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Static and dynamic monitoring of a Cultural Heritage bell-tower in Monza, Italy

Antonella Saisi[a], Carmelo Gentile[a]*, Antonello Ruccolo[a]

[a]*Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milan, Italy*

Abstract

A recent survey carried on the historic complex of *Santa Maria del Carrobiolo* in Monza (Italy) highlighted that the two sides of the bell-tower are directly supported by the load-bearing walls of the apse and South aisle of the neighboring church. After the discovery of the weak structural arrangement of the building, static and dynamic monitoring systems were installed in the tower to address its preservation. After a brief description of the tower and the results of the preliminary survey, the paper presents selected results of the continuous dynamic monitoring as well as the evidences provided by the static monitoring.

Keywords: Automated OMA; Environmental effects; Masonry tower; Modal frequencies; Static / Dynamic Monitoring.

1. Introduction

The historic religious complex of *Santa Maria del Carrobiolo* in Monza (Italy) [1] owns to the Barnabite order since 1574 and includes a monastery, a church, a bell-tower and other minor buildings. Based on historical documents, the construction of the church and monastery dates back to the 13th century, whereas the bell-tower (Fig. 1a), about 33.7 m high, was completed in 1339. A recent program of cataloguing the main religious buildings in Monza included a pre-diagnostic survey of the historic complex [2]: direct survey of the masonry discontinuities confirmed that the bell-tower was built after the church and revealed that two sides of the tower are directly supported by the load-bearing walls of the church apse and the last part of right aisle (Figs. 2b and 2c); moreover, the

* Corresponding author. Tel.: +39-02-23994242; fax: +39-02-23994220.
E-mail address: carmelo.gentile@polimi.it

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two load-bearing walls of the tower, which are continuous from base to roof, are just leant against (i.e. not toothed or linked to) the existing walls of the church (Fig. 2d). The construction sequence adopted for the tower, not identified before, raised obvious concern about the performance of the structure under wind and seismic actions. In addition, the recent construction of an under-ground car park adjacent to the bell-tower conceivably activated movement of the pre-existing cracks and of the structural discontinuities related to construction phases.

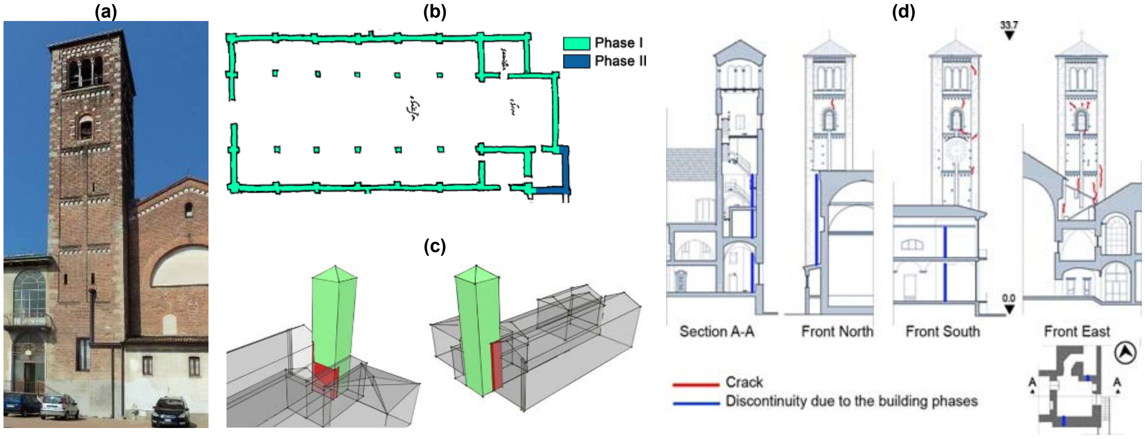

Fig. 1. (a) View of the *Santa Maria del Carrobiolo* bell-tower (Monza, Italy); (b) Building phases in a plan dating back to 1572; (c) Schematic representation of the interaction between the bell-tower and the church apse; (d) Section and fronts of the bell-tower.

In order to check the opening variations of the main cracks, a network of 10 displacement transducers, integrated by 5 temperature sensors, was installed in the building [2]. Subsequently, ambient vibration tests of the tower were performed and the dynamic characteristics of the tower turned out to be quite different from those obtained in past experimental studies of similar structures (see e.g. [3-5]), with the differences being conceivably related to the weak structural arrangement of the building. Hence, a simple dynamic monitoring system, consisting of 4 accelerometers, was installed in the tower to complete the health monitoring aimed at the preservation of the historic structure [2].

The paper, after a brief summary of selected evidences provided by the static monitoring and the dynamic characteristics identified in the preliminary ambient vibration tests, presents the main results of one-year dynamic monitoring.

2. Static monitoring of the main cracks

The recent re-opening of the repaired cracks suggested the installation of a static monitoring system in the tower. Hence, a network of 10 displacement transducers, integrated by 5 temperature sensors, was installed in the building to monitor the opening variations of the main cracks. Fig. 2a shows the general layout of the static monitoring system, installed on June 2014 and still active. The displacement transducers are linear sensors (potentiometers) with a maximum stroke of 25 mm and a maximum error on the linearity of 0.2%.

It is worth mentioning that: (a) each couple of displacement transducers, along with one temperature sensor, is connected to a wireless data logger for the automatic data acquisition, storage and transmission by GSM-GPRS modem; (b) the automatic acquisition has been set to record the displacements and the temperatures every 10'; (c) the displacement transducers denoted as 1-2, 3-4 and 5-8 in Fig. 2a are placed inside the tower in order to check the opening of the main cracks at Level 0, Level 1 and Level 2, respectively; (d) the last couple of sensors (9-10 in Fig. 2a) is installed on the outer wall of the church, in the close vicinity of the tower. Hence, the 5 thermocouples belonging to the static monitoring system allow to measure both the indoor temperature at different levels of the tower and the outdoor temperature on the South side of the structure (Fig. 2a).

It is further noticed that (Fig. 2b) that a metallic tie-rod is placed above a main crack of the West side, which is surveyed by transducer TL2_SOCH2.

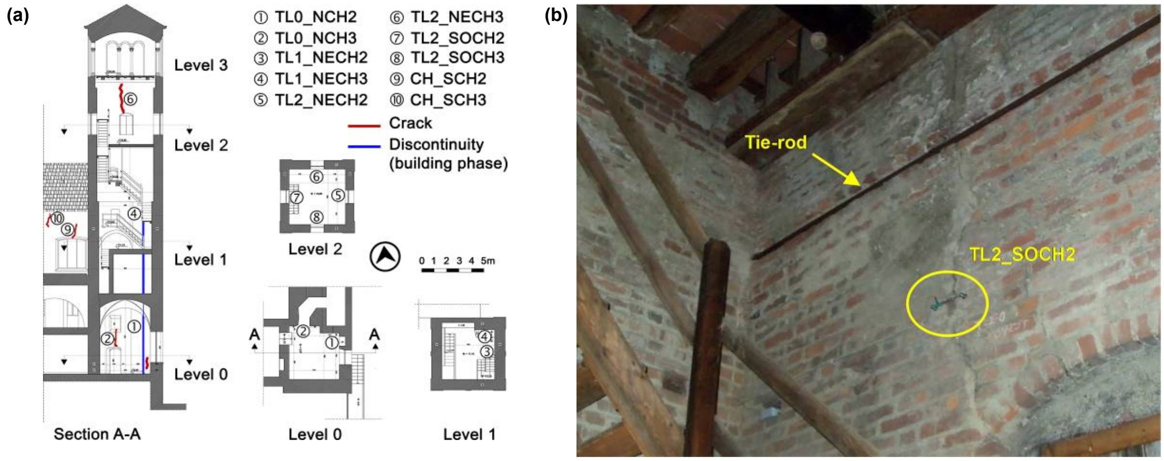

Fig. 2. (a) General layout of the static monitoring system; (b) Metallic tie-rod installed above the transducer (crack) TL2_SOCH2.

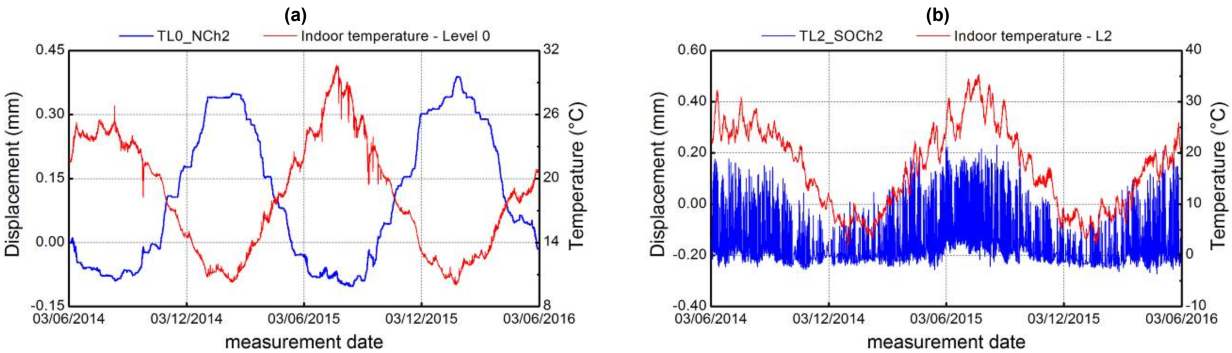

Fig. 3. (a) Indoor temperature (Level 0) and displacement TL0_NCH2; (b) Indoor temperature (Level 2) and displacement TL2_SOCH2.

The most significant opening affects the cracks at ground level (Fig. 3a) but the thermal effects turned out to be largely dominant, so that possible settlements at the foundation level could have been conceivably very small. As shown in Fig. 3a, the evolution in time of measured temperature and displacement exhibits a regular trend, with periodic repetition of the displacements measured in similar temperature conditions and inverse correlation between temperature and displacement.

As it has to be expected, all the main cracks tend to close with increased temperature, with the exception of the one denoted as TL2_SOCH2: Fig. 3b shows that the crack opening exhibits significant daily variation, with the displacement envelope closely following the evolution of indoor temperature. This unexpected trend is conceivably associated to the structural effect exerted by the metallic tie-rod (Fig. 2b) installed above the crack and connecting the North and South load-bearing walls: as the temperature increases, the loss of tension in the tie-rod induces the opening of the cracks.

3. Ambient vibration tests and continuous dynamic monitoring

Two series of ambient vibration tests (AVTs) were carried out on September-October 2015 with the main objective of evaluating the baseline dynamic characteristics before the installation of a continuous dynamic monitoring system in the building [3-5].

The first AVT was performed on 23/09/2015 and high sensitivity (10 V/g) accelerometers measured the response of the tower to ambient excitation at a sampling frequency of 200 Hz; the accelerometers were installed at Levels 1, 2 and 3 of Fig. 2a, according to the layout schematically illustrated in Fig. 4.

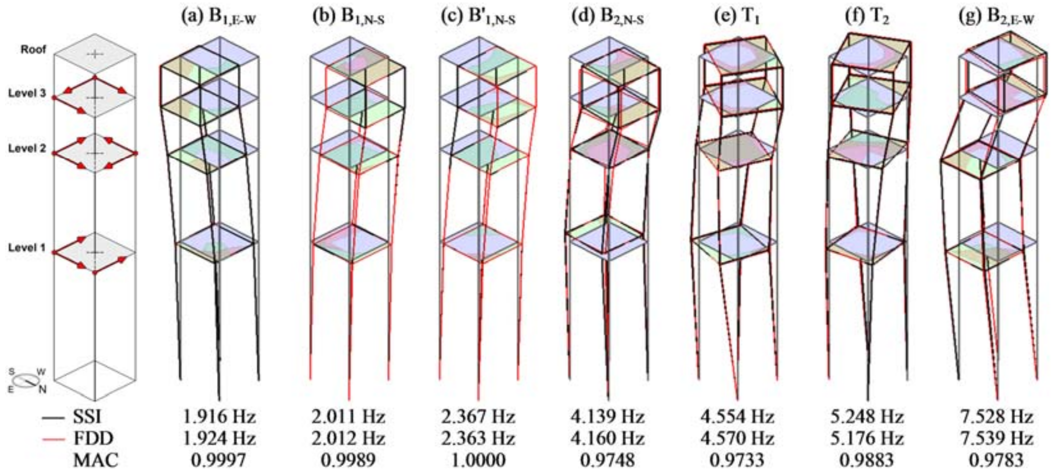

Fig. 4. Schematic of accelerometers layout and vibration modes identified from ambient vibration data (23/09/2015).

The modal identification was performed using time windows of 3600 s and applying both the Frequency Domain Decomposition (FDD) [6] and the covariance driven Stochastic Subspace Identification (SSI-Cov) [7] methods.

The identified mode shapes are presented in Fig. 4 and reveal very peculiar dynamic characteristics of the tower, that are conceivably related to its structural layout (i.e., the construction phases). In more details, the sequence of identified mode shapes is very different from the expected [3-5] regular succession of two bending modes – one for each principal plane of the structure – and one torsion mode. On the contrary, the sequence of mode shapes of the investigated tower (Fig. 4) involves: (a) one bending mode in the E-W direction (Fig. 4a); (b) two bending modes in the N-S direction (Figs. 4b and 4c), that are characterized by closely spaced frequencies and very similar mode shapes; (c) another mode of dominant bending, again in the N-S plane (Fig. 4d); (d) two torsion modes (Figs. 4e and 4f) with very similar mode shapes; (e) a second bending mode (Fig. 4g) in the E-W direction.

Between 2/10/2015 and 9/10/2015, a second series of AVTs was performed by installing 4 accelerometers at the Level 2 and continuously collecting the dynamic response of the tower for about one week at a sampling rate of 200 Hz [2]. It should be noticed that the instrumented level − although not optimal for the identification of all modes since the deflections of the fourth mode (Fig. 4d) are negligible at this level − is the higher one suitable to the installation of a continuous dynamic monitoring system. Since the second series of AVTs allowed to identify with high occurrence 5 vibration modes of the tower and also considering the possibility of increasing the knowledge of the historic building through the combined use of static and dynamic monitoring, it was decided to permanently instrument the tower with the same sensor layout (4 accelerometers at Level 2) adopted in the second series of dynamic tests.

The continuous dynamic monitoring system is now active since 22/10/2015. The devices installed inside the tower consisted of 4 accelerometers, one Ethernet carrier with NI 9234 data acquisition module (24-bit resolution, 102 dB dynamic range and anti-aliasing filters) and one local PC for the management of the continuous acquisition and the data storage. Data are recorded at 200 Hz and stored on the local PC in separate files of 60 minutes. The collected acceleration data are processed through a series of tools developed in the LabVIEW environment [8] and comprising the following tasks: (a) signal pre-processing with de-trending and de-spiking of the raw data; (b) automatic detection and extraction of the time series associated to swinging of bells and numerical integration to estimate velocity time histories; (c) statistical analysis of the data previously preprocessed and/or extracted; (d) low-pass filtering and decimation of the each "bell-free" dataset and creation of a database of files (in binary or text format) appropriate for the application of modal identification tools.

Each set of "bell-free" time histories (low-pass filtered using 7th order Butterworth filter with cut-off frequency of 12.5 Hz and decimated to reduce the sampling frequency from 200 Hz to 25 Hz) were reduced to a uniform time window of 3000 s before applying a fully automated SSI-Cov modal identification procedure [9-10].

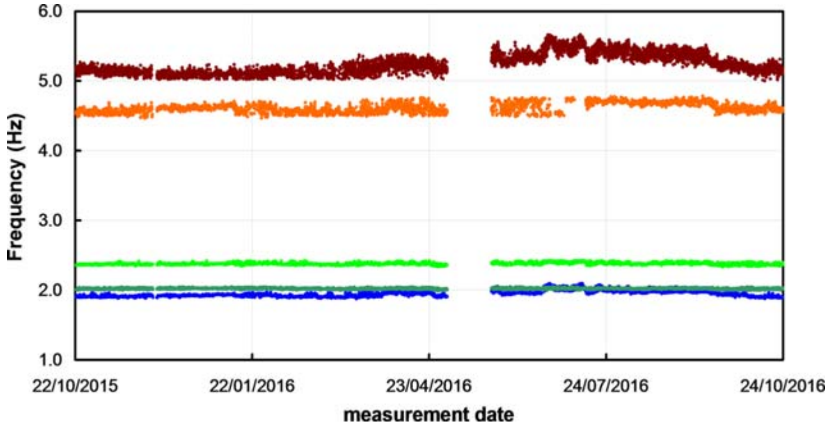

Fig. 5. Variation of automatically identified natural frequencies in one-year continuous monitoring (from 22/10/2015 to 23/10/2016).

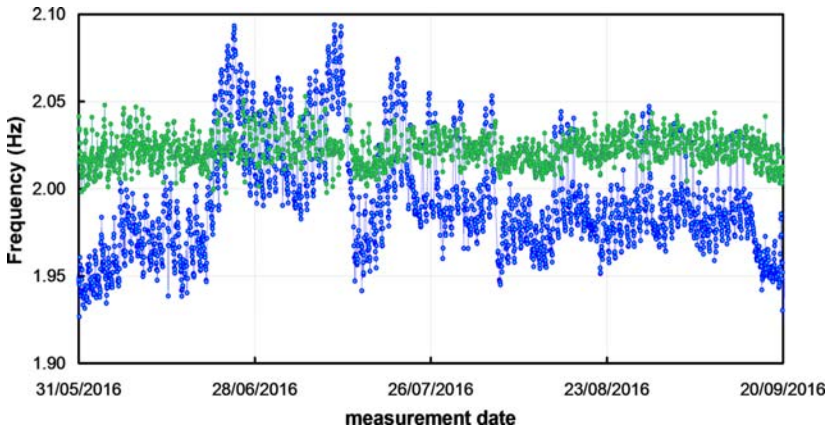

Fig. 6. Crossing between the natural frequencies of the lower modes in Summer months.

Table 1. Statistics of the automatically identified (SSI-Cov) natural frequencies in one-year continuous monitoring.

Mode Id.	f_{ave} (Hz)	σ_f (Hz)	f_{min} (Hz)	f_{max} (Hz)
$B_{1,E\text{-}W}$	1.946	0.041	1.876	2.094
$B_{1,N\text{-}S}$	2.020	0.009	1.990	2.053
$B'_{1,N\text{-}S}$	2.379	0.015	2.333	2.423
T_1	4.598	0.065	4.467	4.782
T_2	5.265	0.141	5.001	5.663

Fig. 5 presents the evolution of the natural frequencies identified in the first year on continuous dynamic (i.e., between 22/10/2015 and 23/10/2016), whereas the relevant statistics are summarized in Table 1 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. 5 and Table 1, along with the correlation between modal frequencies and the measured temperatures, allow the following comments:

- Notwithstanding the low level of the ambient excitation, 5 normal modes were identified with high occurrence;

- The identification rate is higher for the lower 3 modes (ranging from 86.0% for mode $B_{1,N\text{-}S}$ to 99.3% for mode $B'_{1,N\text{-}S}$). The identification rate is 77.6% for torsion mode T_2 and decreases to 63.5% for mode T_1;
- The identification of mode T_1 is characterized by the lower rate of success and, probably, the higher uncertainty (Fig. 5);
- The variation of the natural frequency of modes $B_{1,E\text{-}W}$ and T_2 is strongly dominated by the temperature and, as it had to be expected from previous studies [3-5] on masonry towers, the frequency of those modes clearly increases with increased temperature
- The natural frequency of modes $B_{1,N\text{-}S}$ and $B'_{1,N\text{-}S}$ exhibits very limited variation, with the standard deviation being equal to 0.009 and 0.015 Hz, respectively. For those modes, the trend of modal frequency to increase with increased temperature is balanced by the loss of tension [5] in the tie-rod (Fig. 2b) connecting the North and South load-bearing walls of the tower;
- As shown in Fig. 6, the natural frequencies of the two lower modes ($B_{1,E\text{-}W}$ and $B_{1,N\text{-}S}$) exhibit crossing in Summer months. In addition, the shape of mode $B_{1,N\text{-}S}$ seems to hybridize when crossing occurs (i.e., the mode shape of $B_{1,N\text{-}S}$ is no more orthogonal to the mode shape of $B_{1,E\text{-}W}$, as illustrated in Figs. 4b and 4a).

4. Conclusions and future developments

The paper exemplifies the importance of a global approach in the assessment of historic buildings. The available information on historic evolution, masonry inspection and on-site survey could help in the damage interpretation but also in driving further investigation. In the case of the *Santa Maria del Carrobiolo* bell-tower, the detailed knowledge of the building allowed to recognize the weakness of the structural layout and suggested the subsequent static and dynamic monitoring. In turn, the results of static and dynamic monitoring allowed to highlight the absence of abnormal increase of the crack openings, as well as some peculiar structural behavior (i.e., existence of closely spaced modes with similar mode shapes and the crossing of lower modal frequencies driven by increased temperature), which will be of utmost importance for both the numerical modeling and the preservation of the tower.

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