Journal of Cultural Heritage 15 (2014) 275–282

Available online at
SciVerse ScienceDirect
www.sciencedirect.com

Elsevier Masson France
EM|consulte
www.em-consulte.com/en

Original article

Dynamic identification of historic masonry towers through an expeditious and no-contact approach: Application to the "Torre del Mangia" in Siena (Italy)

Massimiliano Pieraccini [a,*], Devis Dei [a], Michele Betti [b], Gianni Bartoli [b], Grazia Tucci [b], Nadia Guardini [b]

[a] DINFO Department of Information Engineering, University of Florence, via Santa Marta 3, 50139 Florence, Italy
[b] DICeA Department of Civil and Environmental Engineering, University of Florence, via Santa Marta 3, 50139 Florence, Italy

ARTICLE INFO

Article history:
Received 18 March 2013
Accepted 9 July 2013
Available online 2 August 2013

Keywords:
Remote sensing
Microwave interferometry
Laser scanning techniques
Heritage conservation
FE modeling
Dynamic identification.

ABSTRACT

The paper presents a synergic and multidisciplinary approach where laser scanner survey, radar interferometric monitoring and finite element (FE) numerical modelling are used for expeditious and no-contact dynamic identification of monumental masonry towers. The methodology is applied to a real case of great historical interest: the "Torre del Mangia" (Mangia's tower) in Siena (Italy). The tower geometry was acquired through Terrestrial Laser Scanning (TLS) techniques. The tower oscillations were detected using an interferometric radar in "Piazza del Campo", the square facing the Mangia's Tower, along three alignments, and movement of the structure at several heights were recorded. A FE model, built on the basis of the geometry acquired through the TLS, was used to interpret and verify the physical meaning of the experimental results. Through the discussion of the case study, the paper shows that the proposed approach can be considered as an effective and expeditious method for assessing the dynamic behavior of monumental buildings (and to plan interventions) on territorial scale.

1. Research aims

Health monitoring of historic masonry towers, because of their intrinsic vulnerability, is a priority in Italy as in many other countries. A complete structural analysis of such architectonic structures need preliminarily the identification and characterization of the vibration modes, i.e. the dynamic behavior of the structure. The aim of this paper is to present an expeditious method, based on laser scanner and interferometric radar, for dynamic identification of masonry towers that could be used even on territorial scale.

2. Introduction

The number of ancient masonry towers in Europe and worldwide is huge. Each of these deserves a specific structural analysis, based on an accurate survey and a series of dynamic tests, to assess its safety level with respect to both static and dynamic loads (i.e. the assessment of their static and seismic vulnerability) [1]. The experimental survey, if developed with traditional techniques, could be expensive and time-consuming; moreover in some cases the need to preserve the integrity of historic constructions makes difficult the development of an extensive experimental investigation with the traditional techniques. Nevertheless local authorities and agencies devoted to Cultural Heritage preservation need complete and updated databases for planning interventions on territorial scale and also for preventing possible damages. For these reasons there is a great interest in expeditious and no-contact methods. Laser scanner is undoubtedly a versatile and powerful tool for rapid no-contact survey, but does not provide information about the dynamic characteristics of the structure under test. Interferometer radar is a more recent equipment [2–5] able to remotely detect the dynamic behavior of a large structure [6,7], but it does not provide an image able to be used as a geometric survey. The combination of both provides rapid survey and dynamic characterization operating quickly without physical contact with the structure under test. The information obtained through laser scanner and interferometer radar need to be interpreted according to a model of the historic construction able to reproduce and to assess its structural behavior. In this context the Finite Element (FE) techniques has been shown to be an effective tool for the interpretation of physical behavior of historic *fabricæ* [1,8,9]. FE models can be used as a numerical laboratory where the sensitivity of the results to unknown input material parameters, boundary conditions

* Corresponding author. Tel.: +39 (0) 554796273.
E-mail addresses: massimiliano.pieraccini@unifi.it (M. Pieraccini), devis.dei@unifi.it (D. Dei), mbetti@dicea.unifi.it (M. Betti), gbartoli@dicea.unifi.it (G. Bartoli), grazia.tucci@unifi.it (G. Tucci), nadia.guardini@unifi.it (N. Guardini).

1296-2074/$ – see front matter
http://dx.doi.org/10.1016/j.culher.2013.07.006

and actions can be efficiently analyzed, offering invaluable information in the understanding of in-situ survey and dynamic monitoring. In addition, as any damage changes the physical properties and then the modal response changes accordingly, a dynamic investigation repeated over time combined with a FE model of the structure (able to assess the sensitivity of the modal parameters according to changes in the structural system) can be used for a Structural Health Monitoring (SHM) [10,11].

Based on this background, the paper proposes a synergic and multidisciplinary approach composed of laser scanner survey, radar interferometric monitoring and FE numerical modeling for expeditious and no-contact dynamic identification of monumental towers. The methodology is applied to a real case of great historical interest: the “Torre del Mangia” (Mangia’s tower) in Siena (Italy). The paper is organized as follows: in section 2 the main historical and architectonical features of the tower are briefly sketched. In section 3 the laser scanning survey together with the main results is reported, while the experimental dynamic investigation by means of the interferometer radar is described in section 4. Next section 5, finally, describes the identified FE model employed to interpret the results of the experimental investigation and to assess the actual dynamic behavior of the tower.

3. The Mangia’s tower

The Mangia’s tower in Siena is famous all over the world together with the shell-shaped square (named “Piazza del Campo”) in front of it. The tower’s curious name comes from the nickname of the first bell-ringer.

It is one of the tallest Italian medieval towers, about 88 m height from the ground level on the northern corner, and it has a square section of about 7 m. The tower is substantially a masonry structure with a belfry in white travertine. Over the belfry a metallic structure supports the huge bell named “Campanone” (Big bell). Light rods bring the overall height of the tower up to about 102 m.

The technical and executive plan of the tower is attributed to Muccio and Francesco di Rinaldo, masters from Perugia, but there is no definite information about neither the construction stages nor their chronology. What is certain is that the laying of the foundation stones took place in 1325, simultaneously at the beginning of the last enlargement phase of the Palace, and it is assumed that the travertine crowning dates back to 1348 [12], at the end of construction works. The tower and the Palace became a model for the later civic buildings, marking the transition from the fortress to the palace; therefore they play a very important role in the history of architecture [13].

During its life, some restoration and maintenance interventions were carried out in order to fix the damages caused by lightning and fires. However, the tower seems to have stood up well over the centuries, even against a disastrous earthquake that hit Siena in 1798, which did not cause substantial damages to the structure.

4. The architectural survey

The survey of the tower was carried out through Terrestrial Laser Scanning (TLS) techniques. Three-dimensional scanning techniques combine accuracy and sampling density. This allows the creation of a three-dimensional database from which the needed information can be extracted [14–16].

The tower’s geometry and its position within the historical center required special attentions. The most critical aspect is related to the tower’s height and to the non-availability of enough elevated accessible places from which data could be acquired. The tower’s sides overlooking the market square and the City Hall are within the buildings up to about 20 m in height while the visible part is about 68 m high. The other two tower’s sides are outside the buildings and they are about 88 m high (towards Piazza del Campo and via Salicotto). These conditions led to use two different instruments: a phase-based scanner (Leica HDS6000) for the lower sides and a pulse-based scanner (RIEGL LMS-Z420i) for the taller ones (Fig. 1). The range of the first is not enough to reach the top of the higher sides, but the later has lower resolution. The phase-based scanner has a nominal accuracy on positioning of $\pm$ 10 mm (up to 50 m distance, 1sigma) and sampling density of about 1.5 cm (at 100 m distance). The pulse-based scanner has a nominal accuracy on positioning ranging from $\pm$ 5 mm to $\pm$ 10 mm ($\pm$ 20 ppm up to 100 m distance) while the sampling density is about 5 cm (at 100 m distance).

Data have been referred to a local reference system determined by a topographic network. The alignment was solved at first with an automatic procedure using topographic targets as reference points. After that, an ICP algorithm was performed to add constraints between scans couples. The root mean square error of the alignment is lower than 1 cm. The overlapping percentage between point clouds is dependent on the scan positions, as we can identify two groups of point clouds–the one in the square and the one on the reverse side of the tower. The overlapping percentage is about 70% between scans belonging to the same group. We made this choice in order to guarantee the completeness of data and to reduce lacks of information. The overlapping between the two data sets is whereas about 10%. This difference is due to the conformation of the site.

A first analysis of the fronts showed that the exterior surfaces are out of plumb and the tower is tilted towards North. These preliminary results had led to perform more detailed analyses.

From the 3D points model of the tower’s upper part — located on top of the building — ten horizontal sections were extracted from every 4 m vertical distance. Once imported into a CAD-software, maintaining their referencing, the geometric center of each one was positioned, in order to observe its relative displacement between different levels. The obtained graph is shown on Fig. 2. The detected out-of-plumb, although interesting from a geometrical point of view, is very small: 18 cm in the North/East-South/West direction, 8 cm in the North/West-South/East direction. This corresponds to about 0.31° that, taking into account the aim of the structural analyses herein developed, can be considered as not significant. Nevertheless the possibility to have instruments that expeditiously and precisely allow for the correct evaluation of the actual tilt of such typology of structures can be very important in those cases where it becomes significant from a structural point of view.

5. The interferometric radar measurements

In order to detect the dynamic characteristics of the tower under environmental loads (mainly a light wind as downtown is closed to vehicular traffic), a radar survey was planned in May 2012 to record ambient vibrations. The measurements were carried out by placing the radar in Piazza del Campo, facing the Mangia’s Tower, at the three positions indicated with the letters A, B, C in Fig. 3. The aim of the measurement is to observe the movement of the structure at several heights, along both the direction orthogonal to the faces of the structure and one of the two diagonals. Each measurement position provides information about a projection of the real movement and by combining all information an estimate of the mode shape and the direction of the movement at each resonance frequency can be obtained. As measurements from different points of view were carried out at different times, possible changes on the environmental conditions (noise sources, weather conditions,