Some remarks on the seismic safety management of existing health facilities

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SUMMARY
Safety of critical buildings such as health facilities (hospitals) is only partially related to the performance of primary structural members. 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. Safety assessment of existing facilities is by far more complex than the design of new ones, thus in the present paper the opportunities provided by a monitoring plan in the objective structural and non-structural characterization of a hospital located in a seismically prone area are investigated. Data driven experimental methods (in particular, vibration based methods) are primarily considered to assess performance and health state of the systems under operational conditions. The outcomes of the study are not comprehensive, but provide encouraging recommendations for future developments and experimental studies.

Keywords: Health facilities, Non-structural components, Operational Limit State

1. INTRODUCTION

Hospitals are very complex facilities performing 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. However, Italian hospitals are often built according to outdated code of practice and they often do not fulfil the above-mentioned requirement. Thus, attention has been recently focused on their seismic safety.

Even if hospitals play a fundamental role in the case of an earthquake, they are also very vulnerable due to their complexity, occupancy level and the presence of specific equipments and installations. Thus, their vulnerability has to be assessed by taking into account not only structural aspects but also non-structural and administrative ones (Pan American Health Organization 2008, World Health Organization – Regional Office for Europe 2006). It is therefore imperative that the structure is able to resist the force of natural disasters that equipments and furnishing are not damaged, that vital connections (water, electricity, medical gases, and so on) are in service and the personnel are able to provide medical assistance even in emergency conditions.

The PAHO Disaster Mitigation Advisory Group has defined a “safe hospital” as 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 (Pan American Health Organization 2008). They have also observed that after an earthquake hospitals are rarely out of service because of structural damage. Service interruption is more often the consequence of functional breakdown. Since safe hospitals have the following tasks (Pan American Health Organization 2008):

- Protect the life of patients, visitors and hospital staff,

- Protect the investment in equipments and furnishing,
- Protect the performance of the health facility,

an effective protection strategy has to ensure not only that the hospital remain standing in the case of an earthquake, but above all that it remain in service without interruption. This is critical in particular in the case of frequent earthquakes, when slight or no structural damage is usually observed, but the health facility can experience service interruptions due to non-structural damage or damage to equipments and installations. A prompt assessment of the health state of equipments and installations after a ground motion and near real time identification and localization of eventual damage play a fundamental role in the safety enhancement of the health facility, taking also into account that indirect losses due to the loss of functions are often more relevant than those associated to structural damage.

Building codes are mainly devoted to the regulation of design and construction of structural members. These play a primary role in preventing the collapse of the building in the case of an earthquake, but damage may occur. Even if there is little or no structural damage, the hospital could be not fully operational if the non-structural damage has affected critical equipments and installations such as tanks, lifeline services and so on.

The latest advances in aseismic design and, in particular, the concept of performance-based design define different levels of acceptable damage based on its consequences on the user community and the frequency of occurrence of such a damage level. Thus, a thorough assessment of the seismic vulnerability of health facilities and the definition of countermeasure to identify and eventually mitigate the consequences of earthquakes on the capability of the system to respond to the emergencies is advisable. A reliable and comprehensive assessment of the seismic vulnerability of hospitals can be carried out only by taking into account all the different categories of vulnerability: structural, non-structural and administrative/operational. Rapid and effective diagnostic tools have to be developed to assess the performance and health state of a hospital in the case of seismic events.

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 (Trendafiloski 2003, Lang 2002). 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 for health and vulnerability assessment of structures, 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. The concept of health monitoring can be easily extended to equipments and installations in the hospital by a proper choice of sensors and data processing strategies. The results of continuous monitoring provide significant information about the performance of the system in operational conditions and in the case of extreme events such as earthquakes. The collected data and information allow the formulation of a more objective judgement about the system, providing almost in real time a scenario about its health conditions and performance; moreover, the combination of effective monitoring strategies with control and early warning system can improve the global safety of health facilities against hazardous events.

In the present paper the opportunities provided by a monitoring plan in the objective structural and non-structural characterization of a hospital located in a seismically prone area in Central Italy are investigated. The objective of the monitoring strategy are:

- the definition of a standardized and objective approach to assess health and performance of a hospital struck by an earthquake, in order to realize also if it is able to function immediately after the quake,

- definition of adequate countermeasures to improve hospital safety based on the information collected from the continuous monitoring of the system,

- the support to the emergency management and risk reduction.

Apart from specific aspects related the sample structure, the paper deals in particular with elements related to the non-structural safety of hospitals. 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 and data acquisition. Taking into account that a high percentage of public spending (Ministero della Salute 2003) 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 (ATC51-1, 2002; ATC51-2, 2003).

Data driven experimental methods (in particular, vibration based methods) are primarily considered to assess performance and health state of the systems under operational conditions. Even if damage detection algorithms are continuously developed and improved by the scientific community involved in structural health assessment and monitoring of industrial and civil engineering systems, those strategies can certainly provide useful and, above all, objective information about presence and location of damage in a system and help the authorities to manage an emergency and determine which facilities most urgently need interventions. Continuous monitoring, even in operational conditions, can help also to appropriately plan maintenance interventions, ranking the priority of interventions on the basis of the type and location of identified damage or risk. The outcomes of the present study are in their infancy and certainly not comprehensive, but they provide encouraging recommendations for future developments and experimental studies.

2. SAFETY OF HEALTH FACILITIES

Seismic protection of health facilities can take advantage of the recent progresses in civionics (Klowak et al. 2005) and in the development of smart structures and systems able to provide information about their health state in an automated way. They are based on the implementation of appropriate monitoring strategies consisting in the installation of a number of sensors on the system and in automated data processing procedures able to extract relevant information about the health and performance of the monitored system from the raw data collected by the sensors.

The data and information collected by a monitoring system over time play a fundamental role also in the enhancement of the knowledge about the monitored facility. Thus, they can be useful not only for health and performance assessment in operational conditions or in the case of an earthquake but also to get relevant hints for vulnerability and, therefore, risk reduction. 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. The contribution of continuous monitoring plan to the enhancement of the knowledge about the performance of health facilities in operational conditions and in the case of earthquake (even frequent earthquakes mainly affecting non-structural members, installations and equipments) can lead to a reduction of their seismic vulnerability.

The following factors make health facilities vulnerable (World Health Organization – Regional Office for Europe 2006):

- 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.

Thus, the overall vulnerability of health facilities can be reduced by taking into account the different categories of vulnerability (structural, non-structural and administrative) and their interaction (World Health Organization – Regional Office for Europe 2006).

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 (Doebling et al. 1996). The development of automated output-only modal identification techniques (Rainieri and Fabbrocino 2010, Rainieri et al. 2011) has determined a renewed interest also towards modal based damage detection (Doebling et al. 1996). 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 (World Health Organization – Regional Office for Europe 2006) 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 lifethreatening. 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 (Widodo and Yang 2007) 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.

A "smart" health facility, 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. 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 (Rainieri et al. 2010). 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 (World Health Organization – Regional Office for Europe 2006) 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. This is essential for the proper management of complex infrastructures such as hospitals.

3. CRITERIA FOR IMPLEMENTATION OF SMART HEALTH FACILITIES

An effective "smart health facility" (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.

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 (McConnell and Reiley 1987). However, with the rapid increase in the number and type of installed sensors, modular 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.

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.

In some cases 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.

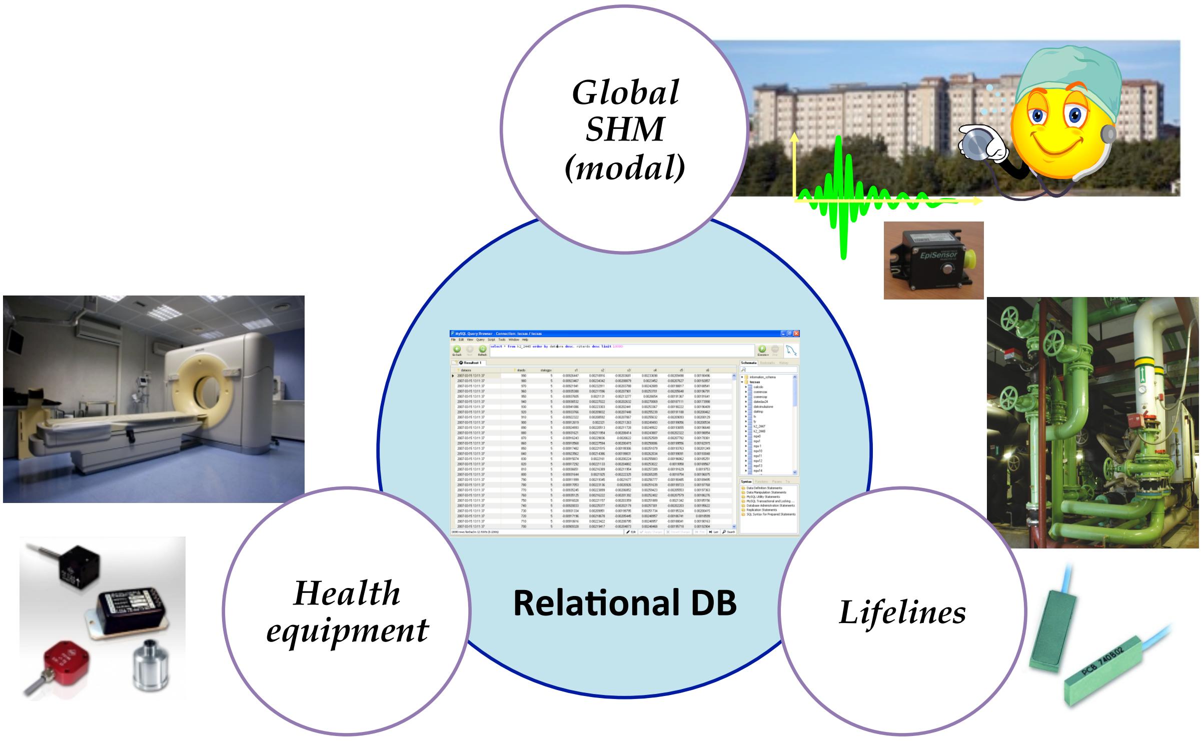

Figure 1. Sensor and data integration in a Smart Health Facility.

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. 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.

A typical architecture is based on remote sensors wired directly to a centralized data acquisition system, as sketched in Figure 2. The role of the centralized data server is to aggregate, store and process the data. However, as the number of sensors increases, modular architectures or, whenever possible, wireless sensing units should be adopted, in order to minimize also the impact of the monitoring system on the functions in the hospital.

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 (Fujino and Abe 2001, Various Authors 2007).

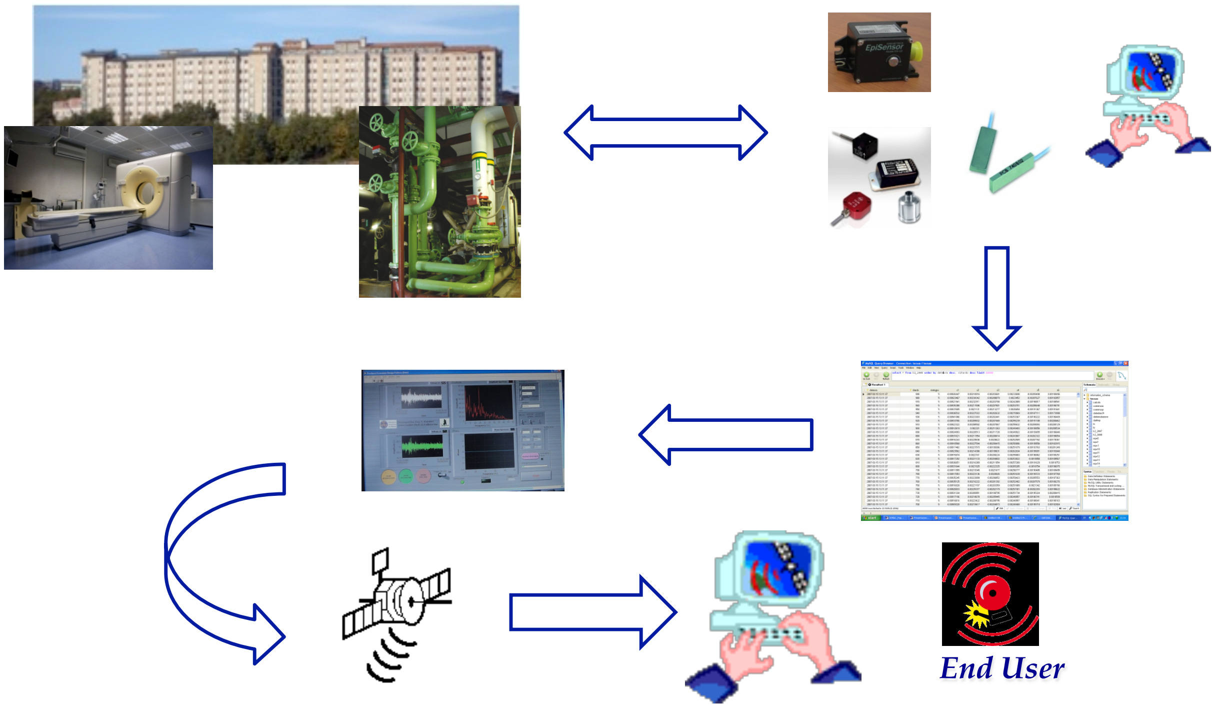

Figure 2. Schematic architecture of a SHM for a Health Facility.

As mentioned before, modal-based algorithms, aiming at tracking changes in structural response which are directly or indirectly related to the dynamic characteristics (such as natural frequencies, mode shapes, and so on) of the structure before and after damage (Doebling et al. 1996), are suitable for a global assessment of the structure. 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 (Aktan et al. 2005). Apart from vibration-based methods, static data can be also effectively used for damage detection (Lanata 2008). An extensive review of techniques for machine condition monitoring and fault diagnosis useful for the assessment of non-structural components such as equipment and installations (medical equipment, HVAC and so on) can be found elsewhere (Widodo and Yang 2007).

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,

- 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. Shut-down of lifts and critical systems and closure of valves in the case of damage to distribution systems are possible applications. Finally, 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.

As a final result, the continuous condition assessment and performance-based maintenance of health facilities plays a primary role in the assessment of the short-term impact due to earthquakes and the long-term deterioration process due to physical aging and routine operation. Furthermore, anomalies can be detected by 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 (Ministero della Salute 2003). 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 above mentioned different applications, related to operational and extreme event conditions, have different requirements in terms of reliability and speed of communication. The recent advances in Information and Communication Technology allow real-time monitoring of structures. However, the consequences of extreme events on data transmission systems have to be taken into account when early warning applications and disaster management are considered. In order to deal with the limited bandwidth for data transmission, two strategies can be considered: employment of redundant vectors for data transmission and reduction of the amount of data to be transmitted (Li et al. 2008). Redundant measurement systems are the result of a compromise between high spatial resolution of sensors, which implies a high volume of data to be processed, and the need of continuous monitoring, to depict the details of time-variant phenomena.

4. CONCLUSIONS

Safety of critical buildings such as health facilities is only partially related to the performance of primary structural members. Stiffness and ductility are relevant design parameters but their impact is limited to life safety of occupants. Their relevance on the resilience of the system is, instead, limited. 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, 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.

Safety assessment of existing facilities is by far more complex than the design of new ones. Standardized approaches, criteria and indicators for a reliable assessment and management are therefore needed. In the present paper the opportunities provided by a monitoring plan in the objective structural and non-structural characterization of a hospital located in a seismically prone area in Central Italy have been investigated.

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.

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 not comprehensive, but provide encouraging recommendations for future developments and experimental studies.

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