MEMSCON Newsletter

April 20, 2010

Issue 2

Radio Frequency Identification Tags Linked to on Board Micro-Electro-Mechanical Systems in a Wireless, Remote and Intelligent Monitoring and Assessment System for the Maintenance of CONstructed Facilities

MEMSCON Facts:

- Contract No: 036887
- Project total cost: 4.632.430 €
  EC contribution: 3.814.816 €
- Project Start Date: 1/10/2008
  Duration: 36 Months
- Coordinator:

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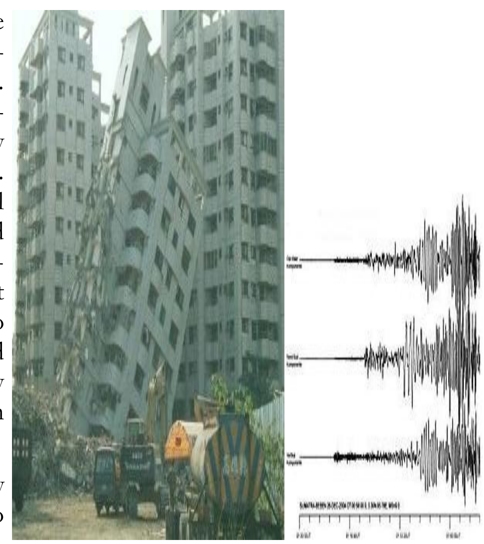
Inside this issue:

Wireless Technology for Seismic Assessment of Buildings

A year ago, on April 8, 2009, an earthquake struck the city of L'Aquila, in central Italy. Compared with the more recent event in Haiti, the shock in Italy shows that today European countries are well able to face seismic hazards and handle emergencies. However the economic effects of the L'Aquila earthquake will remain, in years to come. Most of the city was evacuated immediately after the shock, awaiting safety surveys of the buildings involved. Damage appraisal was based on visual inspection by more than four thousand volunteer engineers; but the huge number of damaged buildings meant that more than two months were needed to complete the survey. Only then could people re-enter their homes. It is easy to imagine the impact of this situation on the economy of the region.

MEMSCON is a project, co-funded by the European Commission, aiming to develop MEMS-based sensors for construction monitoring and to integrate them into an intelligent Decision Support System. Information from the sensors can then aid decisions on reconstruction and repair in reinforced concrete buildings. There has been rapid progress in sensing and data transmission techniques; this suggests that in the future we will be able to rely on a new generation of small and low cost networked sensors. These sensors can be installed in structures to provide accurate quantitative information on the physical status of the buildings while in service. This information can then be elaborated to assess the condition of the structure and to help decide what to do to ensure safety at reasonable cost.

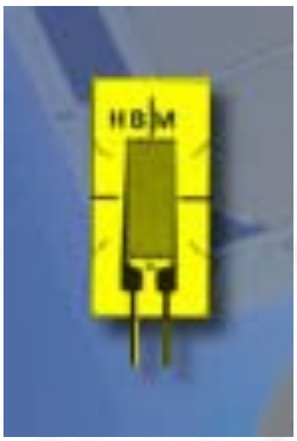


MEMSCON was launched in October 2008 and has since successfully produced and validated wireless sensor prototypes for seismic applications. This Newsletter presents advances in sensors, data acquisition hardware and wireless communication, as well as the first results of laboratory testing. MEMSCON Newsletters are sent to all members of the MEMSCON Mailing List: you are welcome to join if interested: please see details in the Contact Section on the back cover.

SEVENTH FRAMEWORK PROGRAMME

Grant Agreement No: CP-TP 212004-2
Project funded by : European Commission
Theme 4 - NMP-Nanosciences, Nanotechnologies, Materials and new Production Technologies

Development of the Hardware



Strain Gauge element

Wireless Acceleration Sensor Enclosure

This newsletter refers to the work performed for the first development phase of EC co-funded Research Project MEMSCON. Included are short descriptions of the system concept, the prototype modules for acceleration and strain measurements, the interrogator system and the antenna, the calibration and the factory testing procedures.

Wireless Strain Sensor

Wireless Strain Sensor Module is the key component to create a network of sensor nodes for building stress analysis. The basic sensor element is a resistive strain gauge which is placed directly on a steel reinforcement bar. Four such sensors are placed on each one of the column corner bars while special precautions are taken to protect the sensitive sensor from concrete. The commercial strain gauge selected is manufactured from HBM and have a measurement range of -30000 up to +30000 micro strains.

Since the strain gauge is the only component permanently buried within the column concrete, an external electronic device is connected to it via a 2-wire cable and the appropriate connector. The device which is battery operated, was designed to fulfill MEMSCON basic specifications: Ultra Low Power Consumption (no battery replacement ideally for the product life time of 10 years), accurate measurement of strain, wireless transmission of measurements through the radio network to the interrogator and includes:

1. Analog input management subsystem including Strain Gauge Bridge, Programmable Amplifier with digital offset and gain adjustments and Low Pass Filter.
2. Zigbee Wireless Rx/Tx module which allows connection of the device to a wireless Zigbee network for communication with the interrogator.
3. Microprocessor for global control of the device and reading of the analog strain measurements into digital format.
4. Real time clock that operates continuously measuring the actual date and time with 1 sec resolution.
5. Power supply subsystem that enables ultra low power consumption of the device.

Special firmware was developed that allows the device to wake up from “sleep” upon specified time intervals, connect to the RF network, take strain measurements and transmitting them to the interrogator and returning back to sleep. This time interval is expected to be 2-4 months, allowing the device to keep battery power consumption at very low levels. It should be noted that during sleep the device consumes only 54μW of power while when active it consumes 100 mW.

The electronic system, battery, antenna and strain input connector is all included in a small plastic box.

Wireless Acceleration Sensor

Wireless Acceleration Sensor Module measures, records and transmits on an RF network 3-axis acceleration data from specific building locations when an earthquake occurs.

Acceleration is measured by a 3-axis MEMS sensor commercially available from Analog Devices Inc. It is a completely digital output device that communicates with the system through an SPI interface.

The design of the acceleration measurement system is basically the same to the strain measurement system with the following differences:

1. Acceleration MEMS 3-axis sensor on board the system.
2. A serial EPROM memory has been added to permanently store acceleration measurements. This has been added for reliability purposes to ensure that the earthquake valuable data will not be lost in any case.
3. A micro vibration sensor, which is a small switch that is activated will very low force and wakes up the system from sleep at the beginning of an earthquake.

The firmware developed allows wake up of device upon activation of the micro vibration sensor, fast setup of the system devices (Accelerometer, Zigbee Transceiver) from the microprocessor, and recording of the acceleration measurements into the EPROM.

Special algorithms have been developed to minimize activation of the unit by false alarms (vibrations caused by other reasons than earthquakes).

Development of the Hardware (cont)

When recording is finished and data are safe into the EPROM, the system attempts to connect to the wireless network and transmit the measurements along with timestamps acquired from the real time clock to the interrogator.

The power consumption of the unit is similar to the strain sensor unit.

Interrogator System and Antenna

The interrogator connects to the base control and data recording PC system, controls the wireless network assigning addresses to the network nodes and acquires measurement data from all the nodes. The interrogator connects to the network nodes through a 4-element patch antenna array that was designed to offer high RF gain to the system. Simulation and verification of the manufactured antenna shows that a reliable link can be expected up to 1 km distances in an urban environment when sight of view is available. This distance will fall rapidly when obstacles exist. Signals from the four elements are combined and delivered to the radio transceiver unit which connects to PC via a USB link.

Network Setup & Testing

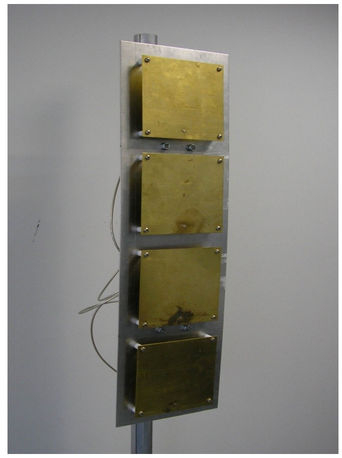
The network consists of the following units:

The interrogator which controls the network nodes and receives measurement data.

The end router device which is placed on the top of the building and have sight-of-view contact with the interrogator. It gathers data from the entire building internal network and transmits them to the interrogator.

The intermediate router devices. These are used to gather data from their lower building store router and pass them to the router above them until data reach the top router. Intermediate routers are actually the acceleration sensors which have this dual role in the system.

The end devices which are the strain sensor units placed on the building columns at the building base level. They connect to the last intermediate router placed in the basement and pass their data through the router sequence to the end router and finally to the interrogator.



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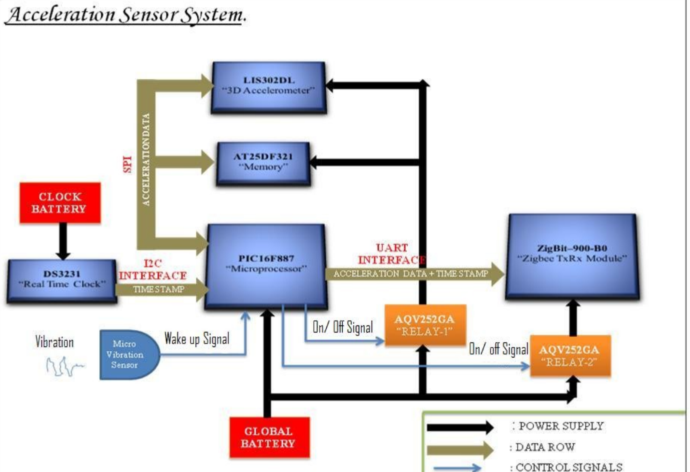
Acceleration Sensor System.



Design, factory testing and procedures

The design and manufacturing of the above prototypes was carried in several phases:

1. Determine the basic specifications of MEMSCON applicable to the design of the electronic units.

2. Evaluate main components (sensors, accelerometer, microprocessor, Zigbee modules etc) with commercially available evaluation boards.

3. Evaluate, using the Zigbee network, feasibility though extensive measurements (RF link quality and data BER) in urban and non-urban environments. Determine best network structure setup and link setup including design of interrogator antenna.

4. Manufacture prototype interrogator system. Test with small scale network to evaluate basic operation.

5. Design and manufacture prototypes of strain and acceleration sensor radio modules. Working on firmware, extensive testing and redesign for minor failures detected have been carried out.

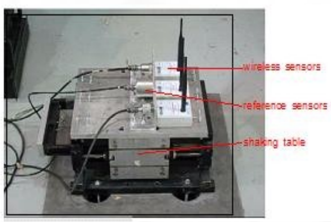
6. Manufacture of final strain and acceleration sensor radio modules. This task was developed as prototypes first and after that as full scale production of 66 strain sensor radio modules and 18 acceleration sensor radio modules. All modules were tested and passed a series of Factory Acceptance Tests.

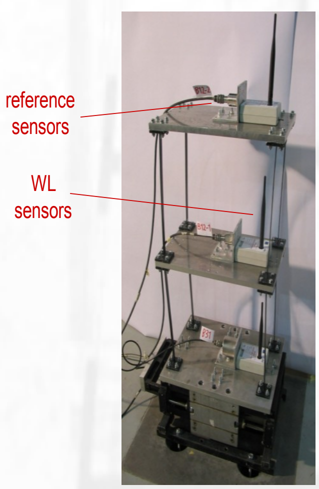
7. Calibration of every strain and acceleration sensor radio module. This was a sensitive procedure and special calibration apparatus was designed and manufactured. The calibration standard simulated the signal expected from the actual strain gauge and allowed accurate adjustment of the strain sensor unit analog input stage for gain and offset. Special calibration software was designed in a LABVIEW environment. All the calibration parameters and measured errors for every strain sensor have been recorded within this software.

8. Special arrangements in some strain and acceleration sensors for purposes of testing in a laboratory environment at the University of Trento, as reported in the following.

Validation of the accelerometers wireless network

The network of accelerometer sensors produced in the MEMSCON project is intended as a cost-efficient tool to estimate the damage related to seismic events. As a key test in the development process is to validate quantitatively the performance of the network, at the end of October 2009, when the first prototypes of three axial accelerometer nodes were ready, they were tested in a laboratory campaign. Three wireless nodes were mounted on a shaking table, back to back with high precision, wired piezo-electrical seismic accelerometers, and they underwent several vibration tests, using excitations of various shape, frequency and amplitude. The aim of the campaign was to investigate the accuracy and reliability of the wireless sensing system in condition similar to that experienced in field during a seismic event.





Installation of the system

The whole sensing system proved to be easy to install and manage. The nodes are activated by a switch and the base station can be connected via a USB cable to a standard PC. Acceleration measurements endowed with sensor identification tag and time-stamp are received via Microsoft Hyperterminal and can be easily stored and post-processed to plot graphs and tables. The direct connection between nodes and base station is reliable, as it experienced virtually no loss of packets during the whole laboratory campaign.

Node activation via vibration

To reduce the energy consumption, each sensing node is controlled by a hardware trigger using the micro vibration sensor, so that the node becomes active only when a vibration threshold of 20mg is overcome. Below this level, the node remains sleeping, saving batteries for a span of years. Once activated by a vibration sufficiently high, the node keeps on acquiring acceleration for a maximum period of 30 seconds, estimating every 5 seconds the amplitude (RMS) of the vibration along each of the 3 axes. Only if that amplitude is significant (according to a software threshold) the node does consider the signal relevant and transmits it to the base station. The conjunction of these hardware and software thresholds permits to minimize the power consumption of the node, avoiding the transmission of signals that are irrelevant for the seismic analysis: in this way a long life of the network is expected.

In the laboratory tests, we validated the efficiency of both the hardware and the software thresholds, finding out a totally reliably behavior, according to the prediction.

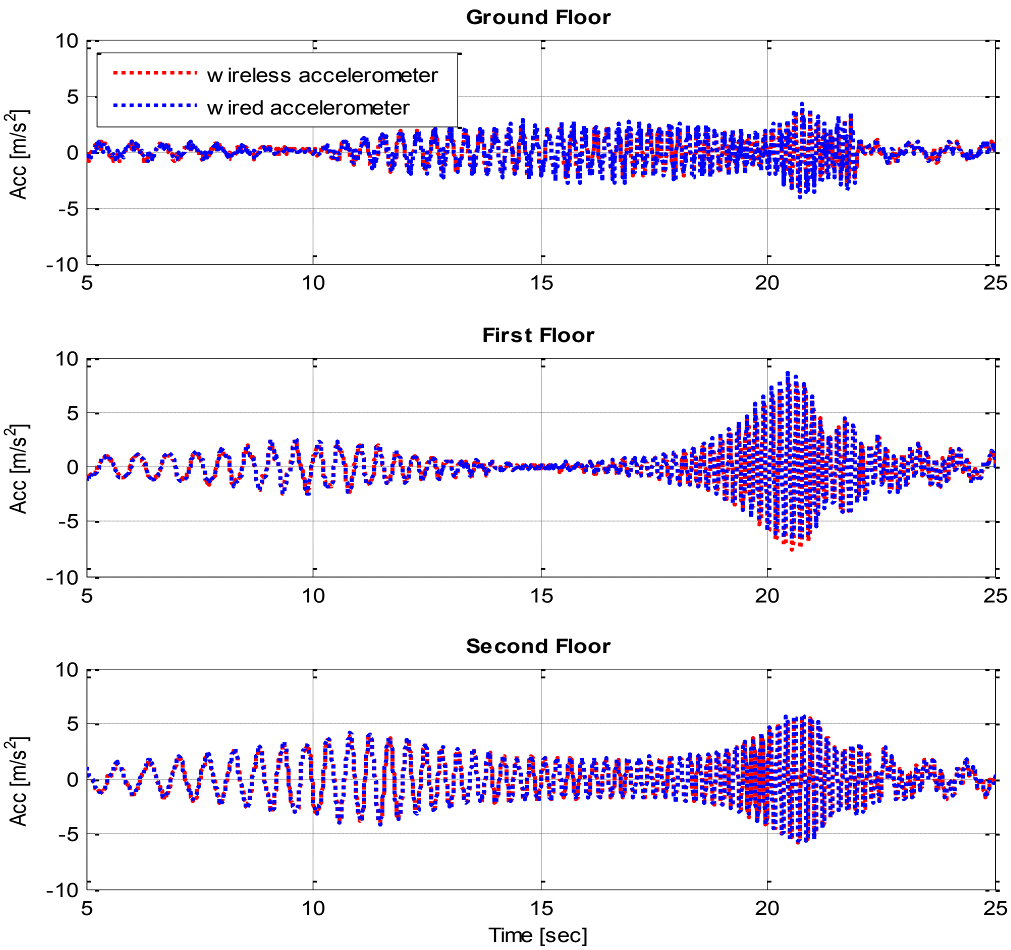
Testing Campaign

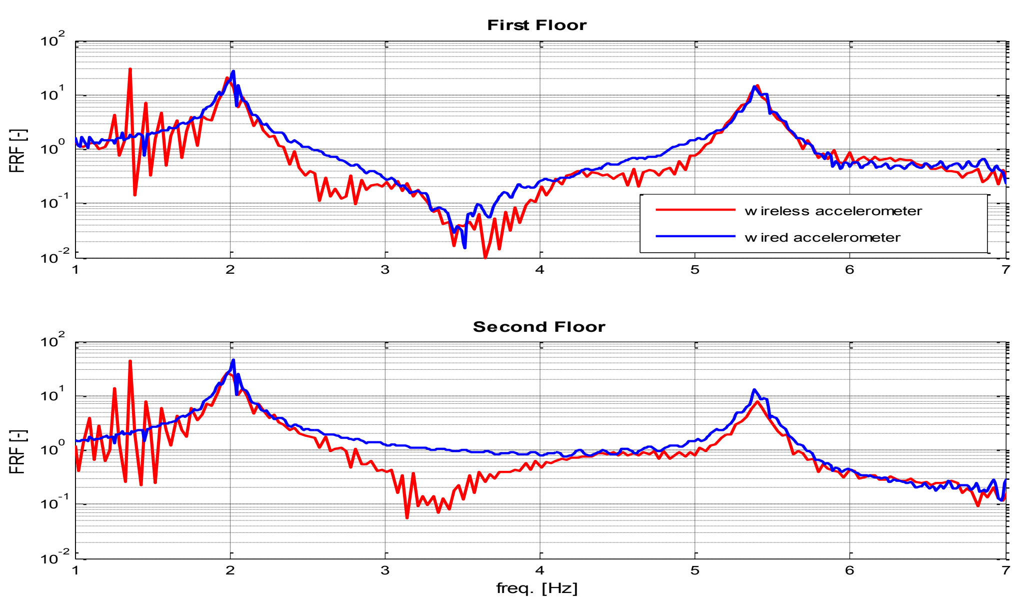
Two types of tests were performed:

- In the calibration tests, the three wireless nodes were mounted in parallel on the table. A double-sided adhesive tape was used to fix the nodes. Each axis was tested with harmonic excitation at different frequency in the range 1-20Hz, at amplitude ranging from +/-1m/s² to +/-4m/s². This sequence allowed calibrating the sensitivity of each node. As an outcome, the response of the wireless network presents a maximum discrepancy respect to the wired system in the order of 3%.

- To better simulate the operative conditions, the wireless sensors were later mounted on a two-storey metal frame, again back to back with the wired instruments. One sensor was placed on the table, to record the "ground" vibration, and the other two at the upper floors, to measure the frame response. We exited the frame both with frequency-sweeps and with seismic-like waves. The comparison between the vibrations recoded by the wired and the wireless systems, at each floor, during a sweep shows a very good agreement , in the same order of the resolution of the wireless system, which is equal to 18mg (=0.18m/s²). This kind of tests allows also estimating the mechanical properties of the structure employed in the tests (i.e. the metal frame) that corresponds to the building potentially damaged during an earthquake. The Frequency Response Functions between the ground excitation and the vibration on each floor, as estimated by the wired and wireless sensors are reported in the next page identifying the resonance and anti-resonance frequencies of the structure, which remains linear during the tests. The agreement is once again good, especially above 2Hz.

Validation of the accelerometers wireless network (cont)





Evaluation of the network and further steps

The accelerometer network proves to be reliable in the frequency range relevant to the seismic analysis, with an accuracy in the order of 20mg (=0.20m/s^2), and several three axial nodes can be employed simultaneously. Thus, the system seems easily applicable to an in-field construction.

The further steps in the development of the accelerometer nodes will be related to:

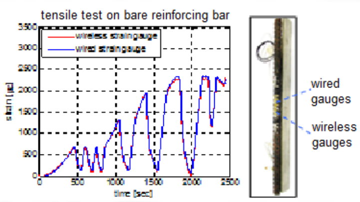
- the improvement of sensing resolution;

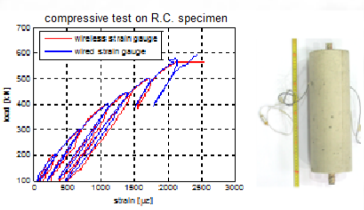
- the real-time synchronization of the nodes, allowing acquiring a reliable time-stamp years after installation;

- the extension of the threshold criteria to the whole network, not only to a single node; in fact, in the nodes produced in the phase II, the actual data transmission from all the sensors will be required only when different "sentinel" accelerometers, placed at different places along the structure, will perceive a significant level of vibration at the same time.

The accelerometer network proves to be reliable in the frequency range relevant to the seismic analysis, with an accuracy in the order of 20mg (=0.20m/s^2)

Validation of the strain-gauge wireless network





The validating campaign for the strain-gauge nodes aims at reproducing in the laboratory the operative conditions of a r.c. element inside a building, up to extreme scenarios.

In this preliminary phase of the MEMSCON project, the strain sensors employed are foil gauges available off-the-shelf, produced by HBM GmbH (with carrier dimensions 11x6mm and resistance 700 Ohms). The gauges are attached to ordinary reinforcing bars (made of steel B450C, with 20mm diameter), as those that are likely to be used in the construction of new buildings, utilizing a standard glue made of cyanoacrylate-adhesive and a silicon protective coating. The installation procedure follows step-by-step the instructions recommended by HBM, so that the time required to fix a gauge is about 30 minutes.

The sensors are connected one-to-one to the nodes via a standard transmission cable, and a single base station acquires signals from the many sensing nodes.

In the first laboratory campaign, that completed so far, the performance of the gauges were investigated in small specimens, tested under tensile and compressive load cycles.

The bars and the whole specimens were also instrumented with additional strain gauges wired to a high-precision interrogation unit, to compare in real-time the measurements flow deriving from the wireless network with reference values.

Despite in the in-field applications the network will be set to acquire few strain data per month, during the laboratory tests each wireless node acquired at a sample frequency of 3Hz, with a resolution of 20 micro-strains, and a maximum of two nodes were activated simultaneously. The measurement flow was gathered by using Microsoft Hyperterminal and post-processed.

The procedure proves to be very user-friendly: to make the network works and store the strain measures endowed with timestamp and sensor identification tag into a database, it is sufficient to activate the nodes and lunch the corresponding software.

Speciments and test outcomes

To investigate various performances of the network, three types of specimens have been produced and tested.

- The simplest way to check the accuracy of the system is

Workshop Announcement

First MEMSCON event:

The partners in MEMSCON are organizing a workshop on Structural Monitoring and Assessment of Civil Engineering Structures. It will take place on October 7, 2010 in Bucharest, Romania. The goal of this workshop is to provide a state-of-the-art report on recent research activities, technological utilization and commercialization activities in structural monitoring systems and software for the status-dependent maintenance and repair of constructed facilities.

This event will bring together European construction companies, owners of constructed facilities, insurance companies, policy makers and sector experts.

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Validation of the strain-gauge wireless network (cont)

to instrument bare reinforcing bars, not embedded in concrete; in facts, this allows avoiding all the uncertainties related to the random behaviour of the concrete. Therefore, two bare bars have been tested in tensile cycles of increasing amplitude, up to yielding and failure. The upper figure shows the outcome of a test: both the strain recorded by the wireless and that of the wired system are plotted vs time. The agreement between the two is very good, and can be quantified in 20micro-strains, in the same order of the resolution of the wireless system. Note that, independently of the acquisition mode (wired of wireless), the gauges becomes inactive at a strain of about 2200micro-strains, which is a predictable limit for the fatigue life of a glued sensor.

- To investigate the performance of gauges inside concrete, three instrumented reinforcing bars were embedded in a cylinder of concrete (length: 60cm, diameter: 13cm). The gauges were placed at the middle of the bar and protected by a sealant made of Butylrubber with aluminium foil. When the concrete was poured, a weakening was introduced into the mould, to induce a crack exactly at the instrumented section. The specimens were also instrumented with external sensors to measure the crack opening.

The last tests were devoted to analyze the behaviour of the gauges embedded into concrete in compression. Three concrete specimens (length: 30cm, diameter: 13cm) were produced, reinforced by the instrumented bar surrounded by a spiral stirrup to reproduce the effect of confinement. External long-base strain gauges were also applied to the concrete surface, to record the behaviour of the cover during the test. The specimens underwent cycles of increasing magnitude, up to the spalling of the cover and the crashing of the concrete core. Lower figure shows the load vs strain cycles, for both the wireless and the wired system. The measure, now in compression, ranges once again up to 2000-2500micro-strains, and the agreement is in the same order of the resolution.

Evaluation of the System Performance

The wireless network of strain gauges sensors works very well, without any problem in data acquisition or transmission. The gauges works in any operative conditions, and the limitation in the measurement ranges (about +/- 2.2millistrain) is related to the gluing technology, that is the standard one commonly used in civil application. These limits only permit to follow the beginning of the yielding

Dissemination

Most important conferences relevant to MEMSCON research area:

IEEE RFID 2010
14-15 April 2010
Orlando, FL, USA
http://ewh.ieee.org/mu/rfid2010/

Wireless
12-15 Apri 2010
Lucca, Italy
http://www.ew2010.org/

European Workshop on Structural Health Monitoring (EWSHM-2010)
29 June - 2 July 2010
Sorrento, Naples - Grand Hotel Vesuvio - Italy
http://structure.stanford.edu/workshop/past/announcement _ewshm2010_final.pdf

9th U.S. Nat'l & 10th Canadian Conf. on EQ Eng.: Reaching Beyond Borders
23-29 August 2010
Toronto - Westin Harbour Castle Hotel - Canada
http://www.2010eqconf.org

14th European Conference on Earthquake Engineering
30 August - 3 September 2010
Skopje-Ohrid, FYROM
http://www.eaee.boun.edu.tr/ecee/skopje2008.pdf

IEEE Sensors 2010
1-4 November 2010
Waikoloa, Hawaii, USA
www.ieee-sensors2010.org/

SPIE Smart Structures and Materials + Nondestructive Evaluation and Health Monitoring
6-10 March 2011
San Diego, CA, USA
http://spie.org/smart-structures-nde.xml

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Consortium

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