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Dynamic characterization of five historical bell towers in the Mugello basin (Italy)

E. Diego Mercerat¹[0000-0003-3154-584X], Arnaud Montabert²[0000-0002-0590-5410], Cedric Giry^{2,3}[0000-0003-4200-0570], Andrea Arrighetti⁴[0000-0003-0575-9473], and Maria Lancieri⁵[0000-0003-3992-5644]

¹ Cerema, Géoazur, 06903, Valbonne, France

² Université Paris-Saclay, CentraleSupélec, ENS Paris-Saclay, CNRS, Laboratoire de Mécanique. Paris-Saclay, 91190, Gif-sur-Yvette, France

³ EPF Ecole d'ingénieurs, 55 avenue du Président Wilson, Cachan, 94230, France

⁴ AOROC, Ecole Normale Supérieure - Paris Sciences & Lettres (ENS-PSL), F-75230 Paris, France.

⁵ Institut de Radioprotection et de Sécurité Nucléaire (IRSN), PSE-ENV/SCAN/BERSIN, 92262 Fontenay-aux-Roses, France.

⁶ diego.mercerat@cerema.fr

Abstract. Structural and dynamic identifications of historical buildings provide key input parameters in present archeo-seismological research. The ambition of the research project ACROSS (ArChaeology, inventory of RecOnstruction, Seismology and Structural engineering), involving different institutions in France and Italy, is to study past earthquakes through their impact on historical masonry buildings. Within this context, and among the first tasks, an ambient vibrations recording campaign was carried out to characterize five ancient bell towers in the Mugello basin in Tuscany (Italy) that suffered damage from at least one strong earthquake during medieval times. Operational Modal Analysis (OMA) allows us to identify the five slender masonry towers' main vibration modes (frequencies, modal shapes, and damping coefficients). Mode shapes exhibit the singularities of the bell towers related to their geometrical complexity, the use of numerous building techniques, and the relationships with other structures, particularly the adjacent naves. Of particular interest is the study of the response of one of the bell towers (pieve di St Cresci in Valcava) to bell-swinging excitation that has given insight into its non-linear dynamic response. Apart from helpful information about the relation between slenderness, irregularities in height, and main resonance frequencies, the results of the OMA study serve as the basis for building numerical models of slender structures that will help understand past (and future) dynamic behavior under different earthquake scenarios.

Keywords: Ambient vibrations · Operational Modal Analysis · Historical building · Bell tower

1 Introduction

The knowledge of pre-instrumental earthquakes lies in the historical archives and in the (often limited) availability of documents describing their impact on the affected territories. Indeed, the historical monuments are silent witnesses of past ground shaking and structural disorders, and the reparations are evidence of the ground motion intensity they experienced. The challenge is how to use this evidence to retrieve the characteristics of the ground shaking causing them. This question is at the heart of the discipline currently known as Archeoseismology [12]. In this framework, the ambition of the ACROSS (“ArChaeology, inventory of RecOnstruction, Seismology and Structural engineering”) research project is to establish a multi-disciplinary methodology to answer that question, bringing data from archaeology, history, petrography, structural engineering, and seismology.

One of the main steps of the procedure is the implementation of digital twins of existing historic buildings to use them in numerical experiments. This task demands a detailed knowledge of geometry and the structure’s mechanical properties, plus the details on the building phases characterizing it. In this paper, we describe the analyses performed on five monuments in the Mugello basin in Tuscany (Italy), focusing on the ambient vibration surveys that helped build the numerical models. These five bell towers suffered many past earthquakes, among them the 1542 and 1919 macroseismic moment magnitude of Mw 6 and Mw 6.5, respectively. None of the concerned towers experimented with the complete ruin, but traces of extended repairs are detected by the archaeological reading [9]. For each bell tower, the geometry is constrained by acquiring 3D laser scanner data. Concerning the mechanical parameters, in the linear elastic regime, several campaigns of ambient vibration data acquisition have been performed to retrieve the main normal modes of the historic structures following the procedure described in [5],[6],[13].

The following results are presented, beginning with an overview of the bell towers and their geometrical and architectural characteristics. Then, the main part of this study concentrates on the acquisition and data processing of the OMA surveys is presented. In the last section, the preliminary results of the slight non-linear behavior of one of the bell towers are discussed in light of bell-swinging recordings acquired during one of the ambient vibration surveys.

2 Structural characteristics of the bell towers

The studied structures are located in the Mugello basin, 50 km north of Florence in Tuscany, Italy. It corresponds to an intermontane basin in the Apennines encircled by two main fault systems: the Ronta fault system in the north and the Siève fault system in the south. These faults were surely responsible for the main historical earthquakes known in the area that hit the towers in different ways.

Building archaeological studies benefit of 3D laser scanner measures (Fig. 2) and their derived products: elevation maps evidencing the walls deformations,

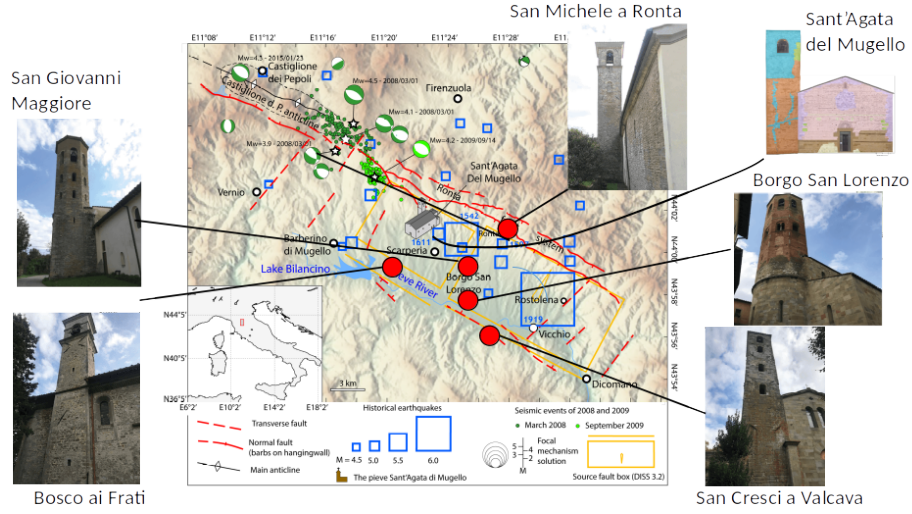


Fig. 1. Location of the five studied bell towers in the Mugello basin. The Sant Agata di Mugello case has been largely studied in the previous works of [8] and [11].

georeferenced orthophotos, and 3D CAD-based geometry of the structure integrating information on building material[1].

The structures consist of stone masonry walls with timber slabs along the height. San Michele a Ronta and San Cresci a Valcava present relatively regular shapes in height (Fig. 2a and Fig. 2c). San Giovanni Maggiore and Borgo San Lorenzo (Fig. 2b and Fig. 2d) exhibit an irregular shape in height (square or circular at the basement, octagonal or hexagonal in the last two floors) which further complexifies its dynamic response.

3 Operational Modal Analysis of the bell towers

Ambient vibration analysis enables the structural identification of buildings in the linear regime [14]. Measured modal characteristics can then be used to calibrate an elastic linear numerical model as a fundamental step to investigate the non-linear behavior of the structure under seismic loadings later. In the framework of quantitative archeoseismology, the interest lies in the built-up of realistic numerical models of the masonry structures at present and in inferring the ground motion that could have damaged the structure in the past [9,2]. As a necessary first step, the dynamic characterization consists of estimating the modal parameters, i.e., frequencies, modal shapes, and damping coefficients, to constrain the numerical model at low strain. One of the main advantages of Operational Modal Analysis is the fact that the modal identification is done under “in-situ” conditions and, contrary to experimental modal analysis, without any

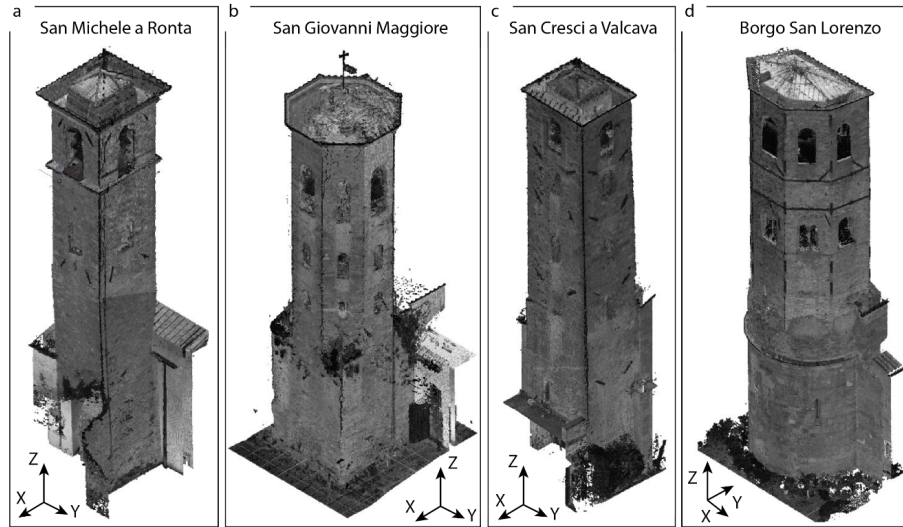


Fig. 2. 3D point clouds of the four studied Mugellan bell towers: a) San Michel a Ronta, b) San Giovanni Maggiore, c) San Cresci a Valcava, d) Borgo San Lorenzo. Courtesy of Marco Repole.

need for cumbersome external devices to excite the normal modes of structures most of the time protected under cultural heritage regulations.

In this work, Operational Modal Analysis is carried out using the Enhanced Frequency Domain Decomposition (EFDD), a non-parametric frequency domain technique for modal identification of output-only systems. It is based on the Singular Value Decomposition (SVD) of the Cross-Power Spectral Density (CPSD) matrix of the recorded signals as a function of frequency [4]. The sensor's location was measured inside each structure during the fieldwork and re-positioned from the point cloud for each bell tower (Fig 1.) to minimize the positioning error of the instruments.

The OMA has been carried out by analyzing ambient vibration data recorded by CMG40T velocimeters (plugged into City and MiniShark digitizers) placed, when possible, at the corners of the masonry walls at different heights where timber or concrete slabs are found. Each instrumental set-up lasted 30 minutes at a recording frequency of 200 Hz. Windows of 20-sec duration have been used to estimate the CPSD matrices. The EFDD calculation is done using the MACity software [7]. In all five cases, the analysis allows the identification of the first principal modes: the two bending modes in the two orthogonal directions and the first torsional mode.

The results are summarized in Table 1, where the first frequencies for the bending and torsion modes extracted from the SVD peak picking (Fig 3) are shown. From Fig 3, it is noticeable the similarity of the first SV shapes for the Ronta, Maggiore, and Valcava cases, where two close peaks corresponding to

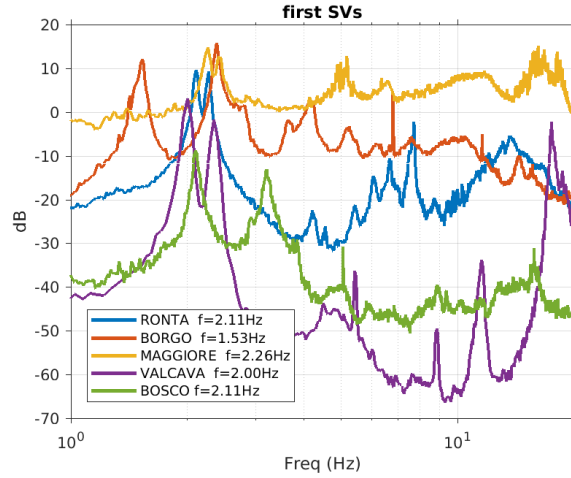


Fig. 3. First Singular Values after EFDD of the five bell towers under study. The first bending mode frequency of each tower is indicated in the legend.

the first bending modes in the two orthogonal directions are seen. These three towers share a relatively regular shape in height with almost similar horizontal extensions (from 5 m to 10 m on each side). On the contrary, the first SV for the Borgo San Lorenzo church is entirely different: the two first bending modes are well separated (1.5 Hz and 2.2 Hz), due mainly to the irregular shape in plan (irregular hexagon) and strong heterogeneity of building materials in height. We find the example of the Bosco-ai-Frati bell tower halfway between both groups, which presents both bending frequency peaks entirely separated despite its regular section (rectangular in height). This bell tower is built along the nave, favoring significant nave-tower interaction. The interface between the bell tower and the nave also underwent significant reinforcement following the earthquake in 2019. We discuss this effect in the forthcoming subsection.

Table 1. Table summary of first natural frequencies and corresponding damping coefficients of each bell tower.

Bell tower	Bending 1	Damp ξ_1	Bending 2	Damp ξ_2	Torsion	Damp ξ_T
	[Hz]	[%]	[Hz]	[%]	[Hz]	[%]
St Michele à Ronta	2.1	0.59	2.3	0.63	6.6	0.76
Borgo San Lorenzo	1.5	0.96	2.4	0.97	4.1	1.97
St Cresci in Valcava	2.0	1.26	2.3	1.03	4.5	-
San Giovanni Maggiore	2.3	1.22	2.4	1.55	5.3	1.28
Bosco ai Frati	2.1	1.54	3.2	1.43	8.8	1.76

3.1 Nave-tower interaction: the Ronta case

One interesting example of nave-tower dynamic interactions is found in the San Michele a Ronta church, where the bell tower is leaned against the nave, presenting two of its four sides somehow blocked against the nave walls at around one-third of its total height (6.31 m of 22 m). From field inspection, there are two connections between the nave and the tower: a longitudinal connection along the entire height, and a transverse connection on top.

The first ambient vibration characterization done in 2021 has already put forward interesting features of the dynamic behavior of the bell tower. For example, the first two bending modes found around 2.1 Hz are not parallel to the tower walls, as shown in the modal shapes shown in Fig. 5. This is probably due to the lateral connection and the tilting of the Ronta bell tower. This is surprising as the tower is entirely regular in height, although some differences in construction materials are reported. One explanation can be found by looking at the tower-nave spatial configuration, the tower is built against one interior corner of the cross-shaped nave (see Fig. 5). Additionally, the analysis of several peaks of the first Singular Value, starting from 4 Hz, gives similar shapes that could be interpreted as the second-order bending mode (i.e., with one nodal point in height). However, their frequencies were relatively lower than expected (at least three times the frequency of the first bending mode).

After the second ambient vibration survey in the church, during summer 2022, the analysis of SVD peaks obtained from a standard set-up with sensors placed at the same time in the tower and in the nave walls bring light on the interpretation of the different SVD peaks : (i) similar fundamental bending modes in both orthogonal directions, though not parallel to main directions, are readily identified at 2.1 and 2.3 Hz; (ii) the following modes at 4.2 Hz, 5.4 Hz, and 6.1 Hz (see Fig 5), even if they present similar shapes that suggest second order bending modes, are on the contrary, nave modes that induce significant motion to the bell tower at such specific frequencies. The second order bending mode at 7.7 Hz follows as it is shown in Fig 5.

3.2 Bosco ai Frati case

The Bosco ai Frati convent represents one interesting case as, despite its regular rectangular shape in height (see Fig 1), it presents bending frequencies in the longitudinal and transversal directions quite separated from each other (2.1 Hz and 3.2 Hz). Additionally, the first torsion mode is found at 8.8 Hz, then relatively at higher frequency than expected. The intermediate peak identified near 5 Hz, which could have been associated with the first torsion mode, corresponds on the contrary to the nave-tower interaction as it does not show apparent rotation. This dynamic behavior is undoubtedly related to its building condition 'inside' the body of the nave up to a height of 8 meters. Then the effective height [10] is significantly reduced, leading to the first torsion mode at a relatively high frequency of 8.8 Hz. Similarly to the Ronta case, future analysis will be done to

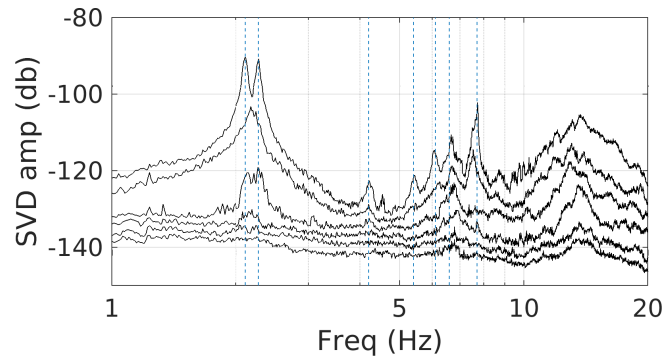


Fig. 4. First Singular Values after EFDD of the San Michele a Ronta bell tower. The identified frequencies are indicated with vertical dashed lines.

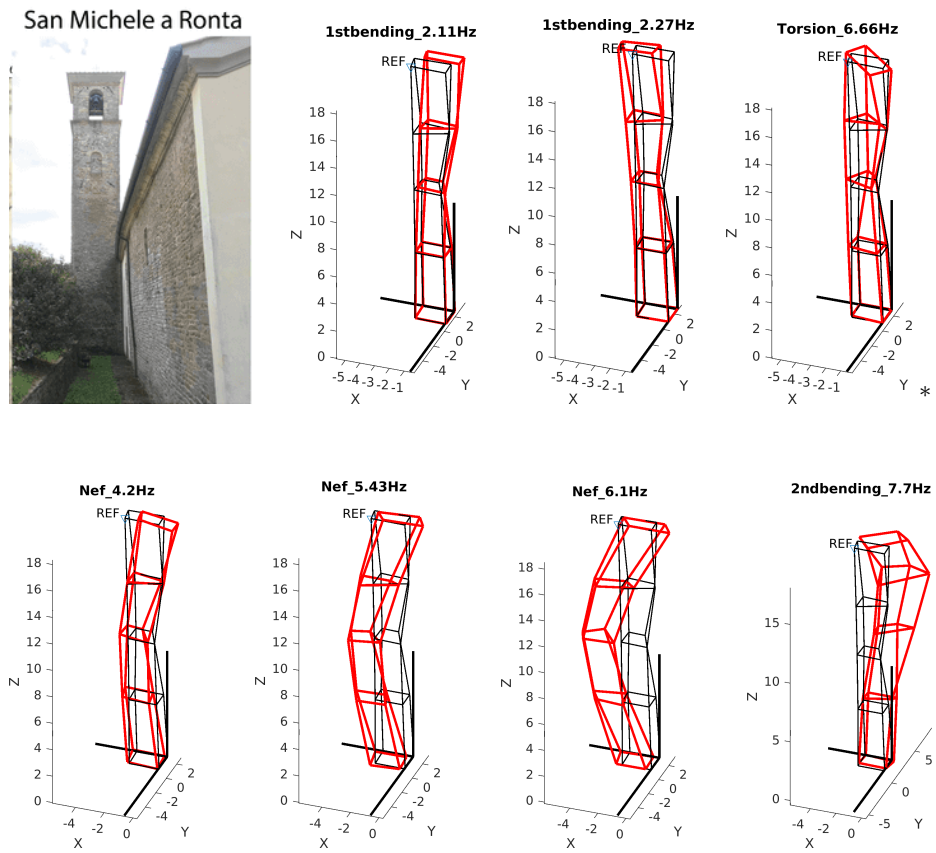


Fig. 5. a) Ronta bell tower. b) First bending and torsion modes. The nave walls are marked by thick black lines at the bottom of the tower. c) High-order modes that correspond to the nave-tower interaction.

investigate the identification of exclusive nave modes and their impact on the bell tower motion.

These two examples highlight the importance of considering nave-tower interactions in estimating natural frequencies and modal shapes for historic slender structures.

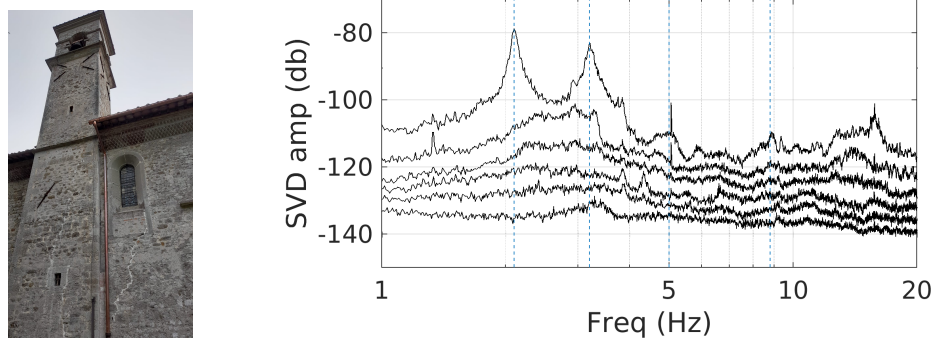


Fig. 6. a) Bosco-ai-Frati bell tower embedded in the nave. b) First Singular Values after EFDD of the Bosco-ai-Frati tower. The identified frequencies are indicated with vertical dashed lines. Note the difference between the two first bending modes despite its regularity in height, to be compared with the San Michele a Ronta case shown in Fig. 4.

4 Non-linear characterization of the vibrational response: case of San Cresci in Valcava

During the 2022 survey in San Cresci in Valcava, the bells were activated in order to characterize the dynamic response to excitations of much higher amplitude. The idea behind the experience is to analyze the possible shift and/or splitting in the natural frequencies of the already identified modes.

For the experiment, a vertical array of six CMG5T accelerometers has been deployed, as it had been observed that the velocimeters used for the ambient vibration surveys saturated while the bell system was activated. In Fig 7, the acceleration time series for the three motion components are shown during one of the bell-swinging experiments. It is possible to observe each bell hit at nearly every second, followed by the normal mode excitation (first bending mode in the N direction in this case), particularly in the channels parallel to the bell swinging excitation.

The time-frequency analysis of these signals allows us to study the time-dependent frequency of the first bending mode (2.0 Hz from the EFDD analysis). In Fig 8, it is observed a clear shift from 2.0 Hz (8a) down to 1.6-1.7 Hz during the high amplitudes recorded due to the bell swinging that lasted around 2

minutes. After the bell swinging ends, the frequency value returns to its original values relatively quickly (tens of seconds), as can be seen in Fig 8b. Remarkably, a decrease of 20 % in the frequency value is observed, though it could be expected for such highly heterogeneous masonry structures presenting ubiquitous microcracks and imperfections. As it has been recently presented in other medieval masonry towers [3,15], the possibility to use bell swinging in historical towers opens interesting opportunities to characterize the dynamic response of such structures, not only in the linear regime but also in the non-linear regime under low to moderate input motions : acceleration levels lower than $10^{-2} m/s^2$.

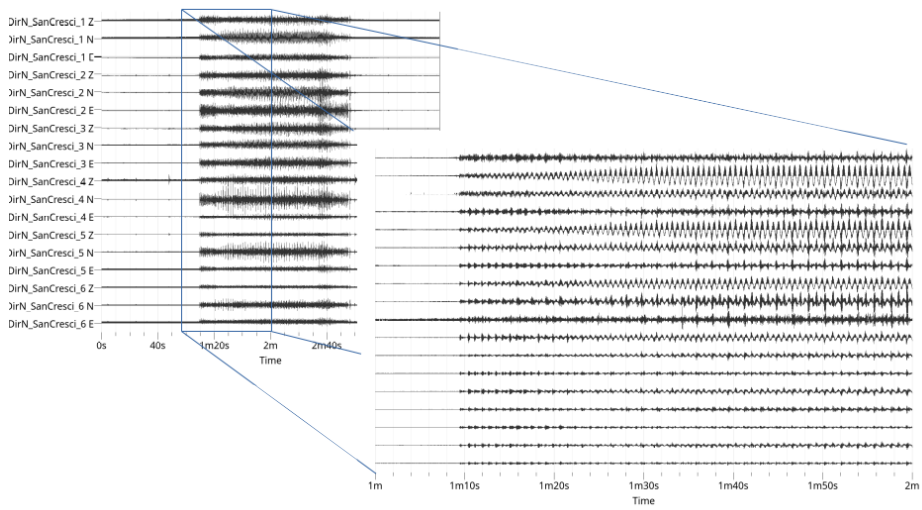


Fig. 7. Acceleration time series of the vertical array (6 x 3 components) during the bell swinging in the N direction. Detail of the first minute of swinging for the 18 channels where the first bending mode at 2.0 Hz is clearly seen particularly in the N components of the topmost sensors.

5 Conclusion

Ambient vibration surveys have been carried out in five bell towers of the Mugello basin (Tuscany, Italy) in June-July 2021 and June 2022 in order to characterize its dynamic behavior. This paper summarizes the main results of the dynamic characterization by OMA using the EFDD technique. Results are jointly discussed to extract helpful information regarding the measured bending mode frequencies and the regularity in height of each bell tower.

The structural identification of the bell tower of San Michele a Ronta is detailed and discussed. After the second survey in June 2022, when additional

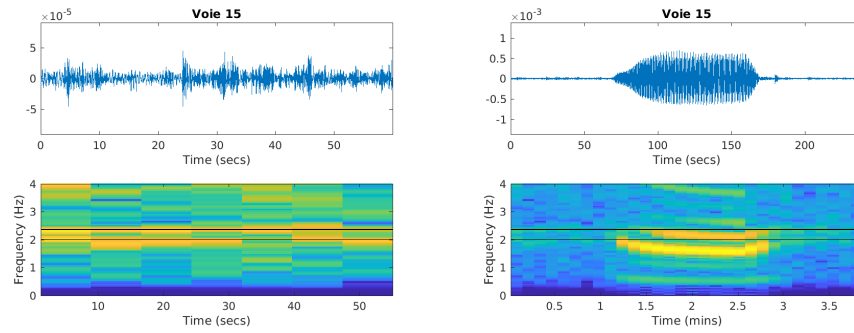


Fig. 8. San Cresci bell tower acceleration time series of channel 15. Top: acceleration time series, Bottom: spectrograms of the latter: a) One minute before the bell starts swinging, b) during the whole bell swinging that lasted around two minutes. In black solid lines, the frequencies of the two first bending modes at 2.0 Hz and 2.3 Hz are marked for comparison.

measurement points inside the church’s nave were acquired, the modal identification highlights the interaction between the bell tower and the nave. Some of the first ‘higher’ modes are exclusive nave modes that induce the bell tower motion at these frequencies.

The non-linear characterization of the San Cresci in Valcava case has been initiated using the bell swinging and a vertical array of accelerometric sensors to follow the shift and recovery of the fundamental frequencies of the first bending modes of the tower. The frequency shift reaches more than 20 % of the observed fundamental frequency under ambient vibrations.

Detailed archaeological and structural analyses of the other bell towers will be presented during the conference as they are currently work in progress.

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