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Structural Health Monitoring: Techniques and it's Civil Engineering Applications

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Abstract:- All structures, even critical infrastructure such as bridge, highways etc., deteriorate with time. Any structure which is serving its design life will need regular maintenance to maintain the integrity and complete the design life without much structural distress. The distress in the structure maybe due to external loading, internal changes or sudden natural calamity. According to ASCE 2017 infrastructure report card, nearly 10% bridges in US have some structural deficiencies. In such cases, means of continuous monitoring of structure to have an assessment of changes in the function of time and to provide an early warning of an unsafe condition in real-time helps mitigate disasters, this process is called as STRUCTURAL HEALTH MONITORING (SHM). Different structures require different types of maintenance due to changes in material, configuration and connection etc. This paper attempts to review the available techniques of structural health monitoring applicable to civil engineering along with its applicability, merits and demerits.

I. INTRODUCTION

The biggest investment of country is civil engineering infrastructure. These are designed to have long service life as they have very high investment and are difficult to replace or repair once they are damaged and it is uneconomical to repair or replace. To avoid the damage of the structures which are irreparable regular and thorough maintenance is very essential.

Infrastructures like bridges, power utilities, nuclear power plant, dam etc., are the most important structures among all others. These structures detoriate physically with time mainly due to result of aging, continuous usage, aggressive exposure conditions and due to unforcing load and loading combination in its service life. All the above factors can cause distress in the structure which can be internal or external and usually manifest as cracks or deflections which can lead to failure if not monitored properly.

To ensure integrity, serviceability and safety of structures have to be continuously monitored. This develops automatic system for continuous monitoring, inspection and proper repair and retrofitting works have to be undertaken to ensure the full service life of the infrastructure.

To ensure systematic monitoring and maintenance and identify distress in the structure various methods have been evolved which can be collectively studied under SHM. SHM develops a framework of systems which can be automatic or manual for continuous monitoring, maintenance or repair of structure, as and when distress is observed.

SHM is preferred to monitor the performance of structures and structural components by detecting distress, damages, and variations of stress, strain and environmental condition which are detrimental to the safe functioning of the structure.

SHM is achieved as a network of various factors which are varying from one element to another and hence employee's different components for monitoring different parameters.

Few of the SHM components include:

- Structure
- Sensors
- Data acquisition systems
- Data transfer and storage mechanism
- Data management
- Data interpretation includes:
- Identification of system
- Structural model alteration
- Structural condition assessment
- Prediction of remaining service life.

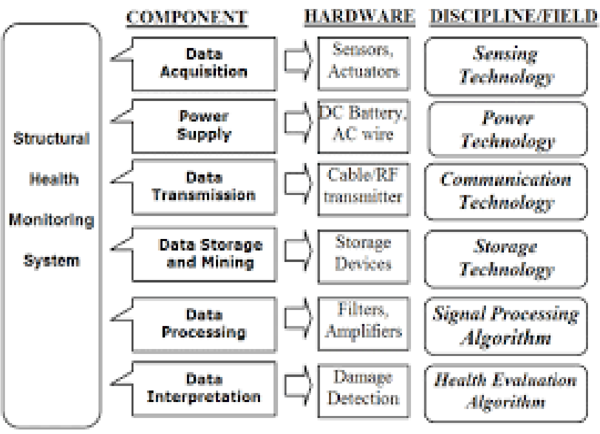

Fig 1
Image courtesy: - Components of SHM by Chirayu Thapa.

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The components of SHM are systematically represented in figure 1. Sensors like fibre optic sensors, piezo metric sensors, etc., are implanted on structures as it possesses high capabilities of sensing changes in physical and chemical parameters. The sensors present will transmit the data provided to the remote data acquisition centres and stored data is analysed and interpret the defects in damages.

II. HOW SHM CAME INTO PRACTICE?

Quantitative and non-continuous empirical methods have been in use since the early ages to detect unfavorable stress and strains which can affect the stability and safety of structures and occupants. An example of this can be the practice of rail road wheel tappers, where the hammer is used to strike, and based on the sound difference the damage was evaluated. In damage detection sector, different kind of research and innovation has been developed. In ancient time people used to find the defect on the structure or in any body by visual inspection and also by hitting the body with hammer and by the sound difference they used to predict the risk zone or defect inside the body or structure. Structural health monitoring techniques are widely used for detection of risky zone or faults or defects on the body whether it may be building, bridges, steel structures like truss and towers, and also in the machines and in equipment. Wired techniques are mostly useful for the bodies which are small and in which the structure is physically in touch with the sensors whereas in wireless technique, the sensors are not in physically in touch with the structure. Revolution and movement of the several techniques give new and precious methods for the damage detection.

III. BENFITS OF SHM

- Proper usage of infrastructure such that sudden failures are minimized.
- Performance of infrastructure can be known.
- A systematic structure is introduced for maintenance services: -

*By aiming to replace scheduled and periodic maintenance inspection with performance based maintenance or at least by reducing the present maintenance. Labor, in particular by avoiding dismounting parts where there is no hidden effect.

*By drastically minimizing the human involvement and consequently reducing labor, downtime and human errors and thus improving safety and reliability.

IV. OBJECTIVES OF SHM

- Performance monitoring of an infrastructure.
- To avoid the failures due to external forces.
- Feedback, such that improvement can be brought.
- Assessment of post disaster structural integrity.

V. HISTORY

SHM has come up mainly for the infrastructures like dams, bridges, vertical buildings, and also for offshore works like gas production.

The term 'SHM' was recently evolved from activities like structural monitoring, structural integrity.

Formal structural monitoring and interpretation using recording instrument began in latter half of the last century and further development with use of electronic data storage and computer acquisition.

A. Bridges

Monitoring programs on bridges implanted to understand its purpose and analyze load structure response chain.

Bridge monitoring was started by CARDER in 1937 by analyzing the dynamic behavior and possibilities of failure due to external agency like earthquake on golden gate and bay bridges in San Francisco.

Motivation for this was found in bridge management programs (2003) and upgrading of projects of bridges.

University of Washington (1954) described first monitoring on TACCOMA NARROW BRIDGE which collapsed due to wind forces.

B. Offshore Installation

Due to the production of oil in North Sea led to offshore installation and also due to the production of concrete at the depth of 150m.

This structure is subjected to extreme environment condition. For requirements of inspection its expense and danger of diver inspection, vibration based diagnostic system came into interest.

C. Buliding and Towers

Building monitoring has come up mainly due to the failure of buildings due the earthquakes and winds.

Vibration test can help us to know low amplitude dynamic responses whereas the large amplitude responses can be known by long term monitoring. It helps builder to know about the loading on infrastructure.

D. Tunnel and Excavation

To know the deformation of tunnel due to weather condition within the limits of stability the concept of tunnel monitoring had shown up. Stress, strain and deflection are determined.

Monitoring of tunnel helps its effects on the side structures when it is deformed. Wireless remote monitoring technology was developed for this tunnel monitoring where the transmission of the data takes place, internet access is used for transmission of data which indicates the deflection in tunnel.

SHM technology mainly applied on land slide monitoring.

Ex; MEMS inclinometers was first developed by Civera in the year 2003 for knowing the ground movements around the excavation with the help of wireless technology.

E. DAMS

SHM had mainly come into existence because of Dams. The failure of 30m dam in United Kingdom which led for the death of more than 500 people, led the scientists for the monitoring of the dams. An early warning for the deflection or failure for the dam can be known with the help of SHM.

VI. STEPS INVOLVED IN SHM

- To find whether the damage occurred.
- To locate the damage.
- To quantify the damage.
- To know the span of structure.

VII. TECHNIQUES INVOLVED IN SHM

A. Visual Inspection Based SHM:-

As the name itself suggests visual inspection. Damage is detected visually, so here the experience matters a lot. One should have expertise in the identification of the damage. It is the oldest and most sort after technique in the SHM. This technique is also augmenting other techniques by hands on verification wherever possible. In figure 2 we can observe that the technician having a visual inspection on bridge.

Fig 2
Image courtesy: - Federal Highway Administration: US Department of Transportation.

B. Non-Destructive Techniques/ Evaluation(NDE):-

Different techniques have been evolved for different purposes but these techniques need a heavy expertise of evaluator. Some of the NDE methods are memorized below:

- *Wired Techniques*:-
- *Electro-mechanical Impedance (EMI) based SHM:-*

This technique is widely accepted as its highly sensitive technique for SHM. Any civil infrastructure component can be monitored with an instrument having piezoelectric transducer patch attached to the surface which is excited due the alternating voltage signal using an impedance analyzer which sweeps through a particular frequency range. At particular frequency, the patch actuates and structural response is simultaneously sensed and measured by the patch in terms of electromechanical admittance ‘Y(ω)’, consisting of conductance ‘G’, and susceptance ‘B’. The two dimensional governing equation for Y(ω) is expanded by Bhalla et al, which is given in

$$Y(\omega)=1/Z=G+iB$$

The figure 3 explains the setup of peizoceramic transducers.

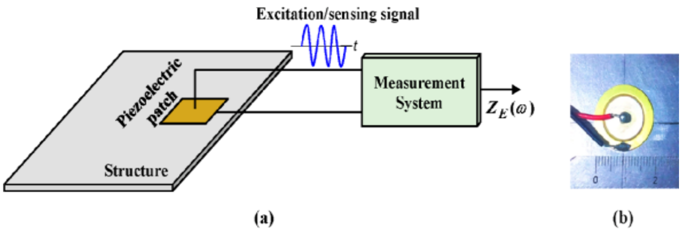

Fig 3
Image Courtesy: -Principle of EMI method

❖ *Working EMI based SHM*: -

In order for the serial sensing method to work, the patches that are connected in series must have different resonance frequency range. This is achieved by surface bonding the PZT patches with plates of different thickness using epoxy resin as shown in Figure 4. Seven PZT patches are taken and are surface bonded with stainless steel plates of increasing thickness (P1 to P7), minimum being 3 mm and maximum being 8 mm. To find the resonant frequencies, the patches with plates are excited at different frequency intervals and the admittance signature is recorded at each interval using an LCR meter connected to a laptop computer. The admittance signature is also obtained by connecting few and all of the patches in series. Among the seven patches, patch 1 is discarded due to improper bonding with plate. The real part of admittance of patch 3 and patch 7 measured individually and in series for a frequency range of 100–200 kHz are shown in Figure 5. From the series signature, the peaks due to different patches have to be identified in order to locate the damage. This is done by comparing the series signature with that of individual patch signatures. In the series signature, the individual peaks due to patch 3 and patch 7 are identified and are shown in circle and square respectively in Figure 5.

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Fig 4:- Setup of PZT Patches Bonded with Plats of different Thickness.

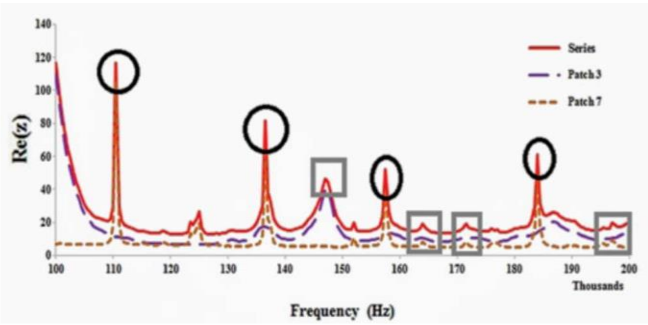

Fig 5:- Plot of Graph Frequency v/s Re(z).

- *Data Fusion Technique:-*

Data fusion techniques involves/combines data from multiple information sources and processes it and related information from the databases to gain more accuracies and accurate result to occur. Data fusion technique gives more accurate detection of fault in structures as compared to the other techniques involved in the SHM. This is due to its capabilities in extracting information from different sources and integrating them into a consistent, accurate, and intelligible dataset. Piezoceramic based active sensing is a useful approach to SHM. The technique involves number of PZT which are distributed throughout. It might be confusing to incorporate each sensor data. This technique is the automated health monitoring which gives out the comprehensive and health monitoring result by interpreting data from all the sensors. The Dempster-Shafer (D-S) evidence theory was proposed to get comprehensive SHM results for a distributed sensor network in a infrastructure. Considering the above evidences from all the different data providing sensors having different levels having their own significance, not all the sensors data is effective for the final result. Different data providing sensors level are considered for evidence by assigning them different weighted coefficients. A Weighted Fusion Damage Index (WFDI) is proposed to perform damage identification.

Damaged index can be computed by calculating the Root mean square deviation between the energy vector of healthy and damaged state of structure, where energy vector of healthy and damaged data are distinguished. Energy vector of healthy structure [$E_h=E_{h,1},\ldots\ldots E_{h,2}{}^n$] and Energy vector of damaged structure is [$E_i=E_{i,1},\ldots\ldots E_{i,2}{}^n$] and hence the damaged index at time 't' is given as

$$I_i = \sqrt{\sum_{j=1}^{2^n}\left(E_{i,j}-E_{h,j}\right)^2 \Big/ \sum_{j=1}^{2^n}\left(E_{h,j}\right)^2}$$

Smart Aggregates concept in data fusion technique: -

The smart aggregate is a piezocermaic based element formed by embedding a water proof piezoelectric patch with lead wires inside the concrete block. The smart aggregates give out the result by performing different task and the three major tasks: - Initial concrete aging, impact detection and SHM. They also propagate a wave of long distance along a structure. Based on the wave propagation the damage is identified.

- *Vibration Control Technique:-*

Stochastic Subspace based Fault Detection Method (SSFD) was first used in France, Inverse Technique, Time domain method, Frequency domain method these techniques were used in vibration control technique. Rytter proposed that there will be 4 levels in detecting damage, where the information regarding the damage in obtained in the incremental manner from step to step:

Level 1:- To detect the damage
Level 2:- To locate the damage
Level 3:- To quantify the damage
Level 4:- To obtain the span of structure
The above levels are also the steps involved in SHM which are mentioned above.

With the help of vibration control technique, the risky zone of Guangzhou new TV tower(GNTV) of height 601 m, modular design was adopted here for detecting the risky zone, which were previously practices in long span bridge of Hong Kong in the year 2009. This concept has six modules which includes data sensing, Acquisition, processing, management and finally monitoring.

Sensory System (SS) are deployed for monitoring of three categories of parameter, 1) Loading 2) Environmental effect and 3) Structural response, which was possible because practice was implemented by placing 800 sensors in different location to collect signal of the proposed structure and digitize the analogue signals which transfer into digital data hence monitoring can be easy. Vibration is critical on structure, for the control of vibration along major and minor axis we have to apply Active mass damper (AMD) along with Tuned mass damper (TMD). But in case of major axis, Vibration is controlled by TMD because AMD will be activated only if wind speed crosses the predefined threshold. The Dynamics of a general non-linear, time varying, damaged structure are described by spatially discrete and coupled system of non-linear equation of motion. The non-linear evolution of damage which is governed by

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$$M(\theta_d, \theta_e, x, t)\&x\& + g(x, x\&, \theta_d, \theta_e, t) = f(t, \theta_d, \theta_e)$$
$$\Theta\&d = \Gamma`(\theta_d, \theta_e, x, \&x, t)$$
$$y(t) = h(\theta_d, \theta_e, x, x\&, t)$$

Where M represents the mass matrix, g is the force vector of elastic forces depending on displacement, velocity and time . These equations describe the non-linear function of evolution of damage parameter and environmental effect. Θ_e is assumed to be constant during vibration data acquisition. Generally, Vibration based SHM approach to damage identification are

1) Model approach
2) Eigen frequencies
3) Eigen frequencies and mode shapes
4) Model force residual
5) Minimum-Rank Pertubation Technique (MRPT)
6) Model curvatures and model energy expression
7) Output residual method
8) Input residual method
9) Frequency response function
10) Projected input residual method
11) Antiresponses
12) Transmissibility
13) Impedance method
14) Time domain method
15) Stochastic Subspace- Based Fault Detection Method (SSFD).

❖ *Cons and Pros of Wired Techniques*: -
- ✓ Sensors will have a physical contact with the structural element; therefore, the precise of damage detection is high.
- ✓ More number of sensors are required, as it will be designed to take care of particular region of structure.
- ✓ Same sensor can be used for various materials.
- ✓ Installation cost is high.

➢ *Wireless Techniques*:-

Wireless technique includes the sensors which are not in physical contact with the structural components and the data is received from the sensors without physical connection and the data is analyzed. SHM including wireless techniques requires high resolution images and the data. This stimulates the load carrying capacity, vibration control due to external agencies and crack detection. Wireless techniques require more time and fund during the installation but it can be used for longer time without any extra fund investment. Bridge structure is analyzed mainly with the help of this wireless technique. Active and passive sensors are used in this technique. These sensors capture high resolution images and evaluated with the help of Arc GOS. the expensive cost for purchase and installation of the SHM system components, such as sensors, data loggers, computers, and connecting cables, is tough. To guarantee that measurement data are reliably collected, SHM systems generally employ coaxial wires for communication between sensors and the repository. Even the installation of co axial wires is expensive and also there is a lot requirement of labors for the installation which again an expensive. This technique finds out the information regarding land use and land cover due to the presence of GIS which obtains the high resolution images. It was not that used in the past decades but due to the installation of sensors made to obtain attention in the field of monitoring. Wireless sensors are both economical and time saving.

Different wireless sensors used in SHM are:- *Microelectromechanical system (MEMS).*

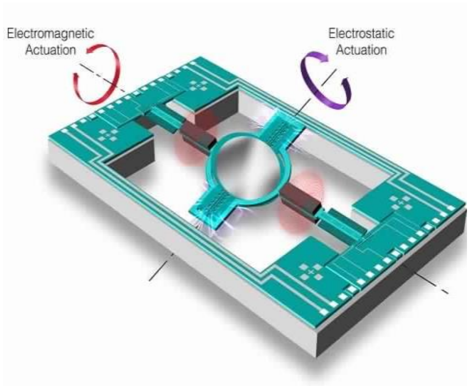

Fig 6
Image Courtesy: - http://www.icym.edu.my/v13/about-us/our-news/general/915-microelectromechanical-systems-mems.html

Nuclear magnetic resonance (NMR).

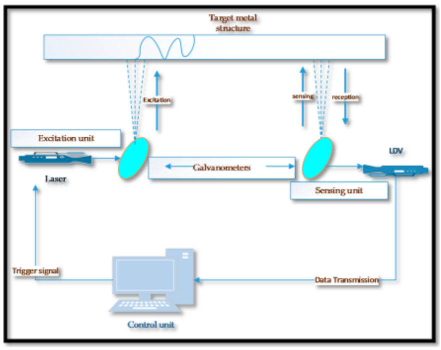

Fig 7
Image courtesy: - https://www.researchgate.net

❖ *Cons and Pros of Wireless Techniques*: -
- ✓ As sensors won't be having a physical contact with the structure, so the precise of damage detection can't be expected.
- ✓ Limited number of sensors is used in this technique.
- ✓ One sensor will only be limited to only one material.
- ✓ Initial cost is too high but in life time it's economical.

➢ *SHM using Smart materials and structures(SMS).*

From 1980s, the new concept had come up in the field of monitoring with the help of smart materials. These were helpful mainly in the field of aerospace and civil engineering. Day by day the usage of Smart materials is increasing drastically. This can be implemented during construction and result can obtained till the failure of either sensor or the infrastructure.

The invention of new smart materials can be in such a way that it should adopt to all environmental conditions by making them sensitive, controllable and active. The different levels of this intelligence corresponds to the existence of one, two or all three qualities.

Classically, three types of SMS exist: -

1. Smart material controlling their shape.
2. Smart material controlling their vibrations.
3. Smart material controlling their health.

Based on the requirement particular SMS is used for the monitoring of structural health.

SMS can be included with SHAPE MEMORY ALLOY (SMA) and also Smart Aggregate, the researches on these are still going on.

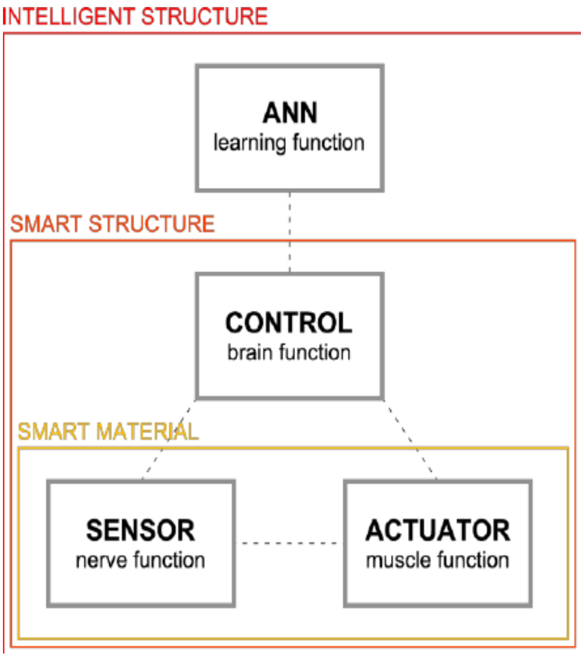

Fig 8
Image courtesy: - Active monitoring by Agnieszka Jędrzejewska.

- *Non Destructive Technique:-*

Usually this type of technique is used for investing and evaluating the actual condition of structure. Comparatively it is easy, fast and economical. Selection of specific NDT method relies on property of material.

- *Rebound Hammer Test:-*

One of the oldest and common method which predict the quality of concrete and indirectly assess its strength. Rebound of the hammer depends on the hardness of the surface on which this elastic mass strikes. The main application is to find elastic properties like compressive strength and determining variation of strength within structure.

- *Strain Gauges:-*

These are used in situations where a structure is subjected to force, its demension change resulting in strain. As it is fixed to structural component directly, any distortion will cause distortion in gaugs. Therefore any changes like tensile, compressive or shear can be measured by the strain gauges.

- *Low strain integrity test:*

This test is conducted to determine whether structure is free from cracks or not and also to check prsence of expansion of concrete. It is based on wave propogation theory, mainly it is applicable in pile foundation. When pile is subjected to impact load, variation in cross section such as change in dia or length. This impact produces downward wave propogation.

- *GPS:-*

According to the principle the GPS consists of three parts, which are Satellite orbiting the Earth, Control and monitoring station on earth and receivers. Kinematic GPS allows sub centimeter accuracy achieved at a rate of 20Hertz, and maximum distance from GPS receiver to Bridge receiver is up to 30km. It is mainly used in long span bridges. It has several advantages such as Wind independence and do not require a line of sight between target points.

VIII. CASE STUDY

A. *Real Time Monitoring of Burj Khalifa:-*

Burj Khalifa is the man made tallest structure. Height of the building is 828 meters. It has the total floor area of 460,000 square meters. It consists of residential, hotel, commercial, office, entertainment, shopping, and parking area. Overall it has 160 floors.

- *Temporary Monitoring:-*
  - The acceleration level during construction of building.
  - GPS system including the rover at level 138 and a static station at the office annex, to know the real time displacement of building.
  - Weather station to know the temperature, humidity, wind speed at level 138.

- *Present Health Monitoring:-*
  - Three pairs of accelerometers at the foundation to capture base accelerations.
  - Six pairs of accelerometers at levels 73, 123, 155 (top of concrete), 160M3, Tier23A, and top of the pinnacle to measure the tower acceleration simultaneously at all levels.
  - A GPS system to measure the building displacement at level 160M3.
  - Twenty-three sonimometers at all terrace and setback levels, including the top of the pinnacle at 828m above ground, to measure wind speed and direction.
  - The weather station at level 160M3 to measure, wind speed & direction, relative humidity, and temperature.

The present health monitoring is extension of already existing temporary health monitoring.

IX. BARRIERS OF SHM

- As there is use of conventional cables, so there should be always connection with ground.
- Sensors nowadays are costly therefore the installation cost is high.
- Risk due to ambient signal noise corruption.
- Risk caused due to earthquake conditions.
- Based on the size of structure the number of sensors are required.

X. APPLICATIONS OF SHM

- Places are more likely to affected by earthquake, it helps to evaluate such kind of places.
- Sensor data should be taken on regular basis so that the health of the particular structure can be known.
- Nondestructive evaluation technique makes structures have prolonged service life.
- SHM can provide a post warning for earthquake and validate retrofitting operations.

XI. LIMITATIONS

- To estimate the benefits of SHM, cost benefit analysis should be introduced apart from installation cost, its operation and maintains cost can be estimated.
- As in growing world, installation of sensors number as increased through which inappropriate data is not obtained.
- Due to over load of n number of data, data acquisition and its analysis in data interpretation and diagnosis is difficult.

XII. CONCLUSION

This paper work conveys all about SHM applications on various infrastructure, its merits and demerits. It also present benefits regarding safety and sustainability, but improvement and further research need to be done for its advancement in future. As interpretation of damages and deflection are done by regular inspection with use of expensive instruments, so there need to cost effective and more efficient techniques to make this world better. Improvement on sensors can be done as one sensor can be used in different condition and materials and also improvement on wired techniques as its installation is difficult. All though newly emerging wireless technology as more scope on economic aspects and its easiness as its transmission and processing data before transmission can solve bulk data management practically. Indeed, all SHM plays important role especially on public structures like bridges, towers, transportation, dams for human safety and sustainability.

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