Health Monitoring of Concrete Bridges Utilizing Sensor Technology

Ammar Zalt

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HEALTH MONITORING OF CONCRETE BRIDGES UTILIZING SENSOR TECHNOLOGY

by

Ammar Zalt

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Science
Department of Civil and Construction Engineering

Western Michigan University
Kalamazoo, Michigan
August 2007
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First and foremost my gratitude to Allah for giving me the strength to complete this thesis. It was only by the strength Allah gave me that I could bear till the end.

My foremost appreciation and thank goes to my thesis advisers; Dr. Sherif Yehia and Dr. Osama Abudayyeh. Without them, this search would not have been possible. I thank them for their patience and encouragement that carried me on through difficult times, and for their insights and suggestions that helped to shape my research skills. Their valuable feedback contributed greatly to this thesis. I would also like to thank Dr. Ikhlas Abdelqader for her encouragement, support, and help that she provides through the course of this research.

I would like to thank my father and mother for their infinite love, without whom none of this would have been even possible. Thanks to all my family members specially my brother Bachar for his helps and love which always helped me in hard times and made me continue to the end.

Finally, I would like to thanks my friends here in the United States and back home.

Ammar Zalt
HEALTH MONITORING OF CONCRETE BRIDGES UTILIZING SENSOR TECHNOLOGY

Ammar Zalt, M.S.

Western Michigan University, 2007

Structural health monitoring using sensor technology is a promising way to provide excellent means for protecting important structures such as bridges, dams, and nuclear reactors. These sensors provide real-time information about structural conditions. They work together as a nervous system to provide timely information for emergency and risk mitigation. The information obtained from these sensors can later be analyzed and compared to the design data so that the problem can be detected and fixed before it develops into a serious and costly hazard.

Throughout the course of this thesis the feasibility and performance of two types of sensors will be assessed and evaluated. Different mechanical properties of concrete will be also studied. The short-term evaluation of these sensors shows that both has the potential to be embedded inside concrete bridges and would be able to detect defects at their onset.
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1.1 Problem Statement

Bridges are one of the most important elements in the transportation network in the United States. Most of the bridges are deteriorating in a rapid way because the available inspection techniques are not able to verify the problem at its occurrence. Therefore, problems may develop with time, creating serious and dangerous effects on bridges and the public using the highway systems.

Recent advances in sensor technology, materials processing, damage modeling, and system integration have enabled new developments in structural evaluation/inspection technologies to overcome the shortcomings of existing inspection techniques. From these methodologies comes the concept of structural health monitoring. As a result, the problem will be identified at its onset, resulting in better structural performance and prolonging the lifespan of the bridge.

The most common types of sensors used for structural health monitoring purposes are strain sensors. Strain sensors are measuring elements that translate force, pressure, tension, etc., into a different type of output. Various types of sensors have been used successfully in this field, such as electrical resistance strain gages, vibrating wire strain gages, fiber optic sensors, and wireless sensors.

This research study is based on an extensive experimental evaluation of the strain sensors to assess their feasibility when embedding them inside concrete structures.
1.2 Research Objectives and Methodology

The objectives of the research are as follows:

- Study the different types of sensors used for structural health monitoring purposes.
- Select the most applicable, most promising sensor for strain monitoring in a concrete bridge.
- Develop test specimens to validate and verify the feasibility of the selected sensors.
- Prepare three-dimensional finite element model to optimize the sensor locations and come up with an instrumentation layout as a case study.

This research involves studying the concept of structural health monitoring. The focus is to evaluate the ability of the strain sensors to detect the most common bridge defects and provide real-time monitoring of the bridge. The research will achieve its objectives through the following phases:

- Literature review phase: extensive literature review is conducted to investigate structural health monitoring tools and instrumentation.
- Specimen preparation phase: the second step is to prepare test specimens as bridge deck prototypes to evaluate the sensor performance and behavior inside the concrete.
- Specimen testing and data collection phase: the third step is to test those prototype specimens under a controlled environment to determine which sensor type would be the best candidate for bridge applications.
- Finite element model and sensor location layout: the final step is to come up with a sensor location layout using the sensor chosen from the previous step to optimize the sensor locations using SAP2000.
1.3 Thesis Layout

This thesis covers the research findings and will be organized as follows.

Chapter Two provides a literature review about various methods used for structural health monitoring purposes.

Chapter Three contains the experimental program designed to evaluate the sensor and assess the concrete behavior in the fresh and hardened stages using the embedded sensors.

Chapter Four includes a preparation of 3D finite element model of the sensor that will be used in the case study to optimize its location inside the concrete deck.

Chapter Five explains the conclusion drawn during the various phases of this research. Limitations, contributions of the research, and recommendations for future work are also included in this chapter.
CHAPTER II

STRUCTURAL HEALTH MONITORING

2.1 Introduction

Bridges represent an enormous infrastructure investment across the United States. Maintenance, repair, and replacement of these structures are ongoing expenses. Many structures, especially those built in the first half of the 20th century, are now near or at the end of their service life. Managing these resources is particularly acute today, and the possibilities of vehicular accidents, earthquakes, and other factors add to the management difficulties. Regular usage of current structural inspection practices is expensive and labor intensive. Current techniques, such as visual inspection and chain drag, are time consuming, expensive, and rely heavily on human interpretation.

Recent advances in sensor technology have enabled new developments in structural evaluation and inspection technologies to overcome the shortcomings of existing inspection techniques. Among them is the concept of structural health monitoring.

2.2 Structural Health Monitoring

Structural health monitoring (SHM) refers to the monitoring of the integrity of the structure for the purpose of hazard mitigation, whether the hazard is due to live load, wind, earthquake, aging, or other factors. This monitoring mainly entails non-destructive sensing of any damage in the structure.

In other words, SHM can be defined as "the ability to proactively manage the structural health by diagnosing deterioration and damage at its onset, and to deliver an
effective response to operational incident, accident, natural hazards, or other emergencies.  

2.2.1 Design Procedures for Health Monitoring

The principal steps in the design process of health monitoring system are summarized in Figure 2.1. Each of these procedures will be discussed in the following subsections.

![Diagram](image)

Figure 2.1. Design Procedures for Health Monitoring
2.2.1.1 Characterization

This stage involves understanding the project needs and goals. It includes studying the behavior of the structure and how it will respond to various types of loading.

2.2.1.2 Identification

In the identification stage, the physical parameters such as loading, environmental, and operational effects need to be measured and identified. The location of sensors, physical requirements, and environmental constraints are also identified.

2.2.1.3 Sensor Selection

Sensors are selected based on the project’s needs and budget as well as what is commercially available.

2.2.1.4 Calibration

Calibration is a necessary step used to identify the performance of the components in a controlled setting before they are placed within or on the structure. Verification of the supplier’s specifications is achieved and any undesirable characteristics of the sensor can be identified at this stage.

2.2.1.5 Data Quality Assurance

Calibration of the in-place system, followed by periodic checks to ensure accurate data collection is necessary to provide accurate sensor readings. Recalibration may be necessary again at a later date based on the results of periodic field inspections.
2.2.1.6 Decision Criteria

Decision criteria must be established in order to compare measurements and make decisions. If certain measurements exceed a given value, an alert must be made and proper actions must be taken to resolve the issue.

2.2.2 When to Consider Health Monitoring

For structures with high replacement costs or those which could cause significant public impacts if damaged, regular physical inspections are insufficient. Large toll bridges, suspension bridges, and other critical structures in high seismic areas are examples of structures where health monitoring should be considered. Table 2.1 shows some examples of when health monitoring has shown its merits.

Table 2.1. Examples of When to Consider Structural Health Monitoring

<table>
<thead>
<tr>
<th>Seismic Importance</th>
<th>It is of supreme importance to monitor the seismic behavior of the bridges in high earthquake risk areas to help quickly assess the bridge’s condition and evaluate short and long term safety concerns and recovery strategies.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Creep and Shrinkage</td>
<td>It is well known that the creep and shrinkage play vital roles in the redistribution of internal forces like bending and shear. Health monitoring can aid in tracking these complex time dependent affects.</td>
</tr>
<tr>
<td>New Construction Techniques</td>
<td>When a new construction techniques is employed on any structure. It is important to fully monitor this structure and see whether or not this is a valid construction technique or not.</td>
</tr>
</tbody>
</table>

2.2.3 What to Monitor Using Health Monitoring

Once the necessity for a health monitoring technique has been established, the focus then must be placed on what exactly needs to be monitored. Various factors can be monitored, such as deflection, rotation, strain, temperature, creep, shrinkage, seismic behavior, and environmental conditions.
2.2.4 How to Monitor Using Health Monitoring

After establishing what needs to be monitored for a certain structure, the details of how to collect the information need to be developed. Table 2.2 shows the monitoring tools used to collect the information.

Table 2.2. Monitoring Tools for Collecting the Data

<table>
<thead>
<tr>
<th>What to Monitor</th>
<th>How to Monitor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deflection</td>
<td>Base line</td>
</tr>
<tr>
<td></td>
<td>Optical survey</td>
</tr>
<tr>
<td></td>
<td>GPS and video capture</td>
</tr>
<tr>
<td></td>
<td>Direct deflection measurement</td>
</tr>
<tr>
<td>Change in length</td>
<td>Extensometers</td>
</tr>
<tr>
<td></td>
<td>Linear variable displacement transducer</td>
</tr>
<tr>
<td>Rotation</td>
<td>Tilt meters</td>
</tr>
<tr>
<td>Strain</td>
<td>Vibrating wire sensors</td>
</tr>
<tr>
<td></td>
<td>Fiber optic sensors</td>
</tr>
<tr>
<td></td>
<td>Electrical resistance sensors</td>
</tr>
<tr>
<td></td>
<td>Wireless sensors</td>
</tr>
</tbody>
</table>

2.3 Health Monitoring Instrumentation

The most common measurements required during the load test on a bridge are the material’s strain and the members’ deformation. Strain is generally measured using different kinds of strain gages, while the member deformation can be monitored using displacement transducers, GPS, or base line. Ambient temperature is another factor that should be monitored during a load test on the bridge. Each one of these measuring methods will be discussed in the following subsections.
2.3.1 Deflection Measurements

Deflection measurements give an indication of the structural performance of the bridge during loading. Different systems are used for that purpose, some of which are discussed in the following subsections.

2.3.1.1 Optical Survey

Optical survey is one of the simplest methods for evaluating the deflected shape of a structural element. An initial survey is done prior to applying the load to the bridge to compare with subsequent surveys under load to produce a deflected shape. Survey points should be determined and marked before the load test. Elevation readings should include the supports, quarter span, and midspan at both sides of the deck and along the centerline of the roadway. Optical surveys are time consuming and have limited correctness.

2.3.1.2 Direct Deflection Measurement

In certain cases it may be possible to perform direct deflection measurements, which can be done from the ground to the bridge structure. This is the most commonly-used method when access below the bridge is available, but it may also be used in other locations. A displacement transducer can be attached to the soffit of a bridge with spring loaded line extending to the ground below. Movement between the bridge and the ground will then represent the deflection of the bridge under loading. Care should be taken not to place a ground-based sensor close the structure’s foundation as the movement of the substructure under load may affect the ground surface adjacent to the foundation.
2.3.1.3 Base Line System

This method of deflection measurement consists of a taut piano wire, which is tied between the bridge’s piers. This system is based on a reference line provided by the piano wire, and the measurement between the reference and the bridge girder or deck. One end of the piano wire is fixed to the pier while the other end passes over a pulley at the opposite end of the span and supports a weight between 60% to 80% of the breaking strength of the piano wire. Measurements then are conducted using a digital caliper between the baseline and fixed location on the bridge’s girder or deck.

2.3.1.4 Tiltmeters

Tiltmeters can be placed along a bridge’s span to measure their respective girders’ rotations. The deformed shape can then be determined from the slopes at each tiltmeter location.

2.3.1.5 GPS Deflection Monitors

The Global Positioning System (GPS) can be used for measuring the deflection of a bridge. A reference sensor should be located a known distance away from the bridge’s structure to be used as a point of reference. GPS sensors are placed at locations on the bridge where deflection measurements are required, generally where maximum displacement is expected. By correcting their location with respect to the known reference sensor, the local sensors will provide accurate three-dimensional coordinates of their locations during loading.
2.3.1.6 Video Capture

Deformation can be detected by using high-resolution camera images located adjacent to the bridge structure during a load test. The computer analysis of successive digital images can be used to determine the deflection of the bridge.

2.3.2 Ambient Weather Conditions

The ambient weather conditions may affect the data collected during the load test. The most significant effect will generally result from rapid changes in the ambient and the surface temperatures of the bridge. It is recommended that a load test be performed during the morning hours when the air temperature is relatively constant and solar radiation does not significantly affect the surface temperature of the bridge. If a load test is extended beyond mid-morning, it may be important to adjust the instrument’s readings and the measured deflections for these thermal effects. The top surface of a bridge warms considerably due to daily solar radiation, while the temperature of the rest of the bridge remains relatively constant. This will result in temperature-induced strains in the top surface and consequently, the deformation of the bridge’s elements.

2.3.3 Strain Measurements

Strain is a measurement of the amount of deformation that is caused when an object is subject to an applied load. Strain is the ratio of the change in the length of an element to its original length and therefore is a dimensionless quantity. The most common instruments used for measuring strain in bridge applications are: electrical resistance strain gages, vibrating wire gages, and fiber optic sensors.
The unit that is generally used for measuring strain is the micro strain. One micro strain is the strain that produces a deformation of one part per million ($10^{-6}$).

Two types of strain should be considered: short and long term strain. Short term strains are those changes that occur over a period of hours; whereas long terms are those changes occurring over a period of months or years. Short term strain is generally caused by changes in dead and live load, daily temperature cycles, or wind. Long term strain is caused by seasonal temperature changes, creep, and shrinkage in the concrete structures.
2.4 Introduction to the Sensor Technology

A sensor is an instrument that converts energy from one form to another. The input energy to a sensor represents the physical phenomena being measured. The input is referred to as the measurand and the output is measurement. Different forms of input energy include: mechanical energy, magnetic energy, chemical energy, and electrical energy. A sensor consists of two discrete components; the sensing elements and the sensor packaging. The sensor element is the main transduction mechanism that converts energy from one form to another. The sensor packaging includes the materials that contain the sensing elements as well as any external connection to the sensor. Sensors are categorized as either active (self generating), where the sensors produce their own output energy, or passive (modulating) where the sensors need an external excitation to generate output energy. Figure 2.2 shows the schematic of the sensor’s working mechanism\(^5\).

![Figure 2.2. Sensor Working Mechanism\(^5\)](image)

Many advantages can be established by using sensors to instrument a certain structure for long term monitoring. There could be long-term savings in money, labor, and time. Problems that develop in the bridge can be detected before they become too severe to address\(^9\).
2.4.1 Sensor Selection Considerations

There are several important criteria that should be taken into consideration in selecting a sensor. Sensor selection considerations can be categorized according to sensor performance characteristics, environmental constraints, and economic considerations. Table 2.3 shows the sensor selection considerations and criteria.

**Table 2.3. Sensor Selection Considerations**

<table>
<thead>
<tr>
<th>Performance Characteristics</th>
<th>Environmental Constraints</th>
<th>Economic Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>Humidity</td>
<td>Availability</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>Size</td>
<td>Cost</td>
</tr>
<tr>
<td>Limit of detection</td>
<td>Temperature</td>
<td>Reliability</td>
</tr>
<tr>
<td>Range</td>
<td>Packaging</td>
<td>Ease of installation</td>
</tr>
<tr>
<td>Linearity</td>
<td>Thermal effects</td>
<td>Data acquisition need</td>
</tr>
<tr>
<td>Accuracy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Response time</td>
<td></td>
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</tr>
</tbody>
</table>

2.4.1.1 Sensor Performance

Sensor performance indicates how a sensor will act under typical use conditions. Sensor performance includes both static characteristics, which describe the sensor performance due to slowly varying measurand; and dynamic characteristics, which describe the sensor’s response with variation in the measurand with time. Table 2.4 summarizes the factors that affect sensor performance.
Table 2.4. Sensor Selection Consideration (Sensor Performance)\textsuperscript{5}

<table>
<thead>
<tr>
<th>Sensor Performance Characteristics</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>The smallest measurable change in input that will produce the smallest change in the sensor’s output.</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>The change of the output of the sensor in response to the sensor’s input. This value provides an indication of the ability of the sensor to detect changes in the measurand.</td>
</tr>
<tr>
<td>Limit of Detection</td>
<td>The smallest increment of a measurement that can be discerned.</td>
</tr>
<tr>
<td>Linearity</td>
<td>The degree to which the calibration curve of a sensor agrees with straight line. The amount of deviation from the line is known as nonlinearity error.</td>
</tr>
<tr>
<td>Stability</td>
<td>The ability of the sensor to maintain its calibration value over a period of time. It is the ability of the sensor to give the same output when measuring a constant input.</td>
</tr>
<tr>
<td>Response Time</td>
<td>The amount of time that the sensor needs to reach a stable value.</td>
</tr>
<tr>
<td>Accuracy</td>
<td>The ability of the sensor to give a true accepted value. This value is generally compared to the sensor measurement recorded during calibration.</td>
</tr>
<tr>
<td>Range</td>
<td>The difference between the minimum and the maximum value in the sensor output over a certain operating range.</td>
</tr>
</tbody>
</table>

Generally a sensor’s performance characteristics will be provided by the manufacturer, but further investigation of the sensor’s performance inside the concrete structures should be verified.
2.4.1.2 Environmental Constraints

The factors that affect the sensor selection related to environmental constraints are summarized in Table 2.5.

Table 2.5. Sensor Selection Considerations (Environmental Constraints)

<table>
<thead>
<tr>
<th>Environmental Constraints</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature Range</td>
<td>The range of temperatures in which the sensor can function. For most of sensors applications this range is -20°C to 80°C.</td>
</tr>
<tr>
<td>Humidity Range</td>
<td>Many sensors are designed to work reliably in a certain humidity range. Humidity can alter the sensitive elements in many electrical sensors causing stability losses and corrosion. Care should be taken to determine the expected conditions in order to verify the sensor that will be compatible with these conditions.</td>
</tr>
<tr>
<td>Size</td>
<td>The measurement location might restrict the sensor size that can be used.</td>
</tr>
<tr>
<td>Packaging</td>
<td>Packaging is a way to protect the sensor from the effects that might have an effect on the sensors performance such as humidity. Sensors designed for bridges applications should be rough and constructed from durable materials.</td>
</tr>
<tr>
<td>Thermal Effect</td>
<td>Many sensors will respond to temperature in addition to the parameter that is intended to be measured. This will affect the measurements and cause the data to drift from the true value. Many sensors are now available to compensate for this to minimize the thermal effects. Thermal effect can be accounted for by the correction applied to the measurements.</td>
</tr>
</tbody>
</table>
2.4.1.3 Economic Considerations

The factors that affect the sensor selection related to economic considerations are summarized in Table 2.6.

Table 2.6. Sensor Selection Considerations (Economic Considerations)  

<table>
<thead>
<tr>
<th>Economic Considerations</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>It is one of the most important factors in the sensor selection. It is the sum of the cost to procure the sensor, the cost to deploy it, and the cost of maintain it in the future.</td>
</tr>
<tr>
<td>Availability</td>
<td>The availability of a certain sensor should be established as early as possible to avoid delivery delays and the costs associated with them.</td>
</tr>
<tr>
<td>Reliability</td>
<td>It represents the minimum length of time over which the sensor will operate without any degradation in its performance.</td>
</tr>
<tr>
<td>Ease of installation</td>
<td>This is a measure of the skill level required to install the sensor and how much time is required to get the sensor up and running.</td>
</tr>
<tr>
<td>Data acquisition needs</td>
<td>Most sensors have certain requirements related to data acquisition. These requirements include: signals conditioning, excitation, and cabling. The cost of the measurement application will increase as the data acquisition system gets more complicated.</td>
</tr>
</tbody>
</table>

2.5 Sensors for Bridge Health Monitoring

The most common types of sensors used in bridge health monitoring are strain sensors. Strain sensors are measuring elements that convert force, pressure, tension, etc., into a strain reading\(^\text{10}\). Various types of sensors have been used successfully in bridge health monitoring, such as electrical resistance strain gages, vibrating wire strain gages, fiber optic sensors, and wireless sensors.

According to recently published literature, the most common sensor types used in civil engineering infrastructure applications are vibrating wire strain gages and fiber optic sensors (either Bragg grating or Fabry Perot sensors). Table 2.7 gives a comparison between the different parameters of both fiber optic sensors and vibrating wire strain gages.
gages. Table 2.8 shows the advantages and the disadvantages of all the sensor systems mentioned thus far, their respective applications, and an approximate cost estimate for each unit.

Table 2.7. Comparison between the Parameters of Fiber Optic and Vibrating Wire Sensors

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Fiber optic sensor</th>
<th>Vibrating Strain gage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gage length</td>
<td>1 to 500 mm</td>
<td>50 to 300 mm</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.01% FS</td>
<td>1 Microstrain</td>
</tr>
<tr>
<td>Measurement range</td>
<td>±5000 to ±10000 Microstrain</td>
<td>±2000 to ±3000 Microstrain</td>
</tr>
<tr>
<td>Sensor corrosion resistance</td>
<td>Very good</td>
<td>moderate</td>
</tr>
<tr>
<td>Sensor long term stability</td>
<td>Very good</td>
<td>Good</td>
</tr>
<tr>
<td>Remote operations possibility</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Working Principle</td>
<td>Measuring the change in optical characteristics such as intensity, wave length, phase</td>
<td>Measuring the frequency of a taut wire</td>
</tr>
<tr>
<td>Availability for embedment and surface mounting types</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Sensor material</td>
<td>High strength silica</td>
<td>High strength steel piano wire</td>
</tr>
<tr>
<td>Structural response capabilities</td>
<td>Static and dynamic loads</td>
<td>Just static loads</td>
</tr>
<tr>
<td>Temperature range</td>
<td>-20 to 60 °C</td>
<td>-20 to 80 °C</td>
</tr>
<tr>
<td>Immunity to electromagnetic interface</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Ability for multiplexing</td>
<td>Yes for long and short term monitoring</td>
<td>Yes for long term monitoring</td>
</tr>
<tr>
<td>Bonding with concrete</td>
<td>Very good</td>
<td>good</td>
</tr>
</tbody>
</table>
Table 2.8. Advantages and Disadvantages of Electrical, Vibrating Wire, Fiber Optic, and Wireless Sensors\textsuperscript{1, 5, 11, 13, 14, 15}

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Function</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Sensor Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Resistance</td>
<td>Short Term Monitoring</td>
<td>Operate over a wide range of temperatures</td>
<td>Data read out equipment is expensive</td>
<td>$200</td>
</tr>
<tr>
<td>Strain Gages</td>
<td></td>
<td>Inexpensive</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vista for dynamic loads</td>
<td></td>
<td>Suitable for dynamic loads</td>
<td>Affected by electromagnetic interference</td>
<td></td>
</tr>
<tr>
<td>Available in a wide variety of gage lengths</td>
<td></td>
<td></td>
<td>Lead length limitation</td>
<td></td>
</tr>
<tr>
<td>Provides an electrical signal that can be measured with a wide variety of circuits</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vibrating Wire Gages</td>
<td>Long Term Monitoring</td>
<td>Long term reliability</td>
<td>May require long lengths of wire</td>
<td>$100-$400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Multiplexing ability</td>
<td>Cannot monitor live loads</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Easy installation</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Immune to electromagnetic interference</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rugged housing resistant to impact and corrosion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fiber Optic Sensors</td>
<td>Long Term Monitoring</td>
<td>Measures temperature as well as strain</td>
<td></td>
<td>$200-$1500</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Light weight</td>
<td>May require long lengths of wire</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Small size</td>
<td>Expensive</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Multiplexing ability</td>
<td>Long term behavior unknown</td>
<td></td>
</tr>
<tr>
<td>Wireless Sensors</td>
<td>Short Term Monitoring</td>
<td>Immune to electromagnetic interference</td>
<td></td>
<td>$500-$2000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Environmental ruggedness</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extremely accurate</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>No cables are required for data transfer</td>
<td>Restricted battery life</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low cost of deployment</td>
<td>Still under investigation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Each mote works independently</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\textbf{Long Term Effects}: changes caused by seasonal temperature effects, creep, and shrinkage.

\textbf{Short Term Effects}: changes caused by variations in the dead and live loads, the daily temperature cycles and wind load.
2.6 Data Acquisition System

A data acquisition system is a device that facilitates the flow of information from the sensors to a computer. The purpose of the data acquisition system is to collect the data from the sensor, which represents the physical phenomena, converts this data into a suitable form, and transmits the signal into a computer. Data acquisition systems can have different configurations ranging from a simple readout box to complex and distributed systems that are networked to a central server. Figure 2.3 shows a schematic of the flow of information in a measurement application.

![Figure 2.3. Schematic of the Flow of Information in a Measurement Application]

Any data acquisition system, whether it is simple or complex, consists of three main parts: Data acquisition hardware, data acquisition peripherals, and data acquisition software.

Data acquisition hardware consists of a number of electronic components that collect, condition, convert, and transmit sensor signals to a computer, including a signal conditioner, memory, and power supply. Data acquisition peripherals include the cables, terminal blocks, connectors, and junction boxes necessary to physically connect the sensor to the data acquisition system hardware and to protect the hardware components.
Data acquisition software generally consists of two forms of software; driver software and application software. Driver software facilitates communication between the data acquisition hardware and the computer’s operating system software. The application software provides a link between the user and the data acquisition system, and permits the user to configure and control the data acquisition hardware, and to read, display, store, and analyze the measurements. Figure 2.4 shows a sample of readout boxes for vibrating wire and fiber optic sensors.

![Simple Readout Boxes for Vibrating Wire and Fiber Optic Sensors](image)

(A): Vibrating wire sensor readout box  (B): Fiber optic sensor readout box

Figure 2.4. Simple Readout Boxes for Vibrating Wire and Fiber Optic Sensors

2.6.1 Data Acquisition Systems for Bridge Health Monitoring

There are several parameters that should be taken into consideration when selecting a data acquisition system for bridge health monitoring. Some of these parameters include: number of sensors, sensor type, and speed of collecting the data. Descriptions of these parameters are shown in Table 2.9.
Table 2.9. Bridge Data Acquisition System Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Sensors</td>
<td>The performance of the data acquisition hardware will depend on the number of the sensor channels being scanned. The maximum sampling rate of the data acquisition system is total value that decreases with an increase in the number of sensor channels. Therefore, in cases where a large number of sensors are required it is important to identify any degradation in the system’s performance that could affect the reliability of the measurements. On the other hand, the modularity is another concern related to the number of the sensors being used.</td>
</tr>
<tr>
<td>Sensor Types</td>
<td>The data acquisition system will typically change for each type of sensor depending on the type of output given by certain sensor.</td>
</tr>
<tr>
<td>Speed</td>
<td>This parameter relates the rate at which the sensors signals are sampled by the data acquisition system. This may be considered as measurement speed of the data acquisition hardware. This parameter considers an important factor in the applications that require a real time display of the measurements.</td>
</tr>
</tbody>
</table>

For a large number of sensors, the system will require multiplexers to act as connectors between the sensors and the data logger. This allows the data logging device to collect data from a greater number of sensors. Figure 2.5 shows a general configuration using multiplexers. The data logging device must be housed in a weather-resistant casing, connected to a local power supply, and it contain a means to transmit data offsite for analysis. Two options are available for the power; supply from the local power source or from a battery charged by a solar panel. Power lines will provide reliability but may ultimately be more costly than a self-sustained system. A self-sustained system such as a solar panel connected to a battery could save on costs, but precautions must be made to protect the solar panel. Data transmission will depend on the distance from the bridge to the offsite computer. Several options are available including radio, satellite, cable, or phone modem.
2.8 SHM Examples

In this section two case studies will be presented: the Hillsborough County Bridge and the Saco Bridge. Each of these will be discussed in the following subsections.

2.8.1 Remote Health Monitoring of Hillsborough County Bridge

The East Bay Bridge in Gibsonton, Hillsborough County, Florida, is considered to be the first smart bridge. Static and dynamic testing of the bridge was performed as well as a finite element analysis; in addition, the smart sensors were connected to the data acquisition system permanently installed on site. The proposed remote sensing system consists of the following components:

- Fabry Perot fiber optic sensors placed on critical locations of the bridge
Fiber optic cables that connect the sensors to their data acquisition systems

Power supply for charging the signal conditioner provided from nearby power lines

Phone line or fast DSL connection to connect the signal conditioner to the internet.

The embedded fiber optic sensors transmit the data to their data acquisition system through an optic cable, which should be protected from the environment by placing it in conduit. The data acquisition is connected to the internet, where data could be retrieved and processed easily from the office.

**Installation of FOS**

Accuracy and good quality of data is directly related to proper installation of sensors. The researchers have exercised a great deal of patience and care during each step of every sensor installation.

**Embedded sensors**

The sensors were placed on the rebars and held down with electrical tape and adhesive materials. Soon after the sensors were bonded to the rebars, a reading using the readout box should be made to ensure that the sensor is in a good condition after installation. Fiber optic sensors are very sensitive to bends, kinks, sharp curves, and impact; therefore, cables should be placed in a conduit to protect them from the environment. This conduit should be tightly secured to rebars and should be guided to the edge of the slab. The cables should then be placed in a small box to house the cables at the point of exit.
**Surface mounted sensors**

The concrete surface should be sanded a number of times to make sure it is completely clean prior to placing the sensor. After sanding, the dust should be wiped off. This process should be repeated as needed to avoid any surface contamination\textsuperscript{16}.

**Data acquisition system housing**

The data acquisition system was fixed to the face of concrete parapet. All the conduits were attached to side of bridge and the data acquisition case. The tip of each fiber optic cable was thoroughly cleaned with cotton swabs and alcohol prior to connecting the cable to the data acquisition system ports. Sensor tags should be provided to distinguish each of sensor’s locations. The cost of the 16-channel data acquisition system for this project was about $14,000, which accounts for less than 1\% of the overall cost of the bridge. The data acquisition system weighs 10 pounds and its sampling rate is 20 Hz\textsuperscript{16}.

**Electricity and telephone line installation**

Remote communication with the data acquisition system is established using an internal modem. The data acquisition system has a 12-volt rechargeable battery to power up the equipment, but the operation time of this battery is short. Therefore, to operate the data acquisition system efficiently and continuously, telephone and electric services were required. Telephone and power lines were brought to bridge from about 200 feet south of the structure. The lines were in conduits and were buried 30 inches below the grade\textsuperscript{16}. 


**Static and dynamic testing of the bridge**

Different types of dynamic and static tests were performed to evaluate the effectiveness of the fiber optic sensors \(^{16}\).

**Finite element modeling**

A finite element model for the bridge was developed using SAP2000. The bridge deck was modeled and subjected to the same real static and dynamic loads mentioned before. The maximum strain value was compared with the maximum strain value from the real test of the sensor and the values were found to be almost the same. Therefore, using this finite element model is considered a good indication for the sensors’ critical locations \(^{16}\).

2.8.2 Structural Health Monitoring System for Saco Bridge, Montana

The Montana Department of Transportation (MDT) decided to evaluate the bridge deck design of three bridges constructed less than one mile from the small town of Saco, Montana. Each one of these three bridges experiences the same demands from weather, traffic, and winter maintenance. The first bridge was constructed using conventional concrete and steel reinforcement. The second was constructed using high-performance concrete, and the last bridge was constructed using conventional concrete with reinforcement reduction in the top layer of the slab, which reduces the opportunity for reinforcement deterioration. All three types of slabs rested on prestressed beams. During the planning phase of the project, finite element analysis was done on the three decks to evaluate the critical locations in the bridge for placing the strain gages. The strain gages were placed in each bridge deck prior to casting the concrete. The gages were positioned
to monitor both longitudinal and transverse strain and were mounted on the rebar, which reduces the effects of local bending so only axial forces are recorded. Electrical resistance gages were used to monitor live loads while vibrating wire gages were used for long-term strain monitoring. Information was collected at each bridge using a single data acquisition device attached to the underside of each of the three bridges. Two multiplexers were required and the system was powered by a 12-volt battery connected to a solar panel. Live load strain gages were pre-attached to reinforcing steel bars. The steel bars were then installed after the rebar cages were installed in the deck. Vibrating wire gages were attached to the rebar cages once they were installed, and plastic inserts were placed in the sides of the formwork in order to leave a mark on the concrete to locate the gage lines in the future. Sensor cables were bundled and attached to the underside of the reinforcing steel and routed out through the bottom of the deck through predrilled holes. Live load tests were done on the bridge that yielded behavior regarding: longitudinal cracks, in-plane stresses, how each bridge carries load, transverse deck integrity over the girders, and general non-linear behavior. Data for long-term strain was measured continuously in one hour increments. Vibrating wire strain gages were found to reflect cracking over the interior bents. If the crack intercepted the gage, strain due to temperature variation was increased. After the crack formed, gages detected differential movement of the separate concrete parts. Sensors indicated a change in strain from about 10 to 20 microstrains before cracking up to 250 microstrains after cracking. Smaller fluctuations from 20 to 70 microstrains indicated temperature fluctuations and no cracking. Lower temperatures were found to cause a decrease in strain while higher
temperatures caused an increase. This behavior was found to reverse once the crack formed due to shrinkage on either side of the crack.

Differences in temperature were found to be at most 10 degrees during curing of the concrete, but settled into a cyclical behavior due to temperature fluctuations throughout the day\textsuperscript{17}.

2.9 Summary

Intelligent or smart civil structure can be defined as a structural system that is instrumented with sensors that monitor and assess the current condition of the structure itself and its environment. This technology shows a promising alternative for the traditional inspection methods and a way for better assessment of bridge conditions.
CHAPTER III
EVALUATION OF SENSOR CHARACTERISTICS

3.1 Introduction

Existing bridges, especially those made of reinforced concrete, are deteriorating at a rapid rate. Corrosion, fatigue, and other degradations result in limited service and increased maintenance costs. Many bridges built in the 1950s and 1960s are now considered deficient by today’s design standards. The appearance of widespread failures in bridges has highlighted the importance of effective monitoring systems, which are able to identify structural problems at an early stage, thereby increasing public safety.

New concrete bridges would benefit greatly from in situ structural monitoring, which could detect a decrease in the structure’s performance or its imminent failure. These smart bridges would enable engineers to add a nervous system to their designs, providing damage assessment, vibration damping, and many other capabilities to structures that would be very difficult to monitor by other means.

This chapter presents laboratory experimental results on two types of sensors to verify their behavior, accuracy, and applicability for strain monitoring of engineering materials and structures. The research program consisted of thermal tests, compression tests, and other tests necessary to assess the mechanical properties of concrete with embedded sensors. This chapter covers the objectives of the experimental study, the design of the test specimens, and the procurement of the health monitoring equipment.
3.2 Experimental Program

This section describes the main characteristics of the tested specimen, the properties of their constituent materials, the instrumentation, the loading conditions, the apparatus used, and the data acquisition systems.

3.2.1 Objective of the Experimental Study

The objective of the experimental investigation through the course of this research is to study the effects of different variables that could be found on real bridges on the sensor response, durability, and behavior. Two types of embeddable sensors were used to conduct this extensive evaluation and found to be superior and have the capability to be used inside the concrete structures: vibrating wire strain gages (VWSGs), and embeddable fiber optic sensors (EFOSs). The first part of the experimental study will focus on the sensors’ performance parameters, such as accuracy, repeatability, reproducibility, range, and other factors to find the most accurate and reliable sensor. The second part will focus on studying the concrete mechanical properties using the sensors such as modulus of elasticity, creep, and shrinkage using the concrete cylinders and prisms, and comparing the results with the traditionally available strain gages.

3.2.2 Testing Equipment

The testing equipment was selected to be state of the art equipment suitable for the application on concrete bridges. A survey was done to find the most suitable, up-to-date specifications in the market. The specifications of the selected VWSGs and EFOSs are shown in Table 3.1.
Table 3.1. Fiber Optic and Vibrating Wire Sensor Specifications

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Fiber Optic Sensor Fabry-Perot</th>
<th>Fiber Optic Sensor Fabry-Perot</th>
<th>Vibrating Wire Gage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company</td>
<td>OPSens</td>
<td>Roctest</td>
<td>Goekon</td>
</tr>
<tr>
<td>Model</td>
<td>CFO-A</td>
<td>EFO</td>
<td>4200-A</td>
</tr>
<tr>
<td>Gage length</td>
<td>70 mm</td>
<td>70 mm</td>
<td>153 mm</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.2 Microstrain</td>
<td>0.2 Microstrain</td>
<td>1 Microstrain</td>
</tr>
<tr>
<td>Measurement range</td>
<td>±2000 Microstrain</td>
<td>±2000 Microstrain</td>
<td>±2000 Microstrain</td>
</tr>
<tr>
<td>Principle of working</td>
<td>Measuring the change in optical characteristics such as intensity, wave length, phase</td>
<td>Measuring the change in optical characteristics such as intensity, wave length, phase</td>
<td>Measuring the frequency of a taut wire</td>
</tr>
<tr>
<td>Availability for embedment</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Sensor material</td>
<td>High strength silica</td>
<td>High strength silica</td>
<td>High strength steel piano wire</td>
</tr>
<tr>
<td>Structural response capabilities</td>
<td>Static and dynamic loads</td>
<td>Static and dynamic loads</td>
<td>Just static loads</td>
</tr>
<tr>
<td>Temperature range</td>
<td>- 40 to 55 °C</td>
<td>- 40 to 55 °C</td>
<td>-20 to 80 °C</td>
</tr>
<tr>
<td>Ability to multiplexing</td>
<td>Yes for long and short term monitoring</td>
<td>Yes for long and short term monitoring</td>
<td>Yes for long term monitoring</td>
</tr>
<tr>
<td>Immunity to EMI/RFI software</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Data logger</td>
<td>Four channels</td>
<td>1 channel</td>
<td>1 channel</td>
</tr>
<tr>
<td>Effect of wire length on readings</td>
<td>No effect</td>
<td>No effect</td>
<td>No effect</td>
</tr>
<tr>
<td>Need to protect the cable inside the concrete</td>
<td>Yes, using plastic or any flexible conduit</td>
<td>Yes, using plastic or any flexible conduit</td>
<td>Preferable, using plastic or any flexible conduit</td>
</tr>
<tr>
<td>Ability to splice the cables</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Temperature Reading</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Long term stability</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

EMI: Electromagnetic Interference  
RFI: Radio Frequency Interface
3.2.3 Specimen Design and Test Parameters

Several concrete specimens were used to evaluate the sensors’ behavior and responses to different load conditions. Each specimen contained both VWSG and FOS sensors for the purpose of comparison. The specimens used were:

1. **Concrete Cylinders**: The concrete cylinders used were 6 x 12 inch; these test specimens were intended to evaluate accuracy, sensitivity, range, thermal effects, and other mechanical properties of concrete. One VWSG and one EFOS were embedded inside the concrete cylinder. Various factors such as eccentricity in placement of sensor, small size variations in the concrete block while pouring concrete and offset errors in sensor location can attribute to variation in the measured value and were considered. The sensors were placed along the same axis, equidistant from each other and from the edges of the cylinder. **Figure 3.1** shows a schematic of the experimental setup.

![Figure 3.1. Concrete Cylinder Layout](image-url)
2. Concrete Prisms: The concrete prisms used were 4 x 4 x 24 inch. This specimen was intended to evaluate the mechanical strain measurement effect of creep and shrinkage on the concrete and compare the results with the DEMEC point’s measurement. One FWSG and one EFOS were embedded inside the concrete prisms. Factors such as eccentricity in placement of sensor, small size variations in the concrete block while pouring concrete and offset errors in sensor location can attribute to variation in the measured value and were considered. The two sensors were placed along the same axis, equidistant from each other and from the edges of the prism mold. Figure 3.2 shows the schematic of the experimental setup.

Figure 3.2. Concrete Prisms Layout
3. **Concrete Slab and Beam:** A concrete slab 4 ft. x 4 ft. x 5.5 in. was cast with two vibrating wires and two fiber optic sensors in order to monitor strains in both directions, particularly the temperature strain. Figure 3.3 shows a schematic of the slab. This concrete specimen is intended for long-term evaluation of the sensors.

![Concrete Slab Layout](image)

**Figure 3.3. Concrete Slab Layout**

A concrete beam (9 in. x 11 in. x 8 ft.) was cast with longitudinal rebar and minimum shear confinement. Strain gages were placed transversely between the tension steel at a
distance of 3 inches from the bottom of the beam. The sensors are distributed across the length of the beam in order to fully monitor behavior under loading. Figure 3.4 shows a schematic of the beam and the sensors embedded inside it.

![Concrete Beam Layout](image)

**Figure 3.4. Concrete Beam Layout**

### 3.2.4 Concrete Mix Design

A concrete mix, which is commonly used for bridge decks by the Michigan Department of Transportation (MDOT), is used in this study. The mix was designed to be high-strength with a compressive strength at 28 days about 10,000 psi. Table 3.2 shows the mix design proportioning.

<table>
<thead>
<tr>
<th>Mix</th>
<th>Cement Type I (Lb)</th>
<th>Fly Ash Type C (Lb)</th>
<th>CA (Lb)</th>
<th>FA (Lb)</th>
<th>Silica Fume (Lb)</th>
<th>Water (Lb)</th>
<th>HRWR (Ounce)</th>
<th>w/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSC</td>
<td>27.5</td>
<td>5.4</td>
<td>60</td>
<td>40</td>
<td>5.4</td>
<td>11.5</td>
<td>5</td>
<td>0.30</td>
</tr>
</tbody>
</table>
3.3 Specimen Preparation and Casting

After the initial design of the concrete specimens was approved, the specimens were fabricated. **Figures 3.5 to 3.8** show the specimens before casting concrete. Careful handling of the sensors during casting concrete is needed to make sure not to damage the sensors.

![Figure 3.5. Slab before Casting](Image)

![Figure 3.6. Beam before Casting](Image)
After installing the sensors inside the molds, the concrete was cast. Care was taken not to damage the sensors during the consolidation process. Figures 3.9 to 3.12 show the specimens during casting.
Figure 3.9. Concrete Prism Casting

Figure 3.10. Concrete Cylinder Casting
Figure 3.11. Concrete Beam Casting

Figure 3.12. Concrete Slab Casting
3.4 Concrete Specimens Used for Sensor Evaluation

The OPSens fiber optic sensors were used in the concrete slab and beam while the cylinders and the prisms used both OPSens and Roctest. Unfortunately, most of the fiber optic sensors from OPSens were broken down during the curing period and during the tests. Therefore, the focus in the following sections will be on the results obtained from fiber optic sensors from Roctest and the vibrating wire strain sensors from Goekon.

Eight vibrating and fiber sensors were used for this evaluation. The sensors were labeled as “V” for the vibrating wire strain gages and “F” for the fiber optic sensors. The description of the test specimens and the sensor labels are summarized in Table 3.3.

Table 3.3. Summary of the Test Specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Description</th>
<th>Sensor Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Concrete Cylinder</td>
<td>V1, F1</td>
</tr>
<tr>
<td>C2</td>
<td>Concrete Cylinder</td>
<td>V2, F2</td>
</tr>
<tr>
<td>C3</td>
<td>Concrete Cylinder</td>
<td>V3, F3</td>
</tr>
<tr>
<td>C4</td>
<td>Concrete Cylinder</td>
<td>V4, F4</td>
</tr>
<tr>
<td>P1</td>
<td>Concrete Prism</td>
<td>V5</td>
</tr>
<tr>
<td>P2</td>
<td>Concrete Prism</td>
<td>F5</td>
</tr>
<tr>
<td>P3</td>
<td>Concrete Prism</td>
<td>V6</td>
</tr>
<tr>
<td>P4</td>
<td>Concrete Prism</td>
<td>F6</td>
</tr>
<tr>
<td>P5</td>
<td>Concrete Prism</td>
<td>V7, F7</td>
</tr>
<tr>
<td>P6</td>
<td>Concrete Prism</td>
<td>V8, F8</td>
</tr>
</tbody>
</table>

Throughout the following section the shortcut (FFOS: Embeddable Fiber Optic Sensor and VWSG: Vibrating wire Strain Gage) will be used to refer to each type of sensor throughout the discussion.
3.5 Sensor Performance Evaluation

In this section the sensors' performance will be assessed. The objective of this evaluation is to select the sensors that are most compatible with the parameters that characterize the measurand and the monitoring environment. This will ensure that the selected sensors maximize the reliability and efficiency of the measurements while minimizing the uncertainty associated with them.

Sensor performance characteristics describe the way a sensor behaves under pre-identified conditions including performance under static and dynamic conditions. Static characteristics describe the sensors' performance with respect to slowly varying measurand, while dynamic characteristics describe how the sensors would respond to the variation of the measurand with time. The sensor parameters that will be evaluated and assessed in the following subsections are summarized in Table 3.4.
Table 3.4. Sensor Parameters Considered During Evaluation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Test Specimen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curing Strain</td>
<td>Study behavior and response of the sensors during the concrete curing</td>
<td>Concrete Prisms and Cylinders</td>
</tr>
<tr>
<td>Thermal Strain</td>
<td>Study the effect of temperature variation on the sensors response and performance</td>
<td>Concrete Cylinders</td>
</tr>
<tr>
<td>Accuracy</td>
<td>Measure the degree of conformity of the measured value to its actual or true value</td>
<td>Concrete Cylinders</td>
</tr>
<tr>
<td>Precision (Repeatability)</td>
<td>Measure of the agreement between the results of successive measurements of the same measurand under the same conditions</td>
<td>Concrete Cylinders</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>Measure the agreement between the results of measurements of the same force carried out under different conditions of measurements</td>
<td>Concrete Cylinders</td>
</tr>
<tr>
<td>Range</td>
<td>Determine the upper limit of the measurand within which a sensor is intended to measure</td>
<td>Concrete Cylinders</td>
</tr>
<tr>
<td>Creep at Recovery</td>
<td>Measure the amount of time required for a sensor’s output to reach a stable value after releasing the applied load</td>
<td>Concrete Cylinders</td>
</tr>
<tr>
<td>Concrete Mechanical Property</td>
<td>Use the sensors to obtain the concrete mechanical properties such as the modulus of elasticity, creep, and shrinkage and confirm the results with the traditional measuring methods</td>
<td>Concrete Prisms and Cylinders</td>
</tr>
</tbody>
</table>
3.5.1 Sensor Performance under Curing Strain

• **Background and Strain Interpretation**

Curing is an important factor for durable concrete structures. Proper curing will produce strong concrete while improper curing will lead to several serviceability problems including cracking, spalling, scaling, and erosion.

Strain was determined by noting the difference between the initial readings after pouring the concrete and the subsequent readings. For vibrating wire sensors, the difference must be multiplied by a batch gage factor supplied by the manufacturer. Temperature readings were also taken in order to correct for temperature strain. The equation used to find the **Actual Strain** or the total strain in the concrete is:

\[
(R_1 - R_0) \times B + (T_1 - T_0) \times C_s
\]

Where:
- \( R_1 \) = Reading from vibrating wire sensor
- \( R_0 \) = Initial reading
- \( B \) = Batch gage factor
- \( T_1 \) = Temperature reading
- \( T_0 \) = Initial temperature
- \( C_s \) = Coefficient of thermal expansion of the steel gage = 12.2 microstrain/°C

The strain on the concrete due to temperature effects is found by:

\[
(T_1 - T_0) \times C_c
\]

Where:
- \( C_c \) = Coefficient of thermal expansion of concrete = 10.4 microstrain/°C

**Load Related Strain.** or strain due to effects such as loading, creep, and shrinkage without the temperature effect, can be found by correcting the first equation for temperature expansion in the concrete:

\[
(R_1 - R_0) \times B + (T_1 - T_0) \times (C_s - C_c)
\]

Fiber optic sensors are initially calibrated with a gage factor for each sensor supplied by the manufacturer. The gage factor is stored in the readout box and the readings are adjusted for the gage factor automatically. The **Apparent Strain** is given by
the sensor by taking the difference between the initial reading and subsequent readings. There is no need for temperature correction in the case of fiber optic sensors because the coefficient of expansion of gage steel is very close to that of the concrete, so correction factors for temperature effects caused by differential expansion are usually negligible. Therefore, the apparent strain given by the EFOSs should be compared to the load related strain given by the VWSGs to get the curing strain, taking into consideration that a negative value indicates a compressive strain while a positive indicates a tensile strain.

• **Testing Samples and Data Collection**

Specimens “P1, P2, P3, F4” (see Table 3.3) were excluded because they were used for the evaluation of creep and shrinkage, and they were no longer in curing condition. Curing behavior was monitored using the sensors by taking daily readings for 28 days for all the remaining specimens. For the specimen labeled “C1”, the curing strain was monitored continuously on one hour intervals for 28 days.

• **Results and Discussion for C1**

As mentioned the curing strain in cylinder “C1” was monitored continuously for 28 days in one hour intervals. The raw data were automatically captured by Labiew software and analyzed later on. The results of the curing strain for cylinder “C1” are presented in Figure 3.13.
The results show that the curing strain difference between the two sensors increased rapidly to about 105µε in the first 24 hours of the curing process. It became almost constant during the following days until the end of the 28 days of curing with a mean difference of about 50µε and a standard deviation of about 14.4µε. Figure 3.13 shows clearly that the strain obtained from the VWSG is higher than that of the EFOS. The reason for this trend could be attributed to the size difference between the two sensors. The VWSG is almost double the size of the EFOS, which makes it strongly held within the surrounding cement and possibly able to transfer the strain more effectively than the EFOS during the first curing period. Another observation that can be seen during the first 20 hours of curing is that the strain of the EFOS fluctuates between tension and compression. This could be caused by several phenomena, all due to autogenous shrinkage. Autogenous shrinkage is the shrinkage occurring from the
nonexistence of moisture exchange due to hydration, and other chemical reactions that cause local fractures (microcraking and crystal failure), recrystallization, and formation of new physical bonds\textsuperscript{20}. This microcraking could cause the expansive forces in the already-compressed gage to begin to release. Generally, these cracks grow near large aggregates when these aggregates are close to one another\textsuperscript{21}. Another reason could be not developing adequate bonding around the strain gage, which would make the strain fluctuate until the bonding fully develops. Another phenomenon that was observed was the fluctuation of the strain up and down but within the compression zone. The reason for this could be that some drying shrinkage is being recovered from the specimen being saturated in the moist condition. The curing method used involved covering the specimens with burlap, which could get dry from time to time, making the specimen expand and contract.

\textbf{Results and Discussion for the All the Specimens}

As mentioned previously, curing strain was monitored for all specimens by taking a reading every day for 28 days, excluding specimens P1, P2, P3, and P4 because they were used for creep and shrinkage tests. The results of the daily curing strain measurements are shown in \textbf{Figure 3.14}. 
Figure 3.14 shows that the strain in the prism specimens is smaller compared to those in the cylinder specimens. The reason for this difference could be attributed to the difference in the curing conditions between the prisms and the cylinders. The prisms were in better curing conditions as compared to the cylinders, because the cylinders were usually connected to the read out box. Another reason could be the size difference between the two specimens which could lead to a difference in strain. Another observation of the same figure is that the strain in cylinder four “C4” had a higher magnitude compared to the rest. The reason for this is that this cylinder was used a couple of times during the curing period to calculate the modulus of elasticity, which
might have led to residual stresses that in turn created higher strains with the passage of time.

As mentioned before, vibrating wire strain gages are equipped with a thermistor for temperature corrections. The temperatures obtained from the thermistor were used to compute the strain in the concrete due to the temperature and temperature variations as shown in Figure 3.15 and Figure 3.16, respectively.

Figure 3.15. Concrete Temperature Strain

- **CTS** represents (Cylinder Temperature Strain)
- **PTS** represents (Prism Temperature Strain)
It can be seen from the two previous figures that the peak of the temperature strain occurred during the first day; it then decreased and then varied from day to another according to the ambient room temperature.

• **Overall Sensor Performance During Curing (Standard Deviation Analysis)**

To evaluate the overall performance of both types of sensors during the curing period, the standard deviation of each sensor was compared based on the average daily strain readings of similar concrete samples. The variance of the sensor reading from the mean was calculated using readings from the 28-day curing period for the specimens. From the variance, the standard deviation was then computed for the sensor comparison. Creep and shrinkage specimens were excluded after they were removed from curing so
that all readings were taken from specimens under identical conditions. Figure 3.17 shows the comparison between the standard deviation of the sensors. The overall standard deviation was about $34\mu e$ for concrete cylinders with fiber optics and about $55\mu e$ for the cylinders with VWSG. For prisms the difference was smaller, due to better curing conditions: the overall standard deviation was about $5\mu e$ for the concrete prisms with fiber optic sensors and about $16\mu e$ for prisms with VWSG.

The results obtained from this analysis reveal that in both the concrete cylinders and prisms the fiber optic sensors are more stable and consistent compared to the
vibrating wire strain gages. The overall strain losses during the 28 days of curing are shown in Table 3.5.

Table 3.5. Strain Losses during the Curing Period

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Strain Loss (Microstrain)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VWSG</td>
</tr>
<tr>
<td>C1</td>
<td>-421</td>
</tr>
<tr>
<td>C2</td>
<td>-347</td>
</tr>
<tr>
<td>C3</td>
<td>-381</td>
</tr>
<tr>
<td>C4</td>
<td>-529</td>
</tr>
<tr>
<td>P5</td>
<td>-207</td>
</tr>
<tr>
<td>P6</td>
<td>-181</td>
</tr>
</tbody>
</table>

The curing strain will be subtracted form the sensor range to get the left over strain available which will be the zero strain for the rest of the tests.
3.5.2 Sensor Response to Temperature Effect

- **Experimental Setup**

Temperature effects generate the most major strains on bridges and other infrastructure. To evaluate the performance of the EFOSs and VWSGs due to temperature variations, the specimens labeled as C1, C2, C3, and C4 were subjected to one cycle of freezing and thawing to get the coefficient of thermal expansion of concrete. First the four specimens were placed in a cold chamber as shown in **Figure 3.18**, and then were placed in an area of ambient temperature as shown in **Figure 3.19**.

![Figure 3.18. Concrete Specimens in a Cold Chamber](image1)

![Figure 3.19. Concrete Specimens in Ambient Temperature](image2)
Results and Discussion

To get the temperature strain from the VWSGs, the actual strain or the total strain in concrete should be calculated as mentioned previously, while for the EFOSs no temperature correction is needed. The final coefficient of thermal expansion in both freezing and thawing for both types of sensors is shown in Figure 3.20.

![Coefficient of Thermal Expansion](image)

Figure 3.20. The Coefficient of Thermal Expansion of Concrete

As shown in Figure 3.20 the obtained mean value of the coefficient of thermal expansion is about 9.7µε /°C for the VWSGs and about 8.1µε /°C for the EFOSs with an almost 3.8% difference in the coefficient between freezing and thawing obtained from the VWSGs and a 2.4% difference in the coefficient between freezing and thawing obtained from the EFOSs. It can also be seen from the same figure that there is a significant difference in the coefficients obtained from each sensor. The reason could be that the EFOSs gage thermal coefficient is very close to that of concrete but not identical, possibly creating this difference in results.
Figures 3.21 and 3.22 show the typical response of the sensors to the variations of the temperature in the cold chamber as well as in the ambient temperature condition. It shows that the longitudinal thermal expansion of concrete increases linearly with the temperature, which is to be expected.
• **Results Verification**

During this test it was found that there was some variation in the coefficient of thermal expansion for concrete from one specimen to another. To validate these results one cylinder, marked as “C4” was subjected to three cycles of freezing and thawing as mentioned before.

The results were consistent and the coefficient of thermal expansion was almost the same for each freezing/thawing cycle, but the coefficient was higher in the thawing cycles compared to the freezing cycles, which is consistent to what was found in the literature. The results of this test are summarized in Table 3.6, and graphical representations of the results are shown in Figure 3.23.

Table 3.6. Summary of the Test Specimens

<table>
<thead>
<tr>
<th>Cycle 1</th>
<th>Freezing</th>
<th>Thawing</th>
<th>Cycle 2</th>
<th>Freezing</th>
<th>Thawing</th>
<th>Cycle 3</th>
<th>Freezing</th>
<th>Thawing</th>
</tr>
</thead>
<tbody>
<tr>
<td>VWSG</td>
<td>10.26</td>
<td>10.83</td>
<td>VWSG</td>
<td>10.28</td>
<td>10.66</td>
<td>VWSG</td>
<td>10.20</td>
<td>10.59</td>
</tr>
<tr>
<td>EFOS</td>
<td>7.65</td>
<td>8.79</td>
<td>EFOS</td>
<td>7.92</td>
<td>8.95</td>
<td>EFOS</td>
<td>7.82</td>
<td>8.91</td>
</tr>
</tbody>
</table>
3.5.3 Sensor Accuracy

Sensor accuracy is the degree of conformity of the measured quantity to its actual or true value. This value is generally expressed as a maximum positive or negative percentage of the full scale output. For instance, if the specified sensor accuracy is (±4%) of the full-scale output and the range of the sensor is 2,000 lbs, the measurement can be expected to be within ± 80 lbs of the true reading. In order to demonstrate the accuracy parameters for the two types of sensors, four cylinders were tested. A known value of the load was applied and the corresponding strain was calculated. This value represented the known strain, which the resulting strain from both sensors will be compared with. It is important to mention that the modulus of elasticity of the concrete was required to get the strain value, and this was calculated according to ASTM Standard using the LVDT method. The results of the accuracy tests are shown in Figure 3.24.
Figure 3.24 shows linearity and agreement in the readings of both sensors. The experimental results also show that the compressive strain measured with EFOSs is smaller compared to that obtained with VWSGs. It can be also seen that both sensors deviated from the theoretical strain. The overall deviation from the theoretical strain was found to be 3% of full-scale output of the applied force from the VWSGs and 2.4% of full-scale output of the applied force from the EFOSs.

3.5.4 Sensor Repeatability (Precision)

Sensor repeatability is the measure of agreement between the results of successive measurements of the same measurand under the same conditions. The most important factor that has to be taken into consideration for measuring the repeatability of a sensor is that the measurements should be carried out over a short period of time, with the same equipment, the same timing, and the same observer. Figures 3.25 and 3.26 show the
results of the repeatability test. The overall error was found to be 2.7% of the full-scale output of the applied force from the VWSGs and 2.0% of the full-scale output of the applied force from the EFOSs. A higher degree of agreement was found using the EFOSs compared to the VWSGs. It is important to mention that a small readout box was used to measure the strain of the VWSG, which allowed for capturing the dynamic loading conditions.

Figure 3.25. Repeatability Test Results from the VWSGs
3.5.5 Sensor Reproducibility

Sensor reproducibility is the closeness of the agreement between the results of measurements of the same force carried out under different conditions. In this test, the measurements were taken on two different days with different operators and different loading machines. The results show good agreement in the readings from the first and the second days with an overall error obtained from the VWSGs being 2.2% of the full-scale output of the applied force; 2.1% of the full-scale output of the applied force was observed from EFOSs. The results of the reproducibility test are shown in Figures 3.27 and 3.28.
Figure 3.27. Reproducibility Test Results from VWSGs

Figure 3.28. Reproducibility Test Results from EFOSs
3.5.6 Sensor Range

Sensor range is the maximum and minimum limits of the measurand within which a sensor is intended to measure\(^5\). \(^{22}\). Range is generally given by the manufacturer. The range of the VWSGs is 3,000µε; 2,000µε in compression and 1,000µε in tension, while the EFOS range is ± 2000µε. This test was intended to understand and observe the sensor behavior when it goes over range. The compression machine and the cylinder specimen labeled “C2” were used to perform this test. The results of the range test are shown in Figure 3.29.

![Range Test](image)

**Figure 3.29. Range Test Results**

The results in **Figure 3.29** show that as soon as the VWSG reached its limit it started giving inconsistent readings, fluctuating between tension and compression; the EFOS sensor never went out of range. The results were discussed with the EFOS
manufacturer, who claims that the sensor sometimes reads more than what it is designed for. Further investigation about EFOS should be conducted in future tests.

### 3.5.7 Sensor Creep at Load and Recovery

Creep at load and recovery of the sensor describe how fast a sensor will respond to a change in measurand. Creep of a sensor is the change of output within the time when the measurand and all environmental conditions are held constant. Figure 3.30 shows an example of a creep curve where the sensor exhibits a change in the output from $S_1$ to $S_2$ over a period of time from $t_1$ to $t_2$ after a step change between 0 and $t_1$. With creep at recovery, when the applied stress is nullified, the sensor exhibits a step change from $S_2$ to $S_3$ over a period of time $t_2$ to $t_3$, but takes some more time to reach the zero value. For both creep at load and creep at recovery, the results will depend on how long the strain applied has been at zero or the rated value, respectively, before the change in strain is made.

![Figure 3.30. Creep at Load and Recovery Behavior](image)

To conduct this test a compressive strength was verified. According to ASTM standards, the concrete should be within the elastic limit if loaded below 40% of its
compressive strength. Therefore, one specimen was loaded below 40%, the load was released, and the strain values were monitored as shown in Figure 3.31. The results show that immediately after releasing the load, the residual strain was about $9.7 \mu e$ for the VWSG and $10.5 \mu e$ for EFOS. After a period of almost 279 seconds the strain reading went back to its original value in the EFOS, but in case of the VWSG there was almost $3 \mu e$ left, which could be attributed to the larger size of the gage. These results indicate that even when loading below the elastic limit of concrete, some residual stress will affect the strain sensor reading until the material goes back to its initial shape before loading, which in this case took 279 seconds. The creep at the load was not performed due to the unavailability of the proper instruments.

Figure 3.31. Creep at Recovery Test (Beyond the Elastic Limit)
Another test was conducted to load the concrete cylinder over the elastic limit, which is more than 40% of the concrete's compressive strength. The results show that both sensors in this case of loading need a longer time to go back to the original value with almost a 5-8µε residual strain left in each sensor. The time of recovery in this case was around 50 minutes. The results of this test are shown in Figure 3.32.

![Creep at Recovery Test](image)

**Figure 3.32. Creep at Recovery Test (Over the Elastic Limit)**

### 3.5.8 Determination of the Mechanical Properties of Concrete Using Sensors

The hardened stage properties of the concrete mix were extensively tested using the embedded sensors inside the concrete cylinders and prisms. Two tests were performed during this stage; the modulus of elasticity test and the creep and shrinkage test. The results obtained from the sensors were then compared to those of traditional measuring techniques. The following subsections will discuss the details of these tests.
3.5.8. Modulus of Elasticity

The modulus of elasticity was conducted according to ASTM C 469-02. The test was conducted at 2, 7, 14, 21, and 28 days. The results obtained from each sensor were compared to the LVDT results. Figure 3.33 shows the tested specimen inside the compression machine ready to be loaded.

![Figure 3.33. Modulus of Elasticity Experimental Setup](image)

(A): Modulus Obtained from Sensors    (B): Modulus Obtained from LVDT

The final results of the modulus from LVDT and the strain sensors are summarized in Table 3.7.
Table 3.7. Modulus of Elasticity Results

<table>
<thead>
<tr>
<th>Measuring Method</th>
<th>LVDT 2</th>
<th>VWSG 7</th>
<th>EFOS 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus at 2 Days (Psi)</td>
<td>3,720,666</td>
<td>3,958,523</td>
<td>3,811,034</td>
</tr>
<tr>
<td>Modulus at 7 Days (Psi)</td>
<td>5,313,125</td>
<td>4,393,472</td>
<td>5,308,074</td>
</tr>
<tr>
<td>Modulus at 14 Days (Psi)</td>
<td>5,812,424</td>
<td>4,554,225</td>
<td>5,406,223</td>
</tr>
<tr>
<td>Modulus at 21 Days (Psi)</td>
<td>5,978,591</td>
<td>5,002,093</td>
<td>5,837,602</td>
</tr>
<tr>
<td>Modulus at 28 Days (Psi)</td>
<td>5,990,555</td>
<td>5,051,954</td>
<td>5,962,777</td>
</tr>
</tbody>
</table>

The results summarized in Table 3.6 show that the modulus values obtained from the EFOS are closer to that of the LVDT result. To give a better understanding of what was causing this; stress strain diagrams were constructed and shown in Figures 3.34 to 3.37.

![Modulus of Elasticity at 7 Days](image_url)

Figure 3.34. Modulus of Elasticity Results at 7 Days
Figure 3.35. Modulus of Elasticity Results at 14 Days

Figure 3.36. Modulus of Elasticity Results at 21 Days
The results shown in the previous figures prove that EFOSs have more correlation with the theoretical strain compared to VWSGs. That in fact correlates to what was obtained from the accuracy test.

3.5.8.2 Creep and Shrinkage

Concrete specimens will undergo a change in volume due to loss of water called shrinkage, but when concrete is subjected to a sustained stress, creep strain will develop gradually with time. Creep and shrinkage strain measurements were performed on specimens using VWSGs and EFOSs. Readings were taken for comparison using DEMEC points attached to two surfaces of the prisms using three points spaced at approximately 8 inches.

Creep tests were performed according to ASTM C512-02. Creep specimens were cast with a sensor embedded inside. The sensors were oriented longitudinally in the center of the specimen. Since the concrete prisms do not contain rebar, the sensors were
suspended in the forms from above. The prisms were wrapped in moist burlap for curing and placed in a spring-loaded creep frame for the creep tests. Load was applied using a hydraulic jack and monitored with a load cell. Figure 3.38 shows the creep frame while applying the load to the specimen. The evolution of creep and shrinkage started two days after casting the concrete.

![Creep Frame Being Loaded with Hydraulic Jack](image)

Figure 3.38. Creep Frame Being Loaded with Hydraulic Jack

The results of the creep and shrinkage are shown in Figures 3.39 and 3.40.
Creep and Shrinkage for VWSG and DEMAC Points

Figure 3.39. Creep and Shrinkage Comparison between VWSG and DEMAC Points

Creep and Shrinkage for EFOS and DEMAC Points

Figure 3.40. Creep and Shrinkage Comparison between EFOS and DEMAC Points
In both figures it can be seen that the DEMAC points give more strain compared to that of the sensor readings. The reason could be that the surface of the concrete prisms has more strain due to its direct contact to the environment; also, this surface is easier to deform due to the load compared to the core of the prisms where the sensors are embedded. After finishing the creep and shrinkage test the frames were released and the strain was tracked. It was noticed that the sensor will attain the elastic strain during loading the prism. The elastic strain retained after releasing the frame with VWSG was about 601µε while the original one was around 620µε. For the EFOS the retained strain was around 450µε, while the original one was around 475µε. This means that most of the elastic strain was obtained after releasing the frame, while the other strain stayed as permanent deformation.

Another creep and shrinkage test was conducted, but this time both sensors were embedded in the same prisms without DEMAC points to compare their behavior under a sustained load. The results are shown in Figure 3.41. The results were monitored every day for a week.
Figure 3.41. Creep and Shrinkage for the Prism Containing Both Sensors

The results show disagreement of the strain, which could be attributed to the size difference of the sensors, misalignment while placing the sensor, or eccentricity of the load applied.

3.5.8.3 Bonding Issues

One of the concrete cylinders was broken while conducting the range test. This gave the opportunity to see the bonding between the concrete and the sensor gage. Figure 3.42 shows the bonding between the concrete and the steel gages.
Figure 3.42. Bonding between the Concrete and the Steel Gages

As the picture shows, there is a complete bonding in the case of the EFOS, while for the VWSG most of the bonding was at the two end blocks, keeping in mind that the EFOS is half the length of the VWSG and is smaller in dimension, which could be the reason for its good bonding with the concrete.

3.6 Summary

Various tests were conducted to evaluate the performance characteristics of the strain sensor. The experimental study was intended to provide a data base to understand the sensor behavior and response when deployed on actual structures. Laboratory test results show that both sensors have a good load and temperature response. Other studies will investigate the long-term performance and durability of the sensors under field conditions. Table 3.8 provides a summary of the experimental evaluation of the sensors.
Table 3.8. Sensors Experimental Results Summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Vibrating Wires Strain Gage</th>
<th>Fiber Optic Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curing Strain</td>
<td>Less Consistent and Stable Behavior</td>
<td>More Consistent and Stable Behavior</td>
</tr>
<tr>
<td>Thermal Strain</td>
<td>10µε/°C the Average value of the Coefficient of Thermal Expansion of Concrete</td>
<td>8µε/°C the Average value of the Coefficient of Thermal Expansion of Concrete</td>
</tr>
<tr>
<td>Accuracy</td>
<td>3% of Full Scale Output</td>
<td>2.4% of Full Scale Output</td>
</tr>
<tr>
<td>Precision (Repeatability)</td>
<td>2.7% of Full Scale Output</td>
<td>2% of Full Scale Output</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>2.2% of Full Scale Output</td>
<td>2.1% of Full Scale Output</td>
</tr>
<tr>
<td>Range</td>
<td>Exactly as Provided</td>
<td>Read More than its Range</td>
</tr>
<tr>
<td>Bonding</td>
<td>Good Bonding Develops Around the End Block Comparing to the Sensor Body</td>
<td>Good and Complete Bonding with Concrete</td>
</tr>
<tr>
<td>Creep at Recovery</td>
<td>Not Fully Recover Due to its Size which Generate Higher Residual Stresses</td>
<td>Fully Recover Below Concrete Elastic Limit</td>
</tr>
<tr>
<td>Concrete Mechanical Property</td>
<td>Good Agreement with Theoretical Value</td>
<td>Good Agreement with Theoretical Value</td>
</tr>
</tbody>
</table>
CHAPTER IV

HEALTH MONITORING PLAN UTILIZING SENSOR TECHNOLOGY
(CASE STUDY)

4.1 Introduction

The Parkview Avenue Bridge at US-131 in Kalamazoo, MI, is scheduled for replacement in the summer of 2008. This bridge will be replaced using rapid bridge replacement techniques with embedded sensors inside the deck panels as part of a joint study between the Michigan Department of Transportation (MDOT) and Western Michigan University (WMU). The study will focus on long-term evaluation of the bridge; therefore, vibrating wire strain gages were decided to be used.

This chapter will present some information about the present and the proposed Parkview Bridge, as well as the structural analysis and design of the proposed bridge, and the suggested sensor location layout.

4.2 Existing Parkview Bridge

The existing Parkview Bridge was built in 1962. The bridge is typical; composed of cast-in-place concrete deck and steel girders. The bridge’s current condition shows noticeable signs of bridge deck deterioration in the form of: cracks, spalling, and efflorescence in addition to the heavily-corroded steel girders. Figures 4.1 to 4.4 show pictures of the existing Parkview Bridge; note the heavily-corroded steel beam and leaching underneath the bridge deck.
Figure 4.1. General View of the Existing Parkview Bridge

Figure 4.2. Heavily Corroded Steel Beam
Figure 4.3. Heavily Corroded Steel Diaphragm

Figure 4.4. Leaching Underneath the Bridge
4.3 Proposed Parkview Bridge

According to the most current plans for the replacement of this bridge, it will consist of a combination of traditional cast-in-place concrete and prefabricated concrete elements. H-piles will act as the load-bearing elements at the bridge ends. They will directly support the precast stub abutment and wing wall. A cast-in-place concrete diaphragm will be placed atop the abutment, which will support girders and the bridge deck. A cast-in-place spread footing will be used to support the center pier structure, which will be completely precast. The center pier will consist of four precast columns that will be three feet in diameter with a precast pier cap. Seven type III AASHTO precast prestressed beams will support the precast deck across spans of approximately 83 ft. and 43 ft. Likewise, deck panels, which have a thickness of nine inches will be composed of 48 precast concrete panels measuring approximately 34 and 24 feet in the transverse direction, and approximately 9 feet in the longitudinal direction. A cast-in-place closure joint will be used between the two precast decks. These panels will be longitudinally post-tensioned together and epoxy match-cast. The bridge is approximately 249 feet in length with almost 53 feet of clear roadway width; three 11-foot lanes and two 10-foot wide shoulders.

Figures 4.5 to 4.7 show a picture of the proposed Parkview Bridge after construction.
Figure 4.5. Side View of the Proposed Precast Parkview Bridge

Figure 4.6. Elevation View of the Proposed Precast Parkview Bridge
4.4 Bridge Construction Phases

The Parkview Bridge will be a completely precast system except for the foundation, closure joints, and diaphragms, which will be cast-in place-concrete. The construction will consist of four phases that are summarized as follows:

**Phase 1:** Phase one includes the following activities.

- Cast pier footings in place
- Once footing concrete reaches a minimum of 2,500 psi
- Erect precast pier columns and rout connections to footings
- Once grout reaches a minimum strength of 3,000 psi erect precast pier caps and grout connections to columns
- Drive piles and erect precast abutment stems on piles
- Top of abutment stems shall be constructed level and to the plan elevations
- Grout connections to piles and allow grout at pier cap and pile connection to reach a minimum strength of 3000 psi prior to erecting beams
- Install elastomeric gearing at piers and fabric pads at abutments
- Erect prestressed concrete I-beams
- Erect midspan steel diaphragms and install formwork and rebar or pier diaphragms
- Cast concrete pier diaphragms

**Phase II:** Phase two includes the following activities.
- Conduct an as-built survey of beam elevations
- Calculate shim pack thickness for each support location
- Install shim packs on top of beams
- Erect precast deck panels from center support on shim packs
- Install backing rod and connect post tensioning ducts
- Conduct an as-built survey after all precast deck panels are erected
- Perform adjustments to shim packs as required
- Install formwork and rebar for longitudinal cast-in-place (CIP) closure
- Cast longitudinal CIP closure

**Phase III:** Phase three includes the following activities.
- Once longitudinal CIP closure concrete and deck panel joint grout reach a minimum strength of 3,000 psi,
- Install and stress longitudinal PT tendons according to the stressing sequence and force specified in the plans
- Cast longitudinal CIP closures
- Install coil bolts
- Grout haunch and shear connection pockets

**Phase IV:** Phase four includes the following activities.
- Install formwork and rebar and cast concrete back wall
- Install formwork and rebar and cast concrete bridge railing
- Install aesthetic parapet tube.
- Place waterproofing membrane and bituminous overlay.

4.5 Structural Analysis and Finite Element Model

The main purpose of constructing a 3D finite element model of the bridge is to conceptualize the bridge and to use the model as a tool to localize the places of maximum stress on the bridge to obtain the proper instrumentations. SAP2000 is the software that is used to conduct the analysis in this research. The bridge deck was modeled and subjected to same real dynamic and static load. Stress resulting from this model will be used for comparison due to traffic loads. Different types of loading were considered during the design, including dead load, vehicle load, future wearing surface load, and post tensioning load. The vehicle live load used is HS20-44 with a total gross vehicle weight of 72,000 lbs. HS trucks have variable spacing between the two rear axles. This distance varies from 14 to 30 feet, and is used to create the live load situation that induces maximum movement in a span. **Figure 4.8** shows a schematic of the HS20-44 vehicle.
The model was first drawn on CAD using the 3D surface element for the deck, beam, liner element for the columns, and bent cap. The model then exported to SAP2000 to apply the load and run the structural analysis. The model was used to study the behavior of the bridge under static and dynamic loads. The vehicle wheel loads were modeled as point loads, and placed in locations to produce the maximum internal stresses. The pretension force was applied in the girders, while the post-tension force was applied on the deck panels. The prestressing strands were 0.6″ low relaxation steel with $f_c = 270,000$ psi. The number of the strands used varied depending on the location, but each one of them gave an initial prestress of 44,000 lbs each. The post-tension strands helped with holding the panels together and providing lateral and torsional stability. The post-tension strands consisted of four 0.6″ low relaxation steel with $f_c = 270,000$ psi. The stressing force was about 0.67 of the yielding stress of the steel, which was around 182.8 Kips. Different load combinations were considered according to AASHTO LRFD specifications.
The deformed shape of the model for different load cases is shown in Figures 4.9 to 4.12.

Figure 4.9. Deformed Shape due to Dead Load Case

Figure 4.10. Deformed Shape due to Pretension Force
Each load combination was then studied carefully to see which one gave higher stresses. The maximum stress obtained from this model was about 150 ksf as a compression stress in the panels labeled as 7, 8, and 9 N&S and 15, 16, and 17 N&S,
which is very close to what provided by the consultant (160 Ksf). The analytical strain contour lines for the maximum stresses are shown in Figure 4.13.

![Figure 4.13. Analytical Strain Contour Lines](image)

The maximum stresses in the deck provided by the consultant are shown in Figure 4.14.
Figure 4.14. Maximum Stresses in the Concrete Deck

The maximum stresses are located in the second and third spans. The maximum stresses were around 160 ksf. Small tension stresses were developed at the support; its maximum magnitude was around 40 ksf, which correlates to what was obtained using SAP2000.

Sensor locations were determined based on the maximum stresses obtained from the finite element model and from the design information provided from the consultant. The
sensor that was chosen is a vibrating wire strain gage sensor provided from the Goekon Company with a range of 3000 microstrain. The sensors were distributed in both the bending and traffic directions to capture high stress in either direction. Most of the sensors were placed in the upper steel mesh where the highest stresses are expected to develop because the upper surface of the panels are in direct contact with the traffic and weather variations. Some sensors were also placed in the upper and lower steel mesh in panels 7, 8, and 9 N&S and 15, 16, and 17 N&S where the stresses are expected to be high in both levels. The final sensor location layout is shown in Figure 4.15.
Figure 4.15. Sensor Location Layout

Note: the sensor size was exaggerated for clearance purpose
4.6 Further Recommendations

As mentioned earlier, the bridge will consist of precast deck panels. Therefore, the sensors’ mounting should be accomplished in the precast plant. The sensors will be labeled based on the labeling system mentioned before. Calibration of the sensors before going to the precast plant is also important. The sensors should be tied to the rebar in one of two configurations: The first is to suspend the gage between the rebar, and the second is to attach the gage directly to the rebar; in this case, a piece of wood or Styrofoam should be provided to protect the sensor. In both cases a piece of rubber tape should be provided in two places to absorb and dampen any vibration before casting the concrete that could effect the sensor reliability and performance after casting concrete. The two attaching methods are shown in Figure 4.16.

![Figure 4.16. Attaching Vibrating Wire Strain Gage to Rebar](image)

(A): Suspended between rebar (B): Attached to rebar with blocking

Calibration of the sensors is recommended before and after tiding the sensor on the rebars. The zero-strain value should be taken directly after casting the concrete. This value will be the initial strain value, and all subsequent strain values will be subtracted
from this value to get the actual strain value. During the curing period, daily readings
could provide valuable information about the autogenous and drying shrinkage as well as
the strain lost from the sensor during this period. After moving and placing the precast
deck panels in place, another calibration should be done to ensure that the sensor was not
affected or damaged due to the transportation. Sensor readings should be taken before
opening the bridge to the public because the value obtained will be the zero reading and
all strain readings taken later will be compared to it. During the bridge service, one hour
per day should provide decent information about the bridge behavior and response to
loading and environmental conditions.

4.7 Summary

Structural deficiencies can be observed and future repair costs can be reduced by
actively monitoring the state of the bridge. A study by the FHWA cited that over half of
the condition ratings done using the tradition inspection method (visual inspection) were
incorrect. A health monitoring system (HMS) can monitor the condition of a bridge in
order to determine where and how much stress is being applied to the bridge. The use of
embedded sensors for health monitoring can provide real-time data for up-to-date
assessments. Sensors can be linked to satellite or the internet in order to monitor a
bridge’s performance from a remote location. During this chapter a structural analysis
and finite element model was developed to investigate the proper sensor locations. 192
vibrating wire strain sensors with a 3000-microstrain range were used. Two data loggers
and 12 multiplexers were also used to accommodate that number of sensors.
CHAPTER V
CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

Structural health monitoring and sensor technology is one of the most promising techniques for providing an excellent means of protecting important structures such as bridges, dams, and nuclear reactors. These sensors will provide real-time information about these structures’ conditions. These sensor networks provide timely information for emergency and risk mitigation. The information obtained from these sensors can later be analyzed and compared to the design data so the problem can be fixed before it develops into a serious and costly hazard.

Using sensor technology side by side with the precast concrete will lead to huge savings in maintenance costs and will provide safe structures for the public. Sensors for infrastructure monitoring and evaluation utilize different types of sensors, which are placed at strategic locations to monitor the behavior of structures and provide valuable data such as strain, temperature, and vibration. A sensor network helps in identifying structural problems at early stages, prolonging the life of these structures, and improving public safety.

This thesis focused on the structural health monitoring concept and its tools. The most appropriate sensors for the bridge applications were selected for future study. Vibrating wire strain gages and fiber optic sensors proved to be good tools for detection of the different defects and problem inside the bridges.

An experimental program was developed. The two chosen sensors were embedded inside concrete specimens for evaluation. Different tests were conducted to
evaluate the sensor behavior and the response in the lab before deploying them on real structures.

5.2 Conclusions

This study reached the following conclusions

- During the curing of the concrete, the sensors were able to provide real-time information about the hydration and autogenous shrinkage. Some difference was noticed between the VWSG and EFOS sensors during curing. The reason could be due to the size difference between the two sensors and the difference of the coefficient of thermal expansion. Some sensor readings started fluctuating between tension and compression in the first 20 hours of the concrete curing. The reason could be attributed to autogenous shrinkage, microcraking, and debonding between the concrete and the steel gage. Another phenomenon was observed during the first 28 days while the concrete starts hardening is that some sensor readings were fluctuating up and down but within the compression zone. The reason could be that some of the drying shrinkage was recovered after the specimens were removed from the curing tank.

- Both sensors responded well to temperature variations. The VWSG gage is provided with a thermistor for strain reading correction, while the EFOS sensor was manufactured with a coefficient of thermal expansion very close to that of the concrete. Because of this, temperature correction for the EFOS is not required.
• The coefficient of thermal expansion of concrete was calculated using both sensors. Some differences were noticed, which could be attributed to the fact that the steel gage of the EFOS sensor has a very close thermal coefficient to that of concrete but it is not exactly the same. This leads to the conclusion that the VWSG gage is more accurate regarding the temperature effect.

• The coefficient of thermal expansion of concrete obtained from both sensors in the cold chamber is higher than that of the ambient temperature, which is consistent to what was found in the literature.

• The results of the accuracy test conducted on the concrete cylinders showed an excellent agreement between the theoretical strain and the one obtained from both sensors. Based on the same validation method, the repeatability and reproducibility tests were conducted and both sensors showed good agreements and consistent results.

• A creep at the recovery test was conducted to verify the time that the sensor required to get back to its original value before loading. The strain readings of both sensors were fully recovered when loading below 40% of the compressive strength. Some residual stresses were observed when the load exceeded 40% of the compressive strength.

• A range test was conducted to verify the sensors’ actual range. The VWSG range was exactly as mentioned in the manufacturer specification, while the EFOS sensor was able to read more strain than what was mentioned in the manufacturer specification. The manufacturer did indicate that the sensor sometimes can read over its range.
- Modulus of elasticity of concrete was obtained using the sensors and the conventional method. The results showed that the EFOS correlates better when compared to the results of conventional methods.

- Creep and shrinkage strain were obtained using the sensors and compared to that of DEMAC points. The results showed that the strain output from the sensors is less than the results of DEMAC points. The reason is that the surface of the concrete withstands higher strain relative to the interior of the concrete.

- Overall, both sensors demonstrated good response and performance inside the concrete and good correlation to the theoretical or calculated strains. Both sensors are excellent candidates for bridges and infrastructure applications. Both sensors’ advantages and disadvantages should be taken into consideration.

- The sensor location layout was determined based on the results obtained from the finite element model and the information provided from the consultant. The sensors were placed in the most critical locations to provide real-time information about the strain variations. 192 sensors, two data loggers, and 12 multiplexers were required to achieve the structural health monitoring objective.

5.3 Contributions

The study has made the following contributions:

- Conducted comprehensive study of the structural health monitoring and sensor technology.
• Validated the capabilities of the sensors to be embedded inside the concrete
• Evaluated the abilities of the sensors to respond to different variables and circumstances encountered on real structures.
• Established a database for the sensor responses to different effects, which will help to analyze and understand the information obtained from real structures.
• Provided a health monitoring plan based on the finite element model.

5.4 Future Research

The following are future research areas that can support and enhance this study:

• Test the sensor on real structures to validate the results obtained from the experimental study.
• Develop a database for the response of the sensor to different situations and scenarios encountered on real structures.
• Study the long-term behavior of both sensors in the lab before deploying them on real structures.
• Study the multiplexing principle for the EFOS sensors.
• Expand the experimental program to include different types of EFOSs with different work principles.
• Expand the experimental program to include large scale specimens.
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