Fiber Optic Sensors in Structural Health Monitoring

José Miguel López-Higuera, *Senior Member, IEEE, Member, OSA*, Luis Rodriguez Cobo, Antonio Quintela Incera, and Adolfo Cobo, *Member, IEEE*

(Invited Tutorial)

***Abstract*—Structural Health Monitoring (SHM) can be understood as the integration of sensing and intelligence to enable the structure loading and damage-provoking conditions to be recorded, analyzed, localized, and predicted in such a way that nondestructive testing becomes an integral part of them. In addition, SHM systems can include actuation devices to take proper reaction or correction actions. SHM sensing requirements are very well suited for the application of optical fiber sensors (OFS), in particular, to provide integrated, quasi-distributed or fully distributed technologies. In this tutorial, after a brief introduction of the basic SHM concepts, the main fiber optic techniques available for this application are reviewed, emphasizing the four most successful ones. Then, several examples of the use of OFS in real structures are also addressed, including those from the renewable energy, transportation, civil engineering and the oil and gas industry sectors. Finally, the most relevant current technical challenges and the key sector markets are identified. This paper provides a tutorial introduction, a comprehensive background on this subject and also a forecast of the future of OFS for SHM. In addition, some of the challenges to be faced in the near future are addressed.**

***Index Terms*—Optical fiber sensors (OFS), OFS applications, OFS market, optical transducers, structural health monitoring (SHM), SHM and OFS challenges.**

I. Introduction

In the prehistory, the facilities available for human beings were practically inexistent. However, with the advances of the last centuries, specially during the last one, in our current globalized world it is difficult to imagine our lives without cars, planes, ships, railways, roads, bridges, tunnels, dams, wind, hydro or nuclear turbines, oil and gas wells, long energy and communication lines and, of course, without our houses or corporative buildings.

These structures form our current environment and affect human, social, ecological, economic, cultural, and many other aspects of our societies. Therefore, good design, quality construction, and durable and safe exploitation of structures are goals of structural engineering.

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The authors are with the Photonics Engineering Group, University of Cantabria, 39005 Santander, Spain (e-mail: lopezhjm@unican.es; rcobol@unican.es; quintela@unican.es; cobog@unican.es).

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However, in the course of their lifetimes, structures are subject to adverse changes in their structural health conditions due to potential damage or deterioration induced by environmental degradation, wear, errors in design and construction, overloads and some unexpected events like earthquakes or impacts or, simply, through their normal working life [1].

Structural degradation can be induced by a wide set of factors [2].

1) Unsatisfactory inspection and monitoring of existing infrastructure mean problems become apparent only when structures are in dire need of repair and then, repair costs can be comparable to replacement costs.
2) Corrosion of conventional steel reinforcement within concrete can provoke expansion of steel, which leads to cracking, fragmentation (spalling) or further deterioration. It leads to a reduction in strength and serviceability resulting in the need for repair and/or replacement.
3) Increased loads or design requirements over time (heavier trucks, overload on ships, planes, etc.) induce deterioration due to overloads or to structural inadequacies resulting from design. Then the structures are deemed unsafe or unserviceable and strengthening or replacement is required. For example, it is today recognized that hull fatigue (induced by cumulative effects from dynamic stresses acting on the hull as a result of ballast, cargo loads, and sea movements) is a major cause of damage in ships.
4) The overall deterioration and/or aging can induce detrimental effects on structural performance, safety and serviceability, and then repair, rehabilitation, strengthening or replacement may be needed.

Examples of sudden collapse of structures with all the trouble and costs (even with loss of human lives) can be found worldwide: 1) for instance, although less than a week before an engineer inspected the viaduct and found *"no visible structural issues,"* on August 21, 2009, the viaduct of the Belfast-Dublin Railway Line collapsed; 2) a second example is the collapse of the I-35W Minneapolis Bridge, which is a very sad reminder of the consequence of structural failure (loss of 13 lives, while 145 people were injured). The unavailability of the river crossing generated economic losses of US $ 400 000 per day for road-users [3]; 3) on November 12, 2001, flight AA587 crashed presumably due to hard landings and tail damage in the years before [4]; 4) according to the Caithness Windfarms Information Forum (*www.caithnesswindfarms.co.uk*) averages of 16.0 and 66.9 accidents per year from 1995 to 2001 and from 2002 to 2008, respectively, were recorded on wind turbines farms. This trend suggests that as more turbines are built, more accidents occur. Moreover, that may only be the "tip of the iceberg" in terms of number of accidents and their frequency in this very promising and "fashionable" renewable energy sector.

On the other hand, there are currently no quantifiable methods to determine whether buildings are safe for reoccupation after a significant overload or an earthquake. The prompt reoccupation of buildings, particularly those associated with manufacturing, can significantly mitigate economic losses associated with major seismic events. In addition, many portions of our technical infrastructure are approaching or exceeding their initial design life.

From the aforementioned, it can be deduced that structures are subjected to changes and it is desirable to assess their structural health conditions in order to mitigate risks, prevent disasters, and plan maintenance activities in an optimized manner. All these facts lead us to the central questions: When dealing with existing structures or building new ones, without compromising safety, could we:

1) detect possible degradation/damage over a period of time?
2) estimate the effects of the external loads?
3) estimate the remaining service life?
4) make the structures: more lightweight, more reliable and more cost efficient?

The answer is YES, we can do so! By making sensors (and possibly also actuators) an integral part of the structure and equipping structural systems with "intelligence."

II. Structural Health Monitoring

A modern structure must be able to reliably *generate* information concerning the changes in its structural health condition and *communicate* it to the responsible operators and decision makers both in time and either automatically or on-demand. To achieve this, a modern structure should be equipped with a system that includes a *"nervous subsystem,"* a "*brain,"* and *"voice lines,"* which is continuously in operation and able to sense structural conditions. The system should be able to automatically detect the damage, characterize it (recognize, localize, quantify, or rate), and report it, providing important input for structure managers or for the *system intelligence*. The data resulting from a monitoring program can be used to optimize the operation, maintenance, repair, and replacement of the structure based on reliable and objective data. This kind of system is named as Structural Health Monitoring system (SHM).

Probably, as all of us have observations about our own body, the SHM concept can be easily understood from comparison with the way the human body works. An unhealthy condition of the body is detected by the nervous system, information is transmitted to the brain, the brain processes the information and informs the patient that he/she is ill and should visit a doctor in order to prevent further development of the illness. The doctor undertakes detailed examinations, establishes a diagnosis and proposes a cure. Then, the doctor's instructions are carried out by the patient, who waits for the body's reaction. The patient will then contact the doctor again if necessary, and the doctor will take a new decision about how to cure the patient, and so on. Then the patient recovers and, even if the condition persists, the doctor can provide expectations of the *patient lifetime* in given

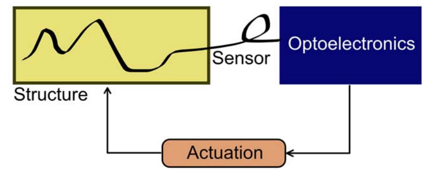

Fig. 1. Illustration of the concept of a general SHM system.

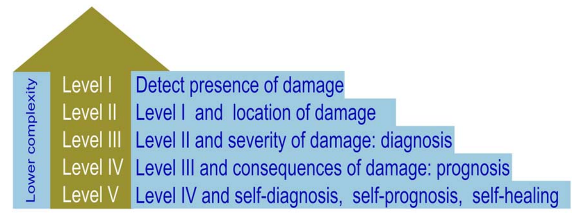

Fig. 2. Staircase of the SHM: levels in Health Monitoring systems. Higher the level, the higher the complexity.

working conditions. It must be mentioned that if the patients are doctors then they themselves can do, the diagnosis and the prognosis processes.

The main aim of SHM systems, similar to the human body, is to detect unusual structural behaviors that indicate a malfunction in the structure, which is an unhealthy structural condition. Detection of an unhealthy condition calls for a detailed inspection (examination) of the structure, diagnosis, and finally the SHM system can supply orders to do the refurbishment or repair work. Depending on the complexity level of the SHM system, it can even perform the diagnosis and the prognosis steps, supplying the required information to carry out the most suitable actuation. According to their sophistication, SHM systems could even be considered as a full smart structure, equipped with sensing, intelligence (algorithms, programs, etc.), and actuation subsystems as illustrated in Fig. 1.

In line with the previous comments, in summary SHM can be understood as a system that includes the integration of sensing intelligence and possibly also actuation devices to enable a structure's conditions of loading and damage to be recorded, analyzed, localized, and predicted in such a way that nondestructive testing becomes an integral part of the structure.

According to the functionality and degree of complexity, SHM systems can be classified in five levels, as is illustrated in Fig. 2.

From the *staircase of the SHM systems* (as Fig. 2 can be named) it can be observed that the higher the level, the higher the complexity and functionality. In fact, it is a logical consequence of the example described using the human body to describe the SHM concept. Level I SHM systems (the simplest) only detect the presence of damage without locating it on the structure. However, the Level IV SHM systems are able to carry out the prognosis or to estimate the remaining service life. SHM systems of level V are constituted by very complex hardware, custom algorithms and the software to enable, by itself, the diagnosis and/or the prognosis and even the healing functions.

With SHM systems unusual structural behavior can be detected at an early stage, decreasing the risk of sudden collapse, and preserving human lives, the environment and goods. SHM

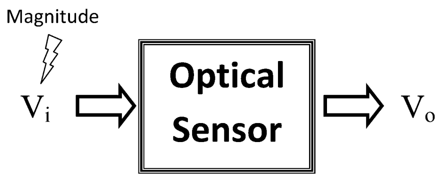

Fig. 3. Conceptual illustration of an Optical Sensor.

systems enable the detection in advance of a structural malfunction and allow for an in-time refurbishment intervention that involves limited maintenance costs, enabling the extension of the life-time and decreasing the direct economic losses (repair, maintenance, and reconstruction) and also helping to avoid losses for users due to structural failures. Using SHM systems, hidden (unknown) structural threats can be detected early, enabling better exploitation of the materials and components of the current structures. That is, the same structure can withstand higher loads, improving its performance without additional construction costs.

But, what do we need to know to develop SHM systems?

The five main important factors to be considered are: 1) the structural behavior and performance; 2) the expected loads; 3) the design principles; 4) the maintenance requirements; 4) the available systems or devices for structural assessment and, of course; 5) the emerging technologies suitable for use with SHM.

To identify which measurands must be monitored, issues, such as the type and the purpose of a structure, construction materials, environmental conditions and expected degradation phenomena, among others, must be considered. The more common ones are *Chemical* (pH, oxidation, corrosion, carbonation, penetration, and timber decay); *Mechanical* (strain, deformation, displacement, crack opening, stress, and load); and *Physical* (temperature, humidity, pore pressure etc.).

In addition to nondestructive *in situ* structural evaluation methods (thermography, acoustic, Eddy currents, etc.), sensor devices are key elements in knowing the structural state. Several types of sensors, embedded or attached to the structure, can be used for this purpose (strain gauges, piezoelectric, electrical time-domain reflectometers (ETDR), etc.). However, only those based on fiber technology offer the capability to perform integrated, quasi-distributed, and distributed measurements on or even inside the structure, over long lengths, in addition to other advantages.

III. Optical Fiber Sensors

Devices into which the measured object or input signal V_i introduces modifications or modulations in some of the characteristics of light in an optical system can be considered Photonic/Optical Sensors (OS). After being detected, processed and conditioned, the system will deliver an output signal V_o, usually in the electric domain, which should be a valid reproduction of the object variable (see Fig. 3).

The transmitted or reflected light can be modulated by the measurand by changes in its amplitude, phase, frequency or polarization state. If fiber-optic technology is used in any of the processes or parts, then the OS can be considered an Optical Fiber Sensor (OFS). The main advantages of OFS are derived from the particular characteristics of the silica: it is passive, dielectric, and with low losses at optical frequencies. For that reasons, optical fiber sensors are immune to electromagnetic interferences, chemically inert, biocompatible, withstand high temperatures, and are potentially small and lightweight. The distance to the measuring point can be of many kilometers, thanks to the excellent transmission capabilities of the optical fiber. Besides, a lot of measuring points can be multiplexed along a single optical fiber, and fully distributed measures with great spatial resolution are also possible [5].

In general terms, an OFS is usually made up of a transducer device, a communication channel and a subsystem for generating and/or detecting, processing, and conditioning the signal, all of these being either integrated or not. (see Fig. 4).

According to the spatial distribution of the measurand, fiber optic sensors can be classified as (see Fig. 5).

1) *Point*, when the measurement is carried out at discrete points accessed by different channels. In other words, each sensor detects at only one point.
2) *Integrated*, when the measurement is integrated from all the values of the object variable contributing into only one resultant value.
3) *Quasi-distributed*, have the capacity to measure the value of the state of the variable at discrete points of space situated in a single optical channel.
4) *Distributed*, when they can measure the value of the state of the measurand along a line of space to be measured with a given spatial resolution. They are sensors which allow the determination of the value of the object variable in a continuous way at each point of space; that is, distributed. When distributed sensors determine both the level—with a specific accuracy and precision—and the spatial position (with a specific spatial resolution), they allow the "*spatial mapping*" of the input variable.

IV. OFS Technologies for SHM

A wide range of techniques and approaches have been presented for measuring a very wide set of measurands in a no less wide range of application sectors. Many companies have been created to commercially exploit the new OFS technologies. However, not all have followed appropriate strategies to survive successfully [6]. Here, the basic concepts of the four more successful OFS technologies suitable for use with SHM applications are very briefly reviewed. Other technologies useful for SHM will also be briefly addressed.

V. Successful Techniques

Here, the four most successful OFS techniques (mainly for physical and/or mechanical parameters) will be commented on. One is very successful for integrated (long gauge), another, for point and quasi-distributed and, the other two, for distributed measurements.

A. Long Transducers for Elongation Measurements

Several approaches have been tested for measuring the integrated elongation of a structure using long fiber gauges. Typically, this kind of transducers is useful to measure the integrity

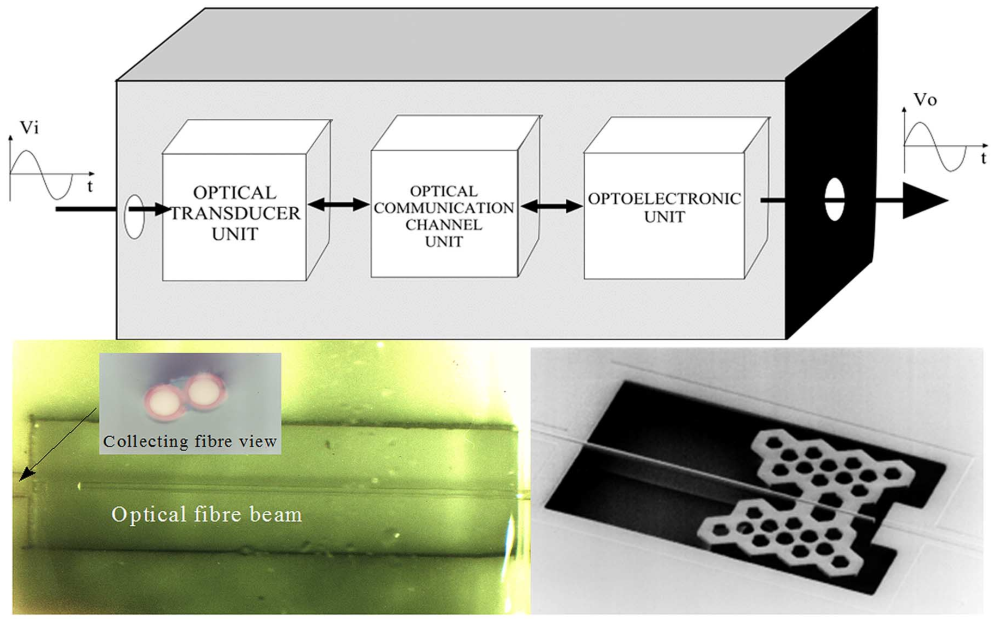

Fig. 4. Main blocks of an OFS (upper). Very low-frequency accelerometer transducers in fiber and Integrated Optic technologies developed in the framework of the European Brite Euram 7289 project (Lower). Courtesy of Photonics Engineering Group of the University of Cantabria and CEA-LETI, Grenoble, France, respectively.

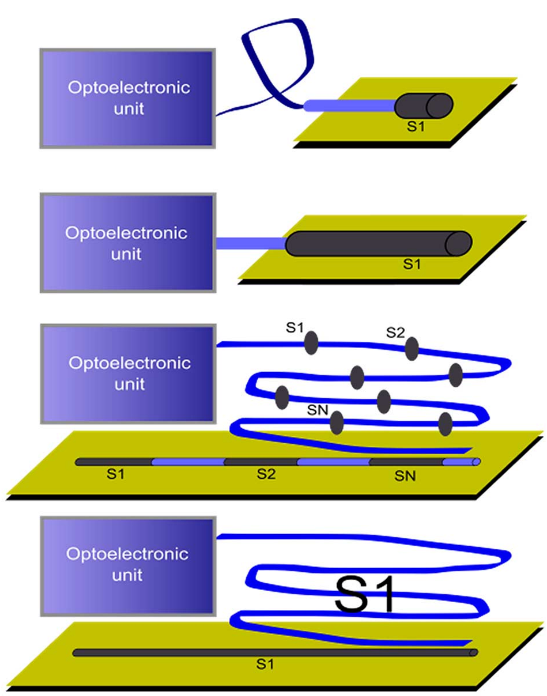

Fig. 5. Optical fiber sensor types according to the spatial distribution of the measurands: (a) point; (b) integrated; (c) distributed; (d) quasi-distributed.

of structures in a wide range of application sectors including architectural heritage and civil engineering applications [7]. When long gauge transducers have been required, the most successful technology is the SOFO (both the Static and Dynamic) systems. For both kinds of SOFO sensors, the transducer consists of a pair of single-mode fibers installed in the structure to be monitored. One of the fibers, called measurement fiber, is in mechanical contact with the host structure itself. It is attached with its two extremities and prestressed between them. On the other hand, the other fiber, the reference fiber, is placed loosely within the same cable.

In static SOFO, to make an absolute measurement of the path unbalance, a low-coherence double Michelson interferometer is used. The first interferometer is made of the measurement and reference fibers, while the second is contained in the portable reading unit. This second interferometer can introduce, by means of a scanning mirror, a well-defined path unbalance between the two arms. The precision and stability obtained by this setup (quantified in laboratory and field tests) is 2 μm, independently of the sensor length over more than one year. Even a change in the fiber transmission properties does not affect the precision, since the displacement information is encoded in the coherence of the light and not in its intensity. Since the measurement of the length difference between the fibers is absolute, there is no need to maintain a permanent connection between the reading unit and the sensors.

At this moment, five improved generations of the SOFO systems for static measurements have been developed and commercialized, and now there is also a version for dynamic measurements [8]. It is based on the same transducer approach, but the reading or optoelectronic unit is based on a Mach–Zehnder interferometer instead of a mobile mirror used in the static SOFO unit (see Fig. 6).

The SOFO system is a nice and illustrative history of how a Ph.D. thesis is carried out and concludes in a successful commercial product [6]. It was developed at the IMAC laboratory of the Swiss Federal Institute of Technology in Lausanne (EPFL) and is fabricated and commercialized by Smartec SA (*www.smartec.ch*) now at the Roctest Group.

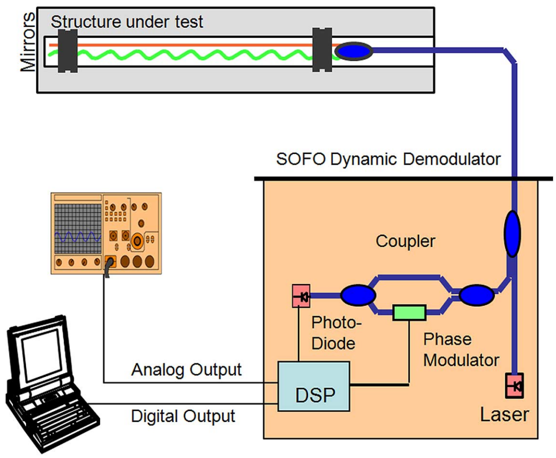

Fig. 6. Conceptual illustration of SOFO Dynamic. Courtesy of Smartec.

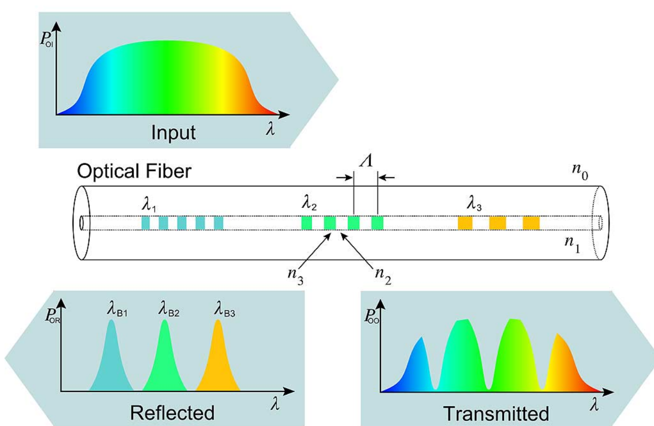

Fig. 7. Illustration of the fiber Bragg grating concept and its optical function. It should be noted that $\lambda_{Bx} = 2n_{\text{effx}}\Lambda_x$.

B. Transducers Based on Fiber Bragg Grating Technology

In core optical fiber gratings are one of the most intensively studied optical structures because of their great possibilities to create devices for both sensing and telecommunication applications [9].

In sensing, both short period (Bragg) and long period (much longer than the wavelength of the light) are used [10]. The former is used because of its capability to measure both the strain and temperature (and an ample variety of indirect measurands) of the structure. Long-period gratings are used, mainly, because of their high sensitivity to the cladding modes [11].

An Optical Fiber Grating (FBG) can be understood as an optical fiber with a periodic refractive index perturbation pattern inscribed in the core such that it diffracts the optical signal in the guided mode at specific wavelengths into other core-bounded modes, cladding modes, or radiation modes [10]. In one possible approach, the fiber grating in the core can be made up of alternate sections with a period Λ, of index $(n_c + \Delta n_c)$, followed by an index of n_c (see Fig. 7).

If an optical signal P_{oi} is launched into the core of the structure as a guided mode, a fraction of the incident guided light is scattered due to the index mismatch Δn_c at each interface or grating plane. This scattered radiation adds up in phase only in certain directions if a phase-matching condition is satisfied. In a particular example, at the resonant or Bragg wavelength λ_B, if single-mode propagation conditions are satisfied, at each grating plane a proportion of the mode photons are weakly reflected in phase with previous reflections and a backward propagating mode is generated.

The power in this mode is determined by integrating the scattered radiation at λ_B shown as P_{OR}. The rest of the optical power P_{OO} is transmitted as a forward-propagating mode. In this case, the peak of mode coupling in the reflected-spectrum occurs at the resonant wavelength λ_B given by

$$\lambda_B = 2n_{\text{eff}}\Lambda. \tag{1}$$

In this expression, n_{eff} is the effective index of the mode in the grating. Measurement of the peak reflected wavelength results in the direct measurement of the optical product $n_{\text{eff}}\Lambda$ of the grating. Any perturbation that modifies the n_{eff} and/or the grating period Λ will alter the measured Bragg wavelength. Thus, the fiber grating can be used as an intrinsic optical transducer which changes the spectrum of the reflected light. By means of an FBG, both the temperature and the strain can be measured as can the hydrostatic pressure and many other measurands that can be correlated with the three previous ones [12]. FBG can be used either as point or as a quasi-distributed sensor system.

A very important attribute of this technology is its capability to multiplex many FBGs in the wavelength domain [12], enabling the very effective development of quasi-distributed sensor systems. Several FBGs can be written in the same fiber but with different period Λ_{x} and/or effective index n_{effx}, and hence, several different Bragg wavelengths can be clearly resolved using the same fiber line (see Fig. 7).

Their in-line optical connection property makes it feasible for FBGs to build up fiber optic sensor networks using wavelength (WDM), time (TDM) and/or both active and passive hybrid multiplexing schemes [13]. In addition to its wavelength encoded responses (transmissive and/or reflective), FBG technology offers the possibility to build up sensors with linear output, higher sensitivities, high dynamic ranges and resolutions, insensitive to electromagnetic interference, flexible size (lengths from 0.1 mm to several centimeters) among other characteristics [14].

Today a wide range of companies sell transducers and optoelectronic units for sensor systems based on FBG technologies suitable for use in SHMs. Three of them are: Fibersensing (*www.fibersensing.com*), Micron Optics (*www.micron-optics.com*), and FOS&S (*www.fos-s.com*). Samples of their transducers and optoelectronic units are shown in Fig. 8.

C. Distributed Sensors: The Fiber as a Nervous System

The ability to understand and monitor the distributed behaviors of extended critical structures is recognized as a matter of great importance. Optical fiber technology offers unique advantages for spatially distributed measurement because it enables a one-dimensional optical radar to be built. That is, a fiber LIDAR able to measure along the fiber with a given spatial resolution can be implemented!

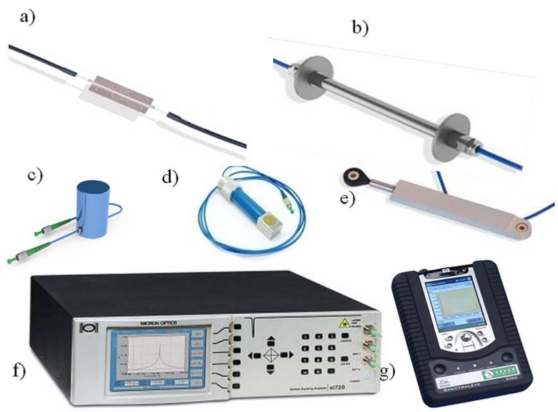

Fig. 8. Bragg grating transducers from Fibersensing: temperature (a) strain (b), acceleration (c), pressure (d), and displacement (e). Optoelectronic units: from Micron Optics (f) and from FOSS (g).

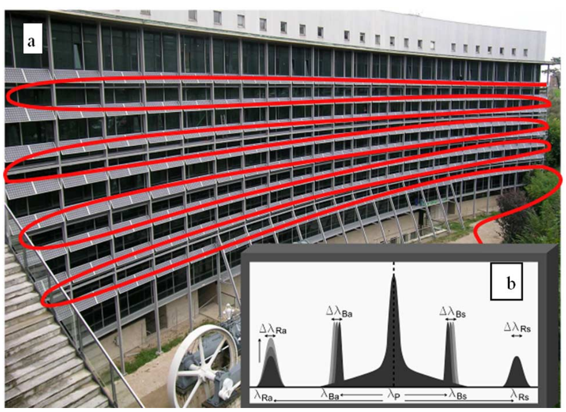

Fig. 9. Distributed temperature fiber Sensor illustrated on the front wall of the Ind. and Telecommunications School at the University of Cantabria, UC. (a) Distributed transducer (red color). (b) Optoelectronic Unit, OU. Courtesy of the Photonic Engineering Group of UC.

In these sensors, optical fibers attached to or embedded inside the material or/and the structure work as their nervous system. They act simultaneously both as the optical channel and as the distributed optical transducer. For that reason, it is recognized as the most promising fiber optic sensing technique.

Just to illustrate the concept, one could imagine that a fiber optic cable of 2 km length making up a distributed sensor system in which the resolution is 0.5 m (see Fig. 9) is placed on the thousands of solar cell panels on the front of a modern corporative building. Then, the temperature or/and the strain can be obtained along the fiber in 4 000 simultaneous measurement points on the reading unit. That is, the sensor is equivalent to a quasi-distributed sensor of 4 000 points separated 0.5 m, but with the advantage that the points can be located anywhere on the fiber, and hence, the full distribution of the temperature of the solar panels on the building can be determined in quasi-real time.

But, how does this fiber LIDAR work?

A pumped optical pulse is launched into the fiber and light is continuously backscattered from it as it propagates, as a result of the linear or nonlinear effects in the fiber. The backscattered light power emerges at the launch end and is time-resolved to provide a differential map of the spatial distribution of the optical state of the fiber. This can be correlated with its spatial physical-mechanical situation. The time information is converted into distance through the speed of light in the fiber. Then, the required measurand along the fiber (and hence of the material or structure in which it is placed) is obtained.

An illustration of the spectra of the backscattered light from one fiber end (pumped with a power P_{Pi} and a wavelength λ_p) is depicted schematically on the front of the reading unit in Fig. 9, for a better understanding of the sensing effects. The linear Rayleigh scattering (photons at the same pump wavelength λ_p) and nonlinear Brillouin or Raman scattering (photons at λ_B or λ_R, respectively) are currently being used in conjunction with optical reflectometric and signal processing techniques to interrogate the fiber transducer [12]. Optical Kerr effects have been also used in some fiber sensing approaches.

The Brillouin scattering is a backward process, while both the Raman and Rayleigh scattering are backward and forward processes [15]. Raman and Brillouin scattering effects present completely different spectral characteristics because they are associated with different dynamic inhomogeneities in the silica fibers. Both Brillouin and Raman produce components around the exciting (pump) wavelength provoking lower photon energy (Stokes emissions) and higher photon energy (anti-Stokes emissions). These scattering components can be understood as the result of the pump wave collisions with optical and acoustic phonon waves for Raman and Brillouin scattering, respectively. As a consequence, the Stokes and antiStokes drifts of scattered photons ($\Delta\lambda_{B,R} = /\lambda_{\rm s} - \lambda_{\rm o}/$) are lower for Brillouin than for Raman, being dependent on the kind of medium (about $\sim$100 nm for Raman, and about $\sim \pm$ 10$-$11 GHz at 1 555 nm of pump light for Brillouin, both for silica glasses). In general, Raman scattering is weaker than Brillouin (between 0 and 10 dB for antistokes-Raman scattering) and, the latter is weaker than Rayleigh scattering (around 20 dB). Raman antiStokes amplitude emission is temperature dependent, and Brillouin drifts are both temperature and strain dependent. The emission amplitude of the Stokes component is constant [15].

The Rayleigh-scattered light is used to measure the attenuation profiles of long-haul fiber-optic links using Optical Time Domain Reflectometry (OTDR) [16]. These profiles are very useful to localize breaks, to evaluate splices and connectors and, in general, to assess the overall quality of a fiber link.

The Raman-scattered light is used for temperature distributed sensors, recording the ratio between the antiStokes and Stokes side-lobes ratio $\mathrm{R}_{(\mathrm{T})}$ of the Raman scattering spectrum [12]:

$$\mathbf{R}_{(\mathrm{T})} = (\lambda_s/\lambda_a)^4 e^{(-hc\Delta\nu/k\mathrm{T})} \tag{2}$$

where λ_s and λ_a are the Stokes and antiStokes wavelengths, h and k are Planck's and Boltzman's constants, $\Delta\nu$ is the frequency shift from the pump signal at which the measurement is made, c is the speed of light, and T is the temperature in K.

It should be noted that due to the low level of the spontaneous Raman backscattered light (approximately 10 dB below spontaneous Brillouin scattering), high numerical aperture multimode fibers are used in order to maximize the guided intensity of the backscattered light. However, the relatively high attenuation characteristics of multimode fibers limit the distance range of Raman-based systems to about 8–10 km.

Brillouin scattering was proposed for the first time to measure temperature in 1989 [17]. Nowadays, it is used for distributed temperature and strain sensing because the Stokes side-lobe is temperature and strain dependent. It can be used in long transducers (even very long for temperature) because the short Brillouin frequency shift is very low (about 10–11 GHz at 1 550 nm), and so, both the pumped light and the scattered light can by placed (without problems) in the third window of a standard monomode telecommunication silica fiber [18].

A very interesting approach to the Brillouin scattering effect for sensing is to interpret it as the diffraction of light on a *dynamic* grating generated by an acoustic wave (an acoustic wave is actually a pressure wave that introduces a modulation of the index of refraction through the elasto-optic effect). The diffracted light experiences a Doppler shift, since the grating propagates at the acoustic velocity in the fiber. The acoustic velocity is directly related to the density of the medium, which is temperature and strain dependent. As a result, the so-called Brillouin frequency shift carries the information about the local temperature and strain of the fiber.

As is well known, the Brillouin scattered light spectrum is characterized by the Brillouin scattering coefficient α_B; the Brillouin linewidth $\Delta\nu_B$, and the Brillouin shift ν_B. Up to now, although $\Delta\nu_B$ (20–50 MHz) is inversely proportional to the lifetime of the acoustic phonon and is believed to be independent of strain, it shows a little temperature dependence and $\alpha_{\rm B}$ is thought to have temperature and strain dependence. The main research for sensing purposes has been focused on the use of Brillouin shift ν_B dependencies on temperature and strain. The latter, according to Horiguchi [19], is given by

$$\nu_B = 2 \cdot n \cdot V_a/\lambda_p \tag{3}$$

in which λ_p is the pump wavelength, n is the core index, and V_a is the speed of sound in the fiber material, which is both strain and temperature dependent. According to Kurasima [20] these dependencies at $\lambda_p = 1320$ nm are 58 kHz/microstrain, and 1.2 MHz/K, respectively.

Stimulated Brillouin Scattering (SBS) can be achieved by using two optical light waves. In addition to the optical pulse, usually called the pump, a continuous wave (CW), the so-called probe signal, is used to probe the Brillouin frequency profile of the fiber [21].

A stimulation of the Brillouin scattering process occurs when the frequency difference (or wavelength separation) of the pulse and the CW signal corresponds to the Brillouin shift (resonance condition) and provided that both optical signals are counter-propagating in the fiber. The interaction leads to a larger scattering efficiency, resulting in an energy transfer from the pulse to the probe signal and an amplification of the probe signal. The frequency difference between the pulse and probe can be scanned for precise and global mapping of the Brillouin shift along the sensing fiber. At every location, the maximum of the Brillouin gain is computed and the information transformed to temperature or strain using the appropriate calibration coefficients. This Brillouin Optical Time Domain Analysis (BOTDA) technique is currently being used in distributed fiber sensing. A BOTDA elemental fiber circuit is depicted in Fig. 10.

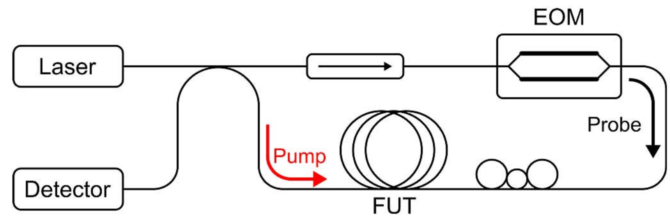

Fig. 10. Illustration of a basic setup scheme for BOTDA.

It must also be mentioned that continuous and pulsed optical waves either in the time or in the frequency domain, with some variations, has been used to demonstrate distributed fiber sensing approaches. Optical reflectometric techniques such as Optical Continuous Wave Reflectometry (OCWR) [22], Optical Frequency Domain Reflectometry (OFDR) [23], Low Coherence Reflectometry (LCR) [24], and variations of the aforementioned techniques such as, Polarization Time Domain Reflectometry (POTDR) [18], Raman Optical Time Domain Reflectometry (ROTDR) [25], Brillouin Optical Time Domain Reflectometry (BOTDR) [26], and techniques including optical amplification using nonlinear phenomena such as the aforementioned BOTDA and rare-earth-doped optical fibers [27] interrogated in the time domain have been demonstrated and used.

It should be noted that time-domain techniques have shown difficulties in providing satisfactory performance, such as when achieving a high spatial resolution and a high sampling rate. To overcome these difficulties, optical correlation domain techniques using continuous light waves have been proposed [28]. By using a Brillouin Optical Correlation Domain Analysis (BOCDA) technique, a 1 cm spatial resolution and a 57 Hz sampling rate, which are 100 times finer and 10^4 times faster than those of the time-domain technologies, respectively, were demonstrated [29].

To reach very high spatial resolution a Rayleigh backscatter and Interferometric hybrid technique have been demonstrated [30]. The Optical Backscatter Reflectometer (OBR) uses swept wavelength interferometry (SWI) to measure the Rayleigh backscatter as a function of optical fiber length. The external measurand (strain or temperature) causes temporal and spectral shifts in the local Rayleigh backscatter pattern. By measuring these shifts a distributed temperature or strain measurement profile can be obtained. The SWI approach enables robust and practical distributed temperature and strain measurements in standard fiber with centimeter-scale spatial resolution up to 70 m of fiber with strain and temperature resolution as fine as 1 μm strain and 0.1°C.

It must also be mentioned that using amplification techniques, distributed fiber sensors up to 150 km long have been demonstrated [31].

Significant R&D efforts were and are being made today in order to develop new knowledge and techniques to improve the resolution [31], the dynamic range [33], [34] and spurious effects [35], [36], and to obtain reliable and accurate measurements with the new generation of distributed fiber sensors.

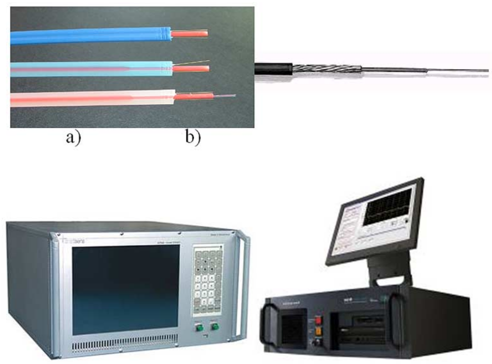

Fig. 11. Two commercial transducers (aforementioned) and two optoelectronic units (in the following). Fiber transducers for both temperature and strain (a), for temperature (b). DiTest Brillouin (c) and Raman (d) scattering interrogation units. Courtesy of Smartech, Omnisens and Sensornet.

Nowadays, several companies fabricate and commercialize transducers and optoelectronic units for distributed sensor systems able to be used in SHM. Samples of some transducers and optoelectronics units are shown in Fig. 11.

The commercial companies include: 1) based on Brillouin scattering: Omnisens (*www.omnnisens.ch*), ANDO (*tmi.yokogawa.com*), Sensornet (*www.sensornet.co.uk*), Neubrex (*www.neubrex.com*), and OZ Optics (*www.ozoptics.com*); 2) based on Raman to measure distributed temperature (DTS): Sensa-Shlumberger (*www.sensa.org*), Agilent (*www.agilent.com*), and Sensornet; 3) based on Rayleigh scattering: Luna Technologies (*www.lunatechnologies.com*). Specific cables for sensing are produced by Smartec (*www.smartec.ch*).

VI. Other Techniques for SHM

A. Fabry–Perot Interferometers

Fabry–Perot (FP) cavities (both passive and active) have been successfully used in sensing applications exploiting measurand-induced changes in one of their cavity parameters. They can be used both as the basis for the transducer mechanism or as fixed or tunable devices in the optoelectronic unit. The cavity can be active, for instance integrating a fiber laser sensor, or passive. One very well tested approach is the Extrinsic Fabry–Perot Interferometer (EFPI), which is constituted by a capillary silica tube containing two cleaved optical fibers facing each other, but leaving an air gap of a few micrometers or tens of micrometers between them.

When light is launched into one of the fibers, a back-reflected interference signal is obtained. This is due to the reflection of the incoming light on the glass-to-air and on the air-to-glass interfaces. This interference can be demodulated using coherent or low-coherence techniques to reconstruct the changes in the fiber spacing [37]. This structure has been used in a wide set of applications. For instance, in [38] and [39] a sensor head for long-term, high-precision strain measurements of very small deformations of a mechanical diaphragm is based on a fiber optic Fabry–Perot interferometer. Because of its nanosize and high sensitivity to many parameters (strain, pressure, vibration, chemical- humidity, breathing, etc.), these FP cavities obtained by molecular self-assembly chemistry have received special attention in the last decade [40], [41].

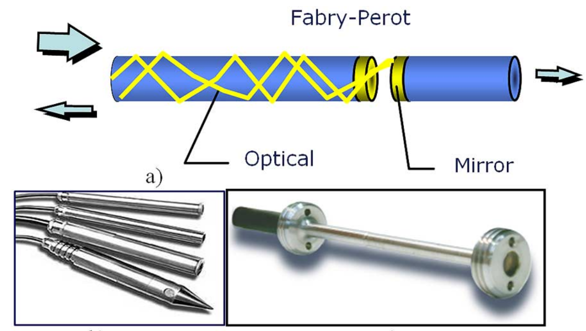

Fig. 12. Schematic illustration of an EFPI transducer used for both chemical and physical point transducers (a). Commercial transducer for pressure (b) and strain (c). Courtesy of Roctest.

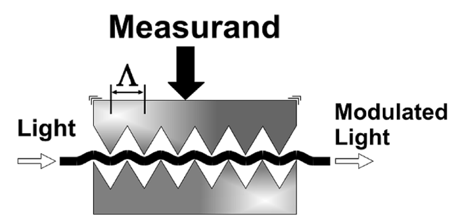

Fig. 13. Point transducer based on periodic microbends.

Commercial FP transducers (see Fig. 12) and optoelectronic units can be found from several companies, such as Roctest (*www.roctest.com*), Fiso (*www.fiso.com*), Luna (*www.lunainovations.com*), and Bam (*www.bam.de*). These commercial sensor systems are able to offer typical characteristics such as: 1) resolutions of strain: 0.1 $\mu\varepsilon$; 2) temperature: 0.1 °C; 3) pressure: 0.1 KPa; 4) displacement: 20 μm; measurement speeds ranging from 1 to 500 Hz, and up to 32 channels.

B. Fiber Bend-Based Transducers

Micro- and macrobends is one of the earliest fiber-optic measurement OFS approaches [12]. Optical losses are induced by the measurand modulating the amplitude of the light propagating in the fiber. As is illustrated in Fig. 13, a transducer fiber is installed between two plates with saw-shaped edges. Upon compression, the plates attached to the structure draw away from the fiber, leading to a decrease in the light level, while in decompression the effect is the opposite.

Another transducer bend structure can be obtained with a spiral wire wrapped around the whole length of the fiber to enable distributed pressure measurement, but it is also possible to measure the integrated strain between the anchoring points with a suitable package [42].

Typically bend sensors are point, but using the capability of OTDR techniques for analyzing small losses, distributed [43] and quasi-distributed [12] sensor systems can be implemented for SHM applications.

Two mechanisms have been identified for the power loss at the bend of single-mode fibers [44]: 1) the energy can be forced at some point of the curvature to travel at higher speed than the speed in the medium, a fraction of the light being coupled to cladding modes, which are highly attenuated by the optical fiber; and 2) a power loss can be produced by the mismatch of the mode profile when the light propagated by the straight optical fiber enters the bent segment at the sensor head.

Regarding highly multimode fibers, it seems clear that the induced perturbation on the waveguide produces a redistribution of the propagated light, producing a strong coupling to cladding modes under certain conditions. In both cases, if the newly generated modes guided by the cladding have high propagation losses, which depends on the shape of the curvature/s, the expected amplitude modulation of the light exiting the sensor head is obtained.

Commercial microbending deformation sensors (with precisions and sampling rates typically of 1 $\mu\varepsilon$ and 100 Hz, respectively, and with a gauge-length of 10 cm–10 m) can be found from companies such as OSMOS (*www.osmos-group.com*).

C. Other OFS Sensing Structures

Other approaches in the design of optical fiber sensors have been proposed to provide an interaction zone between the light and the sensitive material. Fig. 14 shows some generic configurations that have been reported (i.e., for chemical, humidity, and pH optical fiber sensors): extrinsic transmissive (a) and reflective (b) configurations usually result in high coupling losses, specially for monomode fiber; an evanescent wave to interact with the surrounding medium can be created with a stripped cladding (c), a taper (d) or with a curvature in the fiber (e), resulting typically in a low sensitivity because most of the optical field is still confined within the fiber.

The measurand typically modulates the light either directly or through an intermediate material whose optical or mechanical properties are sensitive to it. For instance, without any intermediate material, in some chemical sensing approaches, thanks to their spectral fingerprint, the measurand compound can be directly detected and measured by using spectroscopic analysis [45]. Indirect measurements can be obtained by employing materials such as hydrogel polymers or dye indicators sensitive to particular chemical species.

Hydrogel polymers, when exposed to moisture, undergo changes in their optical absorption or in their volume, provoking a relative displacement that modulates the intensity of the light (on sensing structures such as (a) or (b) in Fig. 14). It can also be detected with some of the aforementioned OFS displacement techniques (such as FBGs or FPIs).

In Table I, a summary of typical performance of some of the commercially available OFS products is presented.

VII. OFS for Chemical Parameters

Some of the structural issues that affect the performance and expected service life of structures can be monitored by chemical sensing. Corrosion, i.e., the chemical degradation of the materials and, in particular, the electrochemical oxidation of the metallic parts, is a major problem. Many alloys corrode through exposure to moisture in air, but the process is accelerated by substances such as chloride, microbes or exposure to high temperatures. For this reason, common parameters to be measured,

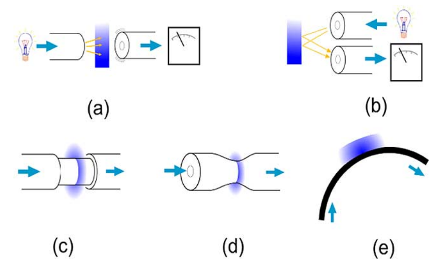

Fig. 14. Generic configurations of optical fiber sensors for chemical sensing in structural health monitoring: extrinsic transmissive (a) and reflective (b), with a stripped cladding (c), a taper (d), or with a curvature in the fiber (e).

to monitor or prevent material degradation are: chloride, sulphate and carbonatation penetration, humidity, pH, oxidation, and presence of biological agents [46]. The inert properties of the fiber optic sensors offer reliable solutions in all these sensing scenarios.

A. Humidity

Measurement of humidity in the atmosphere and in the surrounding medium has been one of the first proposed applications for optical fiber sensors. They are usually based on a moisture-sensitive materials added to the optical fiber, which translate changes of the surrounding humidity into pressure, movement or absorption changes. For example, a distributed sensor interrogated by an Optical Time-Domain Reflectometer (OTDR) can be based on water-swellable hydrogel polymers, which translate changes in the surrounding water pressure into losses of a multimode optical fiber [47]. This is accomplished thanks to the design of the optical cable, which translates mechanical pressure from the environment into curvatures of the optical fiber inside the cable. This approach can be useful to detect water penetration in materials, and it provides a resolution of 50 cm over dozens of meters of measurement range.

Extrinsic Fabry–Perot sensing structures at the fiber's end have also been proposed for humidity sensing. In [45], the transducer consists of a stack of nanoporous dielectric metal oxide films forming a Fabry–Perot filter with a reflection minimum at about 800 nm. It is based on the reversible adsorption and desorption of water molecules in the pores, which affects the optical refractive indexes of the porous layers and the spectral minimum of the Fabry–Perot filter.

In other configurations, the moisture-sensitive material is placed around the optical fiber, and the transducer works in transmissive mode. This usually represents an advantage to form a multiple-point network of sensors, which is interesting for large structures. With this approach, one of the most problematic issues is how to increase the interaction between the light (confined within the fiber's core) with the material [48]. One possible solution is a tapered optical fiber, in which its outer diameter is stretched at some point to allow light propagation outside the cladding and within the humidity-sensitive coating [49]. One of the drawbacks of humidity sensors, namely its speed of response and the presence of hysteresis, can be minimized with very small sensitive coatings based on nanofilms [50].

However, the aforementioned technology is difficult to apply to solid materials in structures. One proposal is focused on humidity absorption of concrete during both its curing and its operational life [51]. The sensor is based on an FBG coated with a polymeric moisture-sensitive compound that translates humidity into longitudinal strain.

B. Corrosion

Several technologies of optical fiber sensors have been proposed to detect material degradation, in particular, corrosion of reinforced concrete caused mainly by the penetration of water and chloride ions into the steel surface. The corrosion products are deposited in the restricted space around the steel, setting up expansive stress, cracking, and the progressive deterioration of the concrete [52]. Chloride penetration is a major problem not only in marine environments, but in roadways and bridges due to the use of deicing salts.

To identify corrosion, usually multiparameter sensors are required, and optical fiber techniques have shown superior performance for this application [53]. One interesting approach is the spectroscopic analysis of the surface of the materials, as the material degradation is always associated with color changes. Two optical fibers are embedded in concrete and placed with their ends over the steel surface, one fiber carries white light from a broadband source and the other is attached to a simple spectrometer in the visible range [52]. Changes in the reflective spectrum of the steel have been detected at different corrosion stages in accelerated tests. A similar approach can be used for detection of chloride ion penetration, using a sensitive membrane at the distal end of a fiber optic bundle, in contact with the material. This sensor has been successfully embedded in mortar cubes and tested in simulated maritime environments [54].

The determination of the pH-value is also a good indicator of corrosion. For example, embedded steel structures in concrete exhibit long-term stability (i.e., resistance to corrosion) only at pH-values of 9 or higher [55]. Concrete is a highly alkaline environment that produces a passivation and protects it from corrosion, but the carbon dioxide in the air reacts with the cement and makes the material more acidic. Thus, a lowering of the pH may be a signal of corrosion. Optical fiber sensors for pH sensing are usually based on an immobilized dye whose absorption spectrum is pH-dependent and can be analyzed with simple spectroscopic methods. Some drawbacks of this approach are its low sensitivity (flourescence in pH indicators has shown to improve it [56] and the dynamic range of pH values, for which a mixture of different dyes has been proposed [57].

Optical fiber pH sensors have been applied to diverse materials and corrosion processes in SHM. One proposal is the monitoring of humidity and pH with an integrated optical fiber sensor. As a moisture indicator, Pyridinium-N-Phenolat Betainital dye, embedded in a polymer matrix, was used. The shift in the absorption spectrum with the water concentration was monitored in the ultraviolet-visible spectral range (UV-VIS). The pH measurement was based on the same sensor structure, with a pH-indicator dye immobilized in a highly hydrophilic polymer matrix. Any change in pH-value of the wet concrete material was indicated by a color change in the dye/polymer system. This sensor system showed long-term stability even in aggressive media of pH 12–13 [55].

Multiple-fiber imaging sensors represent an improvement over single-point sensors, in which fine spatial resolution, depending on the fibers' geometries, is achieved. A multifiber sensor with an immobilized pH-sensitive fluorescent dye in contact with the material has been proposed for this task [56].

Another approach is based on long-period gratings (LPGs), in which the fiber's cladding is exposed to an aqueous solution, and changes in sodium chloride concentrations are expected to affect the transmission spectrum of the grating [58]. This work used two LPGs separated by around 30 mm and fabricated with an excimer ultraviolet laser with the amplitude mask technique. The basis of the measurement using the LPG was refractive index monitoring, with the sensor being calibrated using solutions of known refractive indexes (RIs). The spectral shift of both LPGs is monitored as an indication of the RI change, and this double-LPG structure allows a measurement of changes in RI as low as ± 0.003, which is equivalent to 10 ppm changes in chloride ion concentration. To reach a commercial stage, two main issues need to be addressed: long-term reliability of the embedded sensors and cross-sensitivity to other substances.

More direct approaches to assess corrosion have been proposed, for example, a simple intrinsic sensor in which a section of the optical fiber has its cladding stripped, coated with a thermally deposited aluminum layer on a fiber segment, to detect corrosion in aeronautical structures [59]. The same approach can be used for reinforced concrete structures, using a layer of electroplated nickel [60]. It is expected that the corrosion process affecting the reinforced concrete structure will also degrade the metal layer and hence the transmission efficiency of the optical fiber in the stripped cladding segment. This work draws attention to one particular issue of this kind of intensity-based sensors that have to operate over a long period: the need for referencing, to reduce the impact of unwanted changes in optical source power, optical fiber losses or long-term sensor degradation on sensor performance. This problem has been addressed, in this case, by taking measurements with different injection angles of the light source. Another goal is to improve the sensitivity of these sensors, for which the Surface Plasmon Resonance (SPR) technique [61] has been actively investigated, for example, to analyze the presence of chloride ions in water [62].

The specific corrosion process produced by microbiological agents has also attracted research interest. Sulphide corrosion results from bacterially produced hydrogen sulphide gas that is oxidized in the presence of moisture to form sulphuric acid, a corrosive agent for many materials such as concrete or steel [63]. In a first phase, the abundant sulphates dissolved in marine or fresh water are converted to hydrogen sulphide gas by sulphate reducing bacteria (SRB) in the absence of oxygen. Then, the sulphur oxidizing bacteria (SOB), which colonize pipes, walls, and other surfaces in structures, oxidize it to sulphuric acid in the presence of humidity and atmospheric oxygen. Other microbes directly oxidize iron to iron oxides and iron hydroxides, or enhance galvanic corrosion. The sensing approach is typically based on texture or color changes in the material's surface, for which the embedded optical fiber acts as a mere transport medium for the reflected and scattered light [64].

One area of active research at this moment is reliability and packing issues in order to move these in-lab prototypes to the field [65]. However, the main challenge with fiber optic corrosion sensors is how to move from single-point measurement to a fully distributed system for large structures. Some recent works try to apply the Brillouin effect to detect the microcracks induced by the corrosion process [66].

C. *Curing of FRPs and Concrete*

Although the previous paragraphs have been focused on the monitoring of material degradation during the structure's operational life, there is also considerable interest in the chemical changes that some materials undergo during their fabrication. One example is the monitoring of the curing process of Fiber Reinforced Plastics—FRP (and their variants), optical fiber sensors being ideal candidates to be embedded for this task due to their small dimensions and compatibility with the resin matrix. One of the first proposed techniques was based in near-infrared Fourier spectroscopy, as the chemical changes are expected to modify the transmission spectrum of the epoxy resin. The changes in the refractive index of the material during the curing process have been exploited, usually with extrinsic Fabry–Perot optical fiber sensors [67]. Other works have explored the use of FBG sensors to monitor the distribution of strain and temperature [68], showing its feasibility to detect the onset of vitrification and to measure the residual strain after curing. Considerable research effort is currently aimed at this particular application of FBG sensors.

Another process that could benefit from optical monitoring is the curing (hydration) of concrete, as it has been demonstrated that proper handling of this procedure is critical for a long operational life of structures [69]. The measurement of humidity and pH has been proposed as indicators of the curing progress. One possible technology is based on sensitive hydrogel polymer-coated optical fibers interrogated by an OTDR [70].

VIII. Some Significant Examples of SHM With OFSs

It is today recognized that OFS technology is attractive in those cases where it offers superior performance compared with the more proven conventional sensors, and offers in addition: 1) improved quality of the measurements; 2) better reliability; 3) the possibility of replacing manual readings and operator judgment with automatic measurements; 4) easier installation and maintenance or a lower lifetime cost.

Although fiber-optic sensors are apparently expensive for widespread use in health monitoring, they are, however, better approaches for applications where reliability in challenging environments is essential. In those cases, price is often no longer an obstacle when the security or efficient management of structures could avoid catastrophic events.

The application area for OFS in structural monitoring is vast, including civil or industrial structure monitoring (concrete beam tests, bridge girders, ore mines, nuclear containers, tunnels, hydroelectric dams, etc.), for composite materials (spacecraft, aircraft tail spars, helicopters and windmill rotor blades, ship and submarine hulls, composite cure monitoring, composite girders for bridges, etc.). OFS Technology can also be employed in acoustic sensing (towed hydrophone arrays, down-hole sensors for oil wells) on in-plant or distribution of electric power utilities, for gas pipelines and, in general, for industrial control, monitoring and processes; and even with potential environmental applications [14].

Fig. 15. Sea-wave turbine in experimental phase in Santoña Spain. Placed at 10 km from the coast, the device converts the vertical movement of the sea waves into electric energy by means of a conventional generator. Courtesy of Sodercan.

To illustrate the potential of the OFS in SHM applications, examples framed on four of these vast application areas with high interest in sensing solutions will be briefly discussed in the following sections: renewable energies, transportation, civil engineering, and oil and gas.

A. *OFS Systems in Renewable Energy Structures*

Humans desire a much more sustainable environment and the current crisis requires new clean energy sources. In order to harvest renewable energy more efficiently, the size of the current (in R&D process) device structures has become physically larger and more complex, making maintenance and repair work difficult. The latter is exponentially increased with the extreme severity of the remote working environments. To improve safety considerations, to minimize down time, to lower the frequency of sudden breakdowns and associated huge maintenance and logistic costs and to provide reliable power generation, renewable energy generator devices and plants must be monitored to ensure that they are in suitable working condition. Among all the monitoring systems, SHM systems are of primary importance because they provide integrity of devices and renewable energy plants or farms.

Initiatives such as the marine power plant [71] installed in Uldolmok (Korea) reflect the current social concern about renewable energy. This plant is based on tidal devices and employs FBGs to measure the dynamic and static strain. With this system, designers will be able to validate tidal technology and collect data for a subsequent facility improvement. Other initiatives such as the Idermar Buoy in Spain (*www.idermar.com*), the Iberdrola renewable Sodercan (see Fig. 15), or Martifer Energy in Portugal (*www.martifer.pt*) are still in early stages, just collecting data for environmental analysis.

The latter was fitted with a quasi-distributed system based on FBG technology (180 points) to assess its structural integrity.

SHM systems are required and will play a key role in established technologies such as wind turbines. The number of optical fiber monitoring systems applied to wind farms has increased during the last years, and the potential offered by these

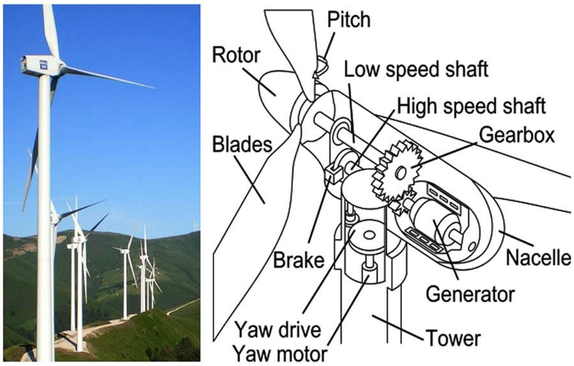

Fig. 16. Wind turbine and details of key subsystems to be monitored. Photo courtesy of COPSESA.

systems could be very attractive or crucial for off-shore renewable energy generation devices (see Fig. 16).

From previous studies, it is known that the failures for mechanical components range from 4 % for structural parts/housing and gearbox to 7 % for rotor blades. Although structural damage can happen to any structural component, the most common type of damage is rotor or blade damage and tower damage. Extensive attention has been given to the structural health of blades as they are the key elements in a wind power generation system, and also because the cost of the blades can account for 15–20 % of the total turbine cost [72]. So, a relevant application of optical fiber sensors to wind turbines is the measurement of the blade deformation using FBGs [73]. By attaching FBG sensors along the blade, the system could measure temperature and strain in critical points of the large blades (53 m length) of 4.5 MW wind turbines.

Based on this idea, some specific commercial systems have been developed. Vestas Vibration Condition Monitoring System (*www.vestas.com*) and Insensys Rotor Monitoring System (*www.insensys.com*) are two examples. In the latter, the strain measurements can be used to balance the blades in order to increase the power generation efficiency.

Although blade condition monitoring is the most typical application of optical fiber sensors, these can be placed in almost the whole wind turbine starting from the fabrication stage, in which temperature and strain can be monitored in the curing processes using FBGs [68] or Brillouin technology [74] to assess the mechanical properties of the carbon fiber reinforced plastic (CFRP) pieces.

From the structural point of view, a wind turbine is a vertical structure in which some critical parts should be monitored (see Fig. 15). For instance, concrete foundations can be monitored using FBGs [75] during the construction stage, measuring the strain and temperature in the pouring and curing processes, and operation, by detecting deformations in the structure with the same optical fiber sensor. Furthermore, the natural frequency of the tower can be measured during operation with FBGs [76] placed throughout the tower. However, for large structures, distributed optical fiber sensing techniques [77] can be used for monitoring the main tower or even for detecting defects using Brillouin technology [78].

In extreme environmental conditions, it can be interesting to detect events that could affect the structural integrity such as extreme temperatures or corrosion. Some examples include the use of optical fibers with a special cladding for ice detection [79] and detecting corrosion by embedding optical fiber sensors in concrete structures [52]. Other possible damage can be produced by impacts on the structure. By using FBGs [80], [81] to recognize such cases by observing the strain in the structure after the impact, the possible damage can be detected. This damage can also arise from a lightning strike, therefore locating the impact [82] position could help in designing stages.

Optical fiber sensors, such as FBGs can also be installed inside the nacelle to monitor the pressure in the hydraulic circuit of yaw and pitch control [83] or to quantify mechanical vibrations by means of optical fiber accelerometers [84]. The force transmission between the rotor and the generator in a wind turbine is critical in terms of efficiency. Attaching FBGs [85], [86] to the gearbox, shafts and brakes, the torsion forces and deformations can be monitored to determine the current system status and efficiency.

Due to the huge levels of energy handled inside a wind turbine, it is also necessary to monitor possible electronic issues. In this regard, optical fiber sensors could help by monitoring the temperature in the power stage or the generated current [87].

B. *OFS in Transportation Structures*

The ever increasing needs for improved safety, reliability and efficiency are among the most important aspects in the transport industry. To meet these requirements, SHM systems capable of evaluating the structural status under diverse conditions are necessary. Optical fiber sensors can be used in these monitoring systems by adapting them to the different scenarios.

A train is the best example of an optical fiber monitoring system in transport by land. In this means of transport, there are several subsystems in which optical techniques can be applied, for example, measuring railway deviations. FBGs can be installed to measure the rail imbalance [88] in order to improve safety and, with the same sensor network, other parameters such as the train speed or weight can be measured for use in obtaining traffic information. Material properties such as thermal rail deformation [89] can also be measured with FBGs. Additionally, other relevant railway parameters can be obtained with distributed sensors such as Brillouin [90] ones.

Another example in the rail industry is monitoring a critical point in electric trains, the current collector, which is exposed to fast variations in the pressure forces of the overhead contact line during train operation. These variations can also be measured by using FBGs attached to the current collector [45].

Optical fiber sensors are interesting in the naval sector for the characterization of materials and designs. The application of optical fiber sensors to help in the development of new marine structures has been demonstrated with the use of FBGs in scaled vehicles [91], or for the detection of vibrations and damage using a Laser Doppler Velocimeter and backscattered light [92]. Examples such as the Research Vessel Triton [93], equipped with FBGs to monitor the structural integrity, or a fast patrol with FBGs [94] to measure the health of the hull are some fields of application of these techniques.

With the arrival of new materials in the naval field, such as composites, the requirements for optical fiber sensors have changed. Some examples are the characterization of composite ship joints using FBGs [95] or the monitoring of a carbon fiber yacht mast [96].

The aerospace industry is one of the most demanding industries, which uses optical fiber sensors to monitor their higher performance structures and designs. Some examples can be seen in spacecraft in which, using FBGs as multiparameter sensing technology [97], strain and temperature can be mapped in adaptive composite structures. This technology is also used to monitor the spacecraft integrity during the reentry or to evaluate the temperature of the propulsion stage.

Likewise, the aircraft industry also has very demanding requirements. Starting from the fabrication process, optical fiber sensors can be used to assess the quality of the manufactured parts, for example by using FBGs to monitor the composite curing processes [98] and its further application to the measurement of loads in operation.

Due to the complexity of an aircraft (see Fig. 17) maintenance is not a trivial issue. To guarantee the correct operation of a repaired aircraft, the restored areas have to be highly tested. This may be done with optical fiber sensors by attaching FBG sensors [99] to the repaired area in order to decrease maintenance time and costs.

Besides fabrication issues, optical fiber sensors can be employed to monitor the structural response of an aircraft. An example taken from spacecraft is the monitor system of the main structure in the X-38 Crew Reentry Vehicle prototype for the International Space Station [100]. In this case, some FBG sensors were attached to the rear aluminum structure to measure the high loads during the release and propulsion stages.

In addition to the monitoring of the main structure, other relevant parts such as wings can be fitted with optical fiber sensors. FBGs can be employed to monitor dynamic strain in the wings [101] and in this way, obtain structural properties such as natural frequencies [102]. Furthermore, FBGs installed in composites can detect impact damage by using the spectrum change of the sensor output [103]. Other parameters such as in-flight wing loads can be also measured with FBG sensors [96], even flap deformations or cracking detection [104] at critical points can be detected by embedding FBGs.

In the landing process, another outstanding structural part is the landing gear. Loads applied to this part can be measured with FBGs [105] to determine the remaining life of the landing gear. In addition to that, some subsystems can also be monitored with optical fiber sensors such as pressure in the hydraulic systems (for example with FBGs [92]) or even to make a full diagnosis of the engines [106] by measuring temperature, vibrations, pressure, air speed, etc. in order to obtain a complete in-flight monitoring system to make more reliable structures.

Funded by the European Space Agency (ESA), a fully quasi-distributed fiber optic sensing subsystem for Spacecraft Health Monitoring in Telecommunication Satellites has been demonstrated (AO/1-4970/NL/CP). It is based on a single interrogation unit encompassing hundreds of FBG sensing elements for measuring temperature, mechanical stress and pressure anywhere throughout the spacecraft in a unified and autonomous manner.

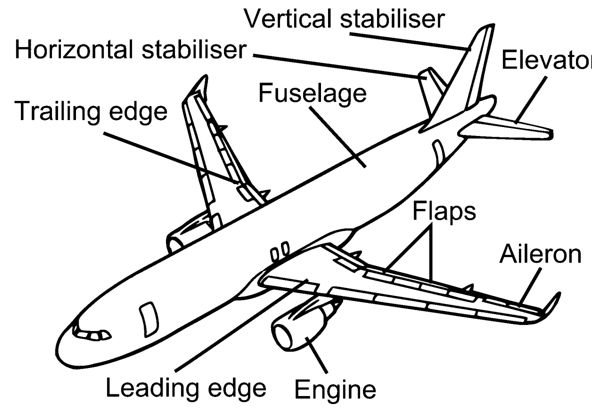

Fig. 17. Illustration of key parts of a typical aircraft to be monitored.

Although it is quite clear that FBGs are one of the most mature optical fiber technologies applied in the aerospace industry, it is not the only one. Distributed Brillouin technology [107] has also been reported in the monitoring of a business jet fuselage health during a test flight.

C. *OFS in Civil Engineering Structures*

A wide range of work using SHM systems based on OFS technologies has been carried out on Civil Engineering structures, usually understood as large concrete or steel ones such as bridges, tunnels, dams, geostructures, power plants, high-rise buildings, and historical monuments. It is also common to include pipelines in this kind of structures. Key materials and parts of these structures must be strictly monitored to find out the global structural status using the appropriate algorithms. Monitoring of piles, foundation slabs, slabs, columns, cores, and walls in building structures; monitoring of beams, girders, arches, and cables, in bridges, dams, and tunnels, among others, are of paramount importance. A very interesting and useful extended review on monitoring of Civil Engineering Structures using OFS can be found in paper [1], chapter of book [7], and book [46] formats. They include the methodology developed to approach the topic and the experience extracted from the fitting of several hundreds of civil structures with SHM systems.

Monitoring systems based on FBG, SOFO, FP, Brillouin, and Raman-based techniques have been successfully demonstrated, in many cases being marketed by specialized companies.

One of the first studies with bridges was carried out in Canada [108]. The monitoring system (developed by Intelligent Sensing for Innovate structures, ISIS) included 20 FBGs embedded in the concrete girders supporting the bridge. Other structures, such as the Taylor Bridge and the Navas viaduct were also fitted with FBG-based systems. The Taylor Bridge (of 165.1 m length and with 40 prestressed concrete AASHTO-type girders) was equipped by ISIS with a monitoring system comprising 63 FBG transducers installed at different locations along the girders. Las Navas viaduct integrated by a symmetric and repetitive structure formed by ten identical sections, limited by two piles each, was also fitted with a SHM system developed by the University of Cantabria [109]. 42 FBG transducers (60

Fig. 18. 35 lorries with 35 tons each during the load test of Las Navas viaduct on the A8 motorway, in Cantabria, Spain. The insets show one of the transducers during its installation, and two sections where the transducers were embedded. Courtesy of the PhotonicsEngineering Group at the University of Cantabria.

cm long) able to measure both the temperature and the elongation were placed on top of one pile and between two piles of sections. In each section, the transducers were embedded inside the concrete structures in vertical, transversal, and longitudinal positions (see Fig. 18).

In this field experiment, excellent correlation of the OFS system results with the expected design parameters and also with the results obtained with traditional technologies was found during the final load test [109].

In some cases, it is not possible to embed the transducer because the structure is metallic or it is already made. In these cases, it is necessary to attach them (glued, mechanical fixing, etc.). One example is the monitoring of a circular pedestrian steel bridge in Aveiro, Portugal [110]. In this case, the transducers installed were metallic and were welded to the bridge structure. The installation consisted of 32 strain transducers and eight temperature ones, in a star configuration in eight branches. Its installation was done after the bridge construction and all transducer were protected (with waterproof sealant tape). The bridge was monitored during two load tests, and in both cases it was observed that the numerical model used in the structural design reproduced the real behavior of the structure. Another example could be the monitoring of the Viaducte des Vaux Bridge, a concrete bridge with 12 strain transducers based on FBG [111]. The transducers were attached to the interior walls of a section of a box girder.

Using SOFO technology, a large number of bridges such as Siggenthal, Versoix, and I-35W have been monitored. On the 117 m arch span of the Siggenthal Bridge, 58 SOFO transducers were installed on the top and bottom of arch surfaces in pairs. Each pair measured the deformations in one arch segment [112]. With the data obtained from the transducer, curvatures and perpendicular displacements were determined. On the Versoix bridge, 104 transducers were installed during the reconstruction and widening of an old bridge [113].

At the location where the I-35W bridge over the Mississippi River in Minneapolis collapsed on August 1, 2007, killing several people, two twin prestressed, reinforced concrete bridges were built in record time. To support the construction process, record the structural behavior of the bridge, and contribute to the bridge security, a hybrid SHM system was installed on the new I-35W St. Anthony Falls Bridge to measure dynamic and static parameters. To enable close behavioral monitoring during the bridge's life span, the comprehensive SHM system includes 323 Sensors (vibrating wire strain gauges with temperature reading, linear potentiometers, accelerometers, chloride penetration sensors, and SOFO long-gauge fiber optic deformation sensors. The SOFO comprises deformation transducers of 4 m length installed in pairs on the upper and lower sides of the second span. The system measured: the average strain, strain distribution along the main span, average curvature, deformed shape, detection of cracks, in addition to the dynamic strains, dynamic deformed shape, vertical mode shapes, and dynamic dampings [114].

The system is continuously gathering data on the bridge performance and health evolution through appropriate analysis. The data provided will be used for both operational functions as well as for the management of the bridge maintenance, complementing and targeting the information gathered with routine inspections.

The I-35 bridge SHM project is considered a landmark in bridge history, not only because of the tragic events that lead to its construction, but also as it is the first Smart Bridge of this scale constructed in the United States.

SHM systems for measuring distributed strain in Bridges have also been demonstrated. Based on Brillouin distributed sensors, the strain profiles along the steel girders of a continuous slab-on-girder bridge were measured [115]. The 1.16 km fiber circuit along the web of four girders was composed of bare optical fiber sensors and an adhesively bonded fiber glass tape with embedded fibers to measure strain and temperature.

SHM systems based on OFS have been used to monitor buildings. In the "Hyaku-Nen Kan" Japan Women's University, Japan (a seismic controlled steel-framed building), FBG-based optical fiber sensor modules were attached at the dampers to monitor their capacity and to estimate their soundness after a severe earthquake. The system enables responses of the building to be automatically recorded during earthquakes and sent via internet [116]. To measure the strain, displacement, and temperature, the 64-FBG transducer (in six branches) system was embedded on the 12th floor of the damage tolerant building.

FOS based on FBG has also been installed in historical buildings and monuments in Italy. In the city of Como, the buildings were reinforced with carbon fiber composites after an earthquake [117]. The old cathedral [118] was monitored with four long-gauge Bragg transducers, for the measurement of strain and temperature.

In dams and tunnels SHM systems are also very useful. Long-gauge deformation, FBG, and distributed Raman and Brillouin sensors are particularly interesting to monitor such large structures.

To check the concrete pouring process of the Luzzone dam (raised by 17 m to increase the capacity of the reservoir) the distributed temperature of a concrete block of 3 m was measured using a Brillouin based sensor [7]. The transducer was constituted by an armored telecom cable installed in serpentine during concrete pouring. Using the reading unit developed at EPFL, the temperature distribution was measured after pouring

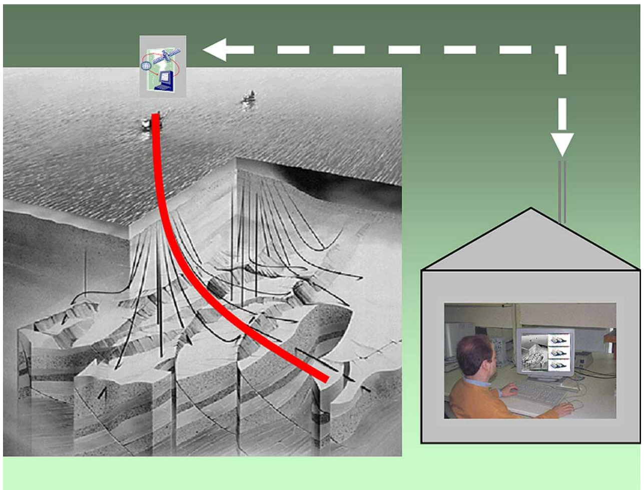

Fig. 19. *Smart well and field* concept illustration in an off-shore oil field. Measurand data are obtained in real time or in quasi-real time and it can be made available in the central monitoring office. Appropriate reactions or actuations may even be done, automatically.

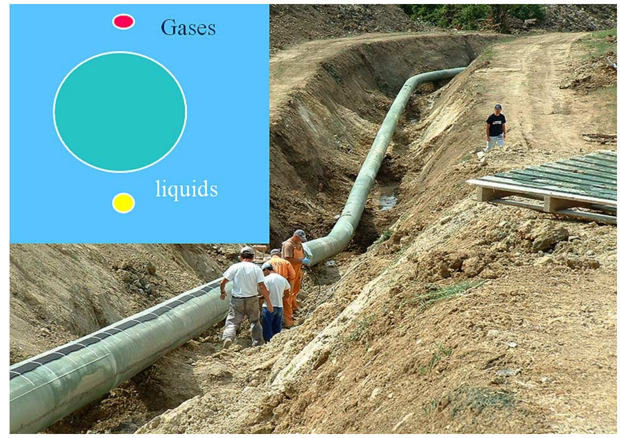

Fig. 20. Fluid leakage detection in pipelines using fiber distributed sensing technologies. Inset: illustration of situation of fiber cable transducer (in relation to the pipeline) for gases and liquids. Photo: installation of the transducer cable on a pipeline. Courtesy of D. Inaudi.

and extended over 6 months. The measurement system proved to be reliable even in the demanding environment at the dam (dust, snow, and large temperature variations). It demonstrated that fiber distributed sensing is particularly adapted to the monitoring of large structures where the use of more conventional sensors would require extensive cabling.

Finally as a peculiar civil engineering structure fitted with OFS-based monitoring systems, the Condamine Floating Dock case, is very briefly mentioned. The Condamine Marina in Monaco enlarged its surface area by 60 000 m^2. To achieve this, a floating caisson of 352.72 m was built in a dry dock (*www.ishmii.org*). It was prepared in the Algeciras Bay (Cádiz-Spain) and towed to Monaco in August 2002. To assure that bending moments induced by sea action during the whole transport process do not surpass the maximum values foreseen in the design, the structure was fitted with a hybrid SHM system. It included 39 OFSs to measure the strain in key elements. The complete history of controlled magnitudes during transport was obtained (with records every 10 min) of each sensor, as well as the evolution of statistical parameters. Analysis of the maximum moments during transport proved that they were well below the design values foreseen [119]. The dock is working successfully in Monaco.

D. OFS in Oil and Gas

To increase the productivity and the exploitation safety of oil wells, it is necessary to obtain reliable data about both physical and some chemical parameters from the wells in the oil fields. According to oil experts, it is possible to increase the wells production by up to 30 % and, probably, recent accidents such as happened on the USA Coast (2010) can be avoided or, at least, their probability of occurrence decreased. As illustrated in Fig. 19, there is great interest in building "*smart wells and oil fields*." For this kind of SHM infrastructures, OFS is a key technology.

The use of OFS in the Gas and Oil industry has increased substantially in recent years. Their utilization has been mainly centered in the monitoring of the pipeline and in the downhole, in order to detect and minimize the leakage, control the temperature, the pressure, etc., with the aim of maximizing the oil production. However, OFS could also be used for safety and security of the installations. Although several techniques are used, the distributed and the quasi-distributed ones mainly based on Brillouin and FBG technologies, respectively, are the most common.

FBG sensors have been used mostly in the monitoring of the downhole. Accurate and long-term fluid pressure and temperature measurement were demonstrated [120]–[122]. They were based on two FBGs: one to convert the pressure to strain and another, unstrained, to compensate and measure the temperature. They were checked in working conditions up to 100 mPa and 230°C. To improve the behavior FBGs were also used on non conventional fibers. Using FBGs written in side-hole single-mode fibers, high resolution pressure transducers with a dynamic range of 40 MPa were demonstrated [123]. To monitor temperature and pressure in gas and oil reservoirs, sensor networks based on FBGs were demonstrated [124].

Based on Extrinsic Fabry–Perot cavities, pressure transducers with dynamic ranges of 10 kpsi were also demonstrated [125], [126]. Sagnac interferometers in combination with Photonic Crystal Fibers have also been proposed to develop high-pressure sensors for high-pressure downhole monitoring [127].

Brillouin and Raman scattering-based distributed sensors are used to monitor elongated structures. Pipeline: leakages and failure detection, operational parameter verification, and oil production and well monitoring are several of the main applications. Recent developments in distributed fiber sensing technology allow the monitoring of up to 300 km with the use of optical amplifiers.

The positioning of the sensing cable or cables around the pipeline is a critical element for its successful monitoring [46]. As suggested in the inset of Fig. 20, for leakage detection of fluids and gases the ideal positions are below and on the pipeline, respectively. For gas leakages, the sensing cable should be placed in thermal contact with the steel pipeline,

TABLE I
OFS FOR SHM SUMMARY: SOME TYPICAL CHARACTERISTICS OF COMMERCIAL APPROACHES

Technology	*Transducer type*	*Main Measurands*	*Resolution*	*Accuracy*	*Range*	*Speed (bandwidth)*	*Companies*
SOFO V *SOFO Dynamic*	Long gauge (100 mm- 20 m)	Displacement Strain	2μm 0.01 μm, range of ±5 mm	1μm	Up to 50 points (multichannel)	Less than 7 s. per transducer. 0-10khz	Smartec
Fiber Bragg Grating	Quasidistributed	Strain Temperature Displacement	0.2 με; 0.02 ºC		Up to 100 channels	Low freq. up to 100Hz.High freq.up to 10KHz.	Micron-Optics Fibersensing FS&S
Raman Scattering	Distributed	Temperature	1m in 1 km 2m in 10 km	0.1 ºC	Up to 10 Km /10000 points online	Measurement time: 3 minutes	Sensa; Geso Sensornet
Brillouin Scattering	Distributed	Strain Temperature	Spatial : 1m* ; +-3με*; +-1ºC*, 10 cm**	21 0.2 ºC	30 Km*. -2500-6000 με * 1km **		*Onnisens Ando, OZ Opt. **Neubrex Co.
Fabry Perot Cavities	Point	Strain, Temp, Pressure, Displ.	0.1με; 0.1 ºC; 0.1 Kp,; 20 μm		Up to 32 channels	Up to 500 Hz	Roctest, Bam, Fiso, Luna
Microbending	Point; Quasidis. Distributed.	Displacement, Pressure			10cm to 10m	100Hz	Osmos

at any position around it. For strain and deformation sensing, the strain-sensing cable must be placed in direct contact with the pipeline steel and firmly attached to it in order to correctly transfer strain.

The high added value expected for gas and oil pipelines using distributed technologies is proven by the very recent industrial publications [128]–[132].

Other technologies, such as optical interferometers have been applied for distributed pipeline sensing and leakage detection. Sagnac interferometers [133] and hybrid configuration Sagnac–Mach–Zender interferometers [134] have been used to detect the leakage position in gas pipelines.

IX. CHALLENGES

To enable a massive use of SHM systems and, specially, those based on or that include OFS technologies, several challenging topics must be suitably dealt with. With the basic premise that damage will alter specific material or structural behavior, which must be detected in early stages, and that the final results must be presented to the owner or user in an easily understood format, several technical challenges both about SHM technology itself and about OFS have been identified. In both cases, the never-ending task of agreeing on standards constitutes a common and key issue that must be dealt with [135].

A. Challenges for SHM Systems

Considering that damage is typically a local phenomenon, which may not significantly influence the global response of a structure that is normally measured during system operation, *a first and fundamental challenge is:*

1) The development of reliable and sensitive techniques for early detection of structural malfunction or unusual structural behavior.

Most of the current technologies do not entirely fulfill the requirement for reliable early detection of unusual structural characteristics [136].

As damage identification must be performed in an unsupervised learning mode and as damage can accumulate over widely varying time-scales, *a second challenge is:*

2) Data selection, data storage and data processing models, and robust algorithms to detect structural malfunctions.

This challenge is supplemented by many practical issues associated with making accurate and repeatable measurements over long periods of time at a limited number of locations on complex structures often operating in adverse environments.

Closely related to the two aforementioned challenges, some specific challenges for SHM are as follows.

1) Capability to define the required sensing system properties before field deployment bearing in mind the lack of monitoring and installation experience.
2) Environmental effects on SHM data.
3) Correlation of the analytical model to the actual structure using SHM data.
4) Data interpretation techniques often lead to inverse problems.
5) Sensor selection and placement.

B. Challenges for OFS for SHM

Probably, for sensors in SHM systems, the main challenge (common to all technologies) is to assure that the sensor system itself is not damaged either when deployed in the field or during the working life. It is necessary to guarantee that the data from the sensors represent the real behavior of the material or the structure and are not corrupted due to a sensor malfunction. For that reason, it could be necessary to monitor the sensors themselves. This fact leads to the very challenging tasks of developing new techniques for:

a) *sensor self validation or by means of reports on each other's condition*;
b) *"fail-safe" sensor networks*.

If a sensor fails, the damage identification algorithms must be able to adapt the network. This adaptive capability implies that a certain amount of redundancy must be built into the sensor network [136].

Other challenging tasks for OFS closely related to the previous ones are as follows:

a) to reduce the sensor crossed sensitivities;
b) to improve the resolution and/or the dynamic range;
c) to improve the stability, reliability, etc. in real situations; and
d) new concepts, techniques, components, and fabrication processes to achieve cost effective sensors.

C. Nontechnical Challenges

Several nontechnical topics must be addressed before SHM technology can make the transition from a research topic to actual practice. Among them, probably, the two more relevant ones are *to convince:*

a) Structural system owners and users that SHM technology provides an economic benefit over their current maintenance approaches.
b) The regulatory agencies and owners that this technology provides a significant safety benefit.

X. OFS Market Forecast

One of the difficult tasks of the chairmen, heads of groups, R&D leaders and researchers in this field, is to take decisions concerning the lines to follow both in R&D and on the commercialization of the OFS products. Probably, one common idea is to invest resources on the subjects with most expectations of added value or with best market prospects. As OFS are key devices for SHM, some comments about their future will be given.

According to the OIDA studies [137], the OFS market is expected to grow strongly over the decade 2009–2020 with a Compound Annual Growth Rate (CAGR) of 9.8 % and to achieve revenues of $1.95 billion by 2020. As shown in Fig. 21, the share of this global OFS market can be considered composed of point and distributed OFS (including in the latter the quasi-distributed ones). From Fig. 21, it can be deduced that during the past years, the distributed fiber optic sensor market has experienced very strong demand from both commercial and government sectors. The distributed sensor market grew 40 % with $302 million revenue in 2007, and 26 % with $382 million revenue in 2008.

The forecast for distributed OFS sensors over the next decade is strong, showing a 2009–2020 CAGR of 11.8 % with revenues approaching $1.4 billion. The growth rate of the market does will slow down toward the end of the decade and reduce to a 2015–2020 CAGR of 6.2 %. Considering the OFS sector applications with higher shares and growths, it is observed that at the end of the decade, in 2020, the market segment shares will change considerably from those in 2008.

As observed from Fig. 22, the key emerging application markets for distributed fiber optic sensors are wells, security, smart structures, and seismic detection (oil industry). These four application areas together contributed an average of 64 % to the total annual revenue in 2008, and are expected to consistently maintain this share through 2020 with an end of decade combined total of 67 %.

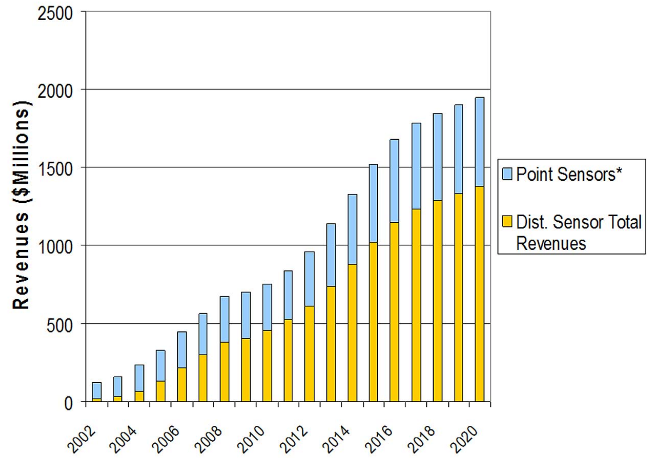

Fig. 21. Point sensor versus distributed sensor market revenue and forecast, 2002–2020. Sources: historical data from Light Wave Ventures, OIDA forecast from member input. Courtesy of OIDA.

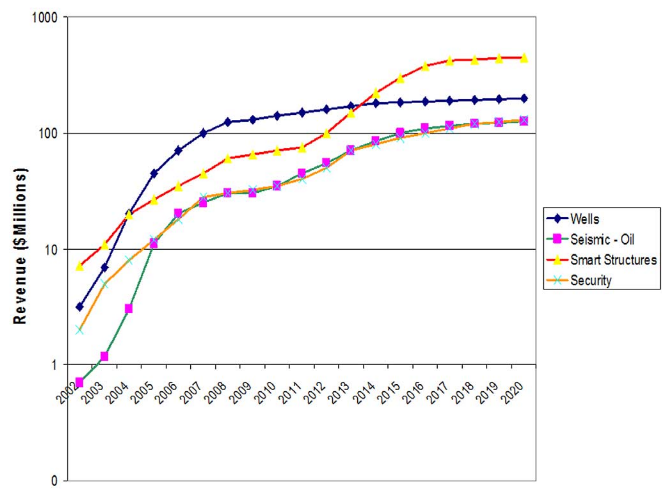

Fig. 22. Key distributed fiber optic sensor markets (log scale), 2002–2020. Courtesy of OIDA.

The forecast assumptions favored a strong commercial market and government investment in buildings and bridge infrastructure. The study expected initial investment by the government to catalyze the market, which then will be followed by strong commercial support. However, due the global crisis, the mentioned assumptions may not be fully accomplished and, probably, the rates and shares displayed should be considered with some tolerances.

XI. Summary and Conclusion

SHM can be understood as the system that includes the integration of sensing, intelligence and possibly also actuation devices to allow the loading and damage-causing conditions of a structure to be recorded, analyzed, localized, and predicted in such a way that nondestructive testing becomes an integral part of the structure.

According to the functionality and degree of complexity, SHM systems can be classified in five levels ranging from simple failure detection to automatic diagnosis, prognosis and, even, healing. The higher the level, the higher the complexity and functionalities.

SHM is naturally linked with safe-working, maintenance, optimized technical and economic exploitation of the structures in addition to the minimization of the potential social, economic, and other impacts. With SHM systems, unusual structural behavior can be detected at an early stage decreasing the risks of sudden collapse and conserving nature, goods and even human lives. In addition, these systems enable in-time refurbishment intervention, the extension of their life-time guaranteeing fewer direct economic losses (repair, maintenance, and reconstruction) and also helping to avoid losses for users due to structural failures. Using SHM systems, hidden (unknown) structural issues can be detected early, enabling better exploitation of the materials and components of the current structures.

A key issue in the SHM systems is the measurement of *Chemical* (pH, oxidation, corrosion, penetration, and timber decay); *Mechanical* (strain, deformation, displacement, crack opening, stress, and load); and *Physical* (temperature, humidity, pore pressure, etc.). Several types of sensors, embedded or attached to a structure, can be used for this task, but only those based on fiber technology offer the capability to perform integrated, quasi-distributed, and distributed measurements on or even within the structure, in addition to other advantages.

An OFS can be understood as the device in which the measurand, introduces modifications or modulates characteristics of light in some part of an optical fiber system (the transducer), reproducing it faithfully in the electric domain. In general terms, an OFS is usually made up of a transducer device, a communication channe,l and an optoelectronic unit.

The four most successful OFS techniques for SHM (mainly for physical and or mechanical parameters) have been discussed: SOFO for integrated (long gauge), FBG for point and quasi-distributed, and Brillouin and Raman-based techniques for distributed measurements, respectively. Other technologies such as fiber bending, FP and other intensity and spectroscopic approaches have also been briefly described. A review of OFS techniques already demonstrated for chemical sensing is also included. The main technical characteristics, their principal measurands, and some of the manufacturers and commercial distributors are also summarized.

It is today recognized that OFS technology is attractive in those cases where it offers superior performance compared to the more proven conventional sensors offering, in addition: 1) improved quality in the measurements; 2) better reliability; 3) the possibility of replacing manual readings and operator judgment with automatic measurements; 4) easier installation and maintenance or a lower lifetime cost.

Although fiber-optic sensors are apparently expensive for widespread use in health monitoring, they are, however, better approaches for applications where reliability in challenging environments is essential. When reliability is a key problem in certain critical health monitoring applications, price is often no longer an issue.

The application potential for OFSs in structural monitoring is vast, including civil or industrial structure monitoring (concrete beam tests, bridge girders, ore mines, nuclear containers, tunnels, and hydroelectric dams), composite materials (spacecraft, aircraft tail spars, helicopter and windmill rotor blades, ship and submarine hulls, composite cure monitoring, and composite girders for bridges), acoustic sensing (towed hydrophone arrays and down-hole sensors for oil wells); in-plant or distribution of electric power utilities, gas pipelines and, in general, industrial control, monitoring and processes.

To illustrate the potential of OFSs in SHM applications, examples framed in four of these vast application areas with high interest for sensing solutions have been discussed. With emphasis on one relevant example, cases of OFS for SHM systems already demonstrated and checked with real in-field validations are mentioned in the fields of renewable energies, transportation, civil engineering, and oil and gas.

In order to enable a massive and profitable use of SHM systems, several technical challenges both in the SHM technology itself and in the OFS are identified. In both cases, there is still a lack of suitable and commonly agreed standards.

As main Challenges for SHM systems, two fundamental technical challenges are identified: the development of reliable and sensitive techniques to detect early structural malfunction or unusual structural behavior; and the development of data selection, storage and processing models, and robust algorithms to detect structural malfunctions. In addition, user-friendly and simple interfaces with the infrastructure are needed.

The two main challenges identified for OFS sensors to develop new techniques are: sensor self validation or/and validation by means of reports on each other's condition; and "fail-safe" sensor networks.

To convince the structural system owners and users that SHM technology provides an economic benefit over their current maintenance approaches and, to convince the regulatory agencies and owners that this technology provides a significant life-safety benefit are the two main nontechnical challenges.

Finally, to encourage chairmen, heads of groups, R&D leaders and researchers, in general, to invest resources in the subjects with most expected added value or highest market growth rates, a brief OFS market forecast has been provided.

Distributed and quasi-distributed OFSs have been identified with high impact on the four key emerging application markets: wells, security, smart structures, and seismic detection (oil industry).

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José Miguel López-Higuera (SM'98) was born in February, 1954, in the village of Ramales de la Victoria, Cantabria, Spain. He received the Technical Engineering degree in telecommunications from the Universidad Laboral de Alcalá de Henares, Madrid, Spain, and the Telecommunications Engineering degree from the Universidad Politécnica de Madrid (UPM). He received the Ph.D. degree in telecommunications engineering, with an extraordinary award, from UPM.

In 1976, he was with the Universidad Laboral de Alcalá de Henares as an Assistant Professor. He joined UPM in 1986, where he became an Associate Professor in 1991. Since 2001, he has been a Full Professor in the University of Cantabria (UC), Santander, Spain, where he teaches courses in electronics and

photonics. He was the Head of the Components and Technology Department, and the Director of the Technical School of Telecommunications Engineers in the Universidad Laboral de Alcalá de Henares. He was the Director of the COIE and founded and heads the Photonics Engineering Group of the UC. He fabricated the first lithium niobate integrated optic devices in Spain. Currently, he is involved in the development of new devices and subsystems for optical communications and sensors, in photonic instrumentation, optical fiber sources and sensor systems, and in materials detection and characterization using photonic techniques. He worked on more than 78 R&D&I projects acting as a manager, coordinator, or main researcher in more than 60 of them. He has also been involved in journal and book publishing in both editorial and authorial roles. He has written or cowritten more than 500 publications in the form of books, chapters, papers, and conferences, and has obtained 15 patents. He has acted as a Technical Reviewer for many journals, conferences and R&D&I Agencies in the field of photonics. He is the editor and coauthor of the *Handbook on Fiber Sensing Technology* (Wiley, 2002) and a coeditor of the book *Engineering a High-Tech Business: Entrepreneurial Experiences and Insights* (SPIE, 2008).

Dr. Lopez-Higuera has directed 12 Ph.D. thesis several with European Mention being four awarded with the Consejo Social Award or/and with the University of Cantabria Award to the best thesis and promoted the creation of the several new tech-based spin-off companies. He is a member of the External Committee of the Central de Tecnología del Instituto de Sistemas Optoelectrónicos y Microtecnología de la Universidad Politécnica de Madrid (CT-ISOM). He has been a member of Steering Committee of the International Optical Fiber Conference, OFS. General Chairman of the Second European Workshop on Optical Fiber Sensors EWOFS04 and Co-Chairman of OFS20. He was Technical co-chairman of EWOFS07 and EWOFS10. Technical Program Committee, TPC of OFS, Workshop on Fiber and Optical Passive Components, WFOPC; Topical Meeting on Optoelectronic Displacement Measurement and Applications, ODIMAP; Bragg Gratings, Photosensitivity and Poling in Glass Waveguides (BGPP) and the First Mediterranean Photonics Conference, WSOF, SPIE Photonics Asia, and the 37º IAHS World Congress 2010. He also acted as TPC at Spanish conferences such as URSI and OPTOEL. among others. He will also be the chairman of Optoel 2011 and the General Chairman of the OFS23, to be held in Santander, Spain, 2014. He was an Associate Senior Member of the Institute of Electrical Engineers (IEE) and a member of the Optical Society of America (OSA) and SPIE.

Luis Rodriguez Cobo received the degree in telecommunication engineering from the University of Cantabria, Santander, Spain, in 2009. Since 2009, he has been working toward the Ph.D. degree at the Photonics Engineering Group (GIF) in the Department of Electronic Technology Industrial Automation and System Engineering, University of Cantabria.

His research is about applying optical technologies to structural health monitoring systems in renewable energies field.

Antonio Quintela Incera was born in Santander, Spain, in 1975. He received the Telecommunication Technical Engineering and Telecommunication Engineering degrees from the University of Cantabria, Santander, Spain, and the Ph.D. degree from the University of Cantabria, in 2006.

He joined the Photonics Engineering Group of the University of Cantabria in 1999 as a Ph.D. degree student. Since December 2008, he has been a permanent teacher at the University of Cantabria. He has coauthored more than 75 papers presented in conferences and scientific journals. His primary research interests include the writing of fiber Bragg grating (FBG) and fabrication of transducers based on FBG.

Adolfo Cobo (M'05) received the Ph.D. degree in telecommunication engineering from the University of Cantabria, Santander, Spain, in 1999.

Since 1994, he has been an Associate Professor (*Profesor Titular de Universidad*) at the Photonics Engineering Group (GIF) in the Department of Electronic Technology, Industrial Automation and System Engineering, University of Cantabria, with both teaching and R&D duties. He has been enrolled in research projects funded by the European Union (3), Spanish (14), and Local Government (6). Additionally, he has participated in 16 research contracts with local and national private companies. He has coauthored 24 ISI journal papers, more than 80 papers at peer-reviewed conferences, and nine patent applications. His research interests include nondestructive testing methods based on plasma spectroscopy for industrial applications, in particular, for quality assurance of the arc and laser welding process, and intelligent processing of sensor data for structural health monitoring.