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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.

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 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

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their capacities and ultimately could lead to a collapse of the structure and all that it entails, as happened for the San Marco belltower 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 characteristics 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,

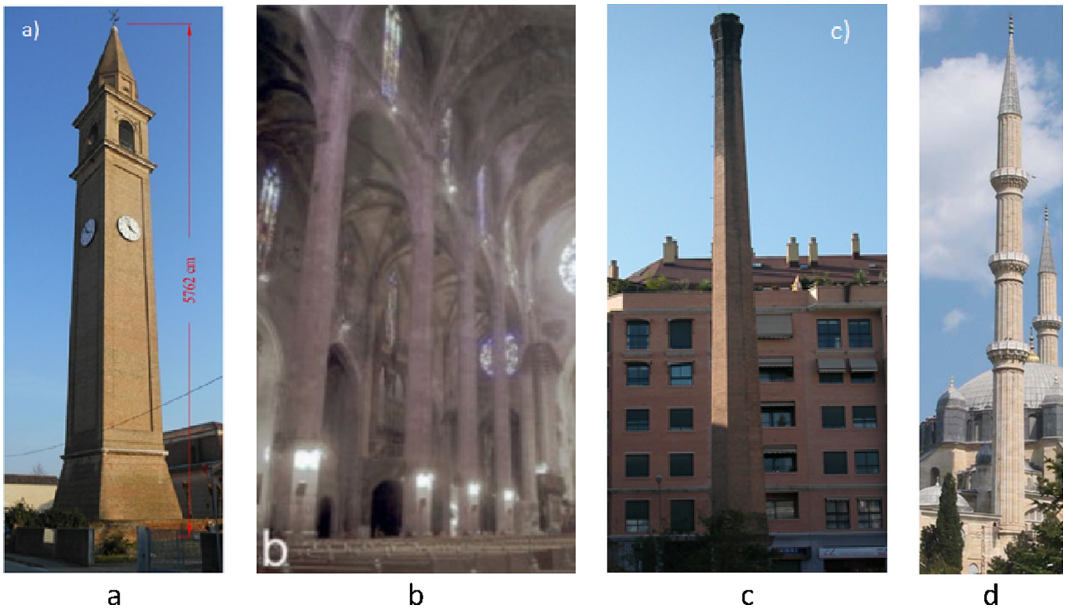

Fig. 1. a) Bell-tower [88], b) columns [61], c) chimney, d) minaret [132].

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 surroundings 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))		bell tower				167th-17th c	6 flat jacks 3 sonic tests pseudocreep tests					
			Bell Tower of the Collegiata of San Vittore at Arcisate (Italy)		bell tower	36	5.8 × 5.8			4 sonic tests	around 2000 m/s				
			Torre Sineo, Alba, Italy.		tower	39				8 Acoustic Emission (AE)			around 1 year (earthquake recorded)		
			Torre Astesiano, Alba, Italy.		tower	36				8 Acoustic Emission (AE)					
			Torre Bonino, Alba, Italy.		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 = 4.25·10^9 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 = 4.5·10^9 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 unixial 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	Hacıbasi 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
			Gülbahar 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 unixial acclerometers 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 Announziata 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 tower	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	civic tower bell tower	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	civic tower bell tower	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	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 iezoelectric 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 piezoeletronics 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 Straing gauges for steel			12 months	every 30 min	
[95]	De Stefano & Ceravolo	2007	SS. Annunziata church bell-tower in Roccaverano, Asti, 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)
			Bell-tower of S. Lorenzo Cathedral in Alba, Italy.							3 accelerometers fixed and 10 moving (San Lorenzo)	1.25 Hz 1.44 Hz				
			Matilde’s Tower in San Miniato, Pisa, Italy.			35		bounded	12th c.	23 accelerometers Matilde’s Tower in San Miniato, Pisa, Italy	2.7 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 Announziata (Corfù, 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]	Ditommaso 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
							Horizontal to Vertical Spectral Ratio (HVSR); Short Time Fourier Transform (STFT); Empirical Mode Decomposition (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	2.03 Hz 2.05 Hz		5 sets of 2 min	100 Hz	PSD
[44]	Ellis	1997	chimney at the Building Research Establishment	AVT	chimney	–				Laser interferometer	chimney 3.17 Hz		8 s		ASD
			pinnacle clock tower Big Ben	AVT		3.6				Laser interferometer	pinnacle 14.95 Hz		82 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		

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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
[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
						SSI-cov; Eigensystem Realization Algorithm (ERA); Poly-reference Least Squares Complex Frequency-domain (p-LSCF)									
[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
												ANNs: Autoassociative Neural Networks			
[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		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 piezolectric accelerometers (20 points with 2 fixed)	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	Pulse sonic tests 1st campaign: 12 accelerometers 2nd campaign: 3 piezoelectric accelerometers and one thermocouple	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]	Hacıefendioglu 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	2.73x2.74	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. ϕ = 100 mm			Ultrasonic testing Impact echo testing Metallography	4800–5500 m/s. 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 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

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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
			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		ϕ = 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 2: 2.78 Hz, 3.13 Hz 3: 2.69 Hz, 3.32 Hz 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 × 7.6	bounded	13th c.	Thermo-vision Double flat-jack	0.957 Hz 1.006 Hz	E = 3500 MPa, fc = 2.5 MPa (double flat jack)			MAC FDD SSI
[80]	Masciotta et al.	2014	chimney in Guimarães, North of Portugal.	AVT	chimney	27	ϕ = 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	
[174]	Milani & Clementi	2021	Ferrara Cathedral, Italy.		bell tower						1.023 Hz 1.054 Hz	E ≅ 4500 Mpa			MAC
			San Benedetto tower, Ferrara, Italy,		bell tower						0.737 Hz 0.756 Hz	E ≅ 1500 Mpa			MAC
			Matilde's tower, Ferrara, Italy.		bell tower						1.478 Hz 1.521 Hz	E ≅ 1500 Mpa			MAC
			Belfry of Pomposa Abbey, Ferrara, Italy.		bell tower						0.934 Hz 1.024 Hz	E ≅ 1500 Mpa			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 Double flat jack test Sonic velocity tests 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	ϕ = 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 63.20 44.96 74.40 54.90 23.02 38.65 41.6 51.7 48.7		isolated		Three 3D accelerometers. Total 9 components	1.26 Hz 1.17 Hz 1.03 Hz 0.97 Hz 0.65 Hz 1.69 Hz 1.36 Hz 0.84 Hz 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 × 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 Y		3 measurements, 10 min each.		EFDD SSI
[112]	Palermo et al.	2015	Asinelli Tower, Bologna, Italy.	AVT	bell tower	87	8.5 × 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 × 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 × 8.3	bounded bounded		Terrestrial laser scanning (TLS)					
[113]	Pieraccini et al.	2007	bell tower of the church of Pratolino, Florence, Italy.	Bells	bell tower	20	5 × 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.	AVT Bells	bell tower	87.4	14.45 × 14.45	bounded	14th c.	Microwave remote sensing (radar interferometry)	0.62 Hz		12.5 min	300 kHz	
			Arnolfo’s Tower, found at PalazzoVecchio. Florence, Italy.	AVT Bells	tower	94	5.4 × 7.6	bounded	14th c.	Microwave remote sensing (radar interferometry)	0.49 Hz X 0.79 Hz Y				
[32]	Pieraccini et al.	2014	Torre del Mangia” (Mangia’s tower) in Siena (Italy).	AVT	bell tower	88 *m*	7 × 7	bounded	1348	Terrestrial Laser Scanning (TLS) Radar interferometry	0.35 Hz 0.39 Hz	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 × 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 × 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 × 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 Inclinometer Georadar Flat jacks	2.4 Hz	E = 3.5 kN/mm2			
[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 acquisitons, 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 acquisitons, 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 acquisitons, 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 acquisitons, 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 accelrmtrs 8 temperature sensors 2 humidity sensors			9 months	1600 Hz (downsampled to 40 Hz) Every 30 min for enviromental 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 accelrmtrs 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 Photogrammetry 12 uniaxial piezoelectric accelerometers 6 MEMS (2 orthogonal directions) Temperature in MEMS units	1.38 Hz 1.44 Hz	E = 2430 MPa		200 Hz accelerometers 80 Hz MEMS accelerometers	EFDD EMD 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 0.79 Hz, 0.87 Hz after restoration		300 s	192 Hz (subsampled 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

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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
[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 Four thermocouples			> 3 years monitoring tilt	Every 10 min	
			The Matilde Tower in Livorno (Italy).			29	12	bounded		12 accelerometers	2.7 Hz 3.7 Hz			400 Hz downsampled to 40 Hz	FDD SSI MAC
[181]	Zonta&Pozzi	2015	The bell-tower of the Cathedral of S. Andrea in Portogruaro		civic tower	59	7.3 × 7.3		13th c.	Optical inclinometer Four thermocouples			> 3 years monitoring tilt	Every 10 min	

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 Table1 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

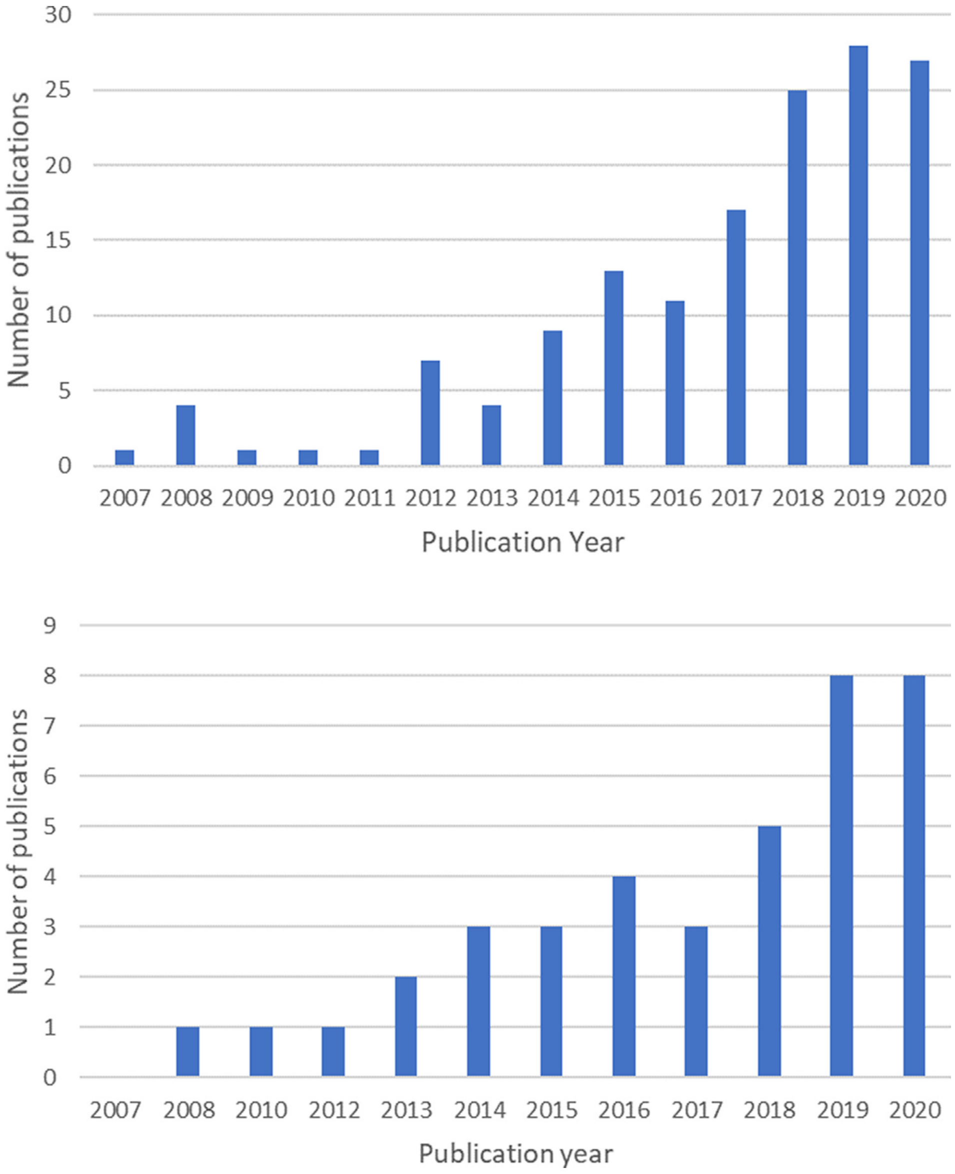

Fig. 2. Search: keywords 'structural health monitoring' and 'masonry' (top), together with 'tower', 'chimney', 'column' or 'minaret' (bottom).

[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 intereferometry. 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

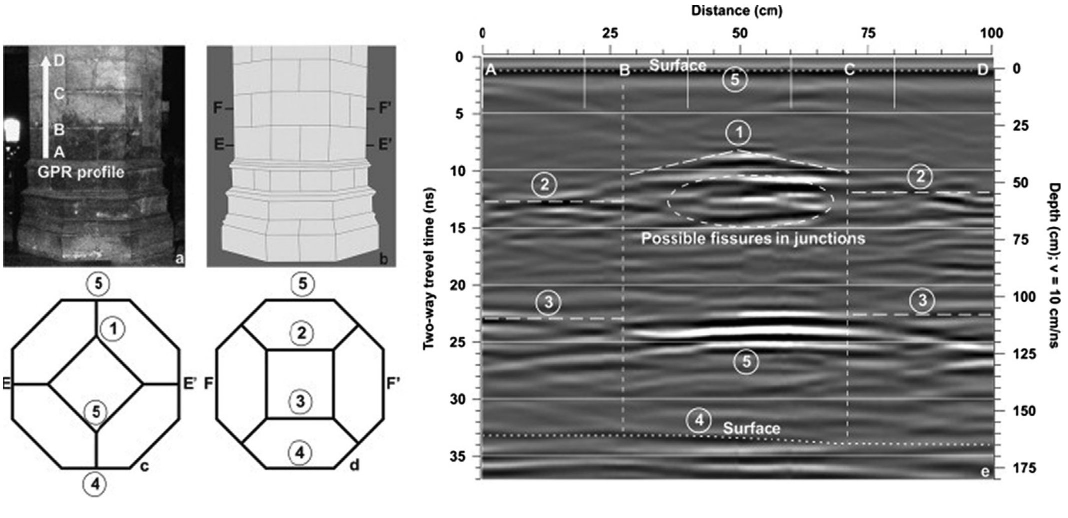

Fig. 4. Radar profile on column and interpretation [61].

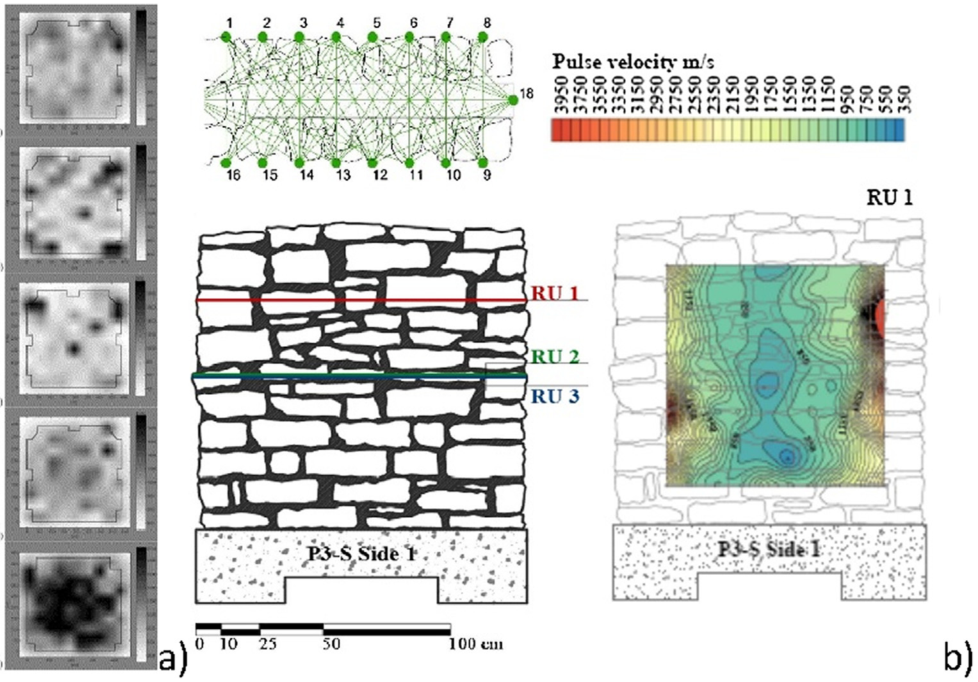

Fig. 5. Sonic tomography with distribution of velocities on several sections of column (a) [62] and wall (b) [131].

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 nonlinear 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 rowers). 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.

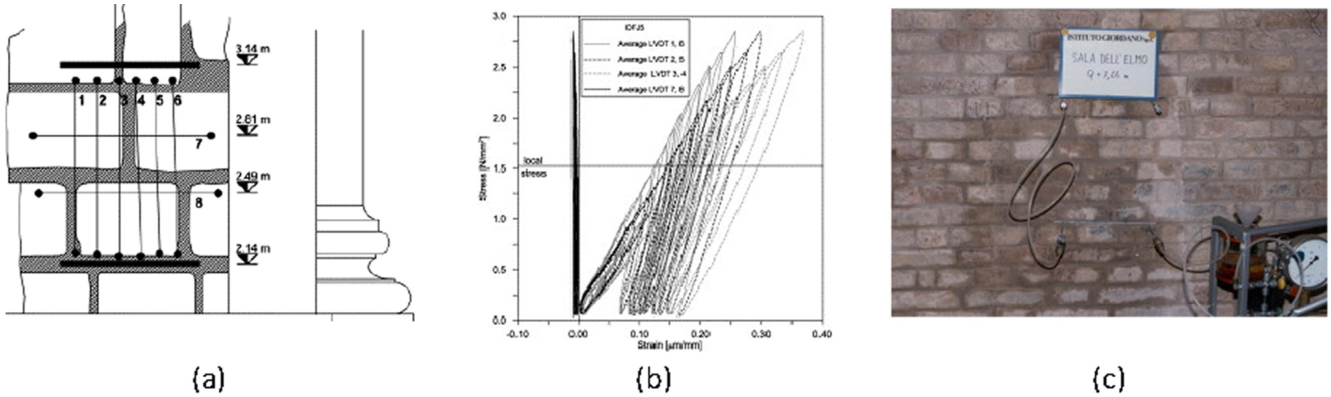

Fig. 6. Flat jack test: (a) typical layout and LVDT sensors [62]; (b) stress–strain curve [62] and (c) real test [84].

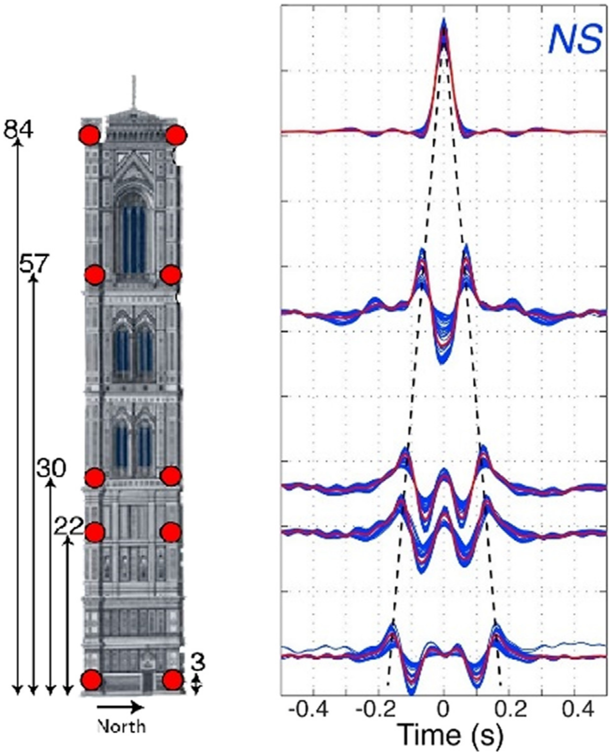

Fig. 7. Schematic deconvolution considering a virtual source at the top level and location of seismic stations [48].

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-

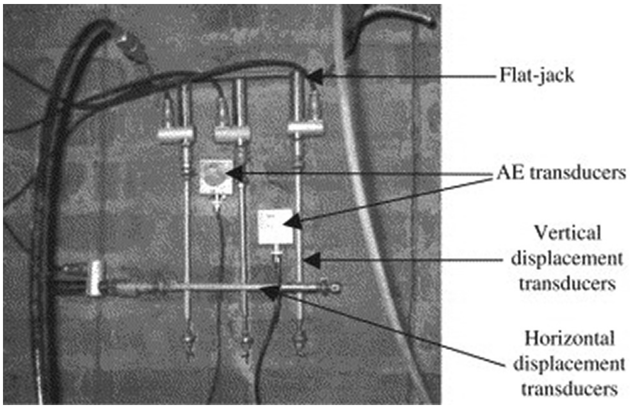

Fig. 8. Combined flat-jack test and AE monitoring [58].

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 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 where 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].

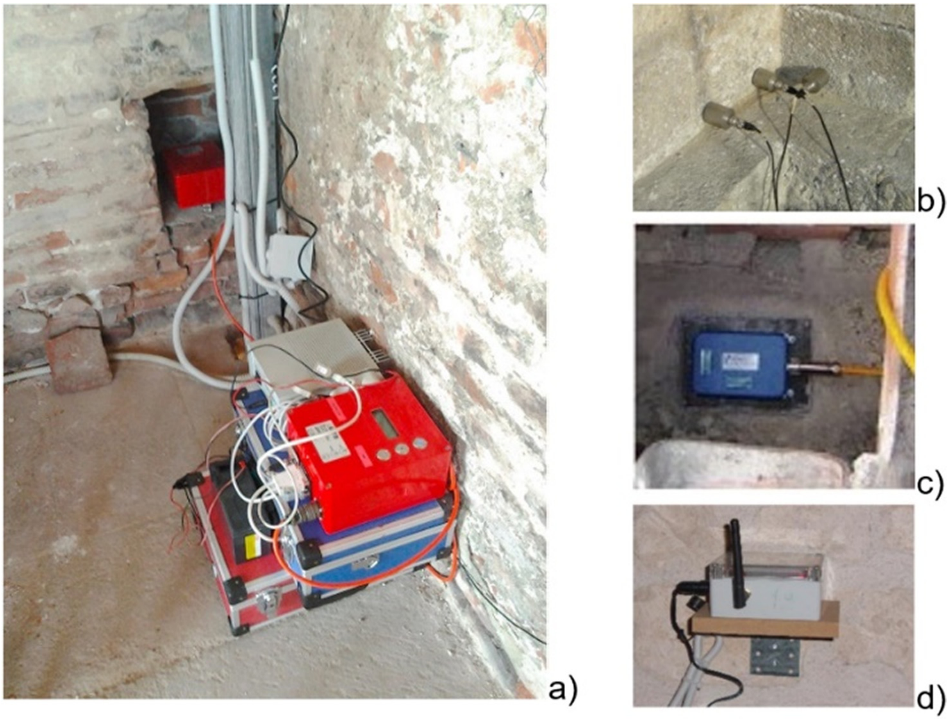

Fig. 10. a) Seismometric station [25], b) Piezoelectric accelerometers [111], c) force-balance accelerometer [7], d) wireless sensor [22].

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]).

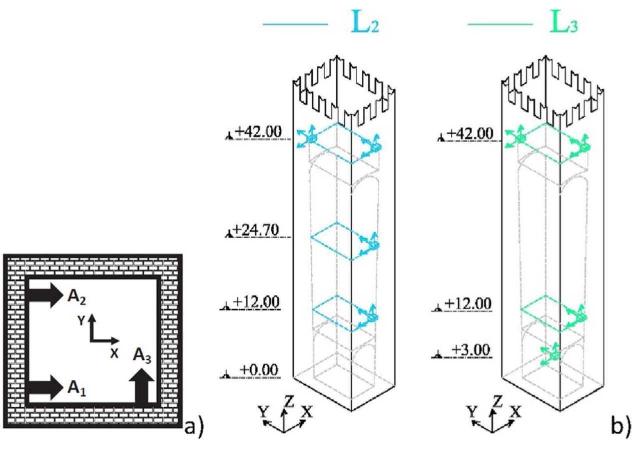

Fig. 11. a) Plan view basic deployment [22], b) 3D view complex arrangement [25].

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 all. [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

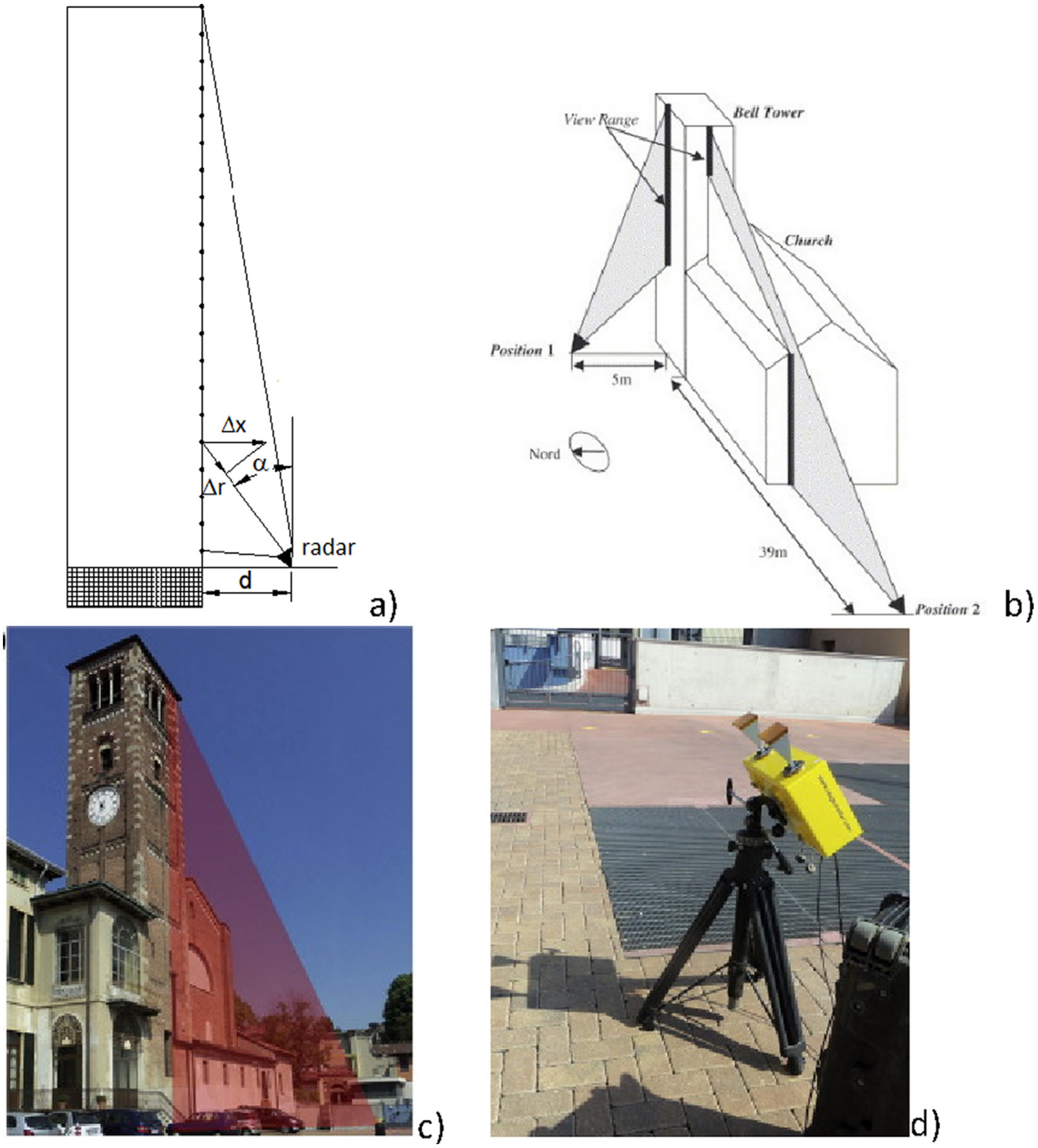

Fig. 12. a) Displacement calculation and b) Measurement positions [113], c) Line of sight [46], d) Sensor [46].

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 that 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

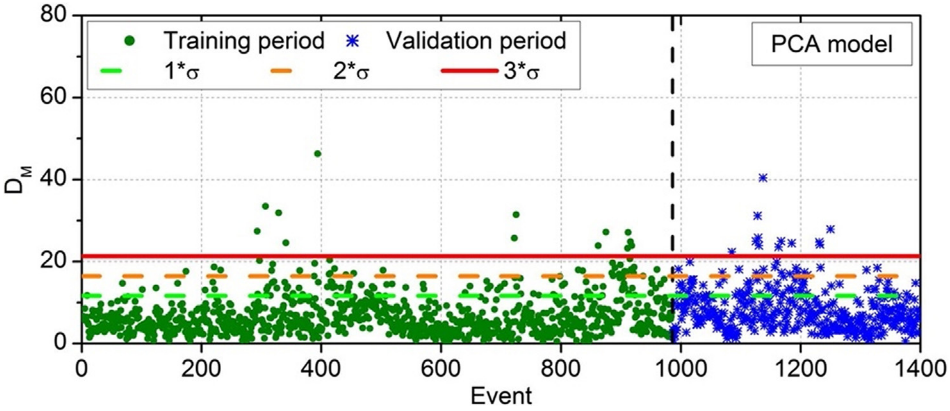

Fig. 13. Temperature effects and damage detection based on PCA [49].

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 Announziata (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, Eigensystem 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 Table1 ('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 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.

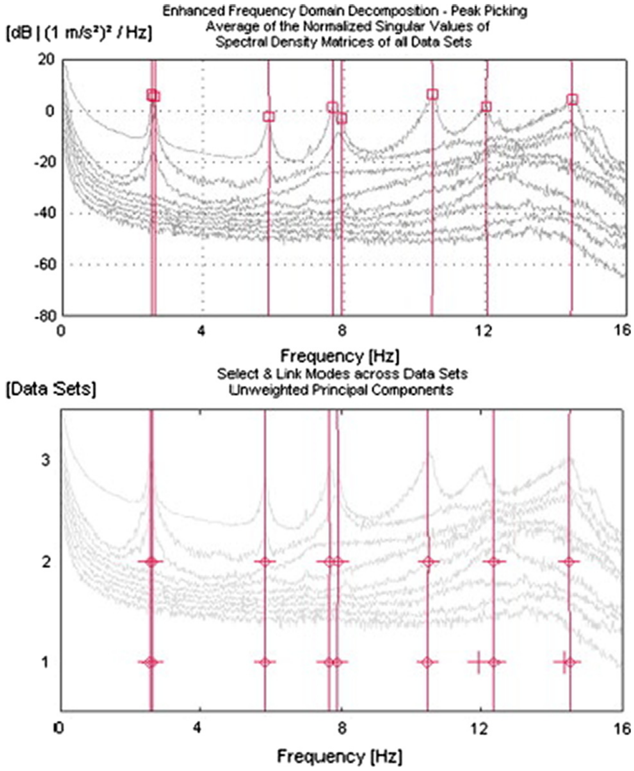

Fig. 14. Singular Values of the PSD function from EFDD technique (top), singular values from SSI-UPC technique (bottom) [111].

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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