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Original article

Multisensor surveys of tall historical buildings in high seismic hazard areas before and during a seismic sequence

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ABSTRACT

A seismic sequence that included a moment magnitude $M_W = 5.9$ earthquake struck three regions of Northern Italy (Emilia Romagna, Veneto and Lombardy) in May–June 2012. The sequence caused significant damage to several historical buildings and in some cases caused complete structural collapse. Cracks appeared in the belfry and cusp of the 69 m high, ~3° leaning bell tower of Ficarolo (Rovigo). A project aimed at studying the geometry of the tower, possible local seismic amplification and soil-structure interaction began in early 2013 before the earthquake. The data were provided by terrestrial laser scanning, low-cost operational modal analysis and geophysical measurements. The repetition of the surveys during and after the seismic sequence, which was augmented by thermal imaging measurements, allowed an evaluation of the changes caused by the earthquake. In addition to an evaluation of the damage, the data allowed the development of a method based on fast and relatively low-cost measurements that provide useful information for cultural heritage management purposes. The results highlighted that the surveys can be carried out during a seismic emergency and that preventive measures can be carried out under reasonable time and budget constraints in high seismic hazard areas.

1. Research aim

The 69-m high bell tower of Ficarolo (Rovigo province, Northern Italy) leans at a significant angle (~3° in the shaft). To characterize the tower's geometry in detail and evaluate possible soil-structure interaction (SSI), terrestrial laser scanning (TLS), simplified operational modal analysis (OMA) and geophysical surveys were performed at the beginning of 2012. After the Emilia Romagna seismic sequence (May–June 2012), new surveys were performed, and infrared thermography (IRT) measurements were also collected. A comparison between the data acquired before and after the seismic sequence led to two main results:

- an estimate of earthquake-induced damage to the bell tower;
- an evaluation of the amount of information that can be obtained by fast and relatively low-cost measurements that can be repeated during earthquake emergencies.

The second point is particularly important from the viewpoint of cultural heritage preservation, particularly in Italy, where many historical buildings are located in areas of high seismic hazard.

2. Introduction

Good cultural heritage management requires the periodic evaluation of the condition of historical buildings to highlight possible needs for remediation and restoration, particularly in areas of significant seismic risk. Such evaluations require data from several observational techniques, including non-destructive testing (NDT) methods and those that have minimal impacts on the structure.

Accurate geometric modeling of a historical building provides information that is useful for cultural heritage preservation [1]. In particular, data provided by TLS allow the generation of a detailed 3D model of a complex building with an accuracy of ~1.5 cm. Therefore, it is possible to evaluate deviations from the expected shape of the structure. If multitemporal data are available, variations in shape can be assessed [2]. For example, TLS data allow the detailed characterization of the shape of a slender leaning tower [3].

The IRT, or thermal imaging, is able to detect near surface defects or features of a masonry structure [4]. Examples of integrated use of IRT and TLS also exists. In particular, [5] shows a technique aimed at IRT data mapping on TLS-based digital model for building

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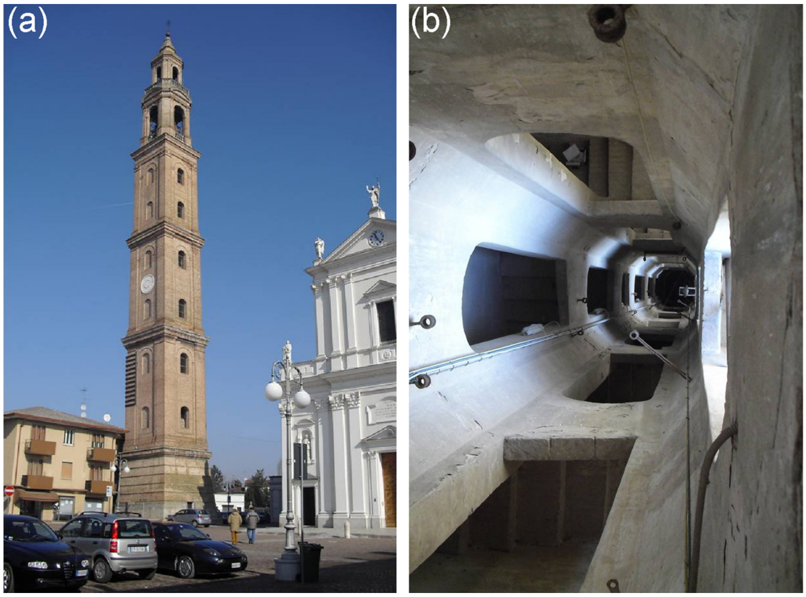

Fig. 1. Ficarolo bell tower: a: view from the church square; b: internal view of double shaft.

diagnostics purposes. The key factor of IRT is the recognition of differences in the thermal transfer efficiency between different parts of the object, which can be related to such factors as changes in material properties, voids, or water percolation behind the surface.

Experimental modal analysis (EMA) is based on the evaluation of the response of a structure to vibrations and is aimed at evaluating the structure's natural frequencies and the corresponding modal shapes and damping. These characteristics can change significantly as structural damage occurs [6]. The output-only EMA, or operational modal analysis (OMA), which uses ambient noise as the vibration source, also provides reasonable quality results [7].

The ground is also characterized by natural frequencies that depend on the stratigraphic setting. These frequencies can be used to evaluate seismic amplification both at the scales of a town and of a single building for seismic microzonation. Moreover, if a low order natural frequency of a building is similar to a natural frequency of the ground, soil-structure interaction (SSI) can cause other amplification effects [8].

Each of these techniques is able to quickly provide important and accurate but generally incomplete information about the conditions of a historical building and its interaction with the ground. To obtain a reliable and sufficiently complete assessment of these conditions, the data provided by these techniques must be used together.

3. The Ficarolo bell tower

The architect Gaetano Barbieri designed the Ficarolo bell tower (BT) (Fig. 1) to complete the S. Antonino Martire Catholic church, which was built between 1763 and 1772. Construction of the BT began in 1777, but stability problems, including partial sinking of the foundation and leaning of the structure, interrupted construction. The tower was completed after changing the design and allowing the ground to settle naturally. To partially compensate for the inclination, the axis of the belfry and cusp was designed to be unaligned with the shaft, leading to a curved shape of the tower.

The elegant brick masonry BT has a double shaft with a staircase between the inner and outer shafts (Fig. 1b), heavily protruding cornices that subdivide the shaft into three equal parts, each of which with two windows that open towards the church's square, and corners of Doric-Tuscan pillars. The current mean leaning angles are approximately 2.6–3° for the shaft and 1.9–2.2° for the belfry and cusp. The corresponding out-of-plumbs are approximately 2.4 m for the 46-m high shaft and 3.1 m for the cusp apex, which is located 66 m above the ground. The total height of the tower, including the cross, is 69 m. Because the combination of height and leaning angle is visually impressive, Ficarolo is also known as the "Pisa of Polesine" (Polesine is the Venetian bank of the Po River), referring to the well-known 55-m high, 4° leaning tower of Pisa.

Because the leaning angle has increased with time, leading to worries about the long-term stability of the structure, stabilization work was carried out in 2003. In particular, micro-piles were placed to consolidate the foundations. A straight pendulum was also placed to continuously measure the leaning angle of the shaft. This instrument showed that the leaning angle did not change until the 2012 seismic sequence occurred. The inclinometer showed that the base was unchanged and that the upper part of the shaft had moved by 2.5 cm. More information about the 2012 seismic sequence can be found in the Online Supplementary Material (OSM), Section OSM1.

4. TLS surveys and geometric analysis

4.1. Data acquisition, georeferencing and modeling

Three surveys were carried out on April 10 (before the earthquake), May 26 and June 8, 2012. An Optech ILRIS 3D ER instrument [9] was used in all three surveys, and similar viewpoints (VPs) were used so the data could be compared (Fig. 2). The ILRIS is a time-of-flight (TOF) instrument that can acquire data at distances between 3 m and 1500 m with a 2.5 kHz pulse repetition frequency and 40 × 40° field of view (FOV). The accuracy of single point measurements is ~7 mm at 100 m, but the corresponding modeling accuracy is ~3–4 mm. The choice of an appropriate sampling step leads to a spatial resolution better than 20 mm at a distance of 100 m [10]. The climatic conditions were similar for each survey and, in particular, wind was always absent.

To cover the entire BT at conditions that were not excessively far from normal incidence, the scans were taken from five VPs at distances of 45 m to 102 m and at spatial sampling steps of 0.9 cm to 1.6 cm (Fig. 2). Three scans, which focused on three partially overlapping vertical portions of the BT, were taken from VPs 1, 2 and