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A wireless system for crack monitoring in concrete structures

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A WIRELESS SYSTEM FOR CRACK MONITORING
IN CONCRETE STRUCTURES

An Abstract of a Thesis

Submitted

in Partial Fulfillment

of the Requirements for the Degree

Master of Science

Souhail M. Saad

University of Northern Iowa

May 2011

ABSTRACT

The formation of cracks in concrete is a normal phenomenon. However, effective control and prevention of the formation of cracks is the key for successful life of concrete structures. Specifically, cracks represent a path of least resistance for moisture and corrosive ionic agents from de-icing salts to reach embedded steel in concrete. Commercial wireless sensor networks utilizing crack gauge sensors can be applied for crack monitoring in the common concrete structure. The crack sensors circuits' boards, which are used to stimulate the cracks, are currently unavailable for the SG-Link module platform.

The SG-Link module is an ultra-low-power module for use in sensor networks, monitoring applications and rapid application prototyping. Therefore, a crack sensor circuit board for the SG-Link module platform has been developed. The development of a smart wireless sensor network for the crack monitoring system is divided into four parts: a crack gauge sensor, signal conditioning, the SG-Link module, and a base station unit. The signal conditioning module consists of a crack gauge sensor, a wheatstone bridge, an amplifier, and a filter. The SG-Link module consists of an analog to digital converter (ADC), a microcontroller unit (MCU), and a transmitter with an antenna. The base station unit includes an antenna and a receiver module connected to the base station or computer. In this study, cracks are monitored based on the change of the electrical resistance between the sensor's two terminals that are taken from the simulation model of the crack sensor board consisting of a crack gauge sensor and signal conditioning. This thesis looked at the effectiveness of a wireless system for crack monitoring in concrete structures. Tests were conducted in a laboratory to monitor the cracks in the structures and explore the validity and reliability of the monitoring mechanism and data transmission.

Keywords: crack propagation, concrete structure monitoring, wireless structural health monitoring system

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has been approved as meeting the thesis requirement for the

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Date Dr. M. D. Salim, Chair, Thesis Committee

Date Dr. Nageswara Rao Posinasetti, Thesis Committee Member

Date Dr. Tim Strauss, Thesis Committee Member

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CHAPTER I

INTRODUCTION

High-rise buildings, arenas/stadiums, and concrete bridges, as well as historical monuments, are complex civil engineering structures. They are made of multiple elements and components that are stressed and interact with one another when exposed to external forces. Buildings and bridges vary widely in size, geometry, structural systems, construction materials, and foundation characteristics. These attributes influence how a structure performs under dynamic loading conditions or under the stress of natural events.

Concrete is one of the major components in civil structures. Civil structures have a long service life when compared to other commercial products, and they are costly to maintain and replace once they are built (Chong, 1999). In general, structural concrete consists of a mixture of Portland cement, coarse and fine aggregates, water, and chemical admixtures. The cement acts as the binding to the aggregate, which achieves its strength as a result of the hydration process. The blend of mortar aggregates and their subsequent processing directly influences the structural properties of the concrete. Structural design codes have proven to be successful in preventing catastrophic failures. Steel is commonly included in the design of concrete structures to provide tensile strength, shear capacity and ductility. Steel reinforced concrete (R/C) has been in general use in the United States for more than 100 years and is governed today by a number of standard codes including the ACI Building Code (e.g., ACI 318-08; MacGreger & Wight, 2005). Although very high compressive strengths can be achieved in concrete structures, these structures are deteriorating over years of stresses. Structural damage can be initiated by different load sources including extreme stresses, like those experienced during earthquakes or from a combination of live loads and poor structural maintenance. Examples of structural damage that have occurred from natural disasters such as the tsunami created by the 2004 Indian Ocean earthquake and the 2005 Hurricane Katrina in New Orleans, Louisiana. Furthermore, extreme events can cause enormous damage to the health of concrete structures without producing any apparent visible signs. Such damages can lead to a catastrophic condition without sufficient prior warning.

While concrete has been a highly successful material for civil structures, some challenges do exist when constructing and maintaining concrete structures. The formation of cracks in concrete is a normal phenomenon. However, effective control and prevention of the formation of cracks is the key for the longevity of concrete structures. Specifically, cracks represent a path of least resistance for moisture and corrosive ionic agents from de-icing salts to reach embedded steel in concrete. Moisture and ionic agents can lead to the corrosion of steel reinforcement. Corrosion of reinforcement results in a loss of the steel bar cross-section and can cause tensile stresses in the concrete in its vicinity. Such tensile stress causes more cracks and can result in spalling of the concrete to cover the reinforcement. In addition, cracks can result from structural overloading and fatigue. Cracks are closely associated with structural deterioration and have a significant bearing on the structural integrity of the component. Formation of the cracks results in the loss of impermeability in concrete structures during their service. Cracks lead to corrosion of the reinforcing steels, promotion of chemical reactions, and attacks on the reinforcing bars, which can result in structural failure if ignored. In other words, fine cracks in concrete structures can propagate under the influence of mechanical and environmental factors.

When making an assessment of the general state of the health of concrete structures, cracks must be reliably quantified. Detailed visual inspection of the surface of the structure remains a common method for detecting cracks; systematic crack mapping allows inspectors to monitor the progression of cracks and to hypothesize the nature of their origins (Bungey, Millard, & Grantham, 2006). Frequency of inspection depends on the design, past performance, or age of the civil structure. After suspicious cracks are encountered, non-destructive (e.g., ultrasonic) and partially-destructive (e.g., core holes) testing can be carried out by trained inspectors to determine crack features that may fall below the surface (ACI-318, 2008). However, all of these methods require the use of trained personnel for execution, causing them to be tedious, time consuming, and expensive.

The Structure Health Monitoring System (SHM) was the first system developed in order to monitor civil structures, to increase their safety, and to optimize their operational and maintenance activities (Liu & Tomizuka, 2003a, 2003b). SHM offers an automated method for tracking the health of a structure by combining damage detection algorithms with structural monitoring systems (Kolakowski, 2007). SHM is a real-time monitoring system that can measure the response of a structure before, during, and after a natural or man-made disaster and can estimate the remaining lifetime of the structure. Thus, periodic monitoring can be used to provide information about the civil structure over its operational life, to identify a fault, and to localize the damage area. Therefore, SHM is the process of detecting damage while the structure is in use (Inman, Farrar, Lopes, & Steffen, 2005). SHM of civil structures has attracted great interest for several decades. SHM aims to enhance safety and reliability in civil structures by recognizing the damage before it becomes catastrophic.

SHM is primarily responsible for collecting the measurement output from sensors installed in the structure and storing the measurement data within a central data repository. To guarantee that the measurement data is reliably collected, structural monitoring systems use coaxial wires for communication between sensors and the repository. While coaxial wires provide a very reliable communication link, their installation in structures can be expensive and labor-intensive (MacGillivray & Goddard, 1997). To overcome the many disadvantages of wired systems, Straser and Kiremidjian (1998) proposed the design of a low-cost wireless structural health monitoring system (WSHMs) for civil structures. Interest in wireless sensors was initially motivated by the low cost. Therefore, researchers in both academia and industry are increasingly focusing on the development of WSHMs applications.

Statement of the Problem

The problem addressed in the current study was to develop a wireless structural health monitoring system (WSHMs) to detect the crack formation and to monitor the propagation of cracks in concrete structures, especially during and after a natural or man-made disaster. Concrete structures undergo gradual deterioration or fail over their life span due to corrosion and fatigue without any prior warning. The information from the WSHMs may allow better understanding of concrete structures' behavior and help improve current maintenance schedules. A near real-time wireless structural health monitoring system can significantly reduce the loss of human lives by early warnings of hazardous structures, impending collapses, and providing information to emergency response services.

Statement of Purpose

The purpose of the study was to investigate the ability of a wireless structural health monitoring system (WSHMs) platform to detect cracks formation and record the propagation of growing structural cracks over long periods of time. In contrast to other research, this study did not seek to directly correlate crack propagation to any other physical phenomena; rather it sought to record quantitatively, repeatedly, and accurately existing and propagating cracks in structures, specifically to supplement regular inspections of concrete civil structures. This wireless system could be applied to any structure that exhibits cracking over time. As concrete materials are widely used in the construction field, the Wireless Health Monitoring System can provide a complete assessment of the health of concrete structural elements. Tracking crack states and crack propagation during the operational lifetime of concrete elements provides engineers with information necessary to more accurately evaluate a structural element's health, safety margin, and anticipated future performance. While many response characteristics could be monitored and used to advance understanding of a material, this study selected crack assessment as a high priority response characteristic to be monitored. Crack assessment was selected because crack is one of the major features of concrete materials, and quantification of cracking can lead to a better understanding of the energy dissipation mechanisms. Also, quantifying cracks can be useful for identifying those cracks that are associated with a reduction in the strength, capacity and durability of the structure (i.e., structural damage). Crack monitoring can also be a powerful management tool because identification of cracks can alert engineers to locations of potential future corrosion of buried reinforcement bars.

Statement of Need

Monitoring the safety and functionality of the civil structure is critical to improve maintenance practices, to minimize the cost associated with repair, and ultimately to improve public safety. The monitoring of civil structures is especially important after extreme events have occurred, such as following the Northridge earthquake where the cost of inspecting the connections of steel frame buildings was between $200 and $1,000 per welded connection (Hamburger, 2002).

WSHM is a real-time monitoring system that can measure the response of a structure before, during and after a natural or man-made disaster. WSHM can be used in damage detection algorithms to assess the post-event condition of a structure. WSHM of civil engineering structures has attracted great interests for several decades. Deploying WSHM on concrete structures can provide early warnings about potential damage. Moreover, continuous monitoring of civil structures may enable engineers to move from the current schedule-based maintenance to condition-based maintenance. This should save millions of dollars and allow for the effective allocation of resources.

SHM offers an automated method for tracking the health of a structure by combining damage detection algorithms with structural monitoring systems (Kolakowski, 2007). Though the SHM can be applied to any structure that exhibits cracking over time, the primary motivation in the development of this technique was to supplement the in-service inspection of cracks in concrete structures. Detection of ongoing cracks was used to discriminate deviations from the design performance. Monitoring data was integrated in structural management systems and increased the quality of decisions by providing reliable and unbiased information. Without appropriate management, structures may partially or entirely collapse, which could not only create safety and economic issues, but could also create an irreversible cultural loss.

This information could then be used in general to:

1. Design verification:

    (a) To provide data on structural dynamic response to verify design assumptions used for a strong wind and earthquake.

    (b) To provide data for developing a better design in a more rational way.

2. Improve structural maintenance:

    (a) To provide data for analyzing and evaluating the health behavior of a concrete structure.

    (b) To provide data for assessing structural deterioration and performance degradation.

3. Review safety management:

    (a) To provide data to adjust levels of safety traffic control due to an earthquake or strong wind.

    (b) Crack detection can also be a powerful management tool because identification of cracks could alert engineers to locations of potential future corrosion of buried reinforcement bars.

The Statement of Research Hypothesis

It was hypothesized that the wireless structural health monitoring system will detect the crack formation and crack propagation during the operational lifetime of concrete elements and store and transmit the data from the concrete structure site back to a local office, via the Wireless Access in Vehicular Environment (WAVE) system.

Statement of the Research Questions

1. Is it possible to detect and localize the crack formation in a concrete structure?
2. Is it possible to track the crack propagation in a concrete structure?
3. Is it feasible to transmit the data from the site back to the local office through utilizing the Wireless Access in Vehicular Environment (WAVE) system?
4. Does the system transmit 100% of the measuring data?

Assumptions

The following assumptions were made in pursuit of this study:

1. An estimate of the maintenance cycle is made based on the power consumption of the sensor unit.
2. Self-organized WSHMs will increase flexibility because each device uses its own embedded and limited power supply.
3. If one node fails, the others will still work fine to provide reliable monitoring.
4. The self-organized WSHMs will transmit data from the bridge site back to the local office through utilizing the Wireless Access in Vehicular Environment (WAVE) system.
5. The sensor or set of sensors is the most able instrument to detect the damage, and it is assumed that the damage is localized close to these sensors.
6. Information from small, limited portions of the structure may provide a complete picture of the structural condition.

Delimitations

The following limitations were applied to guide this study:

1. The need to limit the network to be used only "on demand" and for a limited time when needed to save energy.
2. The decentralized architecture of the network should rely on the fewest possible number of messages exchanged.
3. The depth of information that current SHM practices can provide and the ongoing advances in sensing and data processing will lead to enhanced infrastructure management for a wide range of purposes.

Definition of Terms

The following definitions were used for this study:

1. Structural health monitoring: the ability to monitor the structure and detect damage automatically (Kolakowski, 2007).
2. Damage: changes that adversely affect the current or future performance of the system (Inman et al., 2005).
3. Wired Structural Health Monitoring System: sensors installed in a structure, with response measurements communicated by coaxial cables to centralized data repositories where data is stored and processed (Liu & Tomizuka, 2003a, 2003b).
4. Wireless Structural Health Monitoring Systems (WSHMs): wireless sensors installed in a structure, with response measurements communicated by wireless sensors. The data repositories where data is stored and processed are either centralized or decentralized (Straser & Kiremidjian,1998)

5. Sensors: A device that measures or detects a real-world condition, and converts the condition into an analog or digital representation (Wilson, 2008).
6. Smart sensor nodes: low-power devices equipped with one or more sensors. Smart sensor nodes are defined by their frequency and shape, which are sensitive to the health of the structure (Wilson, 2008).
7. Wave: 75MHz of Dedicated Short Range Communications (DSRC) spectrum at 5.9 GHz, is free but licensed spectrum to be used exclusively for vehicle-to-vehicle and infrastructure-to-vehicle communication (Salim & Zhu, 2010)

CHAPTER II

LITERATURE REVIEW

Structural Health Monitoring System Overview

Structural health monitoring systems (SHMs) are widely used to record the health of civil engineering structures subjected to harsh environmental conditions or extreme loadings. SHMs use sensors installed in and around the structure of interest to reliably collect data pertaining to the structural response and the environment (e.g., temperature). To ensure that structures safely meet life-safety standards over their operational lives, early identification and assessment of structural damage is necessary. SHMs can alternatively be employed to avoid the subjective and labor-intensive nature of visual inspections. These health monitoring systems involve the complete process of obtaining and analyzing dynamic response data; SHMs implement an array of sensors/actuators on the structure, periodically obtain structural response measurements, analyze the measurements and extract damage sensitive features. This process allows the systems to statistically analyze the extracted data to describe the current health of the structure while the structure is in use (Inman et al., 2005).

High-fidelity sensor data is required to build accurate models. This key data can be gained through a clear understanding of structural behavior in order to allow a reasonable assessment of its as-built condition. Additionally, potentially damaging structural changes, including corrosion, cracking, buckling, and fracturing, occur locally within a structure. Structural damage is a local phenomenon, and responses from sensors close to the damaged location are anticipated to be more heavily affected than sensors away from the damage site (Nagayama, Spencer, & Rice, 2009). A dense array of sensors is required to pinpoint an effective monitoring system capable of generating informative structural models and revealing critical structural changes. Due to the high cost of deployment and the potential for data saturation with traditional structural monitoring technology, a dense instrumentation system is not practically achieved.

Traditionally, SHMs are composed of a network of sensors distributed throughout a structure. The networks generally rely on a central source of power and data acquisition which requires cables to link the sensors with the power and acquisition hardware hub. Positioning the cabling is very expensive and time consuming. Even a small system consisting of 10 to 15 sensor channels installed in a building can cost roughly $5,000 per sensor channel (Celebi, 2002). However, larger monitoring systems are more commonly used, often with 100 or more sensors, in long-spanning bridges. For example, 61 of California's long-spanning bridges have been equipped with over 900 sensing channels. The larger number of sensors is typically used because the size of the structure is large and the points where the sensors are installed are generally difficult to access. In the event of an earthquake or other extreme event, wired links are prone to break, resulting in unreliability of the data links.

To avoid the many downfalls of wired systems, the use of wireless technologies called a Wireless Structural Health Monitoring System (WSHMs) has been proposed for structural monitoring (Straser & Kiremidjian, 1998). Initial interest in wireless sensors was motivated by their low cost. Undoubtedly, the elimination of extensive lengths of wire gives wireless structural monitoring systems the advantage of easier installation and substantially reduced costs (Lynch & Loh, 2006).

Wireless Health Monitoring System

With recent technological improvements, the size and cost of MEMS (Micro Electro-Mechanical System) sensors, microcontrollers, wireless communication equipment and circuit designs have been reduced. Furthermore, a new kind of system called wireless health monitoring system (WSHM) has recently been explored for use (Xu et al., 2004). Researchers in academic circles and industries have increasingly focused on developing WSHM applications. Wireless health monitoring systems have civil applications; for example, smart sensors can be utilized to benefit structural health. Smart sensors are defined as sensors which contain an onboard microprocessor, giving intelligence capabilities to the system (Spencer, Ruiz-Sandoval, & Kurata, 2004).

A variety of wireless sensor networks communication technologies have been investigated in recent years. Straser and Kiremidjian (1998) expressed one of the earliest attempts to develop a wireless structural health monitoring system for civil infrastructures. Recently, advances have been made in the development of wireless smart sensor and actuator technology. The wireless sensor developments for aircrafts, rotorcrafts, and civil structures may reduce the need for visual inspection as a method of assessing structural integrity and reduce potential safety risks in large civil structures such as highways, bridges and buildings.

Using wireless links in structural monitoring has generally been implemented by pushing the process of digitization of the vibration information to the remote sensor units and then replacing wired links with wireless links to provide more effective data communication. It is essential to remember that these wireless networks use smart sensors to add value to the sensed signal by processing and collaborating with other devices.

Individual devices within the network can be called sensor nodes, a node, or even mote as a reference to the miniaturization of the instrument. The smallness of the device is not the only advantage of the wireless sensor networks technology. It is also important to note that network implementation is much easier through the wireless communication unit. Moreover, a network of tiny mobile agents created by the wireless technology increases the flexibility of the network structure. Other key points include that the target cost of the device is low, and it becomes possible to process information in a decentralized manner. With these characteristics, wireless sensor networks add more value than other technologies; they create networked systems that are scalable (because of the possibility to more easily increase the number of devices in the network) and robust (because if a node in the network fails, the remaining nodes can still perform the global task).

Although the sensor network approach is appropriate for SHMs, the design of wireless sensor networks presents many challenges. A sensor network must make suitable adjustments for strong operation when the environment and network change (Römer, 2004). Communication hardware and protocols must ensure a minimal loss of data to protect the quality of the sensed data and maintain the strong performance of the network. To be successful, the sensor network must maintain an acceptable performance level as the network expands to a larger sensing area or requires higher resolution. Continuous network operation during hardware or software failure relies on a system with many built-in fault tolerance features. Additionally, multiple applications or tasks are performed concurrently over a single-sensor network. For example, a building monitoring system may need to simultaneously examine the temperature and luminance, monitor cracks in the wall, track navigating persons, and communicate with systems in nearby buildings (Yu, Krishnamachari, & Prasanna, 2004).

Generally, wireless sensors have their designs broken into three or four functional subsystems: a sensing interface, computational cores, wireless transceivers, and an actuation interface. When measurement data has been collected by the sensing interface, the computational core stores, processes, and readies the data for communication. Specifically, a radio transceiver is one type of electrical component that can be used to transmit and receive data (Karl & Willig, 2003). Many systems simply receive data from a structure and wirelessly forward this unprocessed information at a later time for analysis. Using different types of sensors, including accelerometers, strain gages, fiber-optic sensors and piezoelectric sensors, most current SHM systems can measure the response of a structure. Vibration-based SHM is a system that can be used. This method acts under the assumption that if stiffness reduction of the structure takes place due to damage, the vibration response will be significantly altered. Moreover, structural dynamic signals can be used to evaluate damage metrics such as the energy of signals and the curvature of mode shapes. Furthermore, structural dynamic signals can assess the natural frequency components in time domain, frequency domain, or wavelet domain. Researchers have used the proper domain for damage metrics to show that one can differentiate between a healthy and unhealthy structure. Also, researchers have shown that the use of reference operation to classify the structural health was helpful in determining the need for maintenance or repair of concrete structures.

Wireless Communication Technology for WSHMs

The major feature of a wireless system node is the fact that data is transmitted wirelessly with the use of radio frequency (RF) communication. Operation of the node is typically provided by a radio chip incorporated in the wireless sensor node design; this allows the sensors in a network to communicate with one another or with a central data sink node.

The majority of wireless sensor platforms operate on 900 MHz, 2.4 GHz, or 5 GHz frequencies, with the lower frequencies resulting in longer ranges. These frequencies have been designated as unlicensed industrial, scientific, and medical (ISM) frequency bands by the Federal Communications Commission (FCC) in the United States. Depending on the intended bandwidth and application, some RF communication protocols from the Institute of Electrical and Electronics Engineers (IEEE) are available. Wi-Fi IEEE 802.11 is the air interface standard for Wireless Local Area Network (WLAN). Wireless personal area network (WPAN) standards include Bluetooth (IEEE 802.15.1), UWB (IEEE 802.15.3), and ZigBee (IEEE 802.15.4).

According to Salim and Zhu (2010), IEEE 802.15.4 is the strongest choice for monitoring the infrastructure. IEEE 802.15.4 operates in the ISM radio bands at 868 MHz in Europe, 915 MHz in the United States, and 2.4 GHz worldwide. The IEEE 802.15.4 protocol defines air interface, such as the lower layers of the network communication protocol stack-physical (PHY) and medium access control (MAC). Furthermore, IEEE 802.15.4 standard-compliant wireless transceivers are primarily from the following companies: the CC2420/CC2430/CC2530 series from Texas Instruments; the MC1319x, MC1320x, MC1321x series from Freescale; and the EM250/260 series from Ember.

Specifically, in 2006, the United States FCC allocated 75 MHz of the Dedicated Short Range Communications (DSRC) spectrum at 5.9 GHz to be exclusively used for vehicle-to-vehicle and infrastructure-to-vehicle communications. The DSRC is a free, licensed spectrum that solves the interference and co-existence problems of WLANs. Additionally, the IEEE 802.11 WGp workgroup has been modifying the 802.11 Wireless Local Area Networks (WLAN) standards to the DSRC 5.9 GHz spectrum. The standard amendment 802.11p (2010) was ratified in July of 2010 (Salim & Zhu, 2010).

Available Wireless Sensor Platforms

While interest in the smart wireless sensors increases in the civil, mechanical, and aerospace engineering fields, smart wireless sensor platforms have also been developed in the field of academia. Straser and Kiremidjian (1998) initially proposed a design for a low-cost wireless modular monitoring system (WiMMS) for civil structures; this design was to function by integrating a microcontroller with a wireless radio. A Proxim ProxLink MSU2 wireless modem operating on the 902-928 MHz ISM band was used for reliable wireless communication. Based on the study, the maximum available outdoor space range of the wireless radio was determined to be approximately 300 m.

Lynch et al. (2001, 2002a, 2002b) proposed a wireless sensor prototype that emphasized a powerful computational core. Using original components, the researchers combined a wireless transmission and sensing circuits with a computational core; this process aided in effective decentralized data collection, analysis, and broadcast monitoring results. Similar to the unit proposed by Straser and Kiremidjian (1998), the Proxim ProxLink MSU2 wireless modem was integrated with the wireless sensor and operated on the 902-928 MHz ISM radio band.

Mitchell, Rao, & Pottinger (2002) proposed a two-layered wireless SHM system that was renowned for its seamless interface to the Internet. Using the World Wide Web (WWW), structural management professionals have remote access to structural response data. Furthermore, researchers can analyze results executed by the monitoring system (Mitchell et al). Wireless data cluster nodes are equipped with cellular modems for long-range communication to a single web server that is accessible from the Internet.

Similarly, Basheer, Rao, and Derriso (2003) proposed the design of a wireless sensor. The proposal sought a sensor whose hardware design was optimized for communication between wireless sensors for collaborative data processing, such as damage detection. The wireless sensors proposed form steps of a self-organizing network called the Redundant Link Network (RLN). Researchers chose the Phillips Blueberry 2.4 GHz Bluetooth wireless radio for integration.

Additionally Aoki, Fujino, and Abe (2003) proposed a remote intelligent monitoring system (RIMS) designed for structural health monitoring of bridges and infrastructures. The RIMS controlled the system via Ethernet protocol by utilizing a high-clock microcontroller, a 3-axis MEMS piezoresistive accelerometer, and an Internet-based wireless modem.

Furthermore, Chung et al. (2004) developed a wireless sensor platform (DuraNode). In addition to the wireless sensor platforms, this sensor enabled the wired Internet data communication for building structures with an established Local Area Network (LAN).

Sazonov, Janoyan, and Jha (2004) projected the design of a low-power wireless sensor based on the IEEE802.15.4 wireless standard. The unit used the Chipcon CC2420 wireless transceiver for wireless communication. IEEE802.15.4- compliant, the radio operates with a range of 10 m to75 m on the 2.4 GHz radio spectrum.

The WiMMS platform has been improved further by Wang, Lynch, and Law (2005). These researchers implemented a software that allows multiple threads (e.g., processing or transmitting data while collecting data) to be performed simultaneously to maximize the computational power of the wireless sensor. Wang et al. (2005) proposed the integration of the MaxStream 9XCite wireless modem, which was capable of a communication range of 300 m on the 900 MHz radio band.

Farrar, Allen, Ball, Masquelier, and Park (2005) developed Husky, a smart wireless sensor platform. This platform executed a series of damage detection algorithms by networking with the DIAMOND II damage detection algorithm package written in Java. Similarly, Jamil, Zain, Krishnamurthy, Sazonov, and Ismail (2009) developed a WISAN sensor network to reconstruct mode shapes from a pre-cast, pre-stressed concrete bridge and to identify natural frequencies. Frequencies and mode shapes that were identified were similar to the results of a similar sized steel girder bridge classified with comparable excitation levels. The sensors communicated with each other, as well as with their base stations, by using global positioning system (GPS) technology.

Lastly, Salim and Zhu (2010) proposed the design for a low-power wireless sensor used to monitor the behavior and integrity of highway bridges. This radio operated on the wave dimensions (74 MHz radio in 5.9 GHZ) and was capable of a communication range of 22.86 m.

Commercial Wireless Sensor Platforms

Aside from the smart wireless sensor platforms developed in academia, commercial smart wireless sensor platforms have also been developed for SHM applications in the industry. Mote was initially developed at the University of California-Berkeley and then commercialized by Crossbow (Zhao & Guibas, 2004). Consequently, Intel released a new smart sensor platform in 2003 called the iMote. This new technology was a result of the research collaboration between the Intel Research Berkeley Laboratory and the University of California-Berkeley.

Likewise, the Mica2 is an open source wireless sensor platform whose hardware and software (TinyOS) designs are available to the public (Lynch, Wang, Loh, Yi, & Yun, 2006; Crossbow, 2007). The MicaZ mote, which has similar hardware to the Mica2, is the most recent development of Mica. However, it has a smaller physical size and incorporates an 802.15.4 2.4 GHz radio. The Mica2 and MicaZ platforms have been used in many applications for a variety of purposes. For example, Mainwaring, Culler, Polastre, Szewczyk, and Anderson (2002) reported the use of 32 motes for habitat monitoring in Maine.

Additionally, MicroStrain (2008) listed a wide variety of wireless sensors available. Some of these technologies including strain sensors, accelerometers and generic analog input nodes. The nodes utilize IEEE 802.15.4 2.4 GHz wireless communication with sampling rates of up to 2048 Hz and real-time data streaming up to 4 KHz for single channel operation. Furthermore, synchronization between the nodes occurs at an estimated 100 microseconds. With the use of high-gain antennas, the nodes can communicate up to 300 m. MicroStrain (2008) demonstrated the capabilities of its wireless strain and temperature modules with the installation of a network of sensors on the Benjamin Franklin Bridge in Philadelphia, Pennsylvania (Arms, Galbreath, Newhard, & Townsend, 2004).

Existing Technologies for Crack Detection

A wide variety of approaches has been proposed for automated structural health monitoring of concrete structures. In one case, Shah and Choi (1999) investigated the employment of AE piezoelectric elements to capture the stress waves generated by cracks in concrete structures. Likewise, Lecompte, Vantomme, and Sol (2006) implemented the use of charge-coupled device (CCD) cameras to capture photographic images of concrete structural elements. Using this technology, the identification of crack locations and widths was automatically available through the application of digital imaging processing techniques. Carino (2004) characterized the cracks in a concrete structure by using a piezoelectric transducer. Also, pulse-echo (using one transducer) and pitch-catch (using two transducers) are strong techniques for characterizing cracks in actual concrete structures. Han, van Beek, and Koenders (2005) investigated the use of electrical properties during hardening for tracking the formation of micro structural issues. Furthermore, Chen and Zoughi (2006) used a semi-empirical forward model for their research. This method showed the response of an open-ended rectangular waveguide probe in surface-breaking cracks in mortar through hardened cement paste samples. Park, Lee, and Sohn (2009) studied dereference-free methodology for crack detection, which was investigated via a series of experiments conducted in a laboratory setting using an aluminum plate.

Additionally, Johnson and Robertson (2007) used a built C-shaped crack gauge to observe the surface crack in concrete members. The C-shaped gauge measured the relative movement between the two ends of the mechanism. The results of this study were very promising. Similarly, Butrym (2010) studied a method similar to the vibration method, using frequency shifts. He also researched an impedance method for small cracks detection that seemed very useful. The researcher found that the impedance method was capable of detecting much smaller cracks than the vibration method. Nguyen and Tran (2010) used a moving vehicle to measure the active response of a cracked beam-like bridge. The researchers applied this technique and detected the existing crack by the large peaks in the dynamic response in the wave system. Furthermore, the position of the crack could be easily determined from the velocity of the vehicle and the location of the peaks in the wavelet transformation. Kuang, Akmaluddin, Cantwell, and Thomas (2002) proposed the use of optical fibers to detect hairline cracks and ultimate failure cracks in civil engineering structures. Once the cracks were detected, Kuang et al. (2002) hoped to monitor crack propagation up to the point of ultimate failure. The authors discovered that agreement between the sensor output and crack progression during loading in concrete beams was necessary to detect the initiation of a crack.

CHAPTER III

METHODOLOGY

Wireless Sensor Network

The wireless sensor network investigated in this study consisted of a base station and wireless sensor nodes for detecting the crack propagation in concrete structures. Instead of a PC-based system, each of the sensor nodes was capable of collecting the data and routing it back to the laptop via the USB port (see Figure 1). The USB base station functioned as a receiver to collect the data from sensors and to send commands to the sensors nodes (see Figure 2). This network arrangement was a self-healing process where the flow of the data was maintained even if some of nodes were blocked due to a lack of power, physical damage, or interference.

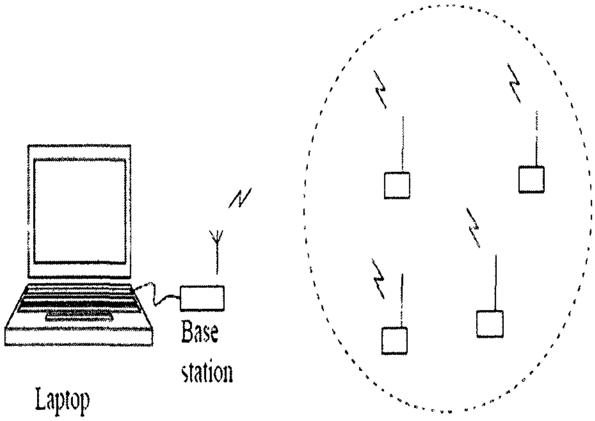

Figure 1. Diagram of the Wireless Network

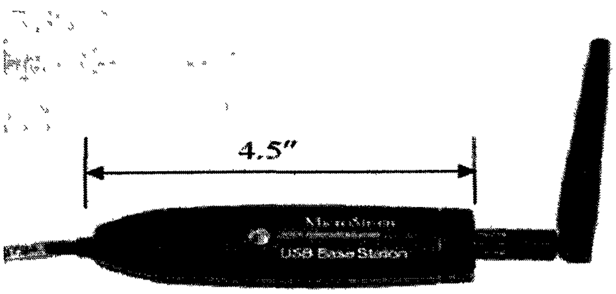

Figure 2. The Base Station

Node

The SG-Link module wireless sensor node manufactured and sold by MicroStrain was selected (see Figure 3). The SG-Link module has a small size, flexible software, ability to operate without a PC on site, relatively low cost, and a catalogue of add-on sensor boards. These characteristics made it the ideal choice to use to develop a wireless structural monitoring system. In addition, The SG-Link module's robust design made it an attractive platform for deployment in the harsh operating environment of in-service concrete structures. It is equally important to note that a SG-Link module end-user does not need to manually program the system to function properly, which is attractive to civil engineers.

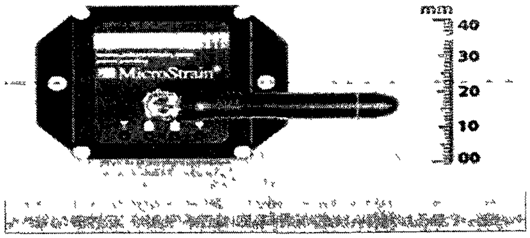

Figure 3. SG-Link Module Node

The SG-Link module node used a CC2420 chip for wireless transceivers for low-power consumption and could easily work with Wheatstone bridge type sensors. They came with a 3.7V 200mAHour lithium rechargeable battery. The available sampling rates were 64, 128, 256, 512 and 1024 Hz for normal operation and from 1 Hz to 1 sample per hour for the low duty cycle logging mode. The sampling rate stability was ±25ppm for a sampling rate 64Hz or above, ±10% for sample rate ≤ 1Hz. Each wireless sensor node had a 2 Mbytes on-board memory. For normal data collection, the user could choose how many samples (up to 65500 sample points) needed to be collected for each logging session.

A sensor node was the key element of the network. It was comprised of five major components: sensing and signal conditioning, communication, a microprocessor, memory or storage, and a power unit. The sensing units were also composed of two subunits: analog-to-digital converters (ADC) and sensors. Analog signals produced by a physical phenomenon were converted to digital signals by ADCs and sent to the processing unit of the sensor node. The processing unit managed the procedures that alerted the sensor node to respond and perform assigned sensing tasks and collaborate with base stations or other nodes. These units were responsible for pre-processing (encoding, decoding, etc.) the data for transmission. The transceiver unit connected the node to the sensor network via a wireless link such as a radio module. The end nodes converted and transmitted the signal remotely to the wireless collector node. Lastly, the power unit was the source of power for the node, which powered all activities on the sensor node including communication, data processing, and sensing. Figure 4 summarizes the tasks processed by those units on the sensor board.

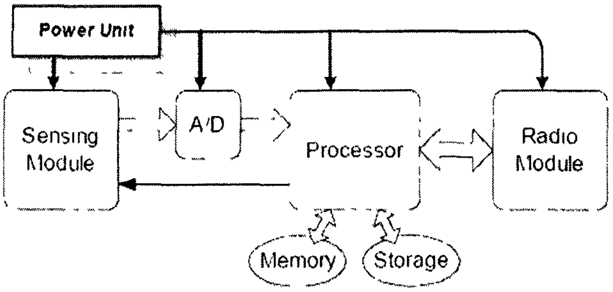

Figure 4. System Block Diagram for a Wireless Sensor

Radio

In a wireless sensor network, communicating nodes are linked by a wireless medium such as radio, infrared or optical media. The transmission medium options for radio links are 75 MHZ of the DSRC (Dedicated Short Range Communications) bands spectrum at 5.9 GHz to be used exclusively to vehicle-to-vehicle and infrastructure-to- vehicle communications in 2006. DSRC is available for free communication but licensed spectrum. The IEEE 802.11 WGp workgroup has been working on modifying the 802.11 wireless Local Area Networks (WLAN) standards to DSRC 5.9 GHz spectrum.

The Available Machine and Sample Dimensions

In order to verify the possibility to develop WSHMs based on the designed wireless sensor nodes, a laboratory experiment was deployed to monitor crack propagation in a concrete beam. The experiment took place in a University of Northern Iowa laboratory. The available machine in UNI laboratory had been examined, and the appropriate machine, the Digital Versa-Tester (loading machine), was chosen (see Figure 5).

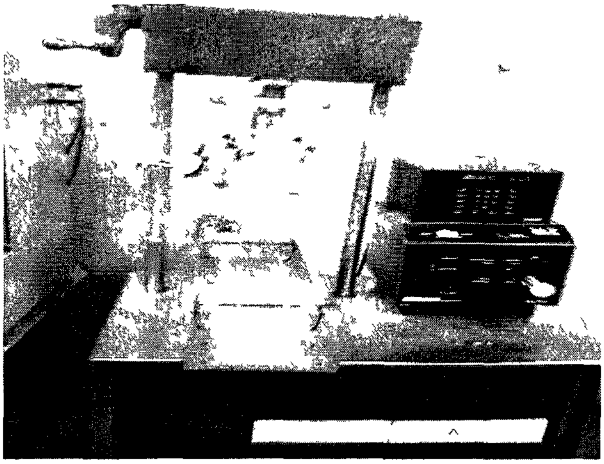

Figure 5. The Digital Versa-Tester

The Sample Dimensions

The maximum sample size that fit in the Digital Versa-Tester was 6 x 6 x 21 inches Eight samples were created. The samples were designed, and sample specification was determined as follows:

1. Size of samples was 6 x 6 x 21 inches.
2. Concrete mix Cement type 1-A, 4000 psi
3. Reinforcement 3 # 5 at the top and 3 # 5 at the bottom
4. Stirrups No 3 @ 3 1/2 in
5. Cover. 1 inch all around the sample.

Concrete Sample Casting and Curing

The samples formworks were made using standard wood with inner dimensions of 6 x 6 x 21 inches Five ready-mix cement bags were used The ready-mix cement and about half of the water were mixed for one minute The remaining water was then added, and the concrete was mixed for another minute. The beams were cast in two even lifts with a rod used after each lift. The form was also hammered against the side of the forms after each lift to help create smooth, hole-free surfaces on the sides of the beams (surfaces where the crack propagation gauges would later be attached). The top surface was carefully finished with a trowel. The beams and cylinders were removed from the forms within three days after they were created. This time allowed the beams to gain enough strength to prevent them from breaking during removal. The beams and cylinders were labeled and placed in a laboratory can filled with pure water. They remained submerged for 15 days.

The Crack Gauge Specification

DP-Series Crack Detection Gages were designed to provide a convenient, economical method to indicate the crack formation and indicate the rate of crack propagation in the concrete structure. Direct measurement of the elongation of a crack was measured with a crack propagation pattern, which is a brittle, paper-thin coupon on which a ladder-like pattern of electrically conductive material is printed. This coupon was glued to the surface of the material at the tip of the crack (see Figure 6). When the crack elongated and broke the rungs of the pattern, the electrical resistance between the sensor's two terminals changed. This resistance was read using the SG-Link module node to record the distance the crack has propagated. Vishay Intertechnology, Inc. commercially manufactured a series of these crack propagation patterns. One of these sensors was chosen for use in the WSHM system: the TK-09-CPA02- 005/DP, as shown in Figure 7. The sensors allowed for the measurement of twenty distinct crack lengths with twenty breakable grid lines. The crack gauge's grid lines were spaced 0.02 inches apart. Additionally, the crack gauge's resistance varied non-linearly with the number of rungs broken, as shown in Figure 8.

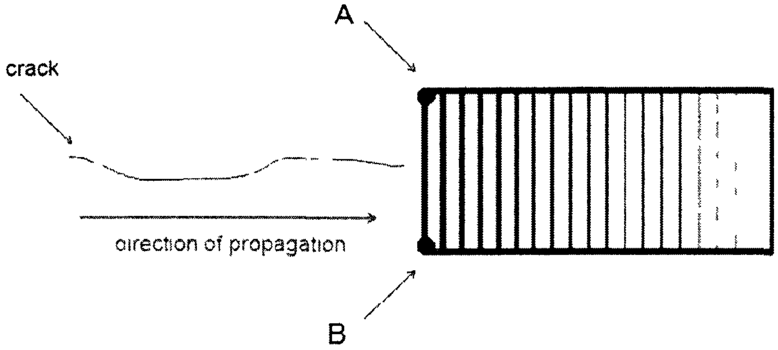

Figure 6. Illustration of a Crack Propagation Pattern (configured to measure the growth of a crack; resistance is measured between points A and B)

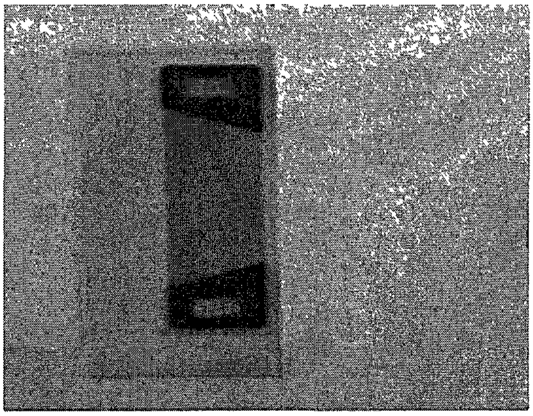

Figure 7. Crack Propagation Patterns TK-09-CPA02-005/DP

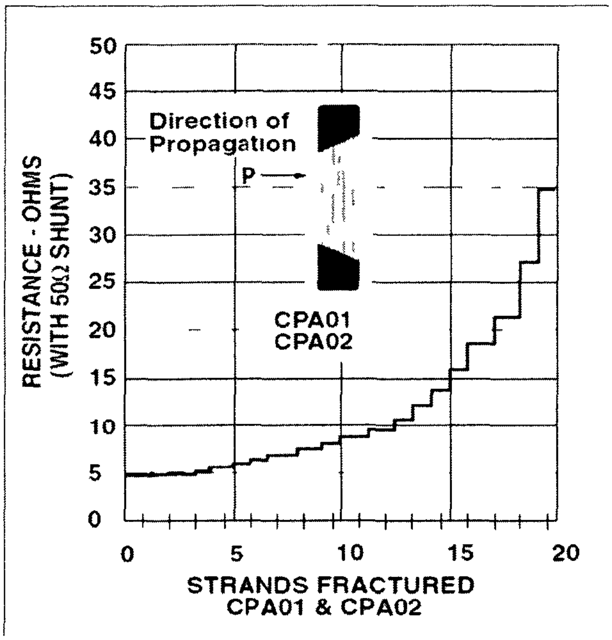

Figure 8. Crack Propagation Resistance Versus Rungs Broken (for TK-09-CPA02-005/DP –narrow)

Sensor Readout Circuit

The crack gauge pattern has a 3Ω resistance, which increased as its rungs were broken, acting as open circuits when all rungs had been broken (see Figure 8). Because the crack propagation patterns were purely resistive sensors and the SG-Link module node was able to record voltages, two precision resistors were used to create a circuit to convert the resistance output into a voltage. The 50 Ω resistor was placed in parallel with the two terminals of the crack propagation pattern while the 350Ω resistor was placed in a series with the node itself. Figure 9 shows a schematic of this circuit.

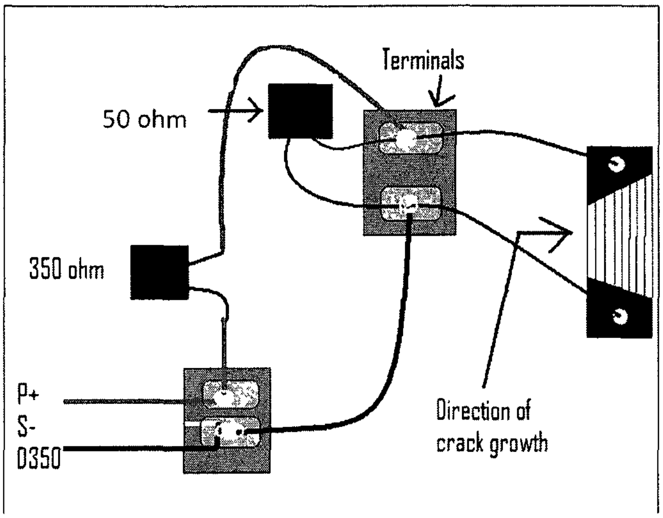

Figure 9. Diagram of Sensor Readout Circuit, adapted from Vishay Inter technology, Inc. (2008)

The Experiment Setup

An experiment was designed to test both the effectiveness of the crack propagation gauges in measuring cracking in the concrete beam and the ability, reliability, and accuracy of the SG-link sensor nodes. Eight concrete sample beams 6 x 6 x 21 were fabricated. The sample was placed in a mechanical testing apparatus, Digital Versa-Tester, to apply a compression load at its mid span to initiate a crack in the specimen.

The location of the crack propagation gauge was predetermined and was about 10.5 inches away from the supported end of the beams. A suitable area on the beams was selected so that there were no significant surface imperfections—namely, large holes or voids—near or under the crack propagation gauge in the mid span. These areas were then sanded with fine grit sand paper to create a smooth surface. The surface was conditioned with acetone, and a damp cotton swab was used in one direction to remove the resulting concrete dust. After the acetone in the area evaporated, the surface was conditioned with an acidic cleaner followed by a neutralizer, both applied with cotton swabs in one direction. After these solutions had evaporated, the adhesive was placed on the area. The adhesive mixture (resin and hardener) was placed on the concrete surface Next, the adhesive was spread to form a very thin and smooth layer. The adhesive was used to create a bondable surface for attaching the crack gauge. A thin coat of the super glue (SG401) was applied to a sample surface 10 minutes before applying it the crack gauge. A small mirror was treated with the acid and neutralizer. The crack gauge was removed from its casing and was placed on the mirror. The crack gauge was attached by clear tape to its back side and then placed on the beam. A firm pressure was applied on top of the gauge for one minute. After about an hour, the tape was removed and the strain gauge was attached to the concrete The crack propagation gauge and its exposed wires received a few protective coats of polyurethane An additional layer of an inert sealant—duct seal in this case—and aluminum tape were applied. These were used to help waterproof the crack propagation gauge. The sealant also prevented the aluminum tape from electrically reacting with the crack propagation gauge and its wires, as shown in Figure 10.

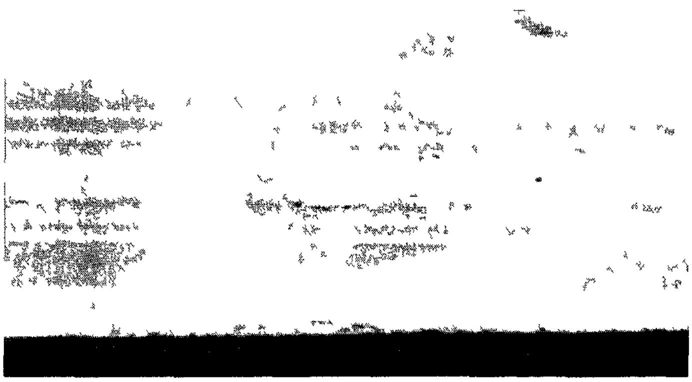

Figure 10. Crack Propagation Gauge Installation

Experimental Procedure

One crack gauge and one sensor had been chosen to use for the experiment. The crack propagation gauge was affixed to the concrete beam sample; the sample was placed into the mechanical testing machine. The crack propagation gauge was wired to the circuit and the circuit was wired to SG-Link module node, as shown in Figure 11.

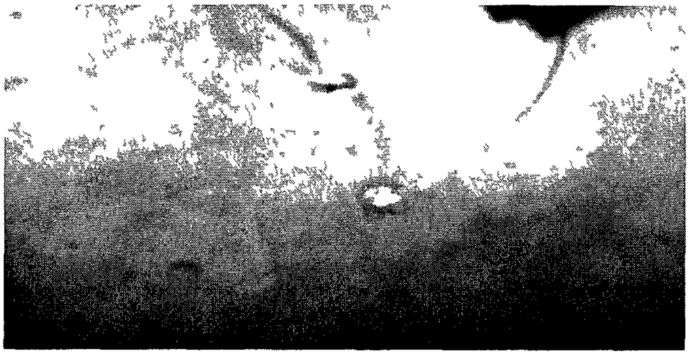

Figure 11. Wired Crack Propagation Gauge

The load was applied to the concrete specimen at its mid span. The load was increased gradually with a constant minimum rate, having enough stress at the top surface of the sample to create a crack in the lower surface, but not overloading the beams beyond their elastic behavior or to the point of failure. The crack propagation was recorded and collected via the wireless sensor nodes, as shown in Figure 12.

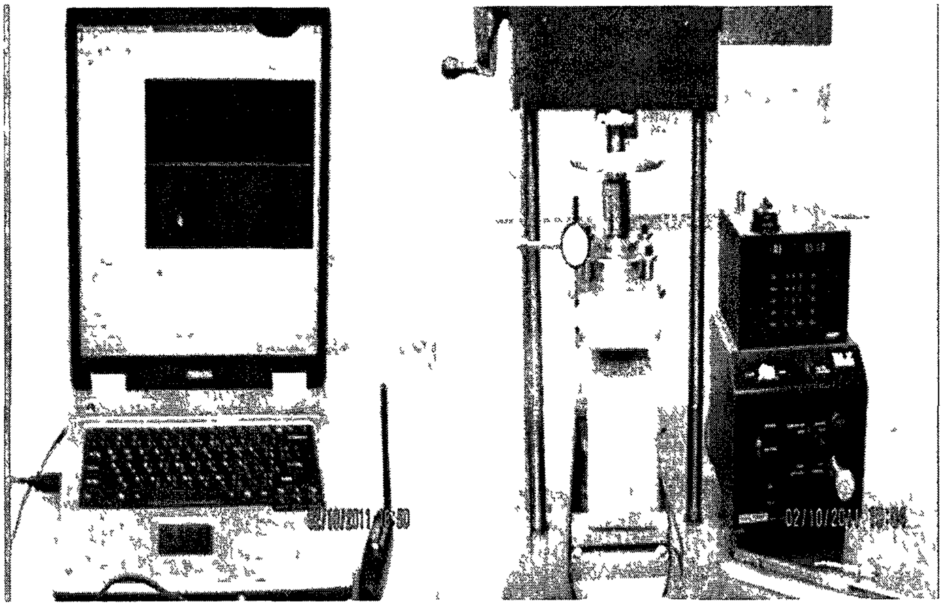

Figure 12. Testing and Collecting Crack Propagation Gauge Data (on Concrete Beam Sample)

A total of eight beams were tested under varying loading conditions. In these tests, the load was applied gradually up to crack formation, pausing periodically to make sure the crack formation allowed a further analysis to be undertaken after completion of the tests. For all of the samples, only one sensor was used. The sensor was attached to the lower surface of the sample beam Locating the sensor on the lower end of the surface facilitated the crack formation under flexural. This allowed the operator to ascertain that changes in the sensor signal were a result of crack formation in the vicinity of the sensor. Since the crack was expected to propagate in the mid span on the lower surface of the beam, the sensor was located on the lower end of the sample beam. This was done to minimize any time delay between the detection of a crack by the sensor and the actual moment when cracks were initiated on the lower surface.

CHAPTER IV

ANALYSIS OF DATA

Results and Discussion

To validate the proposed automated wireless network ability to detect the crack formation and record the crack propagation, two series of laboratory tests were carried out on eight concrete samples, four concrete sample for each series. Tests were performed for both series under varying loads. The crack formation was detected by a crack gauge installed at the lower surface of the concrete samples and the loads were applied on the upper surface at mid span of the concrete sample. The data recorded by the SG-Link module node transmitted wirelessly to the laptop via USB base station.

In the first series, the sensor readout circuit consisting of 50 Ω resistor placed in parallel with the two terminals of the crack gauge while the 350 Ω resistor placed in a series with the wireless node itself (see Figure 9).

The results of the first series tests on the concrete samples are summarized in Figure 13. The graph in Figure 13 represents the data recorded by the SG-Link module node during tests of the concrete beam under varying load with low rate, the load was enough to form a crack in the sample without breaking it. The graph showed the nonlinear change of voltage (number of broken rungs) versus the number of reading /sec. 15 rung breaks are easily identifiable from the graph in Figure 13. The author's visual inspection shows that all twenty rungs have been broken by the formation and propagation of the crack under varying load at the end of the tests, and that is presented in Figure 14, but the graph in Figure 13 only shows fifteen discernible increases in voltage. That is due to the 12-bit analog-to-digital conversion unit and the sensor readout circuit (5o Ω resistor was placed in parallel with the two terminals of the crack propagation pattern) combine to limit the minimum-viewable change in voltage output of any sensor to approximately 3 mV. This resolution is not suitable for measuring the breakage of the first 0-5 rungs of the crack propagation gauge. The Vishay specification graph (see Figure 7) shows that the resistance change exhibited by a crack propagation gauge for the first 1-10 rung-breaks is significantly lower than the last 11-20 rung-breaks, therefore the voltage change exhibited by the readout circuit will also be lower for the first 10-12 rung-breaks.

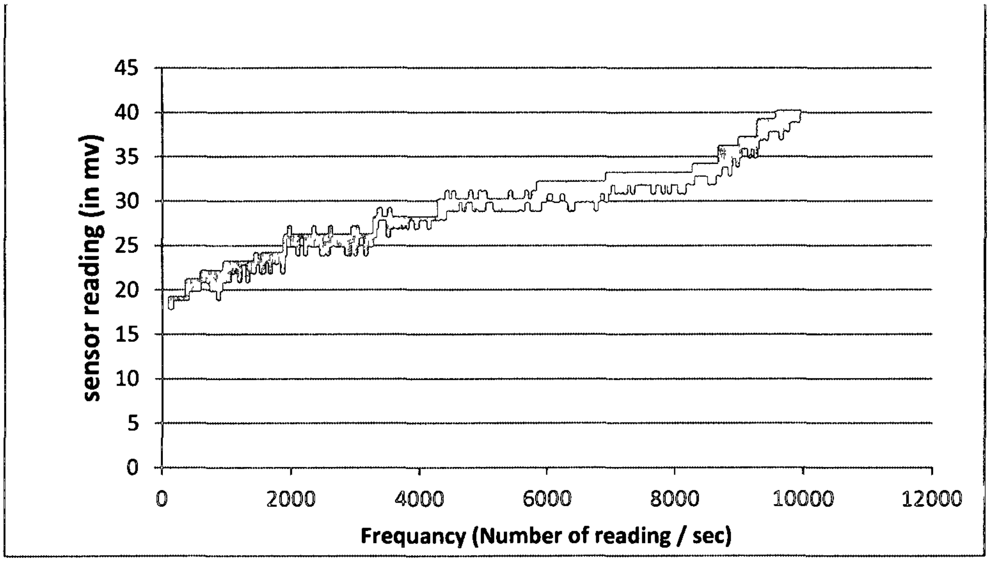

Figure 13. Data Recorded by SG-Link Module Node First Series

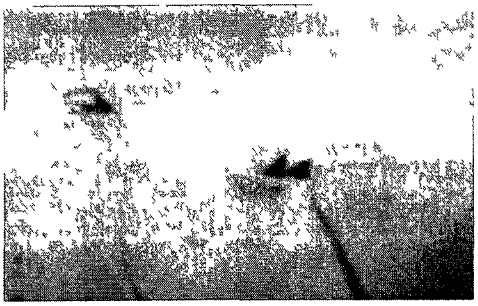

Figure 14. All twenty rungs of the crack gauge have been broken

In the second series, the sensor readout circuit consisting of 5 Ω resistor placed in parallel with the two terminals of the crack gauge while the 350Ω resistor was placed in a series with the wireless mode itself has been used. To increase the sensitivity and the resolution of SG-Link module node. The sensor readout circuit was connected to the crack propagation gauge, and to register an increase of approximately 10 millivolts on the SG-Link module node by manifesting rung breaks.

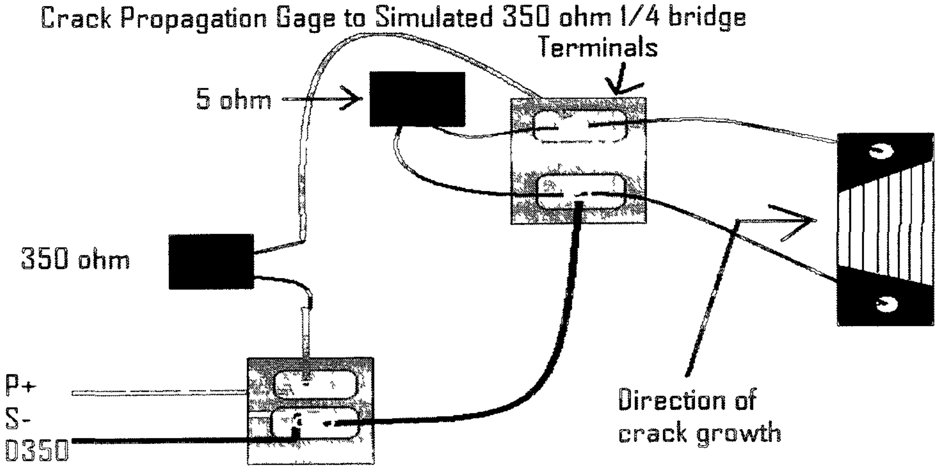

Figure 15. Diagram of Sensor Readout Circuit, adapted from Vishay Inter technology, Inc. (2010)

The results from the second series tests on the concrete samples are summarized in Figure 16. The graph in figure 16 provides clear evidence that the crack propagation under varying load was accompanied by a significant increase in the sensor response. The detailed data recorded by the SG-Link module node during the tests of the concrete beam samples in Figure 15 showed the change in voltage versus number of reading/sec. All twenty broken rungs could be identified by visual inspection. After testing, the graph in Figure 15 also shows all the twenty discernible increases in voltage. This result was expected because the sensor readout circuit was designed carefully to record the reading for a small change in the resistance. The 12-bit analog-to-digital conversion unit and the sensor readout circuit are combined to increase the minimum-viewable change in voltage output of any sensor to be recorded by the SG-Link module node. This resolution was suitable for measuring a rung-break on the crack propagation gauge.

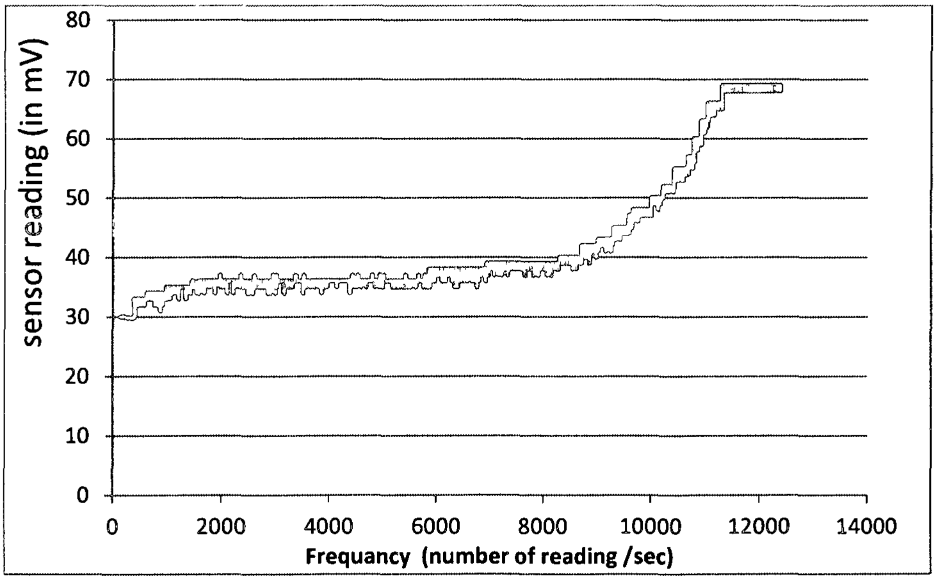

Figure 16. Data Recorded by SG-Link Module Node Second Series

It is apparent that the SG-Link module node appeared to be more sensitive to measure initial crack formation and propagation as shown in Figure 15 under varying loads. Furthermore, this increase in sensitivity suggested that the crack gauge could be optimized to monitor crack propagation during loading. This change in sensor response before and after crack formation at varying loads was clearly identified. Particularly, the crack detected by the first 0-5 rungs, which might be considered a typical hairline crack in a sample, indicated that the crack gauge sensor was highly sensitive to the presence of cracks and was able to provide a clear indication of crack formation and its propagation.

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The research presented in this thesis laid the foundation for the first implementation of wireless smart sensor networks (WSSN) for monitoring crack formation and recording crack propagation in concrete structures. WSHM systems used crack propagation sensors affixed to concrete beams to track the propagation of existing cracks, alerting stakeholders to any growth in cracks. Wired versions of these systems are expensive to install and intrusive to the users of the structures they monitor. As wireless sensor networks (WSNs) decrease in size and cost, and increase in capability and longevity, migrating to wireless structural health monitoring systems from the wired domain will drastically decrease the time and cost of system installation as well as the disruption to the users of instrumented structures.

Chapter II described the extensive background on structural health monitoring and wireless sensor technology, which indicates the potential of wireless smart sensors (WSS) to dramatically transform SHM practices by providing pertinent information regarding the condition of a structure at a lower cost and higher density than traditional monitoring systems. However, while much of the technology associated with smart sensors has been available for nearly a decade, there have been limited numbers of crack propagation autonomous implementations due to the lack of critical hardware and software elements. These elements include modular software for simplified application development and deployment, flexible and accurate sensor hardware to interface with the smart sensor platform being utilized, appropriate communication hardware and configuration, and the integration and validation of each of the system components on a full-scale structure.

Chapter III introduced the architecture of the wireless health monitoring system. The network system was used instead of a local office and PC based to monitor the concrete structures. The system implemented included a base station and multiple end sensor nodes. The base station was connected to a laptop via USB port. Each node has the ability to communicate individually with base station, which ensures the reliability of the network if one or more node is failed. In addition, this system has the ability to increase or decrease the number of wireless sensors according to information needed. This system will maintain an acceptable performance level as the network expands to a larger sensing area or requires higher resolution.

Furthermore, Chapter III introduced and described the SG-Link module from the Microstrain platform. The SG-link sensor nodes used a CC2420 chip for wireless transceivers for low-power consumption and adopted a WAVE system to transmit the data back. Sampling rates were 64,128, 256, 512 and 1024 Hz for normal operation. Chapter three also described the circuit readout board that helps to simulate and measure the broken rungs in the crack propagation gauge. In addition, chapter three described the commercial crack propagation sensors that were designed to detect the crack. It is glued directly to the concrete structure in which a crack had formed or was expected to form.

Chapter IV described the experiment in which the type of commercially available sensors was integrated with the SG-link sensor node and attached to concrete beam under compression load. The pre-manufactured test samples were functional and performed as designed when affixed to the sample using elevated temperature curing adhesive, but the first five rung-breaks of the crack propagation gauge were not recorded by the SG-link sensor nodes due to their small voltage changes in the first experiment series. In the second series all the twenty rungs breaks of the crack propagation gauge has been detected.

The elevated temperature curing conditions were difficult to achieve on in-service concrete structures and because the propagation direction of a crack are difficult to predict. Therefore, generally, the proper orientation in which to install a pre-manufactured gauge may not be known at the time of installation.

Conclusions

The thesis has introduced wireless structural health monitoring system and the evaluated using of the available crack propagation gauge. It has also examined the potential of the SG-link Wireless node for use in a wireless structural health monitoring system.

The SG-link is suitable for use in wireless structural health monitoring system. Special care is taken to accommodate its limited on-board analog-to-digital conversion hardware. Although the evaluated commercially available crack propagation gauge can be used for a wireless structural health monitoring system, it has some distinct advantages. The TK-09-CPA02-005/DP can track crack tip position with a finer resolution; however, its non-linear output due to the breaking of its 10 rungs causes small change which hard to be undetectable by the SG-link sensor, except by design a sensor readout circuit suitable for it. Nevertheless, the remaining of its rung breaks can be easily detected.

Hypothesis Findings

The purpose of the hypothesis was to prove that Autonomous Crack Propagation Sensing to detect the crack propagation during the operational lifetime of concrete elements and store and transmit the data from the concrete structure site back to a PC via a USB base station, through utilizing the Wireless Access in Vehicular Environment (WAVE) system. The hypothesis was tested and proved in the laboratory test results.

Future Work

Much work still remains before current SHM systems can be relied upon to replace standard inspection and maintenance sequence.

The Wireless Crack Propagation system has been proven in the lab and it can be applied to real world projects employing greater numbers of nodes for further reinforcement.

Employing WAVE system to monitor concrete structure requires more researches and experiments. The WAVE system also needs to be modified to work with any wireless structural health monitoring system.

Further experiments need to be conducted to investigate the correlation between the actual crack width and resistances vary with broken rungs by employing a linear resistance crack propagation gauge “each rung has a constant resistance.”

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