an anarchist in July 1900, the building was not used anymore by the royal family and was devoted to different public utilizations. In the last few decades, the Villa has been in practice abandoned.

The building is surrounded by the Royal Gardens and by one of the largest parks in Europe, which includes the famous Formula 1 circuit.

After an agreement was reached among the proprietors: the Italian Government, represented by the Soprintendenza per i Beni Architettonici ed il Paesaggio of Milan, the city administrations of Monza and Milan (subsequently the administration of Regione Lombardia), a global restoration program has been launched in 1999. The first phase of this program consisted in the realization of a Museum in the south wing of the villa, where the apartments of King Umberto I and of his wife, Queen Margherita were located, and in the refurbishment of the roofs. Restoration works for this first phase are currently under way.

The main part of the villa (Figure 2) is consisting of a central body, aligned in the North-South direction. Two side wings depart westward, perpendicularly to this axis, ending with two lower bodies, originally destined to the chapel, to the North, and the covered riding field (Cavallerizza), to the South.

The central body presents a ground floor for service functions, and two upper floors. The first floor holds the receiving rooms of the royal apartments and the second the imperial apartment. In the middle of the central body, an elevated floor forms the "Belvedere".

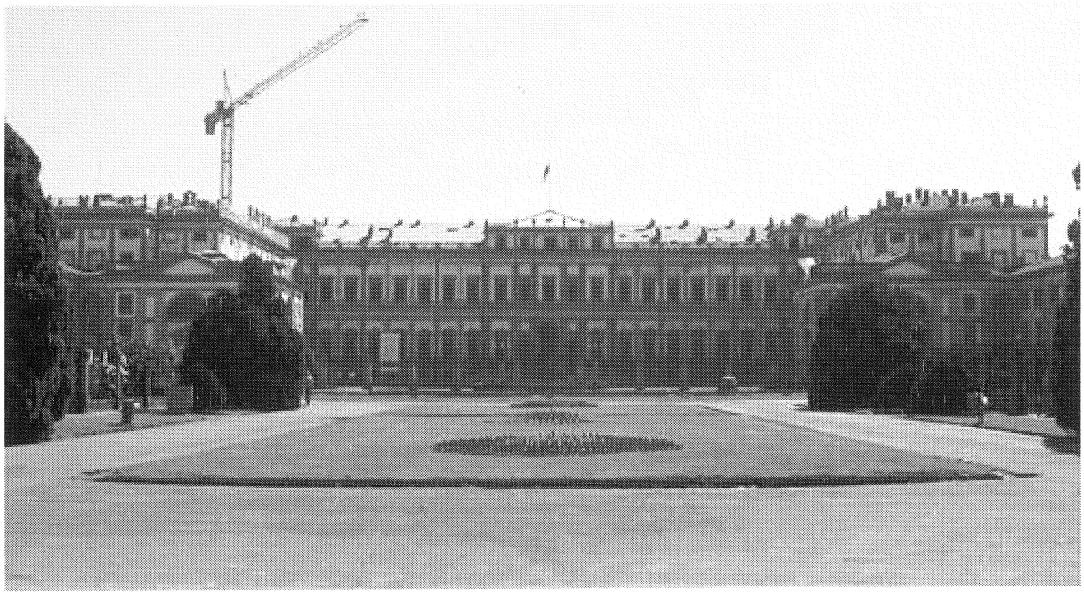

Figure 2. View of the Royal Villa

The wings, consisting of a ground floor, two noble floors and two mezzanines, are of regular masonry construction, based on a repetitive pattern of similarly sized rooms, laid out, at each level, in such a way to determine four principal blocks divided by a longitudinal and a transversal corridor.

The main concern about the Villa's structural condition consisted in the presence of a significant system of longitudinal cracks along the barrel vaults of the central corridor at various levels, both in the north and in the south wings, and in the degradation of several wooden structures, the most important of which was represented by the 18-meters long truss structures sustaining the roof of the "Belvedere".

The design process for the restoration of the south wing of the Villa began with an extensive campaign of geotechnical and diagnostic investigations on the two wings. The results of these surveys showed that the crack pattern was referable to foundation settlements, due to the presence below ground of cavities or loose portions of granular soil of glacial origin, mainly located in the areas close to the central body of the Villa. The soil density characteristics, however, resulted significantly variable and this, together with its granular nature and a very deep water table, led to the conclusion that progression of the settlements should not be expected.

For this reason, when designing the interventions for the south wing and the "Cavallerizza" restoration, it was decided to avoid strengthening of the foundation system, as it would have resulted in expensive and invasive works, and the installation of a permanent monitoring system to control the movements of the structure was instead preferred. The analysis of the structural behavior resulting from the monitoring data in the two years preceding the start of restoration works has confirmed the hypothesis on settlement stabilisation. In the future, the presence of the permanent monitoring system will guarantee the possibility of verifying the

effectiveness of the interventions that are being carried out in the present phase and of eventually defining local interventions to improve soil conditions.

With the same aim, a monitoring system has also been installed in the north wing, in anticipation of its future restoration program.

As far as the "Belvedere" is concerned, the diagnostic campaign on the roof timber structure showed timber degradation phenomena particularly significant at one of the main trusses. These phenomena were already known and led in the 80's to the need of adding two steel trusses, one on each side of the original structure, in order to take over its static function.

The intervention carried out on the timber structure has been, in this case, purely conservative, and consisted in replacing only the degraded timber portions with new prosthesis. The steel trusses have been, of course, dismantled. A system of steel tendons has been added to resist the horizontal thrusts.

The uncertainties on the mechanical timber characteristics and the accentuated torsional deformation observed on the chain of the truss were leaving some doubts on the effective reliability conditions of the structure after the intervention. Therefore, the installation of a permanent monitoring system, able to allow the verification of the effectiveness of the interventions and, eventually, the definition of future corrective measures has been decided.

## CHARACTERISTICS OF THE MONITORING SYSTEMS

As explained in the previous paragraph, actually three separate monitoring systems have been installed in the building at different times and with different purposes. The systems have however been designed in view of their integration in a unique system.

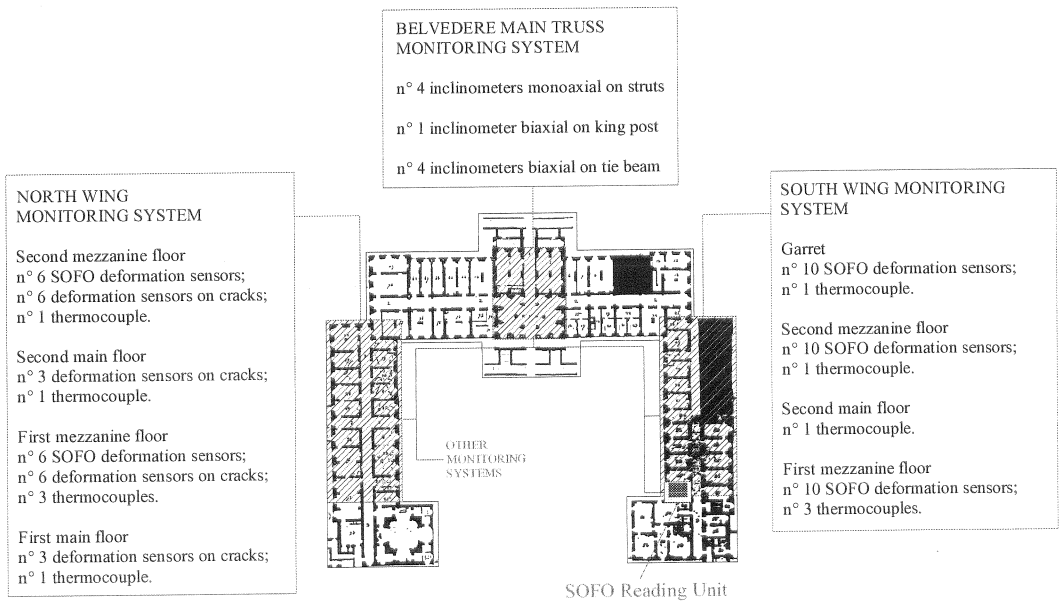


Figure 3. Location and characteristics of the three subsystems

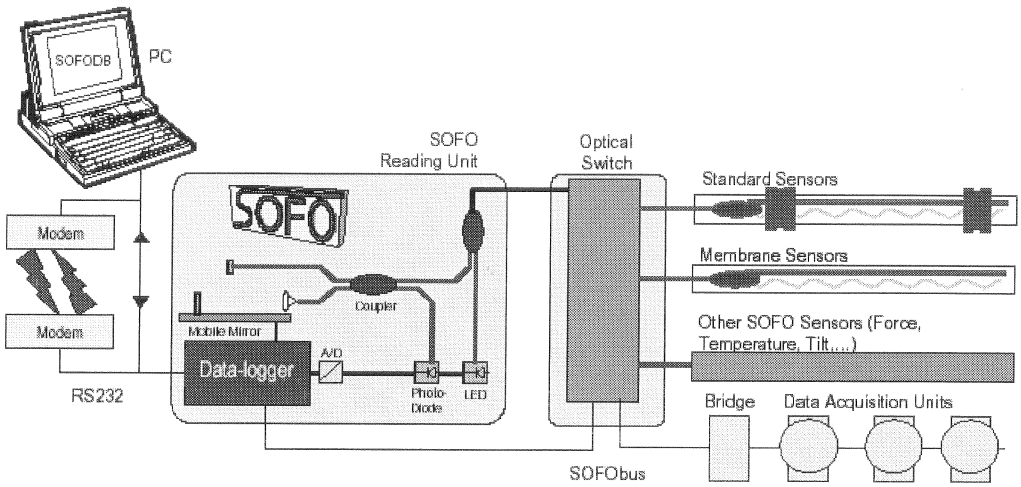


Figure 4. SOFO™ system architecture

The location and the characteristics of the subsystems are graphically summarised in Figure 3. The architecture of the system has been also conceived in order to integrate other monitoring subsystems that could be installed in the future. To this aim, the provision for cable paths has been accounted for in the M&E design.

The base component of the monitoring systems, allowing for system integration, is represented by the SOFO™ fibre optics system. Indeed, the SOFO system (Figure 4) is able to incorporate through the reading unit SOFO deformation sensors [1], consisting in long-base temperature compensated fibre optic gages as well as conventional sensors. The fibre optic gages can be manufactured in length varying from 10 cm to 10 m and fixed on different supports. The sensors can measure the variation in length between an active and a reference fibre up to a precision of 2 microns. The active fibre is attached to the structure at its end points. Each optical sensor must be connected to the reading unit trough optical switches. One position of the switch can be attached to an ADAM bridge, able to address a chain of data acquisition modules (ADAM) suitable for driving nets of conventional electric sensors.

The reading unit possesses local capabilities for data acquisition and storage [2]. For data processing and interpretation, the unit can be accessed locally or remotely by a computer system.

In the Villa, the reading unit is actually connected in a provisional location only to the subsystem in the south wing and it is being expanded to include the other two subsystems. Final positioning will be in the M&E control room of the south wing (Figure 3).

## South Wing Monitoring System

As schematically indicated in Figure 3, the south wing has been equipped with a total of 30 SOFO deformation sensors and 6 conventional thermocouples.

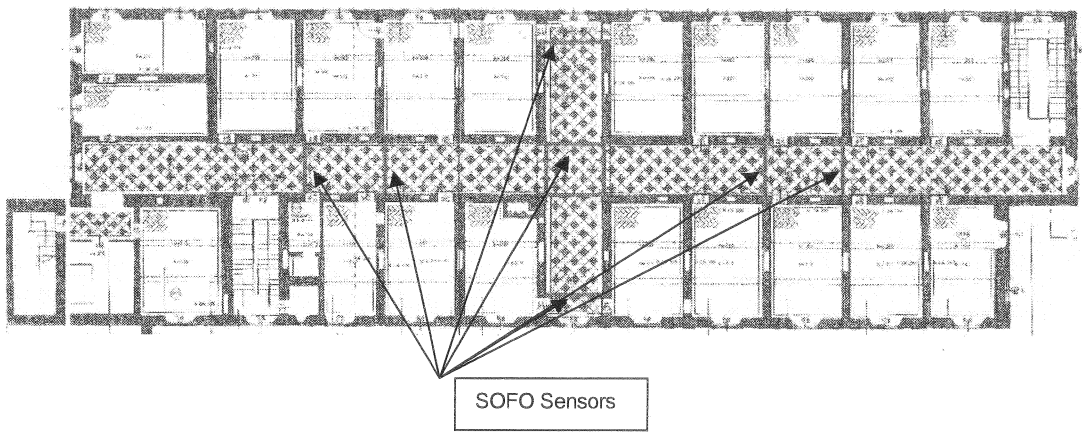


Figure 5. Location of the SOFO sensors in a mezzanine plan

In each of the two mezzanines and in the garret, ten sensors are located in such a way (Figure 5) to measure the relative movements of the four masonry blocks that, in consideration of the crack pattern, have been supposed to behave rigidly. The thermocouples measure the internal and the external temperature.

Provisionally, the sensors whose base is roughly equal to the width of the corridor (circa 3 m) are fixed at the walls in correspondence of the departure of the vault. For permanent operation, the sensors will be fixed inside the consolidation layer that will be placed over the vaults.

Reading of the instruments is performed every four ours. A special purpose computer program [3] has been used in order to correlate the relative displacements to their geometrical position in space and to external and internal temperatures. Analyses have shown that movements of the building are only correlated with temperature variation and that no foundation movement is taking place.

## North Wing Monitoring System

As indicated in Figure 3, the monitoring system installed in the north wing comprises SOFO long-base sensors as well as conventional potentiometric deformation sensors and thermocouples.

The position of the SOFO sensors in a typical mezzanine plan reflects the same scheme used for the south wing, but less sensors have been placed. Cracking in the north wing is much more extensive and severe than in the south wing. Consequently, it has been preferred to install a significant number of conventional sensors to measure crack opening.

Readings have been performed at periodical intervals manually, using portable reading units for the different type of sensors. Monitoring has been extended over a period of one year, from June 2002 to June 2003, and data analysis and interpretation have shown that even for the north wing movements are only correlated with temperature variation. Crack opening/closing and global movements look to be consistent. The system is actually being integrated into the reading unit of the south wing for automatic operation and data processing.

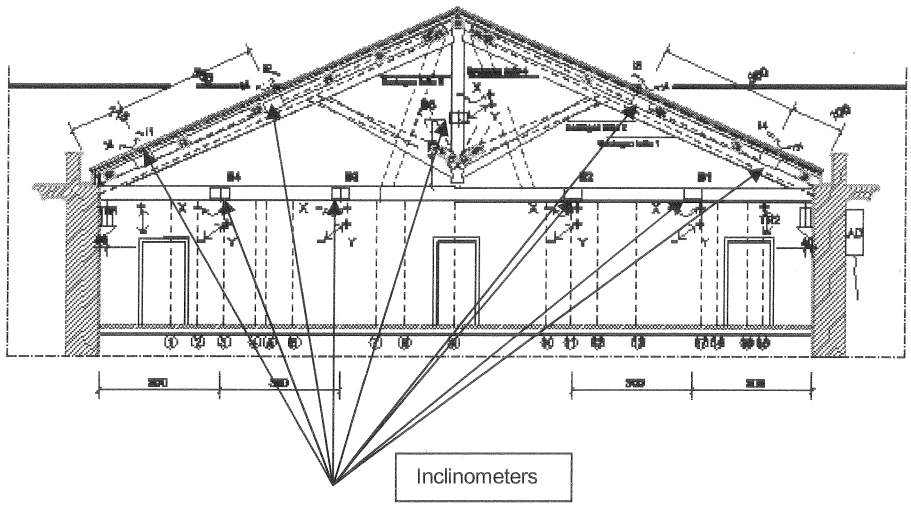


Figure 6. Location of instruments at Belvedere

## Belvedere Monitoring System

As explained previously, the concerns with the rehabilitated timber structures at the Belvedere were mainly related to the torsional deformation of the chain. Spatial arrangement of such a large-span old timber structure is also inducing out-of-plane displacements of the truss elements. Consequently, a network of conventional single and biaxial inclinometers was installed on the main truss as indicated in Figure 6. A temperature and humidity sensor was also placed in order to control environmental parameters. The system is equipped with a self-standing automatic data acquisition hardware that is being connected to the SOFO reading unit in the south wing through an ADAM device.

Instruments were installed after execution of the prostheses on the main elements and before loading of the restored structure with the weight of the other structures of the roof, temporarily supported during the works. Continuous measurements are being taken every four ours since July 2004.

Measured rotations have been compared with data predicted with a computer model, showing a satisfactory agreement between predicted and observed behavior.

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