

# Structural health monitoring (SHM) and Nondestructive testing (NDT) of slender masonry structures: A practical review

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## HIGHLIGHTS

- SHM of slender masonry elements: towers, minarets, chimneys and columns.
- NDT of slender masonry elements: towers, minarets, chimneys and columns.
- Experimental techniques on masonry towers, minarets, chimneys and columns.
- OMA, AVT, numerical modeling and signal processing on slender masonry elements.
- State of the art of dynamic identification of slender masonry elements.

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## ABSTRACT

The scientific community is hardly working to propose reliable methodologies of analysis and non-invasive technologies of investigation to assess the current state of conservation of historic buildings to verify their ability to resist future threats. These structures, mostly made of masonry, are difficult to assess due to the heterogeneity of materials and their mechanical behavior, but it is vital to preserve this invaluable cultural heritage by suitable structural assessment techniques. A great deal of research attention has been paid to monitoring their structural health; in many recent publications new advanced technological methods have been provided such as cheaper sensors, wireless connections, non-contact surveys and continuous monitoring. A bibliometric study has shown that more than half of the papers on Structural Health Monitoring (SHM) and Nondestructive Testing (NDT) on masonry have been published between 2018 and 2020, and 30% of those published in 2020 were on 'slender' elements like towers, chimneys or minarets. This paper presents a wide-ranging review of static and dynamic studies published on SHM and NDT of slender masonry structures summarizing and discussing the different experimental techniques used. With respect to the dynamic testing, Operational Modal Analysis (OMA) by accelerometers is the mostly frequent used technique by scholars, but other promising methods such as radar interferometry are also reported. This overall discussion is concluded with a short review of some examples on numerical structural health assessment and signal processing tools. An inclusive list of papers is provided describing the most important slender masonry structures characteristics, natural frequencies, experimental and numerical techniques employed and reference values. This paper, set on a practical perspective, is expected to be of interest to those researchers and practitioners who require an extensive and up-to-date review of this topic.

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## 1. Introduction

The effort entangled in constructing buildings requires, to be feasible, long building lifespans, which means that proper actions to control or verify their state of conservation must be planned

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and implemented. On occasions, structures have fulfilled along the centuries the function for which they were conceived, and many of these belong today to the so-called architectural heritage. Sometimes buildings undergo changes of use and must then be upgraded and/or strengthened; hence they must be investigated and analyzed to determine their current state of conservation. Whether they are 'modern' or they can be considered 'ancient', the daily use, external factors or the simple passage of time reduce

their capacities and ultimately could lead to a collapse of the structure and all that it entails, as happened for the San Marco bell-tower in Venice or the civic tower of Pavia [1] in Italy which have collapsed with no apparent signs of damage. Other times collapse may occur due to unforeseen extraordinary events, such as earthquakes ([135,136]).

The assessment of the current structural health of a building can be done once or continuously. The monitoring of certain key parameters provides information on its level of performance and information to judge its state of conservation. When this is done once, the results of the survey can be employed for specific goals (vulnerability and damage assessment, upgrading and retrofitting evaluation, etc.). When this is done continuously, the evolution of its structural health over time can be assessed. In all cases, initial data collection is the necessary step to be performed for interpretation and subsequent analysis to indicate whether intervention is required and the type of intervention to be carried out. This can be done within the framework of the so-called Structural Health Monitoring (SHM), which can be defined as the process of implementing a damage detection strategy through the measure of the structural response of certain key parameters under environmental or operational conditions [2,151]. In a general perspective, a successful SHM procedure would require a preliminary identification of proper health metrics together with the formulation of quantitative criteria for the assessment of the limit states that must not be exceeded during the life cycle of the structure (e.g. safety, durability, serviceability, etc.). Some authors [3] state that a SHM system is the result of the integration of several sensors, devices, and auxiliary tools, such as: a measurement system, an acquisition system, a data processing system, a communication/warning system, an identification/modeling system, and a decision-making system. In this respect, long-term continuous measurements of certain key parameter of the structural response can provide the necessary information about both the global health and the expected performance of the structure.

Many research papers have been published on the structural assessment of masonry structures by using different techniques and structural identification methods; many of them have been devoted to the study of slender masonry buildings, which are driving the advance of the knowledge in this field. In fact, although SHM can be today considered a mature concept in the engineering field, still a number of challenges for its effective application in the preservation of heritage structures must be addressed (e.g. [20,183,184]). In addition, when dealing with historic and/or monumental buildings that are outstanding human property to be passed on to future generations, preservation must be approached as a multidisciplinary process. Consequently, the decision making scenarios results of a SHM program should comply with international conservation principles such as the one included in the ICOMOS/ISCARSAH "Recommendations for the analysis and Restoration of Structures of Architectural Heritage" [160] and in the ICOMOS International Charters ([161–164]). The interested reader is referred to [165] for a comprehensive discussion of these concepts, while a comprehensive review of about 300 seismic and masonry codes from all over the world is reported in [166]. It is here worth remembering the Guidelines issued by the Italian Ministry of Cultural Heritage for the assessment and mitigation of the seismic risk of the cultural heritage [138], where a rational path of investigation and assessment for architectural heritage which is connected to different methodologies of analysis is outlined.

This paper describes from a practical perspective the state of the art of research on Structural Health Monitoring and Nondestructive Testing in slender masonry structures. With respect to the SHM, even if SHM methods can be divided into static and dynamic-based methods (the former is based on measuring the change in the static response, the latter uses vibration characteris-

tics of a structure to assess its health state), this paper mainly reports on vibration-based damage detection studies. Section 2 first guides the reader through the definition of purposes of SHM and NDT, defining what 'slender masonry structures' are in the context of this review. A brief summary on the related scientific literature (a bibliometric study) of the current state of this topic is reported in Section 3, while a review of the experimental techniques for NDT and SHM is reported in Section 4. This section includes a specific subsection to Operational Modal Analysis and Ambient Vibration Testing using accelerometers, as frequently used for dynamic vibration identification technique on masonry towers. There follows a review of the different techniques employed to assess slender masonry structures, numerical techniques (Section 5), considering the finite element method and the commonest signal-processing algorithms (mainly, Enhanced Frequency Domain Decomposition (EFDD) and Stochastic Subspace Identification (SSI)). The conclusions are given in Section 6. A table at the end of the paper contains all the information from the review process in a single place for easy access, which, although sometimes variable, incomplete or heterogeneous, is always useful. This paper could be useful for researchers or practitioners who look for an extensive and up-to-date view of this topic.

## 2. General approach

### 2.1. Structural health monitoring (SHM)

Many authors have defined SHM or explained its concept by its aims. By starting from the definition introduced in the seminal review [151], some additional examples are given in the following paragraphs:

- Bassoli et al. [4], 'Structural Health Monitoring (SHM) is the process of characterization of existing civil structures for structural identification and damage detection purposes.'
- Saisi et al. [5] 'SHM is the continuous interrogation of sensors installed in the structure aimed at extracting features which are representative of the current state of structural health.'
- Guidorzi et al. [6] 'Structural Health Monitoring aims to give a continuous diagnosis of the 'state' of the different parts and of the full assembly of these parts constituting the structure as a whole.'

The basic idea is that SHM comprises the characterization of a structural system using its response under loading. The approach can be done using model-based methods, where a large number of uncertainties and simplifications (materials, geometry, boundary conditions, etc.) are met with during the modeling process that can lead to differences between the model predictions and the actual structural behavior. Structural identification techniques are used in SHM to validate the numerical models to enable predictions of the structural responses in different scenarios. When used continuously, SHM can evaluate the effects of interventions or damage assessment [7]. On the other hand, the approach can be based on data-driven methods to by-pass the construction of complex (and possibly inaccurate) models. In this strategy, the 'real' model is substituted by a model based on acquired data provided by sensors, which recently have overcome the limitations of sensor capabilities and data collection, offering assessment, damage detection and prognosis. Neural networks and learning algorithms are used to improve pattern recognition.

According to Foti [8], in its beginnings the process of damage detection was performed by visual inspection, or techniques which required the knowledge of the damage in specific easily accessible areas, where X-ray methods, magnetic fields, acoustic techniques

or thermal measurements could be used to measure the damage. Given the need to know the global state of damage or the response to certain situations, in recent years new sensing technologies have emerged, allowing the study of variables that shed more light on structural performance, helping in the decision-making process. Many recent constructions are equipped with real-time monitoring systems in both the in-construction and in-service stages to ensure their safety and reliability, especially in large infrastructures such as bridges [9], dams [10] tunnels [11], buildings [12], etc., although their number is increasing thanks to new cheaper monitoring systems: new sensors, microprocessors and wireless communications are generalizing SHM in long-term monitoring of structures. It is very common to find advanced sensor technologies working in combination with efficient identification methods controlled by a processor unit accessible online in real time.

To sum up, from a general point of view, continuous SHM comprises the analyses of the information collected by sensors according to a sampling rate due to the external loads acting on the structure and introduced into a model for validation or comparison with the support of statistical analysis to determine the state of the system, damage progression or the effectiveness of interventions.

## 2.2. SHM and NDT in masonry structures

The 'classical' construction materials, such as iron, masonry or wood are now not often used in construction as there are other alternatives with lower costs, providing better performance and faster execution times. Many existing constructions made of these materials are considered "ancient" or "historical", and can be any age from 100 to thousands of years old, built with other standards and may belong to the historical heritage, e.g. a 19th century industrial masonry chimney [13,14], or even to the world heritage like the 13th century Qutb Minar [15,185]. Because they are currently still performing the function for which they were conceived and may even be subjected to new demands greater than those initially planned, to protect them against the passage of time (aging) or extraordinary events such as earthquakes, due to their special relevance, for the preservation of cultural and social traditions, it is necessary to assess their state of conservation and health for the upcoming future. For these reasons, 'historical' constructions or 'monuments' are ideal candidates for SHM as emerges from the analysis of the scientific literature. Two examples of the monitoring of historic structures in operational conditions are described in [16] (a 16th centenary iron bridge and a masonry bell tower, which are being continuously monitored to assess their structural health) and in [25,167] (two medieval masonry towers which were monitored over the period 2015–2018 with the aim of assessing the influence of environmental parameters on the main frequencies of the towers).

Although masonry structures seldom suffer failures in operational conditions, their preservation makes it necessary to be able to detect any indication of damage as soon as possible by feasible methods to provide information on their structural health.

Many historical constructions have suffered modifications or been strengthened, have a great level of uncertainty about how they were built, or exhibit complex behavior. From the references mentioned in this paper it is clear that the assessment path for these invaluable monuments should include: a) Structural inspection and information: this phase comprises: studies about the place where the structure is located, especially if it is in a hazardous area, for the definition of the hazard/vulnerability/risk chain; geometry characterization and a damage survey, by identifying the crack patterns and the irregularities; ageing, material and element identification; arrangement or construction technique, boundary conditions and connections among different elements.

This phase is usually accomplished by a visual inspection with the help of new technologies and tools like laser scanning, drones, digital photogrammetry, etc. A historical overview, as well the analysis of maps, drawings and photographic documentation are always advisable in this type of monument, since hidden elements, structural changes through time and relevant information is often obtained [17]. Historical/documentary research in the archives (when documents are available) and stratigraphic survey can help in the description of geometry and evolution phases. The relevance of this step has been also highlighted by [138]. b) Experimental investigation: the evaluation of the structural state is quantified through on-site tests. Regarding the degree of intrusiveness, they can be classified as non-destructive tests (NDT) and minor destructive tests (MDT), since destructive tests (DT) are not allowed in the case of heritage structures. Two types of tests, roughly, can be carried out: static and dynamic, and they may be periodic or continuous. The technology is rapidly evolving, and new techniques arise; a few examples of the most common tests performed to date in historical masonry structures are listed below: i) Static tests: infrared thermography, X-ray imaging, tomography, ultrasound/sonic test, sonic tomography, georadar, acoustic emission, thermography, flat-jack tests, endoscopy/videoboroscopy inspection, impact echo testing, coring, hardness tests, penetration tests, ground penetrating radar, etc. and ii) Dynamic tests: all kinds of tests related f. i. to ambient vibration tests, radar/laser interferometry, seismic interferometry, etc.

After having collected the experimental data, the analysis of the structural behavior and the assessment of the global health state is usually accomplished by numerical models (model-driven approach) whose calibration may result particularly difficult due to the level of uncertainties related to the input parameters of the model. Amongst others, the structural geometry of the building and its evolution along the centuries, the mechanical properties of the materials, the restraining level imposed by neighboring structures, etc. are all elements whose uncertainty may negatively affect the results of any calibration procedure if no proper experimental tests are performed. When dealing with dynamic tests, as it is often done, Operational Modal Analysis (OMA) is the mostly frequent used experimental technique for modal updating: after the structure modal properties are identified by statistical tools using the vibration data collected by sensors in operational conditions, an objective function measuring differences between the experimental data and the corresponding numerical output is built and minimized with an optimization algorithm ([173–175]). Subsequently, the validated numerical model is used to determine the response of the structure under different conditions, for damage prediction, assessment of the effectiveness of interventions, seismic vulnerability, etc. and to implement preventive or corrective actions [176,178].

## 2.3. Slender masonry structures

Slender structures are a special type of the many types of structural classifications, in which one of their dimensions (length) is much greater than the dimensions of their cross section. From a theoretical point of view related to the theory of beams, linear elements with slenderness ratios of 1/10 or less between the length and its greatest cross dimension allow the establishment of certain hypotheses and kinematic simplifications in the calculation that provide valid analytical solutions. Due to the nature of the behavior of masonry as a construction material, mainly due to its low tensile strength, 'historical' masonry constructions have been massive.

In this paper, slender masonry structures are referred to as those masonry structures with a predominant vertical dimension (Fig. 1), usually in the form of towers (bell towers, civic towers,

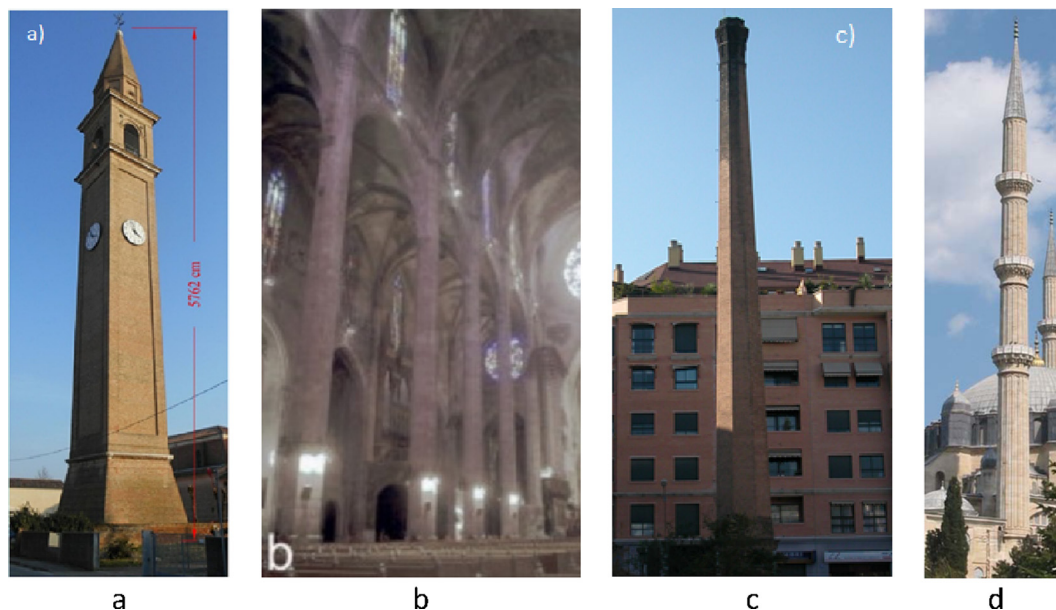


Fig. 1. a) Bell-tower [88], b) columns [61], c) chimney, d) minaret [132].

clock towers, tower-houses, defensive towers, watch towers), minarets, columns, pinnacles and chimneys, and they generally carry significant loads. These structures are mainly characterized by cantilever-like behavior and are especially sensitive to horizontal and dynamic loads such as earthquakes, bell swinging, and sometimes wind or traffic. This is not the case of columns or pillars, which are usually slender elements restrained at both edges.

Towers, minarets and chimneys are characterized by specific geometrical and constructional features, as stated by Colapietro et al. [17,123], significant dead loads at the bottom and, in cases, the presence of wide openings and protruding elements at the top. Connection to adjacent buildings or walls is another important aspect, which strongly affects in many cases their failure modes and response to earthquakes [158,159,168,169]. These elements are at risk, not only because of the high stresses at the bottom but also because of their great susceptibility to dynamic actions: tolling bells, wind forces, micro-tremors, traffic and earthquakes [18,19], requiring specific studies. Temperature and humidity (e.g. [7,20] respectively) are also factors to be taken into account in this type of structures, as will be commented next. The main feature of all these slender elements is that they are sensitive to ambient excitation, which together with their cantilever-like behavior makes them good subjects for structural health and global dynamic assessment using operational modal analysis to monitor their response to ambient vibration.

The structures classified as 'towers' in the literature often form part of a bigger system like cathedrals, town halls, fortresses, etc. They were built for different purposes, such as landmarks or to announce important events, give the time, or warn of an attack. In medieval Italy some civic towers were built as symbols of wealth and power [21]. This type of element is by far the most frequently studied structure in the scientific papers reviewed here (77 references).

Towers were built isolated or adjacent to other buildings, often sharing walls or connecting elements with them. This boundary condition strongly influences their dynamic response and could make them vulnerable to some external actions (such as earthquakes). Different empirical or analytical formulas to estimate the main natural frequencies of masonry towers, even considering if the towers were isolated or bounded by surrounding walls or

constructions, were proposed by both National Recommendations and research papers. Among the National Recommendations, empirical formulations are proposed by the Italian and the Spanish codes. The Italian Recommendation proposes two formulas to predict the fundamental frequency of a building. The first is reported in the NTC (2008) [137], but is a general formulation where the frequency is evaluated as a function of the height of the structure and it is supposed to be applicable for structures with a height up to 40 m. The second one is included in the DPCM (2011) [138] and was proposed by Faccio et al. [139]. This formulation still provides the main frequency as a function of only the tower height, but it is specifically intended for masonry towers. The Spanish standard NCSE (2002) [140] provides, although even this is not specifically intended for slender structures, a formulation that takes into account not only the height but also the plan dimension of the structure along the direction of oscillation. An empirical formulation that maintains the basic structure of the one provided by the Italian Recommendation was proposed by Rainieri and Fabbrocino [141], according to the results of an extensive experimental campaign based on output-only modal identification of about 30 masonry towers in southern Italy. Four empirical formulations were proposed by Shakya et al. [142], analyzing a wider database composed of 58 slender structures (32 masonry towers, 16 minarets, 7 chimneys, and 3 pagoda temples). According to the experimental data, different coefficients of the empirical correlations were evaluated for three main typologies of slender structures: (1) all type of slender masonry structures; (2) bell towers, clock towers, and civic towers; and (3) minarets. The above formulations do not explicitly account for the parameters that rule the interaction with the surrounding buildings when the tower is not an isolated construction. Based on the experimental results collected on a homogeneous database composed of about 45 not isolated towers, Bartoli et al. [143], introducing the concept of effective height of the tower (i.e. the length of the portion of the tower that is free from the restraint offered by adjacent buildings) proposed a semi-empirical formulation by operating on the theoretical expression for the main frequency of cantilever beams. Similar considerations were subsequently developed by Diaferio et al. [22], through a database of experimental results, and by Najafgholipour et al. [129], through a database of numerical results. The role played



by the openings in the main frequency estimation for historic masonry towers was discussed by Bartoli et al. [144]. The formulation proposed by the Authors, considering a wide database composed of 11 isolated towers and 45 confined ones, is able to explain the cross-contribution of mass and stiffness introduced by the opening through the definition of a physical parameter called neutral height.

These procedures could be the starting point in any tower assessment to get at least the first natural frequency in a simple way. They can be used for a preliminary validation of a more complex numerical model and can be useful to choose best-fit sensors according to the predicted characteristics of the system. Table 1 ('Restraint') gives the isolated or bounded character of the elements mentioned.

In the case of bell towers, the estimation of the first natural frequency is particularly relevant also because the possible coupling between any of the frequencies introduced by swinging bells and any of the tower frequencies [18,145] can give rise to numerous pathologies.

Minarets are also slender elements very similar to towers, built attached to mosques to call Muslims to daily prayer, and often have high architectural value. Minarets can be integral to the main mosque structure or can be stand-alone from it having their own foundation system. A minaret is composed of a cylindrical shaft with a staircase and one or more balconies. The cross section can be octagonal, circular, square, etc., depending on the style, but three parts are usually identified: base, shaft and balcony. Oliveira et al. [110] proposed an empirical formula to estimate the fundamental frequency of minarets based on experimental calibration from ambient vibration tests of 11 minarets in Turkey. This formula represents a simple method to estimate the modal parameters of minarets in structural assessment studies. The research studies dealing with minarets (14 references) are also shown in Table 1.

Industrial masonry chimneys are also slender elements with several possible cross sections, and somehow very similar to minarets. They appeared in the XIX and XX centuries during the industrial revolution for Hoffman-type mass production ovens. Nowadays many of them have survived urban pressures, earthquakes, lightnings, and other different threats; often, they are considered cultural heritage to be preserved, becoming a landmark in local communities. Many studies have been done on the evaluation of their seismic assessment and on the study of their characteristics for the implementation of retrofitting techniques [14,78,80]. Parallel to the empirical proposals to estimate natural frequencies in towers, there are also formulas to estimate natural frequencies in chimneys and recommendations for construction which can be checked to propose numerical models [23]. Table 1 contains 6 references to chimneys.

Columns and pillars are other slender elements with restricted ends, mainly found in temples, churches or cathedrals in the references shown in Table 1 (6 references).

### 3. Bibliometric study

This section provides the results of a bibliometric study about the presence of the topics SHM and NDT in the current scientific literature in masonry towers using the Scopus database and considering the following parameters:

- Presence of terms such as 'structural health monitoring' or 'SHM' and 'masonry', 'chimney', 'tower' or 'column' in the title, abstract or keywords of the publication.
- From 1960 to the present.
- Articles published as 'Article' or 'Review'.

As for December 2020 the terms 'structural health monitoring' and 'masonry' appear in 149 articles (Fig. 2). A considerable increase is observed between 2017 and 2018, arising the effects of the 2016 Central earthquake in Italy. In fact, 54% of the articles including these terms have been published between 2018 and 2020.

The Journal containing that highest number of publications related to these keywords is Structural Control and Health Monitoring, with 17 articles, followed by the Journal of Civil Structural Health Monitoring with 16 and Construction and Building Materials with 10 articles. The most cited paper is Ramos et al. [7], cited 186 times.

Refining the search by adding the terms 'tower', 'chimney', 'column' or 'minaret', the results are restricted to 39 articles (Fig. 2). In this case, there was a significant increase in the number of publications during 2019 and 2020 (16 publications), representing 41% of the total, while 30% of the articles published in 2020 about SHM and masonry dealt with slender masonry elements, showing the current interest in the topic. Most of the contributions were carried out by Italian researchers (>65%).

The Journal 'Mechanical Systems and Signal Processing' published most articles related to these keywords, with 6 articles, and the most cited paper was Ubertini et al. [54], cited 49 times.

### 4. Experimental techniques

When dealing with cultural heritage it is not possible to carry out destructive tests to determine the mechanical parameters and conduct a global assessment. MDT or NDT can provide information about local characteristics (e.g. wall arrangement, layers, existence of voids, local damage, local strength, mapping nonhomogeneous materials, mechanical and physical properties of materials, moisture content, etc.), but the whole information would require a great number of tests. As commented, in this type of constructions there is a need of knowledge about the conservation state of the structure and its global response to different loads, in order to assess its structural health. The choice of a technique for the assessment or the monitoring of a masonry structure is related to the type of structure, the data pursued and the aims of the analyses.

From the long list of techniques adopted and/or proposed by researchers and collected in Sect. 2, only the most relevant, most promising or those most often used, will be treated here, either static or dynamic: visual inspection, Operational Modal Analysis, terrestrial laser scanning, seismic interferometry, acoustic emission, ground penetrating radar, sonic tests, flat-jacks and thermography.

In slender masonry structures, monitoring based on dynamic behavior considering output-only modal identification techniques, where the input force is unknown, is a very powerful tool to obtain modal parameters of the whole structure in operational conditions [22]. This is why Operational Modal Analysis (OMA) has become a prevailing technique with efficient results obtaining full-scale structural modal properties from recorded data based on vibrations without artificial excitation (hence under operational conditions), and the most frequently used technique by researchers among all those listed here. It can not only serve to estimate modal information (natural frequencies, modal shapes and damping ratios), but also constraint conditions [24] and any damage [25,26], if properly used.

OMA is related to but also opposite to EMA (Experimental Modal Analysis), where the structure is excited by known forces (impact hammers, vibrodynes, shakers, etc.) and the modal parameters are obtained from the input-output data. Theoretically, both EMA and OMA are inverse problems where the output response is known, and the matrices of the systems are to be determined. The

**Table 1**  
Summary of information related to SHM and NDT in slender masonry elements found in references.

|       | Author/s         | Year | Element  | Dynamic excitation | Type of element | Height (m) | Base (m)  | Restraint | Date             | Instruments/ Technique  | Main results: 1st/ 2nd nat. freq. Sonic test velocities | Elastic modulus E adjusted  | Campaign Time duration              | Sampling rate   | Signal processing technique      |
|-------|------------------|------|--|--------------------|-----------------|------------|-----------|-----------|------------------|---|---|-----------------------------|-------------------------------------|---|----------------------------------|
| [68]  | D'Ambrisi et al. | 2012 | civic tower of Soncino (Cremona, Italy)  | AVT                | bell tower      | 41.8       | 6 × 6     | bounded   | 12th c. and 1575 | 4 recording stations (3D accelerations)   | x) 1.08 Hz y) 1.11 Hz                                   | E = 1000 MPa                |                                     |   | PSD MAC                          |
| [82]  | Anzani et al.    | 2010 | The Tower Masserano of Palace Ferrero (Italy) (La Marmora at Biella (Italy))<br>Bell Tower of the Collegiata of San Vittore at Arcisate (Italy)<br>Torre Sineo, Alba, Italy. |                    | bell tower      | 36         | 5.8 × 5.8 |           | 167th-17th c.    | 6 flat jacks 3 sonic tests pseudocreep tests  |   |                             |                                     |   |                                  |
|       |                  |      | Torre Astesiano, Alba, Italy.  |                    | bell tower      | 39         |           |           |                  | 4 sonic tests   | around 2000 m/s   |                             | around 1 year (earthquake recorded) |   |                                  |
|       |                  |      | Torre Bonino, Alba, Italy.   |                    | tower           | 36         |           |           |                  | 8 Acoustic Emission (AE)  |   |                             |                                     |   |                                  |
|       |                  |      |  |                    | tower           | 35         |           |           |                  | 8 Acoustic Emission (AE)  |   |                             |                                     |   |                                  |
| [43]  | Atzeni et al.    | 2010 | Leaning Tower of Pisa, Italy.  | AVT                | tower           | 55         | φ = 19.6  | isolated  | 14th c.          | microwave radar interferometry  | 1.01 Hz 1.04 Hz   |                             | 1800 s                              | 96 Hz   | FDD (PSD, SVD)                   |
| [25]  | Azzara et al.    | 2018 | San Frediano bell tower in Lucca, Italy.   | AVT                | bell tower      | 52         |           | bounded   | 11th c.          | 4 triaxial seismometric stations (electrodynamic velocity transducer).  | 1.1 Hz  |                             | 1 year (earthquake recorded)        | 100 Hz  | SSI-cov ARX kernel PCA           |
| [167] | Azzara et al.    | 2021 | the San Frediano belfry in Lucca, Italy.   | AVT                | bell tower      | 52.25      |           | bounded   | 11th c.          | 4 triaxial seismometric stations (velocimeters) two tri-axial accelerometers  | 1.1 Hz  | E = 4.25·10 <sup>9</sup> Pa | 22 months                           | 100 Hz 20 Hz  |                                  |
|       |                  |      | the Clock Tower in Lucca, Italy.   | AVT                | clock tower     | 53.51      |           | isolated  |                  | 4 triaxial seismometric stations (velocimeters) two tri-axial accelerometers  | 1.03 Hz   | E = 4.5·10 <sup>9</sup> Pa  | 5 months                            | 100 Hz 20 Hz  |                                  |
| [83]  | Bani-Hani et al. | 2008 | Ajloun minaret, Jordan.  | AVT                | minaret         | 45.9       | 4.5 × 4.5 | isolated  | 1263             | 3 accelerometers  | 1.278 Hz  |                             | 6.5 h                               | 200 Hz  | N4SID                            |
| [79]  | Barsocchi et al. | 2018 | the San Frediano bell tower in Lucca, Italy  | AVT Bells swinging | bell tower      | 52         |           |           | 11th c.          | MEMS accelerometers, 6 triaxial nodes Temperature and humidity sensors  | 1.10 Hz 1.38 Hz   |                             | 6 months, data 30 min per week      |   |                                  |
| [77]  | Barsocchi et al. | 2020 | the Matilde Tower in Livorno (Italy).  | AVT                | tower           | 29         | φ = 12    | bounded   | 13th c.          | 1st campaign: 12 high sensitivity piezoelectric accelerometers [78] Wireless Sensor Network Mono-axial MEMS transducers Strains gauges Displacement transducers Temperature/ humidity sensors | 2.6 HZ 3.4 Hz   | E = 2500 MPa                | Automated analysis: 12 months       | 1st campaign: 400 Hz downsampled to 30 Hz [78] Automated analysis: 50 Hz downsampled to 25 Hz | FDD, SSI Automated analysis: SSI |

Table 1 (continued)

|       | Author/s         | Year | Element   | Dynamic excitation                   | Type of element | Height (m) | Base (m)   | Restraint | Date    | Instruments/ Technique  | Main results: 1st/ 2nd nat. freq. Sonic test velocities                | Elastic modulus E adjusted   | Campaign Time duration            | Sampling rate | Signal processing technique |
|-------|------------------|------|---|--------------------------------------|-----------------|------------|------------|-----------|---------|---|--|------------------------------|-----------------------------------|---------------|-----------------------------|
| [84]  | Bartoli et al.   | 2013 | Torre Grossa of San Gimignano, Italy.   | Vibrodyne Bells                      | bell tower      | 55         | 9.5 × 9.5  | bounded   | 13th c. | Static test: flat-jack (single and double) Coring tests Dynamic tests: seven piezoelectric accelerometers | y) 1.31 Hz x) 1.33 Hz  |                              |                                   | 100 Hz        | PP                          |
| [24]  | Bartoli et al.   | 2012 | columns Siena Cathedral, Italy.   | Impulsive loads (hammer impact test) | columns         | 2500 mm    | φ = 160 mm |           |         | Ultrasonic transducers Six accelerometers   | 4000–5000 m/s 3400 m/s (damaged columns) 76.16 Hz                      | 4.7E10 Pa                    | 50 s                              | 1200 Hz       | NN (Neural Network)         |
| [4]   | Bassoli et al.   | 2015 | The Ficarolo bell tower (Italy)   | AVT                                  | bell tower      | 68         | 8.5 × 8.5  | isolated  | 1777    | 11 biaxial MEMS units. (two orthogonal axes and temperature) Six single-axis piezoelectric accelerometers | y) 0.552 Hz x) 0.577 Hz  |                              | 3 days in summer 3 days in winter | 40 Hz         | EFDD                        |
| [85]  | Bassoli et al.   | 2018 | Main tower of the San Felice sul Panaro medieval fortress (Italy)             | AVT                                  | tower           | 32         | 10 × 10    | bounded   |         | 10 uniaxial piezoelectric accelerometers  | y) 1.72 Hz x) 1.76 Hz  | E = 825 MPa (highly cracked) |                                   | 200 Hz        | EFDD                        |
| [86]  | Bayraktar et al. | 2009 | bell-tower of the Hagia Sophia church in Trabzon, Turkey                      | AVT                                  | bell tower      | 23         | 5 × 5.5    |           | 13th c. | a) 12 uniaxial accelerometers b) 4 triaxial moving accelerometers plus one uniaxial kept fixed            | 2.6 Hz   |                              | 5 min                             |               | EFDD SSI                    |
| [124] | Bayraktar et al. | 2011 | The Iskenderpasa minaret, Trabzon, Turkey.                                    | AVT                                  | minaret         | 20.5       |            |           | 16th c. | 4 triaxial accelerometers   | 1.29 Hz 1.39 Hz  |                              |                                   |               | PP SSI                      |
| [125] | Bayraktar et al. | 2008 | The Iskenderpasa minaret, Trabzon, Turkey.                                    | AVT                                  | minaret         | 20.5       |            |           | 16th c. | 4 triaxial accelerometers   | 1.29 Hz 1.39 Hz  |                              |                                   |               | PP SSI                      |
| [128] | Bayraktar et al. | 2018 | Hacibasi mosque minaret, Cayeli Rize, Turkey                                  | AVT                                  | minaret         | 21.63      | φ = 2.54   | bounded   | 1708    | 8 accelerometers  | 2.32 Hz, 2.69 Hz before restoration 1.99 Hz, 2.17 Hz after restoration |                              | 30 min                            |               | EFDD                        |
|       |                  |      | Gu lbahar mosque minaret, Rize, Turkey  | AVT                                  | minaret         | 26.91      | φ = 2.25   | bounded   | 1660    | 8 accelerometers  | 1.26 Hz, 1.46 Hz before restoration 1.42 Hz, 1.62 Hz after restoration |                              | 30 min                            |               | EFDD                        |
|       |                  |      | Hacı Kasım mosque minaret, Trabzon, Turkey                                    | AVT                                  | minaret         | 22.6       | φ = 1.80   | bounded   | 1821    | 8 accelerometers  | 3.07 Hz, 3.25 Hz before restoration 3.22 Hz, 3.39 Hz after restoration |                              | 30 min                            |               | EFDD                        |
| [87]  | Beconcini et al. | 2001 | “Matilde” bell tower in San Miniato (Pisa, Italy)                             | Bells                                | bell tower      | 35         | 12.5 × 8.2 | bounded   | 12th c. | 4 accelerometers  | 1.21 Hz  |                              |                                   |               |                             |
| [18]  | Bennati et al.   | 2005 | Tower of Matilde, the bell tower of the Cathedral of San Miniato, Pisa, Italy | Bells                                | bell tower      | 35         | 12.5 × 8.2 | bounded   |         | 8 accelerometers  | 1.2 Hz   |                              |                                   |               |                             |

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Table 1 (continued)

|       | Author/s               | Year | Element   | Dynamic excitation | Type of element | Height (m) | Base (m)    | Restraint | Date          | Instruments/ Technique   | Main results: 1st/ 2nd nat. freq. Sonic test velocities | Elastic modulus E adjusted | Campaign Time duration   | Sampling rate  | Signal processing technique          |
|-------|------------------------|------|---|--------------------|-----------------|------------|-------------|-----------|---------------|--|---|----------------------------|--|--|--------------------------------------|
| [88]  | Bergamo et al.         | 2017 | Sant Andrea bell tower, Venice, Italy                         | AVT Bells          | bell tower      | 57.62      | 8.1 × 8.1   |           | 1870          | Four digital tromometers (each has three accelerometric channels and three velocimetric channels).                       | 0.6 Hz  | 2250 MPa                   |  | 128 Hz   |                                      |
| [62]  | Binda et al.           | 2003 | stone pillars of the temple of S. Nicolo' l'Arena (Italy)     |                    | pillars         |            |             |           | 1780          | Drilling, Cores and sampling Flat-jack tests Sonic tomography Radar tests  |   |                            |  |  |                                      |
| [89]  | Bonato et al.          | 2000 | bell-tower in Roccaverano (Asti-Italy)                        | AVT Bells          | bell tower      | 22.5       | 3.25 × 4.25 | bounded   | 16th c.       | 4 accelerometers (two fixed, two moving)   | 1.66 Hz 2.26 Hz   | E = 976 MPa                |  |  | PSD                                  |
| [90]  | Bru et al.             | 2015 | La Paz, Agost (Alicante, Spain)                               | AVT                | chimney         | 24.7       | 2.84 × 2.84 | isolated  | 1950          | 8 uniaxial accelerometers in 12 points   | 1.55 Hz   |                            | 10 min   | 100 Hz   | PP FDD MAC                           |
| [145] | Bru et al.             | 2019 | historic Fiesole's Cathedral bell-tower near Florence (Italy) | AVT Bells swinging | bell tower      | 40         | 5.1 × 4.1   | bounded   |               | Six uniaxial accelerometers in a triaxial configuration  | x) 0.87 Hz y) 0.98 Hz                                   |                            | 3 records of 5' 1 record of 6'   | 400 Hz decimated by a factor of 8 to obtain a frequency of 50 Hz | FDD EFDD CFDD SSI (UPC, PC, CVA) MAC |
| [49]  | Cabboi et al.          | 2017 | San Vittore belltower, Italy                                  | AVT                | bell tower      | 37         | 5.7 × 5.8   | bounded   | 18th c.       | Static: 15 displacement transducers and 8 thermocouples 15 accelerometers  | 1.2 Hz  | E = 2.97 GPa E = 1.6 GPa   | 3 years + 3 months for LVDT and temperatures 1 month, 15 accelerometers 9 months, 3 accelerometers | 200 Hz   | SSI-Cov MAC PCA                      |
| [176] | Capanna et al.         | 2021 | The St.Silvestro Belfry, L'Aquila, Italy.                     | AVT                | bell tower      | 33         | 5.5 × 6.9   | bounded   | 13th- 14th c. | Sonic test Endoscopic test Mortar test (chemical-physical analysis) 10 force-balance mono-axial accelerometers (2 fixed) | 940 m/s, ≈909 m/s 2.367 Hz                              |                            | 48 min   | 200 Hz, cut-off filter 20 Hz                                     | SSI PCA MAC                          |
| [91]  | Carone et al.          | 2013 | bell tower of Annunziata in Corfù, Greece                     | AVT                | bell tower      | 20         | 3.5 × 3.5   | bounded   | 14th c.       | 24 seismic accelerometers  | 2.6 Hz  |                            | 10 measurements of 10 min  | 256 Hz   | EFDD SSI (UPC) MAC                   |
| [92]  | Carpinteri et al.      | 2005 | Torre Sineo, Alba, Italy                                      |                    | tower           | 39         | 5.9 × 5.9   |           | 8th c.        | Single and double flat-jack Thermography   |   | Flat jack: 5000 MPa        |  |  |                                      |
| [57]  | Carpinteri et al.      | 2016 | Asinelli tower, Bologna, Italy                                | AVT                | tower           | 97.3       | 8 × 8       |           | 12th c.       | Acoustic Emission (AE) technique. 6 piezoelectric sensors  |   |                            | 4 months   |  |                                      |
| [58]  | Carpinteri & Lacidogna | 2007 | Torre Sineo, Italy.   | AVT                | tower           | 39         |             |           | 13th c.       | Acoustic Emission (AE) Flat jack (single and double) 8 piezoelectric transducers   |   | Flat jack: 5000 MPa        | 60 days  |  |                                      |
|       |                        |      | Torre Astesiano, Italy.                                       | AVT                | tower           | 36         |             |           | 13th c.       | Acoustic Emission (AE) Flat jack (single and double) 8 piezoelectric transducers   |   | Flat jack: 3000 MPa        | 146 days   |  |                                      |



Table 1 (continued)

|       | Author/s             | Year | Element  | Dynamic excitation               | Type of element  | Height (m) | Base (m)    | Restraint | Date          | Instruments/ Technique  | Main results: 1st/ 2nd nat. freq. Sonic test velocities                      | Elastic modulus E adjusted                        | Campaign Time duration                          | Sampling rate                               | Signal processing technique |
|-------|----------------------|------|--|----------------------------------|------------------|------------|-------------|-----------|---------------|---|--|---|---|---|-----------------------------|
|       |                      |      | Torre Bonino, Italy.   | AVT                              | tower            | 35         |             |           | 13th c.       | Acoustic Emission (AE) Flat jack (single and double) 8 piezoelectric transducers  |  | –   | 58 days   |   |                             |
| [93]  | Carpinteri et al.    | 2007 | Torre Sineo, Italy.  |                                  | tower            | 39         |             |           | 13th c.       | Acoustic Emission   |  |   |   |   |                             |
|       |                      |      | Torre Astesiano, Italy.  |                                  | tower            | 36         |             |           | 13th c.       | Acoustic Emission   |  |   |   |   |                             |
|       |                      |      | Torre Bonino, Italy.   |                                  | tower            | 35         |             |           | 13th c.       | Acoustic Emission   |  |   |   |   |                             |
| [691] | Casciati & Al-Saleh  | 2010 | Soncino civic tower, Italy.  | AVT Impact hammer striking bells | civic tower bell | 39.24      | 5.96 × 5.96 | bounded   | 1128 and 1575 | 4 stations, 1 uniaxial accelerometer and 1 triaxial velocimeter   | y) 1.05 Hz x) 1.15 Hz  | 3400 MPa  |   |   |                             |
| [40]  | Casciati et al.      | 2014 | Soncino civic tower, Italy.  | AVT                              | tower bell       | 41.5       |             | bounded   |               | 4 stations with 3D velocimetric sensors   |  |   | 15 days   | 125 Hz                                      | Fourier analysis            |
| [19]  | Casciati & Faravelli | 2010 | Soncino civic tower, in Lombardia, Italy   | AVT Bells                        | tower bell       | 39.5       |             | bounded   |               | accelerometers  | y) 1.05 Hz x) 1.15 Hz  | 2400 MPa (half in areas with distributed damage). |   |   |                             |
| [38]  | Castagnetti et al.   | 2019 | Saint Prospero bell tower (Northern Italy). Saint Prospero (Reggio Emilia, Northern Italy) | AVT Bells                        | tower bell tower |            |             |           | 1571          | Terrestrial Radar Interferometer 6 MEMS accelerometers (two orthogonal directions) 12 uniaxial piezoelectric accelerometers | x) 1.39 Hz y) 1.44 Hz  |   | 1 h (10 min for AVT, 50 min for bells swinging) | 100 Hz                                      | EFDD                        |
| [33]  | Castellano et al.    | 2018 | bell tower of the S.Maria Assunta, Italy Cathedral in Ruvo di Puglia, Apulia, Italy        | AVT                              | bell tower       | 34         | 6 × 6       | isolated  | 12th c.       | Radar interferometry  | 1 Hz   |   | 15 min  | 128 Hz (interferometry)                     | FFT PP                      |
| [26]  | Cavalagli et al.     | 2017 | Gabbia tower in Mantua, Italy.   | AVT                              | tower            | 54         |             | bounded   | 13th c.       | 3 piezoelectric accelerometers 1 Temperature sensor   | 0.985 Hz   |   |   |   | SSI-Cov                     |
|       |                      |      | The San Pietro Bell-Tower in Perugia, Italy.   | AVT                              | bell tower       | 61.4       |             | bounded   | 13th c.       | 3 piezoelectric accelerometers 2 Temperature sensor   | 1.468 Hz   |   | 2 years   | 100 Hz                                      | SSI                         |
| [3]   | Ceravolo et al.      | 2016 | bell tower of the Cathedral of S. Giovenale in Fossano, Italy                              | AVT                              | bell tower       | 35         | 9 × 9.7     | bounded   | 13th c.       | 4 uniaxial piezoelectronics capacitive accelerometers   | 1.28 Hz 1.34 Hz  |   | 20 min  | 400 Hz                                      | SSI MAC                     |
| [37]  | Colapietro et al.    | 2015 | Santa Maria di San Luca, Italy.  | AVT                              | bell tower       | 46         | 6.25 × 6.25 | bounded   | 1774          | Radar scanning Semi-direct mode sonic testing   | sonic testing: 1300 m/s (heterogeneous, bottom part), 1964 m/s (upper part). | Ebottom = 1935 MPa and Etop = 3200 MPa.           |   | 1024 Hz radar scanning 250 Hz sonic testing |                             |
|       |                      |      |  |                                  |                  |            |             |           |               | 9 force-balance accelerometers  |  |   | 2 months  | maximum rate 1 kHz                          |                             |

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Table 1 (continued)

|      | Author/s              | Year | Element   | Dynamic excitation                   | Type of element | Height (m) | Base (m)   | Restraint | Date    | Instruments/Technique  | Main results: 1st/2nd nat. freq. Sonic test velocities                    | Elastic modulus E adjusted                                 | Campaign Time duration   | Sampling rate                                       | Signal processing technique                    |
|------|-----------------------|------|---|--------------------------------------|-----------------|------------|------------|-----------|---------|--|---|--|--|---|--|
| [17] | Colapietro et al.     | 2017 | Bell Tower of the "monastery of St. Clare" in the city of Casamassima, Italy  | AVT                                  | bell tower      |            | 3 × 3      |           | 1660    | Force-balance accelerometers   | 1.39 Hz 1.40 Hz   | Ebottom = 1935 MPa and Etop = 3200 MPa                     | 2 months   | 1000 Hz   | FDD FFT  |
| [94] | Cosenza & Iervolino   | 2007 | bell tower in Serra San Quirico Ancona, Italy   | AVT Unidirectional vibrating machine | bell tower      | 30         |            | bounded   | 15th c. | 16 accelerometers  | 1.95 Hz   |  |  |   |  |
| [39] | Cunha et al.          | 2014 | Tower of Clérigos, Porto, Portugal  | AVT                                  | bell tower      | 75.6       | 7.7 × 8.15 | bounded   | 18th c. | Boroscopic camera Sonic testing Flat jack and tube jack tests 7 triaxial accelerometers, (3 fixed, 4 moving)   | x) 1.022 Hz y) 1.213 Hz   |  | 16 min   | 100 Hz  | EFDD (FFT and SVD) SSI MAC                     |
| [53] | DelloRusso et al.     | 2008 | Masonry Tower of the Milwaukee City Hall, USA.  |                                      | bell tower      | 119.8      |            | bounded   | 19th c. | 8 crackmeters 3 groups of thermocouples at four depths through the wall thickness for stress gradient (thermistors and thermocouples). Total = 12 Straining gauges for steel |   |  | 12 months  | every 30 min  |  |
| [95] | De Stefano & Ceravolo | 2007 | SS. Annunziata church bell-tower in Roccaverano, Asti, Italy. Bell-tower of S. Lorenzo Cathedral in Alba, Italy. Matilde's Tower in San Miniato, Pisa, Italy. | AVT Bells                            |                 |            |            |           |         | 2 fixed accelerometers and 2 moving per landing  | 1.66 Hz, 1.97 Hz (after restoration) 2.26 Hz, 2.34 Hz (after restoration) | E = 12.3e8 N/m2 before repair E = 18.8e8 N/m2 after repair |  |   | TFIE (time-frequency instantaneous estimators) |
|      |                       |      |   |                                      |                 | 35         |            | bounded   | 12th c. | 3 accelerometers fixed and 10 moving (San Lorenzo)   | 1.25 Hz 1.44 Hz   |  |  |   |  |
| [96] | Diaferio et al.       | 2014 | clock tower of the Castle of Trani (Bari, Italy).   | AVT Vibrodyne                        | clock tower     | 9          | 3.9 × 3.9  | bounded   | 1848    | 23 piezoelectric accelerometers  | y) 7.5 Hz x) 10.3 Hz  |  | 4 series of 15 min = 60 min                                      | 1024 Hz, undersampled to 128 Hz                     | EFDD SSI (UPC)                                 |
| [41] | Diaferio et al.       | 2015 | the bell tower of the Cathedral of Trani, Italy.  | AVT                                  | bell tower      | 57         | 7.5 × 7.5  | bounded   | 12th c. | Microwave remote sensing (radar-based technology, interferometry) 28 piezoelectric accelerometers  | y) 2.04 Hz x) 2.26 Hz   |  | 11 sets of 10 min for accelerometers 30 min and 60 min for radar | Accel. 256 Hz (1024 Hz decimated by 4) Radar 100 Hz | EFDD SSI                                       |
| [67] | Diaferio et al.       | 2016 | bell tower of Annunziata (Corfu, Greece),   | AVT                                  | bell tower      | 20         | 3.5 × 3.5  | bounded   | 1394    | 24 accelerometers in 12 locations (x,y directions)   | y) 2.61 Hz x) 2.83 Hz   |  | 10 measurements of 10 min for accelerometers                     | Accel. 256 Hz (1024 Hz decimated by 4)              | EFDD SSI (UPC)                                 |
| [22] | Diaferio et al.       | 2018 |   |                                      |                 |            |            |           |         |  |   |  |  |   |  |
| [97] | Diaferio & Foti       | 2017 | bell tower of the Trani's Cathedral, Italy.   | AVT                                  | bell tower      | 57         | 7.5 × 7.5  | bounded   | 14th c. | 28 uniaxial piezoelectric accelerometers Ground penetrating radar (GPR) tests  |   |  | 11 measurements of 10 min for accelerometers                     | Accel. 256 Hz (1024 Hz decimated by 4)              | EFDD SSI                                       |

Table 1 (continued)

|       | Author/s            | Year | Element   | Dynamic excitation | Type of element | Height (m) | Base (m)    | Restraint | Date    | Instruments/ Technique  | Main results: 1st/ 2nd nat. freq. Sonic test velocities           | Elastic modulus E adjusted   | Campaign Time duration                       | Sampling rate                          | Signal processing technique |
|-------|---------------------|------|---|--------------------|-----------------|------------|-------------|-----------|---------|---|---|--|--|--|-----------------------------|
| [73]  | Ditomaso et al.     | 2012 | Falkenhof Tower (Potsdam, Germany)  | AVT Explosion      | tower           | 16         | 4 × 4       | bounded   |         | 8 velocimetric stations in the tower, 3 on the ground   | y) 2.73 Hz x) 2.87 Hz   |  | several hours                                | 100 Hz                                 | HVSR STFT EMD S-Transform   |
| [98]  | El-Attar et al.     | 2005 | Manjaq Al-Yusufi minaret, El Cairo, Egypt.                                  | AVT                | minaret         | 26.45      | 3.8 × 3.8   | isolated  | 1349    | Test cores to know the construction material Boreholes to know soil condition 5 triaxial accelerometers Laser interferometer                            | 2.03 Hz 2.05 Hz   | Horizontal to Vertical Spectral Ratio (HVSR); Short Time Fourier Transform (STFT); Empirical Mode Decomposition (EMD); S-Transform | 5 sets of 2 min                              | 100 Hz                                 | PSD                         |
| [44]  | Ellis               | 1997 | chimney at the Building Research Establishment pinnacle clock tower Big Ben | AVT                | chimney         | –          |             |           |         | Laser interferometer  | chimney 3.17 Hz   |  | 8 s  |  | ASD                         |
| [130] | Erdil et al.        | 2018 | minaret of Van Ulu Mosque   | microtremors       | minaret         |            | φ = 3.80    | isolated  | 13th c. | 3 components  | 2.08 Hz   | E = 1.8 GPa  | 20 min                                       | 100 Hz                                 |                             |
| [127] | Erdogan et al.      | 2019 | Minaret of the Sultan Ahmed Mosque, Istanbul, Turkey.                       | AVT                | minaret         | 51         |             | bounded   | 17th c. | Uniaxial compression and bending tests from restoration. Density and water absorption Ultrasonic pulse tests. 5 uniaxial and 1 triaxial accelerometers. | 0.87 Hz 3.23 Hz   | E = 12000 MPa  | 2 sets of 20 min                             | 12800 Hz subsampled to 100 Hz          | EFDD SSI                    |
| [99]  | Foti et al.         | 2015 | bell tower of the Cathedral of Trani (Bari, Italy)                          | AVT Bells          | bell tower      | 57         | 7.5 × 7.5   | bounded   | 1200    | 28 uniaxial piezoelectric accelerometers GPR  | y) 2.04 Hz x) 2.26 Hz   |  | 11 measurements of 10 min for accelerometers | Accel. 256 Hz (1024 Hz decimated by 4) | EFDD SSI                    |
| [100] | Foti                | 2016 | bell tower Santa Maria della Natività, Noci (Bari, Italy)                   |                    | bell tower      | 35         |             | bounded   | 1761    | Endoscopic inspection; 2D and 3D radar tomography Thermographic inspections Flat jacks tests Rebound hammer tests                                       |   |  |  |  |                             |
| [30]  | Foti et al.         | 2012 | bell tower of the Chiesa della Maddalena (Mola di Bari, Italy)              | AVT                | bell tower      | 34.7       | 4.38 × 4.11 | bounded   | 18th c. | Four piezoelectric accelerometers   | 4.57 Hz 8.05 Hz   |  | 3 sets of 15 min = 45 min for AVT            | 1653 Hz                                | PP (FFT) PSD                |
| [81]  | Garcia-Macias et al | 2019 | the Sciri Tower in Perugia  | AVT                | bell tower      | 41         | 7.15 × 7.35 | bounded   | 13th c. | 12 high sensitivity uniaxial accelerometers 1st campaign: 5 accelerometers, 2nd campaign: 12 accelerometers Seismic interferometry                      | 1.72 Hz, 1.91 Hz  |  | 90 min                                       | 1652 Hz downsampled to 200 Hz 100 Hz   | SSI MAC                     |
|       |                     |      | the bell-tower of the Basilica of San Pietro in Perugia.                    | AVT                | bell tower      | 61.4       |             |           | 13th c. | (same as previous)  | 1.45 Hz (2015) vs 1.46 Hz (2016) 1.52 Hz (2015) vs 1.53 Hz (2016) |  | 30 min                                       |  |                             |

(continued on next page)

Table 1 (continued)

|       | Author/s                 | Year | Element   | Dynamic excitation      | Type of element | Height (m) | Base (m)    | Restraint | Date    | Instruments/Technique   | Main results: 1st/2nd nat. freq. Sonic test velocities                          | Elastic modulus E adjusted            | Campaign Time duration  | Sampling rate   | Signal processing technique |
|-------|--------------------------|------|---|-------------------------|-----------------|------------|-------------|-----------|---------|---|---|---------------------------------------|---|---|-----------------------------|
| [20]  | García-Macías & Ubertini | 2020 | Sciri Tower in Perugia, Italy   | AVT                     | civic tower     | 41         | 7.15 × 7.35 | bounded   | 13th c. | 12 uniaxial accelerometers 2 thermocouples Seismic interferometry   | 1.69 Hz 1.89 Hz   |                                       | 3 weeks   | 200 Hz, 1000 Hz and 5000 Hz (downsampled to 40 Hz) 0.4 Hz for temperature | SSI-cov ERA p-LSCF EFDD MAC |
| [183] | García-Macías et al.     | 2020 | the Sciri Tower in Perugia  | AVT                     | civic tower     | 41         | 7.15 × 7.35 | bounded   | 13th c. | 12 uniaxial accelerometers 2 thermocouples Seismic interferometry   | 1.69 Hz 1.89 Hz   |                                       | 3 weeks   | 1652 Hz downsampled to 40 Hz  | MLR PCA ANN MAC Cov-SSI     |
| [184] | García-Macías et al.     | 2021 | the Sciri Tower in Perugia  | AVT                     | civic tower     | 41         | 7.15 × 7.35 | bounded   | 13th c. | 12 uniaxial accelerometers 2 thermocouples Seismic interferometry   | 1.69 Hz 1.89 Hz   | ANNs: Autoassociative Neural Networks | 3 weeks   | 1652 Hz downsampled to 40 Hz  | COV-SSI MPC MAC             |
| [101] | Gazzani et al.           | 2018 | The bell tower of Pomposa Abbey, located in the Ferrara Province (Italy).       | AVT                     | bell tower      | 48         | 7 × 7       | isolated  | 1063    | 8 monoaxial piezoelectric accelerometers  |   |                                       | between 40' and 60'   | 12.5 Hz (1000 Hz decimated by 40)   | SSI-Cov MAC                 |
| [102] | Gentile et al.           | 2015 | bell tower of the church Chiesa Collegiata in Arcisate (Varese, northern Italy) | AVT Micro-tremors Bells | bell tower      | 37         | 5.8 × 5.8   | bounded   | 16th c. | 15 piezoelectric accelerometers Sonic test Two double flat jack   | 1.22 Hz 1.28 Hz   | E = 3 Gpa                             | 3600 s in June 2007 for wind and micro tremors 2000 s for swinging bells in June 2008   | 200 Hz (decimation to 20 Hz)  | SSI FDD                     |
| [16]  | Gentile & Saisi          | 2013 | bell tower of the church Chiesa Collegiata in Arcisate (Varese, northern Italy) | AVT Micro-tremors Bells | bell tower      | 37         |             | bounded   | 16th c. | 15 piezoelectric accelerometers   | 1.21 Hz 1.29 Hz   |                                       | 3600 s in June 2007 for wind and micro tremors 2000 s for swinging bells in June 2008   |   | FDD SSI                     |
| [35]  | Gentile & Saisi          | 2007 | bell-tower adjacent to the Cathedral of Monza, Italy.                           | AVT                     | bell tower      | 74         |             | bounded   | 17th c. | 1st campaign (1995): Visual inspection, flat-jack, double flat-jack, 4 servo-accelerometers 2nd campaign (2001): 11 piezoelectric accelerometers (20 points with 2 fixed) Pulse sonic tests 1st campaign: 12 accelerometers 2nd campaign: 3 piezoelectric accelerometers and one thermocouple | 0.59 Hz 0.71 Hz   |                                       | 2280 s  | 200 Hz  | PP FDD MAC                  |
| [50]  | Gentile et al.           | 2016 | the Gabbia tower in Mantua, Italy   | AVT Earthquake          | tower           | 54         |             | bounded   | 1227    |   | 0.918 Hz 0.986 Hz (600 m/s damage area, between 1100 m/s y 1600 m/s good state) |                                       | 1st campaign: two hours with time windows of 3600 s for modal identification 2nd campaign: 15 months (time windows of 3600 s) | 40 Hz (200 Hz decimated by 5)   | SSI-Cov                     |
| [52]  | Gentile et al.           | 2019 | bell-tower of Santa Maria del Carrobiolo in Monza (Italy)                       | AVT                     | bell tower      | 33.7       | 5.9 × 5.7   | bounded   | 1339    | Static monitoring of cracks by 10 displacement transducers 5 temperature sensors 4 MEMS accelerometers  | 1.92 Hz   |                                       | 1 year (time windows of 3600 s)   | 200 Hz  | FDD SSI-Cov                 |
| [134] | Hacıefendiog Ju et al.   | 2016 | Minaret of the Büyük Mosque, Samsun, Turkey                                     | AVT                     | minaret         | 32.07      | 3.13 × 3.13 | bounded   | 1884    | 4 axial wireless accelerometers   | 1.03 Hz 1.27 Hz   |                                       | 20 min  |   | FDD                         |

Table 1 (continued)

|       | Author/s          | Year | Element  | Dynamic excitation | Type of element | Height (m)  | Base (m)                | Restraint | Date    | Instruments/ Technique                                       | Main results: 1st/ 2nd nat. freq. Sonic test velocities | Elastic modulus E adjusted | Campaign Time duration | Sampling rate              | Signal processing technique |
|-------|-------------------|------|--|--------------------|-----------------|-------------|-------------------------|-----------|---------|--|---|----------------------------|------------------------|----------------------------|-----------------------------|
| [133] | Hamed et al.      | 2017 | Qaitbay minaret, Al-Azhar Mosque, Cairo, Egypt.                                  | AVT                | minaret         | 37.86       | 3.15 × 3.15             | bounded   | 1432    | 2 triaxial capacitance acceleration sensors                  |   |                            | 651 days               | every 5 min, avg. per hour |                             |
|       |                   |      | Al-Ghuri Minaret, Al-Azhar Mosque, Cairo, Egypt                                  | AVT                | minaret         | 52.5        | 3.15 × 3.15             | bounded   | 1509    | 3 triaxial capacitance acceleration sensors                  |   |                            | 651 days               | every 5 min, avg. per hour |                             |
|       |                   |      | Aqbaghawya Minaret, Al-Azhar Mosque, Cairo, Egypt                                | AVT                | minaret         | 34.62       | 2.68 × 2.71             | bounded   |         | 2 triaxial capacitance acceleration sensors                  |   |                            | 651 days               | every 5 min, avg. per hour |                             |
|       |                   |      | Bab Al-Shorba minaret, Al-Azhar Mosque, Cairo, Egypt                             | AVT                | minaret         | 33.12       | 2.43 × 2.57             | bounded   |         | 1 triaxial capacitance acceleration sensor                   |   |                            | 651 days               | every 5 min, avg. per hour |                             |
|       |                   |      | Bab Al-Saida minaret, Al-Azhar Mosque, Cairo, Egypt                              | AVT                | minaret         | 33.12       | 2.73×2.74               | bounded   |         | 1 triaxial capacitance acceleration sensor                   |   |                            | 651 days               | every 5 min, avg. per hour |                             |
| [66]  | Invernizzi et al. | 2019 | The Asinelli Tower in Bologna, Italy.  |                    |                 |             |                         |           |         |  |   |                            |                        |                            |                             |
| [103] | Ivorra et al.     | 2010 | bell tower of the Church of Santas Justa and Rufina in Orihuela, Alicante, Spain | Bells              | bell tower      | 35.5        |                         | bounded   | 15th c. | 8 piezoelectric seismic accelerometers                       | 2.15 Hz 2.24 Hz   | E = 1400 N/mm2             |                        | 200 Hz                     | PP (FFT) PSD                |
| [31]  | Ivorra et al.     | 2019 | squat masonry tower situated in the Swabian Castle of Trani (Italy).             | AVT Vibrodyne      | tower           | 20          | 4.25 × 4.25             | bounded   | 19th c. | 23 seismic accelerometers                                    | 7.5 Hz 10.3 Hz  |                            | 4 sets of 15 min       | 1024 Hz                    | EFDD SSI                    |
| [104] | Ivorra & Pallarés | 2006 | bell tower of "Nuestra Sra. De la Misericordia Church" (Valencia, Spain).        | AVT Bells          | bell tower      | 41          | 5.6 × 5.6               | bounded   | 1740    | Two piezoelectric accelerometers                             | 1.29 Hz 1.49 Hz   | E = 2819 N/mm2             |                        | 200 Hz                     | PSD                         |
| [105] | Julio et al.      | 2008 | tower of University of Coimbra, Portugal.  | AVT Bells          | bell tower      |             |                         | bounded   | 1733    | 8 accelerometers: 4 fixed and 4 moving, measuring 20 points. | 2.133 Hz 2.473 Hz                                       | E = 5.5 GPa                | 4 sets of 45 min each  | 102.4 Hz                   | PP FDD                      |
| [126] | Korumaz et al.    | 2017 | Eğri Minaret in Aksaray (central Turkey).  |                    | minaret         |             |                         |           |         | Terrestrial laser scanning (TLS)                             |   |                            |                        |                            |                             |
| [63]  | Kumar et al.      | 2008 | stone pillars of the Vitthala Temple, India.                                     |                    | pillars         | approx. 1 m | approx. $\phi$ = 100 mm |           |         | Ultrasonic testing<br>Impact echo testing<br>Metallography   | 4800–5500 m/s.<br>3800–4200 m/s if damaged pillars.     |                            |                        |                            |                             |
| [48]  | Lacanna et al.    | 2019 | Giotto's bell tower, Firenze, Italy.   | AVT                | bell tower      | 84.7        | 14.45 × 14.45           | bounded   | 14th c. | 10 triaxial seismic stations<br>Seismic interferometry       | 0.623 Hz 0.647 Hz                                       |                            | 36 h                   | 100 Hz                     | EFDD                        |
| [106] | Livaoglu et al.   | 2016 | Minaret of Bedrettin Mosque, Bursa, Turkey.                                      | AVT                | minaret         | 20.52       |                         | isolated  | 1443    | 4 accelerometers   | 2.85 Hz   |                            |                        |                            | EFDD                        |

(continued on next page)



Table 1 (continued)

| Author/s | Year              | Element   | Dynamic excitation | Type of element          | Height (m) | Base (m)         | Restraint | Date                  | Instruments/Technique  | Main results: 1st/2nd nat. freq. Sonic test velocities                                   | Elastic modulus E adjusted                         | Campaign Time duration            | Sampling rate | Signal processing technique |
|----------|-------------------|---|--------------------|--------------------------|------------|------------------|-----------|-----------------------|--|--|--|-----------------------------------|---------------|-----------------------------|
|          |                   | Minaret of Hacýlar Mosque, Bursa, Turkey.   | AVT                | minaret                  | 24.45      |                  | isolated  |                       | 4 accelerometers   | 1,36 Hz  |  |                                   |               | EFDD                        |
|          |                   | Minaret of Hoca Tabip Mosque, Bursa, Turkey.  | AVT                | minaret                  | 14.3       |                  | isolated  | 15th c.               | 4 accelerometers   | 2,25 Hz  |  |                                   |               | EFDD                        |
|          |                   | Minaret of Kayhan Mosque, Bursa, Turkey.  | AVT                | minaret                  | 19.42      |                  | isolated  | 1497, rebuilt 1873    | 4 accelerometers   | 1,81 Hz  |  |                                   |               | EFDD                        |
|          |                   | Minaret of Emir Sultan Mosque, Bursa, Turkey.   | AVT                | minaret                  | 30.85      |                  | isolated  | 15th c., rebuilt 1805 | 4 accelerometers   | 1,21 Hz  |  |                                   |               | EFDD                        |
|          |                   | Minaret of Hoca Muslihiddin Mosque, Bursa, Turkey.  | AVT                | minaret                  | 21.6       |                  | isolated  | 1615                  | 4 accelerometers   | 2,29 Hz  |  |                                   |               | EFDD                        |
|          |                   | Minaret of Hocaalizade Mosque, Bursa, Turkey.   | AVT                | minaret                  | 24.59      |                  | isolated  | 1439                  | 4 accelerometers   | 1,00 Hz  |  |                                   |               | EFDD                        |
| [34]     | Livitsanos et al. | 2019 chimney in the Leonardo campus of the Politecnico di Milano, Italy.  | AVT                | chimney                  | 50         |                  | isolated  |                       |  | 0.75 Hz  |  | 9 sets of 45 min each measurement |               | EFDD PP                     |
| [107]    | Llorens et al.    | 2001 stone columns located in cloister of Girona Cathedral in Spain   | Impact hammer      | stone columns            |            | $\phi = 15$ cm   |           | 11th c.               | 2 tests per column. 1 ceramic accelerometer per test   |  |  |                                   | 30000 Hz      |                             |
| [108]    | Lorenzoni et al.  | 2017 four water towers in Pompeii, Italy.   | AVT                | water towers             |            |                  | isolated  | 10–20 BC              | 6 measuring points and 3 acceleration registers per tower  | 1: 2.98 Hz, 3.17 Hz<br>2: 2.78 Hz, 3.13 Hz<br>3: 2.69 Hz, 3.32 Hz<br>4: 3.08 Hz, 3.13 Hz |  | 3 sets per tower, 10 min each     | 100 Hz        | FDD EFDD MAC                |
| [158]    | Magrinelli et al. | 2021 Gabbia Tower in Mantua (northern Italy)  | AVT                | tower                    | 54         | $7.6 \times 7.6$ | bounded   | 13th c.               | Thermo-vision Double flat-jack   | 0.957 Hz 1.006 Hz  | $E = 3500$ MPa, $f_c = 2.5$ MPa (double flat jack) |                                   |               | MAC FDD SSI                 |
| [80]     | Masciotta et al.  | 2014 chimney in Guimarões, North of Portugal.   | AVT                | chimney                  | 27         | $\phi = 2.93$    | isolated  |                       | 2 test, 12 uniaxial piezoelectric accelerometers   | 1.01 Hz, 1.15 Hz before restoration<br>1.02 Hz, 1.1 Hz after restoration                 |  | 2 sets of measurements of 10 min  | 200 Hz        |                             |
| [174]    | Milani & Clementi | 2021 Ferrara Cathedral, Italy. San Benedetto tower, Ferrara, Italy, Matilde's tower, Ferrara, Italy. Belfry of Pomposa Abbey, Ferrara, Italy. |                    | bell tower<br>bell tower |            |                  |           |                       |  | 1.023 Hz 1.054 Hz<br>0.737 Hz 0.756 Hz   | $E \cong 4500$ Mpa<br>$E \cong 1500$ Mpa           |                                   |               | MAC<br>MAC                  |
|          |                   |   |                    | bell tower<br>bell tower |            |                  |           |                       |  | 1.478 Hz 1.521 Hz<br>0.934 Hz 1.024 Hz   | $E \cong 1500$ Mpa<br>$E \cong 1500$ Mpa           |                                   |               | MAC<br>MAC                  |
| [36]     | Modena et al.     | 2002 bell-tower of the cathedral of Monza, Italy.   | AVT Bells          | bell tower               |            |                  | bounded   | 16th c.               | 7 single flat jack<br>Double flat jack test<br>Sonic velocity tests<br>Six horizontal servo-accelerometers | 0.654 Hz 0,663 Hz  |  |                                   |               |                             |

Table 1 (continued)

|       | Author/s            | Year | Element   | Dynamic excitation | Type of element | Height (m)  | Base (m)             | Restraint          | Date    | Instruments/ Technique  | Main results: 1st/ 2nd nat. freq. Sonic test velocities                             | Elastic modulus E adjusted | Campaign Time duration       | Sampling rate | Signal processing technique             |
|-------|---------------------|------|---|--------------------|-----------------|---|----------------------|--------------------|---------|---|---|----------------------------|------------------------------|---------------|---|
| [109] | Nohutcu             | 2019 | Imaret Mosque Minaret, in Afyon, Turkey   | AVT                | minaret         | 24.5  | $\phi = 2.66$        | isolated           | 1481    | Twelve uniaxial accelerometers  | 1.425 Hz  | E = 5200 MPa               |                              |               | SSI                                     |
| [110] | Oliveira et al.     | 2012 | 11 minarets in Istanbul   | AVT                | minaret         | 66.55<br>63.20<br>44.96<br>74.40<br>54.90<br>23.02<br>38.65<br>41.6<br>51.7<br>48.7 |                      | isolated           |         | Three 3D accelerometers. Total 9 components   | 1.26 Hz 1.17 Hz<br>1.03 Hz 0.97 Hz<br>0.65 Hz 1.69 Hz<br>1.36 Hz 0.84 Hz<br>1.18 Hz |                            | 100 Hz                       | EFDD SSI      |   |
| [111] | Osmancikli et al.   | 2012 | bell-tower of Hagia Sophia Church in Trabzon, Turkey  | AVT Impact loads   | bell tower      | 23.5  | $5 \times 5.5$       | isolated           | 13th c. | 9 uniaxial accelerometers: 1 fixed and 8 moving 3 times (24 uniaxial accelerations were recorded)   | 2.55 Hz X 2.63 Hz<br>Y  |                            | 3 measurements, 10 min each. |               | EFDD SSI                                |
| [112] | Palermo et al.      | 2015 | Asinelli Tower, Bologna, Italy.   | AVT                | bell tower      | 87  | $8.5 \times 8.5$     | isolated           | 12th c. | Flat jack tests (one compression test and two shear test) 6 Standard and pointing hardness tests with the hammer pendulum. Four triaxial seismometers |   |                            |                              |               |   |
| [179] | Pavlovic et al.     | 2019 | The bell tower of Basilica dei Frari in Venice, Italy.  | AVT                | bell tower      | 56.6  | $9.4 \times 9.2$     | bounded            | 1396    | 1 Digital tromograph (three vibration sensors with velocimeter and accelerometer each)  | 1.05 Hz   | E = 2200 MPa               | 7 measurmnts, 16 min each    | 512 Hz        | FDD                                     |
| [61]  | Pérez-Gracia et al. | 2013 | columns of the Mallorca cathedral, Spain.   |                    | stone columns   |   |                      |                    |         | Ground penetrating radar (GPR) Seismic tomography   |   |                            |                              |               |   |
| [56]  | Pesci et al.        | 2013 | San Giacomo Roncole campanile (bell tower), Italy. Asinelli leaning tower (Bologna), Italy.                           |                    | bell tower      | 35 97   | $- 8.3 \times 8.3$   | bounded<br>bounded |         | Terrestrial laser scanning (TLS)  |   |                            |                              |               |   |
| [113] | Pieraccini et al.   | 2007 | bell tower of the church of Pratomino, Florence, Italy.   | Bells              | bell tower      | 20  | $5 \times 5$         | bounded            | 15th c. | Interferometric radar   | 2 Hz 2.45 Hz  |                            |                              |               | short-time Fourier transform (STFT) FFT |
| [42]  | Pieraccini et al.   | 2009 | Giotto's Tower, cathedral of Santa Maria del Fiore, Italy. Arnolfo's Tower, found at PalazzoVecchio. Florence, Italy. | AVT Bells          | bell tower      | 87.4  | $14.45 \times 14.45$ | bounded            | 14th c. | Microwave remote sensing (radar interferometry)   | 0.62 Hz   |                            | 12.5 min                     | 300 kHz       |   |
| [32]  | Pieraccini et al.   | 2014 | Torre del Mangia" (Mangia's tower) in Siena (Italy).  | AVT                | bell tower      | 88 m  | $7 \times 7$         | bounded            | 1348    | Microwave remote sensing (radar interferometry)<br>Terrestrial Laser Scanning (TLS) Radar interferometry  | 0.49 Hz X 0.79 Hz<br>Y  | E = 2400 N/mm2             |                              |               | PSD FFT FDD                             |

(continued on next page)

Table 1 (continued)

|       | Author/s          | Year | Element  | Dynamic excitation            | Type of element | Height (m) | Base (m)          | Restraint | Date    | Instruments/ Technique  | Main results: 1st/ 2nd nat. freq. Sonic test velocities               | Elastic modulus E adjusted | Campaign Time duration   | Sampling rate                    | Signal processing technique              |
|-------|-------------------|------|--|-------------------------------|-----------------|------------|-------------------|-----------|---------|---|---|----------------------------|--|----------------------------------|--|
| [172] | Pieraccini        | 2017 | 15 towers in San Gimignano village in Italy                          |                               | tower           |            |                   |           |         | Radar interferometry  | between 1.25 Hz and 3.35 Hz   |                            | 20 min   | 100 Hz                           | PSD FDD                                  |
| [15]  | Ramos et al.      | 2006 | The Qutb Minar, New Delhi, India.                                    | AVT                           | minaret         | 72.45      | $\phi = 14.07$    |           | 13th c. | 8 uniax. piezoelectric accel. in 4 points (2 triaxial + 2 axial) in 5 sections Sonic pulse velocity tests   | 0.79 Hz 0.81 Hz   |                            | 20 min   | 100 Hz                           | SSI (UPC) Principal Component (PC). MAC  |
| [7]   | Ramos et al.      | 2010 | The Mogadouro Clock Tower, Portugal.                                 | AVT                           | clock tower     | 20.4       | $4.7 \times 4.5$  | isolated  | 1559    | 1st campaign: 4 uniaxial piezo electric accel. 2nd campaign: 3 piezoelectric accel., temperature, humidity  | 2.15 Hz 2.58 Hz before restoration 2.56 Hz, 2.76 Hz after restoration |                            | 1st campaign: 10'40' per measurement 2nd campaign: 10' every hour during 1.5 years         | 256 Hz                           | SSI PCA MLR ARX                          |
| [78]  | Ramos et al.      | 2013 | chimney in Guimarães, North of Portugal.                             | AVT                           | chimney         | 27         | $\phi = 2.93$     | isolated  |         | 2 test, 12 uniaxial piezoelectric accelerometers  | 1.01 Hz, 1.15 Hz before restoration 1.02 Hz, 1.1 Hz after restoration |                            | 2 sets of measurements of 10 min   | 200 Hz                           | EFDD SSI MAC                             |
| [114] | Russo et al.      | 2010 | "Saint Andrea" Bell Tower in Venice, Italy.                          | AVT Bells Instrumental hammer | bell tower      | 58         | $7.6 \times 7.64$ | isolated  | 19th c. | Georadar analysis Flat Jack analysis Inclinometer Accelerometers  | 0.61 Hz   |                            |  |                                  |  |
| [45]  | Saisi et al.      | 2015 | the Gabbia Tower in Mantua, Italy                                    | AVT                           | tower           | 54         |                   | bounded   | 13th c. | Single and double flat jack tests Pulse sonic tests 1st campaign: 12 accel. 2nd campaign: 3 piezoelectric accel. and 1 thermocouple                     | 0.918 Hz 0.986 Hz   |                            | 1st campaign: 28 h acquiring accelerations (time windows of 3600 s) 2nd campaign: 8 months | 200 Hz                           | SSI-Cov                                  |
| [46]  | Saisi et al.      | 2016 | bell-tower of the Church Santa Maria del Carrobiolo in Monza, Italy. | AVT Bells                     | bell tower      | 33.7       | $5.93 \times 5.7$ | bounded   | 1339    | Microwave interferometer 2nd campaign, static: 10 displacements transducers (crack opening), and 5 temperature sensors. 3rd campaign: 10 accelerometers | 1.93 Hz   |                            | static monitoring (temperature and crack wide) every 10' during 20 months                  | 25 Hz (200 Hz decimated 8 times) | FDD SSI-Cov MAC                          |
| [115] | Saisi et al.      | 2016 | the Gabbia tower in Mantua, Italy.                                   | AVT Earthquake                | tower           |            | see [52]          |           |         |   |   |                            |  |                                  |  |
| [116] | Saisi & Gentile   | 2015 | the Gabbia tower in Mantua, Italy.                                   | AVT                           | tower           |            | see [52]          |           |         |   |   |                            |  |                                  |  |
| [5]   | Saisi et al.      | 2018 | bell-tower of the Church Santa Maria del Carrobiolo in Monza, Italy. | AVT                           |                 |            |                   |           |         | [48] (Saisi et al. 2016) plus 4 MEMS accelerometers for continuous monitoring   |   |                            |  | MEMS at 200 Hz                   | SSI-Cov Multiple linear regression (MLR) |
| [117] | Saisi et al.      | 2019 | Zuccaro's Tower situated in Mantua, Italy.                           | AVT                           | tower           | 43         |                   | bounded   | 12th c. | 16 accelerometers   | 1.23 Hz 1.28 Hz   |                            |  | 200 Hz                           | SSI FDD                                  |
| [118] | Sancibrian et al. | 2017 | chimney in Cantabria (North of Spain)                                | AVT                           | chimney         | 38.3       | $\phi = 4.02$     | isolated  | 20th c. | Laparoscopy Double flat-jack test Uniaxial capacitive accelerometers  | 0.76 Hz 8.41 Hz   | E = 6519 MPa flat-jack     |  |                                  | PP FDD MAC                               |

Table 1 (continued)

|       | Author/s               | Year | Element   | Dynamic excitation              | Type of element | Height (m) | Base (m)    | Restraint | Date    | Instruments/ Technique  | Main results: 1st/ 2nd nat. freq. Sonic test velocities                  | Elastic modulus E adjusted | Campaign Time duration        | Sampling rate   | Signal processing technique |
|-------|------------------------|------|---|---------------------------------|-----------------|------------|-------------|-----------|---------|---|--|----------------------------|-------------------------------|---|-----------------------------|
| [27]  | Sepe et al.            | 2008 | Febonio tower in Trasacco, Italy.   | AVT Person jumping rhythmically | tower           | 28         | 8.2 × 8.2   | isolated  |         | 3 accelerometers<br>Inclinometer<br>Georadar Flat jacks   | 2.4 Hz   | E = 3.5 kN/mm <sup>2</sup> |                               |   |                             |
| [175] | Standoli et al.        | 2021 | San Giorgio Cathedral Belfry, Ferrara, Italy.                                   | AVT                             | bell tower      | 50.78      | 11.7 × 11.7 | isolated  | 1412    | 8 uniaxial accelerometers   | 1.030 Hz   |                            | 4 acquisitions, 20 min to 1 h | 1000 Hz decimated to 0–6.25 Hz  | EFDD SSI                    |
|       |                        |      | San Benedetto Church Belfry, Ferrara, Italy.                                    | AVT                             | bell tower      | 52.06      | 7.33 × 7.33 | isolated  | 1621    | 8 uniaxial accelerometers   | 0.759 Hz   |                            | 7 acquisitions, 20 min to 1 h | 1000 Hz decimated to 0–6.25 Hz  | EFDD SSI                    |
|       |                        |      | Matilde's tower, of the Santa Maria church in Bondeno, Italy.                   | AVT                             | bell tower      | 29.96      | 7.2 × 7.2   | bounded   | 12th c. | 8 uniaxial accelerometers   | 1.472 Hz   |                            | 3 acquisitions, 20 min to 1 h | 1000 Hz decimated to 0–6.25 Hz  | EFDD SSI                    |
|       |                        |      | Belfry of Pomposa Abbey, Codigoro, Italy.                                       | AVT                             | bell tower      | 49.9       | 7.7 × 7.7   |           | 1063    | 8 uniaxial accelerometers   | 0.939 Hz   |                            | 6 acquisitions, 20 min to 1 h | 1000 Hz decimated to 0–6.25 Hz  | EFDD SSI MAC (CrossMAC)     |
| [119] | Tomaszewska & Szymczak | 2012 | Vistula Mounting Fortress tower in Gdansk, Poland                               | AVT                             | tower           | 22.65      | φ = 7.7     | isolated  | s. XV   | 4 fixed accelmtrs and 8 moving, measuring 36 points in 4 steps.   | 1.416 Hz 1.446 Hz  |                            | 1024 s each measurement       | 256 Hz  | PP                          |
| [120] | Tsogka et al.          | 2017 | bell tower of the Benedictine Abbey of San Pietro, Perugia, Italy.              | AVT Bells                       | bell tower      | 61.4       |             | bounded   | 14th c. | 3 piezoelectric uniaxial accelmtrs 2 temperature sensors (thermocouples)  | 1.47 Hz  |                            | 4 months                      | 40 Hz   | FDD SSI                     |
| [47]  | Ubertini et al.        | 2017 | bell tower of the Benedictine Abbey of San Pietro in Perugia, Italy.            | AVT                             | bell tower      | 61.45      |             | bounded   | 14th c. | 9 uniaxial accelmtrs 8 temperature sensors 2 humidity sensors   |  |                            | 9 months                      | 1600 Hz (downsampled to 40 Hz) Every 30 min for environmental sensors | SSI PCA                     |
| [54]  | Ubertini et al.        | 2018 | bell tower of the Benedictine Abbey of San Pietro in Perugia, Italy.            | AVT Bells Earthquake            | bell tower      | 61.4       |             | bounded   |         | 9 uniaxial accelmtrs 8 temperature sensors 2 humidity sensors   |  |                            | 2 years                       | 100 Hz  | SSI PCA                     |
| [55]  | Vincenzi et al.        | 2019 | bell tower of Saint Prospero (Reggio Emilia, Northern Italy)                    | AVT Bells swinging              | bell tower      |            |             | bounded   | 1571    | TLS terrestrial laser scan<br>Photogrammetry 12 uniaxial piezoelectric accelerometers 6 MEMS (2 orthogonal directions)<br>Temperature in MEMS units | 1.38 Hz 1.44 Hz  | E = 2430 MPa               |                               | 200 Hz accelerometers<br>80 Hz MEMS accelerometers                    | EFDD EMD<br>MAC FFT         |
| [121] | Zanotti et al.         | 2017 | bell tower of the Santa Maria Maggiore cathedral, located in Mirandola (Italy). | AVT                             | bell tower      | 48         | 5.9 × 5.9   | bounded   | 17th c. | Eight uniaxial piezoelectric accelerometers   | 0.68 Hz 0.72 Hz before restoration<br>0.79 Hz, 0.87 Hz after restoration |                            | 300 s                         | 192 Hz (subsamped to 48 Hz)   | SSI MAC                     |
| [76]  | Zini et al.            | 2018 | Torre Grossa of San Gimignano (Italy).  |                                 |                 | 55         | 9.5 × 9.5   | bounded   |         | 12 accelerometers   | 1.3 Hz 1.3 Hz  |                            |                               | 400 Hz downsampled to 25 Hz   | FDD SSI MAC                 |

(continued on next page)

Table 1 (continued)

| Author/s           | Year | Element   | Dynamic excitation | Type of element | Height (m) | Base (m)  | Restraint | Date    | Instruments/Technique                      | Main results: 1st/2nd nat. freq. Sonic test velocities | Elastic modulus E adjusted | Campaign Time duration    | Sampling rate                               | Signal processing technique |
|--------------------|------|---|--------------------|-----------------|------------|-----------|-----------|---------|--|--|----------------------------|---------------------------|---|-----------------------------|
| [122] Zonta et al. | 2008 | bell-tower of the Cathedral of S.Andrea in Portogruaro, Italy |                    | bell tower      | 59         | 7.3 × 7.3 |           | 13th c. | Optical inclinometer<br>Four thermocouples |  |                            | > 3 years monitoring tilt | Every 10 min                                |                             |
| [181] Zonta&Pozzi  | 2015 | The bell-tower of the Cathedral of S. Andrea in Portogruaro   |                    | civic tower     | 59         | 7.3 × 7.3 | bounded   | 13th c. | Optical inclinometer<br>Four thermocouples | 2.7 Hz 3.7 Hz  |                            | > 3 years monitoring tilt | 400 Hz downsampled to 40 Hz<br>Every 10 min | FDD SSI MAC                 |

artificial excitation of a massive masonry structure is hard to achieve, expensive and can cause damage, as it requires a lot of energy and excites only at specific frequencies. OMA based on Ambient Vibration Testing (AVT) has thus become very popular among scientists for dynamic assessments, being a cheap and effective tool [27]. Few references in Table 1 (see column ‘Dynamic excitation’) can be named here as those using vibrodynes or artificial actuators to force vibration in the masonry structure.

This Section reviews the aforementioned most widely used techniques for the structural assessment of different types of slender masonry structures, showing the state of the art of the topic. The elements under study, main features and techniques applied together with technical data are identified in Table 1. Information from all the sections in this paper is presented in Table 1 for easy identification.

#### 4.1. Visual inspection

The first, and simplest, approaches for the assessment of any masonry structure should include the visual identification of irregularities, discontinuities, out-of-plumb elements, cracks and damages, settlements and a detailed geometric, material and technological survey. It is also important to find an explanation for pathologies, the arrangement of the different elements and the characteristics of the masonry materials. For example, dark spots on the surface could be signs of humidity in a wall, or different materials together could indicate previous interventions, filled openings, etc. This survey must be done with the aim of highlighting anomalies or key factors that could influence the structural response. A historical overview, as well as the analysis of maps, drawings and photographic documentation, are always advisable (when available) in this type of monument since hidden elements, structural changes through time and relevant information can be highlighted, being factors that affects the structural response.

Simple tools can be used in this phase, such as a measuring tape or laser meter to determine column dimensions, thickness of elements, etc., or more sophisticated ones like drones for visual inspection of inaccessible locations or to find links to adjacent buildings. The support of optical instruments and CAD assistance is usually employed, while new tools like laser scanning or digital photogrammetry are gaining terrain [55]. All the papers referenced in this work performed a visual inspection of the monuments under study, with damage detection, description of the structure, main features, etc., sometimes including previous restoration work or historical references (e.g. [128]).

#### 4.2. Terrestrial laser scanning

This survey technique is a non-contact method aimed at obtaining a dense cloud of points to capture the whole geometry of the monument accurately and rapidly. This remote sensing technology allows geometrical surveys of inaccessible structures, although they usually require several scan positions (e.g. 5 scans were done in [126]); moreover, the shadow effects and modeling distortion due to high incidence angles should be avoided [56]. It is based on the emission of laser pulses to different points of the structure (targets), obtaining angles and distances to the sensor, after which 3D coordinates with reference to the station are extracted. Different categories of sensors (Fig. 3) can be found, depending on the distance to be travelled by the laser. The phase-based scanner has a lower range but better resolution, while the pulse-based scanner has a better range but lower resolution. Digital photogrammetry is a related technique that obtains similar results.

It is possible to track changes in geometry or deformations between different events by multi-temporal observations, as in



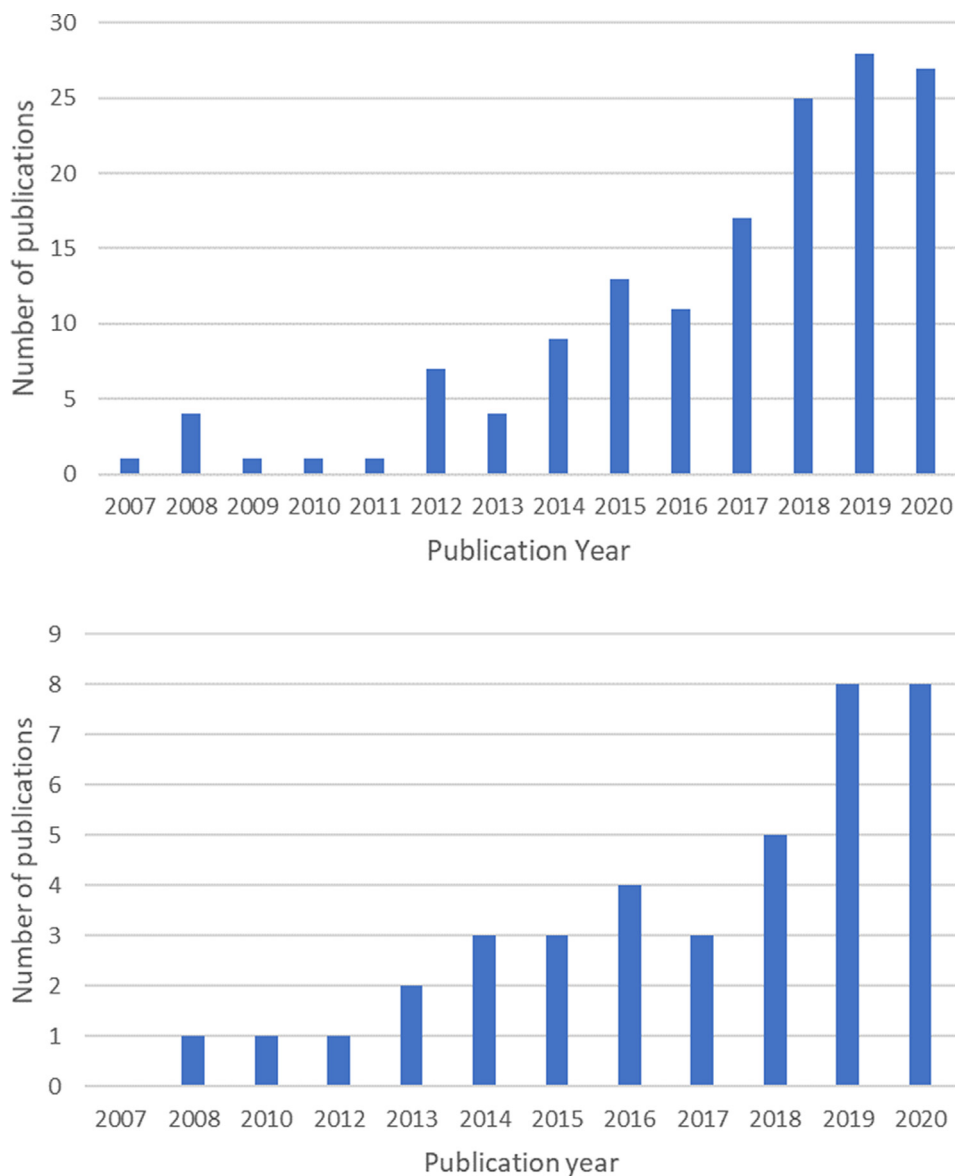


Fig. 2. Search: keywords 'structural health monitoring' and 'masonry' (top), together with 'tower', 'chimney', 'column' or 'minaret' (bottom).

[56], which compared the acquisitions before and after an earthquake in the Asinelli Tower.



Fig. 3. Laser sensor [56].

The point cloud is converted into a grid and a triangular element of networks can be generated by processing the data to provide a 3D geometric model of the structure for use in finite element modeling. Pieraccini et al. [32] analyzed Mangia's Tower (Italy) by combining this technique with radar interferometry. This procedure is promising for expeditious dynamic identification and numerical modelling of masonry towers, since no contact with the monument is required and the geometry is rapidly and accurately acquired. Castellazzi et al. [171] proposed a semi-automatic procedure, named CLOUD2FEM, to transform point clouds to 3D finite element models. The procedure, specifically designed for terrestrial laser scanner survey applied to historic buildings, produces a solid volume made by voxel elements suitable for finite element analysis.

#### 4.3. Thermography

As masonry is a heterogeneous material with different thermal properties, it is feasible to identify wall areas with different thermal signatures, or infrared radiation, which can be captured by

the sensor (infrared camera) resulting in an image of the wall with pixels referring to temperature levels and heterogeneities.

This NDT is useful for the inspection and diagnosis of historical buildings based on thermal conductivity of the materials with the advantage of covering large surfaces with high resolution. It is helpful in the detection of cracks, disconnected elements, moisture, flaws covered by plaster, cavities, shallow damage, different materials, etc. It can also serve as a quality control method allowing fast and reliable assessment of grouted masonry walls [60].

The range of this technique is limited to low penetration, although forced heating of the wall can provide more insight on depth.

#### 4.4. Ground penetrating radar (GPR), geo-radar, radar scanning

When dealing with masonry tower walls it is important to know the location of voids that could affect their dynamic behavior, the presence of cracks or the separation between elements that influence boundary conditions, moisture distribution, the thickness of internal layers or lack of homogeneity in the masonry [59].

Radar scanning is a non-invasive technique, widely used in geophysics, able to view the subsurface by using electromagnetic pulses transmitted by a high-frequency antenna (between 500 MHz and 3000 MHz) studying their reflections, attenuations and altered phases produced on the interfaces of materials with different electromagnetic properties. The transmitter and receiver are positioned on the surfaces of the element, not necessarily in contact, which is useful for delicate surface cases. It can also identify wall morphology, stratigraphy, depth of cracks, existence of voids, flaws, etc., providing enough resolution to identify irregular boundaries, although these are not easy to relate to mechanical properties. The antenna can be easily moved between different points and it is usual to get vertical or horizontal profiles of walls or columns (e.g. [60,61]). An example of a radargram obtained from [61] can be seen in Fig. 4, where the horizontal axis represents the antenna position and the vertical axis the depth. [61] contains an example of tomography based on GPR tests. Expertise is required for an effective design, conducting a GPR survey and interpreting the radargrams.

#### 4.5. Sonic tests, impact echo testing, sonic tomography

Sonic tests have been widely used in masonry structures because they can provide valuable and fast information about

mechanical properties of elements. The basis and goals of this technique are similar to those of GPR. Sonic tests are based on the generation of short sonic or ultrasonic pulses, usually in the range between 20 Hz and 20 kHz for sonic pulses, and up to 20 MHz for ultrasonic pulses, using a transmitter and a receiver, so that the time-travel of the wave along the path between the sensors is recorded. As the pulse velocities of homogenous and isotropic materials are known, deviations from the expected arrival time between the sensors are indicative of the type of material penetrated. Low velocities can be a sign of damage. The pulse velocity is related to the material density and elastic modulus. Using several accelerometers as receivers and one emitter [62], sonic tomography can be performed to provide insight into a cross-section (Fig. 5).

The frequency must be chosen according to the type of element and the goals of the investigation. For a given velocity, higher frequencies provide greater resolutions but greater attenuation (not practical in thick walls or non-homogeneous materials) and this is why sonic tests are more often used than ultrasonic tests in masonry elements.

Direct sonic tests refer to the opposing positions of the transmitter and receiver through the wall, while indirect sonic tests refer to transmitters and receivers on the same side of the wall. Direct tests allow the measuring of features of elastic compression P-type waves passing through the element, while indirect tests deal with surface waves (R-type). If the data recorded by the sensor are analyzed in the frequency domain (e.g. by using a Fast Fourier Transform), information about frequency content, attenuation and wavelength is extracted and can be related to discontinuities in the material. Attenuation may indicate non-elastic behavior, cracks, voids, etc.

In accessible slender elements like columns, sonic tomography provides a precise idea of the internal composition because a regular and dense distribution of pulses can be designed, as shown in [61] and [62]. A large number of measurements can reproduce the internal composition of a cross section of the element under study based on the velocity distribution (Fig. 5).

In the impact echo test, the transient pulse is introduced by a mechanical force using an instrumented hammer as transmitter; an accelerometer registers the 'echo' of the transmitted wave reflected from internal defects and external boundaries. In [63] the authors combine ultrasonic testing and impact echo testing to investigate the musical pillars of the Vitthala Temple at Hampi (India). Bartoli et al. [24] analyzed the stone columns using an

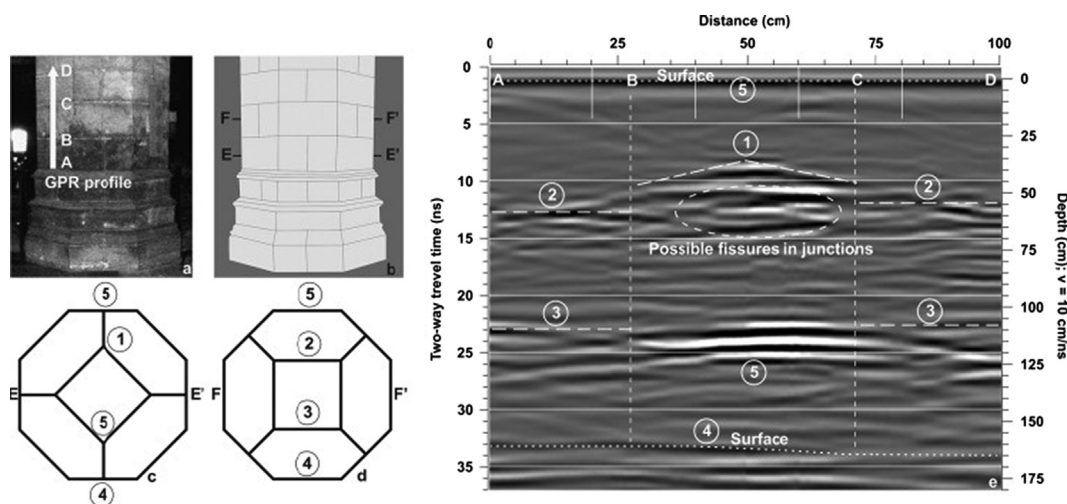


Fig. 4. Radar profile on column and interpretation [61].

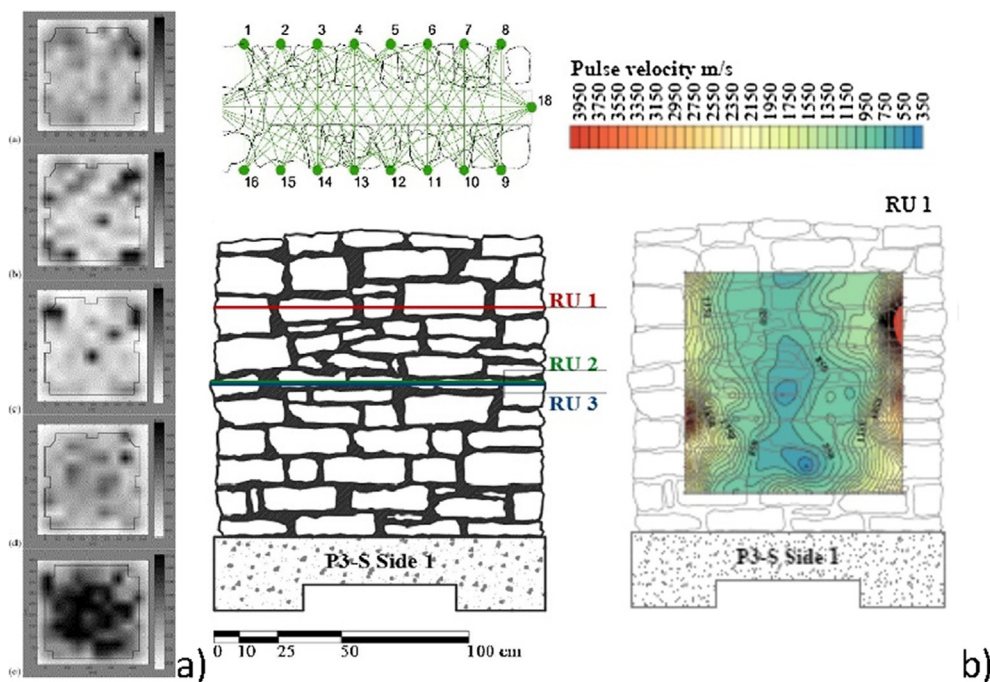


Fig. 5. Sonic tomography with distribution of velocities on several sections of column (a) [62] and wall (b) [131].

impact hammer without recording the input signal while the output signal was recorded by accelerometers.

The high degree of heterogeneity in many masonry structures makes this technique useful for qualitative purposes. However, in combination with other techniques it can provide interesting results. An example of combination of different NDT to get valuable information can be found in [60], where the authors made a preliminary study using sonic tests and radar to detect anomalies inside a wall and detected a hidden void, a former fireplace, which was later confirmed by a videoboroscopy inspection. A similar study is discussed in [64], where sonic tests allowed to reveal the presence of discontinuous masonry and the ineffectiveness of strengthening injections in a masonry wall; impact test allowed to obtain the elastic modulus, later confirmed by flat jack tests.

#### 4.6. Flat-jack test

This technique is commonly used to determine the mechanical properties of masonry walls. Originally employed to assess the mechanical properties of rock masses, was adapted at the end of the '70 s to investigate brick masonry walls. Today this investigation is standardized and flat-jacks are used in two types of tests: the single [65] and the double [170] flat-jack test.

In the former the local stress state of the masonry is determined by cutting the masonry surface using a saw (usually in a mortar joint), then releasing the stresses around the slot and letting the edges to get closer due to the compression stresses. The flat-jack is introduced into the cut and the pressure inside the jack is increased until the distance between both sides of the slot is restored, thus providing an estimation of the local stress before the cutting phase.

In the double flat-jack test the elastic modulus of the masonry is evaluated by introducing two flat-jacks into two slots separated by a size representative of the element composition (Fig. 6). With the help of vertical linear displacement transducers (or strain gages) the distance between the two edges is measured while the pressure on the jacks is increased, performing a local in-situ elastic modulus test between the two slots. If horizontal transducers are

also set, the test allows to estimate the apparent value of the Poisson's ratio.

The test is slightly destructive and can be classified as an MDT since small cuts are required in the masonry to introduce the flat-jacks, but it is widely used because it provides significant information on the mechanical properties of the masonry elements strength, elastic modulus and quality, useful for diagnosis and numerical modelling. As an example, it has been used in [58] in combination with Acoustic Emission (AE) to assess the evolution of damage phenomena in three medieval towers.

Taking advantage of the cutting in the masonry surface introduced by this test, several Authors in the same places where flat-jacks have been carried out conducted 'coring' or 'videoboroscopy' investigations [62].

Despite flat-jack technique is a useful and widespread test, still there are several critical issues concerning its use for masonry structures. These are connected to the interpretation of the non-linear phenomena that may occur as a result of localized cracks in the cutting area due to the high pressures in the walls (especially in tall towers). In addition, since the masonry walls are usually multi-leaf ones this technique allows the investigation of only the external parameters of the walls.

#### 4.7. Seismic interferometry

Unlike OMA, this technique is not based on extracting modal information but on the deconvolution of the recorded signal at a reference station with the signal recorded at a generic station [48,81]. Sensors are deployed on the structure and the wave propagation is tracked up and down throughout the structure, getting a spatial distribution of the seismic wave velocity, as can be observed in Fig. 7. The wave attenuation and scattering depend on the characteristics of the structure. When local damage or stiffness degradation are passed through the waves, delays in the velocity between sensors are detected. Differences in the stiffness of different areas of the monument, local damage or boundary conditions and restraints with neighboring buildings can be assessed.



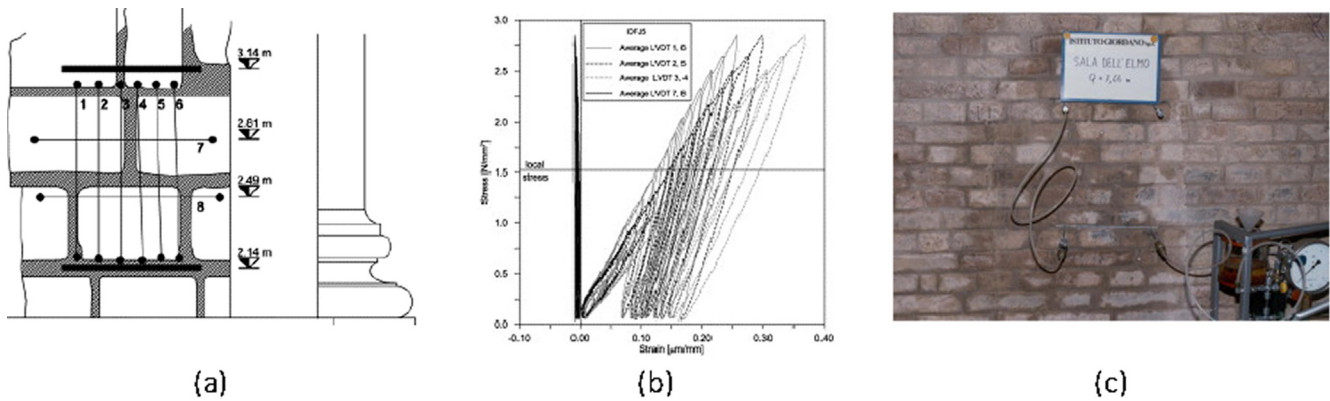


Fig. 6. Flat jack test: (a) typical layout and LVDT sensors [62]; (b) stress–strain curve [62] and (c) real test [84].

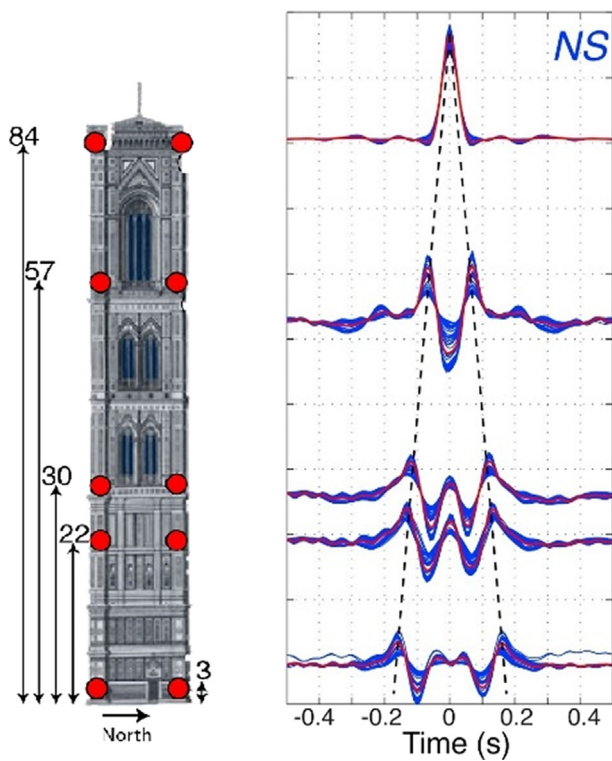


Fig. 7. Schematic deconvolution considering a virtual source at the top level and location of seismic stations [48].

Since this technique can provide information about local damage while OMA is more focused on global behavior, skipping local damage without influencing modal properties, a combination of both techniques can reveal useful local and global structural information. The waves travelling through the structure have larger wavelengths than ultrasonic techniques (see next sections) and require an energy source with limited capacity, hence little wave attenuation is found in regular conditions and large structures can be evaluated. However, since the effect of early damage is less than the environmental effects, high sampling is required for early damage detection [48].

#### 4.8. Acoustic emission (AE)

This NDT is used to obtain information on damage evolution based on the release of the strain energy stored in the material and the stress redistribution when cracking or microcracking

appears/advances. This phenomenon leads to the propagation of elastic waves through the material that can be captured by surface sensors in the ultrasonic range between 50 kHz and 1 MHz. The waves are analyzed by their frequency, amplitude or duration to get information about the kind of damage. Continuous monitoring can be used to predict the evolution of damage and decide whether corrective measures should be adopted [59]. These authors studied the effect of heavy vehicle traffic by acoustic emissions on the preservation of Bologna’s historic center.

The interpretation of this technique in masonry structures is not straightforward, since all its heterogeneities make it hard to analyze, particularly in large structures. Carpinteri and Lacidogna [58] combined this technique with flat-jack tests to correlate cracking processes in parts of the structure with the acoustic emission technique (Fig. 8). It is also useful to characterize acoustic emissions for different vibration sources (wind, traffic, earthquakes) to evaluate their potential damage. Measuring the rate of AE activity from visible cracks and their growth rate, and considering the reflections of waves from masonry layers, AE can be used to locate additional cracks.

It can also help to locate damage zones if enough sensors are used to discard attenuation phenomena and can warn of non-visible long-term deterioration in masonry structures due to different actions, even aging, by measuring the crack growth rate.

#### 4.9. Miscellanea

Currently it is possible to install hundreds of sensors in a masonry structure and get data in real time from different places performing continuous monitoring. The most frequently used sen-

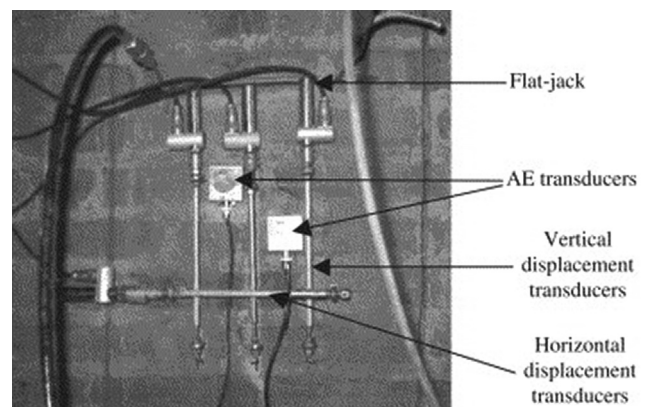


Fig. 8. Combined flat-jack test and AE monitoring [58].

sors and techniques in slender masonry structures have been mentioned in the previous sections, but there are others that can be useful for different circumstances. These are included in Table 1 and are: hardness test, inclinometers, crackmeters and strain gauges, the latter used in combination with thermocouples or thermistors to account for thermal effects. Crackmeters are formed by a wire sensor installed at both edges of the crack providing values of the relative movement of one side of the crack with respect to the other. DelloRusso et al. [53] conducted an extensive study for 12 months using this type of sensors.

#### 4.10. Operational modal analysis

Ambient vibration testing is based on recording vibrations induced in the structure by unknown environmental forces, where the use of impact hammers, vibrodynes or shakers would be impractical. In Operational Modal Analysis the input excitation is assumed to be a zero mean Gaussian white-noise. This is usually accomplished with measurement time windows in proportion to the fundamental period of the structure. According to the Brincker criterion [28], the time series should be at least 1000 times longer than the fundamental period to obtain accurate modal properties, although some authors specify a period 2000 times longer [29].

Slender structures are particularly suitable for dynamic identification methods since they are sensitive to ambient actions and together with their cantilever-like behavior only a limited number of sensors is required for good modal characterization, as only few modes contribute to their global dynamic response. In these slender-type structures clear signals are obtained from sensors with a low noise-to-signal ratio due to the particular geometry (as is advisable in all circumstances), and usually allow obtaining at least 5 modal frequencies in most of the references in Table 1. The 'Main Results' column in Table 1 shows the first two natural frequencies identified by OMA, together with the main dimensions (height and base) of the element under study, when provided. Values around 1 Hz or 2 Hz are usually found for all slender structures except columns, although great variability can be found depending on the boundary conditions (see 'Restraint' in Table 1) or the particularities of the element (e.g. [30,31]).

Ambient vibration testing with few accelerometers at key points has become the preferred method of dynamic identification because of its effectiveness and low cost. However, other successful techniques are also used to extract modal parameters using contactless technologies, even at long distances from the structures by laser or radar interferometry to reduce the operational cost (e.g. [32–34]).

One of the main aims of the OMA dynamic identification process is the definition of a reliable numerical model, usually based on Finite Element (FE) modelling, which will be the basis for additional assessments. It can reduce the number of on-site or laboratory tests, provide a tool for the evaluation of the effectiveness of interventions for rehabilitation or strengthening and support continuous monitoring for damage assessment. An interesting application is shown in [24], where the authors found that the column frequencies were not significantly sensitive to changes in normal stresses, but were quite affected by both their height and restraints conditions as well as on the value of the modulus of elasticity, which led to identifying both parameters for the structural model. They also concluded that the columns boundary conditions were something between double-clamped and double-pinned in the radial direction, and double-clamped in the circumferential direction. The numerical models will be commented in Section 5.

Since EMA requires an artificial excitation of the structure which is hard to carry out and expensive, only few studies report this approach. In EMA the structure is excited by known forces and the modal parameters are obtained from the input–output

data. Only selected frequencies are excited and the level of the introduced forces must be carefully selected in order to protect the monument from any damage. Fig. 9 shows a vibrodyne used in dynamic test of a masonry tower [84], and Table 1 ('Dynamic excitation') shows the different type of generated dynamic excitation used in EMA: vibrodynes, swinging bells, impact hammer, explosions or rhythmic jumping.

##### 4.10.1. AVT using accelerometers

Accelerometers are normally used for structural identification in slender masonry elements to record data under ambient vibrations produced by wind, micro-tremors, traffic or human activity, such as the swinging bells movement sometimes used to introduce vibration in bell towers (Table 1-'Dynamic excitation'). The reduced cost of these sensors makes them suitable for AVT Structural Health Monitoring, even for continuous assessments.

The accelerometers employed are always high-sensitivity, able to capture ambient vibration up to 200 Hz. Mainly, two types are used: piezoelectric ones (Fig. 10b), which are based on the generation of electric signal when subjected to a force, are stable and robust instruments [22]; servo-accelerometers, which are based on force-balance technology (Fig. 10c), are specified for use in seismic studies with low frequency motion (<1 Hz), heavier and bigger, with higher cost. Table 1 ('Instruments/Technique') shows the type of accelerometers and the number used in each study, when the information is available. Only two papers studying the same masonry structure, the Monza Cathedral bell-tower, mention the use of servo-accelerometers: [35] (by reporting on a previous experimental campaign performed in 1995 by different authors) and [36], while 'force-balanced' accelerometers were used in were used in: [17], [37] and [176].

A few papers described the use of seismometric stations (using electrodynamic velocity transducers to capture accelerations and velocities) (Fig. 10a), optic fiber sensors and MEMS sensors (Micro Electro-Mechanical Systems). The latter are becoming popular together with the installation of wireless sensor networks [77,79] (Fig. 10d). These MEMS sensors transmit the data in digital form without electromagnetic interference. They are able to perform some analysis directly on-board with open-source software (e.g. comparing measurements, local filtering, fast Fourier transforms, etc.) to transmit the processed data. The drawback is that their signal-to-noise ratio is lower than piezoelectric sensors and they do not always identify as many modes as piezoelectric accelerom-



Fig. 9. Vibrodyne used in [84].



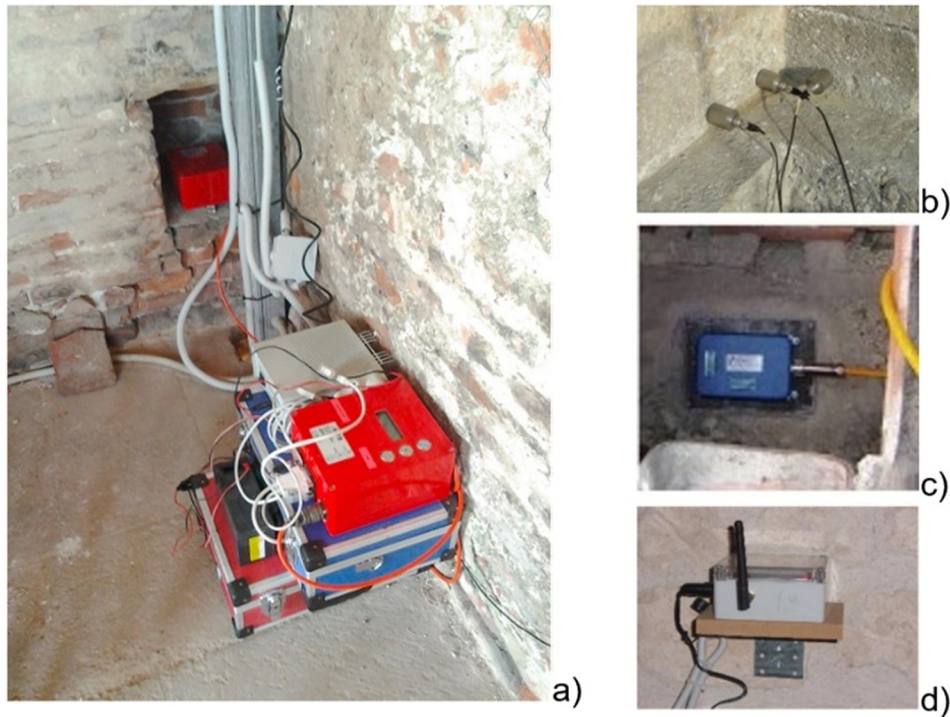


Fig. 10. a) Seismometric station [25], b) Piezoelectric accelerometers [111], c) force-balance accelerometer [7], d) wireless sensor [22].

eters in low-excitation operational conditions, and their frequency range is more limited [38].

The location of the accelerometers is often conditioned by the accessibility to the monument, although it is usual to look for the best coupling sensor-structure to obtain the largest number of vibrating modes without affecting the structural integrity. Bending modes are easier to identify than torsional modes due to the low level of excitation, but most of the references shown in this review reported the possibility of capturing capture at least 5 modes with on-site ambient vibration testing. A common and effective scheme to capture bending and torsional modes with the minimum number of accelerometers in one measurement is shown in Fig. 11a. With more resources, schemes like the one shown in Fig. 11b are preferred.

As it can be observed in Table 1 ('Instruments/Technique'), the range in the number of accelerometers to be used for monitoring is wide. With the reducing cost of technology, it can be observed

that the more recent is the paper, the more sensors are used. Sometimes, to overcome the reduced number of available sensors, one or few accelerometers are kept fixed while others are moved in different measurement locations, hence allowing to increase the number of registered points. (e.g. [39]).

Regarding the duration of the measurement, the references shown in Table 1 ('Campaign Time duration') vary from some minutes to months or years. Sometimes the measurement time per set together with the sampling rate are shown, and sometimes the duration of the whole campaign. Casciati et al. [40] state that, as a general recommendation, at least a couple of days would be desirable, but for important structures the winter-summer variation should also be considered. The reason is because it has been shown that temperature and humidity significantly influence the modal parameters (see Sub-section 4.10.3).

Table 1 ('Dynamic excitation', 'Instruments/Technique') shows works by different authors dealing with ambient vibration testing of masonry towers and accelerometers. It can be seen how, on occasions, different authors have studied the same monument by different techniques.

#### 4.10.2. Interferometry

Some novel and very promising techniques used for SHM in masonry structures are based on interferometry, where the phase shift of the received signal is evaluated when compared to the transmitted one.

##### - Radar interferometry

The sensor consists on a 3D rotating head (Fig. 12d) that can be pointed in any direction, carrying the transmitter, receiver and two antennas in the front to focus the modulated electromagnetic microwaves at a specific frequency in the form of a beam and to collect the reflected signal.

The system is able to provide information about time-history displacements of points with good line-of-sight electromagnetic

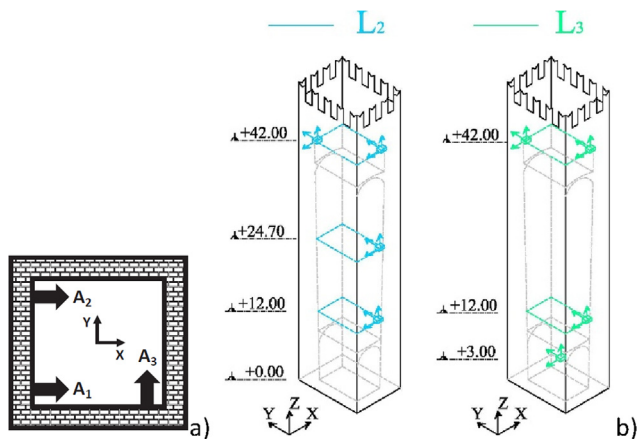


Fig. 11. a) Plan view basic deployment [22], b) 3D view complex arrangement [25].

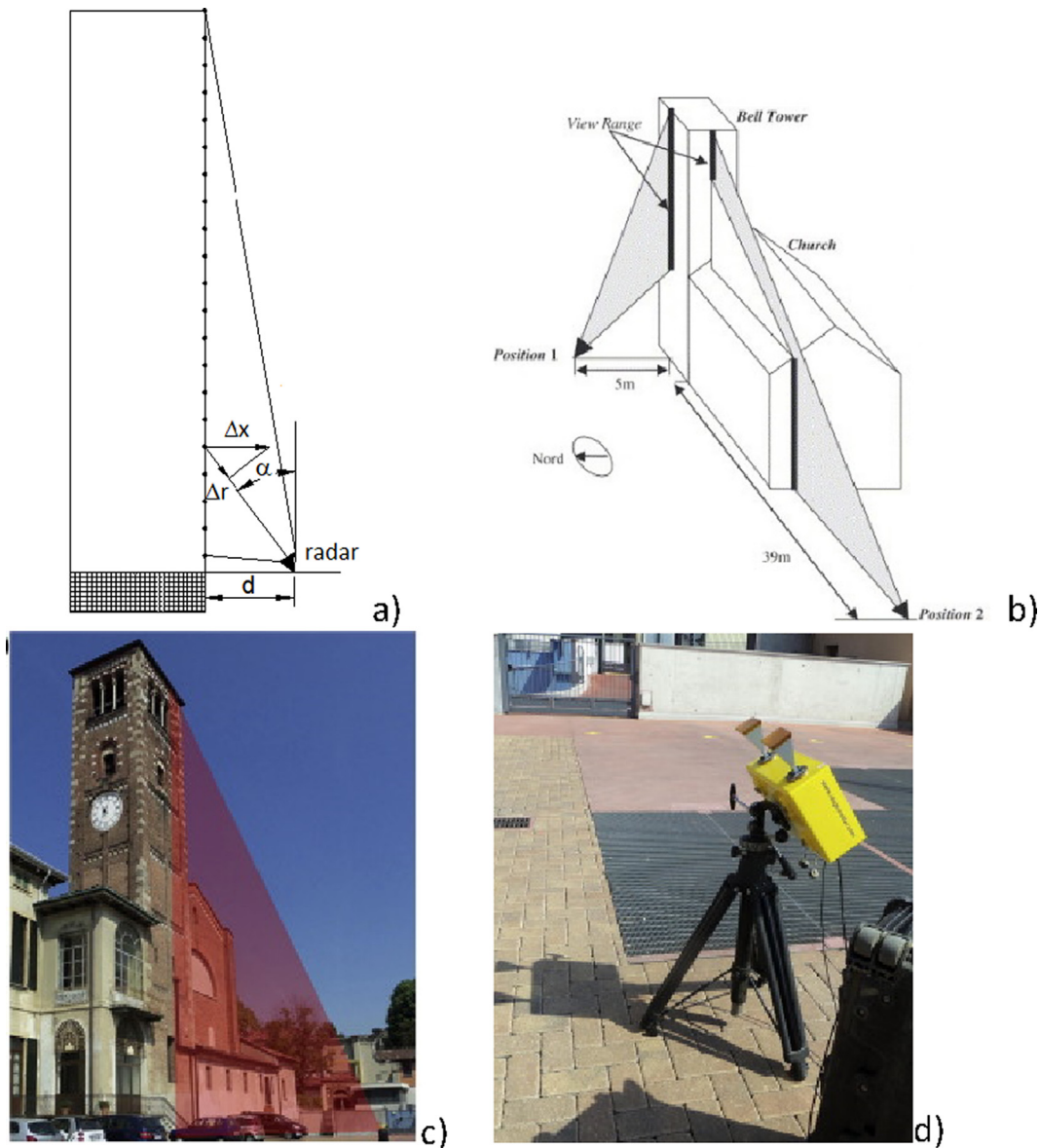


Fig. 12. a) Displacement calculation and b) Measurement positions [113], c) Line of sight [46], d) Sensor [46].

reflectivity (targets). It is able to deliver 1-dimensional information (along the line-of-sight), so that simple calculations are required to get the real displacement based on the direction of the motion (Fig. 12a). The radar preserves the phase information of the received signal, so two profiles captured at different times differ in the phase, depending on the motion of the target along the line-of-sight (Fig. 12c). The accuracy of the system depends on the signal-noise ratio, which was usually lower than 0.1 mm in the cases analyzed.

Some Authors have compared the results obtained from this technique with conventional accelerometer tests, with satisfactory results [41]. In Livitsanos et al. [34] the authors took measurements at a distance of one hundred meters with a displacement accuracy of 0.02 mm, while Pieraccini et al. [42] tested the radar for long range distances around 645 m (Arnolfo's Old Palace Tower in Florence, Italy) and 1 km (Giotto's Tower in Florence, Italy), with promising results. The accuracy of the system depends on the high-resolution waveforms used, and the signal can be processed in real time by the appropriate software. Other examples of the use of this technology can be found in [33,41,43], with the complete list

reported in Table 1 ('Instruments/Technique'). Castagnetti et al. [38] compared displacements along the height of a tower using MEMS and conventional accelerometers and radar, and some authors recommend the radar for flexible structures or slow movements; however, the capability of the system to identify natural frequencies is not compromised.

To sum up, the main characteristics of this technique are: contactless, non-destructive, accurate and fast. It can provide displacement measurements from long distances (up to hundreds of meters) at inaccessible points, e.g. the top of a tower, with high accuracy (tenths of millimeters) and good results for natural frequencies, so there is no need to install sensors or get close to the structure, reducing the risks for the operators. Its main drawback is that the technique allows measuring along the line-of-sight, so a careful planning of the survey must be done if the structural movements are complex, and several measurement points could be required (Fig. 12b). Moreover, masonry is a poor reflective material, hence weak reflected signals could be obtained leading to uncertainties. Furthermore, the sensor itself is excited by ambient vibrations while performing the measurements in the same

way as the monument is; this source of noise in the signal can be countered by installing one accelerometer in the equipment. An extensive measurement campaign using this technique has been recently reported by Pieraccini [172] investigating about 10 historic towers in the city center of San Gimignano (Italy). Due to the narrow streets of the city center, with the towers embedded in the urban tissue, the Author performed radar measurements of the towers installing the instrument on the top of the City Hall tower which is in a central position. This tower, while provided an optimal view of the remaining towers, was indeed not a stable arrangement for the instrument. To filter out the tripod movements from the radar measurements, the Author tested the use of an accelerometer fixed to the radar head for detecting and removing its own movement. This technique resulted able to separate them even when the two towers had similar oscillation frequencies. Indeed, the accelerometer fixed on the radar head detected the oscillation of the tower in which the radar was installed and removed it from the signal of the tower under test.

- Laser interferometry

The use of laser for measuring vibrations in-line with the laser beam is based on the same principle explained above, with the same characteristics. In this case, Ellis [44] obtained an output voltage proportional to the velocity of the motion of the targets. The laser is capable of measuring submicron vibration and is suitable for low levels of vibration and in the frequency range between 0.1 Hz and 1 kHz.

4.10.3. Temperature effects

It has recently been shown that temperature effects (and humidity [7]) could greatly influence the dynamic characteristics of structures, driving to changes in modal frequencies often more significantly than slight damages; hence, the effect of temperature should also be included in SHM to characterize any slender masonry structure and considered in damage assessment. As a general rule, thermal expansion leads to closing of the cracks, increasing the stiffness of the structure and affecting modal parameters (frequencies and damping ratios tend to increase) [45–47]. This is usually observed over long monitoring periods when collecting seasonal fluctuations (the frequency can vary by 5–6% yearly [25]), but also in short periods collecting daily temperatures (daily variation of about 2–3% were recorded [25,48]). Only two cases were found (and reported in this review) about possible reduction of natural frequencies with rising temperatures. In [34] a chimney was reinforced with a steel rod which was assumed to expand and relax with rising temperatures and led to a more flexible chimney. The second case was in Cabboi et al. [49], where all

resonant frequencies increased in winter because of ice in the cracks, which stiffened the structure. The Authors used a regression model to reduce the temperature effect in future similar thermal conditions.

Procedures have been developed to remove the temperature effect on the identification of the natural frequencies, mainly based on multivariate linear [35,50,51] and nonlinear [25] regressions, able to automatically detect anomalies in the structural dynamic response. An example dealing with the treatment of temperature effects by a PCA (Principal Component Analysis) procedure can be found in [49]; during a significant training period (Fig. 13), environmental parameters are measured and relations with natural frequencies are obtained with supervised learning algorithms, non-supervised ones could be used for the unmeasured parameters [49,52].

Thermocouples are usually employed to capture temperature in vary positions, (Table 1 ‘Instruments/Technique’). The location of these sensors must be carefully planned, since their readings will be representative of all the environmental parameters and the correlations with modal properties will be based on them. Saisi et al. [46] set sensors on the inner and outer walls of a tower and concluded that external sensors were more representative of the environmental conditions. DelloRusso et al. [53] installed three sets of thermistors or thermocouples at four different wall depths to acquire data on temperature differences to determine the stress gradient.

4.10.4. Damage detection

Based on the assumption that every structure has its own dynamic parameters, and that any damage would lead to changes in these parameters, it results that modal parameters are effective damage-sensitive features for damage detection even at stages when it is not yet detectable by visual inspections. Consequently, monitoring of historic structures based on OMA procedures can provide useful information on their structural health based on the dynamic behavior and extracting modal properties. If the stiffness properties change, this can point to a structural damage which is linked to the reduced stiffness.

It must be however highlighted that main frequencies, as previously commented, have the main drawback of being strongly affected by the environmental conditions (such as temperature and humidity) and changes around 5–6% can be expected [25]. This means that the environmental influence should be removed if these quantities are employed as damage-features. This can be accomplished using a measuring training period to build reliable statistical models applied to the series of modal frequencies identified by OMA. A limited number of sensors then detect any damage by permanent changes in the natural frequencies. The

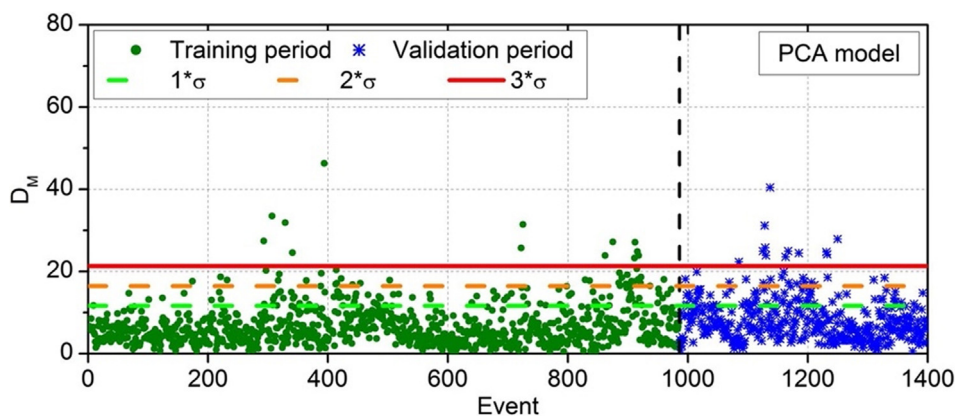


Fig. 13. Temperature effects and damage detection based on PCA [49].



temperature effects can be removed by multivariate linear regression models and Principal Component Analysis (PCA).

Permanent changes of 1–2% in the natural frequencies after seismic shocks were found by AVT in the Gabbia Tower and the San Pietro bell-tower in Perugia, in [25] and [26]. Frequencies can also be assessed by short data series in which the structural parameters can be assumed to be not affected by environmental effects, since the variation in temperature or humidity are slower than structural vibration (daily period versus seconds). In this way the structure is assumed to behave as a linear time-independent system.

Automated OMA procedures allow remote sensing and assessment of the structural health and early detection of damage. Ubertini et al. [54] continuously tested a masonry tower before and after the 2016 Central Italy seismic sequence and identified earthquake damage in the form of reduced natural frequencies when it was not yet detectable by visual inspection (microcracks at the base of the belfry columns compatible with the predictions of the nonlinear model).

## 5. Numerical techniques

### 5.1. Finite element modelling

In a model-based strategy, for a comprehensive structural health monitoring project, a numerical model must be used, able to reproduce the different situations the structure can be exposed to and not tested in real conditions. It can also provide information for decision making regarding changes in the use, strengthening interventions, damage detection, seismic vulnerability, etc. In this context, Finite Element (FE) modeling is the most frequently used technique: a FE model of the real structure is built, the response under different typology of loads can be estimated, parametric studies can be conducted, and it is possible to investigate the influence of boundary conditions, etc. [158,159].

Although the FE method results to be the most frequently used technique for the modeling of masonry towers, other modelling approaches are developed and/or employed in the literature. Among these it is possible to mention the fiber models [152], the rigid body and spring model (RBSM) [153] and the Non-Smooth Contact Dynamics [154,155,177]. Simplified mono-dimensional approaches have been also proposed, and successfully employed, through no tension material models [156] or equivalent Bouc & Wen hysteretic models [157].

The numerical model is based on assumptions and simplifications that lead to discrepancies between the real and the expected behavior, so that a match between reality and the model is required. Most of the references provided in this paper have the calibration of a finite element model as one of their goals.

For convergence between model and reality, parameters in the numerical model needs to be tuned in order to get a reliable estimation of the structural response from the model. This process is called model updating ([175,179,180]), the purpose of which is to minimize the differences between analytically and experimentally obtained modal properties. Furthermore, if the numerical model is fed with data from a continuous monitoring system, damage detection and health monitoring are trusty and valuable outcomes.

The validation process is usually done by extracting the dynamic characteristics of the structure from the monitoring campaign, usually natural frequencies and mode shapes, and subsequently tuning the FE model to match them. In [66] the Authors developed three FE models of different degrees of complexity for masonry towers based on experimental results and addressed the difficulties found in building these numerical models.

The most used approach in literature to address the model updating has been to combine the parametrized numerical model with an optimization algorithm which minimizes an objective function measuring differences between the experimental data and the corresponding numerical output. Depending on the available data, the objective function is built by considering frequencies and/or mode shapes. It can be observed that this deterministic-optimization procedure suffers of some well-known drawbacks (there is not guarantee of the uniqueness of the solution) and, in addition, since the sources of uncertainty on the parameters are not explicitly taken into account, it provides a single optimal solution that may neglect other equally probable representations of the same structure. In this respect, the Bayesian framework adopted by some scholars (e.g. [181,182]), is, among others, a reliable identification procedure able to overcome the drawbacks that may arise when adopting deterministic optimization-based methods.

Apart the adopted model updating technique, the most used parameter selected for the process is obviously represented by some mechanical parameters describing the structural behavior in the elastic range, such as the equivalent Young's elastic modulus of the masonry (E). This was done in many of the references shown in Table 1, and the final identified E value is reported in the corresponding column when it is a global parameter for the whole element. Sometimes the E values obtained are not in accordance with real values and lose their physical meaning, so that more parameters are incorporated into the matching process such as, e.g., densities for different materials, different E values for different parts of the structure to account for different materials and/or to account for possible damages (e.g. [19]). Dealing with deterministic approaches only, for simplified cases the tuning process can be done manually, while in complicated cases it is recommended to use algorithms for system identification, like the Inverse Eigen-Sensitivity algorithm or Douglas-Reid (DR) [35,67].

Another important parameter that is often considered for model updating in many towers or minarets is the stiffness of some spring elements used to model the boundary conditions, mainly with neighboring buildings, e.g. [69]. In [24], the boundary conditions from pinned to clamped were changed in the numerical model to match the natural frequencies of the columns obtained in the experimental results. Diaferio et al. [67] updated up to eleven parameters (stiffness of the springs, Young's modulus E values and densities of different materials) in the numerical model of the bell tower of Annunziata (Corfu, Greece). Foti et al. [30] used elastic modulus and density for cyclopic masonry as updating parameters and added masses to account for non-structural elements. Casciati and Al-Saleh [69] installed a retrofit solution made of shape memory alloy wires based on the numerical model capturing the dynamic signature of the Soncino bell tower (Italy).

After the updating process, it is usual to analyze relative error for frequencies and to use the MAC coefficient (Modal Assurance Criterion) for mode shapes, in order to compare numerical and experimental values, which give an idea of the quality of the updating. In AVT less accurate estimation for higher frequencies are usually obtained than lower ones, so it is usually intended to minimize the error in the lower modes, which are the most important. Sometimes even the torsional mode is difficult to be identified (e.g. [69]).

### 5.2. Signal processing and modal parameter estimation

Output-only system identification methods are used to obtain modal parameters from the data collected during the experimental campaign in OMA, which are later used to update numerical models. These methods belong to the class of inverse problems, where the input is unknown and the properties of the structure are obtained from experimental output data. To solve this problem a

large number of algorithms have been developed, like Peak-Picking (PP), Frequency Domain Decomposition (FDD), Stochastic Subspace Identification (SSI), PolyMAX modal parameter estimation, Eigen-system Realization Algorithm (ERA), Natural Excitation Technique (NExT), Blind Source Separation (BSS), empirical mode decomposition (EMD), etc.

This Section is not intended to cover the whole range of methods or the theoretical basis, but to collect those most often used when processing OMA data in slender masonry structures. Nevertheless, all the methods are collected in Table 1 ('Signal processing technique') and the reader is referred to the bibliographic references there provided. An extensive discussion of many methods can also be found in Reynders [70]. Despite the degree of maturity reached by the research in this field, to extract the modal features through OMA data, almost all the Authors develop identification procedures by means of their own codes, often in a MATLAB® environment, being the number of software solutions allowing the implementation of SHM systems still quite limited. Among the available software packages it is possible to mention the codes ARTEMIS [146], MACEC [147] and PULSE [148]. Two integrated software solutions for SHM (MOVA, focusing on AVT and MOSS dedicated to the online management of permanent integrated SHM systems) were recently developed by García-Macías and Ubertini [149] and the reader is referred to this paper for a critical discussion of the functionality of these codes.

The main assumption of OMA is the white noise loading process and the low structural damping. As previously commented, this is reasonable in OMA for wind at low frequencies and if long enough periods of time are taken for the measurements (minimum duration around 1000 and 2000 times the fundamental period of the structure). Furthermore, as stated by Ellis [44], even when stationary data are not usually encountered, modal frequencies do not vary significantly with gradually changing excitation, so they can be identified with confidence in these cases. Table 1 ('Campaign Time duration') collects the measurement/campaign time periods used, ranging from seconds to years.

There are several different methods for extracting modal parameters, and sometimes researchers use more than one in the same survey to compare the results. There are two main ways of conducting the analysis of the data, namely in time-domain or in frequency-domain, leading to the two most commonly used techniques for modal parameter identification in Operational Modal Analysis: Frequency Domain Decomposition (FDD) [71] and Stochastic Subspace Identification (SSI) [72].

The Frequency Domain Decomposition (FDD) technique is a frequency domain method where the system is decomposed into a set of independent single degree of freedom systems. It is based on the diagonalization of the Power Spectral Density matrix (PSD) computed from the registered accelerations through a Singular Value Decomposition (SVD). The peak picking of singular values and the singular vectors correspond to the amplification factors in resonance and the mode shapes. It is a non-parametric technique in which the modes are estimated from signal processing. The estimation of modal damping ratios together with natural frequencies is often done by Enhanced Frequency Domain Decomposition (EFDD).

The Stochastic Subspace Identification (SSI) technique is a time-domain method where the statistical state space matrices are identified from time data to obtain modal parameters. The eigenvalue decomposition of these state-space matrices yields the natural frequencies of the system. The modes are identified using stabilization diagrams in which the modal parameters are represented. SSI in literature is proposed in two variants differing in terms of the data on which they operate [150]. The data-driven (SSI-Data) version operates directly on the output response data without any processing, and requires that covariance functions are first

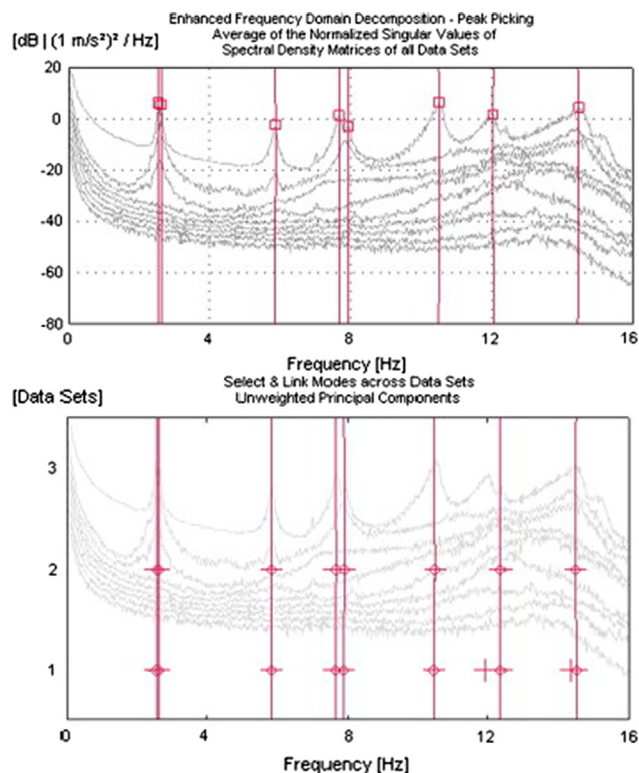


Fig. 14. Singular Values of the PSD function from EFDD technique (top), singular values from SSI-UPC technique (bottom) [111].

estimated from the output response. The covariance-driven (SSI-Cov) version employ the covariance functions, and different formulations of this algorithm are proposed depending on how the covariance functions are arranged.

Comparison between results obtained by standard frequency domain analysis with those derived from different time-frequency methods can be found in [73] and [76], among others. Examples of singular values obtained using these techniques are shown in Fig. 14. The SSI technique is frequently used and the results confirmed by the peaks of the PSD matrix for natural frequencies. If very closely spaced frequencies are expected, e.g. because of symmetry, SSI techniques are preferred, given the difficulty of estimating closely spaced modes by frequency domain methods [15].

When continuous monitoring is used, automated modal identification algorithms and multivariate statistical analysis or Principal Component Analysis (PCA) can remove environmental effects and detect damage; e.g. [26,50,52,54,74,75].

## 6. Conclusions

Conservation of heritage structures and evaluation of their ability to resist future threats (especially earthquakes) is considered an important issue in modern societies. As these structures are often made of masonry, sometimes resulting in a composite mixture of added, substituted or renovated structural elements strongly interacting among each other, they are difficult to assess due to this heterogeneity and the lack of information. Slender masonry structures are of concerns, carrying significant loads, and towers, minarets and chimneys are especially vulnerable under lateral loads.

A huge amount of work has been done by the scientific community on developing non-invasive technologies of investigation and to propose reliable methodologies of analysis for evaluating the structural health of these structures based on their local or global experimental response. This paper has reported a wide review of



static and dynamic-based experimental techniques used for Structural Health Monitoring and Nondestructive Testing of slender masonry structures, together with the works in which they were used, putting into evidence their advantages, drawbacks, types of sensors, some particular cases, and fields of application.

According to the bibliometric study performed, Operational Modal Analysis with ambient vibrations results one the most frequently used techniques to obtain full-scale structural modal properties of slender masonry structures. This structural typology is in fact highly sensitive to ambient vibrations, and output displacements/accelerations can be easily recorded today without the need for artificial excitation. In addition, only a limited number of sensors is needed to obtain valuable results to be subsequently employed, for instance, to update numerical models.

The influence of environmental effects on data has also been reported with a brief summary on the ways to remove these effects from the data by statistical approaches. This point is particularly significant when the subject of the study is the automated continuous operational modal analysis for damage assessment and decision-making purposes. The development of continuous monitoring is an ongoing task that still needs to overcome additional difficulties like processing the large amount of data generated in the design of a proper monitoring survey. However, progress is being achieved thanks to the experience acquired from new cases and the lower cost of new technologies that allows for the use of wireless network sensors.

A current trend is the use of technologies such as Terrestrial Laser Scanning and Radar interferometry. They are able to rapidly provide accurate results, and are increasingly used because of their non-contact nature. With respect to the Terrestrial Laser Scanning, researchers are currently working in automatic or semi-automatic procedures to directly transform the point clouds data into 3D Finite Element Models. For the cases referenced in this review, the FE method is shown as the main used tool for the numerical modeling, and one of the main goals of all the experimental campaigns is its validation for subsequent structural assessment. The most frequently used parameters for modal updating are the Young's modulus of different materials, and the stiffness of springs simulating links to neighboring buildings (when the structure is not an isolated one) while minimization of the differences between the experimental data and the corresponding numerical output is mostly performed considering modal parameters (frequencies and/or mode shapes). In this respect this paper has included a review of the different signal processing methods reporting a preference in the reviewed literature for two of these: the Enhanced Frequency Domain Decomposition and the Stochastic Subspace Identification techniques.

In general, the different techniques can achieve similar goals. Taking into consideration the structure under study and the available means, researchers should use their expertise to choose the technique that best fits a particular case. It seems wise to use a combination of techniques that allow the validation of the results and provide a more reliable assessment. In the Authors' opinion, future trends for the conservation of historical buildings would incorporate laser scanning and digital photogrammetry, MEMS and self-powered sensors, new sensors and technologies based on contactless procedures, continuous updating of the structural properties (real-time) with cloud-based computation and deep-learning based SHM integrated with Internet of Things (IoT). Valuable information will be extracted from a large number of data and integrated into learning algorithms to get smart constructions with low cost. However, preliminary inspections considering classical techniques (e.g. historical information and documents, visual inspection and stratigraphic survey) will never be out of date. There are still some open questions about automation to get fully automated techniques, since human factor and manual operations

are still significant; and to expand the database to get accurate trained models. In the same sense, it is still expected to solve issues with the acquisition, transmission, storage and processing of the huge amount of data collected by networks and sensors. More effort is required to get sustainable sensors and technologies with minimum maintenance, and the integration with IoT will also become a challenge in the near future.

## CRediT authorship contribution statement

**Francisco J. Pallarés:** Conceptualization, Data curation, Investigation, Methodology, Resources, Supervision, Visualization, Writing - original draft, Writing - review & editing. **Michele Betti:** Conceptualization, Investigation, Supervision, Visualization, Writing - review & editing. **Gianni Bartoli:** Supervision, Writing - review & editing. **Luis Pallarés:** Investigation, Methodology, Supervision, Visualization, Writing - original draft.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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