Structural Health Monitoring (SHM) by a wireless mesh network of accelerometers: the example of L'Aquila (Italy) seismic sequence, 2009.

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ABSTRACT:
After the recent moment magnitude (Mw) 6.3 Central Italy Earthquake of the 6th April 2009, an Earthquake Task Force (from the GFZ Potsdam and University of Basilicata) has carried out a wide characterization of sites, buildings and damages. In Navelli, a town about 35 km far from epicenter, heavy damage occurred on a reinforced concrete (RC) building that represents an anomalous case of damage. For this reason, the building has been selected for the installation of an innovative seismological wireless network and monitored through the aftershock sequence. Analysis of the strong motion data recorded in the building allowed the monitoring of building response during the aftershocks. Moreover, the damage state was characterized, and measurements of noise using tri-directional tromometers and a geological survey were performed.

Keywords: Structural Monitoring, Wireless Mesh Network, Interferometry, Time-Frequency Analysis

1. INTRODUCTION

Structural health monitoring (SHM) allows improving the knowledge of the safety and maintainability of civil structures. Moreover, monitoring buildings in earthquake-prone areas represents a task of major importance, both for ensuring their structural integrity, and for obtaining an insight into their responses in the event of an earthquake in order to mitigate urban earthquake risk by new, effective seismic design provisions.
The rapid improvement in telemetry and computer technology is literally driving a revolution in earthquake engineering, and, in particular, in the monitoring of civil built infrastructures. The earliest applications of wireless communication technology for structural monitoring purposes were proposed in the late 90s by Straser and Kiremidjian,1998. These earlier applications showed that real-time processing of data can be performed locally, and that wireless monitoring systems are feasible, reliable and cost-effective. Over the last few years, prototype structural wireless monitoring systems have been validated by tests performed on bridges and other structures, where they have been found to be a highly cost-competitive, completely autonomous and very reliable alternative to traditional wired systems.
Recently, the *Helmholtz-Zentrum Potsdam Deutsches GeoForschungsZentrum* (GFZ Potsdam) and *Humboldt University of Berlin* (HUB) developed a self-organizing wireless mesh information networks made up of low cost sensors that can be used for seismic early warning and SHM purposes. The system is named Self-Organizing Seismic Early Warning Information Network (SOSEWIN), and a test version has been deployed since July, 2008, in Istanbul, Turkey, with the aim of setting up a new earthquake early warning system for the mega city (Fleming et al., 2009).

The suitability of the SOSEWIN system for SHM purposes has been verified during an experiment involving ad-hoc ambient vibration recordings performed on the Fatih Sultan Mehmet suspension bridge spanning the Bosphorus Strait in Istanbul (Turkey) in June 2008 (Picozzi et al., 2009a).
Immediately after the recent 6th April 2009 Mw 6.3 Central Italy Earthquake, which caused the deaths of about 300 people, an earthquake task force from the GFZ Potsdam and University of Basilicata installed the novel wireless accelerometric sensing units within selected strategic infrastructures, both damaged and undamaged, for the recording of aftershocks, and for determining in real time characteristic building parameters.
The Navelli's town hall, a municipality about 30 km southward of L'Aquila, suffered by a severe level of damage, but anomalously high if compared with those occurred in the neighboring area, after the main shock. For this reason, and considering also its strategic importance for the community of the area, the 8th April 2009, the SOSEWIN system was installed within the Navelli's town hall. The system was operated for some weeks, and allowed the collection of a large data set of more than fifty aftershocks with Ml higher than 3 (including the third strongest aftershock, Ml 5.1, of the seismic sequence).
Picozzi et al. (2009b) presented an overview of the innovative system and its application for the monitoring of structures during earthquake task force missions. Mucciarelli et al. (2010) presented a report dealing with: the geological-geotechnical survey of the area, results of seismological analysis for the site effects characterization carried out by measurements of noise using tri-directional tromometers, the structural engineering survey of the damage affecting Navelli's town hall, and the results of the preliminary analysis of strong motion data collected within the structure by the SOSEWIN system based on standard frequency-domain approaches to SHM. Finally, Picozzi et al. (2010) presented the results obtained by applying an interferometric analysis to the collected earthquake data set. In particular, following the approach of Snieder and Şafak, (2006), by deconvolving the signals recorded at the different building levels, they estimated the empirical Green's Functions of the structure. These were later in turn used to study the propagation of seismic waves inside the building, and thus, to estimate the velocity and attenuation of S-waves within the structure, as well as for investigating their variation during the ten strongest aftershocks. This paper provides a summary of results obtained in the different studies.

2. EARTHQUAKE SEQUENCE AND SITE DESCRIPTION

The Abruzzo region (Central Italy), a zone characterized by a high level of seismic hazard, was struck on 2009 April 6 at 01:32:39 GMT by a magnitude Mw = 6.3 (Global Centroid Moment Tensor Project, www.globalcmt.org) earthquake.
The epicentral area corresponds to the upper and middle Aterno valley, an area characterized by a complex tectonic evolution, which is reflected by the large variability in the geological and geomorphologic patterns. The town of L'Aquila (pop. ~ 70.000), which is located at about 6 km northeast of the main shock epicenter, suffered a severe level of damage, as well as several smaller villages located nearby. An overview of the strong motion recordings of the whole sequence is provided, among others Bindi et al. (2009).
The village of Navelli, located at about 30 km southward of L'Aquila and for which an average Macroseismic Intensity of VI was estimated, exhibited a particular damage pattern. Mucciarelli et al. (2010) performed a detailed geological survey of the area, and drilled a 30-metres-deep geognostic borehole close to the city hall building. The historical center of Navelli is located on a rock site (Mesozoic limestones), while the new settlement area lies on soft Pleistocene lacustrine sand-silt-clay deposits (Figure 1). The results of the deep geognostic borehole indicate that in the proximity of the city hall, the seismic bedrock, which is represented by the Mesozoic limestone, is deeper than 30 meters. Results from a downhole S-wave survey indicate that the velocity

increases almost monotonically with depth, starting from about 200 m/s at the surface, and reaching about 600 m/s at 30 meters depth. The Vs_{30} is equal to 381 m/s, corresponding to a B site according to EuroCode 8 (Mucciarelli et al., 2010).

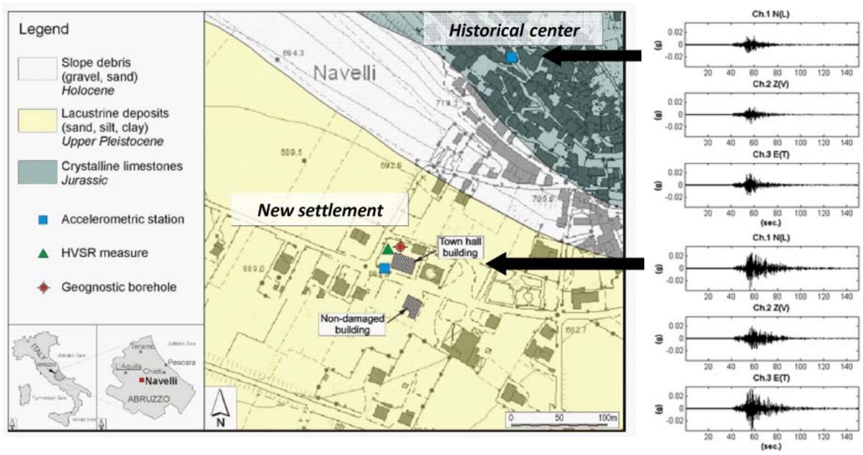

Figure 1: Geological map of the southern sector of Navelli; location of accelerometric stations in the town hall and at historical center; ground motion recorded at the historical centre of Navelli during the 2 event (Table 1), and at the new settlements in the plain.

In order to characterize the site response of the new settlement area, a Kinematrics Altus K2 accelerometer was installed at the ground floor of Navelli's town hall in the plain, while another K2 accelerometer was installed at the historical center of Navelli. Figure (1) shows a comparison of waveforms recorded by two stations during the 2^{nd} strongest aftershock of the sequence (i.e. the Ml = 5.1 of the April 9). It is clear that for the same seismic input, the city hall experienced much larger ground motion amplitudes with respect to the historical center.

3. DESCRIPTION OF BUILDING CHARACTERISTICS AND DAMAGE STATE

The Navelli's town hall is a Reinforced Concrete (RC) framed structure with three stories and two by four bays (Figure 2). It was designed and constructed in the '60s. Hence, it does not follow the current seismic design criteria of symmetry, bi-directional resistance, stiffness, capacity design, and the local and global ductility demand. In fact, owing to the presence of a stiff stair structure placed in an eccentric position, the structure is irregular in a plan-view drawing. The structure has the dimensions of 23.55 m and 12.42 m for the longitudinal and transversal directions. By contrast, in elevation the building's shape is approximately regular, with an inter-storey height of 3.5m. Unfortunately, a direct inspection of the foundations was not possible. Therefore, we assume that they are shallow, according to the standard of building design at the time when the structure was built.
Mucciarelli et al. (2010) found that the strong damage resulting from the main shock compromised the usability of the building, and affected beams, columns, beam-column joints and the staircase (Figure 2).
It is worth noting that columns' damage was particularly heavy and extensive at the first level. Furthermore, cracking on the external masonry infill were observed along the longitudinal and transversal frame at the ground and first stories. Moreover, several cracks occurred across the diagonals of external panels and also on internal partitions. A possible contribute to the resulting structural damage might have been caused by the presence of a historic archive of the municipality, which was placed on the upper floor in an eccentric position.

Mucciarelli et al. (2010) did not found evidence of structural damage evolution during the aftershock sequence, with the buildings showing the same damage mechanism caused by the main shock.

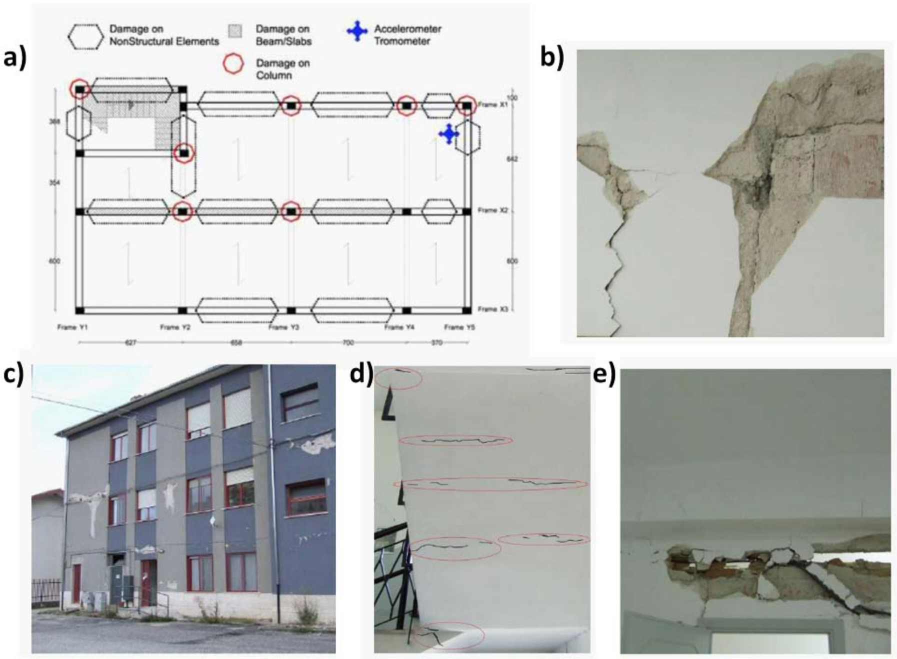

Figure 2: Damage state of the Navelli’s town hall. *a)* View of the building plan showing where the accelerometric sensors were installed, and the location of significant structural and non-structural damage. *b)* Damage on columns along the frame at the first storey. *c)* Damage on infill panels along the transversal direction. *d)* Damage on staircase structural elements. *e)* Damage on non-structural elements in the frame at the first storey.

4. STRUCTURAL HEALTH MONITORING SOSEWIN

The SOSEWIN system employs advances in various technologies to incorporate off-the-shelf sensor, processing and communications components into low-cost accelerometric seismic sensing units that are linked by advanced, robust and rapid communications routing and network organizational protocols appropriate for wireless mesh networks (Fleming et al., 2009). The reduced cost of the instruments (less than one tenth of a standard instrument) and the possibility of creating dense, self-organizing and decentralized seismic monitoring networks are characteristics that make the SOSEWIN system particularly attractive for the SHM. In particular, the decentralized, self-organizing character guarantees the functionality of the network during a disastrous event, even when some of the sensing units are damaged.
The wireless accelerometers are based on MEMS (Micro Electro Mechanical System) with a measurement range of +/- 1.7 g, a bandwidth of 25 Hz and a noise level of 0.5 mg, which are arranged to sample the three components of the ground motion. The digitizer board has a resolution of 24 bits, effectively providing a resolution of 19 bits. The sample rate is variable between 50 to 400 samples per second (sps), with 100 sps currently used.
The stations are provided of a wireless router applications platform (WRAP) board, an embedded PC with a 266 MHz CPU and a Linux OPENWRT operating system, which actually accomplished the roles of storage, communication of raw data by WLAN (wireless local area network) in the unlicensed 2.4GHz or 5GHz bands, and real time data analysis. Thanks to the

reduced dimension and weight of the novel accelerometric stations, the SOSEWIN stations are easy to install, and therefore resulted very suitable for rapid deployment during the emergency conditions we were operating (Picozzi et al., 2009b). Finally, it is worth mentioning that the stations create a wireless mesh network by which raw data and computed parameters can be communicated to a user's laptop connected to any node that belongs to the network. Therefore, the wireless technology resulted to be particularly useful in the post-event operational conditions we faced in Central Italy, making it possible for the operators to download the aftershock waveform data remotely without visiting the actual site, thus, allowing the safe retrieval of data from the damaged town hall.

In order to perform a continuous monitoring of the building, the town hall was instrumented with four SOSEWIN accelerometric stations. The network was composed by one station for each floor (Figure 3a, b), installed on the same vertical along the building height, and one station buried in the ground near the building. The data collected by the system were analyzed for SHM purposes by both standard frequency-domain and innovative time domain approaches.

Mucciarelli et al. (2010) used the earthquake data and seismic noise recordings acquired by a digital tri-directional tromometers (Micromed Tromino) to estimate the town hall's transfer function, which was computed by the top-to-base amplitude spectral ratio. By the analysis of the building's transfer function, translational mode of vibration was identified at 2.9 Hz (0.345 sec.) for the transversal direction and at 3.4 Hz (0.294 sec.) for the longitudinal one. Finally, at 4.4 Hz (0.227 sec.) a peak comparable amplitude in both directions was identified as rotational mode. Moreover, to study the inter-event variation, Mucciarelli et al. (2010) evaluated the response spectra for the accelerometric recordings collected at the second storey for the stronger recorded events (Table 1). The authors found an amplitude-dependent behaviour of the building during each aftershock (not shown here). In fact, they observed an increase of the building's period of vibration with respect to maximum spectral amplitude of the event, obtaining for amplitudes of the motion smaller than 0.05g, period of vibration of about 0.34 sec. (2.94 Hz). On the contrary, during events with larger amplitudes (up to 0.37g), the periods of vibration were about 0.40 s (2.5 Hz).

Table 1: Aftershocks selected for the analysis.

ID	ML	Date	day	time (UTC)	D (km)
1	4.3	08/04/2009	98	22.59	51.3
2	5.3	09/04/2009	99	0.53	53.0
3	4.2	09/04/2009	99	3.13	38.5
4	4	09/04/2009	99	4.31	42.0
5	4.9	09/04/2009	99	19.38	53.4
6	4.9	13/04/2009	103	21.13	50.7
7	3.9	14/04/2009	104	13.53	58.1

The time domain approach used for estimating the building response is based on the idea proposed by Kanai (1965) that the structure's response can be represented in the time domain by the superposition of waves that propagate from the soil through the structure and waves that are reflected at internal impedance contrast boundaries. Recently, several authors proposed theoretical advances in the SHM by the application of wave propagation analysis approaches (e.g. Şafak, 1998; Snieder and Şafak, 2006; Todorovska and Trifunac, 2008) for the estimation of the empirical Green's Functions (i.e. the impulse response function, IRF) of the structure. In order to retrieve the IRF of the structure, Picozzi et al. (2010) performed the interferometric analysis of the data, by deconvolving the signals recorded at the different building levels. With respect to the milestone of Snieder and Şafak (2006), Picozzi et al. (2010) proposed the application of a time-frequency analysis based on the S-transform (Stockwell et al., 1996) on the estimated IRF. In

fact, differently from the analysis of signals performed by the Fourier Transform, which do not allow the changes in the stiffness of a structure to be followed over time, the time-frequency analysis provides a view of the temporal evolution of the signal characteristics, and, of particular interest for SHM purposes, it allows one to identify the occurrence in time of decreases in the modal frequency of the structure.
Figures (3c) shows the IRF and the relevant S-transform estimated for an event with magnitude ML equal to 5.1. The analysis has been performed using the whole earthquake recording, that is to say including P, S and the following phases, for a total time of 40 seconds. The IRF was obtained from the deconvolution of signals using the recording at the top and at the base as reference. By picking the maximum of the pulses showing up for the different levels, it was possible to retrieve the wave travel time, and hence, the interval (i.e. relevant to the single floors) and the global velocities (i.e. from the travel time difference of the sensors at top and at the base) were estimated (Figures 3c).

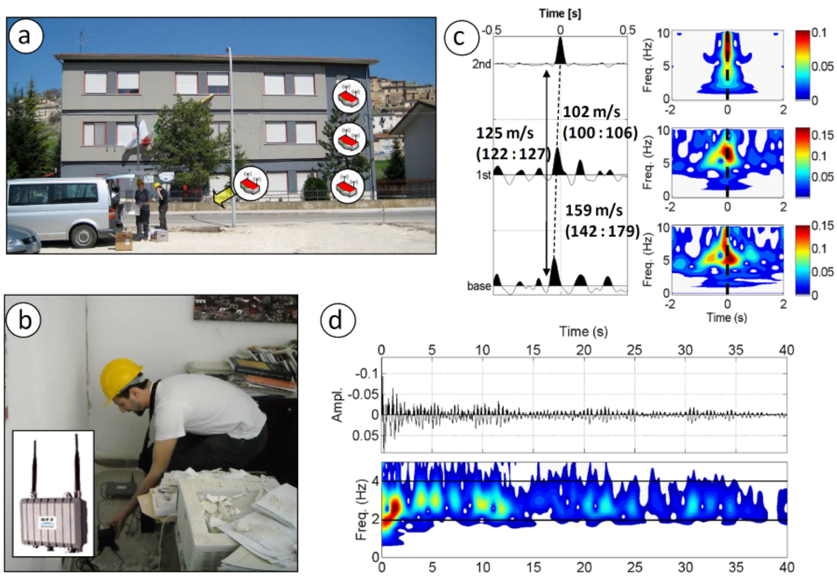

Figure 3: *a)* and *b)* The Navelli's city hall and installation of the SOSEWIN units. *c)* IRF from interferometry (*left panels*) for event 2 and using the sensor at the top of the Navelli city hall as reference, and their time-frequency representation by S-transform (*right panel*). The interval and global velocity estimates are also indicated together with the uncertainty interval, as well as the travel times between the pulses at different floors. *d)* IRF for the 2nd floor and event 2 (*upper panel*) using the signal at the base as reference, and its time-frequency representation (*lower panel*) by S-transform.

Figure (3d) shows the IRF and it time-frequency representation. This latter allows observing the variation between about 2 Hz (0.5 sec.) and about 3 Hz (0.33 sec.) of the maximum of the energy over time. Considering that the IRF functions was estimated by deconvolving signals recorded within the structure, it is independent both of the excitation of the building, and of soil-structure interactions. Therefore, the resonance frequencies estimated from the time-frequency representation of IRF in Figure (3d) is interpreted as the fundamental resonance frequency (f_1) of the building.
Figure (4a) provides an overview for the 2nd floor of the town hall of the velocities estimated from the interferometric analysis of the stronger recorded aftershocks (Table 1). The analysis was carried out using the whole window length of the signal for the smallest events (i.e. ID 1, 3, 5, and 7), and a moving window of 3 seconds for the largest aftershocks (i.e. ID 2, 4, and 6). We observe that the interval velocity oscillates between 100 and 200 m/s, with the higher velocity

values occurring at the beginning of the event when the shacking is smaller (i.e. the moving windows $2_{(1)}$, $2_{(2)}$, $4_{(1)}$, $4_{(2)}$, and $6_{(1)}$), and the smaller velocities during the larger shacking (i.e. $2_{(3),}$). Although the interval velocities show several fluctuations, we did not observe any permanent velocity drop that could be interpreted as the occurrence of further structural damage. As suggested by Todorovska and Trifunac (2008), a possible cause for the (recoverable) nonlinear building's behaviour is opening of existing cracks in the concrete during the earthquake response. Figure (4b) shows the estimates of f_1 obtained from 40 second windows of IRF for the seven strongest events (Table 1). We observe a drop in f_1 only between the events 1 and 2. During the following events, f_1 shows local temporary fluctuations, but its trend is almost constant. The values of f_1 for the last event 7 (i.e. between 2.5 and 2.6 Hz) are comparable with those of the event 2 (Figure 4b). These observations are in agreement with those of Mucciarelli et al. (2010), who observed from ambient vibration measurements rather stable resonance frequency values during the aftershock sequence. The results from the velocity analysis do not provide clear evidences of structural damage increase, as well as the observations of Mucciarelli et al. (2010). Hence, we think that variation in f_1 between events 1 and 2 might be related to the different shacking amplitude. This might indicate that during the event 1 the building responded in an essentially linear way, while during the other events, it responded with a nonlinear behavior.

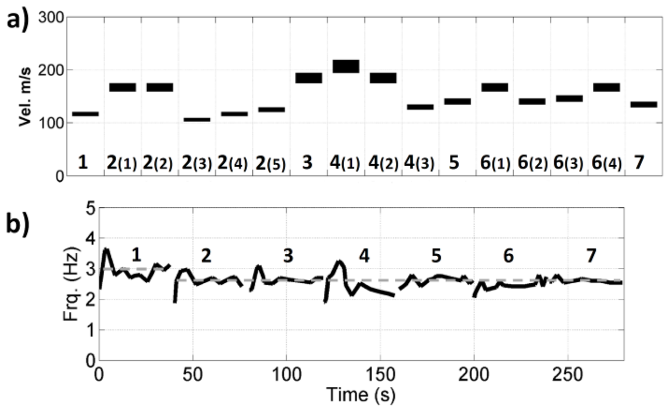

Figure 4: *a)* Shear wave velocity for the 2nd floor estimated for the larger events of Table 1. The thickness of the symbols represents the uncertainty. The different events are identified by a code (Table1). For the three largest events, the time interval used in the interferometric analysis is indicated by a small number between brackets. *b)* f_1 of the Navelli city hall estimated for a 40 seconds portion of the IRF using the recordings at the 2nd floor for the larger events in Table 1.

5. CONCLUSION

In this study we report on the application of an innovative wireless accelerometric network to structural health monitoring during a Task Force mission following the recent L'Aquila (Italy) seismic sequence, 2009. The principal aim of the monitoring campaign was to detect possible variation of the building dynamic behaviour during the seismic sequence linked to damage evolution. Notwithstanding several aftershocks with M > 5 that caused floor spectral acceleration exceeding 0.35g, any permanent variation of the dynamic proprieties was observed. By interferometric analysis it was possible to estimate the shear wave velocity of seismic phases propagating throughout the structure, and to monitor the velocity variations during the aftershock sequence. Interestingly, any permanent velocity drop was observed, but rather a reliance of the velocity on the shacking amplitude. Hence, the velocity fluctuations are interpreted as evidence of recoverable nonlinear building's behaviour related to the opening of existing cracks in the concrete during the occurrence of the larger shacking. Innovatively, the S-transform was used to study the building response functions retrieved by interferometry, and thus, to estimate the fundamental resonance frequency of the building. This latter parameter showed through the aftershock sequence local temporary fluctuations, but its trend resulted to be constant, supporting the other evidences that after the main shock any further significant structural damage occurred.

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