MONITORING OF HERITAGE STRUCTURES AND HISTORICAL MONUMENTS USING LONG-GAGE FIBER OPTIC INTERFEROMETRIC SENSORS – AN OVERVIEW

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Abstract

Heritage structures and historical monuments have a central cultural place in any society; old stone bridges, palaces, churches, cathedrals, monuments, etc., but also modern structures with very particular architectural or structural design represent an enormous civilizing value. Nevertheless, degradation processes generated by natural or human actions lead to deterioration, damaging or even loss of these inestimable treasures. Thus, regular maintenance and remedial works are unavoidable. The challenges, frequently met in practice, are related to the evaluation of structural health conditions and structural design. Aged and insufficiently known construction materials, as well as the lack of written documents explaining the design and construction of structural members, makes structural assessment difficult. In order to assess the structural health condition, including structural design issues, and also to help register and understand future developments, to performing structural health monitoring using an appropriate monitoring system is recommended. The long-gage fiber optic interferometric sensors have shown excellent performance on several heritage structures and historical monuments, including old church in Switzerland, the Royal palace in Italy, a heritage bridge in Russia, and a temple monument in Korea, just to name a few. A number of important parameters have been monitored allowing a sound assessment of the structural health condition and understanding of real structural behavior. Selected applications using long-gage fiber optic interferometric sensors are presented in this paper.

INTRODUCTION

Heritage structures are historical constructions that have an important role in the cultural heritage of society. They may be appreciated for several reasons – age, architectural beauty, religious reasons, historical events or persons they hosted, construction challenges they had in era they were built, etc.

Being built many years ago, using old techniques and being exposed to environmental conditions for very long times, the heritage structures can show different degrees of malfunctioning. Without appropriate management, the structure may partially or entirely collapse, which would not create safety and economic issues, but will also create an irreversible cultural loss.

The management and the security of heritage structures in particular require periodic monitoring, maintenance and conservation. Furthermore, an accurate knowledge of the behavior of a structure is becoming more important as new building and conservation techniques are introduced and existing construction is often required to survive nearby constructions undamaged.

Lack of technical details (drawings, static system) and structural conditions makes monitoring of heritage structures very challenging – it is necessary first to understand the structure and its behavior and then to define a full monitoring strategy. Long-term monitoring helps to increase the knowledge of the real behavior of the structure and in the planning of maintenance intervention. In the long term, static monitoring requires accurate and very stable systems, able to relate measurements often spaced over long periods of time. Furthermore sensors should be installed with minimal invasion to the aesthetics and functionality of the structure under test.

From many points of view, fiber optic sensors are the ideal transducers for civil structural monitoring in general. Being durable, stable and insensitive to external influences, they are particularly interesting for the long-term assessment of structural health conditions. On the other hand, heritage structures were commonly built as masonry, having material and physical discontinuity. Consequently, their structural behavior is to be monitoring with long-gauge sensors. The SOFO interferometric sensors [1] were selected for the applications presented in this paper.

Different monitoring strategies can be applied for the monitoring of heritage structures, depending on the structural system and the type of the structure. A few application examples are briefly presented aimed at presenting some monitoring strategies, highlighting potential and demonstrating the applicability of optical fiber sensors in the domain of the monitoring of heritage structures.

SAN VIGILIO CHURCH, GANDRIA, SWITZERLAND

San Vigilio church is situated in the small city of Gandria, on Lugano lake in Switzerland. It was built in the XVI/XVII century, while the frontal façade and portal date from XIX century. It consists of three boards with niches and a chapel. A post-Romanic bell tower from 1525 attracts by its beauty. Repair and reconstruction works were performed by the Rabaglio brothers in 1771 – 1786. The interior of the church is covered with frescos. The church presents significant cracks running along the center of the cylindrical vault (see Figure 1). Other smaller cracks are partially present on the upper convex side of the vault [2]. The crack position is presented in Figure 1.
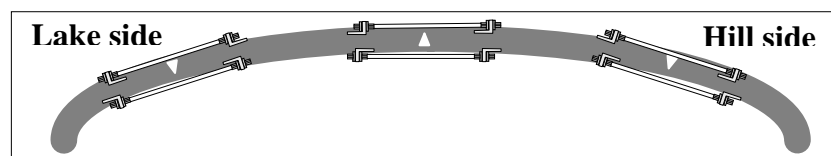

Figure 1. Position of cracks and sensors in the vault (cross-sectional view)

Since the static system of the church and the evolution of the crack openings are not very well known, the decision was made to install ten sensors to monitor the cracks and the curvature variations of the vault. The sensors are 30-50 cm long and are attached to both sides of the vault using L-brackets. All optical connections are joined in the sacristy and the sensors are measured regularly without the need to install scaffoldings in the church, which is still in use. The position of sensors is presented in Figures 1 and 2. The sensor installation was carried out in just one day and the sensors are barely visible to the uninformed observer. A view of the installed sensors is presented in Figure 3.
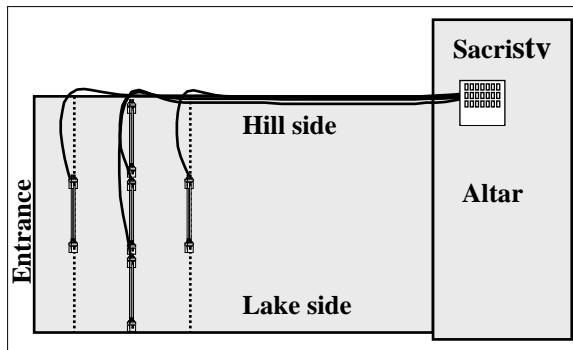
Figure 2. Position of the sensors, top view

Figure 3. View of sensors installed in the vaults

Due to budget restrictions and since the deformations were expected to evolve smoothly, it was decided against installing a reading unit permanently in the church. Instead, measurement campaigns of at least one week were carried out at intervals of about three months. This monitoring program allows the observation of the deformations due to the daily and seasonal temperature variations. An example of results obtained by two of the sensors is shown in Figure 4.
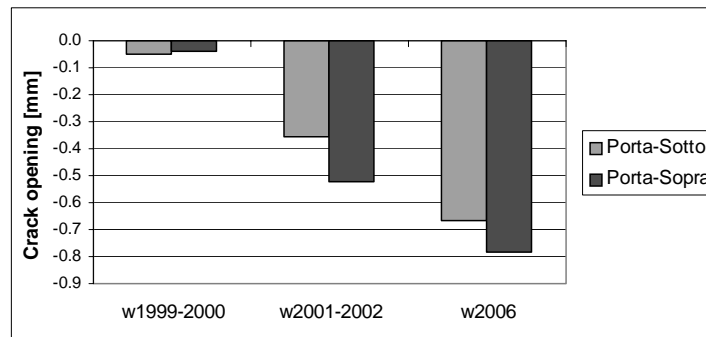

Figure 4. Example of results collected on San Vigilio church

The results shown in the figure confirm closing of the observed crack. This indicates slow redistribution of the loads inside the vault that is subject to further investigation.

ROYAL VILLA, MONZA, ITALY

Royal villa in Monza, close to Milan, Northern Italy, was built in 1777 – 1779 by architect Piermarini for Maria-Therese of Austria [3]. It was modified by the Italian King Umberto I. After the king was killed in 1900, the villa was not used by the Royal family any more, and it was practically abandoned during last decades of the XX century. The following issues developed over time of abandon:

- System of cracks along barrel vaults of central corridor at various levels in North and South wing
- Degradation of several wooden structures, and notably in the 18-meters long truss in the Belvedere

Italian government and authorities of Milan and Monza decided to renew the villa and to transform it into a museum. The repair and conservation work had to be done to both the building and roof. Due to complex static system and uncertainties related to structural behavior it was decided to monitor the villa before, during and after the work. Monitoring data was practically used to "govern" renewal works [3]. Both conventional and optical fiber sensors were used. The view to Royal villa is shown in Figure 5.

Figure 5. View to Royal villa in Monza

Optical fibre sensors were mainly used as extensometers installed between the walls, orthogonal to the corridor axes, but shorter sensors were also used for crack monitoring. The sensors installed between the walls are shown in Figure 6.

Sophisticated modeling and analysis of data was performed by University of Genoa. An example of results, the analysis of displacement – temperature correlation is presented in Figure 7 [3]. The regression coefficient between displacements and temperature changed in July 2003. High correlation coefficients between displacements and temperature were calculated in both cases. Therefore, it was concluded that the change in the regression coefficient indicated that some non-linear effect occurred.
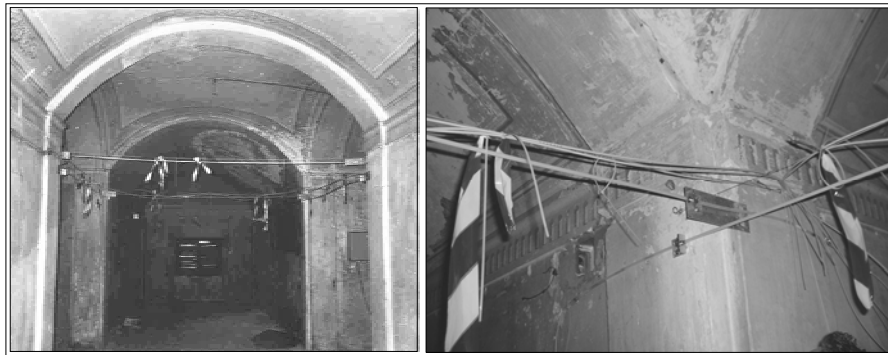

Figure 6. Long-gauge sensors installed between the walls in main corridors (courtesy of Tecniter)
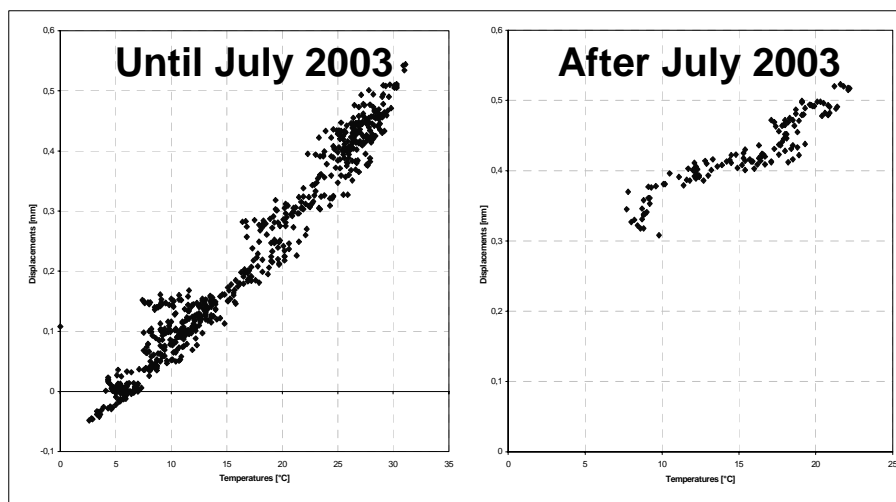

Figure 7. Example of results obtained during Royal villa monitoring [3]

The data interpretation and analysis in wings has been statistically carried out, due to the complexity of the structure and uncertainty related to its static system and structural behavior. The Belvedere Main truss displacements are interpreted by means of a numerical model optimized by fitting the response observed with the computed rotations. The monitoring systems installed in the Royal Villa of Monza have allowed the monitoring-based rehabilitation process.

BOLSHOI MOSKVORETSKIY BRIDGE, MOSCOW, RUSSIA

Bolshoi Moskvoretskiy Bridge was built in 1936-37, over the Moscow River. It is situated in the centre of Moscow, next to the Kremlin, and leads one of the main traffic lines to the Red Square. The bridge consists of three parallel 100m long reinforced concrete arches hidden behind stonewall. The cross-section of each arch contains three merged boxes. The super-structure of the bridge is supported by columns. Four traffic lanes cross the bridge in each direction. The view to the bridge is given in Figure 8.
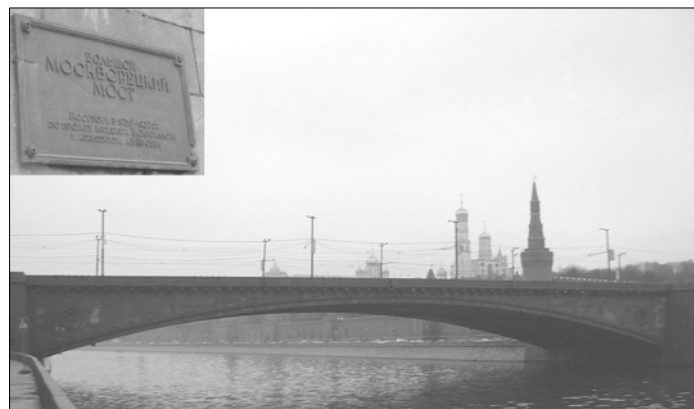

Figure 8. View to Bolshoi Moskvoretskiy Bridge; Kremlin is visible behind

Two types of degradation are noticed on the bridge. Settlement in the centre of the arch which provoked the cracking of the stone walls near the abutments on both sides of the bridge, and the chloride diffusion that practically transverses the upper wall of the arch boxes in some sections, and penetrates inside the boxes. The condition of the bridge after nearly 70 years of service and its functional and historical importance have led the authorities to decide to continuously monitor the structural behavior of the bridge.

The aim of monitoring is to increase the knowledge concerning the structural behavior of this very old structure, to increase safety and reduce maintenance costs. A total of 16 long-gauge sensors were installed in parallel topologies in order to continuously monitor the average strain along the arch, curvature in both the horizontal and vertical direction, and the deformed shape. In order to distinguish the thermal influence, six temperature sensors were also installed. The views to surface mounted sensors before and after the metallic protection is installed, are presented in Figure 9. The bridge is permanently monitored and the data is sent remotely to the control room using a telephone line. Results of the monitoring are not disclosed and therefore are not presented.

Figure 9. View to sensors installed in Bolshoi Moskvoretskiy Bridge (courtesy of Triada Holding)

SEOK-GA PAGODA, KYUNG-JU, KOREA

Seok-Ga Pagoda was built in the VIII century in the court of the Bulkook (Bulguksa) temple, Kyung-Ju, Korea. The three-story pagoda is admired for its proportions and simple but graceful style. It represents the finest style of Korean Buddhist pagodas that evolved from China's multistoried pavilion-type wooden pagodas. Together with Tabotap pagoda, it makes a unique composition: none of the some thousand stone pagodas scattered across Korea exceeed them for their profound philosophical depth and aesthetic charm. A paper scroll of the Pure Light Dharani Sutra, printed between 706 and 751 was found in the pagoda in 1966, which is recognized as the world's oldest printed material.

Ageing of material, exposure to outdoor conditions, and differential settlements make the pagoda stones move. Since there is no mortar between the stones, the movement is relatively free and there is an elevated risk of pagoda distortion or serious damage. A view to Seok-Ga pagoda is shown in Figure 10, and the view to the openings created between the stones is highlighted in Figure 11.

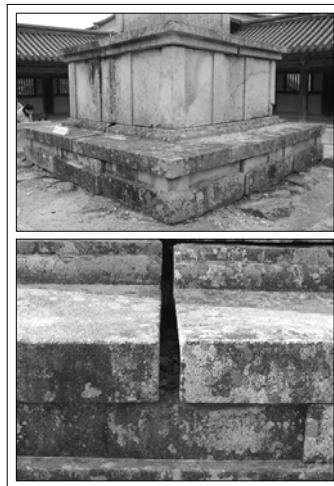Figure 10. View to Seok-Ga Pagoda   Figure 11. Openings created between the
stones (courtesy of Golden Wheel)

It was decided to monitor the pagoda in order to understand its structural behavior and control dimensional variations and movement of the base. The results of monitoring are used to model the behavior and plan and

optimize maintenance and conservation works. Long gauge sensors were installed along the base while the inclinometers (tilt-meters) were installed on the second floor stereo bate. The sensor position is schematically presented in Figure 12 and a view of the sensors upon the installation in Figure 13.The sensors were surface mounted and protected with metallic plates. Inclinometers were also protected with for the purpose constructed boxes. Long-term continuous monitoring is performed. The results are not disclosed.
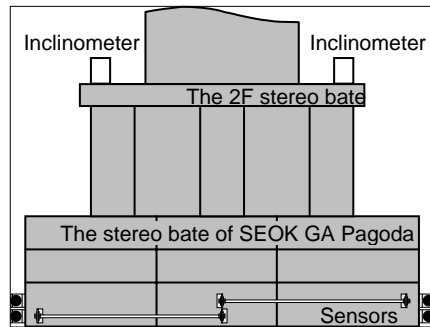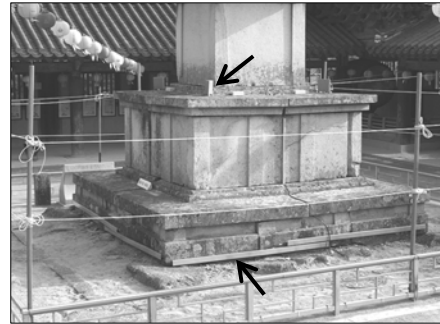

Figure 12. Sensors position

Figure 13. View to sensors and inclino-meters installed on Seok-Ga Pagoda (courtesy of Golden Wheel)

ACKNOWLEDGEMENTS

REFERENCES

1. www.smartec.ch (2007)
2. Inaudi D., Casanova N. & Glisic B., Long-term deformation monitoring of historical constructions with fiber optic sensors, 3rd International Seminar on structural analysis of historical constructions, pp 421-430, Guimaraes, Portugal, 2001
3. Del Grosso A., Torre A, Rosa M. and Lattuada B., Application of SHM techniques in the restoration of historical buildings: the Royal Villa of Monza, 2nd European Conference on Health Monitoring, Munich, Germany, 2004