Optical fiber strain sensors for use in civil engineering: State-of-the-art, industrial applications and outlook

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ABSTRACT

Optical fiber sensors prove to be outstanding tools for structural health monitoring. The current article is intended to produce a state-of-the-art assessment of optical fiber strain sensor use in civil engineering, nearly 20 years after their initial development. Following a series of rudimentary descriptions of fiber optics, the different types of optical fiber sensors will be presented in a pragmatic manner, by listing device performance and limitations, along with a progress report and, for more advanced readers, the relevant suppliers and costs. Three categories of optical fiber sensors will thus be distinguished: site-specific sensors, long-gauge-length extensometer, and sensors performing truly distributed measurements, i.e. continuous along the optical fiber. A second section will be devoted to describing various industrial applications specific to the field of civil engineering and developed by two French firms. Lastly, the example of developing an long-gauge-length extensometer designed to be embedded in concrete will be displayed, beginning with the design stage and lasting all the way through tests carried out both in the laboratory and on a portal bridge near the western French city of Angoulême.

Extensomètres à fibre optique pour le génie civil : état de l’art, applications industrielles et perspectives

RÉSUMÉ

Les capteurs à fibre optique sont des outils exceptionnels pour le contrôle de santé des structures. Le présent article vise à dresser l’état de l’art des extensomètres à fibre optique en génie civil, près de 20 ans après leurs premiers développements. *Après des descriptions béotiennes de la fibre optique, les différents types de capteurs à fibre optique sont présentés de manière pragmatique, en listant les performances et les limitations, l’état d’avancement, et pour les plus avancées les fournisseurs et le coût. Trois catégories de capteurs à fibre optique sont ainsi distinguées : les capteurs ponctuels, les extensomètres de longue base de mesure, et les capteurs réalisant des mesures réparties, c’est-à-dire continues tout le long de la fibre optique. Dans une seconde partie, différentes applications industrielles spécifiques au génie civil développées par deux entreprises françaises sont décrites. Enfin, l’exemple du développement d’un extensomètre de longue base de mesure destiné à être noyé dans le béton est présenté, depuis la conception, jusqu’aux tests en laboratoire et sur un pont à béquilles près d’Angoulême.*

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INTRODUCTION

Instrumentation now gets included in the specifications for large-sized engineering structures like the Millau Viaduct, not only during the construction period, but long-term monitoring as well **[1]**. Controlling the state of a structure's health, more commonly designated by the acronym SHM (Structural Health Monitoring), requires a large number of long-lasting sensors. For this application, optical fiber sensors are found to be exceptional tools. Some 20 years of developments will have been necessary to overcome the initial disappointments and fully utilize the specificities of these sensors, whose application has since become mandatory.

Following a series of rudimentary descriptions of optical fiber technology and the various types of sensors employed, a state-of-the-art of optical fiber strain sensors used in civil engineering will be presented, along with the description of several recent industrial applications. Lastly, an example of extensometer development with a long-gauge-length will be examined.

WHAT EXACTLY IS FIBER OPTICS?

• Fiber optics (**Figure 1a**) is now a fixture in our daily lives since in many urban areas, it serves to route Internet to individual homes, is installed in the latest cars, and crisscrosses the planet's oceans (**Figure 1b**).

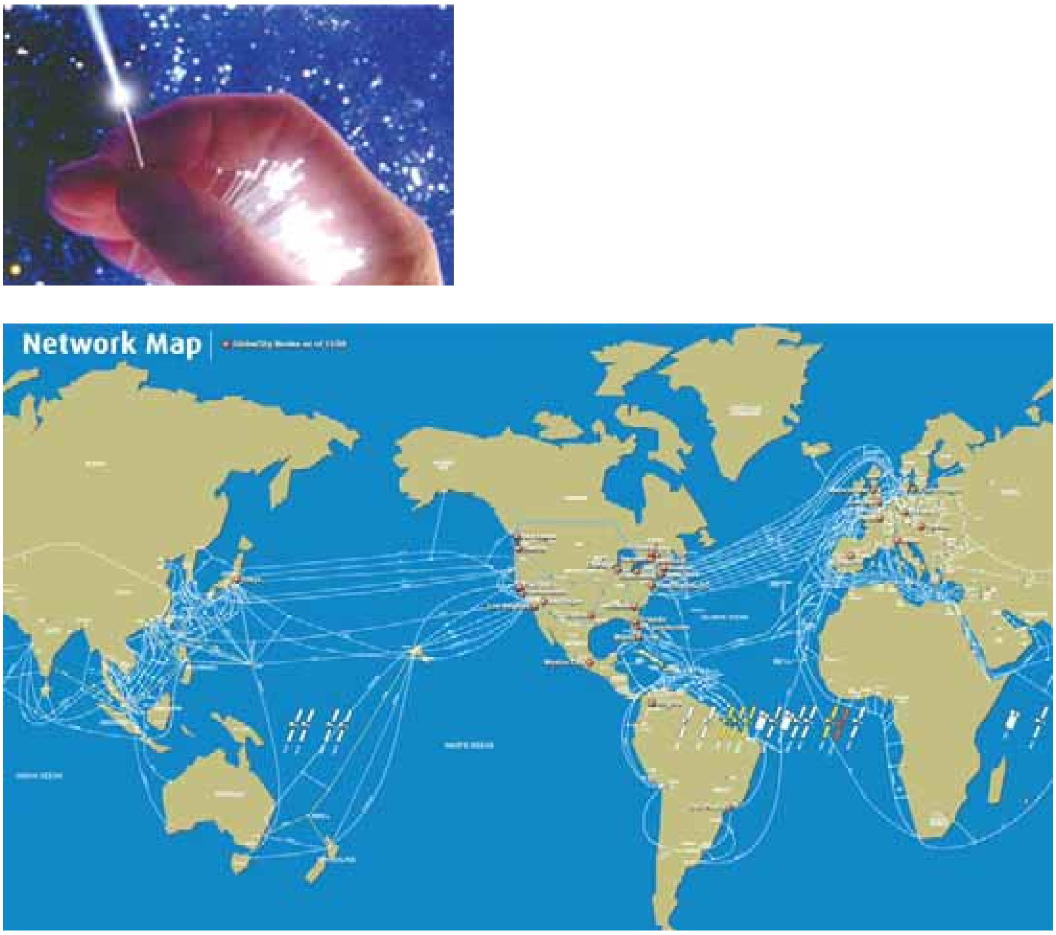


Figure 1
a: illustration of an optical fiber
b: map display of the world's fiber-optic telecom network

A wide array of optical fibers, called single-mode or multimode, have been developed in either glass or plastic, with solid or hollow cores, packaged in very diverse shapes to convey signals that may be visible or invisible **[2]**. These various parameters are chosen depending on the specificities of the given application.

An optical fiber is a waveguide the size of a single hair (0.1 mm) that enables conveying light,i.e. an electromagnetic wave with frequencies on the order of 100 THz. The optical cladding and core are generally composed of the same material, yet contain different proportions of impurities (dopants) so that their refraction indices, i.e. the ratio between light propagation velocities in the void and in the material, vary by several tenths of a percent. As an example, the most common optical fiber,

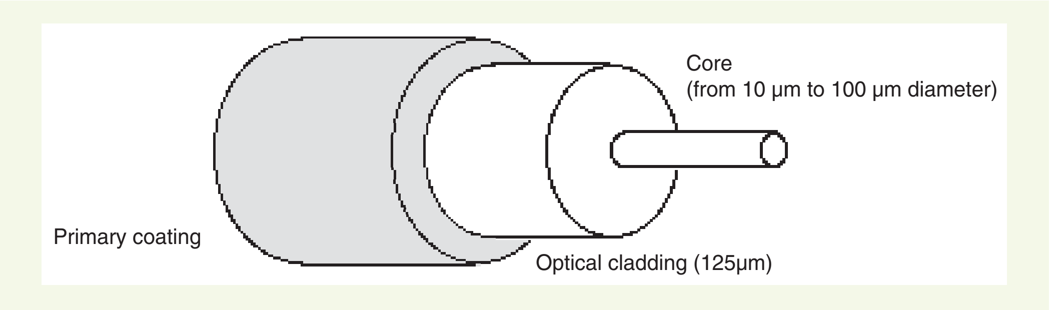


Figure 2
Structure of a single mode type of optical fiber

often denoted by the acronym SMF28 or G652, is made from silica with a germanium additive for the purpose of creating a difference in refractive index on the order of $5\cdot10^{-3}$ between the duct and the 10 µm central fibers, where the energy is concentrated. This geometry leads to a heavier reliance upon the single-mode guide over the range of near-infrared wavelength, i.e. from 1.3 µm to 1.6 µm.

From these characteristics, a number of specificities regarding optical fiber sensors (or OFS) can be stated:

- As opposed to electronic sensors, an optical fiber does not radiate. The electromagnetic parasites that limit the dimensions of coaxial cables connecting conventional sensors along with any lightning risk are thereby eliminated.
- Since glass exhibits a very high melting point, OFS may be applied with very high temperature settings. These sensors also resist very high pressures, even in the presence of ionizing radiation. However, the protective envelope (also called primary coating) depicted in **Figure 2**, which proves critical to the effective mechanical resistance of silica, must be chosen on the basis of actual use conditions: standard acrylate does not withstand high temperature. Moreover, some specific internal treatments, such as Bragg grating inscription (which gets deleted beyond a temperature of 300^{o}C), may constrain the actual range of application.
- Given that the transverse dimensions are so small (millimeter scale), relatively non-intrusive sensors can be created, along with unobtrusive transmission cables and cases.
- Signal propagation losses are extremely low: for the G652 fiber described above, at the 1.55 µm wavelength, losses lie below 5% per kilometer of propagation. Within an optical fiber several kilometers long, a signal can therefore propagate without practically any distortion. This characteristic becomes essential when remotely interrogating sensors placed inside inaccessible zones, such as boreholes. It also proves advantageous when developing long-gauge-length sensors (dimensions at the scale of a meter or even a kilometer).
- The OFS family of sensors displays a greater level of sensitivity and dynamic than conventional sensors, while maintaining relative resolutions on the order of the wavelength, i.e. 10^{-6} m, thanks to the interferometric setups.
- Since the bandwidth generated from telecommunications transmissions is extremely broad, multiplexing capabilities are significant: tens of sensors placed on the same optical fiber can all be read simultaneously as long as the corresponding spectral ranges remain offset over the silica transmission window, 0.8 µm-1,7 µm. The sensor network created in this manner makes it possible to anticipate a sizable measurement cost reduction, provided that the measurement system and optoelectronic demultiplexing constitute basic components in the instrumentation pricing. Furthermore, such an architecture provides the user with data from each sensor in homogeneous form, which allows data fusion to become intrinsic. OFS networking thus leads to optimized instrumentation systems. Also, sensor signal acquisition speeds are solely limited by the electronic sensor interrogation system.

However, given that the useful signal is propagating over the 10-µm (0.01-mm) central axes of the typical single-mode optical fiber, the connections between fiber segments offer sensitive points that simple dust is able to degrade; this aspect necessitates extreme care during any handling. With this consideration in mind, the majority of connections are routed far from construction site conditions. An alternative solution calls for the use of multimode optical fibers, yet with fiber lengths being limited to roughly a hundred meters.

For civil engineering applications, one potentially key characteristic needs to be kept in mind:silica optical fibers break beyond a few percent (4%) of tensile load. Although this value is critical and in line with most applications, bridge instrumentation at the level of prestressing cables or stay cables is indeed compromised or requires the use of plastic optical fibers **[3]**.

ARRAY OF OPTICAL FIBER STRAIN SENSOR TECHNOLOGIES

This discussion will focus on intrinsic OFS, in which the optical fiber constitutes the sensitive element, as opposed to extrinsic sensors whose optical fiber is merely used as a vector to convey information. In classical terms, the various types of intrinsic OFS are distinguished according to the magnitude of their influence **[4]**, which might be signal intensity, wavelength, polarization or phase.

History sensors

From an historical perspective, the first OFS were based on a study of intensity variations in a signal transmitted within a multimode optical fiber since the components required for such systems were the only ones available at reasonable cost.

The most basic measurement system, called *All-or-Nothing*, consists of examining the propagation or non-propagation of light transmitted within the optical fiber, as diagrammed in **Figure 3**: the signal transmitted in an optical fiber undergoes a strong reduction to reach a near-zero value when the fiber breaks. These All-or-Nothing systems on OFS were implemented in order to monitor the state of concrete structure cracking **[5]**. This type of sensor does not yield any information on either crack size or evolution over time. To overcome this limitation, the microbend type of sensor **[6]** was developed. As an optical fiber bends, a portion of the light is lost by means of radiation at the exact point of bending. These losses can be accurately detected by measuring light intensity attenuation. The sensor effect relies upon correlation between this attenuation and the longitudinal deformation of the optical fiber component. In an effort to enhance sensitivity of the optical fiber to bending, various technologies have been developed, including winding an iron wire around the primary optical fiber coating, as sketched in **Figure 4a**. Such microbend sensors have, among other things, enabled a vehicle weigh-in-motion system through the instrumentation of a bridge supporting device **[7]**, as illustrated in **Figure 4b**.

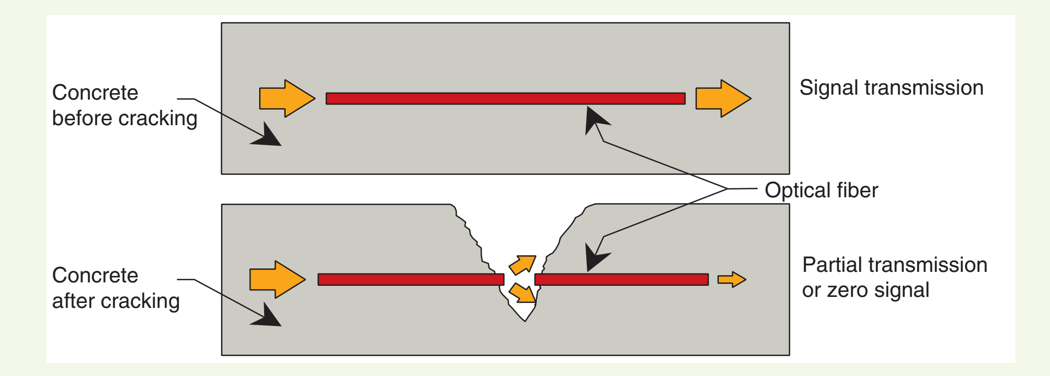


Figure 3
Principle behind optical fiber sensors with an All or Nothing system, according to **[8]**

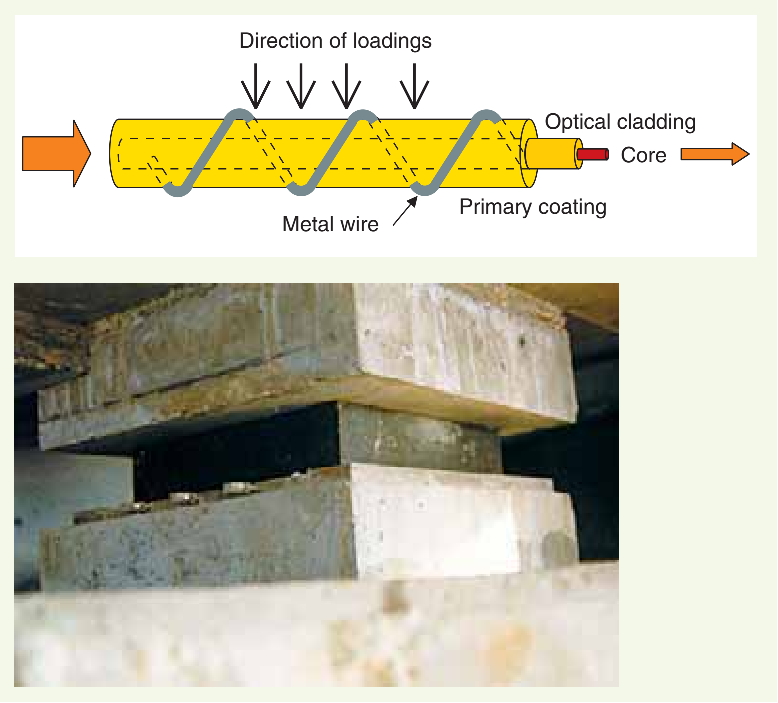


Figure 4
a: optical fiber sensor with a helical winding type of microbend packing
b: bridge support device instrumented with a microbend sensor

While these sensors are remarkable by virtue of their simplicity and only require very inexpensive equipment, their major difficulty lies in generating a stable intensity reference. As a case in point, the slightest dust accumulating on sensor connectors partially obstructs light transmission, and the corresponding loss of light intensity then cannot be distinguished from the useful signals. A system devoid of connectors, where the links between optical fibers are soldered, does not allow for any manipulation. Moreover, if the signal-transmitting optical fibers are exposed to partial degradation, e.g. by strong curvature at the interfaces (protruding concrete blocks), the signal intensity losses will also be interpreted as a significant evolution in the proportion of sensor-packed fibers. For this reason, the majority of OFS are now of the interferometric type.

Interferometric optical fiber sensors

At present, information coding is primarily interferometric **[4]**. Three main families of interferometric optical fiber strain sensors can thus be differentiated according to whether their measurements are site-specific, over a long-gauge-length or truly distributed (i.e. continuous along the optical fiber).

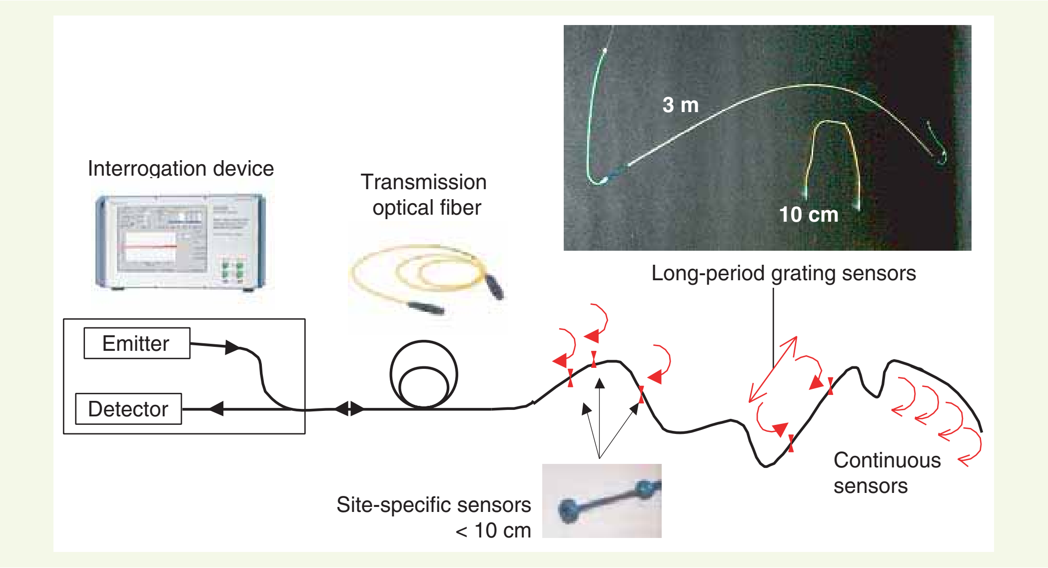


Figure 5
Diagram of an optical fiber measurement system: An acquisition device is connected to an optical fiber containing sensors used to convey information. The sensors are site-specific (red arrows), long-gauge (where the sensor corresponds to the distance between arrows), or even distributed (where the fiber itself becomes a sensor, hence with no further need for specific points)

Site-specific optical fiber strain sensors

According to the site-specific OFS configuration, measurement only gets carried out at specific points, which are sites of special treatment, such as Fabry-Perot cavities or Bragg gratings.

Fabry-Perot interferometric strain sensors were among the first OFS available on the market **[9]**. The cavities were generated by inserting air interstices, which therefore meant dealing with extrinsic sensors. In contrast, intrinsic site-specific interferometric strain sensors are essentially created using Bragg gratings **[10]**.

A Bragg grating consists of modulating the refractive index of the optical fiber core by applying a pattern sized at less than a micron and then repeated over several millimeters. This modulation may be obtained thanks to the photosensitivity of silica, whose atomic arrangement can be lastingly modified by means of special lighting sequences. Should this modulation be performed in accordancewith a specific geometry labeled Bragg grating, it then displays a reflective power over a very narrow spectral bandwidth centered at wavelength λ_B, which is directly proportional to the grating pitch Λ ($\approx 0.5\ \mu\text{m}$) and to the refractive index n $\lambda_B = 2\,n\,\Lambda$. Any elongation or contraction thereby *displaces* λ_B, whose spectral monitoring enables determining the inductive phenomena. More precisely, the dependence of Bragg wavelength on temperature T, elongation ΔL and pressure P can be expressed as follows:

$$\frac{\Delta\lambda_B}{\lambda_B} = a\Delta T + b\frac{\Delta L}{L} + c\Delta P \qquad \textbf{(1)}$$

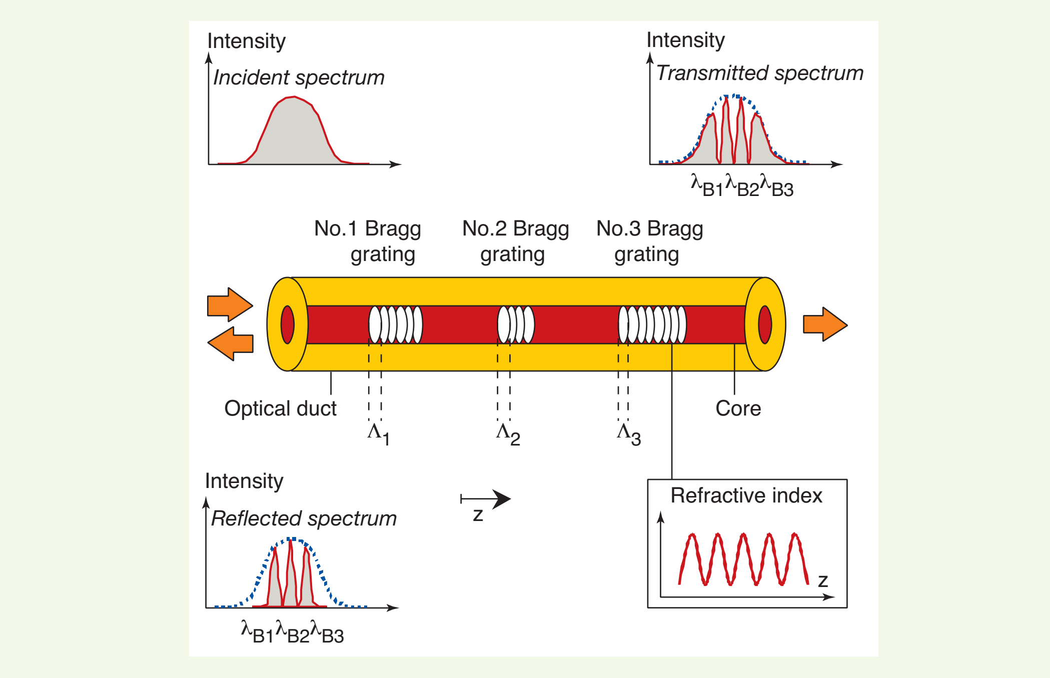
where a ≈ $8 \cdot 10^{-6} \cdot {}^{\circ}\text{C}^{-1}$, b ≈ $0.8 \cdot 10^{-6} \cdot \mu\text{m}^{-1} \cdot \text{m}$, and c ≈ $3 \cdot 10^{-6} \cdot \text{MPa}^{-1}$ respectively.

Since 1°C and 10 $\mu\varepsilon$ exert roughly the same influence on the Bragg wavelength, for the majority of applications, it would be necessary to introduce specific systems to decorrelate these two phenomena. As such, each Bragg grating strain sensor is often associated with a second Bragg grating sensor dedicated to just the temperature measurement.

Sensitivities and resolutions obtained are most attractive: 1 $\mu\varepsilon$ and 0.1°C turn out to be typical values. Moreover, acquisition frequencies exceed one kHz. Since this technique has reached full maturation, many suppliers are now available (Smartec in Switzerland, FOS&S in Belgium, Insensys in the United

Figure 6

Bragg grating operating principle, according to **[8]**



Kingdom, Advoptics in France and Fibersensing in Portugal, to name a few) and propose products adapted to a wide array of applications, some examples of which will be presented below in the section dedicated to the industrial applications.

Though this performance can be rated similar to that of LVDT sensors, one chief advantage herein is the great simplicity of implementation by virtue of both a significant reduction in cable requirements and automatic sensor addressing. Such simplicity of use offers economic savings given that the electrical cable component (cost and installation) constitutes the top cost item of a conventional structural instrumentation system. As diagrammed in **Figure 6**, several Bragg gratings are easily multiplexed on the same optical fiber, regardless of the mesurand, i.e. temperature or elongation. To proceed, it is simply necessary to sequence the gratings with a slightly different pitch Λ. The incident light is successively reflected at $\lambda_{B1}\ \lambda_{B2}\ \lambda_{Bn}$ by the different gratings, and the spectral variations of these distinct wavelengths are analyzed by the instrument located at the extremity. The sole limitation with this set-up is that each sensor addresses a specific spectral window. According to Equation (1), variations of 70°C or 5,000 μm/m — which represent the extreme values for civil engineering applications — correspond respectively to 1 nm and 6 nm. In order to avoid overlapping therefore, a 50-nm wide source can only illuminate 50 thermometers or eight strain sensors. To increase multiplexing capabilities, several optical fibers configured in parallel can then be introduced. The cost of a Bragg OFS optoelectronic reading unit that gives rise to a dynamic acquisition (kHz) of around fifty sensors amounts to less than 20 k€.

Nonetheless, even if a hundred measurementpoints could easily be generated thanks to Bragg OFS, sensor positioning would still have to be prudent since the connecting optical fiber is not sensitive, i.e. only allows for data transmission.

› Long-gauge fiber-optic strain sensors

Measurements output by long-gauge sensors represent an average of two specific points on the fiber (mirrors), with a spacing between 10 cm and several meters. As depicted in **Figure 5**, these sensors are complementary to the site-specific category since as they are sensitive to the distance separating reference points. Their use is particularly beneficial should the exact location of disorders to be monitored be difficult to anticipate.

Besides the availability of support packing specific to Bragg gratings resembling vibrating wire sensors **[11]**, the most standard measurement system for deriving this reading is a Michelson interferometer, whose corresponding diagram is shown in **Figure 7**. A low-coherence light emitted by an electroluminescent diode (DED) is separated into two parts, one illuminating the sensor (measurement arm), reflecting a portion of the incident light, while the other illuminates a delay line or reference arm. The reflected signals stemming from the two paths are then recombined onto a photodetector. Mirror displacement then enables equalizing the optical paths of the measurement arm and delay line, so as to yield the distance data. When the lag time between the two reflections (at the end of each arm) is zero, the interferences are constructive and an intensity peak is measured **[12, 13]**. As illustrated in **Figure 8**, the determination is absolute (and not to within 2π) given that the light source is set to be only slightly coherent: beyond the source coherence length, i.e. at a few μm, interference fringes become blurred **[13]**. With precise knowledge of the mirror position, cavity length can be determined. Any sensor length change will correspond to a new mirror position, at which interferences are constructive, i.e. a new delay line length. As the structure undergoes deformation, whether in tension or compression, the fiber bonded to or incorporated in the structure extends or retracts in consequence. The value obtained is the measurement arm length from the coupling out to its extremity.

Such strain sensors are very sensitive, i.e. up to 2 $\mu\varepsilon$ of resolution regardless of strain sensor length.

One underlying technological difficulty pertains to developing a precise and reliable miniature motor suitable for field use. The SOFO product created by Smartec (see photo in **Figures 9b** and **9c**) has dominated over the past five years, chosen for installation on many engineering structures,

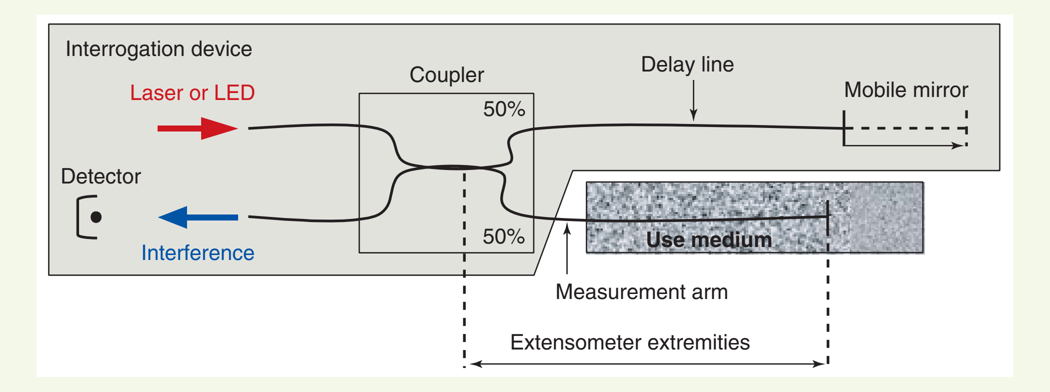


Figure 7
Interferential extension sensor

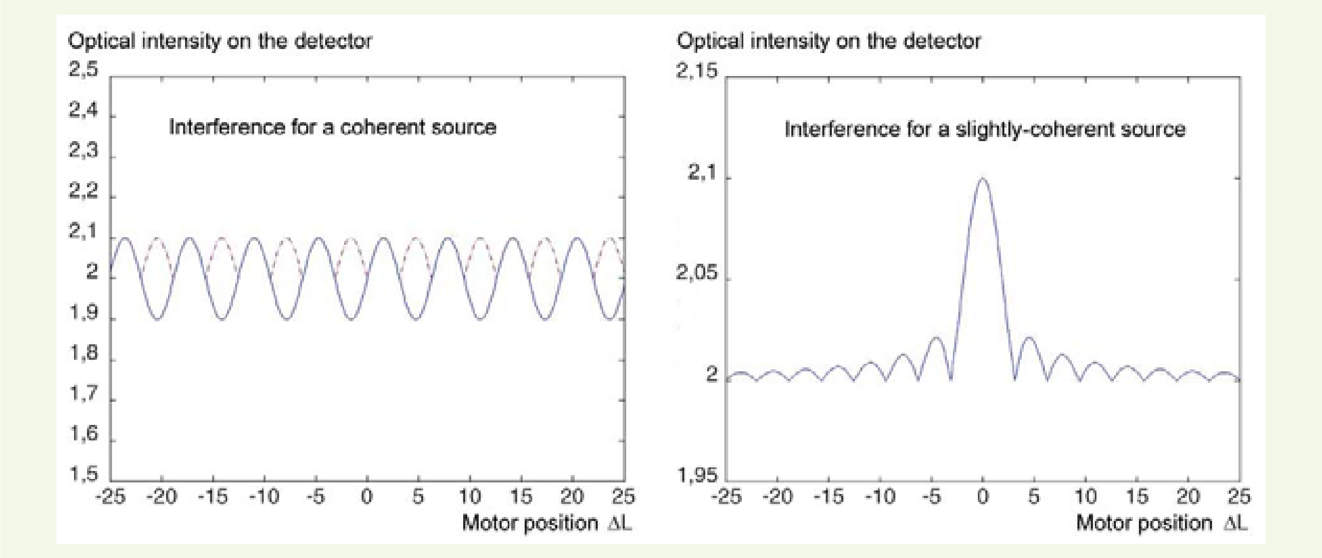


Figure 8
Intensity received by the detector of an interferometric assembly, such as that diagrammed in Figure 7, vs. reference arm length position for two distinct optical sources, either significantly (a) or slightly (b) coherent

notably on the Millau Viaduct. The two interferometer arms are placed in a tube, the first being tensioned between two structural anchorages, while the second left free to dilate with temperature variations, which tend to be self-compensating. The length offset between these two optical fibers is reproduced in the instrumentation via an architecture similar to the principle depicted in **Figure 7**, yet still reproduced twice (leading to a two-stage Michelson interferometer). While this optical fiber strain sensor resembles the vibrating wire sensor (VWS), its length is capable of reaching several meters without compromising measurement precision. Deriving an equivalent without the use of fiber optics, by means of purely electronic technologies, had until recently only been available in the laboratory **[14, 15]**, but is now being marketed by the French company DYNAOPT.

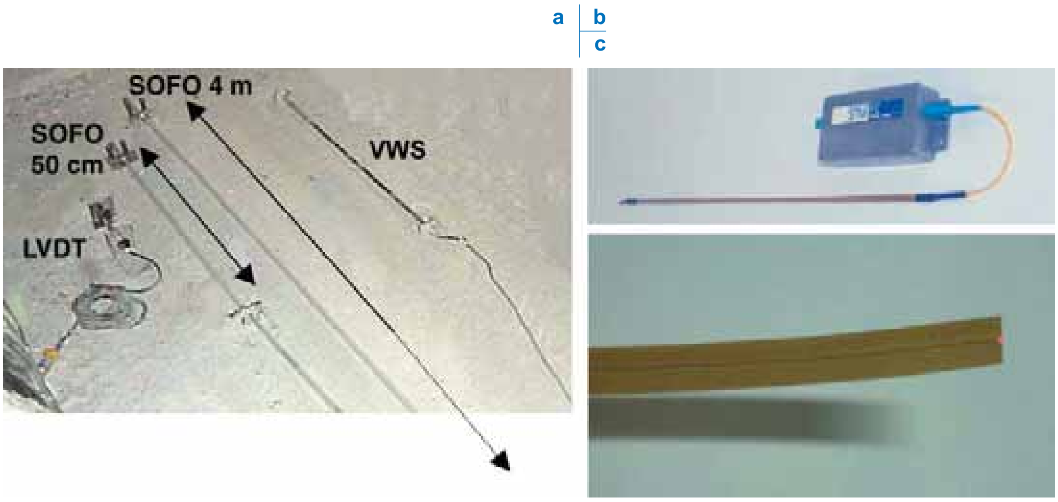


Figure 9
a: conventional sensors (LVDT, VWS) placed in parallel with 50-cm and 4-m SOFO strain sensors installed in the central arch of a concrete bridge **[15]**
b: flexibility of the SOFO SMARTape sensor

The latest research conducted on long-gauge strain sensors has focused on optical fiber coatings that enable maintaining their flexibility and ensuring a continuous bond with the host material **[16]**, even on curved surfaces. An image of the SMARTape product created by Smartec is shown in **Figure 9b**. The coupler would still need to be placed in immediate proximity of the sensor; moreover, sensor multiplexing could only be carried out in parallel, thereby removing one of the major advantages associated with optical fiber sensors.

Some laboratories have overcome this limitation through use of partial mirrors placed end-to-end along the optical fiber, followed by shifting the reference arm of the Michelson interferometer inside the reading device **[17].** Section Development example of a long-period grating strain sensor will present the development and production of long-gauge strain sensor, which offers flexibility and multiplexing capabilities in the aim of yielding a quasi-distributed measurement of strains over distances reaching the hundred-meter range. Yet, the number of sensors lying on the same fiber is currently still capped at around ten. Beyond a hundred meters of instrumented span, in seeking to lay out kilometer-long strain sensors, the use of truly-distributed optical fiber sensors becomes mandatory.

› Distributed (continuous) optical fiber sensors

The term distributed sensor designates the case in which the optical fiber itself becomes a sensor **[18]**. It is thus no longer necessary to implement anticipated sensor positions since measurements are being performed all along the optical fiber hooked up to the reading device (as well as within the extension cables!). In addition, the processing and manipulations required to generate Bragg gratings or mirrors delimiting the long-gauge-length strain sensors act to significantly weaken the optical fiber. On the other hand, for distributed OFS, the commercial optical fiber (G652 and others) is placed directly inside its mechanical protective external coating, which would suggest a more robust instrumentation.

Various techniques may be utilized to develop a continuously-distributed measurement system within an optical fiber. The most common would be OTDR (for Optical Time Domain Reflectometry) **[19]**, which could eventually be combined with a study of light-matter interactions such as the (temperature-dependent) Raman effect and the (temperature and deformation-dependent) Brillouin effect. Initially created to analyze losses inside optical telecommunication lines **[20]**, OTDR is categorized as an optical pulse-echo technique. As diagrammed in **Figure 10**, this technique consists of injecting a laser pulse within an optical fiber and then measuring the backscattered intensity vs. time: a period Δt corresponds to a pulse round-trip between the fiber extremity and a given point on the fiber located at $c/(2n\Delta t)$ from the extremity. The temporal width of the pulse is proportional to the OTDR spatial resolution; a 10-ns width corresponds to a resolution of 1 m.

Optical Time Domain Reflectometry (OTDR) serves to carry out intensity variation measurements over distances in the tens of kilometers, with a spatial resolution at the meter scale. In order to lower

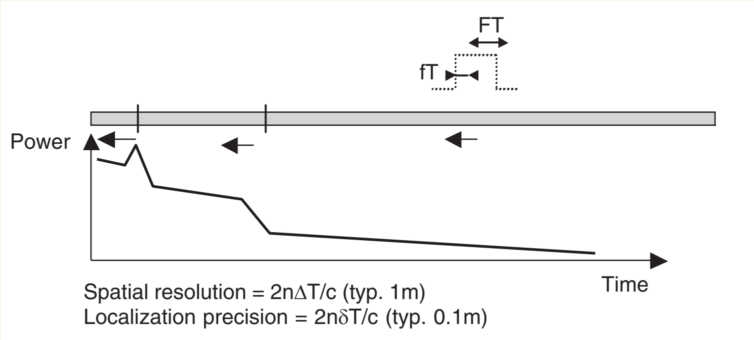
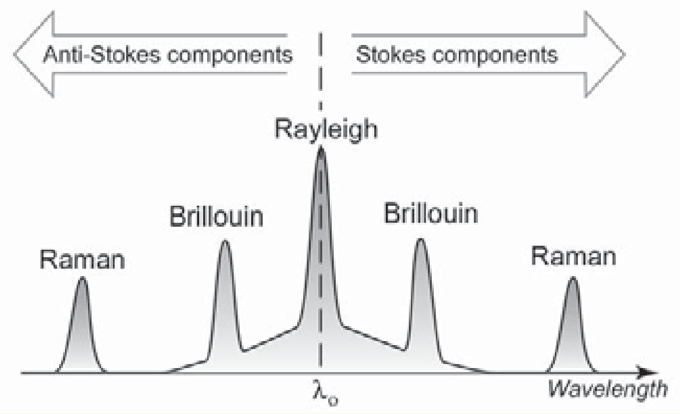


Figure 10
OTDR operating principle

the spatial resolution, other techniques are available, some for example based on frequency modulations, hence the acronym OFDR (Optical Frequency Domain Reflectometry). OFDR spatial resolution can reach 10 μm, although the range diminishes considerably to around 100 meters.

Figure 11
Backscattering spectrum of a monochromatic wave within an optical fiber



To better comprehend what an OTDR-type device actually measures, emphasis must be placed on the backscattering phenomenon taking place within optical fibers.
As shown in **Figure 11**, the light backscattered by an optical fiber segment without any defects or abnormal 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 fiber core interacts with the scattering centers, silica impurities and enhancing additives with dimensions well below the wavelength; these interactions give rise to a partial reflection in the vicinity of $10^{-7} \cdot m^{-1}$. By measuring intensity variations in the backscattered signal at the same wavelength as the injected wave, local optical fiber modifications may be detected: an abrupt return peak is interpreted as a mirror reflection (connector or damage on the fiber), and a sudden drop in intensity corresponds for example to shear loss. As pointed out in Section *History sensors however*, light intensity variations cannot be directly correlated with deformations of the medium where the optical fiber has been embedded. To conduct the actual strain measurement, the value of the Rayleigh backscattering signal in optical fibers may be associated with optical fibers preliminarily equipped with site-specific sensors, such as microbend sensors or another configuration that incorporates pre-calibrated losses **[21]** or Bragg gratings, in which case the continuously-distributedaspect of the measurement would be lost. Another approach consists of carrying out a relative measurement. The American firm Luna Technologies has been marketing since spring 2006 an optoelectronic device that enables measuring optical fiber deformations (at homogeneous temperature) over 150 m with a millimeter-sized spatial resolution and a level of precision equal to a few microdeformations. This performance has been obtained by OFDR, in association with an advanced correlation method between the ongoing measurement and a reference state; the spectral variations of the Rayleigh backscattering peak can thus be analyzed **[22]**.

The Raman effect 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. Several optoelectronic devices that conduct distributed temperature measurements using the Raman effect are in fact available on the market and have already profoundly modified certain fields such as fire detection **[23]**. As a case in point, SIEMENS' sensor CEREBERUS was installed on the Mont-Blanc Tunnel subsequent to the 1999 disaster.

Similarly, it is possible to undertake continuously-distributed measurements of strains by reliance upon the Brillouin effect **[24]**. Given its sensitivity to both fiber geometry and density, the Brillouin effect depends on temperature and strain, as illustrated in **Figure 12**.

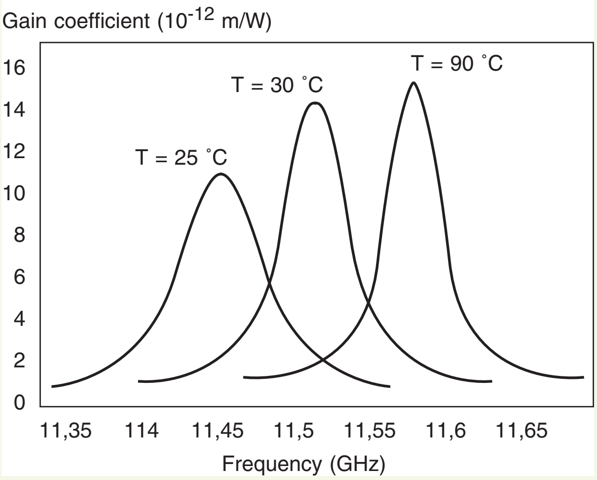


Figure 12
Displacement of the Brillouin shift with temperature variation

In 2002, the first commercial system based on the Brillouin effect was implemented; by 2007, the market had expanded to include at least five suppliers of Brillouin interrogation systems (Omnisens in Switzerland, Sensornet in England, OZOptics in Canada, Yokogawa and Neubrex in Japan). The performance derived lies on the order of 1°C, 20 $\mu\varepsilon$ and 1 m of spatial resolution, over spans extending several tens of kilometers. The most widespread application is currently pipeline leak detection. Nonetheless, two shortcomings are restricting this technology solely to the realm of research. First, separating temperature from deformation influences requires the use of cables incorporating two optical fibers, one of which being mechanically isolated **[25-27]**. Second, the price of interrogation systems, in the neighborhood of 100 k€, limits technology profitability to cases where the number of site-specific sensors replaced by a distributed measurement exceeds three digits. Research on the topic is extremely active, with respect to both the interrogation techniques for reaching centimeter-scale spatial resolutions **[29,30]** and the choice of new optical fibers to enable decorrelating thermal and mechanical influences **[31,32]**.

INDUSTRIAL APPLICATIONS

The very first OFS began appearing in the 1970's, along with the first optical fibers. Even though today's prevailing concepts and feasibility demonstrations still date back to the 1980's **[33]**, nearly twenty years of developments have been necessary for OFS performance to rival that of conventional sensors, as evidenced by the set of advantages mentioned above. Even under these conditions, as recently as the year 2000, the only optical fiber sensor to have generated large-scale commercial interest was the optical fiber gyroscope, while optical fiber strain sensors remained relatively unknown. Why was this so?

The answer has to start with the measurement chain cost. While the sensor itself is affordable (about 100 € for a Bragg grating), the optoelectronic reading system represents a considerable investment, reaching into the several tens of thousands of euros. To ease this cost burden, the number of OFS employed must be high. For this reason, Bragg gratings have been clearly preferred over traditional instrumentation whenever the number of measurement channels surpasses double digits **[34]**. Furthermore, the cost of OFS has begun to drop noticeably and this trend should continue as a result of the larger production volumes required to meet increased demand.

The second part of the answer has to do with the fact that sensor responses within their use environment do not always correspond with theoretical predictions, nor with the experimental calibration curves provided with sensors. One hypothesis **[8]** serves to better understand the influence of mechanically coating the optical fiber (choice and form of coating materials) on measurements output by OFS. This aspect has been neglected for a long time by suppliers, which happen to be companies specialized in the fieldof optoelectronics and not in mechanics; it has also led to weaker performance after sensor installation under actual use conditions. Since that time, this particular difficulty has underpinned the line of products developed by certain manufacturers, who have taken advantage of the OFS capability to assimilate with materials during the fabrication process. Let's now take a look at the example of two French firms.

Advoptics (formerly OFSystems) has devised Bragg grating packaging by means of composites, so as to adapt this kind of sensor to wind turbine instrumentation, as illustrated in **Figure 13**. Another specific packaging has been developed to transform Bragg gratings into long-gauge-length strain sensors. Deformations on the Monaco floating breakwater could thus be measured using twelve 1-m long sensors. Distributed longitudinally on the top and bottom of the breakwater, the sensors had been connected to a central interrogation unit supplying compensated data to the centralized operations system, which was responsible for managing all instrumentation. Classical gauges may be similarly packed, yet their life cycle is totally incompatible with Structural Health Monitoring needs, especially given the fact that half the sensors herein are submerged.

Since 2002, TenCate GEOSYNTHETICS (formerly BIDIM) has been proposing geotextiles instrumented with site-specific optical fiber sensors of the Bragg grating type, as displayed in **Figure 14**. OFS are directly inserted into the geotextile material during manufacturing. Installed on many civil engineering structures throughout the world, this product is intended to monitor earthen structures **[35]**. Within the scope of the national HydroDetect project (Civil and Urban Engineering network, 2004), a new generation of OFS-instrumented geotextiles has been developed in the aim of

Figure 13
Wind turbine instrumentation (left), using Bragg grating sensors coated in composite material (right) by Advoptics/OFSystems

Figure 14
Monitoring of earthen, geosynthetic-reinforced structures with incorporated optical fiber sensors: Geodetec system produced by TenCate

detecting and localizing hydraulic leaks to serve as precursors of failure in dikes designed to protect against floods and storms.

In conjunction with these specific applications in which OFS are inserted into the material core, OFS suppliers are now in a position to establish contacts with major companies responsible for conducting structural health monitoring. Along these lines, some tracks on France's high-speed TGV rail network have been instrumented with OFS: TenCate geotextiles are now able to detect, over the long term, the eventual appearance of cavities beneath the most recent TGV tracks; and Advoptics' OFS have been embedded in test track made of concrete (without ballast) in the vicinity of Meaux (Paris Region) for the purpose of carrying out static and dynamic measurements (1 kHz). Moreover, continuous, Raman-effect temperature sensors were being evaluated as of 1995 by France's EDF electricity utility with the objective of detecting leaks in dikes. After several mishaps encountered with the first generation of devices available on the market **[36]**, the technology now seems mature, robust and efficient **[37]**, to such an extent that EDF has adopted Brillouin-type distributed measurements in order to gain access to strain measurements as well.

Site-specific, optical fiber sensors have thus drawn attention for a variety of industrial applications, and not just when electromagnetic neutrality proves crucial, but also within the scope of Structural Health Monitoring and intelligent structures. More recently, distributed temperature sensors have been employed in the laboratory, and their strain measurement equivalent, i.e. Brillouin sensors, now appear ready for industrialization. For the time being, let's indicate the development steps for multiplexable long-gauge strain sensors, in proceeding with quasi-distributed measurements.

DEVELOPMENT EXAMPLE OF A LONG-GAUGE-LENGTH STRAIN SENSOR

The EOLBUS project, a French acronym for Optical, uniformly-sensitive long-gauge-length strain sensor has focused on the design, construction, laboratory and field tests of an optical fiber strain sensor continuously attached to its host material, the concrete; this project has made it possible to achieve quasi-distributed measurements. As described above, such sensors actually measure the average deformations between specific points on the optical fiber, as indicated by partial mirrors previously set in the silica core.

Subsidized between 2004 and 2006 by the French Public Works Ministry via the Civil and Urban Engineering network, this project has combined the talents of two private-sector firms, along with the Bordeaux regional civil engineering laboratory and the LCPC national civil engineering laboratory. Fogale-Nanotech, the project leader, assumed responsibility for building the interrogation device, and IDIL-Fibres-Optiques was in charge of the sensors. The mechanical design of optical fiber external coating, followed by experimental validation work on the entire measurement chain with sensors embedded into the host material, was assigned to LCPC and the Bordeaux LRPC.

Twooriginal features were emphasized in this work program.

Sensor description

The first originality consists of the optical fiber sensor external coating, a glass-epoxy composite braid **(Fig. 15a)**. Designed by means of finite element simulations **[38]** **(Fig. 15b)**, this external coating ensures bonding with the concrete even if sliding is locally maximized at the interface of the two materials and moreover offers an optimal transfer of concrete deformation to the optical fiber.

Inside this external coating, two types of sensors were juxtaposed **(Fig. 16)**. The strain sensors are optical cavities composed of two partial wideband mirrors, with a spacing of between 10 cm and several meters. A small proportion of the energy (just a few percent) is reflected onto each mirror, to a point where more than ten strain sensors can be placed end-to-end. Their elongation depends on both mechanical and thermal loadings. In order to distinguish the influence of these two parameters, Bragg gratings were placed adjacent to the strain sensors, yet remained inside capillaries so as to enable isolating the mechanical stresses. Their behavior resembled that of thermometers, which then allowed subtracting out the influence of temperature on the strain sensors through calculation.

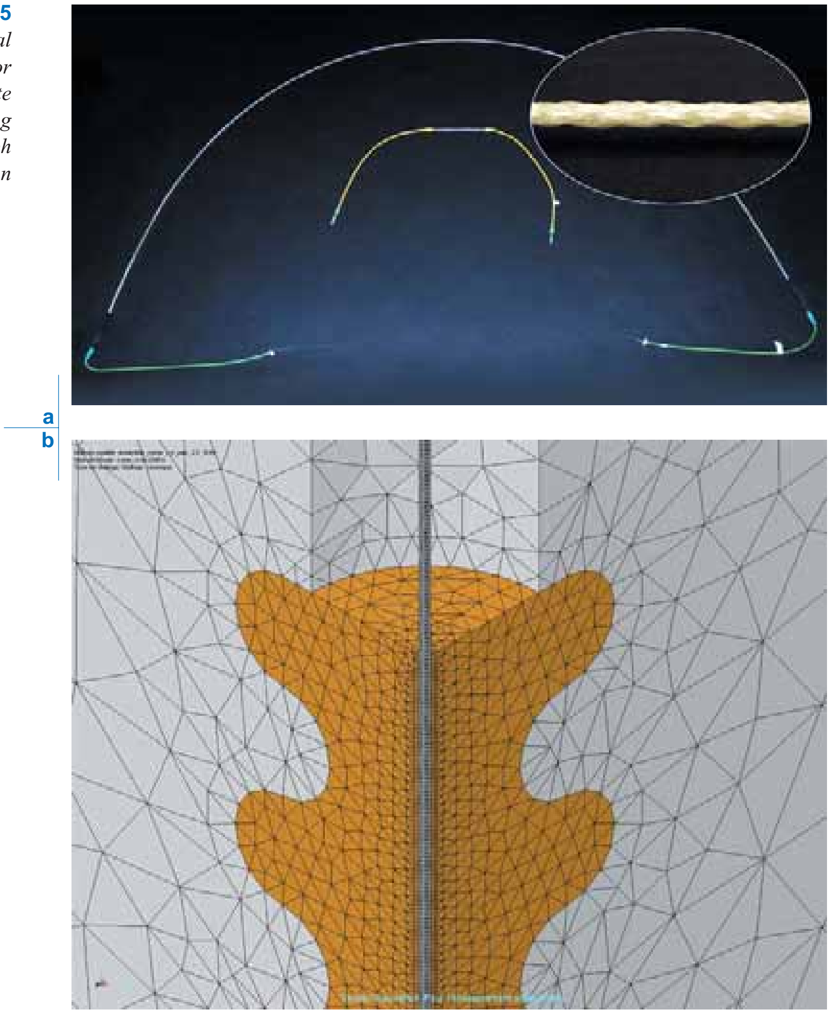
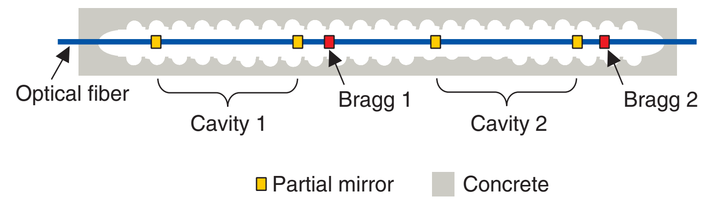


Figure 15
Structure of the optical fiber strain sensor intended for concrete embedding
a: Photograph
b: Modeling depiction

Figure 16
Diagram of continuously-sensitive, temperature-compensated strain sensors



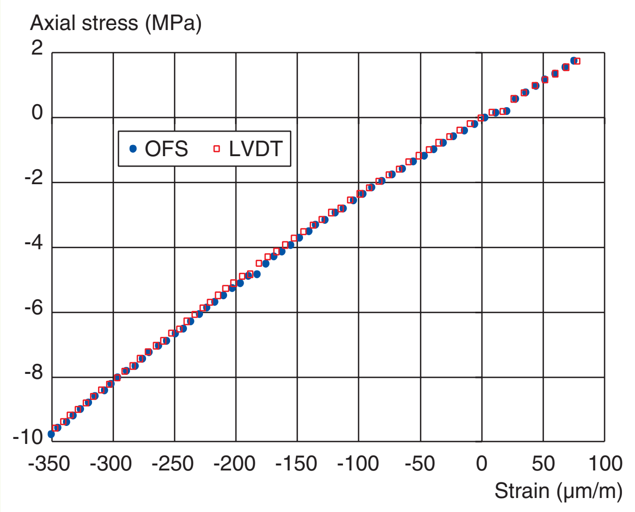
Optoelectronic reading system

The second originality of the measurement system developed in EOLBUS consists of using the same architecture to read two types of very distinct sensors: strain sensors and Bragg gratings **[39]**. To proceed, a Michelson interferometer with low coherence was applied over two different spectral ranges, 1.3 μm and 1.5 μm, each of which has been dedicated to one of the two sensor types. The light reflected by the Bragg grating was analyzed using the interference technique, with a second reference Bragg grating positioned inside the device and featuring stabilized and known temperature. According to **[17]**, a strain sensor was isolated from strain for use as a dummy gauge. Yet, by being placed within the instrument, sensor measurement lacked the precision to be used for thermal correction; it did serve however to overcome eventual measurement system instabilities that could for example arise from electromagnetic wave polarization.

Experimental validation in the laboratory

Once embedded in concrete cylinders (32 cm high, 16 cm diameter) and placed under a press, 10-cm optical fiber strain sensors yielded measurements identical to those of the external LVDT sensors, as depicted in **Figure 17**. In addition, the thermal compensation principle was validated by placing the sensors in an oven.

Figure 17
Strain measurements vs. force applied on the concrete cylinders containing the embedded optical fiber strain sensor (solid circles) and LVDT sensors at the surface (yellow squares)



Instrumentation of the Chauvauds Bridge

The complete measurement chain developed in the EOLBUS project has also been tested in the field, on the Chauvauds Bridge near the city of Angoulême in western France. This structure, under construction during the summer of 2005, is a portal bridge with a prestressed deck. The presence of clays in the underlying soil led to building a mixed-material foundation with inclined and vertical micropiles, though at the project outset just a shallow foundation had been planned. The instrumentation installed by the Bordeaux regional laboratory was intended to detect any eventual foundation block movements and control strain distribution within the eastern arch base. To accomplish this task, both classical electrical strain gauges and OFS were fastened to the reinforcement cage (**Fig. 18**). These instruments were not damaged by the use of vibrating needles during concrete casting.

Figure 18
a) Placement of the sensors
b) Acceptance testing of the Chauvauds Bridge

As shown in **Figure 19a**, the initial series of long-term measurements (over a six-month period) revealed an excellent level of agreement between electrical strain gauges and the contiguous optical fiber sensors (complete measurement chain with thermal effect correction). The sensors were next read during the bridge acceptance testing campaign (**Figure 18b**) ; these results, in part displayed in **Figure 19b**, confirm the efficient state of OFS operations, with the current advantage of wireless data transmission feasibility.

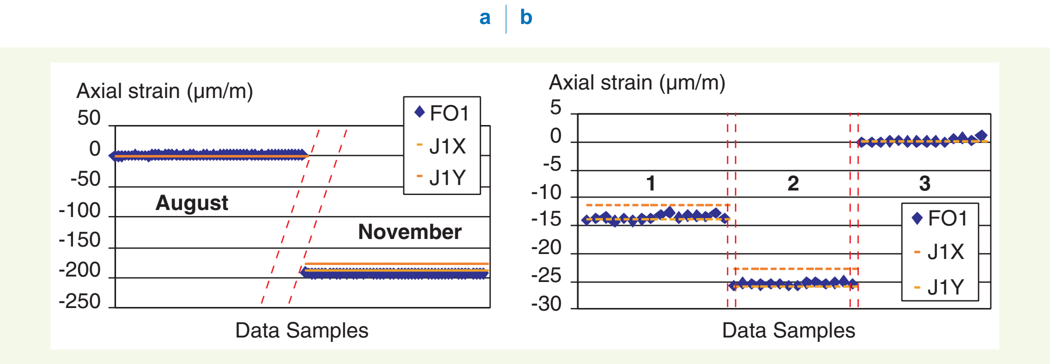


Figure 19
Measurements obtained from an OFS and two contiguous electrical strain gauges
a: during bridge construction, first in August when just the arch base had been cast and then in November once the bridge was completed
b: during project acceptance testing 1) the load is midway over the bridge 2) on the instrumented base and 3) the bridge in a load-free state

CONCLUSION

Over the last twenty years, optical fiber sensors have been developed for niche applications, i.e. very specific uses where conventional sensors prove ineffectual, particularly for instrumenting sites where electromagnetic neutrality is of critical importance. In the past, reliability issues had been detrimental to the market penetration of OFS. These difficulties have since been resolved by means of restriction to basically the interferometric family of techniques. Since 2002, products built by inserting optical fibers at the core of new materials such as composites or geotextiles have been rapidly gaining favor. The development example of an optical fiber strain sensor designed for embedding in concrete was presented in this article.

Thanks to encouraging results obtained over the past few years, OFS have successfully convinced major firms to undertake evaluation campaigns, especially now that the sensors are widespread enough for their multiplexing to make costs relatively attractive. OFS have now become an integral part of the Structural Health Monitoring toolbox.

The future of OFS is now aimed at distributed technologies, i.e. continuous measurements along the optical fiber without requiring a preliminary definition of the exact measurement location, which has generated extremely promising prospects in the field of instrumentation.

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