A Brillouin smart FRP material and a strain data post processing software for structural health monitoring through laboratory testing and field application on a highway bridge

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ABSTRACT

Strain and temperature sensing obtained through frequency shift evaluation of Brillouin scattered light is a technology that seems extremely promising for Structural Health Monitoring (SHM). Due to the intrinsic distributed sensing capability, Brillouin can measure the deformation of any individual segment of huge lengths of inexpensive single-mode fiber. In addition, Brillouin retains other typical advantages of Fiber Optic Sensors (FOS), such as harsh environment durability and interference rejection. Despite these advantages, the diffusion of Brillouin for SHM is constrained by different factors, such as the high equipment cost, the commercial unavailability of specific SHM oriented fiber products and even some prejudices on the required sensitivity performances.

In the present work, a complete SHM pilot application was developed, installed and successfully operated during a diagnostic load test on the High Performance Steel (HPS) bridge A6358 located at the Lake of the Ozarks (Miller County, MO, USA). Four out of five girders were extensively instrumented with a “smart” Glass Fiber Reinforced Polymer (GFRP) tape having embedded fibers for strain sensing and thermal compensation. Data collected during a diagnostic load test were elaborated through a specific post-processing software, and the strain profiles retrieved were compared to traditional strain gauges and theoretical results based on the AASHTO LRFD Bridge Design Specifications for structural assessment purposes. The excellent results obtained confirm the effectiveness of Brillouin SHM systems for the monitoring of real applications.

Keywords: Brillouin, distributed sensing, fiber optic, smart material, bridge, monitoring, SHM, load test.

1. INTRODUCTION

The constant reduction of the maintenance funds for the transportation infrastructure leads to the deferment of routine inspections and repairs. Such policies may contribute to severe damages and even occasional failures that eventually result in more costly rehabilitation actions and cause further relevant social costs. Structural Health Monitoring (SHM) can provide a day-by-day assessment of the condition of structure that allows for a policy of deferment of routine maintenance that is not in contrast with the full preservation of the investments. SHM is therefore believed to play a role of increasing relevance for the management of strategic infrastructures. Many researchers have proposed FOS for SHM of civil infrastructure\textsuperscript{1}, pointing out some advantages over traditional electronic systems, such as harsh environment withstanding capability, electromagnetic interference immunity, high durability and superior miniaturization grade. Recent trends, however, tend to downsize the diffusion perspective of most FOS in the near future, based on economical considerations, since FOS cost is much higher than its electronic alternative and many of the claimed exclusive advantages are not key points for a typical SHM application.

Brillouin FOS is to be considered an exception to this trend, since its peculiarity of distributed quantitative strain sensing over long fibers represents a breakthrough without any comparable alternative among traditional electronic sensors. Although Brillouin FOS appears as a powerful SHM tool, its diffusion seems to be impeded by several factors. The high investment needed for the Brillouin test equipment is considered one of the main difficulties, a problem amplified by the test equipment software that is rigidly “optical testing” oriented and not easily usable for SHM purposes. These difficulties are often accompanied by a misconception that considers Brillouin performances insufficient for SHM applications. In addition, since only few large-scale industrial applications of the Brillouin system are known, sensor installation technologies seem to be still at an early research stage, as often confirmed by the scarce commercial availability of specific Brillouin sensor products.

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2. THEORETICAL BACKGROUND

The Brillouin effect is an anelastic scattering process that arises from the interaction between optical (photons) and acoustic waves (phonons) propagating in the same physical medium. The process is characterized by a partial energy transfer between the colliding photons and phonons that, when the medium is illuminated with a monochromatic light source, produces scattered photons characterized by a certain frequency shift with respect to the incident photons. Due to entropy considerations, frequency downshifting (“Stokes”) process is found to be prevalent, and in the ’70s the phenomenon was first observed in single-mode silica optical fibers.

More recently, the development of self-heterodyne techniques allowed to scan the spectrum of Brillouin scattered light with better resolution, allowing the assessment of an empirical correlation between strain level and Brillouin frequency shift, suitable to be used for sensing purposes.

3. EQUIPMENT STATE-OF-THE-ART

Different equipments for Brillouin distributed sensing have been reported in literature. Most of them split the strain vs. fiber length (or temperature vs. fiber length) dependence by evaluating the delay between the detected Brillouin shift and a pulse modulation of the stimulus (“pump”) light, being known the speed of the light in the fiber. Similar equipments are named Brillouin Optical Time Domain Reflectometers (BOTDRs).

Some BOTDRs rely on spontaneous Brillouin Scattering (BS): short (“pump”) pulses of monochromatic light are injected into one end of the sensing fiber, while the light backscattered at the same end is self-heterodyned with the pump source in order to exploit its own spectrum changes. The first equipment arrangements of this type used an optical spectrum scanning system based on light re-circulation ring, while the latter feature coherent heterodyne detection followed by solid-state microwave spectrum analysis. BS based devices (AQ8603B) are at present commercially available from Yokogawa Electric Corp. (Tokyo, Japan). Improvements in the spatial resolution and length range have been recently reported using a similar BS-based technique but are still commercially unavailable.

Other equipments rely on Stimulated Brillouin Scattering (SBS), which requires simultaneous “pump” and “probe” pulses counter-propagating in the sensing fiber, where the “probe” pulse has the same frequency of the Brillouin scattered component whose amplitude has to be measured. In this case the spectrum of the Brillouin scattered light is evaluated in terms of “coefficient of Brillouin amplification” rather than in terms of absolute Brillouin scattered power. Omnisens SA (Losanne, Switzerland) manufactures SBS based BOTDR equipments in which both the pump and the probe pulses are obtained from the same laser source through a Mach-Zender (MZ) modulator. These equipments seem to be the only SBS-based ones that are at present commercially available. Recent developments of the same technique based on laser injection locking have been reported in the literature and may disclose future enhancements.

Other different SBS-based analyzer configurations which use separate MZ modulators for the pump and probe beams, have been reported in the literature but do not seem to be commercially available for the moment.

Considerable improvements in spatial resolution and test speed have been reported with Brillouin Optical Correlation Domain Analysis (BOCDA), an equipment set-up fundamentally different from the BOTDR system. BOCDA seems currently not commercially available. Table 1 summarizes the indicative performance limits for some of the different Brillouin sensing technologies. Please note that the values listed are to be considered purely indicative for the best performance achieved, and may not be simultaneously attainable.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Accuracy</th>
<th>Distance resolution</th>
<th>Length range</th>
<th>Acquisition time</th>
<th>Fiber loop</th>
<th>Fiber continuity</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS BOTDR</td>
<td>30.0 µε</td>
<td>1 m</td>
<td>80 km</td>
<td>1200&quot;</td>
<td>not required</td>
<td>not required</td>
</tr>
<tr>
<td>enhanced coherent BS BOTDR</td>
<td>20.0 µε</td>
<td>0.6 m</td>
<td>30 km</td>
<td>n. a.</td>
<td>not required</td>
<td>not required</td>
</tr>
<tr>
<td>single modulator SBS BOTDR</td>
<td>20.0 µε</td>
<td>0.6 m</td>
<td>20 km</td>
<td>120&quot;</td>
<td>not required</td>
<td>required</td>
</tr>
<tr>
<td>dual modulator SBS BOTDR</td>
<td>2.1 µε</td>
<td>3 m</td>
<td>n. a.</td>
<td>n. a.</td>
<td>required</td>
<td>required</td>
</tr>
<tr>
<td>BOCDA</td>
<td>43.5 µε</td>
<td>0.012 m</td>
<td>n. a.</td>
<td>0.01&quot;</td>
<td>required</td>
<td>required</td>
</tr>
</tbody>
</table>

Table 1: indicative performance limits of some different Brillouin sensing technologies
4. PRACTICAL CONSIDERATIONS ON TEST EQUIPMENT

BOCDA and SBS based techniques require access to both ends of the sensing fiber and cannot operate in case of sensor damage, even with reduced performances. Furthermore, some equipment requires to be directly plugged to both fiber ends, a condition that forces the sensing fiber in a folded (“loop”) configuration, thus halving the maximum useful length range. On the other hand, BS-based BOTDR devices have the remarkable capability to be able to scan the survival length of a damaged sensing circuit, up to the interruption point. In case of single interruption, if both fiber ends are accessible, it is possible to continue using the entire sensor by doing two separate scans. In addition, when failure is not a fiber interruption but a loss point due for example to a sharp bending, BS-BOTDR can generally continue to work with a single scan, even if with reduced performances.

In reality, SHM application sensing fiber damages are rather common, and can be due not only to errors and accidents during installation, but also to vandalism and ageing. For this reason BS-BOTDR systems seem a valuable choice. A further practical consideration is concerned with the claimed equipment performances, especially in terms of strain accuracy and distance resolution limits. Since most of SHM technicians are used to the sub-µ punctual accuracy of resistive strain gauges, Brillouin strain accuracy seem at first sight very poor and unsuitable for quantitative measurements. However, it should to be considered that the specified values are given for a step-like strain level transition, a condition that is much more demanding than the continuous strain distribution typical of most structural members subjected to flexure.

In addition, by performing Brillouin strain measurements during a diagnostic load test, it is possible to obtain strain levels that fully comply with the sensitivity capability of the equipment. It should also be considered that in many practical situations it is much more significative to know the overall strain distribution in a significative part of the structure even if with a low degree of confidence rather than few point values characterized by better accuracy.

For what concerns the high equipment investment required, which remains relevant even considering that Brillouin technology provides the unique advantage of distributed sensing, payoff could be accelerated by spreading the investment over multiple monitored infrastructures, since the sensors are certainly affordable. Brillouin sensing technology is therefore to be considered a promising SHM tool for large-scale applications, as shown in the investigation herein described.

5. BRILLOUIN FIBER SENSORS AND SMART MATERIALS

One of the most powerful advantages of Brillouin technology is the capability to use a conventional telecom-grade single-mode fiber as a sensor. Although this potentially means the immediate commercial availability of inexpensive sensors of any required length, conventional fiber cables are not generally well suited for SHM applications. In fact most of the commercial fiber cables are designed in order to decouple the optical fibers from any sort of applied strain, while integral strain transmission is a strict requirement for deformation measurement. Pioneer Brillouin SHM applications used bare fibers and tight polyamide (PA) coated fibers, bonded to the substrate with polyurethane adhesive either directly or using an intermediate protective FRP layer in case of rough surfaces. Although installation of bare and tight fibers is still considered as the most economical option, the extreme fragility of these fibers, their thinness that make them almost invisible, and the tendency to jamming render field installation a troublesome task, thereby increasing both the installation cost and the probability of damage. Furthermore some additional protective coating is required in case of permanent installation, and sensitive parameters such as the thickness of the bonding layer are hardly kept under control. These problems have been overcome using smart materials in which the optical fiber was embedded into a tape-like product made of woven structural fibers, that could be cut at the desired length and bonded to the structure using an epoxy or polyester saturant. Experimental applications on fiberglass components and building structures confirmed that this smart-FRP material solves the handling and installation problems, provides a durable protection without any additional cost and ensures a reasonable homogeneity of the bonding thickness.

Moreover, the smart FRP material can carry multiple optical fibers without additional installation cost, besides that of the fibers themselves: it is thus possible to add loose coupled fibers to allow a distributed thermal compensation, along with more strain sensing fibers in order either to provide a redundancy (spare circuits) or to increase the system accuracy by correlating more sensing segments. Using a smart FRP tape with at least two sensing fibers placed at a certain distance between each other, it is also possible to obtain a differential strain detector for neutral axis location in bent sections. However, the effectiveness of a similar configuration is dependent on geometrical considerations.

The smart-FRP product can be custom ordered with the preferred warp/weft material, density choice, and sensing fiber combination. It is made available in continuous spools up to some km long and can be easily cut and spliced on site.
Optical attenuation in embedded fibers depends on the application quality, and has been measured as low as 0.29 dB/km in typical field conditions. Other application-specific sensor products are reported in the literature, especially embedded into concrete elements\(^1\), while a smart-FRP laminated product with strain sensing and compensation fibers in barycentral position, based on thermoplastic saturant, has been recently made available, with factory lengths up to 400 m.

6. BRIDGE DESCRIPTION

The pilot Brillouin SHM application has been installed on bridge A6358 (Figure 1), located on US Rt. 54/Osage River close to the Lake of the Ozarks in Miller County, MO, USA. The bridge is built with five continuous symmetrical spans: the two external are 45 m and 56 m long, respectively, while the central one has a length of 61 m, resulting in a total bridge length of 263 m. Each internal support consists of reinforced concrete (RC) bents supported by two RC circular piers with a 2 m diameter. The cross section comprises five composite I-girders spaced at 2.6 m center-to-center acting compositely with a 216 mm thick RC deck, with an out-to-out deck and roadway width of 12.4 m and 11.6 m, respectively. The girders are made of ASTM A709 Grade HPS 485 W steel. The framing plan of the bridge portion instrumented is shown in Figure 2.

7. SMART SENSOR DETAILS

Different sensing fibers were selected for strain detection and thermal compensation:

a) 9/125 µm silica single mode fiber with ∅ 900 µm tight PA buffer coating;
b) 9/125 µm silica single mode fiber with ∅ 900 µm loose dry coupled Polyvinyl Chloride (PVC) buffer coating;
c) 9/125 µm silica single mode fiber with ∅ 900 µm wet coupled Polyethylene (PE) buffer coating.

A smart-FRP tape with embedded sensing fibers was designed and manufactured (Figure 4). The tape, which is woven with a proprietary technology from E-glass fiber strands with a 435 g/m² warp and a 68 TEX weft, has a width of 100 mm and carries two strain-sensing and two temperature-sensing fibers (Figure 3). Glass fibers were chosen instead of other type of fibers (i.e., carbon) since they do not have electrical conductivity, thereby minimizing the risk of corrosion of the steel substrate due to stray currents.
8. CALIBRATION

The correlation between the strain and the Brillouin frequency shift, that is a characteristic of the fiber used, was determined using a strain calibration fixture capable to impose a known amount of strain ($\varepsilon = \Delta L / L$) over a base length, $L$, of 7.42 m (see Figure 5). Using the strain data collected with the calibration fixture, a specific set of correction coefficients was calculated for each fiber used in the experimental test, in order to improve accuracy and linearity with respect to the standard equipment settings (Figure 7). The best linear relation was obtained with the sensing fiber embedded into the FRP tape.

9. SHM SYSTEM INSTALLATION AND TESTING

Brillouin sensing elements were installed on Girder 1, 2, 4 and 5 (Figure 2). Both the bare optical fibers and the smart-FRP tape were adhesively bonded onto the girder webs using an epoxy encapsulation resin (Wabo MBrace), after manual surface roughening with steel brushes followed by degreasing with lacquer thinner. Detailed location and characteristics of the fibers are summarized in Figure 8, Figure 9 and Table 2. The smart-FRP tape was drawn through the web gaps between the vertical stiffeners and the bottom flange of the plate girder and then installed on the web about 10 mm above the bottom flange surface, in order to allow detection of a strain level reasonably close to the actual maximum attained. Girder 1 was instrumented on Span 1 using the smart tape. The circuit end was also lengthened for 10 m after Pier 2. These fibers, installed on the web at a distance of 380 mm from the adjacent surface of the top flange (Figure 10), were intended to gain additional data to estimate the position of the neutral axis. Since it was not possible to keep the tape perfectly flat in the vicinity of the cross frames, a certain disturbance of the data retrieved in those areas was expected. Girder 2 was instrumented on Span 1 and 2. The smart tape was installed at 10 mm from the bottom flange surface. In addition, two bare fibers, one for strain sensing and the other for thermal compensation, were bonded at 711 mm from the bottom flange (i.e. at one third of the height of the plate web, $h = 2,046$ mm), as depicted in Figure 11. However, the need to draw the fibers through the holes between the welded vertical stiffeners and the plate girder required several
sharp bending areas of the fibers, as shown in Figure 12, which are believed to be the cause of an undesired increase of the optical losses and significant perturbations of the strain distribution measured. Girder 4 was instrumented on Span 1 and 2 with FRP tape only, bonded at the web base. Girder 5 was instrumented on Span 1 and 2 with optical fiber-embedded smart composite tape at the web base. In addition, two bare fibers, one for strain sensing and the other for thermal compensation, were installed at 76 mm from the upper flange surface, in order to retrieve data to estimate the temperature gradient throughout the web height, and of the strain profile, especially in the negative moment zone.

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evidenced some unwanted sources of optical loss, likely due to fiber damages which occurred during installation. The amount of optical losses in the sensing circuit is of crucial importance in BOTDR systems, since it may be detrimental to the strain sensitivity and accuracy. The hals were series-connected in the field using a fiber optic fusion splicer, obtaining a single circuit with a total length of 1,159 m. The solution allowed containing the total optical loss within a value of 6 dB in the first 1,026 m from the optical test end, thus enabling strain measurement with an accuracy of 0.004% (±0.004 microstrain) on a length resolution of 2 m, setting the AQ8603 analyzer for pump pulses of 20 ns. Since a significant optical loss was detected before the last portion of the circuit, i.e. Girder 4, Location A, the correspondent measured strain profiles were expected to have a lower degree of accuracy.

In addition to Brillouin sensors, some resistive strain gauges were installed on Girder 1 and 2, in order to have a strain detection reference independent from the BOTDR system, while three additional gauges were used to evaluate the...
thermal drift compensation. Table 3 summarizes the type and location of the strain gauges installed.

<table>
<thead>
<tr>
<th>Gauge ID</th>
<th>Type*</th>
<th>Girder  Location</th>
<th>Distance from Abutment 1 (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>TC</td>
<td>1</td>
<td>Top flange</td>
</tr>
<tr>
<td>G2</td>
<td>SM</td>
<td>1</td>
<td>Top flange</td>
</tr>
<tr>
<td>G3</td>
<td>SM</td>
<td>1</td>
<td>Bottom flange</td>
</tr>
<tr>
<td>G4</td>
<td>TC</td>
<td>1</td>
<td>Bottom flange</td>
</tr>
<tr>
<td>G5</td>
<td>SM</td>
<td>2</td>
<td>B (h/3)</td>
</tr>
<tr>
<td>G6</td>
<td>SM</td>
<td>2</td>
<td>Bottom flange</td>
</tr>
<tr>
<td>G7</td>
<td>TC</td>
<td>2</td>
<td>Bottom flange</td>
</tr>
</tbody>
</table>

* TC = thermal compensation; SM = strain measurement

Table 3: type and location of the strain gauges installed.

**10. DIAGNOSTIC LOAD TEST PROCEDURE**

The load test was carried out using six fully loaded dump trucks, as shown in Figure 14. The geometrical characteristics of the trucks are summarized in Figure 15. The trucks were weighed before testing and coded with a number from 1 to 6. Table 4 summarizes weight and load distribution between front and rear axles. A total of eight stops were planned. Marks were made on the concrete deck to indicate the trucks stops, and the distance between the front axle of each truck and the rear axle of the preceding truck in the line load was 2740 mm.

![Figure 14: positioning trucks for load test](image1)

![Figure 15: geometrical features of dump trucks used for load test (dimensions in mm)](image2)

The position of the trucks at each stop is shown in Figure 16 and Figure 17. Stop 1, 2 and 7 were intended to produce the maximum deflections on Girder 1 and 5 using both directions of traffic with two symmetrical lanes of two (stop 1) and three (stop 2 and 7) trucks each. Stops 3, 4 and 6 were intended to produce the maximum deflections on Girder 5 in Span 3, 2 and 1, respectively, using a train of six trucks. Stop 5 was planned to induce the maximum negative moment on Girder 5, at Pier 2. Finally, stop 8 was intended to produce the maximum deflections on Girder 1 in Span 1 using a single lane of six trucks.

![Figure 16: transverse position of trucks at stop 1, 2 and 7. Distance from deck edges is the same the other stops, but trucks are located in a single row.](image3)

<table>
<thead>
<tr>
<th>Truck Code</th>
<th>Total Weight (kN)</th>
<th>Front Axle $P_1$, kN</th>
<th>Each Rear Axle $P_2$, kN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>202.2</td>
<td>75.8</td>
<td>63.2</td>
</tr>
<tr>
<td>2</td>
<td>192.8</td>
<td>72.3</td>
<td>60.2</td>
</tr>
<tr>
<td>3</td>
<td>236.5</td>
<td>88.7</td>
<td>73.9</td>
</tr>
<tr>
<td>4</td>
<td>244.1</td>
<td>91.5</td>
<td>76.3</td>
</tr>
<tr>
<td>5</td>
<td>268.1</td>
<td>100.5</td>
<td>83.8</td>
</tr>
<tr>
<td>6</td>
<td>251.8</td>
<td>94.4</td>
<td>78.7</td>
</tr>
</tbody>
</table>

Table 4: weight distribution of dump trucks
The equipment for strain measurement and recording consists of an AQ8603B BOTDR analyzer connected as a slave unit to a laptop PC via standard ethernet interface (Figure 18). The raw data exported by the strain analyzer were elaborated through proprietary software (Figure 19) in order to properly account for the distributed thermal compensation, thereby retrieving the experimental load-induced strain profile along each monitored girder.

![Strain analyzer unit](image1.png)  
**Figure 18:** field equipment for distributed strain measurement

![Proprietary software](image2.png)  
**Figure 19:** proprietary software for strain data processing

### 11. EXPERIMENTAL RESULTS AND DISCUSSION

Assessment of structural safety was done by comparing the experimental deflections of Girder 1, 2, 4 and 5 with results based on 1-D beam analysis, wherein the girder distribution factors, GDFs (defined as the ratio of the maximum moment on a girder at a given live load condition, and the maximum theoretical moment determined by applying the entire load truck to a single composite girder), were determined according to the AASHTO Bridge Design Specifications (1998). A multiple presence factor \( m = 1 \) was assumed when using the lever rule. Adjustments in the negative moment region near the interior support due to continuity effects were neglected. The loads reported in Table 4 were used. Figure 20 to Figure 27 show the comparison between the measured and analytical strain profiles at stop 1, stop 2, stop 4, stop 7 and
Strain gauge readings are also included. The strain readings from the optical fibers embedded in the GFRP tape fairly follow the analytical profiles in all the girders in case of one load lane (stop 4 and 8), and in the exterior members, Girder 1 and Girder 5, in case of two load lanes (stop 1, 2 and 7), when the distribution factor in the interior girders is not representative of the actual load test conditions. The offset is generally consistent with the strain gauge readings, thus confirming the inherent conservativeness of the theoretical approach based on the AASHTO provisions. As expected, the strain measurement on Girder 4, Location A (adjacent to the bottom flange), clearly yields less accurate results, due to the significant optical loss before the interested portion of the circuit. The experimental results apparently point out a correlation between measurement accuracy and strain level, with reliable outputs generally provided at strain levels indicatively beyond 100 με.

The BOTDR experimental data on Girder 1, stop 8 (Figure 27) show the clear tendency to approach the theoretical values, in accordance with the experimental deflections obtained with a different method not described in this paper, which may call for further assessment. Local effects, such as that at the bolted joints, may result in disturbances that affect the strain readings in a relatively large adjacent portion of the circuit, although the profiles are qualitatively correct as they often reflect the presence of local strain gradients at the stress-free locations. This is evident in Girder 5, stop 1 (Figure 21) and stop 2 (Figure 23) on Span 1, and Girder 5, stop 4 (Figure 24) on Span 1, whereas it seems not of concern in case of relatively high strain levels (indicatively beyond 100 με) in positive moment regions. Localized inconsistencies may be essentially due to initial fiber misalignment and/or local debond, with reduced effect as the fibers are progressively stretched.

It is finally noticed that the data retrieved from the bare fibers did not have the same quality of that from the smart GFRP tape, in particular in Girder 2, Location B (at h/3), where practically zero strain was detected. This may be principally due to the presence of several vertical circuit portions, sometimes partially unbonded, in the vicinity of the transverse stiffeners, which likely caused undesired perturbations on the signals detected (Figure 12).
Figure 24: comparison between experimental and AASHTO strain profiles (Girder 5, stop 4)

Figure 25: comparison between experimental and AASHTO strain profiles (Girder 1 and 2, stop 7)

Figure 26: comparison between experimental and AASHTO strain profiles (Girder 4 and 5, stop 7)

Figure 27: comparison between experimental and AASHTO strain profiles (Girder 1 and 2, stop 8)

12. CONCLUSIONS

This investigation introduces an essentially industry-ready SHM solution based on Brillouin FOS for bridges and structures. The complete range of application-specific problems have been experienced and operatively solved: mass-production of the smart-FRP sensing tape, field application on a real structure, in-situ optical interconnections, development of a specific SHM oriented software for de-noising, thermal compensation, and graphical data presentation capable of producing a real time feedback during the execution of the diagnostic load test.
The application itself represents a relevant and positively feasibility assessment for Brillouin industrial SHM applications, and the positive strain results obtained during the load test confirm that, despite the suspected Brillouin poor performances, the quantitative data should be considered sufficiently reliable for diagnostic SHM. Therefore, BOTDR is confirmed as a promising, novel method for global structural assessment, with the unique ability to detect the distributed strain along a structural member. In particular, the adhesively bonded custom-made smart GFRP tape with embedded optical fibers for strain measurement provided a far better performance than bare fibers and should be preferred in future SHM applications.

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