A Survey on Current Heritage Structural Health Monitoring Practices Around the Globe

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Abstract. Heritage structures have a significant role in the nation's history. They may be acknowledged for several reasons – age, structural magnificence, religious reasons, historical events or persons they hosted, construction challenges they had in era they were built, and so on. Preserving heritage structures is prestigious and challenging task. Furthermore, an accurate knowledge of the behavior of a structure is becoming more important as new construction and conservation techniques are introduced. Historical Structures have been exposed to environmental conditions for very long time leading to the different degrees of malfunctioning at elemental or global level. In order to assess the health of the structure, this paper presents the review on various methodologies adopted by different countries around the world in assessing and monitoring of Heritage structures. Special focus on latest technologies like Artificial intelligence and sensors are discussed to address these challenges. A number of meaningful features have been monitored through extracting from SHM data.

Keywords: Heritage structure · Structural health monitoring · Artificial intelligence · Heritage structure preservation

1 Introduction

The preservation of the heritage structures is a thought of concern from governing authorities to a common person, largely due to fear of loosing identity, details of history and cultural significance. The major challenge is to conserve and restore these historical structures as they represent important event in the history of any city or a nation [1]. During the 2nd Congress of Architects and Specialits of Historic Buildings, at venice in 1964 provided for the creation of the International Council of Monuments and Sites (ICOMOS) for the protection of historical buildings [2]. In 1972, United Nations Educational, Scientific and Cultural Oragnization (UNESCO) has started World Heritage Convention for listing, protection and conservation of reneowed heritage sites and monuments all over the world [3]. In the year 1975, European Charter of the Architectural Heritage mentioned that apart from historical buildings, even natural and artificial minor

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buildings in ancient towns are also to be considered in Heritage [4]. Following to that, all the nations rich in heritage and historical sites have started their own conservation and preservation of heritage organizations at both city and national level [5]. Even though there are many preservation organizations, Heritage structures are still at the large risk due to lack of appreciation, architectural significance, constructional values and improper structural health assessment apart from rapid growth of urbanization. In the past few decades, there were many heritage structures which have lost their structural stability and integrity leading to the partial damage. To name the few the Civic Tower of Pavia, Italy [6]; the bell tower of St.Magdalena in Goch, Germany (Gantert Engineering Studio 1993); Cathedral of Noto, Italy [7]; the bell tower of the St. Willibrordus Church in Meldert, Belgium [8]; "Maagdentoren" in Zichem, Belgium [9]; Church of Kerksken, Belgium [10]; Chowmahalla Palace partial collapsed after heavy downpour in India [11]. Largely it is living historical structures which built a bridge of knowledge between the past and future generations [12]. So, it becomes very important to conserve, preserve, protect and if needed restoration to be carried of the heritage structures.

World Heritage Convention (WHC) of UNESCO has divided the world into five geographic zones namely Africa, Arab states, Asia and the Pacific, Europe and North America, and Latin America and the carribbean and listed 1121 properties by Jun 2020 as seen in the Fig. 1 all over the globe as the heritage sites. Further, it is taking all the necessary actions to preserve and protect with the help of nations government [13].

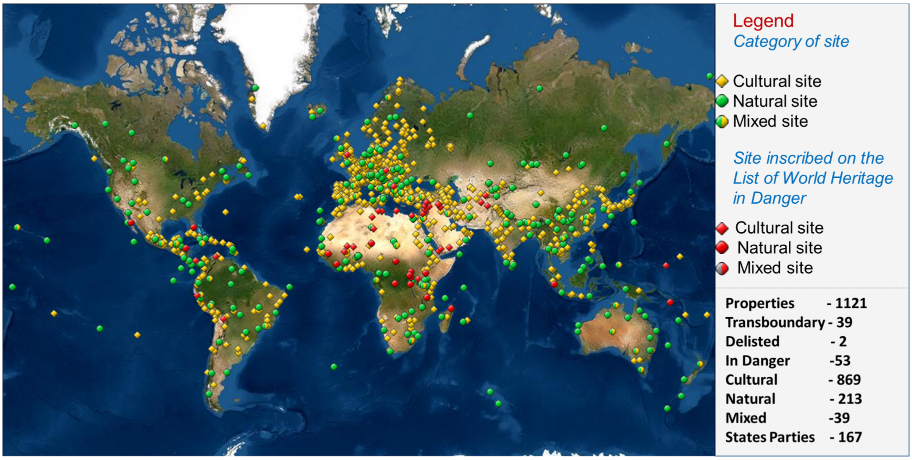

Fig. 1. World heritage list [Ref. 13]

This study also follows the same order in detailing various methodologies adopted in various geographic locations for heritage structural health assessment and monitoring.

2 Background of Structural Health Assessment and Monitoring

To understand and access the phenominal change in geometry, material, boundary conditions and loading compared to its original state is known to be Structural Health

Assessment (SHA) and if the same is continued to observe day by day changes is called Structural Health Monitoring (SHM). Largely these changes are termed to be deterioration or damage assessment. Extensive research on SHA and SHM is being undertaken form past three decades, but only in last one decade there were approximately 17000 research papers published in various national and international journals [14]. Out of which less than one percent have been published on SHM of heritage structures, where as there has been much research carried on Nondestructive Techniques (NDT) for the assessment and preservation of heritage structures. Most commonly used NDT tests are multispectral images, geophysics data (ground-penetrating radar [GPR]), flat-jack tests, infrared thermographic images, laser scanning data and ultrasound [15–17]. Choosing the most appropiate method requires careful decision that always takes into account of structural significance and parallely considering its physical condition. SHA is carried in three steps, first on-site visual inspection which requires prior experience and expertise, works only in accessible regions of structure, has interruption and down time, labour intensive, second, carrying out NDT tests and sample extraction for laboratory analysis and finally detailed analysis which is time consuming [18]. Considering the limitations of NDT, rise in digital technology has led to quantify heritage detrioration and detrioration live monitoring [19]. Figure 2 shows the complete structural health monitoring process in detail without much focus on the instrumentaion, largely detailing the methodologies used. Methodology choosen is directly related to structure type and parameters measured [20].

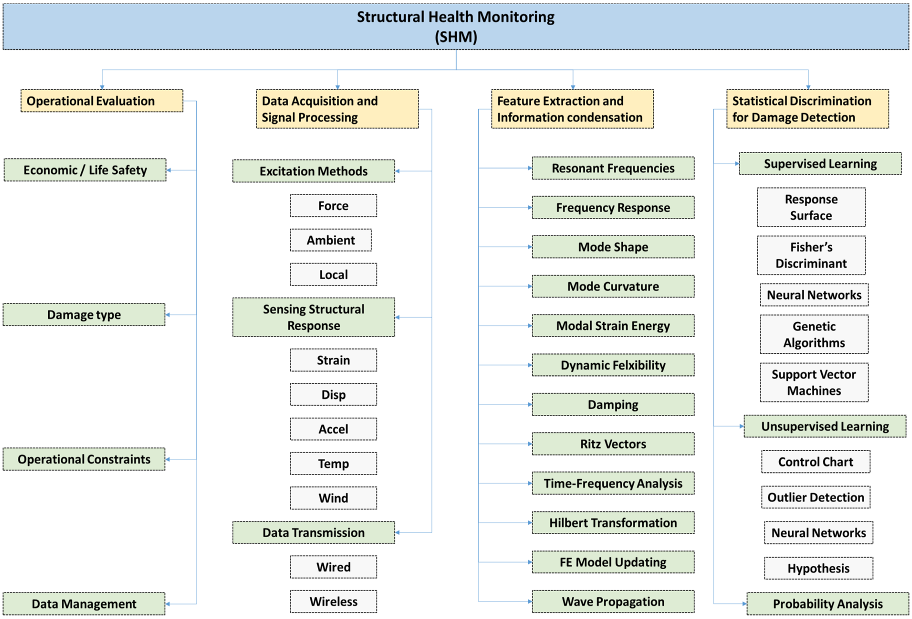

Fig. 2. Structural health monitoring process [modified from Sohn et al. 2003]

In SHM, three major aspects of sensor sub-system are variable, sensor and location of sensors. Variable largely deals with loads, environmental conditions, global or local responses. Global response deals with acceleration and deformation whereas local response includes strain, displacements, crack and fatigue at the elemental level [21]. Health monitoring system of heritage structures has started in the early 1970's, one of the early structures which was monitored was Hangzhou Tiger Hill tower, which is also called leaning tower of China to observe its tilt, settlement, ground subsidence and displacement in the year 1978 [22]. Structural health monitoring of historical structures and monuments with temporary or permanent may lead to optimal economic resources for repair or rehabilitation activities especially after natural or man-made disasters [23].

3 SHM of Heritage Structures Around the World

As mentioned above for systematic consideration of case studies around the world which are being health monitored, this study has chosen region wise which were classified based on the geographical locations by World Heritage Convention (WHC) of UNESCO are Africa, Arab states, Asia and the Pacific, Europe and North America, and Latin America and the Caribbean. Lot of research work has been carried by various organizations and research based academic institutes on prototype and actual scale structural health monitoring. But there is significant difference in use of SHM in various geographical locations and same has been discussed in detail.

Back bone of SHM is vibration response of the structure as it directly depends on basic characteristics such as mass, stiffness and damping, and structural deterioration or damage can alter the vibration response assuming the known response of actual state of the structure [24]. In the last two decades' vibration-based concept for monitoring the heritage structures has improved and seen exponential raise in studies and implementation [25–27]. Continued with improvement of methodologies to find the damage but the basic fundamental was based on vibrations and then calculated in terms of frequencies or modal analysis. In the early 1990's, collaboration between civil engineers and physicists worked on different fiber optic technologies and decided to adopt low-coherence interferometry as they offer an excellent long-term stability, a high resolution and the possibility of creating long-gauge sensors suitable for the monitoring of large civil structures. And in 1993 the SOFO "Surveillance des Ouvrages par Fibers Optiques", was named for Structural monitoring with Optical Fibers [28, 29]. In early 2000's structural health monitoring was added with the latest technology of Artificial Intelligence, but still it is in the naïve stage for the application to heritage structures [30].

3.1 SHM in Africa

According to the world heritage convention there are 34 nations under the geographical location of Africa. And there are approximately 102 heritage properties which are being focused for the preservation by UNESCO.

Rock-hewn Churches of Lalibela (Ethiopia): Rock-hewn churches of Lalibela situated in the northern-central part of Ethiopia known to be carved 800 years ago on a living volcanic rock. Due to the continuous weathering and human activities the churches have resulted in structural damages. The first restoration is of damaged churches is said to be taken during 1920 and now they are continuously monitored [31]. Rüther and Palumbo have presented structural health assessment and conservation by laser scanners, photogrammetry, GPS and total stations, which will help in creating the three-dimensional digital model which will become the base for continuous assessment [32]. Authors have not found any heritage structure in Africa under the lense of structural health monitoring. But there are many active initiatives all around the African continent of the conservation and preservation of heritage structures and their culture [33].

3.2 SHM in Arab States

According to the world heritage convention there are 19 nations under the geographical location of Arab States. And there are approximately 86 heritage properties which are being focused for the preservation by UNESCO.

The minaret of Ajloun's mosque, Ajloun, Jordan: Hamdaoui et al., presented a work on Structural Health Monitoring of the minaret of Ajloun's mosque, Ajloun, Jordon which is seven and half century old using ambient vibrations largely from wind forces. Figure 3a shows the complete dimensions of the historical monument and Fig. 3b shows the original structure from the site, Fig. 3c shows the locations of accelerometer sensors deployed to record the vibrations and Fig. 3d shows the first 12 modes obtained from the analytical solution. Dynamic characteristics obtained from the SHM and material properties obtained from the extraction samples are incorporated in the analytical solution and compared experimentally and analytically, which were in the good agreement [34, 35]. Similarly, El-Attar and Osman, 2004 have studied Al-Sultaniya minaret located in Egypt and constructed in the year 1340 both experimentally and analytically [36].

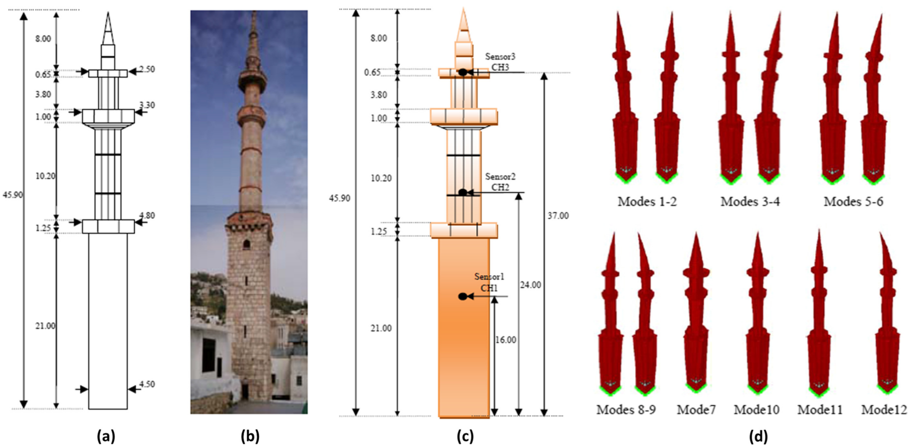

Fig. 3. a. Dimensions of Ajloun Mosque Minaret b. Ajlourn Mosque Minaret c. Location of sensors d. modes obtained from analytical analysis [34]

3.3 SHM in Asia and Pacific

According to the world heritage convention there are 36 nations under the geographical location of Asia and Pacific. And there are approximately 284 heritage properties which are being focused for the preservation by UNESCO. There has been lot of research carried on SHM of heritage structures in this region. This research work as restricted to different SHM Techniques used.

Seok-Ga Pagoda, Kyung-Ju, Korea: Seok-Ga Pagoda constructed in 8th century in the court of the Bulkook (Bulguksa) temple, Kyung-Ju, Korea. The three-story pagoda represents the finest style of Korean Buddhist pagodas that evolved from China's multistoried pavilion-type wooden pagodas. Deterioration of material, environmental exposure and non-uniform settlements made stones to move and tilt. Absence of mortar between the stones is leading to free movement of stones putting the entire structure at risk. Long base sensors and inclinometers were installed to calculate the differential settlement as seen in the Fig. 4 [37].

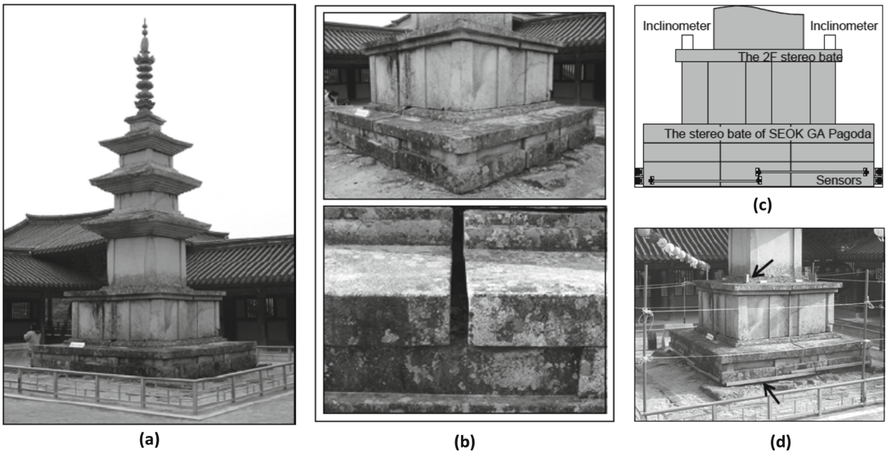

Fig. 4. a. Seok-Ga Pagoda b. Openings created between the stones c. Schematic diagram representing the locations of sensors d. Installed sensors [37].

In continuation that most of the nations under Asia and Pacific started SHM in early 1990's for understanding the responses of heritage structures. To name few, in 2007 sensors were installed in BaoGuo Temple to assess the material deterioration and structural deformations [38]. Shi has presented optical fiber monitoring methodology to monitor the deformation and temperature of the wall of DongHua Gate of the Forbidden City [39]. Wang has used Fiber Brag Grating sensors for the Tibetan ancient wooden structure to assess the deformations and joint behavior [40]. Toshikazu et al.. used the CCD imaging system as a structural health monitoring of Jojakkoji Temple in Kyoto, Japan to observe the response for natural disasters like earthquakes and typhoons [41]. Dhapekar and Saha have presented implementation of SHM using Rapid Visual Survey (RVS) for Bhand Dev temple, India [42]. Salvatore and Eleonora have carried SHM using digital portable tromometre for dynamic vibrations on Radha Krishna temple (Teku) and Pancha Deval complex (Pashupati) which were damaged due to 2015 Gorkha earthquake [43]. Annamdas et al., have briefly detailed the SHM applications and developments specially form the view of Asia [44].

3.4 SHM in Europe and North America

According to the world heritage convention there are 61 nations under the geographical location of Europe and North America. And there are approximately 626 heritage properties which are being focused for the preservation by UNESCO. There has been lot of research carried on SHM of heritage structures in this region too. Infact most of the structural health monitoring of heritage structures is largely taken up in Europe compared to the whole world. Apart from that regular international conferences and workshops related to SHM of heritage structures are conducted.

Villa Reale Monza, Italy: The instrumentation of the Villa Reale in Monza was one of the first applications of permanent remote monitoring using 'Surveillance des Ouvrages par Fibres Optiques' SOFO sensors. It also showed that the advantages of long-gauge sensors were also relevant to the monitoring of timber and masonry structures [45].

The Roman Arena of Verona: Very recently it was equipped with a health monitoring system to get the vibration characteristics of the monument using accelerometers and control the surveyed crack pattern through displacement transducers [46]. Figure 5a shows the aerial view of the Arena, Fig. 5b shows the Arena's wing; Fig. 5c shows the structural strengthening scheme and Fig. 5d shows the location of the static sensors deployed at the site.

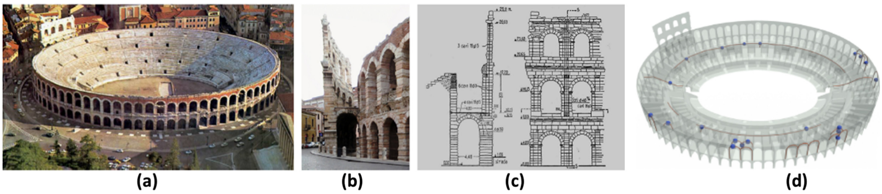

Fig. 5. a. Aerial view of the Arena; b. Detailed picture of the Arena's Wing; c. scheme of the strengthening; d. Location of static sensors [46].

As mentioned above there are many structures in Europe which are currently instrumented with live monitoring system. Casarin et al., presented the use of non - contact monitoring system for evaluating the crack openings in fresco surface for SaladeiBattuti – Conegliano Cathedral [47]. Anastasi et al., presented SHM using wireless sensors of the church of St. Teresa in the Kalsa district in Palermo, Italy. The main objective of the study was to observe structural deformations and stresses due to consolidation process which is taken up, the church was damaged due to earthquake occurred in the year 2002 [48]. Duvnjak et al., used the method of residual strain measurement on Peristyle of Diocletian's Palace in Split. This method involves attaching single strain gauge to the surface, drilling a hole in the vicinity of the gauge and then measuring the residual strains [49]. Ferraioli et al., has presented a research on health monitoring of Santa Maria a Vico bell tower using ambient vibration measurements and incorporation in the numerical model [50]. The Morris Island Lighthouse is instrumented with a discrete SHM system that consists of crack meters and temperature sensors. The system was implemented in 2007 prior to the start of a foundation stabilization to monitor any adverse effects due to intervention works [51].

4 Artificial Intelligence in SHM

Largely research related to Heritage Structures should address the following questions.

1. What is the life time of a cultural heritage structure?
2. What do we have to protect the monuments from?
3. How can we preserve and/or improve the level of safety of monuments?
4. What should we do to extend the life time of cultural heritage structures?

And the two important factors should be accounted for: to know the history of the construction and its architectural and structural characteristics and managing the maintenance of the structure. For the second aspect, the usual maintenance procedures are the classic maintenance on request, which implies a retrofitting intervention only if a damage is already occurred, and the recurring preventive maintenance, which is aimed to prevent any damage [52]. The limitation of the first approach is that the damage is already occurred and the maintenance works, if still possible, require the interruption of the use of the building with obvious negative economic effects. The disadvantage of the second approach is the difficulty in the definition of the optimum maintenance period.

Artificial Intelligence (AI) provides suitable alternative solutions for such challenges. AI strategies have been progressively received over the most recent decade for demonstrating real time issues concerning basic structural assessment and monitoring. This is a direct result of their huge ability to catch relations among input and output data that are nonlinear or complicated to figure mathematically. The first uses of AI techniques in structural engineering have dealt with problems such as the development of management tools for structural safety and information acquisition through the continuous monitoring, which is to be preferred, whenever possible. In general, AI methods have been utilized for SHM and damage identification and detection, performance assessment, structural sustainability, reliability [53, 54]. The second focus is on how AI is applied to conservation of heritage buildings. This can progress by investigating and developing a new automated tool for preventive conservation of heritage structures in urban centers based on models of AI. Indeed, AI transforms a problem with high dimensionality to a lower dimensional representation.

Using AI in the heritage structural assessment and monitoring, our survey around the globe understands the various case studies demonstrated by few authors. Ebrahim Nazarian et al. [55] describes development of a machine learning (ML)-based platform for condition assessment of building structures in the aftermath of extreme events. Evaluation of the proposed method was accomplished by using it for the characterization of damage in a turn-of-the-century, six-story building with timber frames and masonry walls. Tawfik et al. [56] the study has mainly concerned with the crack damage and do not considers the other pathologies that can affect a surface structure such as Alkali-silica reaction (ASR), efflorescence, carbonation of concrete, and scaling. Author proposed the method of pre-trained learning Deep Convolutional Neural Networks (DCNN) model with Transfer learning for the detection of seven classes of old building damage in Medina of Fez and Meknes in Morocco. Rachel Martini et al. [57] has proposed a methodology based on non-destructive tests used to characterize historical masonry and later to obtain information regarding the mechanical parameters of these elements. A mechanical characterization tool was developed applying the Artificial Neural Networks (ANN), which can be used for historic granite walls. From all the trained ANNs, based on the errors attributed to the estimated elastic modulus, networks with acceptable errors were selected. Andres Jose Prieto et al. [58] demonstrated the functional service life of built heritage. A fuzzy inference system and a multiple linear regression models were proposed and a multiple linear regression analysis is applied in order to rank the variables in terms of influence in the serviceability estimation of heritage buildings. The experiment is carried on a sample of 100 parish churches, located in Seville, Spain.

The final goal in our study is the reduction of the damage and so of the maintenance works and costs, and the increase of the safety check level by understanding the background concepts of AI and finding the necessity of AI through the various case studies of SHM system for monitoring civil engineering structures. The study clearly presents the potential of intelligent software applications like AI in the field of SHA and SHM. Therefore, AI enables exploiting the interaction from all these formulated problems, which in turn leads to robust solutions using various methods within.

5 Conclusions

The paper reports the application of structural health monitoring techniques and methodologies for the structural safety and reliability assessment of historic buildings and monuments. Advanced SHM data processing for uncertainty quantification and reduction in static and dynamic monitoring parameters have been demonstrated. The main aim is to determine, with a high level of confidence, the structural behavior of historic buildings. A special consideration was given for SHM platforms. A benchmark report was carried out aiming to understand and illustrate the current state-of-the-art in the field of SHA and SHM for heritage structures. Case studies described in the literature presents the review on various methodologies adopted by different countries around the world in assessing and monitoring of Heritage structures. Special focus on latest technologies like Artificial intelligence and sensors are discussed to address these challenges. The survey made in the paper on the assessment and monitoring of heritage structures and the inclusion of latest technologies will become baseline of understanding and scope for the researchers in this field to develop new strategies for conservation and preservation of Heritage structures.

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