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Health Monitoring of Civil Structures-Current Status and Perspectives

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Abstract
This paper focuses on the modern concept of health assessment of structures, just like medical doctors monitoring the health of their patients during and after major illnesses via appropriate measurements. Recently, the idea of structural health monitoring (SHM) has received considerable attention worldwide due to the fact that civil infrastructures form the back bone of any modern economy. Failure of structures such as bridges, dams, high rise buildings and power plants to perform at their best might have serious repercussions on the economy. It is therefore pragmatic to instrument important structures so that they can be continuously monitored in preventive mode and any possible malfunctioning can be predicted in advance, before it gets transformed into a catastrophe. This paper provides a glimpse of the available sensor technologies and methodologies for SHM, along with several case studies. Challenges ahead, especially with respect to the state-of-the-art are also highlighted.

Keywords
Structural Health Monitoring (SHM), Damage, Sensors, Piezo-Impedance Transducers

1. Introduction

Vast economic resources are are spent for constructon of bridges, power plants, dams and other infrastructues of national importance. However, not much attention is generally paid to sudy their behaviour after construction. During economic booms, rapid emergence of new infrastructures is a common phenomenon. However, their aging in the later years often creates problems for which the maintainence engineers are not prepared. These facts have prompted the structural engineering research community to investigate the development of techniques by means of which a structure could be automatially monitored in the real-time through appropriate instrumentation. This becomes more important in circumstances where unfamiliar construction technologies are used or a current technique is used under unfamiliar cionditions. This fact is very well highlighted by the accident involving the construction of an underground station for mass rapid transit (MRT) circle line in Singapore on 20 April 2004. In this accident, a temporary wall supporting 33m deep excavation adjacent to Nicoll Highway collapsed without warning, leading to a caving-in of an area as large as two basketball courts in the highway, as shown in Fig. 1. The accident resulted in loss of four lives and left several others injured, besides untimely closing a vital transportation link. Fortunately, no mtorists were travelling at that time along the usually congested highway, otherwise the casualities could have been much higher. Invesitgation by the committee of inquiry pointed suspicion at the design and construction of jet grout piles that formed vital part of the soil retaining system. The committee pointed out that being unfamiliar construction, more emphasis should have been laid on monitoring these after construction. The incident

Figure 1: The site at Nicoll Highway after collapse

strongly highlihts the need of comprehensive monitoring during constuction, especially in urban centres where critical structures are likely to be situated adjacent to the excavation sites. The scarcity of land often compells the town planners to look for space underground, just below existing structures.

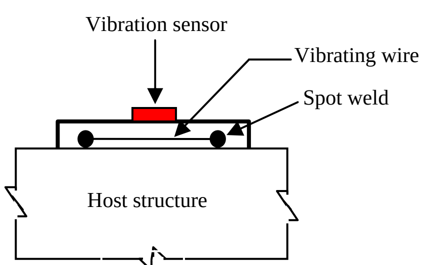
The concept of SHM is similar to monitoring thecritical parameters of an aircraft or an automobile or a patient in hospital so that any adverse changes in subject's condition can be timely detected and preventive action be taken. SHM is defined as the acquisition, validation and analysis of appropriate response data of the structure so as to detect any adverse 'changes' in sructural respnse (Kessler *et al.*, 2002). Seveal bridges have been instrumented for SHM during the recent years, such as the Second Link bride connecting Malaysia and Singapore (Moyo and Brownjohn, 2002), the I-40 bridge in New Mexico (Farrar and Jauregui, 1998) and the Tsing Ma suspension bridge in Hong Kong (Lynch *et al.*, 2003). Several algorithms have been proposed to access the condition of bridge structures using vibration response data (Farrar and Jauregui, 1998). However, not many studies devoted to building structures, which exhibit a behaviour of far greater complexity, can be found in the literature.

Although Civil Engineers are now widely recognising the importance of SHM, the concept has not yet matured to the stage of being mandatory part of the existing codes of practice for design and construction. This paper briefly addresses the important issues related to SHM of civil structures. A brief description of sensing technologies is covered followed by their pactical benefits highlighted by means of several case studies.

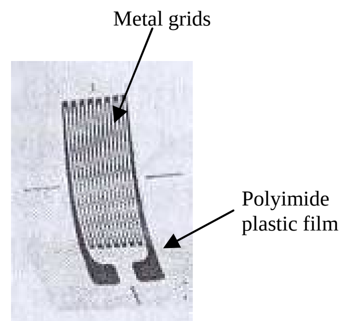
2. SHM: Available Sensors and Technologies

To carry out comprehensive SHM, critical locations of the structure should be instrumented with complementary sensor systems. The sensing system should have sufficient redundancy so that it is capable of tackling the failure of a few of the sensors without affacting the efficacy of the overall system (Bhalla *et al.*, 2005). In general, SHM sensors could either be 'surface bonded' type or 'embedded' type. The embedded sensors are generally installed at the time of construction, such as in the case of the Second link bridge connecting Malaysia and Singapore. Although they have prolonged life and robustness, they, however, cannot be replaced if they develop any fault during the service life of the structure. In addition, their installation on existing structures, constructed some time back, cannot be carried out in an easy manner.

Of all the available sensors, strain gauges are most widely used for structural behaviour monitoring. Strains on a structural surface result from axial forces, bending moments, shear and torsion. Hence, these sensors can easily capture an element's structural behaviour quite well. Strain measurement could be based on vibrating wire principle, that is change in natural frequency of a pretensioned wire bonded between two points of the structure, as shown in Fig. 2(a). These type of strain gauges are called vibrating wire strain gauges (VWSGs). Alternativly, it could be based on change in resistance of thin mettlic foil grids bonded to the structure (Fig. 2b). Such strain gauges are caled electrical strain gauges (ESGs). ESGs are preferred over VWSGs due to their low cost (about 1/50th of VWSG), especially for short term measurements. On reinforced concrete (RC) structures, they can be easily surface bonded or embedded, as shown in Fig. 3. However, they tend to be unstable over long periods of time or where exposed to moisture, under which circumstances VWSGs are preferred. VWSGs do not undergo any decay with time since they are based on the vibration principle. VWSGs were installed on the reinforcement bars in the case of the Second link bridge and reported to work well even after five years (Moyo, 2002). Main disadvantage of ESGs and VWSGs is that both types require long wires from each sensor to the data logger, are prone to electrical/ ambient noise and exhibit a low success rate on civil structure due to daamging effects of construction related activities.

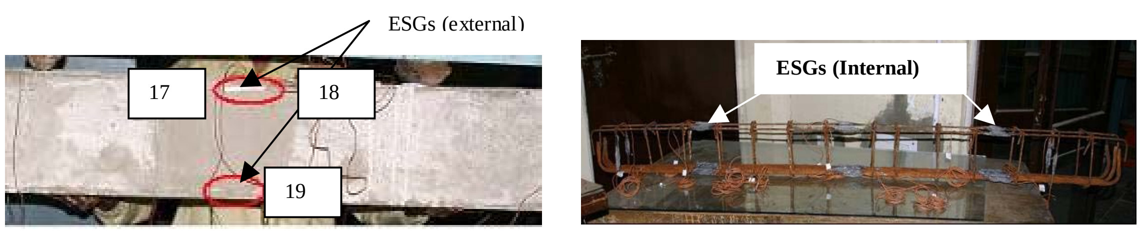


(a)



(b)

Figure 2: (a) Vibrating wire strain gauge (b) Electrical strain gauge



(a) (b)

Figure 3: Installation of ESGs (a) On surface (b) On rebars embedded inside

Besides VWSGs and ESGs, fibre-Bragg grating (FBG) based strain gauges, which are based on opto-electronic principles, have recently entered the domain of SHM. The optical fibres were originally developed for telecommunication purposes but have found tremendous recognition as sensors since the 1990s. A Bragg grating is a periodic structure, fabricated by exposng a photosensitised fibre to ultra violet light. When light from a broad source interacts with the grating, a single wavelength, known as the Bragg wavelength, is reflected back. Any external mechanical strain in the fibre shifts the Bragg wavelength and provides a means of measuring the induced strain. The FBG strain gauges are small, light-weight and durable. Unlike ESGs and VWSGs, they are immune to electro-magnetic interferece and can be multiplexed, thus eliminating long cables. However, they are very fragile and yet to fully mature into field proven sensors. In addition, the sensors themselves as well as the required interrogation system are relatively expensive as compared to the ESGs and VWSGs.

Unlike the three types of strain gauges described above, piezo-impedance transducers are relatively new sensor types, barely 12 years old. They do not measure any direct physical parameter like stresses or strains. Once bonded to the structure, they extract an electro-mechanical signature which contains information concerning the phenomenological nature of the structure. The sensors themselves are made up of piezo-electric ceramic (PZT) materials and are surface bonded to the host structure, just like the ESGs (Fig. 4). Their cost is of the same order as the ESGs. They are electrically excited to high frequencies of the order of kHz and the electrical admittance (real and imaginary components) as a function of frequency serves as a frequency response function (FRF) of the structure. Any damage to the structure changes this signature and provides an indication of the damage (Bhalla *et al*., 2005). Due to high frequency of excitation, this technique has much higher sensitivity to damage as compared to the conventional global vibration techniques. Bhalla and Soh (2004) demonstrated that the piezo-impedance transducers can typically dtect flexural cracks in the RC structures much before these could be visible to the naked eyes. Although the potential of these sensors has been well proven through numerous research studies, details such as sensor packaging, instrumentation and long term protection are yet to be standardized. Intensive reseach is currently underway at the Indian Institute of Technology Delhi to integrate piezo-impedance transducers with global low frequency vibration techniques to utilize their full potential. Research groups in the USA (Peairs *et al.*, 2004) are striving for the development of low-cost wireless based system for signature acquisition from these sensors.

There are numerous other sensors which can aid in structural monitoring, based on static/ dynamic response, such as accelerometers, pressure transducers and temperature sensors. A complete description of these is beyond the scope of this paper and can be found in Dally *et al.* (1984).

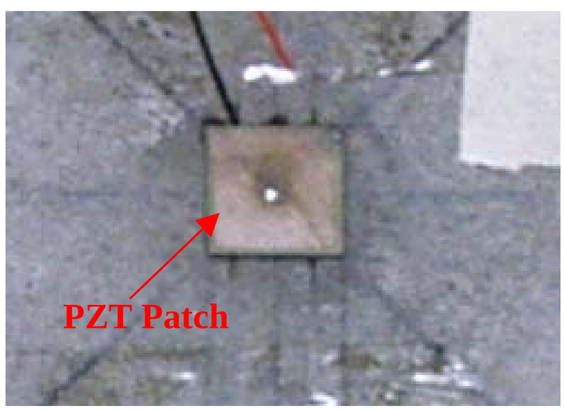


Figure 4: A PZT patch bonded on concrete surface as impedance transducer

3. Benefits from SHM

SHM has immense benefits for the structure, both during and after construction . A basic instrumentation of structures during construction can pave way for for long term monitoring of external loads, stress distributions, deflections and occurrence of damages in a continuous manner, thereby ensuring a high level of safety. Bhalla *etal.* (2007) recently demonstrated estimation of key deflections, bending moments, external loads and modal frequencies with reasonable accuracy for steel and RC structures, using spatially discrete strain measurements. Moyo (2002) demonstrated feasibility of monitoring the construction process of the Second Link bridge connecting Malaysia and Singapore using static strain measurements. In addition, post-construction behaviour was also successfully monitored for quite long period (more than five years) using the same sensors. Soh *et al.* (2000) demonstarted for the first time the successful detection of damage on prototype RC bridge structures using piezo-impedance transducers (Fig. 5). Bhalla *et al.* (2007) illustarted using the same piezo-impedance transducers for extraction of structural natural frequencies (Fig. 6).

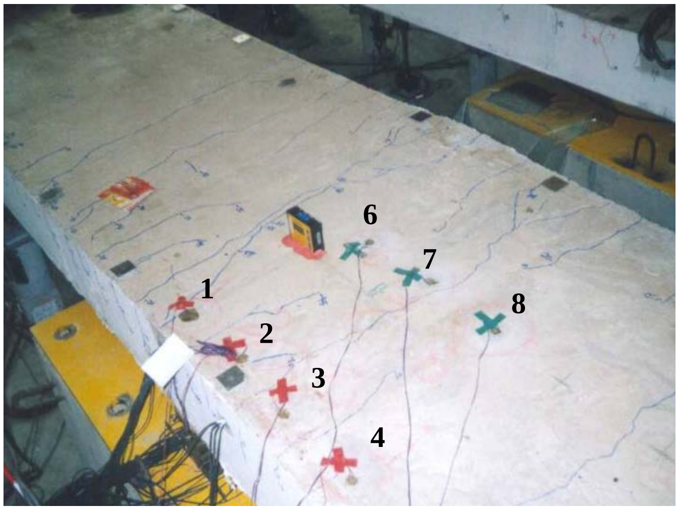


Figure 5: SHM of prototype RC bridge using piezo-impedance transducers (Soh *et al.*, 2000)

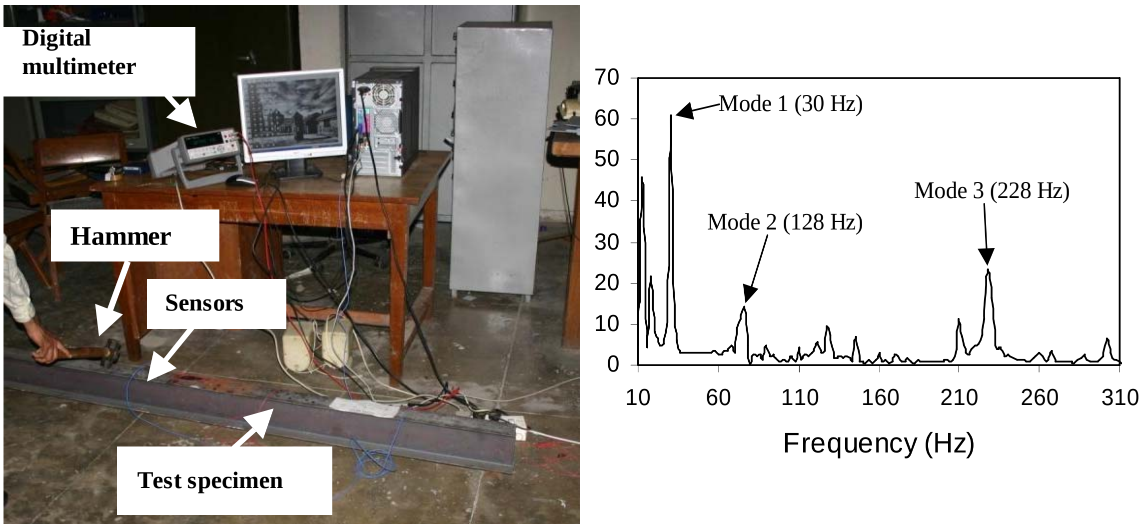


Figure 6: Monitoring of global dynamic response using PZT patches

SHM becomes more relevant for unconventional constructions, such as underground structures where several parameters cannot be accurately estimated at the design stage and must be validated after construction. Fig. 7 illustrates a model tunnel being monitored using ESGs. Fig. 8 provides a comparison of the load estimated using the ESGs with the actual external load. Reasonable agreement can be observed between the two. Numerous other case studies can be found in the literature highlighting the advantages of monitoring. Any instrumentation, however elementary, promises significant information

Figure 7: Monitoring of model tunnel lining using ESGs

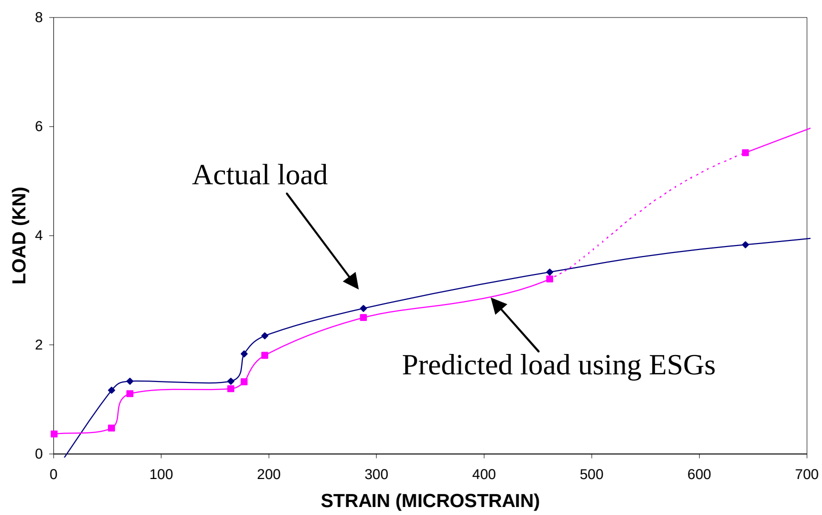


Figure 8: Comparison between actual and predicted load

that could help better understand its behaviour as well as play important role in validation of key design parameters. Sensors are especially useful in providing information for inaccessible regions of the structure for which regular manual inspection could be totally unfeasible. The initial investment in instrumentation would be only a small fraction of the overall structural cost and it ensures additional service with high benefit-cost ratio.

4. SHM: The path Forward

At present, SHM is not a codal requirement. The problem is further aggravated by the fact that there is no unique solution in terms of instrumentation technology or the data procesing algorithms since each structure is unique in itself. The harsh and rough environment in civil-structures necessitates further research for the development of robust packaged sensors and the data retrieval systems. Research should also focus on wireless technology which can eliminate several impediments associated with the current wire-based sensors. Another direction for future research should be to develop 'self-powered' sensors, which could derive the necessary energy from ambient vibrations or solar energy or ambient structural vibrations, thereby minimising energy required for sensing, data retrieval and transmission.

5. Conclusions

This paper has presented an overview of the present state-of-the art in SHM. Necessity of SHM has been strongly highlighted. Common sensing technologies, along with their novel features and limitations have been briefly described. Practical benefits of SHM have been emphasized by means of several case studies and a vision for future research in SHM has been spelt out.

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