Technologies for seismic safety management of existing health facilities

C. Rainieri[1], G. Fabbrocino[2]

[1]Ph.D., Research associate, Dipartimento di Bioscienze e Territorio, Structural and Geotechnical Dynamics Lab. *StreGa*, University of Molise, Via Duca degli Abruzzi – 86039 Termoli, Italy, carlo.rainieri@unimol.it

[2]Associate Professor, Dipartimento di Bioscienze e Territorio, Structural and Geotechnical Dynamics Lab. *StreGa*, University of Molise, Via Duca degli Abruzzi – 86039 Termoli, Italy, giovanni.fabbrocino@unimol.it

Abstract

Safety of health facilities is only partially related to the performance of primary structural members. Stiffness and ductility are relevant for life safety of occupants but they have limited influence on the resilience of the system. Thus, modern seismic codes provide strict requirements to structural and non-structural components. They are aimed at ensuring that the system remains fully operational in the case of frequent earthquakes. Electro-mechanical and medical equipments, tanks and distribution systems, heat, ventilation and air conditioning (HVAC) systems, elevators and power supply systems have a predominant position in the safety hierarchy over the mechanical performance of structural members. In the present paper the opportunities provided by state-of-the-art monitoring technologies for seismic safety management of existing health facilities are investigated. Attention is focused on the implementation of a methodology able to cover the needs of knowledge, storage and monitoring of crucial information and physical data by taking advantage of the most recent developments in sensing, data acquisition and processing. This is not a trivial task, since system resilience depends also on the ability of inspectors and managers to integrate theoretical evaluations and interpretation of field measurements.

Keywords: Health facilities, non-structural components, operational limit state, monitoring system, seismic protection.

Introduction

Health facilities are usually very complex systems. They perform a large number of functions: they provide health care but also function as office for the medical staff and administration, laboratories and warehouses. They are also strategic structures, which should remain fully operational after earthquakes.

Many hospitals worldwide and mainly in European regions exposed to medium or high seismic hazards, i.e. Italy, Greece and Turkey, are often built according to outdated codes of practice and they often do not fulfil the above-mentioned requirement. Thus, attention has been recently focused on their seismic safety at National and International level [1].

Hospitals play a fundamental role in the case of an earthquake, but they are also very vulnerable due to their complexity, occupancy level and the presence of specific equipments and installations. Vulnerability assessment requires consideration of both structural aspects and non-structural and administrative ones [1, 2]. As a consequence, the structure has to be able to resist the force of natural disasters and equipments and furnishing should remain undamaged, vital connections (water, electricity, medical gases, and so on) have to be in service and the personnel has to be able to provide medical assistance even in emergency conditions.

A “safe hospital” is a facility whose services remain accessible and functioning at maximum capacity and in the same infrastructure during and immediately after the impact of a natural hazard [1]. Actually, existing hospitals are rarely out of service after an earthquake because of structural damage. Functional breakdown is usually the reason for service interruption. Thus, 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 [1]:

- Protect the life of patients, visitors and hospital staff,
- Protect the investment in equipments and furnishing,
- Protect the performance of the health facility.

The definition of an operational limit state is critical in particular in the case of frequent earthquakes, when slight or no structural damage can be observed, but the health facility experiences service interruptions due to non-structural damage or damage to equipments and installations. A prompt fault detection of equipments and installations after a ground motion and near real time identification and localization of eventual structural damage are the main tasks in the development of "smart health facilities" (SHFs). The attention focused on the performance of equipments and installation is fundamental to assess also the indirect losses due to the loss of functions, that are often more relevant than those associated to structural damage.

Taking into account that the damage of critical equipments and installations, such as tanks, lifeline services and so on, might cause downtime in health facilities, different levels of acceptable damage can be defined based on the related consequences on the user community and the frequency of occurrence of such a damage level, in compliance with the concept of performance-based design. Thus, a thorough assessment of health facilities requires an integrated performance evaluation based on continuous monitoring of structural, non-structural and operational safety.

When earthquake is the main natural hazard in the geographic area of interest, a reliable seismic vulnerability assessment plays a primary role in the definition of the expected performance of the structure in the case of a seismic event. The vulnerability assessment of health facilities is currently carried out according to various methods depending on the objectives of the assessment and the availability of data and technology [3, 4]. From a general point of view, they can be classified as qualitative and quantitative methods. The former are usually used to analyze large building stocks and to prioritize interventions in hospitals while the latter are used for individual buildings requiring more detailed assessment and analyses.

Among the qualitative methods, score assignment methods and, in particular, rapid visual screening (RVS) procedures are often adopted. However, such methods suffer the subjectivity of the expert judgement. This drawback can be overcome by the implementation of effective monitoring strategies where relevant parameters related to the system response and environmental factors are continuously recorded and processed in order to get relevant information about the health status of the system itself. An integrated monitoring strategy, focused not only on the structural behaviour but also on equipments and installations by a proper choice of sensors and data processing strategies, provides significant information about the overall performance of the health facility both in operational conditions and in the case of extreme events such as earthquakes. The collected data and information lead to the formulation of a more objective judgement about the system. This result can be obtained through the integration of different sensing elements and data processing procedures, so that the combination of information and data coming from each monitored subsystem is able to provide, almost in real time, a scenario about the health conditions and performance of the facility. Eventually, the combination of effective monitoring strategies with control and early warning systems can improve the global safety of health facilities against hazardous events.

The advantage of development and implementation of SHFs is in the setting of a platform able to assist the management committee of the hospital in the prompt and effective maintenance of structure and equipment under operational conditions, and in decision making and emergency management in the case of seismic events, thus extending the lifespan of the facility. However, the continuous monitoring of structural and non-structural components requires the definition of a sustainable monitoring strategy in terms of sensor type and number, architecture of the monitoring system and computational burden associated to data acquisition and processing. The Structural Health Monitoring (SHM) system has to be robust and reliable, and its lifespan has to be comparable to that of the monitored facility. Durability requires additional efforts in the design of the monitoring system, related to the choice of the measurement chain and, above all, its organization in a way able to prevent downtime when single components may require replacement because out of order or obsolete. Moreover, in order to fulfil the objective of assisting the maintenance and management of the monitored infrastructure, ease of use of the monitoring system and report of a few intelligible information instead of large amounts of raw data are key requirements in the design and development of an SHF.

In the present paper criteria and methods adopted in the design of a sample SHF in a seismically prone area are investigated. Attention is focused on the sustainable implementation of an SHF able to cover the needs of knowledge, storage and monitoring of crucial information and physical data by taking advantage of the most recent developments in sensing, data acquisition and processing. Taking into account that a high percentage of public spending [5] is for specialized health personnel and sophisticated and costly equipment, it is critical that hospitals continue to work even in the case of an earthquake. This is not a trivial task, since functions and resilience of the system as a whole depend also on the ability

of inspectors and managers to integrate theoretical evaluations with field measurements and their effective physical interpretation [6, 7].

Safety issues in health facilities

Seismic protection of health facilities can take advantage of the recent advances in civionics [8] and in the development of smart structures and systems in order to provide information about their health state in an automated way. SHFs are based on the implementation of appropriate monitoring strategies consisting in the installation of a number of sensors on structural and non-structural components and in automated data processing procedures able to extract relevant information about their performance from the raw measurements.

The collected data and information provide a relevant contribution to risk reduction since effective management and maintenance strategies can be implemented in order to reduce vulnerability and enhance the overall performance of the facility. Disaster risk, defined as the probability that damages will overwhelm the ability of the affected community to respond, is in fact the combination of a hazard with vulnerability. The (natural or man-made) hazard, which is the probability that a potentially damaging phenomenon will occur, interacts with vulnerability, which is the likelihood that a community will be adversely affected by that hazard. While hazard can be of natural origin, vulnerability is always the result of human activities (planning, construction and development). Thus, different communities have different resilience to disasters occurring at their location and the extent and severity of damage is inversely proportional to the level of resilience. A comprehensive assessment of the risk in the case of a health facility starts from the identification of the hazard in the geographic area where it is located. This information is critical for performance evaluation and determination of safety levels in structural and non-structural components. Thus, an effective SHF requires also the collection of data about ground motions eventually occurring in the area.

On the other hand, the factors making health facilities vulnerable [2] have to be clearly identified. They can be summarized as follows:

- Complexity, related to the large number of functions accomplished in hospitals, ranging from health care to office and administration, laboratory, warehouse and so on;
- High level of occupancy 24 hours a day and presence of medical equipment, potentially dangerous gases and life support equipment requiring continuous power supply;
- High level of dependence on public services and infrastructures (power supply, water, clinical gases, oxygen, fuel, communications), and critical supplies (medicines, splints, bandages, and so on);
- Presence of heavy medical equipment (X-ray machines, backup generators, autoclaves and other pieces of specialized equipment) which can be damaged as a result of intense ground motions;
- Presence of hazardous materials which can cause indirect losses or, at least, contamination if they spill or leak.

Issues related to structural safety, non-structural safety and safety based on functional capacity have to be therefore identified and analyzed.

Structural safety involves monitoring of structural components and materials and their response to hazards. The objective is the assessment of the performance of the structure under operational conditions, the identification of incipient damage and eventual degradation phenomena, and the assessment of the impact of earthquakes or other hazards on structural integrity and functional capacity. Vibration based techniques able to identify and locate structural damage [9] have a potential in the development of effective SHFs.

The failure of non-structural elements mainly endangers people and the contents of a building. The monitoring strategy has to focus the attention on the stability of non-structural elements (supports, anchors...) and check whether equipment can function during and after an earthquake. In particular, the continuous observation and analysis of the performance of critical systems reduces downtimes for checks of equipments and networks after the impact of an earthquake, since eventual failures are automatically detected by the SHF. This leads also to an optimization of emergency management procedures, since economic and human resources can be entirely devoted to the maintenance of damaged systems only.

The information coming from processing of the data collected by different sensors deployed throughout the health facility plays a fundamental role not only in the definition of appropriate and effective maintenance actions, but also in the organization and optimization of the response of the personnel after an earthquake. Disaster preparedness of the staff can take advantage of the monitoring results to organize assistance in the early earthquake aftershock based on still working equipment and networks.

The above mentioned critical aspects and the opportunities provided by the implementation of an SHF point out how an effective reduction of the overall vulnerability of health facilities requires an integrated monitoring and management strategy which takes into account the different structural, non-structural and administrative components, their interaction and the related safety issues [2].

Criteria for sustainable implementation of smart health facilities

An effective SHF requires the installation of an appropriate number of sensors, of different types and performance, and, above all, an efficient data processing system. The latter acquires sensor output, processes data and eventually provides an alarm. Thus, data processing, reduction and storage, sampling frequency and simultaneous sampling are the fundamental issues, especially with the use of a large number of installed sensors. However, it is worth pointing out how all installations must have also a minimum impact on functions in the hospital.

The different nature of structural and non-structural components requires different strategies for data acquisition and processing. Since there is no sensor able to fit the needs of every monitoring application, sensor choice has to take into account the nature and type of the monitored component and the objectives of monitoring. Sensor selection depends on the physical quantity of interest, and this varies depending on the nature of the component and the expected vulnerability issues. Protection of sensors, wires and connections is fundamental to ensure durability of the SHM system and data quality. For some types of sensors electromagnetic radiation (EMR) effects must be considered.

About the choice of sensors, they must be able to resolve the system response both in operational conditions and in the case of an earthquake. The type of sensor depends also on the monitoring requirements: if a global assessment based on a number of accelerometers deployed on the structure and vibration based damage detection algorithms can provide relevant information about the health state of the structure, different sensors and data processing strategies are required for non-structural elements. For instance, connections and anchorages of tanks, large medical devices (CAT scanners, X-ray machines) can be more effectively monitored by strain gauges, settlements of distribution systems by FBG sensors, losses in tanks and distribution systems by pressure measurements, while medical equipments sensitive to vibrations require acceleration measurements. A summary of typical safety issues in health facilities and of the most appropriate sensors for different monitoring objectives is reported in Table 1.

Item	Monitoring objective	Sensors
Structural safety	Overall structural performance and health assessment	High sensitivity accelerometers
	Structural detailing (connections, joints...)	Strain gauges, displacement transducers, fiber optic sensors
	Foundations (vulnerability to floods, differential settlement, liquefaction)	Fiber optic sensors,
Non-structural safety	Connections and anchorages	Strain gauges, displacement transducers
	Large medical devices (CAT scanners, X-ray machines), medical equipments sensitive to vibrations	Accelerometers, displacement transducers
	Settlements of distribution systems	Fiber optic sensors
	Losses in tanks and distribution systems	Pressure sensors
	Antennas and lightning rods	Anemometers, corrosion sensors, accelerometers
	HVAC, pipes, connection, valves	Humidity sensors, fiber optic sensors, temperature sensors, pressure sensors, accelerometers
Safety based on functional capacity	Fire protection systems	Pressure sensors
	Alarm activation/deactivation	Accelerometers, displacement transducers
	Elevators	Seismic switches
	Valve shut off	Seismic switches
Hazard	Seismic hazard	Accelerometers, velocimeters, seismometers

Table 1. Sensor classes for different monitoring objectives and safety issues

An integrated platform for seismic protection of health facilities should also take into account the following measures:

- Prevention during the years before an earthquake, through seismic design, strengthening of buildings, and the installation of earthquake early warning systems, seismic alarms and earthquake rapid response systems;
- Early Warning, represented by the measures which can be carried out whenever a relevant seismic event is detected by a seismic network such as the evacuation of buildings or shut-down of critical systems. The SEWS

must be able to calculate in real-time the seismic parameters. Whenever a given threshold is exceeded, a warning signal must be transmitted to the interested receivers in order to take adequate countermeasures [10];
- Emergency management, represented by all actions to be taken in the early aftershock hours or whenever the structural conditions of critical buildings have to be assessed to ensure the safety of rescue and/or emergency functions inside the structure.

In such a framework, the collected data and information are certainly useful to improve the knowledge about the health state and performance of the health facility over time. Thus, also management and maintenance interventions and investments can be addressed towards certain subsystems or installations according to a rational prioritization. However, the combination of monitoring plans with basic early warning and control strategies can further enhance the overall safety of the health facility. The information coming from sensors can be also used for the implementation of control strategies able to improve the overall safety in the case of an earthquake. This is the case, for instance, of lift: the information coming from accelerometers deployed on the structure and eventually from early warning system can be used to activate strategies for the immediate shutdown of elevator systems in the event of a potentially damaging earthquake. Shut-down of lifts and critical systems and closure of valves in the case of damage to distribution systems are other possible applications.

A SHF, able to diagnose its own faults and damage, represents also a primary tool for the reduction of the administrative and organizational vulnerability, acting on the preparedness of personnel in the event of an earthquake and helping in the management and maintenance of structural and non-structural elements over time. For instance, the possibility to have a scenario about the performance of structures and subsystems in a few minutes after the earthquake can help the staff in the emergency management and in the identification of the required interventions (for instance, replacement of components in distribution systems) to maintain the hospital fully operational. In this framework, the combination of monitoring plans with early warning strategies can provide additional level of seismic protections (shut-down of critical equipments, reduction of the risk of indirect losses related to the failure of tanks and distributions systems) at minor costs [11]. The continuous monitoring of the health state and performance of hospitals, including equipment and installations, can help in the formulation also of disaster mitigation plan and in the prioritization of investments for safety of people and goods. The importance rating of clinical and support services [2] can help in the definition of priorities in the implementation of the monitoring system in the presence of budget constraints. The development of a smart system, which analyzes data related to different subsystems (structure, equipment, installations and so on) and provides synthetic information about its overall performance and also eventual warnings in the case of damage or faults, can effectively take into account the critical nature and interdependence of the various processes, buildings and equipment.

For a near real-time response of the system, data must be collected, stored, assessed for validity and processed within a very short time. Sampling frequency has to be carefully chosen in order to acquire and retain an optimized amount of data. Along with filtering, this is an issue related to the data reduction and storage which cannot and should not be neglected. The problem of simultaneous sampling is easily solved when a single data logger is used, as data synchronization is governed by the switch rate of the data logger [12]. However, with the rapid increase in the number and type of installed sensors, modular and wireless architectures are also gaining in existence. If two or more loggers are used definite strategies have to be adopted in order to ensure a simultaneous sampling.

Sensing, power, communication and storage technologies are not the only issues while dealing with such systems. Raw data can provide only limited information about the health of a structure. Thus, data mining, signal processing and health assessment (damage detection and prognosis) algorithms have to be considered as well. The continuous progress in the field of damage detection is yielding algorithms that are able to identify the existence, location and extension of damage in structures on the basis of structural response measurements [13, 14].

Vibration based damage identification techniques represent promising tools for structural health assessment. The efforts of the scientific community in the field are leading to the development of effective methods for incipient damage detection and localization based on measurements of the structural response to ambient vibrations [9]. The development of automated output-only modal identification techniques [15, 16] has determined a renewed interest also towards modal based damage detection [9]. Other approaches are based on post-processing of the measurement data to detect anomalies directly from measurements (ARMA modelling, wavelet decomposition and so on). In both the cases, the trend is to use methods that are able to automate the detection process by taking advantage of the recent advances in information technology [17]. Apart from vibration-based methods, static data can be also effectively used for damage detection [18]. Recent developments in data mining and data fusion are exploiting the opportunities arising from the combination, into the same monitoring system, of information coming from different sensors and related to different physical variables. Thus, a number of tools are already available for an effective assessment of the structural safety of health facilities. However, as

mentioned before, structural damage is not the main cause of failure of health facilities. Non-structural damage affecting critical equipments and installations is more often the cause of service interruptions.

Even if the failure of non-structural elements does not usually put the stability of a building at risk, it can endanger people and contents. In particular, critical equipment such as medical devices, tanks, adduction system, power supply systems and backup generators, heat, ventilation and air conditioning (HVAC) systems have a primary influence on the in-service conditions of health facilities. Earthquakes occurred in the past (Takachi-oki, Japan, 1968; San Fernando, USA, 1971; Nihonkai-Chubu, Japan, 1983; El Salvador, Salvador, 2001) have demonstrated [2] that the cause of service interruption and indirect losses due to contamination or out-of-service of health facilities is often the damage to installations (water, steam, medical gases, fuel, air conditioning, piping) and equipment (medical equipment, furnishings, supplies, clinical files, pharmacy shelving, laboratory shelving). Even low magnitude events can affect the vital aspects of a hospital, that is to say those connected to its functions. For instance, experience has shown that the secondary effects caused by damage to non-structural elements can endanger people like structural damage: fire, explosions and leaks of chemical substances can be life-threatening. Damage to equipment and installations and interruption of services, therefore, can make a modern hospital virtually useless.

In order to protect investments in equipment and technological devices, advanced diagnostic tools and monitoring of critical parts such as joints and connections play a fundamental role in the prompt assessment of the functionality of health facilities after a seismic event. For instance, mechanical equipments are very sensitive to acceleration and monitoring of inertial or shaking effects on critical equipment and installations can provide useful information for the prompt assessment of their functionality. Advanced techniques for machine condition monitoring and fault diagnosis can provide objective data and information about the functionality of equipment and installations, and suggestions about the priority of eventual maintenance interventions. An extensive review of such techniques useful for the assessment of non-structural components such as equipment and installations (medical equipment, HVAC and so on) can be found elsewhere [19].

Conceptual framework for design and implementation of a pilot SHF in Central Italy

An appropriate choice of sensors and consideration of the main issues related to installation and data processing (maintenance of sensors, data volume and processing time) represent key issues for the implementation of effective SHFs, as sketched in Figure 1. This illustrates the architecture adopted for the design of a pilot SHF. Its implementation is expected on a sample existing health facility built according to obsolete design codes in a seismically prone area in Central Italy. It is based on remote sensors wired to local data acquisition modules. These transmit the data to a centralized data acquisition system in wireless mode or via Ethernet. Local data processing for individual subsystem and components can be carried out by local servers. The role of the centralized data server is to aggregate, store and further process the data in order to provide a synthetic overview of the overall performance of the facility. As the number of sensors increases, the adoption of a modular architectures and of wireless sensing units leads also to a minimization of the impact of the monitoring system on the functions in the hospital. The presence of databases on the local and master servers simplify the replacement of components without changes in the overall architecture of the monitoring system, whose durability is therefore ensured.

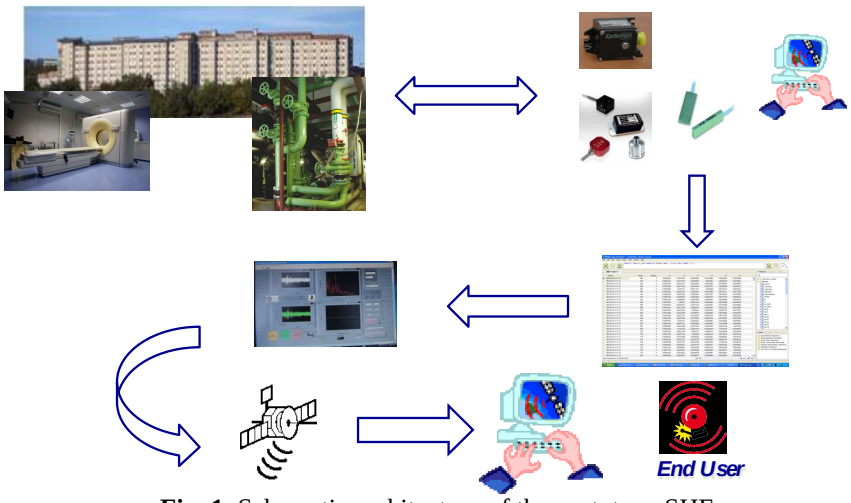


Fig. 1. Schematic architecture of the prototype SHF

The designed SHF system will be able to assess in near real time the health conditions of the structure by continuous tracking of natural frequencies and mode shapes and modal based damage detection algorithms. The automated extrac-

tion of the information about the dynamic properties of the structure from records of the structural response (in terms of acceleration) to the ambient excitation allows for a significant data reduction. In fact, only some days of raw data will be stored on the local database and cyclically deleted, while the estimated modal parameters will be permanently stored on the master server for health assessment and visualization, with significant savings in terms of storage volumes. The continuous monitoring of the modal parameters leads also to a knowledge enhancement about the dynamic behavior of the structure in operational conditions and a statistical characterization of the influence of environmental factors on the structural response. Whenever a seismic event occurs, a link with seismic stations installed over the territory allows for the identification of such events so that related data can be permanently stored. The information about seismic events plays a fundamental role in the characterization of the structural performance and response to ground motions, but it is relevant also to assess the performance and health status of equipment and other non-structural components when an earthquake strikes the facility. Appropriate local data processing procedures can be activated and the information provided by fault diagnosis and machine condition monitoring algorithms can be acquired by the master server in order to support decision making and emergency management. Adoption of local processing reduces the amount of data to be transmitted and this is particularly useful in the post-earthquake phase. However, redundant vectors for data transmission make the SHF more robust in the case of strong motions. The consequences of extreme events on data transmission systems have to be taken into account in particular when early warning and disaster management are primary objectives in the implementation of a SHF.

In summary, the integration of different sensors and continuous condition assessment procedures allows for a performance-based maintenance of health facilities and an assessment of both the short-term impact due to earthquakes and the long-term deterioration process due to physical aging and routine operation. Anomalies can be detected by continuously processing the incoming data. In the case of earthquake risk analysis, monitoring systems can be used to create a database from measurements taken during the life of the structure. In the pre-seismic event phase, these data can be analyzed to evaluate the ability of the building to withstand seismic events on the basis of tremors, such as those due to traffic or wind excitation, by updating the numerical model. At the same time, calibration of the available structural models can improve the ability of structural calculations to make reliable estimations of seismic performance, including the effect of quakes on equipment and installations according to simplified formulation or even the computation of floor spectra [5]. Finally, an in-depth knowledge about the seismic characteristics of the site (such as zone of the epicentre, seismicity, etc.) provides additional useful information. As the database builds over time, this analysis improves, and the detailed characterization of seismicity and structural behaviour allows more reliable predictions of the structural response and of the event that will occur, so decreasing the problem of a false alarm. The design of the prototype SHF is currently undergoing a detailed analysis for the identification of appropriate data acquisition solutions taking into account the characteristics of the monitored structure and the equipments and non-structural components located in the health facility. In fact, they have an influence on the choice of the sensors, since they determine the parameters and physical quantities of interest. Moreover, a detailed characterization of the seismic hazard of the area is in progress [20] and this will have an influence on the architecture of the monitoring system and the design choices for the implementation of a robust data acquisition, processing and transmission, taking into account the probability of extreme events in the area. The outcomes of the present study are preliminary and certainly not comprehensive. However, encouraging recommendations for future developments and experimental studies have been obtained and extensively discussed.

Conclusions

Safety of health facilities mainly depends on the resilience of the overall system rather than on the performance of primary structural members. Thus, stiffness and ductility, which are relevant design parameters, have limited impact on safety of occupants. For this reason, the modern seismic codes provide strict requirements to both structural and non-structural components. They are aimed at ensuring that the system remains fully operational in the case of frequent earthquakes. Electro-mechanical and medical equipments, tanks and distribution systems, heating, ventilation and air-conditioning systems, elevators and power supply systems have a predominant position in the safety hierarchy over the ordinary mechanical (strength and ductility) performance of structural members. Standardized approaches, criteria and indicators for a reliable assessment and management of existing facilities are needed. The present study has investigated the opportunities provided by a monitoring plan in the objective structural and non-structural characterization of existing hospitals. Attention has been focused on the analysis of the factors which make health facilities vulnerable and on the issues related to a rational and objective assessment of performance and health state of structural and non-structural components. This is not a trivial task, since functions and resilience of the system as a whole depend also on the ability of inspectors and managers to integrate theoretical evaluations with field measurements and their effective physical interpretation. In this context the opportunities provided by the implementation of SHFs based on methodologies able to cover the needs of knowledge, storage and monitoring of crucial information and physical data by taking advantage of the most recent developments in sensing and data acquisition have been reviewed. The integration of different sensors and continuous condition assessment procedures allows for a performance-based maintenance of health facilities and an assessment of both the short-term impact due to earthquakes and the long-term deterioration process due to physical aging and routine opera-

tion. Anomalies can be detected by continuously processing the incoming data. Data driven experimental methods (in particular, vibration based methods) have been primarily considered to assess performance and health state of structural and non-structural systems. The outcomes of the study are definitely not comprehensive, but provide encouraging recommendations for future developments and experimental studies.

Acknowledgments

The present study is related to the activities issued by the ASREM Molise Director General Dr. Angelo Percopo on the complex of the P.O. Cardarelli in Campobasso. The Authors wish to thank Dr. Eng. G. Gallina and Dr. Arch. G. Getuli for their contribution in the context of the validation of available seismic assessment data of the above mentioned Health Facility and their valuable support in the definition of operational conditions of structural and non-structural components. In addition, collaboration with ReLUIS Consortium research groups active in the framework of Line 2.2 Special Systems of the ReLuis-DPC Executive Project 2010-2013 "RELUIS II", rep. 823 is also gratefully acknowledged.

References

[1] Pan American Health Organization. (2008). Hospital Safety Index – Guide for Evaluators, Washington, USA.

[2] World Health Organization – Regional Office for Europe. (2006). Health facility seismic vulnerability evaluation – a handbook, Copenhagen, Denmark.

[3] Trendafiloski, G.S. (2003). GIS-oriented method for development of probabilistic earthquake scenarios, Institute of Earthquake Engineering and Engineering Seismology, Skopje, Republic of Macedonia (in Macedonian)

[4] Lang, K. (2002). Seismic vulnerability of existing buildings, Institute of Structural Engineering, Swiss Federal Institute of Technology, Zurich, Switzerland.

[5] Ministero della Salute. (2003). Raccomandazioni per il miglioramento della sicurezza sismica e della funzionalità degli ospedali, Rome, Italy (in Italian).

[6] ATC 51-1 (2002). Recommended U.S. – Italy collaborative procedures for earthquake emergency response planning for hospitals in Italy. APPLIED TECHNOLOGY COUNCIL, Redwood City, USA.

[7] ATC 51-2 (2003). Recommended U.S. – Italy collaborative guidelines for bracing and anchoring non-structural components in Italian hospitals. APPLIED TECHNOLOGY COUNCIL, Redwood City, USA.

[8] Klowak, C., Rivera, E. and Mufti, A. (2005). Implementation of civionics in a second generation steel-free bridge deck, Proceedings SPIE – The International Society For Optical Engineering, 5767.

[9] Doebling, S.W., Farrar, C.R., Prime, M.B. and Shevitz, D.W. (1996). Damage Identification and Health Monitoring of Structural and Mechanical Systems from Changes in their Vibration Characteristics: A Literature Review, Technical Report LA-13070-MS, UC-900, Los Alamos National Laboratory, New Mexico 87545, USA.

[10] Salzano, E., Garcia Agreda, A., Di Carluccio, A., Fabbrocino, G. (2009), "Risk assessment and early warning systems for industrial facilities in seismic zones", Reliab. Eng. Syst. Saf., 94(10), 1577-1584.

[11] Rainieri, C., Fabbrocino, G. and Cosenza, E. (2010). Integrated seismic early warning and structural health monitoring of critical civil infrastructures in seismically prone areas, Structural Health Monitoring – An International Journal, Vol. 10(3), pp. 291-308.

[12] McConnell, K.G. and Reiley, W.F. (1987). Strain-gage instrumentation and data analysis, in Handbook on experimental mechanics, A.S. Kobayashi Ed., Prentice-Hall, pp. 79-116.

[13] Fujino, Y. and Abe, M. (2001). Structural health monitoring in civil infrastructures and research on SHM of bridges at University of Tokio, Proceedings of SPIE, 4337.

[14] Various Authors. (2007). Structural Health monitoring 2007 – Quantification, Validation and Implementation. Proceedings of the 6th International Workshop on Structural Health Monitoring, Edited by Fu-Kuo Chang, Stanford University, Stanford, CA, USA.

[15] Rainieri, C. and Fabbrocino, G. (2010). Automated output-only dynamic identification of civil engineering structures, Mechanical Systems and Signal Processing, Vol. 24(3), pp. 678-695

[16] Rainieri, C., Fabbrocino, G. and Cosenza, E. (2011). Near real-time tracking of dynamic properties for standalone structural health monitoring systems, Mechanical Systems and Signal Processing, 25(8), pp. 3010-3026.

[17] Aktan, A.E., Ciloglu, S.K., Grimmelsman, K.A., Pan, Q. and Catbas, F.N. (2005). Opportunities and challenges in health monitoring of constructed systems by modal analysis, Proceedings of the International Conference on Experimental Vibration Analysis for Civil Engineering Structures, Bordeaux, France.

[18] Lanata, F. (2008). Statistical Algorithms for Damage Detection using Static and Dynamic Approaches, Proceedings of the 4th European Workshop on Structural Health Monitoring, pp. 1047-1054, Cracow, Poland.

[19] Widodo, A. and Yang, B.-S. (2007). Support vector machine in machine condition monitoring and fault diagnosis, Mechanical Systems and Signal Processing, Vol. 21(6), pp. 2560–2574.

[20] Caccavale, M. , Convertito, V., Mancini, M., Fabbrocino, G. (2010). Seismic hazard disaggregation in the Molise region, Italy: the case study of Campobasso, Proceedings of the14th European Conference on Earthquake Engineering, Paper 1684, Ohrid, Macedonia.