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IDENTIFICATION THROUGH SEISMOMETRIC MEASUREMENTS OF TRANSIENTS PROPAGATING INSIDE THE ASINELLI AND GARISENDA TOWERS (BOLOGNA, ITALY), IMPLICATION ON STRUCTURAL MODELING AND STATE OF HEALTH MONITORING.

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Abstract

The SHM has a very important role in the diagnostic process of cultural heritage buildings, for which generally, the identification of the structural behaviour is affected by many uncertainties. The use of ambient vibration tests allow to characterize the dynamic behavior of the structures, providing also information to validate numerical modeling. Moreover, continuous monitoring allows to record streams of seismic ambient noise for long time intervals in order to retrieve the temporal evolution of the structural characteristics and to highlight the response of them to seasonal variations of environmental parameters (temperature, humidity) and the stresses due to the human activities or to the rapid (daily or weekly) changes in the ambient conditions (temperature, wind velocity and intensity).

Three seismic monitoring experiments were performed in 2012, 2013 and 2014 at the Asinelli and Garisenda Towers, two masonry leaning tower built in the center of Bologna (Italy). The aim of this work is to present the results of the analysis of the data recorded by seismic monitoring that allowed to clearly identify the normal modes of oscillation of the Two Towers. A particular attention was devoted to the identification of transient that, propagating inside the structures, produce beating effects at the top stations. Implication to the structural modeling and to the State of health monitoring are discussed.

Keywords: Dynamic Structural Health Monitoring, Masonry tower, Ambient vibration

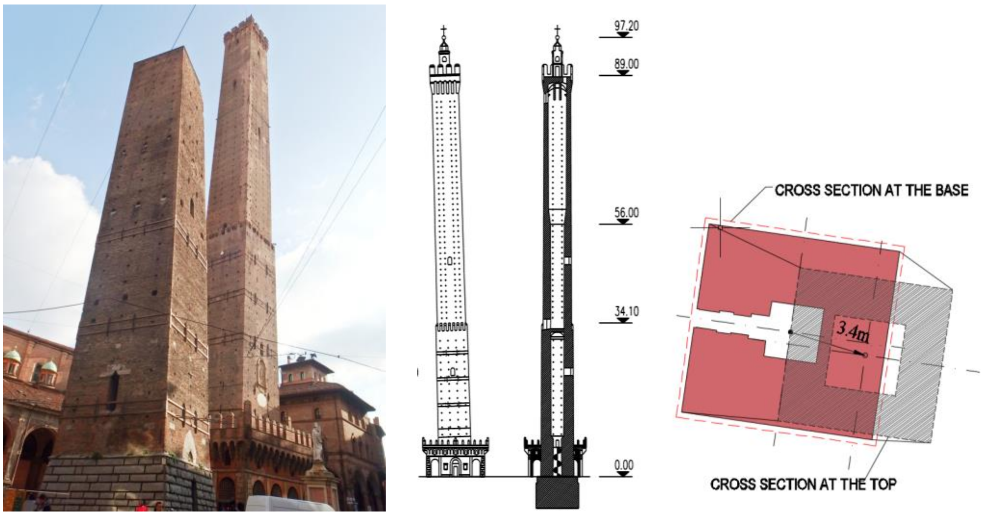
1 INTRODUCTION

The assessment of the structural heath of the historical buildings, through non-destructive techniques, is fundamental in order to preserving their cultural integrity. For this purpose, Structural Health Monitoring (SHM) plays a crucial role in providing information both on the dynamic properties of the structures and the damage caused by earthquakes, impacts or traffic loads. In the last decade, the number of SHM systems designed and implemented on historic structures increased considerably. SHM perfectly meets principles and guidelines of Italian and European seismic codes concerning the historical buildings, which require the preservation of the structural architectural integrity, promoting removable, non-invasive and compatible solutions in the knowledge process, restoration and strengthening [1], [2]. The data obtained from a dynamic monitoring system shall provide information regarding the intrinsic properties of the structure that can be used to develop more accurate models and thus to plan effective strengthening interventions. Vibrations are one of the main factors for fatigue in structures. For this reason, with the increase of heavy traffic in the cities the study of the effects of the road traffic vibrations induced on the historical buildings is becoming another important issue. Continuous monitoring allows to record streams of seismic ambient noise for long time intervals in order to retrieve the temporal evolution of the structural characteristics, the influence on them of the ambient conditions (temperature, wind velocity and intensity) and the stresses due to the human activities (traffic loads). Three seismic monitoring experiments were performed in 2012, 2013 and 2014 at the Asinelli and Garisenda Towers, two masonry leaning tower built in the center of Bologna (Italy). The aim of this work is to present the results of the analysis of the data recorded by seismic monitoring, that allowed to identify the dynamic properties of the Two Towers, and to investigate the effects of the vibrations induced by the traffic loads on the Towers. The information obtained from the monitoring are also used to calibrate FEM models with the purpose of identify models able to better simulate the real behavior of the Towers. Particular attention was paid to the evidence of particular signals propagating inside the Towers that point out clear effects of beatings at the top.

2 GARISENDA AND ASINELLI TOWER

Garisenda and Asinelli Towers, commonly referred to as “The Two Towers”, are the main monument of the city of Bologna, North Italy (Figure 1). The Asinelli Tower is the taller one (97 m) and was built between 1109 -1119. During the Second World War, the Tower was used as a watchtower. It tilts toward South-West of 2.23 m [3]. The external walls were built using solid bricks for the outer skins and rubble masonry fill. The total thickness of the masonry decreases almost linearly from 3.15 m at the base to 0.45 m at the top. Three main discontinuities are present at 11.5 m, 34.0 m and 56.0 m (Figure 1b) [4]. The Garisenda, the older one, can be dated around the last two decades of the eleventh century. During the construction phases, the foundation soil underwent important subsidence phenomena, which caused a visible tilt of the tower [5]. The tower is 48 m high and has a slope of 3.40 m towards South-East. The base of the Garisenda tower presents an external selenitic layer that cover the external wall for the first 3.5 m. The Tower cross section above the selenitic base (built using solid bricks for outer skins and rubble masonry fill) reduces with height as the common construction practice at the time of construction (Figure 1c) [6]. The knowledge of actual state of health the towers is a crucial issue in order to preserve these monuments. For this reason, at the beginning of the 2011 the Municipality decided to installed a static SHM systems in both the Towers [7], [8]. In addition, following the Emilia earthquakes (20th May 2012 and 29th May 2012, respectively 5.8 and 5.6 Mw), seismic monitoring experiments were commissioned to the Istituto Nazionale di Geofisica e Vulcanologia (INGV) in conjunction with the

University of Bologna with the purpose of obtaining information on the dynamic behaviour of the Two Towers.

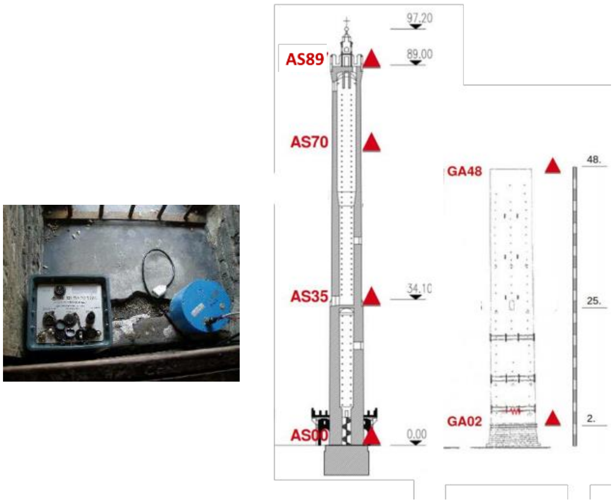


(a) (b) (c)

Figure 1- (a) The Two Towers of Bologna, (b) The Asinelli Tower elevation with the indication of the main discontinuities, (c) Garisenda Tower cross section at two different heights

2.1 The monitoring system and the tests developed

The Towers' vibrations induced by natural or artificial sources (ambient noise) have been recorded in order to evaluate their dynamic properties. The first experiment [9] was performed from June 2012 to September 2012. Six seismic stations, equipped with three-axial seismometers (Lennartz Le3d5s coupled to 24-bit digitizers Reftek 72A-07/08) were installed along the height of each Towers (4 in the Asinelli, 2 in the Garisenda), see Figure 2. A second experiment was repeated the year after, from September 2013 to March 2014 (Lennartz Le3d5s coupled to 24-bit digitizers Reftek 130). A third experiment was performed from August to October 2014 (three seismic stations in the Asinelli, SS20 2Hz seismometer coupled to a SL06 24 bit DAS from Sara Electronics S.r.l.).



(a) (b)

Figure 2-a) Three-axial seismometers (Lennartz Le3d5s coupled to 24-bit digitizers Reftek 72A-07/08; (b)Position of the seismometers on the Asinelli tower (left) and Garisenda tower (right)

At the end of the third experiment (October 2014) additional experimental measurements have been carried out in order to study the effects of the transit of a heavy vehicle on the Asinelli tower, at the end of the monitoring period. For this aim, the oscillations produced by the transit of an heavy truck at different speed along Strada Maggiore (the road at the base of the Asinelli Tower, Figure 3) were recorded by the three seismometric stations, installed at the base, at 35 m high and at the top of the Asinelli Tower.

Figure 3-a) View of the position of the Two Towers (Google Earth);b)Picture of the transit of a truck along Strada Maggiore during the experimental measurements.

3 AMBIENT MODAL FREQUENCIES IDENTIFICATION AND MODELING

Recording natural vibration on built structures gives a way to identify their fundamental frequencies of vibration. Since the use of these techniques allows to make measurements without any damage to the building and without interfering with its normal use, it appear particularly suitable for the analysis of structures of historical and monumental interest. Also, from the spectral-analysis point of view, taking into account the wide frequency band covered by the natural vibration, it is possible to recognize the principal modal frequencies in a single step.

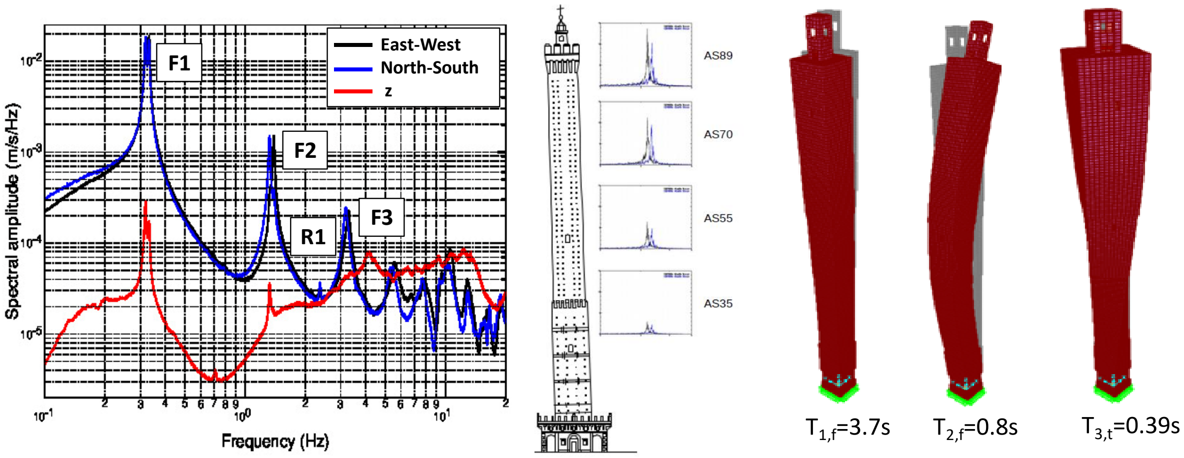
Figure 4 and 5 show the average spectra computed over the entire monitoring period of 2013 for the three components of the top station for the Asinelli and Garisenda, respectively [7, 8]. The first three fundamental flexural frequencies (indicated as F1, F2, F3 in the spectrum of figure 4a) of the Asinelli Tower fall within the range of 0.32-0.33 Hz, 1.3-1.5 Hz and 3.0-3.3 Hz. The third peak (indicated as R1 in figure 4a) of the spectrum of the horizontal components may be associated with a torsional motion. The first three fundamental frequencies of the Garisenda tower, instead, fall within the range of 0.71- 0.73 Hz, 3.7-4 Hz and 8.8 9.0 Hz respectively (Figure 5). It can be noticed that these peaks are split and characterised by different amplitudes between the two horizontal components (figure 4b and 5b). The frequency splitting, not existing in a symmetrical structure, is probably due to the asymmetry in building characteristics and to the leaning angle of the Towers.

A more detailed observation of the spectral response of the Garisenda Tower (Figure 5a) allows to capture a quite interesting phenomena, that is the presence of two small spectral peaks at frequencies corresponding to the fundamental frequencies of the Asinelli Tower. Such phenomena can be interpreted as a mutual induction effect of oscillation. The same effect, on the other hand, is visible only on the vertical average spectrum of the Asinelli Tower that exhibits in this frequency band the minimum spectral amplitude (Figure 4a).

In the last years, the assessment of the structural health was mostly focused on the Asinelli Tower rather than on the Garisenda Tower, mainly because being the larger height of that would probably make it more vulnerable to the effects of lateral vibrations, such as those induced by earthquakes. In the past, some of the authors have conducted numerical studies based on the use of Finite Element Method (FEM) to asses to seismic response of the Tower. FE models of increasing complexity (mono and bi- dimensional models considering different base conditions) have been developed and the results of modal analysis were compared with the data recorded by the dynamic monitoring. Details are available in [10].

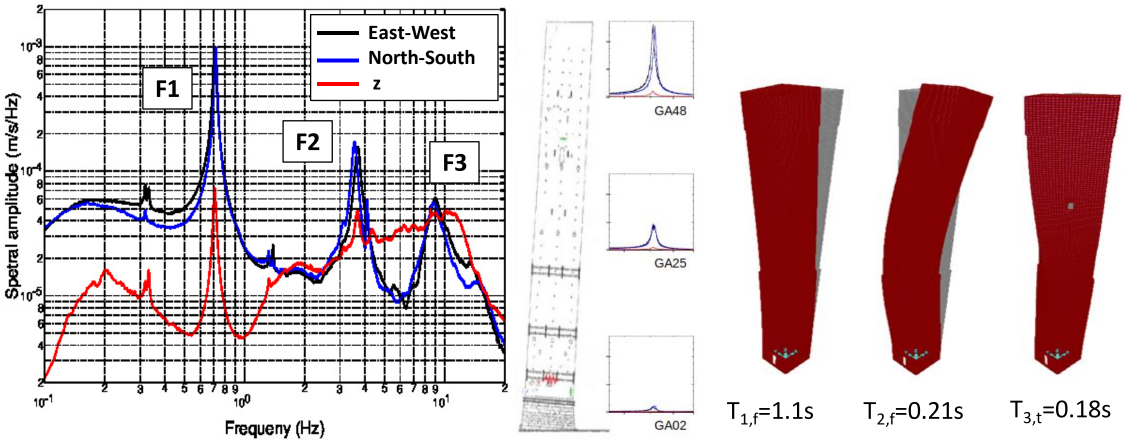
In this work, to investigate the phenomenon of frequency splitting and of beating (that will be presented in the next sections), a further FE model of the Asinelli Tower has been developed. considering isotropic shells elements using the commercial softwareSAP2000. The model reflects faithfully the geometry in the following aspects: inclination, thickness of the walls at the differed sections, windows, holes used to install the scaffolding during the construction phases and steel ties installed during the years to confine the masonry walls. In particular, the openings could influence the structural response of the Tower and could be a possible cause of the frequency splitting detected through the dynamic monitoring. Figure 4c displays the mode shapes obtained by the FE model. It can be noticed that the fundamental periods obtained from the model analysis are in good agreement with those obtained from the measurements. Time history analyses, using the recorded data at the base of the Tower as input, are under development to better investigate the cause of the beating phenomenon observed.

In 2018, a possible material degradation at the base of the Garisenda tower has been revealed pointing out the necessity to assess its current structural health. Several models (bi-dimensional and three-dimensional finite element models) of the Garisenda have been developed. Particular attention has been paid to the modelling of the base of the Tower composed by an external and internal perimeter of selenitic stones (thickness of around 50-60 cm) and an internal filling. The measured frequencies have been used to calibrate these models, which will be used to investigate the consequences of the natural decay of material properties in terms of safety and stability. For sake of brevity, only the mode shapes as obtained by the bi-dimensional model are reported in Figure 4c. The material properties used in the models of both Towers, characterized through in situ tests (both destructive and non-destructive), are summarized in Table 1.



(a) (b) (c)

Figure 4- a) Average spectra computed over the entire monitoring (2013) for the top station. b) Example of the distribution of the FFT spectra along the vertical profile inside the Asinelli Tower. c) Modal shape obtained by a finite element model developed by the authors.



(a) (b) (c)

Figure 5- a) Average spectra computed over the entire monitoring (2013) for the top station. b) Example of the distribution of the FFT spectra along the vertical profile inside the Garisenda Tower.
c) Modal shape obtained by a finite element model developed by the authors.

Material	Specific Weight γ	υ	Elastic Modulus E_m	Compressive strength f_m	Shear strength $f_{v,m}$
	[KN/m^3]		[MPa]	[MPa]	[MPa]
Masonry bricks	18	0.2	3000	4	0.5
Selenitic stone	24	0.2	5000	7	0.7
infill	17	0.2	2500	4	0.5

Table 1: Material properties of the Asinelli and Garisenda towers

4 CHANGES IN THE OSCILLATION DUE TO VARIATION OF AMBIENT CONDITION

Dynamic monitoring, if performed continuously and for a long period, can be an effective tool to describe the health status of a built structure. The recording of long data flows allows to follow the variation of the modal parameters with time and to correlate it to the changes in the environmental conditions, natural or artificial, that can influence the behavior of the structure and can produce fatigue or rapid modification of the mechanical-physical properties. It is the case of the Two Towers, which have been monitored for several months over several years, allowing not only to depict a snapshot of the modal parameters but also to observe how the Towers are solicited by the variation of ambient parameters.

A first aspect taken into account was to measure the variation of the amplitude of oscillation with the variation of anthropic noise due to the daily increment of the vehicular traffic at the base of the Towers. As representative example of an average behaviour for both Asinelli and Garisenda Tower, Fig. 6 shows the daily oscillation recorded at the Asinelli top station during August 2012 between 1–20 Hz, the frequency band where the seismic ambient noise is known to be dominated by “cultural sources”. It is clear the similarity of the trend during the working days, showing a sharp increment in the amplitude of oscillation when the human activity rises (about at 6: am, local time), a reduction during the evening and an almost instant decrease in the night, after the 01 a.m. (local time). On the other hand, also during holidays (15, 17, 18 August 2012) the pattern is similar but the interval when the oscillation amplitude is increasing reduces its duration only in the central part of the day.

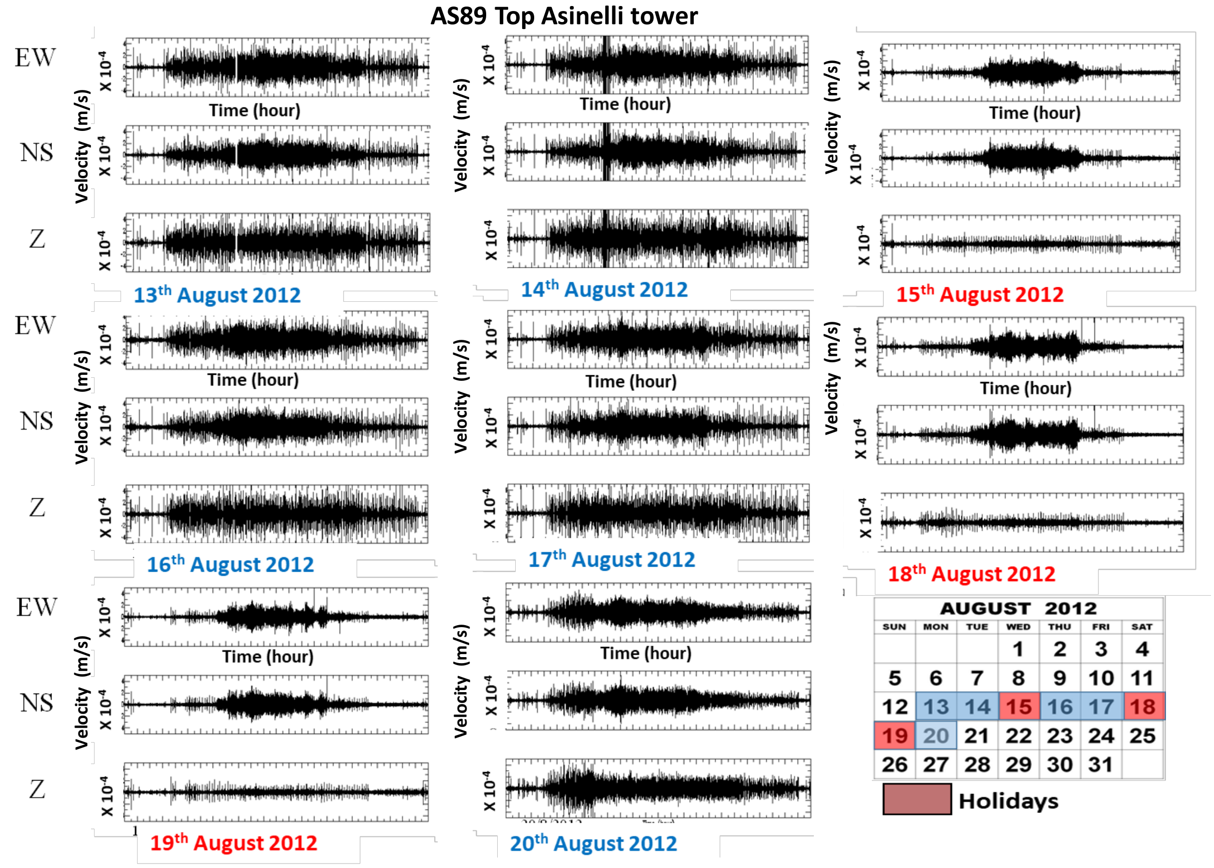


Figure 6- Daily trend of the oscillation recorded by the top station of the Asinelli Tower from 13th to 20th August 2012. The signal has been filtered in the 1-20 Hz frequency band, in order to point out the content associated with the anthropic noise surrounding the Tower.

To evaluate the amplitude ratio of the oscillation between night and day periods and between weekdays and holidays, the trends of the maximum amplitudes of oscillation in the different periods have been calculated, performing the averages of the maximums. It can be noticed that the oscillation between day and night is between 2 and 6 times greater on weekdays and doesn’t exhibit evident differences between weekday and holidays.

The continuous monitoring has allowed recognizing the propagation inside the Towers of transients that trigger beatings at the top of the Asinelli Tower. Figure 7 shows the time history of the three components of recorded signals (200 s) recorded by the three stations. The signals recorded by the station at the top clearly show beatings. The phenomenon has been investigated by some of the authors Palermo et al [11] using a simplified eccentric planar model with an equivalent eccentric and torsional stiffness. The results indicated that the equivalent eccentricity could be compatible with some partial wall disconnections due to cracks propagating along the openings.

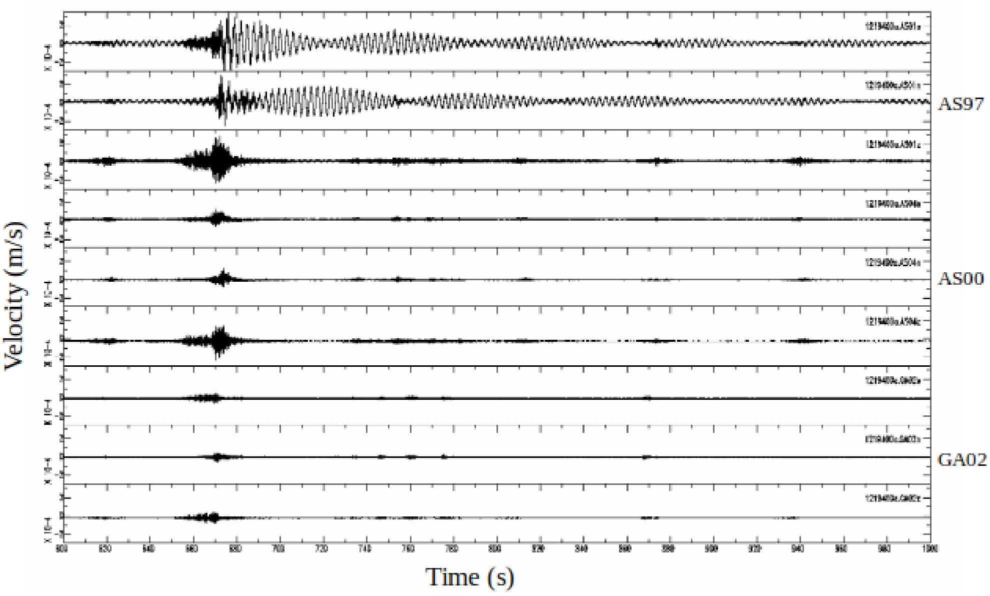


Figure 7. Example of transient propagating inside the Towers and triggering beatings at the Top level of Asinelli Tower. Each set of three signals are the waveforms on the Z, NS, EW directions, from down to top respectively for GA02, AS00 and AS97 measurements point.

In order to individuate the possible source of the impulse at the base, a horizontal particle motion analysis of the signal recorded at the base of the Two Towers has been performed. Figure 8 shows that the cross point of the composition of the horizontal components, taking into account the position of the instrumentation inside the Towers, points toward the intersections of roads “Via Rizzoli” and “Strada Maggiore”, daily traveled by heavy vehicular traffic.

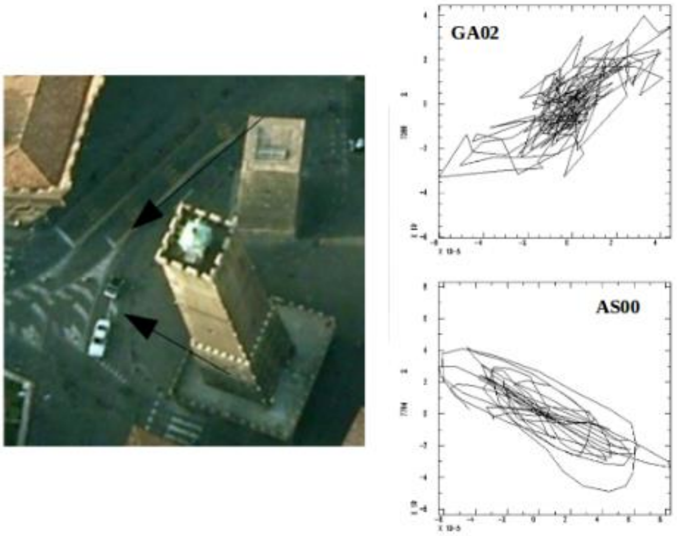


Figure 8. Particle motion analysis along the horizontal directions for the two seismic stations installed at the base of the Two Towers

5 VIBRATION INDUCED BY HEAVY TRAFFIC: EXPERIMENTAL TEST

In October 2014, during the execution of some maintenance works along road “Strada Maggiore” that required the road closure, an experimental test has been performed in order to record the Asinelli Tower vibrations induced by the passage of a heavy truck along the road (Figure 3). Three seismic station equipped with three-axial seismometrs (SARA SS20 and SL06) were installed at the base, at 35 m and at the top level of the Tower. The signal was sampled at 100 sps. The truck made five passages at different speeds (10, 20, 30 km / h). The presence of a sudden discontinuity in the pavement was also accounted for by placing an obstacle in the road, namely a wooden beam in the direction perpendicular to the road. For each measurement, the following tests have been conducted (Figure 9):

A. truck moving at 20km/h with no obstacle
B. truck moving at 30km/h with no obstacle
C. truck moving at 10km/h in correspondence of the storm drain
D. truck moving at 30km/h with obstacle
E. truck moving at 10km/h with obstacle

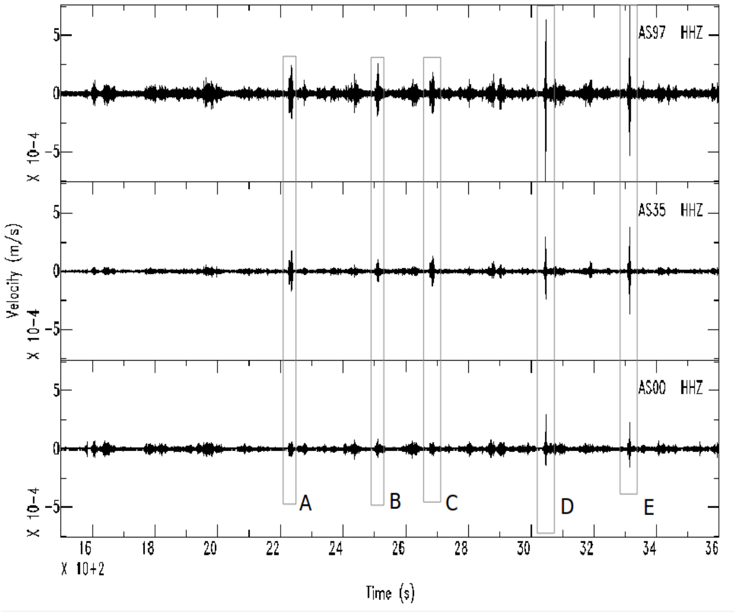


Figure 9. Vertical component waveforms recorded at the three measurement points during the five passages of the truck.

As is evident from Figure 9, during the first three passages (A,B,C) the amplitude of motion along the vertical component of the base didn’t exceed the maximum average vibration recorded in absence of input. During the last two tests (D and E), the input at the base was significantly stronger. In these cases at both the stations inside the Tower beatings were recorded, similar to those observed during the continuous monitoring (Figure 10). This seems to confirm that the input at the base produced by heavy traffic along the roads surrounding the Towers is responsible for the observed beatings. The acceleration and displacement peak values (PGA and PGD) recorded during the tests were computed and collected in Table 2. The maximum values of PGA and PGD recorded at the top along the horizontal direction refer, as expected, to the two most energetic tests (D, E). They are equal to 3 mg and 0.4 mm respectively (Table 2).

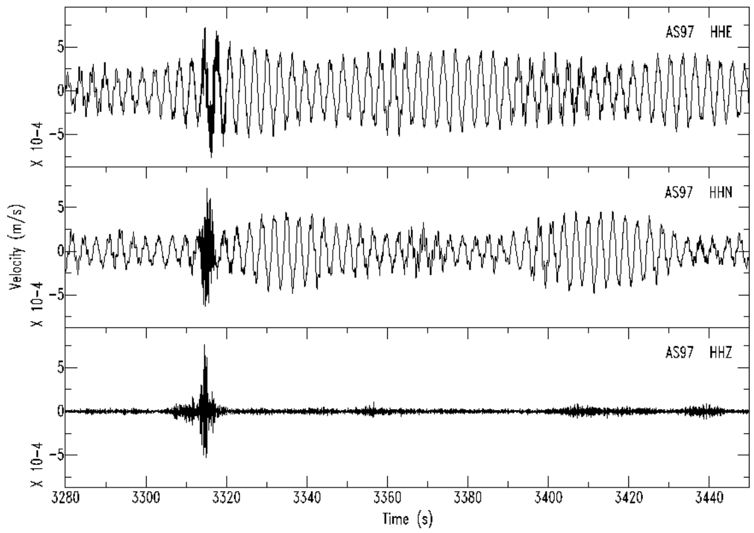


Figure 10. Waveforms recorded during the most energetic test (E) at the top level station, from top to down respectively EW, NS and Z components.

Acceleration		Test A	Test B	Test C	Test D	Test E
		mg	mg	mg	mg	mg
AS00	E	0.08	0.11	0.05	0.28	0.19
	N	0.07	0.10	0.05	0.48	0.33
	Z	0.24	0.45	0.19	1.71	1.08
AS35	E	0.36	0.45	0.21	1.31	0.62
	N	0.34	0.34	0.18	1.41	0.91
	Z	0.38	0.37	0.25	1.13	1.09
AS97	E	0.62	0.84	0.50	1.23	1.24
	N	0.86	0.64	0.49	2.71	1.41
	Z	0.63	1.14	0.53	2.89	1.81
Displacement		Test A	Test B	Test C	Test D	Test E
		μm	μm	μm	μm	μm
AS00	E	1.72	1.93	1.81	1.96	2.12
	N	2.16	1.55	2.02	2.03	1.89
	Z	3.40	2.13	2.81	5.06	4.56
AS35	E	50.7	72.2	66.6	73.7	62.7
	N	32.4	55.0	43.5	95.8	67.0
	Z	10.7	8.63	9.51	12.4	16.4
AS97	E	162.9	193.0	278.8	369.5	261.8
	N	138.9	286.0	260.2	375.0	204.2
	Z	16.1	11.92	11.32	19.3	24.6

Table 2: The acceleration and displacement peak values (PGA and PGD) recorded during the tests.

CONCLUSIONS

The main conclusions of the study can be summarized as follows:

- The experimental modal frequencies determined from the dynamic monitoring performed between 2012 and 2014 result in good agreement with those obtained from modal analysis performed on the FE models.
- The long duration and the repetition over several years of the survey allowed to recognize a typical trend of the vibration of the Towers that at high frequency (1-20 Hz) seems to be strongly correlated to the surrounding anthropic sources. In particular, some specific transients propagating inside the Asinelli Towers triggered beatings that are evident at the top of the Tower.
- The passage of an heavy truck monitored during one specific experiment induced beatings that resulted to be similar to those evidenced during the long term monitoring.
- Further analyses are necessary to better interpret the observed beatings in order to identify possible relations between structural and material irregularities and the peculiar dynamic response.

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