Second Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures

SMAR 2013

Advances in Discrete and Distributed Health Monitoring of Civil Structures by Fiber Optic Sensors

Farhad Ansari[1]

[1] Department of Civil and Materials Engineering, University of Illinois at Chicago, USA

ABSTRACT: The subject of Civil structural health monitoring (CSHM) is rapidly gaining stature due to the importance of condition assessment for safety of the infrastructure systems. CSHM pertains to methodologies and systems that together provide the necessary tools for diagnostics of the structures both old and new. Fiber optic sensors are very efficient in such applications. In addition to high resolution sensing, they can provide distributed measurements and or serial multiplexing capabilities. This article provides brief background information about optical fiber sensors, and in particular describes recent CSHM activities with discrete and distributed sensors. Fiber Bragg Gratings (FBG) based sensors and their applications in civil structures are described first followed by description of recent research in distributed sensing with Brillouin Scattering based sensors.

1 INTRODUCTION

Civil structural health monitoring pertains to instrumented assessment of structural behavior (Mufti, et al, 2004). The process is ideally optimized in terms of the cost and the outcome (Karbhari, et al, 2009). While the cost for placing multitudes of sensors may be justifiable in some applications, it is only good engineering design and planning that enables effective diagnostic outcomes. Optical fiber sensors provide competitive solutions when the optimized design calls for high quality interpretive data for the least total cost (Ansari,2005). The attributes of optical fiber sensors include low noise, immunity to electrical and electromagnetic interference, high sensitivity and resolution and capability for distributed sensing which enables efficient sensing opportunities both in terms of installation costs within large structures and sensing abilities (Measures, 2001). This article provides some basic background information about optical fiber sensors as well as recent research and applications. The main topics covered include applications of Fiber Bragg Grating (FBG) sensors in CSHM and recent developments in Brillouin Scattering based distributed sensors.

1.1 Background

Optical fibers transduce the mechanical perturbations by modulating the transmitted lightwave through change in length and refractive index of the fiber core. Sensor designs take advantage of the modulated optical signal for sensing of strain and temperature. Various interrogation techniques have been developed for conversion of the optical signals to the measurand of interest, including those based on signal intensity variations, phase and frequency shifts, and wavelength changes (Ansari, 1997). In a manner similar to strain gages, calibration of optical fibers is related to the strain and temperature sensitivities by appropriate gage factors. A complete review of theoretical basis for the establishment of strain and temperature sensitivities is given by Measures (2001). Some of the basic principles and methodologies for structural monitoring are given in Ansari (2007). This article focuses on practical examples in structural monitoring with FBG sensors and some recent structural monitoring experiments with Brillouin scattering based systems.

1.2 FBG Sensors

Principle of operation in FBG sensors is based on interrogation of strain induced wavelength shifts in optical fibers. The opto-thermo-mechanical process involved in fiber optic sensing relies on the optical path length, L_n, which is the product of the gauge length, L, and the core refractive index, n:

$$L_n = Ln \tag{1}$$

While L corresponds to the gauge length of the interferometric sensor, for FBG, L corresponds to the period of the Bragg and not the length of grating. FBG is sensitive to both changes in strain, $\Delta\varepsilon$ and in temperature ΔT. In the case of uniaxial strain field and the absence of thermal gradients, the strain is related to the change in the optical path length by way of the gauge factor, G_ε:

$$\frac{\Delta L_n}{L_n} = G_\varepsilon \Delta\varepsilon \tag{2}$$

In Eq. (2) the change in optical path length is proportional to the wavelength change:

$$\frac{\Delta L_n}{L_n} = \frac{\Delta\lambda}{\lambda} \tag{3}$$

Where, λ and $\Delta\lambda$ are the Bragg wavelength, and the wavelength shift in FBG, respectively. Therefore, the gage factors for FBG sensor is defined as:

$$G_F = \frac{\Delta\lambda / \lambda}{\varepsilon} \tag{4}$$

The calibration process for any of the FBG sensor is accomplished by mounting of the sensor to a calibration beam which is deflected to produce a known strain ε. The wavelength change is measured and the corresponding gauge factor is determined by Eq. (4). As shown in Figure 1, proper packaging of FBG sensors provides protection against damage and allows for configuration of the sensors to measure various types of structural effects (Ansari, 2007).

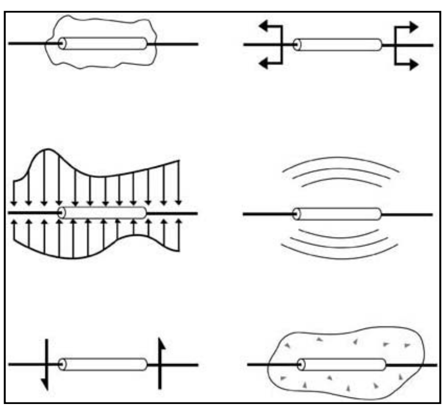


Figure 1 FBG packages for monitoring of structural perturbations (Ansari, 2007).

1.3 Brillouin Scattering Based sensors

The prevalent method for distributed sensing is based on Brillouin backscattering. It provides the local strain or temperature information in each spatial resolution over the fiber path (Horigochi, *et al.* 1995). Brillouin scattering occurs when light along the length of an optical fiber interacts with time dependent density variations in the core of the optical fiber resulting in a frequency shift in the optical signal. The frequency shift is calibrated against strain and or temperature and employed in structural sensing applications (Bao, et al., 1996, 2011).

Spatial resolution defines the smallest segment over which the distributed sensor is capable of discerning the average strain or temperature along the optical fiber length. Systems capable of resolving the strain distribution over shorter lengths provide higher resolution strain measurements and result in more accurate portrayal of strain gradients along the length of the optical fiber. Sensing of the distributed strains is achieved by resolving the average strains within the spatial resolution of the system at preprogrammed intervals along the lengths of structural elements. In general, the capability of the Brillouin Scattering based sensing system in interpreting the strain distribution is dependent on the spatial resolution of the system as well as the strain gradient over the sensing segment. Various approaches have been used in Brillouin-based sensing. One of the methods is Brillouin optical time-domain reflectometry (BOTDR) which is based on spontaneous scattering (Horiguchi *et al.*, 1995, 1989). The spatial resolution in conventional BOTDR systems is one meter. Recently, the theoretical as well as experimental investigations have been performed to characterize the Brillouin-based optical fiber sensors for CSHM applications (Motamedi, *et al*, 2012, Wu *et al.*, 2006).

The Brillouin frequency shift is linearly dependent on both the temperature and strain in a fiber. For isothermal conditions (i.e. ΔT =0) the relationship between strains and the Brillouin frequency shift is given by:

$$\varepsilon = \frac{1}{C_\varepsilon}[\nu_B(T_0,\varepsilon) - \nu_{B0}(T_0,\varepsilon_0) + \varepsilon_0 \quad (5)$$

Where ε is the strain at points along the optical fiber averaged over the spatial resolution, C_ε is the strain coefficient and determined by calibration. T_0 and ε_0 are the strain and temperature corresponding to the reference Brillouin frequency, ν_{B0}.

2 FBG IN STRUCTURES

FBG sensors provide advantages over the conventional sensors in this respect as they can be serially multiplexed. Serial multiplexing is achieved through wavelength division multiplexing (WDM) in which each FBG is designed to operate at a specific wavelength (Figure 2). Therefore, a number of sensors can operate along a single line of optical fiber. WDM also allows for tagging the location of the specific sensors within the structural system. The maximum number of FBG sensors that can be used in series is dependent on the strain requirements. This in turn depends on the fact that strains can only vary within the scanning bandwidth of the system which currently ranges between 60 to 90 nm. A wavelength shift of ±1.2nm corresponds to about $\pm 1000\ \mu\varepsilon$/ Therefore, for strains in the order of $\pm 2000\ \mu\varepsilon$, it will be possible to practically install around fifteen sensors along a single line of optical fiber. It is possible to install more sensors in lower strain applications, but the numbers will reduce for applications that require larger strains (Ansari, 2007).

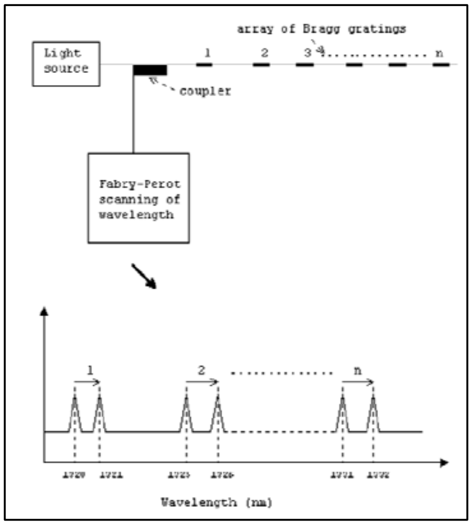


Figure 2Serial multiplexing of FBG sensors (Ansari, 1997).

2.1 Crack Sensors in Seismic Tests

Bassam, et al (2011) reports on seismic tests on a quarter scale of a 4-span bridge that was designed and constructed per near-fault provisions of the California Department of Transportation (Caltrans, 2004). The bridge piers were each secured on a 4.3 m x 4.3 m shaking table. The shaking tables had a force rating of 734 kN; a maximum dynamic displacement range of ±300 mm, and a maximum velocity and acceleration of ±1270 mm/sec and 1 g at 45.352 tons, respectively. The bridge is shown in Figure 3.

Figure 3 Quarter scale prototype of the four span bridge on shaking tables.

The experiments involved application of pre-programmed seismic motions to the bridge through the shaking tables. Monitoring of the column curvatures was achieved by instrumenting two bridge bents with surface adhered fiber optic Bragg grating sensors (FBG). The sensors measured the column deformations over 100 mm gauge lengths. Moreover, it was desirable to limit the number of sensor leads from the bridge to a minimum in these experiments and FBG sensors provided the capability for serial splicing of several sensors on one lead-line. The columns were expected to crack at the plastic hinge zones and for this reason the FBG sensor assembly (package) was designed to withstand the large dynamic deformation reversals, and with capability for measuring large crack opening displacements (i.e. 10 mm). Figure 4 shows a number of the crack sensors on the bridge pier.

Figure 4 FBG crack sensors on the bridge piers (Bassam, et al, 2011).

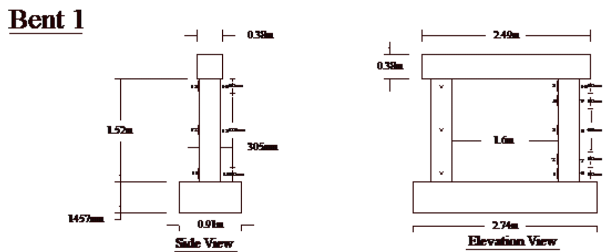


Figure 5 Displacement sensors along the lenght of the piers (Bassam, et al, 2011).

In addition to the location of plastic hinge zone, the FBG displacement sensors were also bonded along the length of the column (Figure 5). The measured deformations along the length of the columns were used for computation of curvatures and for the computation of pier lateral displacements. To evaluate the accuracy of this approach, the bent displacements were also directly measured in the laboratory by string sensors using the laboratory strong walls as the sensor references. The direct measurements by the string sensors and the deformation based lateral displacements of the bents are compared in Figure 6. As shown, results agree well. Details regarding this application can be found in Bassam, et al (2011). Moreover, these types of crack sensors were also employed in monitoring the cracks in the masonry vaults of the Brooklyn Bridge in New Yourk City (Talebinejad, et al, 2011).

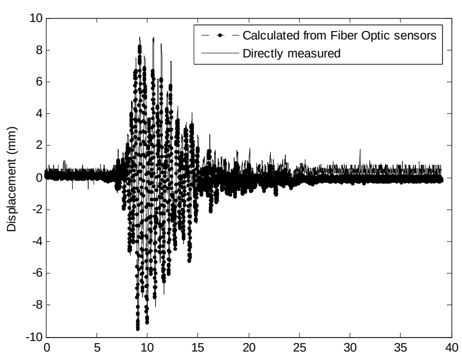


Figure 6 Typical time history comparison between calculated displacements and direct measurement (Bassam, et al, 2011)

2.2 FBG Accelerometers

Talebinejad, et al (2009) describes development of an FBG based accelerometer for use in structural health monitoring of bridges. The accelerometer utilizes the stiffness of the optical fiber and a lumped mass in the design. Acceleration is measured by the FBG in response to the vibration of the fiber optic mass system. The wavelength shift of FBG is proportional to the change in acceleration, and the gauge factor pertains to the shift in wavelength as a function of acceleration. The accelerometer is shown in Figure 7. The accelerometer was first evaluated in laboratory settings and then employed in a demonstration project for condition assessment of a bridge. Laboratory experiments involved evaluation of the sensitivity and resolution of measurements under a series of low frequency low amplitude conditions.

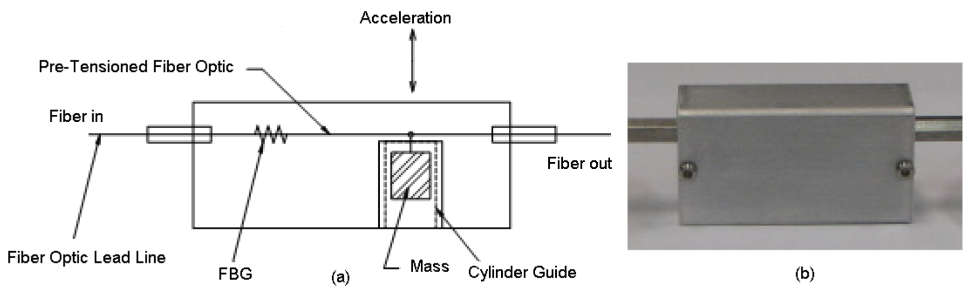


Figure 7; (a) schematic design of the FBG accelerometer; (b) photo of the FBG accelerometer (Talebinejad, et al, 2009).

The performance of the FBG accelerometers was verified by using them to monitor the vibrations of a full scale bridge. The structure used in this study was a single span slab-on-girders Bridge located in a western suburb of Chicago. Figure 8 shows the location of FBG accelerometers on the two sides of the bridge. Conventional accelerometers were also employed in order to compare and evaluate the performance of the accelerometers.

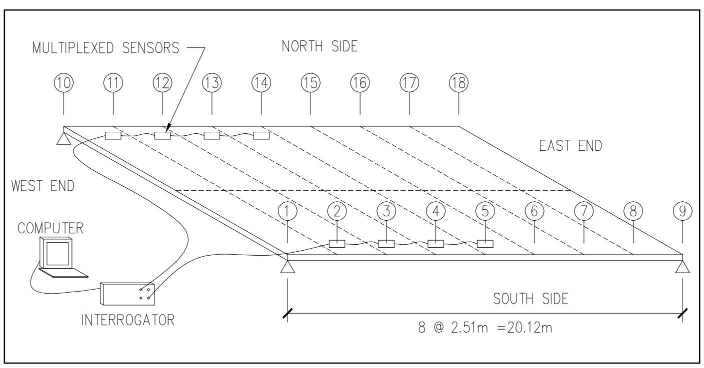


Figure 8 Accelerometer locations on the bridge (Talebinejad, et al, 2009).

The FDD identification method was used to extract the modal properties of the bridge from ambient vibration data. Figure 9 corresponds to the estimated first mode shapes from both the FBG and conventional accelerometers. They provide identical results. The advantage of FBG sensors in this case was that all of the sensors were connected to two channels of data acquisition, whereas for the conventional accelerometers data acquisition required8 independent channels and therefore eight leads to the sensor lines in the bridge.

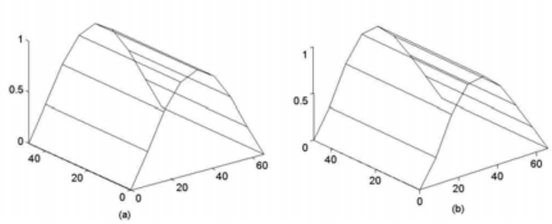
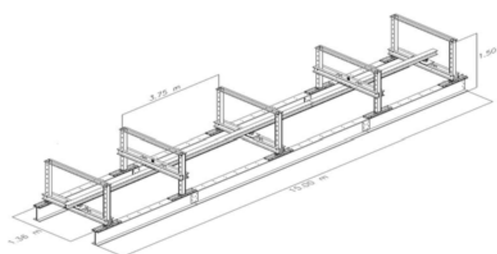
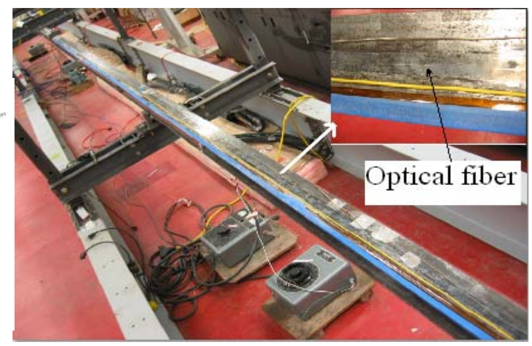


Figure 9 First bending mode shape a) conventional accelerometer b) FBG accelerometer (Talebinejad, et al, 2009).

3. Distributed Sensing with BOTDR

The distributed sensing capability of BOTDR based sensors was recently evaluated by Motamedi, et al (2012). Their study pertained to building of a large scale laboratory test bed to perform basic experiments and to study the effect of low spatial resolution measurements on the sensed strains. Motamedi, et al (2012) also developed a numerical aproach for quantification of defects such as cracks and their growth on the measured strains. The 15 meter long beam in the test frame is shown in Figure 10. The beam had two simulated defects each at 4.6 meters away from the beam ends. Also shown in Figure 10b is the close up view of the adhered fiber optic distributed sensor. The beam was subjected to several different load pattens and load intensities. Results from Motamedi, et al's (2012) study indicated that the one meter spatial resolution of the BOTDR was sufficient to indicate the abnormalities at the defects (Figure 11), but not adequate to exactly quantify the location of the cracks. They were able to develop a finite element based approach in order to pinpoint the defect locations. Typical results from a four-point loading pattern by the BOTDR and comparison with FEM computations are shown in Figure. 12.





(a) Schematics of the test setup **(b) 15 meter long beam with optical fiber sensor**

Figure 10 Experimental setup (Motamedi, et al, 2012).

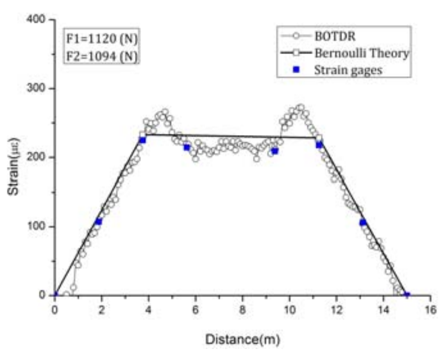


Figure 12 Comparison of the BOTDR with conventional strain gauges and FEM results (Motamedi, et al, 2012)

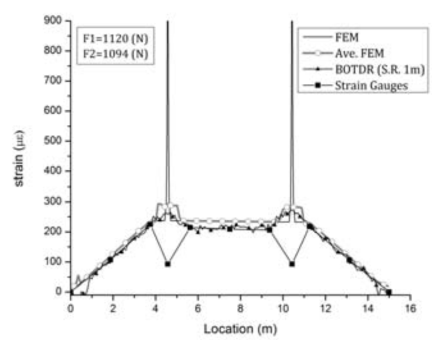


Figure 11Comparison of the BOTDR results with FEM enhanced crack detection capabilities (Motamedi, et al, 2012)

4. Conclusions

This article provided a brief review of basic principles of discrete and distributed optical fiber sensors.

Examples were provided demonstrating the applicability of the sensors in monitoring of civil structures and elements. In terms of FBG sensors, the examples demonstrated that with proper packaging FBG sensors possess capability for sensing of a variety of perturbations including strains, displacements, accelerations, and other types of effects. Two examples were given for completeness. In the case of distributed sensors, results from basic experiments on a long beam with defects were provided in order to demonstrate the potential applications of the sensor in structural monitoring. Further details regarding the applications covered in this article can be found in the references cited.

5. References

Ansari, F. (1997). State-of-the-art in the Applications of Fiber Optic Sensors to Cementitious Composites, Journal of Cement & Concrete Composites, 19(1):3-19.

Ansari, F., (2005).Sensing Issues in Civil Structural Health Monitoring, Springer Publishing Co., The Netherlands. 2005, p. 527.

Ansari, F. (2007). Practical Implementation of Optical Fiber Sensors in Civil Structural Health Monitoring. Journal of Intelligent Material Systems and Structures , 18 (8): 879-889.

Bao, X., Webb, D.J., and Jackson, D.A. (1996). Distributed temperature sensor based on Brillouin loss in an optical fiber for transient threshold monitoring. Canadian Journal of Physics. 74(1–2): 1–3.

Bao, X., and Chen, L. (2011). Recent progress in Brillouin scattering based fiber sensors. Sensors 11(4): 4152–4187.

Bassam, A., Iranmanesh, A., Ansari, F. (2011).A simple quantitative approach for post earthquake damage assessment of flexure dominant reinforced concrete bridges. Journal of Engineering Structures. 33(12):3218-3225.

Caltrans, (2004). Bridge design specifications. Technical Publications. Section 8: 1–58.

Horiguchi, T., and Tateda, M. (1989). Tensile strain dependence of Brillouin frequency shift in silica optical fibers. IEEE Photonics Technology Letters. 1(5): 107–108.

Horiguchi, T., Shimizu, K., Kurashima, T., Tateda, M., and Koyamada, Y. (1995). Development of a distributed sensing technology using Brillouin scattering. Journal of Lightwave Technology, 13(7):1296-1302.

Karbhari, V., Ansari, F., (2009).Structural Health Monitoring of Civil Infrastructure Systems. Woodhead Publishing, Ltd. p. 517.

Measures, R. (2001). Structural Monitoring with Fiber Optic Technology. London: Academic Press.

Motamedi,H., Feng, X., Zhang, X., Sun, C., and Ansari, F. (2012). Quantitative investigation in distributed sensing of structural defects with Brillouin optical time domain Reflectometry. Journal of Intelligent Material Systems and Structures. DOI: 10.1177/1045389X12470309

Mufti, A., Ansari,F., (2004).Structural Health Monitoring. Proceedings of Second International Workshop on Structural Health Monitoring of Innovative Civil Engineering Structures. Winnipeg, Canada. p. 617.

Talebinejad, I., Fischer, C., Ansari, F. (2011). A hybrid approach for safety assessment of the double span masonry vaults of the Brooklyn Bridge. Journal of Civil Structural Health Monitoring. 1(1-2):3-15.

Talebinejad, I; Fischer, C; Ansari, F. (2009). Serially Multiplexed FBG Accelerometer for Structural Health Monitoring of Bridges. Journal of Smart Structures and Systems. 5(4):345-355.

Wu, Z., Xu, B., Hayashi, K., et al. (2006).Distributed optic fiber sensing for a full-scale PC girder strengthened with prestressed PBO sheets. Journal of Engineering Structures 28(7):1049–1059.