

Optical fiber distributed sensors: a tool for *in-situ* structural and environmental monitoring

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ABSTRACT: Permanent monitoring techniques are opening new ways for the management of large civil and geotechnical structures (bridges, dams, pipelines, dikes, slopes etc.), especially to evaluate their efficiency and safety during the lifetime, and for environmental risk assessment also through early-warning systems. In this framework, optical fiber distributed sensors represent an instrument exhibiting great potentiality. In fact, in addition to the field of telecommunication, optical fibers are used, since many years, also for the realization of sensors, due to their characteristics in terms of minimal invasiveness, high sensitivity, immunity to electromagnetic interferences, possibility to be integrated in the structures, use in harsh environment and easiness of multiplexing. Optical fiber distributed sensors technology will be addressed, with special emphasis on sensors based on stimulated Brillouin scattering, and some recent results on structural and environmental monitoring will be presented, as well.

1 INTRODUCTION

Optical fibers are made from fused silica, are about the diameter of a human hair, and transmit light over large distances with very little loss. They can also be made to be sensitive to their state and environment and are therefore well suited as sensors. Optical fibers sensors have been the subject of a remarkable interest in the last 20 years, since they present some distinct advantages over other technologies. The principal single attractive feature of optical-fiber sensors is undoubtedly their ability to function without any interaction with electromagnetic fields. This opens applications in the electrical power industry and assists very significantly where long transmission distances of relatively weak signals are an essential part of the sensing process. The lack of electrical connections has other, broader implications. Optical sensors have major advantages when conductive fluids, such as blood or sea water, are involved. Also, the need for intrinsic safety (for example, in monitoring the presence of explosives gases or in assessing petrochemical plants) is often paramount. The optical fiber is also remarkably strong, elastic, and durable, and has found its place as an instrumentation medium for addressing smart structures, where the sensors must tolerate the environment to which the structure is subjected and

therefore to be immune to large physical strain excursions, substantial temperature excursions, and often a chemically corrosive operating environment.

A very important and unique feature of fiber-optics technology consists in its capability for long-range distributed sensing. These measurements allow the values of the measurand of interest to be extracted, as a function of position, along the length of the sensing fiber. Distributed sensors are particularly attractive for use in applications where monitoring of the measurand is required at a large number of points or continuously over the path of the fiber. Typical examples of applications areas include:

a) Stress monitoring of large structures such as buildings, bridges, dams, storage tanks, pipelines, ships;

b) Temperature profiling in electrical power transformers, generators, reactor systems, process control systems and fire detection systems;

c) Leakage detection in pipelines, fault diagnostics and detection of magnetic/electrical field anomalies in power distribution systems and intrusion alarm systems;

d) Embedded sensors in composite materials for use in real-time evaluation of stress, vibration and temperature in structures.

Truly distributed sensing techniques are commonly based on some kind of light scattering mechanism occurring inside the fiber. Spatial resolution is typically achieved by using the optical time do-

main reflectometry (OTDR) (Barnosky & Jensen 1976), in which optical pulses are launched into an optical fiber and the variations in backscattering intensity caused by measurand is detected as a function of time. Alternative detection techniques, such as frequency-domain approaches, have been also demonstrated.

2 LINEAR BACKSCATTERING SYSTEMS

Distributed sensing in the linear regime is commonly based on the use of OTDR systems. The latter were first developed, in order to locate fiber breaks or bad splices along a fiber link. Within the linear regime, backscattered light is due to Rayleigh scattering, and exhibits the same wavelength than that of the incident pulse. Measuring the intensity of Rayleigh backscatter as function of time, optical attenuation can be measured all along the fiber. Spatial resolution is directly related to the pulse temporal width: narrower pulses give rise to higher spatial resolution (but also weaker backscatter signals). Standard OTDR equipment, featuring a spatial resolution of 1 meter or higher, gives information only about optical attenuation, and it can not be related to other measurands such as temperature or strain. In order to achieve sensitivity to these measurands by standard OTDR equipment, specialty fibers must be employed, such as liquid-core fibers (Hartog 1983) or doped fibers (Farries et al. 1986), by which the measurand of interest modulates the optical attenuation. These approaches have been demonstrated with a relatively poor spatial resolution (in the order of 10 meters) and temperature accuracy (in order of 2 °C). Consequently, whilst such systems may well have uses in particular applications in which high accuracy and resolution are not required (e.g. fire alarms in buildings), they are unlikely to find general application as temperature monitors in industrial plant.

A recent, very interesting approach makes use of the very high spatial resolution allowed by swept-wavelength interferometry, in order to correlate temperature and strain of the fiber with the spectrum of the Rayleigh backscatter spatial fluctuations (Soller et al. 2006). The most appreciable features of this approach are: a) standard telecommunication fibers can be used, instead of specialty fibers; b) very high spatial resolution (a few millimeters) has been demonstrated, allowing, for example, monitoring of aerospace structures where very large strain gradients may exist. On the other hand, the main disadvantages are the equipment cost (a tunable laser source is needed for the measurements), and the limited number of sensing points (≈ 100).

Another approach, in which standard fibers can be used for temperature and strain monitoring, is the polarization-optical-time-domain reflectometry (POTDR). It represents a polarimetric extension of

OTDR (Rogers 1980, Rogers 1981). Whereas, in OTDR, the power level of the Rayleigh-backscattered radiation, from a propagating optical pulse, is time-resolved to provide the distribution of attenuation along the length of the fiber, in POTDR it is the polarization state of the backscattered light which is time resolved; this provides the spatial distribution of the fiber's polarization properties. With the determination of the spatial distribution of the polarization properties of the fiber comes the capability of measuring the distribution of any external field which modifies those properties, such as strain, pressure, temperature, electrical field and magnetic field. While the reported performances for POTDR systems compare very well with other techniques, (e.g. (Ross 1981) reports an inaccuracy of 1% for measurement of 3 μ strain over 0.1 m of spatial resolution), the technique possesses several disadvantages. Firstly, it cannot discriminate amongst the various effects (e.g. simultaneous temperature and strain) all of which are capable of modifying the polarization properties. Secondly, polarization information is partly lost in backscattering. Any rotation of the polarization state which occurs on the forward passage of light through the fiber is cancelled on back-reflection through the fiber: hence all knowledge of a pure rotation is lost in backscatter. Consequently, the loss of information prevents one from having full knowledge of the distribution of the fiber's polarization properties (Rogers 1999).

3 NONLINEAR BACKSCATTERING SYSTEMS BASED ON BRILLOUIN SCATTERING

In Brillouin effect an optical pump wave is scattered by acoustic waves leading to Stokes (a longer wavelength than that of the pump) or anti-Stokes (a shorter wavelength than that of the pump) components (Fig. 1).

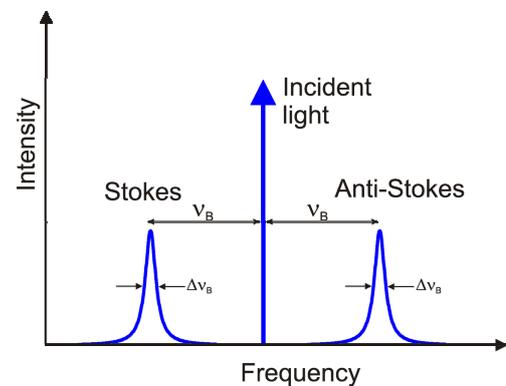


Figure 1. The Brillouin spectrum.

Essentially, scattering occurs as a result of a Bragg-type reflection from moving diffraction gratings created from the refractive-index variations caused by acoustic waves propagating axially in the fiber mate-

rial. These acoustic waves can be generated spontaneously by thermal excitation and, when this is the case, the resulting scattering effect on optical waves is known as ‘spontaneous’ Brillouin scattering. Thus, the Stokes scattered wave will be from an axially propagating acoustic wave moving away from an optical ‘pump’ pulse and the anti-Stokes wave from one moving towards it. The Brillouin effect leads to a Stokes and anti-Stokes frequency shift in the optical fiber which is given by (Agrawal 2001):

$$v_B = \pm \frac{2nV_A}{\lambda} \quad (1)$$

where n is the refractive index of the fiber material, V_A is the acoustic velocity and λ is the free-space pumping wavelength. For silica fiber at a pumping wavelength of $1.55 \mu\text{m}$ we have $v_B \approx 10.8 \text{ GHz}$.

As Brillouin frequency shift depends on both the optical refractive index and the acoustic wave velocity, it changes whenever these quantities change in response to local environmental variations and can be used to deduce the temperature and strain along the fiber. Several experiments have demonstrated an excellent linearity of the Brillouin frequency shift with respect to both fiber strain and temperature, for a wide range of these quantities. At a pump wavelength of $1.32 \mu\text{m}$, a typical temperature coefficient of $1.36 \text{ MHz}/^\circ\text{C}$ and strain coefficient of $594.1 \text{ MHz}/\%$ are reported (Ippen & Stolen 1972).

In spontaneous Brillouin scattering based systems, the scattered power level is also dependent on the temperature and longitudinal strain, since the scattering cross-section depends upon these measurand parameters. Hence it is possible to exploit the simultaneous dependence of Brillouin shift and power from temperature and strain, in order to measure both measurands. A considerable amount of work has been done in this area (Parker et al. 1997, Parker et al. 1998, Wait & Hartog 2001, Alahababi et al. 2004). The technique has been designated Brillouin optical time-domain reflectometry (BOTDR).

If an acoustic wave propagates in a medium, the variations in pressure give rise to variations in the refractive index of the medium, via the strain-optical effect.

Some acoustic waves will always be present in a medium, above the absolute zero of temperature, since the molecules are in motion and will couple some of their energy into the dynamic modes of the structure.

Optical scattering from these thermally excited acoustic waves comprises the phenomenon of spontaneous Brillouin scattering. However, as the optical pump power is increased the wave scattered backwards from an acoustic wave will increase in amplitude and will interfere significantly with the forward-traveling pump wave. An optical beat signal arises within the fiber, which generates a pressure

wave having the same frequency as the optical beat signal, via the phenomenon of electrostriction (Fig. 2); this pump-induced index grating scatters the pump light through Bragg diffraction.

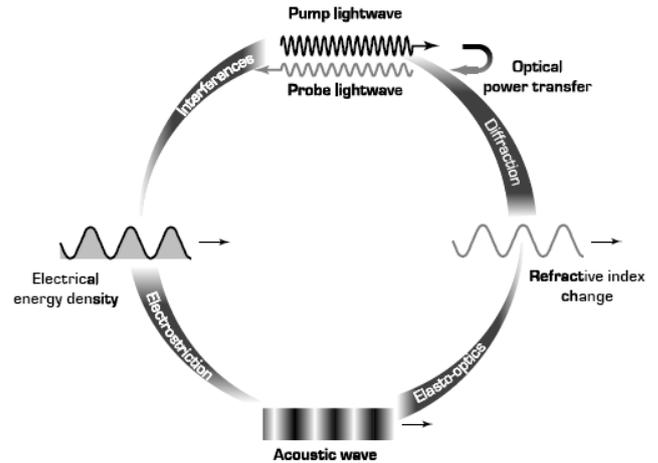


Figure 2. Principles of stimulated Brillouin scattering in optical fibers (after Thèvenaz L. et al. 1998).

Scattered light is down-shifted or up-shifted in frequency because of the Doppler shift associated with a grating moving at the acoustic velocity V_A . This positive feedback, backscattering process is known as the ‘stimulated Brillouin scattering’ (SBS). It leads to much larger backscattering at the Stokes and anti-Stokes frequencies than in the spontaneous case and, indeed, causes depletion problems in narrow-band optical-fiber telecommunications systems (Cotter 1983), although several schemes have been proposed to overcome this limit. These schemes include the use of fibers with a Brillouin frequency shift distribution (Shiraki et al. 1996), Bragg gratings which are used for reflection of the scattered light (Lee & Agrawal 2003), and the simultaneous amplification of more than one lasing frequency (Tsubokawa et al. 1986, Weßels et al. 2004).

The basic arrangement of a Brillouin Optical Time-Domain analysis (BOTDA) system is shown in Figure 3. A coherent pulse of light acts as the pump, and a counterpropagating CW is scanned in frequency around the Stokes line. When it coincides with the Stokes line it will receive gain from the pump via the SBS process. Essentially what is happening in this case is that the CW is giving rise to a large-amplitude interference with the pump, thus generating the acoustic wave from which the pump is strongly reflected.

By observing the probe level as a function of time and frequency as the pump propagates, the Stokes frequency can be mapped as a function of position along the fiber.

The first experiments along this line achieved a strain resolution of $2 \cdot 10^{-5}$, equivalent to a temperature resolution of $3 \text{ }^\circ\text{C}$, with a spatial resolution of 100 m over 1.2 km (Horiguchi & Tateda 1989, Tat-

eda et al. 1990). Later systems have improved the spatial resolution to 1 m over a 22 km fiber (Horiguchi et al. 1994). Further developments of the system have attempted to overcome the problem of pump depletion, as a result of the strong backscattering, by using the anti-Stokes, rather than the Stokes line. In this case the CW probe is attenuated and the pump is amplified. This technique, designated “loss BOTDA” has achieved a 1 °C temperature resolution, a spatial resolution of 5 m and a total length of 51 km (Bao et al. 1995).

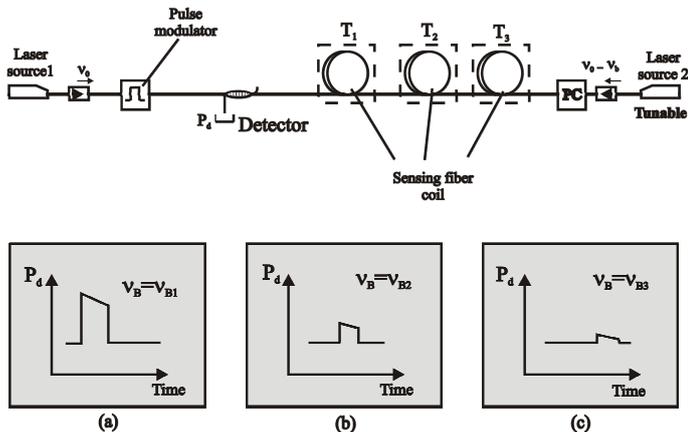


Figure 3. Basic configuration for BOTDA. (a), (b) and (c) show the Stokes signals acquired when the frequency offset between the two lasers is tuned to the Brillouin frequency shift at region 1, 2 and 3, respectively.

Spatial resolution in SBS-based sensors is limited by the phonon lifetime: Brillouin profile is broadened to a Gaussian-like profile as the pulse width decreases below the phonon lifetime (i.e. when sub-meter spatial resolution is needed), thus reducing the accuracy of temperature/strain measurements (Horiguchi et al. 1995a). An intense research activity has been devoted to overcome this limit. As regards time-domain schemes, many proposed approaches are based on the use of opportunely shaped pump pulses. Specifically, it has been demonstrated that using a pump beam with a small dc component, results in a spectral narrowing of the Brillouin gain spectrum. Such a narrowing arises from the background acoustic intensity generated by interaction of the cw beam with the baseline of the pulsed beam (Bao et al. 1999, Lecoecue et al. 2000). Other approaches based on pre-pump (Kishida et al. 2005) or dark pulse (Brown et al. 2005) have been demonstrated. However, the use of complex pulse shapes also results in a distortion of the Brillouin gain curves, leading to errors in the determination of the Brillouin frequency (Bao et al. 1999, Bao et al. 2006). The opportunity to use accurate reconstruction algorithms has been suggested, which would allow corrections of the recorded spectra and thus a more-precise estimation of the fiber condition (Bao et al. 1999, Minardo et al. 2007). Different approaches working in the frequency-domain have

been also demonstrated, in which the dependence of the Brillouin gain on the modulation frequency is taken into account in order to compensate from Brillouin spectrum distortion (Bernini et al. 2006a).

The major advantage of BOTDA, with respect to spontaneous scattering based systems, is that of a strong signal, thus an easing of detection problems, with the associated beneficial spatial resolution trade-off. This provides valuable performance over very large distances. The major disadvantage, apart from a more demanding requirement on the source coherence, is that there is now no dependence of the signal power on temperature or strain, since the scattering process is now controlled by the wave interference rather than by the intrinsic fiber properties. Consequently, it is no longer possible to measure strain and temperature simultaneously, as in the spontaneous case. Each can only be measured if variations in the other are known to be absent, or are independently determined. The most practical way to achieve this consists in deploying the fiber in such a way that half of it is subjected to only temperature changes, whereas the other half is mechanically attached to the structure to be monitored, so that both temperature and strain changes are detected. Brillouin frequency shift measurement in the first region allows subtracting temperature effects from the measurement taken in the second half (Smith et al. 1999). Another solution exploits the weak dependence of the Brillouin gain peak on temperature, so that the combined measurement of Brillouin frequency shift and Brillouin power can provide the additional information required for temperature/strain discrimination (Bao et al. 2002). Finally, another interesting approach involving the use of dispersion-shifted fibers (DSF) is worthy to be reported (Lee et al. 2001). In DSF fibers, the non-uniform refractive index transverse profile gives rise to multiple peaks in the Brillouin gain spectrum, each resonance peak being associated to a definite acoustic mode of the fiber. Lee and his co-workers reported simultaneous temperature and strain sensing by monitoring the frequency position of more than one peak in the Brillouin spectrum (Lee et al. 2001).

Temperature sensing capabilities of Brillouin-based distributed sensor can be exploited for electrical power cables monitoring, in particular for hot-spot localization (Bernini et al. 2007). For this purpose the fibers can be bundled in the screen layer of the power cable: The perfect dielectric properties of the fiber, makes light propagation insensitive to the extreme electromagnetic environment of such a cable. Brillouin-distributed temperature sensing can be also of use for temperature monitoring in lakes, oceans, for environmental issues, or in tunnels for realizing an alarm detection system. A demonstration of the use of a Brillouin-distributed temperature sensor for monitoring the thermal gradients in bore-

holes in volcanic areas has been recently reported (Zeni et al. 2007).

As regards strain sensing capabilities, fiber strain is an important parameter to be measured for assessing the reliability of optical-fiber cables, because strain can cause degradation in fiber strength (stress corrosion), leading eventually to fiber failure. Therefore, Brillouin-based strain measurement has found many applications in the research and development of optical fibers and cables and their related technologies (Horiguchi et al. 2005b). Reports have been published on the strain evaluation of optical-fiber communications cables (Tateda et al. 2000).

Strain sensing also permits structural health monitoring (SHM) of civil structures. For many engineering works of strategic significance like bridges, pipes, high rise buildings, dams and tunnels, safety should be continuously assessed over their complete lifetimes. It is worthy of note that the response of these structures, which by their nature could be damaged by severe load conditions, has to be monitored throughout the whole construction process. Several experimental demonstrations of SHM by use of SBS-based distributed optical fiber sensors have been reported (Bernini et al. 2003, Bao et al. 2001, Murajama et al. 2004). On the other hands, strain sensing via SBS permits also environmental risk assessment through early-warning systems. For example, pipeline monitoring could be of use in geotechnical applications, in which the deformation of a buried pipeline can be correlated to landslide movements.

4 STRUCTURAL MONITORING BY DISTRIBUTED FIBER-OPTICS SENSORS

Structural health monitoring systems have the potential to reduce operational maintenance costs by identifying problems at an early stage, and to verify the effectiveness of repair procedures. Moreover, monitoring systems help increase understanding of the real behaviour of a structure, such as a bridge, and aids in planning maintenance interventions [Burder 1998].

Distributed fiber-optic sensors have a great potentiality in the field of structural health monitoring, as they permit to measure continuously the deformation (strain) of civil structures. In particular, fiber-optic sensors based on stimulated Brillouin scattering (SBS) have the unique capability of allowing the measurement of strain at each point along the fiber, on a truly distributed basis.

As an example of application of distributed sensors in the field of SHM, we report the results of strain measurements carried out along an 8-meters-long "I" steel beam subjected to load (Bernini et al. 2006). In particular, the measurements were carried out by using a transportable prototype able to carry

out SBS distributed sensing in the time-domain. Two tests were performed: the first one refers to the integral beam, while the second one was performed after the intentional formation of a defect localized over a 10cm-long portion of the beam. The results, shown in Figures 4 and 5, demonstrated the capability of the sensor to identify both position and amount of damage.

Distributed strain measurements can be carried out also by using a detection scheme operating in the frequency-domain. In this case, pump beam intensity is sinusoidally-modulated, and the corresponding modulation induced on the cw probe beam is coherently measured in amplitude and phase.

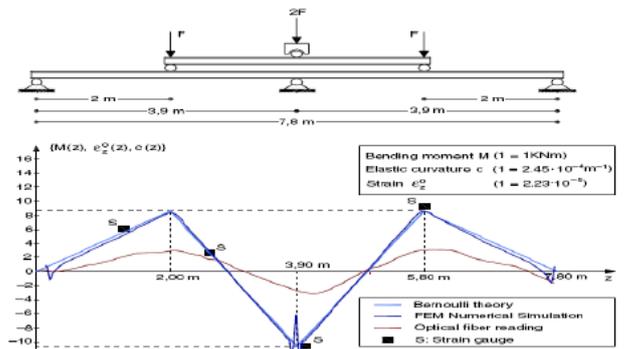


Figure 4. Strain profile measured along the integral beam, and comparison with the theoretical profile (after Bernini et al. 2006).

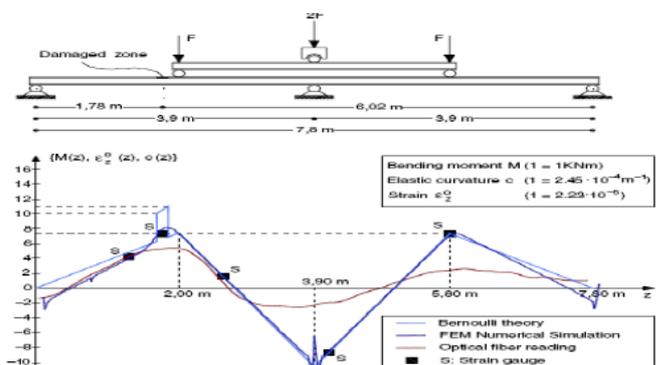


Figure 5. Strain profile measured along the beam with a defect, and comparison with the theoretical profile (after Bernini et al. 2006).

Synchronous detection offered by frequency-domain schemes allow for spatial resolution and accuracy typically higher than time-domain approaches (Bernini et al. 2002). As an example, we report strain measurements carried out along a 4m-long, L-shaped aluminium beam, subjected to a 2kg-load at the beam middle section (Bernini et al. 2007).

The comparison between the measurement and the strain profile calculated by a finite-elements method (FEM), shown in Figure 6, demonstrates the high level of accuracy offered by frequency-domain SBS approaches.

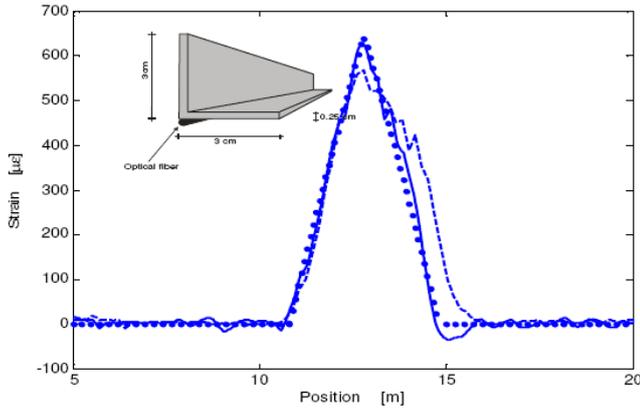


Figure 6. Strain profile measured along a 4-meter beam, and comparison with the theoretical profile (after Bernini et al. 2007).

Another interesting application of fiber-optic distributed sensor, consists in the monitoring of pipelines. In particular, it has been demonstrated that by measuring the strain profile along three longitudinal directions of the pipe, it is possible to identify the position and the vectorial amount of pipe dislocation (Bernini et al. 2008). Such a technique can be applied, both directly for pipeline integrity monitoring, both in the geotechnical field for the monitoring of deformation of the soil surrounding the pipe itself. Experimental tests were performed by using a frequency-domain SBS-based sensor. In particular, a 1.5m-long polyethylene (PE) pipe was used, along which strains were read by attaching an optical fiber running along three longitudinal directions angularly spaced of 120° . As an example, we show in Figure 7 the measurements carried out after displacing a 25cm-long section of the pipe of 20cm along the $-x$ direction.

An appealing aspect of such measurements is the possibility to reconstruct, section by section, the spatial deformation of the pipe. Actually, by making simple calculations based on the Bernoulli theory, pipe dislocation along the x - and y - directions can be deduced at each pipe section. A 3D reconstruction of the deformed pipe, obtained by opportune processing of the data shown in Figure 7, is reported in Figure 8, along with the ideal reconstruction obtained by using the numerically calculated deformations.

5 LANDSLIDE MONITORING BY DISTRIBUTED FIBER-OPTICS SENSORS

Monitoring of active landslides is fundamental for the design of stabilization measures, but is also important to check the behavior of stable slopes which may suddenly become unstable, as a consequence of any change in boundary conditions, experiencing a catastrophic failure. The information provided by fiber-optics sensors can be of great help for the rapid assessment of flowslide development as well as to

further clarify the physical process leading to slope failure.

A quasi-distributed fiber-optic sensor for landslide monitoring was recently proposed, based on a multiplexed fiber optic bend-loss type sensor (Kwon et al. 2006). The sensor employed an OTDR equipment in order to detect the bending of each segment. However, the sensor provided only five sensing points, and tests were performed only in the laboratory (sensor was not embedded into soil). An experimental demonstration of the capability of such a sensor for landslide monitoring was later given (Higuchi et al. 2007), on a test bed located at the Takisaka Landslide (eastern Japan). OTDR was employed in order to perform displacement measurements at up to five sensing points for each optical fiber cable, with a minimum detectable displacement of 1 mm. Figure 9 shows some results obtained over about 1 year of monitoring, demonstrating the consistence of optical-fiber measurements when compared to conventional sensors.

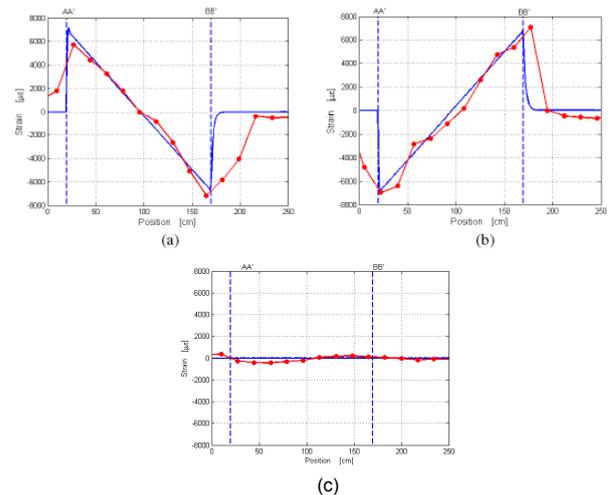


Figure 7. Experimental (marked, red line) and numerically calculated (blue line) strain profiles along fiber A (a), fiber B (b) and fiber C (c), for a 20-cm displacement of the pipeline along the negative x -direction (after Bernini et al. 2008).

A more interesting approach is offered by fully distributed sensors, in which soil displacement is detected all over the sensing fiber length. An example of this approach is given by Dai et al. 2008, in which a distributed sensor based on polarization mode coupling in a polarization-maintaining (PM) fiber, was used in order to measure the stress over a range from 0 P to 15 MPa, a spatial resolution of 10 cm and a measuring range 0.5 km. While the proposed sensor showed high spatial resolution, polarization-based sensors generally suffer from the relatively low birefringence sensitivity to stress. Actually, in the cited work every sensing location needed to be embedded in a special assembly formed by a fixed plate and a mobile plate, aimed to convert the external pressure in a periodic stress acting on the PM fiber.

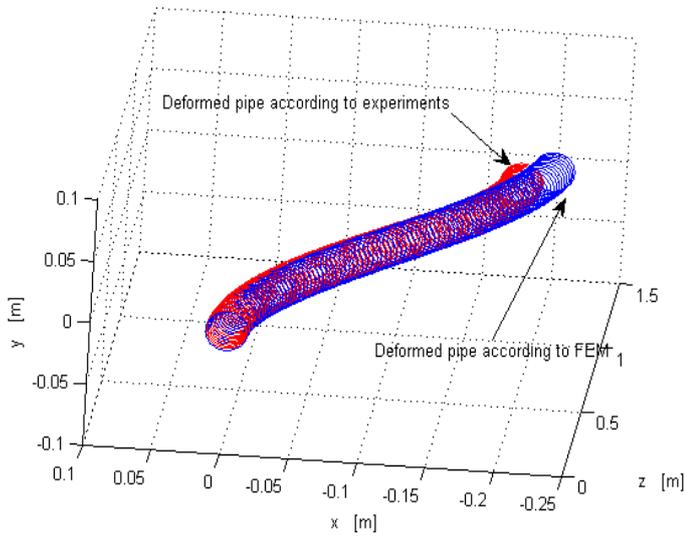


Figure 8. 3D representation of the deformed pipe, estimated according to the experimental strains (leftmost red pipe) and the FEM numerically calculated strains (rightmost blue pipe) (after Bernini et al. 2008).

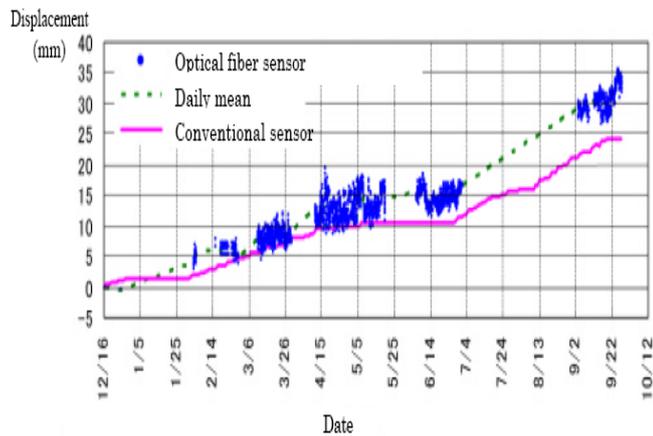


Figure 9. Displacement measurements carried out at Takisaka Landslide by use of an OTDR-based optical fiber sensor, and comparison with measurements provided by a conventional sensor (after Higuchi et al. 2007).

The high strain sensitivity of Brillouin-based sensors suggests the use of these sensors in landslide monitoring (Olivares et al. 2009). A demonstration of the capability of SBS-based sensors for landslide monitoring has been recently given (Zeni et al. 2008), in which experiments were carried out by using an instrumented flume (Fig. 10).

Two strands of optical fiber, each having a length of 1 meter, were embedded into the soil under the longitudinal direction of the flume. Each strand was fixed at both ends of the flume, so as to translate any soil deformation in a tensile strain applied to the embedded fibers. A preliminary measurement of the tensional stress along the sensing fiber was performed before the experiments took place, so that any successive measurements could be compared to it in order to reveal any changes in the measured signals.



Figure 10. Instrumented flume at the Department of Civil Engineering – Second University of Naples – Italy.

After this measurement, the slope of the flume was tilted to an angle of 40° ; then, a uniform rainfall with intensity of 40 mm/h was produced through spray nozzles located 0.4 m above the ground surface, until soil failure occurred.

During the whole experiment, optical measuring set-up was operated continuously, so that an updated strain profile was available every five minutes.

Soil failure occurred about 65 minutes after that the rainfall was started, so that a number of 13 strain profiles were captured during the experiment. It is interesting to show the temporal evolution of the Brillouin frequency shift in correspondence of the embedded fiber section comprised from $z = 14$ m and $z = 15$ m (Fig. 10).

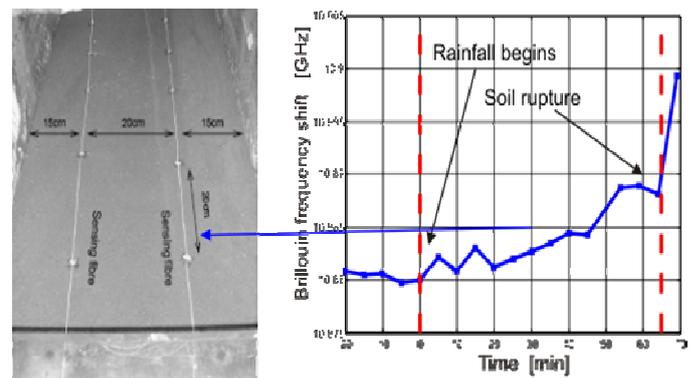


Figure 11. Brillouin frequency shift evolution in correspondence of the first fiber strand embedded into the soil (after Zeni et al. 2008).

It can be seen that the tensile strain of the fiber strand gradually increased during the experiment, indicating a progressive deformation of the soil. Note that the occurrence of soil slipping could be detected much before soil rupture. Actually, Figure 11 indicates that Brillouin frequency shift increased of about 10 MHz before soil rupture, corresponding to a fiber deformation of about $200 \mu\epsilon$.

It is also useful to compare the whole Brillouin frequency shift profile, as acquired at the beginning of the experiment, to the profile acquired immediately before soil rupture. This comparison is shown in Figure 12, in which the increase in Brillouin frequency shift along the second strand is evident. As stated before, such an increase could only be attributed to soil slipping, as independent measurements, carried out by use of a thermocouple, permitted to verify that the local temperature kept constant during the experiment. On the contrary, the changes in Brillouin frequency shift along the fiber regions not embedded into soil, shown in Figure 11, were to be attributed to changes in fiber temperature, resulting from both room temperature changes and rainfall-induced fiber cooling.

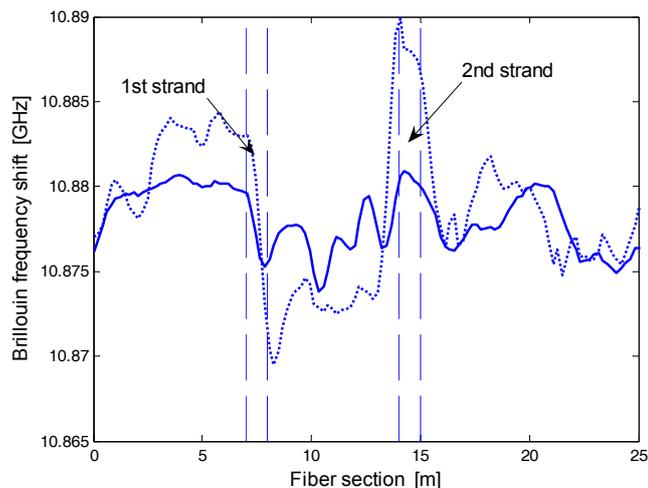


Figure 12. Brillouin frequency shift profile along the fiber, as measured before rain-falling (solid line), and immediately before soil rupture (dotted line). The dashed lines enclose the fiber regions embedded into the soil (after Zeni et al. 2008).

6 CONCLUSIONS

Distributed optical-fiber sensor systems, in particular those based on Brillouin scattering, will have a large part to play in the monitoring and diagnostics of critical extended structures, as well as in the field of environmental monitoring. Despite the unique opportunities offered by fiber-optics sensor technology, commercialization of the ideas emerging has been slow. One of the main obstacles to more effective deployment is the interface problem, i.e. that of ensuring an optimized interaction, between the fiber system and the measurand field. For example, in case of strain sensing, the problem of optimal strain transfer from the host structure to the fiber is still an open issue (Lee et al. 2007). On the more positive side, the rapid advance of optical fiber telecommunications has given rise to a large range of high-performance and low-cost components and fiber types which have assisted considerably in the advance of the fiber sensors technology. As the requirement for ever greater understanding, monitor-

ing and control of large structures increases its demands on sensor technology, more and more technical and commercial attention will be paid to the powerful advantages offered by distributed optical-fiber sensing methods.

Landslide monitoring is expected to take advantage from the development of distributed fiber-optic systems. In particular, the high sensitivity and spatial resolution offered by SBS-based sensors offers the possibility to sense even small soil deformations foregoing soil rupture. This would permit to get continuous spatial and temporal information concerning the slope behavior, prefiguring the use of distributed fiber optical sensors as effective, precocious landslide alerting systems.

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