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CONTINUOUS MONITORING THE CATHEDRAL OF MILAN: DOCUMENTARY AND PRELIMINARY INVESTIGATIONS

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Abstract. *Within the traditional collaboration between Veneranda Fabbrica del Duomo di Milano and Politecnico di Milano, significant efforts were recently devoted by the authors to the critical re-analysis of the past issues experienced by the Cathedral of Milan and to the evaluation of recent experimental evidences, with the objective of designing and implementing a new monitoring system, aimed at assisting the condition-based structural maintenance of the building. Appropriate strategies of Structural Health Monitoring have been developed for 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 conceptual design of the monitoring system is presented and discussed in the paper, as well as the documentary and preliminary investigations carried out to address the main choices. In summary, the new monitoring system of the Milan Cathedral includes different classes of measurements and sensors, such as: (a) quasi-static strain acquisition (through wireless vibrating wire extensometers) in the metallic tie-rods subjected to high tension loads; (b) quasi-static measurements of the biaxial tilt at the top of selected piers and along the height of the main spire (through innovative wireless tilt-meters, with high accuracy and compensation of the temperature effects); (c) quasi-static measurements of environmental parameters (through temperature and humidity sensors placed in the same points where the tilt-meters are installed); (d) dynamic measurement of the velocity at the top of selected piers and along the height of the main spire.*
The monitoring system is characterized by a distributed architecture, allowing easy modifications and/or adding of sensors; furthermore, all quasi-static sensors are wireless and powered through high capacity batteries.

1 INTRODUCTION

During the last decades, several sensing devices have been installed in the Cathedral of Milan to assist the Veneranda Fabbrica del Duomo (VFD) di Milano [1] (i.e., the Institution established in 1387 to manage all operational aspects related to the construction, maintenance and restoration of the Cathedral) during specific preservation/restoration activities. Generally, once each intervention was completed, the sensors were not dismissed even if data storage and analysis was often discontinued.

More recently, the idea to perform condition-based structural maintenance has been taking shape and a new monitoring system was designed with the objectives of providing the information needed for both the condition-based maintenance and the creation of a large archive of experimental data useful to improve the structural knowledge of the monument; in addition, systematic storage and data analysis using state-of-art tools has been planned.

After a brief description of the Cathedral of Milan, the conceptual design of the monitoring system is presented and discussed in the paper, along with selected preliminary investigations carried out to address the adopted main choices.

The complexity and the large dimension of the church suggested the implementation of a monitoring system, that is fully computer based and easily expandable but initially including a relatively limited number of sensors. The monitoring design was initially based on: (i) the prior knowledge of the Cathedral and its history (see e.g. [2-4]); (ii) the results emerged from the completion of a comprehensive dynamic investigations on the metallic tie-rods [5-7] and the preliminary observations on the dynamic characteristics of the Cathedral; (iii) the inventory of the sensors installed in the church and still regularly operating.

The critical analysis of several documents and the inspection of the available experimental information allowed to identify the sub-structures to be specifically considered in the new monitoring system: (a) selected piers of apse, *tiburio*, façade and transept; (b) the tie-rods subjected to high tensile stress (of the order of 100 MPa or higher) or affected by slight damage [5-7] and (c) the main spire [8-9].

The inventory of the sensing devices installed in the Cathedral revealed that, as expected, almost all the sensors were outdated or out of order: only the system based on geometric leveling, established to measure the horizontal deflection of the piers, turned out to be fully operating. Although this system is not computer based, it has been active in measuring the piers deformation at pre-selected intervals (May and November) since more than 50 years (see e.g. [10]) so that it is worth preserving the continuity of a such valuable historic time series, that will be added to the data archive collected by the new sensing devices.

The designed monitoring system, fully computer based and with efficient transmission of the collected data, measures 4 main types of physical quantities: (a) quasi-static measurements of inclination (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; (b) quasi-static strain measurements (using wireless vibrating wire extensometers) on selected tie-rods; (c) measurements of internal and external environmental parameters (temperature and humidity); (d) velocity measurements (using electro-dynamic sensors), again at the top of selected piers and at 3 levels of the main spire. Furthermore, the architecture of the monitoring system has been established to:

- minimize wiring. In particular, all "static" sensors are not wired and powered by batteries with an autonomy of 3-5 years (depending on the sampling rate, which can also be changed according to specific needs). Similarly, the electro-dynamic sensors (geophones) do not require power supply but wired connection to appropriate nodes/recorders is needed; in order to reduce the wiring, no more than 3-6 channels are connected to each recorder (equipped with A/D conversion system, 8 GB memory, synchronization by GPS, back-up battery and UMTS modem for data transmission);

- allow both changes in the position of the installed sensors and the installation of new sensors by simply introducing variations of a few parameters (i.e., the number of data channels to be acquired and some technical characteristics of each channel) in the software codes for data acquisition.

2 THE CATHEDRAL OF MILAN

The Milan Cathedral (Figs. 1-2), partly designed in Gothic style and erected between 1386 and 1813, is one of the largest masonry monuments ever built. The church exhibits the tallest main nave among Gothic Cathedrals, with the height of the vault intrados of the main nave being at about 45 m from the ground.

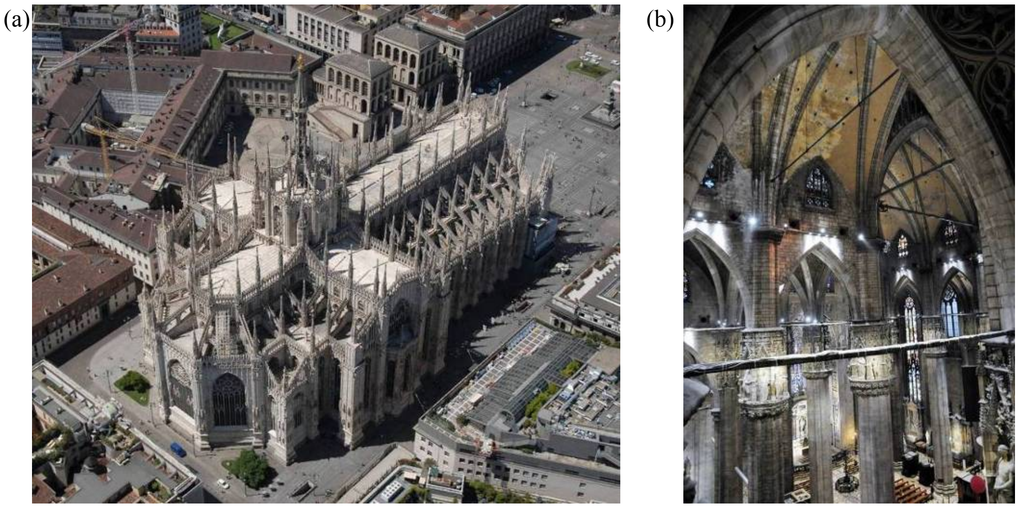

Figure 1: Milan Cathedral: (a) Aerial view; (b) Inside view of arches, vaults and iron tie-rods.

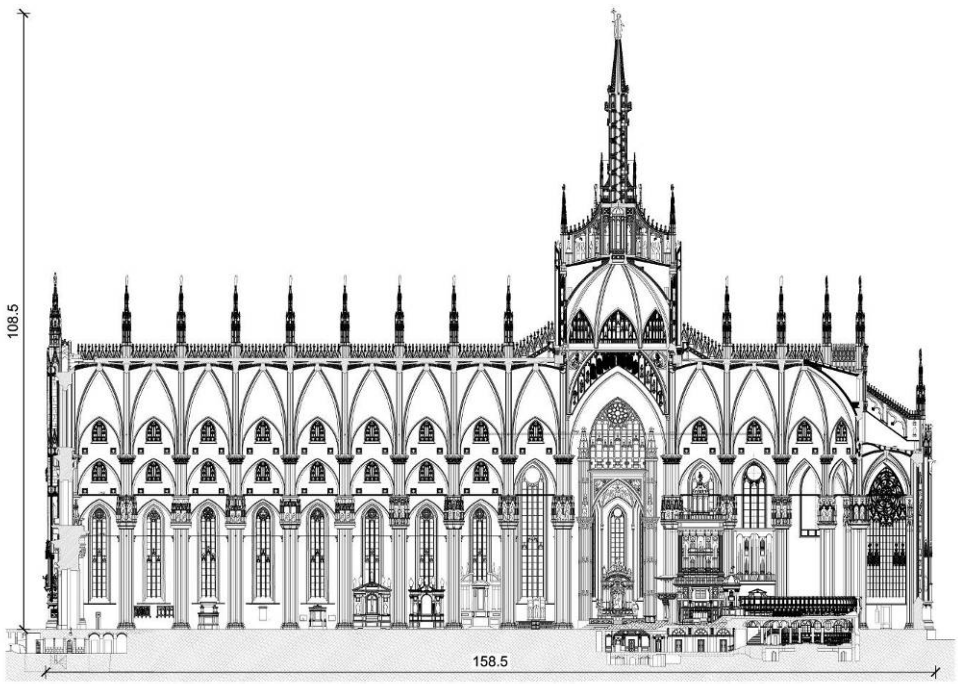

Figure 2: Longitudinal section of the Milan Cathedral (dimensions in m).

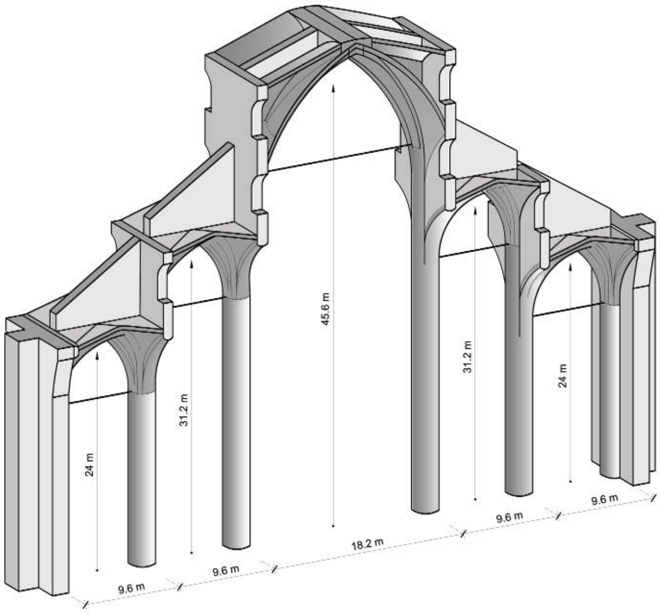

Figure 3: Milan Cathedral: schematic of the structural system exemplified on one bay of the church.

A longitudinal section of the Milan Cathedral is shown in Fig. 2. The church construction started from the half-octagonal apse and East choir, and proceeded with the transept, the main dome, the *tiburio* (i.e., the prismatic structure with octagonal base, which was built around the main dome) and the main spire; subsequently, the five-nave structure (Fig. 3) over eight bays was built and finalized with a neo-Gothic façade. An essential chronology of the construction phases, which took almost six centuries from the beginning of the works to the official ending, is hereby following: (a) 1386, beginning of the works on the area previously occupied by the two churches of *Santa Maria Maggiore* and *Santa Tecla*; (b) 1393, the apse and the polygonal deambulatory were completed; (c) 1480, the transept and the main limb of the Cathedral, up to the 6th bay from the altar, were finished; (d) 1577, the Archbishop Borromeo consecrated the unfinished church; (e) 1762, the main spire (Fig. 2) was erected up to 108.5 m; (f) 1813, the neo-Gothic façade was completed; (g) 6 January 1965, the inauguration of the last gate is generally assumed as the official ending of the monument building.

The Cathedral is cross-shaped in plan, where the longitudinal limb (East-West) is characterized by one main nave and two couples of side aisles, whereas the transept (North-South) has a main nave and two side aisles. The main altar is below the octagonal *tiburio*, which supports the main dome and the main spire, and is surrounded by a semicircular choir and the polygonal deambulatory. The overall dimensions of the Latin cross-shaped plan are about 66 m × 158 m (Fig. 4), with the aisles and the central naves (Fig. 3) spanning 9.6 m and 19.2 m, respectively.

When compared with other Gothic cathedrals, the Milan Cathedral exhibits a peculiar structural system (Fig. 3), with metallic tie-rods being permanently installed under each vault (Figs. 1b and 3) and designed to exert an active part in resisting the lateral thrusts. Historical documents [2], dating back to year 1400, testify that the tension bars in the Milan Cathedral were permanently installed on the top of the piers during the construction with the aim of reducing the horizontal thrust on the lateral buttresses, as those buttresses were judged too slender by the French Architect Jean Mignot. A total of 122 metallic tie-rods (Fig. 1b) is nowadays present in the Milan Cathedral and most of them are the original elements dating back to the age of construction. Only a few ties were replaced across the years: (1) the tie connecting the piers 73 and 39 − or tie 73-39 − was replaced in the ’60; (2) the 4 tie-rods under the *tiburio* were replaced during the restoration of the piers of the *tiburio* [3-4]; (3) the ties 58-88 and 61-91 were replaced in 2011 and 2013, respectively [6].

3 THE MONITORING SYSTEM

Based on knowledge of the monument and the results of the previous experimental tests (see e.g. [2-10]), tilting of piers and of the main spire, strain in a certain number of tie-rods and the dynamic characteristics (i.e., natural frequencies and associated modal deflections) of the church and main spire were identified as key parameters to monitor for assessing the structural health of the Cathedral and addressing its condition-based structural maintenance. Hence, the installation of two long-term monitoring systems is ongoing in the church, one static and the other dynamic.

It should be noticed that the monitoring sub-system installed in the main spire is conceptually similar to the one already used during the restoration of the main spire preceding EXPO 2015 [8-9]. Unfortunately, this sensing sub-system was significantly damaged by a lightning on Summer 2016 so that the replacement was preferred with sensors and devices exhibiting technical characteristics that are fully compatible with the new monitoring system.

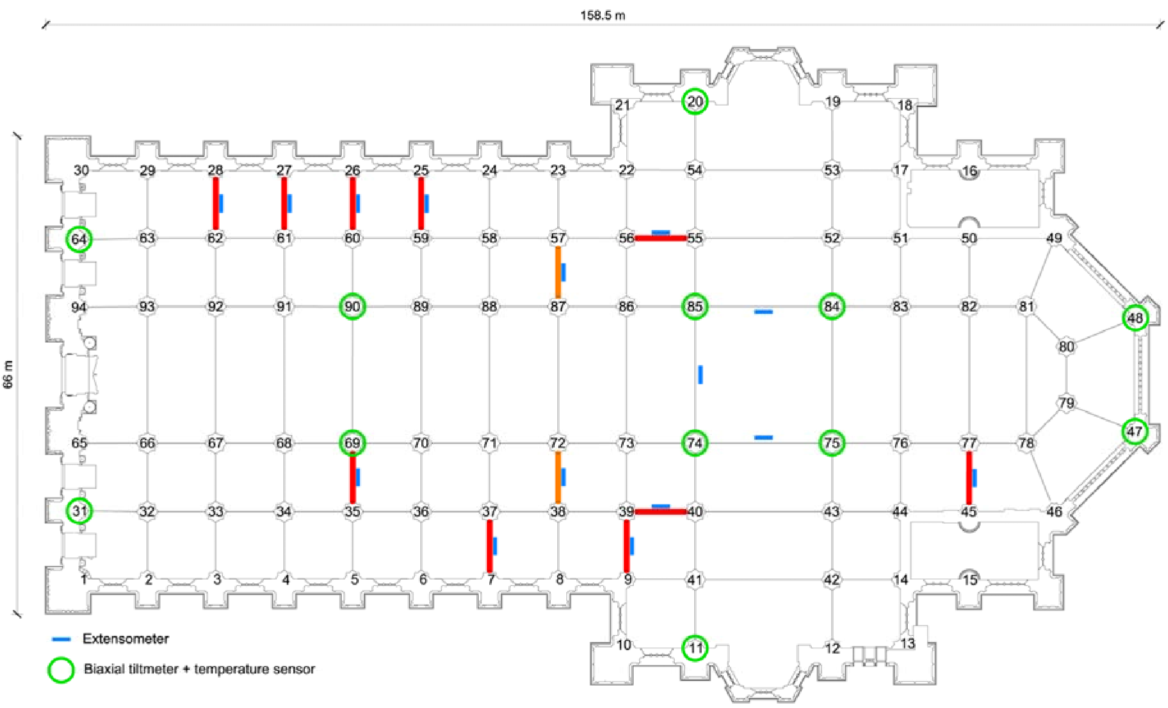

Figure 4: Distribution of the static monitoring sensors inside the Milan Cathedral (dimensions in m).

3.1 Static monitoring

The static monitoring system consists of the following sensors:

- 12 bi-axial tilt-meters, with a measurement range of ±0.5° and a resolution of ±0.5 mm/m, located inside the Cathedral (Fig. 4) on top of piers 31 and 64 (façade), 69 and 90, 11 and 20 (transept), 74-75 and 84-85 (*tiburio*) and 47-48 (apse);
- 3 bi-axial tilt-meters, installed at different levels of the main spire (+74.99 m, +84.03 m and +91.67 m, see Fig. 8b);

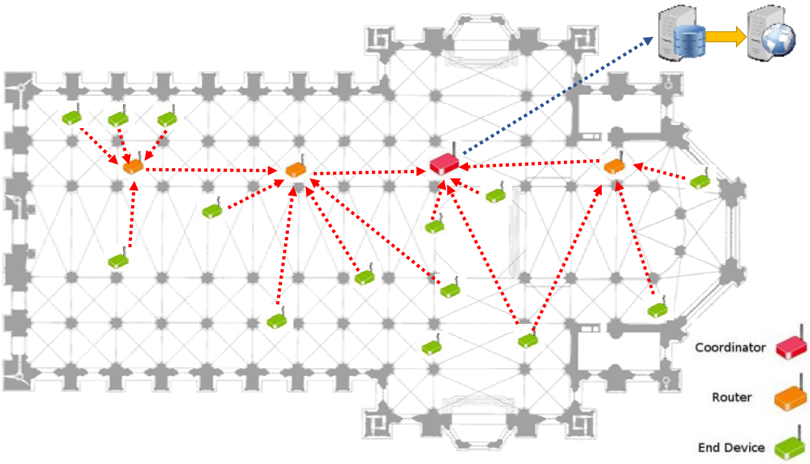

Figure 5: Schematic of the wireless data acquisition and transmission of the static monitoring system.

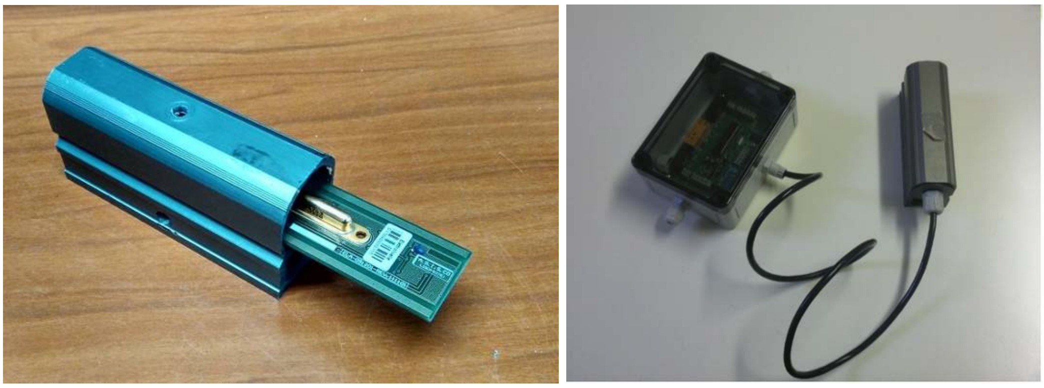

Figure 6: Tilt-meters [11] selected for the static monitoring of the Milan Cathedral.

- 15 sensors, integrated with each bi-axial tilt meter, to measure air temperature and relative humidity (RH). The temperature range is between –20°C and +60°C (with a resolution of 0.2°C), whereas the relative humidity range varies from 0% to 100% (with a resolution of 1%);
- 15 vibrating wire extensometers, with measurement range of ±3000 με and a resolution of 1 με, installed (Fig. 4) on 10 metallic tie-rods subjected [7] to tensile stress exceeding 100 MPa (highlighted in red in Fig. 4), on 3 tension bars (in modern steel) connecting the *tiburio* piers and on tie-rods 38-72 and 57-87 exhibiting slight damage [5-6].

As previously pointed out, all the sensors of the static system are wireless and powered through high capacity batteries; as all measurement records will be conceivably taken with a sampling rate of two per hour, the expected power charge should be longer than 3 years. A schematic of the data acquisition and transmission characterizing the static monitoring is shown in Fig. 5, with several static channels being managed by local nodes or end devices; the data collected by neighboring 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 VFD technical staff. 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. Basically the same system architecture and procedures are adopted for the dynamic monitoring, with the main differences that only the features (natural frequencies, mode shapes and a few time series corresponding to significant events) evaluated at pre-selected time intervals are scheduled to be stored in the VFD archives.

It is worth mentioning that immediately before the installation of the extensometers on the iron ties (scheduled on May 2018), the dynamic assessment previously carried out, according to the flow-chart of Fig. 7, to estimate the tensile load of each tie-rod will be repeated with the two-fold objective of verifying that no significant change occurred (for example, associated to thermal effects) and obtaining a sound estimate of the tensile stress exactly corresponding to the beginning of monitoring activity.

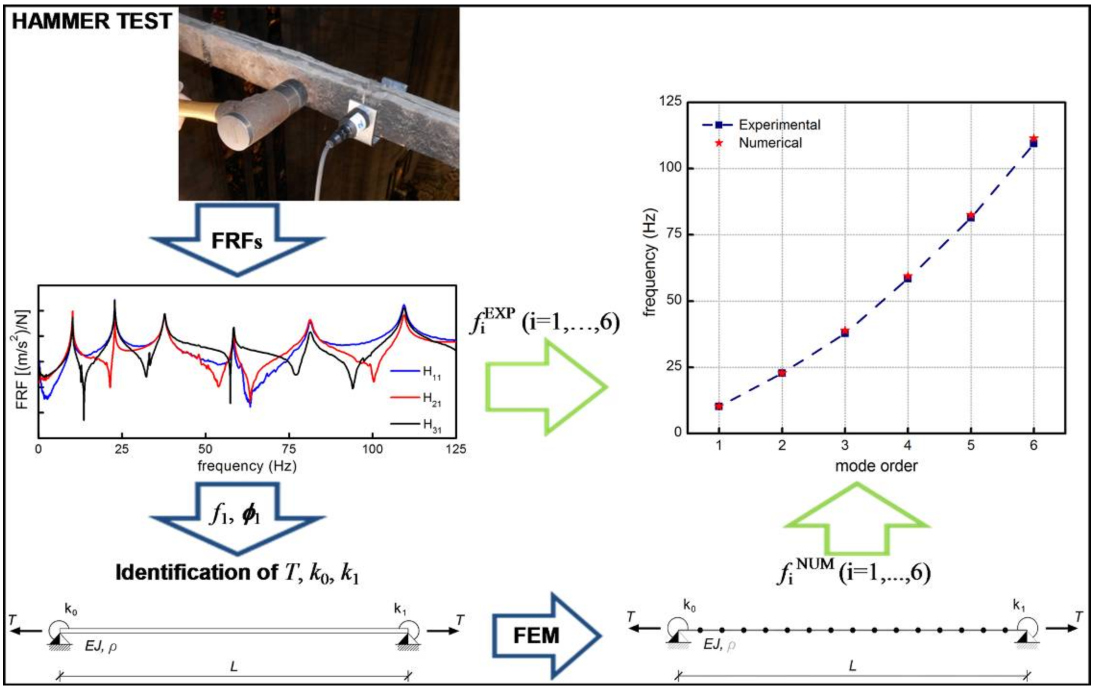

Figure 7: Flow chart of the methodology adopted to evaluate the axial force in the ties of the Milan Cathedral.

3.2 Dynamic monitoring

The dynamic monitoring system is entirely based on SARA SS45 seismometers (electro-dynamic velocity transducers) [12]. The seismometer choice is motivated by:

1. the high sensitivity (78 V/[m/s]) and the excellent performance of electro-dynamic transducers in the low frequency range ($f \leq 100$ Hz);
2. the possibility of obtaining a good estimate of the dynamic displacement time series by integrating the velocity records;
3. the un-necessity of powering the sensors;
4. the reduced cost, when compared to more common accelerometers of comparable technical characteristics.

It should be mentioned that high sensitivity and good performance in the low frequency range makes the electro-dynamic transducers very attractive for the application in vibration testing or monitoring of civil engineering and cultural heritage [13-15] structures. In addition, it is well known from Earthquake Engineering and Seismology that retrieving the displacement time series from acceleration records is not an easy task: on the contrary, measuring the velocity time series through seismometers allows also to obtain an accurate estimate of the dynamic displacement by relatively simple integration. Needless to note that the displacement time series – especially of the slender main spire – will provide the VFD with data generally not available and directly related to the stiffness and structural health.

The dynamic monitoring system (Fig. 8) consists of:

- 14 bi-axial seismometers, installed at the top of selected piers inside the Cathedral (Fig. 8a) 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 four 24-bit digitizers SARA SL06 [12] (6 channels, Sigma-Delta A/D converter, 8 Gb Ram on board for data storage), each equipped with one UMTS modem for data transfer;
- 3 tri-axial seismometers, installed at the same levels of the main spire (+74.99 m, +84.03 m and +91.67 m, see Fig. 8b) hosting the bi-axial tilt-meters belonging to the static monitoring are placed.

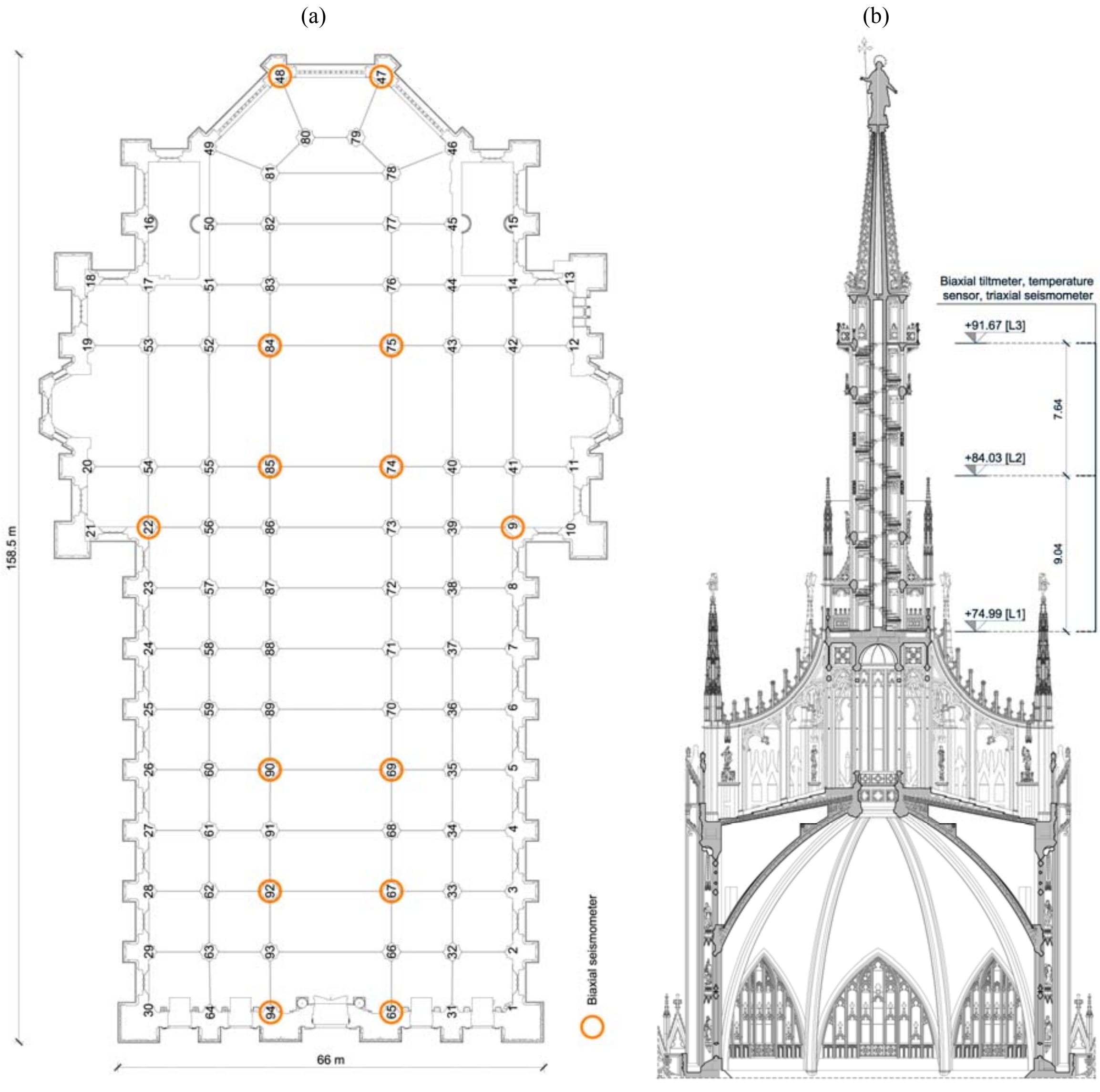

Figure 8: Distribution of the seismometers (a) inside the Milan Cathedral and (b) along the main spire (dimensions in m).

Figure 9: View of the seismometers and recorders to be installed in the Milan Cathedral [12, 13-14].

Pictures of seismometers and recorders selected for the dynamic monitoring system are shown in Fig. 9. It is worth underlining that successful application of the devices is testified by the long-term monitoring of a masonry bell-tower in Lucca, Italy [13] and the *San Gottardo in Corte* bell-tower, neighboring the Milan Cathedral [15], as well by the short-term dynamic tests carried out in the *Zuccaro's Tower* [14] in Mantua, Italy.

Preliminary dynamic tests were performed in the Milan Cathedral, by installing conventional accelerometers: (i) on the top 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 the top of piers 9 and 39 (4 channels of data, with 2+2 sensors oriented along N-S and S-W directions, respectively). As shown in Figs. 10a and 10b, the results of these tests indicate that 3 global modes of the Cathedral are clearly identified (by using the well-known Frequency Domain Decomposition, or FDD, technique [16]). The lower vibration modes involve global motion of the Cathedral in the direction N-S (1.38 Hz) and E-W (1.71 Hz), whereas the third natural (2.67 Hz) is conceivably associate to a torsion mode. In addition, higher (global or local) modes have been detected in the frequency range 0-10 Hz.

The analysis of the signals acquired – in the same hours but not synchronized – on piers 9, 39 and on the main spire has allowed to establish – as it has to be expected – a strong correlation between the dynamic characteristics observed on the Cathedral piers (Figs. 10a and 10b) and on the main spire (Fig. 10c): (a) the first mode observed on the main spire involve deflections in the N-S direction and corresponds (natural frequency and direction) to the first global mode observed inside the church; (b) the second mode observed on the main spire involve deflections in the E-W direction and, again corresponds (natural frequency and direction) to the second global mode of the Cathedral.

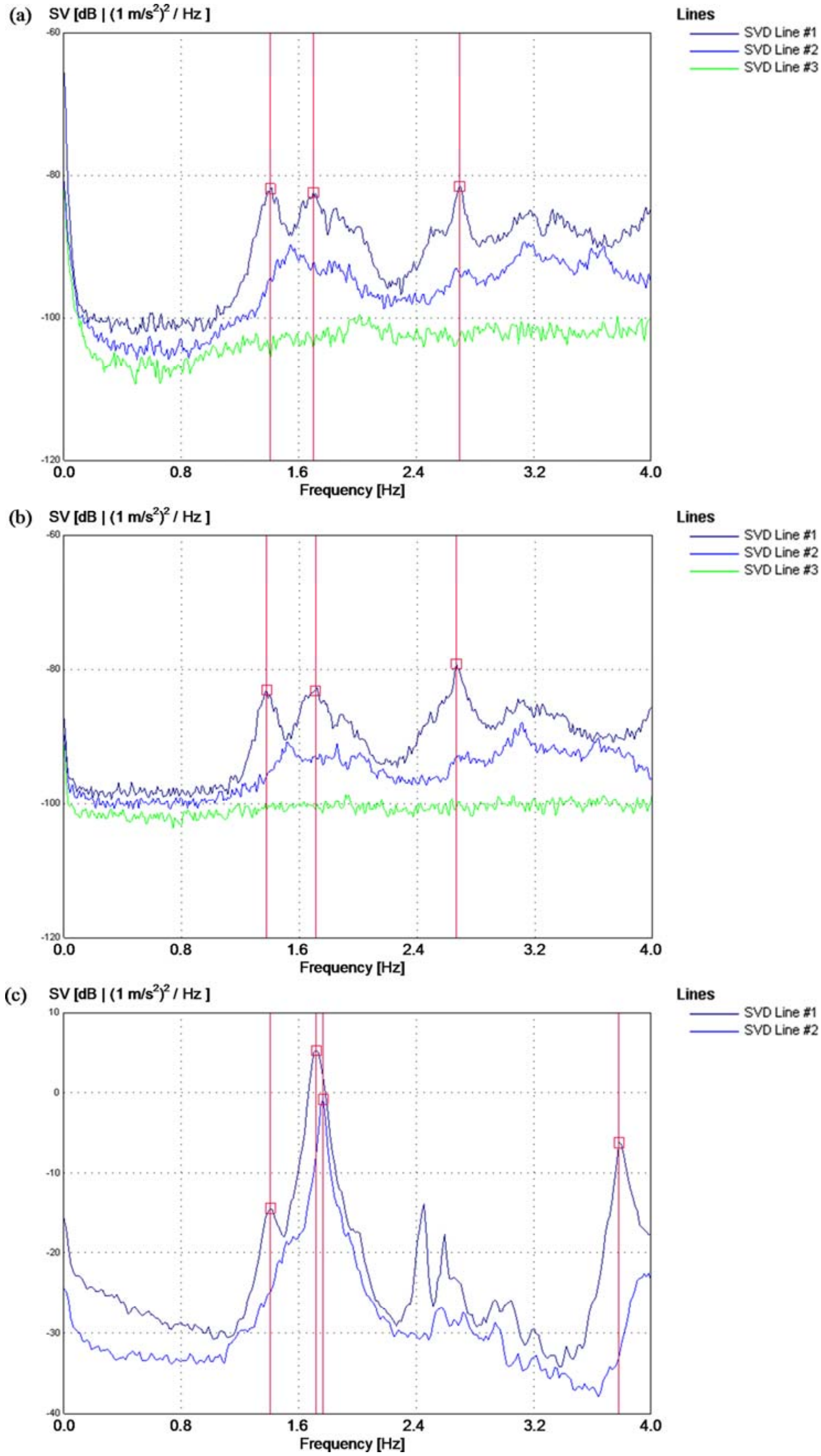

Figure 10: Singular value (SV) lines and identification of natural frequencies (FDD): (a) Piers 22, 54 and 55; (b) Piers 09 and 39; (c) Main spire.

Furthermore, the first local mode of the main spire is characterized by bending in the N-S plane and its natural frequency (1.76 Hz) is very close to the one of the Cathedral's second mode (1.71 Hz, E-W direction). It is marginally noticed that in previous studies [9], referring to data collected during the restoration work of the main spire, the first frequency (N-S direction and corresponding to a global mode of the monument) was not identified (conceivably as a consequence of the presence of the provisional scaffoldings) and a different structural interpretation was given to the observed closely spaced modes.

It is worth mentioning that clear velocity peaks were measured on the piers and associated to metro transits. These relative maxima, even if as frequent as the metro passages, were always much lower than 1.0 mm/s, that is the admissible threshold generally considered for historical constructions. Hence, the management of the dynamic monitoring will be also finalized to estimate the peak particle velocity associated to selected piers (Fig. 8a).

Based on the preliminary dynamic tests, the dynamic monitoring is aimed at: (i) performing the automated modal identification (i.e. the estimation of natural frequencies and mode shapes of local and global vibration modes); (b) tracking the time evolution of the identified modal frequencies and shapes; (c) providing the statistics of the peak velocity at selected points; (d) collecting the displacement time series associated to special events (i.e., maintenance operations, strong winds, far-field seismic events, etc.).

Automated modal identification will be performed using time windows of 1800s (corresponding to about 2500 times the fundamental period of the Cathedral, Fig. 10), in order to comply with the widely agreed recommendation of using an appropriate duration of the acquired time window to obtain accurate estimates from output-only data [17]. The scheduled sampling frequency will be 100 Hz, even if this frequency is higher than that required for the investigated structure. Hence, low pass filtering and decimation will be applied to the data before the use of the modal identification tools. In more details, after low-pass filtering the data through a 7th order Butterworth filter with cut-off frequency of 12.5 Hz, the velocity time series will be down-sampled from 100 Hz to 25 Hz.

4 CONCLUSIONS

- The new monitoring system of the Milan Cathedral, recently designed and currently under installation, has been described in the paper;
- The monitoring system is the largest ever installed in a historic Cathedral. The system includes different classes of measurements and sensors, and is characterized by a distributed architecture and the adoption of tilt-meters with compensation of the temperature effects (static monitoring) and electro-dynamic velocity transducers (dynamic monitoring), allowing accurate estimate of the displacement time series from continuously collected (velocity) data;
- The baseline dynamic characteristics of the Cathedral and main spire have been evaluated through preliminary tests in operational conditions.

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