Structural monitoring in the Villa Reale of Monza (MI), Italy

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ABSTRACT: This paper presents the case study of a long-term monitoring of a historical building, performed through an integrated system of SOFO fiber optic sensors and conventional sensors, designed to control the structure’s movements and the efficiency of the planned strengthening works.

The paper will discuss the features of the monitoring system, data reduction and interpretation techniques, and the usefulness of monitoring techniques in gathering knowledge on the real behaviour of historical structures.

1 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 specialized 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 civilization 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 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 Krakow – 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 concerns the structural characteristics of a monumental building, safety requirements imposed by modern codes lead to strengthening techniques very often conflicting with such 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 analyze. 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
The flow-chart indicates the main steps in the process to be left over shall be very carefully conducted. How­
erver, going into deeper technical details on this subject is not the purpose of the present work. In the remain­
ing 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.

2 MONITORING SYSTEM CONCEPTS

In order to obtain quantitative information about structural behavior, it is necessary to install a network of sensors on the structure. The optimal type, number and location of sensors depends on the structure type, size and predicted performance.

Different options must be considered to obtain the ideal monitoring system:

- The scale in which the structure is observed: at the global scale, the structure is observed from the point of view of the overall performance and response (for example global deformations); at the member scale, a number of selected critical members are observed for their global behavior and, at the local scale, the performance is analyzed looking at the local properties of the construction materials.

- The parameters that are monitored: these parameters can be mechanical (strain, displacement, curvature, rotation...), physical (material temperature, humidity...), environmental (air temperature, humidity...).

- The frequency by which the structural response is controlled: it is possible to carry out a periodic monitoring, with manual measurements at pre-defined intervals, for example once every three months; a semi-continuous monitoring, with automatic measurements over pre-defined time periods (for example one measurement per hour, for one week every 3 months); a continuous monitoring with automatic measurements, for example every hour.

- The response of the structure: the static response, with measurement of slowly varying parameters, and the dynamic response, requiring that measurement of vibrations and other dynamic characteristics be carried out.

- The collection of data: it can be performed manually by an operator on site, off-line, with manual or automatic download through a data line and on-line with data permanently available.

In many cases, the best option can change depending on the evolution of the structure. For example, in an historical structure one can start with a semi-continuous off-line monitoring in order to control the behavior of the structure during the rehabilitation works, then switch to a continuous on-line monitoring during the in-service phase of the structure, or vice-versa.

3 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 practically 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 (Fig. 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”.

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 stabilization. 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 prostheses. The steel trusses have been dismantled. A system of steel tendons has been added to balance 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.
4 CHARACTERISTICS OF THE MONITORING SYSTEM

At the moment 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 an unique system. The base component of the monitoring systems, allowing for system integration, is represented by the SOFO™ fibre optics system.

Indeed, the SOFO system is able to incorporate through its reading unit SOFO deformation sensors, as well as conventional sensors.

The SOFO measuring system (Glisic & Inaudi 2002) is based on the principle of low-coherence interferometry (Fig. 3). The infrared emission of a light emitting diode (LED) is launched into a standard single mode fibre and directed, through a coupler, to the deformation sensors mounted on or embedded in the structure to be monitored, consisting in long-base temperature compensated fibre optic gages, containing two fibres. The measurement fibre is in mechanical contact with the structure itself and will therefore follow its deformations in both elongation and shortening. The second fibre, called reference fibre, is installed free in the same pipe. Mirrors, placed at the end of both fibres, reflect the light back to the coupler which recombines the two beams and directs them towards the analyzer. This is also made of two fibre lines and can introduce a well known path difference between them by means of a mobile mirror.

On moving this mirror, a modulated signal is obtained on the photodiode only when the length difference between the fibres in the analyzer compensates the length difference between the fibres in the structure to better than the coherence length of the source (in our case some hundreds of mm).

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. 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 (Glisic & Inaudi, 2002). 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.

4.1 The South wing monitoring system

The South wing of the royal Villa of Monza has been equipped with 30 SOFO deformation sensors and 6 thermocouples: the deformation sensors are located in the orthogonal direction of the two mezzanine corridors, in such a way to measure the relative movements of the four masonry blocks in ten sections of the wing. Each sensor has nearly the same width of the corridor and has been provisionally fixed at the wall in correspondence of the springer of the vaults, but in their final configuration the sensors will be embedded in the reinforced concrete strengthening of the vaults. The position of the sensors at each level is shown in Figure 4.

Reading of the instruments is automatic and performed every four hours since February 2002, in order to record the daily variations of the temperature and the related displacements.

Due to the structural complexity, the uncertainty of the mechanical characteristics of the masonry and soil, the forecasting of the structural behavior will be carried out through a statistical data processing. A special purpose computer program (Secchi, 2002) has been conceived in order to correlate the relative displacements to their geometrical position in space and to external and internal temperatures. This program is composed from a sequence of modules:

- Three-dimensional geometric model of the South wing.
- Research of the maximum and minimum values.
- Definition of the trends.
- Attenuation of the irregular variations.

Figure 4. Location of the SOFO sensors in a mezzanine plan.
- Definition of the correlation between displacements and temperatures.
- Forecast of the future structural behavior.

The three-dimensional geometric model reproduces, schematically, the four masonry blocks, defined by the sensor position in the undeformed configuration: the relative displacements of the four blocks are obtained by calculating the new sensor coordinates for each session of measurement, supposing that the sensors keep transversally the same position (Fig. 5).

The research of the maximum and minimum values is performed in order to obtain the range in which the displacements occur.

The data sets show an irregular behavior due to short and long term variations. In order to obtain a first indication of the displacement evolution independently from the cyclic and seasonal variations, trends have been defined through least-square regressions on the entire data sets recorded on the monitoring period under consideration.

The attenuation of the irregular variations can be performed, in order to reduce the undesired variations, making a Fourier transformation of the data sets in a period of 1 year.

In Figure 6 the Fourier spectrum of the sensor 4 is represented, where the yearly and monthly variations of the displacements are characterized by the first 10 frequencies, and the daily variations by a peak at higher frequency.

After individuating the main frequencies, a filter function has been created in order to cut the higher frequencies. These frequencies represent the residual displacements (Fig. 7) due to the daily and random displacements and are used in order to obtain the range in which the 85% of the measures are statistically contained. In Figure 8 the displacement attenuation and the related confidence range are represented.

The same operations are performed on the temperature data of and the two trends are compared. Figure 9 shows that the two trends are similar until July 2003, but from that date on the displacements show a divergence from the temperatures.

After the first analyses on the displacements, a correlation between the displacements and the temperatures can be carried out, in order to determine, qualitatively, how the displacements are due to temperature variations.

High correlation coefficients mean that temperature is the main cause of the movement and low correlation coefficients mean that other effects may have caused these displacements.

![Fourier spectrum of displacements at sensor 4.](image)

![Residual displacements due to random and daily variations.](image)
It is possible that the structural response of a building occurs with a delay mainly due to this thermal inertia, particularly significant in a masonry building. The definition of this delay can be carried out through the research of the maximum correlation coefficient, obtained by imposing several delays between the two data sets.

Figure 10 shows the correlation between displacements and temperatures for sensor 4, before and after beginning of the rehabilitation works.

31 July 2003: in this case the delay in the structural response is practically null and the two charts show a high correlation in both cases: this fact indicates that the observed divergence is due to some non-linear effect.

Finally it is possible to performing a forecast of the structural behavior by a regression between displacements and temperatures. The forecast can be made on the data collected before starting the rehabilitation works, in order to compare the measurements that will be obtained during these works with the forecasted values.

Figure 11 shows a first forecast of the structural behavior since the beginning of the rehabilitation works. The time series present a lack of data between November 2003 and April 2004, due to a temporary break of the reading unit. The vertical line on 7 January 2004 represent the start of the rehabilitation works, then the monitoring of the first phase hasn't been performed. The forecast performed to May and June 2004 confirm the displacement hypothesis: in fact, the trends of the measured and forecasted displacements are similar. This is confirmed by the still significant correlation coefficient (0.84) between the displacements and the temperatures.

4.2 The North wing monitoring system

The North wing of the royal Villa of Monza has been equipped with 12 SOFO deformation sensors installed in the two corridors of the two mezzanines in order to measure, as well as in the South wing, the global displacements of the four masonry blocks before the rehabilitation project. To this aim, the evolution of the main cracks has been measured through 18 standard deformation sensors. Finally, the system has been equipped with 6 thermocouples in order to measure the internal temperature variations.

As well as in the South wing, the SOFO sensors are provisionally installed, but the reading has been
performed manually nearly every month. In this case, the low number of data do not allow to carry out a statistical analysis as well as in the South wing. The system is actually being integrated into the reading unit of the South wing for automatic operation and data processing.

4.3 The Belvedere monitoring system

The Belvedere main truss was interested by torsional deformations of the chain and out-of-plane rotation of the king post, induced by three-dimensional effects of the timber structure. In order to control the deformations of the truss during the rehabilitation works and in-service phase, a monitoring system was installed on the main elements since July 2003.

This system, shown in Figure 12, is composed of 4 biaxial standard inclinometers on the chain, 4 mono-axial inclinometers on the struts, 1 biaxial inclinometer on the king post and temperature/humidity sensors, to control the environmental conditions. 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.

Monitoring has been performed in two phases, corresponding to the removal of the temporary supports used during the structural rehabilitation works, and to the first in-service period. The plots of the measured rotations are shown in Figures 13–15: from 23 September to 14 October 2003, the acquisition was accidentally interrupted.

The plots show that in the first phase of loading, a significant torsional deformation of the chain was detected. Due to this deformation it was decided to add a steel tendon by each side of the chain, in order to reduce the stresses in the old timber structure and provide a presidium.

After this intervention, the system has been kept on service with data acquisition every 4 hours, in order to record the displacements due to the thermal variations: in this period, the torsional deformations of the chain follow mainly these variations.

The mono-axial inclinometers on the struts have shown small rotations (<0.2°) during the works on
the timber in July and August 2003, and practically no rotations at all during the first in-service phase.

The biaxial inclinometer on the king post has shown an out-of-plane rotation practically null after the removal of the temporary supports, due to the presence of the steel tendons between the king post and the pitch struts. These rotations increased unexpectedly on 19 February 2004 due to a release of a tendon's clamp. During the fixing of the problem, the monitoring system was used to restore the previous conditions. The in-plane rotation has followed substantially the trend of the temperature.

In order to provide an interpretation of the observed data, a finite element model of the structure has been developed. As indicated in Figure 16, the model comprises the three-dimensional arrangement of the original timber structure and the steel tendons introduced along the perimeter walls and between the king post and the two pitch struts to absorb the horizontal thrust. Eccentric wooden supports are modeled along the chain, in order to simulate its torsional behavior.

The parameters of the model have been optimized by fitting the response observed in the first phase with the computed rotations. The testing results have substantially confirmed these parameters.

The model will then be used to evaluate the conditions of the structure during the subsequent in-service phase.

5 CONCLUSIONS

The monitoring systems installed in the royal Villa of Monza have allowed to control the structural behavior of some parts after and before the rehabilitation works. In the case of the South wing monitoring system the interpretation of the displacements has been statistically carried out, due to the complexity of the structure. The Belvedere main truss displacements are interpreted by means of a numerical model optimized by fitting the response observed in the first phase with the computed rotations.

In the future, the presence of the permanent monitoring system, that include all system described in this paper, 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. For this reason the case described can represent an example of a monitoring-based structural rehabilitation process.

REFERENCES

