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Post-earthquake continuous dynamic monitoring of the *Gabbia Tower* in Mantua, Italy

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HIGHLIGHTS

- Evaluation of the dynamic characteristics of a masonry tower using OMA.
- Installation of a simple continuous dynamic monitoring system in the tower.
- Assessment of the effects of changing temperature on the natural frequencies.
- Identification of earthquake-induced damage from natural frequency shifts.
- Key role of dynamic monitoring in the diagnosis of historic masonry towers.

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ABSTRACT

The *Gabbia Tower*, about 54.0 m high and dating back to the XIII century, is the tallest tower in Mantua, overlooking the historic centre listed within the UNESCO Heritage. After the seismic sequence of May 2012 in Italy, an extensive research program was carried out to assess the structural condition of the tower. The post-earthquake investigation (including direct survey, historic and documentary research, testing of materials and ambient vibration tests) highlighted the poor state of preservation of the upper part of the building and suggested the installation of a dynamic monitoring system to evaluate the response of the tower to the expected sequence of far-field earthquakes and check the possible evolution of the structural behavior. After a brief description of the tower and the post-earthquake survey, the paper presents the results of the continuous dynamic monitoring for a period of 8 months, highlighting the effect of temperature on automatically identified natural frequencies, the practical feasibility of damage detection methods based on natural frequencies shifts and the key role of permanent dynamic monitoring in the diagnosis of the investigated historic building.

1. Introduction

Ambient vibration testing (AVT) and continuous monitoring of the structural response under ambient excitation are well-known non-destructive methodologies, generally aimed at identifying the dynamic characteristics of a structure from output-only records using operational modal analysis (OMA) techniques (see e.g. [1]).

Although AVT has become the primary modal testing method of civil engineering structures, its application to historic structures is still quite limited [2–16]. On the other hand, AVT and Structural Health Monitoring (SHM) using OMA are especially suitable to Cultural Heritage structures because of the fully non destructive and sustainable way of testing, that is performed by just measuring the dynamic response under ambient excitation and does not involve additional loads rather than those associated to normal operational conditions. It is indeed true that the response of historic buildings to ambient excitation is generally low (because the historical urban centers are often closed to road traffic) but this cannot be considered a prohibitive issue as highly sensitive and relatively inexpensive accelerometers are currently available on the market.

AVTs have been performed more frequently to investigate the dynamic behavior of ancient masonry towers [3–5,8,9,11–14,16] as these very common Cultural Heritage structures, that are usually slender and subjected to significant dead loads, might exhibit

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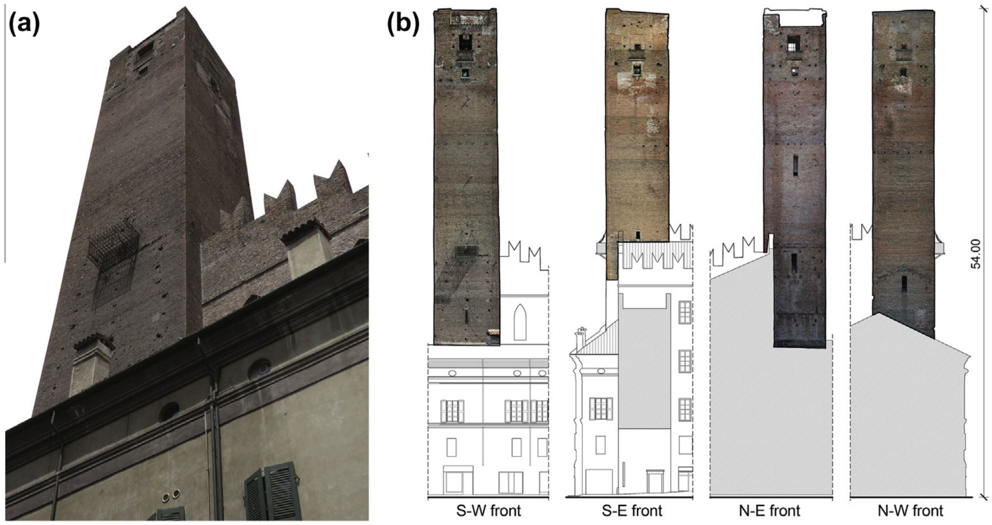

Fig. 1. (a) South-West view of the *Gabbia Tower*; (b) fronts of the tower (dimensions in m).

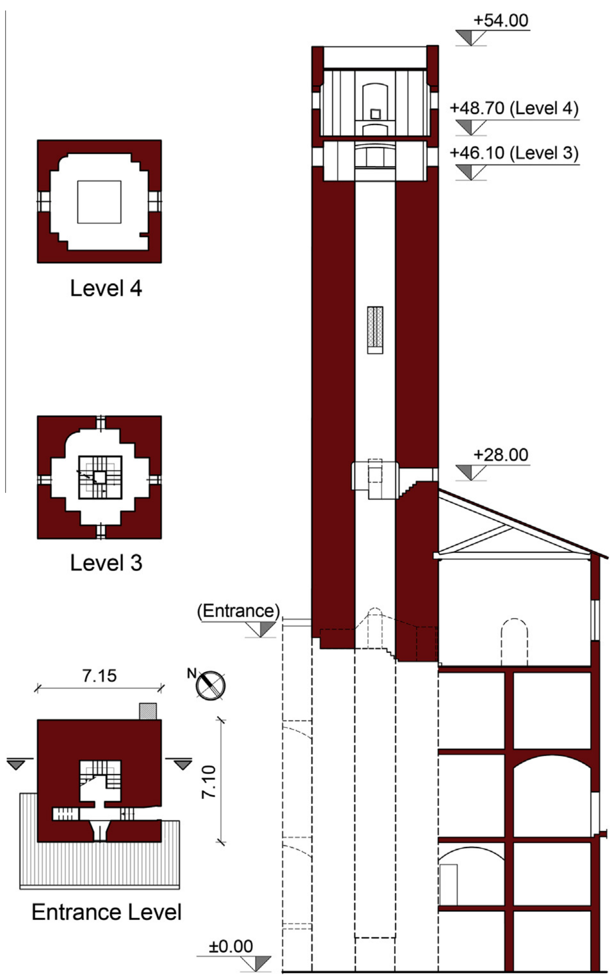

Fig. 2. Section of the tower (dimensions in m).

high sensitivity to dynamic actions, such as traffic-induced micro-tremors, swinging of bells [4,12,14], wind and earthquakes. In addition, the cantilever-like behavior of towers suggests the use of simple dynamic monitoring systems, consisting of few sensors installed in the upper part of the structure, with preventive conservation and/or SHM purposes [9,13,14].

The paper presents the results of a continuous dynamic monitoring program carried out on the historic *Gabbia Tower* in Mantua, Italy [17]. This project follows an extensive diagnostic investigation [18] carried out, between July and November 2012, to assess the state of preservation of the tower after the Italian seismic events of May 2012. The diagnostic procedures included detailed visual inspection and geometric survey, single and double flat jack tests, pulse sonic tests, laboratory tests on sampled materials and preliminary AVTs.

The results of the post-earthquake investigation [18] highlighted the poor structural condition and the high vulnerability of the upper part of the tower, pointing out the need for structural interventions to be carried out. Furthermore, it was decided to install a simple dynamic monitoring system in the tower, as a part of the health monitoring process helping the preservation of the historic building. The instrumentation installed inside the tower consists of a 4-channel data acquisition board, with 3 piezoelectric accelerometers and 1 temperature sensor. A binary file, containing 3 acceleration time series (sampled at 200 Hz) and the temperature data, is created every hour, stored in an industrial PC on site and transmitted to Politecnico di Milano for being processed.

The main objectives of the continuous dynamic monitoring are: (a) evaluating the dynamic response of the tower to the expected sequence of far-field earthquakes; (b) evaluating the effects of temperature on the natural frequencies of the building [9,13,14]; (c) detecting any possible anomaly or change in the structural behavior. Furthermore, another possible long-term goal is evaluating the effects of the future strengthening intervention.

After a brief description of the investigated tower and the results of the post-earthquake assessment, full details are given in the paper on the monitoring system, the methodologies used to process the collected data, the effects of far-field earthquakes and the results of the continuous dynamic monitoring for a period of 8 months.

2. The Gabbia Tower in Mantua, Italy

2.1. Description of the tower and historic background

The *Gabbia Tower* (Figs. 1 and 2) [17], about 54.0 m high, is the tallest tower in Mantua and is named after the hanged dock built in the XVI century on the S-W front and originally used as open-air jail.