Engineering Structures 52 (2013) 718–733

Contents lists available at SciVerse ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

# *In situ* static and dynamic investigations on the "*Torre Grossa*" masonry tower

Gianni Bartoli, Michele Betti *, Saverio Giordano

*University of Florence, Department of Civil and Environmental Engineering (DICeA), Via di Santa Marta, 3, I-50139 Florence, Italy*

ARTICLE INFO

*Article history:*
Received 12 November 2012
Revised 22 January 2013
Accepted 28 January 2013
Available online 29 March 2013

*Keywords:*
Historical masonry tower
*In situ* non-destructive tests
Experimental analysis
FEM identification
Structural identification

ABSTRACT

Many ancient masonry towers represent one of the most relevant characteristics of both the Italian and the whole European territory. To preserve their cultural and economic value, they often call for a deeper investigation to assess their state of conservation. This paper offers a contribution to the issue of monitoring and analysis of monumental masonry tower, by discussing an experimental investigation survey made on an illustrative masonry tower: the Italian Medieval "*Torre Grossa*" (Big Tower) of San Gimignano in Toscana (Italy). The tower is part of the UNESCO cultural heritage after 1990 together with the city centre; it dates back to the thirteenth century and its height is about 55 m (one of the tallest masonry tower in Italy) with a square cross-section whose side is about 9.5 m. During the experimental campaign, both static and dynamic tests were performed. Static tests (flat-jack and laboratory test on cored specimens) were used to estimate the mechanical properties and the ultimate strength of masonry. Dynamic tests led to the measurements of the natural frequencies and corresponding modal shapes of the whole monument. By using the finite element technique, a 3D model of the tower was built (macro-modelling) and it was calibrated on the basis of the *in situ* investigation survey; the degree of restrain offered by the neighbouring buildings was estimated by tuning the numerical results with those obtained from the dynamic tests. The paper, by discussing the design and results of the experimental campaign, aims at offering a contribution to both the investigation and the structural behaviour of historic masonry towers providing useful hints to deepen the knowledge on their structural behaviour.



## 1. Introduction

Historic masonry buildings have a growing economic and social value in many countries. Preservation of the built heritage is considered an important issue in modern societies as, in addition to their historical interest, historical buildings significantly contribute to economy in a context where tourism has become a major industry. Preserving historic constructions is therefore not only a cultural requirement but also an economic and developmental demand [1]. Their conservation, together with their monitoring and structural safety assessment, has become an actual concern also due to some recent dramatic events (like, in Italy, the sudden collapse of the Civic Tower in Pavia [2,3] or the abrupt collapse of the Dome of the Noto Cathedral [4]).

While the structural behaviour of a new masonry construction is a relatively simple task (thanks both to the presence of standard codes and inherent literature), the prediction of the structural response of monumental buildings is a more challenging task due to different aspects [5,6]. At first, each monumental building is "by definition" a unique building, characterized by its own history (often resulting in a composite mixture of added or substituted structural elements, strongly interacting [7,8]). Moreover, the static and dynamic behaviour of ancient buildings is normally too complicated to be interpreted by simple mechanical models and usually cannot be reduced to any standard structural scheme because of the uncertainties that affect both the structural behaviour and the mechanical properties distribution. Therefore the assessment of the static and dynamic behaviour of historical masonry constructions poses important challenges to modern civil engineers and the study of these constructions must be undertaken through modern technologies and knowledge.

The above considerations enlighten the need of specific modelling, analysis and experimental strategies for each historic masonry construction. Engineers involved in the study of cultural heritage are called to have a particular care in the understanding of the historical process as modifications occurred through the building's history produced several uncertainties in the model definition (geometry, materials, connections, etc.). A correct structural evaluation should be based on a deep knowledge of: (i) building history and evolution, (ii) geometry, (iii) structural details, (iv) crack pattern and material damage map, (v) masonry construction technique and materials, (vi) material properties and (vii)

* Corresponding author. Tel.: +39 0554796326.
*E-mail addresses:* gianni.bartoli@unifi.it (G. Bartoli), mbetti@dicea.unifi.it (M. Betti), giordano@dicea.unifi.it (S. Giordano).

0141-0296/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.engstruct.2013.01.030

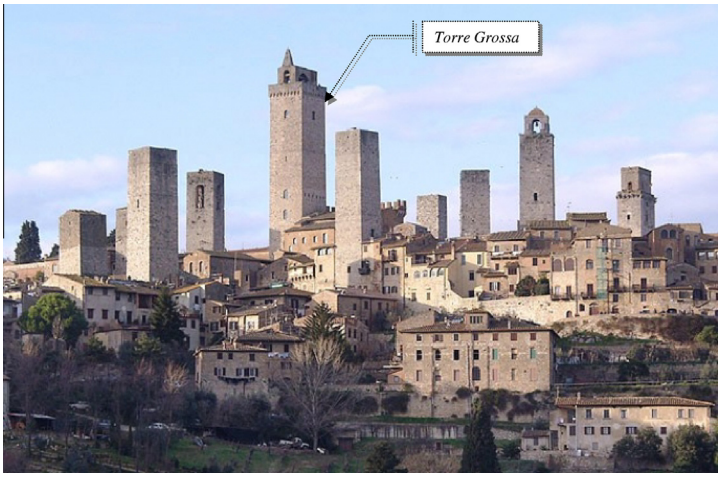


**Fig. 1.** San Gimignano's towers.

global behaviour [9,10]. This knowledge can be reached through both *in situ* and laboratory experimental investigations joined with structural analyses with appropriate models. As in most cases it is quite difficult to perform reliable and extensive quantitative strength evaluations, due to the difficulty of gathering experimental data on the mechanical properties of *in situ* materials [11,12], each experimental campaign requires a specific design aimed at assessing valuable results for structural assessment by identifying them with as fewer destructive and/or non-destructive tests as possible. All these aspects call for experienced analysts capable of combining advanced knowledge in the field and engineering skill [13].

In this context of growing interest towards cultural heritage, masonry towers represent a distinctive class of ancient masonry buildings. These buildings are widely disseminated on the Italian (and the European) territory and in the last decades their investigation and conservation have become an increasing concern, as is reflected by growing research and experimentation on this topic. Some recent examples of these researches are the Saint Andrea masonry bell tower in Venice (Italy) [14], the bell tower of the Monza's Cathedral (Italy) [15], the eighth-century masonry tower called Torre Sineo (Alba, Italy) [16,17], the bell tower of Nuestra Sra. de la Misericordia Church (Valencia, Spain) [18] and the bell tower of the Church of Santas Justa and Rufina in Orihuela (Alicante, Spain) [19]. As a general remark, all these studies involved both analytical and experimental analysis and they are composed by several complementary tasks. Starting from a field survey of the actual configuration (and, if present, of the crack pattern), non-destructive and/or slightly destructive tests (e.g. flat-jack tests, dynamic tests, sonic pulse velocity tests, thermography, etc.) and laboratory tests on cored samples are executed aimed at tuning a finite element model to be used to assess the vulnerability of the tower.

Based on this background, this paper illustrates the case study of the thirteenth century masonry tower named "*Torre Grossa*" (Big Tower; Fig. 1) in San Gimignano (Siena, Italy) discussing the design and reporting the results of an experimental *in situ* investigation. The *in situ* investigation was a field survey including non-destructive and slightly destructive tests, namely flat-jack tests, dynamic tests and extraction of some cored samples by the multi-layered masonry walls which were after used to perform some laboratory tests. The experimental tests were carried out to complement an extensive research program [20] planned to evaluate the global situation of the tower from the structural point of view, also because some concern due to the presence of some major cracks [21]. Static

**Fig. 2.** View of the tower with the neighbour "*Palazzo Comunale*" (Town Hall).

tests (single and double flat-jack performed at different positions both on the external and the internal surface of the masonry walls) were performed to assess the global structural behaviour (vertical compressive stresses) and the local masonry characteristics (mainly the elastic moduli of masonry walls). Dynamic tests, under artificially generated loads (by means of some vibrodynes and by using the bells' movements as excitators), were used to assess the tower's dynamic behaviour and to evaluate the degree of restraint