Research Article

Development of Smart Sensing Technology Approaches in Structural Health Monitoring of Bridge Structures

Arvindan Sivasuriyan [1,2] **D. S. Vijayan** [3] **A. LeemaRose** [4] **J. Revathy** [5] **S. Gayathri Monicka** [6] **U. R. Adithya** [7] **and J. Jebasingh Daniel** [8]

[1]*AarupadaiVeedu Institute of Technology, Vinayaka Missions Research Foundation, Paiyanoor, Chennai 603104, India*
[2]*Anand School of Architecture, Chennai 603103, India*
[3]*Civil Engineering, AarupadaiVeedu Institute of Technology, Vinayaka Missions Research Foundation, Paiyanoor, Chennai 603104, India*
[4]*SRM Valliammai Engineering College, Chennai, Tamil Nadu, India*
[5]*Civil Engineering, B.S. Abdur Rahman Crescent Institute of Science and Technology, Chennai, Tamil Nadu, India*
[6]*EEE, SRMIST Ramapuram, Chennai, Tamil Nadu, India*
[7]*KTH Royal Institute of Technology, Stockholm, Sweden*
[8]*Department of Civil Engineering, Hawassa University, Hawassa, Ethiopia*

Correspondence should be addressed to D. S. Vijayan; vijayan@avit.ac.in

In recent years, immense development in Structural Health Monitoring (SHM) of bridges helps address the life span and reliability of bridge structure at contrasting phases of their service life. This article provides a detailed understanding of bridge monitoring, and it focuses on sensors utilized and all kinds of damage detection (strain, displacement, acceleration, and temperature) according to bridge nature (scour, suspender failure, disconnection of bolt and cables, etc.) and environmental degradation under static and dynamic loading. This paper presents information about various methods, approaches, case studies, advanced technologies, real-time experiments, stimulated models, data acquisition, and predictive analysis. Future scope and research also discussed the implementation of SHM in bridges. The main aim of this research is to assist researchers in better understanding the monitoring mechanism in bridges.

1. Introduction

Civil engineering structures include buildings, bridges, and dams that are beginning to fail from original quality once constructed, and the usage of buildings and infrastructures is unavoidable to the whole world. Therefore, it is necessary to know about the functioning of structures in terms of their life span and usage level. Excess dynamic forces such as earthquakes, heavy wind, environmental changes, and heavy goods-vehicle must track the structural integrity and detect the damage and frequently referred to as structural health monitoring [1]. The main motive of structural health monitoring (SHM) is to evaluate the performance and identify the bridge's physical state and other structures [2].

SHM of the bridge structure is an essential topic among researchers concerning the bridge structure, and the most contemporary studies contain monitoring of dynamic behavior, strain, displacement, acceleration, temperature, and loads. SHM is purely dependent on sensors and their applications. Bridge structures consist of wired and wireless sensor networks, which help monitor the structure and provide data accurately. The placement of sensors in bridge structure will deliberately depend on previous practice. The SHM of the bridge structure is necessary to improve and deserve development in research and development.

This article outlines the proposed policy and plan in SHM of bridge structure and provides valid information about current techniques and technologies in bridge

structures. The applicable bridge structure properties, parameters, loading, and conditions are conferred and discussed. Monitoring of bridge structure has some operational strategies, including selecting sensors, deploying, tools and automated technology, storage, and transmission. SHM in the bridge is highly dependent on automated strategies that are more advanced and easier to use. Therefore, those techniques have been discussed. However, techniques that are related to visual inspection are not examined. This article also addresses feature extraction and advanced data processing in SHM. Structure prediction will assist in anticipating damage to any structure at an early stage. For example, depending on the commutation of automobiles and loads on the bridge, the lifespan of a bridge with loads based on day-to-day traffic may be projected. Similarly, using predictive analysis, the load sustained by any structure over time may be used to determine the building's life span. Sensors installed at various locations (joints) of the structures may be used to monitor the structures.

The sensor receives information from the structure that will be monitored for health. The sensor will be selected based on the database's requirements. The information will instead be conditioned by amplification and filtering. The analog signal data will be transformed into digital form for computational processing in the next stage of data acquisition (DAQ). The processed data is then saved or sent to the appropriate access point.

2. Process of Structural Health Monitoring

In recent years, SHM of civil structures has been a critical topic for research. SHM helps to detect the damage of a structure, and it also provides early caution of a structure that is not in a safe condition for usage. Civil infrastructure like bridges gets damaged with time, and the reason for the damage is heavy vehicles, loading environmental changes, and dynamic forces such as seismic. These types of changes mainly occur at existing structures constructed long ago, and various methods will detect that damage. The strategy of SHM involves observing the structure for a certain period to notice the condition of the structure and the periodic measurements of data will be collected, and the features of data will be extracted from these computation results, and the process of analysis can be done with the help of a featured data to find out the present-day health of the structure. The information collected from the process can be updated periodically to monitor the structure and based on the data collected through monitoring a structure, and the structure can be strengthened and repaired, and rehabilitation and maintenance can be completed [3].

The nondestructive test will be the primary motive for SHM to evaluate the state and conditions of the structure in its lifetime, and the vital role of the SHM is the ability of the system to predict the health status of the structure [4]. SHM can be applicable for few factors in bridge structure to detect the quality of the problem at the right time, bearing capacity of the bridge structure to be checked and technical procedures to be followed to improve bearing capacity; reinforcement and risk factors should be considered based on

test results [5]. Structural problems may occur due to the low-quality execution during construction, lack of inspection and maintenance, and poor design, making the structure functionally low compared to its required strength [6]. To find the natural frequency and corresponding mode shapes of a structure, the global dynamic technique is used, and this technique will display the correct information about the position and sharpness of the damage [7]. The position and severity of cracks will be predicted using baseline data in the model properties [8]. Vibration based SHM technique plays a vital role in both static and dynamic response of a structure, and this technique will indicate the physical properties of a structure such as cracks, loosening and stiffness reduction, and magnitude estimation [9]. SHM of structure purely depends on sensor operations and Principal Compound Analysis (PCA) [10]. Stiffness reduction in structure is also verified by using a finite element model with the help of measured static and dynamic responses [11]. The analysis process can be done using finite element modeling (FEM) software, which is very powerful and shows accurate damage prediction results [12]. Overview of the SHM process is portrayed in Figure 1.

3. Damage Analysis and Prediction

Developing and developed countries should come up with modern structures using modern technologies. SHM plays a vital role among the recent technologies in civil engineering, and it plays an essential role in detecting damage.

There are four stages of damage prediction:

Stage 1: identification of damage present in the structure

Stage 2: geometric location of the damage should be analyzed

Stage 3: critical condition of the damage should be analyzed

Stage 4: predicting the remaining life span of the structure [13]

4. Needs for SHM

(1) Structural damage can be detected on time using SHM that leads to immediate action

(2) Design parameters should be confirmed without flaws because SHM is based on parameters affected by statistical variation and uncertainty

(3) Monitoring the design validation, stress, and external loads and understanding the structural behavior can be simplified by SHM [14]

(4) SHM is an effective way to know about the actual behavior of the structure, and it helps to enhance the future design of the structure

(5) SHM helps to predict the quality standard of the structure due to continuous monitoring

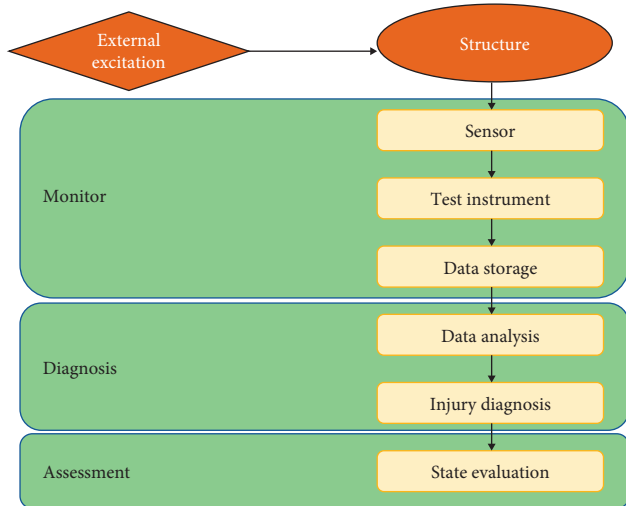(6) Early prediction of damages helps to save many people's lives and give a possible solution to control the damages

FIGURE 1: Overview of SHM.

(7) SHM plays a vital role in studying hidden information

(8) Usage of the SHM technique will avoid catastrophic failure and allow maximum use of structure

(9) The structure can be maintained well for both long terms and short terms

(10) SHM plays an integral part in reducing human error and improving the reliability and safety of a structure

(11) SHM is cost consumption comparing to general manual maintenance [15]

To spot the external sign of damage in structures, some techniques such as ultrasonic, radiography, acoustic, eddy currents, thermal magnetic field, or electromagnetic impedance can be used to predict the intensity of the damage. If needed, test samples may be collected and tested in the laboratory. However, critical parts of the structure may not be approached in this technique, and it is also hard and cost-effective, and it largely depends on the visual inspector with a high level of experience.

Many kinds of research have been discussed in the past decades to automate the visual inspection to predict the damage of the structure quicker and as an alternative is SHM methods which have intelligent materials such as piezoelectric, fiber optic, and shape memory alloys to work innovative according to environmental changes:

(1) Global dynamic techniques in SHM

(2) Electromechanical impedance (EMI) Technique in SHM

5. Global Dynamic Technique

According to this technique, the structure will be tested under the low-frequency stimulation, and this results in some vibrations responses such as velocities, acceleration, and displacements which are noted, and then few modes shapes and corresponding natural frequency have been determined. The health of the structure can be predicted by comparing baseline parameters and current parameters. The disadvantage of this technique is its low sensitivity to elemental damage.

6. Electromechanical Impedance (EMI) Technique in SHM

In this technique, the structure is embedded with a piezoelectric (PZT) sensors patch for monitoring purposes, and the sensor patch is the high-frequency range that forms the standard for monitoring the health of the structure [16].

7. Sensors Used in SHM

SHM technique purely depends on the sensors to monitor the structure, so different sensors can be used. There are many types of sensors used by the industry for structural health monitoring. Few are discussed in the following:

(1) Piezoelectric sensors (PZT)

(2) Fiber optic sensors (FOS)

(3) Microelectromechanical systems (MEMS)

(4) Acceleration sensors

(5) Displacement sensors

(6) Strain sensors

(7) Temperature sensors

These sensors have been used according to the requirement. Sensors are used for quick evaluation for health monitoring of structure when damage occurs. Figure 2 shows a few critical sensors usage in SHM and its operating principle and applications.

Venugopal et al. adopted a PZT sensor for monitoring the concrete cube size 150 mm × 150 mm × 150 mm and PZT patch of size 10 mm × 10 mm × 10 mm to predict the deviations and damage in the concrete structure [17]. Jeong-Tae et al. adopted PZT and acceleration sensors to record the wind speed and vibration responses in a cable strayed bridge under two consecutive typhoons. With the help of vibration monitoring, tension force has been estimated and wireless monitoring system is described [18]. Kim et al. conducted another experiment with piezoelectric sensor-embedded smart skin to analyze the structure's health status using the wireless technique to estimate tension force and vibration using temperature effects [19]. Huynh et al. have observed through their experimental process that PZT size should be maximum to have a flexible section, and it helps to identify the geometric size of the task for detecting damage [20]. Figure 3 depicts five levels of damage in the degree of complexity and SHM performance.

Mujica et al. employed different method to perform statistical analysis by using baseline PCA model in order to collect the sensor information stored in the structure to compare with monitoring outcome [21]. Park et al. used PZT patch for outlier analysis framework to anticipate bolt loosening in multistory building [22]. Annamdas and Soh adopted a PZT transducer, and electromagnetic interference
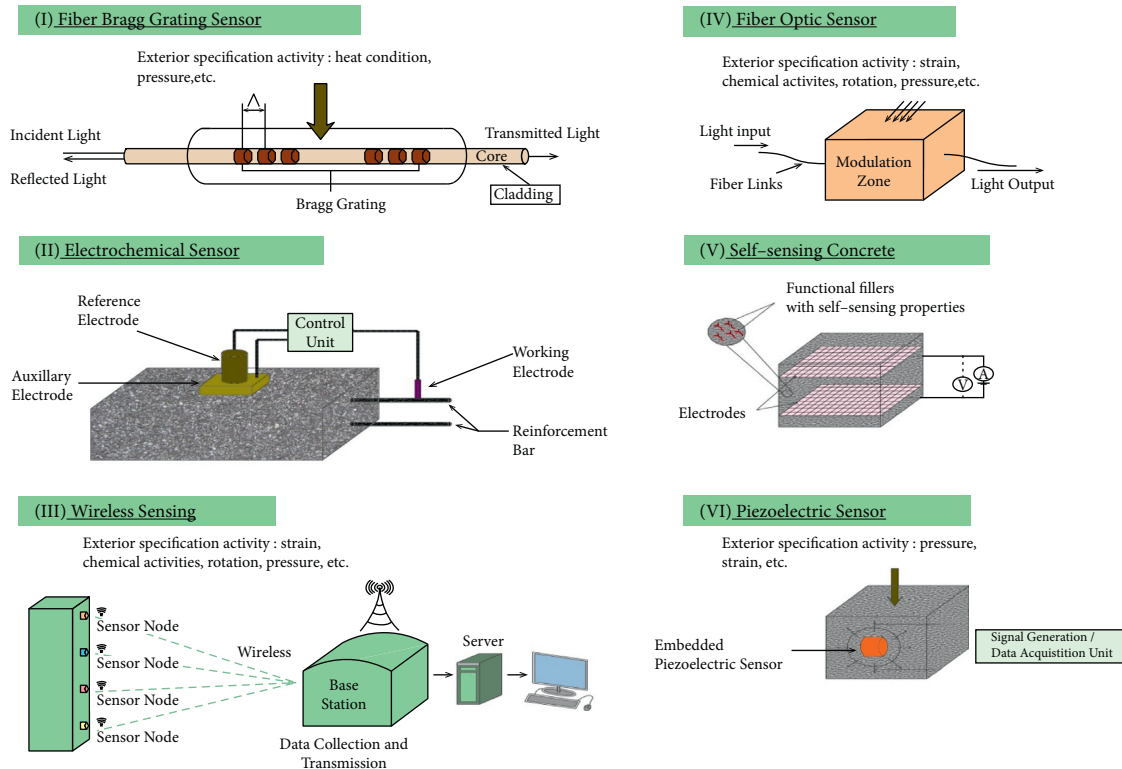
FIGURE 2: Some of the critical sensors used in structural health monitoring of a civil structure.
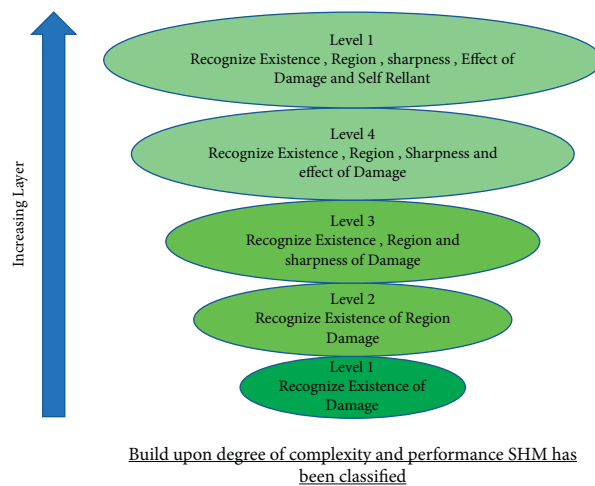

FIGURE 3: Levels of detecting damage in SHM.

(EMI) techniques have been used to monitor the structures. EMI models help analyze the structure, and the author reviewed the engineering structure that SHM techniques have done for the past two decades [23].

Park and Inman used advanced impedance-based SHM techniques to predict the damage, and variation in impedance will result in variation in structure. An autoregressive with Exogenous Variables (ARX) model has been constructed by measuring impedance data to analyze the structural damage with confidence [24]. Nguyen et al. carried out vibration and impedance tests for wind towers and developed a hybrid damage detection for wind towers to

monitor bold loosening due to vibration [25]. Figure 4 shows phases of power supply for piezoelectric sensors. Figure 5 represents the setup for piezoelectric sensors.

Park et al. conducted an advanced experimental study on railway track damage detection by using a two-step support vector machine (SVM) method using piezoelectric sensors, and the study successfully established the optimal separable hyperplanes [26]. Thanh-Canh et al. also implemented an impedance-based damage detection method for civil structures. It applies a high-frequency impedance response and senses the temperature effect, severity of damage, and durability [27]. Radhika and Annamdas used EMI and
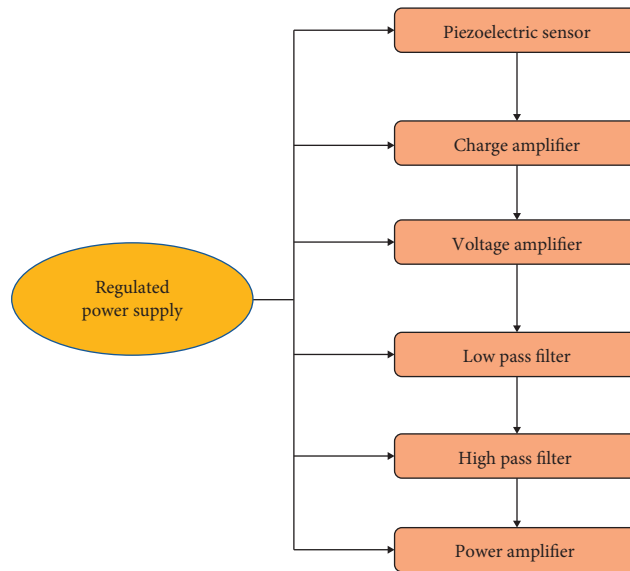
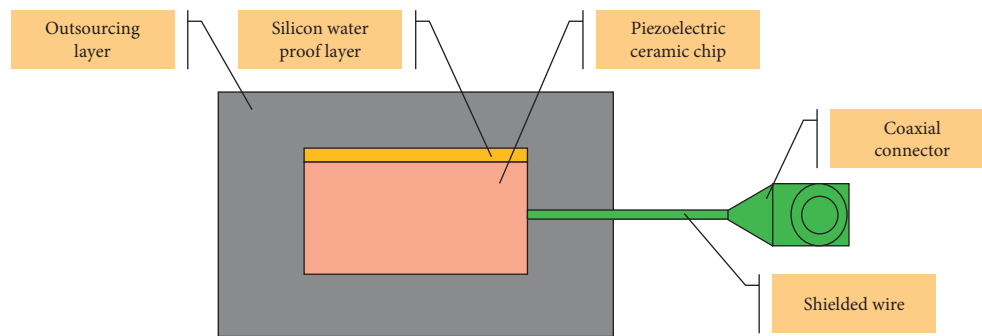Figure 4: Power supply for piezoelectric sensors.

Figure 5: Piezoelectric sensors setup in SHM.

electrical impedance to monitor axial compression loading, fatigue cycling loading, and axial buckling in civil structures [28]. Yang et al. used both FBG and PZT sensors for SHM of tunnel structure. Both sensors can give an accurate response in the monitoring of a tunnel structure. It exposes thermal expansion or temperature variation and vibration monitoring [29].

Annamdas and Radhika have applied electromechanical impedance technique based SHM and also used two sensors such as PZT and macrofiber composite (MFC) for concrete structure, timber structure, and concrete specimen [30]. Annamdas et al. adopted the EMI technique to check the level of stress and damage occurrence possibility in concrete and aluminum specimens in SHM [31]. Annamdas and Soh used the EMI technique with PZT sensors to predict the damage of structure using 3D model and root means square deviation (RMSD) methods for experimental investigation [32]. Suresh et al. used the EMI technique for SHM and nondestructive evaluation techniques applies two PZT sensors sizes, $10 \text{ mm} \times 10 \text{ mm} \times 0.15 \text{ mm}^3$ and $10 \text{ mm} \times 10 \text{ mm} \times 0.15 \text{ mm}^3$, which were used to pledge to the exterior portion of the two aluminum blocks sizes $48 \text{ mm} \times 48 \text{ mm} \times 10 \text{ mm}^3$ for monitoring [33]. Cunha and

Caetano used piezoelectric sensors to identify the damage in civil engineering structure, and experimental model analysis techniques have been obtained [34]. Figure 4 shows phases of power supply for piezoelectric sensors.

Suresh et al. employed cost-intensive impedance analyzers (LCR) meters for practicing EMI techniques with some low-cost equipment such as a digital multimeter and function generator. LCR measurements provide more accuracy compared to results, and excellent reports have been generated [35]. Huynh et al. proposed an EMI for monitoring prestressed tendon anchorages, and temperature effect has good accuracy using PCA based algorithm [36].

Bado et al. presented multiple sensing points as an ideal method to detect deformation and strain by using Distributed Optical Fiber Sensors (DOFS), and the experimental investigation has been carried out in real time by applying load in seven parallel S500 steel reinforcements at 20 mm diameter of rebar [37]. Jayawickrema et al. conducted an experiment using concrete beam dimension of $100 \text{ mm} \times 250 \text{ mm} \times 1400 \text{ mm}$ which was casted using M20 grade of concrete reinforced with 6 mm and 8 mm rebar for top and bottom reinforcement, respectively. The concrete beam was embedded with fiber Bragg grating sensors (FBG)

during casting, later examined under flexural loading up to 20 kN on a three-point bending position without a decrease in the structural strength. The FBG sensors are required to analyze the strain transfer. A finite element model was created by using FEA software ABAQUS, and the outcome of the analysis will be compared with experimental results [38].

Li et al. have presented a review of SHMof primary civil structures such as pile, buildings, pipelines, tunnels, dams, and bridges using fiber optic sensors and pointed out past obstacles. Auspicious investigation with collected information has been discussed. Fiber grating sensors are used to measure the strain displacements and cracks. The process of concrete deformation, shrinkage, period, and thermal swelling period has been monitored consistently and concluded that SHMusing fiber optic sensors show remarkable results. It seems to offer an outstanding improvement in the future [39].

Minutolo et al. have carried out an actual time experiment on concrete beam dimension 1800 mm in length and 200 mm in breadth. The primary and distribution reinforcement consists of 12 mm dia and 8 mm dia, respectively, to measure the tensile and compressive axial strain using Brillouin Optical Time Domain Analysis (BOTDA). The variation in strain within the beam's cross section will be measured using four sensing fibers positioned along with the beam. BOTDA sensors hold a constant report of the structure during load time history with proper reading. It concludes that bending moment and neutral axis are proper, and BOTDA is considered a suitable sensor to monitor the beam's structural behavior [40].

Lopez-Higuera proposed a review article on fiber optics sensors in SHM. Sensors should validate by it because it is necessary to make sure the data provided by sensors will act as an actual behavior of the structure. Optical fiber sensors (OFS) techniques will be used for heavy structures such as bridge girder, tunnel, and pipeline. Acoustic sensing can also be predicted by OFS technology in industrial structures [41]. Ko and Ni discussed SHM systems for large-scale bridges to examine the damage and collapse. Optimal maintenance of structure has been discussed. Significant issues such as recent technological improvement in the bridges, data acquisition, and innovative sensing have been carried out. It also demonstrated the communications signal processing and sensing systems in bridge monitoring. The valuable information has been collected, and it will be helpful to predict the damage and improve the reliability, durability, and integrity of the bridge structure [42].

Barrias et al. presented a review exclusively in SHM using distributed optical fiber sensors (DOFS) for civil structure and examined all the data which has been discussed with accurate results [43]. Taheri presented a review article on five critical sensors in DOFS. Significant advantages and disadvantages of the five critical sensors were discussed, and it was pointed out that fiber optics and Bragg gratings sensors are widely used for SHM [44]. Shu has used piezoelectric ceramic sensors with cement paste to monitor the RCC structure and found that sensors work fine with a concrete structure and point out

that sensitivity varies according to the size and shape of the sensors [45]. Figure 6 represents various types in fiber optic sensors.

8. Analysis and Characteristics of SHM in Bridges

Zhang et al. have presented an overview of SHM for masonry arch bridges using penetrating radar (GPR) and interferometric synthetic aperture radar (InSAR) technologies. GPR contributes structural detailing, and InSAR helps to compute displacements in structure. InSAR research took nearly 21 months to predict the behavior of the bridge structure under both static and dynamic conditions [46]. Alamdari et al. have carried out real-time monitoring on the Sydney Harbor Bridge in Australia with 800 Jack arches and help predict the irregular responses using the K-means clustering algorithm [47]. Saleh et al. carried out real time with 135 laboratory experiments and in situ studies from 2000 to 2019 by using Noncontact Testing (NCT) technologies to monitor the structure easy and quick compared to general methods:

(1) Environmental conditions and materials properties should be considered for GPR analysis

(2) Terrestrial laser scanner (TLS) methods should be used for different environmental conditions for live traffic

(3) For photogrammetric control, close-range photogrammetry (CRP) methods are used

(4) Infrared thermograph (IRT) techniques are used to produce automated data processing algorithms [6]

Roy et al. have used a multihopped wireless sensor network (WSN) for SHM in Kando Bridge, Japan, to predict damage and its location [48]. Eshghi et al. have used Mahalanobis distance (MD) techniques to predict the damage by using piezoelectric sensors network. A surrogate model has been developed to determine the performance of the structure [49].

Rodrigues et al. carried out real-time monitoring in Leziria Bridge, a concrete bridge embedded with vertical displacement transducer and strain transducer based on FBG sensor category to identify cracks, displacement, and damage creep and shrinkage [50]. Chae et al. employed five types of 45 sensors wireless in suspension bridges using ZigBee and code division multiple access (CMDA) approaches for long-distance wireless communications. The monitoring process happened around three months from April 2007 to June 2007 in Yeongjong Grand Bridge [51].

Wan et al. adopted fiber optic sensors for three-span bridge monitored under both static and dynamic loading conditions and pointed out that accuracy level is higher to predict the shape of displacement [2]. Li et al. experimented using OFG sensors embedded with glass fiber reinforced polymer (GFRP-OFBGS) in Ebian bridge to identify the fatigue damage and dynamic response [52].

Chakraborty et al. have carried out a real-time experiment in a natural bridge located in Gliwice (Poland) using various embedded sensors combined for long-term
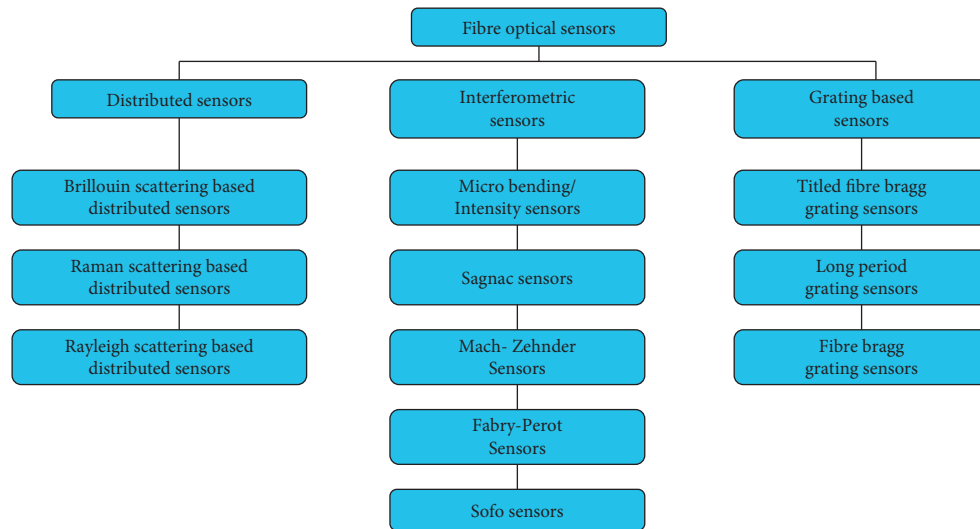
FIGURE 6: Fiber optic sensors in SHM.

monitoring of concrete structure to identify damage in fatigue assessment and strain measurements [53].

Mustaphaa et al. conducted an experiment using FBG sensors and Fiber Optic Sensors (FOSs) to predict loading data and severity of damage by using Convolution Neural Network (CNN) and support vector machine (SVM) techniques in small-scaled test bridge [54]. Pachón et al. carried out a real-time experiment in Historical Bridge of Posadas (Cordoba, Spain) by using optimal sensor placement approach to predict the damage. At the same time, genetic optimization techniques were used to find the dynamic responses and 3D models created for a better understanding of structural behavior [55]. Rodrigues et al. have monitored steel bridges to determine strain using FBG and experiment carried out in Eiffel Bridge, Portugal, and monitored for structural rehabilitation [56].

Chan et al. have used FBG sensors to monitor the Tsing Ma bridge in Hongkong, that is, 1378-meter-long suspension bridge, and it has been provided with 40 FBG sensors to monitor the structural health of a bridge [57]. Bremer et al. have used fiber optic crack sensors and fiber optic moisture sensors to detect crack and moisture and also a chemical reaction in concrete structure [58]. Iqbal and Khan et al. employed piezoelectric sensors in the wireless network to monitor hybrid bridge energy harvester (HBEH) to predict vibrations and damage [59]. Mei et al. have suggested two approaches, such as Mel-frequency cepstral coefficients (MFCCs) and PCA, and also dealt with vehicle bridge interaction (VBI) techniques by fixing sensors for detecting damage in both laboratory and numerical models that have been examined [60].

Wang et al. have carried out in real time in long-span cable-stayed bridge to record the dynamic behavior, acceleration, displacement, and variation in amplitude. Three modes have been considered to determine wind speed, and high frequency should be checked to determine the variation in acceleration [61]. Zheng et al. examined fatigue test and cyclic test in both loading and unloading conditions using

FBG sensors to monitor steel wire in bridge cable force [62]. Abruzzese et al. adopted embedded remotely handled Internet of Things (IoT) sensors to determine the accelerations and stresses in both laboratory and in situ experiments that have been carried out for current and future structures [63].

9. Necessity for SHM in Bridges

The functional supervision of bridges in real time is important for detailed risk assessment and taking measures. Damage surveillance is the sensor's primary input, while damage assessment and then use of information are the sensor's output data. These sensor data will be exploited to verify and determine the health of the structures. The output of this procedure is updated on a regular basis based on the structure's potential, and damage may be effectively treated. Dos Reis et al. employed local strain sensors to measure the strain data in suspension bridges by adopting a heuristic segmentation algorithm, and the statistical control of monitoring shows better results in the daytime. It would not disclose much during the night [64]. Shoukry et al. have carried out real-time monitoring in Star City Bridge in Morantown, WV. The measurement took around 306 meters over spans with 700 sensors for a long time monitoring lightweight bridge decks. The bridge performance has been monitored for 4 years to measure the stress, strain, and expansion joint using the LRFD approach [65]. Oskoui et al. carried out real-time monitoring on a five-span continuous precast posttensioned box girder bridge that is 332 meters long using Brillouin Scattering based on an optical sensor spot the microcracks appear in bridge [66].

Megid et al. used the acoustic emission (AE) technique using multiple sensors to detect dynamic behavior, fatigue, and the severity of cracks of steel bridge which are to be monitored [67]. Kister et al. carried out real-time monitoring on west mill bridge by using OFBG sensors. The bridge has been monitored for three years to detect the damage, and sensors survived successfully. The finite

element model is also used to predict the behavior of the structure [68]. Chilamkuri and Kone have experimented on varadhi road bridge to determine the displacement and vibration using accelerometers [69].

Whelan et al. have carried out real-time vibration monitoring on a long-term bridge using wireless sensors network (MEMS) to predict the vibration and other dynamic activities under traffic loads. Model analysis was also performed using a numerical simulation model [70]. Fujino et al. have carried out real-time monitoring on a bridge in Japan to determine the vibration, seismic isolation, checking of structural components, structural valuation, and damage disclosure by using advanced sensing technology and concluded that the technique serves several benefits to monitor a structure [71].

Moreu et al. used smart wireless sensors (WSS) to measure bridge response. Both field and finite element models have been discussed, and it managed to monitor the traffic load, strain, and vibration, and an experimental setup was made for a double track steel bridge located at the southern part of Chicago [72]. Lee et al. studied different approaches for damage detection called continuous relative wavelet entropy- (CRWE-) based DSI. The experiment has been conducted in truss bridge structure, and the approach is found as effective to identify the levels of damage [73].

10. Detection of Damage in Bridges

Damage detection in SHM is the process of observing and predicting the structures through time utilizing irregular distributed assessments. Numerical analysis of the damage sensitive choices extracted from the measured values, information on the current condition, and subsequent interpretation of the system health is delivered. Çelebi et al. examined the behavior of suspension bridges in Carquinez, CA, by using accelerometers to measure the damage. Dynamic behavior such as frequencies, damping, and modal analysis is examined. The frequencies were taken into account, showing 0.46 Hz and 0.98 Hz for modes and 0.39 translational frequencies. The torsion and longitudinal motions were also discussed [74]. Khoa et al. presented a case study by applying the SHM technique in Sydney Harbor Bridge using modern sensor technology to analyze data. Support Vector Machine (SVM) approach has been proposed for supervised and unsupervised learning to detect damage. Other methods such as Random projection(RP), PCA, piecewise aggregate approximation(PAA) were also used for SHM and concluded that RP with SVM methods works 200 times faster than other methods to detect damage accurately [75].

Li et al. discussed a Nonlinear Principal Component Analysis (NLPCA) approach in cable stayed bridge to determine the depth of the bridge scour by comparing both in-situ and FEM system it helps to determine the damage and dynamic behavior of a bridge structure. The SHM system was carried out at Hangzhou Bay Bridge [76]. Deng et al. experimented with long-span bridges to predict the damage and measuring deflection by adopting multi-sensors. MRLP

and Generalized Pareto Distribution (GDP) methods were compared to determine the vertical deflection [77].

Oshima et al. has conducted a damage detection experiment in a real bridge using a piezoelectric actuator to monitor fatigue, the variant in vibration, and severity and location of the damage. The experiment happened on steel bridge Hokkaido, Japan, using the Power spectrum density (PSD) approach [78]. Li et al. demonstrated a benchmark problem coordinated by the center of structural monitoring and control at the Harbin institute of technology. This method applies to both numerical models and site monitoring of long-span cable-stayed bridges. The main motive of this approach is damage detection of bridge girders, identifying cable stresses, fatigue, and cracks [79].

Dorvash and Pakzad has conducted a laboratory experiment for Golden Gate Bridge by adopting WSN to predict the damage [80]. Furinghetti et al. have discussed cloud computing techniques for data acquisition to detect the damage in structure to be recorded and this approach has been discussed in both software and hardware perspective, which refined at EUCENTRE foundation in Italy [81]. Perry et al. demonstrated a new approach by collecting the images of bridge quality, the severity of the damage, expansion of damage, and a spot of the damage has been monitored using the Unmanned Aerial Vehicles (UAVs) method that is a more convenient approach to access the health of the bridge [82].

Van Le and Nishio has studied Global Positioning System (GPS) monitoring to determine thermal damage of the long-span cable-stayed bridge. Finite element models were created to predict the damage and Autoregressive Integrated Moving Average (ARIMA) coefficient to collect the recorded response of the structure [83]. Neves et al. has applied Artificial Neural Network (ANN) with unsupervised learning access to detect the damage of bridge structure. Optimization in placing a sensor and strategy of detecting damage are considered [84]. List et al. carried out real-time monitoring of Tamar Bridge in UK. It is a suspension bridge 335 meters long, and in the year 2001, extra stay cables and cantilever decks have been provided. The bridge was monitored for around four years to measure damage, dynamic behavior, temperature effect, wind force, and displacement [85].

Fujino and Siringoringo presented an overview SHM of bridges in Japan by converting the monitoring process into three sectors. (i) Reduction of risk and vulnerability possibility has been discussed (ii) sensor technology and practicing techniques are studied (iii) prediction of damage, natural threat and climatic situations are monitored [86].

11. Predictive Analysis in Bridges

Predictive analysis plays a vital role in SHM of bridges, which helps predict the damage and evaluate the bridge's health condition. The predictive analysis approach helps to determine both static and dynamic characteristics of the bridges and also helps to predict the future problems of the bridges.

Xia et al. have carried out both in-situ test and laboratory experiment on two structures in the Tsing Ma Suspension Bridge that has a span of 1377 meters and Guangzhou new television tower is 600 meters height to predict the deviations in vibration and variations in thermal conditions [87]. Thomson et al. studied the economic crisis and maintenance of bridges in the USA by using predictive analysis in SHM and found that around 70000 bridges seem unsatisfactory in structural health and concluded that proper maintenance and rehabilitation are needed [88]. Keenahan et al. studied another method to predict the dynamic behavior of bridge structure by using accelerometers in a truck-trailer vehicle system approach to predict the vibration occurs due to vehicles and used numerical models with both Rayleigh damping hysteresis damping techniques and also concluded that both values are pretty similar [89]. Walia et al. studied damage prediction in a 100-year-old steel bridge with a deck using accelerometers. Time frequency and typical frequency methods have been approached [90]. The following conclusion has been made:

(1) Power Spectral Density (PSD) diagrams are used to predict the amplitude and frequency

(2) The first mode deviation in PSD helps to predict the priority in bridge retrofitting

(3) Prediction of the damage and structural frequency of the bridge STFT approach is considered

(4) Wavelet packet transform (WPT) methods were adopted to predict the flexibility in the modal response

(5) However, WPT will not identify damage spot before retrofitting [90]

Van Le and Nishio has carried out SHM in a cable-stayed bridge in Vietnam by using (ARIMA) model, and data provided by GPS were used to predict the static responses and global deformation [91]. Nishio et al. have used a finite element model to predict the dynamic characteristics of the structure and the possibility of repairing bridges using data acquisition, model parameters, and the possibility of failure and damage prediction [92]. de Almeida Cardoso et al. carried out an unsupervised learning approach of predictive analysis using the wireless technique. Convictable sensors technology and other possible gadgets provide data to predict the irregular behavior of the structure in real time [93].

Nejad et al. adopted WSN to predict the structural response of the bridge piers from a seismic damage perspective. This study only has the prototype numerical model analysis with two receivers and six transmitters with a proposed model of six piers [94]. Sun et al. have carried out real-time monitoring on the long-span bridge in China and proposed three levels of prediction through case study (i) GPS measurement has been considered to predict the bridge health status (ii) with the help of cumulative displacement by viscous damper helps to determine expansion joints of the suspension bridge (iii) wind and vibration are predicted by installing mass dampers [95]. Adriaenssens et al. have carried out a case study in Streicker bridge to demonstrate a piece of adequate information and data from a monitored bridge, and it helps to predict the damage and other health issues of a bridge structure [96].

Górski et al. presented a case study on highway cable-stayed Maxau Rhine Bridge to predict the dynamic behavior, mode shapes, natural frequency, accelerations in the bridge deck, and vibration [97]. Das et al. developed the ARMA model to predict the structure's response and compared under different parameters of the dynamic behavior of structure those study has been applied on real-time practice [98]. Tan et al. approached the "drive bridge inspection" concept to predict dynamic behavior and natural frequency using Fast Fourier Transform (FFT) and Vehicle Bridge Interaction (VBI) algorithm. Predicting of damage and acceleration also monitored using wavelet analysis techniques [99].

Diez et al. researched real-time in Sydney Harbor Bridge using supervised learning KNN based outlier detection methods to monitor bridge damage and detect damage [100]. Biswajit et al. have discussed some case studies on bridges and other structures. Control algorithm and reduction of dimension approaches have been investigated to predict the damage, vibration, damping, and other structural related problems, and, finally, piezoelectricity has been evaluated [101]. Santos et al. have used real-time data of Z-24 Bridge (Switzerland) and Tamar Bridge (UK) by using the Expectation-Maximization (EM) algorithm and Memetic Algorithm (MA) to detect the damages which increase the quality of the structure [102].

Miyamoto et al. have discussed a new method called "State Representation Methodology" (SRM) to monitor a bridge based on the previous data using the SVM approach to predict the dynamic characteristic of the bridge structure [103]. Yu et al. have performed both laboratory and numerical model analysis to monitor the bridge scour. Scour monitoring is essential in SHM, so the sensor's scour sensor and the sensors are easier to handle. This setup helps to predict the severity and depth of the scour [104]. Li et al. examined the deformity of wire breakage in bridge cable using AE techniques, and through waveguide, AE signal should be analyzed to identify the breakage of wire before it happened [105].

Fisher et al. carried out numerical model and lab experiment to predict the scour in the bridges, and the latest sensors are applied to measure the water and soil sedimentation level in the bridges [106]. Praksh et al. have carried out in real-time monitoring by using laboratory data to detect the damage of the structural components by using two-phase modeling and estimation framework approach. The main motive of the experiment is predicting the deflection so that the model of the parameters should be considered using the Bayesian approach [107]. Ballio et al. have carried out bridge management to Borgoforte bridge to monitor the complete response of the bridge such as wind, water, debris flow, loads due to traffic, possibility of scour at the pier, and other damage possibilities [108]. The predictive analysis supports businesses and suppliers in enhancing the performance and resistance of buildings to dynamic loads.

These dynamic loads will be based on current events, natural catastrophes, and disasters. SHM predictive analysis aids in determining the service life of reinforced concrete, which may contribute to a country's infrastructure projects based on existing structures [109].

12. Data Acquisition in Bridges

Data acquisition plays a vital role in converting the sensor data from bridge monitoring into digital presentation. It is an automated technique that helps collect the information from in situ experiment, and that information has been considered input data. It has been converted by using analog-to-digital converter (ADC), and finally using received information health status of the bridge structure has been evaluated.

Lorenzoni et al. adopted DAQ to analysis in the five different types of existing bridges such as Reinforced Cement Concrete Arch Bridge, Masonry Bridge, Multigirder RCC Bridge, Steel Box Bridge, and Steel Trusses Bridge have been monitored for one year to predict the model analysis, natural frequency and mode shapes to safeguard the bridge from structural failures [110]. Neves et al. applied data optimization techniques using Bayesian theorem to practice wise decision-making to ensure the safety of the bridge structure [111].

13. Future Scope of Research and Trends

SHM of bridges is an essential and more convenient technique compared to direct inspection, in particular for bridges, because most of the bridges around the world are almost 40 to 100 years old, and many of them are considered as a heritage structure, so bridge maintenance is considered as a principal requirement across the globe. Therefore, SHM is the most suited and consistent technique to detect all the variety of damages under static and dynamic loading. Here, some of the future scopes of research and trends have been discussed:

(1) Advancement in sensor technologies is mandatory to increase the sensing capability and innovating sensing for long-term monitoring.

(2) Damage should be identified according to the environmental changes, so the bridge monitoring should be appropriately abstracted and even more advanced concerning environmental changes.

(3) Local and global level diagnostics are demonstrated in SHM to contribute the outstanding results along with local level NDE techniques help to identify spot and harshness of the damage, whereas global level techniques produce screening.

(4) Robust optimization algorithm was adopted to measure the static and dynamic response of the structure.

(5) It is essential to monitor creep and shrinkage behavior in bridge structure, but there is a lack and

imperfection due to the flaws in existing code, so it needs to be updated.

(6) Advanced DAQ technique is needed to track the entire monitoring of data without any error.

(7) Positives and negatives should be adequately communicated using the same technical terms worldwide to avoid mistakes.

(8) Developing low-cost dense sensor arrays and innovative methods to powering the sensing system using energy were harvested from the structure's operational environment.

(9) Digital information time-series, prediction modeling strategies can forecast future loads from the present condition of the system.

14. Conclusion

This article provides detailed information about the SHM of bridges and the application of SHM in different bridge structures, and various works reported have been discussed. Based on the detailed discussion, the following points have been specified:

(1) Application and practices of key sensors such as FOS, MEMS, PZT, acceleration sensors, displacement sensors, strain sensors, and temperature sensors are studied. Fiber optic sensors and piezoelectric sensors are widely used sensors for the last two decades for both global and local monitoring, and the various possibilities of predicting damages have been discussed.

(2) Bridge maintenance and rehabilitation according to current trends have been discussed concerning SHM techniques.

(3) Bridges only acquire long-term monitoring processes so that sensors should have surviving capability under all kinds of environmental changes.

(4) A wide range of technical knowledge is necessary to adopt SHM to understand the data and information provided by sensors.

(5) Skilled human resources must install the sensor and another setup in situ to receive the data without any errors and obstacles.

(6) Damage detection has been addressed in this proposed review article, and it is nothing more than a change in the boundary condition and system connection that would have an impact on the system's present or future performance. Damage may build up over time, resulting in fatigue or corrosion buildup in the system. These will change the stiffness, mass, or energy dissipation of a system, potentially altering the system's dynamic response.

(7) The method of predictive analysis has been addressed, and it will be selected based on the structure, environment, operational limitations, and practicality of using the technique. The dynamic

reaction of a structure will be examined in relation to environmental changes.

This article provides a clear vision towards SHM of bridges with its recent technological developments based on the real-time in situ experiments, laboratory studies, and numerical model practices, and it also discussed DAQ and predictive analysis approach to detect the damages on bridge structure to provide the safety and reliability by adopting structural health monitoring technique.

Data Availability

The data used to support the findings of this study are available upon request.

Consent

No human subjects or animals were used for the research in this article. Hence, no consent to participate was required.

Conflicts of Interest

The authors declare that they have no known conflicts of interest or personal relationships that could have appeared to influence the work reported in this article.

Authors' Contributions

Conceptualization was performed by Arvindan Sivasuriyan, D. S. Vijayan, A. LeemaRose, and J. Revathy. Methodology was developed by Arvindan Sivasuriyan and S. Vijayan. Validation was performed by J. Revathy. Formal analysis was done by S. Gayathri Monicka and U. R. Adithya. Investigation was done by Arvindan Sivasuriyan and D. S. Vijayan. Data curation was performed by Arvindan Sivasuriyan, D. S. Vijayan, S. Gayathri Monicka, and J. Revathy. Original draft was written by Arvindan Sivasuriyan. Reviewing and editing were performed by D. S. Vijayan, J. Revathy, and S. Gayathri Monicka. Validation was done by Arvindan Sivasuriyan and D. S. Vijayan. Supervision was done by D. S. Vijayan, J. Revathy, S. Gayathri Monicka, and Jebasingh Daniel Joseph. All authors have read and agreed to the published version of the manuscript.

Acknowledgments

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