A Review on Health Monitoring Methods of Civil Structures and its Recent Advances.

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***Abstract*—** We are seeing an incredible advance in construction activities in the field of structural engineering in the late years. Major structures like buildings, bridges, dams are subjected to intense loading and their performance is likely to change with time. To ensure critical structures safety operation, the structural monitoring system is required. There is also a need to understand the conditions giving rise to past failures and ways to avoid such failures in the future so that loss of life can be minimized. Because of this reason, the need for structural health monitoring (SHM) is emphasized throughout the world. So in this paper, different types of damages that structures are getting affected are discussed and a brief review of structural health monitoring methods conducted in the recent years for monitoring the health of structures is presented.

***Keywords*— Structural health monitoring (SHM); damage detection; vibration; crack; wireless sensor network (WSN)**

I. INTRODUCTION

The process of implementing a damage detection and characterization strategy for engineering structures is called Structural Health Monitoring (SHM) [1]. Damage can be defined as changes in the material or geometric properties of a structural system. It unfavourably influences the system's performance [2]. The Structural health monitoring process incorporates the observation of a system over time utilizing the measurements of sampled dynamic response from an array of sensors, the extraction of damage-sensitive features from these measurements, and the statistical study of these features to determine the present condition of the system. Structures expertise deterioration and harm over their lifetimes due to environmental and excessive load conditions such as humidity, corrosion, earthquakes, gust waves, traffic and others. This leads to structure deformation, cracking, dislocation and even collapse. Structures have a vital role in the safety and economy of the nation. Thus, the increasing demand for the safest and most functional structures has driven the SHM research of data acquisition and its analysis of indicators of the structure health [3].

Advanced sensors and monitoring technologies can play a very important role in prioritizing the repair and rehabilitation process, rising the cost-effectiveness of analysis and maintenance, and ultimately enhancing the longevity and safety of those civil infrastructure systems. Extensive research has recently been performed to check structural integrity using structural vibration data measured by in-structure sensors such as accelerometers. However, one amongst the key obstacles preventing sensor-based observation is that the inaccessibility of reliable, easy-to-install, and efficient sensors [4], [5]. Civil engineering structures place unique demands on sensors. SHM involves five main steps as in Fig. 1.

Fig. 1 Basic steps involved in Structural Health Monitoring

II. TYPES OF DAMAGES AND DEFECTS OF CONCRETE STRUCTURES

The concrete structures deteriorate during their lifetime due to mechanical, physical or chemical attacks [6]. Mechanical damages in a concrete structure can be because of effect of load on the structure. Physical damage in concrete structure might happen because of abrasion, erosion of concrete, efflorescence or leaching, and even because of thermal effects. Chemical attack on concrete structure is usually based on environmental condition or the surroundings. Another sort of chemical damages can be due to bacterial attack, direct chemical exposure or alkali-aggregate reactions. Damages can likewise be caused via carbonation or Stray/Electrical current.

As wonderful as bridges may be, there are certain reasons a mega structure could collapse. Five common causes of bridge collapse [7] are natural disasters, construction & demolition incidents, design & manufacturing defects, improper or neglected maintenance and fire. So, we can say that most bridge failures happen due to the combination of factors.

III. IMPORTANCE OF STRUCTURAL HEALTH MONITORING

In addition to the necessity to stay structures running steadily, maintaining the safety of public is also of great significance. Different mechanized apparatuses and systems have ascended to enhance the investigation forms and analysis of structures for the well-being of society. Benefits of conducting SHM are; Increased Public Safety, Detecting Early Safety Risks i.e. it helps to mitigate catastrophic risks, it helps increase the longevity of structures, Cost Efficiency i.e. by keeping up structural integrity for extended period of time which lessens the overall prices associated with demolition and reconstruction.

IV. WAYS OF CONDUCTING SHM

A structure alludes to an arrangement of associated components used for supporting the load [8]. Vital examples associated with civil engineering includes buildings, bridges and towers and in different branches of engineering; tanks, pressure vessels, ship and aircraft frames, mechanical systems, and electrical supporting structures. Such structures are made out of at least one strong components orchestrated so the entire structures as well as their parts, can keep themselves with no calculable geometric change amid loading and unloading. Structural Health Monitoring can be done in several ways:

A. ***1. Visual Inspection:*** It reveals the useful information about area of structure that needs a closer look. Usually it is primary evaluation of a structure. It is normally a walkthrough observation of the structure and is fully experience-based.

***2. Non-Destructive Evaluation** (NDE):* It is the properties analysis of a structure without any physical damage to the structure. This demands a high degree of expertise [1]. This method is time-consuming and costly. Likewise more often requires an earlier learning of the conceivably harmed region. It works solely in accessible regions of the structure.

B. ***1. Static-Based** SHM:* In this method, the static responses of the structural system are measured due to static loading. It is based on damage to the static properties of the structure like displacements, rotations. But its limitation is for a considerable static deflection it requires great amount of static force.

***2. Vibration-Based** SHM:* It is based on the speculation that harm can change the dynamic properties of the structure.

Here, it is possible to recognize the damage occurrence by measuring the structural response by means of sensors strategically placed on the structure, and intelligently analysing the measured responses. It can be done either in modal domain or physical domain. Vibration Based SHM has two main techniques:

a. Model-Based Techniques: These are based on a model of the structure to be monitored.
b. Data-Based Techniques: These are based on statistical, instead of using physical models of the structure. It is called so because the features extracted from the structural response are obtained by simple operations performed on the response time histories itself, and do not require any physical model assumptions.

V. MONITORING METRICS AND COMMON SENSORS USED FOR SHM

Monitoring metrics are a system of parameters intended to measure bridge condition and performance. Depending on the type of bridge and the needs of the bridge owner, different measurements should be taken in order to properly monitor bridge health. They are: Acceleration, Climatic conditions, Load, Corrosion, Cracking, Strain, Pressures, and Dampness etc.

Common Sensors used for SHM are;

- Vibration measurement sensors like accelerometer, deflection/bending sensor, strain gauge & acoustic sensor.
- Environmental sensors like pressure sensor, temperature sensor, moisture sensor & corrosion sensor.

Many numerical methods which can be used for SHM are there. The most adaptable seems to be the Finite Element Method. The frequently used method is the Spectral Finite Element Method (SFEM). ANSYS, ABAQUS, NISAII, STRAND7 are few available advanced commercial FEM package.

VI. A BRIEF REVIEW ON RECENT DEVELOPMENTS IN SHM

Structural Health Monitoring (SHM) is such an application wherein sensors distributed all through a structure are utilized to evaluate the structure's health. Traditionally, Structural health monitoring systems were designed using the wired network of sensors; despite that, the high dependability and low costs of installation and upkeep of Wireless Sensor Networks (WSN) have made them a convincing alternate platform. A recent study [9] presents an extensive review of SHM using WSNs summarizing the algorithms utilized in damage identification and localization, also outlining the network design challenges and the upcoming research trends. Solutions to these network design problems are compared and discussed. An outline of the key differences between wired sensor networks and WSNs for SHM is presented in Table I [9].

TABLE I
COMPARISON BETWEEN WIRED SENSOR NETWORKS AND WIRELESS SENSOR NETWORKS

Parameters	Wired Sensor Networks	Wireless Sensor Networks
Cost	Expensive	Cheaper
Time of Deployment	Very long	Quicker
Lifespan	Longer because it is usually limited by hardware lifespan	Shorter because it is usually limited by battery life of nodes.
Number of Sensors	Usually, lower due to difficulty of sensor installation	Usually, higher due to ease of sensor installation
Connection Bandwidth	Higher bandwidth because of wired connection	Lesser bandwidth and undependable connection
Sensor Data Rate	Higher	Lower sensor data rates but higher than traditional methods of WSN.
Sensor Synchronicity	Higher because of wired connections	Lower because of wireless connection

In modern years, there has been growing interest in performing Structural Health Monitoring (SHM) by monitoring structural dynamic response via Micro-Electro-Mechanical System (MEMS) accelerometers. For use in SHM applications, MEMS accelerometers are required to perceive the vibrations of low-amplitude and low-frequency. Since the late 1990s, few accelerometer board models have been proposed [10], for achieving precise vibration monitoring. Studies [11] and [12] have shown that how three 1-axis accelerometer is efficient and economical than using one 3-axis accelerometer for monitoring. It is demonstrated that 1-axis accelerometers based device [11] has achieved cost saving of 59.59% with a high sensitivity of 2000 mV/g. Further studies having Building Structure Health Monitoring Device (BSHMD) [12] achieves cost saving of 64.3% using three 1-axis accelerometers with the problem of data synchronization being solved with effortless installation and removal. Compared with the previous structural monitoring device, 89% of area saving is also achieved. These days, large outdoor advertising boards are prevalent in the prosperous area of a city, or along the main road or the highways. These outdoor advertising boards can pose a serious hazard to the public safety. So recently studies [13] are going on in this concern. It helps to assess the safety of the outdoor advertising boards and give early alerts when the boards are being in risk.

There is also a need to improve the lifetime of WSN for SHM system. A sensor node is mainly powered by a non-rechargeable battery with the limited capacity of energy storage. As a result, a WSN can function only for a limited span. A lot of researches have been dedicated to increase the lifetime of a WSN by improving its energy efficiency. One such work is presented in paper [14], in which a solution is proposed by the joint use of optimal power and route selection with and without energy harvesting. The solution is based on the Branch-and-Bound technique with a space reduction algorithm to speed up the computation. The heuristic routing algorithm is used to reduce the computational complexity. It provides the solution for maximizing the lifetime of WSNs. An inductor-less interface circuit for piezoelectric vibration energy harvesting [15], shows high power efficiency over a wide range of excitation levels. Furthermore, it enables a fully CMOS integrated implementation, reducing overall system volume.

A strain is one of the most widely measured quantities to assess whether the loading and fatigue of engineering structure are within safe load levels or not in SHM applications. So many studies over SHM have considered strain as the major parameter in their work. Most WSNs are powered by batteries which have limited lifespan and need to be replaced regularly. Interesting realization of a single piece of macro-fiber composite (MFC) piezoelectric transducer [16] as a multifunctional device for both strain sensing and energy harvesting is done by researchers. The MFC is used as an energy harvester for charging up the storage capacitor or else, the harvested energy is used for powering the system and the MFC is used as a strain sensor for measuring dynamic structural strain. The dynamic strains measured by the MFC are matching extensometer by 95.5 to 99.99 % and can be used for SHM of dynamic strain. Also, "a semi-passive wireless strain gauge sensor" [17] allows measurement accuracy comparable to that of wired strain sensors. It overcomes the limits of devices based on WSNs and those based on similar RFID-based sensors.

An idea of an electronic circuit that has to be embedded in a photodiode sensor as an integrated circuit board for electronic signal processing that detects the energy center of an optical signal, which represents the most accurate position measurement from a light emitter source mounted on a structure is presented [18]. The light emitter is utilized to decide if it has experienced any displacement. It is suitable for any sort of structure surfaces and data storage budget. As Signal processing stage is embedded into the sensor it doesn't require extra software processing, which reduces the time and memory spacing requirements.

Cracks in concrete or cement based materials present a great threat to any civil structures; they are very hazardous and have caused a lot of ruination and damage. Leaving aside manual inspection which is ineffectual and time-consuming, several NDE techniques have been used for crack detection such as ultrasonic technique, vibration technique, and strain-based technique; however, some of the sensors used are either oversized or narrow in resolution. A high resolution microwave imaging technique [19] with ultra-wide band signal for crack detection in concrete structures is proposed for crack detection of small size of 5mm. In the past, several methods for automatic crack detection have been proposed [20], [21], [22]. However, the segmentation of cracks from the concrete image is little difficult because of the irregularities in crack shape and size. These often lead to false detection. Nowadays, the interest in automatic crack detection on concrete structure images for non-destructive evaluation has been expanding. Two pre-processing to remove noises for crack detection, a line filter based on the Hessian matrix to emphasize line structures associated with cracks, thresholding processing to separate cracks from background. These methods are effective for detecting cracks on noisy concrete images [23]. Method to calculate the natural frequencies of a multiple cracked beam and detecting unknown number of multiple cracks from the measured natural frequencies has been studied [24]. Crack parallel to length direction may come up in beams of layered isotropic materials or composites during fabrication and/or in service. An endeavor to study the natural vibration of monolithic beams with longitudinal cracks for developing a way for its detection has been presented [25].

Not only the detection of damage but also localization of damage area very much important task in SHM. Damage localization is based on determining the time for the signal to travel from the source to the damage and reflected i.e. Time of Flight (TOF). Finite element simulation is performed [26], using ABAQUS/Explicit finite element software to study the damage size effect on the damage localization accuracy using the 3-point pulse-echo technique. Wigner-Ville Distribution (WVD) is used for noise elimination and calculates the TOF based on its excellent time-frequency- energy distribution.

Despite the huge technologies developed in recent years, there is still room for further evolution including virtualization of sensors and IoT devices, scalability, heterogeneity, interoperability, and safety. Moreover, techniques for IoT integration [27] into SHM to effectively achieve real-time data collection, data processing, event-driven, and real-time decision-making should be taken into account for future research. As the amount of information generated by sensing devices are expansive and quicker than at any other time, big data solutions are introduced to manage with the complex and huge data gathered from sensors that are installed on the structures. New services that can be delivered to urban environments through big data generated by the public's smartphones, amplifying the relationship between a city and its infrastructure are studied [28]. Mobile sensor networks are conducive to monitoring vibrations of urban bridges regularly, with benefits that are been demonstrated in modern researches.

VII.CONCLUSION

Besides having effective approaches to the regular maintenance of bridges and to keep structures running steadily, maintaining safety and public health is also of great importance. In this paper, the importance of structures, possible causes of damages of structures, ways of conducting structural health monitoring are discussed. Also, the brief review of recent advances in the Structural health monitoring is presented.

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