DEVELOPMENT OF FIBER-OPTIC SENSOR NETWORKS FOR TRANSPORTATION INFRASTRUCTURE MONITORING

Final Report

METRANS Project 10-14

April 2012

Principal Investigator: Chin Chang

College of Engineering/Department of Electrical Engineering

California State University

Long Beach, CA 90840

DISCLAIMER

The contents of this report reflect the view of the author, who is responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the Department of Transportation, University Transportation Centers Program, and California Department of Transportation in the interest of information exchange. The U.S. Government and California Department of Transportation assume no liability for the contents or use thereof. The contents do not necessarily reflect the official views or policies of the State of California or the Department of Transportation. This report does not constitute a standard, specification, or regulation.

ABSTRACT

The problem to be addressed in this project pertains to the monitoring and management of transportation infrastructural health through the use of fiber-optic sensing technology. In the project, we have demonstrated that the fiber-optic sensing technology is capable of offering superior performance and extensive capability to structural heath monitoring applications. We have conducted comprehensive performance evaluation for point and distributed fiber optic sensors aiming at the application for the long-span transportation infrastructural monitoring. In the research effort, validation of point and distributed fiber optic sensors is achieved through laboratory and field tests. A structural health monitoring system using a quasi-distributed sensor network and distributed sensors will be designed based on the results of this field test. The research team plans to collaborate with Caltrans engineers to conduct a field deployment test within the Southern California transportation infrastructure. The field-test data will be reviewed and analysed to obtain important information to justify fiber-optic sensing technology for future system installation. The prototype deployed in the selected section of the transportation infrastructure will continue to collect structural information for technology and design validation. A system design utilizing a fiber-optic sensor network used in the monitoring and management of transportation infrastructures will be proposed as the end of the research effort.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

DISCLOSURE

This project was funded in its entirety under this contract with California Department of Transportation.

ACKNOWLEDGMENTS

The research team and especially Chin Chang are very grateful for the support of the METRANS Transportation Center. In addition, we would like to thank Mr. Etienne Constable of Roctest, Inc., for his valuable product information on the fiber-optic sensors used in the project. We would also like to thank Ms. Ketaki Kunte, graduate student, and Mr. Justin Ray Delos Reyes, undergraduate student of the Electrical Engineering Department at California State University, for their outstanding work in fiber-optic sensors.

1. INTRODUCTION

The improvement of bridge and overpass safety has become a high priority, particularly after the collapse of the Minneapolis Bridge. This is particularly true in California, where frequent earthquakes make continuous real-time monitoring of the integrity of its in-service transportation infrastructure an urgent objective for transportation maintenance teams. The economic factors are of course also central to viable adaption of a technology to the needs of public safety. A cost-effective, innovative technology is imperative for effectively monitoring and managing bridges and overpasses without placing a substantial additional burden on tax payers.

The monitoring of transportation infrastructures is currently reliant on transportation maintenance teams. Scheduled and periodic inspections of most infrastructures are performed by manual and visual operations, which are generally time-consuming and costly procedures. Recently, Erik A. Johnson of the University of Southern California proposed an approach for bridge structural health monitoring based on variable stiffness and damping devices [1]. This approach offers the potential to provide more accurate parametric bridge health monitoring.

The problem to be addressed in this project pertains to the monitoring and management of transportation infrastructural health utilizing fiber-optic sensing technology. The majority of the structural monitoring sensors used in long-span bridge health monitoring systems are still based on conventional transducer technology. The Akashi Kaikyo Bridge in Japan, which is the world's longest suspension bridge, uses a seismometer, anemometer, accelerometer, velocity gauge, global positioning system (GPS), girder edge displacement gauge, tuned mass damper (TMD) displacement gauge, and thermometer for dynamic monitoring [2]. In general, conventional sensors currently used in long-span bridge health monitoring do not provide satisfactory accuracy and long-term measurement stability. For example, a GPS used on the Akashi Kaikyo Bridge for absolute displacement or deflection monitoring has three limitations: (i) the accuracy of the GPS is inadequate for completely meeting bridge health monitoring requirements; (ii) a GPS does not work well for monitoring the displacement of piers beneath the bridge deck (caused by ships colliding, settlement, etc.), and (iii) a GPS is not capable of accurately measuring deflection in a foggy environment. Fiber-optic sensing technology, however, offers superior performance and extensive capability to structural-heath monitoring applications.

The use of fiber-optic sensor technology makes it possible to realize continuous, real-time and automatic health monitoring within transportation infrastructures. This technology offers several advantages, such as minimized downtime, avoidance of catastrophic failure, and reduction in maintenance labor. Moreover, new infrastructure designs can incorporate fiber-optic sensors to create smart structures. With well-developed fiber-optic networking technology, a remote laser source may be used as a signal source to efficiently and accurately detect parametric changes at various locations within a structure. The detected information may be recorded and analyzed in order to obtain precise structural information on the infrastructure. In summary, the realization of a fiber-optic sensor monitoring system for transportation infrastructures may greatly improve public safety and have low operation costs.

The objective of this research project focuses on using fiber-optic sensor technology for monitoring the structural health and integrity of transportation infrastructures. Real-time, computer-automated monitoring of the health of bridges and overpasses is essential to the safety of the residents of major metropolitan areas. This research project will investigate the feasibility and economics of the application of fiber-optic sensor technology to transportation infrastructural health monitoring (TIHM). There are many potential advantages to using the fiber-optic sensor technology within the TIHM applications. In addition to its function as a nondestructive evaluator, it offers the ability to reconsider the enhanced design and full safety management of the structure. Moreover, a central monitoring and evaluation system may be implemented utilizing the existing wide-area network. Thus, the long-term, in-service aging of the structure can be effectively monitored and evaluated. Finally, any acute damage from earthquakes, natural disasters, and terrorist attacks may be observed and assessed immediately for necessary post-disaster actions**.**

2. PROBLEM DEFINITION

A majority of the structural monitoring sensors used in long-span transportation infrastructure health monitoring systems is still based on conventional electric transducers. The Akashi Kaikyo Bridge in Japan, which is the world's longest suspension bridge, uses a seismometer, anemometer, accelerometer, velocity gauge, global positioning system (GPS), girder edge displacement gauge, tuned mass damper (TMD) displacement gauge, and thermometer for dynamic monitoring [2]. Some conventional sensors currently used in long-span bridge health monitoring do not provide adequate accuracy and long-term stability.

In addition to accuracy and stability requirements, continuous, real-time and simultaneous measurements at discrete points of a deteriorating structural system, as provided by monitoring, are required for efficient assessment of the performance of a structure. Conventional sensors have encountered substantial limitations in many crucial measurement operations. A large number of structural monitoring sensors may be deployed at all critical locations in an infrastructure to gather structural information, but the cost of such a system can be extremely high. Therefore, the spatial resolution for measurements may be less than optimal due to the overall cost constraints of the system. On the other hand, structural monitoring can be considered similar to quality assurance and acceptance sampling, and conventional sensors are not practical for continuously monitoring all performance indicators in all critical sections of an entire structural system.

The application of fiber-optic sensor technology to structural health monitoring (SHM) is still not widely accepted for transportation infrastructure monitoring although it has shown promise for such applications. Moreover, research and development in fiber-optic sensors seems to focus on measurements in strain, deformation, and temperature; other key structural parameter monitoring is still in need of research and development effort. In order to take full advantage of this technology, research and development efforts have to be directed into other parameter monitoring applications.

3. METHODOLOGY

Our approach to accomplishing the overall objectives of the proposed project is described in this section. We will conduct comprehensive performance evaluation of the application of point and distributed fiber-optic sensors to long-span transportation infrastructural monitoring. A CSULB research team with multidisciplinary expertise will collaborate with Caltrans to conduct field deployment and testing for system validation and structural data acquisition. Faculty researchers and students from the Electrical Engineering and Civil Engineering Departments of the College of Engineering will jointly conduct the proposed research project.

The point sensor that will first be considered for implementing a quasi-distributed sensor network is the Fiber Bragg Grating (FBG) sensor. The FBG is made by a periodic change of refractive index in the core of a single mode optical fiber. As the input light propagates through the grating and the optical wavelength satisfies the Bragg condition, the maximum reflection occurs. The spectrum of the reflected light is determined by the refractive index in the FBG. In the optical fiber, the refractive index is a function of strain and temperature; hence, the measurement of the spectrum becomes the indication of the changes in the strain and temperature at the location of the FBG sensor.

FBGs used as sensing elements for structural health monitoring have sensitivity, accuracy, and frequency response that is superior to that of conventional electromechanical transducers. For instance, this type of sensor's resolution and accuracy for strain measurement is extremely high—perhaps in the order of $n\varepsilon$. In addition, FBGs may be applied to the design of a variety of sensors for structural health monitoring.

Fiber-optic distributed sensors provide continuous, real-time structural monitoring, which is especially important for collecting structural information in the event of an earthquake and aftershock. The measurement in this application enables structure engineers to access information regarding earthquake damage and to make informed decision concerning repairs. The distributed type of fiber-optic sensors selected for the project is based on “stimulated Brillouin scattering” (SBS).

The SBS sensor is capable of measuring strain and temperature independently and has a high spatial resolution (in the range of a few centimetres). The measured temperature distribution may be applied to calibrate the temperature at each location of the sensor in the quasi-distributed sensor network since the FGB is also sensitive to the temperature. Temperature calibration is necessary for all sensors deployed in the structure health monitoring system, including fiber optic and electromechanical sensors.

In the project, validation of the point and distributed fiber optic sensors will be implemented through laboratory and field tests. A structural health monitoring system using quasi-distributed sensor network and distributed sensor will be then designed, built, and evaluated for field testing viability. Comprehensive testing for the designed sensing network will be performed in the Civil Engineering Laboratory of California State University, Long Beach to qualify the prototype design. The research team has made a preliminary arrangement with Caltrans engineers to conduct field deployment testing within a segment of Southern California’s transportation infrastructure. The field test data will be reviewed and analysed to gather important information to justify the utilization of fiber-optic sensing technology for future systems. The prototype deployed in the selected segment of the transportation infrastructure will continue to collect structural information for technology and design validation. A design for a fiber-optic sensor network to be used in a monitoring and management system for transportation infrastructures based on the research project will be proposed as the end result of the research effort.

4. TASK OVERVIEW

The tasks of the project are designed to validate and test fiber-optic sensing technology for long-span transportation infrastructure health monitoring applications. In the project, we investigate the suitability of FBG and SBS fiber-optic sensors for measuring deformation, strain, and temperature. The project is composed of tasks described as follows:

4.1 Establish sensor performance requirement

Both FBG and SBS sensors are selected for the monitoring application. Performance requirements for transportation infrastructure monitoring will be investigated and proposed for the design of the prototype system.

4.2 Validate sensor performance

We will conduct performance evaluation and validation for FBG and SAS sensors in the Civil Engineering Laboratory of the College of Engineering in CSULB.

4.3 Conduct field tests on sensor networks

A system consisting of FBG and SAS sensors will be designed and deployed in the selected location within the California transportation infrastructure for field testing. FBG sensors will be used for vibration and strain measurement and SAS sensors may be used for temperature and distributed strain measurements.

4.4 Gather and analyze field test data

The research team will gather and analyze field test data for the sensor networks deployed in the field. The results of this task will be evaluated to validate the proposed approach for the practical application.

4.5 Design a monitoring and management system for future installation

The results from the laboratory and field tests will be evaluated and a preliminary prototype system will be suggested for future practical system applications.

5. FIBER-OPTIC SENSORS

The research and development of fiber-optic technology has inspired revolutionary changes to our lives today. Technological advances in fiber optics have paved the way for the widely deployed fiber-optic communication networks commonly known as the “information superhighway.” Today, we rely heavily on fiber-optic networks to transmit and receive data, voice and video signals via the Internet [3, 4].

Fiber-optic sensor technology may be considered an extension of fiber-optic communication technology. It is commonly used in such applications as industrial automation, healthcare, aerospace and aviation. Compared to conventional sensor technology, fiber-optic sensors offer numerous advantages such as high sensitivity, all solid-state construction, no moving parts and a long lifetime.

In this section, we will explore several key fiber-optic sensors which are essential to SHM applications. In addition to the previously mentioned advantages, fiber-optic sensors are also capable of performing continuous, real-time structural parameter measurement functions that conventional sensors cannot perform efficiently. [5]. All fiber-optic sensors considered for transportation infrastructural health monitoring are passive devices; thus, no power system is required at the location of the structure. In an SHM system, optical fiber may also be used as a medium for transmitting measured signals from optical fiber sensor networks which are deployed in the infrastructure, thus making remote monitoring feasible.

From a broad perspective, application of fiber-optic sensors in infrastructure health monitoring and management may be classified into two categories: 1) structural performance monitoring and 2) surveillance applications. While sensitivity requirements for performance monitoring sensors are typically medium-to-low for parameter measurement, surveillance sensors require ultra-high sensitivity to the measurement parameter. Performance monitoring sensors are typically used for: 1) monitoring the strain profile of large structures (e.g., a bridge or a ship hull), 2) monitoring and tracking crucial parameters (e.g., temperature, pressure, or acceleration) at crucial locations of a given system, and 3) vibration monitoring for system identification and damage location. Since a majority of fiber sensors that can be used for performance monitoring measure the strain in the fiber, either directly in the case of strain sensing or indirectly in the case of fiber-optic transducers, we will address sensor requirements in terms of strain resolution. Resolution requirements for performance strain monitoring range from a few nε to tens of mε, depending upon the details of the application. Bandwidth requirements can vary from static (DC) to tens of kHz.

Surveillance sensors, on the other hand, are exploited for measuring very faint signals and require sensors with strain resolution on the order of 10^{-13} to 10^{-14} and a frequency response from tens of Hz to tens of kHz. A good example of a high-performance surveillance sensor is the fiber-optic hydrophone, used for underwater surveillance [6]. Strain resolution of the order of 10^{-14} is difficult to achieve with fiber Bragg grating and until recently surveillance sensors have been the exclusive realm of fiber interferometric sensors. However, fiber Bragg grating laser sensors (FBGLs) have recently demonstrated strain resolution of 10^{-14} [7], thus opening up the possibility of marking novel surveillance sensors.

The most common structural parameters that fiber-optic sensors measure are temperature, strain, pressure, deformation, vibration, and acceleration. The SHM system based on the fiber-optic sensor network may obtain structural parameter measurement of high sensitivity and accuracy for those parameters. In this section, we will provide a review for several major fiber-optic sensors to be used in the SHM applications.

5.1 Michelson Interferometer Sensors

The fiber-optic Michelson interferometer consists of a single-mode fiber directional coupler with reflection mirrors formed on the cleaved ends of both fibers on the same side of the coupler [8] as depicted in Fig. 1. As a sensor, one of the fibers is used as a reference fiber and the other is used to sense structural parameter. Any deformation in a transportation infrastructure will result in a change in the length difference of the two fibers. The interference between the two reflected light beams produces interference fringes. The shift of the fringe is an indirect measurement of the deformation strain.

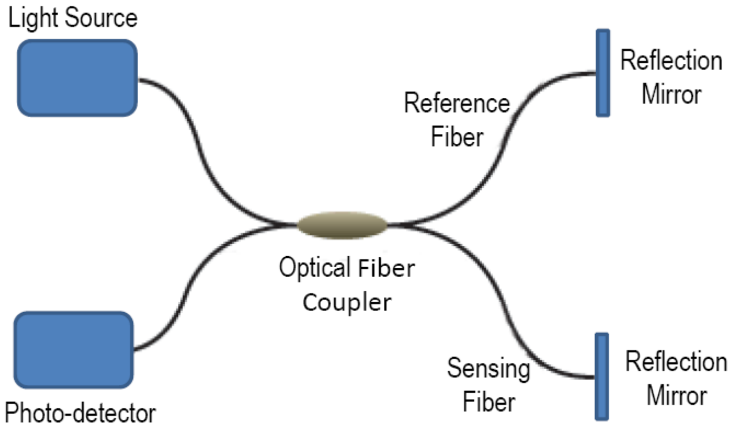


Fig. 1 Fiber-optic Michelson interferometer

To obtain accurate and reliable measurement of the deformation strain, a second mechanically scanning Michelson interferometer will be applied at the input/output port of the first fiber-optic interferometer to directly measure the length difference instead of the shift of the fringe pattern. The scanning Michelson interferometer is to create an optical path length difference such that it is equal to the length difference of the two fibers. Furthermore, a broadband light source or white light source having a low coherent length has to be used for the robust measurement. The scanning Michelson interferometer can accurately measure the optical path length difference by balancing the change of the length difference of the two fibers and hence yields the direct measurement deformation strain.

The fiber-optic sensor based upon Michelson interferometer is a long-gauge sensor for deformation strain measurement with a resolution in the range of micrometers. It has excellent long-term stability and is insensitive to the temperature. The schematic of the sensor for measuring structural deformation strain is illustrated in Fig. 2.

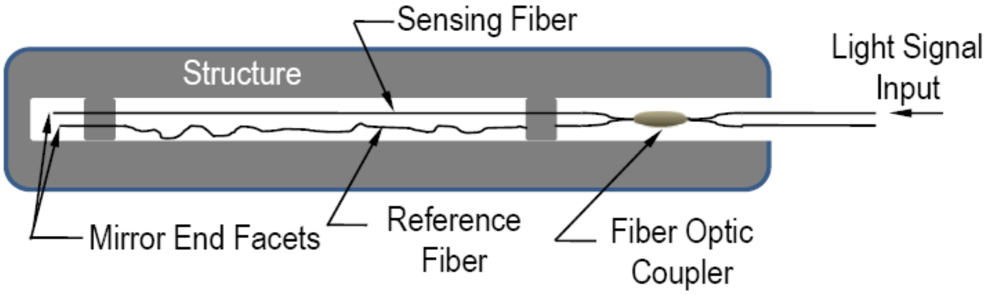


Fig. 2 A long-gauge deformation sensor using fiber-optic Michelson interferometer

5.2 Fiber Bragg Grating Sensors

Since the discovery of photosensitivity in optical fibers in 1978 by Ken Hill [9], and the subsequent demonstration of holographically written gratings in fibers by Gerry Meltz [10], significant progress has been made towards the realization of various types of gratings in optical fibers. Advances in grating fabrication methods and fiber photosensitivity enhancement techniques have made it possible to fabricate a variety of index-modulated structures within the core of an optical fiber including Bragg grating [11], long period gratings [12], π-phase shifted grating [13], blazed or tilted gratings [14], and various types of chirped gratings [15].

Fiber grating devices have seen a wide variety of applications in both telecommunication and sensor fields. Fiber Bragg gratings (FBGs) have been routinely used with semiconductor lasers for producing a stable single frequency light signal with which an extreme broadband communication link may be realized. They will also play an important role in reconfigurable optical networks in the future optical network systems, since it is clear that grating-based devices are seeing great commercial success in the SHM applications. Transducers using FBGs such as pressure and acceleration sensors also have various applications and have now become commercially available. The requirements and designs of several reported grating-based transducers used in SHM applications will be discussed.

A fiber grating is made by periodically changing the refractive index in the glass core of the fiber. The refractive index changes are achieved by exposing the fiber to UV-light with a fixed pattern. The schematic of a fiber-optic grating is illustrated in Fig. 3. As the input light propagates through the grating having a period of Λ and the optical wavelength λ satisfies the Bragg condition, the maximum reflection occurs. The Bragg condition may be expressed as:

$$\lambda = 2n_{eff}\Lambda \tag{1}$$

where n_{eff} is the effective index of refraction of the optical fiber. The reflection and transmission spectra are shown in Fig. 4. Since n_{eff} is determined by the refractive index profit of the fiber, it changes with the variations of ambient temperature and external mechanical stress. As the result, the center frequencies of the reflected and transmitted spectra will shift accordingly. Therefore, the measured frequency shift is an indication of the temperature and strain changes. FBGs can accurately measure local temperature and strain in a small region of the infrastructure with very high sensitivity.

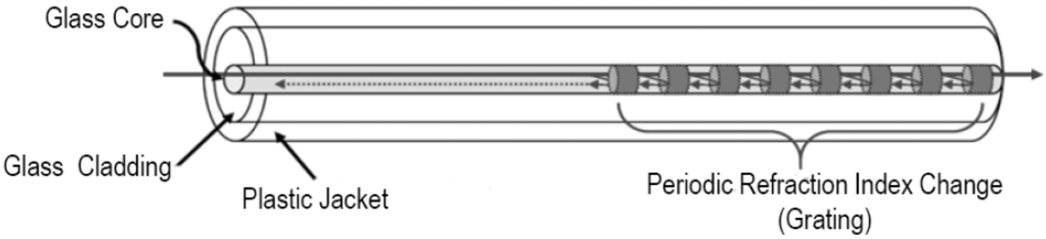


Fig. 3 Schematic of a fiber Bragg grating

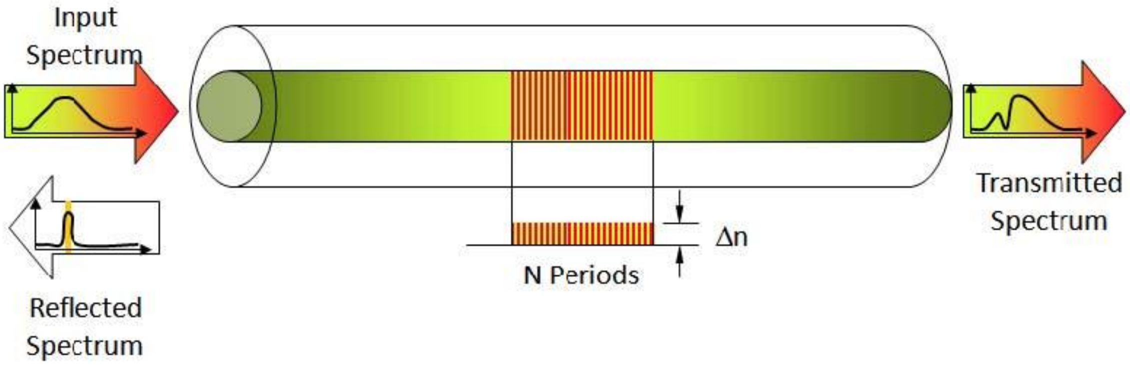
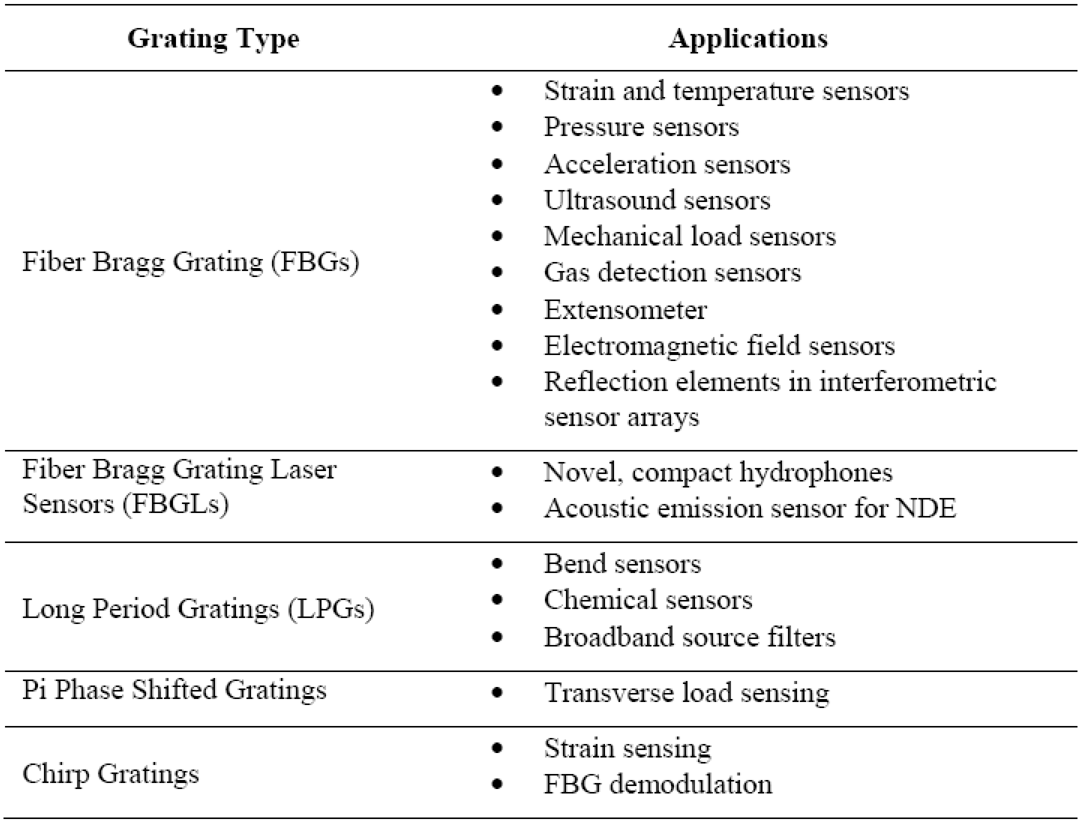


Fig. 4 Reflection and transmission spectra of an FBG

A summary of potential sensing applications of various types of fiber gratings is provided in Table 1. The table is not necessarily meant to be comprehensive and to cover all conceivable application areas in fiber-grating sensors. Of course, there is no one “magic” fiber-optic sensor which covers the full range of sensing requirements for all applications. In this report we only briefly discuss FBG applications and examples from various field tests involving such sensors. Particular emphasis will be given to multiplexed networks based on FBGs for quasi-distributed measurements of parameters such as load, strain, temperature, and vibration. Observation has indicated that in certain cases the technology is fairly well developed and ready for widespread commercialization.

Table 1: Summary of potential sensing applications of various types of fiber gratings



Grating Type	**Applications**
Fiber Bragg Grating (FBGs)	• Strain and temperature sensors • Pressure sensors • Acceleration sensors • Ultrasound sensors • Mechanical load sensors • Gas detection sensors • Extensometer • Electromagnetic field sensors • Reflection elements in interferometric sensor arrays
Fiber Bragg Grating Laser Sensors (FBGLs)	• Novel, compact hydrophones • Acoustic emission sensor for NDE
Long Period Gratings (LPGs)	• Bend sensors • Chemical sensors • Broadband source filters
Pi Phase Shifted Gratings	• Transverse load sensing
Chirp Gratings	• Strain sensing • FBG demodulation

An array of FBGs has great potential for providing high-performance structural sensing systems. Such measurements provide useful information regarding verification of novel construction approaches, infrastructure load rating systems and history of large loading events. Fig. 5 depicts the schematic of a distributed sensor array used for SHM systems. In fact, the distributed array of FBG sensors is a quasi-distributed sensor array, since the FBG sensor is a point sensor. This quasi-distributed sensor array may be deployed over the entire transportation infrastructure to monitor strains and temperature at various locations. As previously discussed, this type of sensor has very high resolution and accuracy of strain measurement—possibly on the order of $n\varepsilon$.

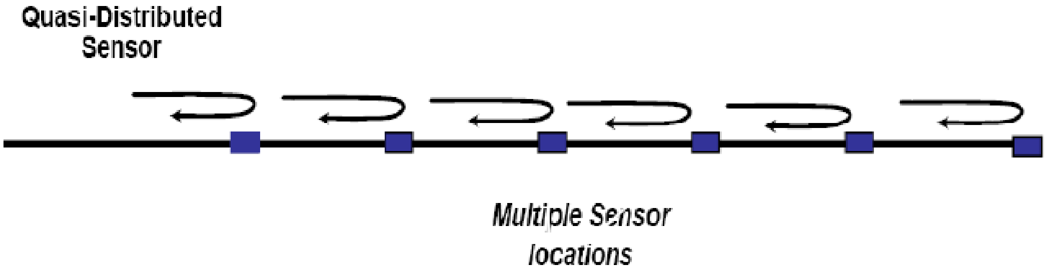


Fig. 5 Quasi-distributed sensor using an array of FBG sensors

Although the quasi-distributed FBG sensor has very good performance in strain measurement, it cannot distinguish strain and temperature as the effective index n_{eff} is dependent on both strain and temperature. Hence, a separated distributed temperature sensor is needed in order to extract the strain information for the system.

5.3 Distributed Fiber Sensors

Distributed fiber-optic sensors are important sensor technologies which may be used in infrastructure health monitoring for large and long structures such as bridges, beams, and clamping ropes, from hundreds of meters to more than ten kilometers in length. Conventional sensor technology is often not feasible for real-time and continuous structural monitoring of the parameters in these infrastructures [16]. Due to the light scattering in the optical fiber, the distributed fiber-optic sensor is capable of continuously monitoring major structural parameters and has high spatial resolution (on the order of a few centimeters); hence, it allows structural engineers to measure parameters in an entire infrastructure system for design verification and damage and reliability assessments.

There are several methods available for extracting distributed strain and temperature information from optical fiber. These include techniques based on Rayleigh, Raman, and Brillouin scattering. Rayleigh scattering is the elastic scattering of light by particles much smaller than the wavelength of the light. It may occur when a light wave travels in optical fiber in which the refractive index along the fiber fluctuates. Rayleigh light is scattered in all directions from the spatial variation of the refractive index along the optical fiber. The intensity of the scattered light at each location along the fiber is sensitive to both local strain and temperature. By measuring the back scattered light with a coherent signal detection method, one can readily extract the average strain and temperature information within a small segment of the fiber. Fiber-optic strain sensor having a gauge length of less than 0.5 m and a strain sensitivity of less than $n\varepsilon/\sqrt{Hz}$ at 2 kHz based on Rayleigh backscatter using a time division multiplexing (TDM) scheme has been demonstrated [17]. Sang et al. [18] present a technique based on measuring the spectral shift of the intrinsic Rayleigh backscatter signal along the optical fiber and converting the spectral shift to temperature. Using optical frequency domain reflectometry (OFDR) to record the coherent Rayleigh scatter pattern results in spatial resolution of around 1 cm and provides temperature measurement with an accuracy of

0.6 % of full-scale temperature up to 850° C. Although a distributed stain and/or temperature sensor with small gauge length and high measurement accuracy may be obtained based on Rayleigh scattering, it requires a separate sensor to either calibrate temperature for measuring strain at a particular location or vice versa.

Raman- and Brillouin-scattering phenomena have been used for distributed sensing applications over the past few years. Whereas Raman scattering was first proposed for sensing applications in the 1980s, Brillouin-scattering was introduced for strain and/or temperature monitoring applications very recently. Both Raman- and Brillouin-scattering effects are associated with different dynamic inhomogeneities in the silica and, therefore, have completely different spectral characteristics.

Raman scattered light is caused by thermally activated molecular vibrations. Because the scattered light is generated by thermal agitation, one may expect a frequency shift from the incident light wave. As the incident light loses a slight amount of its energy to the molecules, this process, referred to as “Stokes scattering,” leads to scattered light with lower optical frequency. On the other hand, as the light wave gains energy from the molecules, it produces scattered light with a slightly higher frequency. This is referred to as “anti-Stokes scattering.” It is found that the amplitude of the anti-Stokes component is strongly temperature-dependent and that of the Stokes component is not. Hence, an optical signal processing technique utilizing Stokes and anti-Stokes components is needed to realize distributed temperature sensors. The magnitude of the anti-Stokes Raman scattering light is about one-thousand times smaller (-30 dB) than that of the Rayleigh scattered light; multimode optical fiber is commonly exploited in the sensing system for improved scattered light capture. However, the attenuation coefficient of the multimode fiber is high; therefore, this technique limits the maximum measurement range to only 8 km.

Brillouin scattering results from the scattering of light and sound waves. Thermally excited acoustic waves (acoustic phonons) produce a periodic modulation of the refractive index. Brillouin scattering occurs when light is diffracted backward on this moving grating, giving rise to frequency shifted Stokes and anti-Stokes components. For intense light (e.g. laser light) travelling in an optical fiber, the variations in the electric field of the beam itself may produce acoustic vibrations in the medium via electrostriction. In a phenomenon known as stimulated Brillouin scattering (SBS), the beam may undergo Brillouin scattering from these vibrations, usually in a direction that is opposite to that of the incoming beam. The working principle of SBS may be schematically illustrated in Figure 6. The Brillouin frequency shift attributed to the strain and temperature may be expressed as:

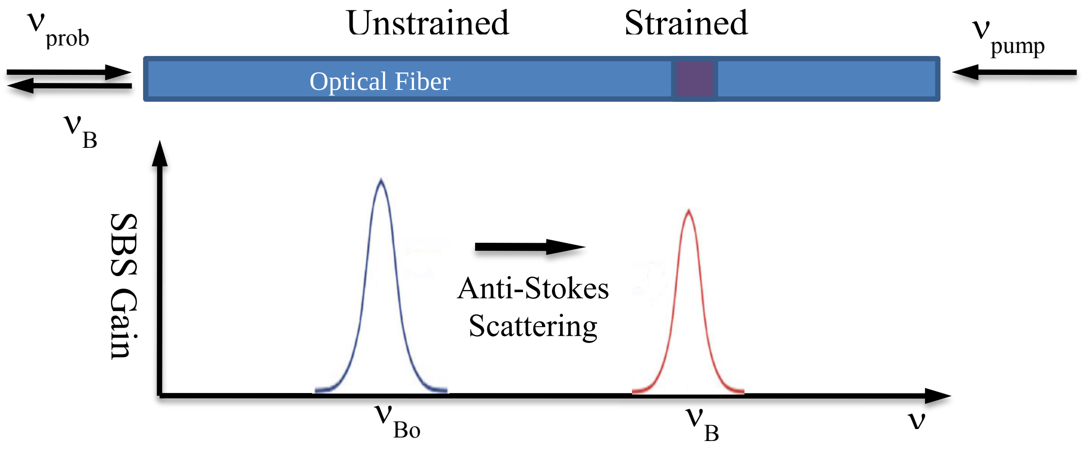


Fig. 6 Stimulated Brillouin Scattering in single mode optical fiber

$$\upsilon_B = \upsilon_{Bo} + B_T(T - T_o) + B_s(\varepsilon - \varepsilon_o) \tag{2}$$

where ν_{Bo} and ν_B are the peak frequencies of the SBS for unstrained and strained fibers, respectively. In equation (2), B_T and B_S are Brillouin thermal and strain coefficiencies.

The distributed sensor based on SBS is most suited for SHM applications. The distributed optical fiber Brillouin sensor based on the SBS has been investigated for pipeline buckling and concrete/FRP column monitoring [19]. Using a coherent detection scheme, the SBS-based sensor offers several advantages, including long measured length, high resolution and accuracy, and stability. The most important feature of the SBS-based Brillouin distributed sensor is its ability to measure strain and temperature separately or simultaneously with high spatial resolution and accuracy.

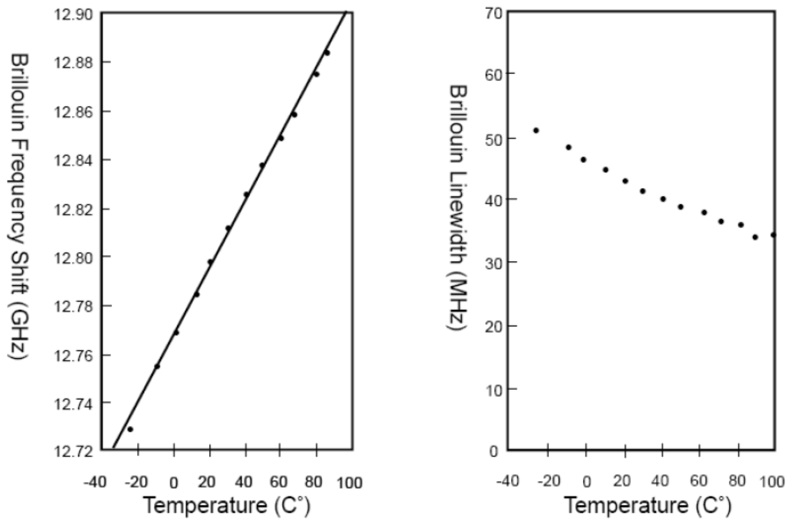


Fig. 7 Temperature characteristics of SBS distributed sensors

Figure 7[20] shows the experiment results of the temperature characteristics of the SBS distributed sensor. The Brillouin frequency shift on an order of tens of GHz exhibits a fairly linear relation with the measure temperature as in Figure 7 (a). Conversely, as can be seen in Figure 7 (b), the Brillouin linewidth decreases when the measured temperature increases. The experimental results in Figure 8 (a) show that the Brillouin frequency shift also linearly depends on the fiber elongation which is the indication of the local strain; however, the linewidth is independent of the elongation, as shown in Figure 8 (b). These measurements conclude that the temperature and strain may be measured separately based on Brillouin frequency shift and linewidth variation.

The Brillouin distributed sensor technology allows fast measurement of strain and temperature to be achieved within a few seconds, owing to the use of straightforward optical signal processing technique. Furthermore, the monitoring system may incorporate an optical amplifier to boost up the optical power to extend the measurement range; this makes the Brillouin distributed sensor a practical choice for the transportation infrastructure monitoring system.

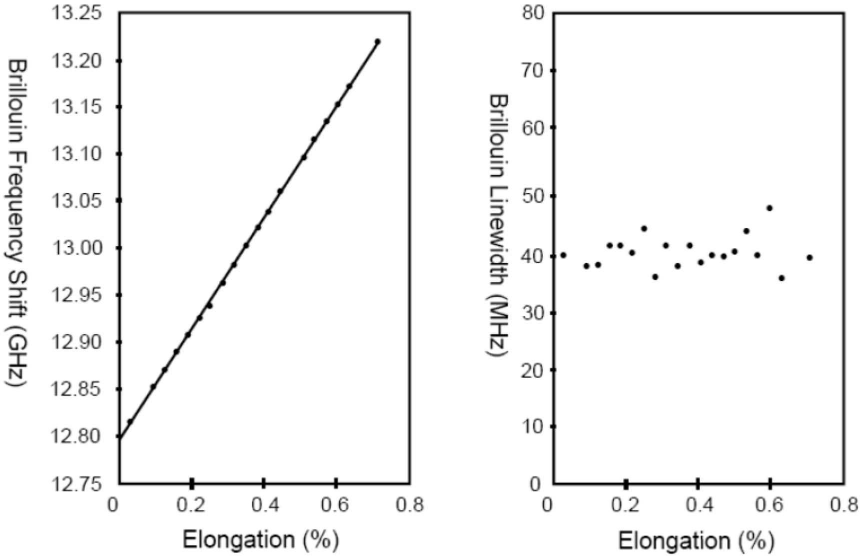


Fig. 8 Spectrum characteristics of SBS distributed sensors

6. RESULTS & DISCUSSION

In this research project we are developing a system to remotely monitor the structural health of key components of the public transportation infrastructure, such as bridges and overpasses, using fiber-optic sensors. Four steps will be followed to keep the structure intact and working: monitoring, inspection, diagnosis and repair. To monitor a structure it is necessary to keep periodical or continuous records of significant parameters over certain periods. In our research, a variety of parameters will be recorded, including: mechanical parameters such as strain and curvature; physical parameters such as temperature, deformation, and humidity; and chemical parameters such as PH, CL-, and SO_3-. These parameters are acquired and logged into the computer using developed frontend Lab View software. Compared to conventional sensor technology, the fiber-optic sensor offers numerous advantages such as high sensitivity, all solid-state components, no moving parts and a long lifetime. Fiber-optic sensors such as point sensors and distributed sensors are used. Fiber-optic sensors will be embedded or glued to the existing transportation infrastructure. Once the data is ready it will be transmitted wirelessly to the control unit. With the use of a fiber-optic readout unit, these parameters will be acquired and further processed.

We have conducted comprehensive performance evaluation for point and distributed fiber optic sensors aiming at application to long-span transportation infrastructural monitoring. Three basic types of point sensors based on the fiber Bragg grating are deployed in different structures in the campus of California State University Long Beach. The fiber Bragg grating point sensors were used to measure the temperature, strain, and deformation at specified locations in the structures being tested.

The measured data are obtained and analyzed and are presented in the report. In addition, a distributed sensor is deployed in the same structures to characterize the sensor's capability for future deployment for infrastructure monitoring. The initial test result is reported and discussion of the measurement result will be provided.

6.1 Fiber Bragg deformation sensors

The FBG deformation sensors are transducers that transform a static or dynamic distance variation into a change in reflected wavelength of a prestressed fiber Bragg grating that can be measured with FBG reading units. These long-gauge sensors are surface mountable or embeddable in concrete and permit static/dynamic deformation measurements with or without temperature compensation. Available configurations are single-ended, double-ended and chained. They are insensitive to corrosion, immune to EMF and present long lifetime. The specifications of the FBGs employed in the project are provided as follows:

Table 2: Specifications of FBG deformation sensor

SPECIFICATIONS	
Length of active zone (measurement basis)	0.25 to 2 m
Pretensioning of the measurement fiber	0.5% length of active zone.
Measurement range	0.5% in shortening 0,75% in enlongation
Strain resolution/accuracy	0.2 $\mu\varepsilon$/2$\mu\varepsilon$
Temperature measurement range	-40°C to +80°C
Temperature resolution/accuracy	0.1°C/0.5°C

Figure 9 shows the schematic of a single-ended fiber optic deformation sensor. In the sensor assembly, an FBG temperature sensor is included for thermal calibration since the FBG is also sensitive to the temperature effect. Therefore, the deformation data

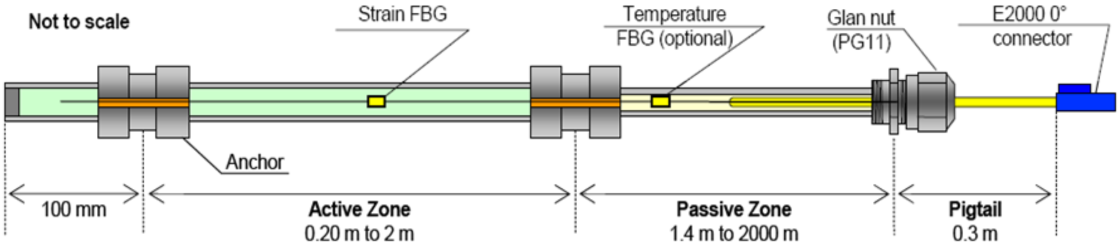


Fig. 9 Single-ended fiber optic deformation sensor

may be accurately obtained by a predetermined thermal calibration data. Figure 10 shows a deformation sensor that was deployed in the CSULB structures for experiments. The sensor is equipped with a fiber-optic connector at one end that served as input/output. It should be pointed out that the single-ended fiber BBG sensor is operated in the reflection mode, in which the sensing signal is the light reflected from the grating.

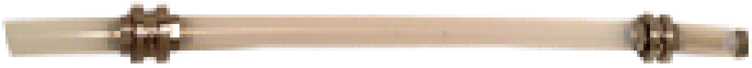


Fig. 10 Fiber optic deformation sensor used in the test

In this report, we report performance evaluation results of temperature and deformation sensors based on FBGs. An effort was made to perform preliminary tests in the laboratory environment and on a small overpass structure on the California State University, Long Beach campus to validate sensors' functions and capabilities. The deformation sensor is used to perform continuous static and dynamic monitoring. The photo in Fig.11 shows the setup installed in an overpass structure to evaluate the performance of the sensor prior to being deployed in a long span infrastructure for field test.

Fig. 11 Fiber optic sensors installed in an overpass for validation test

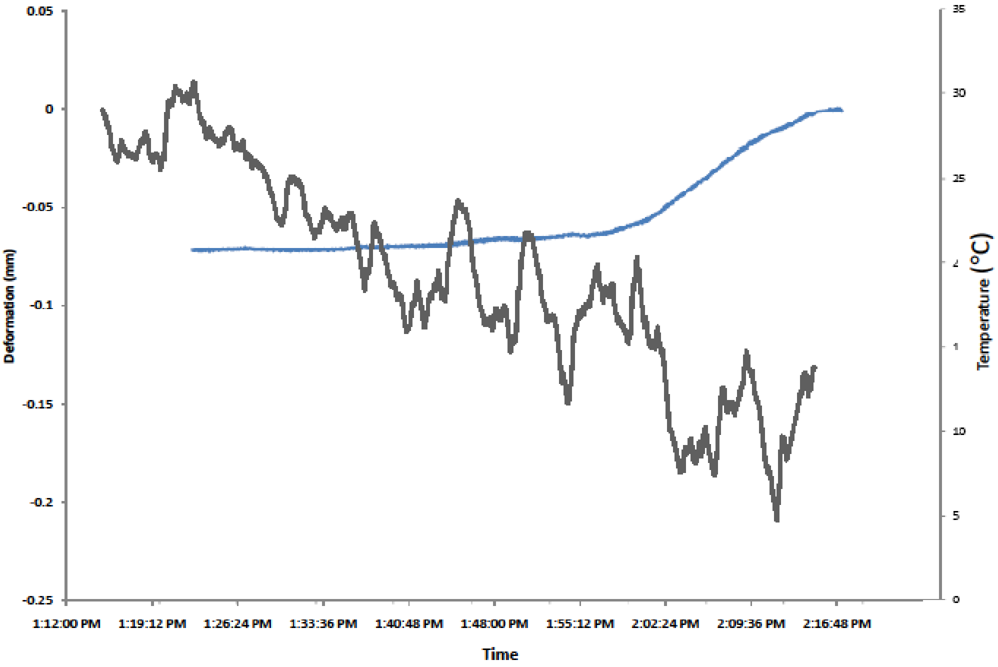


Fig. 12 Measured results of FBG deformation sensor

In Fig. 12, deformation and temperature data of continuous static monitoring during a period of one hour is measured and provided. It shows that measurement accuracy is on an order of micrometer range magnitude, which is expected and clearly superior to that of conventional sensors. In the same figure, the temperature data are also recorded and used for the calibration to obtain the deformation measured data. Longer-term test runs were implemented and the results show that the FBG deformation sensor maintains the same performance. Therefore, the experiment result has confirmed that the sensor may be applied to obtain the knowledge of a structure behavior and follow the evaluation of the degradations.

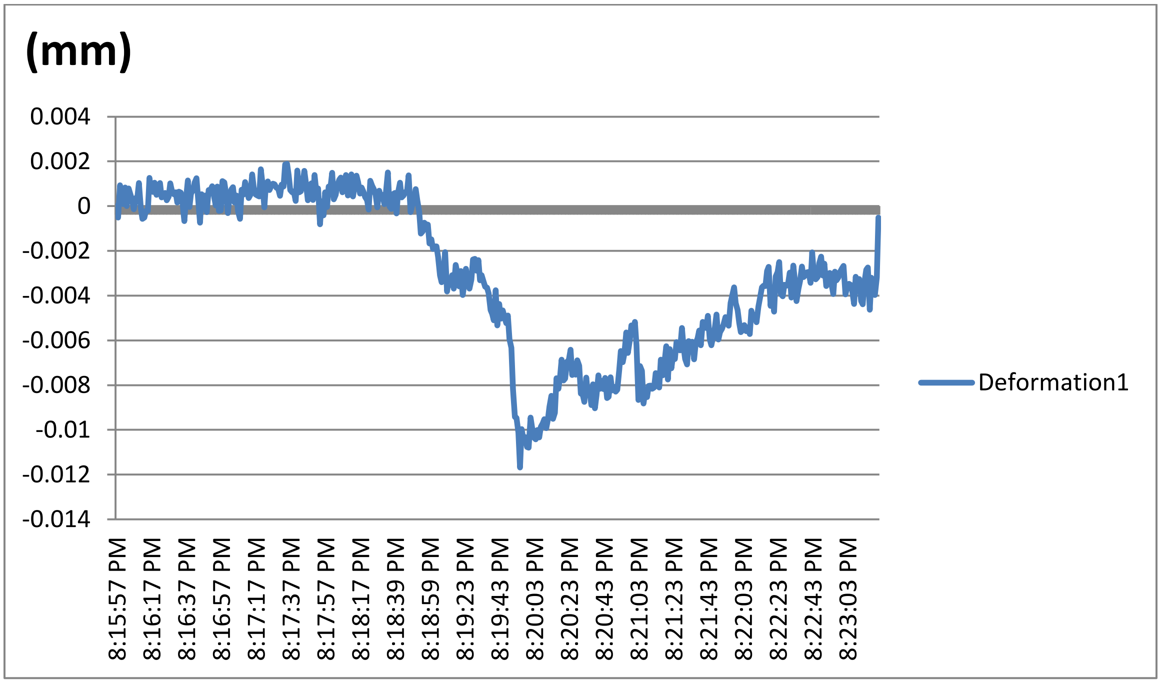


Fig. 13 Dynamic measurement results of FBG deformation sensor

In a dynamic measurement experiment, a jumping was intentionally created to the overpass structure for investigating the dynamic response of the same deformation sensor. As shown In Fig. 13, the FGB deformation sensor instantaneously responds the jumping perturbation very sensitively. However, the structural deformation took approximately 2 minutes to recover; the situation will be reviewed and investigated with the structure engineering to understand the characteristic of the structure. In the same experiment, the temperature is also monitored at the same time to ensure that the deformation measured by the sensor is purely attributed the jumping. As can be seen, the temperature remains the same even there is a jumping as shown in Fig. 14.

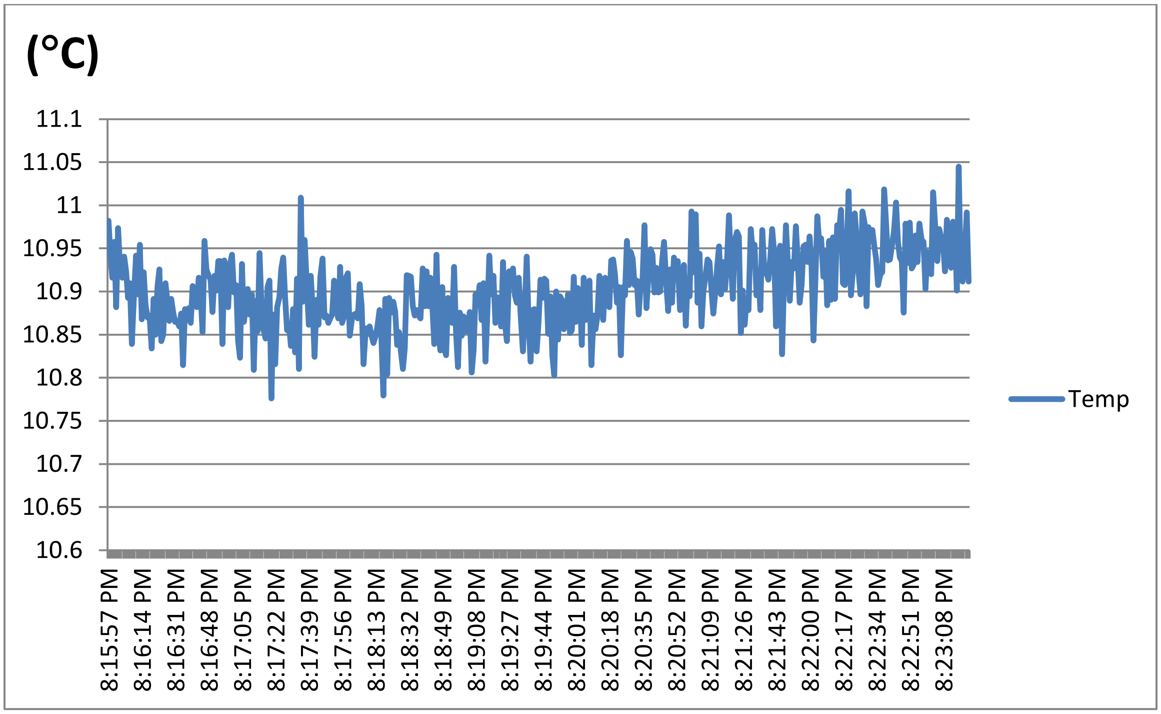


Fig. 14 Temperature measurement results of FBG deformation sensor

In the setup, we employed the FBG strain sensor to test the structural strain characteristics. The strain measurement exhibits accuracy in a range of few tenths of με as shown in Fig. 15. The performance is in a good agreement with the theoretical prediction; the result confirms that the fiber optic sensor, specifically the FBG sensor, has superior measurement accuracy to the conventional sensors. Moreover, it also demonstrates the capability of real-time measurement and high-speed data transportation to the remote monitoring site for the structural monitoring. Hence, we may conclude that the FBG sensor will be an ultimate choice for the structural monitoring application.

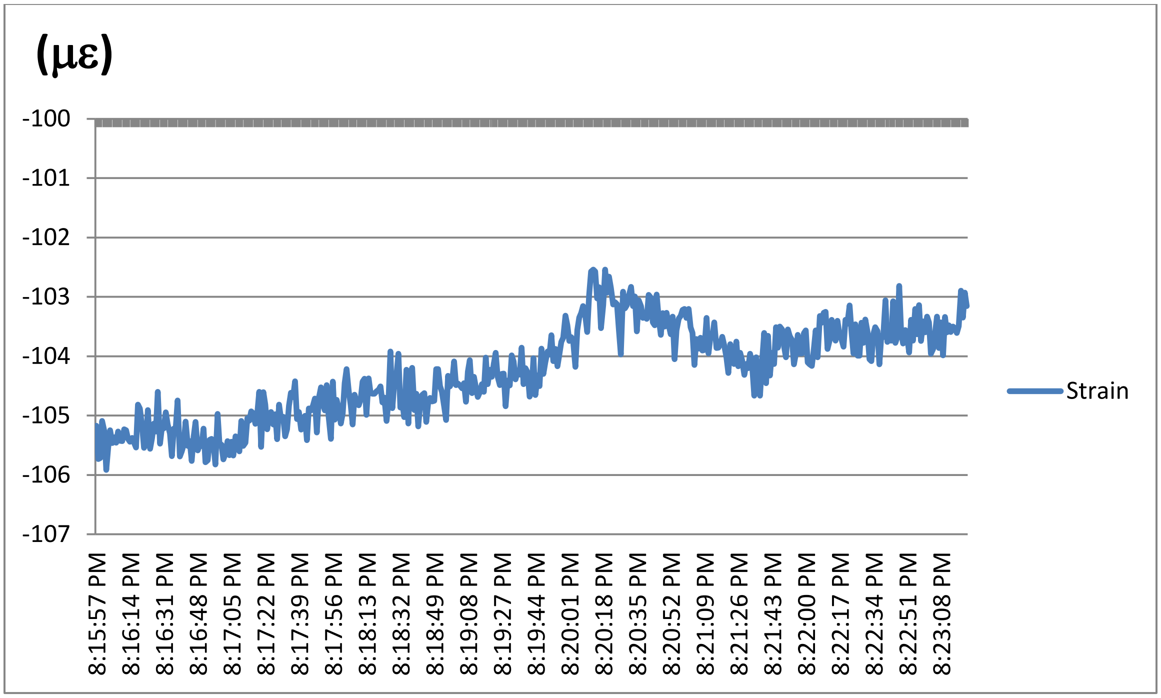


Fig. 15 Measurement results of FBG strain sensor

6.2 Multi-Channel fiber optic Bragg grating sensors

A four-channel FGB sensor array, illustrated in Figure 16, is employed in the preliminary test. In the FGB sensor array, each channel may be equipped with *n* FBG sensors for temperature, deformation, and strain measurements in a structure. Each FBG sensor can be deployed at a selected location and operated at a predetermined wavelength. The measured infrastructure parameters are extracted using optical multiplexing technique. Today’s optical dense demultiplexing technique allows more than one-hundred sensors in a channel.

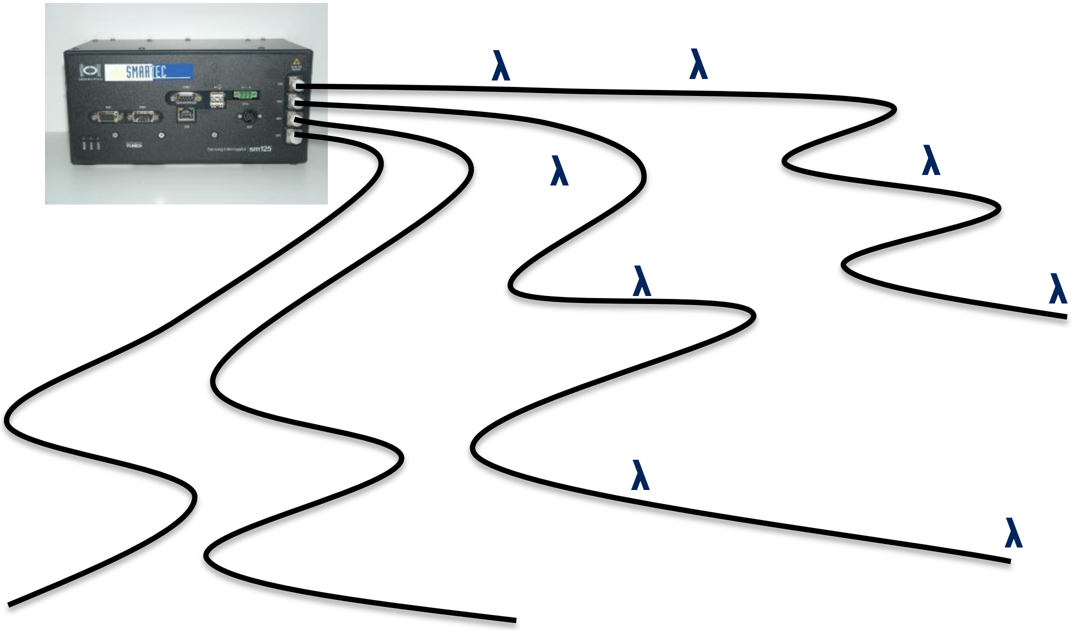


Fig. 16 Four-channel FBG sensor array

During the initial performance evaluation, a single channel was applied to measure three temperatures: one deformation and two strains at three different locations of the small overpass on campus. The measurement result for one hour of monitoring is given. The measured deformations shown in Figure 12 are within a range of a few hundred micron meters, which is as we expected for such a small structure. It also shows that the variation in deformation is small and stable. The measurements of strains are obtained by utilizing two FBG sensors from two separate locations of three meters apart. Figure 17 shows the measured strains, which are on the order of tens of με. The results clearly demonstrate the capability of the FBG sensor array for continuous, real-time monitoring of infrastructural parameters. In addition, the FBG sensors have shown that their outstanding performances in terms of sensitivity and accuracy are superior to conventional sensing devices.

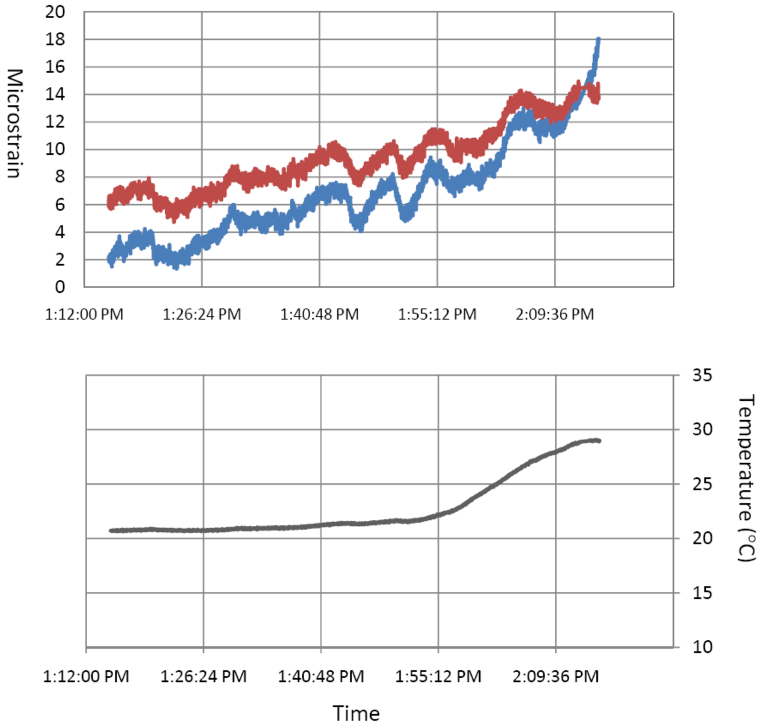


Fig. 17 Strain measurement with FBGs

6.3 Distributed fiber sensors

Fig. 18 Section of distributed fiber optic sensor

The distributed fiber sensor is a relatively new technology compared with point sensors, and is still in the research and development stage. A distributed Brillouin strain sensor used in the test, shown in Fig. 18, is designed for distributed deformation (average strain) monitoring over long distances. We installed a distributed strain sensor array of 200 feet in length in an overpass located in the Engineering Complex of CSULB to observe its functionality. The measurements obtained from the experiment proved to be unstable and not repeatable during several test runs. We reached a conclusion that the technology is not mature enough for the field application; more research and development effort is required to address technical challenges.

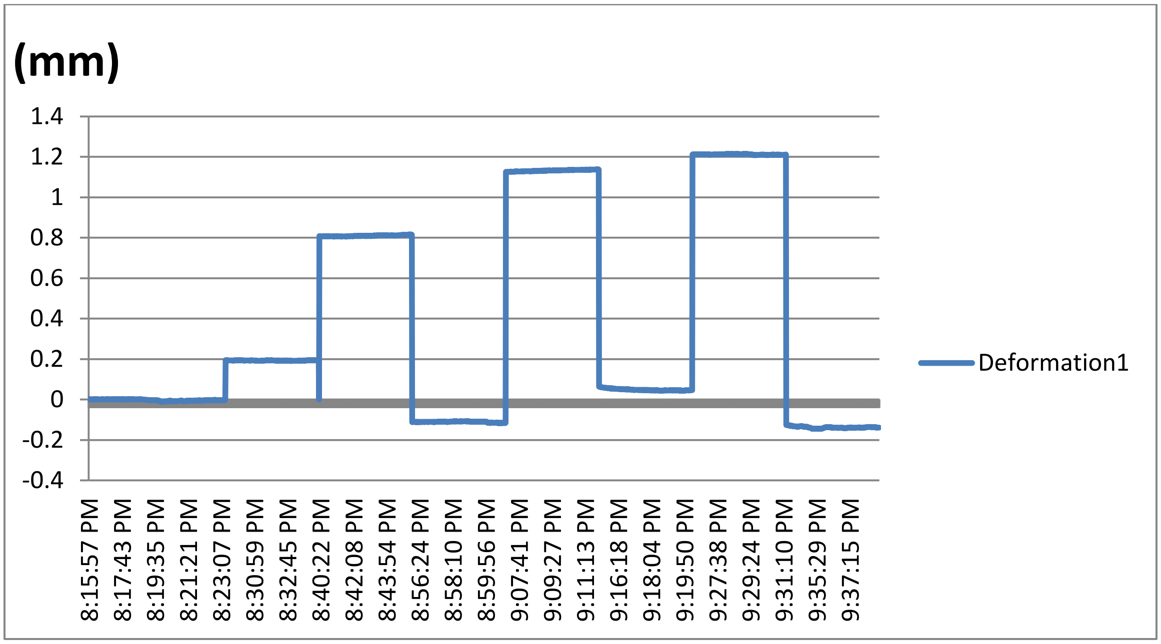


Fig. 19 Deformation measurement results of a distributed fiber optic sensor

Fig. 19 shows the measurement one of the best results of the distributed fiber optic sensor used in the same structure as that for the point sensor. A point sensor was used to take each reading. Every 7 minutes, the sensor was moved to an adjacent part of the bridge. This cycle was repeated until the sensor made its way to the end of the bridge. There are two imperative discoveries; response time of more than one minute and measurement accuracy of about 1000 time worse than that of point sensor. The strain measurement essentially has very similar result as the deformation measurement as see in Fig. 20. Even the accuracy of the distributed sensor is not as good as the point sensor, but it still better than that of the conventional counterparts. In addition, performance improvement is possible; thus, more research and development resource should be devoted.

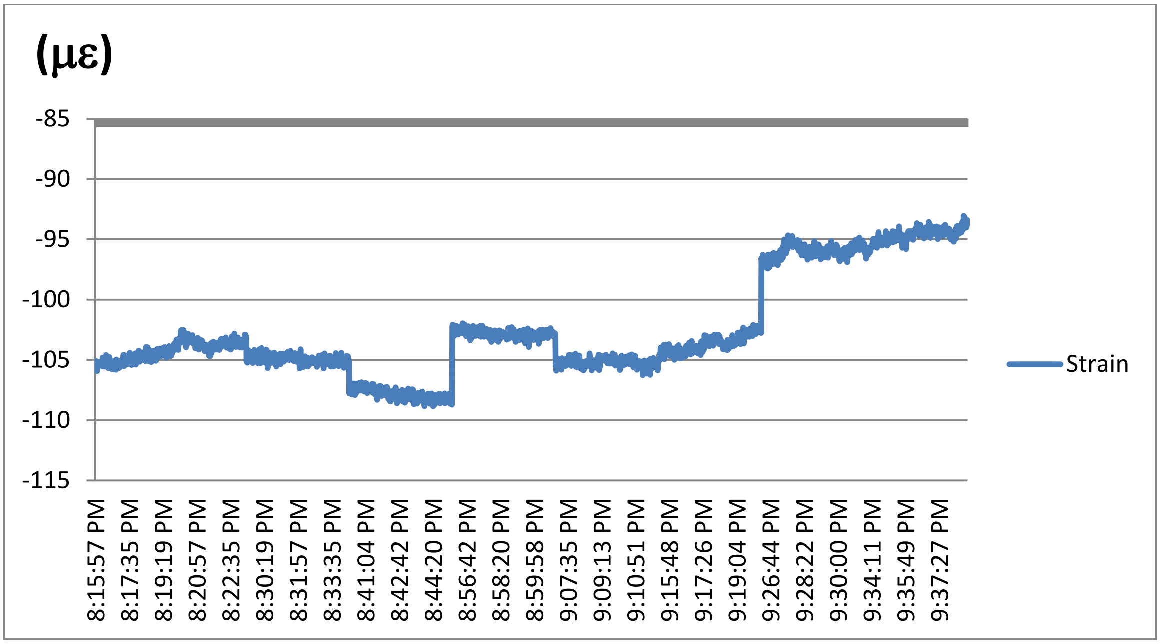


Fig. 20 Deformation measurement results of a distributed fiber optic sensor

6.4 Preliminary System Design Concept

A typical SHM system, as illustrated in Fig. 21, is composed of a network of sensors that measure the parameters related to the state of the structure and its environment. For transportation infrastructures such as bridges, overpasses and tunnels, the most important parameters are: Positions, deformations, strains, pressures, accelerations and vibrations. In addition, chemical parameters such as humidity, pH value and chlorine concentration are almost as important as those physical parameters. Environmental factors often have substantial impact on the condition and operation of the transportation infrastructure. Those environmental parameters of interest are temperature, wind speed and direction, solar irradiation, precipitation, snow accumulation, water level and flow. The SHM system might be additionally equipped with a wireless network for remote monitoring, control and alarm for effective system operations.

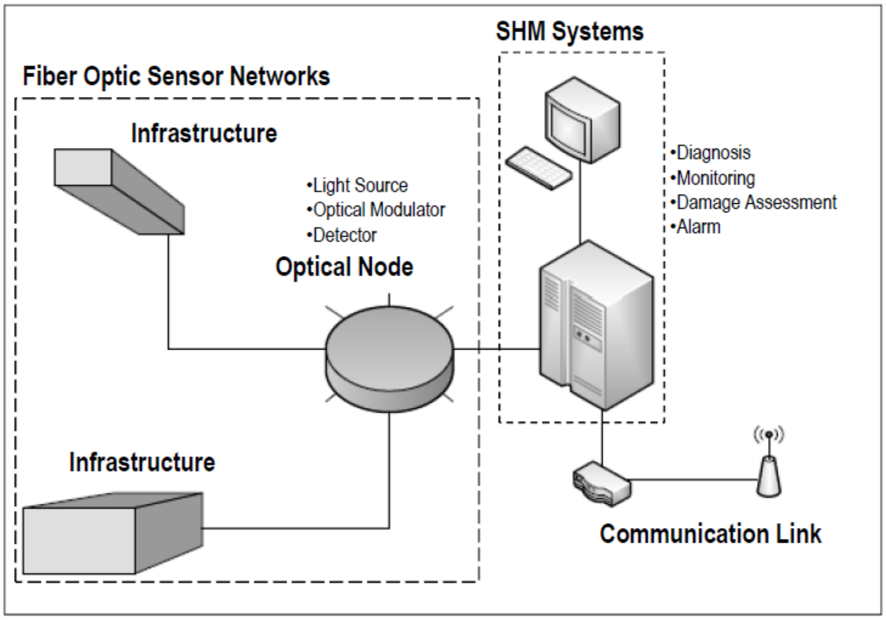


Fig. 21 Schematic of structural health monitoring and management system

In the system, fiber optic FBG sensors may be deployed in locations of a infrastructure where stress and strain monitoring is required. The locations are determined based on specific data needed for the purpose of the system. For monitoring continuous structural parameters, one may apply distributed fiber optic sensors in conjunction with high accuracy point FGB sensors to ensure the fidelity of the measurement by the distributed sensor. The advantage is that we may reduce the number of point sensors required for the entire system; thus the installation cost will be reduced.

Communication nodes may collect all measured data and transport to the central system for monitoring and diagnosis purposes. The ideal choice of the communication node is the optical system since it is comparable to the fiber optic sensor. There will be no interface device needed. Furthermore, the optical node should be equipped with wireless transceivers to allow direct communication with the central office for real time data collection. Detail design for a system will depend on the specific infrastructure; this is beyond the scope of the research effort documented in the report.

7. CONCLUSION AND FUTURE PLAN

The majority of the structural monitoring sensors used in long-span bridge health monitoring systems are still based on conventional transducer technology. The Akashi Kaikyo Bridge in Japan, which is the world's longest suspension bridge, uses a seismometer, anemometer, accelerometer, velocity gauge, global positioning system (GPS), girder edge displacement gauge, tuned mass damper (TMD), displacement gauge and thermometer for dynamic monitoring [2]. Significant progress in the development of fiber-optic sensors and wireless sensors has been made in the past decade and some of these are now commercially available. Whereas fiber-optic sensors have successfully been applied for the long term SHM of large scale bridges such as the Confederation Bridge [21] and the Tsing Ma Bridge [22], wireless sensors for bridge SHM application are still in the technology demonstration stage.

Some conventional sensors currently used in long-span bridge health monitoring are deficient in providing adequate accuracy and long-term stability. For example, a GPS used in the Akashi Kaikyo Bridge for absolute displacement and deflection monitoring has three limitations: 1) the measurement accuracy of a GPS is not sufficient for meeting bridge health monitoring requirements; 2) a GPS does not work well for monitoring the displacement of piers beneath the bridge deck (caused by ships colliding and settlement) and 3) a GPS is not capable of accurately measuring deflection in a foggy environment. A long-gauge deformation sensor using the previously discussed fiber-optic Michelson interferometer becomes an ideal choice for the application because of its long-term stability and capability of measuring the absolute displacement.

Fiber optic sensors such as FBG and SBS sensors are only applied to the measurement of strain and temperature with high sensitivity and accuracy; one may be used to implement a quasi-distributed sensor network and the other is a distributed sensor. Fiber -optic sensors have the additional advantages of low bias drift and high frequency response in addition to those mentioned early. Whereas electrical gauges for strain and vibration monitoring normally encounter technical problems in either bias stability and/or dynamic response, fiber-optic sensors are not subject to such problems. Fiber-optic sensor technology for the SHM application is not as yet widely accepted for transportation infrastructure monitoring. Research and development in fiber-optic sensors seems to focus on measurements in strain, deformation and temperature; other key structural parameter monitoring is still lacking research and development effort. In order to take full advantage of the technology, a research and development effort has to be directed into other parameter monitoring applications.

In our future research, validation of the distributed fiber-optic sensor will be implemented through laboratory and field tests. A structure health monitoring system using a quasi-distributed sensor network and distributed sensor will then be designed, built, and tested for field deployment. Complete testing for the sensing network design will be performed in the Civil Engineering Laboratory of California State University, Long Beach to qualify the prototype design. The research team has made a preliminary arrangement with Caltrans engineers to conduct field deployment tests within Southern California’s transportation infrastructure. The field test data will be reviewed and analyzed to gather important information to justify fiber-optic sensing technology for future systems. The prototype deployed in the selected transportation infrastructure will continue to collect structural information for technology and design validation. A design for fiber-optic sensor networks based on the research project, to be used in monitoring and management systems for transportation infrastructures will be proposed as the end result of the research effort.

8. IMPLEMENTATION

The results of this research project will be based on laboratory and field tests of fiber-optic sensors for infrastructure health monitoring applications and cannot be implemented directly. In this research effort, only two types of point sensors for temperature, strain, and deformation measurements and one distributed sensor for average strain measurement will be deployed over a distance of 200 ft. The point sensors in the experiment show very promising results and may be considered for deployment in field applications. However, the technology only proves its suitability to the application; more product development is required to ensure its reliability and durability for real-world operation. Furthermore, other types of fiber sensors need to be researched and developed to meet all structure monitoring requirements. The test result of the distributed Brillouin fiber optic sensor exhibits problems of stability and repeatability; it is not ready for the application. Substantial research and development is required prior to continued field tests. If the technical hurdles of the distributed sensor are overcome, the existing capability of the transportation SHM will be extended. The results of this report provide comprehensive information regarding feasibility of the implementation of the transportation SHM based on fiber-optic sensors. The most significant finding of this research is that, despite that fact that the application of fiber-optic sensors in the transportation SHM is far from being mature, the potential cost benefit of the fiber-optic sensor system for the transportation SHM is tremendous. Additional research in the development of fiber-optic sensors and system architecture for the transportation SHM will be necessary for the deployment of the transportation SHM systems.

9. REFERENCES

1. J Johnson, E. A., 2003. Innovative Bridge Structural Health Monitoring Using Variable Stiffness and Damping Devices. Metrans Research Project, Project Number 03-17.
2. Sumitro, S., Matsui, Y., Kono, M., Okamoto, T. and Fujii, K., 2001. "Long Span Bridge Health Monitoring System in Japan. Proceedings of SPIE," Vol. 4337, pp. 517-524.
3. Brackett, C. A., editor, 1989. *IEEE Communication Magazine: Special Issue on Lightwave Systems and Components*, Vol. 27.
4. Barry, R. A., editor, 1996. *IEEE Network: Special Issue on Optical Networks, vol. 10*.
5. Frangopol, D. M., Strauss, A., and Kim, S., 2008. "Bridge Reliability Assessment Based on Monitoring." *ASCE Journal of Bridge Engineering*, pp. 258-270.
6. Davis, A. R., Kirkendall, C. K., Dandridge, A., and Kersey, A. D., 1997. 64 "Channel All Optical Deployable Acoustic Arrays." Proc. 12th Conf. Optical Fibre Sensors, pp. 616.
7. Koo, K. P. and Kersey, A.D., 1995. "Bragg Grating Based Laser Sensor Systems with Interferometric Interrogation and Wavelength Division Multiplexing," *Journal of Lightwave Technology*, Vol. 13, pp. 1243-1249.
8. Kashyap, R. and Nayar, B. K., 1983. "An All Single-Mode Fiber Michelson Interferometer Sensor." *Jouranl of Lightwave Technology*, Vol. l1, pp. 619-624.
9. Hill, K. O., Fujii,Y., Johnson, D. C. and. Kawasaki, B. S., 1978. "Photosensitivity in Optical Fiber Waveguides: Application to Reflection Filter Fabrication." *Appl. Phys. Lett.*, Vol. 32, pp, 647-649.

10. Meltz, G., Morey, W. W., and Glenn, W. H., 1989. "Formation of Bragg Gratings in Optical Fibers by a Transverse Holographic Method." *Optics. Lett*., vol. 14, pp. 823-825.
11. Miguel, J. (2002). *Handbook of Optical Fiber Sensing Technology*.
12. Vengsarkar, A. M., Lemaire, P. J., Judkins, J. B., Bhatia, V., Erdogan, T., Sipe, J. E., 1996. "Long-Period Fiber Gratings as Band-Rejection Filters." *Journal Lightwave Technology*, vol. 14, pp. 58-65.
13. Canning, J., and Seats, M.G., 1994. "π-Phase Shifted Periodic Distributed Structures in Optical UV Post Processing." *Electron. Lett.*, vol. 30, pp. 1344-1345.
14. Erdogan, T. and Sipe, J., 1995. "Radiation Mode Coupling Loss in Tilted Fiber Phase Grating." *Optics Lett*. Vol. 20, pp. 1838-1840.
15. Byron, K., Sugden, K., Bircheno, T. and Bennion, I., 1993. "Fabrication Of Chirped Bragg Gratings in Photosensitive Fibers." *Electron. Lett.*, vol. 29, pp. 1659-1660.
16. Frangopol, D. M., Strauss, A., and Kim, S., 2008. "Bridge Reliability Assessment Based on Monitoring." *ASCE Journal of Bridge Engineering*, pp. 258-270.
17. Posey Jr., R., Johnson, G .A., and Vohra, S.T., 2000. "Strain Sensing Based On Coherent Rayleigh Scattering in An Optical Fiber." *Electron. Lett*., Vol. 36, pp. 1688-1689.
18. Sang, A. K., Froggatt, M. E., Gifford, D. K., Kreger, S. T., and Dickerson, B. D., 2008. "One-Centimeter Spatial Resolution Temperature Measurements in a Nuclear Reactor Using Rayleigh Scatter in Optical Fiber." *IEEE Sensors Journal*, Vol. 8, pp. 1375-1380.

19. Bao, X., Ravet, F., and Zou, L., 2006. "Distributed Brillouin Sensor Based on Brillouin Scattering for Structural Health Monitoring." Optical Fiber Communication Conference, 2006 and the 2006 National Fiber Optic Engineers Conference.
20. Nikle`s, M., Th´evenaz, L. and Robert, P. A., 1997. "Brillouin Gain Spectrum Characterization in Single-Mode Optical Fibers." *Journal of Lightwave Technology*, Vol. 15, pp. 1843-1851.
21. Cheung, M. S., Tadros, G. S., Brown, T., Dilger, W. H., Ghali, A., and Lua, D. T., 1997. "Field Monitoring and Research on Performance of the Confederation Bridge." *Canadian Journal of Civil Engineering*, Vol. 26, pp. 951-962.
22. Lau, C. K., Mak, W. P. N., Wong, K. Y., Chan, W. Y. K., and Man, K. L. D., 1999. "Structural Health Monitoring of Three Cable-Supported Bridges in Hong Kong." F. K. Chang, editor. *Structural Health Monitoring*. Lancaster (PA), Technomic; pp 450-460.