Structural Health Monitoring Systems for Smart Heritage and Infrastructures in Spain

F. Javier Baeza, Salvador Ivorra, David Bru and F. Borja Varona

Abstract The development of information and communication technologies (ICT) and robotics is currently demonstrating its potential impact on different fields of application. With regard to cultural heritage, and architectural and engineering heritage in particular, these new technologies are changing the possibilities for structural capacity assessment and health monitoring (SHM). The objective of smart heritage can be achieved thanks to properly designed SHM systems, which when connected to an automated diagnostic system can even self-evaluate retrofitting needs. This chapter includes a brief summary of the SHM technologies applied for cultural heritage management in Spain during the early 2000s.

Introduction

The concept of smart cities (SC) has been proposed as a new urban development strategy in which, through the use of information and communication technologies (ICT), the city itself can adapt to actively improve the quality of life of its citizens and visitors. Spanish standard UNE 178104:2015 [2] defines the main objectives for an SC as an improvement in sustainability, efficiency and the quality of life of its inhabitants, which will be achieved through the use of technology. Actuation guidelines focus on improved management of administration and services, decision-making based on real-time data, and enhanced city resilience (defined as the capacity to meet and overcome unexpected challenges). The early detection of needs was also noted as a key aspect of an SC in a recent study conducted by Deloitte for the Spanish government [15]. The concept of smart heritage thus appears as a definition of an architectural heritage connected to a structural health monitoring (SHM) system (measurement + data management + damage evaluation tool), which is capable of detecting its own service condition, even responding automatically if an alarm threshold is triggered.

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All three aforementioned actuation lines can be directly linked to architectural heritage. The management of historic buildings usually lacks the information needed to optimize the funds available for maintenance tasks. Moreover, structural retrofitting is sometimes proposed only after catastrophic events, such as earthquakes [11]. In this regard, various preventive management methodologies have recently appeared, based on expert systems [45] or fuzzy logic [31], which aid in determining where and when an intervention should be made. These decision-making algorithms could even be applied in the construction stage of infrastructures [29]. In addition, open data from ongoing monitoring systems could be used to improve vulnerability studies—for example, risk management and building performance using geographic information system (GIS) tools applied to Barcelona [6]. Therefore, ideally, smart heritage would help public administrators by offering real-time data and analysis tools to improve service life management and crisis intervention, in which economic investments (maintenance and structural retrofitting) would be optimized through early damage detection and preventive conservation.

The future success of these proposals will depend on the fundamental role played by technological development, both ICT and automated devices (like robots or drones). Civil engineering and building monitoring have traditionally required complicated and expensive wired systems, which in most cases interfered with the normal use of the facility. Wireless communication is simplifying the experimental setup necessary for SHM purposes. However, some issues must be confronted for successful implementation, such as power supply (batteries vs. power harvesters), signal interference or data loss [44].

The SHM system installed in the Humber Bridge is a good example of an automated SHM system that is not only capable of measuring certain variables, but can also automatically diagnose, and consequently take the necessary actions to correct, undesired situations. The objective of this system was the prevention of steel corrosion on the anchorage chambers of the suspension bridge [57]. For this purpose, temperature and relative humidity sensors were distributed along the chambers, and dehumidification units were connected directly to the SHM system. If hygrothermal conditions reached a threshold that could trigger the onset of corrosion, dehumidifiers would be activated to prevent corrosion on the unprotected steel wires.

Traditional monitoring techniques, on the other hand, are also being improved through the implementation of robotics. For example, unmanned aerial vehicles (UAV) have become popular for visual infrastructure inspections [36]. UAV monitoring reduces work safety issues and inspection uncertainties due to human error, and can easily reach almost every part of any structure. Early applications of UAV in engineering include visual inspection and damage detection via digital image correlation (DIC) and thermography, and dynamic characterization with equipped radar devices.

In summary, automation and ICT could have a huge impact in the field of civil engineering and architectural heritage management in the coming years. In this chapter, an overall vision of structural health monitoring in Spain is presented, considering all monitoring stages, including analysis, design, implementation and management.

SHM Systems, Damage Assessment and Structural Analysis

Heritage monitoring comprises a wide variety of fields—works of art, built heritage and written documents. Over the past decade, for example, the Santa María la Real Foundation has developed their Monitoring Heritage System (MHS) as a tool for integrated management of all types of heritage [28]. Initially conceived as simply a monitoring tool for more sustainable management, implementation has recently begun on an expert system for preventive conservation based on pattern recognition [12]. In this chapter, however, only issues related to structural monitoring of built heritage will be considered.

A successful monitoring system usually comprises three or four stages:

- *Preliminary investigation and planning*, in which the objectives of SHM should be defined. A pathology report would help to determine the best techniques for properly evaluating the structure. At this point, a visual inspection is required. In efforts to avoid human errors, automated vision-based techniques are being implemented today to detect surface deterioration [33, 36], cracking patterns [30], geometric characterization of masonry elements [37], or lateral drift or deflections that can jeopardize the stability of the structure [46].

  Another key aspect of SHM planning is the time frame desired for monitoring: permanent monitoring requirements differ from single-day (or a few days) measurement setups. The former aims to characterize long-term behavior of the building (e.g. thermal strains between day and night or between seasons, ongoing settlement due to non-stabilized ground movements, control during construction or retrofitting work). Measurement duration should be at least long enough to register a complete cycle of variable actions— temperature, for example [48]. Hence, the irreversible or cumulative component can be separated from cyclical counterparts. Temporary, or short-term, monitoring is usually undertaken to evaluate the structural performance or state under certain circumstances. Examples include loading tests on bridges just after construction to assess normalized requirements, or dynamic testing to determine the mechanical parameters of a structure (which can later correlate to material degradation).
- *Installation and actuation*. Once the objectives have been defined and the parameters of study identified, the proper sensor and experimental setup should be designed and installed. In this regard, wireless communication allows the locating of sensors without an action that interferes with the normal use of the building. The possibility of installation during construction as a work control system, and retaining the SHM system afterwards for performance monitoring, is an additional advantage of wireless systems [27]. An initial system evaluation

should be conducted to ensure that all sensors work correctly in the specific scenario.

- *Research and parameter control*. Protocols for data recording, transmission and storage should be defined. In short-term systems, data would be analyzed afterwards in a final report, with all the structural models necessary for a future intervention design. In long-term monitoring, threshold values for each parameter are useful as a control in the event that an emergency intervention is necessary. In this case, automated analysis tools would be helpful for optimizing the system. Permanent monitoring objectives should also define the data acquisition frequency, which necessitates a compromise between data volume and analysis requirements.
- *Maintenance and decommissioning*. Long-term monitoring systems will require periodic testing to assess SHM robustness. Wireless devices may also need additional care, depending on the power source selected (e.g. battery replacement). In this regard, recent research has focused on the development of power harvesters to eliminate the need for battery power supply [24, 25]. Finally, the last stage involving the removal of the SHM system should be carefully designed to avoid worker injury and damage to SHM components or the structure itself.

The SHM industry is challenged with implementing wireless networks in order to improve traditional monitoring strategies. A complete guideline was recently published [49], showing the different actors involved in a wireless SHM system and a general overview of the technical problems associated with each stage of monitoring.

Pathologies and Non-destructive Testing (NDT) Techniques

A pathology study is useful for assessing the state of the structure that will be the object of the monitoring system. A complete pathology report comprises not only geometric measurements and representation of the damage distribution, but also a set of physical, chemical and mechanical tests. Microstructural characterization and chemical composition testing to characterize the mineralogy of materials are commonly used in this field to detect the cause of various pathologies. However, they are beyond the scope of the current chapter, in which NDT techniques are presented only insofar as they will benefit from automation and technological development, as will be illustrated in various real-world applications.

First, a brief description of the most frequent types of physico-mechanical damage is presented. Heritage structures are usually constructed in masonry; therefore, the main pathologies that can be distinguished at this stage are cracks and physical alterations of materials (masonry or mortar). In steel structures, the equivalent pathology is corrosion, while reinforced concrete elements involve a

Fig. 1 The most frequently observed pathologies in built heritage: **a** discoloration, **b** spalling, **c** mortar loss, **d** cracking

combination of both scenarios. The main types of deterioration can be summarized as follows:

- *Discoloration of masonry materials*, Fig. 1a which can be directly linked to changes originated by chemical effects. Buildings located in heavily polluted

environments (e.g. industrial or road traffic contamination) present color changes more frequently and more visibly. Some differences are dependent on the level of exposure, for example, to the prevailing winds or moist wind. In addition, differences in the characteristics of each material (e.g. origin, composition or porosity) can be detected after exposure. This type of damage can include humidity-related pathologies, such as efflorescence (which appears due to salt precipitation) or growth of microorganisms (due to moisture). Although the cause of these pathologies is not the same, for the purpose of this chapter, the detection techniques will be identical.
- *Spalling in the surface of stone-like materials*, Fig. 1b. The loss of material can occur due to salt content in the internal water. Damage will be more severe with greater wind exposure or groundwater filtration. In addition, materials with higher porosity are prone to this type of damage.
- *Mortar loss in masonry joints or plaster*, Fig. 1c. Similar to spalling, this pathology is an important factor in the stability of slender structures such as industrial chimneys or bell towers, especially when they are built in masonry bricks, because it can generate loose brick elements. If an external plaster layer is present, its debonding and possible spalling is also a frequent pathology related to hygrothermal effects.
- *Cracks*, Fig. 1d. Unreinforced masonry has almost no tensile strength. Hence, crack initiation and propagation must be controlled to guarantee structural stability. The causes can differ widely—for example, ground movements or seismic events. Crushing cracks in columns can appear due to high compressive stress, which can be a problem if water content is high, as stone strength diminishes in saturated conditions [50]. Because structural performance can be severely compromised if cracks remain active, crack monitoring is an important basic parameter in long-term heritage SHM systems.

Table 1 includes a summary of the most common NDT techniques used in heritage characterization, from visual methods to physical techniques such as thermography or radar. A brief description is given below, highlighting those techniques that are currently being improved through the use of automation and new technologies.

Visual inspection can provide a general idea of the structural conditions and the parameters of interest for monitoring. Traditionally, human inspections have been limited to areas of access or have required specific machinery or equipment for this purpose (e.g. cranes). Today, the development of UAV allows this task to be performed more safely and at lower cost. Figure 2 includes examples of different visual inspections. In Fig. 2a, b the use of cranes was necessary to reach the areas for inspection, with consequent temporary disruption of road traffic in some cases. The UAV shown in Fig. 2c was used to complement the inspection of the masonry chimney in Fig. 2a, d. This robot-aided inspection can even be performed inside buildings, as shown in Fig. 2e.

Image processing or DIC and UAV are being implemented for crack detection, especially in concrete bridges and tall engineering facilities (chimneys or wind

Table 1 NDT techniques for geometric and physical evaluation of heritage buildings

Technique	Applications	References
Human visual inspection	Crack detection, superficial pathologies	[27]
Automated visual inspection	Crack detection, superficial pathologies (digital image correlation)	[30, 36]
Survey	Geometry, drift, deflections	[39, 59]
3D scan	3D geometric modeling, superficial pathologies	[33, 35]
Thermography	Layer and delamination detection, joint and masonry detection, water filtration or condensation	[14, 32]
Ground-penetrating radar (GPR)	Layer definition, void detection	[5, 41]
Synthetic-aperture radar (SAR)	Displacements	[53, 58]
Ultrasound	Mechanical characterization, damage detection	[8, 40]
Vibration-based	Characterization of mechanical properties, damage detection	[9, 21, 38]

turbines). For heritage preservation, crack and spalling detection of a masonry bell tower can also be achieved by combining these techniques [36].

Traditional survey techniques can be useful for geometric definition of buildings or control during structural retrofitting [39]. Structural drift due to subsidence or any type of displacement can be easily assessed, and even their evolution over time can be monitored [59]. However, photogrammetric restitution and 3D scanning are gaining importance for this purpose because more detailed models can be obtained. Moreover, complete cracking and surface defect mapping can be drawn with the aforementioned image-processing algorithms [35].

Both active and passive thermographic techniques are useful for detecting defects in several types of structures, not only masonry. Thermography has already been used commercially as an accessory to UAV for structural monitoring. Typical applications in heritage include the detection of voids (e.g. mortar loss in joints), humidity filtration or moisture content [55], and plaster delamination or cracks [32]. This technique is a good complement to the aforementioned 3D scanning for detecting defects difficult to see with the naked eye [14].

Two radar-based techniques have been included: ground-penetrating radar (GPR) and synthetic-aperture radar (SAR). The former requires direct contact with the element to be measured, and provides in-depth information about material composition [5]. The latter can control displacements across a wide area, and has been used to monitor ground subsidence in public works [53] and heritage [58]. In addition, SAR has recently been incorporated into UAV to widen its range of application [3].

Fig. 2 Human visual inspection: **a** masonry chimney and **b** bell tower, both protected structures in Agost (Alicante). **c** UAV for automated inspection used in **d** masonry chimney and **e** interior inspection of Saint Peter's Church, both in Agost

Structural Analysis of Heritage Structures

This chapter does not pretend to provide an exhaustive assessment of the current state of numerical modeling in architectural heritage. A good review of the evolution of structural analysis of historic constructions can be found in the work of Roca et al. [47].

In SHM design, the objective of structural analysis is twofold: First, numerical modeling is often necessary for the proper design of monitoring systems. The optimal sensor location [20], expected measurement ranges, threshold values and data interpretation can be assessed using a previous model. Second, this same model can be calibrated with experimental data from the monitoring system and will be used in the diagnosis [22] and retrofitting proposal.

Table 2 includes a summary of Spanish heritage structures (mainly towers and churches) for which numerical models were used to assess their stability or as a tool during their restoration. These examples have been selected to show different levels of complexity, from numerical models with only an elastic linear analysis [50], to nonlinear analyses including damage criteria for predicting cracking patterns in masonry structures [18, 46]. The selection of the type of analysis will determine the necessary resources, the reliability of the results and the possible conclusions that can be drawn afterwards.

Structural Health Monitoring in Spain

The aforementioned MHS [Monitoring Heritage System] project of the Santa María la Real Foundation is one of the best examples of how heritage management can benefit from technological development and innovation. The MHS philosophy is premised on a three-legged system: preliminary study, SHM system design and performance monitoring [28]. The preliminary study may comprise a visual inspection and eventually numerical modeling. The objectives of the SHM will then be defined and the parameters of interest determined, after which the most appropriate measuring technique and sensor performance may be selected. Finally, once the system is implemented and running, the use of automated analysis software will aid the decision-making process. These whole-package monitoring solutions are becoming increasingly important for long-term monitoring. In addition to the MHS algorithm example [12], other cloud-based systems can be found in the Spanish market (e.g. www.kbuilding.es). A continuous knowledge transfer between industry and research groups at universities should also be promoted in this field (e.g. www.cal-sens.com).

Table 3 includes examples of SHM systems in heritage structures in Spain reported during the twenty-first century. This list is not exhaustive, but merely affords a view of the different types of monitoring. In some cases, such as MHS, which has been successfully applied in more than 20 heritage sites in northwestern

Table 2 Examples of numerical models of Spanish architectural heritage structures

Site	Structural and analysis details	References
Cathedral of Valencia	Gothic cathedral from 12th century, numerical models only of the cimborio (octagonal lantern) and dome from 15th century. Geometric 3D model by laser scanner and numerical model with solid elements. Linear and nonlinear (isotropic damage) analysis for self-weight hypothesis	[4]
San Martín tower (Toledo)	Mudéjar brick-masonry tower from 13th century. Presented vertical cracks, local buckling of interior elements and tilt. 3D numerical model with solid elements for masonry, and beam and shell elements for reinforced concrete retrofitting. Two linear analyses (vertical and tilted tower) with self-weight and loads transmitted by the annexed church. Reanalysis introducing cracking effect as disconnected elements	[19]
Cathedral of Tortosa (Barcelona)	Fourteenth-century Gothic cathedral, study of a lateral oval dome (18th century) constructed in two brick layers, which failed in 2011. 3D geometry by photogrammetric survey, numerical model with solid elements and nonlinear damage analysis	[26]
Cuatrovitas tower (Sevilla)	Twelfth-century Almohad minaret, 14.8-m-high brick-masonry structure. 3D numerical model with solid elements. Two static analyses: linear and nonlinear (plasticity criteria and cracking effect). Modal analysis for dynamic evaluation, nonlinear time history analyses for dynamic response of two models (3D solid elements and simplified beam elements)	[42]
Árchez tower (Málaga)	Andalusian minaret from 14th century, 16.85-m-high brick-masonry tower. 3D model with solid elements, linear and nonlinear static analyses (plasticity and cracking), modal analysis and seismic analyses. Pushover analyses to evaluate an earlier structural retrofitting	[43]
Cathedral of Mallorca	Fourteenth-century Gothic cathedral. Models consider viscoelastic behavior of masonry, tension-compression damage model, and smeared vs. localized damage. 3D numerical model with solid elements for stage construction analysis and long-term deformations. 2D numerical model for seismic analysis with various damage criteria	[46]
Church of Apostle Santiago (Jerez de la Frontera)	Fifteenth-century church, which suffered several column collapses, and currently showed vertical cracking and damage due to dampness. 3D model with shell and beam elements for linear analysis and gravity loads, and evaluation of retrofitting solution	[50]

(continued)

Table 2 (continued)

Site	Structural and analysis details	References
Basilica of Pilar (Zaragoza)	Original 9th century church, central dome from 19th century and towers in the perimeter from 20th century. Cracking in arches, deterioration of towers, fissures and humidity affecting valuable frescoes. Global 3D model, including soil interaction, for the entire temple, and local model to study the dome's behavior. Different construction stages and retrofitting were considered. Linear and nonlinear (two different criteria) analyses were performed with gravity and thermal loads. Global model considered damage only in tension with a smear crack approach. Local model of the dome also considered compression damage by crushing	[51]
Royal Monastery (Sta. Mª de Poblet)	Twelfth-century monastery with a Romanesque church, which exhibits extensive deformations and material damage due to past fires and corrosion of embedded steel elements. A complete 3D geometric model with the deformed shape was obtained by terrestrial laser scanning. A detailed 3D model of a single bay (considering its deformed shape) was constructed with solid elements. Nonlinear analyses based on damage continuum mechanics under different loading hypotheses (self-weight, ground settlement and seismic pushover analyses)	[52]
Homenaje tower (Granada)	Twelfth-century tower inside the Alhambra complex, 24.8-m-high brick-masonry and rammed earth structure. Graphical limit analysis based on thrust lines. 3D numerical model with solid elements for linear (gravity loads) and nonlinear pushover (concrete damage plasticity) analyses. Simplified 2D model with shell elements for nonlinear pushover analysis	[60]

Spain [13], only the most significant example has been included—in this case, the Cathedral of Palencia. The first system classification relates to the SHM objectives and the forecasted time span (i.e. long-term vs. short-term monitoring). The reasons for long-term measurements include:

- *Health control after retrofitting*, especially for parameters related to the damage actually repaired. Castillo et al. [10] report the complete process (i.e. diagnosis, repair, and SHM installation and performance) involved in the singular reinforced concrete grandstands of the La Zarzuela racecourse in Madrid. In this case, severe corrosion damage had to be repaired in the steel rebars of the roof. During this intervention, electrochemical sensors were embedded in key points in order to control the corrosion levels of the repaired structure.

Table 3 Examples of structural health monitoring of heritage elements in Spain in the twenty-first century

Site	Material	Sensors and techniques	SHM system	References
Fillaboa bridge (Salvaterra do Mino)	Masonry	DIC (digital camera, survey, GPR, FEM)	Single monitoring diagnosis	[5]
Sagrada Familia (Barcelona)	Masonry + RC	Optical fiber, LVDT, Temperature, survey	Preventive during tunnel construction	[7, 23]
La Zarzuela racecourse (Madrid)	RC	Corrosion, water, temperature	Permanent after retrofitting	[10]
Casa Milà (Barcelona)	Masonry + steel	LVDT, survey	Preventive during tunnel construction	[23]
Seminario Mayor (Comillas)	Masonry	Inclinometer, LVDT, temperature, RH, wind.	Pre-retrofitting 1.5-year wireless	[27]
Cernadela bridge (Mondariz)	Masonry	DIC + GPR + FEM	Structural assessment with automated crack detection	[30]
Cathedral of Santiago de Compostela	Masonry	Photogrammetry	Surface pathology mapping	[33]
S Juan Bautista church (Talamanca del Jarama)	Masonry	Temperature, RH	2-week temporary wireless	[34]
Santo Domingo de Silos church (Pinto)	Masonry	Temperature, RH	3-week temporary wireless	[34]
Santa Marina church (Córdoba)	Masonry	LiDAR + DIC	Single surface pathology mapping	[35]
S. Juan de los Caballeros church (Cádiz)	Masonry	Accelerometer (OMA), 3D scan	Preliminary study for structural retrofitting	[38]
Teatro Romano (Cádiz)	Masonry	Survey + accelerometer (OMA)	Control during restoration	[39]
La Giralda (Sevilla)	Masonry + steel	Acceleration, temperature, wind, inclinometer, strain gages, RH, corrosion	Permanent (2-year report)	[54]

(continued)

Table 3 (continued)

Site	Material	Sensors and techniques	SHM system	References
Roman arch bridge (Lugo)	Masonry	GPR	Single-day monitoring for structural characterization	[56]
Cathedral of Palencia	Masonry	MHS (LVDT + temperature + RH + accelerometer)	Permanent wireless	[17]
Sta. Justa and Rufina church (Orihuela)	Masonry	SAR + accelerometer	Structural assessment and long-term subsidence control	[22, 58]
Sta. Mª la Blanca church (Agoncillo)	Masonry	Survey	2-year displacement data	[59]

Another example of monitoring for preventive maintenance can be found in La Giralda, Sevilla [54], in which an SHM system was installed after the restoration of the vane atop the tower, a singular sculpture known as ‘‘the Giraldillo,’’ and the steel structure that connects it to the tower. The SHM comprises several types of sensors, and will be used to determine when the next structural maintenance should occur. Because the system must function outdoors in harsh climate conditions, a five-year revision is scheduled in order to replace the sensors (due to life-cycle exhaustion).

- *Structural control during retrofitting or external works*. This preventive monitoring features continuous control throughout the intervention that may affect the monitored structure. For example, during the construction of an underground railway tunnel in Barcelona, various singular heritage buildings were monitored to ensure that subsidence did not affect the Sagrada Familia [7] or Casa Milà [23].

  The work to uncover the roman theatre in Cádiz required permanent control of the residential buildings currently over the theatre, while structural reinforcement and digging operations were cast [39].
- *Preliminary study for structural diagnosis*. Lombillo et al. [27] developed a wireless monitoring system for a church in Comillas. The objective of this preliminary monitoring phase was twofold: designing and installing a wireless sensor network with remote access, and health monitoring prior to the structural repairs to evaluate the detected damage. The possibility for performance during retrofitting work is another advantage of wireless systems. Preliminary monitoring also serves as calibration for the post-intervention SHM.
- *Time evolution based on periodic measurements*. Another type of long-term monitoring involves the use of intermittent measurements—repeating the same procedure once every several months or years—and comparing geometric differences between measurements. Satellite images obtained by SAR can be useful for detecting structural displacement due to ground movements. This technique was applied by Tomás et al. [58] to evaluate the effect of subsidence in Santa Justa and Rufina Church in Orihuela. Traditional survey methods can also be applied for this geometric control purpose [59].
- *Preventive conservation*. The MHS project is based on the concept of preventive maintenance. The MHS algorithm [12] calibrates specific decay curves for each monitored structure in order to determine the optimal intervention duration as a compromise between structural health and economic investment.

Short-term monitoring can be understood as measurements registered in just one day or over a period of a few days. Incompatibility with the normal use of the structure makes it impossible to apply these techniques over longer periods. Therefore, they focus on obtaining a particular characterization of the structural condition. GPR has been used to detect different layers based on differences in the material’s behavior. It has been applied in several historic masonry bridges in northwestern Spain as the only characterization NDT [56]. In addition, multidisciplinary diagnosis combines GPR with other techniques, such as GPR plus thermography for moisture content in masonry [55], and GPR plus image correlation obtained with digital cameras for a structural 3D model [5] or crack detection [30].

Martínez-Garrido and Fort [34] also performed short-term monitoring (two or three weeks) in several heritage constructions. The purpose in these cases was to develop a wireless monitoring system applicable in different situation. Therefore, they tested the system under real conditions to determine the best protocols, guaranteeing the robustness of the measurements.

A second classification can be made based on the origin of the variables to control—mechanical, ambient or chemical, for example.

- *Ambient conditions*. Most of the damage that affects this type of heritage construction (i.e. masonry structures) is directly related to humidity or temperature [34]. Even the preservation of other works of art, such as frescoes [51], makes the control of these two parameters essential in order to avoid undesirable effects. Thermohygrometer measurements are also necessary to guarantee the precision of other sensors (e.g. strain gauges, fiber optics), whose values have to be corrected depending on the service ambient conditions.
- *Mechanical characteristics of materials*. For structural analysis, the differences between layers of diverse materials should be determined, including layer depth, density and mechanical strength. NDT techniques such as GPR [5], ultrasonic devices [40] or thermography [55] are usually used for that purpose. Typically, this sampling is performed only once during the preliminary studies.
- *Dynamic properties monitoring*. Dynamic behavior analysis can also be a powerful tool for structural assessment of heritage buildings, as was noted in some of the numerical modeling examples. This SHM can be performed as single measures [22] or in long-term monitoring for continuous damage detection.
- *Chemical control*. The presence of certain gases (due to excessive pollution) that can affect heritage buildings or works of art is the object of some monitoring actions [17]. Electrochemical measures are necessary to control rebar corrosion in reinforced concrete elements [10].

Heritage Monitoring Examples: Static Versus Dynamic Monitoring

Two monitoring approaches are discussed below. First, an SHM system was used to control the movements in a sixteenth-century church with severe cracking in different parts of the structure. Second, dynamic monitoring was used to evaluate the possible effects of extreme loading conditions involving blast-induced vibrations on a historic fountain. These two examples are currently being developed by the research group of testing, simulation and modeling of structures (GRESMES) of the University of Alicante.

Church of Saint Andrew Apostle, Jaén

The church of Saint Andrew in Villanueva del Arzobispo (Jaén) was built in the sixteenth century. The structure exhibits several cracks in the area of the transept and the dome. Figure 3a shows structural cracks in one of the arches; in addition, horizontal cracking can be observed in the area of contact with the masonry diaphragm. The possible settlement of the arches and dome also affects the nave next to the transept, and cracks appear in the arch and window, Fig. 3b. In order to study the evolution of these movements, an SHM system was implemented. The instrumentation comprised a total of eight sensors (six linear variable displacement transducers (LVDT) for crack opening-closing measurement, and two thermocouples for temperature control). Data were able to be accessed remotely to obtain real-time images of the structural displacements.

Figure 4 includes images of sensor installation. Figure 4b shows an LVDT that was located in the vertical crack of the keystone of one arch, which supports the dome. Because all monitored cracks were still active after a number of days of monitoring, emergency measures were taken to ensure structural stability. Hence, the scaffolding system shown in Fig. 4c was cast to support the dome's weight in the damaged arches while the structural reinforcement was designed and cast.

An SHM system was also used to evaluate the performance of the scaffolding solution. Figure 5 shows the time evolution of two displacement sensors located in the arch above the high altar, one in the lower part of the keystone and another in the joint between the arch and the upper diaphragm. Temperature measurements obtained in a thermocouple next to the LVDTs are also included in order to exclude thermal effects in the structural displacements. Results for the first five months of

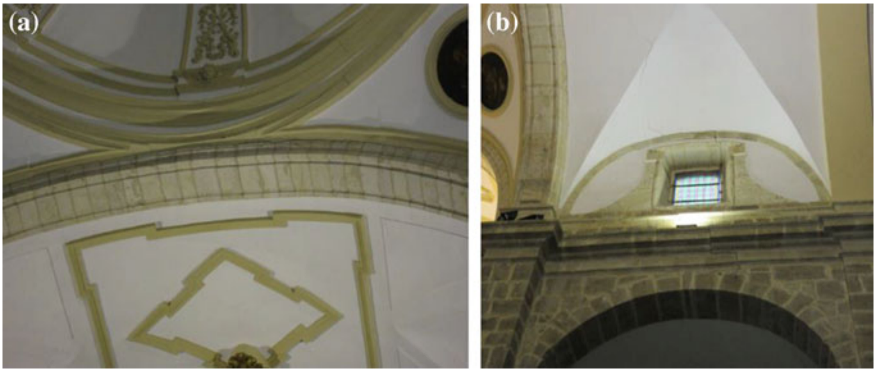

Fig. 3 Main structural cracks: **a** arch and dome junction; **b** nave next to the transept and dome

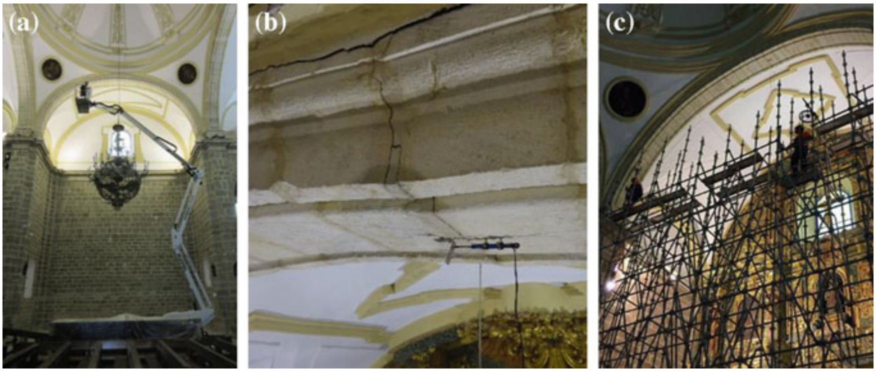

Fig. 4 **a** Sensor installation. **b** LVDT sensor attached to the lower part of the arch over the high altar. **c** Casting of the scaffolding system to unload one of the arches supporting the dome

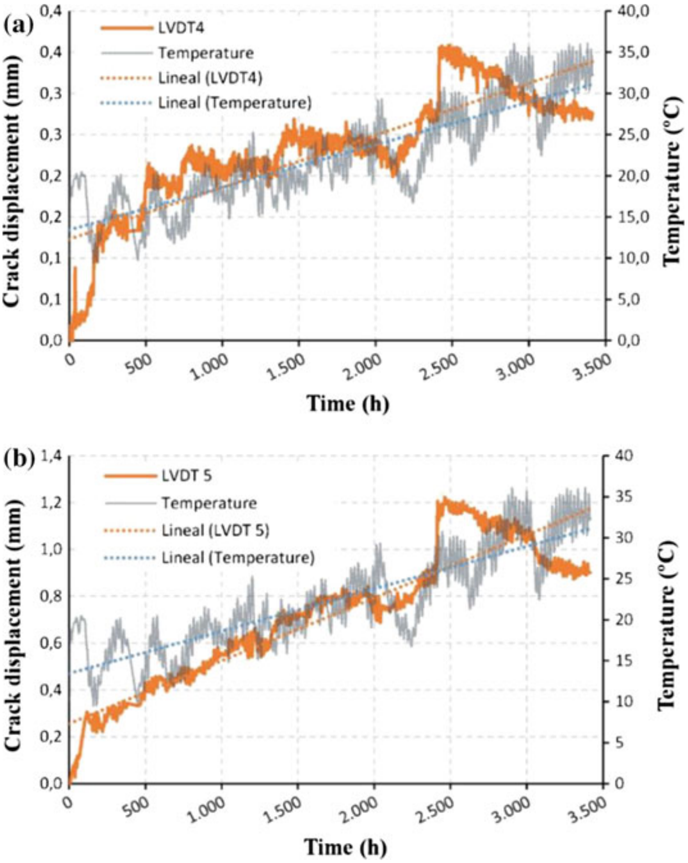

Fig. 5 Temperature and displacement measurements of LVDT located in the arch over the high altar, **a** in the lower part of the keystone and **b** in the joint between the arch and the upper diaphragm

monitoring are included. The effect of the scaffolding can be observed in the changes registered after 2000 h. At around 2500 h, a readjustment of the scaffolding was necessary after the detection of a sudden displacement increase.

Fig. 6 **a** General view of the fountain and the protective screens; **b** sensor installation; **c** triaxial setup; **d** relative position of the fountain and explosives; **e** detail of the fireworks devices; **f** view of the fountain during the spectacle

Subsequently, the widening trend in the crack opening has been reversed. This type of monitoring will also be useful during foundation reinforcement work and structural reloading when the scaffolding is dismantled.

Historic Fountain, Alicante

The fountain in the center of the Plaza de los Luceros in Alicante, Fig. 6a, is one of the city's most important monuments. This modernist structure, built in 1930, is composed of a central body and four horse sculptures. It was repaired several times in the early 2000s, and a retrofitting using composite materials is currently being evaluated. One of these interventions consisted in the total dismantlement and

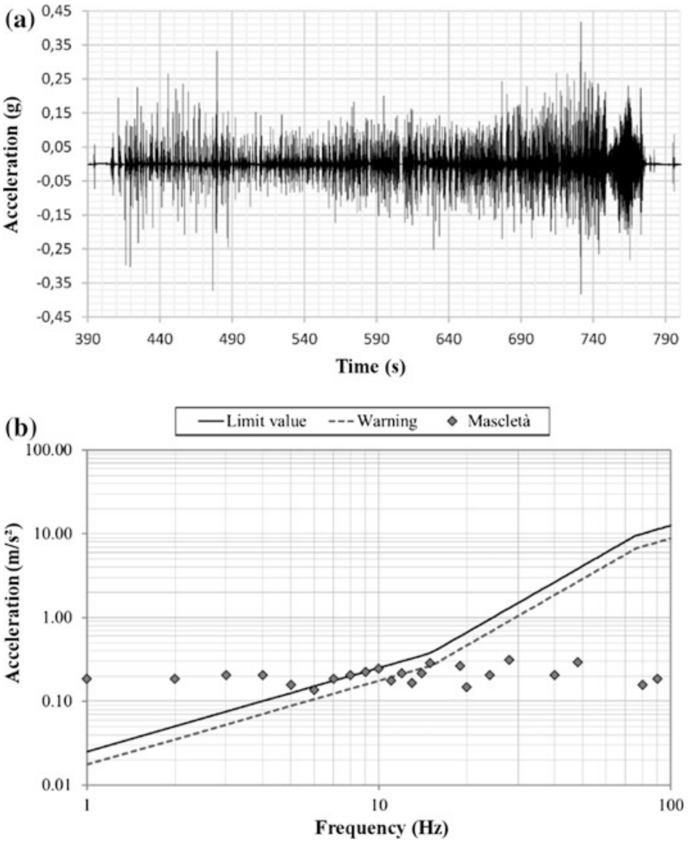

Fig. 7 **a** Vertical acceleration time history registered by a sensor attached to the fountain structure. **b** Maximum accelerations and UNE 22381:1993 limits versus frequency for data registered in a sensor attached to the ground near the structure

subsequent reconstruction of the entire monument, due to the work on an underground railway station under the plaza.

The most common types of damage are superficial cracking and spalling as a result of nearby road traffic, water from the fountain and corrosion of the embedded steel elements of the fountain installation. However, another possible cause should be taken into consideration: Each year during the city festivities, several fireworks displays (called mascletàs) are held in the plaza, near the fountain. These mascletàs, and their location, have led to a public debate on their possible effects on the fountain's health. As a temporary measure, each horse sculpture has been protected with composite protective panels during these events, Fig. 6a.

In this case, dynamic monitoring has been selected to evaluate the effect of the blasts on the fountain elements. A monitoring system comprising eight accelerometers attached to the fountain and on the ground was installed to measure vibration levels due to the fireworks. The sensor installation can be observed in Fig. 6b; an example of a triaxial setup, attached to the ground near the fountain, is included in Fig. 6c. The relative location of the explosive charges with respect to the monument and a detail of them are include in Fig. 6d and e, respectively. An example of the pyrotechnic arrangement for this performance is shown in Fig. 6f.

Accelerations on all sensors were measured at 500 Hz throughout the blast spectacle, lasting approximately 6–7 min. Figure 7a includes the accelerations recorded at the fountain, with peak acceleration of around 0.4 g. After frequency analysis, these values will be compared with different recommendations found in standards UNE 22381:1993 [1] or DIN 4150-3:2015 [16] and in scientific reports. The analysis shown in Fig. 7b represents the maximum vertical accelerations registered in a sensor attached to the ground, which are higher than the limits included in UNE 22381:1993 [1] for low frequencies, in a range of 1–10 Hz. Similar conclusions can be derived for the sensors directly attached to the monument. Therefore, these blasts may produce excessive damage to the fountain, and preventive measures should be taken.

Conclusions

This chapter has presented various systems developed by Spanish research groups and companies in the field of SHM, applied to historic constructions and civil engineering facilities. In recent years, techniques such as wireless or fiber optic sensors, continuous monitoring and trigger alerts have been successfully used for preventive maintenance and serviceability limit states. In some cases, as in the aforementioned spin-off Spanish companies, this research led to a transfer of knowledge between research groups and industry. The future of this industry will require automated processes to aid experts and engineers in the rapid analysis of large volumes of information to identify the correct course of action. Furthermore, new monitoring techniques can lead to significant advances in SHM applications—

for example, UAV equipped with sensor technologies such as hyperspectral cameras, radar or thermography.

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