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Structural and seismic monitoring of the “Cardarelli” Hospital in Campobasso

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Abstract

Recent earthquakes occurred in Italy and throughout the world have once again emphasized the critical role of health facilities for post-earthquake emergency management. Due to earthquake, several hospitals (L'Aquila 2009, Amatrice 2016) have lost their functionality because of damage to structural as well as non-structural members, equipment and installations.

The primary role of hospitals after hazardous events requires the development of specific analysis and monitoring strategies aimed at quickly assessing their health conditions. Turning a hospital into a "Smart Health Facility" (SHF) allows remote assessment of the structural health; moreover, it can effectively support the mitigation of administrative and organizational vulnerability by acting on preparedness of the medical staff and supporting management and maintenance of structural as well as non-structural subsystems over time. Continuous monitoring of health and performance of hospitals can support the formulation of disaster mitigation plans and the definition of investment priorities to ensure the overall safety.

In the present paper, some results of an on-going monitoring project for the main hospital in Campobasso (Southern Italy) are presented, focusing the attention on the response of the structure in operational conditions and after seismic events. Moreover, the results of experimental as well as operational modal analysis tests on a drug dispenser are discussed in order to assess their applicative perspectives for qualification of medical equipment in view of their seismic vulnerability assessment as non-structural elements.

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Keywords: hospital; smart health facility; non-structural elements; structural monitoring.

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1. Introduction

Recent earthquakes occurred in Italy and throughout the world have underlined the critical role of health facilities in the aftermath of a seismic event [1]. Due to earthquake, several hospitals have lost their functionality because of damage to non-structural members and equipment, even in the absence of structural damage [2].

An effective protection strategy has to ensure not only that hospitals remain standing in the case of an earthquake, but above all that they remain in service without interruption, in order to accomplish the following tasks [3]: protect the life of patients, visitors and hospital staff; protect the investment in equipment and furnishing; protect the performance of the health facility. The development of integrated health monitoring systems, specifically designed to assess the functional state of structural as well as non structural elements, equipment and installations, can effectively support the post-earthquake emergency management, providing in near real-time relevant information about damage. A monitoring system can turn a regular health facility into a smart one, able to diagnose its own faults. The development of Smart Health Facilities (SHFs) has, therefore, a positive impact in terms of safety enhancement. Continuous monitoring of health and performance of hospitals can support the formulation of disaster mitigation plans and the definition of investment priorities to ensure the overall safety [4]. SHFs can also effectively support the mitigation of administrative and organizational vulnerability by acting on preparedness of the medical staff and supporting the management and maintenance of structural as well as non-structural subsystems over time [4]. The combination of monitoring programs with early warning strategies can provide additional level of seismic protection [5]. This is the background of the present paper, which refers to an ongoing monitoring project for the main hospital in Campobasso (Southern Italy). Attention is focused on the response of the structure in operational conditions and after seismic events. Moreover, the results of experimental as well as operational modal analysis tests on a drug dispenser are discussed in order to assess their applicative perspectives for qualification of medical equipment in view of their seismic vulnerability assessment as non-structural members.

Nomenclature

SHM	Structural Health Monitoring
SHF	Smart Health Facility
OMA	Operational Modal Analysis
EMA	Experimental Modal Analysis
FDD	Frequency Domain Decomposition
Cov-SSI	Covariance Driven Stochastic Subspace Identification
ARES	Automated modal paRameter Extraction System
BUSTERSPID	Robotized drug dispenser

2. Structural monitoring of the Main Hospital in Campobasso

The development of an SHF starts with the installation of an effective structural health monitoring (SHM) system for continuous recording and processing of the operational and seismic response of the structure. The analysis of the operational response plays a primary role for damage detection [6]. Moreover, the experimental estimates of the modal parameters can be used for the refinement of numerical models. In addition, dynamic testing of equipment might represent an attractive option for their seismic qualification and to design anchoring, fasteners and other countermeasures for seismic risk reduction of non-structural elements [7].

Under this premises a continuous vibration-based SHM system has been installed on the “Cardarelli” Hospital in Campobasso (Fig.1a). The building consists of two adjacent reinforced concrete moment frame structures built in the Seventies and it is representative of typical layouts of existing health facilities. The first building, called block A, covers a rectangular area of 36 m x 13.5 m while the second, block B, covers a rectangular area of 42 m x 13.5 m. They are separated by a small structural joint (Fig. 1b).

Sixteen force-balance accelerometers have been installed at the two upper levels of the structure along two orthogonal directions (Fig. 2). In particular, the sensors have been placed at opposite corners of the floors in order to ensure observability of bending as well as torsion modes.

Data acquisition is carried out by a measurement device with 16 bit resolution and on-board anti-aliasing filter. The data acquisition hardware is managed by software developed in LabView environment. The collected raw data are stored into a local MySQL database. A sampling frequency of 100 Hz is adopted. The acquired data are continuously processed by an innovative fully automated Operational Modal Analysis (OMA) procedure [8]. Estimates of the fundamental modal parameters of the structure are automatically obtained every 30 minutes from 1800 s long record of the ambient vibration response of the structure.

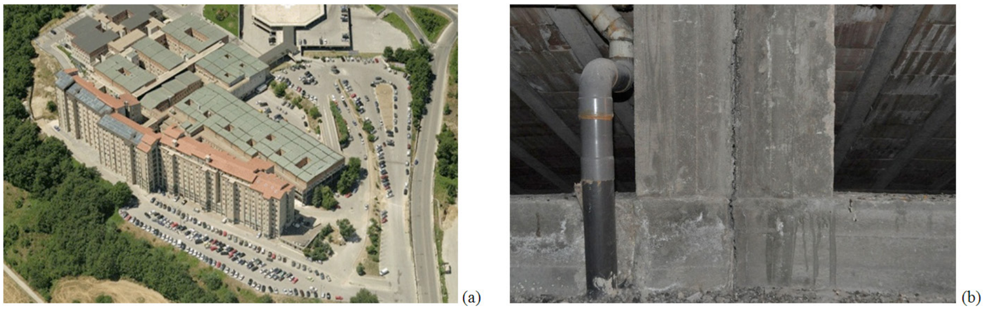

Fig. 1. (a) Campobasso's Main Hospital; (b) detail of the structural joint between the blocks.

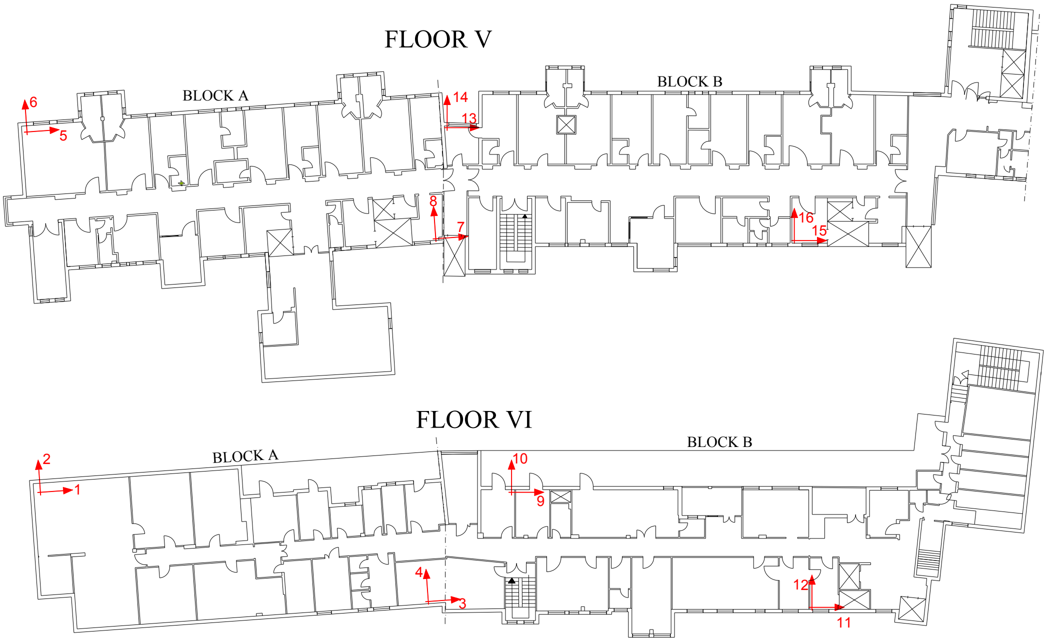

Fig. 2. Sensor layout.

Data acquisition started on March 24th, 2016. Relevant monitoring results after one month of operation of the system are presented in Fig. 3. The fundamental mode shapes of the structure can be described as follows:

- 1th mode: transversal bending mode;
- 2th mode: longitudinal bending mode;
- 3th mode: torsional mode;
- 4th mode: local torsional mode, different for each block.

As shown in Fig. 3, the estimated frequencies are very close each other, making the accurate identification of modes quite challenging.

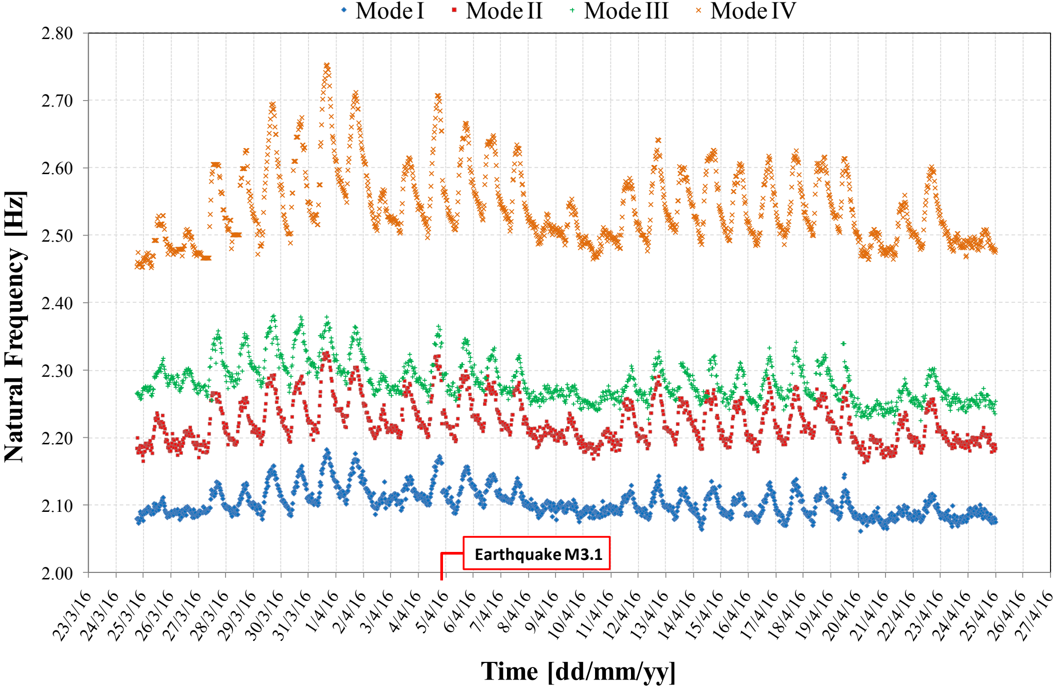

Fig. 3. Monitoring results.

Visual inspection of data highlights that the swing of the estimates systematically recurs every day, with a sudden drop in the night and a gradual increase in the morning up to the maximum value reached in the afternoon. These variations of natural frequencies can be mainly related to the temperature. Taking into account that a small joint divides the two blocks (Fig. 2b), when the temperature increases the distance between the two blocks decreases as a result of thermal expansion, and the interlocking between the blocks yields some stiffness increase in the longitudinal direction. In fact, the influence of thermal variation is more relevant for the longitudinal and torsional modes (modes #2, #3, #4) than for the transversal mode (mode #1). Moreover, because of the orientation of the structure, with the long side exposed to direct sun radiation, the temperature in the structure is not uniform but it is higher for the facade in the longitudinal direction.

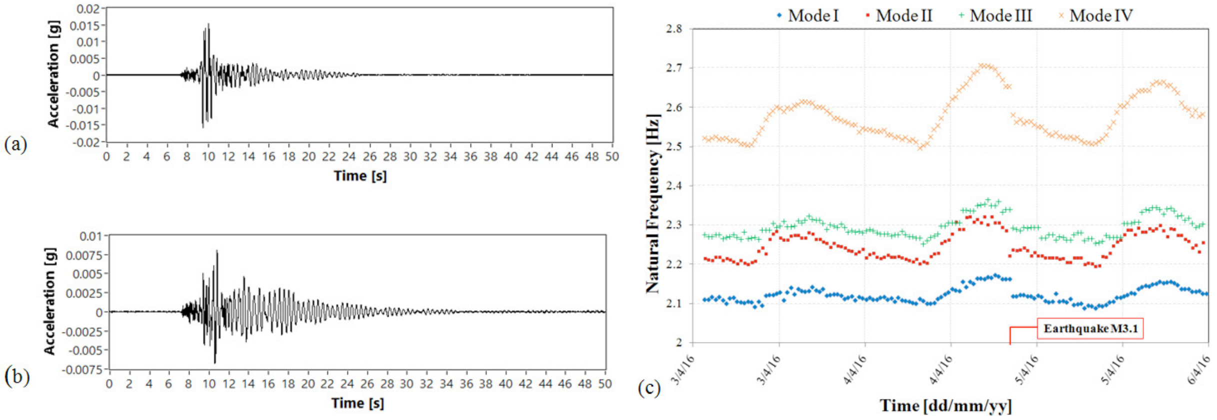

Fig. 4. Time series of the seismic response of the structure: (a) sensor #9 and (b) sensor #10; (c) tracking of the four fundamental frequencies and drop due the earthquake induced ground motion.

A $M_w = 3.1$ earthquake, occurred at 07:36 p.m. on April 4th, 2016 (http://cnt.rm.ingv.it/event/6564571), has been also recorded during the first month of operation of the monitoring system. The epicenter of the earthquake was approximately 1 km far from the hospital. Peak accelerations of 0.015 g and 0.0075 g have been recorded in the longitudinal (Fig. 4a) and transversal direction (Fig. 4b), respectively, on top of the structure. The occurrence of the seismic event is indicated in Fig. 3 and Fig. 4c. It is possible to note a drop of the estimated frequencies after the occurrence of the earthquake. However, this is lower than the average daily variation in the period.

Even if the analysis of data for health assessment is still in progress and not herein reported, it is interesting to note that, after the seismic event, the estimated natural frequencies followed the usual pattern dictated by environmental and operational effects.

3. Dynamic testing of equipment

Monitoring the modal parameters of the structure plays a primary role in model refinement to enhance the accuracy of predictions of the seismic response at different floors of the structure. The acceleration response at a floor becomes the input ground motion for equipment and furniture standing at that floor. Thus, assuming that they are rigidly connected to the structure and that the structural response has been reliably evaluated, experimental modal testing of equipment represents a fundamental step in view of qualification and assessment of seismic vulnerability of these non-structural systems.

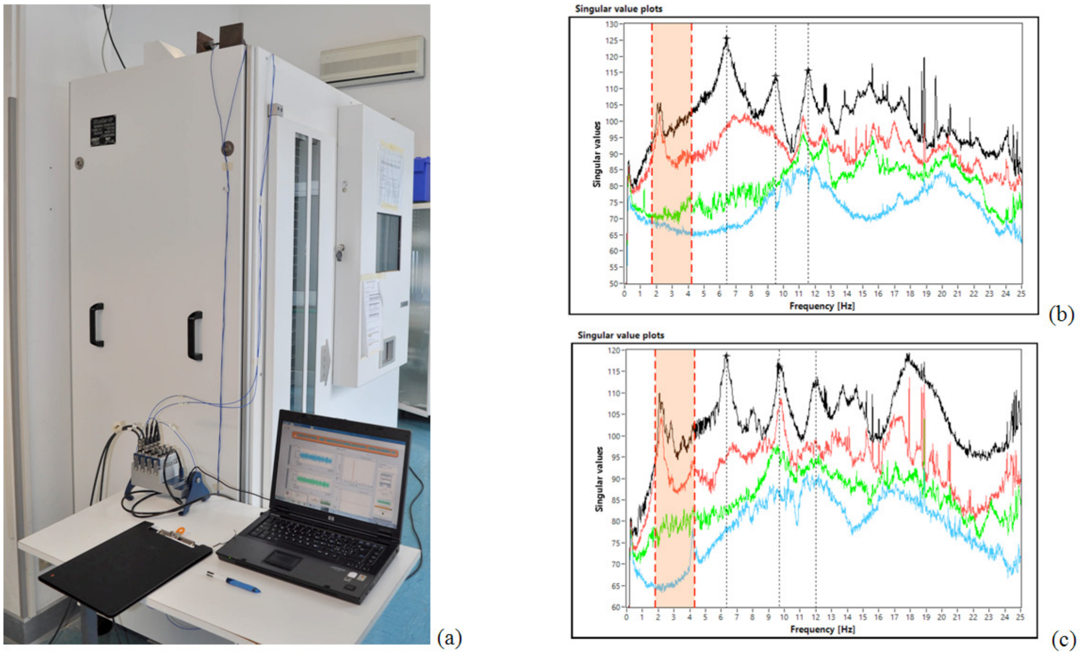

Fig. 5. (a) Operational modal analysis of the drug dispenser; (b) singular value plots: dispenser at the first floor and (c) at the fifth floor - the red area shows the bandwidth of the fundamental structural modes.

Dynamic tests have been carried out on two drug dispensers, the so-called "Busterspid" (Fig. 5a), placed at different floors of the structure. The robotized dispensers have dimensions of 150 x 80 x 210 cm and a weight of about 570 kg. The dynamic tests were carried out on two dispensers placed at the first and the fifth floor, respectively. The objective of the tests was the identification of the dynamic properties of the dispensers and the assessment of the influence of the dynamic response of the structure on the accelerations measured on the equipment. Thus, for each Busterspid output-only and input-output modal identification tests have been carried out. In the latter case, the input was applied by a modal hammer. The first three modes of the dispenser have been clearly identified. The corresponding natural frequencies are reported in Table 1.

Table 1. Estimated natural frequencies of drug dispensers

Mode	$f_{\text{BS-1th floor}}$ [Hz]	$f_{\text{BS-5th floor}}$ [Hz]
I	6.40	6.27
II	9.25	9.65
III	11.57	11.96

The singular value plots obtained from the FDD method (Fig. 5b and Fig. 5c) put in evidence the similar natural frequencies characterizing the tested dispensers and, above all, some effects of the input represented by the dynamic response of the structure in operational conditions. In fact, some peaks can be observed around 2 Hz. They correspond to the fundamental frequencies of the structure. As expected, this inference is more evident for the dispenser located at the fifth floor than for the Busterspid at the first floor. It is worth noting that the fundamental frequency of the Busterspid is about 6 Hz, quite higher than the fundamental frequencies of the structure.

4. Conclusions

The ongoing implementation of an innovative SHM program for health facilities able to take into account the response of non-structural elements has lead to the installation of a structural monitoring system for the inpatient department at the Campobasso's Main Hospital. During the first monitoring period, cyclic variations of natural frequencies have been observed as a result of the influence of environmental and operational factors. The response to a 3.1 M_w earthquake has been also recorded. The earthquake produced a drop of the natural frequencies, but it was within the typical range of variation of the natural frequencies due to environmental and operational factors; the first monitoring results therefore remark the importance of a compensation of environmental effects for effective modal-based damage detection. Finally, a number of dynamic tests have been carried out on two drug dispensers placed at different floors of the structure, putting in evidence the influence of the dynamic response of the structure on the accelerations response of the dispensers.

Acknowledgments

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