Modal-based SHM of hospitals in earthquake prone regions

Carlo Rainieri¹, Danilo Gargaro² and Giovanni Fabbrocino¹
1 University of Molise, Italy, carlo.rainieri@unimol.it, giovanni.fabbrocino@unimol.it
2 S2X s.r.l., Italy, danilo.gargaro@s2x.it

Abstract

A number of earthquakes occurred in Italy and throughout the world have remarked the critical role of health facilities for post-earthquake emergency management. Damage to structural as well as non-structural members, equipment and installations may affect functionality of hospitals in the event of an earthquake. The primary role of hospitals after hazardous events requires the development of specific analysis and monitoring strategies aimed at rapidly assessing their structural conditions and the safety level of ordinary operations. The present paper discusses how modal based SHM can support timely detection of earthquake-induced damage. Two nearby reinforced concrete structures belonging to the main hospital in Campobasso (Southern Italy) are selected as case study. Experimental data are continuously collected and processed. Attention is focused on the response of the structure in operational conditions as well as after seismic events. In the latter case, simulated damage is also considered to assess the damage detection performance of the installed monitoring system. Encouraging results have been obtained, thus confirming the promising applicative perspectives of modal-based SHM for permanent monitoring of strategic structures, such as hospitals, in earthquake prone regions.

1. Introduction

The key role of hospitals in the post-earthquake emergency management has been demonstrated by several events occurred in Italy and worldwide (1, 2). This is the reason why National rules (3, 4) set high performance levels for health facilities in earthquake prone areas hospitals and particularly require that hospitals must be designed and built in a way able to ensure life safety to occupants and assistance to injured people even in the case of strong earthquake motion. Nevertheless, several existing hospitals have lost their functionality because of damage to non-structural members and equipment, even in the absence of structural damage (2). The seismic vulnerability of health facilities, in fact, is often dictated by the effects of earthquakes on non-structural members, such as masonry infills, on one hand, and installations and medical equipment, on the other hand (5) rather than by damage to structural members. Failure of non-structural components and equipment malfunctioning can jeopardize the functionality of the hospital at a time of large demand of medical assistance, as revealed by several events, such as the 1994 Northridge earthquake, the 2010 Chile earthquake, and the 2009 L’Aquila earthquake with several hospitals that were partially or completely inoperable even in the absence of significant structural damage. Thus, new generations of safe hospitals are expected to remain fully operational during and after earthquakes and require the development of passive and active protection strategies in order to ensure the safe continuous operation during earthquake sequences, like those
occurred in some Italian regions in recent years (Emilia 2012, Centro Italia 2016 earthquakes). In this context, the contribution of the technology is of paramount importance not only in the field of design and construction, but also in the field of structural management of the facilities. In such perspective, the combined use of high performance sensors and computational power available today are the pillars of the development of systems able to track relevant physical and mechanical quantities and monitor global parameters of the structure representative of the health status of the structure. The development of integrated health monitoring systems, specifically designed to assess the functional state of structural as well as non structural elements, equipment and installations, can effectively support the post-earthquake emergency management, providing in near real-time relevant information about damage. A monitoring system can turn a regular health facility into a smart one, able to diagnose its own faults. The development of Smart Health Facilities (SHFs) has, therefore, a positive impact in terms of safety enhancement. Continuous monitoring of health and performance of hospitals can support the formulation of disaster mitigation plans and the definition of investment priorities to ensure the overall safety (6). SHFs can also effectively support the mitigation of administrative and organizational vulnerability by acting on preparedness of the medical staff and supporting the management and maintenance of structural as well as non-structural subsystems over time (6). The combination of monitoring programs with early warning strategies can provide additional level of seismic protection. Criteria for design and development of SHFs are extensively discussed elsewhere (6).

The present paper focuses the attention on the prompt structural health assessment of hospitals after earthquakes by near real time detection of damage. Advanced Structural Health Monitoring (SHM) strategies can provide information about the health state of the structure to a remote user in a fully automated way (7). However, they require the implementation of robust automated data processing procedures in order to provide relevant information about the health conditions of the structure. Based on these premises, the potentialities of modal based SHM in ensuring timely detection of earthquake-induced damage are investigated. Two nearby reinforced concrete structures belonging to the main hospital in Campobasso (Southern Italy) are selected as case study. Experimental data are continuously collected and processed. Attention is here focused on the response of the structure in operational conditions as well as after seismic events. In the latter case, simulated damage is also considered to assess the damage detection performance of the installed monitoring system. Encouraging results have been obtained, thus confirming the promising applicative perspectives of modal-based SHM for permanent monitoring of strategic structures, such as hospitals, in earthquake prone regions. However, appropriate data processing procedures have to be developed and tested in order to properly take into account the influence of environmental and operational variable (EOVs) on the performance of the SHM system.

2. Modal-based monitoring of Campobasso’s Main Hospital

2.1 The seismic SHM strategy

An effective SHM requires continuous recording and processing of the vibration
response of the monitored structure. The proposed SHM scheme is based on reliable procedures for the automated analysis of the operational vibration response of the monitored structure. While displacements or interstorey drifts under earthquake loading are often used for remote structural health assessment of hospitals, also because of the sensitivity of non-structural elements to displacements, attention is here focused on the opportunities of modal based SHM for rapid post-earthquake damage assessment. Thus, automated identification and tracking of modal parameters is considered in the proposed SHM scheme. An innovative, recently developed (8) automated modal parameter identification procedure, called ARES® (acronym for Automated modal paRameter Extraction System), has been used to continuously monitor the modal parameters of the Campobasso’s Main Hospital. It is able to provide accurate and precise modal parameter estimates without statically set thresholds and parameters. The key feature of the algorithm is, therefore, the absence of analysis parameters that have to be tuned at each new monitoring application. The algorithm (8) combines relevant analysis stages of different OMA techniques in order to simplify the analysis and interpretation of the stabilization diagram. The covariance driven Stochastic Subspace Identification (SSI) method (9) is used to estimate natural frequencies and damping ratios, but the preliminary application of Second Order Blind Identification (SOBI) (10) makes easier the identification of the physical poles. In fact, the auto-correlation of the extracted sources can be interpreted as the free decay response of the equivalent Single Degree Of Freedom system corresponding to a mode. Covariance-driven SSI can be therefore applied to extract the associated natural frequencies and modal damping ratios, and the approximate separation of the modal contributions by SOBI simplifies the interpretation of the stabilization diagram, which holds the contribution from one relevant mode at a time. The discrimination between physical and spurious poles takes advantage of advanced clustering techniques (11). Mode shapes are finally estimated from Singular Value Decomposition of the output Power Spectral Density matrix at the previously estimated frequency of the mode (12). Effectiveness and accuracy of the algorithm have been demonstrated by a large number of tests based on simulated datasets (8), obtaining a success rate larger than 99% even in the presence of data characterized by low signal-to-noise ratio. Once modal parameters have been monitored for a sufficient amount of time, it is often recognized a relevant influence of EOVs on the collected estimates. For instance, the change of natural frequencies due to EOVs like the temperature is often of the same order of magnitude of the variation caused by damage (13). Thus, the influence of EOVs on reliability and robustness of SHM has to be considered. Direct modeling of the influence of EOVs on the dynamic response of a structure is difficult or even impossible because of the non-linear relationship with the mechanical properties of materials and the boundary conditions, and of the typically large thermal inertia of structures. Black-box models are therefore usually applied as an alternative. Mathematical models mapping the changes of the modal properties with the EOVs are set. An extensive review can be found elsewhere (14). Since selecting the EOVs to measure and the positions of the corresponding sensors is very challenging in the case of full-scale structures (14), data processing methods not requiring explicit measurements of the EOVs are also applied as an alternative to the previous ones. This class of methods looks for a subspace in which the environmental
effects lie, so that they can be removed by the projection of the damage features in the subspace orthogonal to the identified one. In other words, these methods are effective in removing the influence of EOVs as long as the variations in the features due to damage are in some way orthogonal or uncorrelated to those caused by the environmental variability (15). An extensive discussion can be found elsewhere (14).

Compensating the influence of EOVs on the estimated modal properties often requires the availability of large datasets of modal properties referring to the healthy state of the structure (16). In order to make the proposed SHM strategy readily available to detect earthquake-induced damage, a complete characterization of the influence of EOVs is omitted. Moreover, taking into account that the occurrence of an event can be independently reported, limited data collected before and after the event are considered and analyzed for anomaly detection.

Assuming that there is only one dominant EOV (for instance, the temperature), the proposed SHM strategy applies 2-means clustering to the first two principal components obtained from the simultaneous analysis of pre-event data and post-event data. Damage detection is based on a measure of the distance between the identified centroids. In order to quantify the sensitivity to damage of the SHM strategy, seismic damage is simulated by a localized drop in the sequence of natural frequency estimates (17), and a threshold for damage detection is defined according to the results of sensitivity analyses.

2.2 Sensor layout and modal parameter tracking

This section briefly presents the layout of the monitoring system installed at the Campobasso’s Main Hospital and the results of automated identification of the modal parameters, highlighting the influence of temperature and weak earthquakes on the fundamental natural frequencies. The Main Hospital in Campobasso consists of a number of reinforced concrete buildings designed and built according to outdated seismic design codes.

A monitoring system has been installed on two joint buildings of the Hospital hosting the inpatient wards. They have overall dimensions of about 78 m x 14 m in plan and 30 m in elevation. The two buildings are denoted as Block V and Block VI, respectively (Figure 1), and they are separated by a small structural joint.

Sixteen force-balance accelerometers have been installed at the two upper levels to measure the structural response along two orthogonal directions. The sensors are located at opposite corners of the block plans in order to ensure observability of translational as well as torsional modes. The vibration response of the structure is sampled at 100 Hz and the collected raw data are stored into a local MySQL database. ARES continuously processes the acquired data to extract the fundamental modal parameters of the structure. The monitoring system started operating on March 24th, 2016, and the first four modes are continuously monitored over time.

The monitored fundamental modes of the structure are characterized by the following mode shapes:

- global bending of the two blocks in the transverse direction characterizes the first mode;
- global bending of the two blocks in the longitudinal direction characterizes the second mode;
- global torsion involving the two blocks characterizes the third mode;
• torsion with counterrotating blocks is associated to the fourth mode.

The modal parameters are significantly influenced by the small structural joint that divides the two nearby blocks. Visual inspection of natural frequency time series in Figure 2 remarks the systematic swings occurring every day, with a reduction of natural frequencies in the night and a gradual increase in the morning until the maximum value reached in the early afternoon. Comparison of the time history of the fundamental frequency with the local temperature in Campobasso (Figure 2b) seems to confirm the primary influence of temperature on the observed variations of the natural frequency estimates.

The predominant longitudinal extension and direct sun radiation on that side, and the very small joint dividing the two blocks are probably responsible for the increase of the fundamental frequencies with the temperature. The thermal expansion when the temperature increases, in fact, causes a decrease in the distance between the two blocks and the interlocking yields some stiffness increase in the longitudinal direction.

The responses to a number of earthquakes have been also recorded since the beginning of monitoring. Some of these events caused a sudden drop of natural frequencies at the time of the event, while the original pattern was still observed after the event. As an example, the $M_w = 3.1$ earthquake, occurred on April 4th, 2016 (http://cnt.rm.ingv.it/event/6564571) caused peak accelerations of 0.015 g and 0.0075 g on top of the structure in the longitudinal and transverse direction, respectively.

The occurrence of the earthquake is indicated in Figure 2a and Figure 3, and it is associated to a visible drop of the estimated frequencies at the time of the event. It is also worth noting that the induced changes of natural frequencies are well within the typical range of variation associated to the changes of the temperature. Thus, the influence of EOVs on natural frequencies has to be taken into account to enhance the reliability and robustness of anomaly detection.
Figure 2. Sample tracking of the fundamental natural frequencies at the beginning of monitoring (a), local temperature and fundamental frequency patterns in the same period (b).

Figure 3. Seismic response measured on top of the structure in the longitudinal (a) and transverse direction (b); earthquake induced drop of the fundamental natural frequencies (c).
2.3 Influence of environmental factors

Identifying the number and type of relevant EOVs affecting the natural frequency estimates is of primary importance to assess the applicability of the previously described seismic SHM strategy (Section 2.1). To this aim, taking into account that explicit measurements of EOVs were not available, statistical methods have to be applied to model the influence of EOVs on the estimates. Principal Component Analysis – PCA – (16) is probably one the most popular approach in this class of methods. The application of SOBI to assess the influence of EOVs on natural frequency estimates and to identify the patterns of relevant EOVs affecting the estimates has been also recently proposed (12). When SOBI is applied, the natural frequency time series are modelled as a linear combination of sources \{s\} (the unknown environmental factors) through the mixing matrix \([A]\), plus the residue \{\varepsilon\}:

\[
\{f\} = [A]\{s\} + \{\varepsilon\}
\]  

(1)

Mixing matrix and sources are simultaneously estimated from the collected data. In the context of SHM, SOBI can be applied to model the influence of EOVs on the natural frequency estimates. The residue obtained by subtracting the predicted natural frequencies to the corresponding experimental data is insensitive to the considered EOVs, so its variations can be address only to other factors, such as damage. Thus, this residue can be profitably used as damage sensitive features for vibration based SHM (5). However, in the context of the present study, SOBI is mainly applied to support the identification of relevant EOVs affecting the estimates. From a theoretical point of view, in the presence of four natural frequency time series and in the absence of noise, SOBI can separate up to four variables (sources) determining the variability of the estimates. In the present case, its application confirms that temperature is definitely the primary cause of variability of natural frequencies in operational conditions.

![Figure 4. Patterns of predicted temperature of the structure and measured air temperature](image.png)
The predicted temperature pattern by SOBI (Figure 4) shows evident similarities with the local temperature in the area measured by a nearby meteorological station (http://www.paolociraci.it/meteo/campobasso-condizioni-tempo.htm). However, it is worth noting that the measured air temperature is not representative of the actual temperature field in the structure due to solar radiation effects and thermal inertia of materials. As a result, in spite of similar trends, predicted temperature of the structure and measured air temperature obviously show discrepancies.

### 2.4 Anomaly detection

Assuming that only one relevant EOV influences the natural frequency estimates, and that the variations of natural frequencies due to damage are in some way orthogonal or uncorrelated to those caused by the environmental variability (13), anomalies in the structural response can be detected by analyzing the distribution of data in the space spanned by the first two principal components. In fact, if there is a single relevant EOV that is responsible for most of the variability of natural frequencies in operational conditions, the second principal component takes into account the additional source of variability in the data resulting from damage. As a consequence, even assuming that the variability due to environmental factors remains the same after the seismic event and that damage is associated to a permanent drop in the natural frequency time series, damage of increasing magnitude causes a separation of the data in two clusters. The distance between the centroids, which takes into account the effect of the EOV as well as that of damage, can be used to detect anomalies in the structural response by defining an appropriate threshold.

Under the above mentioned assumptions, earthquake induced damage is simulated and applied to monitoring data collected on April 2017 and referring to normal operational conditions (Figure 5). Also these data show a clear influence of temperature on natural frequencies.

Figure 5. Monitoring data in operational conditions collected on April 2017

Since the results of k-means clustering are influenced by relative cluster dimensions,
cluster density and non-globular grouping, different damage levels and different amounts of pre- and post-event data have been considered. Figures 6, 7 and 8 compare the actual clusters of data (pre-event and post-event data) in the space of the first two principal components and the identified clusters for different simulated damage levels and equal consistency of the two groups of data. As expected, 2-means clustering yielded two clusters even in the absence of damage. However, it is interesting to note that the separation between the clusters as well as the distance between the identified centroids increase at increasing damage levels.

Figure 6. Pre- and post-event data and clustering results corresponding to different simulated damage levels and the same number of data in the two groups: no damage.

Figure 7. Pre- and post-event data and clustering results corresponding to different simulated damage levels and the same number of data in the two groups: 2% natural frequency variation

Figure 8. Pre- and post-event data and clustering results corresponding to different simulated damage levels and the same number of data in the two groups: 5% natural frequency variation
Analysing how the distance between the centroids changes for different relative dimensions of pre-event and post-event data and for different percentage changes of natural frequencies (Figure 6, 7 and 8), it is possible to note that the centroid distance reaches its maximum when similar amount of data are present in the pre-event and post-event records for a given percentage change in the natural frequencies, thus obtaining the best sensitivity to the simulated frequency drop. On the other hand, it is confirmed that the distance between the centroids increases when the magnitude of the simulated frequency drop increases.

Visual inspection of Figure 9 shows that damage can be clearly detected if it causes at least 3% frequency changes. Assuming that pre-event and post-event records have the same consistency, an appropriate threshold can be easily set. Thus, even in the presence of limited amount of data (one month of monitoring data in the present case) and of relevant temperature influence, earthquake induced damage can be identified by the previously discussed SHM strategy.

3. Conclusions

A seismic SHM strategy based on earthquake induced natural frequency changes and able to deal with one relevant EOV affecting the modal parameter estimates has been investigated. It is based on 2-means cluster analysis of data in the space of the first two principal components. The SHM strategy has been applied to data collected from the monitoring system installed on Campobasso’s Main Hospital. Damage has been simulated by a frequency drop at the time of the event, in agreement with experimental observations. Results show that the investigated strategy can detect damage causing frequency changes in the order of 3% even in the presence of relevant influence of the temperature.
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