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DYNAMIC MONITORING OF ANCIENT MASONRY TOWERS: ENVIRONMENTAL EFFECTS ON NATURAL FREQUENCIES

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Abstract. *Masonry towers are very common Cultural Heritage buildings in Italy, where churches and bell-towers were built even in smaller towns and a large number of defensive towers dates back to Middle Age. Since ancient towers exhibit a cantilever-like dynamic behavior and are usually sensitive to ambient excitation, such as micro-tremors and wind, a successful dynamic monitoring of these structures can be obtained by permanently installing a few high-sensitivity accelerometers in the upper part of the building. Hence, the idea of performing cost-effective vibration-based Structural Health Monitoring (SHM) of historic towers has been taking shape recently. On the other hand, the use of a limited number of sensors and automated operational modal analysis in SHM often implies the choice of resonant frequencies as damage sensitive features, although 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. In order to highlight the possible effects of changing temperature on the dynamic characteristics of masonry towers, especially in view of the removal of those effects needed for an effective performance assessment, the paper focuses on selected results obtained by continuously monitoring the dynamic response of three historic towers in Italy.*

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1 INTRODUCTION

Ancient masonry towers represent a significant part of the existing Cultural Heritage buildings, as these historic structures were built over the centuries with different characteristics and functions: bell towers, lookout or defensive towers, chimneys and minarets. As a consequence of the slenderness and the relatively high dead loads, masonry tower often exhibit high sensitivity or vulnerability to dynamic actions, such as traffic-induced micro-tremors, swinging of bells, wind and earthquakes. The first vibration measurements on towers date back to the 1970s [1] and were aimed at assessing the effects of bell swinging. In recent studies, dynamic tests in operational conditions are more and more frequently adopted as assessment tools (see e.g. [2] for a list of recent studies reported in the literature). In addition, the cantilever-like behavior of towers have recently suggested the permanent installation of a few accelerometers in the upper part of the building to perform cost-effective long-term dynamic monitoring, with preventive conservation and/or Structural Health Monitoring (SHM) purposes [3-10].

Indeed, the possibility of using a limited number of sensors in the SHM of ancient towers is especially promising to promote extensive and sustainable programs of condition-based maintenance but implies the choice of resonant frequencies as sensitive features for anomaly detection. On the other hand, natural frequencies are also sensitive to factors other than structural changes – such as the environmental and the operational conditions [11] – and especially the temperature turned out to be a dominant driver of modal frequency changes in masonry towers [3-10, 12], so that an effective approach to SHM should include the removal (or minimization) of the temperature effects on identified natural frequencies.

Within this context, a vibration-based strategy for the preventive conservation of masonry towers should include:

1. Dynamic tests in operational conditions, carried out using an appropriate number of sensors in order to identify the dynamic characteristics of the tower and to highlight the most meaningful positions (among the possible ones) to be permanently instrumented;
2. Continuous monitoring and SHM, based on the installation of a limited number of sensors in the structure (at least 3 accelerometers and 1 temperature sensor). Data should be collected periodically [3] or continuously [4-10, 12] and (automated) operational modal analysis (OMA) should be carried out to track the evolution in time of resonant frequencies, understand the environmental effects and detect the occurrence of any structural performance anomaly [5-6, 8-9];
3. After the SHM has revealed a significant deterioration of the structural condition, local assessment of damage should be carried out through detailed visual inspection and complementary non-destructive tests in order to plan strengthening interventions with more confidence, only if and where the interventions are really necessary.

The paper exemplifies the application of the previous tasks (1) and (2) to three historic masonry towers, with the main objectives of understanding the possible "normal" changes of natural frequencies associated to environmental effects. The three investigated towers are the *Gabbia* tower in Mantua [5-6], the *San Vittore* bell-tower in Arcisate, Varese [4-5, 8] and the *Santa Maria del Carrobiolo* bell-tower in Monza [10]. In all cases, the installation of the monitoring devices was preceded by historic and documentary research, visual inspection, topographic survey, non-destructive and minor-destructive tests of materials on site.

The dynamic monitoring systems were composed by: (a) one 4-channels data acquisition system (24-bit resolution and 102 dB dynamic range); (b) 3-4 high-sensitivity accelerometers; (c) at least one temperature sensor and (d) one industrial PC on site, for system management and data storage. Binary files, containing the acceleration time series and the temperature data, are created every hour, stored in the local PC and transmitted to Politecnico di Milano for be-

ing processed. The sampling frequency was 200 Hz, which is much higher than that required for the investigated structures; consequently, low pass filtering and decimation were applied to the data before the use of the modal identification tools.
The data files received from the monitoring systems are managed in LabVIEW, where the following tasks are automatically performed [13]: (a) creation of a database with the original data; (b) preliminary pre-processing (i.e. de-trending, automatic recognition and extraction of the time series corresponding to swinging of bells or possible seismic events); (c) evaluation of hourly-averaged acceleration amplitudes and temperature; (d) low-pass filtering and decimation of each dataset; (e) creation of a second database, with essential data records, to be used for automated OMA. Finally, the modal parameters of the towers are extracted from the measured acceleration data using an automated procedure [14], based on the covariance-driven Stochastic Subspace Identification (SSI-Cov) algorithm [15-16].

2 DYNAMIC MONITORING OF THE *GABBIA* TOWER

The *Gabbia* tower [5-6] (Fig. 1), with its 54.0 m height, is the tallest tower in Mantua. The tower was built in 1227 for defensive purposes by the Bonacolsi family, governing Mantua in the 13th century. The structure is built in solid brick masonry and the load-bearing walls are about 2.4 m thick, except in the upper levels, where the walls thickness decreases to about 0.7 m. As shown in Fig. 1, the tower is nowadays part of an important palace, whose load-bearing walls seem to be not effectively connected to the tower; nevertheless, the several vaults and floors of the palace are directly supported by the tower. 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 damage (with the materials being only affected by superficial decay), the upper part of the tower is in a poor state of preservation. In more details, at a distance of about 8.0 m from the top, the brick surface workmanship changes and the masonry quality significantly decreases (as it was confirmed by pulse sonic tests); furthermore, the presence of several structural discontinuities and the lack of mechanical connection between subsequent addings determined concerns on the seismic behavior of the upper part of the tower.

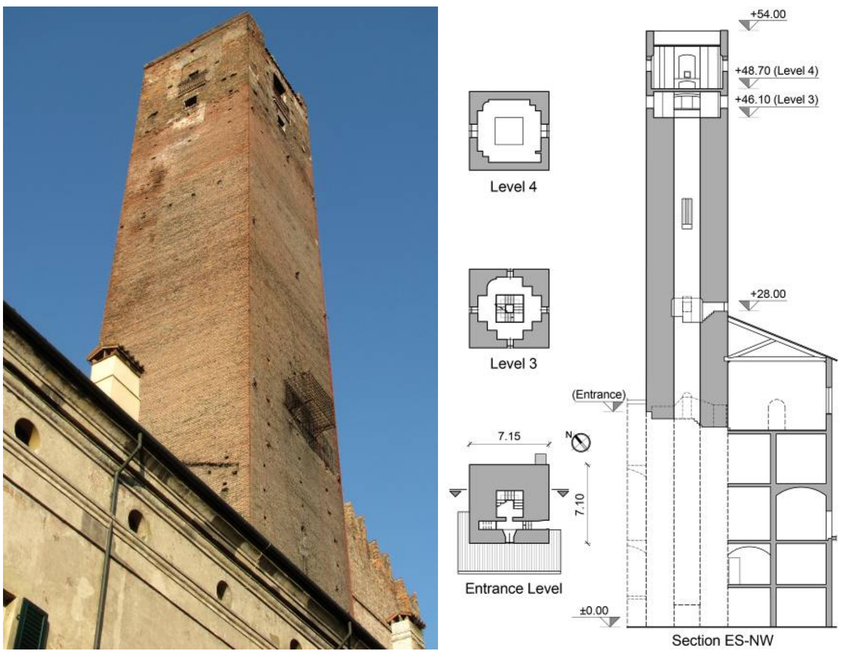

Figure 1: View of the *Gabbia* tower in Mantua, Italy and sections of the tower (dimensions in m).

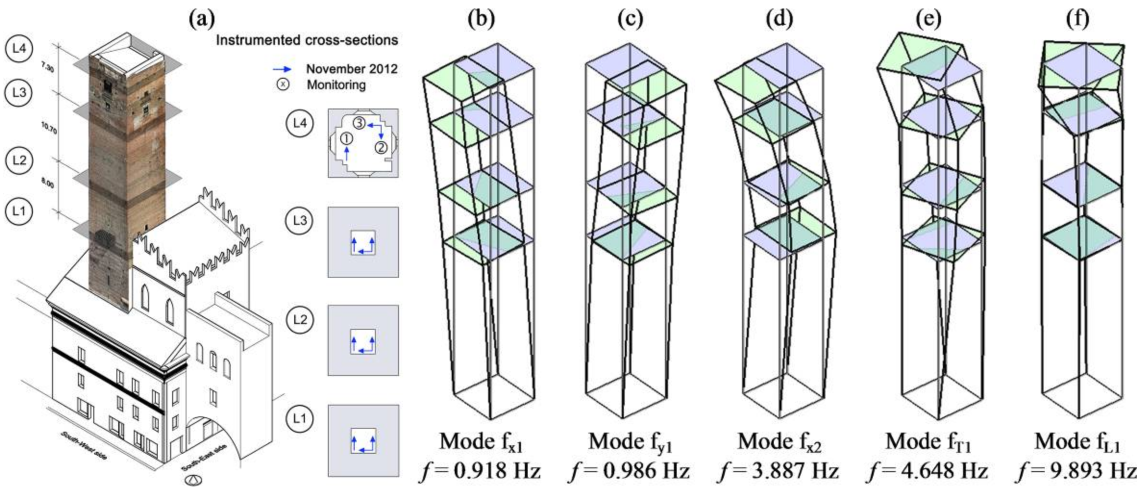

Figure 2: (a) Instrumented cross-sections and layout of the accelerometers during the preliminary tests (November 2012) and the continuous dynamic monitoring; (b)-(f) Identified modes of vibration.

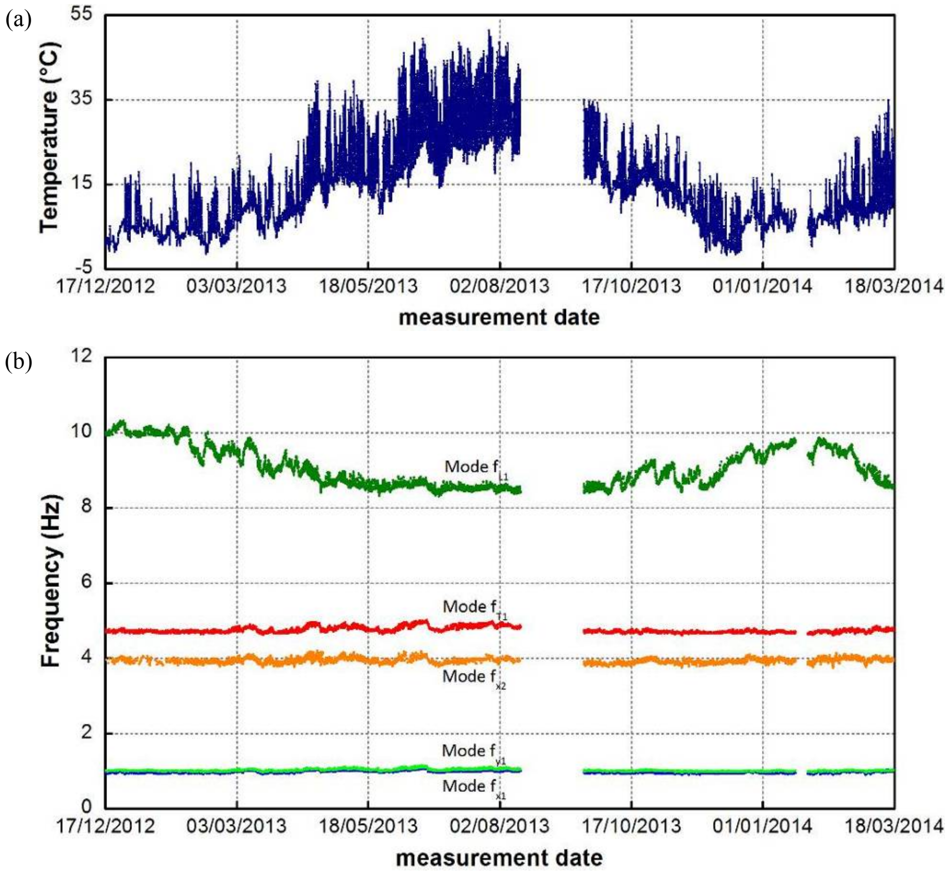

Figure 3: Time evolution (from 17/12/2012 to 17/03/2014) of: (a) the temperature measured on the S-W front of the tower; (b) the automatically identified natural frequencies.

After preliminary ambient vibration tests (November 2012, Fig. 2), a simple dynamic monitoring system was installed in the tower on December 17th, 2012 (and removed at the beginning of July 2015). The sensing devices consisted of: (i) three piezoelectric accelerometers (WR model 731A, 10 V/g sensitivity and ±0.50 g peak), mounted on the cross-section at the crowning level of the tower (Fig. 2a), and (ii) one temperature sensor, installed on the S-W front and measuring the outdoor wall temperature.

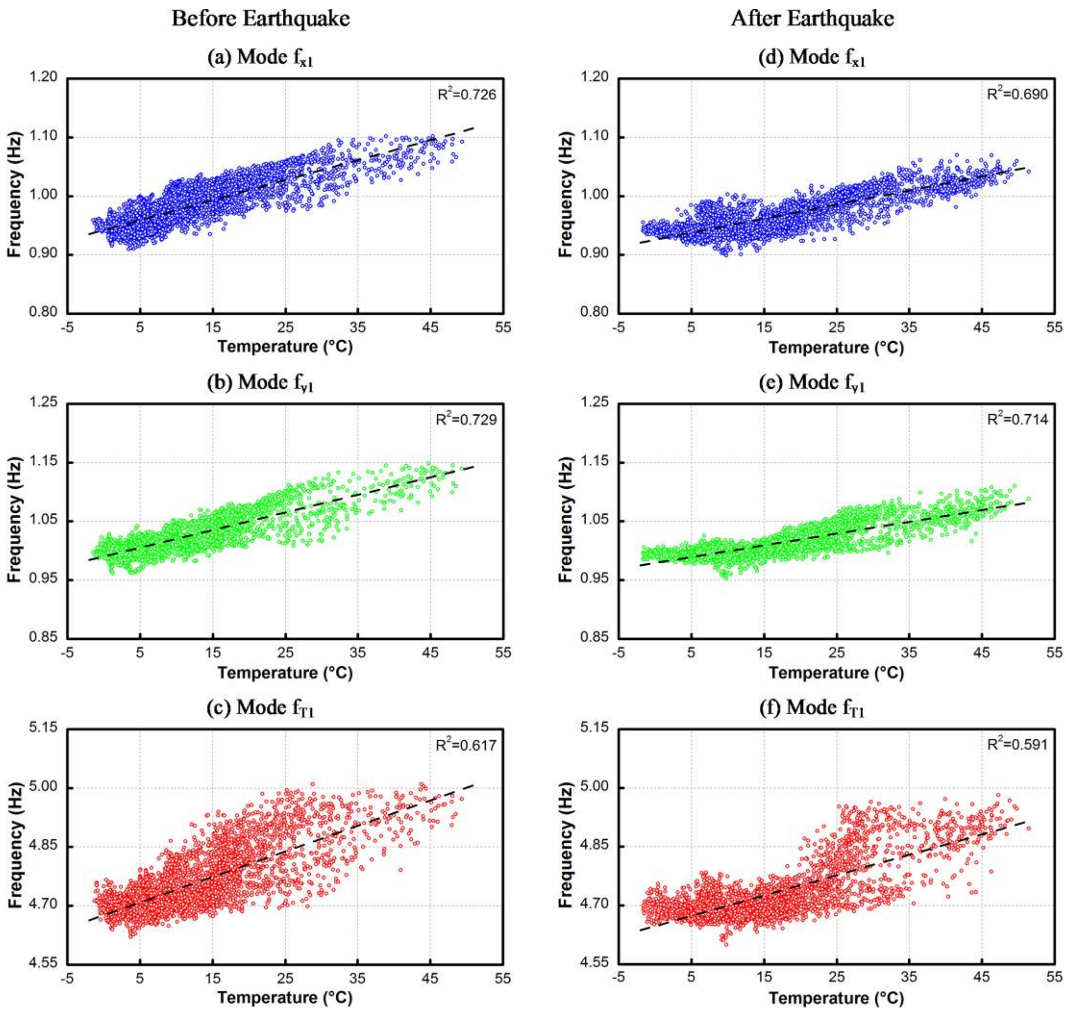

Figure 4: Natural frequency of modes f_{x1}, f_{y1} and f_{T1} plotted versus the outdoor temperature: (a)-(c) from 17/12/2012 to 20/06/2013; (d)-(f) after 21/06/2013.

Five vibration modes were identified in the preliminary ambient vibration tests and the corresponding natural frequencies were successfully tracked during the monitoring period. As shown in Fig. 2, the identified modes correspond to three bending modes (Figs. 2b-d), one torsion mode (Fig. 2e) and one local mode involving the upper part of the structure (Fig. 2f).

It should be noticed that, until June 2013, the tower's response to different far-field earthquakes was recorded. The strongest event – corresponding to an earthquake occurred in the Garfagnana region (Tuscany) on June 21st, 2013 – was characterized by a measured peak acceleration of about 20 cm/s^2, exceeding about 50 times the highest amplitude of normally observed ambient vibrations.

Figure 3 reports the time evolution of the outdoor temperature (S-W front, Fig. 3a) and of the automatically identified modal frequencies (Fig. 3b) for a period of about 15 months, from 17/12/2012 to 17/03/2014.

The temperature tracking reveals large fluctuations, between −2°C and +45°C, with significant daily variations on sunny days. A closer inspection of Fig. 3b highlights that the natural frequencies of global modes (f_{x1}, f_{y1}, f_{x2} and f_{T1}, Fig. 2) vary accordingly with the outdoor temperature. This correlation can be better investigated by plotting each modal frequency with respect to the recorded temperature. Figs. 4a-c show the results obtained for modes f_{x1}, f_{y1} and f_{T1} along with the best fit lines and the coefficient of determination R^2: the three plots refer to the time period from 17/12/2012 to 20/06/2013 and confirm that the frequency of global modes tends to increase with increased temperature. This behavior, observed in all studies of masonry towers [3-10, 12] can be explained by the closure of superficial cracks, minor masonry discontinuities or mortar gaps induced by the thermal expansion of materials.

The frequency-temperature relationships obtained after the Garfagnana earthquake (21/06/2013) are shown in Figs. 4d-f. The comparison with the results referred to the first six months of monitoring (Figs. 4a-c) reveals significant differences: the frequency dependence on temperature still remains roughly linear but the regression lines of all modes exhibit remarkable variations after the earthquake, with the temperature range being almost unchanged. This trend is also confirmed by the general decrease of the statistics of the natural frequencies (mean value, standard deviation, extreme values) summarized in Table 1 and highlights the occurrence of abnormal structural changes.

Mode	f_{ave} (Hz)		σ_f (Hz)		f_{min} (Hz)		f_{max} (Hz)	
	Before	After	Before	After	Before	After	Before	After
f_{x1}	0.985	0.968	0.038	0.031	0.910	0.897	1.102	1.070
f_{y1}	1.024	1.012	0.032	0.025	0.961	0.953	1.148	1.110
f_{x2}	3.941	3.929	0.075	0.063	3.758	3.742	4.194	4.137
f_{T1}	4.754	4.727	0.077	0.066	4.621	4.600	5.010	4.982
f_{L1}	9.222	8.937	0.554	0.433	8.385	8.332	10.327	9.862

Table 1: *Gabbia* tower - Statistics of the natural frequencies identified before and after the seismic event of 21/06/2013.

It worth mentioning that very similar results have been more recently obtained during the seismic monitoring of the *San Pietro* bell-tower in Perugia [9] during the seismic sequence of Central Italy occurred in 2016. In both studies, clear permanent drops of natural frequencies have been observed after the seismic events and the frequency shifts were remarked by changes of the frequency-temperature relationships. In addition, even if the experimental data clearly reveal the occurrence of slight permanent changes [6, 9], the damage on the structures was not detectable through visual inspections.

In order to complete the discussion of the results of the *Gabbia* tower's monitoring with the local mode f_{L1}, Fig. 3b shows that frequency evolution of f_{L1} looks very different from the others and is characterized by significant frequency variations (approximately in the range 10.33-8.33 Hz); similarly, Table 1 confirms that high values of the standard deviation are especially observed for this mode. The observed behavior suggests the progress of a possible damage mechanism, conceivably related to the thrust exerted by the inclined wooden roof with increased temperature, and confirms the poor structural condition and the high vulnerability of the upper part of the tower. This conclusion seems to be confirmed by the frequency loss of the local mode detected after one year of monitoring (and after the earthquake), with the natural frequency being unable to reach the maximum values identified one year before in a similar temperature conditions (Fig. 3b).

3 DYNAMIC MONITORING OF THE *SAN VITTORE* BELL-TOWER

The *San Vittore* bell tower [4-5, 8, 17] is located in the small town of Arcisate (northern Italy) and is connected to the neighboring church *Chiesa Collegiata di San Vittore* (11th century) on the east side and partly on the south side (Fig. 5). The tower, built in stonework masonry, is about 37.0 m high and has a square plan (5.8 m × 5.8 m); the thickness of the load-bearing walls progressively decreases from 135 cm at the ground level to 65 cm at the top.

Extensive visual inspections and few sonic tests generally indicated compactness and fairly good execution of the stone masonry; nevertheless, the texture locally appears highly disordered and characterized by the presence of vertical joints. The crack pattern was accurately surveyed also by using an aerial platform; the inspection allowed to detect long vertical cracks on every side, most of them cutting the entire wall thickness and passing through the keystones of the arch window openings. The visual inspection highlighted that the upper part of the tower, beneath the belfry level, could be probably considered the most vulnerable part, due to the widespread mortar erosion and the in-filled openings, mainly on the East and North fronts; in addition the infillings are often not properly linked to the surrounding load bearing masonry.

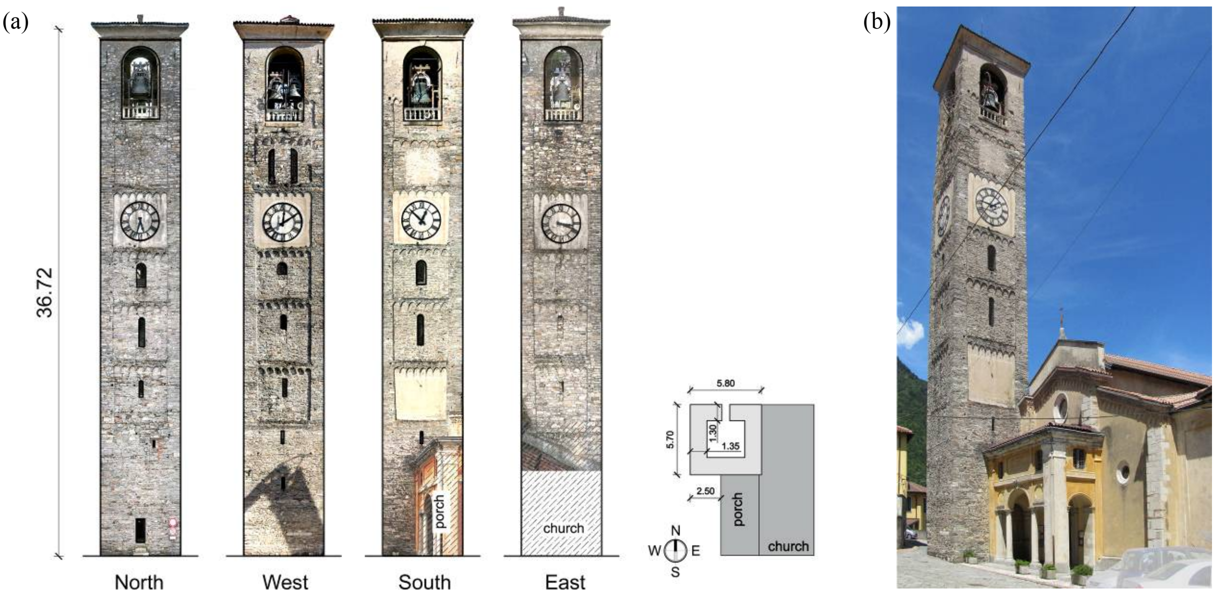

Figure 5: (a) Fronts and cross-section (dimensions in m) of the *San Vittore* bell-tower; (b) View of the bell-tower.

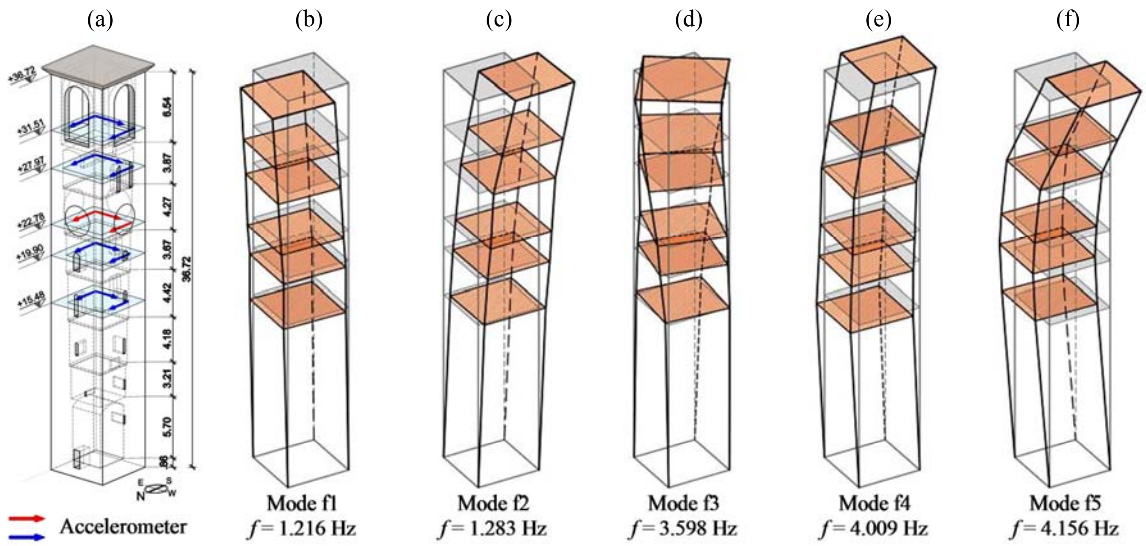

Figure 6: (a) Instrumented cross-sections and layout of accelerometers during the dynamic tests (blue and red arrows) and the continuous monitoring (red arrows); (b) Vibration modes identified from ambient responses.

The *San Vittore* bell tower has been studied by Politecnico di Milano since 2007: early studies included direct survey and testing of materials [17] as well as ambient vibration tests (AVT) and FE modeling [4, 8]. Subsequently, a static monitoring system was installed in the tower [17]; this system, aimed at collecting information on the evolution of crack patterns, included 15 extensometers and 8 temperature sensors, that measured internal and external temperature at different levels of the tower.

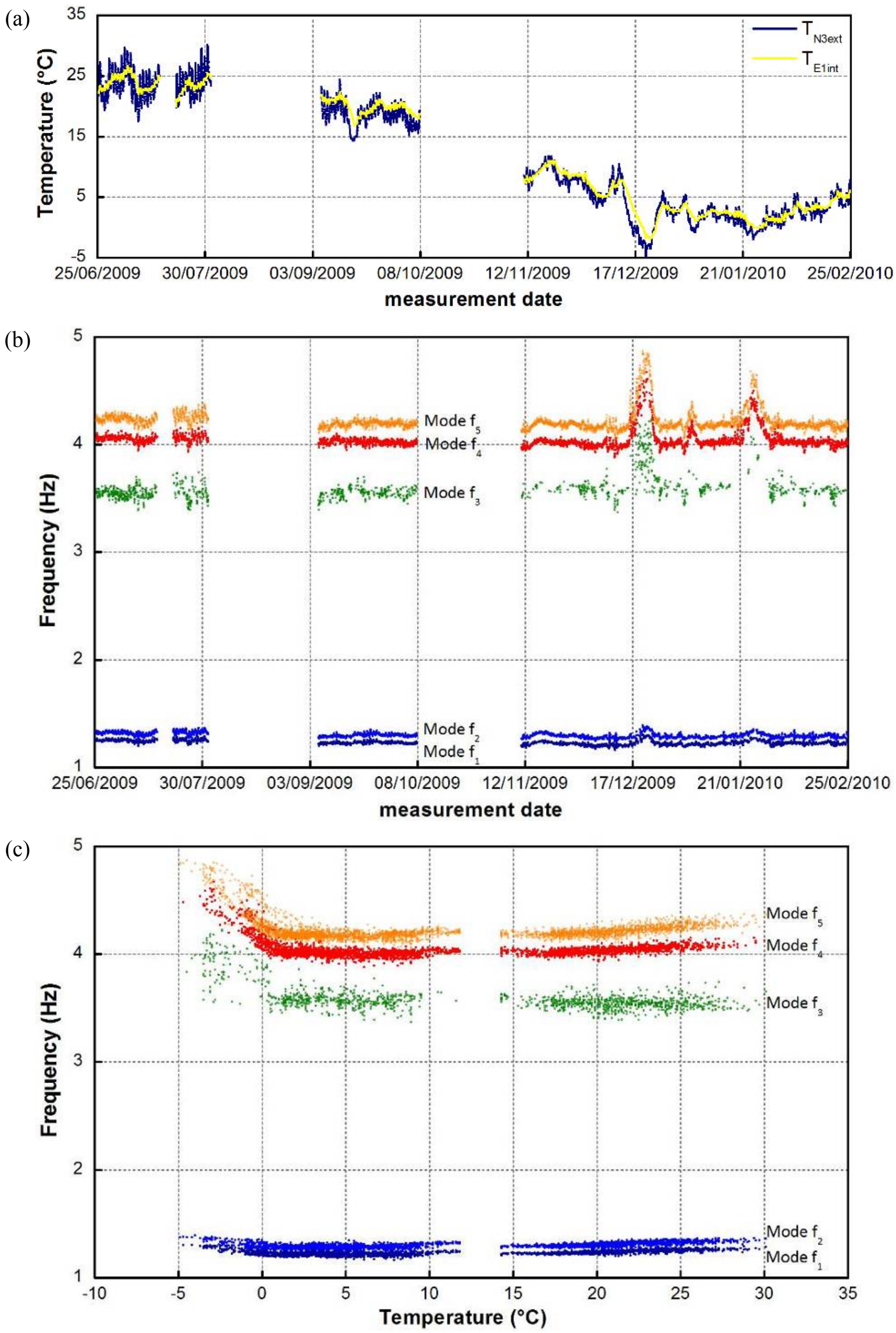

Figure 7: Time evolution (from 25/06/2009 to 24/02/2010) of the temperatures T_{N3ext} and T_{E1int}; (b) Time evolution (from 25/06/2009 to 24/02/2010) of the automatically identified natural frequencies; (c) Natural frequencies plotted with respect to the outdoor temperature (from 25/06/2009 and 24/02/2010).

Mode	f_{ave} (Hz)	σ_f (Hz)	f_{min} (Hz)	f_{max} (Hz)
F_1	1.228	0.019	1.162	1.290
F_2	1.297	0.021	1.240	1.367
F_3	3.552	0.056	3.371	3.774
F_4	4.023	0.033	3.880	4.184
F_5	4.196	0.042	4.043	4.372

Table 2: *San Vittore* bell-tower - Statistics of the natural frequencies identified from 25/06/2009 and 24/02/2010.

Two AVTs were conducted on June 2007 and June 2008. In both tests, the response of the tower was measured in 15 selected points (Fig. 6a) and datasets of 3600 s were collected adopting a sampling frequency of 200 Hz. Five vibration modes were identified in the frequency range 0-6 Hz (Fig. 6b-f). As expected, the identified modes can be classified as bending and torsion: dominant bending modes were identified at 1.22 (f1, Fig. 6b), 1.28 (f2, Fig. 6c), 4.01 (f4, Fig. 6e) and 4.16 Hz (f5, Fig. 6f) while only one torsion mode (f3, Fig. 6d) was identified at 3.60 Hz. It is worth noting that the dominant bending modes of the tower (Figs. 6b-c and 6e-f) involve flexure practically along the diagonals.

In June 2009, a continuous dynamic monitoring system was installed in the bell tower, with the sensing devices consisting of 3 uni-axial Dytran 3191A1 piezoelectric accelerometers (10 V/g sensitivity and ±0.50 g peak). Logistical motivations and the results of the preliminary AVT allowed to identify the level at 22.78 m (Fig. 6a) as the one to be instrumented in order to detect all the previously observed modes.

The continuous dynamic monitoring was carried out for 8 months (from June 2009 to February 2010), during which the monitoring system had to be stopped several times because of both normal maintenance and the installation of a new electrical system in the tower. It is worth mentioning that during the investigated time span, the static monitoring system installed in the tower not only provided temperature data to complement the dynamic monitoring but also indicated that no abnormal changes of the structural condition occurred.

Automated modal identification was performed using time windows of 2500 s [4], which were obtained from each 1-hour recorded dataset after detection and removal of the time series corresponding to the ringing/swinging of bells. Hourly averaged temperature data were also recorded by a previously installed static monitoring system [17]. Among the 8 available temperature measurements, correlation studies [4] indicated that the temperature recorded indoor on the East-side (T_{E1int}) and outdoor on the North-side (T_{N3ext}) are the most representative of the internal and external thermal condition of the tower, respectively. Hence, the temperature data T_{E1int} and T_{N3ext} were selected to investigate the correlation with the automatically identified natural frequencies.

Figure 7 shows the time evolution of temperatures (Fig. 7a) and natural frequencies (Fig. 7b) as well as the correlation between modal frequencies and the outdoor temperature T_{N3ext} (Fig. 7c). The statistics (mean value, standard deviation, minimum and maximum value) of the natural frequencies identified during the monitoring are reported in Table 2.

The inspection of Figs. 7a-c allows the following comments:

1. The bending modes are more frequently identified than the torsion mode, probably as a consequence of the low level of ambient excitation characterizing the tower;
2. Similarly to the global modes of the *Gabbia* tower, the modal frequencies follow almost linearly the daily temperature variation, as their value increases with the increased temperature;

3. Corresponding to below zero temperatures, the natural frequencies rapidly and significantly increase with decreased temperature. This behavior, also observed in [7], is conceivably related to the freezing of the structural system (including its foundation) and to the presence of ice, which fills and closes the cracks, causing a temporary stiffening of the structure.

It is worth mentioning that, although the temperature effects on natural frequencies turned out to be quite complex for the *San Vittore* bell-tower, the well-known principal component analysis (PCA, see e.g. [12]) algorithm does provide a robust tool to remove the environmental effects and to develop effective prediction models of the identified frequencies for SHM purposes [8].

4 DYNAMIC MONITORING OF THE *SANTA MARIA DEL CARROBIOLO* BELL-TOWER

The last investigated structure is the bell-tower belonging to the historic religious complex of *Santa Maria del Carrobiolo* [10] in Monza (Italy). The religious complex includes a church, a bell-tower, a monastery, an oratory and other minor buildings, which were erected at different times. The tower (Fig. 8a), about 33.7 m high, is built in solid brick masonry and has nearly square plan (5.93 m × 5.70 m); the thickness of the load bearing walls slightly decreases from 70 cm at the ground level to 58 cm at the top.

Historical documents testify that the construction of the church and monastery dates to the 13th century, whereas the bell-tower was completed in 1339 (Fig. 8b). The sequence of the construction stages has been confirmed by visual inspection of the masonry discontinuities: (a) the North and West sides of the tower are directly supported by the load-bearing walls of the apse and the right aisle of the church; (b) the Southern and Eastern load-bearing walls of the tower are continuous from the ground to the roof but do not exhibit any mechanical connections with the walls of the church (Figs. 8c and 8d). Moreover, several cracks cut the entire wall thickness, mainly at the level below the belfry (Fig. 8d), and a metallic tie-rod opposes to the opening of a deep crack on the Western wall of the bell-tower.

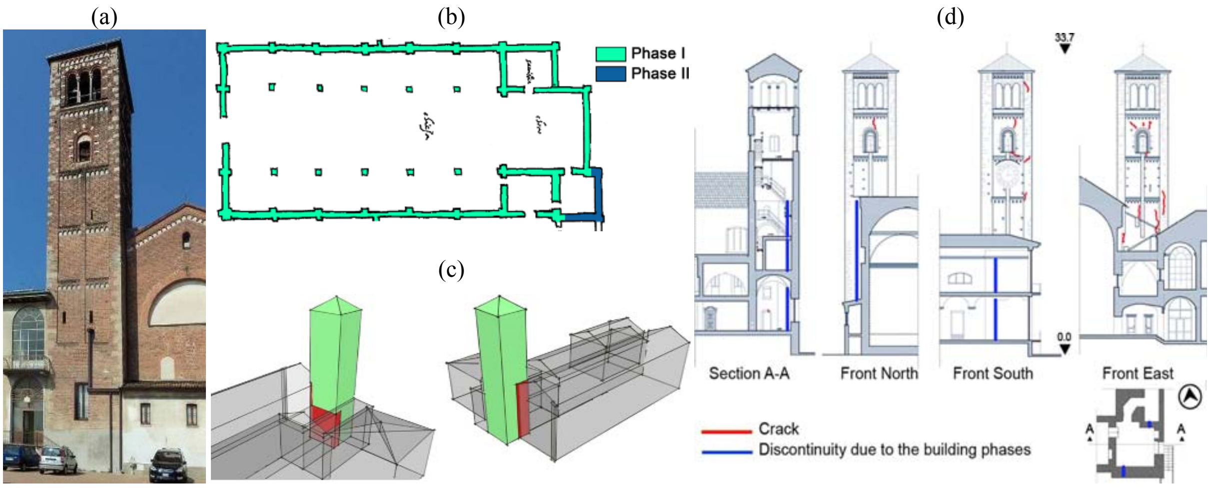

Figure 8: (a) View of the *Santa Maria del Carrobiolo* bell-tower (Monza, Italy); (b) Building phases in a plan dating back to 1572; (c) Schematic representation of the interaction between the bell-tower and the church apse; (d) Section and fronts of the bell-tower.

The construction sequence adopted for the tower, not identified before, raised obvious concern about the performance of the structure under wind and seismic actions. Therefore, a wide research program was planned to assess the structural condition of the building and is currently in progress. In more details, the research consists of the following steps [10]: (a) prompt on-site investigation, including geometric survey and visual inspections; (b) static monitoring of the main cracks through the installation of 10 displacement transducers (as well as 5 temperature sensors) at different levels of the tower; (c) ambient vibration testing and identification of the dynamic characteristics of the tower; (d) installation of a simple dynamic monitoring system in the tower.

AVTs were carried out on 23 September 2015 [10] and mainly aimed at evaluating the baseline dynamic characteristics of the tower before the installation of a continuous dynamic monitoring system in the building. Selected mode shapes identified by applying the SSI-Cov method are presented in Fig. 9 and reveal very peculiar dynamic characteristics of the tower, that are conceivably related to the structural arrangement and construction sequence of the building. In more details, closely spaced modes with similar mode shapes were clearly identified, so that the sequence of identified modes turns out to be very different from the expected regular series of two bending modes (one for each principal plane of the structure) and one torsion mode (see e.g., the *San Vittore* bell-tower). As shown in Fig. 9, the identified sequence of vibration modes (Fig. 9) includes: (a) the fundamental mode (f_{x1} = 1.92 Hz, Fig. 9b), involving dominant bending in the E-W direction; (b) two bending modes in the N-S direction, that are characterized by closely spaced natural frequencies (f_{y1} = 2.01 Hz and f^*_{y1} = 2.37 Hz) and very similar mode shapes (Figs. 9c and 9d).

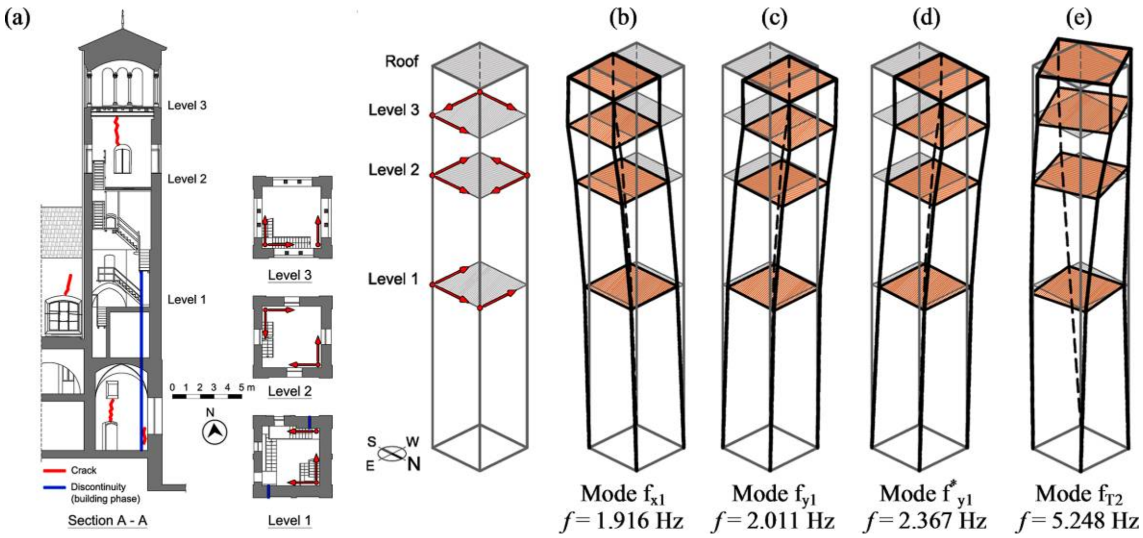

Figure 9: (a) Schematic of accelerometers layout and (b)-(e) selected vibration modes identified from ambient vibration tests.

The continuous dynamic monitoring system (Fig. 10a) installed in the tower since 22 October 2015 includes 4 MEMS accelerometers (Kistler model 8330A3, 1.2 V/g sensitivity, ± 3.00 g peak acceleration, 1.3 μg resolution and 0.4 μg/√Hz r.m.s. noise density), one Ethernet carrier with NI 9234 data acquisition module and one local PC for the management of the continuous acquisition and the data storage. In addition, 5 temperature sensors − denoted as T_{0N}, T_{1E}, T_{2E}, T_{2W} and T_S in Fig. 10a – were available, and measured both the indoor temperature at different levels of the tower and the outdoor temperature on the South side of the structure; hence, a relatively dense representation of the temperature conditions of the tower is achieved.

Figures 10b-c show the hourly averaged value of the measured temperatures in the monitoring period from 22 October 2015 to 21 October 2016. Table 3 summarizes the correlation coefficients between the environmental data during the same period. Figures 10b-c and Table 3 indicate that a large degree of correlation exists between all temperature data, with the measurements T_{1E}, T_{2E}, and T_{2W} being almost perfectly correlated and characterized by correlation coefficients very close to unity.

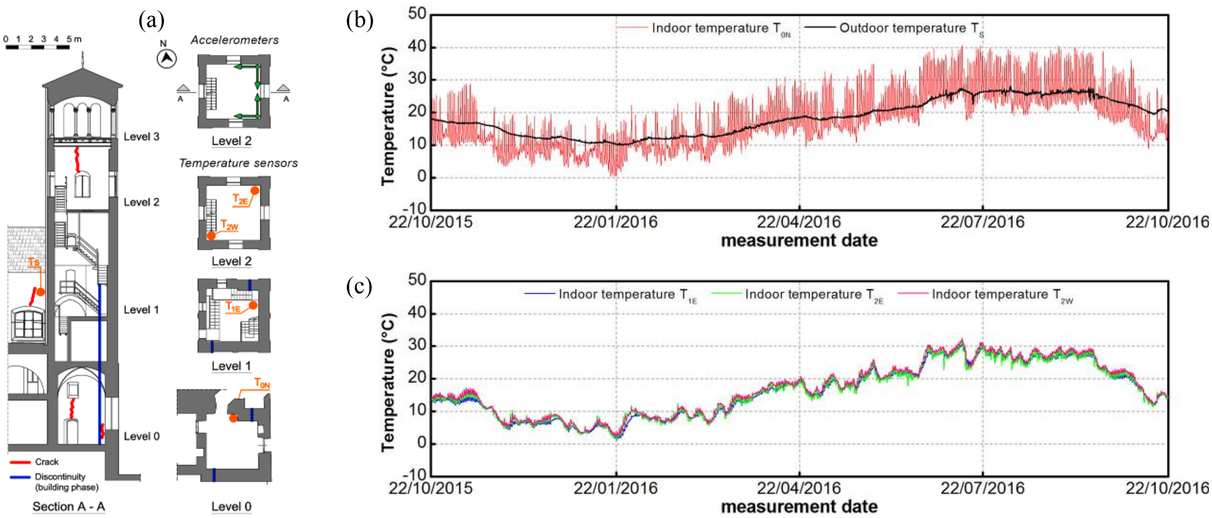

Figure 10: (a) Accelerometers and temperature sensors installed in the tower; (b) Variation in time of the measured temperatures T_{0N} and T_S; (c) Variation in time of the measured temperatures T_{1E}, T_{2E} and T_{2W}.

	T_{0N}	T_{1E}	T_{2E}	T_{2W}	T_S
T_{0N}	1.000	0.967	0.957	0.960	0.837
T_{1E}		1.000	0.995	0.997	0.873
T_{2E}			1.000	0.998	0.900
T_{2W}				1.000	0.885
T_S					1.000

Table 3: Correlation coefficients between the measured temperatures (from 22/10/2015 to 21/10/2016).

The modal identification was performed applying a fully automated OMA procedure [14] to time windows of 3000 s (which were obtained from each 1-hour recorded dataset after detection and removal of the time series corresponding to the swinging of bells). Figure 11 presents the evolution of the identified modal frequencies in the first year of continuous dynamic monitoring (i.e., from 22/10/2015 to 21/10/2016), whereas the relevant statistics are summarized in Table 4 through the mean value (f_{ave}), the standard deviation (σ_f), and the extreme values (f_{min}, f_{max}) of each natural frequency. The results summarized in Fig. 11 and Table 4 allow the following comments:

1. Notwithstanding the low level of the ambient excitation, 4 normal modes were identified with high occurrence and accuracy;
2. The natural frequency of modes f_{x1} and f_{T2} exhibits significant increase in Spring and Summer period. This trend suggests that these modal frequencies are strongly affected by the temperature and − similarly to *Gabbia* tower and *San Vittore* bell-tower − increase with increased temperature;
3. On the contrary, the natural frequency of modes f_{y1} and f^*_{y1} exhibits very limited variation, with the standard deviation being equal to 0.009 and 0.015 Hz, respectively. For those

modes, the frequency trend increase with increased temperature is conceivably balanced by the loss of tension in the metallic tie-rod placed on the West side and connecting the North and South load-bearing walls of the tower;

4. As shown in Fig. 11a, the natural frequencies of the two lower modes f_{x1} and f_{y1} exhibit crossing in Summer months. To the best of the authors' knowledge, this behavior has not been observed before on masonry towers and conceivably depends on the different effect exerted by the temperature on the natural frequencies of the two modes. Furthermore, the mode shape of both modes f_{x1} and f_{y1} tends to hybridize when crossing occurs: in other words, the two modes tend to involve biaxial bending in both the main E-W and N-S directions when the natural frequencies become very close to each other. It is further noticed that this hybridization, suggesting the occurrence of something similar to mode veering (see e.g. [18]), is more significantly detected for mode f_{y1}.

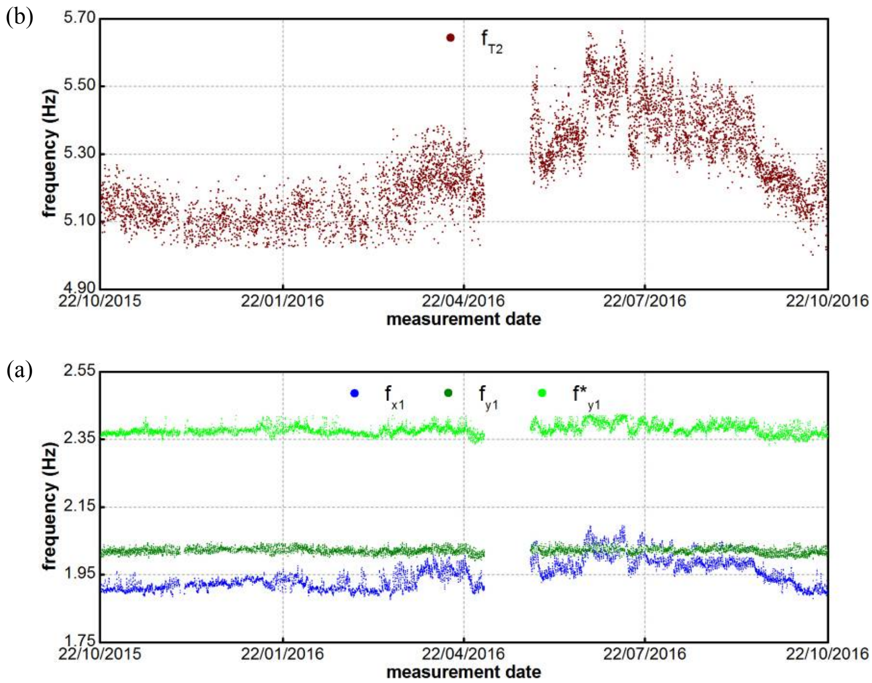

Figure 11: Time evolution of the automatically identified natural frequencies along the first year of monitoring (from 22/10/2015 to 21/10/2016): (a) modes f_{x1}, f_{y1} and f^*_{y1}; (b) mode f_{T2}.

Mode	f_{ave} (Hz)	σ_f (Hz)	f_{min} (Hz)	f_{max} (Hz)
f_{x1}	1.946	0.041	1.876	2.094
f_{y1}	2.020	0.009	1.990	2.053
f^*_{y1}	2.379	0.015	2.333	2.423
f_{T2}	5.265	0.141	5.001	5.663

Table 4: *Santa Maria del Carrobiolo* bell-tower - Statistics of the natural frequencies identified from 22/10/2015 to 21/10/2016.

The identified natural frequencies have been plotted versus the outdoor temperature T_S in Fig. 12, along with the best fit line and the coefficient of determination R^2. Figures 12a and 12d refer to modes f_{x1} and f_{T2} and confirm that the frequency of those modes increases with increased temperature, with slight non linearity being observed in the low temperature range

(T_S < 10°C). Figures 12b and 12c refer to closely spaced and similar modes f_{y1} and f^*_{y1} and confirm the very low effect of the changing environment on the frequency of these modes. It is further noticed that ongoing numerical investigation seems to indicate that the PCA-based regression turned out to be an effective tool to mitigate the environmental effects on automatically identified frequencies, in spite of the relatively small number of monitored frequencies.

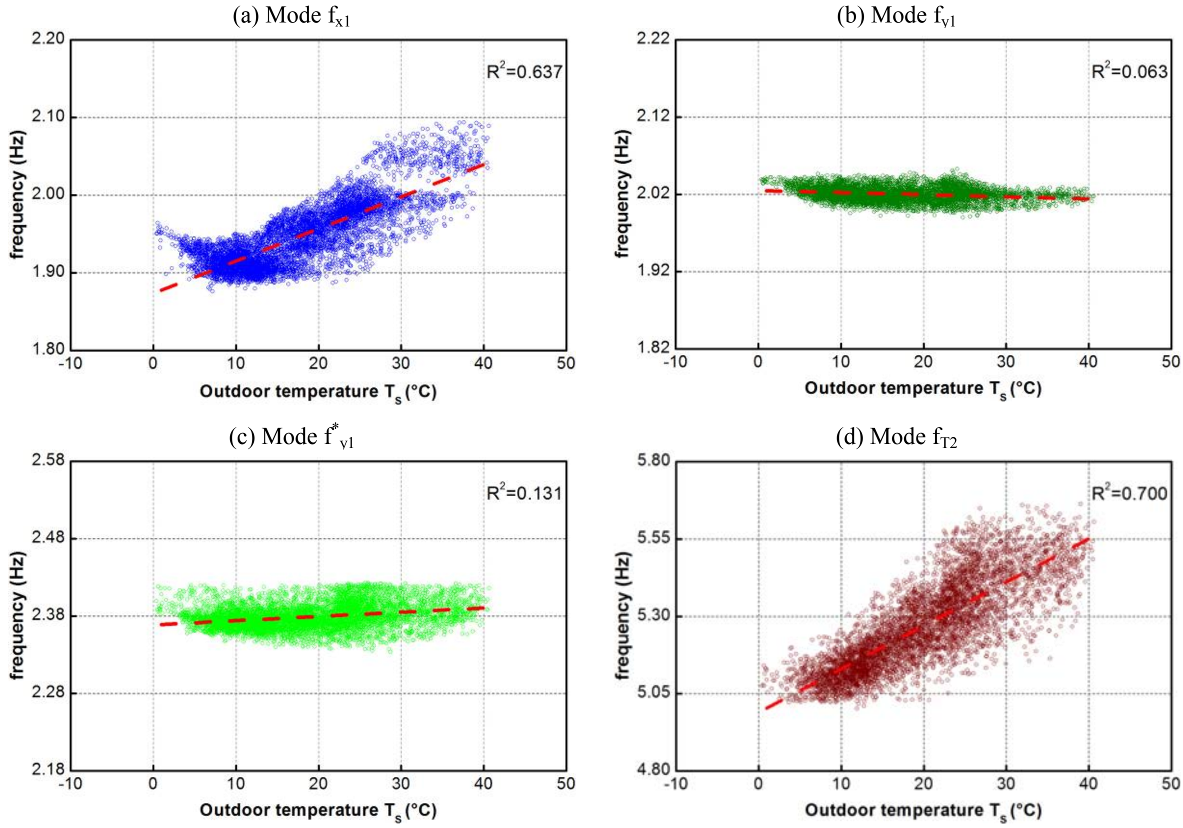

Figure 12: Correlation between outdoor temperature T_S and natural frequencies.

5 CONCLUSIONS

Selected results of the continuous dynamic monitoring of three historic towers have been reported in the paper with the main objective of better understanding the effects of changing temperature on the time evolution of continuously identified modal frequencies. Different temperature-driven effects on frequency changes have been observed [7]:

- The increase of natural frequencies with increased temperature. This behavior, observed in all studies of masonry towers [3-10, 12] can be explained by the closure of superficial cracks and minor masonry discontinuities induced by the thermal expansion of materials. The frequency-temperature correlation tends to be essentially linear when the temperature exceeds 10-15°C but non linear effects are detected in the lower range of temperatures;
- Around the freezing conditions, the natural frequencies rapidly and significantly increase with decreased temperature. This behavior is conceivably related to the freezing of the structural system (including its foundation) and to the presence of ice, which fills and closes the cracks, causing a temporary stiffening of the structure;

- Some effects of the increased temperature at the local level (such as the increase of thrust exerted by inclined structural elements or the slackening of metallic ties) might induce significant frequency reduction (or slight overall change) with increased temperature. In the authors' opinion, this last aspect deserves further investigation as a frequency decrease with increasing temperature could be an easy-to-evaluate symptom of an unsatisfactory state of preservation of the historic building.

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