Distributed Optical Fibre Sensors for Structural Health Monitoring: Upcoming Challenges

Vincent Lanticq[1], Renaud Gabet[2],
Frédéric Taillade[3] and Sylvie Delepine-Lesoille[4]
[1]*Electricité De France R&D*
[2]*Telecom-Paristech*
[3]*Laboratoire Central des Ponts et Chaussées*
[3]*Agence Nationale pour la gestion des Déchets RAdioactifs*
France

1. Introduction: SHM and optical fibre sensing

In the last mid-century, the new civil engineering structures have undergone a revolution in terms of complexity such as large dimensions (Millau Bridge in France, Rion-Antirion Bridge in Greece, Stonecutters Bridge in Hong Kong, Akashi Kaikyo Bridge in Japan, etc.). The authorities managing the old civil structures face the challenge of increasing lifetime of the structures meanwhile maintaining the transportation network limited cost with sparsely perturbations for the users.

In this context, a large sensor network placed inside or surface mounted on the structures is necessary to provide advanced warning of structural state, wear or damage of the structures. The measurement and monitoring often have an essential role in management. The information obtained is used to plan and design maintenance activities, increase the safety, verify hypothesis, etc. This new field of research and development techniques is named Structural Health Monitoring (SHM) (Ou & al., 2005). Typically, several hundred of strain or temperature gauges, accelerometers, etc. are installed in the civil structures. Electrical addressing trough complex wiring harness is fine for laboratory use but *in situ* installations are costly and impractical. Indeed, the wires corrodes, the signals are perturbed by electromagnetic interferences which is physically bulky. To bypass these problems, the recent instrumentations are based on wireless sensor networks but they face the problem of storage and energy recovery. Another solution consists in using the Optical Fibre Sensor technology (Glisic & Inaudi, 2007).

Temperature and strain optical fibre sensor exists in various Forms: pressure, chemical (gaz detection), radiation and even hygrometry may be sensed with commercially available sensors. As described with great details in (Lopez-Higuera, 2002), optical fiber sensors typically involve a light propagating beam which travels along an optical fibre waveguide. The light is then modulated in response to an external physical or chemical stimulus. The modulation induced can change the optic propagation delay, the optical path length, the spectral response, the amplitude transmission, the optical polarisation state or, through non

linear phenomenon, the optical frequency (wavelength). These changes are monitored after transmission through optical fibre. Optical fibre sensors (OFS) have certain advantages including immunity to electromagnetic interference, lightweight, small size, high sensitivity, large bandwidth, and ease in implementing multiplexed or distributed sensors. The serial multiplexed and distributed architectures are especially relevant for structural applications which usually need a lot of measurement points.
OFS can also be configured in point, point multiplexed, integrating or distributed formats as shown in figure 1. A lot of point-like optical fibre sensors based on Bragg gratings or small Fabry-Perot cavities (< 10cm) have been developed in the nineties, and their multiplexing is still an intensive research topic nowadays, mainly on the aim of cutting down the whole sensing system costs. Quasi-distributed sensors perform intrinsically integrated measurement into large Fabry-Perot cavities (> 20cm) induced by several inline partial mirrors in the fibre. The main advantage of this technique compared to point-like measurement is to avoid any Blind-zones (without sensitivity), as shows figure 1.

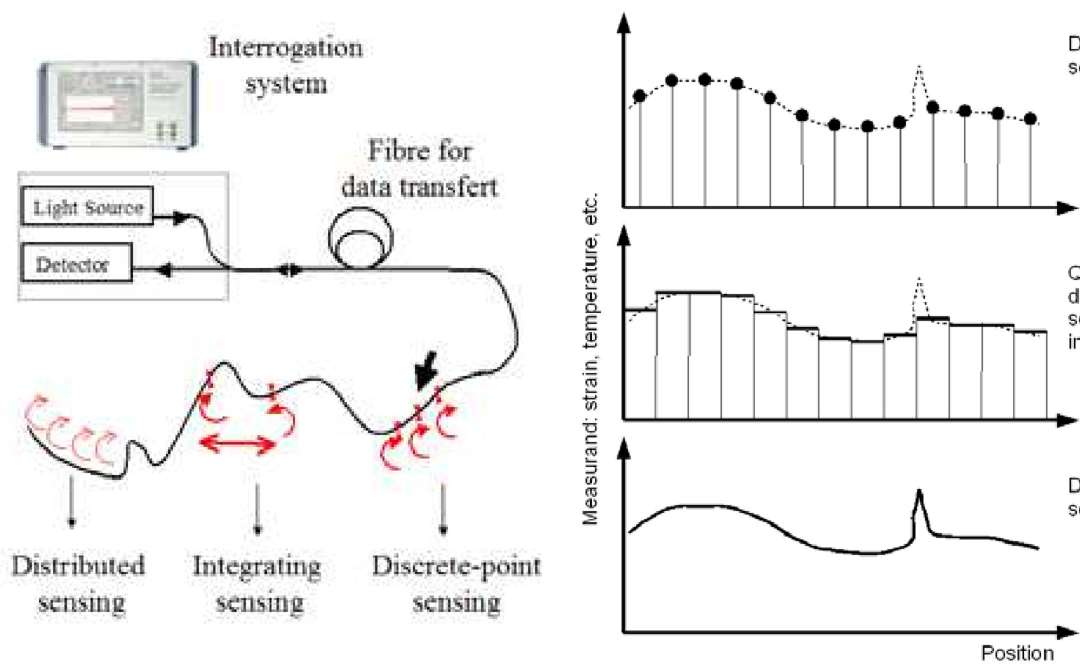

Fig. 1. Concepts of point, integrating and distributed sensing.

About ten years ago, distributed optical fibre sensing technologies appeared, constituting a breakthrough in sensor technology. A truly distributed measurement system for structural monitoring has the considerable advantage that the optical fibre itself can be used as the transduction mechanism without any further modifications to the optical fibre. In consequence, the meshing measurement is considerably improved. It depends on the physical phenomenon implemented and the optoelectronic interrogation unit used.
Those methods, based on elastic optical effect (Rayleigh) or inelastic optical effects (Raman, Brillouin) of the backscattered light, allow to measure temperature and strain into a long range zone (typically 20 km) with a relative small spatial resolution (typically 1 m), bringing consequently offer huge multiplexing possibilities. Now this technology has become quite

mature and suitable for industry, thanks to the creation of many companies providing distributed optical fibre sensing devices.

After a short introduction, the present chapter proposes an overview of the distributed sensing technologies in particular for the temperature and strain monitoring cases. The different technologies based on Optical Time Domain Reflectometry and on inelastic optical effect (Raman and Brillouin) are briefly described. The performances of these systems in term of localisation and spatial resolution of the measurement are discussed in section 3. Finally, the section 4 evokes the problem of the host material inclusion which plays an important role in the transfer mechanisms between the structure and the optical fibre sensor.

2. Distributed sensing for temperature and strain monitoring

The term distributed sensor designates the case in which the optical fibre itself becomes a sensor (Lopez-Higuera, 2002), as opposed to punctual sensors multiplexed in great number. It is thus no longer necessary to implement anticipated sensor positions since measurements are being performed all along the optical fibre hooked up to the reading device (as well as within the extension cables!). In addition, the processing and manipulations required to make Bragg gratings or mirrors delimiting the long-period strain sensors act to significantly weaken the optical fibre. On the other hand, for distributed OFS (D-OFS), the commercial optical fibre (G652 and others) is placed directly inside its mechanical protective coating, which would suggest a more robust instrumentation. Precautions to take while chosing this protective coating are addressed in section 4.

For the last three years, major improvements have occurred in optical fibre sensing area, in particular concerning distributed optical fibre temperature and strain sensing. As detailed in (Rogers, 1999), truly distributed measurements rely on Rayleigh, Raman or Brillouin scattering in optical fibres described in the following sections, paired with a localization process such as Optical Time Domain Reflectometry (OTDR described in this section), Optical Frequency Domain Reflectometry (OFDR, see section 3) or correlation probe-pump technique (section 3).

2.1 Distributed sensing fundamentals

a) Light backscattering

To understand how distributed sensors work, emphasis must be placed on the backscattering phenomenon taking place within optical fibres.

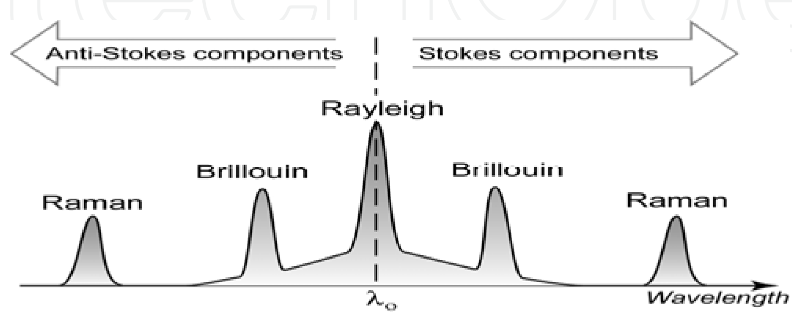

Fig. 2. Backscattering spectrum of a monochromatic wave within an optical fibre extracted from www.epfl.ch

As shown in Fig. 2, the light backscattered by an optical fibre segment without any defects or anormal characteristics is spectrally decomposed into three distinct peaks corresponding to three outstanding phenomena.
The first relates to Rayleigh scattering. The electromagnetic wave propagating in the fibre core interacts with the scattering centres, silica impurities and enhancing additives with dimensions well below the wavelength; these interactions give rise to a partial reflection in the vicinity of 10^{-7} m^{-1}, that can be detected and interpreted as described in the following (b). Raman scattering is an interaction between light and the corresponding coupling matter between a photon and the thermal vibration of silica molecules. As such, this phenomenon is highly dependent on temperature at the spectral level. The Brillouin effect originates from photon-phonon interaction; given its sensitivity to both fibre geometry and density, it depends on temperature and strain.
Temperature and/or strain distributed sensing systems based on these three backscattering phenomena are commercially available. They may take advantage of spontaneous or stimulated phenomenon, paired with a localisation process, the most common being OTDR.

b) Optical time domain reflectometry (OTDR)
Initially created to analyze losses inside optical telecommunication lines (Barnoski & Jensen, 1976), OTDR is categorized as an optical pulse-echo technique. As diagrammed in figure 3, this technique consists of injecting a laser pulse within an optical fibre and then measuring the backscattered intensity as a function of time: A period Δt corresponds to a pulse round-trip between the connector and a given point on the fibre located at distance d from the injection connector:

$$d = \frac{\Delta t}{2n_g} \tag{1}$$

where n_g means the group index. Range d_{max} of OTDR-based devices is limited only by roundtrip linear-loss which can come from material absorption or punctual damages. The width of measurement zones (each point of the trace is integration over this zone) is called spatial resolution and is linked with the temporal width of the pulse T_p by a similar relationship:

$$\delta z = \frac{T_p}{2n_g} \tag{2}$$

Spatial resolution is also the smallest distance to perform independent measurements.

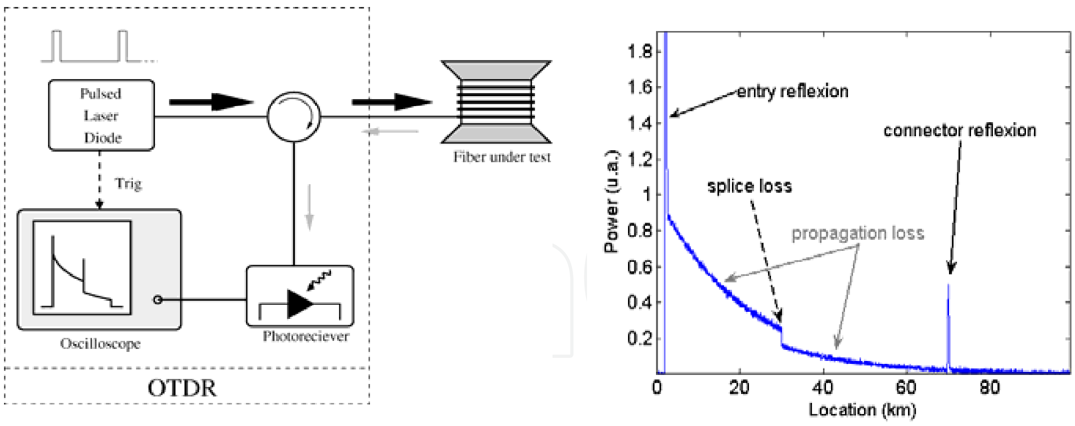

Fig. 3. OTDR (Optical Time Domain Reflectometry) operating principle, and typical trace.

OTDR instruments provide intensity variation measurements over distances in the tens of kilometres, with a spatial resolution at the meter scale. As illustrated in Fig. 3, by measuring intensity variations in the backscattered signal at the same wavelength as the injected wave, local optical fibre modifications may be detected: An abrupt return peak is interpreted as a mirror reflection (connector or damage on the fibre), and a sudden drop in intensity corresponds for example to shear loss.

2.2 Distributed sensing system families

a) Rayleigh backscattering based D-OFS systems

Light intensity variations cannot be precisely correlated with temperature nor deformations of the medium where the optical fibre has been embedded. Thus a simple OTDR be used as a measurement system for these parameters. To conduct the actual strain measurement, the value of the Rayleigh backscattering signal in optical fibres may be associated with optical fibres preliminarily fitted with punctual sensors, such as microbend sensors or another configuration that incorporates pre-calibrated losses (Wan & Leung, 2007) or Bragg gratings (LO et al., 2007) (Crunelle et al., 2009) in which cases the continuously-distributed aspect of the measurement would be lost.

Coherent OTDR showed recently great performances for temperature sensing by self-heterodyne detection, because of relatively long pulse duration, at time *t*, different wavelets backscattering from different locations of the fibre are simultaneously detected. If coherence time of the laser source is higher than the pulse duration, these wavelets can interfere, producing a slight beating signal around the classic OTDR trace. The frequency of the beating is strain and temperature dependent. A resolution about 0.01 °C at 7 km distance with 1m spatial resolution has been performed by (Koyamada et al., 2009). A 10 s pulse is emitted from a coherent monochromatic laser source.

Another principle called OFDR uses Rayleigh scattering spectral properties (local complex reflectivity) to measure local optical path variations and deduce strain or temperature. It will be presented in great details in section 3 of this chapter.

b) Raman based D-OFS systems
Raman scattering originates from laser light photon interaction with thermal vibration of silica molecules (thermal phonons). It occurs into single-mode and multi-mode fibres. Fig. 4 sketches the well-known Stokes and Anti-Stokes process, occurring respectively if the virtual state of energy of a silica molecules is the fundamental or an excited state.

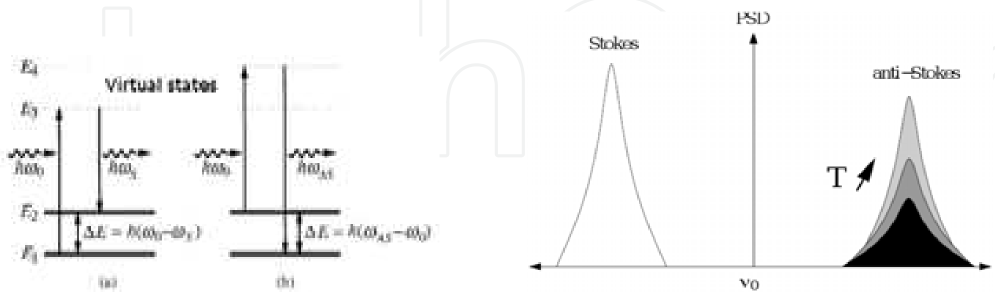

Fig. 4. Origin of Raman scattering (left) and sensitivity to temperature (right). "PSD" stands for power spectral density.

The anti-Stokes absorption mainly depends on temperature (Liu & Kim, 2003). Raman distributed optical fibre sensing systems are using OTDR pulsed technique previously described (in 2.1.b) to perform distributed intensity measurement of the anti-Stokes Backscattered light. This technique is called Raman-OTDR or R-OTDR. However, the anti-Stokes intensity evolution must be augmented with a reference measurement since optical fibre losses vary with time (increase with fibre aging, connector dirt or optical fibre curvatures etc.). Thus, Distributed Temperature Sensing (DTS) devices analyse the ratio between the Anti-Stokes and Stokes absorption line intensities (I_{RAS} and I_{RS}) using equation (3):

$$\frac{I_{RAS}}{I_{RS}} = \left[\frac{\lambda_S}{\lambda_{AS}}\right]^4 \exp\left(\frac{hc\Delta\upsilon}{kT}\right) \tag{3}$$

where λ_{AS} , λ_S are anti-Stokes and Stokes wavelengths, $\Delta\upsilon$ is their wave-number separation from the pump wavelength, h is Planck's constant, c is the velocity of the light, k is Boltzmann's constant, and T is the absolute temperature of the fibre core under measurement.
Nevertheless, Stokes intensity is a few times larger than anti-Stokes intensity and its bandwidth is usually much larger than the pump spectrum. What is more, few phenomena at the origin of optical fibre losses (bending losses especially in single-mode fibres, hydrogen darkening…) are wavelength-dependent and not modelled by formula (3). They may become highly sensitive as Stokes and anti-Stokes lines are separated by 80 nm at 1.55 µm. Recent developments combine various laser wavelengths (Lee et al., 2008). The optical fibre type is also a parameter to choose carefully while designing a Raman DTS: In multimode fibre the Raman scattering is bigger. For instance, (Farahani & Gogolla, 1999) shows that for a 15 km range, a graded-index multimode fibre is the optimum.
Several optoelectronic devices that conduct distributed temperature measurements using the Raman effect are available on the market and have already profoundly modified certain fields such as fire detection (Liu & Kim, 2003). The accuracy derived lies on the order of 0.1°C, 1 m of spatial resolution, over spans extending several tens of kilometres. As a case in point, the sensor Fibolaser from LIOS technologies company, commercialized by Siemens

(Glombitza, 2004) was installed on the Mont-Blanc Tunnel subsequently to the 1999 disaster. For distributed temperature measurements in civil engineering structures, EDF company (Electricité De France) has already implemented various field qualification of Raman scattering in multimode fibres. In the beginning of 2002 (Fry et al., 2004), although the optoelectronic instrument revealed some inabilities with field specificities, the sensing cable inserted inside 2 km of Oraison embankment (France) endured civil engineering construction works. Meanwhile optoelectronic instrument performances have been improved. 3km of Kembs embankment (France) were also instrumented with embedded sensors in 2006 (Hénault, 2006). Now, the focus is given in the way measurements may be interpreted with greater precision and less false alarm using statistics.

c) Brillouin based D-OFS systems

In optical fibres, Brillouin scattering takes origin from coupling between the optical mode and acoustic waves in the material (silica) produced by thermal excitation. Thanks to photo-elasticity of the material, these acoustic waves create an index grating, moving at sound velocity in silica V_A. Thus, when an incident wave (so called pump wave) propagates in the fibre, a frequency-shifted optical wave (Stokes or anti-Stokes) is created, and propagates backward. To satisfy the coupling conditions, the frequency-shift (often pointed as the Brillouin frequency ν_B) is linked to optical and acoustic parameters by the following relationship:

$$\nu_B = \frac{2 n_{eff} V_A}{\lambda_0} \tag{4}$$

where n_{eff} is the effective index of the optical mode *i.e.* the ratio between light speed in vacuum and in a medium, and λ_0 the operating wavelength.

Brillouin sensing consists in measuring the Brillouin frequency assuming it is proportional to temperature variations (ΔT) and strain ε:

$$\Delta \nu_B = C_T \Delta T + C_\varepsilon \varepsilon \tag{5}$$

where C_T and C_ε are characteristics of the fibre type (Standard single mode fibre) and the operating wavelength. At λ_0 = 1550 nm for standard fibres, typical values of these coefficients are C_ε = 0.05 MHz/με and C_T = 1 MHz/°C. Brillouin distributed sensing can be performed by two different means. One consist in the use of a pulsed laser source and the analysis of the spectrum coming from successively backscattered light. That gives plots of distributed Brillouin spectrum like on Fig. 5. This plot sketches measurements from a fibre we had previously coiled in a solid cylinder with 5 strain echelons of 0, 250, 500, 1000 and 200 με (Lanticq et al., 2009a).

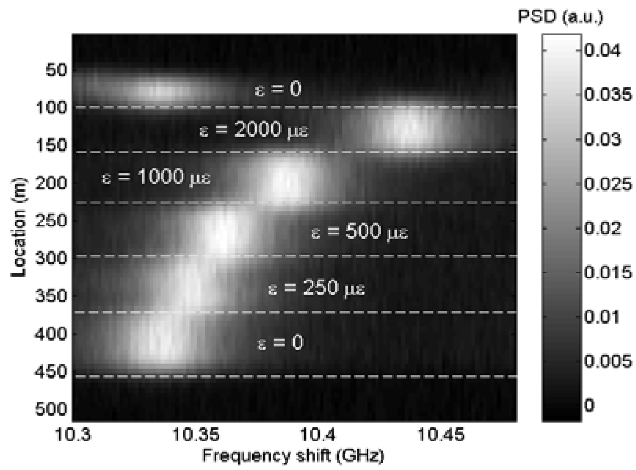

Fig. 5. Distributed Brillouin spectrum along a strained optical fibre.

Another is to use the non-linear effect called Stimulated Brillouin Scattering (SBS). It occurs when, simultaneously with the pump wave, a frequency-shifted wave —so called probe wave— is propagating backward. If the frequency shift between the two waves is close to the Brillouin frequency, then energy can be transferred from the pump to the probe wave. That can be interpreted as a gain spectrum for probe wave (Niklès et al., 1997). Distributed Brillouin spectrum can be recovered by use of a pulsed pump wave and a continuous probe wave, acquiring time traces for several frequency-shifts of the probe. The final trace of this method, called Brillouin Optical Time Domain Analysis (B-OTDA) is similar to B-OTDR one (see Fig. 5).

Various optoelectronic instruments using these techniques are commercially available and may be paired with many different sensing cables to provide either temperature or strain measurements as described in section 4.

In 2002, the first commercial system based on the Brillouin scattering was implemented; by 2007, the market had expanded to include at least five suppliers of Brillouin interrogation systems (Omnisens in Switzerland, Sensornet in England, OZ-Optics in Canada, Yokogawa and Neubrex in Japan). The accuracy derived lies on the order of 1°C, 20 με and 1 m of spatial resolution, over spans extending several tens of kilometres. The most widespread application is currently pipeline leak detection.

Nonetheless, three shortcomings are restricting this technology solely to the realm of research. First, the location of measurement performed by any distributed sensing technique is not perfectly known (uncertainty on index value). Second, using Brillouin sensing, spatial resolution is still fixed by pulse duration but it is limited by the phonon lifetime (Fellay et al., 1997). This latter parameter is in the order of 10 ns which corresponds to a 1 m spatial resolution. Finally, separating temperature from deformation influences requires the use of cables incorporating two optical fibres, one of which being mechanically isolated. Thus, research on the topic is extremely active, with respect to both the interrogation techniques for reaching centimeter-scale spatial resolutions (Imai et al., 2003) (Zou et al., 2005) and the choice of new optical fibres to enable discriminating thermal and mechanical influences (Lee & Chiang, 2001) (Zou & Bao, 2004).

3. Spatial issues of distributed measurement systems

We showed previously that new parameters were necessary to describe distributed OFS systems. We defined, with equation (1), the location of the performed measurement which value is evaluated in terms of time spent since the pulse entered the fibre, and spatial resolution (equation (2)). Improvement on knowledge of measurement location and decrease of the spatial resolution are still very challenging topics of research.

3.1 Spatial resolution

Brillouin devices offer sometimes lower spatial resolution than required by applications. In (Lanticq et al., 2009b) we showed an example of bad detection by such a device.

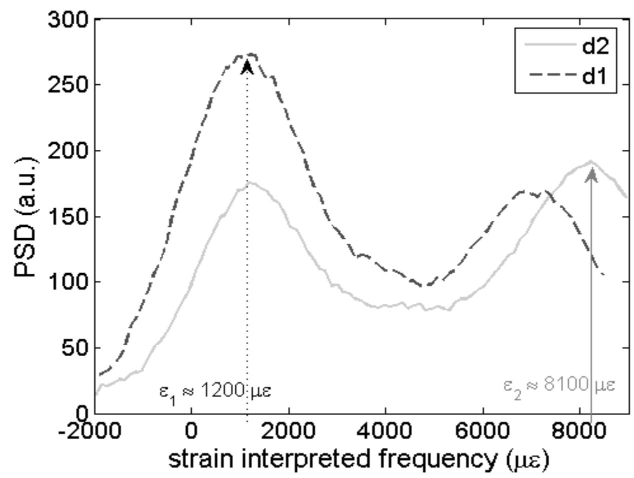

Fig. 6. Brillouin spectra obtained with a sensing system with insufficient spatial resolution

Indeed, as shows Fig. 6, if only one part of the sensing zone is highly strained 2 peaks appear on the spectrum trace. As devices are usually performing peak detection to estimate the Brillouin frequency from the spectrum, 2 cases can then occur:

1. Most power is on the peak corresponding to the high strain (grey curve), then detection is completed without any problem.
2. Most power is on the rest of the spectrum (dashed curve), then detection is missed.

As we mentioned before, the main cause of spatial resolution limitation is phonon lifetime. To get around this difficulty, it necessary to give up any time domain coding method. Thus we are going to deal with two of them: Frequency domain coding for Rayleigh reflectometry and correlation domain coding for pump-probe Brillouin measurement systems.

a) Frequency domain coding of Rayleigh reflectometry

OFDR (Optical Frequency Domain Reflectometry) systems use a tunable laser source and analyse the backscattered light in the spectral domain. Such a device uses ramp wavelength (frequency) modulation of the CW laser source. So at time *t*, the position from which comes the detected wavelet is frequency-domain coded. Similarly with OTDR, OFDR can provide local backscattered light intensity variation after FFT (Fast Fourier Transform) numerical process (see on left part of Fig. 7) of the detected signal. If the sensitivity of those instruments is so high that Rayleigh scattering uniformities in the fibre can be observed, then a simple cross-correlation between two OFDR traces allows evaluating local strain all along the fibre.

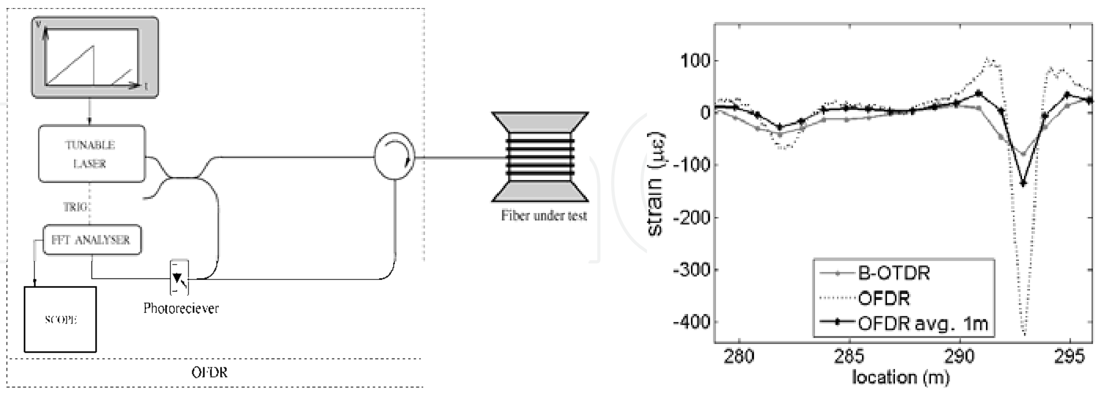

Fig. 7. (left) OFDR system block diagram, (right) strain traces obtained using both OFDR and B-OTDR simultaneously in the same cable; the black curve is drawn averaging OFDR measurements along each B-OTDR measurement zones.

As described in great details in (Glombitza et al. 2006), the OFDR spatial resolution δz is inversely proportional to the bandwidth of the tunable-laser frequency range:

$$\delta z = \frac{c}{2n_g(\Delta\nu)_{\max}} \tag{6}$$

Therefore, this parameter is only limited by $\Delta\nu$ which can reach very high values. On the other hand, measurement range usually decreases when frequency-range increases. Indeed, it is dependent on frequency resolution $\delta\nu$ by a similar relationship:

$$d_{\max} = \frac{c}{2n_g\delta\nu} \tag{7}$$

For example, the American firm Luna Technologies has been marketing since spring 2006 an OFDR based on optoelectronic device called OBR (Optical Backscatter Reflectometer), which constitutes the state of the art of such devices. It enables measuring optical fibre deformations (at homogeneous temperature) over 150 m with a millimetre-sized spatial resolution and a level of precision equal to a few micro-deformations.
This performance has been obtained by OFDR, in association with an advanced correlation method between the ongoing measurement and a reference state. Temperature change (ΔT) and strain (ε) are obtained by calculating local changes on optical path from the correlation function between last OFDR trace and a reference trace (Froggatt & Moore 1998). As shows right part of Fig. 7, we demonstrate in (Lanticq et al., 2009) that this device could be complementary of B-OTDR for short range detection of sub-meters straining events.

b) Correlation domain coding of Brillouin spectrum analysis
The frequency domain reflectometry technique has been adapted to Brillouin devices giving birth to Brillouin Optical Frequency Domain Analyser (Garus et al., 1996). Although they were very promising theoretically, these devices never showed performances much better than B-OTDA in terms of spatial resolution or range. To reach very better spatial resolutions

in Brillouin systems the best technical solution investigated is, to the best of our knowledge, correlation domain spectrum analysis.

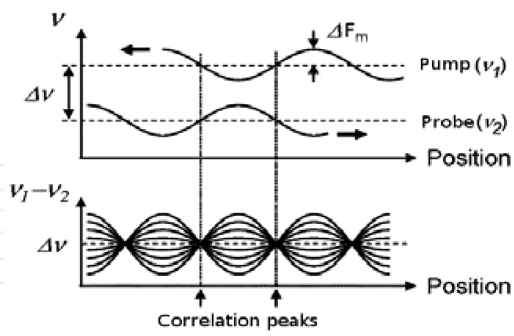

Fig. 8. Principle of correlation coding in B-OCDA systems (from (Hotate & Takemi ,2000)).

(Hotate & Takemi 2000) gives the outline of this method: Pump and probe (which frequency difference is $\Delta\nu$) injected in the fibre under test are created from the same frequency modulated CW wave. As they propagate in opposite directions, then actual frequency difference between the two waves is exactly $\Delta\nu$ only in finite number of location. This number can be reduce to 1, by using a chopped pump wave. If $\Delta\nu = \nu_B$ and if modulation depth ΔF_m is high enough, SBS occurs on only one very tight zone of the fibre. Location can be swept by tuning the modulation frequency f_m. Spatial resolution and range can be redefined with the following relationships:

$$\delta z = 1.52\frac{c}{2\pi n_g \Delta F_m} \quad \text{if } f_m > \frac{\Delta\nu_B}{2} \qquad \text{or} \qquad \delta z = \frac{\Delta\nu_B}{f_m}\frac{c}{2\pi n_g \Delta F_m} \quad \text{if } f_m > \frac{\Delta\nu_B}{2} \tag{8}$$

$$d_{\max} = \frac{c}{2\pi n_g f_m} \tag{9}$$

where $\Delta\nu_B$ is the Brillouin linewidth which value is usually about 40 MHz. As this method uses continuous waves, spatial resolution is no more limited by phonon lifetime.
Indeed, this technique has led to highly resolved distributed measurements. For example, a spatial resolution as low as 2 mm has been reached by (Song et al., 2006). On the other hand range values, usually about several tens of meters, are far from reaching B-OTDR (or B-OTDA) ones. That is why, as Rayleigh OFDR, this technique remains complementary with OTDR-based methods.

3.2 Measurement localisation accuracy

As we mentioned at the beginning of this part, one of the major issue of distributed sensing is the uncertainty on the measurement locations. Indeed, as we showed in (Lanticq et al. 2009b), a lag could exist between measurement location estimated by different commercial devices. This is mainly due to group index value they are using during data processing. Indeed from (1), we can deduce this uncertainty $u(z)$ on location z from the one on the group index $u(n_g)$ and the distance z from the fibre entry:

$$\frac{u(z)}{z} = \frac{u(n_g)}{n_g} \tag{10}$$

assuming time spent from pulse entrance is perfectly known. In addition, the provided information is the curvilinear abscissa along an optical fibre coil, often partially embedded into structures to monitor, often in the km range. So uncertainty of location for the end used can be much higher if a sensor location map is not carefully drawn during installation.

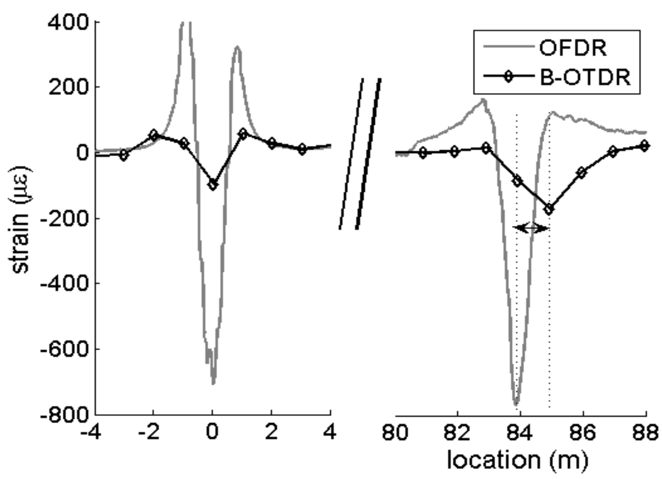

Fig. 9. position lag between two measurement systems interrogating the same sensor.

Fig. 9 highlights a lag of 1% between 2 different instrument traces, after only 85 m propagation into the fibre. This means that for distributed measurements along 20km (typical range of B-OTDR or R-OTDR), those technologies do not suit requirements. Indeed, for instance in the case of underground cavity detection, at 20 km distance the user should dig a 200m large zone to find the hole. Then a good solution for Brillouin devices is to include markers in the sensing line at several well known locations. (Honda et al., 2009) used spans of a different fibre (with a different Brillouin frequency shift) spliced to the sensing fibre (SMF) as absolute location markers. Highly strained or heated spans could be used as well. If it is possible those markers should be located out of the structure giving access to the fibre by the user. Then, high spatial resolution devices can be used on a short part of the sensing line previously identified as interesting (or risky) by the low spatial resolution apparatus.

4. Host material inclusion problems

4.1 Cable choice

The choice of the fibre and its coating is crucial in optical sensor applications, especially for Rayleigh of Brillouin scattering where multi-parameter sensitivity is to be handled. A sensitive optical fibre cable is made of:

- an optical fibre, namely 125 µm of silica (in few cases plastic optical fibres) in which the measurement is made, called the transducer,
- a material that surrounds the fibre, called primary coating, manufactured at the same time as the optical fibre in the drawling tower, usually made of polyimide or acrylate.

An external coating provides contact with the host material, concrete or soil for example. The sensor coating must ensure various functions. First it has to protect the fibre from all kinds of aggression: Chemical (for instance concrete is alkaline, radiations in nuclear power plants), mechanical (concrete pouring and vibrating followed by aggregate solicitation; introduction into ground, vibrating rollers passing) and thermal (temperature reaches 65°C during concrete pouring). As a result, the cable must be robust in order to resist to every stage of implementation as illustrated in Fig. 10. Second, it must ensure an optimal transfer of measured parameter changes from the host material to the sensitive optical fibre. This aspect is of utmost importance as it might strongly degrade the whole measurement system. It is highly dependent on the environment nature and should be targeted to reach optimal performance. So, the incorporation of OFS into civil engineering structures remains challenging. Third, it has to reduce stress concentration around the fibre and hence to minimise the obstrusivity, meanwhile preventing debonding of the sensor. Thanks to their size in the millimetre range, optical fibre sensors are known to be less invasive than traditional sensors. Yet, while designing an optical fibre sensing cable, the cable size should remain an important parameter adjusted to the host environment specificities.

Fig. 10. Sensor cable must be robust: example of concrete pouring . Extracted from (Dubois et al., 2007)

a) Orders of magnitudes of sensing cable influence

For point-like sensors, it has been reported (Caussignac et al., 2002), that commercially-available optical fibre extensometers embedded into concrete may underestimate strain by about 10%, shift correlated by finite element analysis with the shape and the Young's modulus of the sensor external coating.

For Raman distributed temperature sensing into single-mode fibres, sensor coating may even ruin measurements as described in (Dubois et al., 2009).

For Brillouin temperature-only monitoring, as pointed out in introduction, cross-sensitivity with strain may significantly shift the measurements. More precisely, Brillouin temperature sensitivity is modified by mechanical strain created inside the optical fibre by the thermal expansion of the specific coating (Kurashima et al, 1990). As depicted with great details in (Lanticq et al., 2008), (5) becomes (11) for an externally unstrained sensor:

$$\Delta\nu = (C_{T_{fiber}} + C_{\varepsilon}\alpha_{sensor})\Delta T = C'\Delta T \tag{11}$$

where C_{Tfiber} and C_{ε} are the temperature and strain optical fiber sensitivity coefficients and α_{sensor} is the temperature expansion factor. If the sensor is completely bound up with the host material, one must take into account the expansion coefficient of the host material:

$$C"_T = C_T + C_{\varepsilon}\alpha_{hostmaterial} \tag{12}$$

As $\alpha_{concrete} = 10 \times 10^{-6}$/°C, C_{Tfiber} = 0.92 MHz/°C, then C''_{Tfiber} = 1.42 MHz/°C.

Error! Reference source not found. represents the recordings of temperature variations at the center of a 3m long concrete beam instrumented with optical fibre sensors collocated with reference temperature sensors. The Brillouin shift was measured with a commercially available Brillouin optical time-domain reflectometer (BOTDR) operating at 1.55μm. Temperature variations during the 60th hours of concrete hardening were recorded. The dotted curve (no strain S1) represents the raw results, corresponding to equation (5). The black curve represents the temperature curve recorded by the reference sensor. Exothermic chemical reaction causes an increase in temperature until the 25th hour after the pouring of concrete, time of the highest temperatures measured by the sensor. We made a mistake in (Lanticq et al., 2008), claiming that until the 45th, the concrete is considered as a liquid and that the cable is not seen as connected to the structure. Actually, according to the concrete maturometry theory, since the chemical reaction has started, the concrete become solid and its strength is quickly high enough to drag the sensor. Thus, taking into account the strain due to thermal expansion, the thermal coefficient of the sensor is C"T, defined by equation (12), as soon as temperature starts to increase in the material (15h after pouring, in our case). Then, as shows figure 11, if all the Brillouin frequency variations are interpreted as thermally induced (see the raw Brillouin measurement curve), the temperature variation is clearly underestimated, compared to temperature measured by an electronic resistive sensor (solid curve).

This is due to mechanical strain in the beam perturbing Brillouin measurement: it is created in the early hours by the young age autogeneous shrinkage of concrete. On figure 11, this additional compressive strain has been estimated by equation (5) using the measured Brillouin frequency and the electronic temperature sensor measurement. Fourier filtering of the mechanical strain (dashed curve) has been used in the aim of evaluating noise on Brillouin temperature measurement. Standard deviation between strain-compensated Brillouin temperature measurements (gray curve) and reference sensor measurements is 0.4°C. This is promising compared to results available in literature (Rajesh et al., 2006) (Wade et al., 2004), but one shall remember that all the data-processing described here wouldn't have been possible without additional reference measurements.

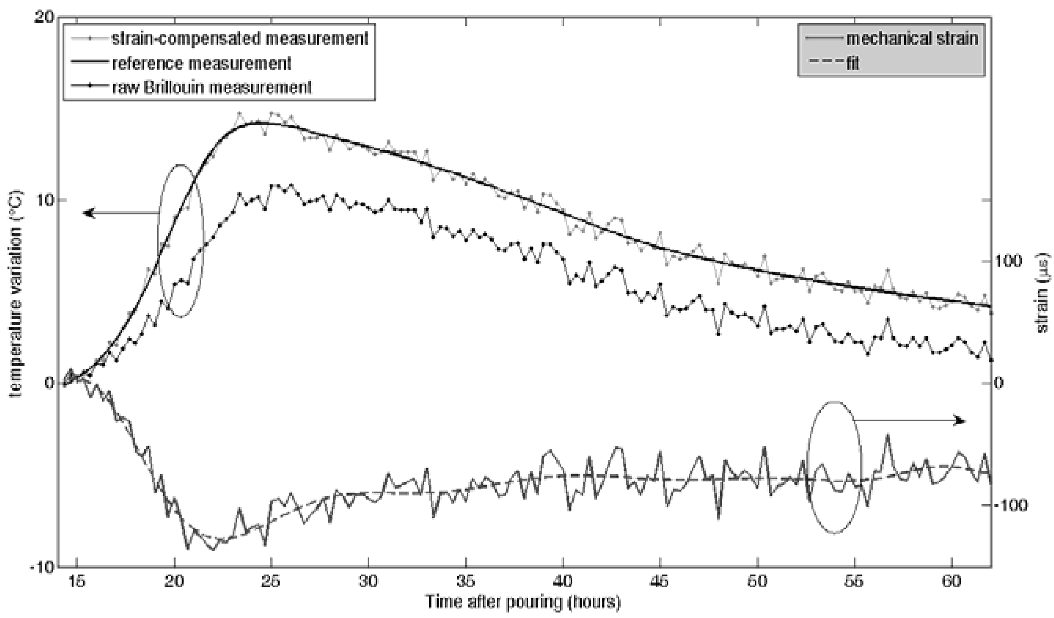

Fig. 11. Use of Brillouin measurements and reference temperature measurements to evaluate the mechanical strain.

For strain measurement, not only the coating must perform optimal strain field transfer from the host material to the optical fibre, but it must also be adjusted to the environment in terms of variation range. Concrete mechanical normal evolution range is smaller than silica that can handle few percent tensile loading. On the contrary, for ground applications (dikes and embankment monitoring), optical fibre use may be restrictive. Fig. 11 presents strain measurements performed by OBR instrument into a sensing cable embedded into an embankment where artificial cavities were created in order to simulate sinkhole formation (Lanticq et al., 2009b). When tensile loading exceeded 0.1% (referred to 'large strain') unexpected strain peaks seem to scramble the measurement. This phenomenon is even worse if strain increases anymore (huge strain ~1%). The optical fibre locally disunited with the cable, involving very close (sub-millimetres) tensile and compressive strain zones. Unfortunately, this effect is irreversible, signifying that this cable is not robust enough for use under strain up to 0.1%.

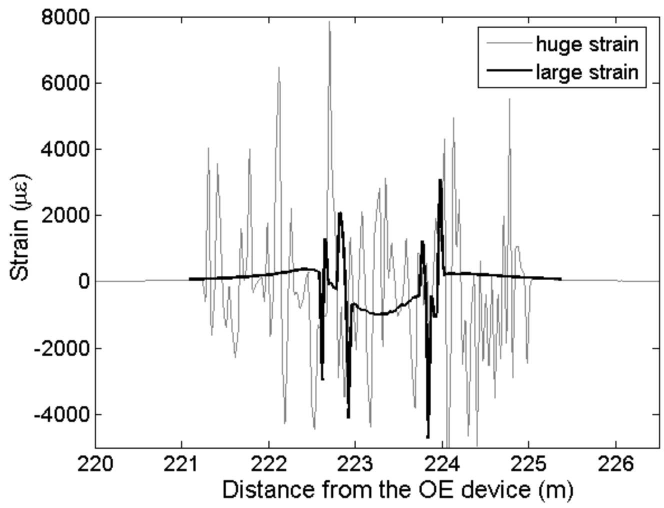

Fig. 11. Strong deformations measurements within an optical fibre embedded into an embankment where sinkhole formation were simulated.

b) Strain sensing optical fibre cable design
One major difficulty is the strain-field transfer from the host material to the embedded optical fibre. Literature reports ways to calculate a calibration factor linked with stiffness difference between a sensor and its host material under uniform loads (Ansari & Libo, 1998) and even with non-uniform strain distribution (Okabe et al., 2002). Moreover, besides materials, the shape of the sensors strongly influences the difference between the strains in the optical fibre and in the host material, and more generally, the sensor response. For point-like sensor a commonly-used I-shaped sensor body has been described and optimized (Winter et al., 2005) (Choquet et al., 2000). For distributed sensors, specific packaging are proposed by various distributors, as shown on Fig. 12, representing different types of Smartec extensometers.


Fig. 12. Range of distributed strain sensors proposed by the Smartec company.

The first step is to list optical fibre sensor specifications: Presence of hydrogen, maximal temperature to be handled, durability (linked with structure), required sensitivity. Then a sensor coating may be found within commercially available products. Corresponding publications (Inaudi & Glisic, 2006) (Dewynter et al., 2007) describing optical fibre sensor coating designs are to be read carefully. Then a qualification process should be realized, as described for dike monitoring by EDF in the previous paragraph. An example can be found in (Delépine-Lesoille et al., 2006) detailing the design and realization of a wave-like sensor specially developed to embed optical fibre extensometers into concrete. As shown on Fig. 13, finite-element analysis performed with thermal and mechanical models enabled optimizing materials and shapes. It resulted in a composite materials with appropriate stiffness, a braid made of glass fibres impregnated with epoxy on top of polyimide primary coating. The realization process has then been defined to reach great accordance with the theoretical design. Temperatures during epoxy reticulations, type of glass to remain compatible with concrete, as well as geometric result were considered. The method for bringing the fibre into the braid was also a challenge so as to ensure that the fibre does not suffer from microbendings (and related losses). Laboratory and field evaluations were carried out. Finally, this coating has been validated with different sensing principles, from point-like sensors (temperature Bragg grating sensors), to long base extensometers (Delépine-Lesoille et al., 2006) to Brillouin sensing chain (Lanticq et al., 2008), the sensitive part also being embedded into concrete.

Fig. 13. Sensor coating. On the left, FEM figure of the sensor developed at LCPC; On the right, the sensor actually made by the IDIL company from the theoretical model.

4.2 Temperature and strain discrimination

In the aim of simultaneously estimate T and ε, one of the more instinctive consists in using two fibres in the same sensing cable, one being strain-free, and the other being bound with the material. Then the first is only submitted to temperature changes and can be used to compensate numerically its effects on the measurement of the second. These kind of cable is commercially available, but it has to be carefully used. Indeed, since the cable is embedded in the material, it is very difficult for the user to guaranty that the first fibre remains strain free during all the sensor lifetime.

Thus, two different parameters p_1 and p_2 are measured by optical methods in the same fibre. Both are varying linearly with temperature and strain, resulting in the following system:

$$\begin{pmatrix} p_1 \\ p_2 \end{pmatrix} = \begin{pmatrix} C_{T1} & C_{\varepsilon 1} \\ C_{T2} & C_{\varepsilon 2} \end{pmatrix} \begin{pmatrix} \Delta T \\ \varepsilon \end{pmatrix} \tag{13}$$

Then temperature and strain can be estimated, inverting the previous system as it follows:

$$\begin{pmatrix} \Delta T \\ \varepsilon \end{pmatrix} = \frac{1}{D} \begin{pmatrix} C_{\varepsilon 2} & -C_{\varepsilon 1} \\ -C_{T2} & C_{T1} \end{pmatrix} \begin{pmatrix} p_1 \\ p_2 \end{pmatrix} \quad (14)$$

Where $D = C_{T1}C_{\varepsilon 2} - C_{\varepsilon 1}C_{T2}$ is the discriminator of the system matrix. The uncertainties $u(T)$ and $u(\varepsilon)$ on T and ε method are then linked to uncertainties $u(p_1)$ and $u(p_2)$ on associated to parameters directly measured p_1 and p_2. Thus, assuming all the calibration coefficient are perfectly well known:

$$u(\Delta T) = \frac{1}{|D|}\left[\left|C_{\varepsilon 2}u(p_1)\right| + \left|C_{\varepsilon 1}u(p_2)\right|\right] \quad (15)$$

$$u(\varepsilon) = \frac{1}{|D|}\left[\left|C_{T2}u(p_1)\right| + \left|C_{T1}u(p_2)\right|\right] \quad (16)$$

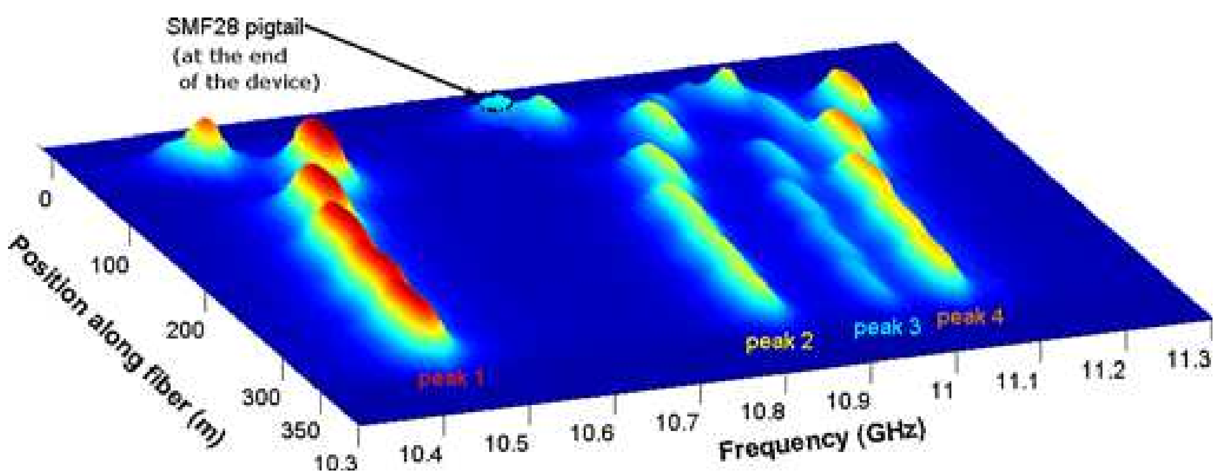

Fig. 14. Distributed spectrum of a strained LEAF fibre. The evolution of 4 Brillouin peaks is clearly visible (Lanticq, 2008a).

As Large Effective Area Fibre (LEAF) have several significant Brillouin peaks at 1.55 μm wavelength, we decided to investigate the suitability of the two of its four peaks to perform simultaneous measurements. To do so, we estimated coefficients C_{Ti} and $C_{\varepsilon i}$ during experimental calibration. One can see on Fig. 14 distributed Brillouin spectrum measurement of a strained LEAF fibre performed with the same experiment as those on Fig. 5. Highest value of $|D|$ were obtained with first and third peaks. Since $|D| = 10^{-3}$ MHz^2.°C^{-1} we estimated uncertainties on T and ε, assuming $u(\nu_i)$=2 MHz (typical value):

$$u(\Delta T) = 35\ °\text{C} \quad (17)$$

$$u(\varepsilon) = 700\ \mu\varepsilon \quad (18)$$

Equations (17) and (18) prove that LEAF fibre is not suitable for simultaneous measurement. Moreover recent works (Zou et al., 2008a) (Zou et al., 2008b) have tended to prove that no solid fibre seems efficient to separate temperature and strain with the use of two Brillouin frequencies.

Then, one can think about using Raman and Brillouin distributed measurement in the same fibre, but Brillouin sensing requires monomode fibre whereas Raman measurements reach an optimal efficiency in multimode fibres (Farahani & Gogolla, 1999). It is possible to design a cable with two fibres (monomode and multimode) but two interrogating systems are necessary and cost would be important.

More promising results have been highlighted using polarisation maintaining fibres: The second parameter is then the local beat length. In this case, the interrogating systems must have a high spatial resolution because beat length is as low as 5 mm in this kind of fibre. Either B-OCDA (Zou et al., 2008b) or OFDR (Froggatt et al., 2006) systems have been implemented for simultaneous measurement and gave very promising result. Nevertheless those apparatus were made of polarisation maintaining components, much more costly. In addition, in the most part of civil engineering structures, temperature gradients are very weak (compared to strain ones), and consequently only a few temperature sensors are necessary to monitor this parameter. Thus, the need of multiplexing is less critical, and standard sensors such as resistive temperature detectors or thermocouples can be regarded as acceptable solution for users.

5. Conclusion

To conclude, we propose the outline of what would be a modern distributed strain monitoring system. In section 4. we demonstrate that time-domain based systems constitutes the only suitable technical solution for kilometre-scale instrumentation. However high-resolution can be complementarily used in small parts of the sensing line, if something has been detected in it. To do so, it is necessary to give an access to the end user in the aim of plugging the high resolution device (HR system on Fig. 15). For better localisation of measurement points, markers can be introduces regularly along the sensing line. Finally, as temperature often varies slowly spatially, a few temperature sensors could be enough to compensate the temperature effect on strain measurement systems. But in certain cases, as bridges, temperature can vary as much in the structures as it must be monitored by distributed measurements. That is why simultaneous strain and temperature sensing methods are still today a very intense research topic.

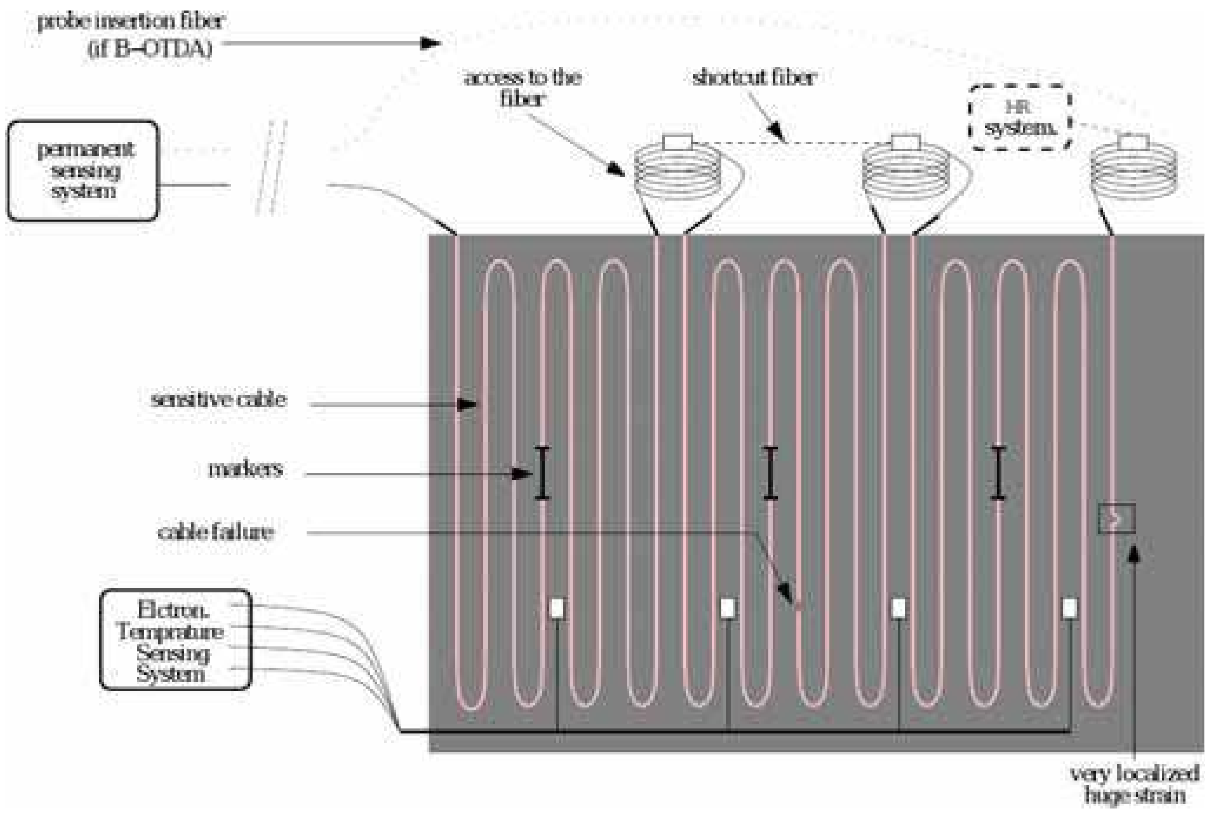

Fig. 15. Modern instrumentation scheme for SHM applications.

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The optical fibre technology is one of the hop topics developed in the beginning of the 21th century and could substantially benefit applications dealing with lighting, sensing and communication systems. Many improvements have been made in the past years to reduce the fibre attenuation and to improve the fibre performance. Nowadays, new applications have been developed over the scientific community and this book fits this paradigm. It summarizes the current status of know-how in optical fibre applications and represents a further source of information dealing with two main topics: the development of fibre optics sensors, and the application of optical fibre for telecommunication systems.