# Structural Health Monitoring of the Basilica S. Maria di Collemaggio

V. Gattulli, F. Graziosi, F. Federici, F. Potenza & A. Colarieti
*CERFIS, University of L'Aquila, Località Monticchio 67040, L'Aquila, Italy*

M. Lepidi
*DICCA, University of Genoa, Via Montallegro 1, Genoa, Italy*

ABSTRACT: The work deals with the main findings obtained during the development of a permanent structural health monitoring system for a monumental church, the Basilica S. Maria di Collemaggio, strongly damaged by the 2009 L'Aquila earthquake. Ongoing studies on the causes of the partial collapse occurred in the transept area have accompanied the monitoring system design and field testing. Benefits and critical issues related with the use of the wireless sensor networks technology are analyzed in the specific case of monumental buildings monitoring. The specific features of the implemented system, purposely designed to detect low-amplitude earthquake-induced vibrations, are discussed. The information collected during one-year data acquisition is summarized, together with critical observations on the operating system. The modal signature extracted from the acceleration measurements has been compared with finite element models, furnishing valuable results to evaluate the effectiveness of the temporary scaffolding structures. Finally, specific features concerning a secondary wireless network of crack propagation sensors are presented.

## 1 INTRODUCTION

Structural health monitoring is an emerging tool for reliable structural assessments. Efficient monitoring programs may help in the characterization of the progressive decay of structural performances, both in the short and in long term, providing useful information for optimized maintenance and safety.

Although the importance of monitoring action is widely recognized, the deployment of monitoring systems is still limited by some critical factors: high costs of the measurement equipment, difficulty in installation due to large instruments size and need of a wired communication and power infrastructure.

In recent years, wireless communication, low power computing and sensing technology has paved the way to overcome these problems, with the application of Wireless Sensor Networks technology to face Structural Health Monitoring problems (Federici et al 2012, Liu et al. 2012).

The paper describes the design, deployment and validation of a wireless sensor network for structural monitoring of a monumental structure, the Basilica Santa Maria di Collemaggio at L'Aquila, Italy. The system is specifically designed for seismic and dynamic response analysis based on acceleration, crack opening and wall inclination measurements.

Since 1999 the Structural Engineering Department (DISAT) of the University of L'Aquila pursued a wide campaign of experimental measurement on the building, leading to the formulation and updating of finite element models (Antonacci et al. 2001).

In April 2009 a 6.3 Mw earthquake struck the city of L'Aquila, causing considerable damage to the Basilica. A partial collapse occurred in the transept area, caused the breakdown of the dome, and dramatically altered the whole structural characteristics.

The assessment of the changes occurred in structure's behavior, together with the analysis of the structural modifications coming out from successive consolidation and restoration interventions, required the setup of a permanent monitoring system. Such a monitoring system is part of a wide monitoring program supported by the Italian Civil Protection, and it is one of the first totally based on Wireless Sensor Networks technology (Antonacci et al. 2011).

The system development can be broadly divided into two distinct phases: the design and deployment of an accelerometric monitoring network (essentially designed to capture the global seismic response) and the design and deployment of a second network for wall inclination and crack width local measurement.

The paper is structured as follows: Section 2 briefly summarizes the state-of-the-art of monitoring systems of infrastructure, specifically concerning systems based on wireless sensor networks. Section 3 briefly describes the operational scenario and details the implementation of the monitoring networks. Section 4 illustrates the analysis of the data collected. Concluding remarks are finally pointed out.

## 2 WIRELESS SENSOR NETWORKS FOR STRUCTURAL HEALTH MONITORING

In recent years, progressive developments in wireless communication, low power computing and sensing technology has led to the application of Wireless Sensor Networks technology to Structural Health Monitoring problems.

A wireless sensor network consists of multiple autonomous sensing devices communicating to each other via a radio connection. New generation sensors (e.g. MEMS technology based accelerometers, fiber optic sensors, piezoelectric sensors) with small size and low power consumption provide greater deployment flexibility.

Wireless technology, however, presents some serious drawbacks: for example, measure synchronization can be extremely more problematic than in the wired case. Moreover, battery-powered nodes heavily relies on duty cycling techniques for energy saving. This aspect is extremely limiting for long term monitoring applications (Park et al. 2005). Several solutions have been presented in literature to address these issues (Paek et al. 2005, Niu et al. 2010, Boyle et al. 2011). Illinois Structural Health Monitoring Project presented a hardware and software wireless sensing platform specifically designed for structural health monitoring applications. The solution (Mechitov et al. 2006) is based on a general purpose wireless communication and computation platform, the Imote2 wireless node manufactured by Memsic. The platform is supplemented by a sensor board (SHM-A) specifically designed for structural monitoring. A custom management software (ISHMP Toolsuite) based on TinyOS operating system allows easy management of sensor data acquisition and communication. The software tool suite integrates a multi-hop routing protocol (AODV) in addition to an original data synchronization protocol, which combines FTSP network synchronization and a specially developed local delay correction algorithm (Rice et al. 2011). ISHMP solution has been successfully employed in Korean Jindo Bridge monitoring project (Nagayama et al. 2011, Cho et al. 2011).

Anyhow, the experimental applications of wireless sensor networks are still limited, with traditional monitoring solution remaining on a dominant position. The Italian Department of Civil Protection maintains and utilizes an extensive accelerometric monitoring network (Spina et al. 2011). The system is often integrated and strengthened by temporary monitoring networks (e.g. after catastrophic events in order to monitor relevant or strategic sites during the post-catastrophe emergency phase), which are managed also by the Department, by local governments or other entities, such as Universities. OSS main monitoring network is an accelerometric monitoring system installed on public buildings, bridges and dams. Each structure is monitored by up to 32 force balance accelerometers wired connected to a central acquisition and transmission unit. Recently, the RAMSES monitoring system, comprising three MEMS accelerometer based sensing wireless unit per building has been introduced. Moreover, a GSM communication based mobile monitoring system (OSM) is frequently used in post-disaster damaged buildings monitoring.

## 3 STRUCTURAL HEALTH MONITORING OF THE BASILICA DI COLLEMAGGIO

The basilica S. Maria di Collemaggio is the most important church in the city of L'Aquila, Italy. The church has a central nave, which measures 61 *m* in length and 11.3 *m* in width and two side aisles measuring 7.8 *m* and 8.0 *m* in width respectively. Naves and side aisles are separated by two series of seven columns with a height of 5.3 *m* and an average central section of about 1 *m* in diameter. Four external walls, with a masonry thickness varying from 0.95 *m* to 1.05 *m* are connected on two sides with the church façade and transept area. Other adjacent structures are partially connected with the Basilica main body: an octagonal tower connected on one side of the façade and another masonry building adjacent for about 40% of the external walls. The church has a wooden roof supported from trusses placed in a cross-sectional direction respect external walls. The dynamic behavior of the Basilica was characterized by means of numerical and experimental studies conducted before the occurrence of the 2009 L'Aquila earthquake. The earthquake caused a partial collapse of the structure in the transept area.

The will to deepen collapse possible causes and to investigate possible modification of structure dynamics response after retrofitting has led to the development and successive deployment of a structural monitoring system along the damaged church. In order to explore possible advantages arising from the use of innovative technologies (e.g. wireless communication and innovative sensing elements), the system has been based on a wireless sensor network. According to the project requirements, the work consists in the implementation of two main system: an accelerometric network for dynamic response measurement and a secondary network for crack width and wall inclination monitoring.

### 3.1 *Accelerometric Monitoring System*

The first phase of the system deployment has included the design, implementation, installation and test of an accelerometric monitoring network. The main goal was an accurate measurement of the building dynamic response, both to environmental actions and to the low-amplitude seismic events which occasionally continue to interest the site.

Memsic Imote2 wireless communication platform, along with ISHMP derived SHM-A board were chosen as main monitoring platform. Each SHM-A board includes ST microelectronics LIS344ALH MEMS tri-axial accelerometer, Sensirion SHT11 temperature and humidity sensor, and TAOS 2561 luminosity sensor. The board features also an advanced 16 bit analog to digital converter, the QF4A512 model by QuikFilter. Performance characteristics of MEMS accelerometer relevant to the present analysis are resumed in Table 1.

Table 1 - LIS344ALH mechanical characteristics

| Feature | Value |
|---|---|
| Input Range | ±2, ±6 g |
| Sensitivity | $V_{dd}/5$ @ ±2 g |
| | $V_{dd}/15$ @ ±6 g |
| Bandwidth | 1.8 KHz |
| Noise Density | 50 μg/√Hz |
| Non linearità | ±0.5 % FS |
| Cross Axis | ±2 % |

Imote2 wireless communication platform includes Marvell Xscale PXA271 processor and Texas Instruments CC2420 2.4 GHz, 802.15.4 compliant radio transceiver. Processor chip features a processor core with a clock frequency of up to 416 MHz, with the possibility of radical downscaling (down to 13 MHz) for low power consumption, SRAM and Flash memory bot for an amount of 32 MB.

The board is actively supported by TinyOS operating system, both in 1.x and 2 versions. ISHMP developed a software tool-suite based on TinyOS 1.x, which address specific problems of Structural Health Monitoring application. Implemented wireless sensor nodes, along with FTSP based synchronization and AODV multi-hop routing from ISHMP toolsuite are the main software components used in the accelerometric monitoring system.

A total of 16 sensor nodes, conveniently installed in custom IP-45 compliant packages, were deployed along the church on June 2011.

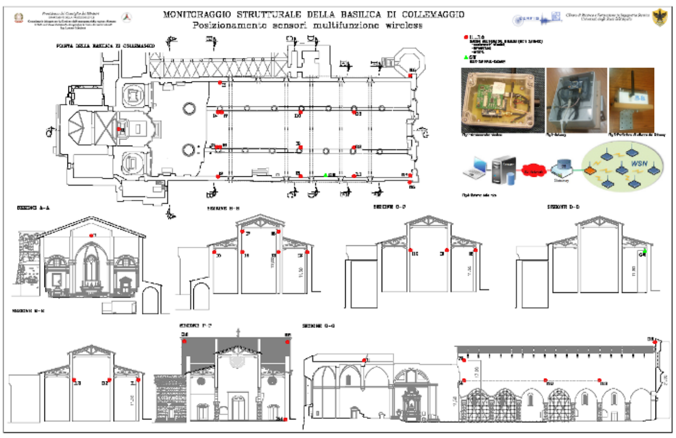


Figure 1. Drawings for the placement of the 16 smart sensors installed at the Basilica di S. Maria di Collemaggio.

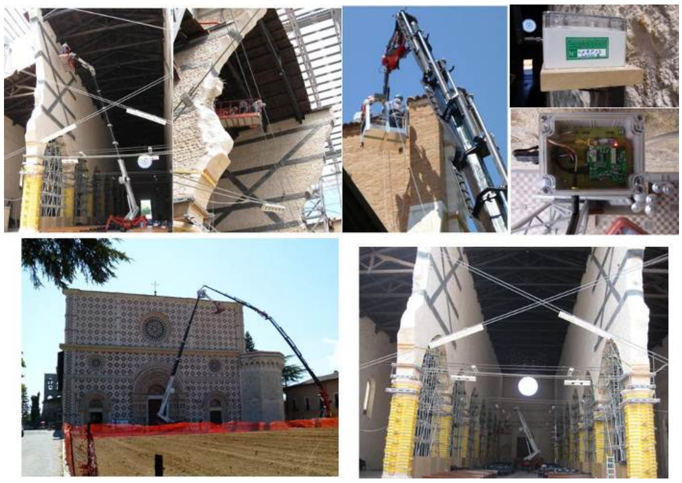

Figure 2. Installation phases of the monitoring system: a) b) sensor positioning on the central walls of the nave, c) sensor positioning beyond the facade, d) f) sensor views, g) on-site testing, h) sensor positioning at the end of the nave walls.

The majority of sensor nodes were placed inside the structure, ten along the main nave, one at the base of a column base and one in the transept area. Two sensor nodes were instead placed externally, at the top corners of the church facade (Fig.1).

A single board computer, connected with a network apparatus, acts as monitoring system gateway. The network apparatus guarantees 3G connectivity (for the automatic uploading of the measurement results to a remote server) and Wi-Fi local connectivity (for the direct access to the monitoring system; this feature is useful when performing local tests – as the operator don't needs an internet access to interact with the network – and as a backup redundant system in case of down of the 3G network access).

The gateway is connected to an Imote2 node, which acts as sink for the network: it forwards operating commands from the gateway to the leaf nodes and collects measurements data. Each leaf node communicates with the sink by means of a multi-hop routing protocol, thus allowing to effectively cover the wide area of the church. The central gateway runs a measurement scheduling application, which automatically handles data acquisition on leaf nodes, measured data collection, data compression and load on a remote server machine.

Both the gateway subsystem and leaf nodes are network powered. This choice, apparently counterintuitive, has two main motivations. First, the research for a coverage of the dynamic response as far as possible temporally extended prevents from the use of duty cycling energy savings techniques. Moreover, any maintenance intervention (such as node battery replacement) requires the use of heavy-duty vehicles (trucks and cranes are needed to reach the heights at which sensor nodes are placed), and should then be avoided given the precarious state of the Basilica. An Uninterruptible Power Supply Device guarantees the continuity of monitoring system operability. Reduced possibility of TinyOS 1.x scheduler prevents the sensor nodes from simultaneously acquire data from sensor and transmit data to the sink node. A scheduling algorithm able to alternate two groups of node in the mentioned operation was developed. In such way it is still possible to obtain a continuous coverage of the dynamic response of the building.

### 3.2 *Crack and wall inclination monitoring system*

Phase two of the monitoring system development involves the deployment of crackmeter and inclinometer sensors in the Basilica. Some of the limitations described in section 3.1 (especially those related to software implementation), along with the end of commercial life cycle of Imote2 platform has led to the development of a novel custom sensing platform. The developed wireless sensing platform is currently at a prototype stage and is going to be installed in the Basilica in the near future. The node is based on Atmel Zigbit 900 module, which features Atmel AT86RF212 868 MHz, 802.15.4 compliant radio transceiver. Software stack won't be based on TinyOS system and will fully implement 802.15.4 protocol stack. Nodes will be battery powered: this choice is appropriate in case of crack width and inclination measurements, as the reduced measurement frequency allows an extensive use of duty cycle power saving techniques. The possibility of implementing energy saving techniques in the case of accelerometric time-extended measures will be also further investigated.

## 4 DATA COLLECTION AND ANALYSIS

The analysis of the data collected by the monitoring system has been anticipated by a preliminary phase, devoted to compare the performance of each single wireless node with a reference wired sensor in a controlled laboratory environment (Fig.3).

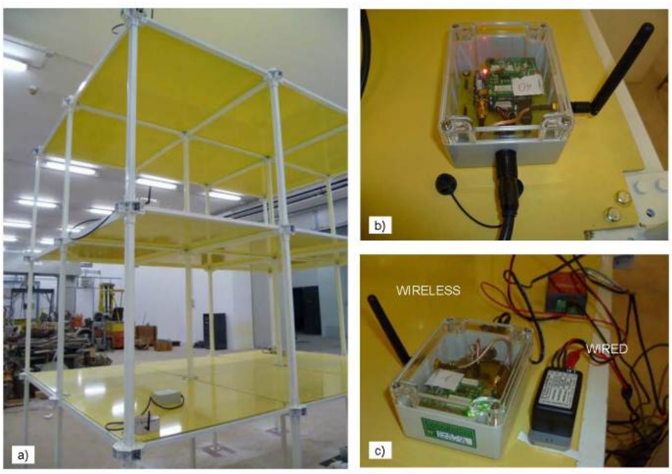


Figure 3. Light model (scale 1:3) of modular steel-made 3D frame: (a) basic configuration, (b) sensor-node of wireless network; (c) comparison with sensor of traditional wired network

### 4.1 *Preliminary validation phase*

The validation phase of the monitoring system had two main goals: the characterization of each wireless sensor node performances and the analysis of the structural dynamic response by means of the measured acceleration signals.

Two different types of test have been conducted using a modular structural steel frame to characterize a SHM-WSN in a laboratory environment. In the first series a direct comparison between a single wireless sensor (the above described IMOTE 2 type) and a wired accelerometer (SA107LN-Columbia) has been conducted (Fig. 3). With this configuration the frame responses both to a little impulse in longitudinal direction and under environmental noise have been recorded. Others tests have been made using six wireless sensors, two for each slab, placed at diagonally opposite corners. This particular experimental setup has been used to identify the main modal frequencies, shapes and damping. Again both impulsive and ambient tests have been performed. The results, here not reported for sake of brevity, were largely satisfying to the project purposes.

### 4.2 *Available on-site pre-earthquake data*

Before the occurring of the 2009 earthquake a numerical and experimental study permitted to characterize the dynamic behavior of the Basilica (Antonacci et al. 2001). The experimental data were firstly used to identify a modal model and then to determine suitable FE models of the church. Preliminary numerical analyses were carried out on the basis of several assumptions regarding: (1) mechanical parameters of masonry, (2) timber trusses of the roof, (3) restraints in walls and columns, (4) links among structural components. Afterwards the Basilica was excited at low vibration levels by an instrumented hammer and a tunable, mono-frequent mechanical exciter (vibrodyne). Several tests have been carried out, with different positions of the instruments and impact locations, in order to excite and to measure as many modes as possible.

The vibrodyne was located on the top of a lateral wall. The frequency responses were directly measured around the first two modes; these are the most important ones that describe the dynamic response of the church. Experimental data were used to identify natural frequencies, modal displacements and damping factors. The first campaign of tests permitted to recognize at least four major resonance peaks in the in the frequency range 0.8÷3.0 *Hz*. The first two peaks were close to the frequency values 1.25 and 1.7 *Hz*. Other peaks were present over 2 *Hz*. Two of them, around 2.5 and 2.7 *Hz*, were well defined in all tests. Secondary peaks, around 2.2, 2.3 and 2.6 *Hz*, were not always visible in all the responses; they indicated highly coupled modes. These peaks, however, were estimated to be less important: numerical analysis indicated that the participating mass of first two modes is at least 85% of total mass in the transverse direction of the church.

After retrofitting, all peaks were shifted to higher frequencies. The first two moved around 1.45 *Hz* and 2.12 *Hz* respectively. Other peaks were clearly visible around 2.6 and 2.95 *Hz*. Secondary peaks, which were not always visible in all the responses, were recognizable even in this case. Higher frequencies were a consequence of the increasing stiffness brought about by retrofitting. Other dynamic testing, performed on the façade, permitted to evidence that out-of-plane local modes of this element were in a frequency range higher than the transversal mode of the nave. Recently, the available data from the previous on-site dynamic campaign have been used to develop complete finite element models of the Basilica, able to reproduce the main modal identified characteristics and the collapse scenario (Gattulli et al. 2013). A campaign of numerical simulations has been conducted to evaluate the dynamic response of the Basilica together with the temporary retrofitting under small earthquakes.

### 4.3 *Experimental on-site post-earthquake data*

During the months following the installation, the monitoring system has been continuously enhanced and brought to complete and automatic management to sense seismic induced vibrations. During this path, test campaigns have been conducted with different induced source of vibrations such as hammer, ambient vibrations and free-vibration tests.

To date, six major events have been detected. Three are associated with the Emilia region and three are local events at L'Aquila. Table 1 shows the maximum accelerations registered during each earthquake. Recorded structural responses show prevailing out-of-plane oscillations of the nave walls.

Table 2. Recorded response of Basilica di Collemaggio.

| Earthquake | Date | Time (UTC) | Magnitude | Peak Response Acceleration [g] |
|---|---|---|---|---|
| Main Shock Emilia | May 5$^{th}$, 2012 | 2:03 AM | 5.9 | 0.0054 |
| Aftershock Emilia | May 5$^{th}$, 2012 | 1:18 PM | 5.1 | 0.0018 |
| Shock Ravenna | June 6$^{th}$, 2012 | 6:08 AM | 4.5 | 0.0014 |
| L'Aquila | October, 14, 2012 | 4:32 PM | 2.8 | 0.0072 |
| L'Aquila | October 10, 2012 | 2:52 AM | 3.6 | 0.0073 |
| L'Aquila | November, 11, 2012 | 3:37 AM | 3.2 | 0.0082 |

Table 3. Main peak frequency of measured acceleration spectra

| Earthquake | Macro-element D (Hz) | Macro-element C (Hz) | Macro-element B (Hz) |
|---|---|---|---|
| 20/5/2012 (main) | | | 0.85 |
| 20/5/2012 (after) | 0.95 | 0.95 | |
| 06/6/2012 | | | 1.02 |
| 14/10/2012 | 0.95 | 0.95 | |
| 30/10/2012 | 1.00 | 1.00 | |
| 16/11/2012 | | | 1.00 |

Low magnitude events furnish a sufficient level of energy to overcome the noise threshold of the monitoring system, allowing acceleration data recording characterized by sufficient vibration signature. Consequently, spectral analysis has been used to extract preliminary information from recorded data clearly evidencing the change in the main natural frequencies with respect the values measured in the pre-earthquake configuration. Table 3 summarizes the main findings emerging from spectral analysis of the recorded data. The main peak frequency of the out-plane acceleration spectra at different sensors located on each macro-element (Fig. 3a) are reported in Table 3, as extracted by different occurred earthquakes. Similar frequency values have been obtained for the first mode of the finite element model of Basilica in the post-earthquake configuration, including temporary scaffolding structures.

Fig. 4b compares the amplitude of the experimental transfer function (red dotted) with the transfer function amplitude of a modal model identified through the modal identification results obtained by the Goyder technique.

Additional information is provided by the comparison of pre- and post- earthquake experimental data. A stiffness reduction of the current configuration with respect to the pre-earthquake is evident. The current configuration is more flexible, since the principal mode period moves from 0.69*s* to 0.95*s*, suffering therefore a 37% increase.

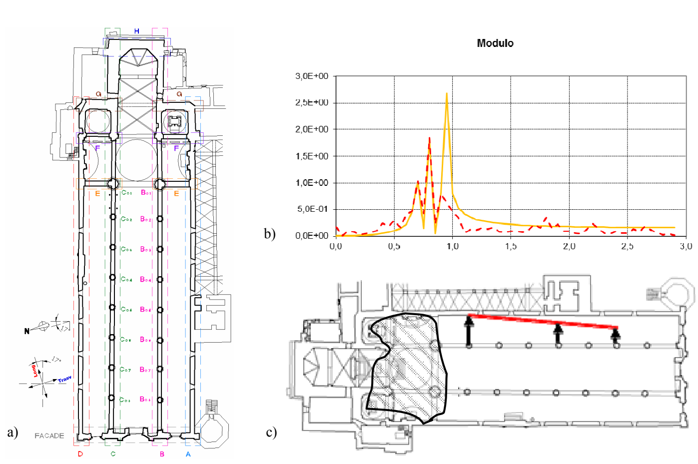


Figure 4. Basilica S. Maria Collemaggio: a) macro-elements definition, b) amplitude of the experimental transfer function c) identified modal shape.

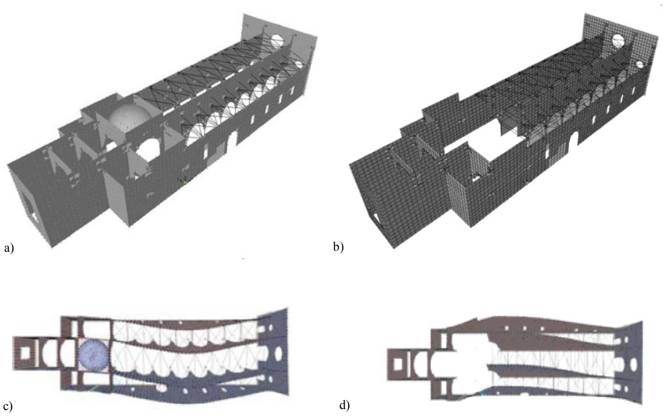


Figure 5. Finite element model and first mode shape: a), c) pre-earthquake, b), d) post-earthquake

### 4.4 *Numerical models*

Structural analyses have been conducted through a finite element model (Fig.5a,c), allowing the characterization of the seismic adequacy, in the pre-earthquake state (Gattulli et al. 2013) and in the post-earthquake taking into account temporary scaffolding structures (Fig.5b,d). Pre-earthquake linear structural analyses using the design response spectrum provided by the Italian code have evidenced the strong vulnerability of the nave walls, especially the interior ones, with respect to transversal seismic actions, even in the presence of the light steel bracing systems connecting them.

The absence of the transverse main arch due to the collapse of the transept reduces the transversal seismic adequacy.

Table 4. Modal period and frequency inferred from Basilica finite elements model, pre and post earthquake comparison

| Mode | Pre-earthquake model | | Post-earthquake model | |
|---|---|---|---|---|
| | Period [s] | Frequency [Hz] | Period [s] | Frequency [Hz] |
| 1 | 0,6902 | 1,4490 | 0,9488 | 1,0540 |
| 2 | 0,4520 | 2,2123 | 0,5161 | 1,9375 |
| 3 | 0,4048 | 2,4701 | 0,4209 | 2,3758 |
| 4 | 0,3450 | 2,8986 | 0,3703 | 2,7005 |
| 5 | 0,3268 | 3,0604 | 0,3365 | 2,9719 |

## 5 CONCLUSIONS

This paper described the design, deployment and verification of a structural health monitoring system for a monumental building, the Basilica S.Maria di Collemaggio in L'Aquila, Italy. Measured and numerical data have been continuously integrated during one-year activity in order to perform a safety assessment before and after the earthquake, which struck the structure in 2009. It has been possible to analyze various critical issues related to the use of a wireless network of sensors, such as synchronization issues and MEMS sensors noise. Among the main results, monitoring action has allowed to identify reliable finite element model which have permitted the evaluation of the seismic adequacy according to the Italian code.

## REFERENCES

Antonacci, E., Beolchini, G. C., Di Fabio, F. & Gattulli, V. 2001. The dynamic behavior of the basilica S. Maria of Collemaggio, *Proc. 2nd Intern. Congr. on Studies in ancient Structures*, Instanbul, Turkey, 2001.

Antonacci, E., Ceci, A., Colarieti, A., Gattulli, V., Graziosi, F., Lepidi, M. & Potenza, F. 2011. Dynamic testing and health monitoring via wireless sensor networks in the post-earthquake assessment of structural condition at L'Aquila. *8th European Conference on Structural Dynamics, Eurodyn11*, Leuven, Belgium, 2011.

Boyle, D., Magno, M., O'Flynn, B., Brunelli, D., Popovici, E. & Benini, L. 2011. Towards persistent structural health monitoring through sustainable wireless sensor networks. *Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP), 2011 Seventh International Conference on,* Pages 323-328, 6-9 Dec. 2011

Cho, S., Park, J., Jo, H., Sim, S. H., Mechitov, K., Jung, H. J., Yun, C. B. & Spencer Jr., B. F. 2011. Structural Health Monitoring of a Cable-stayed Bridge Using Wireless Smart Sensor Network. *Engineering Mechanics Institute Conference (EMI2011)*, Boston, 4-2 June 2011.

Federici, F., Graziosi, F., Faccio, M., Gattulli, V., Lepidi M., & Potenza, F. 2012. An integrated approach to the design of Wireless Sensor Networks for structural health monitoring. *International Journal of Distributed Sensor Networks*, Article ID 594842.

Gattulli, V., Antonacci, E. & Vestroni, F. 2013. Field observations and failure analysis of the basilica S. Maria di Collemaggio after the 2009 L'Aquila earthquake. *Engineering Failure Analysis,* in press 2013.

Liu, W., Fei, X., Tang, T., Wang, P., Luo, H., Deng, B. & Yang, H. 2012. Application specific sensor node architecture optimization. Experiences from field deployments. *Design Automation Conference (ASP-DAC), 2012 17th Asia and South Pacific.*

Mechitov, K., Kim, W. Y., Agha, G. & Nagayama T. 2006. High-Frequency Distributed Sensing for Structure Monitoring. *Trans. of the Society of Instrument and Control Engineers (SICE)*, vol. E-S-1, no. 1.

Nagayama, T., Ushita, M. & Fujino, Y. 2011. Suspension Bridge Vibration Measurement Using Multihop Wireless Sensor Networks. *Procedia Engineering*, Volume 14, Pages 761-768

Niu, J., Deng, Z., Zhou, F., Cao, Z., Liu, Z. & Zhu, F. 2009. A Structural Health Monitoring System Using Wireless Sensor Network. Wireless *Communications, Networking and Mobile Computing, 2009. 5th International Conference on.*

Paek, J., Chintalapudi, K., Govindan, R., Caffrey, J. & Masri, S. 2005. A Wireless Sensor Network for Structural Health Monitoring: Performance and Experience. *Embedded Networked Sensors, 2005. EmNetS-II. The Second IEEE Workshop on.*

Park, C., Xie Q., Chou, P.H. & Shinozuka, M. 2005. , DuraNode: wireless networked sensor for structural health monitoring. *Sensors, 2005 IEEE*, Oct. 30 2005-Nov. 3 2005.

Rice, J. A. & Spencer Jr., B. F. 2008. Structural health monitoring sensor development for the Imote2 platform. *Proc. SPIE Smart Structures/NDE.*

Spina, D., Lamonaca, B. G., Nicoletti, M. & Dolce, M. 2011. Structural monitoring by the Italian Department of Civil Protection and the case of 2009 Abruzzo seismic sequence. *Bulletin of Earthquake Engineering*, Volume 9, Issue 1, pp 325-346