Structural monitoring for the diagnosis and the retrofitting of the monumental heritage

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ABSTRACT: The countries around the Mediterranean basin offer a unique monumental cultural heritage. Its preservation is a priority pursued by their governments and by several international agencies. The structural engineer involved in the single study case has a two-fold task. On one side he must achieve a diagnosis on the state of the structural skeleton. On the other side, when the retrofitting has been accomplished, he must collect evidence of its efficiency. Both steps find help in structural monitoring, whose specific features are discussed throughout this paper.

1 INTRODUCTION

Structural health monitoring is producing its first books (Staszewski et al., 2005) (Inman et al, 2005). They clearly show a core coming from the experience collected in aerospace applications and a trend to extend concepts, procedures and architectures to civil and infrastructure engineering.

It is easy to realize that this area of application covers situations so different one from the other that no single unified approach can be pursued. First one must distinguish between lifelines and nodes. Then, even at the single node, structural analysis underlines how bridges and tall buildings should be discussed in a different framework.

The further anomaly this paper want to emphasize is the existence of construction whose value is actually intangible, since they are mainly the cultural heritage left to the present inhabitants of a region by the peoples who occupied it trough the centuries.

This is specially the case of the countries around the Mediterranean basin which offer a unique monumental cultural heritage. Its preservation is a priority pursued by their governments and by several international agencies.

The structural engineer involved in the single study case finds help in structural monitoring both when moving toward a diagnosis on the state of the structural skeleton and, once the retrofitting was accomplished, when the goal is to collect evidence of its efficiency.

This paper exploits the results of five years of scientific and technological cooperation of the partners in projects funded by the European Union and illustrates the architecture of a single rehabilitation study. Along this path, special demands arise from an application of structural monitoring to the monumental cultural heritage. Among them the non invasive character the solution must possess requires wireless network and power harvesting. These two aspect are emphasized and discussed in detail.

2 SOME CASE STUDIES

Case studies were selected by the WIND-CHIME partners on the basis of different motivations.

The mausoleum in Tunisia (Figure 1) was the target of the monument national agency INP (Institut National du Patrimoine), which is also one of the three Tunisian partners within the project.

By contrast in Egypt, attention was focused on minarets in order to open the way to the retrofitting of a large class of structures quite common in the Islamic world. Nevertheless, the minaret of Figure 2 has the special character of being isolated, thus representing a structural situation which does not show the complication of the interaction with the mosque wall as observed in several existing solutions.

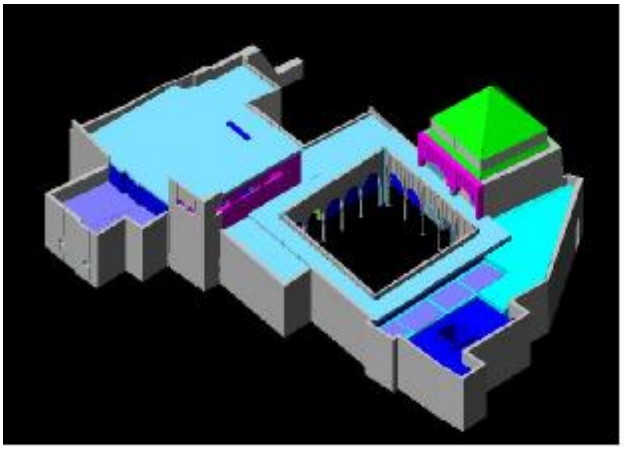

Figure 1 – The Zaouia of Sidi Kassem Djilizi mausoleum in Tunis. It was built in the beginning of the XVIth century by a Moslem refugee from Andalusia: Kassem Djilizi well known for his hand-made ceramics.

Figure 2 – Sultaniya Minaret (Old Cairo, Egypt, – 1340 A.D.). The minaret is separated from mosque building. Total height = 36.69 meters. The square base extends up to 1/4 height, followed by octagonal then circular sections. The bulb (Bassalah) is carried by a narrow short column.

Figure 3 - Aqueduct of Larnaca, Cyprus, called Kamares. Built in 1747 and continued its operation until 1939. Below it is given evidence of the troubles introduced by the sensor cables.

The aqueduct branch which was selected in Cyprus (Figure 3), was preferred for its accessibility, but also for the possibility, offered to the project team, of implementing on it the designed retrofitting device.

3 THE ANALYSIS SCHEME

The preliminary investigation covers the selection of the case study, including site hazard aspects and a first understanding of the structural and material characteristics. A non secondary aspect lies on the effectiveness of the environment excitation all around in view of a structural monitoring of the selected monument.

The first step, then, covers the design of the sensor placements, their deployment and the recording of the relevant data.

Step two is devoted to the creation of a numerical model of the structure, usually a finite element model. Its parameters are calibrated in order to match the results emphasized by the first structural monitoring. Examples for the case studies of this paper are drawn in Figures 4, 5 and 6.

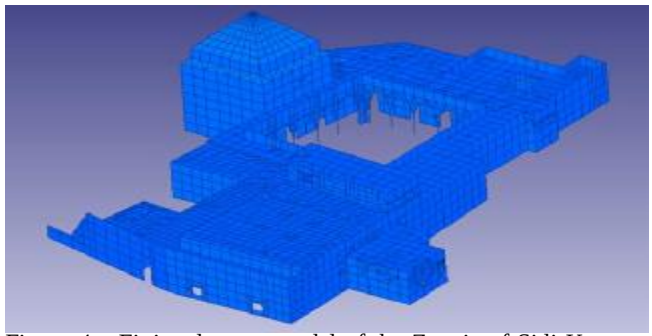

Figure 4 – Finite element model of the Zaouia of Sidi Kassem Djilizi mausoleum in Tunis.

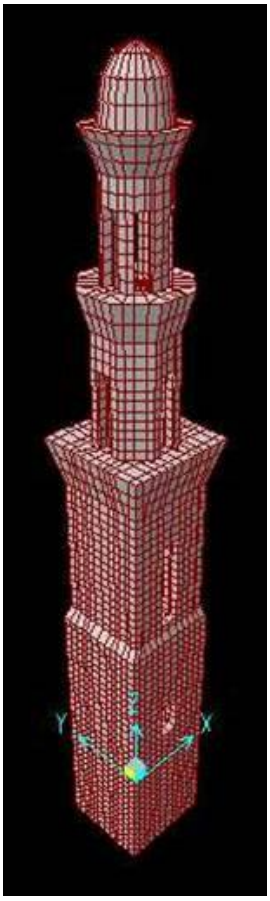

Figure 5 – Finite element model of the Sultaniya Minaret.

Figure 6 – Finite element model of the aqueduct of Larnaca, Cyprus.

The next step is devoted to the design of the suitable retrofitting and, when allowed, to its implementation.

Finally, where it was possible to implement the retrofitting solution, a second structural monitoring stage starts with the purpose of validating that solution.

The whole scheme is summarized in Figure 7.

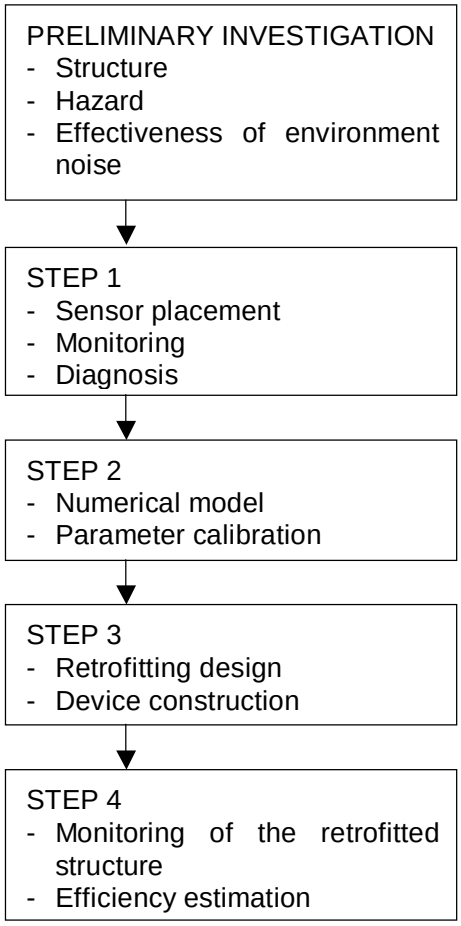

Figure 7 – Flow chart of the interaction between structural monitoring and numerical modeling toward the retrofitting of a monumental building.

The order in which the steps are executed is not rigid. In the case studies of Figures 1 and 2, for instance, the numerical models were realized before the monitoring step aimed at the diagnosis. Indeed, the Tunisian partner paid a lot of attention on the optimal placement of the sensors, which resulted as illustrated in Figure 8.

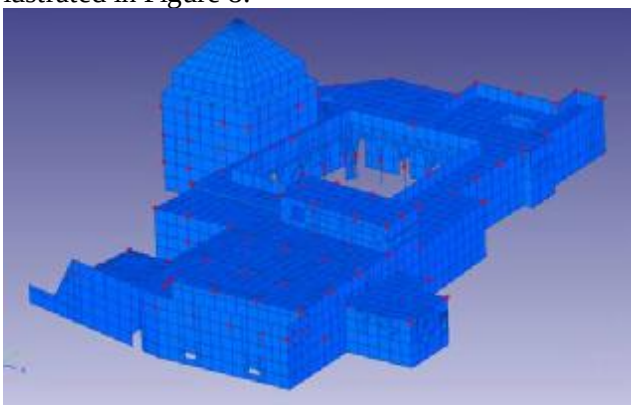

Figure 8 – Finite element model of the Zaouia of Sidi Kassem Djilizi mausoleum in Tunis. The dots give the sensor placement resulting from an optimization process.

On the other side, the Egyptian partner (El Attar-Osman, 2004) preferred to have an informative on the mode of the minaret in order to locate the sensors

in the right way. The estimated modes, and their frequencies, are illustrated in Figure 9. The Tunisian partners recently conducted the experimental campaign, while the Egyptian partner should start in the near future.

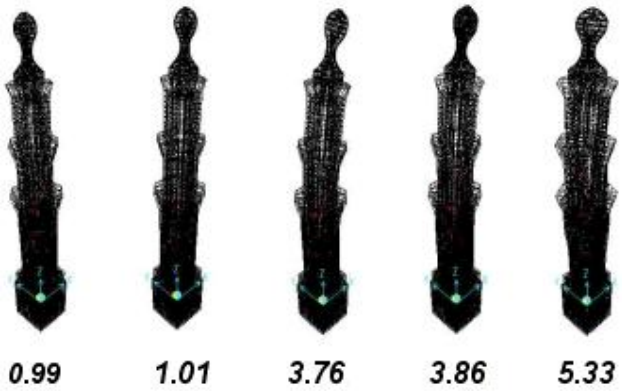

figure 9 – First five modes of the Egyptian minaret: the number provides the relevant frequencies in Hz.

The rather simple structural scheme selected in Cyprus (Chrysostomou et al., 2004) allowed that partner to conduct the experimental campaign, to calibrate the model parameters (Figure 10) and to achieve a diagnosis. The Cyprus partner is now working to the implementation of the retrofitting, which will be then validated in an experimental way by a second experimental campaign.

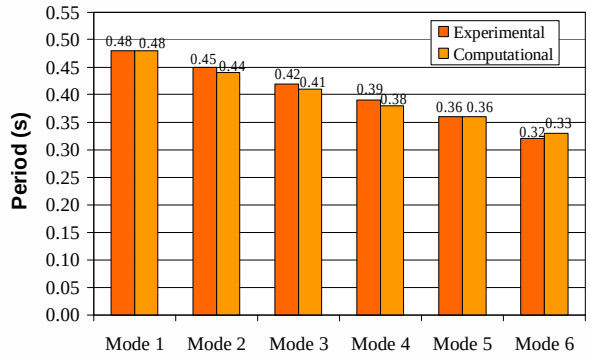

Figure 10 – Comparison of experimkental and numerical results for the Cyprus aqueduct.

4 MONITORING SPECIAL FEATURES

The development of wireless sensor networks is an obvious demand coming from the picture at the bottom of Figure 3. Wired solutions can be accepted a few hours/days, but they result too invasive for long term monitoring, as the one required by the retrofitting validation process.

A prototype platform commercialized in the US, and working on the basis of a dedicated protocol enabling sequential interrogation of sensors by the central unit, was shown to be inadequate for the pursued application (Casciati-Rossi, 2003) (Casciati et al., 2004 and 2005. It is worth noting that the platform enables a sensor to send continuously accelerations to the central unit 10 meters away and loss of data is possible.

Three wireless platforms were assembled at the author's laboratory.

1) The first one mounts a 24XStream is MaxStream's longest range, low power OEM RF module developed for worldwide use (2.4 GHz) (Figure 11). Here is a list of features:

- Plug-and-communicate (default mode - no configuration required).
- True peer-to-peer network (no need to configure a "Master" radio).
- Transparent mode supports existing software applications and legacy systems.
- Addressing capabilities provide for point-to-point and point-to-multipoint networks.
- Uses Standard AT commands and/or fast binary commands for changing parameters.
- Native RS485/422 (multi-drop bus) protocol support.
- Support for the RS232 protocol
- Retry and acknowledgements of packets provides guaranteed delivery of critical packets in difficult environments.
- Networking features allow up to 7 independent pairs (networks) to operate in close proximity.
- Multiple low power modes including shutdown pin, cyclic sleep and serial port sleep for current consumption as low as 26 A.
- Host interface baud rates from 1200 to 57600 bps.
- Signal strength register for link quality monitoring and debugging.
- 9th bit parity support (None, Even, Odd, Mark, Space)

Figure 11.- The 24XStream card

2) AirborneDirect (Figure 12) is a family of fully integrated 802.11b wireless LAN bridge products designed specifically to provide wireless LAN and Internet connectivity to industrial, scientific, medical and automotive applications. The highly integrated hardware and software enables plug-and-play capabil-

ity. This significantly reduces the complexity of wireless system deployment and network connectivity. With three AirborneDirect Serial Bridges, one creates a connection between an 802.11b wireless LAN device and a Serial port. The Bridge transparently conveys data between the device with RS232, RS422 or RS485 interface and a wireless LAN. The Bridge opens up the world of remote device monitoring and management, enabling data loggers, medical and industrial monitors, data acquisition and control systems, programmable controllers and a host of other applications connectivity to the LAN or Internet.

Figure 11 - DPAC AirBorne card

The previous devices were successfully implemented in the laboratory for internal use. But, for the monitoring of monumental systems, the devices described below are promoted.

The WRCV16 is a 16-channel sensor receiver module. Its main features are:

- Power supply range: 6V to 24V;
- Sixteen analog channels are reconstructed from the data coming from nearby transmitters (such as the WSEN03 module);
- RS-232 interface for configuration via an easy-to-use terminal shell (e.g., using Hyperterminal);
- Frequency bands: 402, 424, 426, 429, 433, 447, 449, 469, 868 and 915 MHz;
- -55 to +85°C operation.

The WRCV16 is a 16-channel wireless sensor receiver module. It was designed to receive data coming from nearby WSEN03 modules and to reconstruct the original analog signals. The WRCV16, coupled with a number of WSEN03 modules, can act as a wireless acquisition system. If the original analog signals are not needed, the system can output the signals digitally through its RS-232 interface.

The module is remotely configurable. Once powered-up, it waits for configuration data to be received and then starts sampling the analog channels at the given sampling frequency and with the given input range. Most ISM radio frequency bands are covered by the on-board RF transceivers (402, 424, 426, 429, 433, 447, 449, 469, 868 and 915 MHz).

The WSEN03 is a 3-channel sensor transmitter module. Its own features are:

- Power supply range: 2V to 9V;
- Battery power supply: at least 2 NiMH batteries, but other combinations are allowed as long as the supply voltage does not exceed 9V;
- Three differential, multi-range, 16-bit analog channels (±1.2V, ±2.4V, ±4.8V, ±9.6V), with overvoltage protection up to 100V;
- Remotely configurable;
- Frequency bands: 402, 424, 426, 429, 433, 447, 449, 469, 868 and 915 MHz;
- Optional Silicon Designs Model 1221 low-noise accelerometer on board, jumper selectable;
- -55 to +85°C operation

The WSEN03 is a battery-powered 3-channel wireless sensor transmitter module. It is optimized for use with a power supply ranging from 2V to 9V. Therefore, several battery configurations are allowable, either rechargeable or not. Two inexpensive NiMH batteries, with a voltage between 2V and 2.5V, make the smallest working battery pack.

The analog section features three 16-bit, fully-differential channels. Thanks to an adjustable gain preamplifier, the following input ranges are possible: ±1.2V, ±2.4V, ±4.8V, and ±9.6V, thereby fitting most types of sensors. Overvoltage protection is built-in and protects the unit against overvoltages up to 100V. Single-ended sensors can easily be accommodated by shorting one of the terminals to ground.

The unit is capable of providing power to sensors. Several voltages are generated and made available for direct connection to external sensors (+3V, +5V, +12V and –12V).

Optionally, the board can host a Silicon Designs Model 1221 low-noise accelerometer. Even in this case, the remaining two analog channels may still be connected to external sensors.

The module is remotely configurable. Once powered-up, it waits for configuration data to be received and then starts sampling the analog channels at the given sampling frequency and with the given input range.

Most ISM radio frequency bands are covered by the on-board RF transceiver (402, 424, 426, 429, 433, 447, 449, 469, 868 and 915 MHz).

Diagnosis could be pursued by elaborations in the same microprocessor on this board by developments in the space of observed data (Casciati, 2005).

Each sensor, actuator or associated printed circuit board requires an adequate power supply. However, a wireless sensor is not truly wireless if it requires power supply cables; hence, the need for very low-power systems and for some power harvesting technique. The issue of power harvesting has been around for some time but, as of today, only limited amounts of power can be gathered by power harvesting (Casciati et al. 2003) (Roundy et al., 2003).

For civil engineering applications, three power sources seem particularly suitable: solar power, electromagnetic induction and vibrations.

Solar power is well known. A solar cell sized 1.5 by 1.5 cm gives a power of 5 mW in full sunlight. Unfortunately, this value can drop by 80% depending on weather conditions, but it can still be enough for a very low-power sensor.

Electromagnetic induction is only viable for very short-range and low duty cycle applications. The magnetic fields required fall easily outside of the legal range.

Vibrational energy is very promising, as sensors would be able to convert local vibrations into electrical energy without needing high electromagnetic fields. However, the achievable power density is still low. Two types of such harvesters are available today: magnetic and electrostatic, the electrostatic type being more efficient in principle. Current research is focusing toward developing MEMS electrostatic harvesters. However, as of today, such devices are not yet available.

For the sake of trying a vibrational power harvesting device, the author developed a simple device for converting low-frequency vibrations into electrical power (Casciati et al., 2005). The device is of the magnetic type. A permanent magnet attached to a flexible ledge forms a spring-mass system. Vibrations cause the magnet to oscillate. The magnet moves inside a coil and generates a voltage according to Faraday's law of magnetic induction. The available power is in the range of 1 mW, which could be fine for a very low-power sensor board or for charging a small battery. Granted, rectification of such a voltage with the aim of charging a battery reduces the amount of available power. Schottky-barrier diodes, with their very low forward voltage drop, usually help improve the overall efficiency.

5 CONCLUSIONS

This paper has the ambition to convince the reader that application of structural monitoring to the monumental cultural heritage form a discipline by itself, with a little to share with applications in brother areas of civil and infrastructure engineering.

The main issues lye in the non invasive character that any intervention on monuments must possess. This is specially true when the goal is to verify the efficiency of a retrofitting solution which would require long term observation. As a consequence wireless networks must be adopted and special power harvesting procedures must be pursued.

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