An Overview on the Applications of Structural Health Monitoring Using Wireless Sensor Networks in Bridge Engineering

Ramzi Shaladi, Faesal Alatshan, and Chunhui Yang

Abstract**—**In this paper, we aim to highlight on the latest technologies and developments in the field of Structural health monitoring (SHM) using Wireless sensor networks (WSNs) in bridge engineering. The need for SHM has become inevitable for broad engineering fields including civil engineering sector. Wireless sensor network technology has widely drawn research interests, which can significantly improve the flexibility and versatility of SHM by implementing WSN as a vital tool for practical applications in bridge and building. The attention for WSNs has been greatly increased due to their accuracy, low-cost installation, low-cost sensing and capability to process data on-board and thus there is trend to apply the WSN technology to replace traditional wired monitoring systems.

Even though, successful SHM applications have been done on some critical civil structures using the WSN technology at the Lab and the field, it is still very limited to be employed for practical implementation in full-scale structures. Therefore, ongoing WSNs applications on full-scale civil structures are still needed to be conducted beside the lab evaluation to finally achieve the desired objective which is the SHM.

Keywords**—**Structure Health Monitoring (SHM), Wireless sensor networks (WSNs), damage detection and algorithm, bridge engineering.

I. Introduction

A. Background

THE concerns about maintenance of structures and monitoring structure's conditions have become a big challenge for engineers and researchers in the field of civil engineering. Structures such as towers, high buildings and bridges have to be assessed periodically to realize life safety, maintenance and consequently economic benefits will definitely be gained. Therefore, many researches and applications have been conducted in this field of civil engineering to monitor structures' conditions. Structural health monitoring (SHM) has drawn significant attention in the recent decades in many fields including maritime engineering, aerospace engineering, mechanical and civil engineering. Thus, the potential advantage of SHM in the area such as civil engineering has contributed to reduce the maintenance costs as well as to increase the safety and reliability of civil engineering structures.

The damage process and damage identifications for civil and mechanical engineering are referred to SHM [1]. Thus, SHM has been considered a significant assessment, and it has a numerous of keys that can be utilised in its monitoring applications including, damage detection methods with suitable algorithms, wired cable monitoring system and the recent wireless monitoring systems. Recently, the need for SHM has been increased in the area of civil structures, which often subjected to some loading during their lifetime as well as structures exposed extreme events like an earthquake and typhoon. Therefore, the concerns have been increased about the public safety as well as maintenance of structures especially critical structures including high buildings and bridges [2].

Yet, it cannot be denied that the integration of the emerging technology such as ABAQUS software that has capability to simulate and model structures using its great feature FEA. This integration of WSNs with such means of FEA software can play an important role in the current development of SHM and WSNs applications.

There is a significant difference in both the cost and accuracy of each monitoring system. The installation cost and equipment of SHM in wired monitoring systems are expensive, for instance, it was reported by Celebi [3] that the installation cost of SHM system for tall buildings excess of 5000 US$ per sensing channel. Moreover, it was mentioned that the cost estimation of installing about 350 sensor on Tsing Ma suspension bridge in Hong Kong have exceeded 8 million$ [4]. This economical impediment may prevent installing sufficient number of sensors which consequently, will affect negatively on the accuracy of SHM applications. However, the recent applications of SHM on civil structures have utilized wireless smart sensor networks (WSNs) which are considered an alternative accurate tool to the traditional wired monitoring systems in terms of overcoming the economical impediment of SHM system as well as achieving more accuracy. Using such WSNs monitoring systems have attracted considerable attention in SHM due to their advantages including, low cost, low maintenance, and installation fee and process data on-board.

B. Basic Concepts Of Cable-Stayed Bridges

Cable-stayed Bridges system is considered as one of the most modern systems. Figure 1 A and B show two examples of

Ramzi Shaladi Department of civil engineering, Al-Zawiya University, Subrata, Libya

Faesal Alatshan Department of civil engineering, College of engineering technology, Houn, Libya

Chunhui Yang School of Computing, Engineering and Mathematics, University of Western Sydney (UWS), Penrith, NSW 2751, Australia

cable stayed bridges.

Valuable information related to basic concepts cable stayed bridges now available in many publications. [5]. The distinctive components of cable-stayed bridges are classified as shown below:;

Fig.1.(A) The World's Longest Span Cable-Stayed Bridge In Russia [6]

Fig. 1. (B) The World's Highest Cable-Stayed Bridge In France [7]

B1.1 Cable Arrangement

There are four cable stayed basic longitudinal configurations as it is shown in Figure 2 below:

(1) The radiating type, (2) harp type, (3) fan type, and (4) the star type. The basic arrangements generally have two arranged planes which are either two planes or single plane, and they are represented in four main types. Type (1), is one vertical plane of cable which is positioned on the longitudinal centre-line of the structure whereas type (2) is a vertical plane located laterally from the longitudinal centre-line of the bridge. Type (3) is a double-plane arrangement which has two planes either vertical or intersecting and sloping on a bridge centre outside the roadway. In type (4) V-shape double plane system, subjected to reduce the height of tower without changing the height ratios, this is to avoid staying on tower top and eliminating any lateral sway of the girder deck.

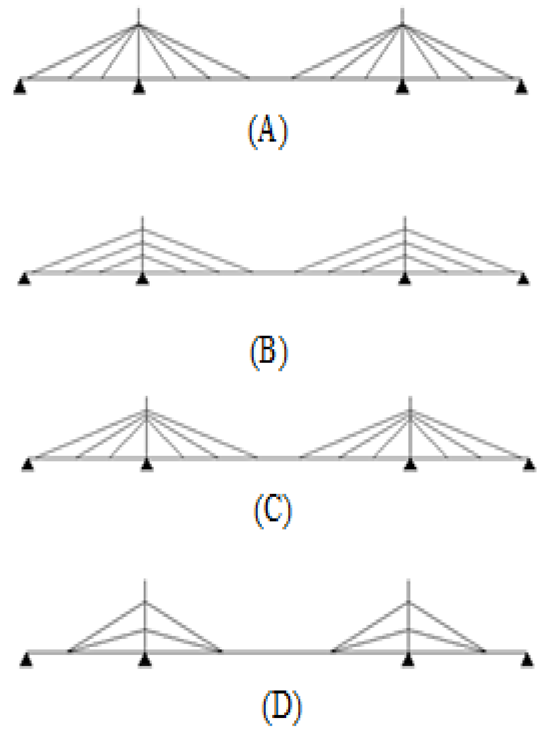

Fig. 2. The Types Of Cable-Stayed Arrangements

B. 1.2 Towers (Pylons)

These are referred to pylons; towers may have a simple form of single cantilever for type (1) arrangement or may consist of two cantilever members for double–plane cable structure. Towers can be hinged or fixed at the base or the form of portal frame. The tower can have three shapes, which are transverse shape, diagonal shape and modified diamond.

B. 1.3 Bridges' Deck Types

Wind effects can affect the deck by causing instability because of wind's velocity also flutter and fatigue induced from vibration of the wind. Live load causes elastic deflection of bridge decks. The basic structural system is stiffened truss and solid web. The trusses are rarely selected because of their high fabrication and maintenance. However, the solid-web girder appears to control the superstructure types. Additionally, the bridges' deck in cable-stayed construction is made from either steel or concrete, and some cases composite forms.

B. 1.4 Span Arrangement

There are three basic types of span arrangements:

(a). two spans, symmetrical or asymmetrical; (b). three spans; (c). multiple spans.

B.1.5 Loads Acting On Cable-Stayed Bridges

Loading conditions:(1)Dead load; (2) live load; (3) dynamic effects on live load ; (4)wind loads; (5)erection loads; (6)other loads such as, longitudinal forces, centrifugal forces, thermal forces, shrinkage, seismic effects and so forth of forces that may be exist.

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II. Literature Review

A. A. Structural Health Monitoring (SHM) Based On Wireless Sensor Networks (Wsns)

The area of autonomous SHM for infrastructures particularly, critical structures such as bridges has become a great challenge for civil engineers and researchers. For example, it was reported in USA by Federal Highway Administration that over 25% of the bridges in the United States classified as either structurally deficient or functionally outdated [8]. Thus, the need for emerging developed WSNs has become very urgent to realize SHM applications.

Utilizing WSNs for monitoring the health of structures such as bridges has been widely deployed in a real life [9]. Morgan [10] has declared that the WSNs were successfully designed based on test validation of the characteristics and the components of WSNs when utilizing the WSNs in his research. Lynch [11] stated that the detection of particular damage using WSNs units has a big motivation and attention to interrogate structure data for the damage sings. Additionally, Lynch [11] cited the Alamosa Canyon Bridge in New Mexico. That was one of the successful field tests by using WSNs duo to the reliability of WSNs in this application that have been validated after completing the software designs of sensing unit.

B. 1. Wireless Sensor Network (WSN) Developments

There are many academic and commercial wireless sensing unit forms, figure 3 shows a verity of wireless sensor platforms.

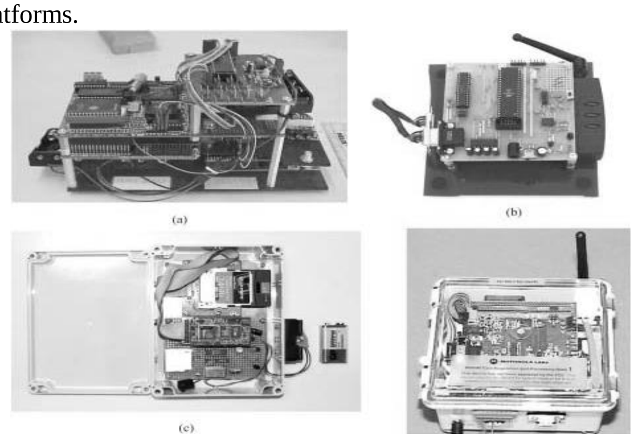

Fig. 3. A Variety Of Wireless Smart Sensor Platforms

A design of low cost WSN has been proposed by Straser and Kiremidjian [12] which was in order to reduce the cost of the traditional wired structural monitoring systems. This system called Wireless modular monitoring system for civil structures (WiMMS). WiMMS has many distinctive features including, low cost, small size (12×21×10 cm³), and high programming languages including a C language in the embedded software. Furthermore, RAM with additional ROM has been equipped for embedded firmware as well as (MSU2) Proxim Proxlink wireless modem was provided with operating 902-928 MHz ISM band in addition. Although, the minimization of power in this design was not realized, this has represented a first step of WSNs and their applications for SHM.

Bennett et al. [13] have introduced a proposed design of WSNs for embedment in flexible asphalt highway surface. Four channel sensing interface was designed for recording measured data from two thermometers and two thin film strain gages. Many valuable features have been included in this design for instance, Hitachi H8/329 8-bit microcontroller, and sufficient memory of the embedded software which operated the sensor with 32 KB of external ROM. A package of completed WSN model was designed in a water tight PTFE cylinder with a 30 cm height and 15 cm diameter in addition to AA alkaline batteries of total voltage 6V.

Lynch et al. [14-16] have suggested a wireless sensor prototype to gain a powerful computational core as well as to realize the aim of minimum power consumption. In terms of power consumption, this proposal is compact (10×10×5 cm³ in size), so relatively lower power has been consumed when comparing with the previous WSNs that proposed by Straser and Kiremidjian [12].

Kottapalli et al. [17] have suggested architecture WSN in order to overcome the limited power availability and time synchronization challenges in wireless SHM systems. A two tiered designed WSNs have been proposed for SHM system and this design included the design of sensing unit and local site master.

Wang et al. [18] have suggested a WSN design in order to report and read the displacement and strain from (PVDF) thin film. IEEE802.15.4 WSN has been developed for SHM. This was a new wireless communication standar[19] . A constrained energy power of WSN was intended and it was possible due to its Special feature such as an extreme power competence.

Allen [20] and Farrar [21] have presented a new strategy of different design for WSN. This proposal has focused on providing computational power to a board array of damage detection algorithms within a SHM wireless system. This was a significant development of WSN technology.

C. 2 Trend Of Using Wsns For SHM Applications

There have been significant improvements of SHM practices because of the new approaches that have been enabled by utilizing of WSNs. Likewise; the availability of new technology associated with WSNs has been developing for around a decade. In addition, the integration of wireless communications with WSNs has reflected positively on WSN technology [22]. Yet, a limited number of full scales of WSNs implementations for SHM have been done so far which is caused by either a lack of appropriate hardware or software. Therefore, many researchers' efforts in both of academic and industrial of WSN technology have been done to address such these challenges.

Rice et al. [23] have proposed a Flexible smart sensor framework for autonomous SHM. This research has addressed the hardware and software requirements which are the key for SHM application’s requirements beside the fidelity of SHM data acquisition. Imote2 smart sensor platforms have been distributed which were equipped with computation and communication networks. A multi metric Imote2 senor board with on-board signal processing has been applied which were designed and validated specifically for SHM implementations. A system of sleep/wake cycle has been also provided to enhance the power for the sensor's battery as well as it allows wide network operations for instance, decentralized model analysis or synchronized sensing. Appropriate software for SHM using WSNs was needed; so many smart sensor platforms have been developed using special operating system such as TinyOS. Even though, the TinyOS system has been a challenge for the non-programmers to develop application software, it has been widely used on WSNs application for SHM. Achieving an autonomous operation for SHM implementation utilizing WSNs required coordinating and maintaining components. Thus, AutoMoniter was presented, and the field experiment has been undertaken on a cable-stayed bridge in South Korea (Jindo). A number of 70 Imote2 leaf nodes have been installed on the Jindo Bridge. Finally, the application of SHM has been achieved by utilizing WSNs which is the main goal utilizing WSN. The goal has been achieved by utilizing autonomous full scale WSNs.

A crucial development in the hardware and software design technology related with WSNs for SHM applications has been made by utilizing the TinyOS system. This system has been possessing to be developed in order to reduce the installed time for commercial wireless sensors. Nevertheless, there was undesired problem in most of WSN systems such as, the high power consumption due to a limited power supply (battery). Thus, there were some low power techniques that used to avoid a high power consumption including Zig Bee or another 802.15.4- based communication protocol. Furthermore, Harms et al. [8] have presented some researchers' proposed solutions; one of these studies was SmartBrick platform. This application has been developed as a fully autonomous system for SHM. The experiment has been conducted by deploying the SmartBrick WSNs on Bridge in Osage Beach. SmartBrick WSN has interested capability including high quality features for the SHM's requirements. SmartBrick's features can be seen in the onboard and external sensors which equipped for environmental measurements and for structural phenomena such as, strain, temperature and vibration. In addition, the most important property of SmartBrick platform is the embedded quad band modem for mobile communications/general packet radio service (GSM/GPRS) which can be used bidirectional long rang communication over the cellular phone infrastructure. Finally, the objective of SHM was realised successfully, which was similar to Imote2's achievement on Jindo Bridge in South Korea. .

In many researches, the approach of SHM that has been adopted can be explained as the following procedure. Firstly, collecting the recorded data from the sensor units or from any extra equipment has captured the data for instance accelerometers. Secondly, comparing results from physical experiments with numerical models including, natural frequencies, displacements and stiffness of intact and damage structures. Finally, analysis and simulation should be conducted for the collected recorded data on computer by utilizing appropriate software such as Sab2000 or the proposed software in this project ABAQUS software.

D.B.. Damage detection

Exploring of damage during the service life of structures at their critical components has been followed as a key for the damage detection in many engineering systems. Nayarko (2011) has declared that there are four points have to be existed to identify and detect the damage.

1- The presence of damage in structure;
2- geometric location of the damage;
3- quantifying the severity of the damage;
4- the damage/failure mechanism.

A perfect SHM system normally consists of two major components; a fitted network of sensors to collect the response measurements also a data analysis of algorithm/software to interpret the measurements in terms of structures' physical condition [24].

The damage detection methods can be classified to two types. First one is local based damage detection and the second one is global based damage detection [25]. Local based damage detection methods try to determine the damage of structures based on screening the component or subcomponent at their length scales. Numerous of non-destructive evaluation technologies (NDE) have adopted the approach of local based damage detection for instance, the ultrasonic inspection. Furthermore, NDE local damage detection is an appropriate scale for damage phenomena such as, cracks and yielding. However, local based inspection technologies need trained professional people to be operated in the field. Consequently, the cost of these inspections has become high. That was clear when doing the inspection cost of all steel moment frame connections in the Los Angeles region when using ultra sonic NDE was reported as 200$ to 1000$ per welded connection [26].

On the other hand, numerical methods have been adopted in global damage detection to determine the damage. This has considered the global characteristics of a structure including, mode shapes and natural frequencies. Global damage detection in wired systems was expensive as well when installing the wired systems on the structure to collect the time histories' response. Furthermore, a number of sensors were insufficient and poorly scaled to localize the behaviour of damage. However, the damage detection by utilizing vibration characteristics is even more challenging in structures such as bridges, buildings and dams which are exposed to widely different operational and environmental loading [27]. In order to advance and address a limitation of current sensing technologies on both local and global based damage detection practises for SHM, a new wireless sensing technology has been developing. The potential of WSN technologies has interest attributes including, their low cost and their ability to be installed in hundreds in a single structure.

Thus, the possibility of WSNs dense deployments was achieved by utilizing a verity of detection algorithms which also increased the attraction of WSNs [28, 29]. In addition, the WSNs monitoring system is equipped to inspect structural damage through monitoring the critical structural components' behaviour which is implementing the local based damage detection.

E.C. Laboratory And Field Validation Of SHM Based On Wsns

F.1.Laboratory Applications

Before conducting any application or experiment on the real structures in the field, as a first step, WSNs have to be deployed within a similar environment and condition that would be faced in field. In order to do so, many laboratory assessments and experiments have been undertaken. These lab tests are mainly conducted to validate the accuracy and reliability of installed WSNs. Thus, many studies and researches recently have been focused on laboratory experiments for SHM applications. In addition, laboratory applications have become a tool to identify the damage based on automated examination of structural response data.

Pines and Lovell (cited in [25]) have proposed a conceptual framework for wireless SHM system. A laboratory data attainment system (Hewlett Packard 35655A) has been developed to validate the achievability of their framework. After observing the WSN system during the test, it was reported that there is no loss in data as well as the communication of long ranges is validated. Similarly, the respective proposed framework of WSN introduced by Straser and Kiremidjian [12], was also able to capture high input excitation with high accuracy.

To validate WSN and validated it in laboratory, Partridge et [30] have suggested prototype unit to be used for the acceleration response measurements with five story aluminium structures which loaded to a shaking table. The findings showed that there was a high accuracy of data collection while there was no data loss during the test. This is similar to the achievement of Straser & Kiremidjian [12].

Casciati et al. [31] have undertaken a series of laboratory tests at ELSA laboratory in European joint Research Centre. These tests were to assess and validate the performance of WSN system by monitoring the acceleration response of Mote WSNs. Thus, Mote WSNs were installed on types of structures. The first experiment was conducted on three story frame structure, and it has been observed during the free vibration examination. The second application was undertaken on a part of Australian steel railway bridge which was motivated by electromagnetic vibrator. The researchers have reported in their results that there is a significant loss of data during wireless communications between wireless and central data [32]. Nevertheless, the researchers attempted to reduce a sample rates to improve the reliability of WSN system. Consequently, the reliability of communications has been improved despite the fact that the meandering was subsequently marked.

Arici and Mosalam (cited in [25]) have presented an application of dense WSNs to monitor and record a dynamic response of full scale residential timber buildings. This experiment was undertaken by using 56 of wireless Motes which have been installed upon the first floor of a three story timber structure. The base of timber structure was subjected to real seismic round motions which were applied utilising a shaking table. In order to measure and record the acceleration response of the structure, accelerators equipped and coupled with each Mote. the results illustrated compatibility between WSN system and traditional piezoresistive accelerometer system. Although, there have been some errors of Motes' communications such as the loss of data, the potential of dense WSN installation for SHM applications has been illustrated in this lab test.

Kurata et al. (cited in [25]) have presented a lab implementation study. The aim of this study was to evaluate the feasibility of wireless Motes application for structural damage detection of two test structures. MICA mote has been installed, and the ground motion records have been monitored. Essential results have been gained from the acceleration response of the instrumented structures. In addition, four phases of progressive global structural failure have been identified by MICA Mote with embedded software to realize SHM of structure.

Hou et al. [33] have proposed four channel wireless sensing units which were developed by Wang et al. [34]. Monitoring the behaviour of loaded bridge pier sample in the laboratory was the main challenge. A sample was made from high performance fibre reinforced cementations composite (HPFRCC) which was a new civil engineering material at that time. The desired goal of this lab application was to prove the capability of WSNs to monitor HPFRCC bridge pier under critical case of earthquake loading. Two linear voltage displacement were equipped with a strain gage as well as an accelerometer was installed upon the test sample. A comparison with wired monitoring system has been made. The results showed that there was a completely agreement between the response data records obtained from the wireless monitoring system and those gained using the cable based monitoring system. Furthermore, there was no data loss from wireless communication software during the days of testing which indicated to the reliability of WSNs also fidelity of their embedded software.

The experiment of estimation of cable-stayed tension force using WiMMS

One of the most important structural parameters is a cable tension force of cable-stayed bridges for SHM measurements and applications during the construction and operations' stages. This study estimates the cable tension force based on the vibration based method [35]. A low cost automated wireless tension force estimation system (WTFES) has been equipped for this implementation [2].The hardware composed of smart wireless sensor (WiMMS) which developed by [34]. A single conditioning circuit with three primary functions, and commercial MEMS accelerometer for acceleration time history measurement of the cable-stayed have been equipped. The vibration based method consisted of 7 formulas relating to the natural frequencies of the cable tension force in many sagging conditions. The automated peak picking algorithm has been developed with considering of typical properties of natural frequencies of cables in order to extract measured acceleration data without human intervention [2].

G.2. Field Testing

SHM of civil engineering structures is the desired objective based on the WSN emerging technology in civil engineering. The approach of WSN deployments on the real civil structures could be also the best way to evaluate and to assess the WSN features. Therefore, a number of research studies have been demonstrated utilizing WSNs to monitor real structures. In particular, critical structures including bridges and buildings have been tested in their real complex environments. This has shown the transition of WSN monitoring systems from the laboratory to the field [25].

Hence, the main aim for all the studies and researches was to assess performance of several wireless sensor platforms for SHM applications on civil engineering structures. To do so, structural accelerations and strain's responses of structure have to be observed with well accuracy. The common way to evaluate the accuracy of WSNs in most of the studies is by comparing recorded data from the WSN system with the data of traditional cable or wired monitoring systems.

Maser et al. [36] have described a validation test of wireless telemetry in field. WSNs have been installed on highway bridges to monitor the bridges' performance. The wireless monitoring system called the Wireless Global Bridge Evaluation and Monitoring System (WGBEMS). This kind of WSNs was expensive, where the total cost of sensor node was1000$ and the repository data of 2000$. Therefore, academic WSNs have been developed by the same group and later on Straser Kiremidjian [12] validated the performance of these WSNs in the field by installing them on Alamosa Canyon Bridge. The WSNs were installed; five sensing units located on the long span's girders and each wireless sensor had accelerometer at the top of the girder. In parallel to WSNs, traditional tethered structural monitoring system has been installed by researchers from Los Alamos National Laboratory. The reliability of communications has been assessed as well as the data acquisition illustrated that the WSNs communicated the response data of bridges without error. Finally, there was a consistency in modal frequencies of bridge once comparing a transfer function calculation of both monitoring systems. Moreover, when comparing the recorded accelerations obtained by WSNs system with the data gained by the wired monitoring system, it has been concluded that there was a strong agreement between the recorded data of the two systems.

Lynch et al.(cited in [25]) have developed a WSN prototype and this WSN has been validated using the Alamosa Canyon Bridge which is the same bridge that has been tested by Straser and Kiremidjian [12]. The bridge's response that induced by modal hammer strikes has been measured as well as the truck traffic has been considered by installing seven WSN units upon the central span of Alamosa Canyon Bridge. Low cost accurate accelerometers (MEMS) have been equipped which interfaced with the WSNs. Traditional wired monitoring system has been installed as well with a reference baseline for data acquisition. It was reported that the time of installing WSN monitoring system was half the installed time of the wired based monitoring system. In addition, there was a robust accord between the recorded collected time acceleration gained by the WSN unit model and those recorded by cable based system when comparing them during the impacts of modal hammer strikes. On the other hand, there was a lack of time synchronization accuracy which could prevent the mode shapes' calculation of the system.

Aoki et al. [37] have proposed a Remote Intelligent Monitoring System Sensor platform (RIMS). A field validation for the performance of RIMS was needed. Thus, RIMS wireless sensors have been installed on Tokyo Rainbow Bridge in Japan to undertake RIMS field application. This application mainly focused on validation the capability of RIMS wireless monitoring sensing to observe long term health of non-structural components. Light poles with a tri axial Microstone MA-3 MEMS accelerometer have been provided also to measure the acceleration of the plot top in three orthogonal directions. The response of the pole has been recorded by utilizing the MA-3 accelerometer which wirelessly connected with a laptop computer to deliver the data. It was reported by Aoki et al. that there was no data loss in wireless communication channels. In addition, the computing features and capabilities of RIMS wireless sensors have been introduced. This has been shown when the histograms have been wirelessly downloaded either upon captured data or by Personal digital assistant (PDA) of inspector. That process was conducted while the calculation of level crossing histograms was being processing by the WSNs.

A WSN system has been developed by researchers at the University of Dayton, Ohio for bridge monitoring. This emerging WSN system has been presented by Binns [38] and it is called Wireless InfraStructure Evaluation System (WISE). The WISE communication system has been realized either by using laptop computer or PDA of the inspector. That has been undertaken while the WISE installation upon the bridge was being processing. The interested advantage of WISE monitoring system beside its compatibility with any off the shelf sensors is the ability to include an ultimate number of channels in the global monitoring system [39]. The WISE monitoring system composed of 16 wireless sensors. The time of installation on Highway Bridge in Ohio was 30 minutes. Finally, it was reported based on the time history records that the WISE system has the ability and accuracy to detect the vibrations of the bridge which caused by truck's traffic.

A number of 14 wireless sensing unit prototypes have been installed to monitor the forced vibration response of Geumdang Bridge in Korea [40]. PCB 3801 capacitive accelerometers with the WSNs have been applied and located on the internal spaces of the box girder to measure the vertical acceleration of the bridge. PCB 393C piezoelectric accelerometers with a cable based monitoring system have been also equipped in parallel with WSN monitoring system. The purpose of this field validation study was to assess the accuracy of WSN measurements. This should be realized by finding out the capability of synchronized time storage of WSNs. Furthermore, the calculation of Fourier capacity spectra has been done by utilizing the recorded accelerations from WSN's accelerometers since the normal traffic of the bridge. Lynch et al. [40] have used different known weights of trucks with different fixed speeds. The findings illustrated that when comparing the recorded time histories of bridges obtained by cable based monitoring system with those were gained by the WSN system, the accuracy of wireless sensor units was confirmed. Moreover, consisted modal frequencies of the bridges have been obtained from both WSN monitoring system and wired monitoring system.

H.D. The Importance Of FEA For SHM

The proper detection of the location and severity of damage usually relay on critical accurate measurement and monitoring of vibration characteristics. However, the experimental measurements are certainly degraded by measurement noise and errors, which could reduce the reliability of most vibration-based structural damage identification algorithms for SHM. This article, through computer simulation and experimental investigation of a simply supported beam, here the displacement modes from accelerometers and long-gage distributed strain measurements has been used comparatively to evaluate the performance of these techniques for practical civil SHM [42].

Nagayama et al. (cited in Weng et .al 2008) mentioned again the study that demonstrated which is application of WSNs on 2sec Jindo cable-stayed bridge in South Korea.

The study has been conducted using the collected acceleration data at the bed-test as technique for SHM. A finite element (FE) model has been constructed based on in depth study of the detailed drawings as prior works. In addition, acceleration data from existing wired monitoring system have been provided in order to be used as reference data of WSNs performance. The output model identification (ID) from FEA and captured from the wired monitoring system were evaluated when comparing them with the extracted model properties from the output-only modal ID method. Finally the results have been found and discussions are made on monitoring performance of WSNs. Therefore, this emphasizes the importance of using FE modelling and simulations which actually integrates complements with WSNs for SHM purposes.

Walther [43] has demonstrated that cable-stayed bridges or suspension bridges are usually subjected to dynamic forces more than any other kind of bridges. So, such these important forces can determine even the feasibility and reliability of any project in such kind of bridges. Generally there are three types of problem need to be taken in account:

1- Aerodynamic stability; 2-Physiological effects; 3-Safety against earthquake .

All of these problems have been threaten and inspected by several vibration assessments. Natural frequencies and principal modes of vibration have been addressed in many studies in order to analyse the dynamic effects and phenomena that acting on the cable-stayed bridges.

Generally bridges are counted as vital mean in the transport network due to their function of joining two inaccessible areas with convenient way. For this reason these structures are used to cross rivers, creeks and other constructions such as the construction of overpasses on freeways. Many common bridges around the world have been built for such functions for instance, Sydney Harbour Bridge in Australia, the Golden Gate Bridge in the United States of America and many more. This study has been done on small cable-stayed bridge which is Werrington cable-stayed bridge in order to inspect its reliability and serviceability by using finite element and modelling its components based on ABAQUS software. Structural analysis purposes have used Finite element methods for a long time.

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