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Detecting earthquake-induced damage in historic masonry towers using continuously monitored dynamic response-only data

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Abstract

The paper summarizes the results obtained during the continuous dynamic monitoring of two iconic Cultural Heritage towers - the Gabbia tower in Mantua and the San Pietro bell-tower in Perugia. The two towers, exhibiting different architectural and structural characteristics, were monitored over a similar time period (of about 2 years) by Politecnico di Milano and University of Perugia, respectively, and similar methodologies of automated operational modal analysis and structural health monitoring were adopted by the two Research Teams. During the monitoring, both the towers underwent far-field seismic events which caused slight structural damage. In both case studies, the limited number of accelerometers installed in the towers allows the tracking of automatically identified modal frequencies and to distinguish between environmental and damage effects on the natural frequencies. Furthermore, the occurrence of structural anomalies corresponding to small drops in frequencies is confirmed through multivariate statistical analysis, based on principal component analysis and novelty detection.

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Keywords: Automated OMA, Damage detection, Environmental effects, Masonry tower, Modal frequencies, Structural Health Monitoring.

1. Introduction

Ancient masonry towers, usually slender and subjected to significant dead loads, are often sensitive to ambient excitation and exhibit a cantilever-like dynamic behavior, so that the successful monitoring of the dynamic characteristics of the structure can be obtained by permanently installing a few high-sensitivity accelerometers in the

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upper part of the building. Hence, the idea to perform cost-effective long-term dynamic monitoring for the preventive conservation of historic towers has been recently taking shape [1].

The use of a limited number of sensors and automated operational modal analysis (OMA) in structural health monitoring (SHM) implies the choice of modal frequencies as features to be assumed as representative of the structural condition [2]. On the other hand, modal frequencies are also affected by factors other than structural changes in a way that is likely more significant than variations induced by a small damage: for example, the modal frequencies of masonry towers generally increase with increasing temperature, due to the closure of mortar gaps, micro-cracks and minor discontinuities in the masonry. The paper reports on the results obtained by the authors during long-term vibration-based monitoring of two symbolic Italian historic towers, the Gabbia tower in Mantua and the San Pietro bell-tower in Perugia, with a specific attention on the ability of the SHM systems in detecting slight structural damage caused by far-field earthquakes. The long-term monitoring systems installed in the two towers are aimed at damage detection by application of statistical process control tools to the time series of the modal frequencies identified by means of automated OMA techniques. Such statistical process control tools have the twofold purpose of (i) removing the effects of changes in environmental and operational conditions from identified natural frequencies and (ii) detecting changes in the frequency data, in the form of statistical outliers, that suggest the possible development of a structural damage. The removal of environmental and operational effects is carried out without using environmental measurements by application of the classical techniques of multivariate linear regression (MLR) and principal component analysis (PCA). Then, a technique of novelty analysis [3] is adopted for damage detection based on T^2 statistics. For a detailed description of the adopted methods in the Gabbia tower and the San Pietro bell-tower the reader is referred to [4] and to [5], respectively.

2. The towers and their monitoring systems

2.1. The Gabbia Tower

The Gabbia tower [6], see Fig. 1, with its 54.0 m height, is the tallest tower in Mantua. The building was constructed for defensive purposes by the Bonacolsi family, governing Mantua in 13th century. The structure is made of brick masonry with load-bearing walls having widths of about 2.4 m, except for the upper levels, where the walls thickness decreases to about 0.7 m. The access to the inside of the tower was not allowed between 1990 and 2012, when it was re-established with the installation of provisional scaffoldings and a light wooden roof on top. While the main part of the building, below the height of about 46.0 m from the ground level, does not exhibit any evident structural deficiency, the upper part of the tower is in a poor state of preservation. In particular, at a distance of about 8.0 m from the top, the brick surface workmanship changes apparently and decreases in quality. Pulse sonic tests confirmed that the material in this portion of the structure is comparatively less performing compared to the rest of the tower. This circumstance, together with some structural discontinuities, determined concerns on the seismic behavior of the upper part of the tower.

On December 17-th 2012 a simple dynamic monitoring system was installed on the tower. The monitoring system is composed of three piezoelectric accelerometers (10 V/g sensitivity), mounted on the cross-section at the crowning level of the tower, one temperature sensor, one 4-channels data acquisition system (24-bit resolution, 102 dB dynamic range and anti-aliasing filters) and one industrial PC on site, for the purpose of system management and data storage. A binary file, containing 3 acceleration time series and the temperature data, is created every hour, stored in the local PC and transmitted to Politecnico di Milano for signal processing. Data recorded by the monitoring system are managed by a LabVIEW toolkit, including the (on-line or offline) execution of the following tasks: (i) creation of a database; (ii) data pre-processing; (iii) statistical data analysis; (iv) low-pass filtering and decimation. Data are successively processed by means of an SSI-Cov procedure for the purpose of automated modal identification. As described in [4], a total of five natural frequencies are successfully tracked during the monitoring period, that correspond to three bending modes, one torsion mode and one local mode in the upper part of the structure. The average value of the first natural frequency during the monitoring period is 0.985 Hz with a standard deviation of 0.038 Hz. The fifth natural frequency has an average value of 9.222 Hz with a standard deviation of 0.554 Hz. For additional details on the natural modes of vibration of the tower, identified in ambient vibration tests (AVTs) and tracked during the monitoring period, the reader is referred to [4].

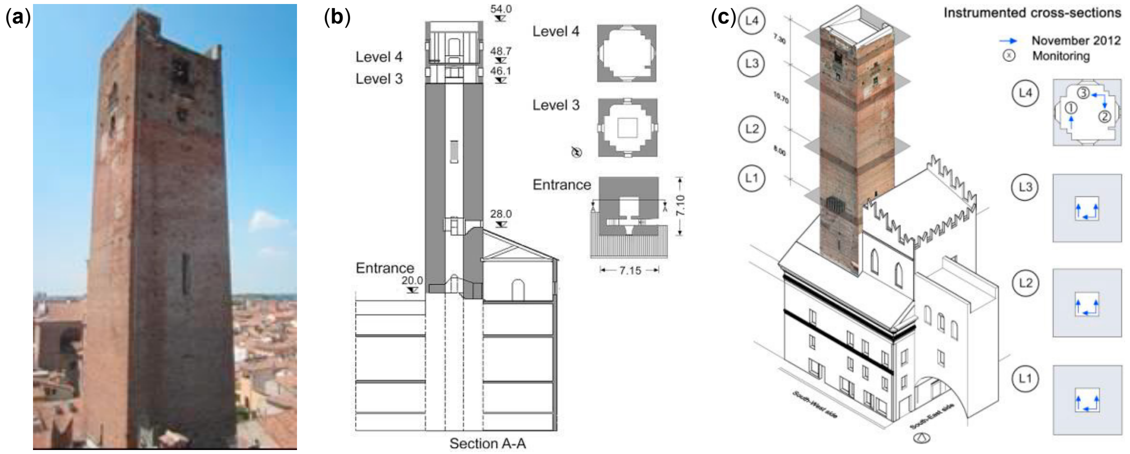

Fig. 1. (a) View of the Gabbia tower in Mantua, Italy; (b) Sections of the tower with dimensions in m; (c) Sketch of the instrumented cross-sections in the preliminary vibration tests (November 2012) and of the monitoring system.

2.2. The San Pietro Bell-Tower

The second iconic tower considered in this paper is the bell-tower of the Basilica of San Pietro, located in the southern part of the city of Perugia (see Fig. 2). The tower was erected for the first time in the 13th century and was subjected to several structural and architectural interventions during the course of the centuries. The last significant restoration and consolidation of the tower was carried out to repair the damages occurred after the strong Umbria-Marche earthquake of 1997.

The bell-tower has a total height of about 61.4 m, but it is restrained in the first 17 m by the surrounding buildings of the Basilica and the Abbey. Three major structural parts can be clearly identified in the tower: (i) a shaft with dodecagonal cross-section in the first 26 m, (ii) a belfry with hexagonal cross section up to about 41 m and (iii) the cusp on the top. The shaft is made of stone masonry, with large external portions in brick masonry probably inserted as structural repairs in past times. The belfry and the cusp are made of brick masonry, with the former being covered by an external curtain of stones. From the architectural point of view, the belfry is strongly characterized by high mullioned windows in each of the six sides, which determine a significant slenderness degree in the upper part of the structure. The long-term vibration-based SHM system was installed on the bell-tower on December 9-th 2014 and comprises three high sensitivity uni-axial piezoelectric accelerometers, having 10 V/g sensitivity, placed at the base of the cusp (Fig. 2 (c)) and two thermocouples to measure the temperature of the masonry in the cusp and the belfry. The information recorded by these temperature sensors is however not used in this paper. The continuous monitoring data are recorded using a multichannel system, carrier model cDAQ-9188 with NI 9234 data acquisition modules (24-bit resolution, 102 dB dynamic range and anti-aliasing filters), connected by a fiber optic cable to a host PC located on site. Data are recorded at 100 Hz, stored in separate files of 30 recording minutes and sent through the Internet to a remote server located in the Laboratory of Structural Dynamics of the Department of Civil and Environmental Engineering of University of Perugia, where they are processed through an ad-hoc developed MatLab code comprising the following steps: (i) a first pre-processing analysis for detecting and correcting spikes and other anomalies in the data; (ii) identification and removal of acceleration data under the excitation of the swinging bells; (iii) low-pass filtering and decimation of the data to 40 Hz; (iv) application of a fully automated SSI modal identification procedure; (v) modal tracking based on a similarity check between estimated modal parameters. As described in [5], a total of five natural frequencies are successfully tracked during the monitoring period, that correspond to five bending modes and one torsion mode. The average value of the first natural frequency during the monitoring period is 1.468 Hz with a standard deviation of 0.019 Hz. The fifth natural frequency is equal to 7.262 Hz with a standard deviation of 0.078 Hz. For additional details on the natural modes of vibration of the tower, identified in ambient vibration tests (AVTs) and tracked during the monitoring period, the reader is referred to [5].

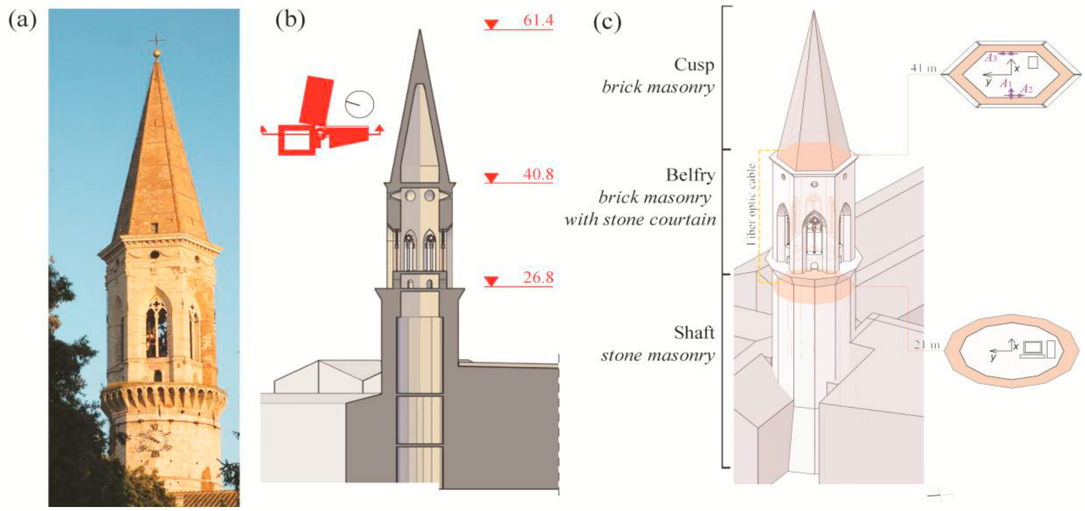

Fig. 2. (a) S–W view of the San Pietro bell-tower in Perugia, Italy; (b) Vertical section of the tower with dimensions in m; (c) Sketch of the monitoring system (A1, A2 and A3 denote the three permanently installed accelerometers).

3. Earthquake-induced damage detection in the two towers

3.1. Damage detection in the Gabbia tower

Among the several far field earthquakes that affected the Gabbia tower during the monitoring period and until June 2013, the strongest seismic event corresponded to an earthquake occurred in the Garfagnana region (Tuscany) on June 21st 2013. This event was characterized by a measured peak acceleration of about 20 cm/s^2, that exceeded about 40–50 times the highest amplitude of normally observed ambient vibrations.

The effect of the Garfagnana earthquake on the natural frequencies is exemplified in Figs. 3(a) and 3(b), where the time evolution of the frequencies of the first two bending modes, denoted as B1 and B2, is shown considering 3

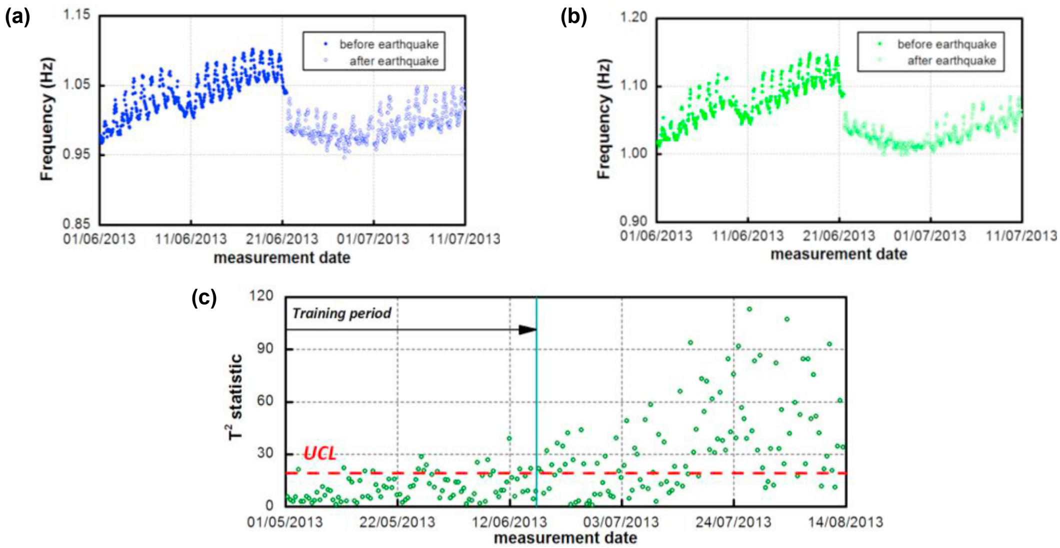

Fig. 3. Gabbia Tower: (a)-(b) Time histories of the natural frequencies of modes B1 and B2, highlighting decays after the Garfagnana earthquake, June 21st 2013; (c) Change in the T^2-statistic induced by the seismic event of June 21st 2013.

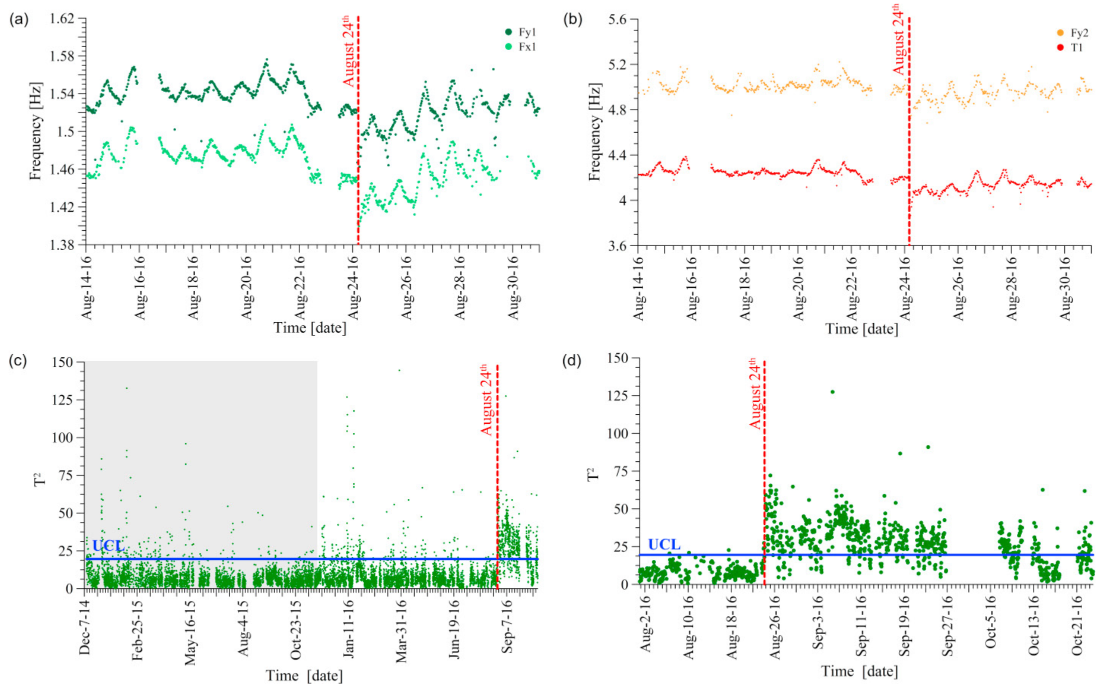

Fig. 4. San Pietro bell-tower: (a) Time histories of the natural frequencies of modes Fx1 and Fy1, highlighting decays after the Accumoli Mw 6.0 earthquake of August 24th 2016; (b) Time histories of the natural frequencies of modes Fy2 and T1; (c) Control chart since the beginning of the monitoring; (d) Detailed view of the control chart, highlighting anomalous frequency of outliers after the earthquake of August 24th 2016.

weeks before and 3 weeks after the earthquake. Clear frequency drops associated to the earthquake are visible from such plots, though very limited and of the same order of the normal daily fluctuations due to changes in environmental conditions. The change in the structural behavior of the Gabbia Tower is clearly revealed also by inspecting the plots of the T^2-statistic shown in Fig. 3(c). The statistical distance of Fig. 3(c) highlights a very clear pattern: before the earthquake, the control chart exhibits limited variations and a few outliers out of the upper control limit (UCL), whereas, right after the earthquake, it abruptly exceeds the defined control region and exhibits a large dispersion. The results of Fig. 3 are quantitatively confirmed by the general decrease of the statistics of the natural frequencies (mean value, standard deviation, extreme values) [4] and demonstrate the occurrence of abnormal structural changes, which were not recovered in the months following the seismic event.

3.2. Damage detection in the San Pietro bell-tower

During the monitoring period, the San Pietro bell-tower experienced several far field earthquakes. In particular, in 2016 the region was affected by the so-called central Italy seismic sequence, which comprised the following major earthquakes: (i) Accumoli Mw6.0 earthquake occurred on August 24-th at 01:36 UTC; (ii) Ussita-Macerata Mw5.9 earthquake occurred on October 26-th at 19:18 UTC and (iii) Norcia Mw6.5 earthquake occurred on October 30-th at 06:40 UTC. In this paper, the first major shock of the seismic sequence, that is, the Accumoli earthquake, is specifically considered.

The San Pietro bell-tower is located at a distance of about 85 km in the NW direction from the epicenter of Accumoli earthquake. In the vicinity of the epicenter, the PGA was very high. In particular, the data recorded by the Italian Accelerometric Network (RAN), managed by the Department of Civil Protection (DPC), and the Italian Seismic Network (RSN), managed by the Istituto Nazionale di Geofisica e Vulcanologia (INGV), report a maximum horizontal PGA in the station located in the town of Amatrice equal to 915.97 cm/s^2. Recorded ground motion data in Perugia for the same earthquake are unfortunately not available. However, by analyzing the records of several stations along the way from the epicenter towards Perugia and by applying the well-known ground motion attenuation empirical law for Italy [7], the PGA at the site of the bell-tower can be roughly estimated as 20-40 cm/s^2.

Fig. 4 shows detailed views of the time histories of the natural frequencies of vibration of the first four tracked modes (denoted as Fx1, Fy1, T1 and Fy2) a few days before and after the earthquake. Daily fluctuations associated to changing environmental conditions and, primarily, ambient temperature, are visible in these plots, as extensively discussed in [8]. However, the plots clearly highlight that permanent frequency decays have occurred after the earthquake that can be roughly estimated to be of the order of 1-2%. The anomaly in the time series of the natural frequencies is clearly highlighted by the control chart representing the T^2 statistical distance, as shown in Fig. 4 (c-d), whereby the relative frequency of outliers changes after the earthquake from 5% to almost 90%. This allows to conclude that a deviation of the structural behavior from normal condition has occurred after Accumoli earthquake. Probably, the existing crack pattern has a little evolved and a little more damage has been accumulated on the structure even though, from a mere visual inspection conducted by the authors right after the earthquake, no significant damage was observed.

4. Conclusions

The two symbolic historic towers under study and, in particular, the Gabbia tower in Mantua and the San Pietro bell-tower in Perugia, underwent far-field seismic events in recent times. As shown in the paper, the application of similar methodologies of automated OMA and SHM strategies by the two Research Teams of Politecnico di Milano and University of Perugia, respectively, clearly highlighted that both towers have accumulated slight structural damage after the seismic events, albeit such damages are not detectable by mere visual inspections. Overall, the presented results demonstrate that, even with a very limited number of accelerometers permanently installed on site, the damage detection task under changing environment can be successfully accomplished with the aid of statistical process control tools, even without any information on environmental conditions. Tools similar to those used by the authors in this paper are thus ready to be used for preventive conservation of heritage structures and, in particular, for highlighting which monuments accumulate more damage during an earthquake sequence, so as to promptly undertake the necessary safety measures to avoid partial or total collapses during the same sequence.

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