Structural Health Monitoring: A Review on Its Application in Historical Structure

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Abstract Historical structure is an integral component of the world's cultural identities. However, despite its cultural significance, it is the most prone type of building due to environmental factors such as aging of the materials, the effect of temperature, soil condition, and natural disasters such as earthquakes and typhoons. Therefore, the preservation of historical structure is one of the growing interests in recent years, and in monitoring the historical structure's state correctly, different methods and tools introduced. One of the methods in determining the health of the historical structure implemented a decade ago is Structural Health Monitoring (SHM). Generally, there are two types of SHM, long-term monitoring or Static SHM, which measures slow varying factors, and Dynamic SHM which determines the dynamic properties of the structure. However, with the continuous advancement of the SHM, the uncertainty and inaccuracy of the model and results are still the most significant gap in the application of SHM. This paper aims to review some of the applications of SHM in the preservation and monitoring of historical structure to provide knowledge about the topic and determine gaps and challenges based on the existing literature and studies.

Keywords Structural Health Monitoring · Wireless Sensor Networks · Structural integrity · Structural stability · Historical structure

1 Introduction

The state of a structure should be assessed similarly to that of a human being, with doctors evaluating human health using medical knowledge and advanced technology. On the other hand, engineers utilize Structural Health Monitoring (SHM) that employs modern sensors to assess the structural integrity and durability based

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on the information obtained. In any case, this evaluation will help to identify problems early on, and engineers can provide guidelines and recommendations. Overall, the fundamental goal of structural health monitoring is to observe in-situ structural behavior under various loading circumstances during a defined period or the structure's lifetime and to detect aggressive environmental conditions [1].

One such structure most applicable to utilizing SHM systems is the Historical Structure, as these are irreplaceable assets. Furthermore, it is a valuable resource of pride and symbol of a country's cultural history worldwide. Therefore, its upkeep and preservation necessitate striking a balance between structural safety and architectural value. This paper attempts to present the viability of applying the SHM system in determining the condition of Historical Structure.

2 Research Methodology

This paper follows the work introduced by Tranfield et al. [2]. This methodology utilizes three stages, namely: (a) formulating a research question, (b) Conducting the review, and (b) Reporting the review. The basis of quality study is a good research question, which is crucial in gathering information, gaining insight into a particular problem [3], identifying the topic of interest, and a guide for methodology [4]. Therefore, researchers have developed the following research question to achieve the objective of this study:

RQ 1: What are the classifications of Structural Health Monitoring?
RQ 2: What are the instruments used in Structural Health Monitoring?
RQ 3: What are the applications of SHM in Historical Structure?
RQ 4: What are the challenges and development of SHM?

The steps in finding a paper that is related to the topics are as follows: (a) established a keyword, (b) database searching using a Boolean syntax which enables users to blend keywords such as AND, OR, and NOT using "Title/Abstract/Keyword" field of the database [5], and lastly (c) document the paper based on its eligibility for the topic by using Preferred Reporting Items for Systematic reviews and Meta-Analyses guide [6], which illustrates in Fig. 1.

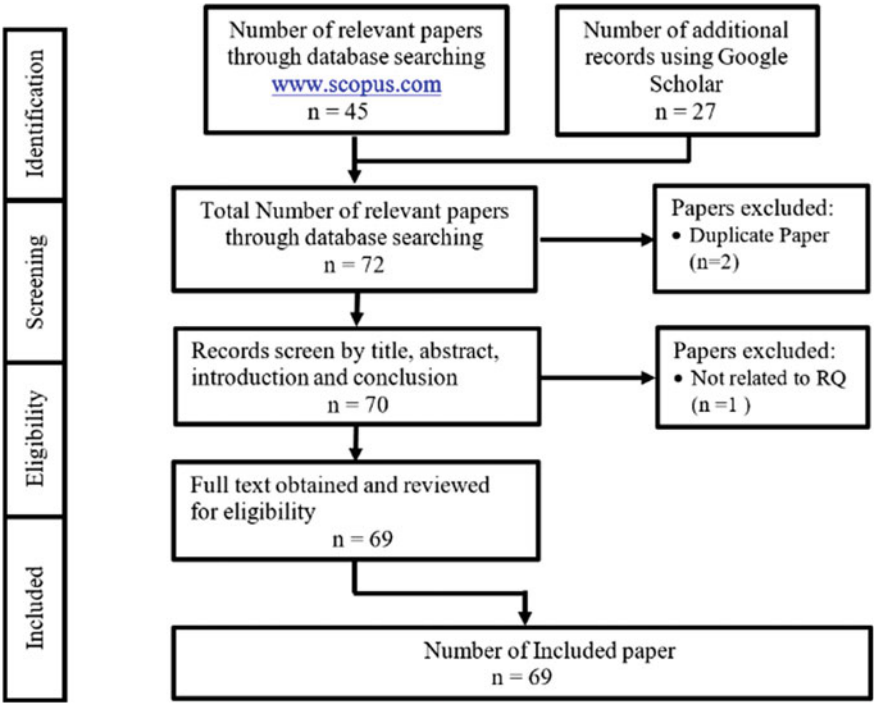

Fig. 1 Systematic related literature selecting process

3 Static and Dynamic Structural Health Monitoring

The building's structural integrity and durability require regularly monitoring especially ancient structures since it is the most vulnerable type of structure due to its deteriorating age and uncertainties in its material behavior. The traditional way of assessing the structure's health is primarily done through visual inspection by technical experts and engineers; however, this is inefficient in assessing the building's real-time condition. SHM has proven to be a powerful tool in addressing this issue.

Generally, there are two main classifications of Structural Health Monitoring: (a) Static SHM and (b) Dynamic SHM. The latter identifies that the dynamic structural reaction must be accounted for by a continuous data acquisition when measuring events like earthquake movements or traffic-related vibrations [7–9]. Conversely, the former involves continuous monitoring of critical slow-varying indicators such as inclination, corrosion, variation in time of cracks opening, settlement, humidity, and temperature [10, 11].

SSHM's fundamental goal is to determine whether the structure under observation is stable. A steady condition implies that the structure is safe; however, a non-stationary response may signal a state of deterioration, thus jeopardizing the monument's structural safety. DSHM, on the other hand, provides the dynamic properties

Table 1 SSHM and DSHM application in the Historical Structure

Ref	Structure	Year it started	Duration (years)	No. of Instrument	SSHM	DSHM
[12]	Santa Maria del Fiore	1987	20 years	150	Yes	No
[13]	Basilica of San Marco	1991	3.5 years	23	Yes	No
[14]	Monastery of Jeronimos	2005	9 years	10	Yes	Yes
[15]	Cathedral of Moderna	2004	8 years	25	Yes	No
[15]	The two towers of Bologna	2011	4 years	58	Yes	No
[16]	Roman Arena of Verona	2011	1.5 years	40	Yes	Yes
[15]	Asinelli Tower	2012	3 months	4	No	Yes
[17]	Baptisery of San Giovanni	2013	3 days	10	No	Yes
[18]	Giotto Bell Tower	2013	3 days	10	No	Yes
[8]	Sciri Tower	2017	8 days	7	No	Yes

of the structure to develop a mathematical model of the building's behavior through theoretical and experimental modal analysis [19]. Some of SSHM and DSHM in historical structure as shown in Table 1. It is noticeable that the duration of static monitoring would take years since it monitors the stationary condition of the building, and it is sometimes called continuous monitoring. Nevertheless, the structure is not limited to only one type of monitoring; in some instances, the structure uses both monitorings, such as in [14, 16].

4 Structural Health Monitoring Sensor

SHM systems contain a collection of small detachable sensors which forms to monitor either the long-term evolution of fractures, settlements, inclinations or dynamic qualities such as frequencies and damping ratios [20]. The SHM's central heart is the sensor since it is necessary for evaluating the structure; hence, the data acquisition element of the structural health monitoring process includes determining the types of sensors, and their use, The main types of sensors used in SHM are (a) Fiber Optic Sensor and (b) Wireless Sensor Network (WSN).

Fiber optic sensor is a device used to detect different parameters such as temperature [7], structural vibrations [8–10], displacement [15, 17], acceleration [21], and rotations. A fiber optic sensor system is composed of fiber optic cable linked to a

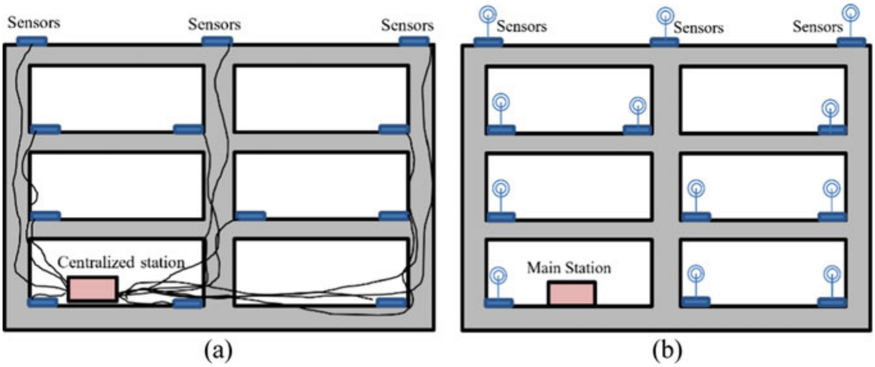

Fig. 2 SHM system set up: **a** Traditional SHM location, and **b** WSN [23]

remote sensor or an amplifier. Some examples of this sensor are (a) an accelerometer for measuring acceleration, (b) a thermometer that measures the temperature that affects the structure's physical properties, and (c) Inclinometers to monitor the subsurface movement and the slope position of the buildings.

Wireless Sensor Networks (WSN) offer the same capability as another sensor at a cheaper cost, allowing for considerably denser monitoring. The difference between utilizing typically wired sensors and wireless systems in SHM is that the latter features sensor nodes that require little maintenance and no wires, allowing them to deploy previously impractical or inaccessible areas [22].

Figure 2a shows the traditional way of installing the sensor in the building for SHM. In this approach, wired sensors may be costly and impractical to use in extensive infrastructure due to economic factors. In recent years, experts have found a way to address the problem using a wireless sensor that connects the sensor to its base station, where all the data keep in place and ready for analysis, as shown in Fig. 2b.

5 Structural Health Monitoring in Historical Structure

The historical structure has been part of human history throughout the centuries; this type of structure is prone to cataclysmic events that can compromise the stability and safety of the structure, mainly degradation, environmental hazards, and aging [24]. Therefore, increasing interest in structural health monitoring (SHM) as a knowledge-based evaluation method to measure and mitigate uncertainty about structural performance of cultural heritage sites has resulted from the need for successful seismic safety and vulnerability assessment [25].

In the study [26], five high-sensitivity accelerometers, three at the base of the drum and two at the Basilica of Saint Mary of the Angels, performed a dynamic identification to implement an effective system for early detection of damage. The affected zone discovered by numerical analysis has established that the dynamic crack pattern seen in the dome is primarily due to seismic activity. In a study in 2013, the SHM system at the Cathedral of Modena in Italy aims to determine the church's prominent cracks, the structure's inclination, and the displacement it induces over the year. The sensors used in this monitoring are two thermometers, two inclinometers, five biaxial and two Trixial joint meters, and two Deformometer [25]. All these studies are significant since it proves that the SHM system is an effective way to monitor the overall state of the building.

Understanding the condition of ancient buildings is critical for preserving and supervising historical structures; ancient masonry constructions make up much of the historical and architectural heritage and by a wide variety of complexities [26]. Heritage structures may be classified as a particular case because they are structural construction that differs from modern ones, with nuanced behavior that is often impossible to measure or understand using existing rules, guidelines, procedures, or devices. Despite the advancement and innovation of the past researcher in SHM, there are still no clear international codes for this topic [27].

6 Challenges and Gap

Considering the evolution of the SHM system in assessing the stability of not just ordinary structure but also historic structure, it is safe to state that SHM is an efficient way to monitor. However, despite the benefits, the limitations and issues must still need to address. Although the experimented investigations of the applications are successful, theoretical and practical issues still hamper a large scale of continuous monitoring. One example to be considered barriers in implementing the SHM is the number of sensors to be installed in the structure [7], this would result in the high cost of fabrication and installation of the system wherein the stakeholders, or the client may have refused the project due to the low return of investment. It is also worth noting that most of the available literature on the application of SHM in historical structure can be located in Mediterranean Europe, mainly in Italy [7–11, 19, 28, 29]; this is because most of the landmark of cultural sites are present in the said part of the world. Focusing more on the objective of this paper, Table 2 shows the challenges imposed by SHM application in historical structure based on the literature gathered.

The vibration-based method has been the most frequent technique in monitoring the structure's condition, and this method is impossible without the instrument; hence it is the most challenging part of implementing SHM. It may include insufficient and unreliable data for modeling, the location of the sensors, and the cost of the device. Similarly, the model may cause uncertainties due to material degradation, operational factors, and environmental factors. The following factors define the uncertainties in the output and result of the SHM: (a) measurement errors, (b) site conditions, (c) calibration and tolerance, (d) transmission and storage issue, and (e) final monitoring are inconclusive.

Table 2 Challenges and Limitations of SHM in Historical Structure

References	Challenges and Limitations
[7, 8, 28, 30–33]	The uncertainty in the output of the instrument
[34, 35]	The uncertainty in the result of model
[9]	Difficulties in where to install the sensors
[36]	Synchronization of wireless sensor network
[24]	The lack of international code and guidelines for SHM
[9]	Disapproval of the usage of SHM due to financial reason

7 Conclusion

Preservation and maintenance of an ancient structure is a daunting task that engineers and experts need to address. SHM is an excellent tool in monitoring the structure's health, whether short-term (DSHM) or long-term (SSHM); the output of this method significantly affects the engineer's decision for preventive measures. In finding the result of the monitoring, sensors with a centralized panel shall be installed on the site.

The duration of the monitoring depends on the type of monitoring, and this will take days, months, years, or continuous depending on what method requires to utilize. Although this monitoring method is beneficial to the existing structure, several gaps and challenges still exist, such as the uncertainties in the instrument's output due to the wrong placement of sensors or not-in-sync device; because of this, the model that forms in the result is questionable. However, the main problem in utilizing the SHM comes with financial reasons; moreover, this is applicable most of the time in developed countries. To conclude this paper, the development of SHM is significant in historical structure since this will be an excellent strategy in minimizing catastrophic losses by foreseeing its damage in the early stages.

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