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Case study

Post-earthquake diagnostic investigation of a historic masonry tower

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ABSTRACT

The paper describes the methodology applied to assess the state of preservation of the tallest historic tower in Mantua, the Gabbia Tower, after the Italian earthquakes of May 2012. An extensive experimental programme – including geometric survey, visual inspections, ambient vibration tests, sonic and flat-jack tests – has been planned and carried out to support the future preservation actions of the tower. The paper focuses especially on the outcomes of on-site survey and dynamic tests and highlights the effectiveness of integrating the information obtained from these tests to assess the structural condition and seismic vulnerability of the tower. The adopted experimental methodology, generally suitable as a prompt diagnostic procedure, successfully detected the local vulnerabilities as well as the overall state of preservation of the tower and addressed the subsequent monitoring phase.

1. Introduction and research aims

The international debate on Cultural Heritage preservation generally agrees on the major role played by effective diagnostic survey in the structural assessment of historic buildings [1]. The diagnostic phase (i.e. the evaluation of the current health condition) – performed by collecting information on the characteristics of the building, the properties of materials, the historic transformation of the structures and existing damage – provides a sound basis for any further evaluation of the safety level [2] as well as for the definition of appropriate intervention measures.

The collected information should include accurate investigation of the actual geometry, survey of the crack pattern and local visual inspections: these tasks, joined to historic research, provide a first interpretation of the structural layout and reveal the presence of masonry discontinuities (generally associated to transformations of the building and/or repair), possible vulnerabilities and ageing issues. Visual inspections also suggest the positions that are more suitable for non-destructive (ND) or minor destructive (MD) tests and material sampling, necessary to evaluate the characteristics of the masonry and to explore local defects. Of course, the extension and deepening of the diagnostic phase is closely related to the observed local and global conditions of the building.

In the process of Architectural Heritage preservation, a still open issue is the linking between the information locally collected and the overall structural behaviour, especially in complex structures evolved over time. Within this context, ambient vibration testing (AVT) and operational modal analysis (OMA, i.e. the identification of modal parameters from ambient vibration responses) seem the most effective tools to support the structural assessment since they are capable of collecting information on the global modal characteristics (i.e. natural frequencies, mode shapes and modal damping ratios) [3–13] and might identify the presence and the position of damage [6,14,15]. In addition, AVT is a fully ND test, especially suitable to Cultural Heritage structures since the test is performed by just measuring the response to ambient excitation (micro-tremors, wind, etc.).

It should be noticed that AVT could be employed in prompt surveys (e.g. post-earthquake emergency) by using either traditional accelerometers mounted on outdoor walls or innovative non-contact sensors [16,17]. Furthermore, the results of AVT should represent the starting point of long-term dynamic monitoring [6,11,13] in order to perform vibration-based damage assessment or to evaluate the effects of repair interventions.

The paper presents the main results of a recent post-earthquake assessment of a masonry tower. The investigated tower (Fig. 1), about 54.0 m high and dating back to the XII century, is known as Gabbia Tower [18,19] and is the tallest tower in Mantua, Italy. The tower is a symbol of the Cultural Heritage in Mantua so that the fall of small masonry pieces from its upper part, reported during the

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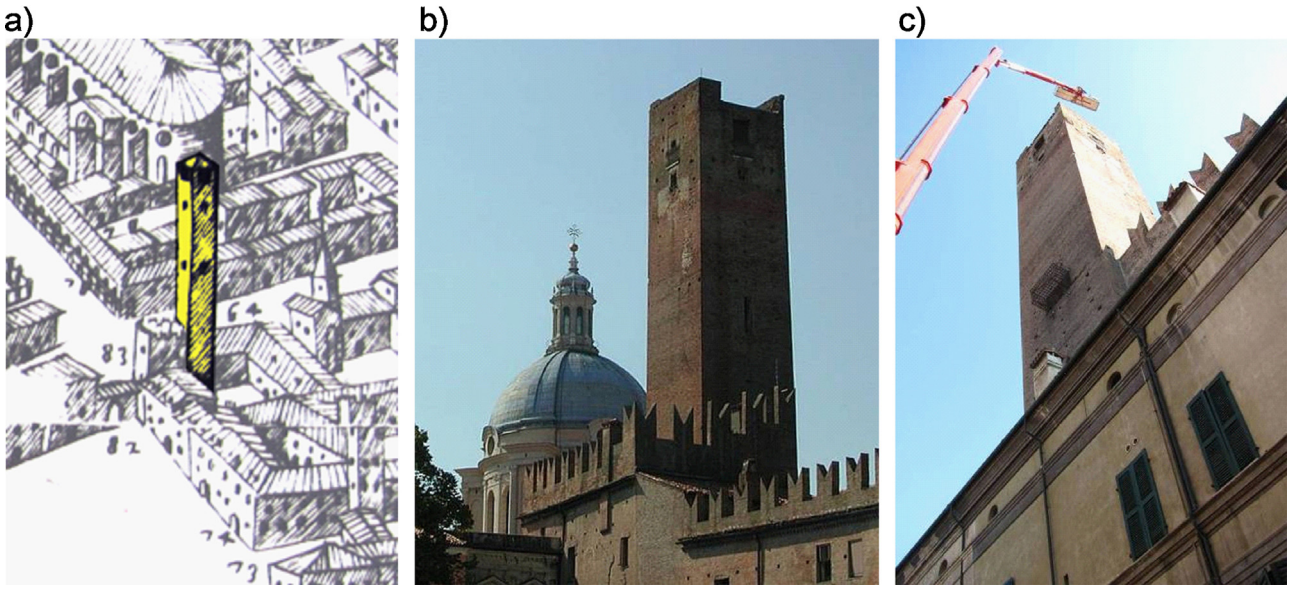

Fig. 1. The Gabbia Tower in Mantua, Italy. a: view of the XVII century [15]; b: recent view; c: view during the inspection (31/07/2012).

earthquake of 29/05/2012, provided strong motivations for deeply investigating the state of preservation and the seismic vulnerability of the building. Hence, an extensive research program was planned and performed to evaluate the structural condition of the tower.

After a brief description of the Gabbia Tower, the paper presents the results of the first part of the research, including: (a) historic and documentary research; (b) geometric survey and visual inspection of the bearing walls; (c) on-site survey of the crack pattern and structural discontinuities; (d) non-destructive and slightly destructive tests of materials on site; (e) ambient vibration tests.

The investigation is especially aimed at highlighting the key role of "global" testing methods, such as visual inspection and dynamic tests, in the diagnostic assessment of masonry towers. In the presented case study, visual inspection of all load-bearing walls clearly indicated that the upper part of the tower is characterized by the presence of several discontinuities due to the historic evolution of the building, local lack of connection and extensive masonry decay. The poor state of preservation of the same region was confirmed by the observed dynamic characteristics and one local mode involving the upper part of the tower was clearly identified by applying different OMA techniques to the response data collected for more than 24 hours on the historic building.

2. Description of the tower and historic background

The Gabbia Tower [18], about 54.0 m high, is the tallest tower in Mantua, overlooking the historic centre listed within the UNESCO Heritage (Figs. 1 and 2). As it can be observed in Fig. 1, it is part of the complex architecture of an important palace, evolved since the XIII century around the tower. Precious frescoes, dating back to XIV and XVI centuries, decorate the tower's fronts embedded in the palace, whereas in 1811 the interior walls of the tower were painted with refined decorations [19].

The tower has been of private ownership for long time and only in the 1980s it passed to the Mantua Municipality.

The tower, built in solid brick masonry, has nearly square plan and the load-bearing walls are about 2.4 m thick until the upper levels (Fig. 2), where the corner masonry section decreases to about 0.7 m. The top part of the building has a two level lodge, which hosted the observation and telegraph post, used for military and communication purposes during the XIX century and at the beginning of the XX century. A wooden staircase reached the lodge but it was no more in function since the 1990s, due to the lack of maintenance. The inner access to the tower was re-established only recently (October 2012) through provisional scaffoldings in order to allow visual inspection and geometric survey of the inner load-bearing walls.

Few historic documents are available on the tower and its evolution [19]. Despite the foundation date is unknown, some recent research dates it back to the late XII century and assumes that the construction was probably concluded in 1227. The tower was part of the defensive system of the Bonacolsi family, which governed Mantua at the time. According to the past building tradition of defensive structures, the entrance is not at the ground level but at a higher position. At present, the entrance to the tower is at about 17.7 m (Fig. 2) and the access to the lower portion and to the base of the building is not possible. In the XVI century, the Gabbia Tower was used as open-air jail, hosting a hanged dock on the S-W front (Figs. 1 and 2).

As previously pointed out, during the centuries a palace progressively evolved around the tower, complicating the geometry of the structure and the mutual links between the walls. In general, the load-bearing walls of the palace seem not effectively linked but just drawn to the tower's masonry walls, while the tower supports directly several floors and vaults.

No extensive information is available on the tower past interventions but the stratigraphic survey and the observation of the masonry texture reveals passing-through discontinuities in the upper part of the building, with those discontinuities being conceivably referable to the tower evolution phases. Traces of past structures are visible on all fronts (Fig. 3) and the presence of merlon-shaped discontinuities (Figs. 3 and 4) suggests modifications and successive adding in the upper part of the tower. Moreover, at about 8.0 m from the top, a clear change of the brick surface workmanship (the bricks of the lower part are superficially scratched) suggests a first addition (Fig. 5); in the same region concentrated changes of the masonry texture reveal local repair.

A first hypothesis, based on the surface discontinuity survey (Fig. 3), could recognize the following construction phases (which are very difficult to date): (i) erection of the main building until the height of 46 m (probably concluded in 1227); (ii) subsequent addition until the merlon level; (iii) adding of 4 corner piers

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