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Review

Structural Health Monitoring and Management of Cultural Heritage Structures: A State-of-the-Art Review

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Abstract: In recent decades, the urgency to protect and upgrade cultural heritage structures (CHS) has become of primary importance due to their unique value and potential areas of impact (economic, social, cultural, and environmental). Structural health monitoring (SHM) and the management of CHS are emerging as decisive safeguard measures aimed at assessing the actual state of the conservation and integrity of the structure. Moreover, the data collected from SHM are essential to plan cost-effective and sustainable maintenance solutions, in compliance with the basic preservation principles for historic buildings, such as minimum intervention. It is evident that, compared to new buildings, the application of SHM to CHS is even more challenging because of the uniqueness of each monitored structure and the need to respect its architectural and historical value. This paper aims to present a state-of-the-art evaluation of the current traditional and innovative SHM techniques adopted for CHS and to identify future research trends. First, a general introduction regarding the use of monitoring strategies and technologies for CHS is presented. Next, various traditional SHM techniques currently used in CHS are described. Then, attention is focused on the most recent technologies, such as fibre optic sensors and smart-sensing materials. Finally, an overview of innovative methods and tools for managing and analysing SHM data, including IoT-SHM systems and the integration of BIM in heritage structures, is provided.

Keywords: structural health monitoring; cultural heritage structures; fibre optic sensors; computer-vision based approach; Internet of things paradigm

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1. Introduction

Historical buildings and monuments represent a large part of our building stock (consider that nearly a quarter of the EU's total buildings have a date of origin before 1945 [1]). The conservation of such structures is important, not only from historical, cultural, and architectural points of view, but also because of their social (identity of the community, sense of place, social cohesion, etc.) and economic (tourist consumption, income from rental, place of living, place of conducting economic activities, etc.) dimensions [2]. However, preserving historical structures is a complex task due to their high vulnerability to natural hazard events (e.g., earthquakes, floods, etc.), pre-existing state of degradation, unique structural and material characteristics, and low energy efficiency. Moreover, the effects of climatic change (e.g., heavy snowloads, rainfall, floods) on the structural integrity of built cultural heritage are progressively becoming more critical [3,4]. In this context, monitoring the health condition and management of heritage constructions represents a fundamental step for their preservation. The use of efficient and accurate SHM systems is not only crucial to assessing structural performance but also to providing valuable information that aims to plan cost-effective and sustainable maintenance and retrofitting solutions [5].

The need for an accurate assessment has become even more relevant with the most recent EU and worldwide policies promoting specific actions to make cities more resilient and sustainable, such as the EU Renovation Wave initiative [6], promoted under the European Green Deal [7] and the New European Bauhaus [8]. These EU policies have raised the interest of the community to evaluate the structural/energy state of the existing buildings, which fulfil both structural and energy upgrading requirements [9–12]. In contrast, integrating seismic and energy upgrading with systems for smart monitoring of CHS was recently proposed as a concept [13].

SHM involves the process of implementing strategies that serve two primary purposes: (1) to evaluate the current health condition (diagnosis) by analysing the collected monitoring data to determine the occurrence, location, and severity of damage [14]; and (2) to predict the future performance (prognosis) of the monitored structure, which is based on predictive models and algorithms [15–17]. The diagnosis and prognosis processes, combined with the basic knowledge of damage mechanisms and behaviour laws, aim to plan the health management (organization of maintenance strategies, repair interventions, etc.) of the structure [15,18].

While there is no current reference standard for SHM in CHS, the importance of monitoring for the conservation of CH buildings has been highlighted by various guidelines, such as the ICOMOS/ISCARSAH committee's Guidelines on the Analysis, Conservation, and Structural Restoration of Architectural Heritage [19] and the Italian guidelines for assessing and mitigating the seismic risk in CH structures [20]. These guidelines embrace the ICOMOS/ISCARSAH principles [21] based on the need for scientific and cultural insight in the study and care of architectural heritage while minimizing interventions to optimally combine structural requirements with heritage preservation and authenticity. SHM for CHS can increase understanding of structural behaviour, estimate the need for strengthening, control damage progression, and evaluate the effectiveness of incremental strengthening interventions.

The field of SHM is wide ranging and includes many techniques that can be grouped according to various classification criteria. The abovementioned guidelines [19,20] distinguish between static monitoring, aimed at the measurement of slowly varying parameters, such as strain, stress, deformation, tilt, and displacement, and dynamic monitoring, used to measure the structural response during the occurrence of phenomena exhibiting rapid variation over time, such as seismic events, wind, traffic, or other dynamic actions. In the literature, different classifications of monitoring techniques can be found depending on several criteria. First, they can be categorized into global and local methods. Global methods, such as vibration-based monitoring techniques, can detect the occurrence of damage that affects the whole structure, but cannot precisely locate the damage. In contrast, local methods detect damage through inspection and investigation at the component level. These two approaches are complementary: global methods can alert for the presence of damage and roughly define its location, while local methods are more precise in localizing and providing information about the damage [22]. Monitoring strategies can then be distinguished as continuous or periodic, depending on the frequency of measurements. The first approach considers continuous acquisition and analysis of data to differentiate and filter out changes caused by exogenous factors [23]. The second approach includes general inspections, such as geometric measures by photogrammetry, that can be executed periodically to improve the knowledge level and reduce uncertainties [24]. Finally, depending on the type and configuration of sensing and data acquisition systems, SHM techniques can be classified as traditional (standard) or innovative (smart) [25].

This paper provides a comprehensive state-of-the-art review of SHM and the management of CHS, focusing on innovative technologies. A description of conventional SHM techniques, subdivided into static and dynamic techniques, follows this introduction (Section 2). Section 3 illustrates the innovative SHM technologies, including smart-sensing, imaging and computer-based methods. Finally, data management strategies for managing the large amount of data collected by new monitoring systems are presented in Section 4.

2. Conventional SHM Techniques

Direct visual inspection is a traditional SHM technique for structural assessment, damage detection, and mapping. It involves examining crack patterns and anomalies to identify potential damage mechanisms. However, visual inspections are limited to surface inspection and rely on subjective expert judgment [26]. Destructive testing (DT) techniques can provide important structural behaviour information. However, they are invasive, time-consuming, and expensive, especially when dealing with CHS. Non-destructive testing (NDT) techniques are a better alternative for in situ applications.

Long-term monitoring systems offer a solution to the limitations of direct visual inspections by gathering detailed information and monitoring the evolution of static and dynamic properties over time. Environmental factors such as temperature and humidity can affect monitoring, and researchers have investigated their impact. To control the environmental effects, statistical models such as multiple data regressions (see, e.g., [27–29]) and principal component analysis (see, e.g., [30–32]) have been proposed to remove them from or minimize their effects on structural behaviour analysis.

The combination of static and dynamic monitoring systems has been applied in CHS, including sites such as churches [23,33–38], towers [39–41], palaces [42,43] (Figure 1), and other types of complex monumental buildings, such as the Roman Arena of Verona [44]. In the Appendix A, Table A1 shows typical examples from the international literature of static and/or dynamic SHM systems applied in CHS, indicating the purpose of these systems to monitor repairs/strengthening. In the following sections, an overview of both conventional static and dynamic methods for CHS is provided.

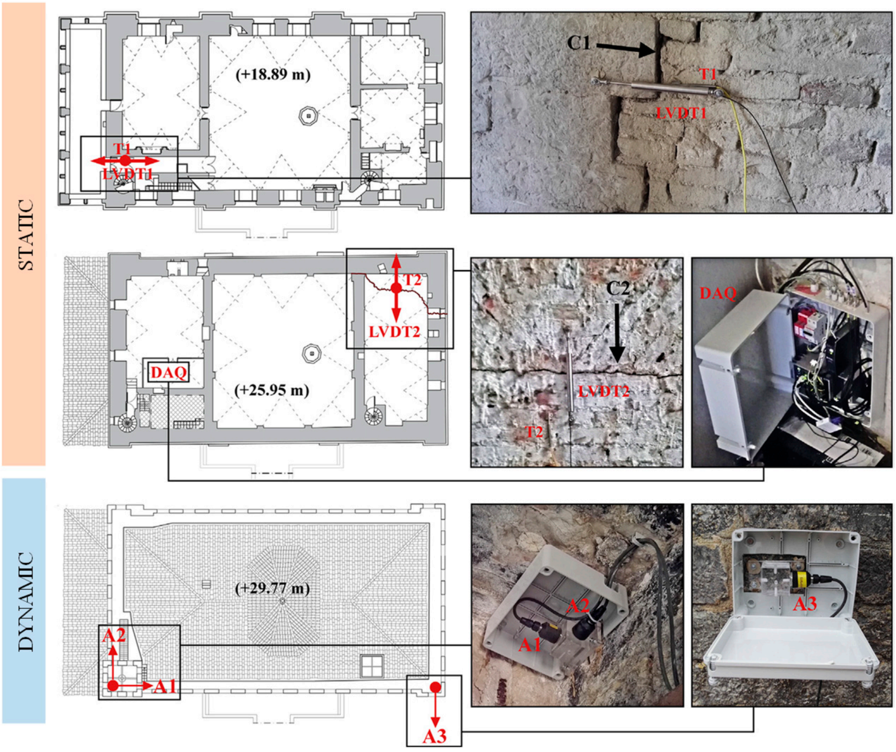


Figure 1. Static-dynamic SHM system installed in Consoli Palace, with crack meters (LVDTs), temperature sensors (T1, T2) and uni-axial piezoelectric accelerometers (A1–A3) (modified from [45]).

2.1. Static Monitoring Systems

Static monitoring continuously measures strain, stress, deformation, tilt, and displacement [46]. These parameters usually fluctuate slowly in the absence of dynamic events (e.g., earthquakes, tsunamis, etc.). Additionally, they are influenced by seasonal cycles and environmental changes (e.g., temperature, humidity, rain, wind, etc.). For these reasons, a monitoring period of at least two years is usually required to deduce meaningful data.

In historical structures, crack patterns can be one of the first indicators of deterioration or even a developing collapse mechanism that could be triggered by future events. Besides a first evaluation with a visual inspection, installing a long-term monitoring system aims to determine whether such cracks are active or dormant. Basic tools are based on manual and periodic controls using a plastic Tell-Tale fixed across the crack (Figure 2a), which, unlike the previously used strips of glass, provides information about the magnitude and direction of the movement. Another system consists of applying some fixed bases or anchor points (usually made of aluminium plates) on each side of the cracks and then manually measuring the distance between these points using a caliper or a deformometer. Continuous monitoring can be conducted using electric/mechanical displacement transducers, such as linear variable differential transformers (LVDTs, Figure 2b) or linear potentiometric displacement transducers (LPDTs).

One of the most notable monitored crack patterns, in terms of extension, complexity and importance of the monument, is that of the dome of Santa Maria del Fiore in Florence, which is also one of the longest continuously monitored monumental buildings in existence (more than 60 years of data) [47]. A static monitoring system has been installed since 1955. Today, it inlcudes more than 160 instruments, such as mechanical and electronic deformometers, thermometers, and piezometers. The large amount of data collected across time allows for a good understanding of the actual behaviour of the structure. A similar example of crack monitoring is applied to the Basilica of Vicoforte's dome, the world's largest masonry oval dome. Ceravolo et al. [27] reported the results of data acquired from 2004 to 2014. The absence of significant trends in the crack opening extracted from the periodic measurements of the crackmeters proved the effectiveness of the strengthening intervention in 1987.

(**a**) (**b**)

Figure 2. Monitoring of cracks employing: (**a**) plastic Tell-Tale crack meter, and (**b**) an LVDT sensor (from [48]).

Tilting is another severe structural problem that can affect the stability of CHS, especially in slender structures such as towers. The main reasons why buildings can develop a lean are usually related to (a) lack of foundation strength and (b) lack of foundation stiffness [49]. Tilt is typically measured through inclinometers, such as that used by Zonta et al. [50], for monitoring the inclination of Portogruaro Civic tower, and Ramos et al. [51], for monitoring the Torcato Church towers. The systems were based on pendulums hanging from the ceilings consisting of steel wires with a heavy mass attached. In the first example, two digital network cameras permanently record the position of the pendulum, and the position of the wire is calculated in real-time using image recognition software. Alternatively, for higher precision, uniaxial tiltmeters, such as those installed in the Church of the Monastery of Jerónimos in Lisbon [33], or biaxial tiltmeters, such as those installed for the monitoring of the Milan Cathedral [37] (Figure 3), can be used.

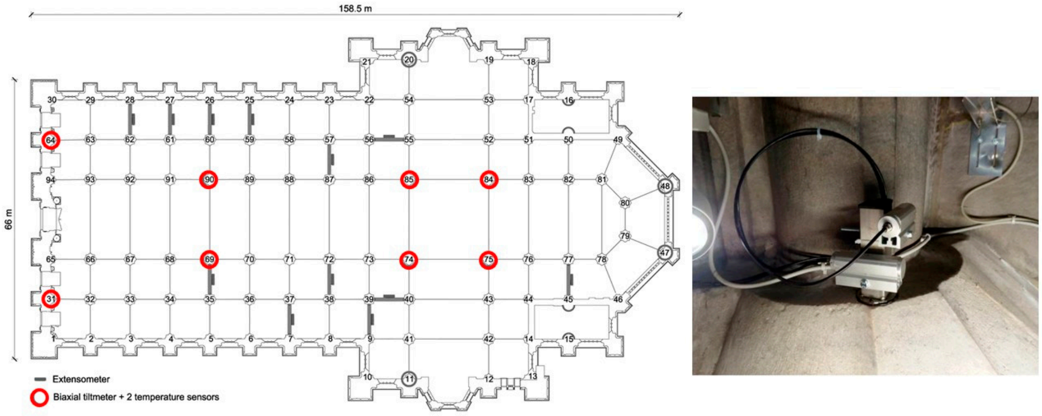


Figure 3. Biaxial tiltmeters installed on eight capitals of the Milan Cathedral (from [37]).

The continuous monitoring of stress variations is another essential aspect for the safety of historic masonry structures, especially considering that the creep phenomenon to which masonry structures can be subject has occasionally led to the collapse of historic buildings [52]. Pressure and load cells can be used to monitor pressure and load variations.

Chiorino et al. [53] described using several pressure cells to monitor the dome–drum system of the Basilica of Vicoforte. Some were placed horizontally to control stress variations in the eight pillars and the dome's buttresses. A pressure cell was placed vertically near the top of the dome to determine the circumferential compression stress. Moreover, the load condition of a system of 56 active tie-bars, applied at the base of the dome as a reinforcement, is constantly monitored by load cells and may be regulated by using jacks.

Blanco et al. [54] developed a new device for the long-term monitoring of stress based on the use of flat jacks and displacement sensors. The new SHM system was applied to monitor, in real-time, the variation in the stress levels of several masonry buttresses of the Church of the Major Seminary of Comillas (Spain) during the actuation of strengthening interventions [54,55]. The authors concluded that although the system still needed further studies to control the influence of thermal variations, it is of great interest to increase the safety of historic buildings and the workers involved in the retrofitting interventions.

Baraccani et al. [56] presented a preliminary assessment of the structural health of Modena Cathedral. The building had experienced various transformations and interventions over the centuries, mainly due to earthquakes and soil settlement effects. This led to a complex and remarkable damage pattern. A static SHM system was installed in 2003 to provide data that can be integrated with structural analysis results. Specifically, the monitoring system installed in the cathedral consisted of biaxial and triaxial joint meters, inclinometers, deformometers, and thermometers which were used to monitor the main cracks across the walls and vaults, the tilting of the external longitudinal walls, the relative displacements between the cathedral and the adjacent tower (the Ghirladina Tower [57]), and the internal temperature. The analysis and interpretation of data revealed the structure's principal vulnerabilities and failure mechanisms. They also provided essential information for developing and calibrating simple and FE models used to investigate the long-term performance of the overall structure.

2.2. Dynamic Monitoring Systems

The key aim of dynamic monitoring is the identification of the structure's modal parameters (e.g., frequencies, mode shapes, damping ratios) that can be used to spot anomalies from the expected global behaviour and plan appropriate and timely interventions. Before installing a proper continuous dynamic monitoring system, preliminary dynamic identification tests are usually performed under forced or ambient noise conditions. In some cases, for economic reasons, for instance, only the first activity is followed by FEM simulations. When the devices are not continuously available, dynamic monitoring can be conventionally achieved through the consecutive repetition of dynamic measurements over time [58].

Proper continuous dynamic monitoring comprises the instrumentation and acquisition systems that record the vibration response of the structure based on a set of sensors deployed at selected locations with sufficient spatial density and frequency resolution. Equipment based on accelerometers is typically adopted, such as force balance (Figure 4a), piezoelectric, and piezoresistive monitors, micro electro mechanical systems (MEMS) (Figure 4b), or seismometers. Concerning dynamic identification techniques, the ambient vibration test (AVT) and operational modal analysis (OMA) are among the first choices used by researchers for the analysis of heritage structures because of (a) the easy and non-destructive methods of testing, performed by measuring only the structural response under ambient excitation; (b) the sustainability of testing, which does not interfere with the everyday use of the structure; and (c) the multiple-input nature of ambient excitation, ensuring that the response includes the contribution of a certain number of modes [40]. The identified modal properties have proved to be well-suited for the optimisation-based calibration of numerical models [59–66]. It is worth noting that vibration-based SHM techniques provide reliable results for slender or flexible structures, such as towers, vaults, domes, etc. The analysis of stiffer buildings, such as palaces and churches, preferably requires a mixed static–dynamic monitoring approach to obtain informative results [67,68].

(**a**) (**b**)

Figure 4. Different types of dynamic sensors: force-balance accelerometers (**a**), from [38], and MEMS accelerometers (**b**), from [40].

Similarly to static monitoring, one crucial aspect that must be considered when processing dynamic monitoring data is removing environmental effects. In particular, natural frequencies tend to exhibit daily and seasonal fluctuations, imputable to temperature and humidity variations, as well as, in the case of slender structures (e.g., towers), wind speed [32,41,69–71]. The optimal location and the minimum number of environmental sensors that are sufficient to achieve about 90% of the statistical prediction accuracy of the natural frequencies was investigated by Ubertini et al. [69]. Besides the well-known influence of temperature on natural frequencies, generally related to increments in frequencies with increasing temperature, Ramos et al. [22] reported a non-negligible effect of humidity on the dynamic response of masonry structures subjected to heavy rain events.

According to the types of instruments involved, dynamic monitoring systems can be classified into two groups: conventional wired-based systems and wireless-based systems. The first system comprises measurement sensors, data acquisition (DAQ) systems, and, in some cases, remote connection systems. Although such systems are still widely used, the recent development of inexpensive wireless monitoring systems and MEMS has increased the interest in their adoption, particularly for historical structures [72].

One of the first publications on the dynamic monitoring of large-scale historical structures was carried out by Erdik et al. [73]. The authors investigated the dynamic behaviour of the Hagia Sophia (Istanbul). First, an ambient vibration survey was conducted by using four seismometers. Then, the structure was instrumented with nine triaxial strong motion accelerometers, registering a minor earthquake of 4.8 magnitude. The vibration shapes and frequencies obtained from ambient vibration were used to calibrate a linear FEM for preliminary seismic analysis of the structures in the linear ranges. The data from the earthquake response showed a drop in frequencies of the first two vibrational modes, even if the earthquake was small and no visible damage was detected in the structures. The authors concluded that microcracking diffused throughout the whole building might be the reason for this change in the dynamic properties.

Ramos et al. [22] presented a methodology based on ambient vibration tests and operational modal analysis for the damage identification of masonry structures. The method comprises four phases: data collection, simplified health monitoring, detailed health monitoring, and local complementary non-destructive testing. The procedure proved to be suitable, even for complex historical constructions, with the analysis of two case studies, the Clock Tower of Mogadouro and the Church of the Jerónimos Monastery in Lisbon.

Dynamic SHM systems have also been used to monitor two monumental Roman heritage structures, the Roman Arena of Verona and the Flavian Amphitheatre (the Colosseum) in Rome. Lorenzoni et al. [44] presented the results of the 1.5-year monitoring of the Roman Arena of Verona, which involved static displacement measurements and tracking the fundamental modal parameters (natural frequencies, damping ratios, and mode shapes). The dynamic monitoring system, comprising 16 uniaxial wired accelerometers, detected moderate seismic events following its implementation in 2012, allowing for the identification of the peak ground acceleration at the foundation, maximum acceleration at the monument's top, and modal parameter variations. The authors developed and implemented robust routines for automatically processing monitoring data, transmitting them online to a central server. This processing software provided nearly real-time information on the structural health condition, acting as an early warning tool

Monti et al. [74] presented the results of the first two years of dynamic monitoring (2014–2015) of the Colosseum in Rome. The system comprised a wireless network of accelerometers and a backend server allowing users to access measures remotely. The system monitored the long-term vibrations induced by vehicles and subways, thus providing experimental support for determining acceptable acceleration levels that would not damage the structure.

Saisi et al. [41] described the application of a dynamic SHM system to three medieval towers, focusing on understanding the effects of temperature variations on natural frequency changes over time. The authors observed that natural frequencies increase with increased temperature, which can be explained by the closure of superficial cracks caused by the material's thermal expansion. The same result occurred in freezing conditions: indeed, the freezing of the structural system and the presence of ice filling the cracks made the structures stiffer.

Azzara et al. [75] presented the results of long-term dynamic monitoring campaigns regarding different monuments in urban areas. The study examines the impact of various vibration sources, especially wind and human activities, on the dynamic behaviour of the monitored structures. Besides the daily and seasonal fluctuations resulting from environmental factors variations, the authors also investigated the impact of reduced high-frequency ambient noise during the SarsCov2 pandemic lockdown on one of the monitored buildings. The authors observed a significant decrease in average noise levels while implementing safety measures.

Other interesting applications and results dealing with the application of dynamic monitoring systems on historic structures can be found in several publications, e.g., [65,70,71,76–79].

3. Innovative SHM Techniques

3.1. Smart Sensing Technologies

The operating principle of smart-sensing technologies is based on their capability to change properties and behaviour under the influence of external physical and chemical parameters related to the health of the structures. Smart sensing technologies include fibre optic sensors (FOS), piezoelectric sensors, magnetostrictive sensors, and self-sensing materials. The working principle of magnetostrictive sensors is based on the inverse magnetostrictive effect, namely the change in the magnetic induction of ferromagnetic materials when they are mechanically deformed. Since most historic structures are made of masonry or non-metallic materials, magnetostrictive sensors are not treated in this review paper. Detailed review studies on smart sensing technologies used for civil engineering structures have already been presented in [80–82], whereas this paper focuses on their application to cultural heritage structures.

3.1.1. Fibre Optic Sensors

FOS are some of the most promising and fastest growing technologies [83] due to several advantages, such as immunity to electric and electromagnetic interference, compatibility with ordinary telecommunication fibres, good resistance to high temperatures, chemical inertia, embedding capability, the low cost of the sensors, and a low size weight. The fibres consist of a flexible strand commonly composed of several layers: a central core, a cladding, and occasionally, an external coating to provide mechanical and environmental protection (Figure 5). External perturbations produce geometrical and optical changes in the guided light, which is translated into a corresponding change in the monitored parameter. The principles and detailed descriptions of fibre-optic technology are out of the scope of this paper. The reader is referred to several relevant articles, e.g., [18,84–88].

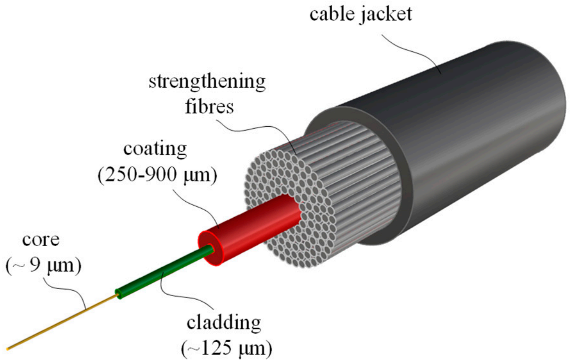


Figure 5. Typical optical fibre cross–section.

Many FOS technologies have been developed during the last decades [88]. Several classifications can be found in the literature according to different criteria (e.g., sensing location, operating principle, or application), as shown in Table 1. The most commonly used types of FOS for the SHM of civil structures are interferometric sensors, fibre Bragg gratings (FBGs), and distributed sensors. The significant parameters detected by each sensor type are given in Table 2.

Table 1. Main criteria for FOS classification.

Criteria	Types
Sensing location	Single point sensors Quasi-distributed sensors Distributed sensors
Operating principle	Intensity sensors Phase sensors Frequency sensors Polarization sensors
Application	Physical sensors Chemical sensors Biomedical sensors

Table 2. FOS types and main measurement parameters.

Parameters	Sensor Technologies				
	Interferometric Sensors	Fibre Bragg Grating	Distributed Sensors		
			Rayleigh Scattering	Raman Scattering	Brillouin Scattering
Strain	x	x	x		x
Temperature	x	x	x	x	x
Pressure	x	*			
Displacement	x	*			
Deformation	x				

* indicates parameters that can be measured by easily adapting the conventional sensor configuration.

The last two decades have seen an increasing number of FOS applications for civil engineering monitoring (during construction and in-service stages), such as on bridges [89–92], geotechnical structures [93], pipelines [94], and high-rise buildings [94]. Although FOS technologies offer several advantages suitable for CHS, such applications are still relatively limited. The benefits that FOS may offer to CHS monitoring comprise their low invasiveness, the potential of integration with textile reinforcements, and the possibility to perform truly distributed measurements because of their sensing capacity at any point along their length. In addition, FOS technologies exhibit high flexibility and versatility, allowing for the measurement of different types of parameters, such as strain, temperature, vibration, humidity, and chemicals (e.g., pH, analyte), even on the same fibre. Another important advantage is that, if appropriately designed and packaged, FOS can be very robust and long lasting, even in harsh environments, allowing for long-term monitoring applications. Finally, optical sensors offer higher sensitivity in detecting movement faster than traditional SHM and allow for remote data acquisition, namely without the presence of technicians in the field, which reduces labour time and costs.

Interferometric Sensors

Interferometric sensors work by measuring interference between beams of light. Two types of sensors are generally used for SHM purposes: Fabry–Perot interferometers (FPI) and the SOFO (a French acronym for surveillance d'ouvrages par fibres optiques) sensors. FPIs are used in various sensing applications on civil infrastructures to measure strain, displacement, pressure, and temperature [95–97]. They are appreciated for their low cost, high sensitivity and ultra-compactness. Despite these advantages, to our knowledge, no applications of FPI sensors on CHS buildings have been found in the literature.

The SOFO measurement system, developed at the Swiss Federal Institute of Technology in Lausanne (EPFL) [98], has mainly been used for the last 20 years for both dynamic and static monitoring of civil [99–102], geotechnical [103,104], and other structures. Some applications of SOFO sensors for the monitoring of CH buildings are depicted in [105–107], in particular for the monitoring of crack displacements and deformations.

Del Grosso et al. [108] described the application of an SHM system based on the combined use of SOFO and conventional sensors for monitoring the Royal Villa in Monza, Italy. Optical fibre sensors were mainly used as extensometers for crack monitoring before, during, and after renovation. The monitoring system proved to be a valuable tool for the monitoring-based rehabilitation process.

Glisic et al. [105] described the application of SOFO sensors on several heritage structures and historical monuments, including San Vigilio Church in Switzerland, where the long-gauge sensors were used to unobtrusively monitor the evolution of cracks and the curvature of the main vault, preserving the view of the frescos.

Uglesic et al. [106] analysed the results of a long-term SHM system installed on the facades of the bell tower of St. Anastasia Cathedral in Zadar, Croatia, to understand the behaviour of existing cracks. The crack displacements were measured via optical deformation SOFO sensors. The authors observed a correlation between crack displacements and daily and seasonal temperature variations, without any cumulative trend showing that the variations would damage the structure permanently.

Fibre Bragg Gratings Sensors

FBGs are one of the most studied and widespread FOS sensing technology applied to SHM because of their great flexibility [107]. An FBG is a microstructure within the core of an optical fibre, which can detect physical parameters (strain, temperature, etc.) based on wavelength reflection. They consist of a glass core characterized by a periodic 'grating' of material with a modulated index of refraction. More technical details about this technology are illustrated in [109,110]. A basic scheme of an FBG sensor is shown in Figure 6.

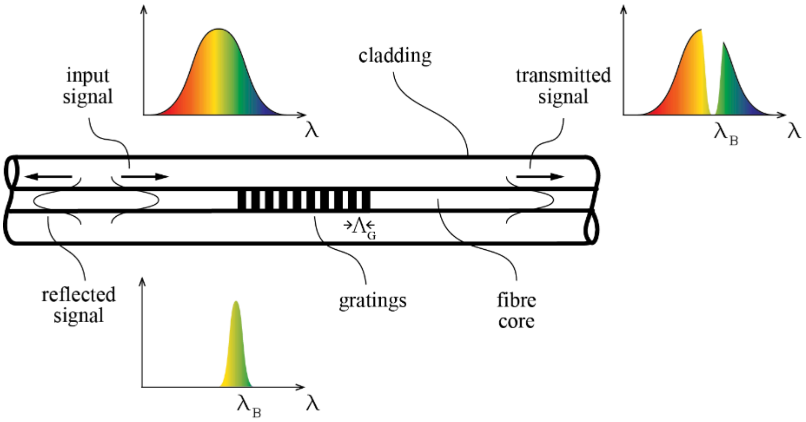


Figure 6. FBG operating principle.

Several works explored the use of FBG to monitor various static and dynamic parameters of historical buildings. Whelan et al. [111] discussed the development of a continuous monitoring system for the Cathedral of Como, Italy, which has always been subject to the risk of subsidence due to changes in the lake level. The system, installed in 2001, consists of a network of different FBG sensors to measure displacement, crack opening, strain, and temperature. The sensors' efficiency was successfully tested during an 8-month demonstration period.

Lima et al. [112] described the design, implementation, and data acquisition of an SHM system based on FBG displacement and temperature sensors to investigate the structural behaviour of the Church of Santa Casa da Misericórdia of Aveiro (Portugal), which presented some relevant cracks in the triumphal arch. The sensors registered displacements associated with both thermomechanical and structural effects. The effect of an earthquake that hit the region in February 2007 was also measured, showing that some displacement sensors measured a structural change unrelated to temperature variations. One of the main requirements of the project was to exert minimum visual impact and damage in the structure; thus, the sensors were bonded to the stone blocks using epoxy resin instead of by drilling methods. After the installation of the sensors, only the small supports could be seen, as the fibres were almost invisible. The authors concluded that this SHM system was optimal when planning restoration and conservation interventions.

A reversible and non-invasive bonding method was developed by Marazzi et al. [113] to install FBG sensors on delicate surfaces (such as frescos) to comply with restoration and conservation requirements. The study demonstrated that FBG sensors could be successfully used to monitor structures having architectural and artistic value.

The possibility of using FBG sensors to identify the fracturing patterns of falling frescos was more recently explored by Glisic et al. [114]. The study was carried out by testing various plaster moulds equipped with short and long-gauge FBG sensors glued on the surface or embedded in the plaster, showing the pros and cons of the two systems. Tests led to the conclusion that using FOS to detect cracks and track their propagation can improve the global understanding of fracturing patterns and complement high-speed camera systems. However, some limitations and room for improvement were also reported. The first limitation was related to the limited range of the FBG peak-tracking algorithm, which led to missing measurements. Secondly, a complete fracture network could not be detected, as it would require a denser array of FBG sensors, which would involve high costs.

Antunes et al. [115] investigated the effectiveness of FBG sensors for the static and dynamic monitoring of structures made of adobe, one of the most common materials used worldwide in the construction of ancient buildings with high historical and cultural value. The study was carried out by testing a full-scale adobe wall subjected to cyclic horizontal loading. The specimen was equipped with a network of 13 FBG displacement sensors and an FBG accelerometer to monitor damage and deterioration evolution during the destructive cyclic test, as well as to identify dynamic properties. The network of sensors proved to be simpler to install, with less cabling and low physical and visual impact on the structure, than traditional techniques. The first natural frequency determined using the FBG accelerometer was compared with that obtained from an electronic accelerometer and a seismograph, showing a low relative error (between 0.74% and 2.08%).

Distributed Sensors

FBG sensors can provide a quasi-distributed measurement by multiplexing many FBG sensors at discrete points along the fibre. This technology, however, allows for a limited number of gratings (usually less than 100) and can be expensive. A truly distributed monitoring can be achieved by using distributed fibre optic sensors (DFOSs), enabling the mapping of parameters at any point along a fibre. Their operating principle is based on the scattering phenomena related to the interaction between light and an optical medium [116]. Three scattering processes may occur in a DFOS: Raman, Brillouin and Rayleigh. An exhaustive review of DFOS and their applications for SHM of civil engineering structures can be found in [116–118]. An essential benefit of DFOS technology is that it only requires a single connection cable to transfer the acquired data to the reading unit. In contrast, discrete sensors typically require many connecting cables. As a result, distributed sensing improves cost-effectiveness and, at the same time, opens a wide range of significant applications, such as the continuous (in space and time) monitoring of structures. However, this is still a recent and developing technology, and few applications in SHM have been found in the literature.

DFOSs based on Brillouin optical time domain reflectometry (BOTDR) were applied by Bastianini et al. [119] to study the behaviour of a 17th century Italian palace severely damaged by the Umbria-Molise earthquake in 1997. The sensors were embedded into carbon fibre reinforced polymers (CFRP) adopted to strengthen and repair damaged walls and vaults. The effectiveness of Brillouin strain monitoring was verified, even for weak strain levels, while the effectiveness of the “smart” composite for crack opening detection was also successfully verified. This application introduced the integration of FOS to retrofitting systems to simultaneously combine strengthening and monitoring sytems for historic structures, which is extensively discussed in the next section.

Barrias et al. [120] implemented a DFOS system based on the optical backscattered reflectometer (OBR) technique [115] to monitor the masonry vaulted floor of Sant Pau Hospital (a UNESCO World Heritage Site) in Barcelona during the replacement of two columns. This system allowed for the successful assessment of the structural stability and safety of the floor by analysing stress redistribution in a distributed and continuous way (in both time and space), without any service interruption.

Acikgoz et al. [121] used three different monitoring systems, namely total stations, laser scanning, and distributed fibre optic cables based on BOTDR, to investigate the structural response of historic barrel vaults to piling-induced settlements during the London Bridge Station Redevelopment project. Compared with the total stations method, distributed sensors provided significantly higher spatial coverage. Moreover, the fibre optic systems were able to estimate the location and width of new intrados radial cracks that formed during piling. This unique capability is helpful for serviceability-based damage assessment.

Integration of FOS in Textile-Based Composites

The fibrous nature of the sensors proved to be suitable for integrating them into technical textiles frequently used as reinforcement for the structural retrofit and seismic upgrade of earthenwork and masonry structures. The integration of FOS for monitoring purposes in technical textiles with reinforcing capabilities has been actively explored in the last 15 years. In particular, their use of unreinforced masonry structures in seismic-prone areas fulfills the market need for research and development [122].

Krebber [123] and Liehr et al. [124] reported the activities carried out by the EU project POLYTECT [125], which focused on the development of novel geotextiles with embedded FOS for monitoring geotechnical and masonry structures. It was found that the use of such smart textiles was a cost-effective solution to reinforce and, at the same time, monitor masonry and heritage structures, enhancing their ductility and providing an alarm signal in case of structural damage. Several novel sensors, data processing techniques, and adhesives were developed and prototyped. Product functionality and performance were evaluated with a series of laboratory field tests on masonry structures and geotechnical sites, as well as with numerical simulations.

Coricciati et al. [126] applied "smart FRP devices", consisting of FRP reinforcing sheets with embedded FBG sensors and FRP pultruded bars with DFOS, for reinforcing and monitoring some masonry vaults and buttresses of the Monastery of Sant'Angelo d'Ocre, L'Aquila. Before the installation, the efficacy of the multifunctional textile to correctly measure the strain of the structural elements was successfully assessed by performing flexural tests on small-scale reinforced masonry beams.

Stempniewski et al. [127] reported the results of the POLYMAST project, which aimed to use a shaking table to test a two-storey stone building reinforced with a "composite seismic wallpaper" made of glass and polymeric multiaxial textile connected to the substrate using a cementitious matrix (see Figure 7). FBG sensors from different companies (some developed in the context of the POLYTECT project [125]) were embedded in the textile fabric, and their SHM capabilities were compared. It was found that, regarding the experimental modal analysis, not all sensors could capture the vibrations induced by the hammer tests. Regarding the strain measurement during the shaking test, the results showed a good correlation between strain measured by the different FBG sensors, and plastic deformations were also detected. The authors concluded that the system could effectively solve the seismic retrofit of existing masonry buildings. Furthermore, the embedded sensors proved to detect seismic-induced damages in terms of crack openings and residual strains.

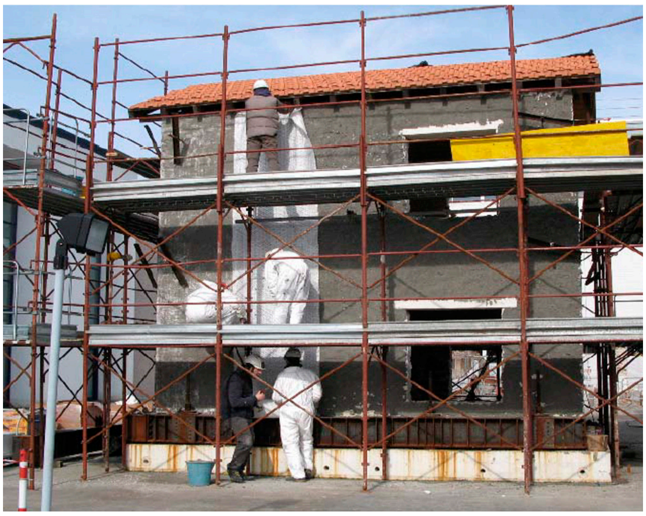


Figure 7. Application of the multiaxial textile with integrated SHM sensors on a stone masonry building within the POLYMAST project (from [127]).

Valvona et al. [128] proposed an innovative seismic retrofitting and monitoring technique for masonries using glass fiber reinforced cement matrix (GFRCM) composites with an integrated fibre optic sensing system based on FBG sensors. The new combined system was designed and applied to an old masonry pavilion vault. The retrofitting technique's effectiveness and the FBG sensors' optimal position were verified through a nonlinear FE model. An experimental campaign verified the valuable information obtainable by the FBG sensors, even in the range of moderate deformations. Finally, the comparison between simulated and measured strain evidenced a reasonable agreement with the obtained results. It was concluded that this system demonstrated its capability to long-term and continuously monitor the mechanical behaviour of strengthened masonry structures and, in particular, to detect on-site masonry damage or detachment phenomena.

The use of FBG sensors integrated with textile reinforced mortar (TRM) was also investigated by Tetta [129], exploiting the TRM composites developed by Tetta et al. [130] (Figure 8). Specifically, three optical FBG sensors were attached at the central roving point of the textile of a TRM coupon tested in tensile. The stress–strain curves of all three optical FBG sensors are presented and compared with the corresponding average response obtained by two LVDTs, showing a good agreement, mainly after the development of the cracking pattern of the TRM coupon. The authors concluded that using optical fibres for monitoring TRM jacketing externally applied to existing structures seems quite promising and worthy of further investigation in future research.

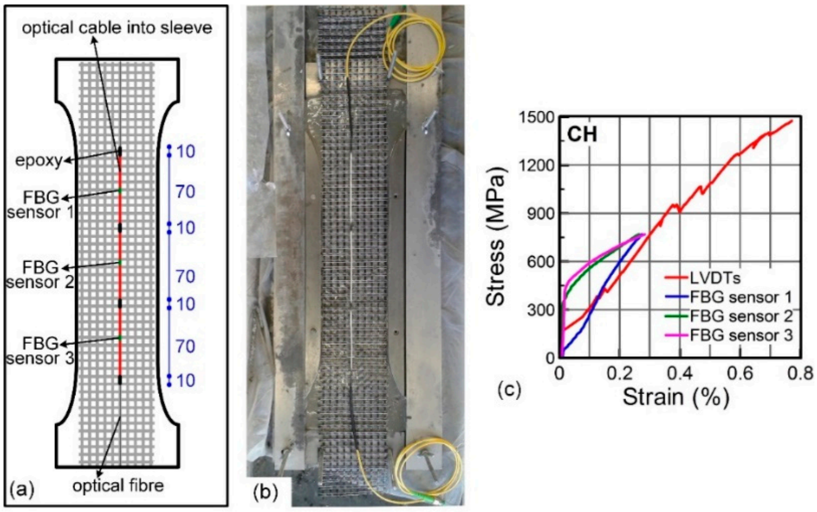


Figure 8. FBG sensors in a TRM coupon tested in tensile: configuration of FBG sensors (**a**); preparation of TRM coupon (**b**); stress versus strain curves (**c**) (from [129]).

Recently, Saidi and Gabor [131] analysed the tensile behaviour of a textile reinforced composite with DFOS embedded in the matrix. Thanks to the DFOS strain measurements, it was possible to identify and analyse the matrix, textile, and textile/matrix interface response along the typical three zones of mechanical behaviour (pre-cracking, crack propagation, and post-cracking zone).

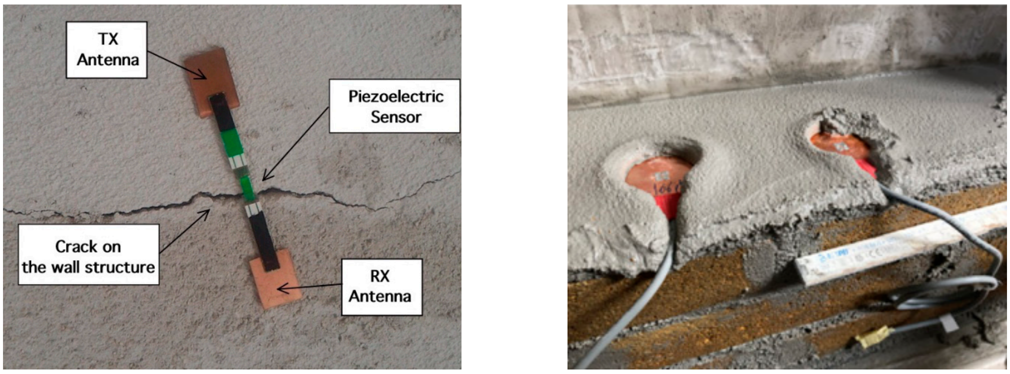
More recently, Bertolesi et al. [132] investigated the interfacial tangential-bond slip behaviour in TRM and FRCM (fiber reinforced cementitious mortar) strengthening materials. Distributed fibre optic strain sensors based on Rayleigh scattering were adopted to monitor the local strain evolution in TRM materials subjected to tensile tests and single laps shear tests on a TRM-strengthened masonry specimen. It was found that DFOS provided valuable data compared with traditional sensors (e.g., LVDTs), and the results could be effectively applied to calibrate the interface law and its subsequent use in an analytical model.

3.1.2. Piezoelectric Sensors

The recent developments in "smart" piezoelectric materials have inspired researchers to establish new non-destructive methods and SHM systems, obtaining flexible, cost-effective, robust, wireless, and mobile software/hardware solutions. Piezoelectric technology is based on different sensing modes, from electromechanical impedance and elastic waves to electrical signals [133]. Besides using the traditional piezoelectric accelerometers previously discussed, limited studies have applied novel piezoelectric systems for monitoring CHS.

Cuadra et al. [134] and Sasaki et al. [135] investigated the applicability of piezoelectric bolt sensors, initially designed for vibration measurements, to detect the development of cracks up to failure during compression tests of brick masonry specimens. By comparing the experimental results with FEM analysis, they concluded that this type of sensor is appropriate for predicting the crack evolution of brick masonry structures caused by compressive loading. Thus, it can potentially be used for the SHM of the masonry in existing historic structures.

Donelli [136] proposed the application of a radio frequency identifier (RFID)-based sensor equipped with a piezoelectric sensor able to detect crack evolution and to communicate recorded measurements to a remote reader within an operative range of a few meters (Figure 9a). The system's efficacy was experimentally assessed in a real scenario for monitoring several cracks in a 110-year-old masonry building, demonstrating the effectiveness of the proposed system.



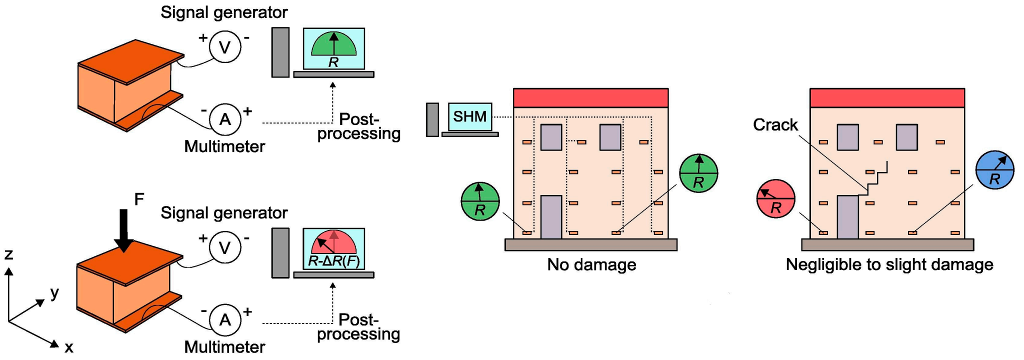
(**a**) (**b**)

Figure 9. An RFID sensor equipped with a piezoelectric sensor for crack detection ((**a**), from [136]; capacity piezoelectric sensors embedded in mortar joints (**b**), from [137]).

Recently, La Mendola et al. [137] conducted tests on twelve masonry specimens to assess two innovative piezoelectric stress sensors (ceramic and capacitive sensors, Figure 9b) embedded in mortar joints for detecting compressive loading variation. It was concluded that both devices could be reasonably implemented in the SHM of new masonry structures. However, further investigations are needed to explore the potential use in existing masonry structures, including CHS. The major key challenges are understanding the effect of existing stress on the masonry and how to install sensors in already built walls. Indeed, this kind of sensor can be used in local rebuilding using the so-called "scuci-cuci" repairing technique [138] to restore structural continuity along cracks or to recover heavily damaged areas of masonry walls.

3.1.3. Self-Sensing Materials

The novel concept of "smart bricks" for the strain-based structural health monitoring of masonry structures is currently under investigation by several researchers [139–143] and has potential for applications in CHS. Smart bricks are modified fired clay bricks made to be electrically conductive and piezoresistive by adding a suitable conductive filler to the clay and embedding or installing electrodes on the surface of the bricks during their manufacturing process (Figure 10a). Smart bricks can be used for strain sensing and damage detection in masonry structures subjected to in-plane compressive loading. Particularly, smart bricks will output changes in their electrical resistance that are proportional to local changes in their stress–strain conditions (assuming the bricks remain in their elastic range of deformation) when a damage or a crack forms within a masonry wall, for instance, due to the activation of a local failure mechanism after an earthquake (Figure 10b). These bricks may be installed when replacing damaged bricks in existing masonry structures following the so–called "scuci-cuci" technique for restoring the wall's structural continuity, as mentioned in the previous section.



(**a**) (**b**)

Figure 10. Concept of smart brick technology (**a**) and an example of its application for strain monitoring within a damaged masonry building using smart brick ((**b**), from [142]).

Downey et al. [139], for the first time, proposed titanium-doped smart bricks with embedded electrodes made of special steel, experimentally demonstrating their effectiveness in detecting minimal strain variations occurring within a small-scale masonry wall subjected to eccentric compression loads (both in small loading conditions and at the ultimate limit state).

Analogously, D'Alessandro et al. [140] proposed a new formulation for smart bricks using stainless steel microfibers as conductive fillers and a copper plate placed horizontally on the top and bottom of the external brick's surfaces as electrodes. The authors concluded that adopting copper electrodes led to more reliable and repeatable results than did the use of embedded electrodes.

Currently, the use of smart bricks for SHM purpose has been tested for (i) the monitoring of strain in masonry panels under compression loads [141], (ii) detecting and locating damage caused by earthquakes in masonry buildings [142], and (iii) strain monitoring and early crack detection in masonry structural elements subjected to in-plane shear loading [143]. The outcomes of this research work evidenced that the smart brick technology is mature enough to be tested in real full-scale masonry buildings.

3.2. Image and Computer-Vision Based Approach

Computer vision (CV) enables computers to analyse, understand, and interpret visual information from static images and video sequences. These methods embody several advantages, such as non-contact and long-distance application, automated inspection, and low interference with the daily operation of the structures. Therefore, their adoption has emerged as a suitable non-destructive method for preventive conservation in CHS. Dong and Cabas [144] presented a comprehensive review of CV-based monitoring approaches with applications at both global (e.g., modal identification, displacement measurement, vibration serviceability) and local (e.g., crack, spalling, delamination) structural levels. They also highlighted some limitations of CV algorithms that can affect the accuracy of the results, including the adverse effect of the hardware used (e.g., electric noise, camera self-heating, lens distortion), as well as the environmental conditions (e.g., illumination change, ground vibration, rain, etc.). Therefore, in applying CV approaches in CHS, the aim should not be to completely replace the conventional SHMs, but to complement them.

Among the most common digital technologies (based on CV methods) that are used for documenting, monitoring, and inspecting historical constructions are photogrammetry and laser scanning [145,146]. A comparison between the two techniques in terms of their main features, advantages, and limitations is summarized in Table A2. As a general rule, laser scanning is more appropriate if a high level of accuracy over ample space is needed. At the same time, photogrammetry is an optimal solution for smaller spaces and for obtaining a more visual photo realism. Due to each method's intrinsic pros and cons, they are usually integrated to ensure complete and accurate documentation [147].

Another technology based on many standard CV techniques is infrared thermography, or thermal imaging, the science of analysing images captured from thermal infrared cameras. The use of infrared thermography can help identify potential structural issues before they become major problems. In addition, this technique can be used to assess the effectiveness of any restoration work that has been performed on the building. However, it is important to note that this technique should be used in conjunction with other methods of structural analysis, as it has limitations, and it may not detect all types of damage.

Some researchers have also explored the use of 2D image-based methods for the monitoring of cracks. Oliveros-Esco et al. [148] investigated the use of this technique for the digital indoor monitoring of cracks in heritage listed buildings of lower social projection, for whose financial resources dedicated to preventive conservation are scarce. This technique proved to be a valid alternative to a higher-cost SHM image-based approach (such as 3D photogrammetry), guaranteeing effectiveness, non-invasiveness, and affordability. The use of thermography and a moisture meter, together with the 2D image-based method, was recommended by the authors to check for the impact of moisture on cracks and to predict any potential future damage to the building's stability.

3.2.1. Photogrammetry

Photogrammetry is a powerful technique for determining metrical and qualitative information (e.g., colour and texture) regarding 3D objects and landscapes, starting with 2D photographs [149,150]. Photogrammetric reconstruction techniques are based on different CV algorithms, such as structure from motion (SfM) and multi-view stereo (MVS) techniques, and they generally include the following steps: selecting common key points in two or more photos; calculating camera positions, orientations, and distortions; and reconstructing 3D information by intersecting key point locations to determine where objects exist in 3D space [146]. Today, these steps can be achieved semi-automatically with the aim of software that generates 3D reconstructions of image-captured objects in the form of sparse 3D point clouds.

Different photogrammetric approaches are available today, from terrestrial photogrammetry, which uses images from ground-based cameras (e.g., Figure 11a) to aerial photogrammetry, based on images acquired with airborne devices, such as aircrafts and satellites, and, more recently, unmanned aerial vehicles (UAVs) (e.g., Figure 11b) [151]. Several studies demonstrated the potential of combining data provided by UAV and terrestrial photogrammetry [152], as well as various terrestrial SHM methods [153,154]. Indeed, UAV photogrammetry easily reaches almost every part of the analysed structure, speeding up and optimizing subsequent work. On the other hand, the terrestrial survey allows for the use of high-performing optics and cameras, which curently cannot be easily installed on commercial drones because of their high weight [152].

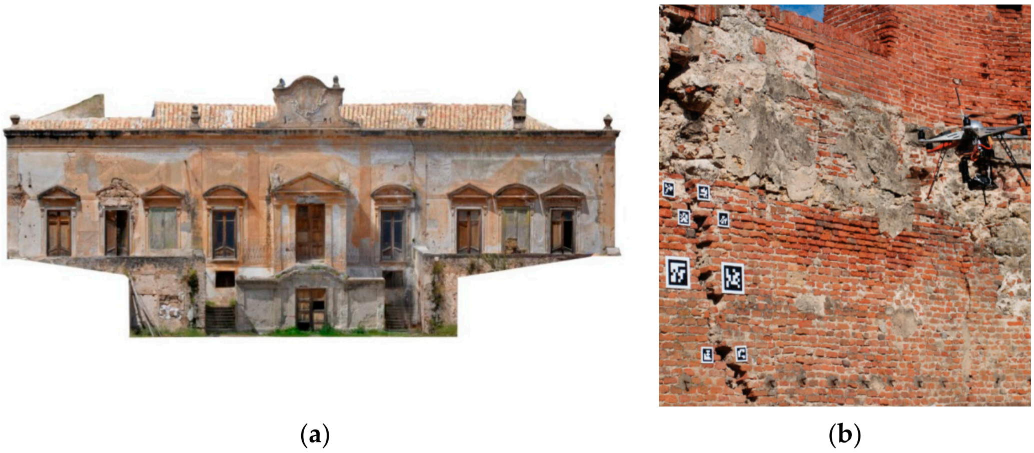

(**a**) (**b**)

Figure 11. Orthophoto from close-range photogrammetry acquisition (**a**), from [155]; UAV image acquisition for marker-based structural defects monitoring (**b**), from [156].

Photogrammetry applications to CHS are increasingly being used to gather 2D and 3D geometric information and for SHM purposes, such as detecting and monitoring alterations and damages on structures and eventually recording them on 3D models [157,158]. In recent years, numerous research articles have been published on this topic.

Mongelli et al. [159] investigated the health condition of a historical bridge in Spoleto (Italy) through photogrammetric scanning performed by a drone. The high-resolution images acquired by the drone were post-processed using the SfM technique to reconstruct the two different 3D models of the bridge, with different point clouds density. The low-density mesh model was used to define a 3D FE model for investigating the dynamic properties through modal analysis. The high-density mesh model was employed to map the crack and damage pattern, which is useful for periodically checking and verifying damage evolution. The authors emphasized the aerial photogrammetry potentiality, mainly when large structures must be analysed cheaply and quickly. However, this technique cannot replace the strength and accuracy of other more expensive techniques, such as the use of laser scanners.

Galantucci and Fatiguso [160] developed a procedure to detect damage on 3D models reconstructed from photogrammetric scanning. The procedure is based on specific algorithms for detecting cracks or alterations using false-colour maps and morphological filters. This technique was tested and validated in a case study of a historical building monitored for 18 months. According to the authors, this technique could be considered proper support for the damage assessment compared to traditional survey techniques.

Russo et al. [161] compared the results obtained from an ultra-lightweight drone (less than 300 g) equipped with a low-cost camera with 3D laser scanning to acquire geometrical data, as well as material and damage information from a huge historical building façade in Bologna (Italy), characterized by a very narrow operating space. The authors concluded that the UAV’s photogrammetry survey, even though of inferior quality, can lead to almost complete acquisition of buildings placed in difficult urban environments, where both ground photogrammetry and laser scanning would provide unsatisfactory results.

Bacco et al. [156] described the application of a remote monitoring system, based on an Internet of things architecture (see Section 4.2) and a virtual reality paradigm, to three historical structures. The system consisted of a network of fixed sensors and a UAV. The latter was used to fulfil two main tasks. First, the UAV was used to obtain a 3D reconstruction of the CHS with the exact position of the sensor nodes, thus allowing an operator to interact dynamically with the real-time readings collected by the IoT network. On the other hand, the UAV was also used as a mobile sensor in the network to monitor crack patterns and anomalies. The authors highlighted several valuable advantages of using a UAV for monitoring CHS, such as versatility, robustness, time-effectiveness, safety for operators, and low cost. However, the authors also identified some limitations regarding the image-based method for crack monitoring, such as the risk of blur effects due to the unstable hovering of the UAV during image acquisition and the inappropriate configuration of the markers installed along a crack for the camera calibration, which may greatly affect the accuracy of the analysis.

The combined application of 3D photogrammetry with FBG sensors was investigated by Bellagamba et al. [162] to evaluate the long-term crack propagation and damage evolution in a tower of the Aurelian Walls in Rome. The 3D photogrammetric reconstruction using SfM was adopted to build a 3D geometrical model, which was the source for creating an FE model to perform modal analysis and identify the dynamic properties of the structure. The FBG could be correctly positioned thanks to the modal analysis results and the map of the cracks reconstructed from the photogrammetric survey. The sensors allowed for monitoring the main cracks, eventually calibrating the FE model and correlating with long-term scheduled 3D photogrammetric surveys.

Dlesk et al. [163] compared the re-processing of analogue archival photogrammetric images of Estonian Padise Abbey captured by a metric camera in 1991 and the results of the new photogrammetric survey using a digital camera in 2017. Both images were processed using the SfM method. In this way, it was possible to evaluate the state of conservation of the abbey walls after 26 years. It was found that the overlay of the two generated orthophotos was the most accessible and understandable way for users to compare the different states of the building.

The amount of information acquired through the use of photogrammetry can also be adopted for creating mixed reality experiences [164] or heritage building information modelling (HBIM) [164–166] (see Section 4.4), which can contain information about monitoring and structural assessment.

3.2.2. Laser Scanning

Laser scanning (LS), also referred to as LiDAR (light detection and ranging) or LaDAR (laser detection and ranging), can record millions of measured points in a short period by emitting laser pulses towards these points and measuring the distance between the target and the measuring device. The result is a 3D point cloud, which can be successfully used to reconstruct the 3D geometry of the analysed structures. The terrestrial laser scanning (TLS) monitoring technique has already been applied to control movements in large civil structures (bridges, dams, tunnels) and specific landscape situations. An extensive review of the TLS application for the deformation monitoring of structures is provided by Mukupa et al. [167]. Building applications, especially regarding historical uses, for monitoring purposes are still rather limited and need further investigation [168]. However, using LS is particularly attractive when dealing with historical structures due to their intrinsic complexity, which is sometimes hard to record in every detail. The integration of an LS survey with other surveying techniques usually represents the best solution for assuring high quality and complete results, especially in the case of large and complex historical buildings where particular attention to preservation and restoration aspects is also required [166,168–170].

Fregonese et al. [169] tested the efficiency of TLS in monitoring the horizontal displacements of the historical Palazzo del Capitano façade in Mantua, Italy. The monitoring was realized by performing seven measurement campaigns from October 2011 to October 2012. By comparing these results with total station measurements, significant divergences appeared. These are mainly ascribable to errors committed by the operator and to the stability of the TLS reference system. This outcome attested to the importance of operational rigour in the methodology to achieve reliable results in detecting or monitoring structural movements.

Furini et al. [171] used several monitoring systems (digital levelling, 3D total stations, TLS, and digital photogrammetry) to control the structural stability of the ancient walls of Ferrara, seriously compromised by the earthquakes of May 2012. The laser scanning survey was repeated yearly from December 2011 to December 2013 to check for possible variations in the wall configurations. The comparison of the vertical sections deriving from the 3D point clouds shows an ongoing tip rotation, with a variation of around 0.1 degrees per year.

Masciotta et al. [172] discussed the combined use of LS and panoramic photography to create geo-referenced enriched digital models and support the design of a proper preventive conservation plan. The authors showcased two case studies demonstrating the successful integration of surveying and virtualization techniques. These studies resulted in value-added reference information that can be utilized for condition mapping and for assisting building owners and facility managers in taking proactive preventive actions.

3.2.3. Infrared Thermography

Infrared thermography (IRT) is another well-established imaging approach, which has been applied for over 40 years for historical building diagnostics [173] and has grown considerably in recent years, with increasingly advanced applications and with development in terms of image post-processing. An IR scanner or camera can detect thermal radiation emitted by surfaces (e.g., walls, floors), which is then converted into a visible image representing their temperature contour map. Thanks to surface temperature differences, the technique may help detect hidden physical characteristics typical of historical structures, such as discontinuities, cavities, inclusions, or embedded elements [174], as well as moisture, capillary rise, and heat leaks [175].

Paoletti et al. [176] presented the results of applying IR thermography to investigate the structural damage of the Church of Santa Maria ad Cryptas (XIII century) hit by the L'Aquila earthquake in 2009. In particular, the results were compared with those obtained from a pre-earthquake thermographic campaign conducted in 2007. It was found that some damages caused by the earthquake corresponded to thermal anomalies previously detected in the IRT of 2007, confirming the effectiveness of thermography as a preventive diagnosis and monitoring tool.

IRT techniques can be combined with other non-destructive techniques to achieve more comprehensive and complete data to assess the conservation state of the analysed structures [155,177]. Costanzo et al. [177] combined TLS and IRT to investigate the conservation of an ancient monumental compound in southern Italy. Different measurement surveys were conducted over one year. The main findings were that the combination of data provided by both TLS and IR thermography allowed for the identification of anomalies in the masonry structures (cracks, detachments, moisture zones) and the presence of different construction materials (corresponding to different phases of rebuilding and restoration). The authors concluded that applying these combined methods could be used to monitor the progression of decay in ancient buildings over time due to permanent loads and accidental events, such as earthquakes.

More recently, Biscarini et al. [155] investigated the state of conservation of a historical Roman masonry bridge in Italy using UAV 3D photogrammetry, IRT, and ground penetration radar. The results demonstrated how the synergetic use of these contactless non-destructive diagnostic tools can provide precious information about the state of structural health and guide the design of restoration interventions in the context of preventive conservation of architectural heritage. In particular, IRT results corroborated the hypothesis that the actual degradation condition of the bridge was mainly caused by water retention within its materials.

4. Data Management

4.1. General Aspects

Novel SHM systems typically require many sensors to record, collect, and process vast amounts of data, opening up the era of big data in the field. Consequently, an efficient

SHM system must also cope with these three main challenges: (1) how to transmit and store data, (2) how to process data to extract meaningful information, and (3) how to make processed data easily serviceable by end-users. To this aim, the recent developments in digital technologies, including the Internet of things (IoT), the development and adoption of new algorithms for data processing (e.g., machine learning techniques), and building information modelling (BIM) are facilitating the management of monitoring datasets [177]. All these relatively new advances contribute to condition-based maintenance, identifying in real-time prognosis and diagnosis, avoiding maintenance based on collapse or guaranteeing non-negligible economic benefits.

The use of all these technologies has undoubtedly benefited from the development of numerous wireless sensor network (WSN) technologies that permit a real-time, pervasive, non-intrusive, low-cost, and highly flexible data collection and analysis [73,178], particularly suitable for historic structure SHM [62,179–185]. Indeed, the artistic/architectonical value of heritage constructions typically requires employing sensors that minimise the use of cables.

An efficient management system should also be easily accessible by people to support and guarantee society's engagement (not just people working specifically in the sector, i.e., engineers or architects) in the conservation processes. Concerning cultural heritage management, although an increasing number of countries are encouraging open cultural heritage data and promoting its safety and reuse, systematic digital tools for the preventive conservation and management of cultural heritage are still lacking [144]. Within this scope, it is worth mentioning the recently concluded EU project "HeritageCare—Monitoring and Preventive Conservation of Historic and Cultural Heritage" [145,186,187], which developed a series of standardised protocols, based on the IoT and Web-GIS system, for the diagnosis and management documentation of built cultural heritage. One of these tools, a web platform combining the latest advances in geodatabase models, interoperability protocols and digitization strategies, named PlusCare [186], was exploited to integrate all data acquired during the digitization of two ancient churches [172]. The system creates enriched digital models to provide owners and curators with an intuitive data-driven tool for planning preventive measures and future interventions based on the actual conservation needs of the building, according to best proactive practices.

The following sections provide a state-of-the-art description of the latest advances in the IoT-SHM systems, novel algorithms for data processing, and BIM in heritage structures.

4.2. IoT-SHM Systems

The combination of SHM systems with smart sensors architecture, cloud computing, and the IoT has enabled rapid, accurate, and low-cost services, as well as powerful transmission, storage, and processing of data beyond the capability of the existing SHM systems [188,189]. In addition to smart sensors, the IoT-SHM systems comprise the gateway, the remote control, and the service room (RCSR), as well as an open platform communications (OPC) server (Figure 12). The gateway of the system is a network node that can manage and optimize data acquired by sensors to check node connectivity and perform system integrity tests. The RCSR hosts a database to store all collected data to be used for big data analysis and connectors to an OPC server. Moreover, from the RCRS, it is possible to perform queries of specific sensor nodes, to acquire the status or other useful management parameters. Furthermore, IoT systems can potentially be used to monitor many monuments concurrently and transmit the acquired information to a remote server, aiming to facilitate maintenance operations and prompt interventions in an emergency [190]. The challenges in adopting IoT-based technologies for SHM, including data privacy issues, the limited battery life of sensors, and the lack of standardization, have recently been analysed by Mishra et al. [191].

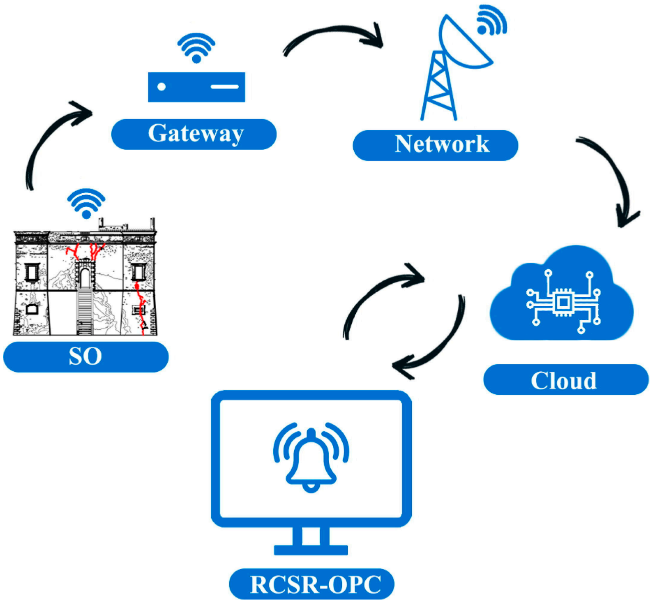


Figure 12. SHM-IoT system schematic (from [188]).

Scuro et al. [188] recently presented an overview of the basic concepts of IoT-SHM systems for masonry structures and two interesting applications on historical masonry structures. The first case was a panel reproducing a typical masonry typology used in Calabria (southern Italy), subjected to diagonal compression in the lab environment. The second was an existing masonry castle in Calabria (prone to high seismic hazards), subjected to dynamic identification. In both examples, the data recorded by the monitoring systems (composed of LVDTs and strain gauges in the first case and piezoelectric accelerometers in the second) were utilized to properly calibrate the FE model in a way that could be representative of the actual behaviour of the structure. These operations can be carried out in quasi real-time, by constantly interfacing with the information provided by the implemented IoT-SHM system that exchanges information continuously and remotely with the numerical model via the Internet.

Bacco et al. [156] implemented a remote monitoring system which integrates a network of fixed sensors and a UAV, testing the system on three ancient structures. The data acquired from the sensor nodes are delivered to a remote server through an IoT protocol for reliable data exchanges, namely MQTT. The images collected through the UAV were used to build a 3D reconstruction of the structures, allowing an operator to interact dynamically with the real-time readings collected by the IoT network.

De Angelis et al. [192] developed a low-cost distributed sensing system for measuring relevant vibrations caused by human activities and earthquakes, which was specifically designed for application to a cultural heritage underground site. The system was based on IoT communication techniques, low-power microcontrollers, event-driven strategy, and self-contained battery-powered electronics, aiming to reduce the costs, impact, and risks associated with the need for periodic maintenance and supervision. First, its operation was assessed uncer laboratory conditions by comparing it with a commercial accelerometer. Later, it was tested in the field. The results showed that the proposed system could successfully monitor acceleration at several locations within the site, detecting the most relevant stresses and allowing for the identification of risks.

4.3. Data Analysis Algorithms for Modern SHM Architecture

The use of innovative sensor networks and the consequent production of a large amount of data has opened up the era of big data in the field of SHM. When dealing with large quantities of sensor data and a structure whose physical characteristics are complex or even unknown (which is very common in heritage structures), data-driven models can be more effective in interpreting and analysing monitoring data than physics-based models [192]. Indeed, the data-driven approaches involve constructing a surrogate model from collected data that substitutes for the high-fidelity model to detect damage efficiently. Conversely, the physical-based model relies on applying analytical methods relating directly to physical parameters and implies a previous deep understanding of the structure, which must be fulfilled in historical constructions.

In this context, the progress towards novel data-driven machine learning (ML) techniques has been gaining increasing attention. A systematic review of various ML techniques applied for SHM of heritage buildings has recently been presented by Mishra [191]. When dealing with optimisation problems, nature-inspired algorithms (e.g., genetic algorithm, auto-associative neural networks, etc.) turn out to be highly efficient for the SHM of historical structures [193,194].

Carmineo et al. [195] presented a monitoring technique based on the artificial neural network (ANN) to predict early risk warnings for historical buildings, with an application for a case study. The approach was based on analysing images of the same subject captured after proper periods. A signal alarm is sent when the ANN-based module recognizes anomalies between different images. The authors concluded that the proposed approach provided a valid system for detection and prediction.

Standoli et al. [196] adopted a genetic algorithm to update a historic Civic Tower numerical model based on vibration-based identification results. The process consisted of updating the FE model's system matrices (mass, stiffness, and possibly damping matrices) until the difference between experimental and numerical modal results was minimized. Using a genetic algorithm allowed for overcoming the limitations associated with manual or approximate updating processes. This method demonstrated the efficiency of metaheuristics compared to time-consuming manual approaches and other automatic approaches unable to solve complex multidimensional optimisation problems.

Once sensors are installed and values of the parameters are recorded, these algorithms allow for the implementation of an automatic process to overcome errors due to human decisions and to generate alerts. Typically, two naturally-inspired algorithms are used in the design of SHM for historic masonry structures: optimal sensor placement (OSP) and damage identification (DI) [197]. These algorithms are typically used to reduce the costs of maintenance of cultural heritage buildings because they can generate punctual and specific alerts, allowing for timely interventions only when and where necessary. Some future developments were also suggested, such as the introduction of an automatic detection technique.

While the use of integrated monitoring systems comprising diverse sensing solutions is becoming a priority for effective local/global damage detection, novel solutions able to process a large amount of data from heterogeneous sensor networks need to be developed. García-Macías and Ubertini [198] developed two innovative software solutions, MOVA and MOSS, for integrated the long-term SHM of structures. These software programs enable the online system identification and damage detection of structures, including vibration-based SHM and data fusion of heterogeneous sensing systems with an innovative algorithm for automated anomaly detection.

4.4. Building Information Modelling in Heritage Structures

Intelligent models created by building information modelling (BIM) or historical/heritage BIM (HBIM [199,200]) technologies are rapidly evolving, aiming to make the SHM information accessible, practical, and understandable in order for end users to facilitate management or monitoring procedures [201]. BIM and HBIM can represent a fundamental tool to collect all the as-built information of buildings, including all the structural/architectural changes and deteriorations experienced over time, in order to monitor the evolution of the conservation state, to design interventions, and to appropriately schedule the maintenance process [166,202,203]. Moreover, an evolution of the HBIM has occurred by adding the concept of th emanagement of data, leading to the heritage/historic building information modelling and management (HBIMM) [204], or built heritage information modelling/management (BHIMM), approach [205]. A critical review of HBIM for the diagnosis, monitoring, and management of existing buildings is given in [204]. Several researchers discussed the integration of SHM information in HBIM, which also allows for real-time updates of the model [206–208].

Banfi et al. [206] investigated an integrated approach based on a 3D survey, advanced modelling techniques, BIMs, the WebShare Cloud, and related technologies for the SHM of complex structures. The methodology was applied to a medieval bridge (Azzone Visconti Bridge in Lecco, Italy), allowing for the creation of an interoperable BIM for different specialists (engineers, architects, etc.). The authors demonstrated that it is possible to collect and manage data, favouring the future dissemination of values of CHS.

Tsilimantou et al. [207] presented a multidisciplinary documentation process including the acquisition, classification, and management of various multisensory data with the development of GIS thematic maps and an HBIM (Figure 13). The methodology was applied to a historical building in Athens. It was demonstrated that incorporating multidisciplinary data of a cultural heritage asset within GIS and HBIM systems supports the diagnosis of actual causes of degradation, thus leading to the optimum restoration work and assuring its health monitoring over time.

Calì et al. [208] applied a methodology based on HBIM, FEM, and operational modal testing for the structural health assessment of a heritage palace in Italy. They concluded that the combined use of information collected by historic/architectural research, the HBIM model, and the dynamic tests allowed for solving the main uncertainties in establishing the numerical model, as well as the assessment of the structural condition of the building in a fully non-destructive way.

Monchetti et al. [209] presented the initial stages of their research project, "CHARMING PISTOIA," which aims to implement an HBIM system to preserve and maintain heritage structures. The project focuses on a case study of the pulpit of Giovanni Pisano in the Church of Sant'Andrea in Pistoia. The proposed three-step process includes designing an HBIM to gather and export structural information, integrating an SHM system for constant updates on structural parameters, and establishing reliable computational models to assess the structure and works of art vulnerability.

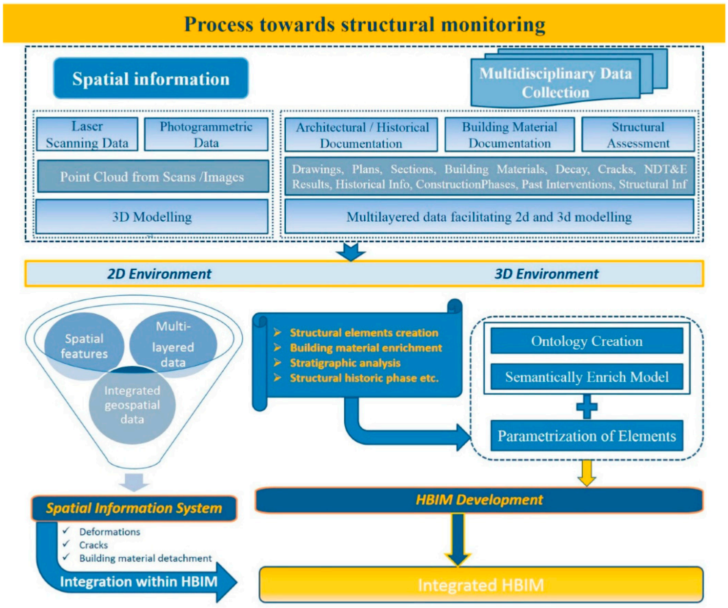


Figure 13. Workflow towards HBIM creation and integration proposed by [207]).

5. Conclusions

This paper provides a comprehensive review of both conventional and innovative techniques for monitoring cultural heritage structures, as well as strategies for data management. Special emphasis is placed on innovative techniques, displaying the potential of smart-sensing technologies, including fibre optic sensors, self-sensing materials, and image- and computer vision-based approaches, such as photogrammetry and infrared thermography. Furthermore, this paper highlights the significance of data management in modern structural health monitoring (SHM) architecture. It discusses the implementation of IoT-SHM systems, the utilization of machine learning algorithms, and the integration of building information modelling (BIM) to effectively manage and analyse the collected data. These advanced data management strategies contribute to the overall effectiveness and efficiency of SHM practices in the context of cultural heritage structures.

From the paper′s comprehensive state-of-the-art review, it is evident that SHM has progressed, with advancements in smart-sensing and digitalization technologies; however, its adoption in cultural heritage structures remains fragmented. In fact, despite these new technologies possessing several advantages for the SHM of heritage structures (e.g., small invasiveness) and their management (e.g., automatic warnings), practitioners still ancounter many difficulties in bringing them into practice. Challenges include sensor overload, unreliable networking, data compression and transmission, energy consumption, storage costs, environmental effects, and difficulties dealing with sensor and methodological heterogeneity due to diversity regarding materials and complexity in CHS.

Finally, although the literature includes standards and guidelines regarding the use of SHM in civil structures, very few recommendations oriented to CHS are available; thus, more efforts in this direction are required. However, it must also be considered that since each heritage structure embodies characteristics of uniqueness and originality, it is not always possible, or even recommended, to adopt standardised approaches. However, general indications can be provided based on exemplars and successful case studies.

Undoubtedly, the proper adoption of innovative techniques can aim to go beyond the difficulties in obtaining and managing information regarding the structural response of historical constructions. New perspectives in regards to the structural health monitoring and management of cultural heritage structures have emerged, including the utilization of advanced multi-sensor data fusions and data analysis techniques for monitoring their condition. These techniques provide real-time data on the structural integrity of the building, facilitating timely maintenance and repair. Future work should be directed towards low-cost and efficient solutions for integrating innovative SHM systems into retrofitting interventions tailored for cultural heritage structures. There is also a growing focus on employing sustainable materials and technologies in managing these structures, combining traditional conservation methods with modern technologies to ensure the preservation of these historic structures for future generations.

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Appendix A

Table A1. Typical SHM systems installed in cultural heritage structures.

Heritage Building	Monitoring Initiated	Monitoring		No. of Instruments	Strengthening	Description
		Static	Dynamic			
Churches						
Santa Maria del Fiore Dome [27]	1955	x		Opera del Duomo: 22 ISMES: 150		Statistical analysis of data collected over 60 years.
Mexico City Cathedral [34,210]	1994	x	x	38 (s) 10 (d)	x	Monitoring the response during and after interventions to reduce differential settlements and monitoring the seismic response.
Saint Torcato Church [23,51]	[51] 1998 (s) 2009 (d)	x	x	~26 (s) 2 (d)		Monitoring results before strengthening to control any progress of damage caused by soil settlement.
	[23] 2009 (s) 2014 (d)	x	x	9 (s) 1 (d)	x	Static/dynamic monitoring to control damage evolution, to appraise the effectiveness of consolidation, and to analyse the environmental variability.
Basilica of Santa Maria degli Angeli in Assisi [35]	2001	x	x	9 (s) 2 (d)		Preliminary analysis of static monitoring results during rehabilitation work, as well as dynamic characterization.
Cathedral of Modena [56]	2003	x		22		Identification of reference quantities from the SHM data to detect anomalies from the usual structural behaviour.
Basilica of Vicoforte [29,47,76,77]	2004(s) 2015(d)	x	x	133 (s) 12 (d)	x	Results from extensive monitoring and strengthening interventions of the world's largest masonry oval dome.
Monastery of the Jerónimos Church [33]	2005	x	x	11 (s) 2 (d)		Use of static/dynamic SHM results combined with FEM analysis for a complete evaluation of the monument preservation state.
Anime Sante Church [36,211]	2009	x	x	8 (s) 28 (d)		Comparison and correlation of static and dynamic monitoring results; control of the effect of temporary safety measures and temperature on the structural response.
Santa Maria di Collemaggio [38,183]	[183] 2013(s) 2011(d)	x	x	11 (s) 16 (d)	x (provisional reinforcements)	Design, positioning, management, and long-term performance of a wireless sensor network.
	[38] 2018	x	x	9 (s) 78 (d) 5 (e)	x	Results of 2-year static/dynamic monitoring and correlation with temperature fluctuations.
Church of the Major Seminary of Comillas [55]	2012	x		67	x	Integrated SHM system consisting of various type of sensors to monitor before, during, and after the intervention process.
Church of the Sant Cugat Monastery [28]	2017	x		16 (s) 6 (e)		Analysis of the static SHM results with the aim of understanding
Cathedral of Milan [37]	2018	x	x	27 (s) 36 (d) 28 (e)		SHM for assisting condition-based structural maintenance of the historic church.

Table A1. *Cont.*

Heritage Building	Monitoring Initiated	Monitoring		No. of Instruments	Strengthening	Description
		Static	Dynamic			
Palaces						
Ducale Palace in Venice [42]	2009	x	x	12 (s) 3 (d)		Integrated monitoring activities to assess the preservation state of the external façade.
Diocletian's Palace in Split [212]	2013	x		17 (s) 1 (e)		Long-term SHM of displacement, strain, and temperature to check anomalies.
Consoli Palace of Gubbio [43]	2017	x	x	10 (s) 12 (d)		Comparison between the outputs of a conventional LVDT system and an innovative remote sensing technique using radar interferometry analysis.
Towers						
Portogruaro Civic Tower [50]	2003	x		1 (s) 4 (e)		Investigation of the tower's inclination trend through the joint use of monitoring and historical documentation.
San Vittore Bell-tower [213,214]	2008 (s) 2009 (d)	x	x	15 (s) 3 (d) 8 (e)		Investigation of the long-term structural behaviour through first a static and then a dynamic monitoring.
Garisenda and Asinelli Towers in Bologna [39]	2011 (s) 2012 (d)	x	x	Garisenda: 25 (s) 4 (d) Asinelli: 33 (s) 4 (d)	x	Analysis of SHM data to distinguish between evolutionary trends and daily/seasonal fluctuations using the well-known FFT algorithm.
Gabbia Tower in Mantova [215]	2012		x	3 (d) 1 (e)		Installation of a continuous dynamic monitoring and analysis to distinguish between damage and environmental effects on the frequencies.
San Pietro Bell-tower in Perugia [69]	2014		x	3 (d) 10 (e)	x	Investigation of the correlation between environmental parameters and natural frequencies and the identification of an optimal location and number of sensors.
Belltower in Monza [40,41]	2014 (s) 2015 (d)	x	x	10 (s) 4 (d) 5 (e)		SHM installed to assess the condition after the detection of a weak structural arrangement.
San Frediano Belltower in Lucca [32]	2015		x	4 (d)		Assessment of the dependence of the tower's frequencies on the ambient temperature variations through long-term vibration monitoring.
Sciri Tower in Perugia [64]	2017		x	3 (d) 2 (e)		Long-term vibration monitoring to assess the evolution of the modal parameters and the calibration of the linear FE model.
Belltower of Palermo Cathedral [216]	-		x	20 (d)		Identification of the main modal parameters using data collected by accelerometers and seismometers and calibration of a FE model.

Table A1. *Cont.*

Heritage Building	Monitoring Initiated	Monitoring		No. of Instruments	Strengthening	Description
		Static	Dynamic			
Other structures						
Roman Arena of Verona [44]	2011	x	x	20 (s) 18 (d) 4 (e)		Analysis of the first 1.5 years of data provided by both static (displacements) and dynamic (fundamental modal parameters) monitoring.
Main Spire of Milan Cathedral [217]	2012	x	x	7 (s) 6 (d) 1 (e)	x	Monitoring carried out during the 4 years of restoration work to assess the structural integrity during the activities.
Colosseum in Rome [74]	2014		x	4 (d)		Analysis of data collected during 2 years of monitoring using a wireless accelerometer network to assess the response induced by traffic (road and subway).

Legend: (s) static; (d) dynamic; (e) environmental sensors.

Table A2. Comparison between 3D laser scanning and photogrammetry techniques.

Characteristics	**3D Laser Scanning**	**Photogrammetry**
Accuracy	Millimetre	Centimetre
Resolution	Millions of points	Hundreds of points
Data volume	Dense point cloud	Image resolution
Scale	Present	Absent
Texture	Absent/Low resolution	Included
Edges	Quite problematic	Excellent
3D data generation	Automatic capture	Post-processing
3D modelling	Automatic meshing and shape extraction	Manual modelling
Commercial software	Yes	Yes
Equipment cost	High	Low
Data collection	Day and night	Daytime only
Required skill	Medium-high	Low
Comparison		
Pros	– High Accuracy over large spaces – Error rate is fixed based on the capabilities of the equipment – Automated process after targets are placed and scanner is started – Less chance for user error – Less time spent on site – Availability of auto-extraction/meshing software for point clouds	– Cheaper equipment – Most improvements are on the software side, so no need to buy new equipment to keep up with progress – Better visual representation of textures
Cons	– Equipment can be prohibitively expensive – Generally need to upgrade physical equipment to keep up with progress – Fuzzy point cloud on highly textured/reflective surfaces	– Accuracy is lower than that of laser scanners over large spaces – Scale limitations based on camera lenses maintaining clarity over long distances – Less automated process allows for more user error—results depend significantly on the experience of the operator – More time spent on site – Auto extraction/meshing software not advanced – Errors when dealing with reflective/transparent surfaces

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