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A Brief Review on Smart Structural Health Monitoring Technologies

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Abstract

Structural Health Monitoring (SHM) is a method to determine the current status of the structure and the damages in the structural elements with minimum labour involvement. Structural health deteriorates over time and depends on loading on the structure and environmental conditions. Therefore, SHM is essential for safety and durability of structures. This chapter deals with different sensing methods like Global Positioning System (GPS) and Internet of Things (IoT) for monitoring the structural health. Application of different sensors like fibre optic sensors, magneto-strictive sensors, piezoelectric sensors and self-diagnosing fibre reinforced composites is involved in the smart sensing technologies. Their merits and demerits of are also mentioned in this chapter.

Keywords

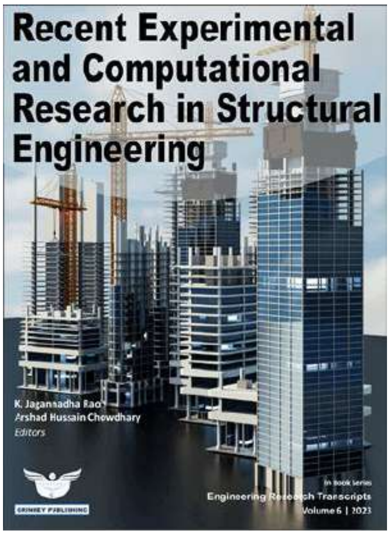
Finite element model (FEM), sensors, Global positioning system (GPS), Internet of things (IoT), Structural health monitoring (SHM).

Received: 20 Mar 2023 | Accepted: 12 Dec 2023 | Online: 20 Dec 2023

Cite this article

P N Nirupama, T Raghavendra, N G Shahanawaz and C V Manjunath (2023). A Brief Review on Smart Structural Health Monitoring Technologies. Engineering Research Transcripts, 6, 81–88.

https://doi.org/10.55084/grinrey/ERT/978-81-964105-2-0_8



1. Introduction

Monitoring the health of the structure is essential for safety and also it helps in reducing cost of reconstruction by increasing the life of existing structures. Energy conservation can also be increased by efficient monitoring of the structure. In recent times, construction of tall buildings is increasing due to lack of adequate construction sites and it has become a dominant means of accommodation in metropolitan cities for business where economy and population grow fast [1]. This makes the SHM crucial.

SHM involves crack detection, corrosion diagnosis, compressive strength etc. Causes of damages in short term include improper curing, vibrations, shrinkage cracks, and improper workmanship whereas long term factors include degradation of materials and weathering of the elements, corrosion of rebars, seepage, type of loading on the structure, lack of maintenance and environmental degradation. Inadequate SHM has led to cases of collapse of structure by formation of embankment cracks, premature removal of scaffolding, excessive tightening of cables and many more [2]. SHM is a powerful tool to detect damage in the structures. Due to advancement in technology, there is a shift from wire-based assessment of structure to internet of things and artificial intelligence. Advancement in the method of structural health assessment has made the process easier and less time consuming. Being aware of the new technologies help future advancement in the process of SHM and practicing professionals can choose a suitable SHM method according to their conditions. This paper deals with different methods involved in SHM and the materials used. It includes different sensors and GPS technologies. Global positioning system (GPS) technology is another advanced monitoring tool which measure real time dynamic characteristics and static displacements. Structure exposed to high temperature is also given emphasis for health monitoring [3].

2. State of development in SHM

The measurement of deformation and strain in different structural components is the starting stage to evaluate damage. Structural health monitoring consists of four stages where first stage involves damage detection, second stage involves tracing of damage growth and its dimension and position. In the third and fourth stages, damage growth is assessed and prevented [3]. Operational protocol of SHM includes four main steps (i) Data acquisition, (ii) System identification, (iii) Condition assessment and (iv) Decision making [4].

In many cases structures are built on weak soil requiring effect of soil structure interaction (SSI). For its numerical analysis, two types on models are available which are direct approach and sub structuring approach. Direct approach uses FEM to discretize the combined system, whereas sub structural approaches study each component independently using semi-analytical or discrete models, then combine them using compatibility and equilibrium conditions at the common interface [4].

Oscillatory movement of the structure due to vibration is measured using accelerometer. Commonly used accelerometers for SHM include piezoelectric, electromagnetic, optical, piezoresistive and micro electromechanical (MEMS) based devices. Many optic sensors used are Fibre Bragg Grating (FBG) sensors which require special encapsulation while measuring vibration as it is fragile. When these sensors are used in high temperature environment, two sensors are required to compensate temperature effect [3], [5], [6].

A dependable, in-situ, non-destructive tool for monitoring, diagnosing, and controlling civil structures is the fiber bragg grating (FBG) sensor. FBG sensors have emerged as an appropriate solution for longitudinal strain measurement in static and dynamic strain sensing and acousto-ultrasonic sensing in a number of application areas due to their inherent qualities, such as light weight, immunity to electromagnetic interference and harsh environments, and ability to be multiplexed for distributive measurement [7].

The placement of the sensors plays a significant role in increasing the modal data quality in SHM. The number of sensors used affects the quality of the data. So optimum placement of sensors must be adopted and its configuration for dynamic response during the course of test is important [8]. IoT sensors are installed at different locations and the data collected is transferred to a cloud-based platform [2].

Finite element modelling (FEM) method deals with condensation of superstructure model to a single degree of freedom oscillator, which represents a basic design quality like the top storey displacement [4]. In reference [1], sixteen accelerometers were adopted to determine how the structure responds to vibration. At the base of the structure the accelerometers are set to threshold value to capture earthquake response. Frequency domain decomposition (FDD) method is used for mode shape identification in the system and modal frequencies which transforms the data from time domain to frequency domain. On the basis of the free decay of the impulse response function, damping identification is done. FEM is created in software platform and FEM updating was performed. It was observed that the damping diminishes with the increase in height of the structure [1].

On comparison of the various vibration-based damage detection techniques, including time series analysis, local diagnostics, non-probabilistic methodology, and fundamental modal analysis, time series analysis is discovered to be more effective than the other methods in identifying damage. All of these methods take into account various structural factors to identify deterioration [9].

Among the smart sensing technologies are applications of sensors like self-diagnosing fiber reinforced composites, piezoelectric sensors, magnetostrictive sensors, and fiber optic sensors. Piezoelectric composites, piezoelectric polymers, and piezoelectric ceramics are some examples of different types of piezoelectric materials [10].

Machine vision-based technology has been extensively utilised to assess structural displacement, dynamic response, strain/stress, crack, and spalling in 2 and 3 dimensions due to their distinct advantages for structural monitoring. In addition to the already used vibration-based analysis techniques, the identification of structural dynamic parameters and damage diagnostics can be done using machine vision technologies [11].

Self-diagnosing fibre reinforced composite contain electrically conductive phase and conductive powder. The magnetostrictive effect causes ferromagnetic materials to mechanically deform when exposed to a magnetic field. Inverse magnetostrictive effect is when a material is deformed, a magnetic field is induced in the opposite direction. Based on these phenomena, magnetostrictive sensors (MsS) are invented. These sensors operate in ferromagnetic materials to produce and detect guided waves without making direct contact with the surface. [10].

Fibre optic sensors (FOS) are implanted in newly built structures as well as positioned on the exterior of existing structures like bridges, buildings, and dams. Static and dynamic stresses, temperature, flaws including corrosion and cracks, and chloride ion concentration are the data collected. Loss of optical transmission and ultrasonic wave technologies are the foundation for crack detection. Colour modulation helps in detecting corrosion, pH and chloride content. Fig. 1. shows measurements where FOS is compared to electrical strain gauges and vibrating wire gauges when stresses are slightly more than 40% of the concrete compressive strength [10], [12].

FOSs have shown to be a useful tool for tracking changes brought on by heat in composite layer architectures. The primary benefit of FOSs in terms of applications is the dispersed kind of measurements, which provide crucial information regarding the local failure of intumescent coatings along the entire sensing fiber without spatial gaps. All embedded sensors should have modest dimensions in order to prevent air inclusion or resin pockets from causing pre-damage to the layer structure. This improves integration into the structure being monitored while also raising measurement sensitivity [13].

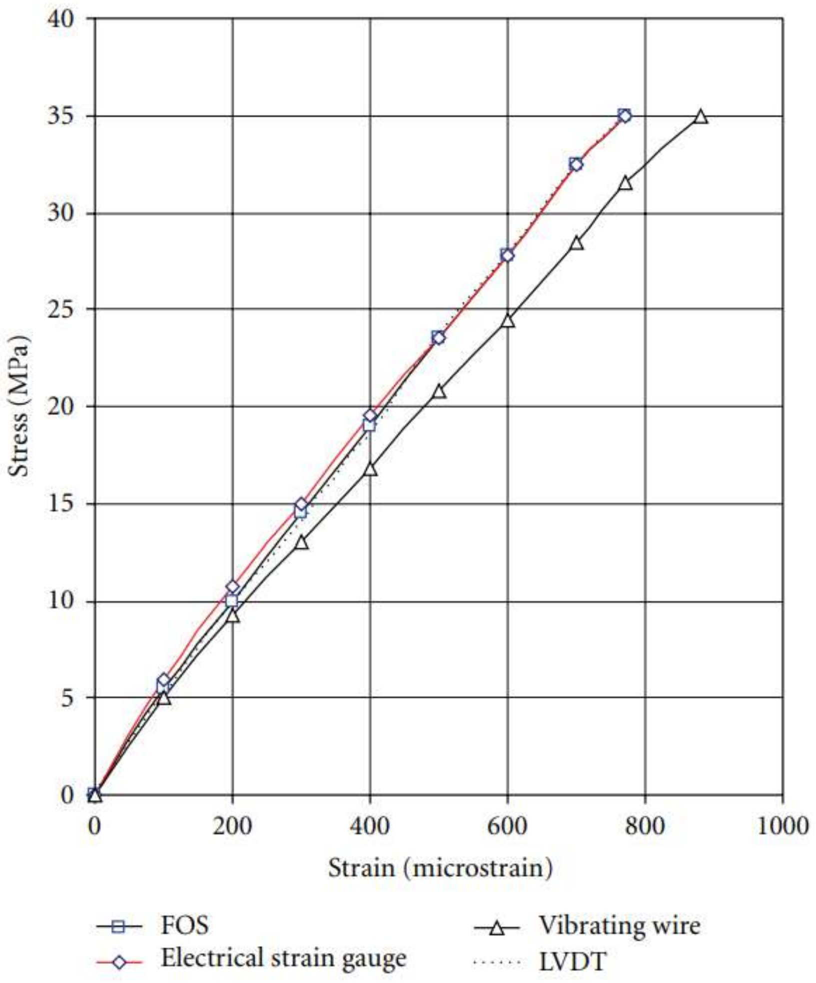


Fig. 1. Comparison of strains in concrete with various sensors [10]

SHM based on IoT consists of five layers as shown in Fig. 2. Layer 1 includes sensors and actuators, helping to generate and collect data through sensor nodes placed on the structural elements. Layer 2 includes internet gateway and network communication, which consists data acquisition systems and internet gateways. Layer 3 includes data analytics and cloud computing which uses machine learning techniques for pre-processing the data before they are sent to the cloud. Layer 4 include data interpretation and layer 5 include session or message, which analyses the pre-processed data from layer 3 and provide the result to broadcast the correct response to the cloud [2].

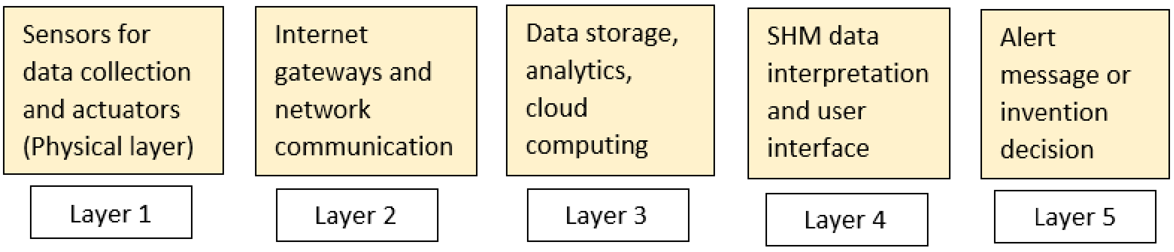


Fig. 2. IoT architecture for SHM applications [2]

Early-stage concrete compressive strength can be monitored by IoT based sensors by detecting the temperature within the concrete mix. This temperature depends on heat of hydration and age of concrete[2].

The application of global positioning system has led to direct measurement of deflections in the structures otherwise the measurement required solutions like liquid levels, laser interferometry, plumb lines, and digital image processing. A satellite-based radio navigation system is called GPS. A differential GPS accurately measures deflection from the radio waves from satellite to receiver. It is used in surveying long span bridges. It is capable to provide quick and precise measurements of the static position. Calculation of distance between receiver and GPS satellite is as shown in Fig. 3.[14].

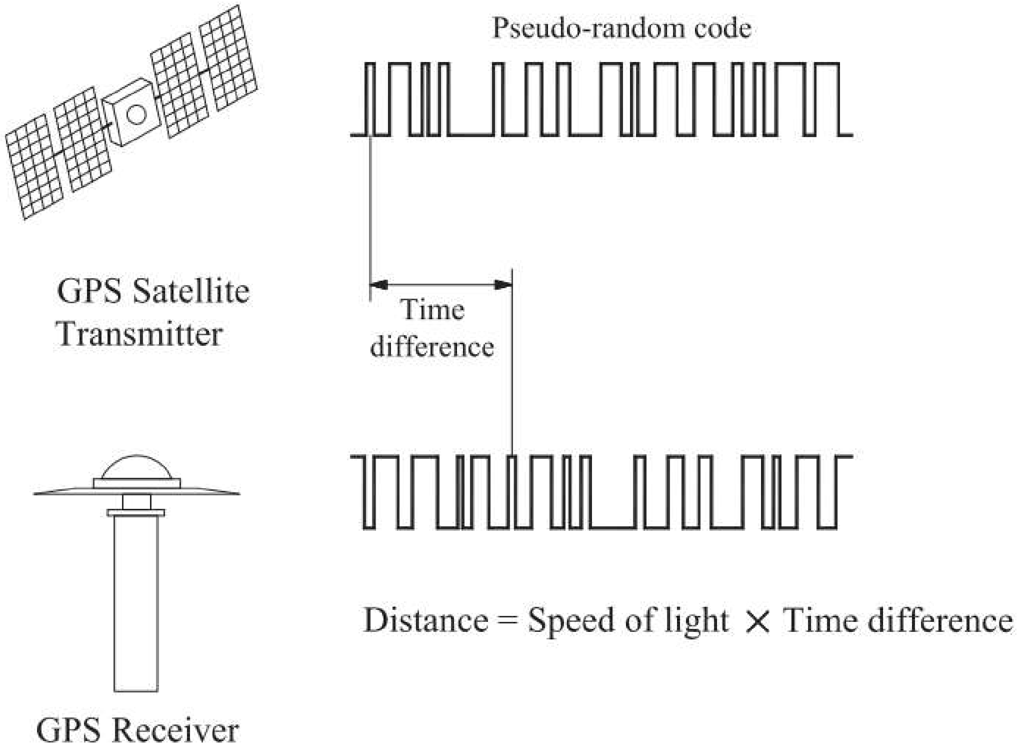


Fig. 3. Calculating the receiver's and the GPS satellites distances [14]

Limitations of the structural health monitoring are,

- System reliability – The system's expenses for purchase, installation, operation, and maintenance should be minimal.
- Inappropriate instrumentation and sensor overload –Tendency of over-instrumentation occurs.
- Data storage and data overload occurs.
- Allowance must be made for the fallibility of sensors as they may not be100% reliable.
- They produce noise and have environmental effects.
- Proper data mining and information presentation has to be made.
- Funding is required
- There exists lack of collaboration among industry and academic background[14].

Environmental factors affect the data measured by the sensors. Conditions like traffic, humidity, wind, solar radiation and temperature affect the data such as modal parameters which prevents the structural damage to be detected. Temperature has huge effect on modal variation, and modal frequency change due to change in temperature may reach 5% to 10% for highway bridges [15].

For the bridges, the spatial placements and significance of each bridge component to the overall bridge system should be taken into account while doing the dependability assessment of the bridge system. Based on real heavy vehicle traffic data from SHM and findings from the structural condition evaluation of the bridge components, several conclusions might be made [16].

Due to historical masonry structures' unpredictability with regard to elements like material properties and boundary conditions, it is possible that an accurate depiction of their actual behaviour will never be possible, especially if they suffer significant external damage like a serious fire. Due to this, historical structures must be tested using non-destructive techniques considerably more regularly, such as the Operational Modal Analysis (OMA) method [17].

Opto-electronics advancements have brought the field of SHM to a very high level, opening up a wide range of designs with excellent potential. Due to its flexibility and lack of electromagnetic interference, araldite-based piezo-optic pressure sensors are therefore very important. The field has made significant advancements in a short period of time and is both mature and developing in different ways. Future restrictions scarcely seemed severe from a technology perspective [18].

3. Conclusion

SHM has become essential for structures to detect early-stage damages. Advancement in technology makes the monitoring process easier to increase the service life of engineering structures. Real time structural data can be obtained from sensors by using IoT technologies. Damping of the structure is necessary for seismic performance. Advantages of FOS is that it can work in severe natural environmental conditions and have huge sensing scope, lower transmission loss and has anti electromagnetic interference. Also, it has a good signal to noise ratio compared to strain gauges. Defect detection in laboratory can be done using FOS but field examples have not been fully investigated [10]. Despite providing reliable findings for a variety of benchmark functions, the human-based metaheuristic optimization technique known as social group optimization (SGO) has not been investigated for structural health monitoring issues in civil engineering [19].

Through integration with various sensing approaches, the vision-based systems have the ability to deliver more useful information for visual inspection and structural monitoring [11].

More and severe research is required in developing sensors that can effectively work in high temperatures [3]. Structures' dynamic behaviour is significantly influenced by non-structural elements [8]. Post processing is necessary for accelerometer systems to minimize integration error [20]. GPS technologies measure displacements in real time. Both static displacement and dynamic properties can be evaluated. The use of GPS is restricted to flexural structures like cable-supported bridges and tall buildings. Real-time stress and strain conditions for structures are provided by the application of both GPS and FEM data [20].

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