Smart Sensor Technics for Structural Health Monitoring of Civil Engineering Structures

Payal B. Rangari[1], Sanjay K. Bhadke[2]
[1]M-Tech Research Scholar, Department of Civil Engineering, Tulsiramji Gaikwad-Patil College of Engineering and Technology, Mohgaon, Nagpur, MH.
[2]Asst. Professor, Department of Civil Engineering,
Tulsiramji Gaikwad-Patil College of Engineering and Technology, Mohgaon, Nagpur, MH.

***Abstract*— Structural Health Monitoring (SHM) aims to develop automated systems for the continuous monitoring, inspection and damage detection of structures with minimum labour involvement. The first step to set up a SHM system is to incorporate a level of structural sensing capability that is reliable and possesses longterm stability. Smart sensing technologies including the applications of fibre optic sensors, piezoelectric sensors, magnetostrictive sensors and self-diagnosing fibre reinforced composites, possess very important capabilities of monitoring various physical or chemical parameters related to the health and therefore, durable service life of structures. In particular, piezoelectric sensors and magnetorestrictive sensors can serve as both sensors and actuators, which make SHM to be an active monitoring system. Thus, smart sensing technologies are now currently available, and can be utilized to the SHM of civil engineering structures. In these paper, the application of smart materials/sensors for the SHM of civil engineering structures is critically reviewed. The major focus is on the evaluations of laboratory and field studies of smart materials/sensors in civil engineering structure.**

Keywords—Structural Health Monitoring, piezoelectric sensor, fibre optic sensor

1. INTRODUCTION

Civil engineering infrastructure is generally the most expensive national investment and asset of any country. In addition, civil engineering structures have long service life compared with other commercial products, and they are costly to maintain and replace once they are erected. Further, there are few prototypes in civil engineering and each structure leads to be unique in terms of materials, design and construction. The most important structures include bridges, high-rise buildings, power utilities, nuclear power plants, and dams. All civil structures age and deteriorate with time. The deterioration is mostly the result of aging of materials, continuous use, overloading, aggressive exposure conditions, lack of sufficient maintenance, and difficulties encountered in proper inspection methods. All of these factors contribute to material and structural degradation as internal and external damages emerge and coalesce, and then evolve and progress.

To ensure structural integrity and safety, civil structures have to be equipped with Structural Health Monitoring (SHM), which aims to develop automated systems for the continuous monitoring, inspection, and damage detection of structures with minimum labour involvement. An effective SHM system can in real time and online to detect various defects and monitor strain, stress, and temperature so that the optimum maintenance of the structures can be carried out to ensure safety and durable service life. In general, a typical SHM system includes three major components: a sensor system, a data processing system (including data acquisition, transmission, and storage), and a health evaluation system (including diagnostic algorithms and information management). The first step to set up this system is to incorporate a level of stable and reliable structural sensing capability. So, this paper is mainly related to the first component of the SHM system: the sensing system formed by smart materials/sensors. Smart materials/sensors, such as fibre optic sensors (FOS), piezoelectric sensors, magnetostrictive sensors, and self-diagnosing fibre reinforced structural composites, possess very important capabilities of sensing various physical and chemical parameters related to the health of the structures. Since shape memory alloys and magnetorheological fluids are often used as actuators, they are not introduced in this paper. FOS, for example, are small and therefore do not affect the performance characteristics of civil engineering structures in which they are embedded. A single fibre can efficiently monitor structural performance at various locations by using multiplexed or distributed sensing technologies. They are unperturbed by electromagnetic interference. Optical waves are suitable for long transmission distances of relatively weak signals. Piezoelectric and magnetorestrictive sensors can serve as both sensors and actuators, which make SHM to be an active monitoring system. Furthermore, they can come in a variety of sizes, allowing them to be placed everywhere, even in remote and inaccessible locations, to actively monitor the conditions of various types of structures. Since the subject matter of SHM has been growing rapidly

and significantly over the last few years, the focus of this paper is on a critical state-of-the-art review of various applications of the above smart materials/sensors in SHM of civil engineering structures. It is beyond the scope of the paper to describe all the relevant theories involved or to report all of practical applications examples. The paper covers the major aspects of fibre optic sensors, piezoelectric sensors, self-diagnosing fibre reinforced composites, and magnetostrictive sensors for applications in civil engineering. Finally, the conclusions of this study are briefly reported.

2. Piezoelectric Sensors

Based on electro-mechanical transformation, piezoelectric materials exhibit simultaneous actuator/sensor behavior. There are various types of piezoelectric materials: piezoelectric ceramics, piezoelectric polymers and piezoelectric composites. More recently, piezoelectric sensors were introduced into SHM of civil engineering structures as an active sensing technology based on the measurement of electrical impedance and elastic waves.

2.1. Electrical Impedance-Based SHM Method.

When a PZT patch attached to a structure is driven by a fixed, alternating electric field, a small deformation is produced in the PZT wafer and the attached structure. Since the frequency of the excitation is very high, the dynamic response of the structure reflects only that of a very local area near the sensor. The response of that local area to mechanical vibration is transferred back to the PZT wafer in the form of an electrical response. When a crack or damage causes change of the mechanical dynamic response, it is manifested in the electrical impedance response of the PZT wafer. Therefore, structural damages can be monitored indirectly through measurement of the electrical impedance of the PZT sensors.

Ayres et al. [1] bonded two PZT patches to a quarter scale steel truss bridge joint for the acquisition of the electrical impedance when the damage was simulated by loosening bolts in the structure. The real part of admittance (reciprocal of impedance) was extracted as a function of the exciting frequency. Admittance was sensitive to the local damage near the PZT, but was insensitive to damage away from the sensor. Similar tests have been done by Park et al. [2]. However, besides the electrical impedance method, Park et al. have also used Lamb wave method to detect damages in a steel bridge component. Park et al. [3] have monitored the cracking process of a small-scale composite-reinforced masonry concrete wall under uniaxial compression using this method. Besides it, the stability of the impedance-based technique was examined with a civil pipe joint under significant temperature variation in the range of 25–75◦C. The impedance changed as temperature varied. However, when damage was introduced, the temperature made little influence on the qualitative detection result. They [4] also developed a compensation technique to minimise the effect of temperature on impedance measurement. The compensation procedure was based on the reconstruction of the damage metric, which is minimised the impedance drifts due to temperature. Further, Yang et al. [4] studied the influence of environmental conditions, temperature and thickness of the bonding layer between PZT patches and aluminum plate on the repeatability of electrical admittance signatures. Experimental investigations revealed that under various environmental conditions electrical admittance was stable for a monitoring period up to one and a half years. The effect of bonding could be neglected even for thickness up to two-thirds of the PZT patch's thickness, provided that the excitation frequency did not exceed 100 kHz. Above this frequency, the adverse effect of thick (larger than one-third of the PZT thickness) bonding was obvious. By comparing the admittance at the high frequency range (200–1000 kHz), a temperature change triggered the shift of the PZT resonance peaks.

Soh et al. [5] carried out an impedance-based health monitoring and damage detection using PZT patches on a prototype reinforced concrete (RC) bridge. The bridge was instrumented with 11 PZT patches at key locations. The patches were scanned for the acquisition of the impedance data at various stages during the loading process. The results showed that the surface mounted PZT patches were very sensitive to the development of cracks in concrete in their local vicinity, but were insensitive to those farther away.

The impedance method has used a self-sensing actuator concept: a single PZT acts both as actuator and sensor. The qualitative nature of this technique makes it very accessible for everyone. Since it does not require any background knowledge in order to interpret the simple output. Its sensing area is the vicinity of the sensor, which helps to isolate the effect of damage from other far-field changes in loading, stiffness and boundary conditions. But, it is a qualitative method because various types of damage such as cracks, corrosion and delamination will all affect the mechanical impedance similarly, which makes the distinction between each type of damage very difficult. So, once the impedance-based technique detects damage, other quantitative techniques have to be used to determine the exact nature of the damage. Otherwise, the impedance analyzers employed are expensive until now, an efficient and inexpensive methodology for electrical impedance measurement is necessary in the future.

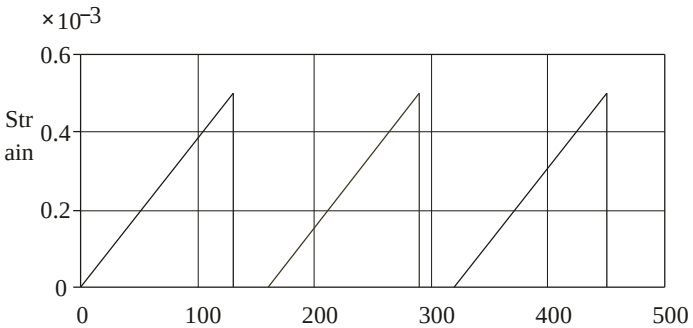
2.2. Elastic Wave-Based SHM Method.

Wang et al. [6] and Wu and Chang [6] conducted preliminary studies to detect the de-bonding between the reinforcing bars and concrete with PZT patches bonded on the steel rebar. A 5-peak burst ultrasonic wave with peak value of 200V was applied on the actuator. Amplitude and time of arrival of the first peak were recorded and analysed. They found that the amplitude of the received signals increased in a linearly proportional manner to the de-bonding size of the steel

bar from the concrete. The arrival time remained constant while the rebar was elastic, but increased as the bar yielded. They also used PZ Flex software to simulate the response of the sensor as parameters in RC structures such as crack width, size of de-bonding and position of the rebar varied. Numerical simulation showed that cracks in RC structures did not affect the sensor output. When both de-bonding damage and cracks existed in the structures, de-bonding damage dominated the output signals. And the depth of the concrete section did not affect the detection of de-bonding damage.
Kawiecki [8] studied the feasibility of non-destructive damage detection by an array of piezo transducers bonded to the surface of a concrete block. Structural damages were simulated by placing objects with different mass at the surface of the tested specimens. Experimental results indicated that there was a strong correlation between the size and location of a simulated damage and the variation of the magnitude of its transfer function and shift of natural frequency. Anomalies in these signals were repeatable and had distinct characters when they were caused by damages.
Song et al. [9] used PZT patches as sensors or actuators to initiate and receive Rayleigh waves propagating along the surface of concrete beam, and longitudinal waves, shear waves propagating through internal concrete. Results showed that from the velocity of Rayleigh waves and longitudinal waves, both the dynamic modulus of elasticity and dynamic Poisson's ratio of concrete could be calculated. Differences in amplitude of received waves were highly sensitive to the cracking process in concrete due to externally applied loads. Changes in the waveforms could thus reflect the effects of internal micro cracking in concrete.
Song et al. [9] have embedded their smart aggregates containing waterproof piezoelectric patches into different types of concrete specimens. The sensor-history damage index matrix and the actuator-sensor damage index matrix were obtained to monitor the time-history and location information of damages in a two-story concrete frame. Their system could also monitor strength of early concrete and impact on the structures.
Elastic wave-based approach can detect larger areas than the impedance-based method. Further, the elastic wave based method can take advantage of more information of the wave propagation to identify damages, such as amplitude and phase of the transfer function, shift in frequencies, amplitude and the arrival time. This method as well as the electrical impedance-based method, is an active sensing method, while most of the SHM techniques are based on passive sensing diagnostics that rely on passive sensor measurements to determine changes in the condition or environment of the structure. However, further studies are needed to verify the feasibility of piezoelectric sensors monitoring methods based on ultrasonic wave propagation to detect various defects in real concrete elements and reinforced concrete structures by combining other technologies such as wireless communication and algorithms for detection of the positions of damages and the severity of damages.

3. Self-Diagnosing Fibre Reinforced Composites

Self-diagnosing (or self-monitoring) fibre reinforced composites contain an electrical conductive phase such as carbon fibre and conductive powder in the cement or polymer matrix. They have the abilities to monitor their own strain, damage, and temperature.
Chen and Chung [11] have reported that CFRC can sense strain and damage by its change in electrical resistance. Figure 3.1 shows the fractional change in resistance along the stress axis as well as the strain during repeated compressive loading within the elastic region. Size of mortar specimens was 5.1×5.1×5.1cm, and the content of short carbon fibre was 0.24 vol%. As shown in Figure3.1, during the first loading, the irreversibly increasing ΔR/R0 is due to the weakening of the fibre-matrix interface; during the second and the subsequent loadings, reversibly decreasing ΔR/R0 during loading is due to fibre push-in, while reversibly increasing ΔR/R0 during unloading is due to fibre pull-out. At high stress amplitude up to failure, resistance increases greatly.



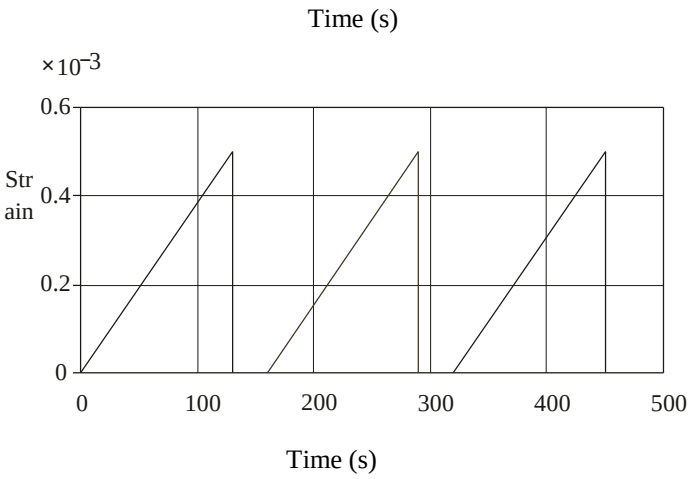


Figure 3.1: ΔR/R0 and compressive versus time obtained during cyclic loading for CFRC [11].

Until now, only some small-scale laboratory studies on smart application of CFRC and CFRP have been conducted. Wen and Chung [12] applied CFRC coatings on the tension and the compression sides of a cement paste beam under flexure. Under cyclic loading and unloading, the resistance of the coating decreased reversibly on the compression face in every cycle, while the resistance increased reversibly on the tension face in every cycle except the first cycle. So, it appears that the CFRC strain-sensing coating was a possible usable form for SHM of concrete structures.
While, Yang and Wu [13] employed a new method to improve the sensing capability of CFRP by pulling the impregnated carbon tows repeatedly through a roller with a diameter of 5cm. Their aim was to pre-set some micro cracks to the carbon tows. Results showed that the pre-treatment could enhance the sensitivity of CFRP to strain more than 100 times, especially in a low strain range.

4. Magnetostrictive Sensors

Ferromagnetic materials have the properties that, when placed in a magnetic field, they are mechanically deformed. This phenomenon is called the magnetostrictive effect. The reverse phenomenon, in which the magnetic induction of the material changes when the material is mechanically deformed, is called the inverse magnetostrictive effect. Based on these phenomena, Kwun and Bartels [14] invented a type of magnetostrictive sensor (MsS) which could generate and detect guided waves in the ferromagnetic materials under testing without direct physical contact to the material surface. Khazem et al. [15] utilized MsS to inspect suspender ropes on the George Washington Bridge in New York. They launched a pulse of 10 kHz longitudinal guided wave along the length of the suspender, detected the reflected signals from geometric features and defects in the suspender.

Na and Kundu [16] used MsS for internal inspection of voids and inclusions in concrete-filled steel pipes. It was shown that the MsS system could generate different guided wave modes propagating along the steel pipe; and these waves were sensitive to the defects in the pipe. The received wave amplitudes decreased as the length of voids and inclusions increased. To overcome the major disadvantage of MsS, that is, the relatively low ultrasonic energy transmitted, Na and Kundu [16] developed a hybrid approach combining PZT and MsS. This method was very effective for steel bar-concrete interface inspection. Bouchilloux et al. [17] measured the stress of the steel cable based on the reverse magnetostrictive effect. The accuracy of the MsS was within 3%; but the perturbation of temperature affected the accuracy. The difference between two extremes of temperature, that is, between 10◦C and 50◦C, was 6%. Rizzo and Di Scalea [18] used the discrete wavelet transform to extract damage-sensitive features from the signals detected by MsS to construct a multidimensional damage index vector. The damage index vector was then fed to an artificial neural network to provide the automatic classification of the size of the notch and the location of the notch of multi-wire strands. MsS can generate different guided wave modes by simply changing the coil or magnet geometry. They can work without any couplants. Guided waves have strong potentials for monitoring because of the capability for long-distance inspections. However, MsS is only suitable for ferromagnetic materials. Relatively low ultrasonic energy with low signal to noise ratio can be transmitted. And the induced energy is critically dependent on the probe proximity to the object being tested.

5. Fibre Optic Sensors (FOSs)

There are several methods to classify FOS. The first method of classifying FOS is based on the light characteristics (intensity, wavelength, phase, or polarization etc.) modulated by the parameters to be sensed. The second method classifies an FOS by whether the light in the sensing segment is modified inside or outside the fiber (intrinsic or extrinsic). FOS can also be classified as local (Fabry-Perot FOS or longgauge FOS etc.), quasidistributed (fibre Bragg grating) and distributed sensors (Brillouin-scattering-based distributed FOS) depending on the sensing range. This method of classification is adopted here. FOS are generally surface mounted on existing structures, or embedded in newly constructed civil structures, including bridges, buildings, and dams, to yield information about strain (static and dynamic), temperature, defects (delamination, cracks and corrosion), and concentration of chloride ions. The obtained data can be used to evaluate the safety of both new-built structures and repaired structures, and diagnose location and degree of damages. In this section, the application of FOS in monitoring of strain, displacement and defects in civil engineering structures is reviewed. Other relevant details may be found in early reviews of FOS by Merzbacher et al. [19], Ansari [20] and Leung [21].

Zeng et al. [22] measured the strain distributed along a 1.65-m reinforced concrete beam using one single-mode fibre, called as Brillouin-scattering-based distributed FOS which could measure temperature and strain simultaneously. Strain measurement accuracy reached ± 5με with the resolvable distance of 5cm. Chen et al. [23] compared two kinds of distributed sensors: Electric Time Domain Reflectometry cable sensor that was based on the propagation of electromagnetic waves in an electrical cable and Brillouin scattering based distributed FOS. They were mounted near the surface of the 80% scale beam-column reinforced concrete assembly. Results showed that the cable sensor could measure a significant change of strain locally while distributed FOS were good candidates for the measurement of slowly-varying strain over a long distance. The cable sensor measured a strain distribution in seconds or shorter and therefore applicable for dynamic signal measurements. However, FOS required several minutes to complete one measurement. Wu et al. [24] installed Brillouin-scattering based distributed FOS to evaluate the performance of a full-scale pre-stressed concrete girder. Compared with the measurement results from strain gage, FOS gave good results for tension strain measurement. But, FOS for compression strain measurement included a relatively large error, especially when the compression strain was small.

Currently, many bridges around the world have been instrumented with FOS sensing system. Benmokrane et al. [25] applied Fabry-Perot FOS to the rehabilitation project of the Joffre Bridge, Quebec, Canada. They were bonded to the CFRP grids and steel girders to monitor the performance of the FRP reinforced structure, strains of the deck and strains of the girder. The results showed that the temperature was the most important factor influencing the strain variation in the bridge deck under service conditions. The field measurements were carried out one year after the opening of the bridge to traffic. Using three 25-ton calibrated trucks to evaluate the strain level in the FRP reinforcements, the measured strains in the FRP reinforcements were less than 20με, and strains in the steel girder were less than 120 με.
Bronnimann¨ et al. [26] reported the application of FBG in two bridges in Switzerland. In the Storchenbrucke in Winterthur, FBG were adhered to CFRP wires to measure the strain of suspension cables. FBG had been working reliably within the strain level around 2000με for three years by March 1st, 1999. The other was a pedestrian bridge with CFRP as the prestressing cable, where the optical fibre was embedded in CFRP wire during the pultrusion of CFRP. Most of the FBG sensors embedded inside suffered from the high curing temperature of the resin of about 170–190◦C and the high level pre-stressing strain of 8000 με, although two of them failed due to de-bonding. They have satisfactorily monitored the strain evolution within the cables and the anchor head during the pre-stressing process and afterwards for over a year.

6. CONCLUSION

Smart materials/sensors are a new development with enormous potential for SHM of civil engineering structures. Some of them are currently being applied in the field, while others are being evaluated under laboratory conditions.
Piezoelectric sensors can be used as an active sensing technology in the SHM of civil engineering structures based on electrical impedance and elastic wave methods. The impedance method depends on the self-sensing actuator concept. It is a qualitative method. Elastic wave based approaches can detect larger areas of damage than the impedance-based method, and this method can take advantage of additional information arising from the wave propagation to identify damages. However, further studies have to be carried out to verify the feasibility of this method to detect various defects in real concrete structures and reinforced concrete structures.

Self-diagnosing fibre reinforced composites are also available as sensors and offer a very simple technology for the SHM of civil engineering structures. One of the most obvious advantages of this type of smart materials is that they work as both structural materials and sensing materials. Laboratory studies have shown that they have the abilities to monitor their own strain, damage and temperature. CPGFRP and HCFRP have better sensitivity than CFGFRP. However, the practical applications of this type of smart materials in civil engineering structures are yet to be developed.

MsS can generate different guided wave modes by simply changing the coil or magnet geometry. They can work without any couplants. Guided waves have strong potentials for structural health monitoring because of their long distance inspection capability. However, it is only suitable for ferromagnetic materials. Relatively low ultrasonic energy with low signal to noise ratio can be transmitted.
SHM system must possess the comprehensive abilities to detect positions and severity of damages. However, until now lots of studies about applications of smart sensors/smart materials in SHM of civil engineering are related to the basic sensing abilities of smart sensors. That is, some damages within structures can be monitored directly using data from sensors, while others can only be detected indirectly through special diagnostic methods. Important civil engineering structures are usually very large. So, many sensors are equipped to make structures sense their health conditions. Wireless transmission and processing the data before transmission will be a useful method to solve the problem of bulk data management in the practical SHM system. And SHM of the practical civil engineering structures will greatly depend on diagnostic algorithms such as inverse problem analysis, artificial neural network, and the expert system. So, real SHM system for civil engineering is the integration of smart sensors/smart materials, data transmission, and advanced diagnostic methods.

FOS are versatile sensors for SHM applications in civil engineering. Various applications of FOS in civil engineering structures, such as monitoring of strain, displacement, vibration, cracks, corrosion, and chloride ion concentration, have been developed. In particular, field tests reported on bridges, hydroelectric projects, and some civil buildings have been found to be effective. FOS can work in a harsh natural environment, and have large sensing scope, joining with low transmission loss, anti-electromagnetic interference and distributed sensing, and so they are advantageous to apply for SHM of civil engineering structures. However, the long-term sensing ability of FOS under field experimental conditions due to aging has not been fully established, and needs to be investigated further. They are fragile in some configurations, and the damage is difficult to repair when embedded. The optical connection parts, which connect the embedded optical fibre with the outer data recording system, are also weak elements of the FOS system. Field examples using FOS to detect defects and damages have not yet been fully investigated and reported.

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