Laboratory validation of intelligent structure technologies

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Abstract

The aim in MEMSCON project is to develop MEMS-based sensors to be integrated in new Reinforced Concrete buildings for their protection against seismic events and settlement. The system involves deployment of both accelerometers and strain sensors. To date prototypes have been assembled from components available on the market, with the necessary design, packaging and programming. These intermediate devices do not now fulfill the target requirements, but they let us investigate the relevant features of the system. The prototypes were tested in the laboratory and this contribution reports the outcomes of the experiments. Validation tests highlighted limitations of commercial sensors: power consumption and accuracy for accelerometers, packaging systems for strain gauges. These limitations will be overcome by production of definitive sensor nodes which is scheduled for the end of the project.

Keywords: laboratory validation, accelerometers, strain gauges, packaging, reinforced concrete

1. Introduction

As explained elsewhere in these proceedings, MEMSCON mission is to develop a reliable and cost-efficient monitoring system to be integrated in new Reinforced Concrete (RC) buildings for their protection against seismic events and settlement. The system includes a wireless network within the building and a base station linking the building to a remote centre for data interpretation. Operating the system involves deployment of both accelerometers and strain sensors. Strain measurements are collected at the lowest level of the building, to estimate the vertical column loads and any variation due to settlement. Horizontal acceleration is measured by dedicated nodes at each level during an earthquake, allowing analysis of the seismic response of the whole structure.

The project has two main tasks: (i) development of the sensing network and (ii) development of software for remote data processing, structure condition assessment and for maintenance planning. The products will be validated both in the laboratory and in on-site applications. Task (i) includes creation of new dedicated instruments for strain and acceleration measurement. Both these devices will be based on RFID in MEMS [1], in small-size packages and with ultra-low power consumption. These nodes have been designed to improve their sensing performance with respect to that of existing technology [2].

Production of the definitive nodes is scheduled for end-2010. To date prototypes have been assembled from components available on the market, with the necessary design, packaging and programming. These devices do not now fulfill the target requirements, but they let us investigate the relevant features of the system. The prototypes were tested in the laboratory and this contribution reports on the current stage of the validation.

2. Strain gauges

The Strain Sensor Wireless Network is devoted to the assessment of settlement and of the activation of plastic hinges during an earthquake. Sensors will be placed directly on steel reinforcement bars, at the corners of each building column.

At this phase of the MEMSCON project, the strain sensors employed are foil gauges available off-the-shelf, produced by HBM GmbH. Since the gauge is the only component permanently buried in the concrete, the external electronic interrogation node is connected via a 2-wire cable with an appropriate connector. This battery-operated device was designed to partially fulfil the basic MEMSCON specifications: ultra low power consumption (no battery replacement ideally for the 10-year product life), accurate measurement of strain (20 $\mu\varepsilon$ resolution), and transmission of measurements via a wireless network to the base station.

The hardware developed for the node includes an analog input management subsystem, with a strain gauge bridge, a programmable amplifier with digital offset and gain adjustments and a low pass filter: when properly calibrated, this subsystem produces a voltage output accurately proportional to the strain applied to the sensor. The data transmission makes use of a Zigbee Wireless Rx/Tx module, and the node also has a microprocessor for global device control, conversion of analog strain measurements to digital format and a clock that operates continuously for current date and time with 1 sec resolution [3].

The electronic system, battery and input connector are all in a plastic box size 11x8x4cm, with an antenna. The base station assigns addresses to the sensing nodes, continuously waits and gives network access to any sensor that asks to transmit data. The acquired data can then be passed to the remote interrogation centre using a 4-element patch antenna array, designed to guarantee a high RF gain to the system.

The validating campaign for the strain-gauge nodes aims at reproducing in the laboratory the operational conditions of an RC element in a building, up to an extreme scenario. During settlement and, more often, during an

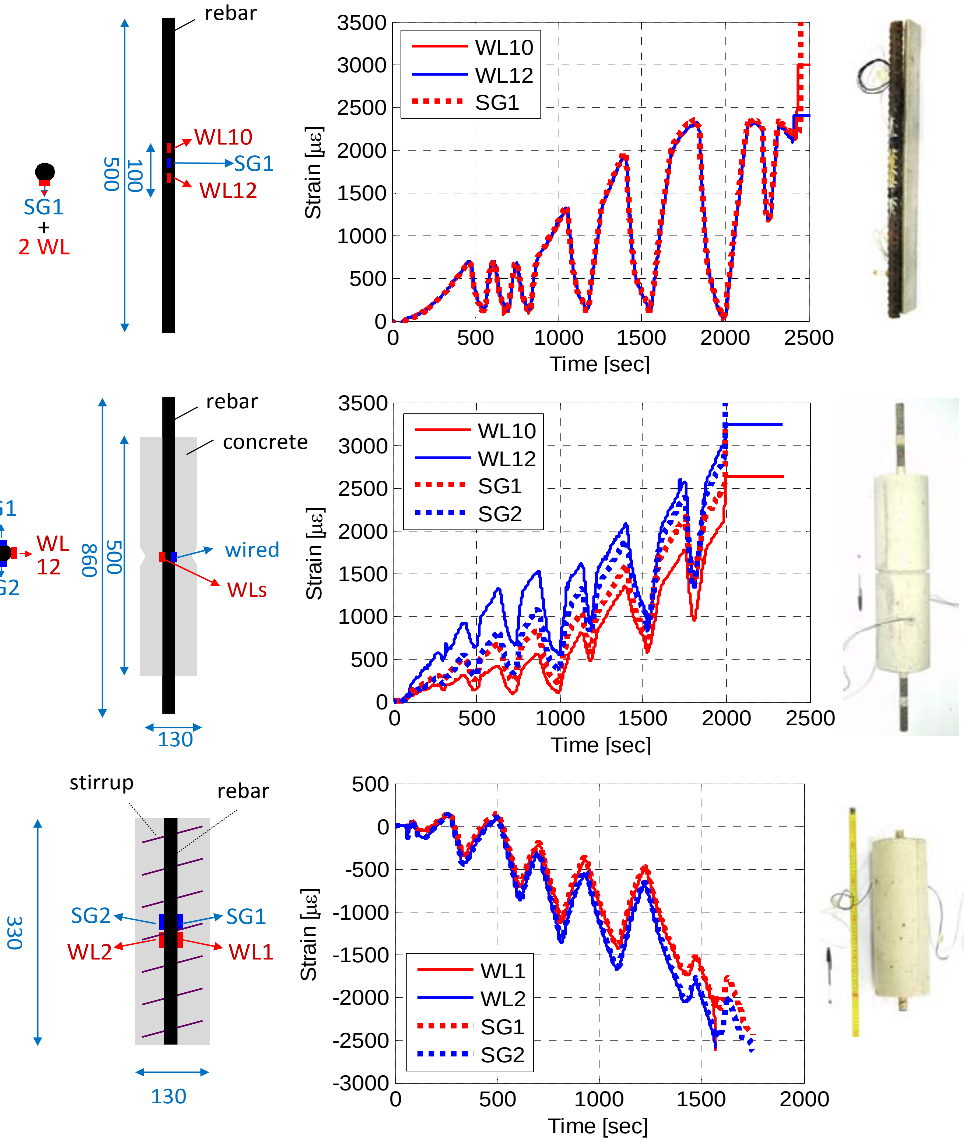

Fig. 1. Outcomes of a test on a bare bar (upper graph), a test on a bar embedded in concrete and tensile test (central graph) and a test on an embedded bar tested in compression (lower graph).

earthquake, the columns can undergo extensive damage including concrete cracks, cover spalling, crushing and reinforcement yield. As we use the wireless network to estimate the damage level during or after these events, we must investigate the network performance and efficiency under the same conditions.

The gauges were attached to ordinary reinforcing bars (steel B450C, 20mm diameter), with a standard cyanoacrylate adhesive and a silicone protective coating. The installation procedure follows the instructions by HBM, and so the time required to fasten a gauge is about 30 minutes. In the first laboratory campaign completed so far, gauge performance was investigated in small specimens, tested in tensile and compression load cycles. The bars and the complete specimens were also instrumented with additional strain gauges wired to a high-precision interrogation unit, to compare in real-time the data flow deriving from the wireless network with reference values. We adopted the same model of foil gauge, so that the difference between the performance of the wired and wireless systems depends only on interrogation and data transmission. Before starting the laboratory tests, both the clock and the voltage sensitivity of the wireless nodes were calibrated, and the sampling frequency set to 3Hz.

The simplest way to check the accuracy of the system is to instrument bare reinforcing bars, not embedded in concrete; this lets us avoid all the uncertainties related to the random behaviour of concrete. Therefore two bare bars, 50cm long, were tested in tensile cycles of increasing amplitude, up to yield and failure. Each bar was instrumented with 1 wired and 2 wireless and gauges, as shown in Figure 1 (upper graph). The same figure reports the outcome of a full test: the strain recorded by the wireless (continuous lines) and by the wired system (dashed line) are plotted against time. The agreement between the two is remarkable, and can be quantified in 20με, of the same order as the resolution of the wireless system. Note that, independently of the acquisition mode (wired or wireless), the gauges become inactive at a strain of about 2300με, which is a predictable value for the fatigue life of a glued sensor.

To investigate the performance of the gauges in concrete, three instrumented reinforcing bars were embedded in a concrete cylinder (length: 50cm, diameter: 13cm). The sensors were placed at the middle of the bar and protected by a Butyl rubber sealant with aluminium foil. When the concrete was poured, the mould was weakened, to induce a crack exactly at the instrumented cross section. The specimens were also instrumented with external sensors to measure the crack opening. Figure 1 (central graph) reports the strain time history, as for the previous test type. Two wireless gauges and two wired were arranged along the same cross section, where a crack is expected. The test shows that the sensors keep working up to the same level of strain as that applied to the bare bar, and the difference between the time histories can be easily attributed to the random behaviour of concrete under tension. In fact, during the test, asymmetrical cracks appeared along the specimen, which altered the load eccentricity and, consequently caused variation of the strain along the rebar cross section. The evolution of the load eccentricity during the test was consistent with the measurements derived by the external sensors.

The last tests were devoted to analysis of the behaviour of the gauges embedded in concrete under compression. Three concrete specimens (length: 33cm, 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 spalling of the cover and crushing of the concrete core. Four gauges were arranged so that 1 wired and 1 wireless sensor were on both sides of the rebar; Figure 1 (lower graph) shows the measurements obtained against time, for both systems. The strain, now in compression, again reaches 2000-2500με, and the agreement is of the same order as the resolution.

3. Accelerometers

Each accelerometer node measures, records and transmits over the RF network 3-axis acceleration data, using a MEMS-based sensor commercially available from Analog Devices Inc. [4]. This is a completely digital output device that communicates with the system through an SPI interface having a serial EPROM memory and a micro vibration sensor. The firmware developed allows device wake-up upon activation of the micro vibration sensor, fast setup of the node (accelerometer and Zigbee transceiver) from the microprocessor, and data recording in the EPROM. The power consumption of the unit is similar to the strain sensor unit. The micro sensor acts as a hardware trigger that activates the node only when substantial vibration (above 20mg) occurs. Below this level, the node remains dormant.

To reduce energy consumption, special algorithms were also developed to minimize unit activation by false alarms. Once activated by sufficiently strong vibration, the node acquires acceleration data for a maximum period of 30 seconds, estimating every 5 seconds the amplitude of the vibration along each of the 3 axes. Only if that amplitude is significant (according to a software threshold defined by the user) does the node consider the signal, transmitting data to the base station. The combination of these hardware and software thresholds minimizes the power consumption of the node, avoiding transmission of signals that are irrelevant for seismic analysis: a battery lifespan of years can be expected.

To test the performance of the network, three wireless nodes were mounted on a shaking table, back to back with high precision wired piezoelectric seismic accelerometers. The nodes underwent several vibration tests, with excitation of various shape, frequency and amplitude. The aim of the campaign was to characterize the dynamic response of the wireless sensing system and to investigate its accuracy and reliability under conditions similar to those experienced in the field during a seismic event.

Two types of test were performed: in the “calibration tests”, the nodes were mounted in parallel on the table, and each axis was tested with harmonic excitation at frequencies in the range 1-20Hz, at amplitude ranging from +/-1m/s^2 to +/-4m/s^2. This sequence allowed calibration of the sensitivity of each node axis and tuning of the internal clock. The resulting response of the wireless network has a maximum discrepancy respect to the wired system of the order of 3%.

Then, to better simulate operational conditions, the wireless sensors were mounted on a two-storey metal frame fixed to the shaking table, again back to back with the wired instruments, as shown in Figure 3 (lower picture). 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 excited the frame both with frequency-sweeps and with seismic-like waves.

Figure 2 (upper graph) shows the comparison between the vibrations recorded by the wired and the wireless systems, at each floor, during a sweep. Agreement is very good, of the same order as the resolution of the wireless system, which is 18mg (=0.18m/s^2).

Figure 2 (lower graph) reports the Frequency Response Functions between the ground excitation and the vibration on each floor, as estimated by the wired and wireless sensors. This graph allows identification of the resonance and anti-resonance frequencies of the structure, which remain linear during the tests. The agreement is once again good, especially above 2Hz.

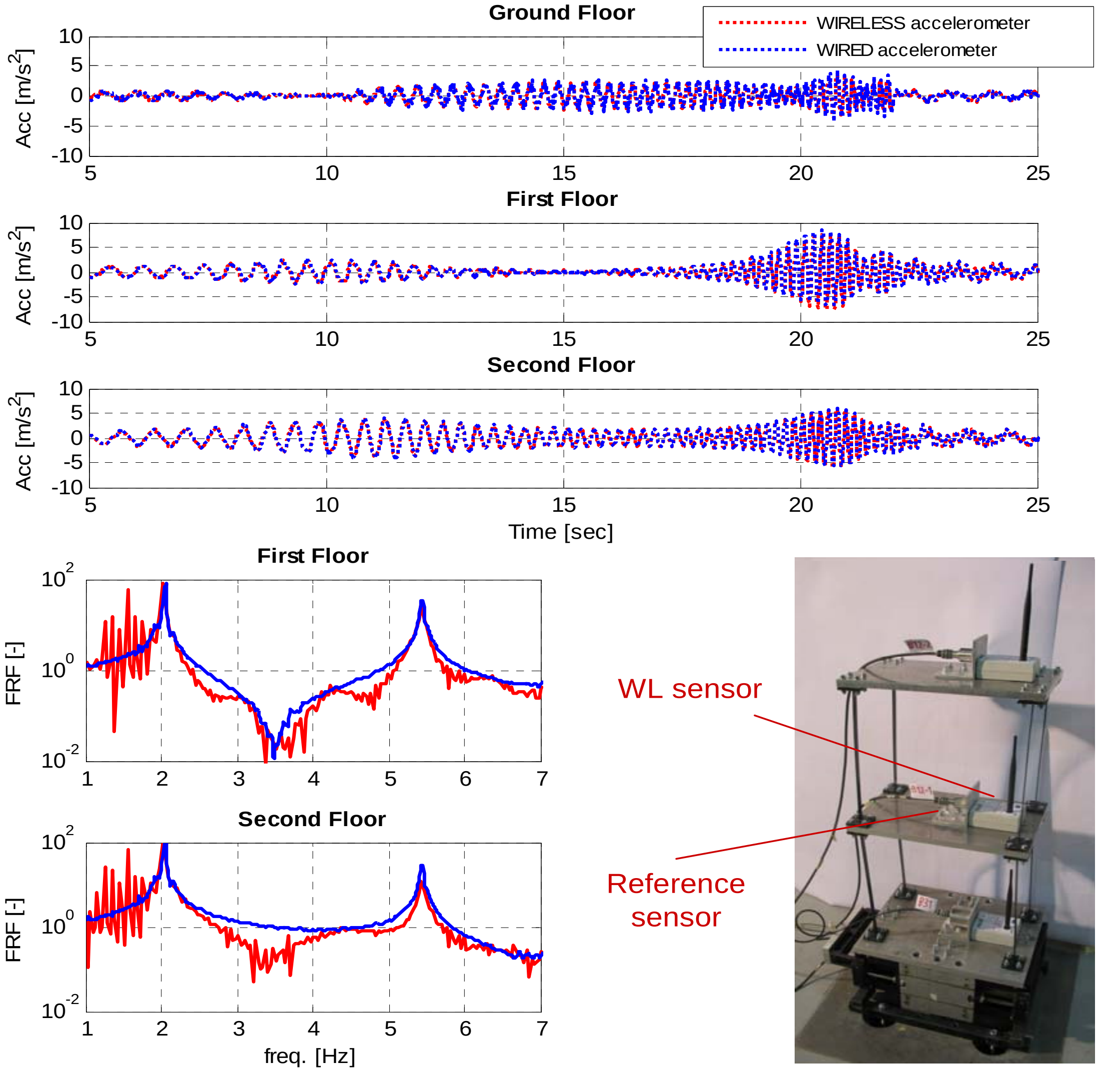

Fig. 2. Example of a frequency-sweep test mounting the sensors on the metal frame: time histories (upper graph), frequency response functions (lower graph) and appearance of the instrumented metal frame on the shaking table (lower picture)

4. Conclusions

MEMSCON project aims to develop a new generation of wireless sensors dedicated to civil engineering applications. To date we tested a first batch of sensors assembled from components available on the market. Validation tests highlighted limitations of commercial sensors: power consumption and accuracy for accelerometers; packaging system for strain gauges. These limitations will be overcome by the definitive version of the developing sensors.

Acknowledgements

The MEMSCON project is funded by the European Community with Grant Agreement n. CP-TP 212004-2. The authors wish to thank all MEMSCON partners and particularly all those contributing to the laboratory tests reported in this paper.

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