Structural Health Monitoring of Existing Bridges in Earthquake Prone Areas: Laboratory Validation

CARLO RAINIERI, DANILO GARGARO, GIOVANNI FABBROCINO, LUIGI DI SARNO, GIUSEPPE MADDALONI, ANDREA PROTA and GAETANO MANFREDI

ABSTRACT

Road infrastructures and particularly bridges can suffer structural damage due to earthquakes threatening the efficiency of the transportation network and the possibility to ensure prompt rescue operation. This particularly applies to existing bridges, most of which have been designed and built according to outdated codes. Structural Health Monitoring (SHM) systems can support the prompt assessment of bridges after seismic events. However, reliability of modal based damage detection currently depends on the accuracy of modal parameter estimates automatically obtained from the analysis of the operational response of the monitored structure, and on the capability of the measurement system to resolve low amplitude as well as strong motions, eventually associated to saturation of sensors.

In the present paper, the performance of a modal-based SHM system for existing bridges in seismic areas is assessed by shaking table tests on a 1:3 scale single span bridge representative of existing highway bridges built in the 60s in Italy. Results show that hidden damage can be identified on a remote basis, thus demonstrating the interesting applicative perspectives of modal based SHM for fast assessment of existing bridges in the early earthquake aftershock. The resilience to earthquake shaking of the SHM system has been also assessed. Finally, specific data processing procedures for earthquake response data are tested and compared with the results of laboratory measurements.

INTRODUCTION

Several Italian reinforced concrete (RC) bridges have been designed and built according to outdated codes, or even without any seismic detailing. Post-earthquake damage surveys have shown that existing RC bridges with circular piers employing poor seismic details often experience brittle failures.

Carlo Rainieri, Danilo Gargaro and Giovanni Fabbrocino, University of Molise, Viale Manzoni, 86100 Campobasso, Italy

Luigi Di Sarno and Giuseppe Maddaloni, University of Sannio, Piazza Roma 21, 82100 Benevento, Italy.

Andrea Prota and Gaetano Manfredi, University of Naples “Federico II”, Via Claudio 21, 80125 Naples, Italy.

Post-earthquake surveys have also remarked the significant impact of strong seismic events on the road network as well as the human life and economy. Thus, effective countermeasures are needed to manage the aftermath of severe earthquakes in the emergency phase.

Recognizing the need of developing further knowledge about the structural behavior of structures built according to obsolete design codes or in the absence of any consideration of seismic action, several Authors investigated the seismic performance of existing bridges. This assessment has been usually based on nonlinear static or dynamic analyses, and fragility curves for individual structures have been proposed to support the definition of post-earthquake scenarios. However, the development of fragility curves for individual bridges in a broad area can be unfeasible because of the associated large computational efforts. Thus, parametric statistical approaches have been proposed [1] in order to set effective decision-making strategies able to support post-earthquake emergency management and rescue operations.

The above-mentioned tools are predictive approaches, which leave aside experimental measurements of the structural response and require a comprehensive and structured assessment of the bridge stock in a given area. Shaking table tests represent an effective alternative to gain knowledge about the seismic behavior of structures, eventually in combination with experimental modal analysis [2, 3]. On the other hand, modal-based damage detection is a promising technique for near real-time health assessment of structures in earthquake prone areas [4, 5]. As a result, a number of research projects have been initiated in the field of civil engineering to assess the potential of modal-based SHM technologies to evaluate the seismic performance of existing bridges and identify structural damage [6]. In this perspective, advanced SHM techniques can be addressed as innovative measures of seismic protection and performance assessment.

Remote vibration-based damage detection in large structures, such as bridges, has been traditionally challenging due to the need of analyzing large amount of data in a fully automated way [7]. However, the recent development of effective automated Operational Modal Analysis (OMA) procedures [8, 9] has promoted the extensive application of dynamic monitoring in civil engineering. Nevertheless, earthquake shaking might also cause saturation of sensors if the measurement chain is optimized to record the ambient vibration response only; inadequate sensors can, in turn, affect the reliability of SHM.

The present paper deals with an experimental laboratory study aimed at assessing the performance of a modal-based SHM system installed on a scaled bridge model subjected to a sequence of shakings by shake tables. The resilience to earthquake shaking of the SHM system is also assessed. Finally, specific data processing procedures for earthquake response data are tested and compared with the results of laboratory measurements.

EXPERIMENTAL TESTS

The tested structure is a 1:3 scaled model of a single span bridge (Figure 1). Two configurations are considered: a) as-built configuration - the deck supports consisted of a steel cylindrical hinge (pinned condition) and a Polytetrafluoroethylene teflon-steel slider (roller) with 1% nominal friction - ; b) retrofitted configuration - friction pendulum isolators were installed under the deck -. The dynamic tests on the bridge model were carried out by means of the 3 m × 3 m bidirectional shake tables of the laboratory of the Department of Structures for Engineering and Architecture at the University of Naples "Federico II", Italy [10]. The tested specimen was densely instrumented to measure the local as well as the global structural response to input ground motions of increasing amplitude. Similar PGA scale factors were adopted for the as-built and the isolated bridge in order to compare the performance of the structure in the two cases.

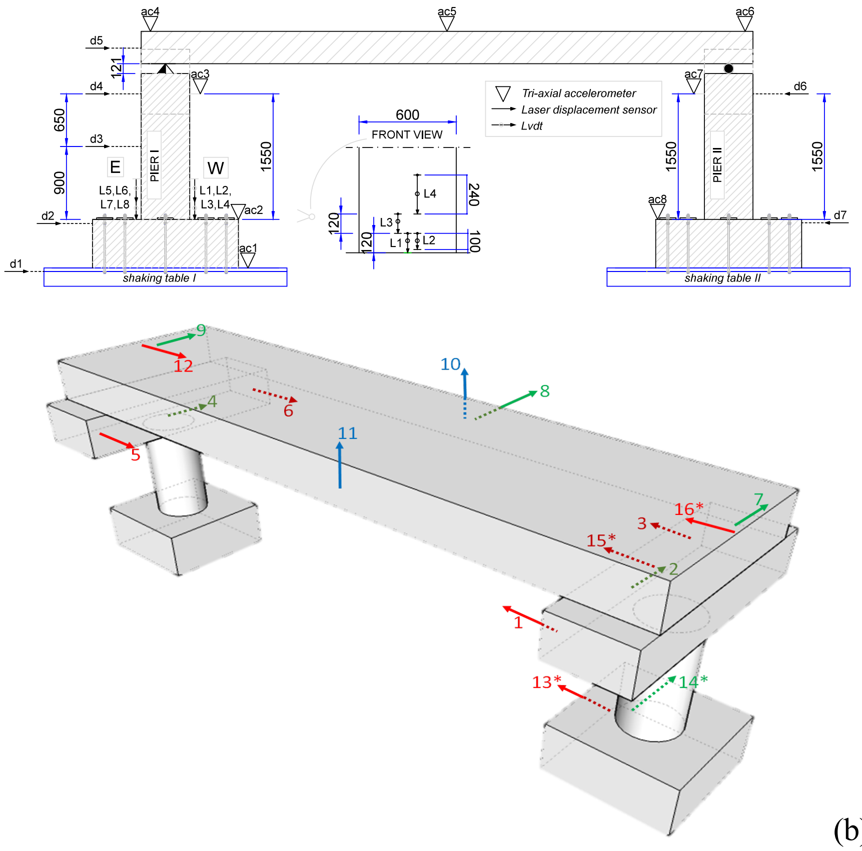


Figure 1. Sensor layout for shaking table tests (a) and vibration based SHM (b)

The measurement system devoted to the shake tests consisted of a number of strain gauges, laser devices and tri-axial accelerometers (Figure 1a). Moreover, eight linear variable displacement transducers (LVDTs) were installed to monitor crack opening at the base of pier I. The Laser Triangulation Displacement Sensors (LTDSs) were instead used to measure the displacements along the two piers and the drifts.

The vibration based health assessment of the structure was carried out by comparing the modal properties, estimated from ambient vibrations, before and after the shakings and with turned off shake tables. Output-only modal identification was based on data collected by an additional measurement system replicating a typical vibration-based SHM system installed on existing bridges. No modal identification was possible in between the shakings because of the disturbance of the pumps when the shake tables were on.

The vibration-based SHM system consisted of sixteen force balance accelerometers wired to a centralized data acquisition and processing unit (Figure 1b). Twelve accelerometers were located on the superstructure in order to observe the fundamental bending and torsional modes, while additional four sensors (denoted by asterisks in Figure 1b) were installed at the base of pier I (sensors #13 and #14), and on top of it on the transverse beam (sensor #15) and on the deck (sensor #16). Processing of the ambient vibration response of the bridge before and after the application of the input ground motions considered only the twelve accelerometers installed on the superstructure. The additional four sensors were, instead, characterized by wider measurement range (±4 g instead of ±0.25 g) and devoted to the analysis of the seismic response. A sampling frequency of 100 Hz was adopted. The collected data were automatically processed to extract the modal properties of the structure by ARES [9] and obtain displacement time histories from double integration of accelerations. Data collected by the measurement system devoted to the shake tests ensured an independent validation of the results obtained from the vibration-based SHM system.

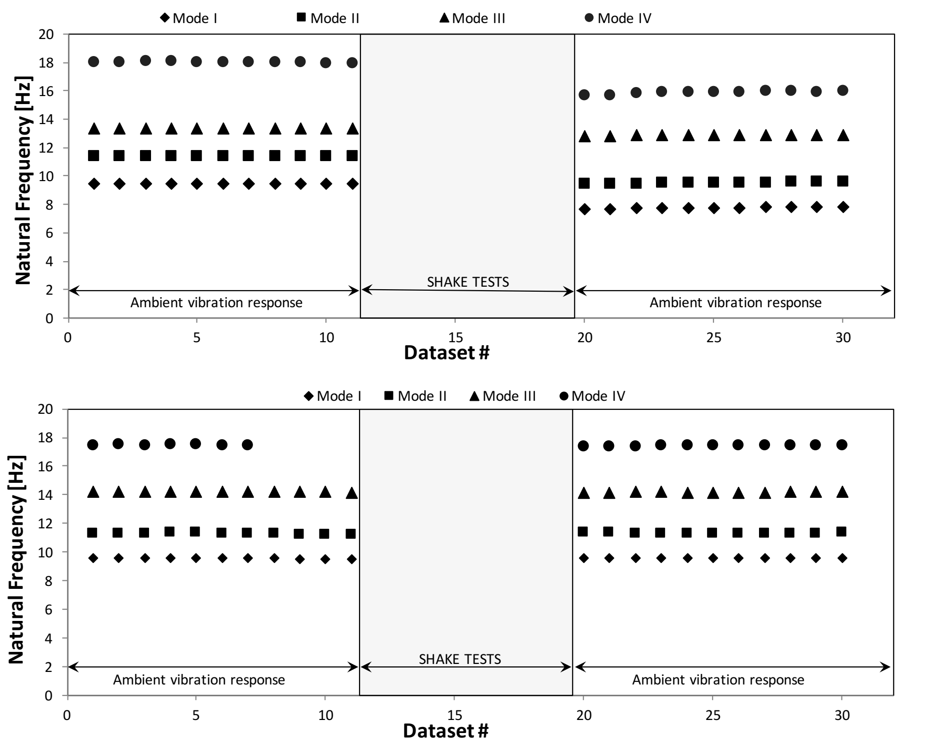
EFFECT OF DAMAGE ON MODAL FREQUENCIES

Automated modal parameter tracking has been carried out for the as-built as well as the retrofitted configuration of the bridge. The latter has been tested first. For each structural configuration, twenty-two records of the ambient vibration response of the bridge have been collected. Each record was 600 s long. The first eleven records referred to the bridge before shakings, while the remaining eleven records were collected after the application of the input ground motions.

While no drops in the natural frequency sequences have been observed for the bridge equipped with friction pendulum isolators (Figure 2a), confirming that no damage occurred as a result of shaking, in the as-built configuration the applied sequence of input ground motions caused a change in the modal frequencies of the fundamental modes (Figure 2b). Figure 2a also shows some missed identifications of the fourth mode. They were due to poor excitation of the mode, as confirmed by an independent (manual) analysis of data.

The shakings caused crack opening at the base of pier I in the as-built configuration. No other cracks were observed along the pier height. The effect of damage was a fairly large variation of the estimated natural frequencies in the absence of significant changes in the environmental and operational conditions (tests were carried out in a relatively short time window and in a controlled environment). The anomalous response of the bridge after the shakings has been confirmed by the fact that the estimated natural frequencies for all modes decreased to values lower than the corresponding lower control limits [11] defined for the natural frequency sequences before shakings. The damage to the pier resulted in a significant change of the dynamic response of the structure even if, at the end of the tests, the crack partially closed, thus limiting the possibility to appreciate the actual level of damage suffered by the structure by a visual inspection, as usual in post-earthquake surveys. The present case study is therefore explanatory of the potentialities of SHM systems in remotely detecting damage, even when it is partially hidden at the end of ground shaking.

Disturbances due to engines and pumps of the shake tables prevented the identification of the natural frequencies in between the shakings, so it was impossible to check the capabilities of ARES to follow the evolution of the natural frequencies in the presence of damage accumulation due to a seismic sequence. In any case, ARES ensured a reliable tracking of the modal parameters of the monitored structure in a fully automated way, that is to say, without any preliminary tuning.



(a)

(b)

Figure 2. Fundamental frequencies of the bridge in the retrofitted (a) and as-built configuration (b)

EFFECT OF LARGE AMPLITUDE MOTION ON MEASUREMENTS

Reliability of damage detection depends on the accuracy of modal parameter estimates. Sensor saturation due to high amplitude vibrations can negatively affect the accuracy of measurements. Thus, assessing the resilience of the measurement chain to large amplitude motion is fundamental to verify the adequacy of a modal-based SHM system for applications in earthquake prone areas.

The previously described tests have shown that sensors with narrow measurement range can easily saturate in the occurrence of an earthquake, depending on the structural configuration, the sensor layout and the magnitude of the input ground motion. In order to check the reliability of vibration measurements right after a strong shaking, the traces of two PSD matrices have been compared (Figure 3). They have been computed from measurements carried out right before and right after the application of an input ground motion able to saturate the sensors. As previously mentioned, the disturbance due to the testing equipment prevented a reliable identification of the modal parameters of the bridge when the shake tables were on. However, Figure 3 shows that the two datasets share common frequency content, with dominant frequency components given by the operation of the testing equipment. This result confirms that the vibration-based monitoring system installed on the structure was able to provide reliable measurements even right after a strong shaking causing saturation of the sensors devoted to resolve the ambient vibration response of the bridge. Resilience of the monitoring system could be negatively affected by a different choice for the sensors. For instance, if the sensor output requires some time (the settling time) to stabilize, inaccurate data are collected right after the shaking and the corresponding automated modal parameter estimates can be prone to errors. However, the obtained results confirm that resilient measurement systems can ensure a reliable monitoring of the modal properties even right after the ground motion and in the presence of sensors not designed to resolve high amplitude vibrations.

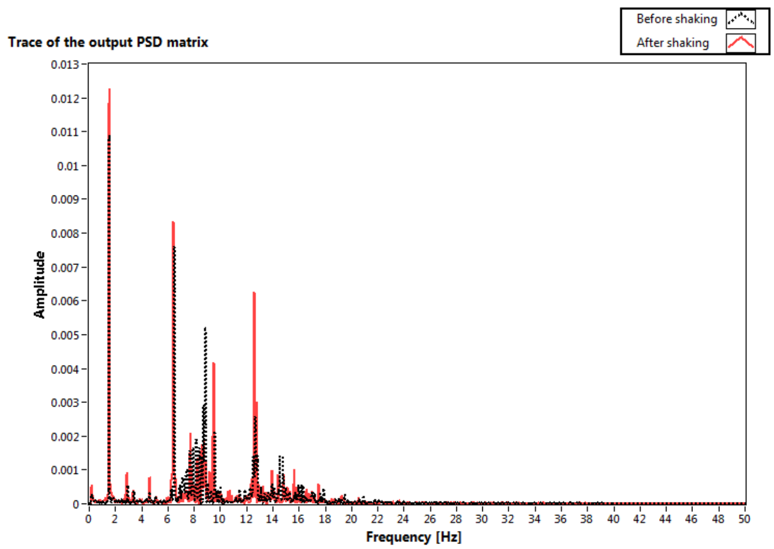


Figure 3. Traces of the output PSD matrix before and after sensor saturation

MEASURING DISPLACEMENTS

Non-linearities and highly non-stationary signals can make OMA techniques ineffective [12]. In the presence of the large transients due to earthquakes, alternative data processing procedures have to be applied for SHM purposes. Displacement measurements are frequently used to analyze the seismic response of a structure and its possible non-linear behavior. Since displacements are usually indirectly estimated by double integration of acceleration data, careful data processing is required in order to minimize the errors. However, neglecting the initial conditions in terms of displacement and velocity yields an error only if they are different from zero [13]. Appropriate filtering can mitigate the effects of slightly different from zero initial conditions and noise in the data. Once displacement time histories are computed, parameters correlated to damage, such as the drift, can be evaluated [14].

In the present study, double integration of accelerations has been applied to the data acquired from accelerometers characterized by ±4 g full scale range. Results have been compared with those obtained from laser measurements obtaining satisfactory results in terms of accuracy. The maximum error was in the order of a few millimeters, with relative error decreasing at increasing PGAs. The latter result can be explained as a reduction of the influence of not exactly zero initial conditions at large amplitude input ground motion. Detailed analysis of errors revealed, in particular, that the estimation error associated to the peak displacement was always not larger than 3.0%. Accuracy was similar for the as-built and the retrofitted configuration.

The computed displacements have been also used to evaluate the drift between deck and foundation in the as-built configuration, thus making possible the assessment of damage accumulation after repeated ground shakings of increasing amplitude. Figure 4 shows the drift computed from double integration of accelerations as a function of the drift obtained from laser measurements for the as-built configuration of the bridge. The resulting plot is very close to the bisector, thus remarking the very similar values of drift obtained in the two cases. In addition, Figure 5 shows, for each test, the peak acceleration measured at the deck as a function of the peak acceleration at the pier foundation for the as-built (Figure 5a) as well as the retrofitted configuration (Figure 5b). The plot in Figure 5a clearly shows the effect of the dynamic amplification of the input motion from the pier foundation to the bridge deck, and the effect of damage. In fact, the peak acceleration at the deck is significantly higher than the peak acceleration at the foundation when the PGA scaling increases. However, the occurrence of the crack at the base of the pier suddenly changes the slope of the curve, and a decrease of the peak acceleration at the deck with respect to the peak acceleration at the foundation can be observed. On the contrary, Figure 5b shows that the peak acceleration at the deck is always significantly lower than the peak acceleration at the foundation, demonstrating the effectiveness of the retrofitting intervention based on friction pendulum isolators.

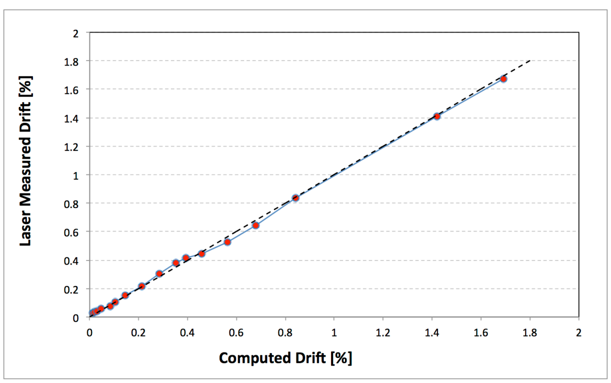
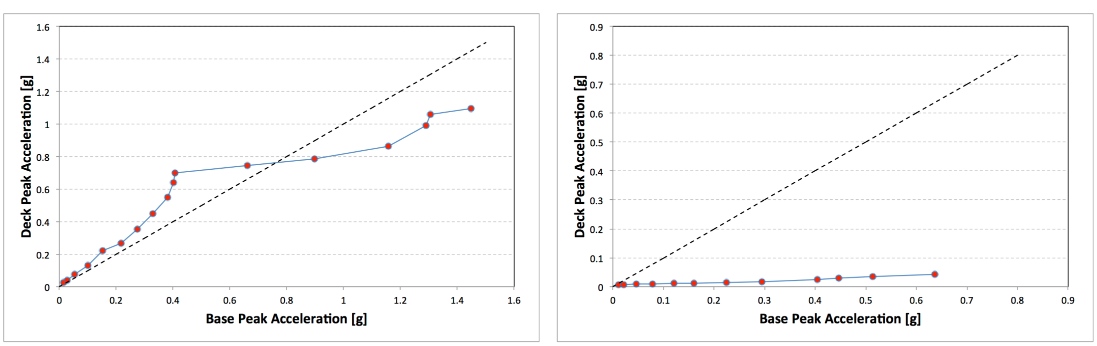


Figure 4. Computed vs. measured drift



(a) (b)

Figure 5. Deck vs. base peak acceleration in the as-built (a) and retrofitted configuration (b)

CONCLUSIONS

The effectiveness of automated modal parameter monitoring for vibration-based SHM of existing bridges in earthquake prone areas has been assessed against real data. Moreover, the herein discussed case study is exemplary in revealing the potentialities of SHM systems in remotely detecting damage, even when it is partially hidden at the end of ground shaking. The resilience of a vibration-based monitoring system to large amplitude motion has been assessed, demonstrating that a reliable SHM in seismic areas by means of automated OMA techniques is possible even in the presence of a measurement chain not specifically designed to resolve high amplitude vibrations. Thus, even if OMA techniques are ineffective in the presence of non-linearities and highly non-stationary signals, they can be confidently applied in the framework of modal-based SHM provided that their use is limited to the analysis of the operational response of the structure. In the presence of the large transients induced by earthquakes, alternative data processing procedures, such as those based on double integration of accelerations, have to be applied in order to extract relevant information about the structural health and performance from vibration measurements.

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