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Application of different structural health monitoring system on bridges: An overview

F.H. Chowdhury, M.T. Raihan & G.M.S. Islam
Department of Civil Engineering, Chittagong University of Engineering & Technology (CUET), Chittagong – 4349, Bangladesh

ABSTRACT: The most common health monitoring system for bridge is visual inspection. Bridges are to be inspected within every two years. This might be suitable for monitoring the structurally sufficient noncritical structures but not reliable when it comes to monitoring actual health of structures. Remote monitoring of structures reduces man hour providing accurate results and up-to date data which allows to assess the integrity of a structure. Recent advances on sensing, communication and storage technologies have also enabled the use of broad-scale Structural Health Monitoring (SHM) system to the infrastructures. In general, a typical SHM system includes three major components: a sensor system, a data processing system and a health evaluation system. Researches have been carried out to improve the monitoring system and their implementation on infrastructures. Various sensing technology and data acquisition system have been proposed. Wireless Sensor Network system (WSNs) and Wireless Smart Sensor Network system (WSSNs) have been studied and applied to replace traditional wired sensor system for monitoring structural health. Generally used wireless technology includes acoustic Emission Technique to detect crack, fiber optic sensors for strain & temperature measurement, LVDT as displacement sensor. This paper gives an overview of the proposed monitoring system, their application and suitability on the bridges based on the existing research.

1 INTRODUCTION

The process of implementing a damage identification strategy for aerospace, Civil & Mechanical Engineering infrastructure is referred to as Structural Health Monitoring (SHM) (Farrar *et al.* 2007). SHM aims to give a diagnosis of the state of the constituent materials, of the different parts and of the full assembly of these parts constituting the structure as a whole (Balageas and Fritzen, 2006). In the field of Civil Engineering, monitoring of different infrastructures is always an important issue. Transportation infrastructures get some special concern among them. A most critical part in every transportation network is Bridge (González, 2011). They are always expensive projects and any failure of the projects has the ability of make a serious disaster. Therefore health monitoring of bridges always holds great significance. After the collapse of the I-35W Mississippi River Bridge located in Minneapolis, Minnesota, USA, in August 2007, bridge health monitoring has become an area of great interest. There can be various reasons for monitoring a bridge, most importantly, to obtain quantitative data about the structural behavior over time in order to confirm design assumptions. In addition this could provide real-time feed-back during construction and can perform a controlled lifetime extension of a bridge with known problems (Inaudi, 2010).

For a proper investigation of estimating the remaining lifetime of the structure, the current stage of the structure is not enough. Detailed knowledge on the deterioration pattern with future stresses is needed for factual monitoring. Traditionally visual inspection is the most common way of monitoring structures. According to the standards set by the Florida Department of Transportation and the Federal Highway Administration (FHWA) of USA, every bridge is required to undergo a visual inspection once every 2 years (Collins *et al.*, 2014). However, this never gives in depth monitoring of the structures.

According to Chang (1999), the main focus of structural health monitoring is to gather all behavioral data of in-service condition of the structure along with real time & continuous assessment. Scheduled maintenance and periodic inspections offer only specific information of structural condition and costly in terms of extensive labor and downtime. But advanced sensing technology offers wide variety of materials and structural damage identification, possible diagnostic technologies to overcome the damage and real time inspection (Gastineau *et al.*, 2009). Remote or wireless monitoring using different sensors serve the users a way to collect information from different period and of different occurrence and then transmit the information to another location from where user can collect the data following the information or signal. This monitoring system can be adopted from the construction period to total service life of the structure. This paper aims to gather available information on remote monitoring system for bridges.

2 STRUCTURAL HEALTH MONITORING OF BRIDGES

Bridges are important infrastructure considering its use and purpose-serving. Bridge may fail due to different loading conditions. It may be due to some permanent loads like dead load, earth & water pressures. There also exists occasional loads like earthquake forces, vehicle live load, wind forces etc. Deformations may occur due to creep shrinkage and settlement. So, all combination of those or independent cases can be the crucial part for damage of structure. For existing bridges corrosion and sea-water effect is a very emerging issue considering the durability concept. Early and proper detection of damages help to save the structure by repairing timely. According to FHWA, a highway bridge is classified as structurally deficient if the deck, superstructure and substructure is rated in "poor" condition which means engineers can identify any major defect in any significant part. If the load carrying capacity of a bridge is significantly below current design standards or if the bridge is frequently overtopped during floods by the waterway below, it can also be classified as structurally deficient (ODOT Manual of Bridge Inspection, 2014, v.8). There require to inspect all bridges 20 feet or longer at least every two years. According to the American Society of Civil Engineers' 2009 Report Card for America's Infrastructure, eliminating all bridge deficiencies in the United States within the next 50 years would require an investment of over $17 billion each year. A complete SHM approach may be consists of four basic level: Identification of damage occurrence in the structure- if any, identification of single or multiple damage locations, quantification of the level of damage and evaluation of structural performance and its remaining lifetime (Bisht, 2005).

2.1 *Evolution of SHM System of Bridges*

Long-term monitoring systems have been implemented on bridges in the United States, Canada, Europe, China, Japan, Korea and other countries over the past decade (Ko and Ni, 2005). Due to experiential dependence, traffic disturbance and high-cost regular visual inspection does not reflect the true performance state of bridge components accurately. The FHWA carried out a study in 2001, which indicates that 56% of medium to short-span bridges were given in an average condition rating by visual inspection and were assessed improperly (Phares *et al.* 2000). The biennial visual inspection of the Brooklyn Bridge in New York is reported to take over 3 months at a cost of $1 million (Dubin & Yanev, 2001; Pines & Aktan, 2002). An alternative to that was Structural Health Monitoring (SHM) which aimed at monitoring structural behavior in real-time by evaluating structural performance under various loads and identifying structural damage or deterioration. A traditional wired SHM system included three major components: a sensor system, a data processing system and a health evaluation system (Yi and Li, 2012). The data of the sensor system are processed intensively by the data processing system after being transmitted through coaxial wires. However, this system has many disadvantages such as high cost, low efficiency, susceptible disturbance, inflexibility. For example changing or addition of new sensors required extra cables for data transmission and also renewal of data management software. Moreover, after completion of the wired SHM system, further modification of the sensor system resulted a lot of auxiliary works. In order to overcome this faults, wireless sensor network (WSN) based SHM system was introduced. The high cost associated with the installation of wired sensors (Celebi, 2002; Farrar, 2001) can be greatly reduced by employing wireless sensors. Usually, when there are a large number of sensors with high sampling frequency, it can generate enormous amount of data from the monitored structure. For instance, the Tsing Ma and Kap Shui Mun Bridges in Hong Kong produce 63 MB of data every hour (Wong, 2004). In this regard, now-a-days intensive researches on smart sensors are going on. Some implementations of different smart sensors are also found in various articles. Smart sensors can locally process measured data and transmit only the important information through wireless communication (Nagayama and Spencer, 2007). Smart sensors allows significant data compression at the node level by taking out only the necessary information and thus reduces the amount of data to be transferred or stored thorough a wireless communication. Computational and communication capabilities of smart sensors have been considered to offer new opportunities for the monitoring of structures. Several smart sensor prototypes have been developed and numerous attempts to employ smart sensors for SHM application are continued. But there exists some problems in perfect monitoring process which needed to be solved for proper implementation of smart sensors. Figure 1 shows a flow chart of SHM which includes common four stages of SHM.

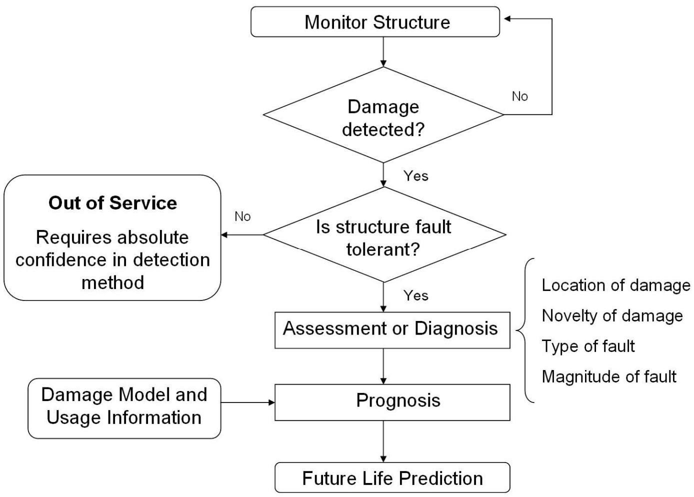

Figure 1. A general flow chart of a SHM system including the 4 stages in which SHM is most commonly divided: Detection, Location, Severity and Prognosis (González, 2011).

2.1.1 *Wireless sensor network system (WSNs)*

Bridge health monitoring using a wireless sensors network is one of the most promising evolving technologies and is seen as the next generation of SHM (Kurata *et al.*2005).Wireless sensors represent one potential sensing technology that can contribute in advancement of the structural engineering field's ability to realize SHM economically (Lynch and Lo, 2006). The new advances of micro electro-mechanical systems (MEMS), wireless sensing technology and integrated circuit technology help to introduce low-cost wireless sensors with onboard computation and wireless communication capabilities (Zhou and Yi, 2013), shown in Figure 2. The extermination of widespread lengths of coaxial wires in a structure caused the wireless systems having low installation costs. The installation of wireless sensors is very easy without deploying complicated cables. As the sensors are organized by wireless transmission, after the initial installation updating, adding moving and replacing of sensor is easy. During the original data acquirement operation the network reorganizing can be done quickly without disturbance (Chae *et al.*, 2012).

The WSNs-based bridge health monitoring system is consist of hardware and software. The hardware is usually comprised of a wireless sensor and central server .The software consists of several components such as network operation, data collecting, data processing, power management, and so forth. In general, a wireless sensor is composed by four functional subsystems: a sensing interface, a computing core, a wireless transceiver, and a power source. However, influencing factors include- type of the structure to monitor, sensor locations, environmental aspect of the structure (Chae *et al.*, 2008). Care should be given for selection of each subsystem.

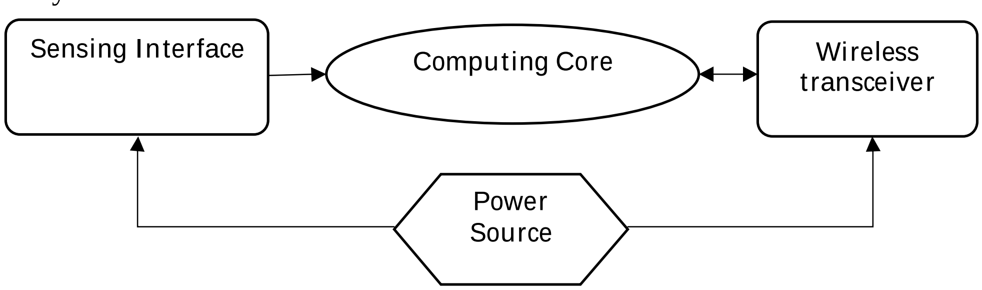

Figure 2. Subsystems of wireless sensor (adapted form Zhou and Yi, 2013)

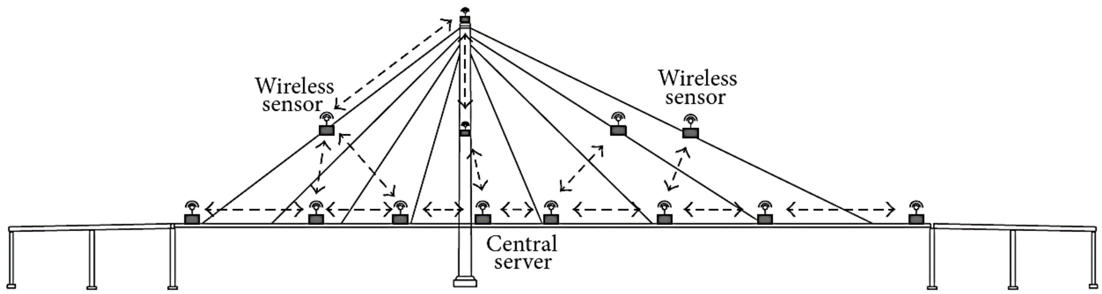

Figure 3. WSNs-based bridge health monitoring system (Zhou and Yi, 2013).

The WSNs-based bridge health monitoring system eliminates the high cost of cable, depending on the WSNs data transmission. Several types of wireless sensors need to be installed on key locations on a bridge. The central server sends commands to activate wireless sensors, establish a WSN and set the monitoring parameters in the beginning; then, the whole WSNs executes time synchronization; after that, the wireless sensors begin collecting data and transmitting raw data or processed results back to the central server. The measured data then can be employed for advanced structural performance evaluation. A typical WSN for bridge health monitoring is displayed in Figure 3.

2.1.2 *Wireless smart sensor network system (WSSNs)*

Most studies using wireless smart sensors to monitor structural health has focused on using the sensors to emulate traditional wired sensor systems (Pakzad *et al.*, 2008). Rapid developments in sensors, wireless communication, MEMS and information technologies have the aptitude for influencing SHM importantly. To deal with the large amount of data generated by a monitoring system, on-board processing at the sensor allows a fraction of the computation to be done locally on the sensor's embedded microprocessor. *Smart* sensors provides such an approach with abilities to self- diagnosis and self-calibration capabilities which reduces that amount of information needs to be transmitted over the network (Spencer *et al.*, 2004). Smart sensor is divided into three parts (i) the sensing element (ii) signal conditioning and (iii) a microprocessor. The feature that distinguishes smart sensor from a standard integrated sensor is its intelligence capabilities. The microprocessor which can enable self-diagnostics, self-identification or self-adaptation functions is normally used for digital processing, analog to digital or frequency to code conversions, calculations and interfacing functions (Kirianaki *et al.*, 2002). Smart sensors are capable of decision-making in case of storing/dumping data and it can also minimize power assumption by controlling when and how long will the sensor fully awake.

Application of WSSNs in SHM has some drawbacks which originated from the lack of adequate resources on smart sensors. In case of hardware, smart sensors are usually battery powered with limited RAM and has relatively slow communication speed. Middleware services for such hardware are not that suitable for SHM. In addition, smart sensors may have intrinsic synchronization error and communication among sensors can be erratic. A well-developed smart sensor platform (Imote2) is released for application in SHM of Civil Infrastructure. This one has significantly richer hardware resources when compared to other smart sensors and suit better in SHM application (Spencer *et al.*, 2004).

Figure 4. The Jindo Bridges, the second Jindo Bridge is the one to the left (Jang *et al.* 2010)

The second Jindo Bridge in South Korea is the first bridge to have autonomous and full-scale wireless monitoring system. Initially, it was installed through a joint effort among the University of Illinois at Urbana-Champaign (UIUC), the Korea Advanced Institute of Science and Technology (KAIST) and the University of

Tokyo (Figure 4). On the girder, pylons and cables seventy-one WSS nodes with a total of 427 sensing channels were installed. The nodes are composed of the Imote2 (including on-board CPU, radio, and power management integrated circuit), a sensor board and a battery (Jang *et al.*, 2010; Rice *et al.*, 2010). By installing WSSNs and wired system, full-scale bridge health monitoring has been performed on the Meriden Bridge. Five Imote2 sensor was installed and wired monitoring system consisted of 38 sensors with different types (Li, 2014).

3 APLLICATION OF DIFFERENT TYPES OF SENSORS IN SHM

Wireless sensors are not the sensor defined by the conventional concept. These are autonomous data acquisition nodes in which structural sensing elements such as strain gauges, accelerometers, linear voltage displacement transducers, inclinometers, among others; the onboard microprocessor and wireless communication components are integrated (Zhou and Yi, 2013). Application of WSNs and WSSNs in SHM includes several types of sensors based on their performance. World's longest suspension bridge, the Akashi Kaikyo Bridge in Japan, uses a seismometer, anemometer, accelerometer, velocity gauge, global positioning system (GPS), girder edge displacement gauge, tuned mass damper (TMD) displacement gauge and thermometer for dynamic monitoring (Sumitro *et al.*, 2001). Some of the common sensors and their application in SHM are discussed here in this section.

3.1 *Accelerometer*

Accelerometers have been the most widely used type of sensor for damage identification and health monitoring algorithms because of their ease of use, robustness, relatively low cost, and ability to detect changes in both local and global properties. Dynamic Phenomena of structures which is an important part of monitoring infrastructure can be measured by using accelerometers (Gastineau *et al.*, 2009). Furthermore, accelerometers are generally robust, easy to install, and relatively inexpensive. This combination of factors has led to the development of an extremely wide variety of different algorithms that utilize acceleration measurements to monitor the health of structures.

Though this system has been used for good many years, there still some error issues that can be propagated during the numerical integration (Park *et al.* 2007). Accelerometers can provide useful measurements, but due to possible error in their use, the data should be corroborated with another type of system. For example, some suggest that accelerometers coupled with GPS can negate the errors that both systems may exhibit (Roberts, 2004). The Bill Emerson Memorial Bridge is instrumented with 84 accelerometer channels. Including installation with an average cost per channel is over $15 K (Jang *et al.*, 2010).

3.2 *Acoustic Emission (AE)*

There are some non-destructive testing (NDT) methods such as radiographic methods, ultrasonic-based methods and acoustic emission (AE) techniques etc. which are used to monitor Civil Infrastructures. Among them AE was found to be the most widely used for highway structural assessment (Rens *et al.*, 1997). AE monitoring is considered exceptional among other NDT methods because it is applied during loading of a structure, whereas most others are applied after or before the loading (Grosse *et al.*, 2004).

AE monitoring is a passive monitoring technique which aims to detect acoustic stress waves being generated by the rapid release of strain energy from micro-structural changes in a material. These waves are usually of low amplitude and can be classified into primary and secondary emissions. Primary emissions originate from the material of interest and all other emissions are secondary emissions (Meo, 2014). AE monitoring system requires two integral components: a material deformation that is the source and transducers that receive the stress waves being generated from the source. The general working principal of AET monitoring system is shown in Figure 5.

Three basic components to measure AE are the generated AE wave, the detection equipment for capturing AE signals, and collected data processing and interpretation (Nair and Cai, 2010). A typical AE wave detected by an AE sensor is a combination of longitudinal, transverse, reflected waves (Kawamoto and Williams, 2002). Resonant sensors are recommended by most researchers because of their highly sensitivity to typical AE sources (Nair and Cai, 2010). For bridge monitoring, unidirectional sensors and sensors sensitive more to in-plane wave modes may prove beneficial in differentiating AE sources in various bridge components (Carter and Holford, 1998).

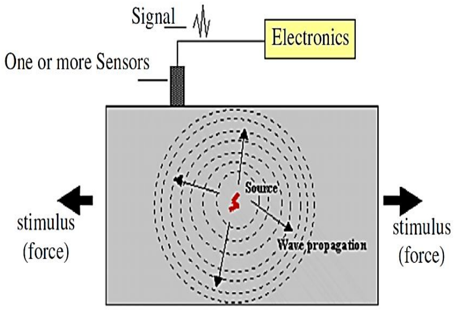

Figure 5. Principle of acoustic emission (Grosse 2002).

Figure 6. Wireless sensing of bridges using radio frequency transmission (Grosse *et al.* 2004).

Attenuation of acoustic waves and geometric spreading in concrete structures causes to install numerous sensors to cover all critical parts. Wired connection between all sensors and the processing facility increases the installation expenses and also makes the AE technique uneconomical. Hence implementations of wireless sensors were proposed by Grosse. Figure 6 provides the basic concept to remotely monitor the AE sensors using wireless technology. In addition to this, performance based Micro electro mechanical systems (MEMS) make this technology more economic for huge structures like bridges (Grosse *et al.* 2004).

Study by Mclasky *et al.* (2009) showed implementation of AE monitoring in a number of concrete structures and laboratory experiments, including a bridge. The damage detection approach is an indirect measurement of the sample which simply estimates the amount of energy released but does not locate the source of the emission. Similar experiment was carried out on steel member by Roberts & Talebzadeh (2003). However, AE based structural health monitoring for bridge cable were extensively studied by numerous researchers (Brevet *et al.*, 2002; Gaillet *et al.*, 2004; Zeilji *et al.*, 2006) and they concluded that AE monitoring is suitable for detecting and locating wire breaks in cable structures.

3.3 *Fiber Optic Sensor (FOS)*

For a durable solution for SHM, fiber optic sensors (FOS) can be an ideal selection in most cases. According to Peters and Inaudi (2014), being durable, stable and insensitive to external perturbations, FOS are especially useful for long term health assessment of Civil Structures, Geo-Structures and Aerospace Structures. It can be used in case of performance monitoring of infrastructure like monitoring the strain profile of large structures, monitoring or tracing important parameters like temperature, pressure at different location. Actually it is one of the promising sensing method which is performed as an internal sensor inside structures to observe and monitor the possible damages (Yang & Yuan, 2009; Afzal *et al.*, 2012). The fiber optic smart structure used for monitoring and managing the health of bridges use an array of fiber optic sensors. This can monitor physical parameters closely related to structural damage in real time basis (Chang, 2010).

Brillouin scattering sensors is an interesting potential for distributed strain and temperature monitoring (Karashima *et al.*, 1990). Sometimes for monitoring dynamic strain or temperature, intensity detection with fixed Brillouin scattering could be used without scanning the Brillouin spectrum (Bao *et al.*, 1996) and thus significantly reduces the measurement time. Cracks and deformation, including the prediction of cracks in concrete structures and buckling in pipelines has been investigated using special signal processing schemes developed from detailed studies of the Brillouin spectrum shape change, with particular attention to asymmetry and broadening in addition to the peak change (Ravet *et al.* 2006).

Another deformation monitoring system named SOFO (the French acronym of “Surveillance d’Ouvrages par Fibres Optiques or structural monitoring by optical fibers) has been developed by the Stress Analysis Laboratory of the Swiss Federal Institute of Technology (IMAC-EPFL) and by SMARTEC SA, Switzerland is based on fiber optic technology and is capable of monitoring micrometer deformations which means relative displacement between two points, over measurement bases up to a few meters (Inaudi, 1997; Inaudi *et al.*, 2001) The SOFO measurement system is based on low-coherence interferometry in single-mode optical fibers (Inaudi, 2005). The measurement fiber is pre-tensioned and mechanically coupled to the structure at two anchorage points in order to follow its deformations, while the reference fiber is free and acts as temperature reference (Inaudi, 2005).

Figure 7. SOFO system reading unit & sensor installation (Inaudi, 2005)

Fiber optic strain gauges known as Fiber-Bragg-Grating Sensors helps to measure changes in strain caused either by external stresses or temperature related issues. Some of the major benefits of FBG sensors relate to their immunity to EMI or RF interference. They measure wavelength shift and not signal amplitude and form a part of the data transmission optical fiber connecting the instrumentation (Tennyson *et al.*, 2001) Moreover Fabry-Perot strain sensors, Raman Distributed Temperature Sensors etc. are also used in SHM purpose.

Optical fibers are composed primarily of silicon dioxide (SiO_2), though very small amounts of other chemicals are often added. Around the core of SiO_2 there exists a protective material cover and then a coating layer. During integration of FOS inside concrete structures, there should provide proper protections like coatings, cobblers.

3.4 *Linear Variable Displacement Transformer (LVDT)*

Although technologies like global positioning system (GPS) helps to determine global changes in position, linear variable differential transformers (LVDTs) or potentiometers helps in traditional displacement measurements. Usually these are connected to two locations on or at the boundary of the structure of interest for measuring relative displacements (Yoder and Adams, 2014). A LVDT sensor is capable of determining the displacement in one direction of one point relative to another point on a bridge. LVDT is quite common to measure displacement. Often LVDTs are used to verify the accuracy of new displacement monitoring systems and prove to be very accurate compared to these other methods (Park 2007, Merkle 2004). To determine the long-term degradation of the structure crack opening displacements can be measured directly using LVDT because of it's the long-term stability (Lovejoy, 2007).

An automated monitoring system for the bridge has been deployed on the Kishwaukee River Bridge, Illinois, USA since December 2001 .To measure the shear crack opening displacement on the box-girders, seven LVDT sensors were installed on the bridge (Wang and Yim, 2010).

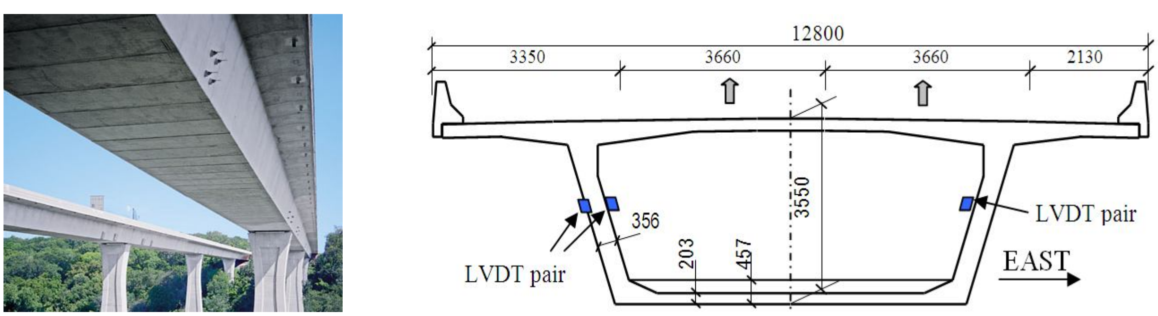

Figure 8. (a) Kishwaukee Bridge (b) Location of LVDT sensors (unit: mm) (Wang and Yim, 2010).

4 CONCLUDING REMARKS

Researches on structural health monitoring of bridges has been carried out for decades. Based on the purpose of the monitoring system (such as long term monitoring, short term monitoring), inspection or for early warning, numerous studies has been conducted. Endless effort have been given by the researchers to replace the traditional wired system with wireless sensor network. Many wireless systems are already capable to substitute the traditional wired monitoring system. In this paper some of them are discussed and their advantage and disadvantage have also been addressed. However, when it comes to long term monitoring of a bridge with full scale wireless network system, the number is still few. It is quite impossible to incorporate all critical global and local response measurement when it comes to long-term health monitoring system. There are a lot of work remains to apply this promising technology to fulfill the requirement of complex bridge monitoring and evaluation.

Technological limitations include power supply, data transmission reliability and network bandwidth. Most WSNs are provided with a limited power supply and hence suffer from power consumption. The hardware and software of a commercial wireless system requires extensive expertise to design because it is designed individually. So many complicated operations make it difficult for the general researchers to face and thus limits the application in long term monitoring. Another problem that WSNs face is to store and process enormous data produced every day with a limited bandwidth. Failing to choose an appropriate data management strategy may lead to system collapse in case of large scale monitoring. In WSNs based health monitoring system, installing a sophisticated system creates inexorable problem in sensor placement. Although cheap wireless sensor helps to install a lot of sensors on the structures, limited radio transmission causes more difficulties than wired sensor in case of sensor placement optimization.

Despite having so many improvements, WSNs based health monitoring is still illusive concept for many administers of bridges. Although application of smart sensor can overcome the limitations of traditional wireless sensors, but smart sensor itself has so many limitations. For a convincing WSNs technology more effort should be contributed. To obtain the most reliable assessment of behavior and performance of a large structure like bridge, it is desirable to instrument as many sensors as possible. But then, it may not practical and feasible. Therefore, several strategies should be implemented to design a long term health monitoring system with the available technologies.

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