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Pre-diagnostic prompt investigation and static monitoring of a historic bell-tower

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HIGHLIGHTS

- Visual inspection revealing a weak structural layout of a masonry bell-tower.
- Evaluation of the fundamental period using microwave remote sensing.
- Installation of a static monitoring system in the bell-tower.
- Evaluation of the dynamic characteristics of the historic tower using OMA.
- Preliminary assessment of the environmental effects on lower natural frequencies.

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ABSTRACT

An extensive research program is currently in progress to assess the structural condition of the bell-tower of the Church *Santa Maria del Carrobiolo* in Monza, Italy and to address the preservation of the historic building. The research program was consequent to the direct survey of the tower, carried out within a wide cataloguing activity of the main religious buildings in Monza and highlighting a weak structural layout of the bell-tower. The paper presents the main results of the investigation program performed to date and including: (a) documentary research, systematic visual inspection on site and experimental evaluation of the fundamental period of the tower, carried out using an industrially engineered microwave interferometer; (b) installation of a static monitoring system aimed at surveying the opening of the main cracks, possibly related to the recent construction of an underground car park in the close neighbourhood of the church; (c) dynamic tests in operational conditions, performed using conventional high-sensitivity accelerometers with the twofold objective of validating a FE model of the tower and implementing the installation of a continuous dynamic monitoring system.

1. Introduction

The technical challenges of historic building preservation involve evaluating possible vulnerabilities as well as addressing damage mitigation and repair actions within a strategy of minimal intervention and maintenance. These objectives require deep knowledge of the materials and structure, the local and global state of preservation, the potential occurrence of damage and its causes. In order to fill the gap between the initial low knowledge and the complexity of historic structures, experimental investigations – including inspections, surveys, laboratory tests on sampled materials and on site tests – are required and recommended by Codes of Standards in several countries [1–5].

Critical issues to be addressed in the structural assessment of the historic structures are: (a) the lack of knowledge about the construction techniques, the structural changes over time and the effects of the decay and local damages (even if mapped in detail); (b) the criteria and the procedures to get these information, (c) merging the pieces of information obtained from several methodologies and disciplines in a diagnostic process [6,7]. For instance, the masonry quality is highly dependent on manufacturing practice and decay, resulting in significant variation of the mechanic characteristics that might be investigated through limited opportunities of sampling and testing. In addition, the discussion on the correlation between the results of local tests and quantitative parameters needed to build up global structural capacity models is still open. Furthermore, the structural model of a historic structure, even when based on accurate field survey, always involves simplified assumptions and several uncertainties in the material properties and their distribution, in the geometric layout and in

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the boundary conditions [8]. Other uncertainties are related to the structure evolution and the modelling of damages and subsequent repairs [7].

In conclusion, the structural assessment of historic structures is a complex and articulated procedure, which could require time-consuming (and expensive) investigations in order to examine in depth several issues. Unfortunately, wide investigation programs are seldom possible, due to economic issues or to emergency conditions (such as the post-earthquake assessment).

The paper firstly presents the procedures adopted and the main results obtained in the prompt assessment carried out on the bell-tower of the Church *Santa Maria del Carrobiolo* in Monza, Italy [9,10]. Subsequently, a wider research program was planned and is currently in progress. In more details, the research consists of 5 successive steps:

(1) Prompt on-site investigation [11], including geometric survey, visual inspections and evaluation of the tower's fundamental period using microwave remote sensing [12–14], aimed at defining the main issues.
(2) Static monitoring of the main cracks.
(3) Ambient vibration testing and complete dynamic characterisation of the tower using Operational Modal Analysis (OMA, see e.g. [15]).
(4) Development of a FE model of the tower and vibration-based structural identification of the uncertain parameters of the model [16,17].
(5) Design and installation of a continuous dynamic monitoring system in the tower [18].

As previously pointed out, within a wide cataloguing program of several religious buildings in Monza, a pre-diagnostic survey of the *Santa Maria del Carrobiolo* bell-tower (Fig. 1) was initially performed. The survey – partially supported by the CARIPLO Foundation and aimed at collecting prompt information on the historic buildings – included topographic survey, visual inspection, documentary research and evaluation of the fundamental period. Direct survey indicated that the tower was built after the church and revealed that two sides of the bell-tower are directly supported by the load-bearing walls of the church apse and right (South) aisle. The construction sequence adopted for the tower, not identified before, raised obvious concern about the performance of the structure under normal and exceptional loads. In addition, the recent construction of an under-ground car park adjacent to the East side of the tower conceivably activated movement of the pre-existing cracks and of the structural discontinuities related to construction phases.

After a brief description of the planned research program and of the investigated bell-tower, the paper fully details the results of the steps (1)–(3) outlined before and emphasis is given on the principles adopted, the importance of the collected information within the diagnostic context and the choice of installing a continuous dynamic monitoring system in the bell-tower.

2. Investigation procedures

The methodology adopted to currently evaluate and to continuously assess the structural condition of the bell-tower at study (calibrated through the progressive refinement of diagnostic procedures [11,16–18]) is based on: (a) geometric survey and local inspections supported by stratigraphic analysis, (b) ambient vibration testing; (c) development of a dynamics-based FE model; (d) static and dynamic monitoring.

On-site inspections are fundamental to collect information on the geometry, the presence of local damage and its extension, and to identify the regions where more accurate observations (e.g. crack monitoring) have to be concentrated [6]. The crack pattern and the masonry discontinuities should be accurately classified and documented by pictures and reported on the geometrical survey.

Concurrently, the historical evolution of the structure has to be investigated through historic and documentary research in order to explain the signs of damage or the irregularities detected on the building. Despite the importance of the historic and documentary research, it may require long time to get exploitable information so that, in emergency conditions, the evaluation of the building evolution has to be initially performed through the analysis of the masonry textures and the available references. Of course, the direct observations should be supplemented at a later time by the refinement and conclusion of the historic and documentary research.

Since the first approaches to the investigated building, the inspection must be addressed to detect anomalies which could affect the structural behaviour. Systematic attention must be paid to the corner layout, the crack pattern, the discontinuities but also to any change of the masonry textures by stratigraphic methods. The latter information is closely related to the construction phases: the quality of the link between each homogeneous masonry por-

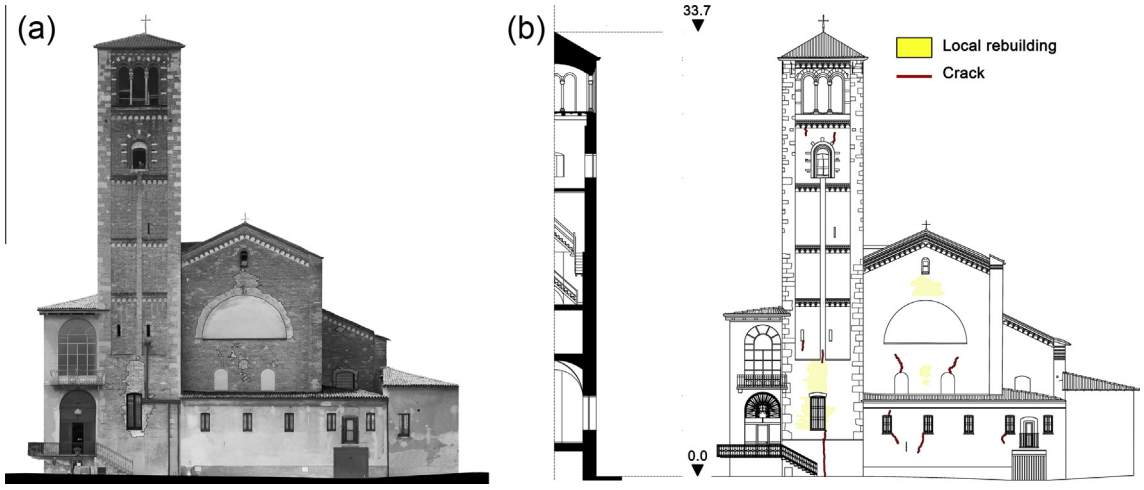

Fig. 1. The Church of *Santa Maria del Carrobiolo* and the bell-tower: (a) Orthoplane; (b) Geometric survey of the East front of the tower and the church apse (cracks and local rebuilding are mapped, dimensions in m).

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