Overview of Recent Bridge Monitoring Applications using Distributed Brillouin Fiber Optic Sensors

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Abstract

Brillouin fiber optic sensor technology is a promising technology for structural health monitoring (SHM) thanks to its unique feature of distributed strain and temperature measurement by means of low-cost optical fibers. Amortization of relatively expensive data acquisition systems can be facilitated by the discontinuous monitoring of multiple structures. However, the lack of specifically developed sensor materials and equipment prevents the advancement of the technology from laboratory testing towards significant practical implementation. This paper presents an overview of recent applications on two small concrete bridges and a five-span, 864-ft long, slab-on-girder bridge in Missouri (USA). The performance of both adhesively bonded bare optical fibers and a novel composite tape with embedded sensors is discussed. Results provide evidence of the feasibility and effectiveness of Brillouin based fiber optic sensor monitoring of civil structures.

INTRODUCTION

Structural health monitoring (SHM) is a practice capable of producing a detailed assessment of the evolution of the structure's health condition during all its life. Such a detailed knowledge database can produce savings through an optimization of the maintenance intervention and through the possibility of extending the life of the infrastructure while at the same time keeping an optimal safety level.

Fiber Optic Sensors (FOS) in general have been often proposed to substitute for traditional electronic sensors in SHM applications. FOSs are generally much more expensive than traditional sensors, and only in rare cases can the cost increment be tolerated by real applications.

Brillouin FOS technology is to be considered an exception to this general trend, since it features distributed strain sensing; that is, the capability to simultaneously measure the strain level and locate the strained point along the sensor. This feature, which has no performance equivalent among the traditional electronic sensors, is to be considered extremely valuable. When the sensors are opportunely installed on the most significant structural members, this system can lead to the comprehension of the real static behavior of the structure rather than merely measuring the punctual strain level on one of its members. In addition, the sensor required by Brillouin technology is an inexpensive, telecom-grade optical fiber that shares most of the typical advantages of FOS such as high resistance to moisture and corrosion and immunity to electro-magnetic fields.

BRILLOUIN SHM

Brillouin effect is an anelastic scattering process between optical photons and vibration waves (phonons), propagating in the same physical medium. In a light guide, such as an optical fiber, pumped with monochromatic light, Brillouin effect produces a few scattered photons with a certain wavelength shift with respect to the original wavelength. This shift has been found to be proportional to the temperature and to the strain condition of the light guide medium, that is, the optical fiber itself. Recently, thanks to advancements in LASER self-heterodyne techniques, equipment with a resolution sufficient for strain measurement as low $20 \cdot 10^{-6}$ ($20\mu\varepsilon$) has been made available [1].

Despite the strong advantages offered by Brillouin FOS, its industrial diffusion is rather small, which is believed to be mainly because of the high cost of the test equipment and because of the scarce diffusion of fiber optic products specifically addressed to SHM installations. A wiser cost analysis should, however, take into account the cost of the sensor, which is extremely low, and the capability to scan up to some thousands of meters of installed sensors "at a glance" from one of the ends of the fiber, with a time consumption of 20-30 minutes. Such a combination of features would make it economically convenient to share the same expensive Brillouin equipment with a large number of different SHM sensor installations that are interrogated periodically.

In addition to the economic aspect, also notice how common optical fiber cables that are commercially available cannot be as easily employed as Brillouin strain sensors can. In fact, most commercial cables adopt features intended to insulate the fibers from any externally induced stress, thus preventing any possibility of using them as strain sensors. Then, the few telecom-grade fibers without strain insulation can be easily damaged by shocks and bending that are common in a construction yard environment and can introduce unwanted optical attenuation if installed on rough surfaces.

To mitigate these problems, some fiber sensors specifically addressed to Brillouin SHM have been developed (Fig. 1):

a) The first known Brillouin fiber sensor for embedding into concrete seems to have been jointly developed by Nippon Telegraph and Telephone (NTT) and Shimizu Corporation. These sensors feature an inner FRP core hosting the optical fiber, and an outer molded coating that carries helical grooves intended to enhance adhesion to concrete.

b) A “smart” composite was obtained by adding one or more optical fibers to the glass, carbon, or aramid weft of a woven textile [2]. The added structural fibers protect the optical sensors both during handling and during the life of the installation; furthermore, they can add structural strengthening when required (*i.e.,* for retrofit and repair porpoises or to achieve intrinsic averaging of the strain measurement on cracked substrates). By embedding multiple optical fibers, additional advantages can be achieved (*e.g.,* sensor redundancy and distributed thermal compensation by using a combination of fibers sensitive to both strain and temperature or temperature only).
c) A thermoplastic ribbon featuring multiple optical fiber for strain sensing and thermal compensations is also known.

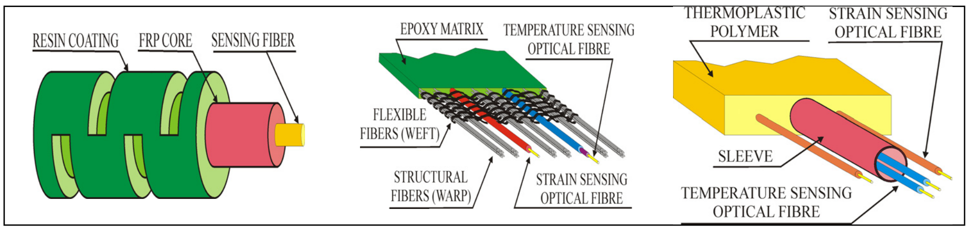

Fig. 1 Brillouin SHM sensors: RC-embeddable cord (left), woven “smart” FRP (center), and extruded rod (right).

APPLICATION TO CONCRETE MEMBERS

Reinforced Concrete (RC) structural members can exhibit cracking even in normal working conditions, and a correct assessment of the strain level in the tensile stress area must take into account the opening of cracks. Most strain sensors’ traditional resistive strain gauges and also innovative FOS devices (*e.g.,* Bragg and Fabry-Perot sensors) are characterized by a measurement basis of a few centimeters or a few millimeters, respectively, which are in general too small for the cited purpose.

“Long measure basis” gauges (*e.g.,* some low-coherence, interferometric FOSs) offer better accuracy performances on cracked concrete. However, these “long gauges” lose all the information about the distribution of the cracks, which is often extremely important to distinguishing a normal static behavior from conditions with a similar average strain value but produced by anomalous behavior.

Brillouin sensing, thanks to the distributed sensing feature, is to be considered the ideal solution to such a problem, being capable to simultaneously measure the strain and locate its distribution. Unfortunately, most of the Brillouin analyzers commercially available at present are characterized by a strong interdependence between the accuracy of the strain measurement and the fiber length over which the deformation is evaluated. Considering a step-like strain distribution, all analyzers show an intolerable accuracy loss when most of the strain becomes concentrated into cracks of few millimeters (or less) each. Some attempts are known to mitigate this problem by gluing the optical fiber sensor to the substrate in discrete points equally distanced 3.3ft (1m) or more or by using multiple fiber loops [3]. However, both methods are difficult to apply to field conditions and may introduce unwanted optical losses.

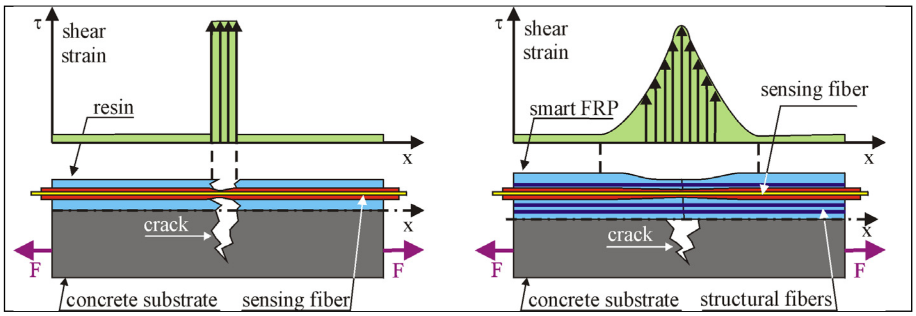

Fig. 2 Stress distribution over a crack for conventional FO sensor (left) and of "smart" FRP (right).

The "smart" Brillouin FRP sensor offers a suitable solution to this problem. Thanks to the stiffening effect of the structural fibers in the weft, when a crack opens in the substrate to which the "smart" sensor is bonded, the deformation is redistributed in a portion of FRP material longer than the crack width. This process happens because the shear transfer process between the substrate and the FRP material is spread on to a certain "transfer length" that is influenced by its own FRP stiffness and, for carbon-FRP materials, is found to be typically several inches long [4].

Furthermore, in similar conditions, the strain distribution on the sensing fiber approaching the crack location becomes much more gradual than the step-like distribution that is assumed without the effect of the stiffening fibers (Fig. 2).

Thanks to both the longer strained length and smoother strain distribution, "smart" FRP Brillouin sensors can maintain sufficient accuracy even in the case of cracked substrates and, therefore, represent an ideal solution for SHM of RC structural members.

EXPERIMENTAL APPLICATIONS ON RC BRIDGES

The accuracy performances of the "smart" FRP Brillouin material described in the previous section have been experimentally evaluated through a comparison between two similar SHM applications. Bridge #1330005, a small RC girder-type bridge with total span of 26ft (7.93m) in Phelps County (MO, USA), has been equipped with a traditional Brillouin SHM. The sensing fibers where installed using a Near to Surface Mounting (NSM) technique, consisting in milling 1" (2.54cm) square grooves in the concrete surface and installing both the tight-buffered (strain sensing) and loose buffered (thermal compensation) 9/125/900µm, single-mode, optical fibers on the bottom of the groove with acrylic adhesive and then filling the groove with epoxy putty to obtain a suitable protection.

The "smart" FRP has been installed on the bridge on Walters St. (St. James County, MO, USA), a 22ft (6.58 m) span slab-type structure featuring Glass-FRP reinforcements. The installations have been selected for the similar span length and for the peak strain expected during the diagnostic load test that followed the SHM installation (around 130µε).

Fig. 3 Side view of bridge#1330005 (left) and bridge on Walters St. (right).

Bridge #1330005 was tested using a calibrated three-axle H15 dump truck that was moved in 15 different positions on the deck. A similar test was performed on the bridge on Walters St. using a calibrated H25 dump truck. During each test, the opening of several cracks was noted in the area of maximum tensile stress, crossing the Brillouin sensors area as well.

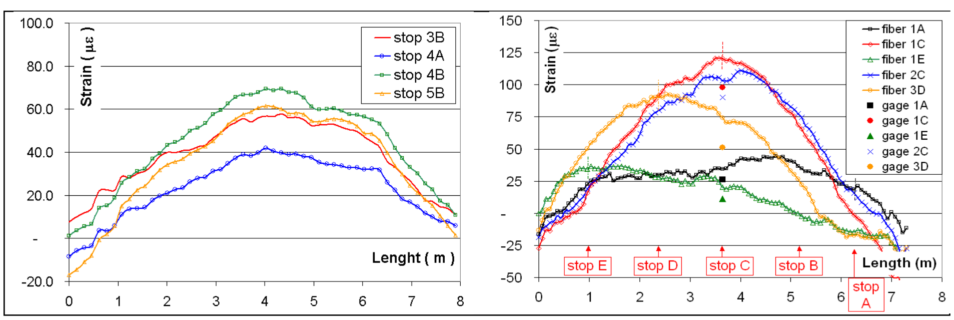

Fig. 4 Strain distribution measured by the Brillouin sensor on bridge #1330005 (left) and on bridge on Walters St. (right).

Some of the strain distributions collected by the Brillouin SHM system are presented in Fig. 4. A closer look at the numerical results shows how the peak strain level detected by the “smart” FRP Brillouin sensor on the bridge on Walters St. (125με) is very close to the one theoretically expected value of 130με, and it is at the same time higher than the 100με measured by traditional resistive strain gauges. On the other hand, on bridge #1330005, the peak strain value measured by the NSM Brillouin sensor (75με) is quite far from the theoretical one (130με), as expected because of the poor accuracy of the bare optical fiber in presence of step-like strain distribution discontinuities located on the cracks.

EXPERIMENTAL APPLICATION ON A LARGE STEEL BRIDGE

To assess the system effectiveness on a large structure, a pilot application of a Brillouin SHM was performed on Bridge A6358 (Fig. 5), a major slab-on-girder highway bridge at the intersection of US Route 54 and the Osage River in Miller County (MO, USA) [6]. The bridge is built with 5 continuous symmetric spans: the 2 exterior spans are 147ft (44.8m) and 185ft (56m) long, respectively, while the central one has a length of 200ft (61m), resulting in a total bridge length of 864ft (263m). Each interior support consists of RC bents supported by 2 circular piers with 6ft (1.8m) diameters. The cross section comprises 5 steel I-girders spaced at 8.7ft (2.6m) on-center, which act compositely with a 8.5in (216mm) thick RC deck having an out-to-out and roadway width of 40.7ft (12.4m) and 38ft (11.6m), respectively. Two spans of the bridge were instrumented with a “smart” FRP Brillouin sensor featuring glass fibers only, to avoid corrosion phenomena induced by stray currents in carbon fibers. A special cart, especially designed to roll over the bottom flanges of two adjacent girders, was used to install the sensors on the bridge sections spanning over the Osage River for about 571 ft (174 m).

Fig. 5 Side view of bridge A6358.

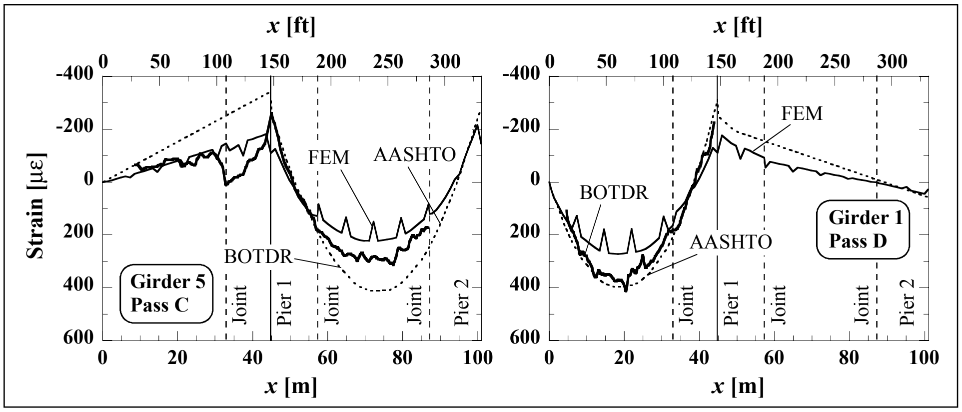

Fig. 6 Strain profiles experimentally measured along two main girders of Bridge A6358 at two different load passes (bold lines) compared with theoretical strains from finite element analysis (FEM) and LRFD design provisions (AASHTO).

A diagnostic load test was performed by positioning six calibrated dump trucks along the bridge to simulate different load configurations. The data collected from the Brillouin system were processed in real-time with a custom software to account for the thermal compensation. The experimental strain profiles were compared with that from three-dimensional finite element analysis and one-dimensional beam analysis using the conservative AASHTO Girder Distribution Factors for live loads [5]. The results, as in the examples in Fig. 6, confirmed the feasibility and effectiveness of Brillouin SHM.

CONCLUSIONS

Analysis of results obtained in the field has proved the effectiveness of the "smart" FRP Brillouin sensor for SHM purposes.

A wide range of practical problems related to sensor installation, fiber connection, and data processing have been successfully solved in the pilot field applications described in this work.

The "smart" FRP Brillouin sensor has been capable of ensuring an acceptable measurement accuracy even when bonded onto cracked substrates, thereby providing reliable experimental strains that were in good agreement with analytical and numerical results.

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