Title: Brillouin Scattering Fiber Optic Strain Sensor for Distributed Applications in Civil Infrastructure

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ABSTRACT

Use of fiber optic sensors is a viable real-time data gathering approach by surface adhering or embedding the optical fiber into a host specimen under evaluation. The specifications and the functionality of the current Brillouin scattering fiber optic sensor developed at Lehigh University are presented and exemplified in this paper. The sensor is tested first for measurement of static, pseudo-dynamic and dynamic strains in civil-infrastructure, and secondly for detection and content measurement of water in soil.

INTRODUCTION

On-line monitoring of civil-infrastructure, such as steel frames, embedded piles and anchors subject to vibrations or environmental effects, is of great interest to civil engineers. Wireless sensors have been shown to provide good monitoring capability. Although highly versatile in open air, such sensors may not be as versatile in the embedded environments. The distributed sensing capability using Brillouin scattering optical fibers offers a viable method to continuously monitor buried structures, as well as those on surface [1,2,3].

The Brillouin scattering in standard optical fibers makes it possible to obtain strain measurements by time domain reflectometry at intermitted positions along a single fiber subject to thermal or mechanical loading. The entire fiber length - in meters or kilometers - can be used for sensing with spatial resolution of measurement varying from about several centimeters to several meters [4].

Strain sensing capability of Brillouin Optical Time Domain Reflectometry (BOTDR) was successfully demonstrated for long gauge lengths for structural

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monitoring [5,6]. The sensor requires access to only one end of the fiber, which simplify the fiber layout on the structure and uses a single laser source preventing measurement errors from two laser emission fluctuations. The measurement technique enables the use of low birefringence optical fibers, which are economical compared to polarization maintaining fibers. Low birefringence fibers can be spliced with inconsequent power losses such that fiber sections can be affixed on separate structural elements and spliced together as the complete structure is assembled.

The strain sensing capability of the fiber can also be used to detect other variations in the host material, such as temperature, liquid and chemical content [7,8]. In these, the fiber is hitched or bonded to a selective polymer material in direct contact with the surrounding medium. The polymer reacts to the surrounding (i.e., moisture, pH, chemical) by swelling as it selectively absorbs the target compound. Swelling of the polymer produces tangential, axial or radial stresses on the fiber depending on the physical coupling, hence axial straining and Brillouin signal. A single line of fiber stringed with polymer mass detectors at predetermined spacing can be embedded into a host medium (i.e. pipeline, under paved surfaces, porous media such as soil or concrete) to detect target chemical(s) by linear positioning of the fiber.

BACKGROUND

Brillouin scattering based sensing

In a dielectric material like the silica of an optical fiber, material tends to compress in the regions of high intensity electrical field (electrostriction). Periodic compression zones create a density wave moving in the material (9). If the speed of this wave corresponds to the speed of sound in the material, an acoustic wave is created. Brillouin Scattering results from the scattering of the incident (pump) light by the acoustic waves. The scattered light is shifted downward in frequency to the Stokes frequency. The separation between the frequencies of the incident and scattered light is called the Brillouin frequency shift, υ_B, given as follows:

$$\upsilon_B = \frac{\omega_p - \omega_S}{2\pi} = \frac{2nV_A}{\lambda_p} \tag{1}$$

where, ω_p, and ω_S, are the frequencies of the pump and the Stokes waves, V_A and n are the acoustic velocity and the refractive index of the fiber core, respectively; and λp, the wavelength of the pump lightwave. According to equation (1), the Brillouin frequency shift, υ_B is directly proportional to the acoustic velocity of the optical fiber. The elastic properties of silica make any induced strain result in locally modified material density, hence change in its acoustic velocity, V_A. When the refractive index, n, of the fiber is known, by measuring the Brillouin shift υ_B, one can determine the local change in the acoustic velocity, hence the induced strain. Knowing the proportionality coefficient between the two quantities, one can obtain the strain corresponding to υ_B measured at discrete points along the fiber, as given in equation (2):

$$\varepsilon - \varepsilon_0 = \frac{\upsilon_B - \upsilon_{B(\varepsilon_0)}}{C\upsilon_{B(\varepsilon_0)}} \qquad (2)$$

where, C is the dimensionless proportionality coefficient that describes the collective change in refractive index, elastic modulus, mass density and Poisson's ratio of the silica core subjected to strain; and $\upsilon_{B(\varepsilon 0)}$ is the Brillouin frequency of the fiber at a reference strain, ε_0. Fiber optic strain measurements should be compensated for temperature perturbations of the environment or the specimen under test. The following equation describes a formulation for strain corrected for temperature:

$$\varepsilon - \varepsilon_0 = \frac{1}{C_1 \upsilon_{B(\varepsilon_0, T_0)}} \left[\upsilon_B - \upsilon_{B(\varepsilon_0, T_0)} (1 + C_2 \Delta T) \right] \qquad (3)$$

where, T_0 is reference temperature and,

$$C_1 = \frac{\partial \upsilon_{B(T_0)}}{\partial \varepsilon} \bullet \frac{1}{\upsilon_{B(\varepsilon_0, T_0)}} \qquad C_2 = \frac{\partial \upsilon_{B(\varepsilon_0)}}{\partial T} \bullet \frac{1}{\upsilon_{B(\varepsilon_0, T_0)}}$$

$\upsilon_{B(\varepsilon 0, T0)}$ = Brillouin frequency measured at reference strain & temperature
$\upsilon_{B(T0)}$ = Brillouin frequency measured at test strain & reference temperature
$\upsilon_{B(\varepsilon 0)}$ = Brillouin frequency measured at test temperature & reference strain

Equation (3) reduces to Equation (2), with C_1=C, for isothermal conditions.

EXPERIMENTAL WORK

Advances in photonics assembly

The current Brillouin Scattering photonics assembly developed and tested at Lehigh University[1] uses a single laser light source. In this assembly (Figure 1) two light waves, the pump and probe, are generated from the same distributed feedback (DFB) laser source at 1550nm. They are passed through a gated electro-optic modulator (EOM) driven by a microwave generator. The "pump" is a forward propagating pulsed light interacting with "probe", a continuous light reflected from the far end of the fiber. The EOM is used for pulsing light to form the pump signal, and for the generation and frequency tuning of the probe light. A microwave signal applied on the EOM electrodes creates side bands. The pulsed pump interacts with the lowest frequency sideband and the energy is transferred when the frequency difference between the two corresponds to the Brillouin frequency shift of the fiber. The signal emerging from the circulator is passed through a 25GHz bandwidth filtering Bragg grating (FBG) and finally recorded on a sampling oscilloscope.

[1] http://www.nees.lehigh.edu http://www.lehigh.edu/optics/

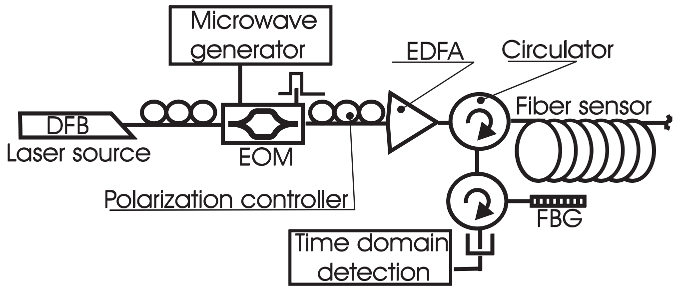

Figure 1. Lehigh's frequency modulated Brillouin photonics assembly

The input polarization state of both pump and probe signals are monitored with a programmable digital polarization controller. This technique was developed and tested to maximize the gain at the strained sections, hence improve the accuracy of locating strains while maintaining a high data acquisition rate. A linear polarizer and an optical power meter were added to the photonics set up for initial calibration runs. First, the linear polarizer is placed at the exit of the fiber at a set angle of θ. The exiting power is maximized while the entry state of polarization (SOP) of the wave is adjusted with the polarization controller. The procedure is repeated with the polarizer rotated by ±π/4 to the initial θ, and the configurations of the polarization controller at maximum optical power for both angles of rotation are stored for calibration. Hence, two superimposed gain profiles polarized at angles separated by π/4 were used for each strain measurement to alleviate the polarization effects.

In a typical test, the pump power is observed to deplete with distance in the fiber and thus reduce the length of fiber usable for measurements. In the current set-up, the probe power launched in the fiber is increased such that the maximum energy transfer from pump to probe through Brillouin interaction is decreased and therefore the pump power depletion is limited. The rate of data acquisition was also improved to meet the demands for dynamic or pseudo dynamic testing. The current assembly can be used in two different modes: (1) fast acquisition for small strain range suitable for measurement of dynamic strains, (2) slow acquisition with full coverage of the possible strain range suitable for static or pseudo dynamic tests.

Calibration of strain sensor

For calibration of the test fiber (*Corning SMF28*) as a distributed strain sensor, 86.4cm section of 120m-fiber was secured at two end points. The fiber was strained incrementally (increments of 230 με) using a translation stage with measurement accuracy of 10με. Next, the same fiber was set in a 3-pulley system and loaded with several calibrated weights– from 1kg to 7kg in 1kg increments. The stress in the fiber was computed using the applied load and the cross-sectional area of the fiber (core and cladding diameter 125 μm). The corresponding Brillouin frequency shift was recorded for each applied stress. The variation of the independently measured Brillouin frequency shift with the applied strain and the stress are shown in Figure 2. Since each frequency corresponds to a unique stress and strain in the fiber, a one-to-one relation is found between the independently measured values.

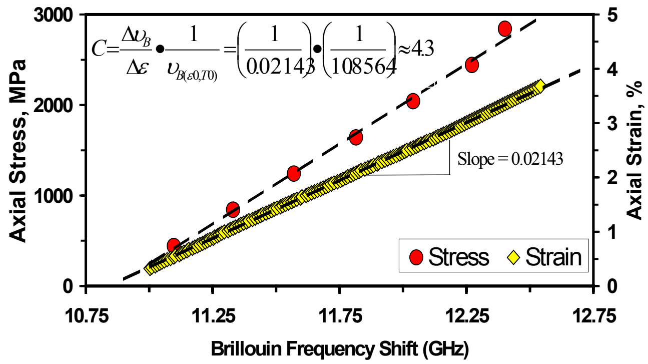

Figure 2. Brillouin frequency with independently measured stress & strain to *Corning SMF28* fiber

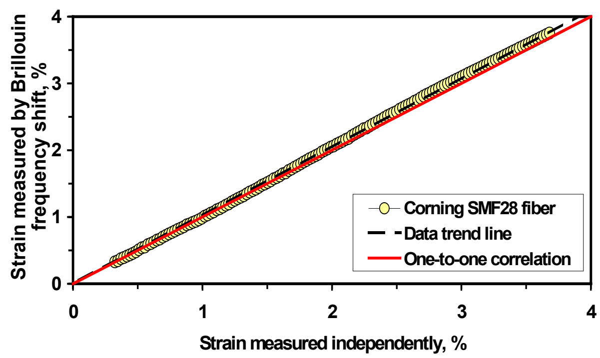

Figure 3. Calibration verification of Brillouin based strain with independently measured strains

Hence, the Brillouin determined stress-strain relation of the test fiber resulted in elastic constant of 79.7GPa, which is slightly higher than that of pure silica fiber (72GPa). This deviation is expected since most of the commercial optical fibers are doped with property enhancing elements (i.e., germanium).

The independently measured strains of the test fiber are compared to those computed by Equation (2) using a theoretical C constant for fused silica (= 4.14). The Brillouin frequency based strains agree well with the measured strains as observed in Figure 3. Since isothermal conditions were maintained the temperature calibration was not used in these tests.

Development and calibration of soil water content sensor

Preliminary work consisted of using hydrophilic polymer rings hinged to optical fiber to detect water in porous media. The dimensions of the polymer rings were 6.5cm OD, 5.5cm ID and 0.8cm wide. The outer edge of the ring was threaded to host tightly wound fiber sections, each 82 cm long. The fiber was glued to the polymer at two points with high strength marine glue. A tightly fitting acrylic disc (5.5cm OD) was inserted inside the ring to prevent inward radial swelling. The volumetric expansion was observed to take place principally in the radial direction due to the orientation of the polymer chains in the material (AEP60[3]). The polymer transducer was specifically manufactured for the liquid content detection in this experimental program. Its maximum volumetric expansion was determined to be 227%, with hydrated tensile modulus of 0.45MPa.

The degree and rate of the volume change of the polymer ring were mapped to local longitudinal strains, hence to Brillouin signals over the coupled sections of the optical fiber. Since Brillouin readings could be recorded for strains as low as 10με,

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[3] IH Polymeric Products, Andrews Wright Limited, Absorption and Expansion Polymers, Kent, UK

very small volume changes due to liquid exposure could be detected in a few minutes. Figure 4 shows the time rate of swelling and shrinkage of the hydrophilic transducers as correlated to the Brillouin signal measurements. The transducers reside on the same line of fiber, yet each is embedded in a compacted clay specimen of different water content (5% to 30%) as shown in the sketch (inset Fig. 4). As observed in Figure 4, the maximum Brillouin signal and its rate increase with increasing soil water-content, while the duration of full swelling decrease.

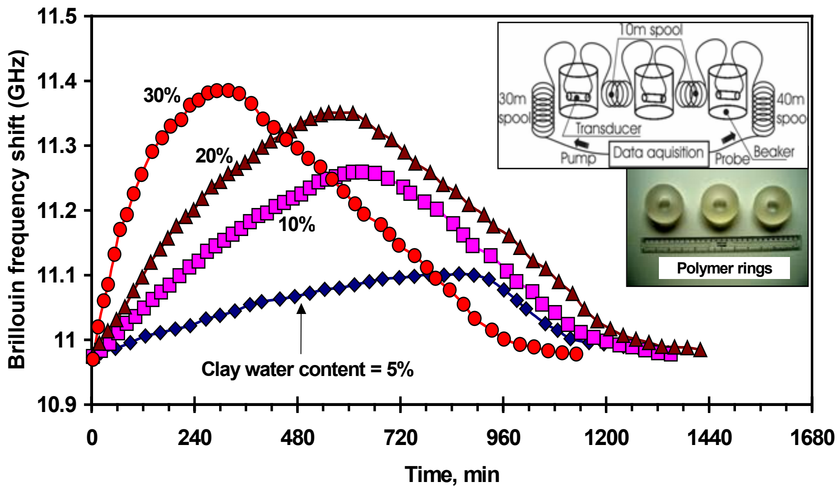

Figure 4. Brillouin signal shift as a function of swelling/shrinkage time and clay water content (inset – sketch of experimental set up and picture of polymer rings)

Strain measurements from a pseudo dynamic test

A 10ft (3.05m) high and 2ft (0.61m) diameter reinforced concrete column with a 4ft (1.22m) high cap was subjected to a shock load by the means of two load actuators at the George E. Brown, Jr. NEES laboratory facilities of Lehigh University. In this application, 157ft (48m) sensing optical fiber (*Corning SMF28*) was wrapped around the column in the middle half section, as shown in Figure 5. The fiber was continuously glued onto the surface of the concrete with a high strength epoxy. The 25 layers were separated by 2.5in (~6.3cm). The two-directional force (each 1000KN) was applied and released for a short duration of time (~ 1s) to simulate an earthquake shock.

The concrete column hoop strain measurements were taken along the fiber at every 0.18 seconds with a resolution of about $2x10^{-5}$ (20με). The maximum strain profiles (ε_{max}) obtained at peak force and those approximately 10 minutes after the cancellation of the actuator thrust ($\varepsilon_{residual}$) are shown in Figure 6. The layer index in these graphs refers to the fiber layer number 1 through 25, from bottom to top, respectively. The strains were measured at two locations on opposite sides of the column cross-sectional axis, one on the side of the actuators and the other on the opposite side. Although the results of this test are not conclusive with independent verification, they exemplify the viability of using distributed fiber optic sensing to measure strains in a specimen under a pseudo dynamic test.

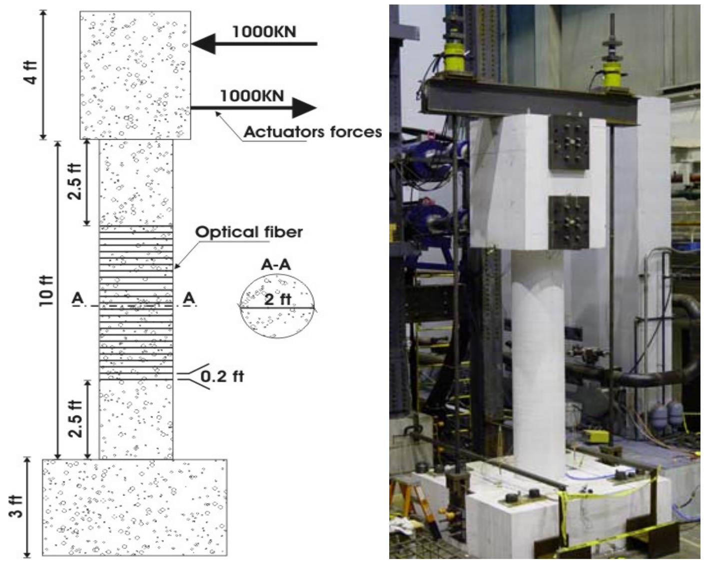

Figure 5. Large-scale test column with optical fiber layout
(Lehigh George E. Brown, Jr. NEES laboratory)

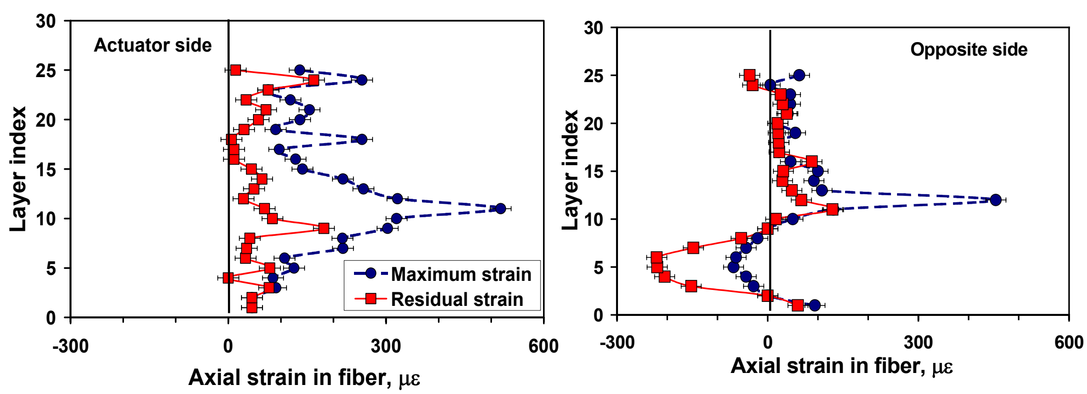

Figure 6. Strain measurement in fiber layers during and after the load

Strain measurements from damped harmonic oscillations

The test set up, as shown in Figure 7 consisted of a 914-mm simply supported steel bar. Lumped masses, each 1360g, were located at 254mm from each end of the bar. The cross section of the bar was 38mm wide and 3.2mm thick. The Young's modulus of elasticity was 203GPa, and the fundamental damped natural frequency was determined 4Hz.

The *Corning SMF28* test fiber was epoxy glued inside a thin groove running over one side of the long span of the steel bar. The total length of the test fiber was 35 meters, of which only 800mm-section was bonded to the test bar. When the bar was flexed towards the fiber side, the fiber stretched measuring positive strains and compressed when the bar was flexed in the opposite direction. A typical test consisted of manually applying about 50 mm deflection at the center of the steel bar and releasing it into free vibration. The sensor readings, averaged over the 800mm bound fiber were recorded every 10ms with 0.01% accuracy. A conventional strain gauge mounted on the bar was used to verify independently the fiber optic sensor measurements. Figure 8 shows a comparison of the strains induced by the free vibration of the steel bar as measured by the fiber optic sensor and the conventional strain gauge. The two plots follow each other very closely with average frequency of oscillation of 4.2Hz (close to the theoretical natural frequency of 4Hz), and a maximum measured strain of approximately 500με.

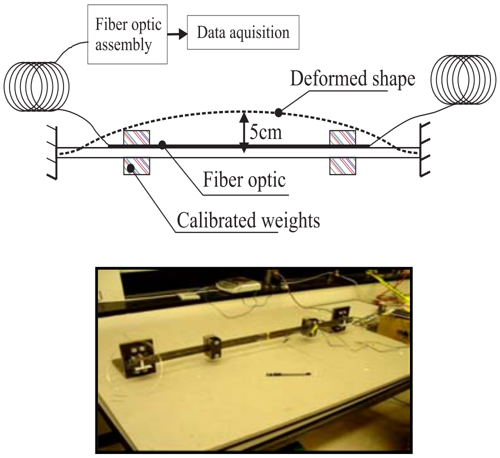

Figure 7. Oscillation test set-up

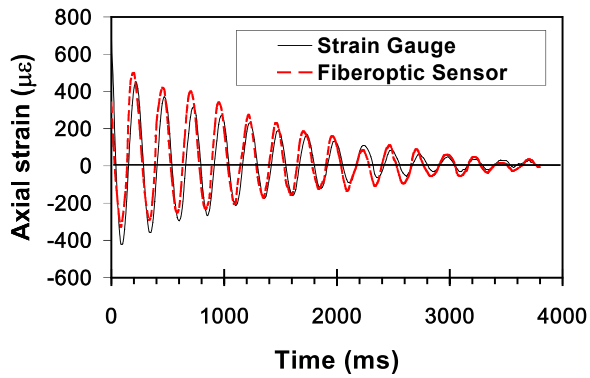

Figure 8. Damped oscillation measurements using the fiber optic sensor and strain gauge

CONCLUSIONS

Strain sensing capability of Brillouin scattering low birefringence optical fiber was used to demonstrate its potential to measure strains in host specimen under dynamic loading. The same capability was also shown to be viable for subsurface measurements such as water content of soil medium.

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