The Evolution of Optical Fiber Sensors Technologies During the 35 Last Years and Their Applications in Structure Health Monitoring

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THE EVOLUTION OF OPTICAL FIBER SENSORS TECHNOLOGIES DURING THE 35 LAST YEARS AND THEIR APPLICATIONS IN STRUCTURAL HEALTH MONITORING

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ABSTRACT

Since late 70s, (quasi-)distributed Optical Fiber Sensors have been developed, 12 countries having produced 85% of the global effort in this field. Since mid-80s, OFSs have caught attention in many sectors where SHM is a matter of concern (civil engineering, composites, oil & gas, renewable energies, safety...). Today, OFS is became a strategic domain, especially in Asia, and China invests a lot since 7-8 years. The top 12 countries involved in SHM are almost the same than in OFS, having published 80% of the total number of SHM papers. Moreover, statistics proves that the “optical fiber” is now the second sensing technology for SHM, and 2/3 concern the FBG-based sensing.

KEYWORDS : *Optical Fiber Sensors (OFS), IWSHM, EWSHM, Bibliometry, Statistics.*

INTRODUCTION

The optimal and real-time knowledge of in-service structures integrity remains an ultimate goal for any manufacturers and for end-users of materials and structures used every day in many sectors of the economy (civil engineering, aeronautics, marine, railway…). A lot of methods have long been used to evaluate their capacity to serve their intended purpose. As examples, since the industrialization period, at the beginning of the 19th century: railroad wheel-tappers have used the sound of a hammer striking the wheels in order to evaluate potential damages, and others have used vibration monitoring as an evaluation technique in rotating machinery. Such techniques were the early steps of the Non Destructive Control, and right now of so-called "*Structural Health Monitoring*" (SHM). More than two decades ago, due to many advances in sensing technologies, strong developments in computing / acquisition and communication means, several SHM technologies have emerged, creating a new technical field.

Today, such technologies are more and more a matter of concern, as they can be applied to various materials and structures, *e.g.* in composite materials in aeronautics, and for concrete structures in civil engineering. In these sectors, when damages to structures are concerned, several increasing levels of difficulty are considered for the SHM, requiring the knowledge of previous stages, namely: detecting, locating, identifying, and quantifying the severity of the damages. In practice, a complete SHM process involves: excitation methods, sensors (including their number and optimal placement), as well as the data logger (hardware depending on the sensing technology) followed by more and more sophisticated software able to normalize, clean, compress the data and extract relevant features, as well as a man-machine-interface (MMI) to display results in a user-friendly format. This process may be completed by interpretation, residual life time estimation, failure prognostics, and Condition-Based Maintenance.

Moreover, we must never forget economical considerations which often play a major role in associated decision making. Although a complete SHM process is complex, in this paper we only focus on sensing aspects and, due to their numerous advantages for SHM, on OFS. The aim of this paper is not to simply present the benefits for the SHM of the Optical Fiber based sensing techniques, as literature fulfills this need, but to put their three decades of development in perspective with works done by the SHM community. To do this, a bibliometric analysis has been performed on a dual corpus: the first one represented by the 22 first events of the international conference on OFS since 1983, and the second one 16 (I or E) SHM Workshops since 1997. This double data base includes more than 7000 papers. The resulting statistics distinguish the countries most involved in these domains, synergies and trends.

1 COUNTRIES INVOLVED IN OFS TECHNOLOGIES

The database containing all the proceedings of the Optical Fiber Sensors conference was used to achieve this bibliometric analysis [1]. From 1983 to 2012, this represents 3827 papers (the last OFS-23 is not considered). One should remind that this lecture series brings together the international OFS community every 18 months and cyclically in Europe, America and Asia. The very first event (OFS-1) was held in London in April 1983 and the last one considered (OFS-22) in Oct. 2012, Beijing, China.

Table 1: Location of 24 International OFS Conferences from 1983 to 2015.

OFS1, Londres, April 1983	OFS9, Florence, May 1993	OFS17, Bruges, May 2005
OFS2, Stuttgart, Sept. 1984	OFS10, Glasgow, Oct 1994	OFS18, Cancun, Nov. 2006
OFS3, San Diego, Feb. 1985	OFS11, Sapporo, May 1996	OFS19, Perth, April 2008
OFS4, Tokyo, Oct. 1986	OFS12, Williamsburg, Oct. 1997	OFS20, Edinburgh, Oct. 2009
OFS5, New Orleans, Jan. 1988	OFS13, Kyongju, Korea, April 1999	OFS21, Ottawa, May, 2011
OFS6, Paris, Sept. 1989	OFS14 (OFS2000), Venice, Oct., 2000	OFS22, Beijing, Oct. 2012
OFS7, Sydney, Dec. 1990	OFS15, Portland, May 2002	OFS23, Santander, June 2014
OFS8, Monterey, Jan. 1992	OFS16, Nara, Oct. 2003	*OFS24, Brazil, fall 2015*

We may observe that OFS has occurred 9 times in Europe, 7 times in America and in Asia. The next event is planned to be hosted by Brazil, in the region of Iguazù falls, *i.e.* close to the triple border area (Brazil, Argentina and Paraguay), during fall 2015. This will be the first time OFS will take place in South America and only the third time in the southern hemisphere. During these 35 last years, 42 countries were involved, with a very variable production of published papers (Fig. 1). In fact, 12 countries produced 85% of the total number of papers. The main contributors are: Japan (16.0%), followed by UK (15.6%), the USA (15.2%) and China (10.6%). The most impressive result of this analysis is certainly the fact that China in now the 4th contributor. The 'production' of this country was quite small from 1983 to roughly 2004. But, during the past 7-8 years China made a so large effort to invest in fiber sensing that it has been able to get the 4th ranking (Fig. 2). So, on this base, we may anticipate that China will become first OFS contributor before the end of this decade.

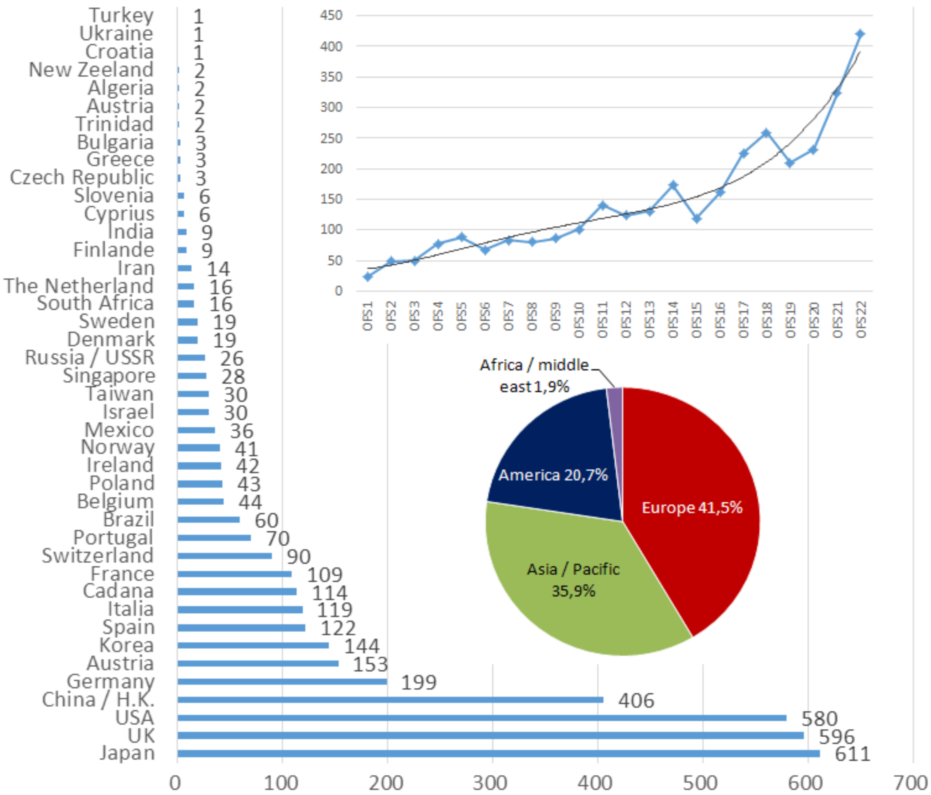


Figure 1: OFS papers per origin (countries, regions) and per event from OFS-1 (1983) to OFS-22 (2012)

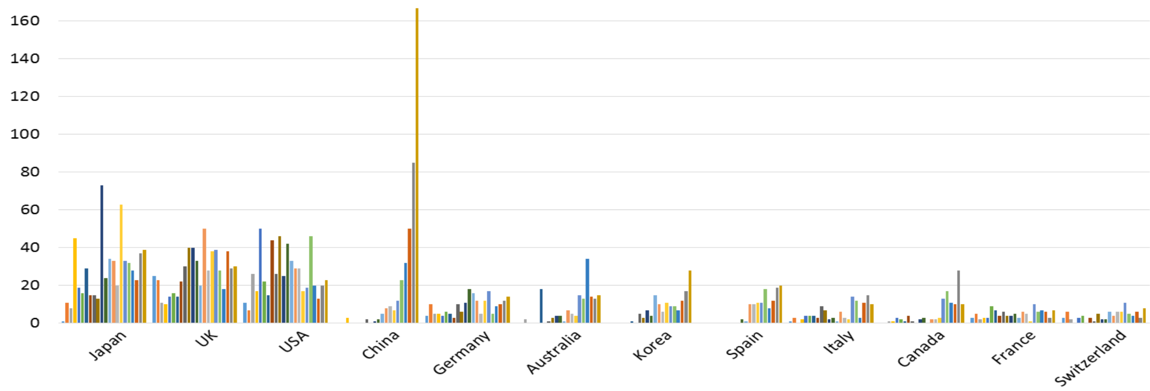


Figure 2: Contribution of top 12 countries involved in OFS, from OFS-1 (1983) to OFS-22 (2012)

2. THE LONG EVOLUTION OF THE OPTICAL FIBER SENSOR TECHNOLOGIES

The field of Optical Fiber Sensors (OFS) concerns a very dynamic community for over 35 years. The late 70s and the following years allowed pioneers to explore the potential of an innovative component: the optical fiber, whose intrinsic features have led some researchers to develop the very first OFS prototypes in the dark rooms of their labs, and others to initiate projects in telecommunications. The 80s gave the opportunity to explore possibilities offered by some OFS mock-ups, thanks to the very first single-mode fibers, some optical components (*e.g.* the famous "3-dB coupler") and to some equipments then available (fusion splicers, multimode optical connectors...). Many principles were explored at that time, particularly those implementing the interferometry (Sagnac, Mach-Zehnder...) respectively for the development of Fiber Optic Gyroscopes (the “FOG”; Sagnac effect), current sensors (Faraday effect), and also hydrophones for the navy. In 1986, the concept of OFS Network (OFSN), distributed and quasi-distributed, was born, *i.e.* the possibility to multiplex sensors on a given fiber, to reduce cabling, sensor data management, and finally the cost-per-measurement-point. Then, by the end of the 80s, new products based on optical reflectometry, *i.e.* the OTDR (Optical Time Domain Reflectometer; somehow a guided optics Radar) appeared, as the Raman DTS (Distributed Temperature Sensor) that provides a selective measurement of the fiber temperature profile.

At the early beginning of the 90s (more accurately in Sept. 1989 at OFS-9, Paris, France [2]), a very important technology for SHM applications has been introduced: the Fiber Bragg Grating (FBG). As a reminder, this transducer (a narrow spectral filter photo-written by laser in the fiber core) reflects a characteristic wavelength used to simultaneously provide its address in the sensor network, and the measurement (temperature, strain...). During this decade, leaving the labs, only robust techniques survived: those based on FBG filters, and to a lesser extent on micro Fabry-Perot (both quasi-distributed sensors), and the reflectometry (distributed sensing) which implement backscattering phenomena, namely Rayleigh effects (OTDR), Raman (DTS) and Brillouin sensing, usually designated by the letters BOTDR (Brillouin Optical Time Domain Reflectometry) and BOTDA (the letter A being for Analysis). Both kind of Brillouin sensing techniques became commercially available towards the end of the 90s. In the same time, the first OFS applications devoted to materials and structures monitoring started to appear [3]. As an example, fibers were soon identified as quasi non-intrusive embeddable sensors, able to monitor composite curing (smart manufacturing), strain testing for qualification, and of course for SHM purposes.

The end of the 90s and the first years of the millennium were that of the optical Telecommunications 'boom', followed in 2001 by the Internet bubble 'crack'. During several years, many SMEs disappeared but others emerged. Some of them were involved in sensors, optoelectronic systems, or applications increasingly SHM-oriented. The 2000s saw the advent of a new optical guides: the "Photonic Crystal Fibers". Indeed, after 30 years of traditional optical fibers manufacturing refinement (OVD, MCVD...), studies concerning fiber design and development have had to adapt to requests from new scientific/industrial sectors (wideband optical sources, sensors, biophotonic...). We may anticipate that these new fibers are likely to offer new opportunities for the SHM in a near future.

3 THE MAIN OPTICAL FIBER SENSOR TECHNOLOGIES USED IN SHM

As explained in the previous paragraph, a lot of OFS technologies have been developed during the last decades. Nevertheless, the screening imposed both by the end user requests and by field experiments may be compared to the Darwin theory of evolution: only best techniques, of well adapted solutions fitting with specifications may stay alive. Others may also survive, but only on small or very specific niches. That's for instance the case for the Fabry-Perot interferometers (non-optically multiplexable), or the interferometry (very good resolution, but un-multiplexable, difficult to use on real applications, sensitivity non constant (sinus), etc.). On the contrary more versatile and flexible solutions, *i.e.* the Bragg gratings (FBG), the king of the quasi-distributed sensors, and several technologies based on Reflectometry (OTDR, OFDR, DTS, BOTDR-A, BOCDA...), using the scattering phenomena in silica, are now widely used. All of them are sensor networks leading to a wide multiplexing of measurement points on a stand-alone remote instrumentation. So, due to this wide multiplexing, additionally to good sensing performances, they allow to reduce the cost-per-measurement-point.

3.1 Fiber Bragg Gratings

Tiny diffraction gratings photo-written inside a single mode optical fiber core, called Fiber Bragg Gratings (FBGs), are now used for many years in sensing applications for numerous industrial fields. Reflecting a narrow spectral line called the Bragg wavelength, these transducers encode the parameter to measure (temperature, strain, pressure, refractive index...) in the form of a wavelength-shift of the Bragg wavelength [2]. As a wavelength does not depend on signal power, therefore FBG-based sensing is insensitive to amplitude fluctuations of the optical signal, as could occur in harsh environments, especially in the case of deployment for nuclear applications with radiation induced attenuation (RIA) in the optical fibers. It's now well known that FBGs feature key advantages for sensing in hostile environments: electromagnetic immunity (EMI), low intrusivity, low power consumption, excellent metrological properties, remote interrogation capabilities and wavelength-encoded measurement information. Although, conventional silica FBGs are usually limited for long-term use in high temperature environments. Through thermal engineering of such gratings, FBGs transducers are now made highly resistant even for temperature, and also the FBG photo-written by fs laser, reaching 900°C during several thousands of hours. The so-called regenerated FBG transducers exhibit considerable improvements of their thermal stability with respect to their conventional counterpart [4-5]. Moreover, FBGs sensors benefit from the wavelength multiplexing technology (called DWDM), used to multiplex the channels in optical telecommunications (Fig. 3). In that sense, several tens of FBG sensors can be distributed over a single optical fiber (or using even more complex routing topology) and each sensor is identified through its own Bragg wavelength, defined during the photo-writing process.

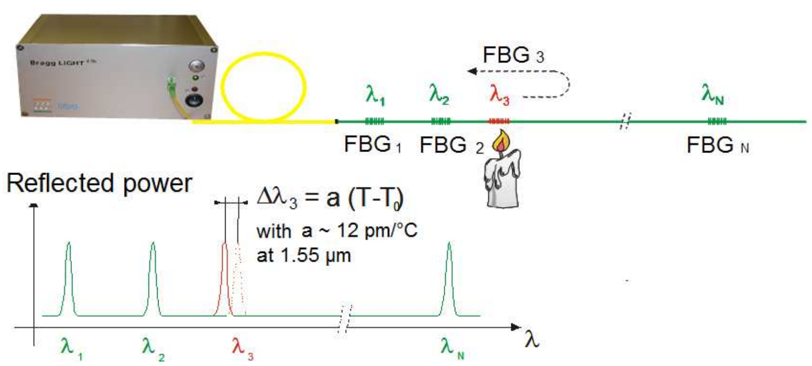


Figure 3: FBG multiplexing and sensing in case of temperature measurement.
For strain sensing the sensitivity b ~ 1.2 pm / (µm/m) at λ = 1.55 µm; for any other wavelength, proportionality may be applied to get the sensitivities)

3.2 Optical Time Domain Reflectometry (OTDR)

For three decades, the OTDR is widely and commonly used in telecommunications as it help ensure the availability of the distribution network (detection of any changes in the fiber attenuation profile, location of specific problems like bending, breakage or bad connection...). Many OTDRs are commercially available and used by operators in this industrial sector. Several types of instruments exist, mainly for long distances (x km) and spatial resolution ~ 1 m, while some provide a fine spatial resolution (a few cm with the "ν-OTDR", based on photon counting). In an OTDR, powerful short optical pulses (10 ns to provide 1 m spatial resolution) are repetitively injected into the fiber core and the Rayleigh backscattering detected from the same fiber end. The backscattering intensity, at the wavelength of laser, is due to the fluctuations of the fiber core refractive index (Rayleigh scattering) and to Fresnel reflections created by discontinuities (connectors, splices, fiber ends). The temporal signal analysis provides a spatial image of losses, defects and discontinuities. So, any temporal evolution of this backscattered light refers to a local modification of the fiber attenuation profile.

3.3 Distributed Temperature Sensor – Raman DTS

The DTS principle, is based on the Raman backscattering in the fiber core analyzed by OTDR, *i.e.* a process of spatial localization along the fiber, based on the spatio-temporal duality (temporal analysis is equivalent to a spatial scaling, the light velocity c/n being known). Traditional OTDRs use the elastic Rayleigh backscattering in the fiber core. However, the Rayleigh effect is not the only scattering phenomenon in optical fibers, Raman and Brillouin effects are also used. In case of Raman scattering, there is interest in the light having undergone a wavelength shift of a few tens of nm from the excitation wavelength (about 40 nm @ 1 μm in wavelength): The inelastic scattering mechanism leads to generate two symmetrical frequencies (two spectral lines) with respect to the laser excitation (Fig. 4). The respectively called ν_0 Stokes line ($\nu_S = \nu_0 - \nu_B$) and anti-Stokes line ($\nu_{AS} = \nu_0 + \nu_B$), ν_B denotes the characteristic vibration frequency of the fiber core. Since I_{AS} the signal corresponding to the anti-Stokes line comes from an energy level higher than the fundamental one, it is strongly temperature-dependent according to the well-known Boltzmann statistics: $\exp(- h\nu_B/kT)$. The Stokes signal I_S, coming from the fundamental energy level, is free from temperature influence. The ratio $R = I_{AS}/I_S$ is defined by: $R(T) = (\lambda_S / \lambda_{AS})^4 . \exp(- h\nu/kT)$ where h and k are respectively the Planck and Boltzmann constants. Such a relation is only function of temperature and vibrational characteristics of the fiber. Thus, any influence of variations in the transfer function of the instrument (power source, detector sensitivity, amplifier gain...) is removed by the normalization of these two intensities, and a very selective temperature measurement may be obtained [6-7]. That means the advantage of the Raman technique lies in the fact that the result does not depend on the local value of the intensity of the initial pulses, and provides high insensitivity to mechanical perturbations applied to the fiber, as well as to local or distributed fiber losses. This technique, in addition to OTDR features used, provides a means to determine the temperature profile all along the fiber under test. Since many years, several DTS are commercially available.

3.4 Distributed Brillouin Optical Time Domain Analyser & Reflectometer (BOTDA – BOTDR)

Distributed sensors founded on the Brillouin effect are based on the inelastic interaction of the light wave propagating in the fiber core with acoustic phonons. The metrological interest lies in the dependence of this shift with temperature (~ 1 MHz/°C) and strain (1 MHz / 20 μm/m) [8]. The R&D led to the development of two Brillouin techniques, BOTDR and BOTDA. The main advantage of the BOTDR is that it does not need to have access to both fiber ends. Its drawback is the lower efficiency leading to long measurement times. The advantage of the BOTDA lies to a better signal-to-noise ratio, but the fiber must be looped on the instrument. Due to Brillouin amplification, the BOTDA provides useful signals whose intensity exceeds by two orders of magnitude Rayleigh backscattering. The spatial resolution obtained today with commercial systems are: 30-50 km range (up to 80-100 km, or even more recently in Labs); 1 m resolution (or even better, but for a smaller range), while the Brillouin

frequency resolution remains about 1 MHz, equivalent to 1°C in temperature and 20 µm/m in strain. So far, half a dozen manufacturers offer Brillouin instruments. Functionalities and performances differ on how to separate the strain measurement from temperature influence, in terms of spatial resolutions, measurement time, without forgetting the ergonomic aspect (the possibility to easily drive the instrument, the quality of the Man Machine Interface...).

3.5 Distributed Rayleigh Optical Frequency Domain Reflectometer (OFDR)

This relatively new approach also involves the Rayleigh backscattering but needs a frequency analysis to determine temperature / strain profiles (it's basically a non-selective measurement). It is based on an homodyne interferometer scan (the source is modulated by frequency ramps), [9]. Within the system, the laser beam is split into two sub-beams one of which is sent into the fiber under test and the other used to interfere with the backscatter light from the fiber. It allows monitoring of a structure, if this one is equipped with an embedded or attached fiber on its surface, with a spatial resolution of 1 cm and a sensing resolution of few µstrains (µm/m), or 0.1°C in temperature. The duration of a typical acquisition is about 10 s without the signal processing and about 5 min including the data treatment. The range (maximum fiber length) is basically limited to 70 m, but a 2 km option (by successive windowing) has recently been proposed. So, in terms of performances, let alone its low measurement speed, this technique is quite equivalent to a chain of hundreds FBGs. Recently a faster instrument (200 Hz) has been proposed but its strain range is quite limited.

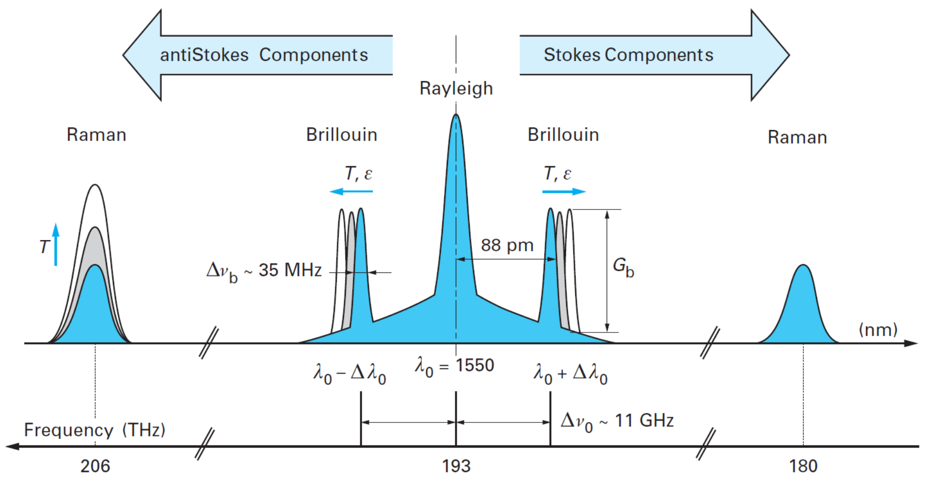
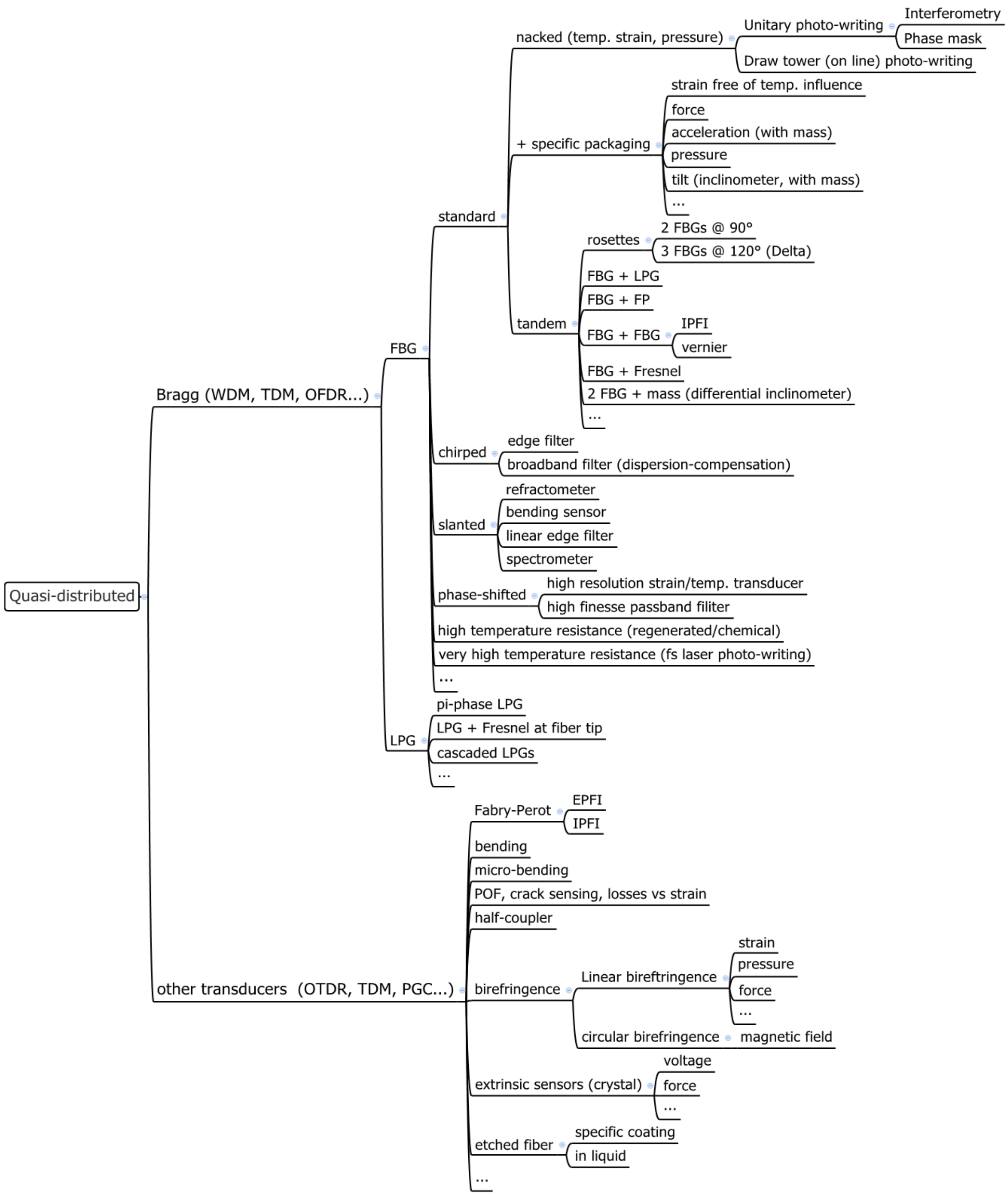


Figure 4: Rayleigh, Raman and Brillouin scattering intensity in silica fibers (excitation at 1.55 µm)

Table 2: Main specifications of distributed and quasi-distributed OFS technologies.

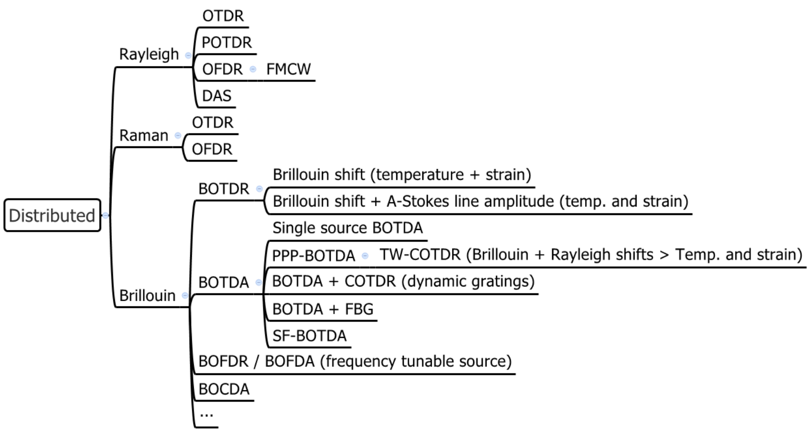
Sensing Specification	Quasi-distributed Fiber Bragg Grating	Distributed Rayleigh OTDR	Distributed Raman DTS	Distributed Brillouin BOTDR/A	Distributed Rayleigh OFDR
Spatial resolution	2 mm (Bragg length)	1 m (ν–OTDR: 1.3 cm)	1 m	50 cm (to 5 cm)	3 cm (OTDR mode: 2 mm)
Spatial Range (L)	up to ~ 10 km	50 km (ν–OTDR: 20 km)	30 km	30 km and more	70 m (N*80 m up to 2 km)
Measur^t. speed	DC-10 kHz up to GHz	10 sec. typ.	10 s to hours	2-3 s up to 10 min	10 s (L<70 m) + post process N*10 s (N=L/80m) + post pro.
Dynamic (budget)	> 20 dB	50 dB (ν–OTDR: 35 dB)	20 dB typ.	10 dB (loop 20 dB)	(OTDR mode: 70 dB)
Temp. resolution	0.01°C (0.1 pm resol.)	---	0.1°C @ 2 σ (1 h averaging)	1°C @ 2 σ (minutes averaging)	+/- 0.1°C
Temp. accuracy	0.1°C (with abs. ref.)	---	+/- 1°C	°C (with calibration)	5µm/m(<70m); 25µm/m(>70m)
Temp. range	1000°C *(limited by fiber specifications)*	---	- 200°C; 700°C *(fiber specif.)*	700°C *(fiber specif.)*	relative +/-175°C (L>70 m)
Strain resolution	0.1 µm/m (0.1 pm)	---	---	+/-10 µm/m (+/- 10^{-5})	+/- 1 µm/m (+/- 10^{-6})
Strain accuracy	---	---	---		< 10 µm/m (L < 70 m) +/- 25 µm/m (L > 70 m)
Strain range	1% to 4% on-line FBG	---	---	> 2% (20 000 µm/m)	+/- 0.425% (L < 70 m) +/- 0.13% (L > 70 m)

Of course, the above presentation is just an overview, as distributed and quasi-distributed technologies offer many possibilities. These extra options have been developed, or are currently under development, in order to enhance sensing performances in many ways (better resolution, faster measurement, possibility to separate strain from temperature influence, possibility to sense a new parameter through an innovative packaging…). At any new solution, a new acronym. The aim of this paper is not to review them all; nevertheless Fig. 5 and 6 present an overview of these options.



TDM: Time Domain Multiplexing; PGC: Phase Generating Carrier; FBG: Fiber Bragg Grating; LPG: Long Period Grating; FP: Fabry-Perot; IPFI: Intrinsic Fabry-Perot Interferometer; EPFI: Extrinsic Fabry-Perot Interferometer; POF: Plastic Optical Fiber

Figure 5: Mind-mapping diagram of quasi-distributed OFS technologies.



OTDR: Optical Time Domain Reflectometry; POTDR: Polarization OTDR; DAS: Distributed Acoustic Sensor; OFDR: Optical Frequency Domain Reflectometry; FWCW: Frequency Modulated Continuous Waves; BOTDR: Brillouin OTDR; BOTDA: Brillouin Optical Time Domain Analyzer; PPP-BOTDA: Pre–Pulse-Pumping-BOTDA; COTDR: Coherent OTDR; TW-COTDR: Tunable Wavelength-COTDR; SF-BOTDA: Sweep Frequency-BOTDA; BOFDR: Brillouin OFDR; BOFDA: Brillouin Optical Frequency Domain Analyzer; BOCDA: Brillouin Optical Correlation-Domain Analyzer.

Figure 6: Mind-mapping diagram of distributed OFS.

4 OFS FOR SHM

4.1 SHM Workshops

Mid-September 1997, the first International Workshop on Structural Health Monitoring (IWSHM) took place at Stanford University. Since then, a series of Workshops have taken place every odd year, organized by the Department of Aeronautics and Astronautics of the Stanford University and chaired by Prof. Fu-Kuo Chang [10]. Later on, considering the increasing activity of the field, a decision was made to establish similar Workshops in Europe (EWSHM) every even year, interleaved by the IWSHM. The first European Workshop was held in 2002, in Cachan France, chaired by Dr Daniel Balageas (ONERA, France) and Dr Dominique Placko (ENS Cachan, France). So, every September, engineers, researchers and academics with interests in SHM and associated research may attend a workshop, in USA or in a European country [11]. The purpose of these International and European SHM workshops is to allow key and emerging technical issues that are critical and unique in SHM to be identified and discussed, as well as to allow current state-of-the-art and R&D activities in this field to be presented. Those workshops are also intended to promote exchanges and cross-fertilization among disciplines.

Twelve years ago, a series of SHM Workshop have been initiated in Asia-Pacific. The first Australian one was held in 2002. While, the first International Workshop on Advanced Sensors, Structural Health Monitoring, and Smart Structures was held in Japan in 2003. During the second Australian workshop in 2004, people observed a drastic increase in the number of researchers in this field in Asia-Pacific region. This led to the extension of these SHM workshops to the Asia-Pacific region. Since, this APWSHM workshop series took place every odd year in December: Yokohama, Japan (2006); Melbourne, Australia (2008 and 2012); Tokyo, Japan (2010). The 5th APWSHM, organized by the Harbin Institute of Technology, will be held in Shenzhen, China on Dec. 4-5, 2014.

Unfortunately, the corpus of this Asia-Pacific series (8 workshops since 2002) has not been included in the SHM statistics presented below, due to the lack of data available. So, the database used to achieve this bibliometric analysis only contains the papers of the IWSHM series and those of the EWSHM events. From 1997 to 2014, this represents 3249 papers. The table below (Tab. 3) presents the location of these events.

Table 3: Location of the 18 International or European SHM Conferences, from 1997 to 2016.

IWSHM 1997 (Stanford Univ., USA)	IWSHM 2005 (Stanford)	IWSHM 2011 (Stanford)
IWSHM 1999 (Stanford)	EWSHM 2006 (Granada, Spain)	EWSHM 2012 (Dresden, Germany)
IWSHM 2000 (Stanford)	IWSHM 2007 (Stanford)	IWSHM 2013 (Stanford)
EWSHM 2002 (Cachan, France)	EWSHM 2008 (Krakov, Poland)	EWSHM 2014 (Nantes, France)
IWSHM 2003 (Stanford)	IWSHM 2009 (Stanford)	*IWSHM 2015 (Stanford)*
EWSHM 2004 (Munich, Germany)	EWSHM 2010 (Sorento, Italy)	*EWSHM 2016 (UK)*

4.2 Countries involved in SHM

The bibliometric analysis shows that 57 countries have contributed to the International or European Workshops, between 1997 and 2014 (Fig. 8). Nevertheless, only a few numbers of countries is very active: the top 10 countries having published 80% of the total (Fig. 7).

The 12 countries most involved in OFS are also among the top 12 in SHM, except Greece which publishes very little in the field of OFS but which ranks in 12th position in SHM, unlike Switzerland which is relatively active in OFS but few in SHM. Statistics shows an increasing number of IWSHM papers year after year: from 65 papers in 1997, to reach about 300 communications in 2013. Since 2002, the EWSHM production was quite stable, ranging from 155 to 210 papers, except this year 2014, when it suddenly jumped to 302 publications. So finally, the IWSHM total contribution reaches 1897 papers, while the European series of SHM workshops reaches a total of 1352 papers.

Two specific points may be noticed: it's somehow obvious that the distance between a given country and the Workshop location influences the volume of its participation: for instance the USA production is triple at Stanford, than for any European event.

Extra point, similar as observed with the OFS bibliometry: China's contribution (ranking 8) is growing “exponentially”; Germany does the same (ranking 2) as well as Poland (ranking 6). Considering the corpus of 3249 papers, we observe the following sharing: USA (36%), Germany (9.9%), Japan and UK (5.8%), France (5.5%). So the top 5 countries produced 63% of the total. The weight of the USA is considerable in this ranking per country, but if we consider the production per world region, the ranking is different: Europe (30 countries involved in SHM) produces 43.1% of the total, with half of them coming from Germany + UK + France, America (38.6%, with 36% for the USA), Asia-Pacific (16.6%) and Africa plus middle-east (1.7%). Ranking becomes also very different if the paper production of these countries is normalized by their National Gross Product!

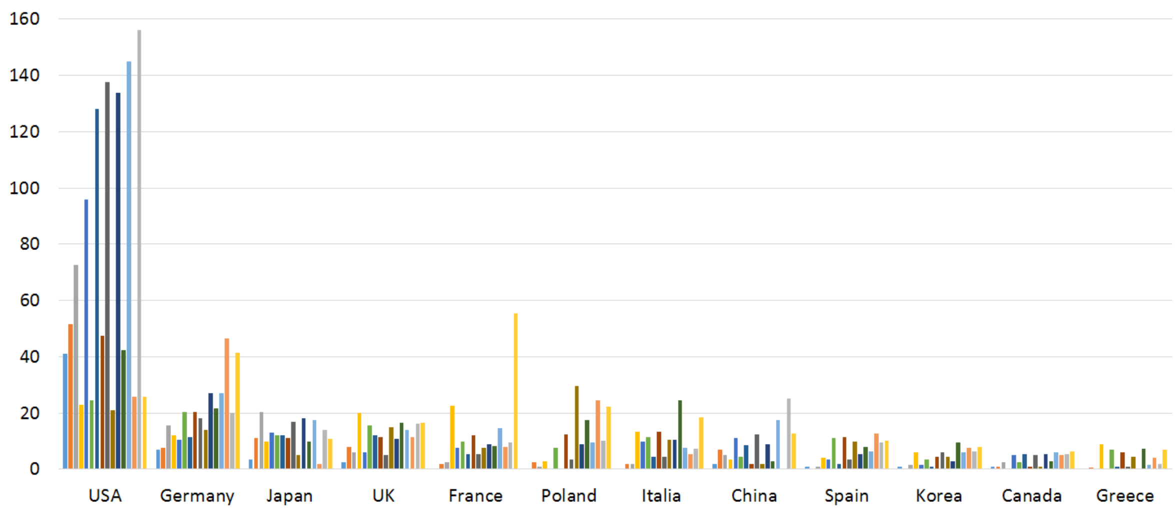


Figure 7: SHM papers per country from IWSHM1999 (Stanford) to EWSHM2014 (Nantes).

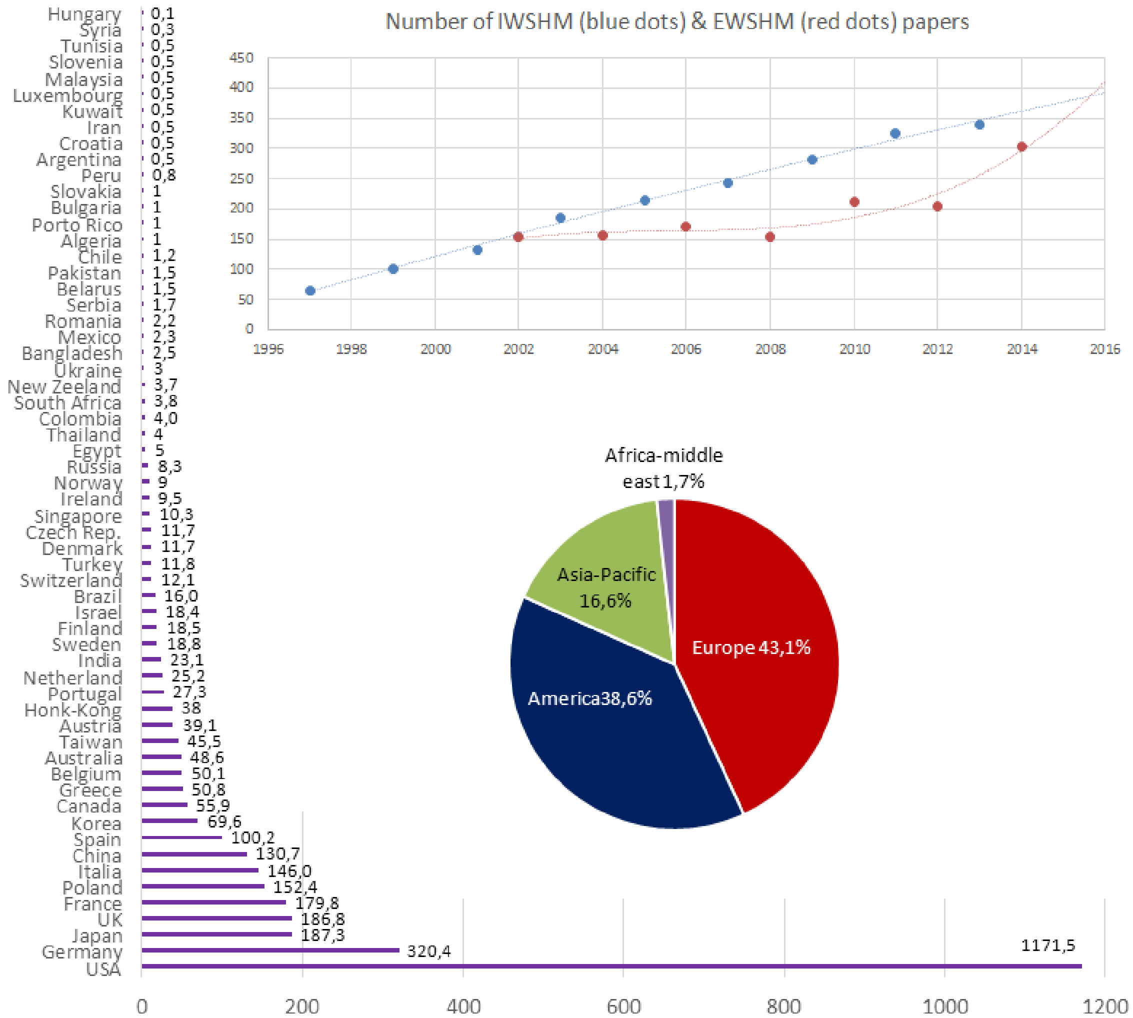


Figure 8: SHM papers per origin (countries, regions) and per event from IWSHM1999 to EWSHM2014

4.3 Sensors for SHM

Concerning sensors, several technologies are considered in the (I or E)WSHM papers, as follows: Piezo, Ultrasonic, Guides waves (Lamb, elastic…), Optical Fiber Sensors (OFS), Sensors arrays, wireless sensors, smart sensors, vibration-based sensors, bio-inspired sensors, etc. As shown on Fig. 9, traditional sensing based on wave propagation (Piezo, Ultrasonic, Lamb waves ...) reaches 20%, and OFS 15%. So, the Optical Fiber Sensing is now the second technology considered for SHM. The total number of IWSHM or EWSHM papers devoted to OFS is quite large: 411 papers, or 12.7% of the total.

More precisely, we may also estimate the influence of the OFS techniques and sub-techniques, presented above. The result is very clear: FBG sensing is widely considered. Since IWSHM1997, an average of 64.2% of the SMH papers involved in fiber sensing are using the FBG technology, the ratio being 50% for this last Workshop EWSHM2014 (Fig. 10). So, we may remember that about 2/3 of the SHM projects which includes fiber sensors, have chosen quasi-distributed Fiber Bragg Gratings. Other optical fiber techniques used in SHM are as follows: the distributed Brillouin sensing (BOTDR - BOTDA), and more recently the Rayleigh OFDR. Other OFS techniques, as Polarimetry and Interferometry (Fabry-Perot…), are less and less considered for SHM.

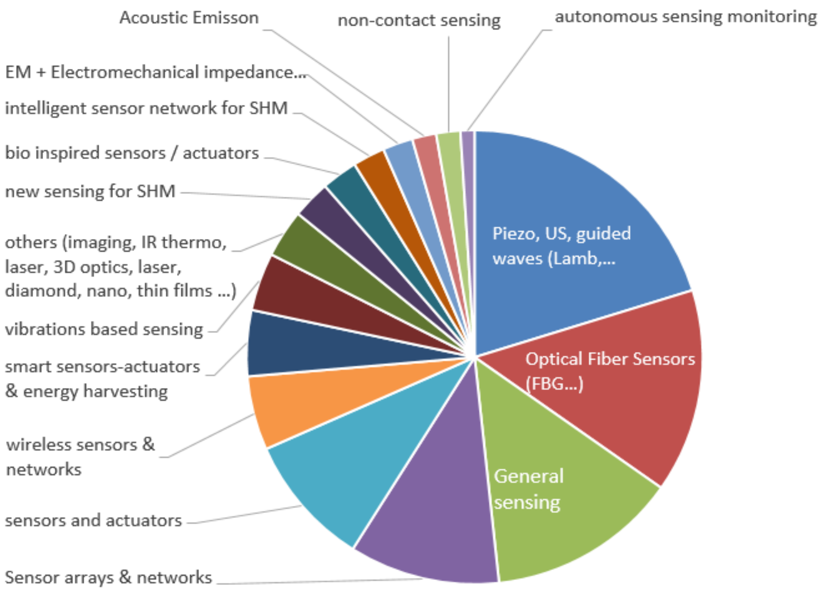


Figure 9: Sensing techniques used in SHM, from IWSHM1999 to EWSHM2014

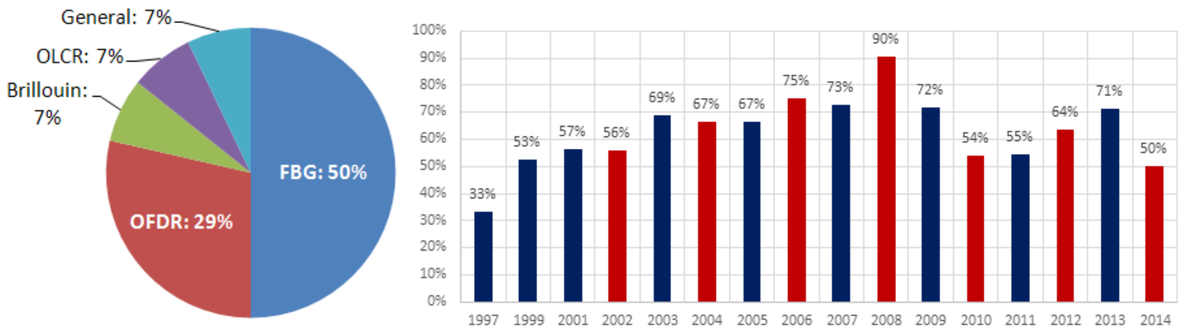


Figure 10: OFS techniques used in SHM (EWSHM2014), and ratio FBG/OFS related papers at (I-E)WSHM

4.4 Sensors for SHM of Composite materials based on OFS

Carbon and Glass Fiber Reinforced Plastics (CFPR and GFRP) are widely used as structural materials due to their high strength/weight ratio *vs.* metallic ones. However, some issues concern their durability, the possibility of damage detection and prediction, the characterization of residual stresses, and the identification of their global mechanical properties. In addition to this, the aerospace sector for instance has specified the need for multi-functional sensor systems. With time, this aim became more and more realistic with optical fibers as they can be embedded at the early stage of structure manufacturing and used up to its end of life. Hence, the same distributed sensor, or the same sensor network, may be used to monitor the manufacturing, to qualify the structure, and in-service to monitor its structural integrity, and to control smart structures. These various uses may be resumed as follows:

- 1/ Smart Manufacturing: An SHM based on optical fibers can readily be applied to any fiber reinforced matrix system. In particular, it may be used to control the injection of resin to avoid voids, or to monitor residual stresses at specified locations within the composite material while curing. This remains important for large and thick composite structures, for which it is very difficult to measure the temperature profile during manufacturing. Furthermore, the quantification of the magnitude of the residual stress is also just as important for composites as these stresses will influence the nature, and extent of damage

development. A better knowledge of manufacturing process would help to understand the material's structural integrity and the inevitable variability of properties induced by this process. In this way, the monitoring of composite material manufacturing is a key feature for better process understanding and quality improvement. To perform such monitoring, *e.g.* in RTM, it's possible to use small and weakly intrusive optical Fibre Bragg Gratings (FBG)-based sensor for both contact pressure and temperature variation measurements [12],

- 2/ In situ Health Monitoring: An SHM based on optical fibers may provide real-time strain data which in turn can be used to assess the composite structure integrity, in-service. Any damage may be detected, as the structure's rigidity will change *versus* the extent of damages. Fiber-based sensing is fully compatible with any fiber reinforced composite technology (prepreg, filament winding, RTM, infusion…) currently used in the aerospace, marine, automotive, or railway industries [22]… The durability of sensors is also a matter of concern for such long term monitoring. On this point too, optical fibers are performing. When embedded into the composite material they have an expected life time equal those of the structure itself, much longer than that of surface mounted sensors [13],
- 3/ Active Vibration & Shape Control: Strain informations provided by an OFS-based SHM can also be used to control the vibration characteristics of a structure (*i.e.* for control damping). In addition, strain data may be useful to control the shape of a composite panel for instance.

Composite materials are now used in more and more industrial sectors. In term of volume, aeronautics is certainly the first one, but others like marine sector and civil engineering are also concerned. In North America for instance, the ISIS Canada network association gained a world leadership position through the use of advance composites materials and their applications of SHM to civil structures, such as bridges. Such composites often used for repairs include OFS.

4.5 SHM of civil structures based on OFS

The civil engineering covers roads, highways, bridges, tunnels, dams, earthworks, as well as some additional areas related to road safety (weather: fog, sleet, snow... state of the surface road: vehicle-pavement interaction ...) and operation (traffic growth, Weigh-In-Motion, driving assistance ...), inducing many needs. Moreover, the monitoring of public works include the need for design assistance for infrastructures and structures still in project, controls during construction phase, and the monitoring to schedule the maintenance for those already in operation.

Many people believe that civil engineering is a traditional sector, but high technologies start to broadcast in this industry. The optical technologies can provide rich information around the needs of the user in real time. End user needs concern reliable systems, turnkey, at optimized cost (purchase + operating + maintenance). This was an impossible mission in the past, but it becomes now possible to fulfill such needs, because costs of optoelectronic components (lasers, detectors, couplers, and fibers) have been drastically reduced by the telecommunications market.

Civil infrastructures deteriorate with time, due to aging of materials, over usage, overloading, climatic influences, corrosion, inadequate maintenance… leading to accelerate their obsolescence. As a consequence, repair, retrofit and rehabilitation become more and more necessary with time to insure safety of use. This is typically the case for bridges. Modern approaches based on optical means include several techniques (imaging, topography, guided laser beam, GPS...). But, they do not provide an analytical sensing and the determination of internal origins of local effects they determine. Considering the age of existing civil works, there is a growing need for performing remote monitoring due to various attacks suffered by structures: pollution, acid, rain ... both for economic reasons induced by increased traffic, as well as traditional/human inspection and maintenance become more and more costly.

An SHM system based on OFS, and especially on FBGs embedded into or attached to a structure may monitor these evolutions throughout his life. Moreover, it may determine the load distribution, strain levels or temperature profiles, internal damages, and trigger alarm if measurements exceed predetermined thresholds [14 to 18]. As for composite materials, such a

system can also monitor structural components during construction phases, possibly leading to improved manufacturing and so increase the quality of building. In addition, for example, in the case of a bridge, the optical SHM may be used to generate the traffic information. We may imagine such a structure properly equipped that can monitor not only the number of vehicles per minute, but also their Weight-In-Motion (vehicle identification / classification), the flow direction or speed as well as detection of incidents or accidents. In terms of degradation, it is also possible to be early informed by the SHM system, allowing an early repair, therefore reducing cost.

4.6 OFS-based SHM in the industry

The SHM is a particularly promising sector that has attracted significant attention in recent years for its wide field of applications, particularly for civil and aircraft structures. Of course, the application sectors for OFS in SHM are numerous; they relate to almost all types of structures at risk or linked to a strategic use. Beyond the fields of civil engineering and sectors using composite materials, as mentioned above, OSF-based SHM may include many other industries, as for instance the nuclear power industry where safety will have to be strengthened after the nuclear accident at the plant Fukushima-Daiichi, Japan, in March 2011 [19], the steel industry seeking new ways to improve the quality of its productions and stay ahead of the competition, the oil and gas industry requesting solutions enabling to improve the security of its production and installations, both new and renewable energy (wind, heat pumps [20]...) without forgetting the rail sector where electromagnetic insensitivity of optical fibers is a great advantage over traditional electrical measurement techniques [21, 22]. Of course, it is irrelevant in this paper to address all these areas in details, but figure 11 illustrates them, while the scientific and technical literature will allow the reader to be more informed if needed.

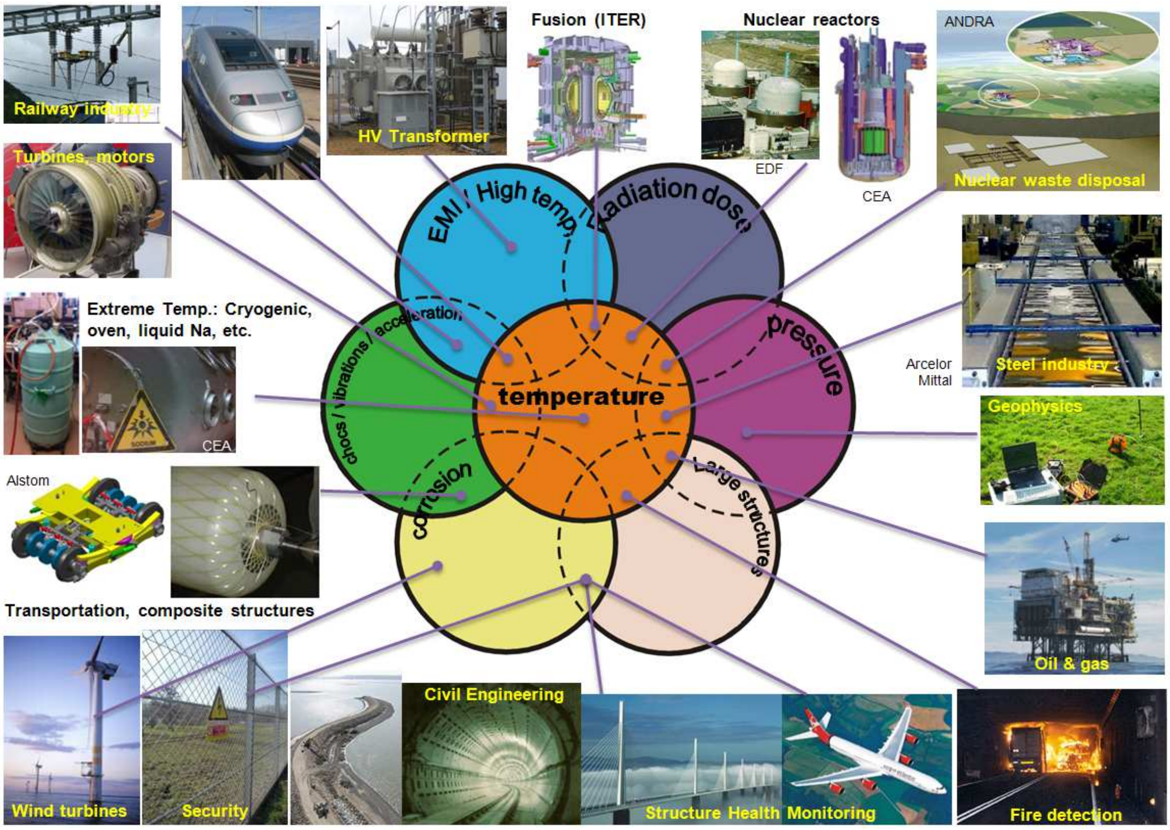


Figure 11: Industrial SHM applications based on Optical Fiber Sensors. From [23]

CONCLUSION

During past decades, OFS have been developed in the more industrial countries, and 12 of them have produced 85% of the global effort. Today, complementary optical fiber technologies, named "Distributed" and "quasi-Distributed" offer the same functionalities as traditional approaches (measurement, detection, alarm...) and many additional benefits due to optical fiber properties (small diameter, flexibility, wide bandwidth, low attenuation, immunity to electromagnetic interferences, resistance to ionizing radiations...) without forgetting those of optoelectronic measurement systems (metrological performances, multi-parameter sensing, wide and remote multiplexing…). The bibliometric analysis for SHM shows that many countries are involved, but the top 10 countries have published 80% of the total. The 12 countries most involved in OFS are almost the same among the top 12 in SHM.

For a given SHM application, the choice of the most appropriate OFS technology is obviously a matter of concern for designers, which in practice depends on a few number of interleaved parameters: Size of the structure, number of measurement points, acquisition speed, and resolution. A wide size structure, *e.g.* 1 km-long, combined to a 1-m spatial resolution specification, *i.e.* thousand sensing points, will definitely drive the user to select the distributed sensing. On the other hand, a fast acquisition request, and a very accurate measurement will orientate the engineer to select the quasi-distributed FBG sensing. By chance, to meet requirements of industrial applications, especially those from SHM, distributed and quasi-distributed sensors are increasingly performing and commercially available. Thus, many market sectors are now looking for these optical technologies (civil engineering, oil & gas, conventional and renewable energies, safety domain, nuclear... and of course those linked to composites materials and structures.

Anyway, two kinds of application fields dominate: the Civil Engineering and sectors related to composite materials applications. So, the technico-economic impact of the corresponding applications is huge, many market shares being concerned: on ground (bridges [16], tunnels [17-18], Plants [19], and underground mines [24-25]), wind turbines, at sea (ships [26], pipelines, platforms), in flight (planes, helicopters), or even in space (satellite, shuttle). As everybody knows, projects are more and more driven by the economy, and this leads to maintain existing structures as longer as possible. Such trend may explain increasing motivations for SHM and health diagnosis of structures, *i.e.* in practice for the measurement of strains, displacements, temperature, corrosion ... In such context, the economic impact (saving in maintenance costs, gains in performances and related to safety [27]) of the concerned monitoring applications (concrete, basements, grounds, civil structures, composites materials...) justify the efforts which are devoted to them. Thus, during past years the growing overlap of the increasingly performing optical fiber sensing technologies with industries' needs has allowed fruitful synergies between the OFS and SHM communities. That’s why since about two decades, OFS has caught increasing attention of SHM people. As a consequence, many SHM oriented field demonstrations have been performed by actors of the OFS community. Finally, products have left R&D labs to reach the market and industrial applications, very often thanks to start-ups.

Literature and quality of projects show that SHM is now became a well-established speciality and, if we refer to the SHM workshops, the bibliometry proves that fiber optics has become the second sensing technology of interest. In the early 2000s, 40% of applications involving the OFS, concerned the FBG technology; it is quite remarkable that in the recent years this figure reached 64%. This is evidence that the FBG technology is now recognised, and considered as a strategic domain all around the world. In particular, China invests a lot in the OFS and FBG domains since 7-8 years, due to their numerous advantages, and due to a large panel of applications in this country.

To complete this analysis, we must always remember that the story is never ended, as scientific or technological breakthroughs may appears at any time, and so opening new opportunities for developers, as well as for users. This is what just happened during the last decade for the Telecommunication community, as well as for the OFS developers, with the invention followed by a strong phase of development of the micro-structured and Photonic Crystal Fibers. More recently other breakthroughs emerged as the possibility to realize FBG transducers able to resist about

1000°C over several years [4-5], which now opens new market possibilities for the OFS and SHM communities. Some new paradigms, as the concept of smart skins, very small diameter optical fibers, connected objects, big data... will probably have an impact on both the background and practices of the SHM community. Should we anticipate, in less than a decade, Internet-connected structures through sensitive optical fibers, acting as nerves and remote links, everywhere in our life? I suggest planning an appointment to discuss this question at EWSHM2024.

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