Journal of Civil Engineering and Environmental Technology
Print ISSN: 2349-8404; Online ISSN: 2349-879X; Volume 2, Number 2; January-March, 2015 pp. 109-112

http://www.krishisanskriti.org/jceet.html

Review Paper on Structural Health Monitoring: Its Benefit and Scope in India

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Abstract—*With the emergence of new materials and technologies, construction of civil structures is now carried out at a faster rate. There is an increased requirement to provide both the cost savings with regard to maintenance and a safer environment by preventing structural failures. India being the home of rich historical background inherits varied amount of historical structures. Due to their historical importance it becomes very important to assess health condition of these structures. Buildings like hospitals stadiums, sports arenas which could cause harm to large number of people at a time and are something to be taken care on a regular basis. Structural health monitoring is a technique aimed at providing accurate and in-time information concerning structural condition and performance on a proactive basis. Information obtained from monitoring is usually used to plan and design maintenance, enhance the safety, reduce ambiguity and to expand the knowledge concerning the structure being monitored. In the recent past, non-destructive techniques are being utilized for the monitoring purpose. Installing structural health monitoring system in a structure is about 0.5% to 3% onetime cost and 2% to 5% for monitoring structure over 10 years period.*

Keywords: *Non-destructive testing, monitoring, strain gauges*

1. INTRODUCTION

Damage can be defined as the changes in material or geometric properties of a system that adversely affect its current and/or future performance.

Damage is not significant without a comparison between two different states of the system, one of which is anticipated to represent the initial, and often undamaged, state.

Damage is stated as a flaw or defect and is existent to some amount in all materials. The term damage does not essentially imply a complete loss of functioning of system, but somewhat that the system is no longer functioning in its optimal manner. As the damage propagates, it will reach a point where it affects the system operation to a point that is no longer acceptable to the user. This point is referred to as failure [5].

The damage state of a system is described as a five-step process to answer the following demands: - Existence, location, type, extent of damage and the prognosis of its remaining life [13].

Structural Health Monitoring (SHM) for civil structures is a process of employing a damaged detection and categorization strategy. It is a non-destructive method which intends to provide, at every instant throughout the life of a structure, an identification of the "state" of the constituent materials, the different parts and the full assembly of these parts constituting the structure as a whole [4].

The principal objectives of the structural health monitoring are:-

i. To monitor the structural behavior,
ii. To assess structure's performance under various service loads,
iii. To detect damage or deterioration and
iv. To determine health or condition of the structure

The SHM system should be able to deliver, on demand, consistent information relating to the safety and integrity of a structure. The data and statistics can then be incorporated into bridge maintenance and management strategies, and enhanced design guidelines [9].

Thus SHM will help us to achieve increased durability and health of structure, reduced maintenance and improved safety.

1.1 SHM benefits in civil structures

There are various advantages and outlines of including Structural Health monitoring in civil structures such as:

a. Detection of damages during construction which can cause any change in properties,

b. Quality Assurance,
c. Complex Structures are effectively managed,
d. To ensure safety of people, nature and property,
e. Economically the cost of installing a system and doing Health monitoring at a given time like construction or repairs is 0.5% to 3% of the total construction or repair costs respectively. The cost of performing Structural Health Monitoring for a period of 10 years is 2% to 5% of total structures building cost [9].

2. STRUCTURAL HEALTH MONITORING (SHM)

2.1 Brief Historical Overview

Rail wheel tappers - used the sound of a hammer when strike against the wheel of train to detect the damage. In rotating machines, monitoring of vibration is used as performance assessment method. Then, these techniques are employed to detect the damages in the structure, besides then a new field emerged namely Structural Health Monitoring. Vibration-based damage assessment of bridge structures and buildings are carried since the early 1980s.

2.2 SHM Process and technique

Health monitoring of civil infrastructures consists of determining by measured parameter, the location and severity of damage in buildings or bridges.

Process of SHM can be categorized [3] under two broad classes of:-
a. Global Health Monitoring methods
b. Local Health Monitoring methods
Most of the health monitoring techniques/methods is centered on:-
i. Either finding shift in natural frequencies or
ii. Changes in structural mode shapes [3].

Damaged members causes change in mode shapes as well as natural frequencies. A normal mode of an oscillating system is a pattern of motion in which all parts of the system move sinusoidally with the same frequency and with a fixed phase relation. The frequency of the normal mode of a system is known as its natural frequency.

If the sources of changes in dynamic characteristics other than damage are considered to be noise (temperature changes, moisture) in the measurement, then the changes due to damage must be significantly larger than noise in order for the techniques to work.

Early works in health monitoring found that loss of a single member in a structure can result in changes in the fundamental natural frequency of one to as much as thirty percent [11]. Researchers have concluded that if the structure was statically determinate, then the loss of any member would result in an unstable structure.

It was also suggested that in concrete structures where concrete contributes to the most of the stiffness, the reinforcing steel deterioration has been shown to have little influence on the natural frequency [6]. The length and position of cracks based on the natural frequency shift could also be estimated using sophisticated method [10]. Matrix update method [8] was also introduced, which is based on the modification of the mass, stiffness and damping matrices of the structure to match measured data as closely as possible on a global level.

But, methods based on the use of stiffness, mass or damping matrices suffer from the fact that these matrices are computed based on idealized situations not likely to be found in real life.

Some of the techniques adopted in monitoring of structures are:-
a. Statistical pattern recognition method:-It uses Bayes theorem to determine the most probable damage event by comparing the relative damage probabilities of different damage events. Statistical data are obtained from continuous or periodic or forced vibration measurements.
b. Artificial Neural Networks (ANN) have recently been used to recognize the strain measurements based on a set of training examples that represent different types of damage in a structure.
c. Acoustic approaches like ultrasonic measurement, impact-echo and tap tests used to evaluate local conditions of the infrastructure.
d. Use of X-ray and Gamma ray to get visual images of the interior of structures such as steel cables and slabs. This method is easy to understand, and has a wide base of acceptance.
e. Radar technology- Radio waves travel at high speeds to obtain 3-D views of reinforcing steel in concrete slabs
f. Fiber optic sensors have made possible measurements of cracks in concrete and corrosion of reinforcing steel in concrete.

2.2.1 Statistical Pattern Recognition Paradigm [5]. It describes the SHM in four-step procedure:-
a. Operational evaluation- it begins to set the limitations on what will be monitored and how the monitoring will be accomplished;
b. Data acquisition, normalizing and cleansing- The data acquisition portion of the SHM process involves selecting the excitation methods, the types of sensors, their number and locations, and the data procurement/storing/transmittal hardware. Data normalization is the method of untying changes in sensor reading caused by damage from those caused by varying operational and environmental conditions. Data

cleansing is the method of selectively picking data to pass on to or discard from the feature selection system.

c. Feature selection- It is concerned with the identification of data features that allows one to distinguish between the undamaged and damaged structure. Also, correlating measured response to the type of damage in the structure is carried out.

d. Statistical model development- It is concerned with the implementation of the methods (pre-defined algorithms) that operate on the extracted features to quantify the damage state of the structure. The statistical models are correspondingly used to reduce false warnings of damage. False suggestions of damage fall into two categories:
i. False-positive damage indication (indication of damage when none is present) and
ii. False-negative damage indication (no indication of damage when damage is present).

2.3 NDT Techniques in SHM

Non-destructive testing (NDT) techniques can be used judiciously for investing and evaluating the actual condition of the structures. These techniques are comparatively fast, easy to use, and economical. It also provides a general indication of the required property of the concrete. The selection of a specific NDT method relies upon the property of concrete to be detected such as corrosion, strength, crack monitoring, etc.

Wide range of the NDT methods have been developed and are available for examining and evaluation of different parameters related to strength, robustness, and overall quality of concrete.

Rebound hammer test- It is one of the oldest and very common methods of comparing the concrete quality in different parts of a structure and indirectly assessing concrete strength. It can be used both in field and in the laboratory. The rebound of an elastic mass depends on the hardness of the surface against which its mass strikes. Some of the applications of rebound hammer test includes finding the elastic properties like compressive strength, determining variations of strength within a structure and evaluating the uniformity of concrete. IS:516-1959 (Reaffirmed 2004) provides method of tests for strength in concrete.

Strain gauges - There are various types of strain gauges that are available like mechanical type, capacitance type but the resistance type strain gauges is most commonly used.

When a structure or its component gets subjected to a force, the length of the structure changes. Strain is this change in dimension from its initial value, and strain gauges are used to measure it. As the strain gauges are glued to the structural component, any distortion will also cause a distortion of the strain gauge. Therefore, any change in the strains, may be tensile, compressive or shear, can be measured by making use of these strain gauges. There are a wide range of strain gauges for different applications and materials.

Low strain integrity test - This test is carried out to determine whether the structure is free from major cracks and discontinuities. Also referred as pile integrity test, it is based on wave propagation theory. When the pile is subjected to a light impact a low strain is produced. This impact produces a compression wave that moves down the pile at a continuous wave. Variations in cross sectional area such as reduction in diameter or deviations in material such as void in concrete produce wave reflections. Consequently, this test can be applied in checking the presence of necking or expansion of concrete, in evaluating presence of major cracks and discontinuities and in checking the overall quality of concrete.

3. CASE STUDIES

Structural Health Monitoring has been done in India on very few bridges. Two such case studies have been discussed:-

3.1 Naini Bridge

The Naini Bridge, is one of the largest cable-stayed bridges in India which connects Allahabad with Naini across the Yamuna River.

National Highways Authority of India (NHAI) required an advanced SHM system that can provide real-time monitoring of the entire bridge as well as advanced communications for remote access and control.

This work was carried out by COWI (a Danish consulting company)/ Devcon Infrastructure Pvt. Ltd.

It was the first installation of new generation GPS combined with advance post processing software to continuously monitor the bridge for various changes in climate and operations with high accuracy.

For example 3D absolute deflections can be measured up to accuracy in mm. The system installed monitors about 400 processed parameters, which comprises of strain and temperature inside the deck, cable vibrations, and displacement of the deck, wind speed and direction at the deck level and at the top of pylon, air temperature, air quality, and rain fall.

From the properly networked, distributed data acquisition arrangement based on NI hardware and LabVIEW and DIAdem software, the consultants were able to economically deploy an advanced and scalable structural health monitoring system that can be remotely operated and managed [15].

3.2 Mahatma Gandhi Setu

The Mahatma Gandhi Bridge was constructed about 33 years ago over the Ganges River in order to connect Patna to the other side of watercourse. The bridge has 46 spans each with span length being 120m. Each span comprises of two cantilever beams on both sides which are free to move at the ends.

It has two lanes one downstream and the other upstream each with a width of around 6m.

Both the lanes are also free from each other and are not connected anywhere. The bridge was constructed by using 3 meter pre-casted parts being joined at both ends to complete the span.

Due to heavy traffic movement and being the only bridge to cross Ganges river the bridge is used heavily now. Hence it has started vibrating with higher amplitude than it was designed for. In addition to this in many spans the cantilever beams were found to have sagged at ends.

3.2.1 The Rehabilitation Process

External Pre-stressing of the bridge using 9 steel cables in a bunch (Fig 3.1). It was decided to pre-stress from 6 places starting from the end towards the center portion.

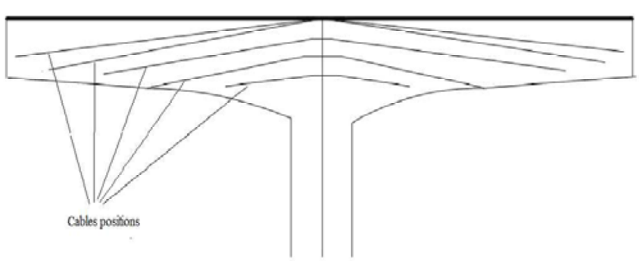

Fig. 3.1: The Rehabilitation using external Pre-Stressing using steel tendons

The task of Rehabilitation was carried out by the Freyssinet Prestressed Concrete Company (FPCC) Ltd.

When the span is externally pre-stressed by cables it causes the tip of the cantilever arms to move up with respect to the middle of the center of span. These cables pull the arms on upward side due to the stressing done.

Deflection measurements- The variation between one side reading and the other side reading gives the deflection and comparing the deflections before and after stressing can give the effective change due to Pre-Stressing.

Temperature measurements- Temperature variations causes change in stress and deflection in the cantilever arms also vary. Temperature sensors are installed at the inside and outside surface of the bridge. Maximum value of strain change due to pre-stressing obtained is 70 $\mu\varepsilon$ and average maximum deflection recovery values have been recorded as 24mm. These values were much lower than theoretical estimates.

4. CONCLUSION

Ageing phenomenon of concrete is very challenging to predict and this can lead to mishaps and damages. Reinforced concrete structures in critical places like nuclear plants make them so imperative that we have to be sure that they are in good condition. India as a developing country needs to be more aware and cautious about its Infrastructure. A major event can lead to irreversible losses and hence should be well informed in time. Lifeline structures like hospitals and important bridges and tunnels should be mandated with monitoring as their failure cause more losses than any other. This is where structural health monitoring has a role to play. Structural Health monitoring is a vital need for all structures to keep a check on their performance and life span. It gives a means to overcome these shortcomings with minimal damage and loss. It has proved to be effective and has a great potential for gaining confidence over the structures we are making so that development happens faster and with accurate results.

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