Using Smart Sensors to Monitor Concrete Infrastructure Assets for Useful Life Prediction Modelling

Peter J. Schemmel
Institute of Photonics and Quantum Sciences
School of Engineering and Physical Sciences
Heriot-Watt University
Edinburgh, Scotland EH14 4AS
email: P.Schemmel@hw.ac.uk

John J. Schemmel
Evan D. Humphries
Ingram School of Engineering
Texas State University
San Marcos, TX 78666 USA
email: john.schemmel@txstate.edu
email: ec1149@txstate.edu

***Abstract*—Cities operating smart infrastructure systems will soon be ubiquitous. Transportation, health, education, water treatment, water resource, storm water management, and waste management systems will all be monitored and controlled remotely by computer programs and asset managers. Researchers continue to make advances in sensor technology, power supplies, communication networks, data storage, and data interpretation methodologies. First generation monitoring systems are currently being deployed and evaluated. However, use of these monitoring systems to develop predictive models for approximating the remaining useful life of an asset is not receiving the same level of attention. This paper will outline a method for using sensor systems to develop empirical lifetime prediction models for concrete structures. Two monitoring systems capable of accomplishing this goal, one well-established and the other in its infancy, are examined. Developing such a tool will provide asset managers with increased warning of impending structural issues such that more efficient and effective repairs can be implemented.**

Keywords-concrete; infrastructure; life prediction; sensor.

I. Introduction

In the coming years, cities across the world will begin to deploy smart sensor systems to monitor local infrastructure. City leaders will support such initiatives as a means to improve quality of life for its citizens though improved safety, functionality, environmental impact, and economic efficiency of its infrastructure. Monitoring of transportation networks, water and waste management systems, hospitals, and other public works using sensors is no longer a novel concept. However, even today, this process relies heavily upon visual inspections carried out sporadically over time, likely by different individuals. Such evaluations are unreliable, in part, due to variances in the knowledge and experience among inspectors. Deploying smart sensor systems across a city's infrastructure will allow asset managers to evaluate structures remotely, continuously, and consistently. Furthermore, the inclusion of intelligent software has the potential to redirect a significant portion of the monitoring burden away from required human involvement. If considered from a different perspective, these systems can also help city leaders assess when any one of its assets is approaching its useful life and whether it makes sense from a safety and economic viewpoint to repair the structure.

Section II of this paper presents the components of a Technology Enhanced Infrastructure system. This section also introduces the premise that sensor data can be used to estimate the remaining useful life of an asset. The steps necessary for developing a useful life predictive model are then outlined in Section III. A simplified example illustrates the methodology involved in creating a predictive model. Section IV further explains the process of creating a model by examining the how a commercial sensor monitors concrete maturity in real time. An innovative means for monitoring stress in a concrete structure using radio waves is discussed next. This remote sensing device uses principles from physics, electrical engineering, and construction materials to measure stress in concrete. The paper concludes with a summary of the process for using sensor data to develop a predictive life model.

II. Technology Enhanced Infrastructure Systems

Technology Enhanced Infrastructure (TEI) systems have four elements in common: an array of physical assets, an inventory of embedded, attached and remote sensors, a data communication and storage network, and a cohort of asset managers. Before engineers and scientists can create an efficient, effective, and comprehensive TEI monitoring system for a city they must have a holistic understanding of the city's structural inventory, be aware of available sensor systems, and understand the informational needs of the asset management team. For example, the type of physical asset, its geographic location, its expected use, and relationship to other assets will all contribute to determining the relevant structural properties and performance data to be monitored. Communication networks, data storage, and power requirements will further define the specifications for a monitoring system. Intentions for quantifying, displaying, and interpreting the transmitted data must also be considered. Lastly, all this information, along with the objectives and goals of the asset managers, must pass through a sensor selection protocol.

Several research groups have begun the process of developing and deploying TEI systems to understand how future systems should be designed and implemented [1] - [4]. While this work is critically important, there is an unrealized

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opportunity to exploit these systems for the betterment of a city and the general public. In addition to current applications, smart sensor technology can be used to inform asset managers of the remaining useful life of a structure and help them predict when and where failures might occur. Proposed herein is a methodology for developing an alternate use for a TEI system. In addition to monitoring a structure, TEI systems can be used to determine the remaining useful life of a structure. Two such systems for use with concrete structures, and capable of accomplishing the desired goal, are examined here. One system uses temperature sensors and maturity concepts to predict strength while the other, still in its infancy, uses radio frequencies to monitor stress.

III. A Methodology for Developing Empirical Life Prediction Models

TEI networks capable of predicting the remaining useful life of a structure would be an invaluable resource for infrastructure asset managers. Having knowledge of an approximate time when major and minor repairs would be required for a structure would allow asset managers to schedule and budget these repairs in a more efficient and cost effective means. Being able to purchase repair materials in advance when prices might be lower, scheduling manpower to limit idle time, and mobilizing manpower in advance of a repair would ultimately improve the economic efficiency of a city's entire infrastructure inventory. For example, specific repairs might be explicitly scheduled on a recurring basis to extend the life of a structure. Alternatively, use of a structure by the public could be managed to prolong its life or maintain adequate safety, such as with load ratings for bridges. To realize these advantages requires an empirical lifetime prediction model based upon actual field data captured by a smart sensor and transmitted over a communication network.

Building a proposed life prediction model involves the following steps. First, one or more sensors must be selected that measure the desired structural parameters, recognizing that these parameters will vary as a function of the structure's age. For example, increases in stress and strain due to the corrosion of reinforcement bars in a concrete slab can lead to cracking and potential structural failure. In this instance the selection of a fiber Bragg grating strain sensor or electrical impedance sensor would be an appropriate selection. Alternatively, anemometers and vibrational measurements, which are often employed in early versions of TEI systems, are not well suited to predicting remaining life. This is because these devices primarily measure transient events. While such events are certainly significant as they can eventually lead to a structural failure, they do not vary with the age of the structure.

With a suitable sensor selected, the relationship between a measured property and a structure's age must be established. Clearly, this step is difficult to accomplish as waiting for full sized structural elements to fail is impractical. Therefore, correlations between measured properties and structural health must be established. One means for defining a correlation is through accelerated laboratory testing. As an example, sensor data can be recorded concurrently with the fatigue testing of metals subject to accelerated heat treatments. Other examples involving concrete include freezing and thawing, alkali-silica, and sulfate attack behavior. Regardless of the material and parameter being evaluated, accelerated laboratory testing must continue to the defined failure of the material. While sensors may still need to be developed to measure some structural parameters in the field, accelerated laboratory tests for many materials are already available or well under development.

An example of an empirical model of measured sensor data as a function of a structures age is shown in Figure 1. This is the next step in establishing a predictive model. This chart plots the value of an expected measured parameter as a function of age. Regions above and below the measured data constitute an acceptable range for the parameter. An empirical model of this nature should be refined and adjusted over time as additional field data is recorded. However, as more monitoring systems are deployed and data is collected, it will be possible to establish an open source library of "standard parameter values."

The final step in predicting life expectancy is to use the library of standard parameter data to estimate the remaining life of a structure. In turn, this will provide asset managers with ample warning of the need for impending repairs. Two cases studies are presented below where work on life prediction models is being conducted.

IV. Concrete Strength Prediction Using Relative Humidity Sensors

Maturity is a relatively simple concept associated with concrete where time, temperature, and relative humidity (RH) are used to estimate the early age in-place strength of concrete. This concept assumes that concrete mixtures with similar maturity indices, a computed value, will have similar strengths regardless of their individual age, temperature, or RH histories. The relationship between maturity index and in-place strength, as shown in Figure 2, is established from laboratory calibration testing for each individual concrete mixture. ASTM C1074 Standard Practice for Estimating Concrete Strength by the Maturity Method [5] defines the protocol for computing the maturity index. Today, several companies market sensors to monitor concrete age, temperature, and RH, though ASTM does not require RH be measured. When in-place, these sensors perform the necessary computations, based on prior laboratory calibration, to establish a measured maturity index. In general, that information is sent to a cellular phone where the maturity index is presented with a calibration curve and the associated concrete strength. An example of a modern sensor and smartphone display are provided in Figure 3 [6] and Figure 4 [7]. While not detecting a "failure" event, these sensors and the maturity concept can be used to create a predictive model. As opposed to considering the development of strength from zero to that associated with a particular maturity index, focus can instead be placed on the later portion of the index/strength curve. Again, refer to Figure 2. Rather than concentrating on the estimated concrete strength at any moment in time, attention can be given to the remaining strength capacity in the concrete. In other words, how much more strength is the concrete likely to develop within some period of time. This information could have ramifications as to the time remaining until formwork can be removed or when vehicles might be allowed to travel across a pavement patch. Although basic in nature, this is a very clear example of how sensor technology and laboratory data can be used to create a predictive model for concrete.

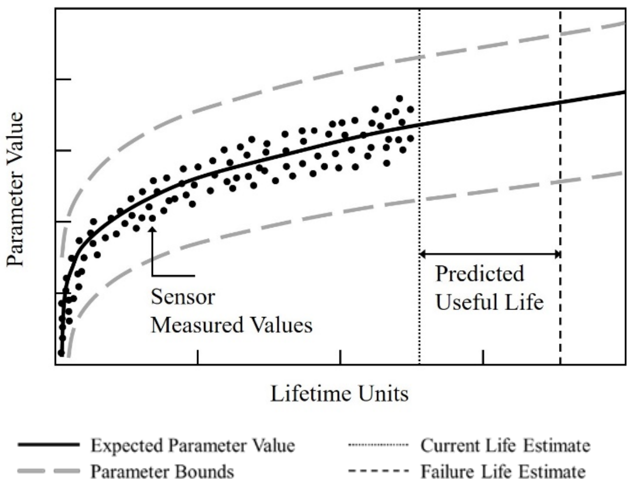

Figure 1. Simulated sensor data with depiction of predictive useful life.

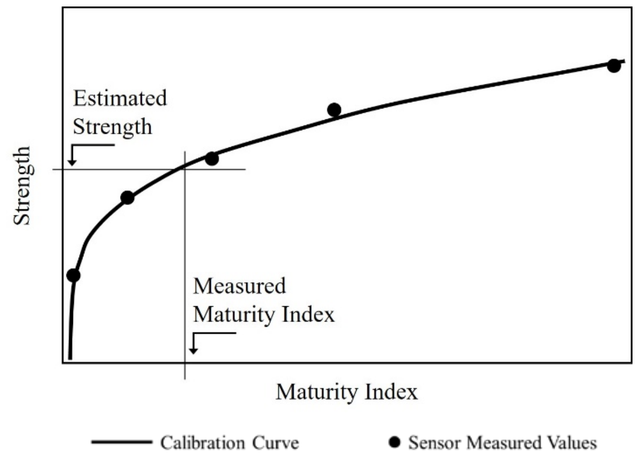

Figure 2. Graphic depiction of the maturity method.

Figure 3. Embedded sensor monitors temperature and relative humidity, calculates strength by ASTM C1074. (Courtesy of ConcreteSensors, http://www.concretesensors.com/products/).

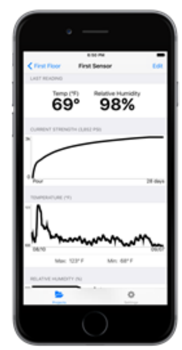

Figure 4. Cellphone interface for embedded maturity sensor. (Courtesy of ConcreteSensors, http://www.concretesensors.com/)

V. Concrete Stress Measurements Using Radio Frequency

A research collaboration housed in the School of Engineering at Texas State University is employing principles from physics, electrical engineering, and construction materials to develop a novel approach for the measurement of stress in concrete. This approach employs radio frequency illumination to measure stress. In this study, properties of concrete specimens are measured remotely using lensed horn antennas connected to a vector network analyzer. The parameters being measured are related to concrete strength and are known to be correlated to the age of concrete. Currently, testing is being conducted to establish an empirical lifetime prediction model with appropriate boundaries on the measured parameters. Calibrating field measurements are planned for the near future. Correlation of the field and laboratory data will then be used to refine the predictive model. Once the predictive model has been validated, research will examine the sensitivity of the model to variations in the concrete's constituent materials and proportions.

VI. Conclusion and Future Work

This paper outlined a method for using TEI systems to develop a predictive model for estimating the remaining life of a structure. Not only will this contribute to more resilient structures it will also extend the functionality and economic feasibility of a monitoring system. While TEI systems will soon become common place, utilizing them to predict the need for major structural repairs is still a novel concept. However, efforts are underway to develop an empirical lifetime prediction model for concrete structures using field data measured and transmitted via a TEI system.

Developing a predictive model is a multi-step process that relies on engineering parameters being measured in the field by smart sensors. The measured parameters must be a function of, and vary with, the age of the structure. Field data is then correlated with comparable laboratory garnered from accelerated testing of the construction material. These two data sets establish the foundation for the predictive model. Over time, an open source library of engineering parameter values with accepted bounds will be populated and routinely updated for use by the engineering community.

Two sensor monitoring systems that can be used to create predictive models were reviewed. One sensor system is based on well-established principles while the other has brought several science and engineering disciplines together to create a novel solution.

The overarching objective of the concept proposed here is to provide asset managers with a new tool which they can use for early warning of impending structural issues, including failure. Such a tool would allow for more efficient and effective repairs to an infrastructure asset with the goal of maintaining, or improving, its safety and value. While this paper has focused on concrete structures and parameters, it is envisioned that this approach can be applied to any infrastructure asset built from a construction material with a time variable behavior.

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