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Long run ambient noise recording for a masonry medieval tower

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Abstract. Ambient vibration techniques are nowadays a very popular tool to assess dynamic properties of buildings. Due to its non destructive character, this method is particularly valuable, especially for health monitoring of historical monuments. The present ambient vibration experiment consists on the evaluation of vibration modes of a Medieval tower. Situated in Soncino (close to Cremona, in the Northern Italian region named Lombardia), the tower of 41.5 meters height has been monitored by seismometers located at different points inside the structure. Spectral ratios of the recorded ambient vibrations clearly identify a fundamental mode at about 1 Hz, with a slight difference in the two horizontal components. A second mode is also evidenced at approx 4-5 Hz, with a moderate degree of uncertainty. The records of a ML 4.4 earthquake, occurred during the monitoring period, confirm the information obtained by microtremor analysis. Daily variations of both 1st and 2nd mode were detected: these variations, of an amount up to 2%, seem to be well related with the temperature.

Keywords: modeling; old masonry structure; retrofit; structural analyses; temperature effects

1. Introduction

Researchers in the area of wood specimens and/or timber structures know the roles of temperature and humidity on any experimental result (Casciati 2007, Casciati and Domaneschi 2007). But the topic had to be extended to the structures inserted in civil infrastructure systems as soon as the technology gave the possibility to carry out long duration records (Peeters and De Roeck 2001, Sohn *et al*. 1999, Wenzel and Pichler 2005).

The variation of the fundamental frequencies of buildings has been observed by several authors. (Herak and Herak 2010) found a seasonal variability, together with a short term variation of fundamental frequency in DGFSM building in Zagreb. They list several possible causes of short term variability: weather conditions, change of amplitude of the excitation, random contributions (and also measurement errors!). Clinton *et al*. (2006) also found at Millikan Library (Caltech) a daily variation of about 1% for the fundamental frequencies (natural frequencies drops in the evening and increases in the day) and suggest, as possible causes, the changing weather conditions

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and the daily building usage. They attempted to explain the phenomenon by thermal expansion of the concrete during the day, changes of stiffness during rare events, etc. In the case study reported in (Chrysostomou *et al*. 2008) the variation of the level of the underground water was indicated as a major cause of these variations. Several papers were also published on the way to be used for compensating such unwished effects (see among others (Kullaa 2009, 2011).

The authors carried out in 2005 an experimental campaign on a medieval, masonry civic tower. Small subsets of data were processed and elaborated for specific purposes during the past 6 years. Eventually, all the set went ready and this manuscript summarizes the main conclusion of such an analysis.

2. The case study

The town of Soncino is located in the Po Valley, near Cremona, in the North of Italy. The first historical document on the town dates back to the VII century. Due to its strategic location, at the end of the X century, the town was an important military centre and was contended by the Republic of Venice and the Dukedom of Milan. Some historical sources date to this period the first phase of construction of the Civic Tower (Fig. 1), while other documents date the construction to the XI century. For sure, in 1103 the tower was completed and it was standing, with battlements, at the height of 31,5 m. In the same century the Old Palace (nowadays the Town Hall) was built close to the south and west tower sides.

In the centuries, the palace was remodeled many times, adding and demolishing parts, and the tower was enclosed in the palace for 3 levels (about 10 m), on the West, East and South side (Fig. 2). In 1575 the tower was heightened up to 41.8 m; the construction phases are shown in Fig. 3. On May 12, 1802 an earthquake occurred in the town, and the complex of the Civic Tower suffered severe damage. The Palace was immediately repaired, while the tower was restored only in 1832.

Fig. 1 Town of Soncino: Civic Tower and Town Hall

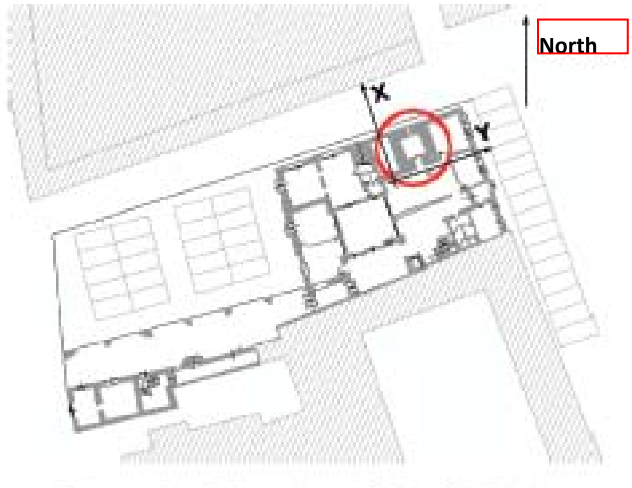

Fig. 2 Plan view of the Old Palace (the red circle indicates the Tower)

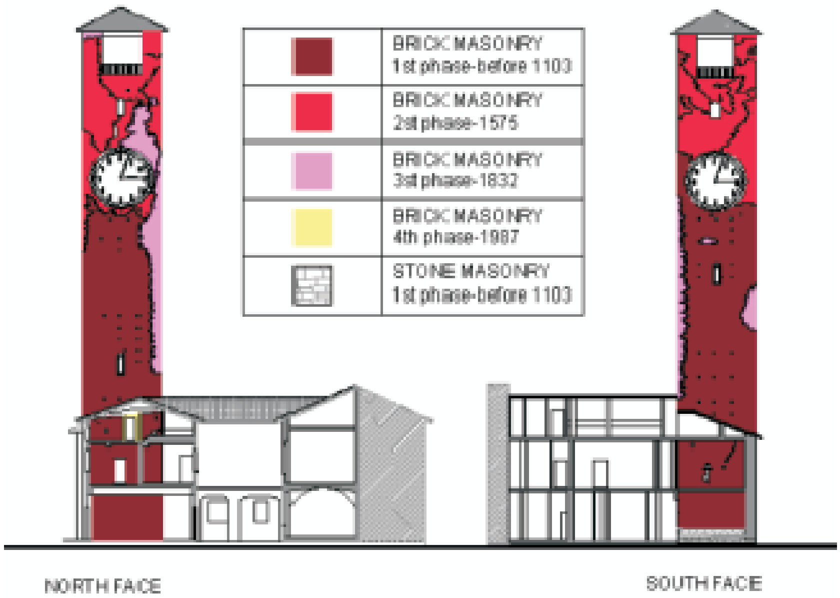

Fig. 3 Construction phases of the Tower (from (Dusi *et al*. 2007))

3. The monitoring campaign

The Tower was monitored with 3D velocimetric sensors (Figs. 4 and 5) with natural period of either 5 s (Lennartz Le3D/5s) or 1 s (Sercel Mark L4C) and sensitivity of 400 and 165 Volt/m/s, respectively. Data were recorded at 125 Hz sampling rate by 24 bits Lennartz M24 data loggers whose synchronization time was provided by a GPS system. The chosen data acquisition full scales ensures non saturated recordings up to 0.003 m/s and an optimal signal resolution even for the quietest ambient noise. Sensors were oriented parallel to the Tower walls, by paying particular attention to find the best coupling system (sensor-structures) while avoiding any damage to the structure.

Fig. 4 TS2 station

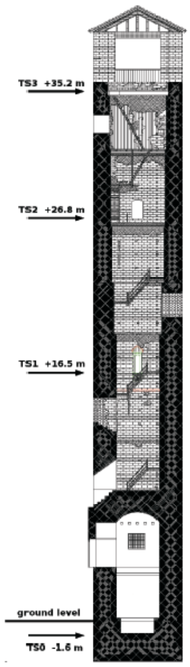

Fig. 5 Location of the sensor devices

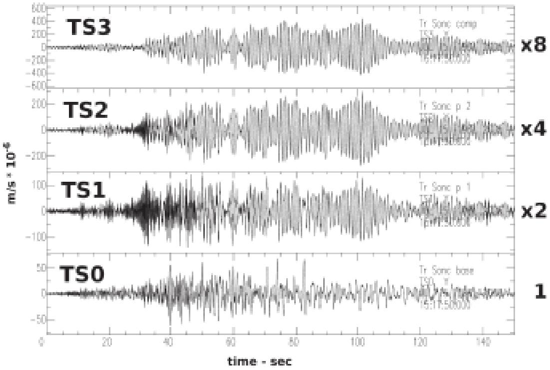

Fig. 6 Velocimeter records obtained at the stations shown in Fig. 5 (Y component (see Fig. 2)) on July 15, 2005, during the recorded earthquake event

The experimental campaign was carried out from July 12, 2005 to July 27, 2005. On July 15, 2005 the instruments recorded a ML 4.4 earthquake located at an epicentral distance of 221 km (Fig. 6).

The collected data was first used to calibrate and to validate a numerical model of the structural system (Casciati and Al-Saleh, 2010, Casciati and Faravelli 2010). For this purpose short records were selected and processed. The work of completing the signal processing for all the records required time and the main conclusions are reported in the next section.

4. First and second mode in the Y direction: frequency variability

The 1st and 2nd vibration natural frequency in the Y direction were evaluated by Fourier analysis of the recorded earthquake; as the green line shows (Fig. 7) TS1 and TS3 stations give exactly the same results as far as the 1st mode is concerned, a slight difference could be observed on the 2nd mode.

The blue line on the same graphs evidences the 2 modes as obtained by microtremors analysis. The data processing has been made following the procedure established in the European Project SESAME (SESAME, 2004).

A few details are added. Fig. 7 compares the analyses conducted in the frequency domain on two different data sets: the record of the seismic event in Fig. 6 and some recorded time series of environmental noise.

The seismic record refers to the Ml 4.4 event. Before entering the analysis steps, the data were first corrected by the instrumental response and then by using a bandpass filter between 0.1 and 12 Hz. The output of this process is drawn in Fig. 6.

For this first set of data the spectral ratios reported in Fig. 7 of the seismic event were computed as follows:

1. instrumental response correction, since two different kinds of sensors did acquire the four records;

2. Fourier transforms on the time window between 30 and 145 seconds from the time histories in Fig. 6;
3. spectral smoothing on the log-frequency: a triangular window of given half-width is used. The half-width is selected to be 0.006 times the frequency value;
4. computation of the spectral ratios for sites 3 and 1 with respect to site 0: in the upper box the Y component of the signals recorded in station 3 is used, while the same component in station 1 characterizes the lower box;
5. normalization to the maximum value of the spectral ratio.

The ambient noise spectra in Fig. 7 were computed by the following steps:
1. selection of a time series of ambient noise, recorded soon after the seismic event, of duration one hour;
2. instrumental response correction;
3. selection of *N* windows (of duration 130 seconds each) with no sharp transient;
4. Fourier transform
5. spectral smoothing as above;
6. evaluation of the mean spectra over the N samples;
7. normalization to the maximum value of the spectral ratio.

The technique of spectral ratio between the stations TS1, TS2, TS3 and the ground station TS0, situated inside the tower was repeated and consistent results were found.

5. The natural frequency wandering

The results of Fig. 8 give evidence of a daily variation of about 2% (mean value) in both the 1st and 2nd mode frequencies along the Y direction.

The mean and standard deviation of the quantities F0 and F1 plotted in Fig. 8 were computed at any hour following the steps below:
1. F0 and F1 of each hour refer to the time series of ambient noise of duration one hour;
2. the instrumental response correction is first carried out;
3. *N* windows (of duration 130 seconds each) with no sharp transient are selected;
4. the Fourier transform is applied;
5. a spectral smoothing is introduced by using a triangular window of half-width of 0.05 Hz;
6. identification of the frequencies of the spectral maxima in the ranges : 0.4 – 2.0 Hz (F0) and 3.5 - 4.5 Hz (F1);
7. mean and standard deviation of F0 and F1 are computed from the *N* windows.

The frequency increases during the day and drops at night-time. The Soncino Tower is a monument and there is not human activity inside.

It is worth noting that this variability is still observable when including also the standard deviation. The 1st and 2nd modes exhibit a similar behavior (Fig. 8, panel C) and show a close relation with the temperature.

A variation up to T=10°C changes the rheological properties of the material of construction to produce a variation of vibration modes sufficient to be detected by the adopted micro-tremor technique.

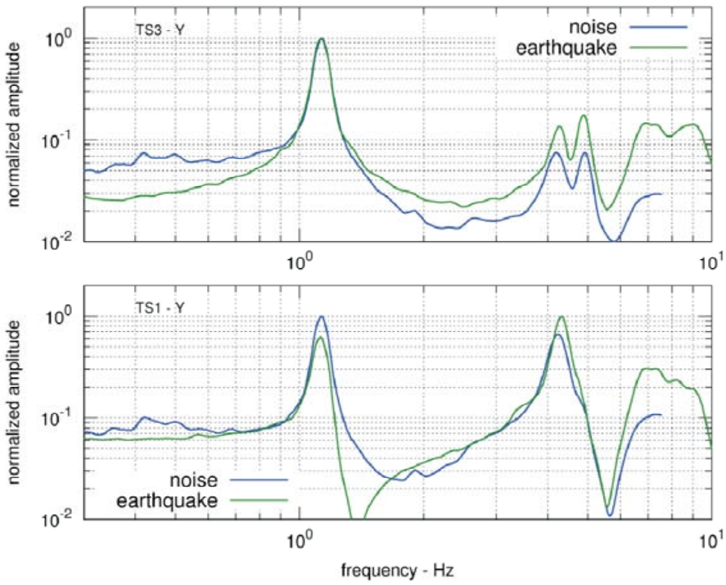

Fig. 7 Normalized spectra at TS3 and TS1 stations obtained by the records of the July 15, 2005 earthquake and the records of the Y component of noise. The word noise is preserved for consistency with the text, but here it assume the physical meaning of structural response to an excitation

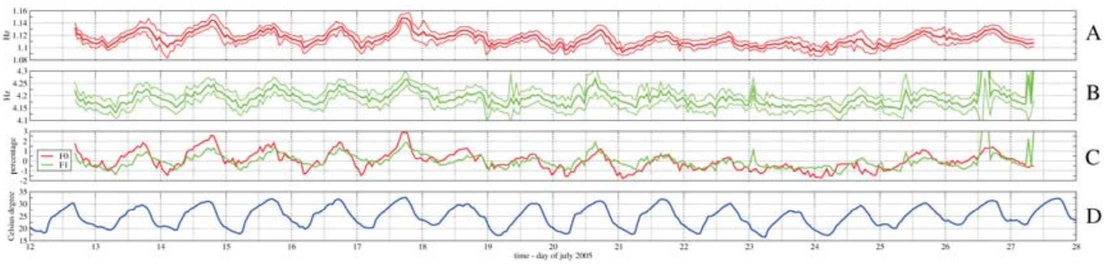

Fig. 8 The common abscissa for the four graphs is the time expressed in days of the month of July of 2005, when the experimental campaign was carried out. The graphs in the ordinates are:

A. Frequency (F0) in Hz of the first fundamental mode in the Y direction (Y component). The three lines are, from the bottom to the top, the mean minus one standard deviation, the mean and the mean plus one standard deviation;

B. Frequency (F1) in Hz of the second fundamental mode in the Y direction (Y component). The three lines are, from the bottom to the top, the mean minus one standard deviation, the mean and the mean plus one standard deviation;

C. Percentage of variation of 1st and 2nd mode frequencies (F0 and F1, respectively) with respect to the mean values.

Temperature recorded in Soncino by ARPA Lombardia (http://ita.arpalombardia.it/meteo.meteo.asp), close to the Soncino Tower

5. Conclusions

From the data available thanks to an experimental campaign held in July 2005 on the medieval civic tower of Soncino, it was possible to emphasize the well-known correlation between the system natural frequencies and the temperature and mainly to quantify it.

As a general recommendation one should carry any experimental text at least for a couple of days, but for very important structures the winter-summer variation should also be considered. When this long monitoring is not possible, the designer should at least account the variability with temperature in a statistical sense.

Of course, different causes as the humidity changes and/or the variation of the underground water level should also be carefully considered.

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Appendix

The operating temperature range of the used sensors is (-15, 50°C). However some device parameters, as the natural frequency, the damping and the sensitivity, could be affected by the temperature.

But the analyses carried out have as target the frequency of the maximum spectral value. In other words one is not interested in the absolute value of the spectrum and/or in its possible modification due to temperature changes.

As said, positions TS1 and TS3 were equipped with two kinds of devices:

1. TS1 with a Lennartz Le3D/5s: it is an active sensor with natural frequency of 0.2 Hz obtained by an electronic device that changes the response of a 2.0 Hz sensor;

1. TS3 with a Mark P. L4/C: it is a passive sensor with natural frequency of 1.0 Hz.

Fig. 9 shows the variation of frequency F0 as observed at the sites TS1 and TS3 in the X and Y directions. The plots give evidence that:

- the variation of F0 is significantly different between the two components of the same sensor
- the values of F0 look to be quite similar at the two sites

In case the F0 variations were due to the effect of the temperature on the sensors, one would have expected a similar variation on the two components and a different variation between the two sites due to the different nature of the devices in the two positions.

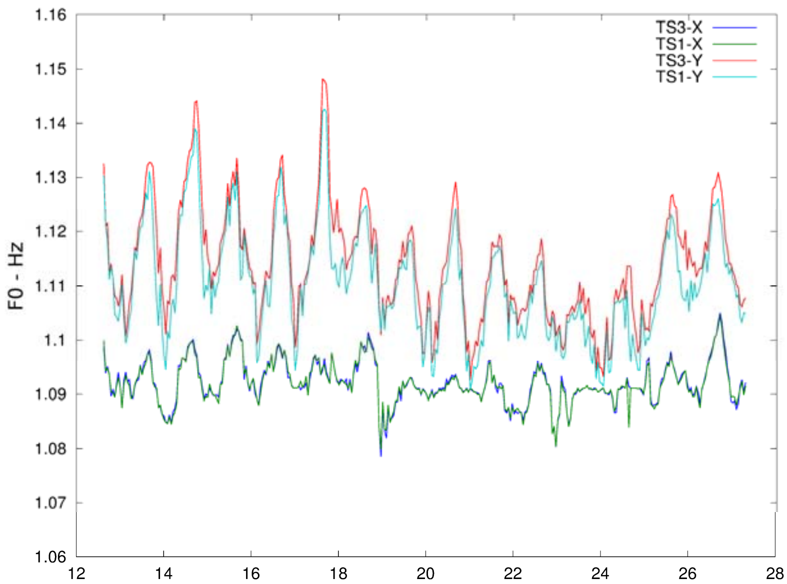

Fig. 9 Variation of frequency F0 as observed at the sites TS1 and TS3 in the X and Y directions