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Continuous monitoring of the Milan Cathedral: dynamic characteristics and vibration-based SHM

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Abstract

The traditional collaboration between Politecnico di Milano and *Veneranda Fabbrica del Duomo di Milano*—the historic institution established by Gian Galeazzo Visconti in 1387 and having in charge all operational aspects related to the Milan Cathedral since more than 600 years—recently focused on the design and installation of a structural monitoring system, with the objective of assisting the condition-based structural maintenance of the historic church through the continuous interrogation of sensors installed in the structure and the extraction from measured data of features which are representative of the current state of structural health. The new monitoring system of the Milan Cathedral includes different types of measurements and sensors: quasi-static acquisition of strain in selected tie-rods and biaxial tilt of selected piers and the main spire, monitoring of inner and outer environmental parameters and dynamic measurement of the velocity response at the top of 14 piers and at 3 levels of the main spire. After a concise description of the historic church and of the monitoring system, the paper focuses on the dynamic characteristics of the Milan Cathedral, their evolution during the first months of monitoring (since October 16th, 2018) and the lessons learned in view of the structural health monitoring of the monument. The presented results from the vibration monitoring highlight that: (a) 8 global modes of vibration are automatically detected in the frequency range 1.0–5.0 Hz; (b) the resonant frequencies exhibit a distinctive trend of variation, which is mainly driven by temperature; (c) the mode shapes of the cathedral do not show appreciable fluctuations associated with the environmental effects.

Keywords Architectural heritage · Dynamic characteristics · Environmental effects · Milan Cathedral · Multi-sensor monitoring · Structural health monitoring

CONTINUOUS MONITORING THE MILAN CATHEDRAL: DYNAMIC CHARACTERISTICS AND VIBRATION-BASED SHM

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ABSTRACT

The traditional collaboration between Politecnico di Milano and *Veneranda Fabbrica del Duomo di Milano* – the historic Institution established by Gian Galeazzo Visconti in 1387 and having in charge all operational aspects related to the Milan Cathedral since more than 600 years – recently focused on the design and installation of a structural monitoring system, with the objective of assisting the condition-based structural maintenance of the historic church through the continuous interrogation of sensors installed in the structure and the extraction from measured data of features which are representative of the current state of structural health.

The new monitoring system of the Milan Cathedral includes different types of measurements and sensors: quasi-static acquisition of strain in selected tie-rods and biaxial tilt of selected piers and the main spire, monitoring of inner and outer environmental parameters and dynamic measurement of the velocity response at the top of 14 piers and at 3 levels of the main spire.

After a concise description of the historic church and of the monitoring system, the paper focuses on the dynamic characteristics of the Milan Cathedral, their evolution during the first months of monitoring (since October 16th, 2018) and the lessons learned in view of the Structural Health Monitoring of the monument. The presented results from the vibration monitoring highlight that: (a) 8 global modes of vibration are automatically detected in the frequency range 1.0-5.0 Hz; (b) the resonant frequencies exhibit a distinctive trend of variation, which is mainly driven by temperature; (c) the mode shapes of the Cathedral do not show appreciable fluctuations associated to the environmental effects.

Keywords: Architectural Heritage, Dynamic characteristics, Environmental effects, Milan Cathedral, Multi-sensor monitoring, Structural Health Monitoring

1. INTRODUCTION

The Milan Cathedral [1] (Figs. 1-2) is the most iconic symbol of Milan and is world-wide known for being one of the largest Heritage monuments ever built, as well as for its unique architectural style [2]. The preservation of the Cathedral is the main mission of the historic Institution named *Veneranda Fabbrica del Duomo di Milano* [3-4] and established in 1387 to manage all operational aspects related to the construction, maintenance and restoration of the historic church.

The normal survey practice adopted in the Milan Cathedral includes the periodic inspection of the huge number of (internal and external) decorative elements and surfaces in Candoglia marble – which is reportedly prone to air pollution [5] – to detect the onset of material degradation. Those direct inspections, aimed also at detecting and surveying possible crack patterns, are currently performed by qualified workmen using temporary scaffoldings and moving platforms.

In the last decades, the traditional inspections have been frequently coupled with the installation of different sensing devices inside the Cathedral, aimed at monitoring local strengthening interventions (see e.g. [6]) or investigating the evolution of possible structural issues. Remarkable examples of sensing systems operating in the past includes: (a) the inverted pendulum installed in the main spire on late September 1904 to measure the horizontal displacements induced by strong winds [7]; (b) the continuous measurement of the relative distance between the main spire and a metallic scaffolding performed during the architectural restoration preceding EXPO 2015 [8]; (c) the traditional monitoring system, based on geometric levelling and established to measure the horizontal deflection of the piers in the late sixties, when structural issues occurred to the Cathedral associated to the lowering of ground water. Although the latter system is not computer based, it has been active in measuring the piers deformation at pre-selected intervals (May and November) for more than 50 years and is still fully operating.

During the recent assessment of the state of preservation and the tensile force of the metallic tie-rods of the Cathedral [9], the idea of implementing a Structural Health Monitoring (SHM) strategy has been taking shape and a monitoring system was designed [10] and implemented with the two-fold objective of providing the information needed for the condition-based structural maintenance and the creation of a large archive of experimental data useful to improve the knowledge of the monument.

The complexity and the large dimension of the church suggested the implementation of a monitoring system, that is fully computer based and easily expandable. The documentary research in the archives as well as the analysis of recent experimental information allowed to identify the sub-structures to be initially involved in the monitoring: (a) the structural elements which underwent important strengthening interventions, such as the piers [6] supporting the *tiburio* (i.e., the prismatic structure with octagonal base, which is built around the dome) and the main spire [1]; (b) the piers of the apse, as the absence of buttresses makes the apse region especially vulnerable in Gothic cathedrals; (c) selected piers of the transepts, because those regions are more exposed to the ambient vibration generated by the metro passages and the traffic in the neighbouring streets; (d) selected the tie-rods, which are subjected to high tensile stress (of the order of 100 MPa or higher) or affected by slight damage [9].

The designed monitoring system includes a relatively large number of sensors for measuring both static (15 bi-axial tilt-meters and 12 vibrating wire extensometers) and dynamic parameters (36 uni-axial seismometers). In addition, the indoor and outdoor environmental conditions (temperature and humidity) are extensively monitored with the two-fold objective of evaluating the risks for the conservation of the main artifacts present in the Cathedral [11] and establishing correlations with the structural parameters changes. The importance of the latter aspect for historic masonry structures has been shown in the long-term monitoring of towers [12-13], churches [14-15], cathedrals [16] and monumental buildings [17]: all those studies have highlighted that resonant frequencies [11-17], as well as static structural parameters [14-15, 17], are significantly affected by changes in the environmental conditions.

It is worth noting that the monitoring system installed in the Milan Cathedral represents a top example in the area of heritage constructions due to its complexity and extension, whereas the previous implementations reported in the literature involve the use of a very limited number of sensing devices, suitable to specific applications (such as controlling the structural effects of restoration processes [14] or monitoring the dynamic characteristics of towers [12-13] and buildings [16-17] in seismic areas).

The present paper is mainly aimed at describing the monitoring system installed in the Milan Cathedral with emphasis on the dynamic measurements, the processing of the continuously collected time series, the automated extraction of dynamic signatures (i.e. resonant frequencies, mode shapes and mode complexity [18-19]) through effective algorithms and the adopted vibration-based SHM strategy. In more detail, the paper starts with a concise historic background of the Milan Cathedral and a brief description of the monitoring hardware and of the software tools that were developed to perform the on-line processing of the continuously acquired data. Subsequently, the dynamic characteristics of the Cathedral, that were identified in the first hours of dynamic monitoring, are presented and discussed. At last, the evolution in time of the environmental and modal parameters during the first months of monitoring is addressed and some preliminary comments regarding the time-invariance of mode shapes and mode complexity are given within a SHM perspective [20].

2. THE MILAN CATHEDRAL: DESCRIPTION AND HISTORIC BACKGROUND

The Milan Cathedral is one of the largest masonry monuments ever built. The construction of the church was promoted by the Archbishop Antonio de' Saluzzi with the objective of building a great cathedral in the site previously occupied by the two Basilicas of *Santa Maria Maggiore* and *Santa Tecla* [2]. The Duke of Milan, Gian Galeazzo Visconti, strongly endorsed the initiative with the political motivation of establishing a symbol of the uprising power of his state, comparable to the major gothic cathedrals of the times in France, Germany and Spain.

Famous architects from France and Germany [1] were involved in the design of the Cathedral, that is characterized by a peculiar architectural style: a mix of Gothic style and regional Lombardy style, where also neo-classic, neo-gothic and even renaissance influences are present due to the long period required by the construction works (from 1386 to 1965). An essential chronology of the construction phases is summarized in Fig. 2 with reference to the longitudinal section of the Cathedral: (a) the progressive demolition of the pre-existing churches began in 1386; (b) the construction proceeded quickly, so that apse and the surrounding ambulatory were completed in 1415; (c) the transepts and the first bay of the main limb were finished in 1465; (d) in the 16th century, the majority of the Cathedral was completed, including the great dome and the *tiburio* above the main altar, as well as the first 6 bays of the main limb; (e) after 1550, the political instability, the Great Plague of Milan (1629-1631) and the foreign invasions significantly obstructed the works, that received a new thrust forward in the 18th century with the erection the iconic Main Spire, reaching the height of about 108 m and supporting the statue of the Virgin Mary (known as *Madonnina* in Italy); (f) the structural completion of the Cathedral was promoted by Napoleone Bonaparte (who was crowned king of Italy on May 1805 in the Milan Cathedral) with the erection of the neo-Gothic façade, which was finalized in 1813-1815. It is further noticed that the installation of the last iron gate in the façade – on January 6th, 1965 – is usually indicated as the official completion of the building works.

The structural arrangement of the main limb is exemplified in Fig. 3, with the central nave and the lateral aisles spanning 18.2 m and 9.6 m, respectively. Figure 3 highlights that the complex structural schematic is characterized by the presence of double masonry vaults (i.e., cross vaults and barrel vaults) and of permanent metallic tie-rods placed under each arch (Figs. 3 and 4). The vaults exhibit decreasing heights from 45.6 (vault intrados of the main nave) to 24.0 m (vault intrados of the shortest aisle).

It is worth mentioning that the adoption of 122 iron tie-rods, still exerting an active role in resisting the lateral thrusts [9], is one of the distinctive characteristics of the Milan Cathedral: the construction Masters decided to connect the capitals of all adjacent piers by means of metallic elements to reduce the thrust on the slender lateral buttresses and in response to the critical comments raised by the French Architect Jean de Mignot [1]. This peculiar structural arrangement is unique in Gothic cathedrals, where wooden or metallic ties were used as provisional elements and removed at the end of the construction.

The Cathedral has a Latin cross shape in plan (Figs. 5a and 7a), with the overall dimensions being about 66 m × 158 m; it should be noticed that the longitudinal limb points the East-West direction, whereas the transversal transept is oriented in the North-South direction.

3. DESCRIPTION OF THE MONITORING SYSTEM

The monitoring system installed in the Milan Cathedral (Figs. 5-7), fully computer based and with efficient transmission of the collected data, involves the measurement of different physical quantities: (a) quasi-static strains (using wireless vibrating wire extensometers) of selected tie-rods; (b) quasi-static rotations (using wireless tilt-meters with individual compensation of the temperature effects) at the top of selected piers and at 3 levels of the main spire; (c) indoor and outdoor environmental parameters (temperature and humidity); (d) velocity (using electro-dynamic sensors), again at the top of selected piers and at 3 levels of the main spire.

Data acquisition (and data analysis) is continuous, even if different sampling rates are adopted for quasi-static and dynamic time series: strains, rotations and environmental data are collected at a rate of two samples per hour, whereas the dynamic monitoring is performed at a sampling frequency of 100 Hz.

It is further noticed that: (a) the installed sensors, as many similar devices available on the market, are individually manufactured and calibrated in order to obtain highly durable performance and service life; (b) the architecture of the monitoring system has been established in order to minimize wiring inside the Cathedral and to allow changes in the position of the installed sensors.

3.1 *Static monitoring hardware*

The static monitoring system includes:

(a) 12 vibrating wire extensometers (Figs. 5a and 5b), with measurement range of ±3000 με and resolution of 1 με, to measure the axial strain of selected tie-rods: the tension bars highlighted in red in Fig. 5a are subjected to tensile stress exceeding 100 MPa, whereas the other tie-rods (orange colour in Fig. 5a) are affected by slight damage [9];

(b) 12 bi-axial tilt-meters (Figs. 5a and 5c), with a measurement range of ±0.5º and resolution of ±0.5 mm/m, located inside the Cathedral on the capital of piers 31 and 64 (façade), 69 and 90, 11 and 20 (transept), 74-75 and 84-85 (*tiburio*), and 47-48 (apse);

(c) 3 bi-axial tilt-meters, installed at different levels of the main spire (+65.87 m, +74.99 m and +91.67 m, Fig. 6);

(d) Indoor and outdoor temperature sensors, with temperature range being between –20 °C and +60 °C and resolution of 0.2 °C. Those sensors are integrated with each tilt-meter (Figs. 5a and 6) and also allow the compensation of the temperature effect on the measurement of each (individually calibrated) tilt-meter;

(e) 12 hygrometers, with measurement range 0-100% and resolution of 1%, mounted in the neighbourhood of the extensometers;

(f) 1 weather station installed on the higher accessible level of the main spire (+91.67 m, Fig. 6). Although the position cannot be considered optimal for the evaluation of wind parameters, its choice was motivated by the possibility of carrying out an easier maintenance of the device. Unlike the other quasi-static measurements, the data from the weather station are collected every 5 minutes.

As previously pointed out, the data transfer of the static devices inside the Cathedral is wireless and each sensor is wired to high capacity batteries, which are placed in walkways over the vaults, quite easy to access for maintenance and substitution. At the sampling rate of two per hour, the expected power charge should be around 3 years. Groups of static sensors (with the number of the sensors for each group depending on the relative distances) are managed by local nodes or end devices; the data collected by neighbouring end devices are transmitted to routers and those routers, in turn, transmit the information – through a "coordinator" node – to a local workstation managed by the technical staff of *Veneranda*

Fabbrica del Duomo di Milano (VFD). The local workstation is equipped with appropriate software codes aimed at the remote management and check of the different devices; in addition, through the Internet, the data are processed by authorized users (such as Politecnico di Milano) and the compressed results come back to VFD workstation for direct check and decision making, as well as for being stored in digital archives.

3.2 *Dynamic monitoring hardware*

The dynamic monitoring system is entirely based on SARA SS45 seismometers (electro-dynamic velocity transducers). The seismometers use is becoming more common in civil engineering (see e.g. [21]) and is motivated by: (a) the high sensitivity (78 V/[m/s]) and the excellent performance of electro-dynamic transducers in the low frequency range ($f \leq 100$ Hz); (b) the un-necessity of powering the sensors; (c) the possibility of obtaining a good estimate of the displacement time series by integrating the velocity signals. It is worth mentioning that the latter technical aspect might provide, especially for the slender main spire, with data usually not available and directly related to the stiffness and the structural health.

The dynamic monitoring system (Figs. 6 and 7a) consists of:

(a) 13 bi-axial seismometers and 1 mono-axial seismometer, installed at the top of selected piers inside the Cathedral (Fig. 7a) and measuring the velocity in the two orthogonal N-S (transversal) and E-W (longitudinal) directions. The sensors installed on piers (94, 92, 90), (65, 67, 69), (22, 85, 84), (9, 74, 75) and (47, 48) are grouped and wired to five 24-bit digitizers SARA SL06, each equipped with one UMTS modem for data transfer to the VFD workstation;

(b) 3×3 mono-axial seismometers, installed at the same levels of the main spire hosting the bi-axial tilt-meters belonging to the static monitoring (Fig. 6). Each sensors triad is wired to 24-bit digitizer, with the digitizers being connected to a switch for data transfer.

3.3 *Signal pre-processing and data analysis*

As previously pointed out, the data continuously collected by static and dynamic sensing devices are transmitted to a local workstation, which is managed by the technical staff of VFD and by authorized users of Politecnico di Milano.

The raw data collected by the static monitoring are, as usual, transformed in engineering data and stored in compact archives. Notwithstanding the relatively high number of static and environmental measurements, the adopted sampling rate makes the dimension of the archives very limited. Simple graphical tools have been developed to show the time evolution of any measured quantity, its correlation with the environmental parameters and the relevant statistical characteristics; furthermore, after an appropriate training period (of about 1 year), the expected – or "normal" – range of variation of each measured quantity should be defined so that, if the limits of the normal behaviour are exceeded, warnings might be generated. It is worth mentioning that the strain in the tie-rods gives a direct estimation of the health condition (i.e. of the stress state) of those elements since the tensile force and stress corresponding to the beginning of the monitoring is known from previous studies [9], as well as the Young's modulus and the yield strength [9].

Of course, the signals continuously recorded by each seismometer provide a huge amount of data and require a more refined pre-processing and data analysis, as well as an appropriate strategy for data storage. The dynamic signals are transferred in real time to the VFD server and stored in separate files (compressed mini-seed format) of 1 hour. Every hour, the collected data are automatically processed through a series of tools:

- Pre-processing the raw data (to compensate the low-frequency attenuation of the sensor) using the SEISMOWIN commercial software and subsequent saving of the time series in text format;
- Data analysis to extract the maximum and the root mean square values and creation of a file in Matlab (.mat) format;
- Low-pass filtering and down-sampling (to reduce the sampling frequency from 100 Hz to 20 Hz), and creation of a database of files (in binary or text format) for the application of the modal identification tools;
- Estimation and tracking of modal parameters.

After the automated modal parameter estimation, only the hourly evaluated features (i.e., the statistical characteristics of each dataset and the modal parameters) and a few time series corresponding to meaningful events are permanently stored in the VFD archives and can be accessed through graphical and reporting tools very similar to the ones developed for summarizing the results of the static monitoring.

The modal parameters of the Cathedral and of the main spire are independently extracted from the acquired time series using an automated procedure based on the covariance-driven Stochastic Subspace Identification (SSI-Cov) algorithm [22-23].

For each dataset of m measured channels of data, the SSI-Cov algorithm firstly involves the evaluation of the covariance matrices of the m available outputs, for positive time lags varying from Δt to $(2i–1)\ \Delta t$, in order to fill a $(mi \times mi)$ block Toeplitz matrix. Subsequently the Toeplitz matrix is decomposed to obtain stochastic subspace models of increasing order n and the results are summarized in a stabilization diagram [23], where the $n/2$ modes corresponding to the increase of model order n are represented together, so that the physical modes of the system should conceivably appear at many orders as stable vertical alignments. The automated procedure involves the two main steps of modal parameters estimation (MPE) and modal tracking (MT):

(1) The MPE is performed through an automatic interpretation of the stabilization diagram, based on the sensitivity of frequency and mode shape to the model order variation. For each dataset, after having filtered the spurious poles by checking the associated damping ratio and mode complexity value [18-19], the poles sharing similar frequencies and mode shapes are clustered together, and a set of representative modal parameters (i.e. resonant frequency, damping and mode shape) is estimated for each cluster. It is worth mentioning that the mode complexity is checked by averaging the information provided by both the Modal Phase Collinearity [18] (MPC) and Mean Phase Deviation [18-19] (MPD) through the Modal Complexity Index (MCI=0.5×[(1-MPC)+(MPD/45°)], varying between 0 and 1, with 0 indicating a mono-phase behaviour of the identified mode shape);

(2) The MT, aimed at providing the time evolution of the parameters of each mode, is based

on frequency and MAC [24] variation with respect to a pre-selected list of baseline modes. It is worth mentioning that this step is performed in an adaptive way, i.e. by updating the MAC and frequency variation threshold of each mode after a new dataset has been analyzed.

In the automated identification of the dynamic characteristics of the Cathedral (27 channels of data, Fig. 7a), the time lag parameter i was set equal to 60 and the data was fitted using stochastic subspace models of order n varying between 20 and 140; furthermore, in the noise modes elimination step, the maximum allowable damping ratio and MCI was set equal to 8% and 0.15, respectively.

It is worth highlighting that the vibration-based methodology adopted for structural condition assessment of the Milan Cathedral is briefly addressed at the end of section 5.

4. DYNAMIC CHARACTERISTICS OF THE MILAN CATHEDRAL

During the assessment of the metallic tie-rods [9], quick preliminary investigation of the overall dynamic behaviour of the Cathedral was carried out using a very limited number of conventional (high-sensitivity) accelerometers. In those preliminary tests the sensors were mounted: (i) on the capital of piers 22, 54 and 55 (6 channels of data, with 3+3 accelerometers oriented along N-S and S-W directions, respectively); (b) on capital of piers 9 and 39 (4 channels of data, with 2+2 sensors oriented along N-S and S-W directions, respectively). As reported in [10], 3 global modes of the building were clearly identified. The 2 lower modes were conceivably associated to global sway in the N-S direction (1.38 Hz) and E-W direction (1.71 Hz), respectively; on the contrary, the classification of the third mode (2.67 Hz) was highly uncertain.

Of course, the regular and quite extended grid of sensors of seismometers permanently installed in the Cathedral (and fully active since October 16th, 2018) allowed the identification and accurate spatial description of a relatively large number of key vibration modes. Typical results obtained in the first day of continuous monitoring, in terms of resonant frequencies and mode shapes, are shown in Figs. 8-10.

Figure 8 exemplifies the stabilization diagram obtained by applying the SSI-Cov method to the dataset (27 channels of data, Fig. 7a) recorded on 17/10/2018 (h 12:00-13:00). The stabilization diagram in Fig 8 is shown after cleaning and selection (clustering) of physical modes, along with the first Singular Value (SV) line of the spectral matrix, which is the mode indication function adopted in the Frequency Domain Decomposition (FDD) method [25]. The inspection of Fig. 8 highlights eight alignments of the stable poles, providing a clear indication of the Cathedral modes and those alignments of stable poles generally correspond to local maxima in the first SV line of the FDD procedure. The corresponding mode shapes are shown in Fig. 9 (dominant modal deflections in the N-S direction) and in Fig. 10 (dominant E-W motion). The inspection of Figs. 8-10 allows the following comments:

(a) As expected, the first two modes, denoted by C1 and C2, correspond to sway (in-phase) motion of all instrumented columns in the N-S (f_{C1}=1.38 Hz, Fig. 9b) and E-W (f_{C2}=1.69 Hz, Fig. 10b) direction, respectively;

(b) Mode C3 (f_{C3}=1.98 Hz, Fig. 9c) is characterized by dominant motion in the N-S direction and transverse bending of the naves, with out-of-phase vibration of apse and façade. It is further noticed that the piers belonging to the transepts (i.e. piers 9 and 22, Fig. 7a) exhibit slight modal deflection along E-W;

(c) Mode C4 (f_{C4}=1.98 Hz, Fig. 9d) is again characterized by transverse (N-S) bending of the naves and the ideal E-W line connecting the capitals exhibits a deformed shape with 3 half-sine waves (i.e., two changes of sign from apse to façade and in-phase motion of those substructures);

(d) Mode C5 (f_{C5}=2.68 Hz, Fig. 9e) and C7 (f_{C7}=3.12 Hz, Fig. 9f) exhibits out-of-phase transverse (N-S) motion of the symmetric columns of each bay. It should be observed that anti-symmetric N-S deflections of the piers tend to involve slight E-W motion of apse and façade (Figs. 9e and 9f);

(e) In mode C6 (f_{C6}=2.76 Hz, Fig. 10c) all the instrumented piers move in the E-W direction but there is a phase inversion corresponding to the *tiburio* (in other words, two columns supporting the *tiburio* and the apse exhibit a π phase shift with respect to all other columns);

(f) Mode C8 (f_{C8}=4.16 Hz, Fig. 10d) has a distinctive shape, with E-W deflection of the façade and N-S (out-of-phase) motion of the neighbouring inner piers;

(g) The N-S modes are characterized by damping ratios ranging between 1.79% (C5) and 4.14% (C1), whereas the damping of the E-W modes varies from 2.21% (C8) to 5.04 (C2). It should be noticed that especially the damping ratio of longitudinal (E-W) modes tends to be larger than generally observed at the low level of excitation existing on historical buildings in operational conditions.

As it will be discussed in section 5, almost all modes identified in the first hours of continuous monitoring, have been automatically detected with high identification rate in the subsequent months.

5. CONTINUOUS DYNAMIC MONITORING: RESULTS

This section summarizes the main results of the continuous dynamic monitoring over a time span of four months (i.e., from 16/10/2018 to 12/02/2019). During this time interval, about 3000 1-hour datasets were collected and automatically processed to identify the modal parameters.

5.1 Environmental parameters

In order to assess the possible dependence of the modal parameters on the environmental factors [12-17, 21], Figs. 11 and 12 show the variation in time of the (outdoor and indoor) temperature and the indoor relative humidity, respectively. As previously pointed out, a quite extended grid of temperature sensors and hygrometers has been installed inside the church with the objective of evaluating the occurrence of preservation issues of statues, paintings and decorative elements as well as to support the SHM program.

Figure 11a presents the evolution of the outdoor temperature measured by the weather station and shows that the temperature changed between −2°C and +28°C. The corresponding indoor temperature variations are exemplified in Fig. 11b. As expected from previous studies on the microclimatic condition in the Milan Cathedral [11] and notwithstanding the large dimensions of the church, Fig. 11b highlights a very limited temperature gradient in space, with the range between the extreme values not exceeding 0.5°C. Moreover, the measured indoor temperatures are almost perfectly correlated, with the correlation coefficients being always larger than 0.99. Therefore, the average indoor temperature might be assumed as a representative quantity for SHM correlations (Fig. 11b).

Figure 12 shows the minimum and maximum value of the relative humidity measured inside the Milan Cathedral along with the average relative humidity: as expected [11], also the humidity time series are highly correlated, with the correlation coefficients being of the order of 0.90 or larger.

5.2 Modal parameters and temperature effects

Figure 13 shows the time variation of the automatically identified resonant frequencies of the Milan Cathedral from 16/10/2018 to 12/02/2019, whereas the statistical characterization of modal frequencies is summarized in Table 1. This table includes the identification rate, the mean value (f_{ave}) and the standard deviation (σ_f) of the frequency estimates as well as the extreme values (f_{min}, f_{max}) of each modal frequency. It should be noticed that the lower 7 modes have been automatically identified with high occurrence during the first 4 months, with the identification rate being larger than 98% for modes C1-C5 and ranging between 91.4% and 85.4% for modes C6 and C7; on the other hand, the identification rate of mode C8 is significantly smaller (27%).

As shown in Table 1 and Fig. 13, all identified resonant frequencies exhibit slight but clear variations in time: the coefficient of variation ranges between 0.34 % (mode C1) and 1.10 % (mode C2) and the frequency fluctuations are almost completely driven by the changing temperature, whereas the average relative humidity slightly affects only the frequency of the fundamental mode (C1). Especially the frequencies associated to modes with dominant motion in the longitudinal direction of the Cathedral (modes C2 and C6, Figs. 10b and 10c) reveal clear daily variations (Fig. 13), with the natural frequencies increasing as (both indoor and outdoor) temperature decreases. The temperature-frequency correlation is better demonstrated in Fig. 14, where all natural frequencies are plotted versus the outdoor temperature, along with best fit lines: even if the observation period is relatively limited, the temperature range seems to be extended enough to conclude that all resonant frequencies of the Cathedral almost linearly increase with decreased temperature.

It is worth noting that the negative dependence of natural frequencies on temperature is a distinctive behaviour of the Milan Cathedral, with this trend being very different from what reported in almost all the long-term studies on masonry structures, both towers [12-13, 21] and churches [14-16]. In those studies, the increase of natural frequencies with increased temperature is generally documented [12-16, 21] and explained [12] as the effect of the closure of cracks, minor masonry discontinuities and mortar gaps induced by the thermal expansion of materials, so that a temporary stiffening of the structure is generated.

In the authors' opinion, the negative frequency-temperature correlation in the Milan Cathedral is determined by the structural arrangement, consisting of double vault system constrained by an extended net of metallic tie-rods (Figs. 3 and 4): as a matter of fact, the extensometers installed in the tie-rods highlight a generalized strain increase with decreased temperature, so that the corresponding increased forces in the tie-rods conceivably exert a stiffening action on the overall structure. The correlation coefficients between the automatically identified frequencies (f_{Ci}, $i = 1, \ldots, 8$) and the strain increase $\Delta\varepsilon$ measured on selected tie-rods (26-60, 57-87, 9-39 and 39-40, see Fig. 5a) are summarized in Table 2. It should be observed that all the correlation coefficients are positive, so that the positive correlation between tie-rods elongation and frequency increase is confirmed and quantitatively assessed. Moreover, the correlation coefficients turn out to be remarkably high (i.e., ranging from 0.510 to 0.794) for the frequency of modes C3-C8.

It is further noticed that a similar negative frequency-temperature correlation is only reported in the literature for a monumental building [17], which is characterized by the presence of metallic tension bars, as well.

Since a quite well distributed grid of seismometers is available in the Cathedral, the investigation of mode shape variations [20] might be very interesting because mode shapes provide both local and global information on the structure. Hence, even for complex systems, the mode shapes are supposed to be less sensitive [20, 21] than natural frequencies to environmental changes (which affect almost uniformly the structure) and conceivably more sensitive to local structural changes. The mode shape variation, in terms of the MAC, is exemplified in Fig. 15 for the lower 6 modes of the Milan Cathedral. The inspection of Fig. 15 confirms that the overall mode shapes are approximately time invariant, even if the standard deviation of the MAC values tend to increase with the increasing mode order (and the increasing spatial complexity of the mode shape, Figs. 9 and 10). Table 3 summarizes the statistical characteristics of the MAC in terms of average value (MAC_{ave}), standard deviation (σ_{MAC}) and minimum value (MAC_{min}); moreover, the coefficient of determination R^2_{MAC-T} is also listed in order to underline that the outdoor temperature practically does not affect the MAC of modes C1-C2 and C4-C6 ($R^2 < 0.03$) and has a minor influence on the MAC of the other modes (with R^2 ranging between 0.125 and 0.175). It is worth mentioning that a similar time invariance is obtained also for the usual measures of mode complexity, such as MPC and MPD.

As a final remark on the lessons learned from the first months of dynamic monitoring of the Milan Cathedral, it should be stated that the future vibration-based preservation and SHM of the monument will involve: (a) the use of both supervised (such as multiple linear regression [26]) and unsupervised (principal component analysis [27] or second order blind identification [28]) algorithms to remove/mitigate the masking effects induced by the temperature changes on the identified resonant frequencies [12-13, 21]; (b) the detection of possible abnormal structural changes from checking both the frequency residual errors through novelty analysis [12-13, 21] and the time invariance of mode shapes and mode complexity [20]. In addition, the availability of several quasi-static measurements should conceivably be exploited in a data fusion framework for an enhanced SHM program.

6. CONCLUSIONS

The Milan Cathedral, built between 1386 and 1813, is one of the largest masonry monuments ever built. The paper firstly focuses on the description of the monitoring system recently installed in the Cathedral, aimed at assisting the condition-based structural maintenance of the historic building. The monitoring system includes more than 120 sensors belonging to different classes (i.e. a network of 12 extensometers, 15 bi-axial tilt-meters, 36 seismometers, 30 temperature sensors, 12 hygrometers and 1 weather station) and is fully computer based and characterized by distributed architecture.

Special emphasis is given on the dynamic measurements, the processing of the continuously collected time series and the automated extraction of dynamic signatures. Based on the time evolution of the modal parameters automatically identified in the first months of continuous monitoring (i.e., between 16/10/2018 and 12/02/2019), the following main conclusions can be drawn:

1. The application of effective tools for automated operational modal analysis allows accurate estimate and tracking of eight resonant frequencies in the frequency interval 0-5 Hz. The automatically identified frequencies involve dominant motion in the main transverse (N-S) and longitudinal (E-W) direction of the Cathedral;
2. The (outdoor and indoor) temperature turned out to be a dominant driver of daily fluctuation of the resonant frequencies of all modes, whereas the relative humidity slightly affects only the frequency of the first mode;
3. Even if the observation period is relatively limited (4 months), the frequency-temperature correlations reveal a distinctive trend, which is very different from what reported in almost all the long-term studies on historic masonry structures. All resonant frequencies of the Milan Cathedral almost linearly increase with decreased temperature, and the negative dependence of modal frequencies on temperature is conceivably determined by the active effects exerted by the metallic tie-rods in the structural arrangement of the monumental building;
4. The mode shapes of the Cathedral and the corresponding mode complexity do not exhibit

appreciable fluctuations associated to the environmental effects, so that an appropriate strategy of SHM should be based on the time invariance of those parameters.

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Table 1. Statistical description of the natural frequencies identified (SSI-Cov) from 16/10/2018 to 12/02/2019

Mode	Id. Rate (%)	f_{ave} (Hz)	σ_f (Hz)	f_{min} (Hz)	f_{max} (Hz)
C1	99.9	1.380	0.005	1.365	1.394
C2	99.9	1.690	0.019	1.637	1.739
C3	98.7	1.996	0.011	1.967	2.036
C4	98.2	2.536	0.016	2.486	2.586
C5	98.9	2.667	0.014	2.617	2.703
C6	91.4	2.779	0.027	2.704	2.861
C7	85.4	3.162	0.023	3.084	3.234
C8	27.0	4.200	0.035	4.107	4.307

Table 2. Correlation coefficients between the natural frequencies (f_{Ci}, i = 1, …, 8) and the strain increase $\Delta\varepsilon$ measured in selected tie-rods of the Milan Cathedral

	$\Delta\varepsilon_{26\text{-}60}$	$\Delta\varepsilon_{57\text{-}87}$	$\Delta\varepsilon_{9\text{-}39}$	$\Delta\varepsilon_{39\text{-}40}$
f_{C1}	0.281	0.290	0.229	0.244
f_{C2}	0.391	0.391	0.380	0.378
f_{C3}	0.525	0.526	0.530	0.510
f_{C4}	0.736	0.732	0.738	0.721
f_{C5}	0.794	0.794	0.782	0.792
f_{C6}	0.605	0.612	0.596	0.603
f_{C7}	0.763	0.757	0.763	0.762
f_{C8}	0.754	0.742	0.751	0.730

Table 3. Statistical description of the MAC values from 16/10/2018 to 12/02/2019

Mode	MAC_{ave}	σ_{MAC}	MAC_{min}	R^2_{MAC-T}
C1	0.997	0.002	0.982	0.002
C2	0.995	0.003	0.981	0.007
C3	0.990	0.007	0.960	0.175
C4	0.986	0.007	0.958	0.028
C5	0.983	0.009	0.943	0.026
C6	0.984	0.011	0.941	0.001
C7	0.975	0.015	0.924	0.125
C8	0.948	0.022	0.901	0.131

(a)

(b)

Fig. 1 Views of the Milan Cathedral (courtesy of *Veneranda Fabbrica del Duomo di Milano*)

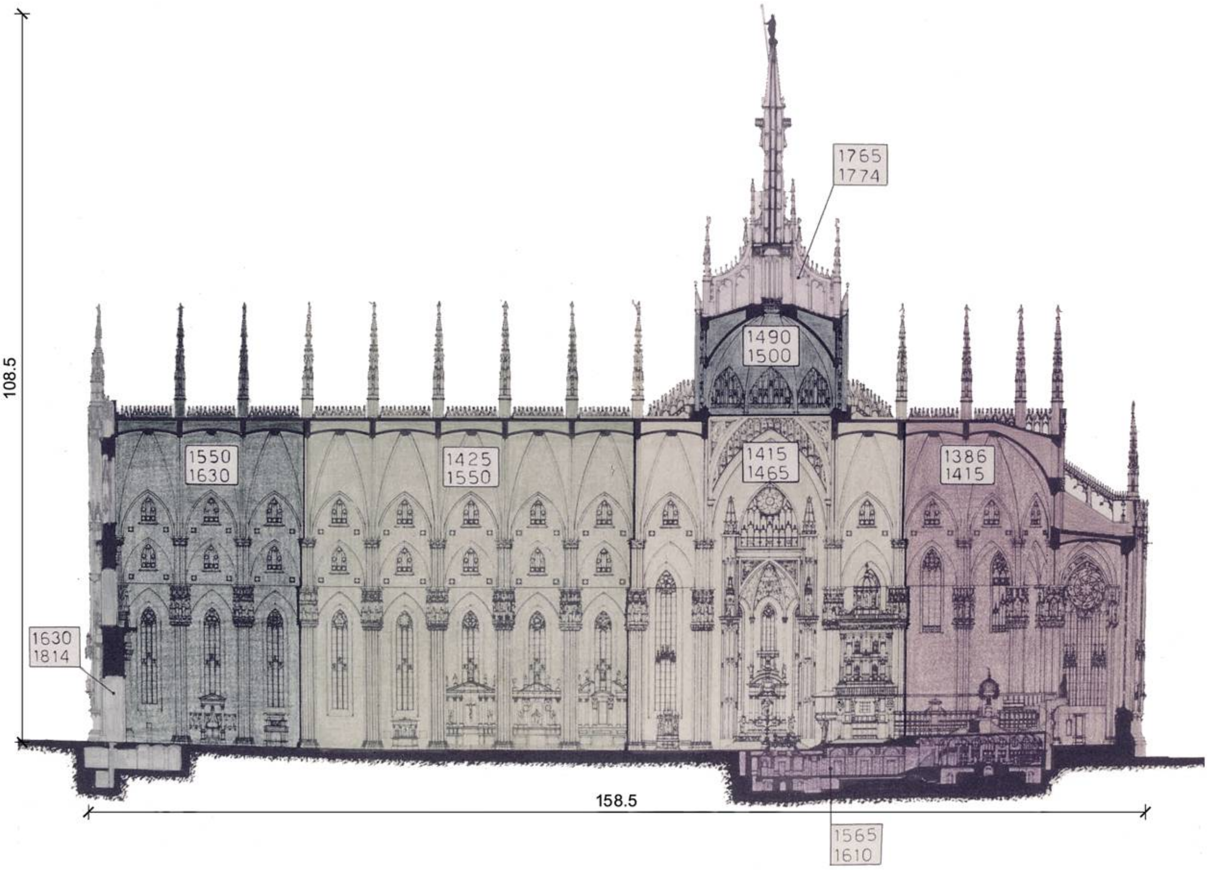

Fig. 2 Longitudinal section of the Milan Cathedral (dimensions in m) and chronology of the main construction phases (courtesy of *Veneranda Fabbrica del Duomo di Milano*)

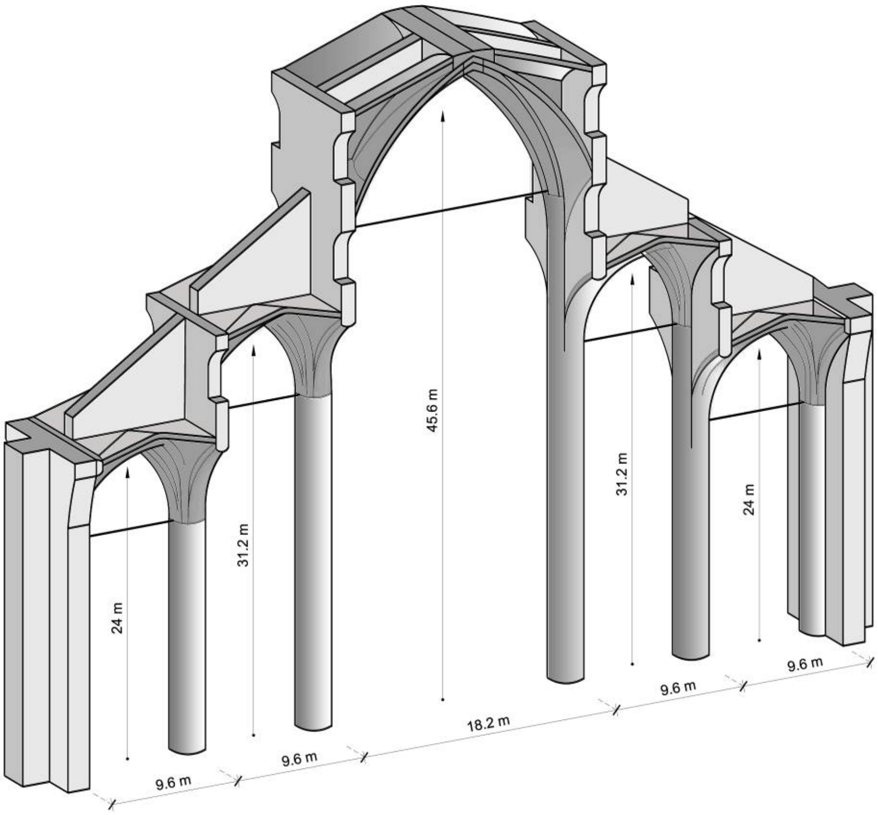

Fig. 3 Milan Cathedral: schematic of the structural arrangement exemplified on one bay of the church

Fig. 4 View of the piers and of the tie-rods inside the Milan Cathedral

FIG. 4

(a)

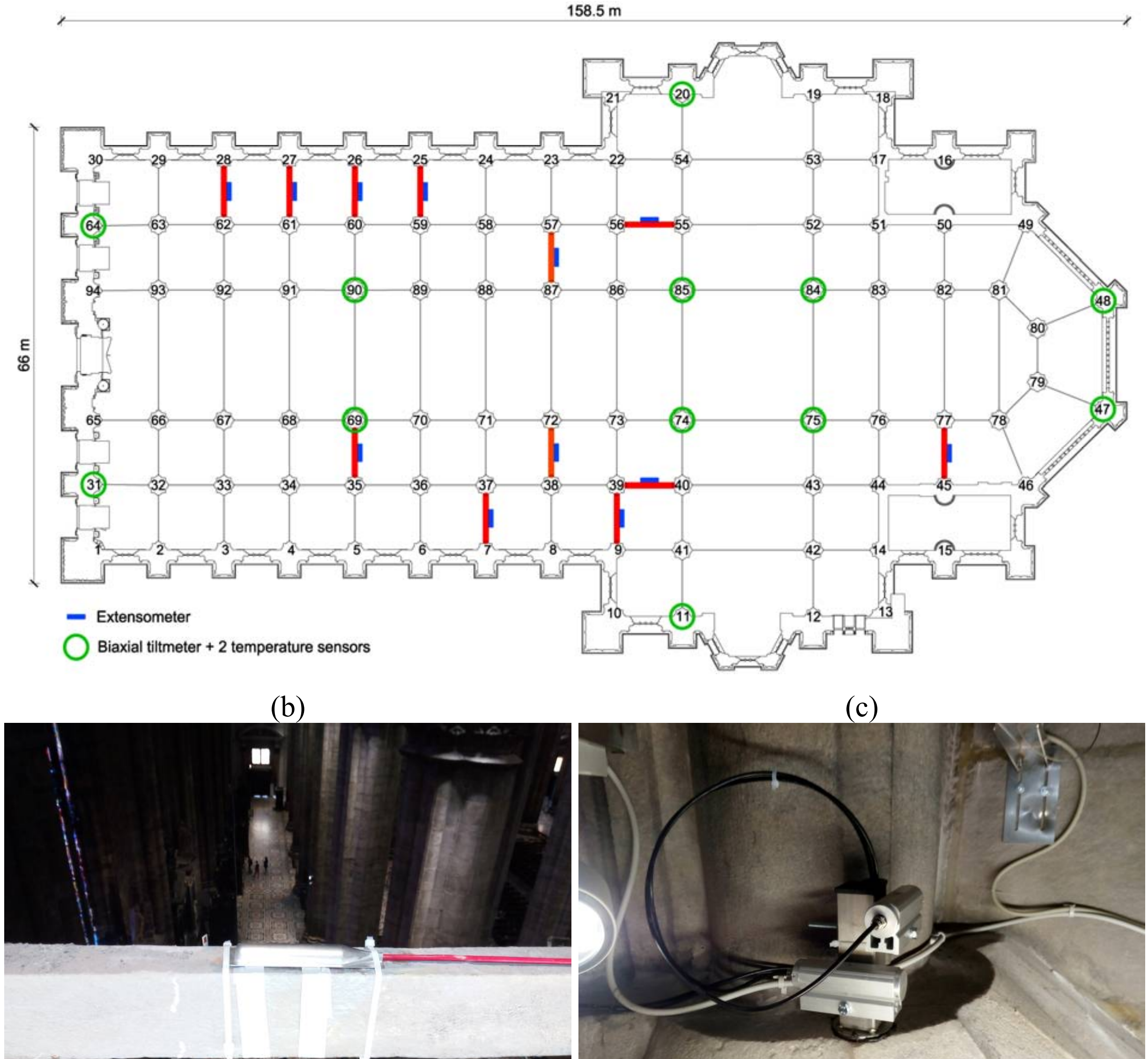

Fig. 5 (a) Map of the static monitoring devices installed inside the Milan Cathedral (dimensions in m); (b) Extensometer mounted on a tie-rod; (c) Bi-axial tilt-meter installed on a capital

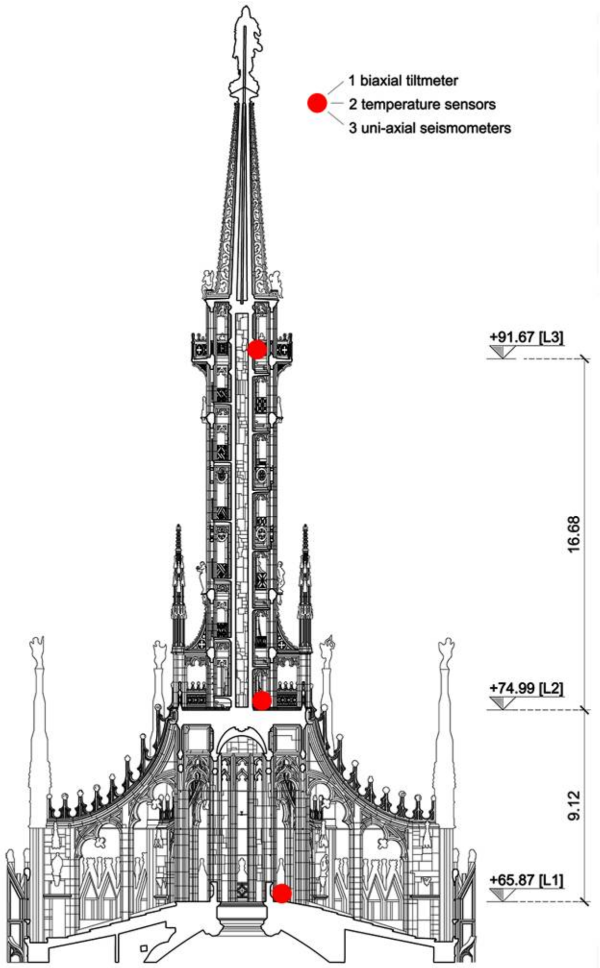

Fig. 6 Sensing devices installed in the Main Spire (dimensions in m)

(a)

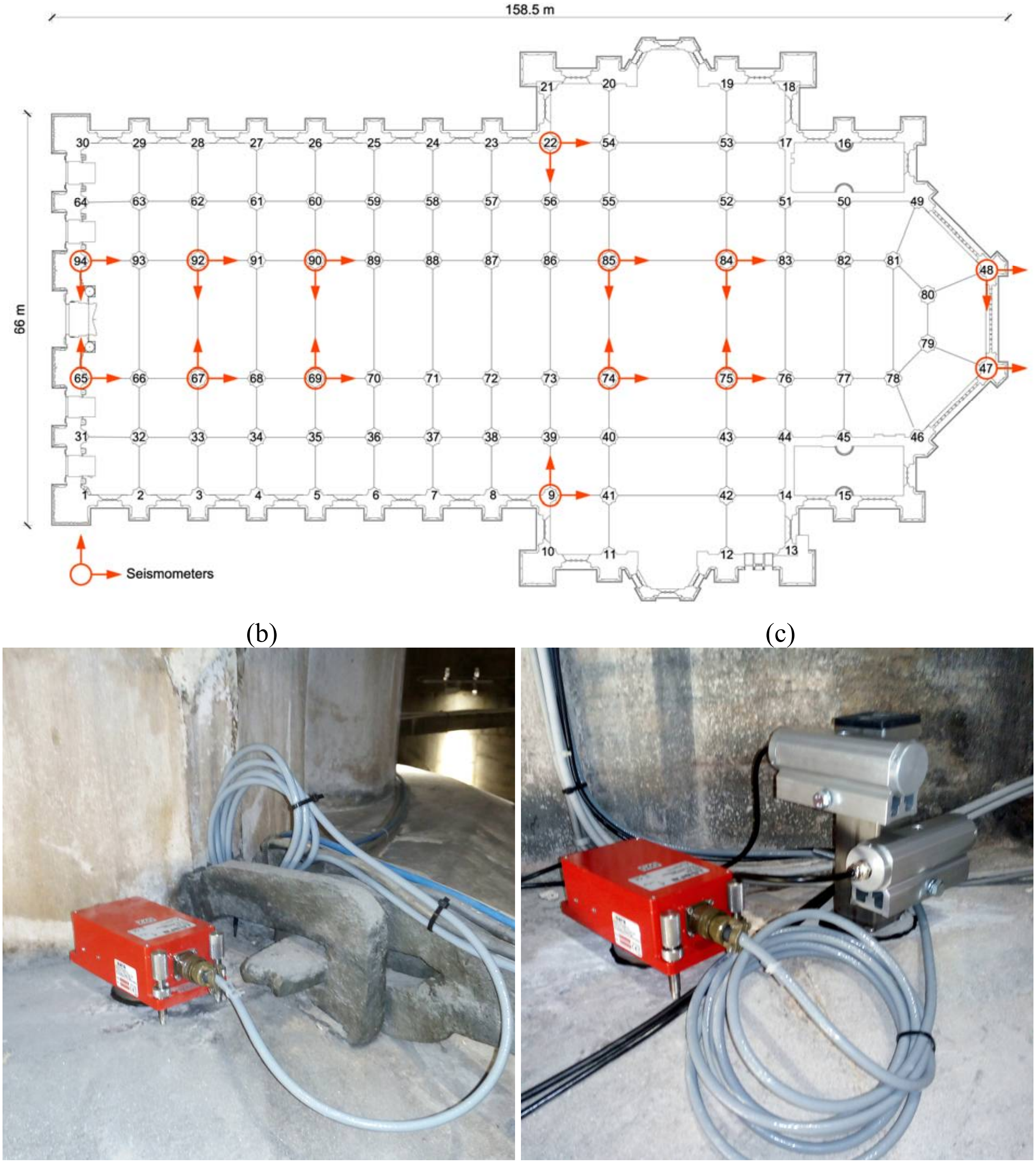

Fig. 7 Map (a) and views (b)-(c) of the seismometers installed inside the Milan Cathedral (dimensions in m)

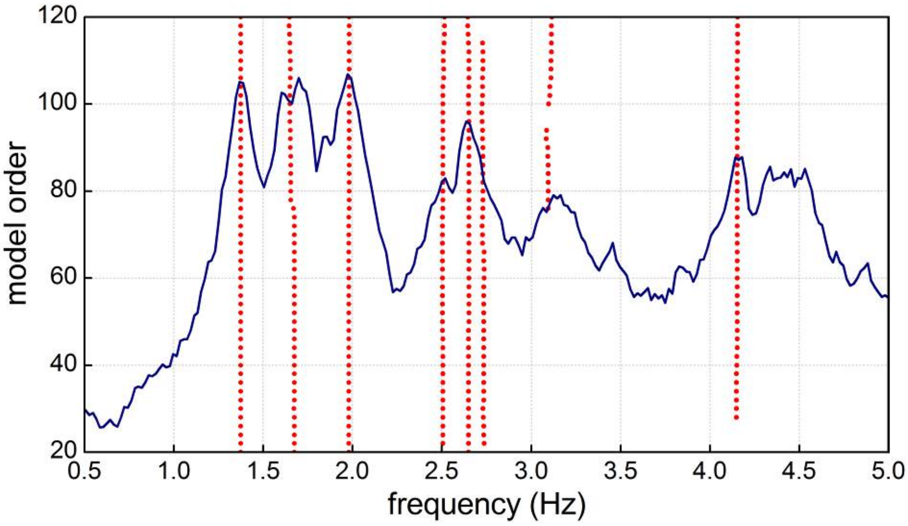

Fig. 8 Typical stabilization diagram obtained by applying the automated SSI-Cov tools to signals collected in the Milan Cathedral (27 channels of velocity data, 17/10/2018, h 12:00-13:00)

FIG. 8

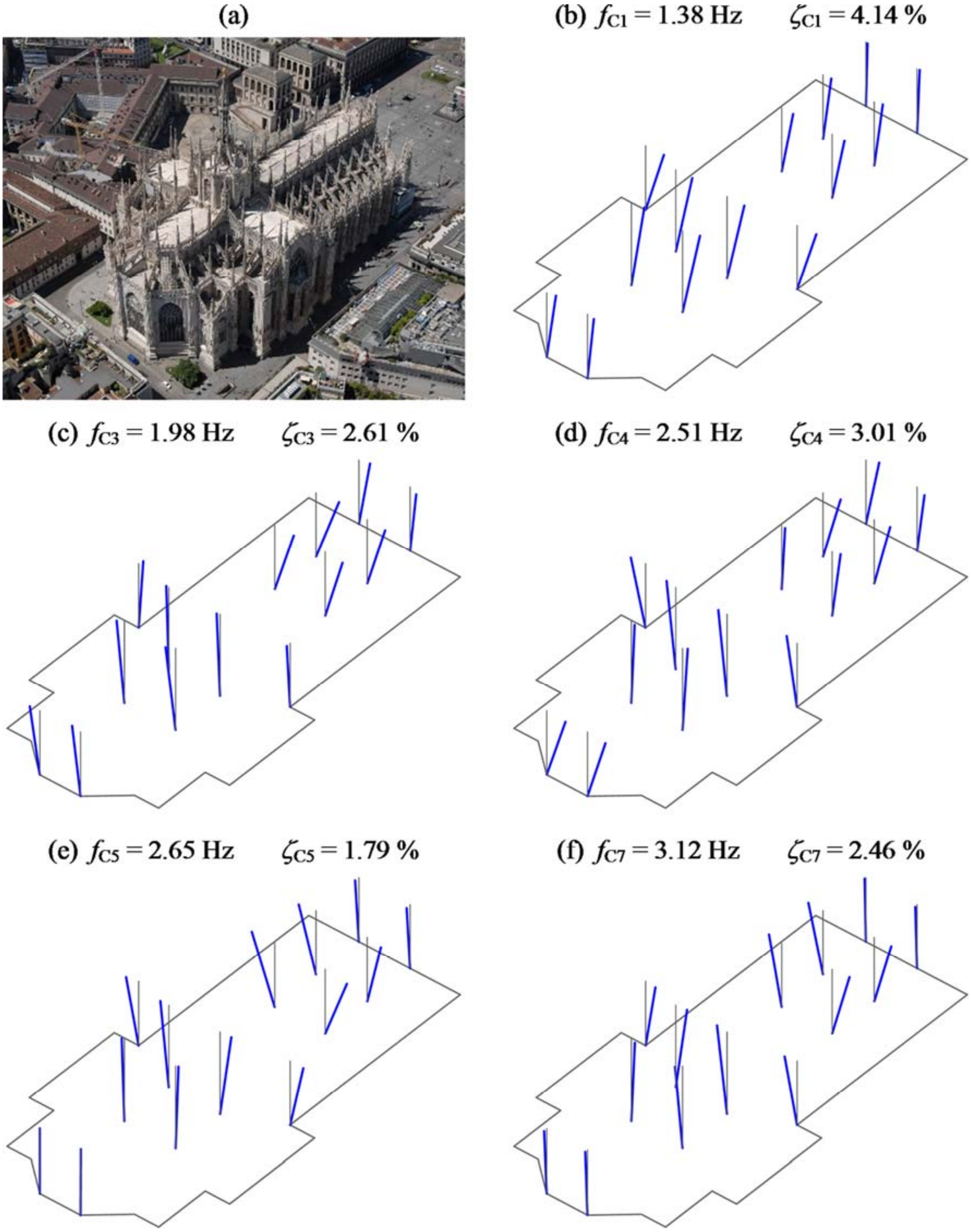

Fig. 9 Aerial view of the Milan Cathedral from apse (a) and identified transverse modes (b)-(f) [17/10/2019, h 12:00-13:00]

FIG. 9

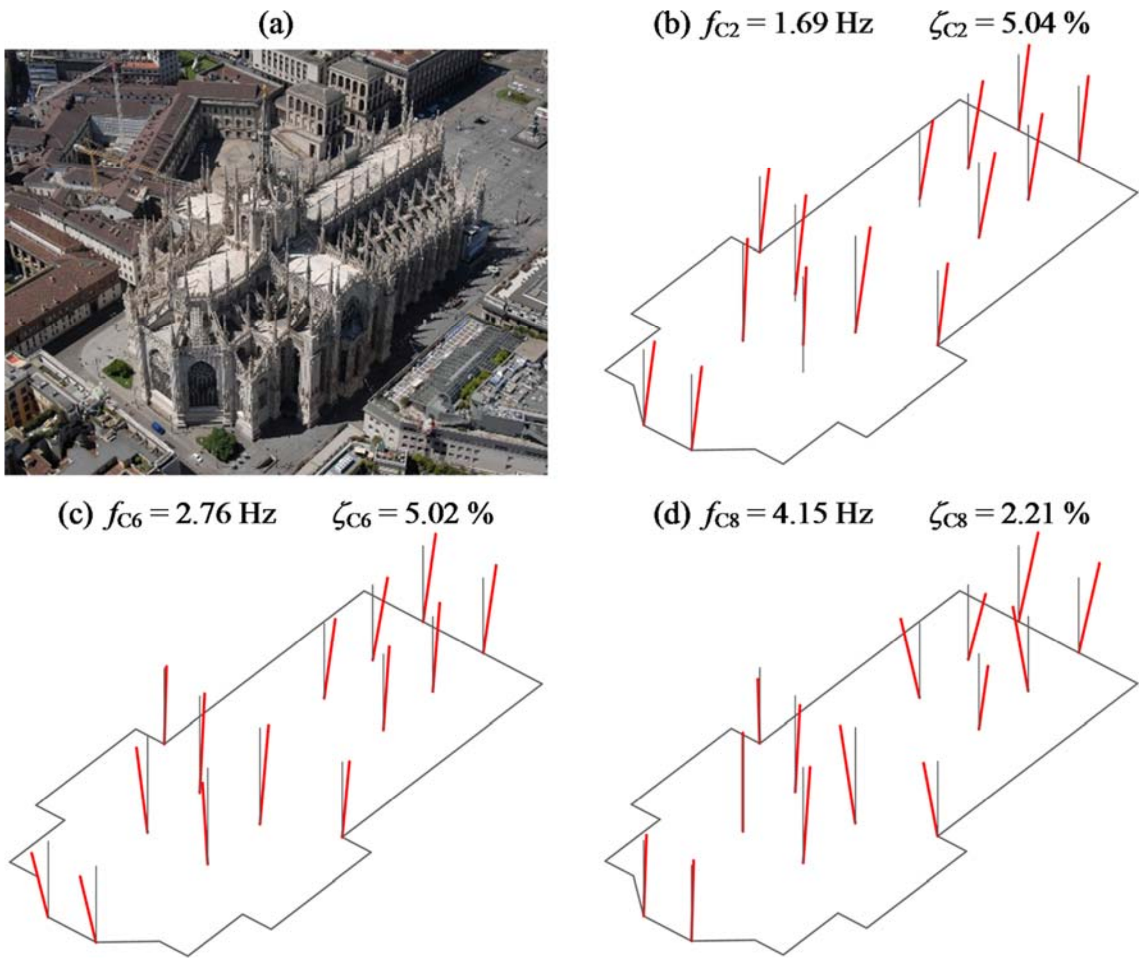

Fig. 10 Aerial view of the Milan Cathedral from apse (a) and identified longitudinal modes (b)-(d) [17/10/2019, h 12:00-13:00]

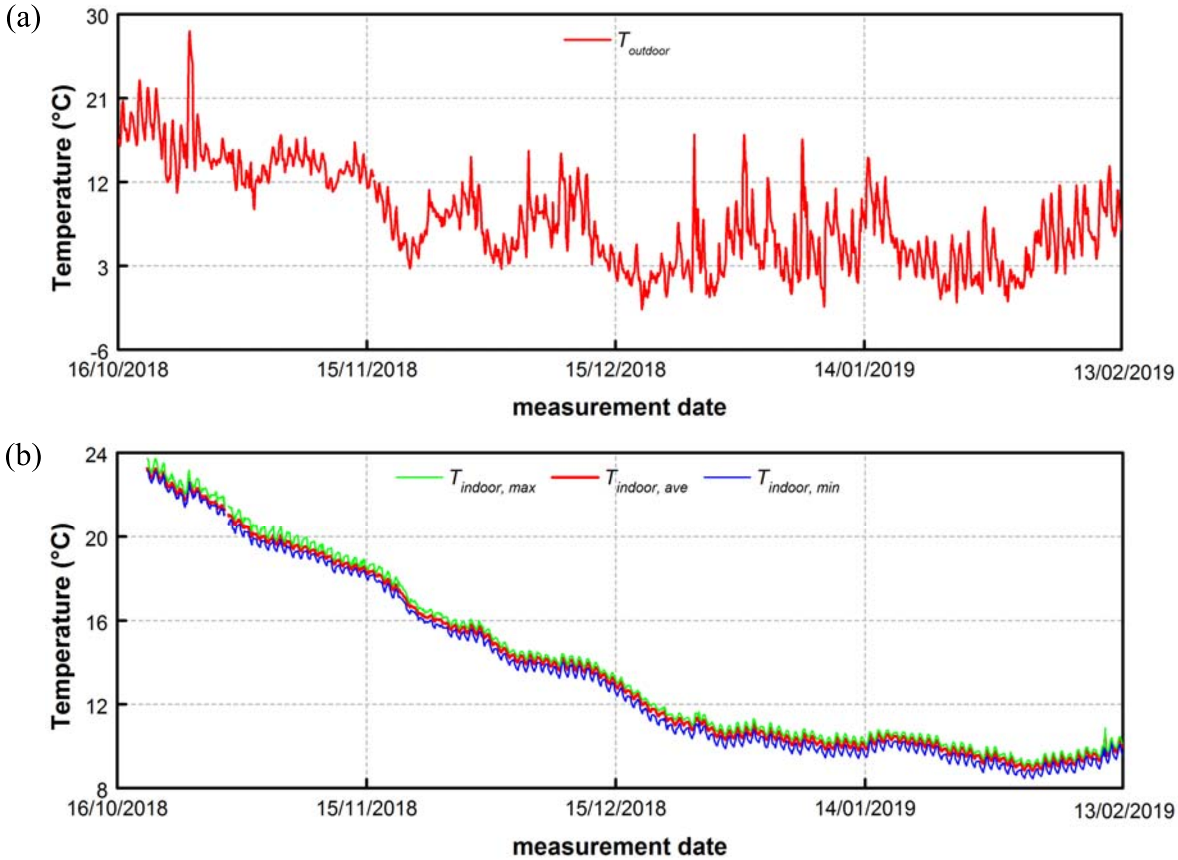

Fig. 11 Variation in time (from 16/10/2018 to 12/02/2019) of the measured temperature: (a) outdoor; (b) inside the Cathedral

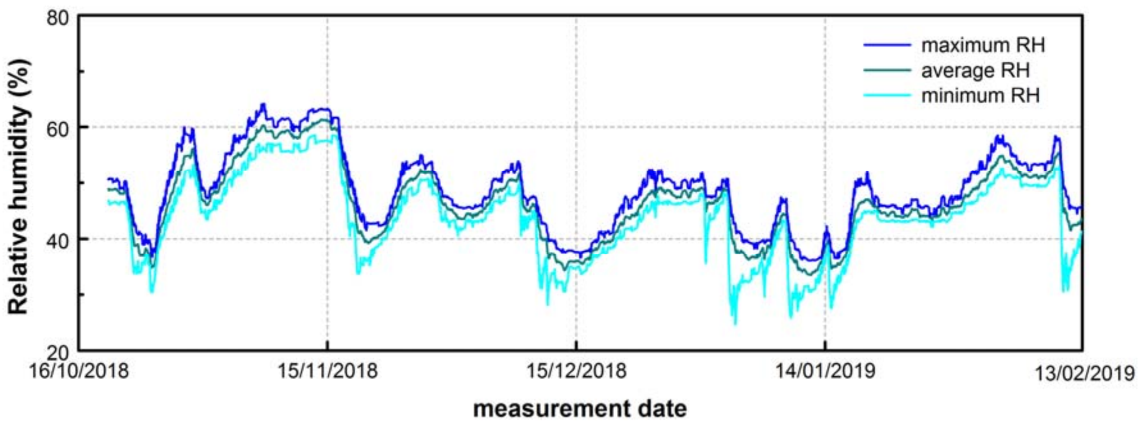

Fig. 12 Variation in time (from 16/10/2018 to 12/02/2019) of the relative humidity inside the Cathedral

FIG. 12

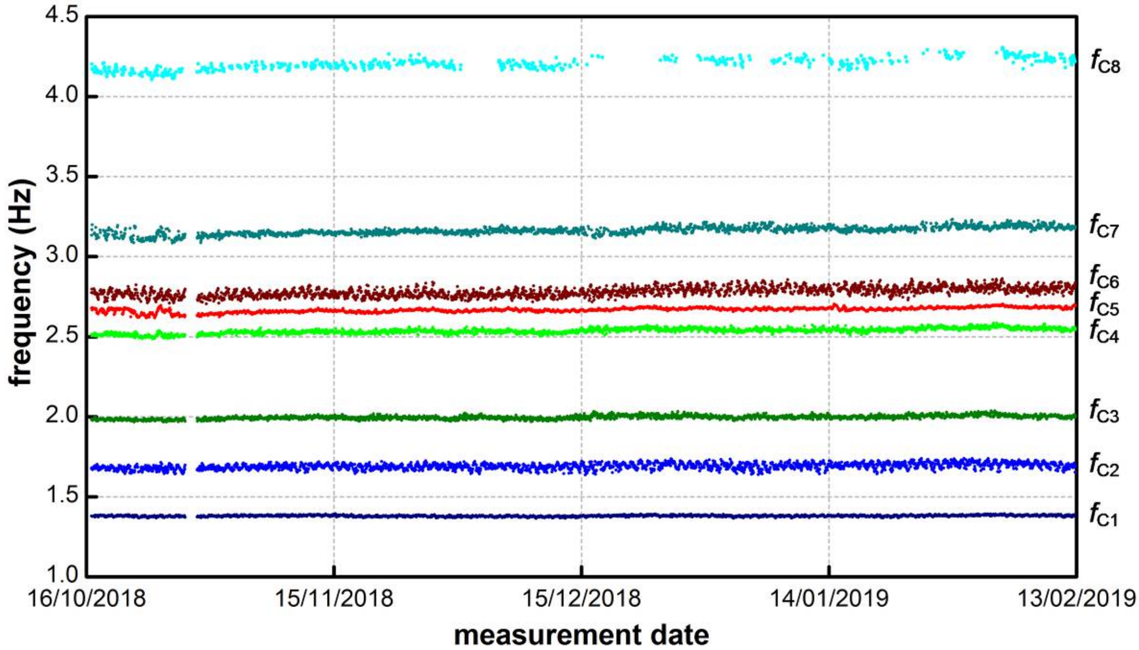

Fig. 13 Automatically identified natural frequencies of the Milan Cathedral versus time (from 16/10/2018 to 12/02/2019, with data missing on 28-29/10/2018)

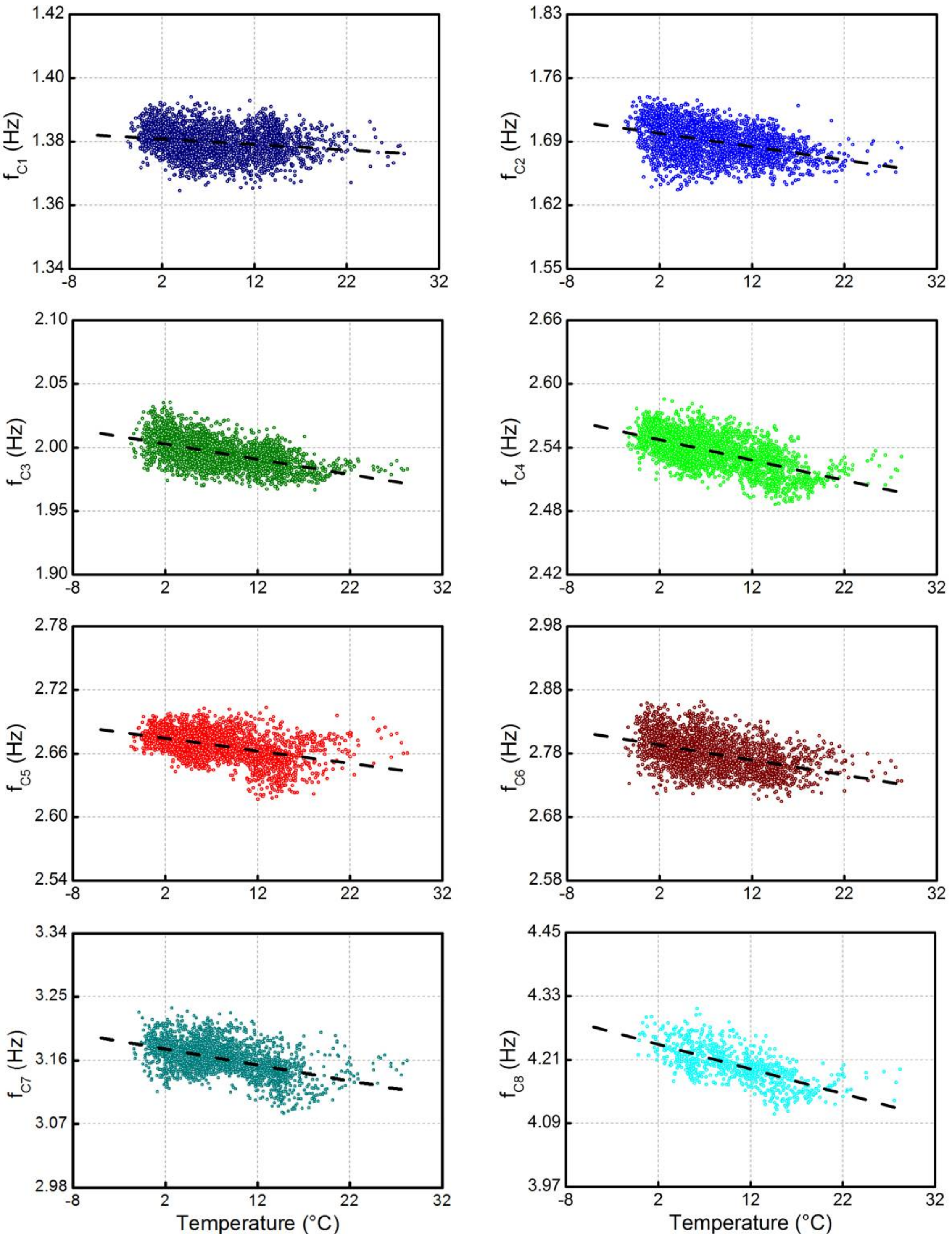

Fig. 14 Correlation between outdoor temperature and identified natural frequencies

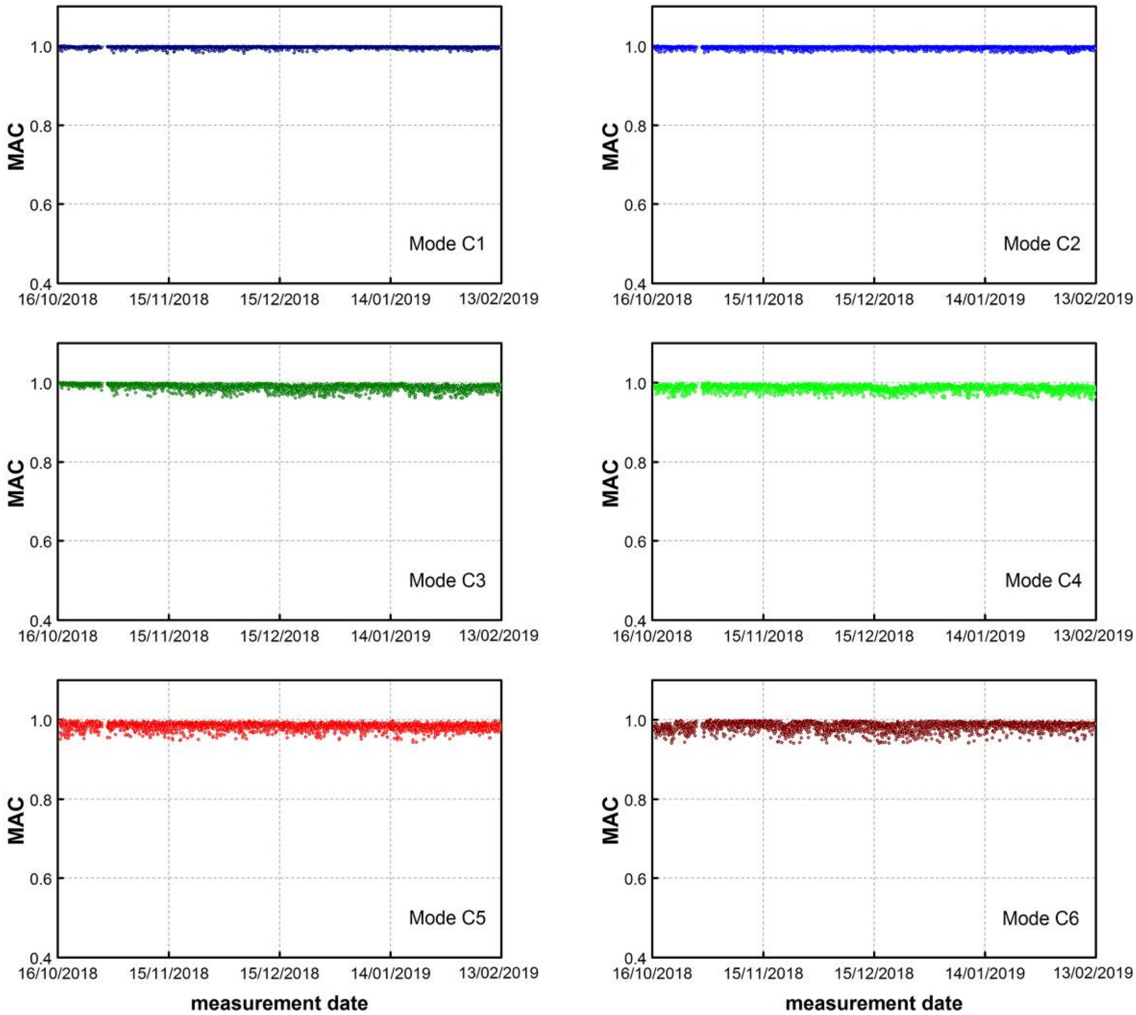

Fig. 15 Variation in time (from 16/10/2018 to 12/02/2019, with data missing on 28-29/10/2018) of the MAC of selected modes