OPTICAL FIBER SENSOR METHODS

FOR

NONDESTRUCTIVE EVALUATION OF BRIDGES

by

Tracey Lynette Garrett

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Project Committee Chairman: Dr. Richard O. Claus
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(ABSTRACT)

This report defines a present problem with U.S. bridges and suggests several reasons for bridge infrastructure deterioration and degradation, such as traffic overload, expired life cycles, environmental and operational conditions, and budget cuts. The most commonly used nondestructive evaluation (NDE) methods for determining the health of bridge infrastructure are summarized and compared. Advantages and disadvantages of each NDE technique are provided, and the lack of an adequate method which can quantitatively monitor the structural integrity of bridges is noted.

This report then discusses the possibility of health monitoring sensor systems for the quantitative NDE of bridge infrastructure. Several types of sensors that may be used to collect passive and quantitative data related to the structural integrity
of bridges are evaluated, and the extrinsic Fabry-Perot interferometric (EFPI) fiber optic sensor is suggested as the preferred sensor.

The fabrication processes and operational principles of EFPIs are presented. Two case studies which demonstrate the performance of EFPI sensors when used in health monitoring sensor systems are provided. Finally, a design criteria checklist suggests several questions that need to be asked (or more thoroughly defined) concerning the usefulness, reliability, durability, and sensitivity of EFPI-based health monitoring sensor systems.
Acknowledgments

"...when dreams come true at last, there is life and joy."
Proverbs 13:12, TLB

Due to time constraints, this report was much more difficult to write than I ever imagined. If it had not been for the timely and wise contributions of several individuals, the completion of this project would not have been achieved.

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Table of Contents

Abstract ................................................................................................................. ii

Acknowledgments ................................................................................................. iv

List of Figures .......................................................................................................... viii

List of Tables .......................................................................................................... ix

1.0 Introduction ....................................................................................................... 1

1.1 The Problem ..................................................................................................... 1

1.2 Comparison of Nondestructive Evaluation Methods ..................................... 6

1.2.1 Ultrasonic Nondestructive Evaluation ....................................................... 7

1.2.2 Liquid Penetrant Nondestructive Evaluation ............................................. 9

1.2.3 Magnetic Particle Nondestructive Evaluation ........................................... 9

1.2.4 Eddy Current Nondestructive Evaluation ................................................. 9

1.2.5 Infrared Nondestructive Evaluation ......................................................... 10

1.2.6 Radiographic Nondestructive Evaluation ................................................ 10

1.2.7 Acoustic Emission Nondestructive Evaluation ......................................... 11

1.3 Health Monitoring Sensors ............................................................................ 13

1.3.1 Capacitive Displacement Transducers ...................................................... 13

1.3.2 Piezoelectric Sensors ................................................................................ 14
List of Figures

Figure 2.1: Extrinsic fiber optic sensors. [Udd, 1991] ......................................................... 21

Figure 2.2: Intrinsic fiber optic sensors. [Udd, 1991] ......................................................... 21

Figure 2.3: Interferometric fiber sensors. [Udd, 1991] ......................................................... 22

Figure 2.4: Schematic of an EFPI sensor and the support system, where \( d \) is the air-gap length. [after Bhatia et al., 1995] ................................................................. 24

Figure 2.5: Output optical intensity signal as the EFPI is displaced from 0 to 400 \( \mu \)m. [de Vries, 1995] ............................................................................................................ 26

Figure 3.1: Actual measured data for crack opening displacement versus beam tip displacement. [Masri, 1993] ................................................................. 33

Figure 3.2: Additional concrete cracking measured during fatigue loading. [Masri, 1993] ................................................................. 34

Figure 3.3: Response of EFPIs embedded in concrete to a half sinusoidal compressive load. Top trace = EFPI in concrete, Bottom trace = EFPI on rebar. [de Vries, 1995] ................................................................. 37

Figure 3.4: Response of EFPI embedded in concrete to a half sinusoidal compressive load towards the end of the 100,000 cycle fatigue load test. [de Vries, 1995] ................................................................. 38
List of Tables

Table 1.1: Mechanical failures. [after Doyle, 1992; Pecht, 1987] ............................................. 6

Table 1.2: Comparison of nondestructive evaluation techniques.
          [after Thomas, 1995; Harding, 1993] ................................................................. 8
1.0 Introduction

This report focuses on how extrinsic Fabry-Perot interferometric (EFPI) fiber optic sensors can be used for monitoring the structural integrity of bridges. This chapter defines a current problem with bridges in the United States, discusses several nondestructive evaluation techniques, compares fiber optic sensor technology with conventional electronic counterparts, and outlines this report’s objectives.

1.1 The Problem

Bridges in the United States that were originally designed and constructed for a smaller society are rapidly deteriorating due to increasing demands and inadequate maintenance. The Federal Highway Administration (FHWA) estimates that more than 575,000 bridges in the United States need to be managed and more than 200,000 of those bridges are deficient. [CERF, 1994; Clements, 1995; Dunker, 1993] In fact, the U.S. spends billions of dollars each year toward constructing, rehabilitating, and maintaining bridges. [Prine, 1995] Approximately 130,000 bridges have posted weight restrictions, and roughly 5,000 bridges have been closed. [Dunker, 1993] In a good year, roughly 10,000 bridges can be improved with sufficient funding ($5 billion), but unfortunately, about 10,000 more bridges get categorized as deficient in that same period. [Prine, 1995] Every year some 200 spans either partially or fully collapse, and current estimates for correcting all deficient U.S. bridges start at $90 billion. [Dunker, 1993]
Hellier (1995) estimates that millions of vehicles and people cross approximately 470,000 bridges every day. When bridges collapse, public safety and convenience decrease dramatically. For example, in 1983, when the Mianus River Bridge in Connecticut collapsed, three people were injured, three were killed, and traffic was disrupted for months. [Dunker, 1993; Hellier, 1995] Of the some 470,000 total bridges Hellier (1995) discusses, approximately 190,000 bridges were built before 1950-- all with designed life cycles of 40 to 50 years. More specifically, 14,000 of the well-traveled bridges were constructed prior to 1900, and roughly 5,000 of those bridges are structurally deficient. [Hellier, 1995]

Perhaps one reason for the large number of deteriorating bridges in the U.S. is that prior to 1968 inspection standards did not exist. In fact, the fall of the Silver Bridge across the Ohio River in December 1967 was what prompted the Federal-Aid Highway (FAH) Act of 1968. When that 39 year old bridge collapsed, it took the lives of 46 people and fell because of poor inspection by local authorities. [Dunker, 1993; Hellier, 1995] The cost of that catastrophe was 175 million dollars. [Prine, 1995] The FAH Act of 1968 provided national bridge inspection standards and required training for all bridge inspectors. Currently, bridges are inspected every two years. [Dunker, 1993; Hellier, 1995]

Recent budget cuts have also contributed to the deterioration of bridges. To comply with those budget cutting measures, a reduced work force has resulted, and some experienced
bridge inspectors have been forced to take early retirement packages. The overall effect of those factors is that present bridge inspectors have less training and experience. [Prine, 1995]

There are a number of misconceptions concerning structurally deficient bridges--those bridges which are unable to carry standard loads. Because maintenance is highly visible on well-traveled bridges, one may think that those bridges are the most deficient. However, a majority of deficient bridges lie along lightly traveled routes and “country” roads. [Dunker, 1993]

Another misconception is that states containing the highest proportions of bridges constructed in the early post World War II period have the highest number of deficient bridges. In fact, there is no correlation between the age of a state’s bridges and its number of deficient spans. However, a relationship does exist between the total number of miles of bridges in a state and the percentage of deficient spans. That suggests that maintenance is an issue. [Dunker, 1993]

Several factors affect the reliability of bridges. The material of which a bridge is constructed is one variable which contributes to the total life cycle of the bridge. Of the 5,000 structurally deficient bridges Hellier (1995) mentions which were built before 1900, four thousand are constructed of steel. In fact, over 60,000 U.S. steel highway bridges
are structurally deficient. [Mandracchia, 1995] Helier (1995) further defines the approximate 470,000 bridges by material construction type:

<table>
<thead>
<tr>
<th>Material</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>197,600</td>
</tr>
<tr>
<td>Concrete</td>
<td>141,500</td>
</tr>
<tr>
<td>Prestressed Concrete</td>
<td>84,500</td>
</tr>
<tr>
<td>Timber</td>
<td>43,500</td>
</tr>
<tr>
<td>Other</td>
<td>3,500</td>
</tr>
</tbody>
</table>

Note that timber bridges, often used for state and country roads, deteriorate faster than steel bridges. For example, one-fourth of the wooden bridges built between 1985 and 1989 are deficient and need either repair or replacement. [Dunker, 1993] Also, new composite materials for future bridges have been proven in laboratory settings, but their life cycles have not yet been determined in practical applications. [CERF, 1994; de Vries, 1995] Therefore, maintenance and reliability data of new composite materials is limited.

Bridges subjected to heavy and/or overweight truck traffic are also more likely to collapse. Heavy trucks place ten times more load on a bridge than compact automobiles do, and that stress is further amplified if the road surface has been poorly maintained. Overweight trucks contribute greatly to the collapse of bridges and are a leading reason for weight restrictions. [Dunker, 1993]

The Woodrow Wilson Bridge which lies over the Potomac River between Alexandria, VA, and Prince George, VA, is an excellent example of a bridge being subjected daily to
almost twice the amount of traffic than the bridge was originally designed to carry. When the bridge opened in 1961, it was designed for 75,000 cars and trucks per day, but the six lane bridge now carries over 167,000 vehicles per day (17,000 of those are trucks). If the Wilson Bridge is to survive another 10 years, the weight and number of vehicles will need to be restricted and about $52 million will need to be spent to fully renovate the bridge. [Fehr, 1994]

Unstable traffic flow presents another loading problem. For example, rush hour traffic normally is heaviest in one direction and is often backed-up or at a standstill. If traffic is stopped on one side of a bridge for an hour while traffic on the other side is flowing smoothly at 65 m.p.h., the bridge will be unevenly loaded, weakening various strain-sensitive spots in the bridge infrastructure. [Fehr, 1994; Garrett, 1995]

There are a number of environmental and operational conditions which bridges are exposed to that decrease their reliability as well. Environmental conditions include such factors as temperature, pressure, humidity, acceleration, vibration, and shock. Operating conditions include water damage, improper drainage, and corrosive environments. [Constantinides, 1992; Dunker, 1993]

All of these conditions have the potential to contribute to mechanical failures. Understanding the types of mechanical failures which can occur and how those failures
affect system reliability is essential. System malfunctions can range from minor to noticeable degradation to complete failures. [Evans, 1992] Table 1.1 summarizes several types of mechanical failure.

<table>
<thead>
<tr>
<th>TYPE OF MECHANICAL FAILURE</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Creep and Stress Rupture Failures</td>
<td>If a material is continuously subjected to a load and the material stretches (creeps), it will probably rupture. Creep always accelerates at high temperatures.</td>
</tr>
<tr>
<td>Fatigue Failures</td>
<td>Fatigue failure results from repeated loading and unloading of a system component. In bridge systems, such cumulative exposure to vibrations leads to cracks and loose bolts.</td>
</tr>
<tr>
<td>Metallurgical Failures</td>
<td>These failures are due to operation under/in extreme environmental conditions. Lengthy exposure to heat, corrosive media, nuclear radiation, and erosion are environmental conditions to be considered.</td>
</tr>
<tr>
<td>Brittle Fracture</td>
<td>Brittle materials (such as glass) are highly susceptible to surface flaws and imperfections, resulting in cracks within the material.</td>
</tr>
<tr>
<td>Failures due to Flaws in Materials</td>
<td>These are generated by poor quality assurance, weld defects, fatigue cracks, and flaws. These cause permanent failure at the flawed area; thus, the material's strength is decreased.</td>
</tr>
</tbody>
</table>

One noticeable sign that a bridge is structurally degrading is a visible crack in its infrastructure. Determining the size and location of crack openings is essential if bridges are to remain safe. Section 1.2 compares several nondestructive evaluation methods which can be used to detect such infrastructure damage.

1.2 Comparison of Nondestructive Evaluation Methods

The goal of nondestructive evaluation (NDE) is to prevent destructive and expensive outcomes which result from material or component failure. Nondestructive evaluation techniques are either global, large area methods or local, high resolution methods. Global,
large area techniques offer rapid inspection of large structures and include acoustic emission and infrared imaging methods. When more precise defect characterization is required, high resolution (local area) methods should be utilized. One cost-effective approach to inspecting the health of bridges is to use a global NDE technique to determine existing and potential defective areas, and next, to use a high resolution method to verify the existence of a defect and accurately locate and size the defect. To optimize bridge inspection, the proper selection of NDE techniques and technologies must be employed. [Thomas, 1995] Table 1.2 summarizes the advantages and disadvantages of various NDE methods.

1.2.1 Ultrasonic Nondestructive Evaluation

Ultrasonic nondestructive evaluation (UNDE) methods measure the properties of materials and locates defects via high-frequency sound waves. Input ultrasonic signals are altered as they propagate through the material they are launched into and are detected by specially designed transducers. The output signal is displayed and interpreted based on its relation to the original signal. Ultrasonic evaluation is used to detect flaws, cracks, voids, and delaminations in metallic and composite materials and can be used to evaluate bond quality and analyze surface characteristics. UNDE is a well established method for routine field inspections. [Thomas, 1995; Tokarz, 1995]
### Table 1.2: Comparison of nondestructive evaluation techniques.

[after Thomas, 1995; Harding, 1993]

<table>
<thead>
<tr>
<th>Method</th>
<th>Typical Inspection Goals</th>
<th>Typical Applications</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiography</td>
<td>Cracks, voids, inclusions, porosity, material uniformity, assembly integrity, alignment of components, joint integrity</td>
<td>Castings, forgings, machined parts, welds, foams, electronic components, composites</td>
<td>Detects internal flaws and conditions; useful on wide range of geometry's and materials; quantitative as well as qualitative; permanent record</td>
<td>High cost; cannot detect tight laminar flaws or very tight cracks; 2D image of 3D structure</td>
</tr>
<tr>
<td>Ultrasonic</td>
<td>Cracks, disbonds, porosity, inclusions, delaminations, corrosion, thickness variations</td>
<td>Welds, brazes, adhesive bonds, diffusion bonds, composites, tubing, piping</td>
<td>Fast, best at crack detection and sizing; can be automated; equipment relatively expensive</td>
<td>Difficult to apply to complex shapes; generally requires water or other sound couplant; interpretation sometimes difficult</td>
</tr>
<tr>
<td>Magnetic Particle</td>
<td>Cracks, laps, voids, delaminations and seams</td>
<td>Ferromagnetic castings, forgings, extrusions</td>
<td>Detects near sub-surface flaws as well as those open to surface; portable, easy to implement</td>
<td>Applicable to Ferromagnetic materials only; flaws must be near surface; requires surface preparation</td>
</tr>
<tr>
<td>Infrared Imaging</td>
<td>Detection of minute temperature differences which correlate to material defects or component performance</td>
<td>Multi-layered circuit boards, detect corrosion in aircraft skins monitor EB, laser and gas tungsten welding, map delaminations in bridge decks</td>
<td>Non-contact; detects conditions which affect heat transfer or generation in materials; real-time inspection capability</td>
<td>Equipment costly; results affected by ambient temperature conditions and surface emissivity variations</td>
</tr>
<tr>
<td>Liquid Penetrant</td>
<td>Cracks, voids (porosity), gouges, seams</td>
<td>Weldments, forgings, critical machined surfaces, castings, components subject to fatigue or stress-corrosion cracking</td>
<td>Inexpensive; easy to implement; portable; easily interpreted</td>
<td>Flaws must be open to surface; requires immersion of part in oil- or water-based penetrant; depth of flaw difficult to estimate; operator dependent</td>
</tr>
<tr>
<td>Eddy Current</td>
<td>Cracks, voids, variation in alloy composition or heat treatment, wall thickness, dimensions</td>
<td>Tubing, alloy sorting, coating thickness measurements</td>
<td>Readily automated; portable</td>
<td>Geometry sensitive; shallow penetration; affected by conditions which change conductivity; difficult to interpret</td>
</tr>
<tr>
<td>Acoustic Emission</td>
<td>Disbonding, fractures, high stress areas, cracks, deformation, welds, leaks, mechanical properties, fiber breakage, delamination of composites</td>
<td>Detect locations of high stress concentration, monitor structure during life, determine degree of debonding, leak detection, mechanical property testing, characterization location</td>
<td>Dynamic inspection method; can detect and evaluate discontinuities throughout entire structure during a single test; only limited access is required</td>
<td>Expensive; requires complex equipment; static deformations and discontinuities will not generate acoustic emission signals and therefore may not be detected</td>
</tr>
</tbody>
</table>
1.2.2 Liquid Penetrant Nondestructive Evaluation

Liquid penetrant nondestructive evaluation (LPNDE) aids in the visualization of surface and near surface crack and defect locations in materials. A visible liquid dye or penetrating fluorescent dye is applied to the surface of nonporous materials. The dye then enters any discontinuities. This method also is used to inspect welds and critical areas of structures. [Thomas, 1995; Tokarz, 1995]

1.2.3 Magnetic Particle Nondestructive Evaluation

Magnetic particle nondestructive evaluation (MPNDE) inspects magnetic materials for discontinuities. The area being inspected is magnetized and magnetic particles are applied to its surface. A leakage field will form where discontinuities exist, making the defect visible. This technique, similar to the LPNDE method, can detect discontinuities in critical areas of structures and welds. [Thomas, 1995; Tokarz, 1995]

1.2.4 Eddy Current Nondestructive Evaluation

Material properties and defects can be examined using eddy current nondestructive evaluation (ECNDE) techniques. This method uses electromagnetic fields and coils to probe the material with electromagnetic waves. Discontinuities in the conductive properties of the material interact with the electromagnetic waves, and the response of the eddy current or magnetic sensors is used to locate discontinuities.
This method is noncontacting and can examine large numbers of materials quickly. However, ECNDE techniques can only penetrate 6-8 mm deep into a material’s surface and are strongly dependent on the frequency of the incoming electromagnetic wave. [Thomas, 1995]

1.2.5 Infrared Nondestructive Evaluation

Infrared nondestructive evaluation (IRNDE) methods are capable of remotely sensing and recording temperature gradients across the area being inspected. IRNDE methods can be used to measure temperatures from -20 to 1500° C with 0.1 to 0.5° accuracy. [Thomas, 1995] When an IRNDE method senses surface temperatures and temperature gradients, their values can be recorded for the given field of view. This technique has been used to inspect bridges for delaminations. [Thomas, 1995]

1.2.6 Radiographic Nondestructive Evaluation

Radiographic nondestructive evaluation (RNDE) methods use penetrating radiation (i.e., X-rays or gamma rays) to examine the internal structure and composition of a structure. Cracks, voids, and material contaminants can be imaged with this technique. RNDE methods can be used during field inspections to examine bridge structures. [Thomas, 1995; Tokarz, 1995]
1.2.7 Acoustic Emission Nondestructive Evaluation

The acoustic emission nondestructive evaluation (AENDE) method can be used as a structural integrity monitoring system and has the capability for characterizing infrastructure material behavior. Unlike ultrasonic and radiographic nondestructive evaluation techniques, the energy that is detected with an AENDE method is not supplied by the AENDE system but instead, is released from the test material. Another difference between an AENDE method and other NDE techniques is that AENDE testing is able to detect the dynamic processes associated with deterioration of the bridge's structure. Local instabilities within the infrastructure create small, dynamic movements, such as crack initiation and growth. Those movements are the major sources of acoustic emission within a test object. [McIntire, 1987]

In summary, advantages of AENDE methods include the ability to 1) dynamically inspect infrastructure for crack growth when the object is stressed; 2) detect and evaluate an entire structure's health during one test; and 3) access areas which are inaccessible to other NDE methods. A major disadvantage of AENDE techniques is that static discontinuities within a structure will not generate acoustic emission signals, and as a result, may not be detected. [McIntire, 1987]

Due to the nature of failures and the increasing number of deficient bridges, it is important that the United States monitor the performance of bridges. A 1991-92 national survey of
bridge designers and managers (conducted by Industrial Research Center in Homestead, Pennsylvania) showed that of the 202 responders, 47.5% said that the number of structurally or functionally deficient bridges in the U.S. would increase by the year 2000. [American Metal Market, 1992; Paint & Coatings Industry, 1992] Although many nondestructive evaluation methods exist and can be used to qualitatively determine the location and types of damage to a structure, an effective bridge management system capable of producing quantitative data is needed. [Prine, 1995]

General procedures for inspecting U.S. bridges involve a great deal of subjectivity. Whether or not any of the NDE methods previously discussed are used to inspect a bridge structure depends largely on whether or not an inspector feels the defects he or she sees are severe enough to require further investigation. [Coleman, 1995; Prine, 1995] Also, if an NDE method is chosen, subjective decisions will again need to be made, because the feasible, most frequently used NDE methods produce qualitative data outputs only. Such subjective decision making creates a large margin of error, because life-threatening cracks and deterioration may be overlooked or categorized as less severe than they truly are. Clearly, in order to eliminate such subjectivity, a quantitative means for monitoring bridges is needed. [Prine, 1995] In fact, the 1992 Intermodal Surface Transportation Efficiency Act mandates the implementation of a bridge management system by 1996. [Prine, 1995] A key component of such a system is a nondestructive monitoring system with a lifetime equal to or greater than 50 years which produces quantitative measurements and limits the
need for subjective visual inspections. [de Vries1, 1995; Prine, 1995] Such systems need to be able to access difficult-to-reach critical spots on the bridge structure, withstand extreme environmental conditions, have high reliability and durability, be compact and lightweight packages, and be immune to electromagnetic interference. [Udd, 1991] Section 1.3 introduces the use of fiber optic sensors for quantitatively monitoring the health of a bridge as compared to other electronic sensors.

1.3 Health Monitoring Sensors

The need for passive (nondestructive) sensory systems that provide more subtle information is gaining much interest and support. [Awato, 1992; Dasgupta, 1991; Lindner, 1994; Udd, 1991] For example, the sensory systems of bridges must be clever enough to detect small growing cracks and accurately locate the crack tip before life-threatening situations arise. [Amato, 1992; Prine, 1995; Udd, 1991] Early crack opening detection in the infrastructure of a bridge will result in easier, less expensive repairs. Various sensors which can be used to monitor the structural integrity of bridges include capacitive displacement transducers, piezoelectric sensors, strain gages, and fiber optic sensors.

1.3.1 Capacitive Displacement Transducers

Capacitive displacement transducers have been successfully used in laboratory and field environments. The output electrical signal closely resembles the actual dynamic surface
displacement, and capacitive displacement transducers are sensitive. In fact, the approximate theoretical minimum displacement measured by a capacitive displacement transducer is on the order of $10^{-10}$ m. [McIntire, 1987] One major disadvantage of capacitive transducers is their size. Capacitive displacement transducers are much larger than fiber optic sensors and thus, are less desirable.

1.3.2 Piezoelectric Sensors

Piezoelectric sensors are small, well demonstrated sensors and are often used in acoustic emission-based nondestructive evaluation methods. These sensors can withstand temperatures up to approximately 550° C and typically have narrow bandwidths but a response range from 50 to 1000 kHz. Piezoelectric sensors can measure amplitude displacements on the order of $10^{-14}$ m. Such sensors are useful for detecting and locating weak emission sources within a structure. Disadvantages of piezoelectric sensors are the presence of electromagnetic interference and ground loops. [Claus, 1994]

1.3.3 Strain Gages

Modern, self-temperature compensated, bonded resistance strain gages are the most widely used tool for structural stress analysis. Advantages of these sensors include being accurate, sensitive, versatile, and easy to use devices, low in cost, able to produce linear outputs, easy to install, and available in sizes, materials, and configurations that allow different temperature and operating conditions. Disadvantages of strain gages include the
potential presence of ground loops, single measurand operation, and decreased performance when subjected to thermal, electromagnetic, magnetic, and electric fields and high pressure. [Claus, 1994; Window, 1992] Thermal EMFs (temperature variations and gradients) produce small d.c. voltages which can cause erroneous output signal readouts. Finally, high pressure environments cause gage resistance changes. Eliminating bubbles in the gage backing when the gage is to be used in high pressure environments is critical, because such voids cause local deformations which produce non-linear outputs and can result in gage failure. Therefore, the application of strain gages for measurements in high pressure environments must be well defined in order to choose an appropriate gage. [Window, 1992]

1.3.4 Fiber Optic Sensors

From an industrial point of view, fiber optic sensor technology has several advantages when compared to electronic technology. Physically, those advantages include being light weight, compact packages and having long lifetimes and low cost; optically, those advantages include all-passive configurations, low power utilization, wide temperature range, electromagnetic interference immunity, high sensitivity and large bandwidth, and compatibility with optical data transmission and processing. [Kao, 1982; Udd, 1991] Fiber optic sensors can also measure numerous parameters, such as vibration, temperature and pressure. [Udd, 1991]
Due to their small size (typically 50 to 200 microns in diameter), the fiber optic sensor elements can be light weight, compact, and contained in rugged packages. [Dean, 1988]

For example, if the sensing region of fiber sensors is limited to the fibers themselves, then the fiber can be attached to or embedded in materials with minimum changes to the overall part dimensions. [Udd, 1991]

For applications where conductive paths are to be avoided, all-passive configurations are important. [Udd, 1991] The optical transmission path provides freedom from ground loops and assures safe installation and protection from such catastrophic situations as lightning strikes. [Seippel, 1984; Udd, 1991] Low power utilization is fundamental for affordable systems consisting of large numbers of sensors. [Udd, 1991]

The wide temperature range of fiber-based sensors is particularly advantageous in those applications where high temperature measurement is required, because electronic strain gages and capacitance gages contain wire bonds and plastic backings that may not survive high temperatures. [Udd, 1991] The typical melting point of silica glass is 1000° C, and the refractive index change with temperature is approximately 0.0001/° C. Although in practice the temperature endurance of the fiber is determined largely by the fiber’s coating material, optical waveguides are typically specified for communication applications to operate between -55 to 125° C, and should work from -250 to 500° C. [Kao, 1982]
Electromagnetic interference immunity is an important consideration with respect to size and weight. For many electrical systems, bulky and heavy cable, the covering used to protect conventional electrical sensors from electromagnetic interference, significantly increases cost, size, and weight. [Kao, 1991; Seippel, 1984; Udd, 1991] With fiber optics, there is immunity to electromagnetic interference, induced noise, and cross talk. [Kao, 1991; Seippel, 1984; Udd, 1991] Consequently, the need for cables with electrical shielding does not exist for fiber optic systems. [Udd, 1991]

When numerous sensors having high sensitivity and dynamic range are used in arrays, the bandwidth of the arrays can become quite high. However, this is not a problem since those sensors may be multiplexed onto a high-bandwidth optical fiber capable of supporting thousands of sensor signals. [Udd, 1991] For electrical systems to achieve equal bandwidth, electrical cabling containing many individual coaxial interconnects might be several centimeters thick. [Udd, 1991] The high sensitivity and large bandwidth of optical fiber sensors also offer better data rates at longer distances than coaxial cabling. [Seippel, 1984; Udd, 1991] Finally, due to industry investments and technological advancements in the optical fiber field, fiber optic components are highly reliable and less expensive. All of the characteristics previously mentioned are particularly advantageous for fiber optic smart structures located in hostile environments where a wide range of sensing capabilities and minimum size and weight are required. [Udd, 1991]
Obviously, fiber optic sensors can be used as structural integrity monitoring systems which, when embedded in or attached to predetermined critical locations on the bridge’s infrastructure, can sense various environmental and operational fluctuations and quantitatively evaluate the health of a bridge. [de Vries, 1995] Bridges equipped with those “fiber optic smart structures” may be more reliable, easier to maintain, and will have longer lifetimes.

This project will focus on the types of fiber optic sensors, particularly extrinsic Fabry-Perot interferometers (EFPIs), available for use in structural integrity monitoring systems. A detailed outline of project objectives is listed in the following section.

1.4 Project Objectives

The objectives of this project are to:

1. define the problem and suggest reasons for the rising number of deteriorating bridges in the U.S.,

2. provide a brief discussion of nondestructive evaluation techniques used for inspecting bridge health and other applications,

3. discuss the advantages and disadvantages of several types of passive sensors,

4. focus on the fabrication and utilization of extrinsic Fabry-Perot interferometers (EFPIs) for sensing strain and determining bridge crack opening displacement sizes and locations,
5. provide results obtained on EFPI reliability and performance, and

6. recommend life cycle improvements of EFPIs.
2.0 Fiber Optic Sensors

Fiber optic sensors are rapidly replacing conventional sensors, and due to their reduced cost and superior performance, fiber optic sensors are entering markets where sensors with similar capabilities do not exist. [Udd, 1991] Civil engineering is one field which is considering the use of fiber optic sensors as a solution to the current bridge infrastructure problem facing the U.S. In particular, much research is underway to determine the usefulness and reliability of fiber optic sensors in structural integrity monitoring systems. [de Vries, 1995; Claus, 1992] This chapter discusses several types of available fiber optic sensors and their applications. Special emphasis is placed on the use of extrinsic Fabry-Perot fiber optic interferometers to measure bridge strain and crack opening displacements.

2.1 Classification

Optical fiber sensors can be broadly classified as either extrinsic or intrinsic fiber optic sensors. As the two names imply, an extrinsic fiber optic sensor has a sensing region outside the fiber while an intrinsic fiber optic sensor has a sensing region inside the fiber. Figures 2.1 and 2.2 summarize different extrinsic and intrinsic fiber optic sensors and their measurands, respectively. [Udd, 1991; Rudraraju, 1994] A subclass of the intrinsic type fiber optic sensors are intrinsic interferometric sensors. [Udd, 1991] Interferometric sensors are briefly discussed in Section 2.1.1.
Figure 2.1: Extrinsic fiber optic sensors. [Udd, 1991]

Figure 2.2: Intrinsic fiber optic sensors. [Udd, 1991]
2.1.1 Interferometric Fiber Optic Sensors

Figure 2.3 illustrates the different types of interferometric fiber optic sensors available and their measurands.

![Interferometric Fiber Optic Sensors Diagram]

**Figure 2.3: Interferometric fiber sensors.** [Udd, 1991]

Extrinsic and intrinsic Fabry-Perot interferometric fiber optic sensors have been developed for end-user sensing applications. The extrinsic Fabry-Perot sensor, first described by Murphy *et al.*, (1991) possesses one attribute that its intrinsic counterpart does not have—the cavity, where the sensing and reference signal reflections occur, is created in air,
instead of in a glass subsection of the optical fiber. The effect of that difference is noted when both types of sensors are embedded in a material or attached. Unlike the extrinsic Fabry-Perot sensor, the intrinsic Fabry-Perot sensor, when embedded, is affected by transverse strains on the sensing region of the optical fiber. In fact, the transverse strains cause a refractive index change in the core of the intrinsic sensor which alters the effective optical path length, resulting in inaccurate strain measurements. Since the cavity of the extrinsic Fabry-Perot sensor consists of an air gap formed between the two fiber ends, its output is not affected by transverse strains, and only axial strain components are monitored. [Bhatia et al., 1995; Murphy, 1991]

2.2 Extrinsic Fabry-Perot Interferometer (EFPI)

Figure 2.4 illustrates the typical geometry of an extrinsic Fabry-Perot interferometric (EFPI) sensor. [Bhatia et al., 1995; Claus, 1992; Claus et al., 1992; Rudraraju, 1994; Tran, 1991; Wang, 1992] The sensor head consists of a single mode input/output fiber which has been inserted into a hollow core silica fiber and glued to the end of the hollow core fiber with epoxy resin. Facing that fiber is a multimode or single mode fiber which has also been inserted into and epoxy glued to the hollow core tube and serves as a Fresnel reflector. Those two cleaved fibers are properly aligned within the hollow tube so as to create an air-gap that acts as a low-finesse EFPI cavity.
Figure 2.4: Schematic of an EFPI sensor and the support system, where $d$ is the air-gap length. [after Bhatia et al., 1995]

When optical power is injected into the coupled EFPI sensor assembly, the reflection ($R_1$) from the single mode fiber end face (at the glass/air interface) serves as the reference reflection signal for the interferometer. The second reflection ($R_2$) from the end face of the multimode fiber (air/glass interface) creates the sensing reflection signal. External disturbances on the sensor cause the two fibers to move. The interference created between those two reflection signals is monitored by the detector at the output of the fiber
coupler and is observed as a sinusoidal variation in optical intensity. Therefore, axial strain induced in the EFPI sensor head can be measured. [Bhatia et al., 1995; Claus et al., 1992; Rudraraju, 1994; Tran, 1991; Wang, 1992] If crack opening displacements are the desired measurand, then the EFPI fabrication is the same as that mentioned above (see Figure 2.4) except the epoxy glue is not applied to the two ends of the hollow tube and fiber assembly; that allows the two fiber ends to move freely within the hollow core tube so no mechanical load is applied directly to the EFPI sensor head (denoted as EFPI in Figure 2.4). [Masri, 1993]

When small perturbations are applied to the EFPI, the change in the output intensity signal is almost linear. However, when large disturbances occur, fringes will be observed, and complex fringe counting schemes must be employed in order to interpret the data. [Bhatia et al., 1995; Claus et al., 1992; Rudraraju, 1994; Tran, 1991; Wang, 1992] Murphy et al., discuss the interferometric approach to analyzing the signal output. [Murphy, 1994] Figure 2.5 shows typical interference fringes observed when the sensor is displaced from 0 to 400 microns.

Claus et al., have demonstrated that the EFPI sensors can successfully withstand temperatures ranging from -200 to 900° C, and Tran et al., have successfully used EFPIs for monitoring surface acoustic waves. [Claus, 1992; Tran, 1991] Section 2.2.1 provides instructions for manufacturing an EFPI sensor.
Figure 2.5: Output optical intensity signal as the EFPI is displaced from 0 to 400 μm. [de Vries, 1995]
2.2.1 Detailed Instructions for EFPI Sensor Fabrication

This section provides more detailed, step-by-step instructions for fabricating an EFPI sensor and connecting it to a support system. The equipment and materials needed in order to manufacture an EFPI sensor include the following:

1. one cleaver
2. one razor blade
3. alcohol
4. tissue wipes
5. epoxy glue
6. toothpicks
7. one hollow core fiber (hollow tube) with a maximum diameter of 240 microns
8. one single mode fiber, cut at the desired length and having a diameter equal to 125 microns (to be used as the front fiber which creates the glass/air interface within the hollow tube)
9. one single mode or multimode fiber, cut at the desired length and having a diameter equal to 125 microns (to be used as the end fiber which creates the air/glass interface within the hollow tube)
10. one laser (light source)
11. an oscilloscope
12. one fiber coupler, detector, and amplifier assembly (known as the EFPI box)
13. two shallow, plastic dishes
14. masking tape

The steps for fabricating an EFPI fiber optic sensor and connecting that sensor to a support system are provided below [Bhatia, 1995]:

**Step 1:** The single mode fiber which will be inserted into the hollow tube must be cleaved. First, tape the two fibers to the work bench with about 4 inches
of the fiber length hanging over the edge of the bench. Using a razor blade, gently remove the entire outer coating of the single mode fiber which will create the glass/air interface (approximately a two inch section). Clean the coating-free section with an alcohol-drenched tissue wipe. Once the coating-free area has been cleaned, do not touch that area again. Next, properly position and align the fiber in the cleaver so as to cleave the coating-free area. The three-step process required to operate the cleaver will lead to a perpendicular surface at the fiber end.

**Step 2:** Repeat Step 1 for the hollow core fiber. Cleave the fiber on both ends in order to obtain a 1 cm long hollow tube. Pick up the cleaved tube with a piece of tape.

**Step 3:** The step is also known as the EFPI fabrication stage. Properly place the hollow tube on one side of the microscope/fabrication assembly. Clamp down on the tube. Properly position the shorter length, air/glass interface generating fiber on the other side of the assembly platform and clamp down on the fiber. Using the positioning knobs and mirror, align the fiber and hollow tube in the x-, y-, and z-directions so that the fiber will slide into the tube without touching the tube end face or inner walls. Insert the fiber into the tube. Next, mix with a toothpick the five-minute epoxy in one shallow, plastic dish. Epoxy the hollow tube and fiber together at the hollow tube end. Wait 10 minutes to ensure that the epoxy glue has dried. Place the fiber/tube assembly at the other side of the platform and clamp it down.

**Step 4:** Cleave and insert the second fiber into the other side of the hollow tube as discussed above. Leave a gap between the two inserted fibers (roughly one-half the length of the single mode core diameter), and epoxy. Now, cleave the opposite (free) end of the second fiber and the EFPI box fiber. Using a splice tube, couple that end of the second fiber to the appropriate EFPI box fiber.

**Step 5:** Make sure that the laser knob on the EFPI box is turned off and that the proper channel has been selected. Turn the EFPI box on. Turn the laser knob to its maximum position. Verify that laser light is propagating through the EFPI assembly by using an infrared card. Next, hook-up an oscilloscope to the EFPI box at the proper channel. Adjust the amplifier knob as needed to control the gain. Fringes can now be observed on the oscilloscope when the EFPI sensor element is subjected to perturbations.
2.2.2 EFPI Manufacturing Process Improvements

Fabricating an EFPI sensor is a delicate process. Much care needs to be taken in order to ensure that the cleaved fibers remain dust and scratch free. The goal of this section is to suggest questions that need to be asked during every phase of the EFPI manufacturing process in order to achieve optimum performance.

1. Has a clean environment been established?

2. Has fiber been cleaved in a way which ensures a perfect perpendicular end face angle?

3. Can EFPIs be identically mass produced? Are they currently being identically mass produced? What measures need to be taken in order to ensure identical production? Have guidelines been established which state the exact cleaved lengths, diameters, etc. of the fibers and hollow tube? Have human factor engineering studies been conducted?

4. Are fibers checked under a microscope after each cleaving step during the EFPI fabrication process to determine if the fibers are clean and have been properly cleaved?

5. Have the fibers been chosen with a coating/protectant which will not have adverse effects on the environment the EFPI assembly would be attached to or embedded in?
6. Has waste been kept at a minimum? Can any of the waste materials be recycled, and if so, are they being recycled? Have equipment and materials been chosen to minimize waste?

Blanchard et al., further detail questions which should be asked and positively answered during the manufacturing stage of products. [Blanchard, 1990]
3.0 Evaluation of Extrinsic Fabry-Perot Interferometers

The reliability of EFPI sensors cannot yet be quantified, because EFPI sensors have not been mass produced, and most applications employing those sensor types have been conducted in laboratory settings. Therefore, performing a failure analysis and obtaining statistically sound results are presently not possible. [Udd, 1991]

Although life cycles for EFPI sensors have not yet been determined, several noteworthy laboratory experiments have been conducted which illustrate their usefulness for monitoring bridge strain and bridge crack opening displacements. This chapter reviews two of those experiments and lists the results from each case study.

3.1 Strain and Crack Opening Displacement Data

Unlike their conventional counterparts which can only be attached to surfaces, optical fiber sensors can be either attached to or embedded in structures. One study conducted by Masri et al., tested the accuracy of EFPI sensors versus reference foil strain gages when embedded in a concrete structure. [Masri, 1993] The EFPI sensors were also used to monitor the structure’s crack opening displacements. Results of that study indicated that [Masri, 1993]:

31
1. the EFPI sensors survived the embedding process,

2. the calibrated output signals from the EFPIs and reference strain gages match with little uncertainty,

3. embedded EFPIs can be used to obtain quantitative strain data about the concrete structure, and

4. embedded EFPIs can be used to monitor crack progression.

Pairs of fiber optic sensors and reference strain gages were mounted on several bridge rebar elements. The EFPI sensors (operating at 1300 nm) were attached to the rebar using epoxy resin before the form was filled with concrete. Quantitative measurements of induced strains were obtained with a 5% difference between the strain gage and EFPI data. Surface strains and the crack opening displacements which resulted from large amplitude loading were monitored near the existing cracks. Electromagnetic interference was visible in the strain gage data, but as expected, the EFPI data was not altered by EMI. [Masri, 1993]

Figure 3.1 illustrates the crack opening displacement data measured locally by an EFPI sensor as the beam structure was cyclically loaded and the tip displacement was increased in 0.1 inch increments. [Masri, 1993]
Figure 3.1: Actual measured data for crack opening displacement versus beam tip displacement. [Masri, 1993]
Figure 3.2 shows optical intensity data obtained at the onset of additional concrete cracking as the beam tip displacement approached 1 inch.

Figure 3.2: Additional concrete cracking measured during fatigue loading. [Masri, 1993]
The intensity output fringes to the left of the top trace in Figure 3.2 show a gradual increase in local strain. When the local crack expands rapidly, large local crack displacements occur, and a strain redistribution within the local region of the concrete is observed. Compression closes the large crack with minute changes in local relative displacement until another strain occurs which re-opens the crack. As can be seen to the right of the top trace in Figure 3.2, additional concrete cracking is observed as an interruption in the regular fringe envelope. [Masri, 1993]

One step in the EFPI sensor embedding process of this experiment worth mentioning is that the fibers used to construct the EFPI sensors were coated with a silicone gel. The purpose of that coating was to protect the silica glass fibers from the water and alkaline-based cement which was poured over the fibers once they were attached to the appropriate rebar elements. [Masri, 1993] However, a suggestion was made in 1984 that several bridges in the United Kingdom were affected by “alkali-aggregate reaction,” a chemical process that decreases the strength of concrete. The reaction occurs when very alkali cement reacts with a silicon-based aggregate. The silicon turns to gel, which expands to crack the concrete. [New Scientist, 1984] Although care must be taken to ensure that the performance of the embedded glass fibers is not degraded, the fiber protectants must not create cracks within the bridge infrastructure. Clearly, much continued research is required in this area before the accurate reliability of embedded sensors is known.
For more information concerning the experimental set-up and operational conditions of this study, see Masri et al. [Masri, 1993]

3.2 Fatigue Loading

EFPI sensors used in bridge monitoring applications must provide accurate, quantitative information about the bridge’s structural integrity. de Vries (1995) conducted fatigue loading tests on two EFPI sensors which were embedded in a rebar reinforced concrete block. Both the embedded and attached EFPIs used during this experiment provided stable, reliable, and consistent strain information throughout the 100,000 cycle fatigue load test. Figures 3.3 and 3.4 illustrate the output signals of the same EFPI at the beginning of the load test and at the end of the 100,000 cycles, respectively. Those two figures show that the EFPI withstood the fatigue testing and produced reliable data throughout the entire test cycle. [de Vries, 1995]
Figure 3.3: Response of EFPIs embedded in concrete to a half sinusoidal compressive load. Top trace = EFPI in concrete, Bottom trace = EFPI on rebar. [de Vries, 1995]
Figure 3.4: Response of EFPI embedded in concrete to a half sinusoidal compressive load towards the end of the 100,000 cycle fatigue load test. [de Vries, 1995]
4.0 Conclusions and Recommendations

Each year billions of dollars are spent toward constructing, rehabilitating, and maintaining some 575,000 U.S. bridges, and presently, more than 200,000 U.S. bridges are deficient. Every year approximately 10,000 bridges can be improved with sufficient funding, but unfortunately, 10,000 more bridges get categorized as deficient in that same period.

4.1 Conclusions

This report defines the present problem with U.S. bridges and suggests several reasons for bridge infrastructure deterioration and degradation, such as traffic overload, expired life cycles, environmental and operational conditions, and budget cuts.

The most commonly used NDE methods for determining the health of bridge structures are summarized and compared. Advantages and disadvantages of each NDE technique are provided, and the lack of an adequate nondestructive evaluation method which can quantitatively monitor the structural integrity of bridges is noted.

This report then discusses the possibility of health monitoring sensor systems for the quantitative, nondestructive evaluation of bridge structures. Several types of sensors that may be used to collect additional passive and quantitative data related to the structural integrity of bridge structures are evaluated, and the extrinsic Fabry-Perot interferometric (EFPI) fiber optic sensor is chosen as the preferred sensor for the following reasons:
1. EFPIs are light weight, compact, and have rugged packages,
2. can be embedded in or attached to a structure,
3. have long estimated lifetimes, large bandwidths, and wide temperature ranges,
4. are highly sensitive and immune to EMI,
5. have no ground loops,
6. can be multiplexed, and
7. are able to measure multiple parameters.

The fabrication processes and general logic of EFPIs are presented. Two case studies which demonstrate the performance of EFPIs when used as health monitoring sensors are provided.

Clearly, there is a need for improved EFPI fabrication techniques in order to achieve identical mass production of those sensor types, as well as a need for "real-life" data on the durability, sensitivity, and reliability of EFPI health monitoring sensor systems.

This author believes that the use of EFPI sensor systems in structural integrity monitoring systems will not have country-wide acceptance by the 1992 Intermodal Surface Transportation Efficiency Act's 1996 deadline which mandates the implementation of an effective bridge management system capable of producing quantitative data. However, this author does believe that with continued research in this area, EFPI sensor systems will prove to be effective and economical nondestructive health monitoring systems capable of
eliminating subjective decisions concerning the structural integrity of bridge infrastructures. The final section of this project provides a design criteria checklist which suggests several questions that need to be asked (or more thoroughly defined) concerning the usefulness, reliability, durability, and sensitivity of EFPI health monitoring sensor systems.

4.2 Recommendations

Blanchard et al., provide an excellent summary of design criteria questions which this author feels apply to the design, implementation, and maintenance of EFPI health monitoring sensor systems. [Blanchard, 1990] Only a few of those questions are recommended in this section, and one should note that possibly each of the questions listed have already been asked. However, this author believes that each question proposed below needs to be continuously asked and quantitatively, as well as, qualitatively defined in order to achieve economical and effective structural integrity monitoring systems.

- Has the operational environment been defined in terms of temperature extremes, humidity, vibration, and shipping and handling?
- Have appropriate effectiveness factors been determined (i.e., availability, reliability, usability, capability, life cycle cost, and maintainability)?
- Have criteria been established for personnel skills at each level of maintenance (including installation)? Are highly trained, skilled professionals (engineers)
required to operate and maintain the system? Is the amount of required personnel training specified?

- Are system components and test support equipment lightweight? Has the total weight been kept at a minimum (less than 10 pounds)? [Prine, 1995] Has the operational environment been defined in terms of accessibility—will equipment "fit" into the environment (is the equipment safe for field operation)? Can the proper use of test/support equipment be conducted in a safe manner while in the operating environment?

- Can EFPIs be identically mass produced from the available fabrication techniques?

- Has an environmental impact study been conducted to determine if the EFPI system will have an adverse impact on the environment? Has a tradeoff study been conducted to determine the benefits and limitations of embedded versus attached EFPIs?

- Are areas of risk and uncertainty identified for EFPIs and EFPI health monitoring systems? Have the high-cost contributors to the implementation of such a system been identified and minimized?

- Are sensors installed in such a way to guarantee easy and safe access to data output signals?

- What tools are required to attach sensors to existing bridges? Are the tools standard? Are sensors easily attached to all critical areas of a bridge structure?
- Have all variable and fixed costs for health monitoring systems been defined and justified, and
- Are the failure rates of EFPIs and health monitoring sensor systems known? Do failure rates meet customer requirements? Has a stress-strength analysis been conducted?

Answering such questions with a "yes" during the design phase of an EFPI-based health monitoring system will lead to optimal design and customer satisfaction. [Blanchard, 1990]
References


