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DYNAMIC TESTING AND MONITORING OF HISTORIC TOWERS FOR SEISMIC DAMAGE DETECTION

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Abstract. *Structural health monitoring (SHM) systems represent an acknowledged low-invasiveness and low-cost solution enabling real time condition assessment of civil structures, providing useful information for preventive conservation and maintenance activities. The various documented successful applications of SHM systems to bridges and large infrastructural systems has recently led many researchers to investigate their effectiveness in the case of monumental and historical buildings, often vulnerable to both anthropogenic a natural (e.g. seismic) hazards. The countries in the Mediterranean Basin are especially committed to this kind of research, being, at the same time, rich of built cultural heritage and highly exposed to seismic and other natural hazards. Among the various types of historic buildings, Italian Cities are especially characterized by an extensive presence of bell and civic masonry towers, which also deserve a special attention because of their slenderness, making them suitably monitored via vibration-based systems, and because of their seismic vulnerability.*

Framing in the afore-depicted scenario, the authors have started in the last years a research activity on vibration-based permanent SHM of slender historic towers, finalized at the implementation of new approaches for the optimal management of the limited available budgets for conservation and restoration activities. In the present paper the results concerning this activity are presented with specific reference to two study cases in the city of Perugia, Italy: the bell tower of the Basilica of San Pietro and the civic tower called "Torre degli Sciri". The two considered monuments present completely different characteristics and complexities from both structural and architectural points of view, making them worth interesting investigating as typological benchmarks. The work discusses both ambient vibration testing and permanent mon-itoring applications, including considerations regarding the adopted sensing hardware. The feasibility of a rapid post-earthquake damage detection via SHM is finally explored with reference to the study case of the San Pietro bell tower, with particular attention to the recent seismic events.

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1 INTRODUCTION

Within the context of seismic hazard and vulnerability of cultural heritage structures, maintenance and conservation of historic monumental buildings is a very onerous duty and a real challenge for public administrations and governments, with a limited budget. For this reason historical monuments and constructions, such as masonry towers, palaces and churches, have been widely studied in the last decades, in order to improve the knowledge and the instruments useful for their conservation and preservation [1, 2, 3]. In this regard, with a real economic potential and a cost-effective management, structural health monitoring (SHM) systems can improve protection and conservation of monumental buildings by providing real-time diagnostic and prognostic data, thus enabling condition-based maintenance for an automated structural performance assessment and early stage damage detection. However, taking into account several challenges of cultural heritage structures like the minimal invasiveness, the historical and architectural respect conforming to international criteria preservation, the selection of the proper sensing hardware, the appropriate number and configuration of sensors and the proper signal processing tools necessary to achieve an effective health assessment, SHM is yet to be broadly implemented.

In order to detect anomalies in the structural behaviour associated with local changes in stiffness and modification of the global dynamic behaviour, typically produced by earthquakes or other types of dynamic loads, vibration-based SHM systems are generally associated to effective statistical tools for the analysis of the structural dynamic parameters. More in details, reliable modal parameter estimates, like natural frequencies of vibration, can be obtained from in-service response data through automated operational modal analysis (OMA) techniques [4], [5], [6], typically using a small number of sensors [7]. In addition, powerful tools recently developed allow to track the evolution in time of the parameters associated with a specific structural mode, which is referred to as modal tracking, and furthermore, to remove the effects given by environmental actions (typically temperature and humidity) through the use of statistical models, such as multiple data regression and principal component analysis [8], and finally to detect anomalies in the structural behaviour corresponding to very small variations in frequencies by means of statistical process control tools, such as control charts. The effectiveness of such procedures allows to observe significant deviations of the data from normal conditions, even in presence of small changes in the structural behaviour, which can be automatically detected, for instance occurred after an earthquake. In this regards, natural frequencies have been rediscovered to be a very effective damage sensitive features for long-term vibration SHM.

Several applications of vibration-based techniques to masonry towers can be found in literature [9, 10, 11, 12, 13, 14], due to the slenderness and quite simple requirements in the interpretation of the structural behaviour. This paper is focused on the analysis of two historical masonry towers, located in Perugia, in the centre of Italy, and is essentially divided in two parts: the San Pietro bell-tower and the civic Sciri tower, both masonry towers. Section 2 presents the monumental bell-tower of San Pietro (brief historical background, as well as geometrical and material survey), its monitoring system (sensing and data acquisition hardware) and the analysis of the dynamic response of the bell-tower, besides to operational conditions, to the 2016 Central Italy seismic sequence and the earthquakes occurred on January 18th 2017 in terms of (i) recorded accelerations, (ii) changes of time histories of the natural frequencies of vibration after the earthquakes and finally (iii) control chart as output of the SHM system. Section 3 presents the Sciri tower with its monitoring system, analysis of ambient vibrations, AVTs carried out in January 2017, spectral analysis and the dynamic response to the earthquakes occurred on

January 18th 2017. Finally, Section 4 concludes the paper.

2 THE SAN PIETRO BELL-TOWER

2.1 Historical and geometrical description

The monumental masonry bell-tower of the Basilica of San Pietro is a 61.45 m high tower situated in the southern part of Perugia, Italy. Restrained in the st 17 m by the surrounding buildings of the Basilica and the Abbey, it is subdivided in three structural portions: (i) the dodecagonal shaft in the first 26 m, made of stone masonry, with large external portions realized in brick masonry as structural rehabilitation measures due to the occurrence of several damages; (ii) the belfry with hexagonal cross section rising up to 40.8 m, architecturally characterized by large Gothic openings and made of brick masonry covered by an external curtain of stone and (iii) the cusp completing the tower on the top, made of brick masonry (see Fig. 1). Erected for the first time in the 13th century, several interventions have been implemented to the tower throughout the centuries. The last important consolidation was carried out in 2002, after being severely damaged by the 1997 Umbria-Marche earthquake, with damages which mostly affected the columns of the belfry and the cusp.

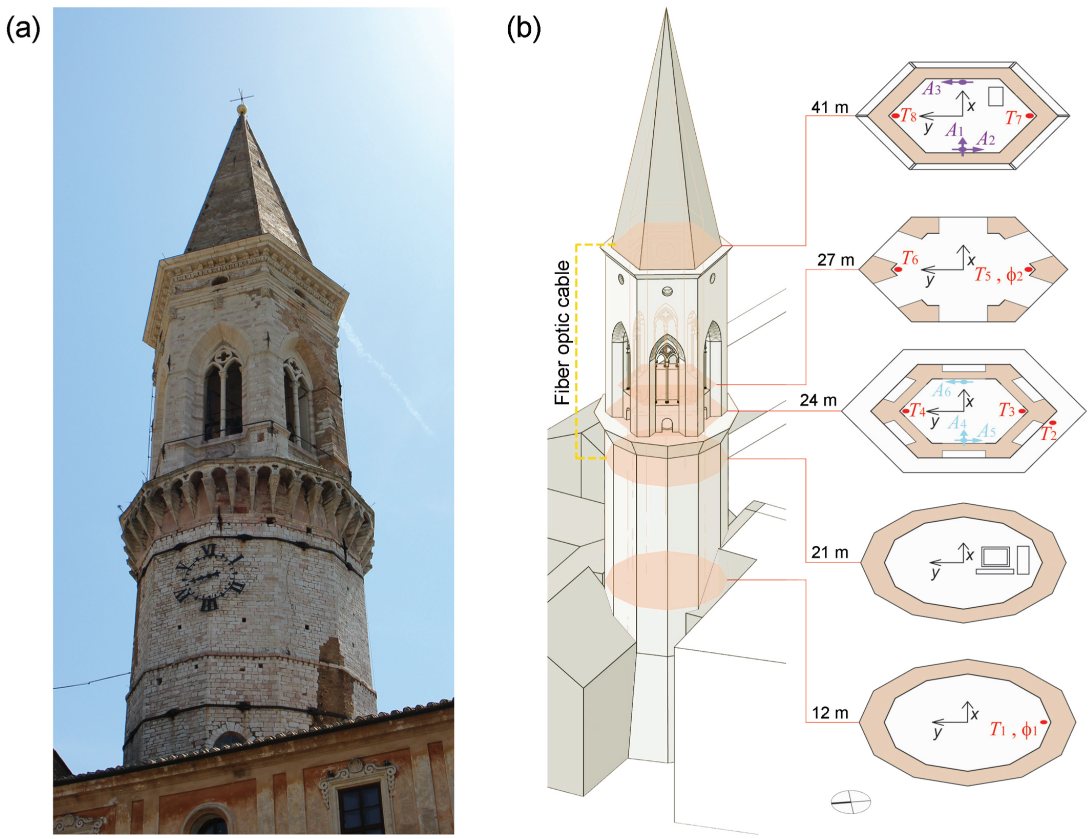


Figure 1: View of the San Pietro bell-tower (a) and sketch of the structural monitoring system: A, T and ϕ denote acceleration, temperature and humidity sensors, respectively (b) (A4, A5 and A6 sensors were only used for ambient vibration testing in February 2015, all other sensors are permanently installed on the tower).

2.2 Vibration-based SHM and damage detection

Continuously monitored since December 9th 2014, through a simple long-term vibration-based SHM system aimed at detecting low return period earthquake-induced damages, there are

three high sensitivity (10 V/g) accelerometers installed at the base of the cusp, able to measure micro tremors induced by traffic and wind. In addition, for environmental conditions characterization, eight temperature and two humidity Tinytag sensors, from Gemini Data Loggers, are also deployed on the structure [14]. A sketch of the monitoring system, with indication of the x-y reference system, is shown in Fig. 1.
Data recorded by the three accelerometers are consecutively stored in files containing 30 minute acceleration time series with a sampling frequency of 100 Hz, and downloaded by a network connection with TCP/IP communication protocol from the computer located on site to a dedicated server placed in the Laboratory of Structural Dynamics of the Department of Civil and Environmental Engineering of University of Perugia. Here, data are processed and modal parameters estimates are extracted, which is a very useful tool for SHM purposes.

In order to identify the main vibration modes of the structure to be tracked by the monitoring system, an ambient vibration test (AVT) was carried out in February 2015, by using six high-sensitivity accelerometers (A1, ..., A6 as shown in Fig. 1(b)). Seven modes of vibration were identified within the range from 0 to 10 Hz. These modes are three flexural modes in x direction (E-W direction), denoted as Fx1, Fx2, Fx3, three flexural modes in y direction (N-S direction), denoted as Fy1, Fy2 and Fy3, and one torsional mode, T1. Five of these modes, namely Fx1, Fy1, T1, Fy2 and Fy3, have been effectively and consistently identified during the whole monitoring period, while modes Fx2 and Fx3 have not allowed a continuous successful identification and are therefore not useful for monitoring purposes.

Given that, significant variations of identified natural frequencies with changing temperature have been observed, the natural frequencies of the seven modes after removing temperature effects have been considered. This removal has been carried out by means of a Multiple Linear Regression (MLR) of natural frequencies versus temperature, using 20°C as the reference temperature. The vibration-based SHM method consists of a MLR model combined with PCA which remove the effects of changes in environmental and operational conditions from time series of natural frequencies and of a control chart which is based on T^2-statistic and detect deviations from normal conditions possibly related to a structural damage.

2.3 Structural responses to the 2016 Central Italy seismic sequence and to the earthquakes occurred on January 18th 2017

The main earthquakes of 2016 Central Italy seismic sequence are the following: (i) Accumoli Mw6.0 earthquake occurred on August 24th at 01:36 UTC ; (ii) Ussita Mw5.9 earthquake occurred on October 26th at 19:18 UTC and (iii) Norcia Mw6.5 earthquake occurred on October 30th at 06:40 UTC. Ground motion records for these earthquakes have been provided by the Italian Strong Motion Network (RAN) of the Department of Civil Protection (DPC) and by the Italian Seismic Network (RSN) of the National Institute of Geophysics and Vulcanology (INGV). Taking into account, that the San Pietro bell-tower is located at a distance of about 80 km in the NW direction from the epicenter of Accumoli earthquake and approximately 65 km from the epicenters of Ussita and Norcia earthquakes, a relatively significant distance from the epicenters, it is very interesting the study of the response of the tower to these earthquakes.

Maximum values and root mean square (RMS) values of response accelerations on top of the bell-tower during the seismic sequence and events of January 18th 2017 are reported in Tab. 1. Measurement channels are numbered as depicted in Fig. 1(b). In particular, Channel 1 and Channel 2 refer to A1 and A2 sensors, measuring accelerations in x (E-W) and y (N-S) directions, respectively, while Channel 3 refers to A3 sensor that is deployed in y direction. In addition,for comparative purposes, Tab. 1 also reports information on the response of the

	Channel 1 $[\mathrm{m/s^2}]$	Channel 2 $[\mathrm{m/s^2}]$	Channel 3 $[\mathrm{m/s^2}]$	Resultant 1-2 $[\mathrm{m/s^2}]$
Accumoli	0.5861 (0.0922)	0.7632 (0.1109)	0.7948 (0.1128)	0.9140 (0.1442)
Ussita	0.6065 (0.0810)	0.3781 (0.0491)	0.3008 (0.0472)	0.6445 (0.0947)
Norcia	0.9423 (0.1596)	0.7627 (0.1018)	0.6487 (0.1008)	0.9469 (0.1893)
Montereale	0.1604 (0.0262)	0.2162 (0.0225)	0.1633 (0.0228)	0.2168 (0.0345)
Capitignano	0.1717 (0.0192)	0.1634 (0.0263)	0.1603 (0.0269)	0.1777 (0.0325)
Capitignano	0.0739 (0.0137)	0.0824 (0.0124)	0.0988 (0.0126)	0.1051 (0.0184)
Cagnano	0.1102 (0.0163)	0.1606 (0.0176)	0.1206 (0.0178)	0.1630 (0.0240)
Bells	0.0339 (0.0114)	0.0278 (0.0087)	0.0269 (0.0084)	0.0351 (0.0143)
Wind storm	0.0249 (0.0011)	0.0447 (0.0009)	0.0242 (0.0009)	0.0719 (0.0019)
Normal conditions	(0.0002)	(0.0002)	(0.0002)	(0.0002)

Table 1: Maximum values of accelerations recorded on top of the bell-tower (corresponding RMS values are reported in brackets) during 2016 Central Italy seismic sequence and earthquakes of January 18th 2017. For comparative aims, accelerations produced by swinging bells on June 5th 2016, during a wind storm occurred from March 4th to March 6th 2015 and in normal everyday conditions (RMS values only) are showed.

structure under relatively strong dynamic excitations and in normal operational conditions. In particular, swinging bells in the morning of June 5th 2016 and a wind storm occurred from March 4th to March 6th 2015, are chosen as two specific cases which represent the relatively strong dynamic excitation. It is noteworthy to stress that earthquake-induced accelerations were at least one order of magnitude greater than those measured in these last two cases and two orders of magnitude greater than those measured in normal everyday conditions. Also, similar values of the peak structural acceleration are observed in Accumoli and Norcia earthquakes, while the peak response to Ussita earthquake was a little smaller.

Fig. 2 shows the time histories of measured accelerations on top of the bell-tower, in x (E-W) and y (N-S) directions, during the earthquakes of the seismic sequence and of January 18th 2017. During Accumoli earthquake, acceleration in y direction was predominant with a peak value of 0.7632 $\mathrm{m/s^2}$. On the contrary, during Ussita and Norcia earthquakes, acceleration in x direction was predominant, with peak values of 0.6065 $\mathrm{m/s^2}$ and 0.9423 $\mathrm{m/s^2}$, respectively. As for measured accelerations during January 18th 2017 earthquakes, they are relatively smaller than the seismic sequence, peak values of 0.2162 $\mathrm{m/s^2}$ in y direction and of 0.1717 $\mathrm{m/s^2}$ in x direction, are observed during the 1st and the 2nd shock, respectively.

Fig. 3 shows the time histories of the natural frequencies of vibration of the five modes of the bell-tower continuously identified and tracked during the monitoring period (modes Fx1, Fy1, T1, Fy2 and Fy3). Daily and seasonal fluctuations associated to changing environmental conditions and, primarily, ambient temperature, are visible in these plots . More importantly, it is clearly highlighted that permanent frequency decays have occurred during the seismic sequence, whereby the horizontal dashed lines in Figs. 3 (a,b,c) represent the mean values of the natural frequencies computed before and after the 1st shock, and the vertical dashed lines represent the dates of the main earthquakes of the seismic sequence, highlighting the instantaneous decays in natural frequencies induced by the same events. In particular, frequency decays are very evident for modes Fx1 and Fy1 in the plot of Fig. 3 (a), as well as for mode T1 and Fy2 in the plot of Fig. 3 (b) and for mode Fy3 in Fig. 3 (c).

Finally, by mean of control chart generated as output of the vibration-based SHM system, permanent earthquake-induced effects on the dynamic response of the bell-tower are high-

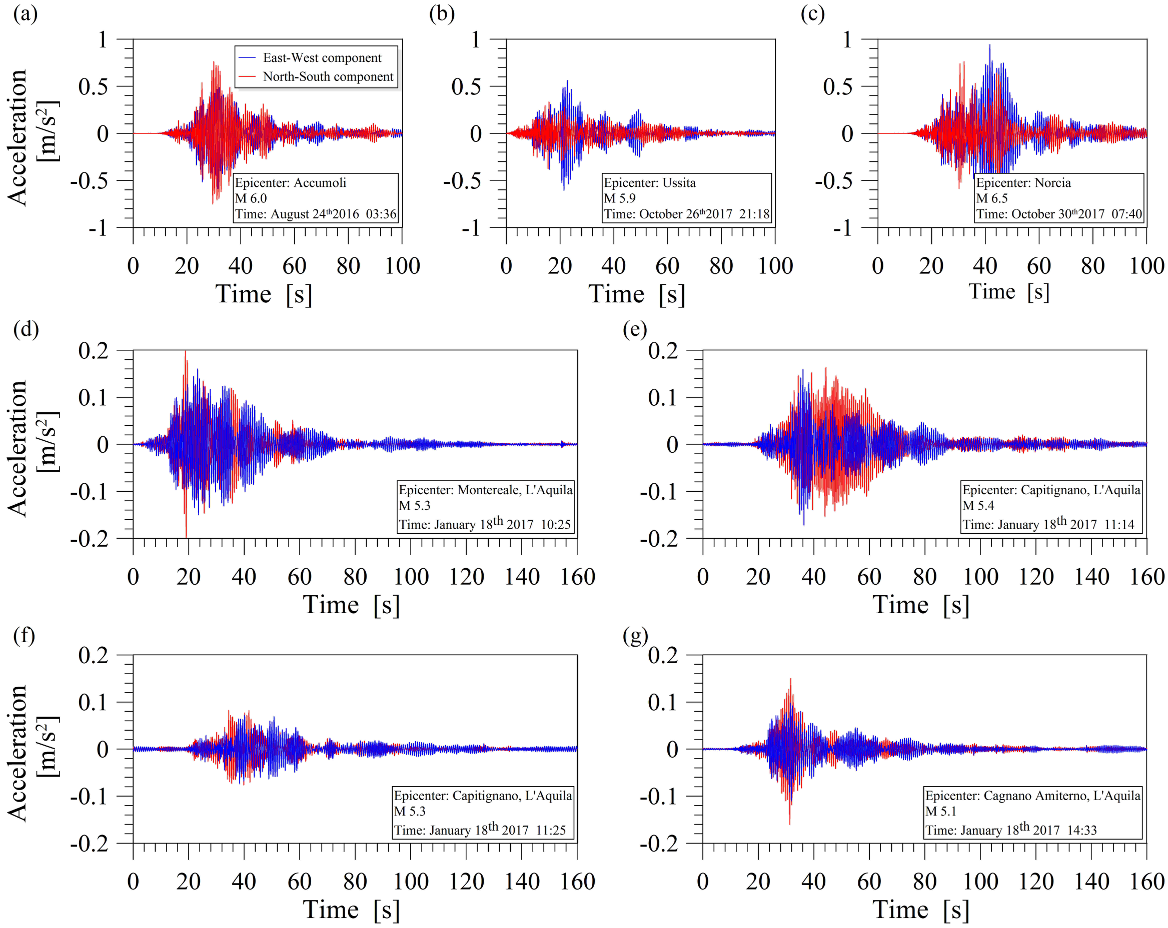


Figure 2: Measured dynamic response of the bell-tower in terms of acceleration during the three main shocks of the seismic sequence: Accumoli earthquake (a), Ussita earthquake (b) and Norcia earthquake (c) and during the four earthquakes occurred on January 18th 2017: Montereale, L'Aquila (d), Capitignano, L'Aquila (e,f) and Cagnano Amiterno, L'Aquila (g).

lighted. The chart is built by using the time series of identified natural frequencies after removal of the effects of changing environmental conditions. Fig. 4 clearly highlights that a deviation of the structural behaviour from normal conditions has occurred after Accumoli earthquake, and a notable increase in the relative frequency of outliers after the shock is observed. In addition, as shown in the detailed view of the control chart in the period of the main earthquakes until January 31st 2017, the effects of Ussita and Norcia earthquakes are also evident, confirming that the structure has accumulated damage during the seismic sequence .

3 THE SCIRI TOWER

3.1 Historical and geometrical description

Built in the 13th century, the civic tower called "Torre degli Sciri" is a 42 m high tower situated in the heart of the historical center of Perugia, Italy (Fig. 5(a)). In the first 16 m the structure is restrained by the bordering masonry buildings (see Fig. 5). Originally built by the noble family of degli Oddi and then later bought by the degli Sciri, today it is the last civic tower of Perugia, remaining from the Middle Age, thus being one of the symbols of the city. Perhaps because it was built with its original function, the defensive one, is the only survivor of about 70 towers mentioned in the cadastral sources, however too many for giving to Perugia

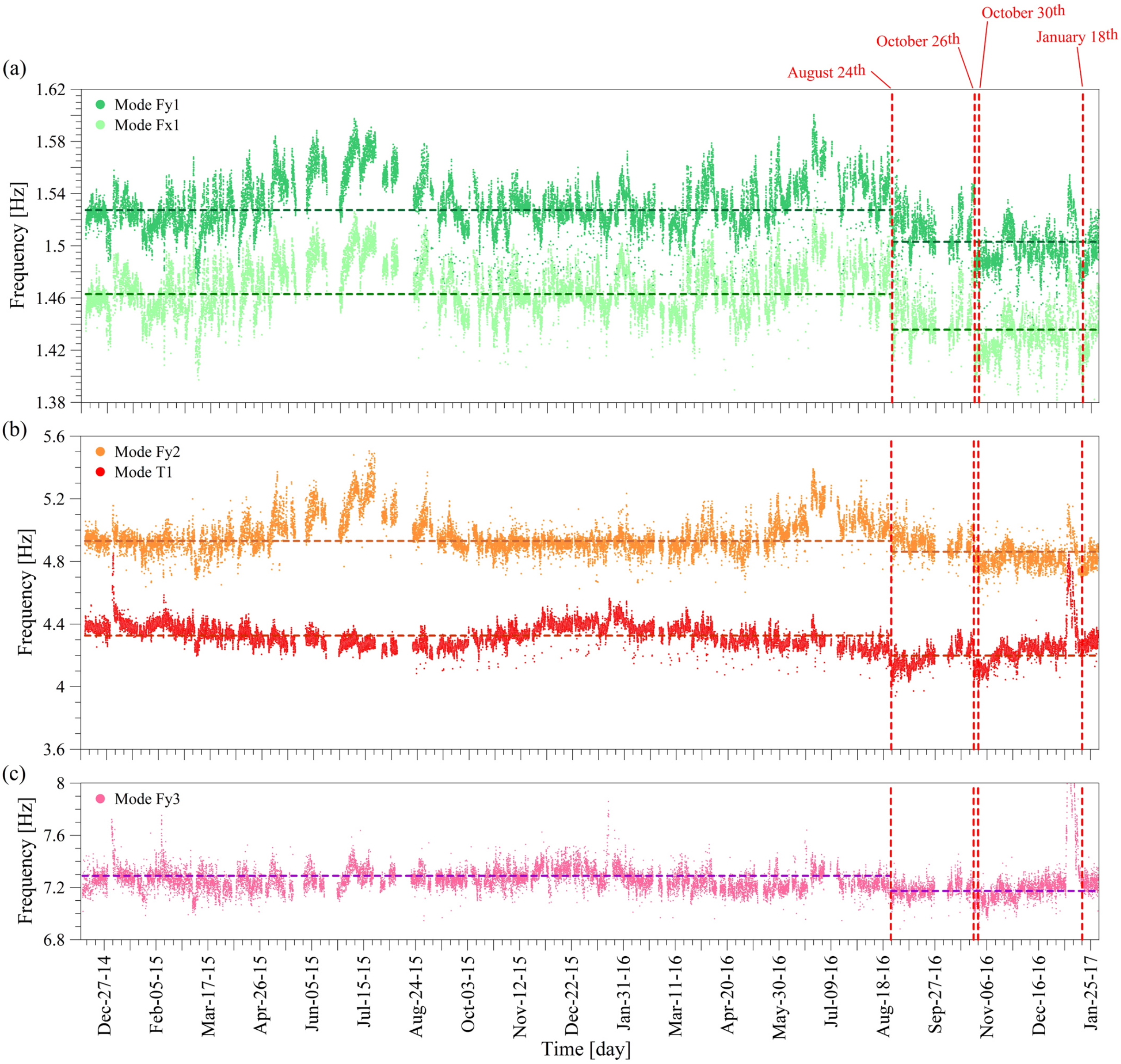


Figure 3: Time histories of identified natural frequencies of the bell-tower showing earthquake-induced decays immediately after the earthquakes (horizontal dashed lines represent the mean values of the natural frequencies): modes Fx1 and Fy1 (a); modes Fy2 and T1 (b) and mode Fy3 (c).

the epithet ”turrita”. With a quadrangular form ,two structural portions can be clearly identified in the tower. These are: (i) the first part in the first 8.5 m, with large stone masonry thick walls, where there are the rooms of an old church ; (ii) the second slender part rising up to 42 m, also in stone masonry. The masonry is made of white limestone blocks of homogeneous measure. Essentially, there are some small openings only in the first part. Recently, in 2015, the tower was restored and consolidated. The intervention did not change in any way the masonry structure of the tower and buildings, it was a structural recovery and conservative restoration of the entire complex paying particular attention to the area of the church and to that of the tower.

3.2 Vibration-based SHM system and data analysis

In the context of an initial dynamic investigation, the tower has been preliminary monitored for one week, from January 16th 2017 to January 23th 2017, through a simple vibration-based

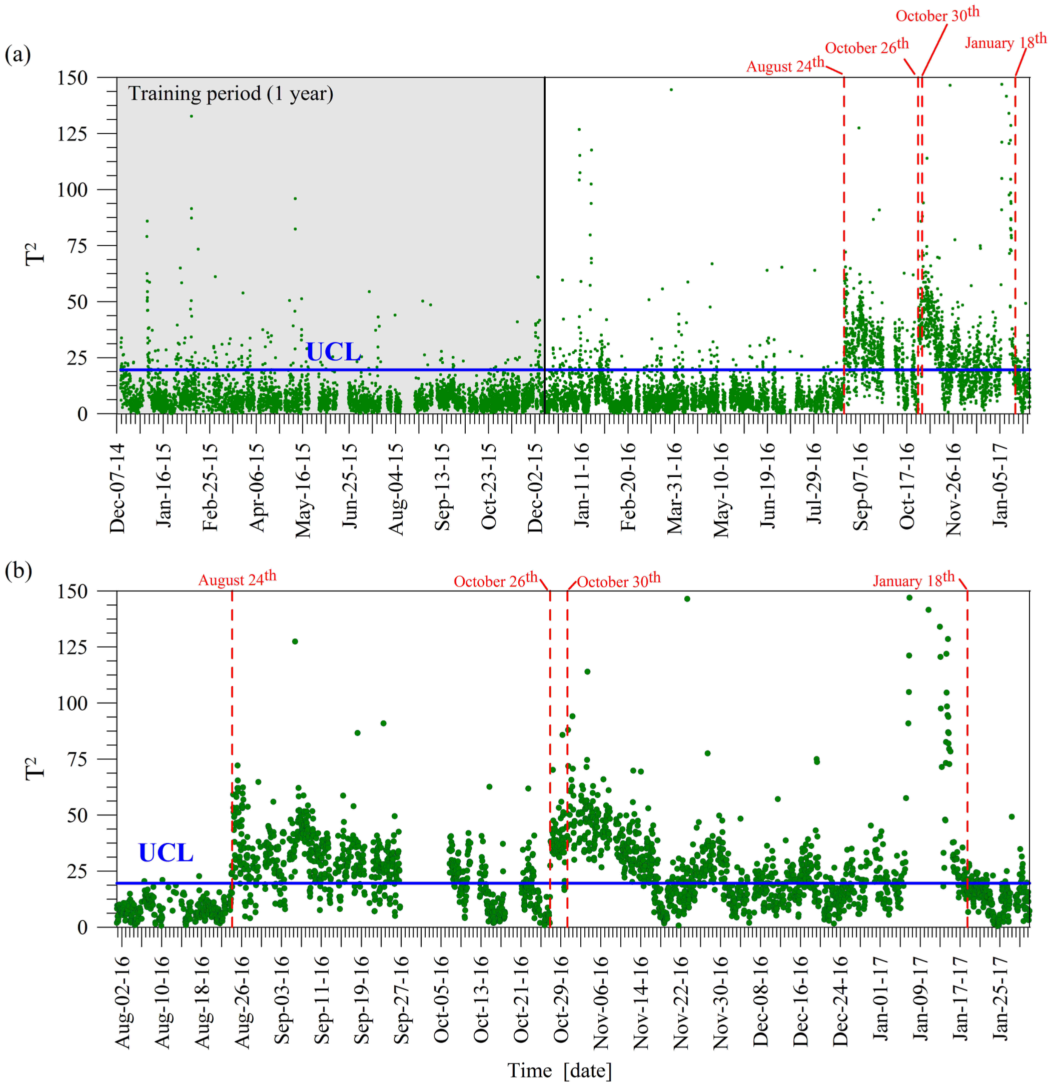
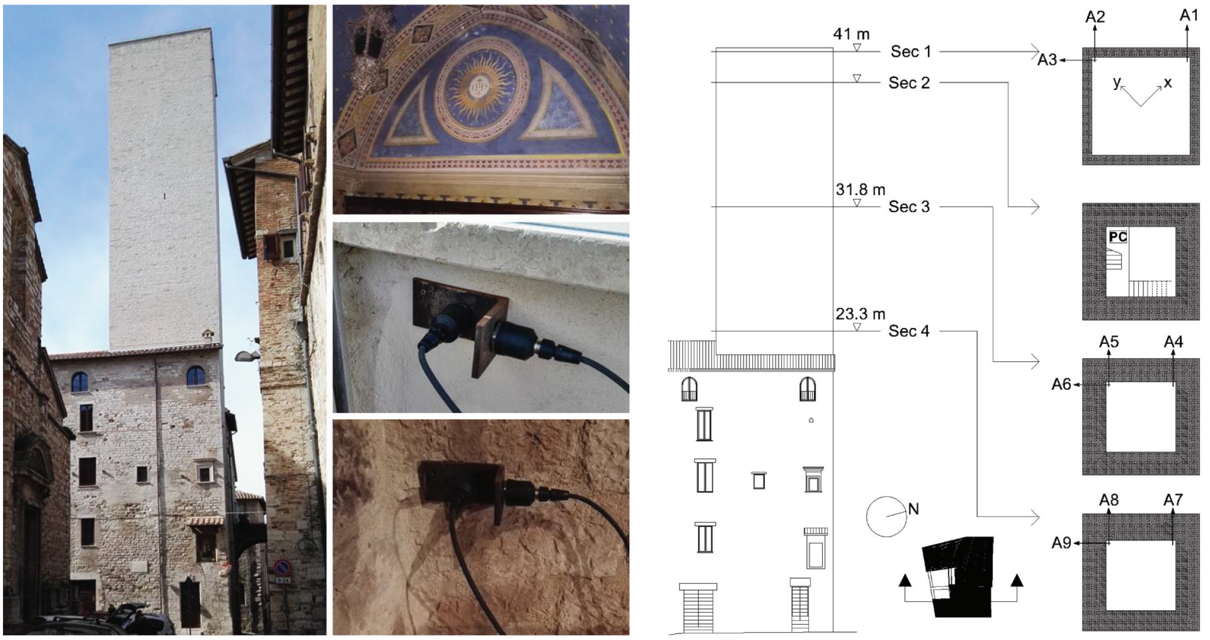


Figure 4: Control chart of the entire monitoring period (a) and detailed view showing increased number of outliers after the earthquakes (b).

SHM system. This continuous dynamic monitoring system comprises three high sensitivity (10 V/g) piezoelectric uniaxial accelerometers (A1, A2 and A3), model PCB 393B12, suitable to measure micro tremors induced by traffic and wind, installed at height of 41 m with the configuration depicted in Fig. 5 (c). They have been placed in the same location which is planned for the permanent monitoring in a near future. Similarly to San Pietro bell-tower, these sensors have a real time data acquisition (via cable) through an acquisition system placed also inside the structure. The continuous monitoring data are recorded using a data acquisition system model NI CompactDAQ-9132 with the following technical characteristics: processor 1.33 GHz Dual-Core Atom, 2 GB RAM, 16 GB SD storage, 4-Slot, operating system Windows Embedded Standard 7 (24-bit resolution, 102-dB dynamic range, and anti-aliasing filters). Data are consecutively stored in separate files containing 30 minute acceleration time series with a sampling frequency of 100 Hz, afterwards processed with the purpose of extracting modal parameters estimates for SHM purposes.



(a) (b) (c)

Figure 5: View of the Sciri tower (a), images of some accelerometers (10 V/g sensitivity) (b) and sketch of the structural monitoring system (c).

3.3 Analysis of ambient vibrations and structural responses to the earthquakes occurred on January 18th 2017

In order to investigate typical levels of vibration of the structure, all recorded data have been analyzed. The purpose of this investigation is to evaluate the dynamic response of the bell-tower in operational conditions, and furthermore to some seismic events. Being monitored for one week, from January 16th 2017 to January 23th 2017, analysis of dynamic responses in operational conditions highlighted very low levels of ambient vibrations. By computing the maximum value of acceleration for each file, Fig. 6 (a) shows a plot of time histories of measured accelerations. In particular, acceleration of channels 2 and 3 remained under values of 0.01 m/s^2 almost all the time of the monitoring period. In addition, Fig. 6 (b) shows a plot of root mean square (RMS) values of acceleration, which did not exceed 0.001 m/s^2, except on January 18th. Main sources of excitation are wind, traffic and small earthquakes. In this case, the largest peak acceleration responses are those induced by small earthquakes.

With the aim of estimating modal parameters of the bell-tower, some ambient vibration tests (AVTs) were carried out on the 1st day of monitoring period using nine accelerometers (A1, . . . , A9) distributed in 3 different levels of the tower, as shown in Figs. 5(b,c), with data containing operational structural responses with excitation mainly provided by wind and traffic. Five modes of vibration were identified within the range from 0 to 10 Hz and identified natural frequencies are summarized in Tab. 2. These modes are two flexural modes in NW direction (x direction as depicted in Fig. 5(c)), denoted as Fx1 and Fx2, two flexural modes in SW direction (y direction), denoted as Fy1 and Fy2 , and one torsional mode, called T1. The 1st AVT is accomplished by the Frequency Domain Decomposition (FDD) technique using all 9 accelerometers of the sensors layout shown in Fig. 5 (c). The 2nd AVT is accomplished by the Frequency Domain Decomposition technique using just 7 accelerometers (A1, A4 . . . , A9). The

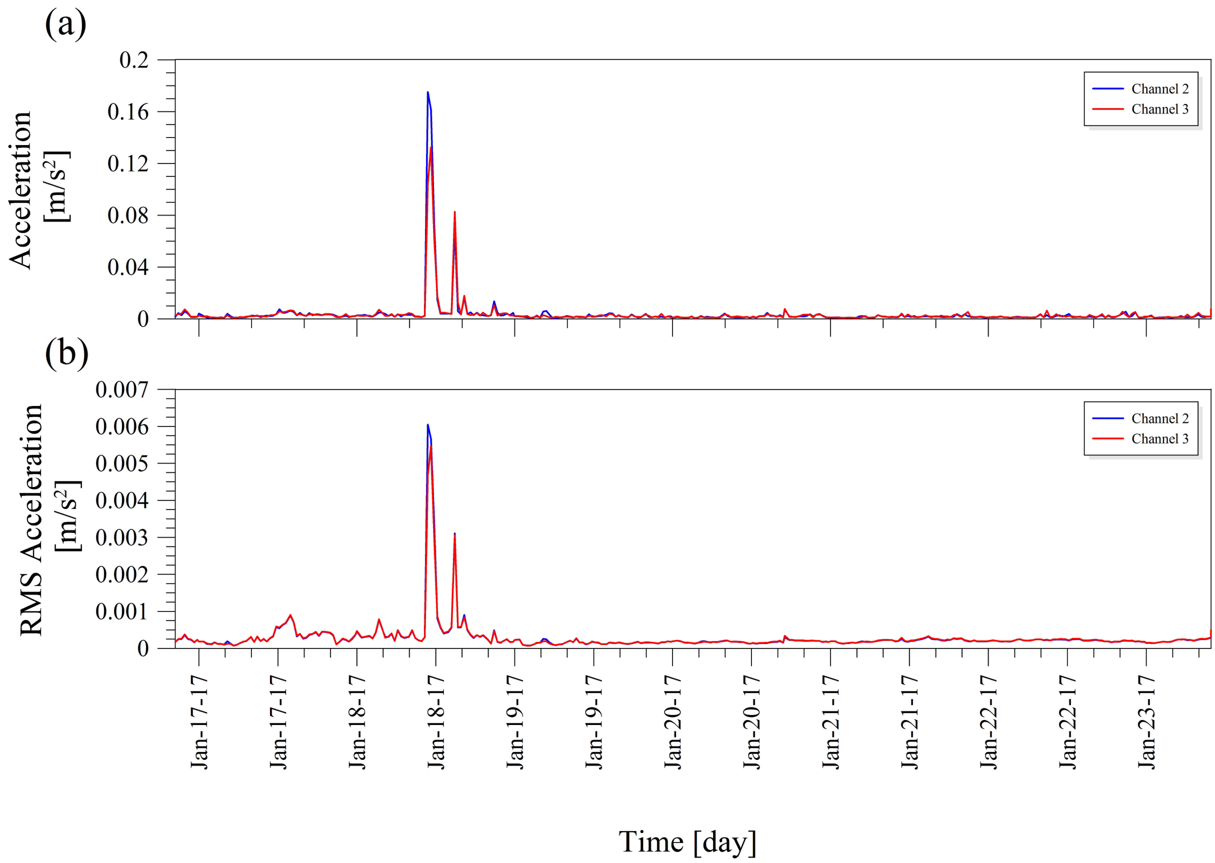


Figure 6: Measured acceleration and RMS acceleration at the top of Sciri tower during the monitoring period from January 16th 2017 to January 23th 2017.

Mode number	Mode type	Frequency [Hz]				
		AVT1	AVT2	AVT3	AVT4	PSD Average
1	Fx1	1.655	1.655	1.662	1.661	1.660
2	Fy1	1.856	1.856	1.853	1.854	1.855
3	T1	5.690	5.676	5.709	5.706	5.674
4	Fx2	8.044	8.004	7.994	7.959	8.027
5	Fy2	9.591	9.604	9.578	9.653	9.570

Table 2: Identified natural frequencies of the bell-tower in the AVT carried out on January 16th 2017 and from the average power spectral density analysis of all records of accelerations in the monitoring period.

3rd and the 4th AVTs are realized with the same sensors layout of the 1st and the 2nd, respectively, but are based on the Enhanced Frequency Domain Decomposition (EFFD) technique. Both techniques are implemented by ARTeMIS [15], an Operational Modal Analysis commercial software, which outputs are validated estimates of the mode shapes, natural frequencies and damping ratios, directly from the raw measured time series data of structures under natural conditions.

In order to consolidate the identification of vibration modes of structure and, in particular, of its natural frequencies, power spectral density (PSD) analysis has been performed. An average of the PSDs of all 30 minute records of accelerations collected within the monitoring period has been computed. With reference to the 1st/2nd singular values of PSD matrix of the recorded accelerations, the main PSD, namely average (see Fig. 7), has been constructed as the average of all PSDs of the 1st singular value (the dominant one) of the monitoring period. Fig. 7 shows also the plot of PSDs associated to Channel 2 and 3, constructed as the average of all PSDs of Channel 2 and 3 of the monitoring period. Tab. 2 summarizes the natural frequencies identified in the AVTs and, for comparative purposes, the natural frequencies obtained from the average power spectral density (PSD) analysis. A good consistency between natural frequencies form the AVTs and those from the Average PSD analysis is observed. In particular, Channel 2 and Channel 3 refer to A2 and A3 sensors, measuring accelerations in East-West and North-South directions, respectively.

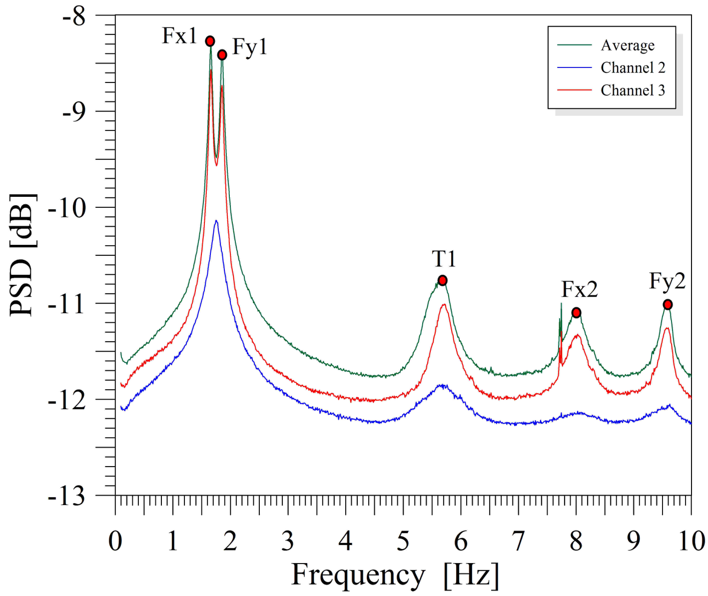


Figure 7: Power spectral density analysis of all 30 minute records of accelerations in the monitoring period from January 16th 2017 to January 23th 2017.

Regarding the analysis of dynamic response of Sciri tower to seismic events, four major earthquakes occurred on January 18th 2017 are considered : (i) Montereale, L'Aquila Mw5.3 earthquake occurred at 9:25 UTC ; (ii) Capitignano, L'Aquila Mw5.4 earthquake occurred at 10:14 UTC ; (iii) Capitignano, L'Aquila Mw5.3 earthquake occurred at 10:25 UTC ; (iv) Cagnano Amiterno, L'Aquila Mw5.1 earthquake occurred at 13:33 UTC. The Sciri tower is located at a distance of about 95 km in the NW direction from these epicenters. The time histories of measured accelerations on top of tower,in East-West direction (channel 2) and in North-South direction (channel 3), during the four earthquakes, are shown in Fig. 8. Despite the distance of the epicenters, located about 95 km far from Sciri tower, it is noteworthy to mention that the highest value of acceleration in North-South direction is observed during the 2nd shock with 0.1325 m/s^2, while, 0.1886 m/s^2 represent the highest value in East-West direction, observed during the 1st shock. The 3rd and the 4th shock are characterized by relatively smaller values of response accelerations.

Maximum values and root mean square (RMS) values of response accelerations during seismic events of January 18th 2017 are reported in Tab. 3. Measurement channels, Channel 1 and Channel 2 refer to A1 and A2 sensors, measuring accelerations in East-West direction, while Channel 3 refers to A3 sensor that is deployed in North-South (see Fig. 5(c)). During the Montereale earthquake, acceleration in East-West direction was predominant with a peak value of

0.1886 m/s^2. Similarly, during the 2nd shock, acceleration in East-West direction was predominant, with peak values of 0.1666 m/s^2. As for the highest value of acceleration in North-South direction it is observed during the second shock with 0.1325 m/s^2. The 3rd and 4th shock presented lower levels of earthquake-induced acceleration.

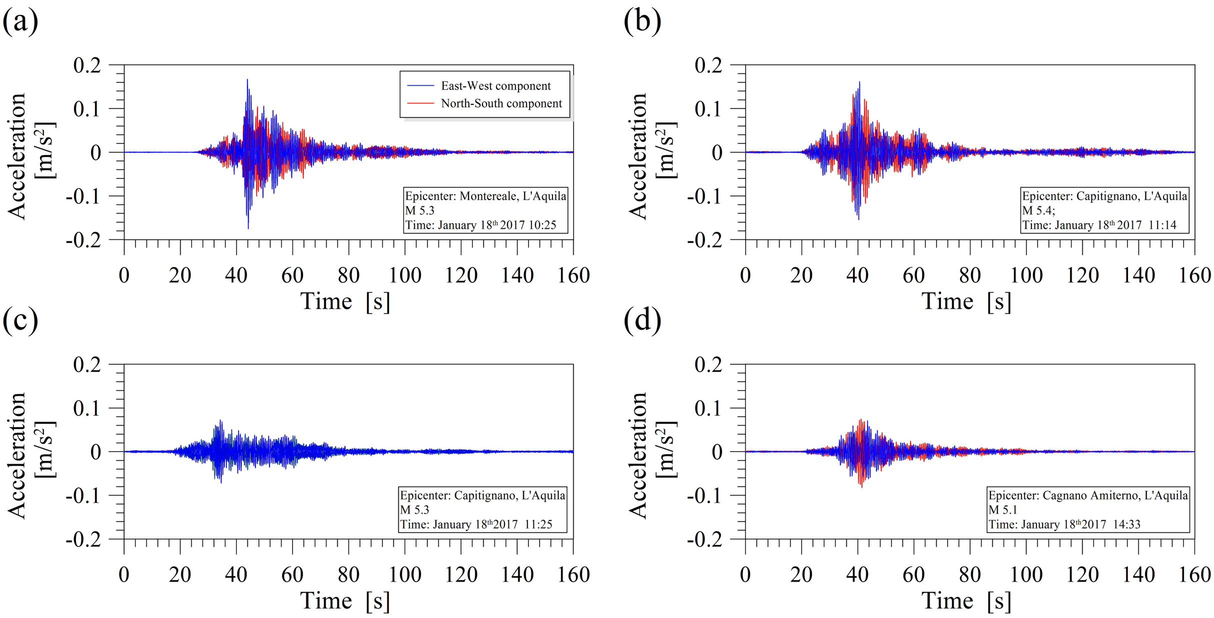


Figure 8: Dynamic responses of the tower in terms of acceleration to the earthquakes occurred on January 18th 2017: Montereale, L'Aquila earthquake (a), Capitignano, L'Aquila earthquake (b,c) and Cagnano Amiterno, L'Aquila earthquake (d) .

	Channel 1 [m/s^2]	Channel 2 [m/s^2]	Channel 3 [m/s^2]	Resultant 2-3 [m/s^2]
Montereale	0.1886 (0.0162)	0.1752 (0.0159)	0.1045 (0.0123)	0.1779 (0.0160)
Capitignano	0.1666 (0.0161)	0.1615 (0.0157)	0.1325 (0.0152)	0.1636 (0.0158)
Capitignano	0.0795 (0.0098)	0.0726 (0.0097)	0.0625 (0.0085)	0.0728 (0.0097)
Cagnano	0.0774 (0.0090)	0.0703 (0.0088)	0.0827 (0.0087)	0.0705 (0.0088)

Table 3: Maximum values of accelerations recorded on top of the Sciri tower (corresponding RMS values are reported in brackets) during the earthquakes of January 18th 2017.

It is noteworthy and very interesting to stress that the same seismic events of January 18th 2017 have presented, in San Pietro bell-tower compared to civic Sciri tower and viceversa, both in historical center of Perugia, different levels of acceleration and highest peak values in different directions. Probably, this is due to different material properties, soil mechanical properties and, off course, different dynamic behavior of these two towers.

4 CONCLUSIONS

This paper has shown the results of vibration-based SHM applied to 2 historical masonry towers situated in Perugia, Italy: the bell-tower of Basilica of San Pietro and the civic Sciri tower.

The 1st case study, being by fare more complete than the 2nd one, and, object of previous studies by the authors, has presented analysis of the response to the 2016 Central Italy seismic sequence and to the earthquakes occurred on January 18th 2017, in terms of acceleration. The seismic events have produced consistent decays in identified natural frequencies after each shock and on the other hand, increasing percentage of outliers as shown in the plot of control chart, thus, validating the SHM procedures for earthquake-induced damage detection.

In the 2nd case of study, the Sciri tower, after a brief historical and geometrical background, preliminary dynamic investigations have been carried out, with the purpose to achieve a reliable knowledge of the structural dynamic behaviour, for the definition of a permanent vibration-based SHM to be installed. The tower has been monitored for one week and some Ambient Vibration Tests were carried out on January 16th 2017, from which the modal properties have been extracted. In particular, spectral analysis have consolidated the natural frequencies identification. Furthermore, the responses to the Mw5.1-5.4 earthquakes occurred on January 18th are shown, which enrich knowledge about the dynamic behavior of the tower and the effectiveness of the vibration-based system to measure low-intensity earthquake-induced accelerations.

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