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A step towards the implementation of a Smart Health Facility: vibration-based identification and monitoring of structures and equipment

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Abstract

The effects of earthquakes on non-structural components and medical equipment very often dictate the seismic vulnerability of health facilities, since their failure affects the functionality of the hospital at a time of large demand of medical assistance. A lot of health facilities in seismically prone areas worldwide are designed and built according to obsolete codes or even in the absence of any consideration of seismic loads. On the other hand, the most advanced seismic codes recognize the relevant influence of non-structural components and equipment on the resilience of hospitals to earthquakes. Thus, the assessment of the seismic performance of health facilities requires due consideration of strong motion as well as moderate earthquakes. The present paper discusses the role of modal identification and vibration-based monitoring for structural health assessment of health facilities in operational conditions and after earthquake. A case study will show how the analysis of the dynamic response of the structure and relevant equipment can represent an attractive option to enhance the overall resilience of the health facility. In particular, while continuous monitoring of the modal parameters of the structure in operational conditions can provide significant information about the influence of environmental factors on the dynamic response of the structure and eventual interactions with nearby structures in the hospital, the experimental modal analysis of medical equipment can effectively support their qualification in view of seismic performance assessment. Thus, experimental modal analysis and continuous vibration-based monitoring provide relevant data and information about the performance and safety conditions of health facilities, supporting ordinary maintenance and seismic emergency management. The installation of high quality measurement chains and the implementation of effective and fully automated data processing procedures represent the first step towards the implementation of Smart Health Facilities, able to diagnose their own faults and damage.

Keywords: Health facilities; medical equipment; structural health monitoring; experimental modal analysis.

1. Introduction

Life safety and assistance to injured people are the priority after a seismic event, and hospitals play a key role in the post-earthquake emergency management, as also demonstrated by recent events occurred in Italy and worldwide [1]. However, in spite of the relevance of hospitals, specific design codes and guidelines are missing in Europe. In particular, little attention is devoted to non-structural components (chimneys, masonry infills, false ceilings, and so on), equipment (such as medical devices) and installations (tanks and distribution systems, heat ventilation and air conditioning systems, and so on) whose damage is often responsible for the loss of functionality of hospitals in the early earthquake aftershock even when the structural system remained undamaged [2].

This circumstance has been observed after several earthquakes, such as the 1994 Northridge earthquake [3] or the 2009 L'Aquila earthquake (Figure 1), with several hospitals that were partially or completely inoperable even in the presence of slight structural damage [4].

(a)

(b)

Fig. 1 –View of the L'Aquila Hospital before (a) and after (b) the 2009 earthquake (StreGa Lab group site visit)

The Pan American Health Organization (PAHO) defined the safe hospital as the one that remains fully operational during and after the earthquakes [5]. Thus, effective strategies for seismic protection of hospitals are crucial to assure life protection of occupants and full operation after earthquakes, when a large number of injured people need instant life support. In the case of hospitals, seismic protection has to focus on structural as well as non-structural components, equipment and installations to ensure uninterrupted services during emergencies.

Recent advances in seismic design and, in particular, the concept of performance-based design define different levels of acceptable damage based on their consequences on the users and their frequency of occurrence. On the other hand, little attention is paid to seismic design of non-structural components and seismic qualification of medical equipment and installations. Nevertheless, a detailed assessment of the seismic vulnerability of health facilities and the definition of possible countermeasures require consideration of the different categories of vulnerability: structural, non-structural and administrative/operational.

Basic research work in this area has been sparse, and the available codes and guidelines [6, 7, 8] are usually based on past experiences, engineering judgment and intuition, rather than objective experimental and analytical results. Design of any structure subjected to a seismic motion should be adhering the demand and specifics of non-structural components, installations, equipment and furnishings so that such members could withstand the movement of the structure. However, till date, only basic actions to reduce non-structural vulnerability, such as anchorage of cabinets, medical equipment and so on, with bolts, cables or other material, are accounted worldwide [9]. One of the main reasons lies in the difficulty of assessing the seismic performance of non-structural elements during a ground shaking because of lack of qualification and dependence on different parameters, such as characteristic of ground acceleration, response of the building to acceleration and displacement, size and weight of the element, location of the element in the building, characteristics of the connection or joint between the components and the structure or between different non-structural components.

Experimental testing is undoubtedly the best approach for qualification and fully understanding of the behavior of non-structural elements subjected to seismic excitations. Recently, several studies have been initiated to analyze the seismic performance of a variety of furniture items, medical appliances, and service utilities of typical hospital buildings. Cosenza et al. [10] conducted seismic performance assessment of a representative layout room having various types of medical equipment either directly connected to the panel board or free standing; fragility curves for medical room were ultimately derived based on acceleration time histories with increasing amplitude. Similarly, a number of shake table tests of medical laboratory components were carried out at UC Berkeley, focusing the attention in particular on freestanding refrigerators on different stories of the buildings [11, 12]. Acceleration time histories recorded at different stories of buildings during past events as well as simulated ground motions were used as input motion and the effects on equipment in terms of sliding, rocking or even overturning were investigated. However, the analysis of the literature remarks the lack of standardized approaches to the analysis and prediction of the seismic response of non-structural elements.

Focus on non-structural elements is critical in particular in the case of frequent earthquakes, when slight or no structural damage is usually observed, but the existing health facility can experience service interruptions due to non-structural damage, such as damage to medical equipment or installations. Their prompt condition assessment after an earthquake and near real time identification and localization of eventual structural damage play a fundamental role in the safety enhancement of health facilities in seismically prone areas. Advanced condition and structural health monitoring strategies can effectively support the automated assessment of the performance of health facilities after earthquakes, thus yielding the so-called Smart Health Facilities (SHFs) [13, 14]. These are expected to provide information about their health state to a remote user in a fully automated way. SHFs, therefore, require the implementation of appropriate monitoring strategies and automated data processing procedures in order to provide relevant information about the health conditions of structural as well as non-structural elements. SHFs can also effectively support the mitigation of administrative and organizational vulnerability by acting on preparedness of the medical staff and supporting management and maintenance, the formulation of disaster mitigation plans and the definition of investment priorities to ensure the overall safety and serviceability. Thus, the implementation of effective and integrated monitoring approaches is crucial for effective seismic protection of hospitals.

The present paper discusses the role of modal identification for vibration-based health monitoring of health facilities in seismically prone areas. Attention is focused on the analysis of the dynamic response of an actual structure, the Main Hospital in Campobasso (Southern Italy), and selected medical equipment. The application points out how integrated monitoring strategies can represent an attractive option to enhance the overall resilience of health facilities. In fact, in the present case continuous monitoring of modal parameters of the structure in operational conditions provides significant information about the influence of environmental factors on the dynamic response of the structure itself; moreover, the experimental modal analysis of medical equipment gives useful hints for their continuous monitoring taking into account the dynamic interaction with the structure, and it may represent a promising approach to their qualification in view of seismic performance assessment. In this context, the installation of a continuous Structural Health Monitoring system and the implementation of effective and fully automated data processing procedures [15] have represented the first step towards the implementation of an SHF.

2. Structural monitoring of Campobasso's Main Hospital

The first stage of development of an SHF is the installation of an effective structural health monitoring system for continuous recording and processing of the vibration response of the structure. As reported in previous studies [13, 14], the analysis of the operational response plays a primary role for structural damage detection [16]. Moreover, experimental estimates of modal properties can be used for refinement of numerical models [17] in view of seismic analyses under frequent earthquakes. The numerical predictions of the seismic response can be compared to vibration limits of equipment sensitive to accelerations. In a similar way, predictions of maximum displacements or interstory drifts under earthquake loading are useful for vulnerability assessment of non-structural elements sensitive to displacements. Finally, modal identification of anchored medical equipment represents a promising approach for their seismic qualification on one hand, and it provides relevant information for design/verification of anchorages on the other hand [18]. The general approach is schematically illustrated in Fig. 2. Attention is herein focused on the experimental steps (continuous monitoring of the modal parameters of the structure, modal identification of selected medical equipment). They do not require, in the current stage, a detailed analysis of the structure and materials as well as identification of existing damage. Thus, these aspects are out of the scope of the present paper.

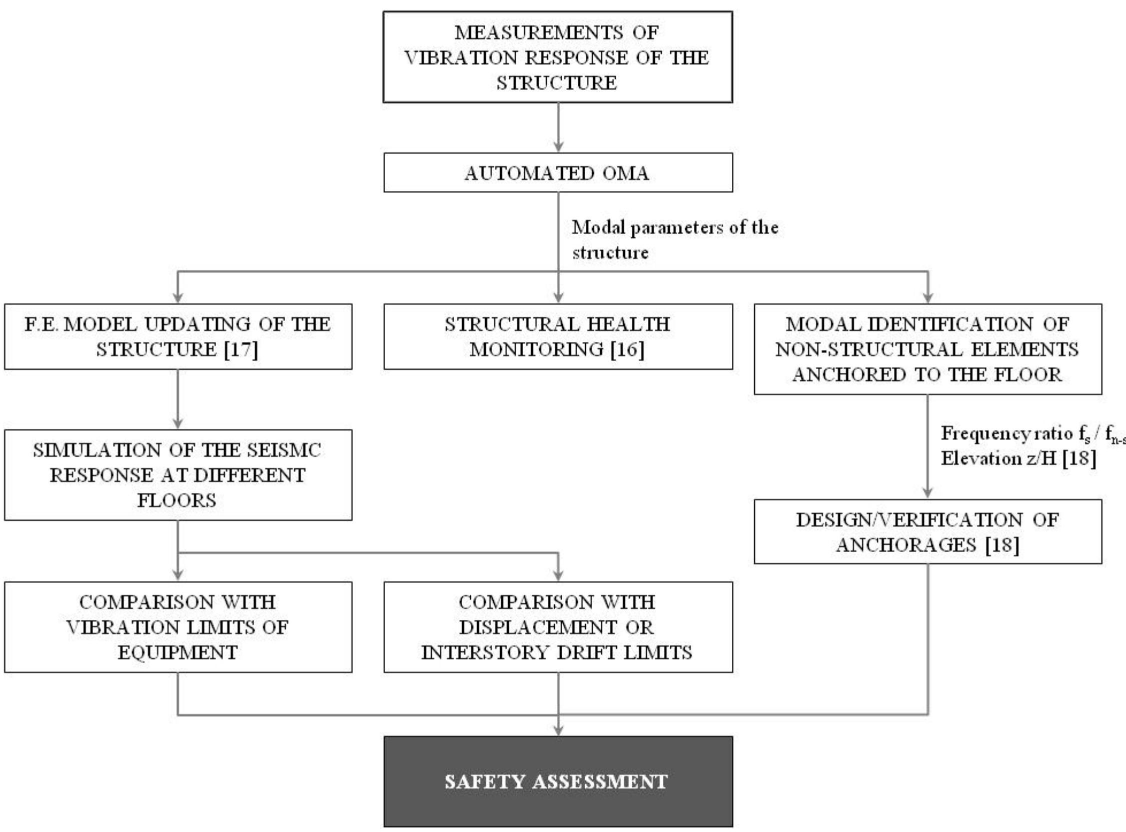
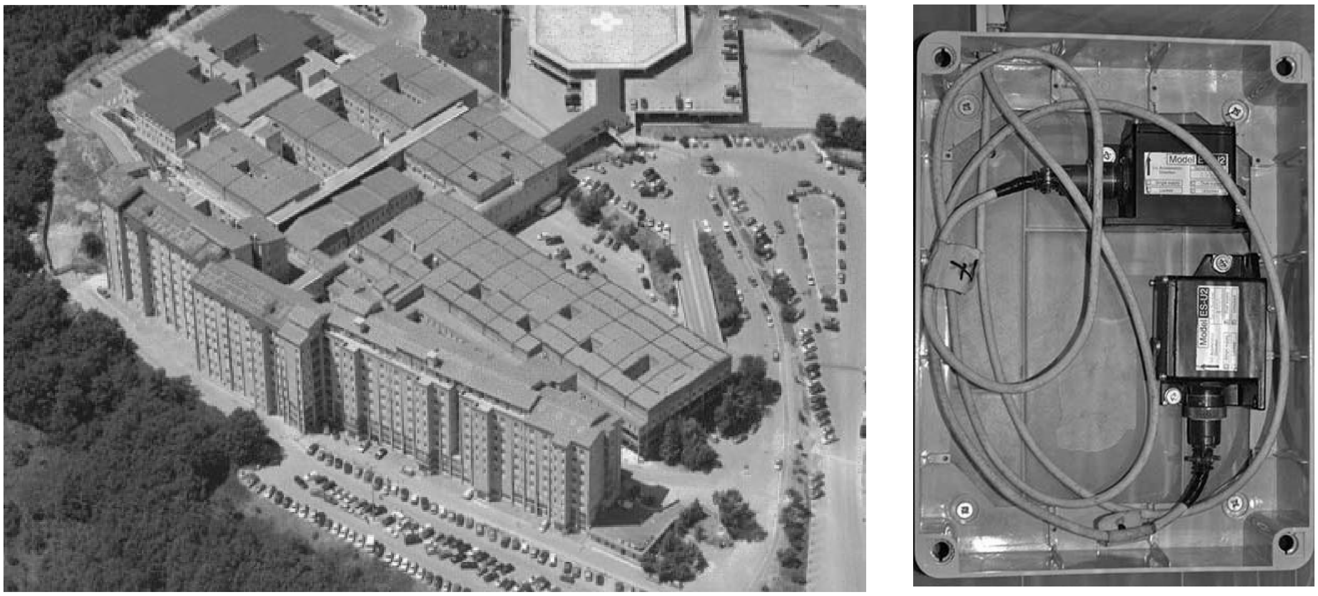


Fig. 2 – Schematic illustration of the proposed approach to dynamic identification and monitoring of health facilies (f_s represents the fundamental frequency of the structure, f_{n-s} is the fundamental frequency of the selected non structural element, z/H is its elevation with respect to the height H of the structure where it is located)

The on-going implementation of a prototype SHF, able to diagnose its own faults and damage, started with the installation of a continuous vibration-based structural monitoring system for the Main Hospital in Campobasso (Fig. 3). The hospital consists of a number of reinforced concrete buildings. Most of them were designed and built in the late Seventies, according to outdated seismic design codes.



(a) (b)

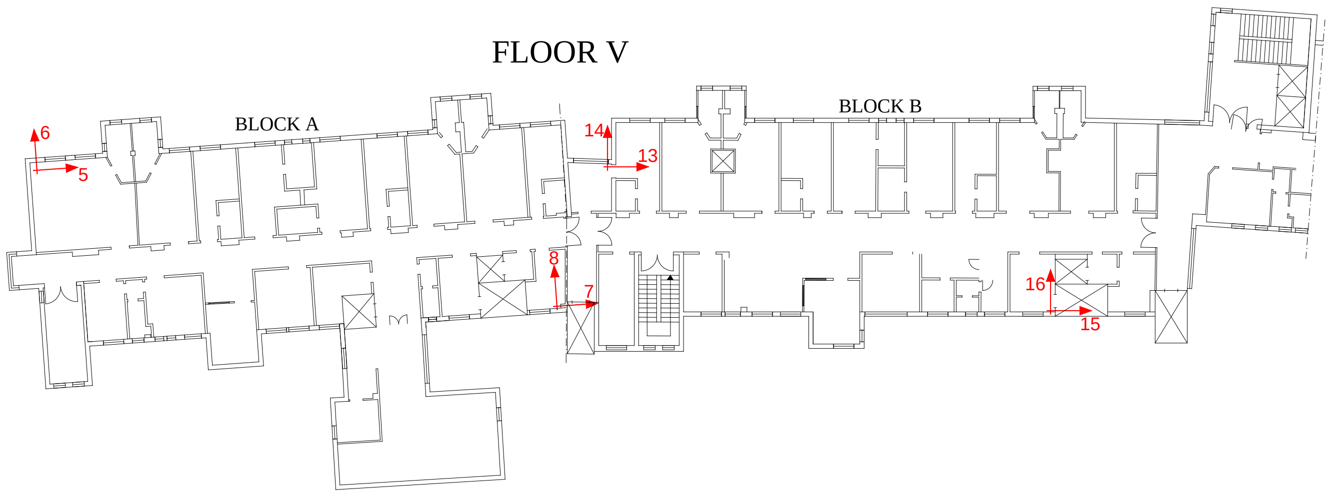
Fig. 3 – Overview of the Main Hospital in Campobasso (a) and installed sensors (b)

The installation of the monitoring system concerned two joint buildings of the Hospital that host the inpatient wards. They have overall dimensions of about 78 m x 14 m in plan and 30 m in elevation. The structural configuration is representative of typical layouts of existing health facilities. The two buildings will be denoted as Block A and Block B in the following (Fig. 4). The former covers a rectangular area of about 36 m x 14 m while the latter covers a rectangular area of about 42 m x 14 m.

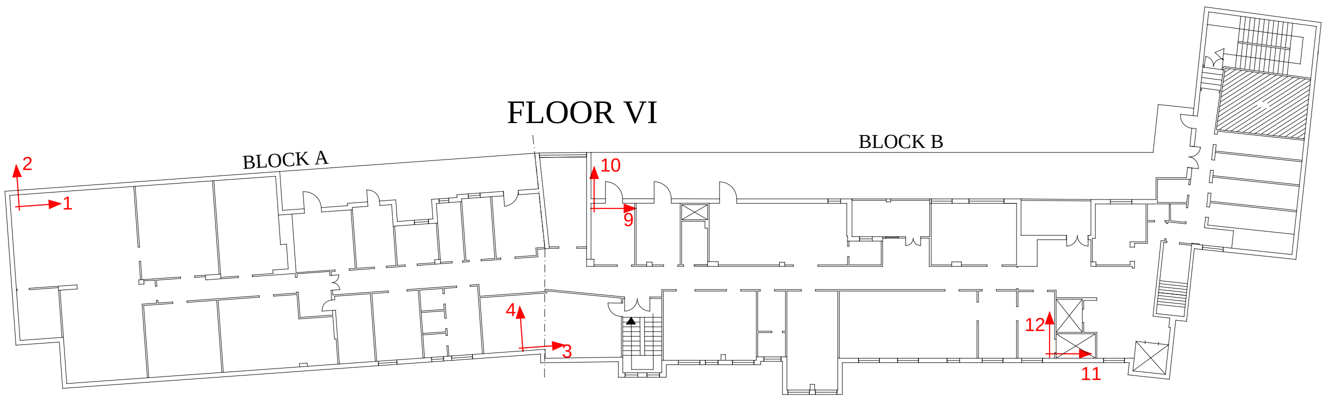
Sixteen force-balance accelerometers (Fig. 3b) have been installed at the two upper levels of the structure along two orthogonal directions (Fig. 4). The sensors have been placed at opposite corners of the block plans in order to ensure observation of translational as well as torsional modes. The main features of the accelerometers are 0.50 g full scale range, 20 V/g sensitivity, 140 dB dynamic range. They ensure high quality measurements in operational conditions.

A 16 bit measurement system with on-board anti-aliasing filter has been used for data acquisition. This 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 [15], ARES®, to estimate the fundamental modal parameters of the structure.

Data acquisition started on March 24th, 2016. Relevant monitoring results after one month of operation of the system are presented in Fig. 5. 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 until the maximum value reached in the afternoon. Moreover, the recorded temperature in this period is representative of the typical range of temperature in Campobasso over the year (average temperature between 2°C and 27°C [19]).



(a)



(b)

Fig. 4 - Sensor layout

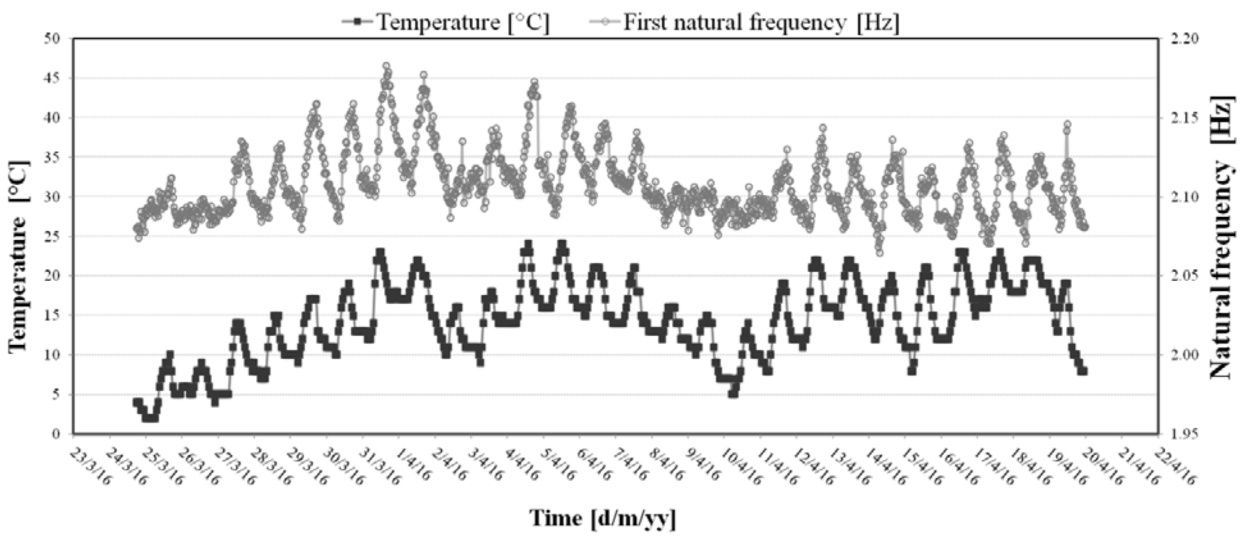


Fig. 5 – Fundamental frequency and local temperature

The observed variations of the natural frequency estimates can definitely be addressed to environmental factors and, in particular, to thermal effects, as confirmed by the comparison between the time histories of the fundamental frequency of the block and the local temperature in Campobasso (Fig. 5). The increase of the fundamental frequency with the temperature can be addressed to the particular structural configuration, characterized by predominant longitudinal extension and direct sun radiation on that side. Moreover, a very small joint divides the two blocks (Fig. 6). As a result of thermal expansion, when the temperature increases the distance between the two blocks decreases and the interlocking between the blocks yields some stiffness increase in the longitudinal direction.

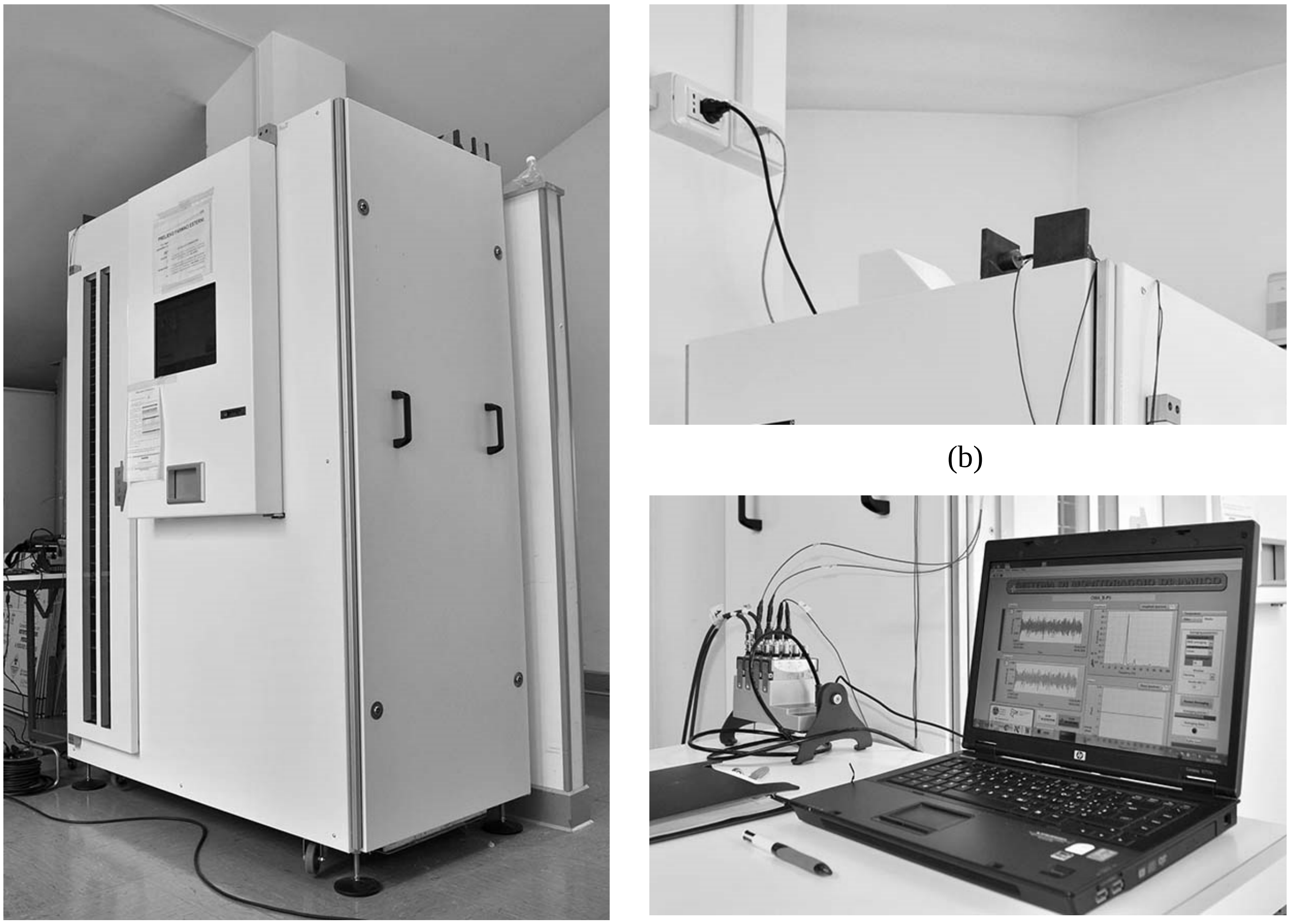
Fig. 6 - The joint between the two monitored blocks

3. Dynamic testing of equipment

The seismic response in terms of acceleration at a floor of the structure becomes the input ground motion for equipment and furniture standing at that floor. If they are rigidly connected to the structure, the seismic force on the non-structural element depends on its elevation z with respect to the structural height H and on the ratio between the fundamental frequency of the structure (f_s) and that of the considered non-structural element (f_{n-s}) [18]. Thus, experimental modal testing of equipment represents a fundamental step in view of its seismic qualification and vulnerability assessment.

Dynamic tests have been carried out on two drug dispensers, the so-called "Busterspid" (Fig. 7a), placed at different floors of the structure. The dispensers have dimensions of 150 x 80 x 210 cm and a weight of about 570 kg. The tested dispensers were placed at the first and the fifth floor. The objectives of the tests were the identification of the dynamic properties of the dispensers and the evaluation of the dynamic interaction with the structure. Thus, for each Busterspid an output-only modal identification test and an input-output modal test have been carried out. In the latter case, the input was applied by a modal hammer.

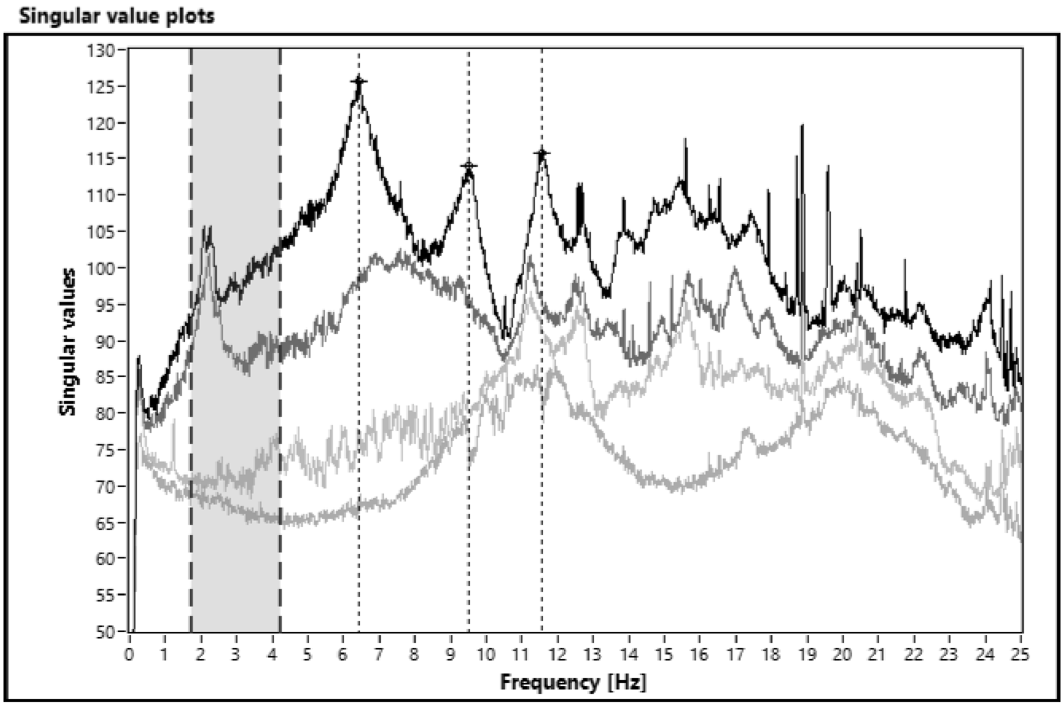
Four piezoelectric accelerometers were installed on top of the Busterspid for output-only modal identification (Fig. 7b). The sensors had the following characteristics: 0.5 g full scale range, 10 V/g sensitivity. Vibration data were acquired by a customized 24 bit data acquisition system based on programmable hardware (Fig. 7c).



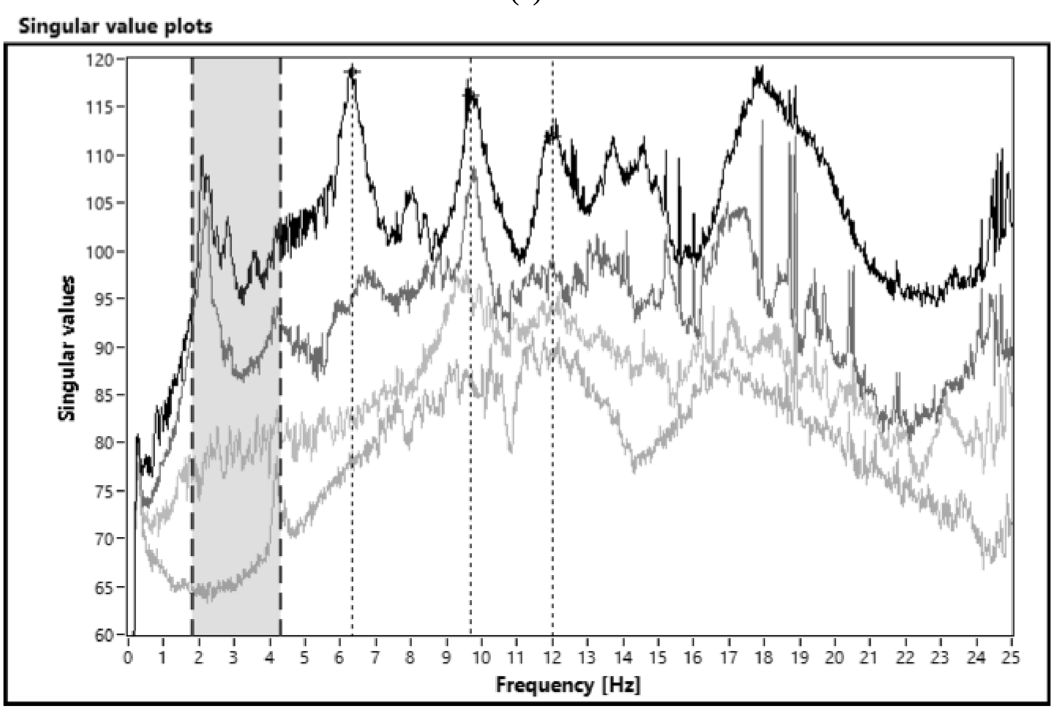
(a) (b) (c)

Fig. 7 – OMA test: the Busterspid (a), the sensors (b) and the data acquisition system (c)

The vibration response of the dispenser was recorded for 3600 s with sampling frequency of 100 Hz. Data pre-treatment has been carried out in order to remove offset and eventual spurious trends. Data have been also visually inspected and analyzed in order to identify eventual measurement anomalies, such as clipping, noise spikes, and so on [20, 21]. Filtering and decimation by a factor of 2 have been carried out before modal parameter identification. The modal parameters have been estimated by means of well-established OMA procedures, such as the Frequency Domain Decomposition (FDD) [20, 22] and the Covariance Driven Stochastic Subspace Identification (Cov-SSI) [20, 23]. Hanning window and 66% overlap have been adopted in the computation of power spectra in the context of the FDD method. When Cov-SSI was applied, a maximum model order of 60 was considered in the construction of the stabilization diagram; the number of block rows was set after a sensitivity analysis in a way able to enhance the quality of the stabilization diagram [24, 25].



(a)



(b)

Fig. 8 - Singular value plots: dispenser at the first floor (a) and at the fifth floor (b), structural frequency bandwidth is shown in grey

The first three modes of the dispensers have been clearly identified. No significant disturbs derived from operation of the dispensers. The corresponding natural frequencies are reported in Table 1. The singular value plots obtained from the FDD method (Fig. 8) 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, corresponding to the fundamental frequencies of the blocks (see also Fig. 5). Dynamic interaction effects are more evident for the dispenser located at the fifth floor than for the one at the first floor. However, in view of seismic assessment, it is worth noting that the fundamental frequency of the Busterspid is about 6 Hz, quite higher than the fundamental frequency of the blocks.

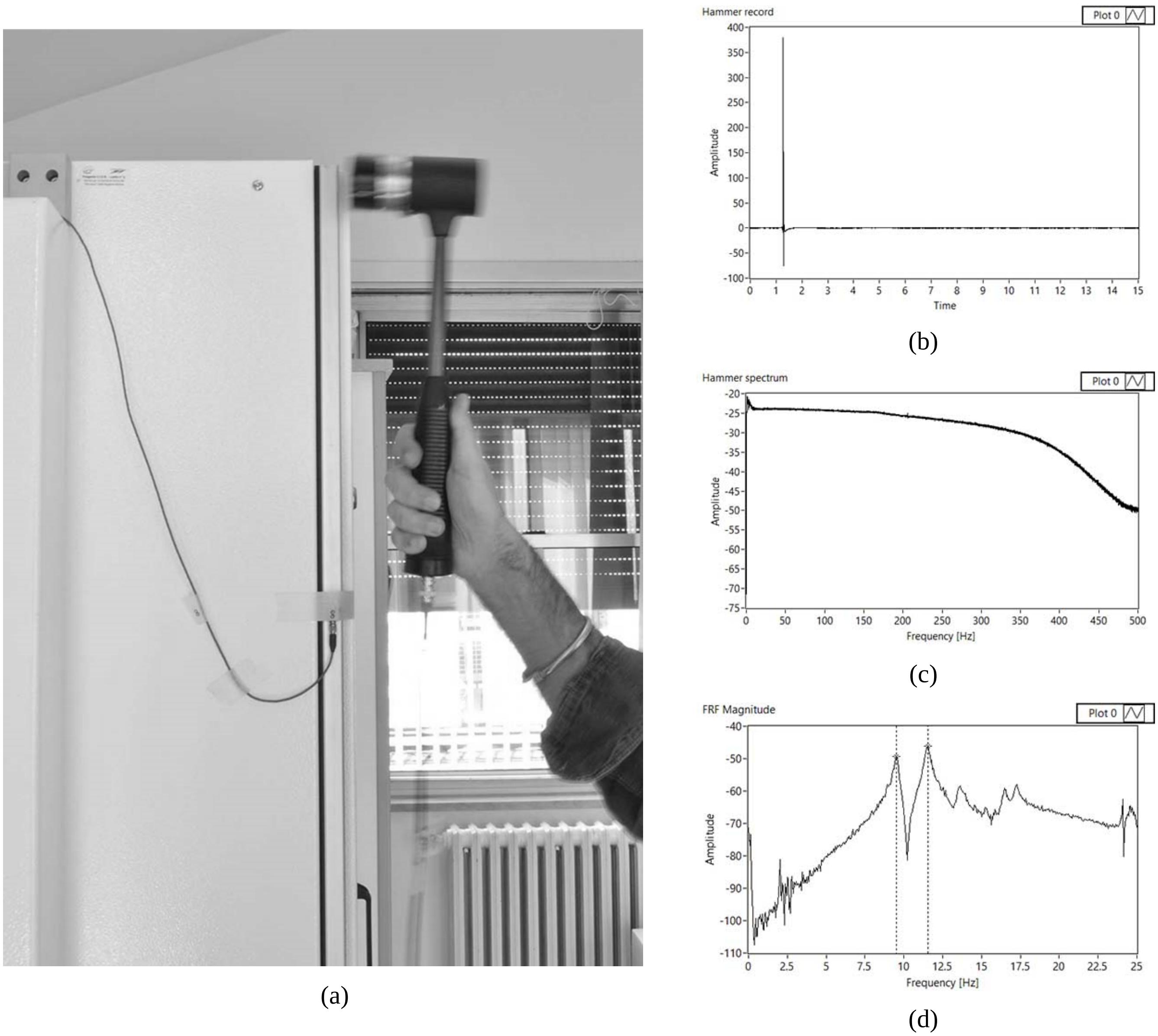


Fig. 9 – Experimental modal analysis of the drug dispenser (a); hammer record (b); hammer spectrum (c); Frequency Response Function (d)

The input-output modal identification test started from measuring the input force and the acceleration response of the dispenser excited by an impact hammer (Fig. 9a) with the following characteristics: ±22 kN pk full scale range, 0.23 mV/N sensitivity. The input force and the acceleration response have been recorded (Fig. 9b) at a sampling frequency at 1000 Hz. Frequency Response Functions (Fig. 8d) have been then estimated and analyzed to extract the modal parameters [26]. Results are reported in Table 1 in comparison with those obtained from the OMA tests, showing a substantial agreement between the corresponding natural frequency estimates. The differences in the modal properties of the two dispensers are limited and within typical uncertainty bounds.

Table 1 - Estimated natural frequencies of drug dispensers

Mode	Operational Modal Analysis		Experimental Modal Analysis	
	$f_{BS\text{-}1th\ floor}$ [Hz]	$f_{BS\text{-}5th\ floor}$ [Hz]	$f_{BS\text{-}1th\ floor}$ [Hz]	$f_{BS\text{-}5th\ floor}$ [Hz]
I	6.40	6.27	6.07	6.30
II	9.25	9.65	9.33	9.51
III	11.57	11.96	11.30	11.52

4. Conclusions

In the present paper, the opportunities related to the implementation of monitoring programs to enhance the seismic safety of health facilities have been discussed, pinpointing the importance of assessing also the performance of non-structural elements. The first stages of implementation of an SHF, able to diagnose its own faults and damage, have been illustrated. In particular, two aspects have been discussed: the continuous monitoring of the modal parameters of the structure and the dynamic identification of two drug dispensers. About the first aspect, the herein presented results pointed out a remarkable influence of the temperature on the natural frequency estimates as a result of the particular structural configuration and the interaction between nearby blocks. As modal testing of equipment is concerned, the interesting applicative perspectives of experimental modal analysis for seismic qualification and vulnerability assessment of non-structural elements have been discussed. Moreover, OMA tests on two drug dispensers located at different floors of the hospital highlighted dynamic interaction effects with the structure resulting in spurious frequencies in the vibration response of the dispensers. Thus, implementation of OMA-based damage detection strategies for medical equipment has to take into account this phenomenon, which might affect the reliability of results. Thus, robust modal identification and monitoring procedures, able to discard spurious frequencies, are necessary. Nevertheless, the present application confirms how high performance measurement systems and well-established OMA procedures can effectively resolve the vibration response of medical equipment in operational conditions.

5. Acknowledgements

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