SPIE Smart Structures and Materials & Nondestructive Evaluation and Health Monitoring
14th International Symposium, 18-22 March 2007, San Diego, California USA
Health Monitoring of Structural and Biological Systems (SSN10 Conference)

Health monitoring with optical fiber sensors: from human body to civil structures

Éric Pinet*[a], Caroline Hamel[a], Branko Glišić[b], Daniele Inaudi[b] & Nicolae Miron[c]
[a] *FISO Technologies Inc*., 500-195, Ave. St-Jean-Baptiste, Québec (Qc) Canada G2E 5R9;
[b] *SMARTEC S.A.*, Via Pobiette 11, CH-6928 Manno, Switzerland;
[c] *Roctest Ltd.*, 665, Ave. Pine, Saint-Lambert (Qc) Canada J4P 2P4

ABSTRACT

Although structural health monitoring and patient monitoring may benefit from the unique advantages of optical fiber sensors (OFS) such as electromagnetic interferences (EMI) immunity, sensor small size and long term reliability, both applications are facing different realities. This paper presents, with practical examples, several OFS technologies ranging from single-point to distributed sensors used to address the health monitoring challenges in medical and in civil engineering fields.

OFS for medical applications are single-point, measuring mainly vital parameters such as pressure or temperature. In the intra-aortic balloon pumping (IABP) therapy, a miniature OFS can monitor *in situ* aortic blood pressure to trigger catheter balloon inflation/deflation in counter-pulsation with heartbeats. Similar sensors reliably monitor the intracranial pressure (ICP) of critical care patients, even during surgical interventions or examinations under medical resonance imaging (MRI). Temperature OFS are also the ideal monitoring solution for such harsh environments.

Most of OFS for structural health monitoring are distributed or have long gage length, although quasi-distributed short gage sensors are also used. Those sensors measure mainly strain/load, temperature, pressure and elongation. *SOFO* type deformation sensors were used to monitor and secure the Bolshoi Moskvoretskiy Bridge in Moscow. Safety of Plavinu dam built on clay and sand in Latvia was increased by monitoring bitumen joints displacement and temperature changes using *SMARTape* and *Temperature Sensitive Cable* read with *DiTeSt* unit. A similar solution was used for monitoring a pipeline built in an unstable area near Rimini in Italy.

Keywords: Single-point sensor, distributed and quasi-distributed sensors, electromagnetic interference immunity, temperature, pressure, strain, elongation, dynamic and static monitoring, miniature sensors, instrumented catheter.

1. INTRODUCTION

A civil structure could be regarded as a human body: once born and grown after completion of the construction, it ages and degrades with time, should eventually be repaired when damaged and finally dies when destructed or worn out. For both civil structures and human bodies, health monitoring is an important concern to increase life expectancy. Important efforts have thus been accomplished in civil engineering and medical fields in order to develop new tools for better inspection, diagnosis and prognosis. Among those tools, measuring physical parameters with optical fiber sensors[1-3] (OFS) is now considered as a reliable technology and probably as the best approach.

Several OFS technologies have been developed with commercially available products that could be used in various health monitoring applications. In this paper, we present how and why such sensors could be successfully applied to health monitoring of human body or civil engineering structures[4,5]. Similarities but also differences of the two realities are further discussed.

* eric.pinet@fiso.com; phone +1 (418) 688-8065; fax +1 (418) 688-8067; www.fiso.com

2. OFS TECHNOLOGIES & HEALTH MONITORING

In the last decade, the tremendous development of the telecommunication market reduced considerably the cost and increased the performances of the optical fibers and of the associated optical components. The fiber-optic sensor segment, which is still a too small industry to justify by itself all the investments done so far in the telecom field, takes however advantage of the progress made in the optical communications. The OFS market will nevertheless increase significantly in the future, as predicted by several market studies. Certainly, high volume applications for OFS has to be addressed commercially in order to be more and more competitive with the usually less expensive and very familiar solutions using electrical sensors. In particular, demanding applications in which conventional sensors are difficult to use present the best opportunities for fiber-optic sensors. Among those applications, the ones involving health monitoring of humans or civil engineering structures offer probably the best opportunities for the different technologies based on OFS.

2.1 Advantages of OFS technologies for health monitoring

Even though OFS are apparently expensive for a widespread use in health monitoring, they are however better approaches for applications where sensor/system costs are not the only important criteria or where reliability in challenging environments is essential. It is sometimes crucial to use a reliable technology for critical health monitoring: price is often no longer a showstopper when life of the human beings is in danger or when the security of very expensive systems such as aircrafts or civil engineering structures could lead to catastrophic consequences. In commercial applications where OFS have been selected for health monitoring, the benefit often more than justifies the higher cost of this type of technology. OFS can even become cost-effective when involving an important number of sensors such as in civil engineering applications using quasi-distributed or fully distributed OFS. In some extreme applications such as in the oil and gas industry, OFS are sometimes the only available solution for reliable and long-term physical parameter monitoring.

The greatest advantages of the OFS are intrinsically linked to the optical fiber which is either simply a link between the sensor and the signal conditioner, or is the sensor itself in long gage and distributed sensors. In almost all OFS applications, the optical fiber is a thin glass fiber that is usually protected mechanically with a polymer coating (or even a metal coating in extreme cases) and often inserted in a cable designed to be suitable for targeted applications. Since glass is an inert material very resistant to almost all chemicals even at elevated temperatures, it is an ideal material for applications in harsh chemical environments such as encountered in oil and gas wells[6], sparkplug engines[7] or inside the human body[8]. It is also interesting since it is resistant to weathering effects and it is not subjected to any corrosion. The later property is a great advantage for long-term reliable health monitoring of civil engineering structures. Some identified problems such as optical fiber hydrogen darkening[9-11] is not necessary a problem when selecting the appropriate interrogation technology and fiber type. Being an inert material, the glass is also fully biocompatible and resistant to common sterilization techniques such as oxidation with ethylene oxide (EtO) gas or water vapor autoclaving.

Since the light confined into the core of the optical fibers used for sensing purposes does not interact with any surrounding electromagnetic (EM) field, OFS are therefore intrinsically immune to any electromagnetic interference (EMI). With such unique advantage over their electrical counterparts, OFS are obviously the ideal sensing solution when the presence of EM, radio frequency (RF) or microwaves (MW) cannot be avoided. For instance, OFS will not be affected by any EM field generated by a lightning hitting a monitored bridge or dam, unless the fiber is damaged thermally. In medical applications where an OFS is connected to a life-supporting device, the EMI immune fiber sensor increases the overall reliability in an environment with strong EMI background such as in surgical rooms crowded with various electrical equipments. Besides increasing sensor reliability, its EMI immunity could be a unique advantage for instance, for hot spots monitoring in high-power electric transformers monitored with temperature OFS. By design, OFS are intrinsically safe and naturally explosion proof, making them particularly suitable for health monitoring applications of risky civil structures such as gas pipelines[12] or chemical plants.

Probably the greatest advantage of OFS is still their small size. In most cases, the diameter of bare OFS, usually in the range of 125 μm to 500 μm, is very appropriate in space-restricted environments such as the instrumented catheters for patients health monitoring or such as thin composite structures. Most frequently, an OFS has an axial geometry suitable also for many applications where this becomes a benefit, such as instrumentation of bolts or similar cylindrical devices.

The ability of measuring over distances of several kilometers, without the need for any electrically active component is also an advantage inherited from the fiber optic telecommunication industry. This is an important feature when monitoring large and remote structures such as pipelines or multiple bridges along a single highway.

All these general advantages make OFS a suitable solution for a variety of health monitoring applications ranging from human bodies to civil structures.

2.2 OFS technologies used for health monitoring

There is a large variety of fiber-optic sensors for health monitoring, developed by both the academic and the industrial institutions. Universities and industrial research centers are developing and producing a large variety of sensors for the most diverse types of measurements and applications. In this overview, we will concentrate on sensors for health monitoring that have reached an industrial level or that are at least at the stage of advanced field trials. The candidate technologies for monitoring a physical parameter with OFS can be classified in four main categories relying on the position where the parameter is measured: single-point, long gage, quasi-distributed and distributed sensors. Several differences exist in each category, depending on how the parameter is converted into light-coded information.

Single-point (short gage) sensors

Among all the point sensing technologies developed for health monitoring, the Fabry-Pérot (FP) technology is probably the most widespread. The sensor design may differ, depending on the parameter to be measured, but always keeping the same concept consisting of two partially reflecting surfaces (mirrors) facing each other in order to create interferences between the beams reflected by them. The monitored parameter (temperature, pressure, strain…) changes the gap size or the index of refraction of the medium between the mirrors, producing changes in the interference between the beams. The interference changes can be monitored by using coherent or low-coherence techniques to measure the gap changes with a relatively low cost such as the patented[13] white-light interferometer technology commercialized by *FISO Technologies*. Several sensor designs are available. One approach uses two cleaved optical fibers facing each other, separated by an air gap of few microns. The two fibers are mounted inside a capillary tube and can be used as sensor either for temperature (*FOT-L*, *FOT-H*) or for strain (*FOS-N*, *EFO*, *SFO-W*). A similar configuration with a flexible reflecting membrane mounted on a glass structure with a vacuumed cavity can be used as an absolute pressure sensor (*FOP-M*, *FOP-MIV*, *FOP-C*). The gap of FP interferometer can be filled also with a semiconductor having a temperature dependant refractive index to obtain a temperature sensor (*FOT-HERO*, *FOT-MSP*). This gap with a fixed length could be open to the environment to obtain a refractive index sensor for gas or liquids (*FRI*). Many single-point FP sensors have found applications in health monitoring from human body[8,14] to civil structures[15].

Other interesting single-point sensors technologies have been used industrially mainly for temperature health monitoring. The GaAs technology uses the temperature-dependent change in reflectivity of this semiconductor in the visible range. A small GaAs chip is simply glued at the end of a multimode optical fiber and is illuminated with a white light. A spectrometer is analyzing the temperature-dependent reflection spectrum with typical ±2°C accuracy that is enough for applications such as hot spots monitoring in high-power electric transformers. A good example for this application could be the *TPT-32* sensors developed by *FISO Technologies*.

The phosphorus decay technology uses a thermo-sensitive phosphorescent material excited usually with a pulsed narrow band source such as flashing light emitting diode (LED). The excited phosphorescent material reemits light at a longer wavelength with an intensity decreasing exponentially with temperature-dependent time decay: the higher the temperature the faster the decay. With ±0.5°C accuracy and about 1 Hz sampling rate, such technology could be used for temperature monitoring in various applications.

Long gage sensors

The *SOFO* system[16,17] is a long gage fiber-optic deformation sensor with a resolution in the micrometer range, an excellent long-term stability and insensitivity to temperature. It was developed at the Swiss *Federal Institute of Technology* in Lausanne (EPFL) and is now commercialized by *SMARTEC* and *Roctest Group*. The measurement setup uses low-coherence interferometry to measure the length difference between two optical fibers installed on the structure to be monitored. The measurement fiber is pre-tensioned and mechanically coupled to the structure at two anchorage points in order to follow its deformations, while the reference fiber is free and acts as a temperature reference. Both fibers are installed inside the same pipe and the measurement basis can be chosen between 200 mm and 10 m. The resolution of the system is of 2 μm independently from the measurement basis and its precision of 0.2% of the measured deformation even over years of operation. The *SOFO* system has been successfully used to monitor so far more than 400 structures, including bridges, tunnels, piles, anchored walls, dams, buildings, historical monuments, nuclear power plants as well as laboratory models.

Quasi-distributed sensors

Quasi-distributed sensors are mainly used in structural health monitoring where a limited number of sensing points are located on the same fiber. The fiber Bragg grating[18] (FBG) is the dominant technology of this type of sensor. Bragg gratings are periodic alterations in the index of refraction of the fiber core that can be produced by adequately exposing the fiber to intense UV light. The produced gratings typically have length of the order of 10 mm. If a tunable light source is injected in the fiber containing the grating, the wavelength corresponding to the grating pitch will be reflected while all other wavelengths will pass through the grating undisturbed. Since the grating period is strain and temperature-dependent, it becomes possible to measure these two parameters by analyzing the intensity of the reflected light as a function of the wavelength. This is typically done using an interrogator such as the *MuST* reading unit from *SMARTEC* or a spectrometer. Resolutions of the order of 1 $\mu\varepsilon$ and 0.1°C can be achieved with such demodulators. If strain and temperature variations are expected simultaneously, it is necessary to use a free reference grating that measures the temperature alone and to use its reading to correct the strain values. Setups allowing the simultaneous measurement of strain and temperature have been proposed, but have yet to prove their reliability in field conditions. The main interest in using Bragg gratings resides in their multiplexing capability. Many gratings can be written in the same fiber at different locations and tuned to reflect at different wavelengths. This allows the measurement of strain at different places along a fiber using a single cable. Typically, 4 to 16 gratings can be measured on a single fiber line. It has to be noticed that since the gratings have to share the spectrum of the source used to illuminate them, there is always a trade-off between the number of gratings and the dynamic range of the measurements on each of them. Because of their length, fiber Bragg gratings can be used as replacements for conventional strain gages and installed by gluing them on metals and other smooth surfaces. With adequate packaging, they can also be used to measure strains in concrete over basis length of typically 100 mm.

Distributed sensors

In fully distributed OFS, the optical fiber itself acts as a sensing medium, which could also be used to discriminate different positions of the measured parameter along the fiber such as for Raman or Brillouin distributed sensors. Each technology has advantages used for different structural health monitoring strategies.

Brillouin scattering sensors[19,20] show an interesting potential for distributed strain and temperature monitoring. Systems able to measure strain or temperature variations of fibers with length up to 30 km and with spatial resolution down in the meter range, are now demonstrating their potential in the first field applications. For temperature measurements, the Brillouin sensor is a strong competitor to systems based on Raman scattering, while for strain measurements it has practically no rivals. Brillouin scattering is the result of the interaction between optical and sound waves in optical fibers. Thermally excited acoustic waves (phonons) produce a periodic modulation of the refractive index. Brillouin scattering occurs when light propagating in the fiber is scattered backward by this moving grating, giving rise to a frequency-shifted component by a phenomenon similar to the Doppler shift. This process is called spontaneous Brillouin scattering.

Acoustic waves can also be generated by injecting in the fiber two counter-propagating waves with a frequency difference equal to the Brillouin shift. Through electrostriction, these two waves will give rise to a traveling acoustic wave that reinforces the phonon population. This process is called stimulated Brillouin amplification. If the probe signal consists in a short light pulse and its reflected intensity is plotted against its time of flight and frequency shift, it will be possible to obtain a profile of the Brillouin shift along the fiber length.

The most interesting aspect of Brillouin scattering for sensing applications resides in the temperature and strain dependence of the Brillouin shift. This is the result of the change in the acoustic velocity according to variation in the silica density of the fiber core. The measurement of the Brillouin shift can be approached using spontaneous or stimulated scattering. The main challenge in using spontaneous Brillouin scattering for sensing applications resides in the extremely low level of the detected signal. This requires sophisticated signal processing and relatively long integration time. Systems based on the stimulated Brillouin amplification have the advantage of working with a relatively stronger signal but also face another challenge. To produce a meaningful signal, the two counter-propagating waves must maintain an extremely stable frequency difference. This usually requires the synchronization of two laser sources that must inject the two signals at the opposite ends of the fiber under test. Another method consists in generating both waves from a single laser source using an integrated optics modulator. This arrangement, used in the *DiTeSt* system commercialized by *SMARTEC*, offers the advantage of eliminating the need for two lasers and intrinsically insures that the frequency difference remains stable independently from the laser drift. Such instruments typically feature a measurement range of 10 km with a spatial resolution of 1 m or a range of 30 km with a resolution of 2 m. The strain resolution is 20 με and the temperature resolution is 1°C. Since the Brillouin frequency shift depends on both the local strain and temperature of the fiber, the sensor setup will determine the actual sensitivity of the system. For measuring temperatures, it is sufficient to use a standard telecommunication cable. These cables are designed to shield the optical fibers from an elongation of the cable. The fiber will therefore remain in its unstrained state and the frequency shifts can be unambiguously assigned to temperature variations. If the frequency shift of the fiber is known at a reference temperature, it will be possible to calculate the absolute temperature at any point along the fiber. Measuring distributed strains requires a specially designed sensor. A mechanical coupling between the sensor and the host structure along the whole length of the fiber has to be guaranteed. To resolve the cross-sensitivity to temperature variations, it is also necessary to install a reference fiber along the strain sensor. The *SMARTprofile* sensor from *SMARTEC* incorporates both the strain and the temperature sensing fibers in a single packaging. Similarly to the temperature case, knowing the frequency shift of the unstrained fiber allows an absolute strain measurement.

Using Raman scattering[21,22], it is possible to obtain distributed temperature measurements over typically a few kilometers. Contrary to Brillouin scattering, no strain measurement is possible. The Raman scattering produces two broadband components at higher and lower frequencies than the exciting pump wave. Measuring the intensity ratio between these bands, called the Stokes and anti-Stokes emissions, allows calculation of the temperature at any given point along the fiber line. Typical spatial resolutions are of the order of one meter and temperature resolution of 0.2°C. The usual range of these instruments is in the order of 8-10 km.

3. PATIENT HEALTH MONITORING WITH OFS

Alike condition monitoring of civil structures or works, evaluation of patient health does not rely only on a single measurement. Certain diagnoses relating to the physiology or the functional defects of certain organs and systems require a physiological follow-up of the conditions or phenomena from several hours to several days. The most common measured parameters are body or tissue temperature, pressure in vessels or drains, and strain applied on tissues or structures during therapies or minimally invasive surgeries. Most fiber-optic sensors used in medical applications are point sensors but some applications involving quasi-distributed sensors are slowly emerging.

Besides biocompatibility and chemical inertness, the two main advantages offered by optical fiber sensors interesting for medical applications are their miniature size and electromagnetic insensitivity. The first allows *in situ* monitoring in small areas such as blood vessels and eases the integration in medical equipments such as instrumented catheters dedicated to minimally invasive surgeries or therapies. The second advantage enables reliable measurements in the presence of electromagnetic interferences such as those encountered in modern operating rooms filled with many types of electronic equipment or created by the intervention method itself that may use electromagnetic waves (such as RF or MW).

With stable and always accurate measurements, a proper patient health monitoring could be performed, allowing a fast feedback loop control in certain interventions (such as in intra-aortic balloon pumping therapy) or slower physiological drift monitoring (such as intracranial pressure or temperature monitoring under magnetic resonance imaging).

3.1 IABP therapy

The intra-aortic balloon pumping[23-25] (IABP) therapy, developed more than 30 years ago, is a life-supporting mechanical assistance usually used when pharmacologic therapy fails or presents a high risk of mortality or morbidity due to high drug doses. Such therapy is often used temporarily to help patients recover from critical heart diseases or to wait until a transplant is performed. It consists of inserting, generally through the femoral artery, a small catheter terminated by an inflatable balloon which is then positioned into the descending aorta (the vessel receiving the blood ejected from the heart) just below the subclavian artery as shown in Fig. 1. Once in place, the balloon inflates between heartbeats (diastolic phases) to help maintaining the arterial pressure especially in arteries feeding blood to the brain and to the heart. The balloon deflates during heartbeats (systolic phases) to ease blood exiting from the heart by creating a local depression. As it is easily understood, synchronization of balloon rapid inflations and deflations is critical for the success of such counter-pulsation therapy. Such synchronization is usually performed using the patient's electrocardiogram (ECG) or preferably using arterial pressure waveform.

Unfortunately, for many patients requiring IABP, abnormal ECG due to atrial fibrillation and other types of arrhythmia related to their condition or the use of a pacemaker or a defibrillator prohibits on the use of ECG signal for synchronization. Furthermore, weak electrical signal of ECG could also be fooled by the use of electrical surgical tools creating a burst of electromagnetic interferences. The other method clearly indicating heartbeat phases is the blood pressure measurement, which is high during the heart contraction (systole) and low during heart relaxation (diastole). However, synchronization with the heart requires very fast and reliable pressure reading, especially with a clear detection of a small pressure event, called the dicrotic notch and corresponding to the aortic valve closure, which separates precisely systolic and diastolic phases. Up to now, the most popular method for pressure measurement relies on a fluid-filled catheter combined with an external pressure electrical transducer. The pressure is transmitted though the catheter from its distal tip located in the aorta and its proximal end connected to a transducer located a few meters away from the patient. Dynamic response of such approach is however limited due to several pressure artifacts generated by fluidic transduction such as delayed response and damping effects caused by catheter elasticity, fluid inertia, wall friction (especially when diameter is reduced) or the presence of tiny bubbles in the system. Pressure measurement is also strongly affected by catheter vibrations[14] and hydrostatic pressure variation occurring each time the patient changes his position (generally, the patient should stay lying down and the correction is performed at the beginning of the therapy) which practically always occurs during emergencies and during patient transportation.

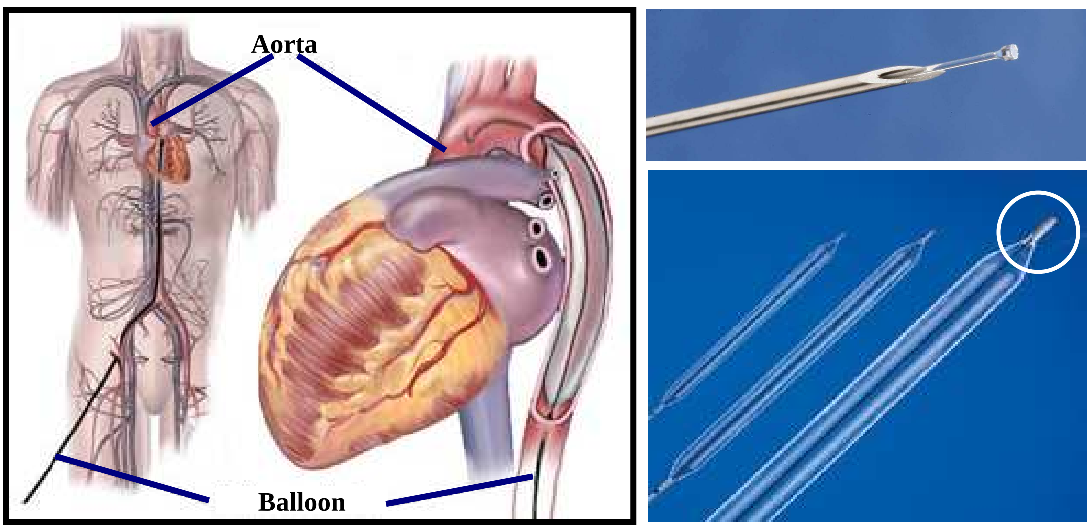

Fig. 1. IABP catheter instrumented with *FOP-MIV* pressure OFS. The catheter is usually inserted through the femoral artery and is positioned in the descending aorta (left). During the therapy, the balloon is cyclically inflated and deflated in counter-pulsation with the heartbeat. The *FOP-MIV* sensor (top right photo: bare sensor inserted in a gage 24 hypodermic needle) positioned at the tip of the balloon (circle in bottom right photo) provides a reliable measurement of the intra-aortic pressure that is used for balloon triggering.

In order to solve all problems associated with fluidic pressure transduction, an original solution consists of integrating a miniature fiber-optic pressure sensor, such as the *FOP-MIV* developed by *FISO Technologies*, directly at the tip of the catheter (Fig. 1), exactly where the aortic pressure waveform has to be measured. This has the definitive advantage of *in situ* pressure monitoring over the fluid-filled catheter without risking EMI in the pressure signal transmitted to the IABP pump system. Since traditional intra-aortic catheter size of 7.5 to 8 French (∅ 2.5 mm to 2.75 mm) is probably the present physical limit for fluid pressure transduction[26], the use of a optical fiber now allows catheter diameter reduction to 7 Fr (∅ 2.3 mm) or below. This size reduction is highly desirable in order to reduce the incidence of IABP vascular complications such as ischemia, caused by obstructed blood flow leading to tissue deficit in oxygen and which represents the highest risk of the therapy. The fact that the optical pressure sensor is insensitive to any electromagnetic interference is highly desirable since the sensor could be used even during surgery with electric tools. The use of OFS for IABP therapy therefore provides a better control of reliable balloon triggering. Thanks to mass production technology and automated assembly with top quality control such as these developed by *FISO Technologies*, a commercial product integrating OFS could advantageously be the solution for IABP therapy[14].

Since front tip mounted miniature OFS are not affected by lateral pressure (contrary to miniature piezoelectric pressure sensors), they could be used for pressure investigation in vessels experiencing peristaltism such as encountered in urologic or digestive systems. Several pressure sensors could also be mounted into the same catheter in order to allow differential pressure measurements, which could be of great interest for pathology diagnosis in cardiology or urology for instance. Integration of miniature OFS into instrumented catheters obviously offers many new advantages and opens the way for the expanding field of minimally invasive surgeries/therapies[8] that reduce risks and overall costs of interventions.

3.2 ICP monitoring

The brain is contained in the skull, a rigid container, and any abnormal liquid accumulation such as blood or cephalospinal fluid (CSF) or mass lesions such as tumors, pus or hematoma may increase intracranial pressure (ICP). High ICP is a common cause of death among neurological patients and sustained high ICP suggests poor prognosis[27]. Forty percent of patients admitted unconscious have high ICP. In this group, high ICP will be the leading cause of death in half of cases[28] and effective treatment of high ICP was proven to reduce mortality[29]. ICP monitoring is therefore critical and it is generally performed by two types of measurements: the punctures (such as lumbar puncture) and continuous pressure measurements with implantable catheters.

In circumstances like head trauma with blood collection or aneurysm, ICP may increase rapidly. In that case, even repeated lumbar punctures may not offer the continuous reading required to identify a dangerously increasing ICP before actual brain damage. Besides the associated risks of infection, it can also be added that the risk of brain displacement due to withdraw of high pressure CSF during punctures and the inaccuracy related to the indirect reading of the pressure in lumbar column instead of the pressure within the skull[30], make the punctures methods not the best ones for safe patient ICP monitoring.

Better results are usually obtained using an implanted fluid-filled catheter for continuous pressure monitoring. One method called hollow skull (also known as Richmond screw), measures pressure at the dura mater level. Dura mater is the first of the three layers of meninx which envelopes the brain. It is composed of two fibrous layers and the external one adheres to the skull. This method does not necessitate a deep catheter insertion into the brain. Therefore, it is easier to achieve, but studies show that, particularly at high ICP, it underestimates the true ICP[31,32] which could have dramatic impacts. A more accurate method, actually considered as the gold standard method, consists to measure the ICP with an intra-ventricular fluid-filled catheter externally connected to a strain gauge that can be externally calibrated against a reference. However, fluid-filled catheters have bigger diameters, which, besides the other problems already described in the previous section, complicates the placement in the ventricle when the later is displaced or squeezed. It also involves potential injury to other parts of the brain and a serious increase in infection risk after three days of implantation[33].

An implantable catheter-tip instrumented with a miniature OFS, such as the *FOP-MIV* developed by *FISO Technologies*, introduced into the catheter offers the possibility of using significantly reduced diameters (∅ 1.2 mm or smaller). It allows easy insertion in the brain tissues and measures an absolute *in vivo* ICP without the need for hydrostatic pressure correction such as the case with fluid-filled catheters. Even though this system cannot be calibrated *in situ*, studies have shown a close correlation between the intra-ventricular method and the catheter-tip transducer method[34-36].

It should be noted that evaluation of brain tissue injuries often rely on computed tomography (CT) scans and magnetic resonance imaging (MRI). However, in some occasions, MRI surpasses CT scan in the visualization of soft tissues like the brain and this imaging method is therefore widely used to evaluate tissue injuries, lesion types and their extent. With the enhancement of MRI devices and adaptation of surgical tools, MRI is now even brought into operating rooms where it is performed as the brain surgery progresses (called interventional MRI). As MRI technology uses high-intensity magnetic fields, any material that may be influenced by EM fields or create imaging artifact should be avoided. Being intrinsically inert to EM fields, optical sensors do not interfere with MRI and offer thus the most appropriate solution for continuous and secure ICP monitoring even during MRI procedures.

In conclusion, the miniature size of pressure optical sensors widens access to brain intra-ventricular pressure measurements, considered as the most accurate method in the evaluation of the patient's ICP status. MRI compatibility of OFS permits continuous monitoring of critical patients during diagnostic and surgery involving MRI.

3.3 Temperature monitoring under MRI

As it was already underlined, MRI equipments are now more common powerful imaging tools in modern hospitals. Contrary to X-Ray or CT scan, which could image tissues with important density contrast such as bones, MRI could be used for finer imaging of body soft tissues and organs having similar density but very different molecular composition, such as nervous structures, ligaments, tendons etc. MRI equipments use very intense magnetic field, usually ranging from 0.2 to 3 T (3 T corresponds to approximately more than 50 000 times terrestrial magnetic field). Such technology has the great advantage of being radiation free and safe imaging method, provided that the patient does not have ferromagnetic implant in his body (such as metal screws, pacemaker or other implanted devices), whereas X-Ray and especially CT scan (corresponding to multiple X-Ray snapshots) give cumulative radiation dose after each exposure. However, in order to get finer details in the image structures that could be also reconstructed in 3 dimensions, the MRI industry trend is to increase the static intense magnetic field (some laboratory MRI equipments have already 11 T or higher). Due to energy transfer to the patient, extreme magnetic field could sometimes create some local heating, especially in areas where biomaterials (although often MRI compatible) have been implanted and some patients could have tingling sensations. In such conditions, it is thus crucial for patient safety to monitor locally the temperature using a sensor that is not affected by electromagnetic interferences. Optical fiber temperature sensors, such as the *FOT-L* sensor from *FISO Technologies* packaged for this application (see Fig. 2), is an adapted solution for skin temperature monitoring of patients under MRI.

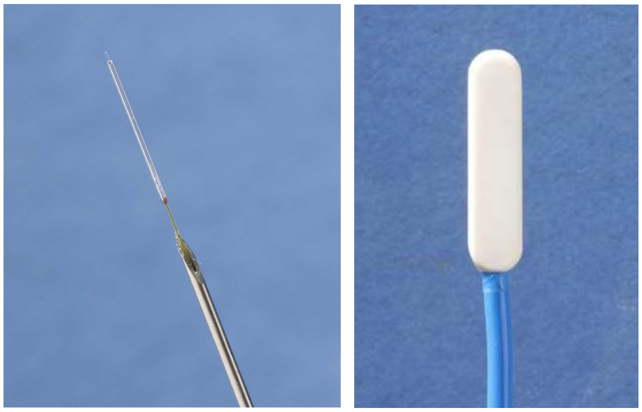

Fig. 2. Bare (left: in a gage 24 hypodermic needle) and packaged (right) FOT-L temperature sensor is suitable for skin temperature monitoring of patients that are under extreme magnetic field during MRI procedures.

Since body temperature is an important vital sign indicating a patient's condition, it is usually continuously monitored for critical care or sedated patients. When diagnostics or surgeries on such patients require MRI, clinicians are faced with the problem of having to stop temperature monitoring during this procedure since it is usually done with conventional electrical sensors. Including the preparation and the MRI examination, this may mean losing several hours of temperature monitoring that in some cases might be critical. When using fiber-optic temperature sensors for critical patient care, the task of medical technical staff is greatly simplified since a single monitoring instrumentation will be operational in all diagnostic and surgical environments the patient could encounter. With further price reduction associated with mass production of OFS for medical applications, such sensors would be probably the ideal and standard solutions for simplified and safer patient health monitoring in future modern hospitals.

4. STRUCTURAL HEALTH MONITORING WITH OFS

When used in civil engineering applications, the mentioned advantages of fiber-optic sensors remain valid. For instance, having a miniature size sensor makes it possible to package it in a way to make it compatible with the rough on-site conditions. Electromagnetic insensitivity is also useful to allow proper function even under lightening strokes or when high electromagnetic fields are present such as encountered in electrical power transformers or in energy transportation applications. High temperature and corrosion resistance are additional advantages for oil and gas or long-term structural health monitoring applications. Nevertheless, one of the greatest advantages of such sensors is definitely the ability to offer long range distributed or quasi-distributed capabilities if proper interrogation technology is used. The main physical parameters for civil health monitoring measured by fiber-optic sensors are mostly strain/load, temperature, pressure and elongation.

The following examples illustrate typical applications of fiber-optic sensing technology to structural health monitoring.

4.1 An historic bridge in Moscow

The Bolshoi Moskvoretskiy Bridge was built in 1936-37, over the Moscow River. It is situated in downtown Moscow, next to the Kremlin, and leads one of the main traffic lines to the Red Square. This relatively long span was very advanced at that time. The bridge consists of three parallel 100 m long reinforced concrete arches hidden behind stone walls. The cross-section of each arch contains three merged boxes. Several columns support the superstructure of the bridge. Four traffic lanes cross the bridge in each direction.

Fig. 3. Cracking of the stone walls (ellipses on left photos) confirms the settlement in the middle of the arch; penetration of chlorides is visible in the interior of the arch boxes (right photo).

Two types of degradation are apparent on the bridge (Fig. 3): 1) settlement in the center of the arch that provoked the cracking of the stone walls near abutments on both sides of the bridge and 2) chloride diffusion that went through the upper wall of the arch boxes in some sections, and have penetrated inside the boxes.

The condition of the bridge after nearly 70 years of service and its functional and historical importance have led the authorities to decide to continuously monitor structural behavior of the bridge. *SMARTEC* supplied the instrumentation and sensors, and *SMARTEC*'s integrator partner in Russia, *Triada Holding*, designed and installed the solution. The aim of monitoring system is to: 1) preserve this historic structure, 2) understand the structural behavior of the structure, 3) increase safety and 4) reduce maintenance costs.

A total of 16 optical sensors (*SMARTEC*'s *SOFO* sensors) are installed in order to continuously monitor average strain along the arch, curvature in both, horizontal and vertical directions and the deformed shape (Fig. 4). In order to distinguish thermal influences, 6 thermocouples are also installed. The data is sent remotely to the control room via a telephone line.

Fig. 4. *SOFO* sensor before (left) and after (right) protective cover was installed.

The installation of all the *SOFO* equipment was completed in June 2003, and the long-term monitoring began. The first year of data was used to establish a baseline to compare to future readings. Optical sensors were chosen for several reasons. Optical sensors are insensitive to corrosion and vibration so they will last for decades on the structure without any degradation. Once sufficient data is collected, the analyzing instrumentation can be disconnected and used for other applications – then returned to the Bolshoi Moskvoretskiy Bridge for periodic checks of the structure. Other reasons were related to the technical progress: the project also aimed to introduce innovative technologies in Russia.

Visual inspections uncovered several worrisome conditions on the bridge. The fiber-optic structural health monitoring system will help the bridge's operators to understand what corrective action, if any, is required to repair the bridge. Perhaps the data will show that the structure remains sound and there is no need to invest too much money for preemptive repairs.

4.2 Bitumen Joint Monitoring in a Dam

Plavinu is a dam belonging to a complex of three highly important hydropower plants (HPP) on the Daugava River in Latvia (see left photo of Fig. 5). In terms of capacity, this is the largest hydropower plant in Latvia and is the third level of the Daugava's hydroelectric cascade. It was constructed at 107 km from the mouth of Daugava River and is unique in terms of its construction: for the first time in the history of hydro-construction practice, a hydropower plant was built on clay and sand foundations with a maximum pressure limit of 40 m of water. The HPP building is merged with a water spillway. The entire building complex is extremely compact. There are ten hydro-aggregates installed at the hydropower plant and its current capacity is 870 MW.

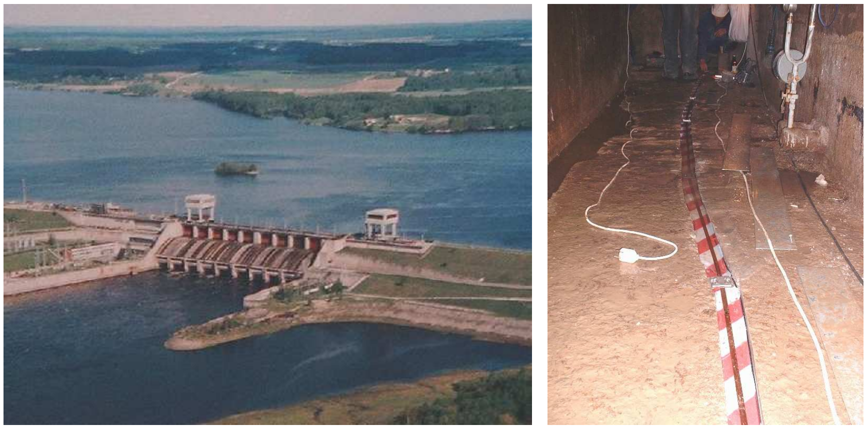

Fig. 5. General view of Plavinu dam in Latvia (left) and *SMARTape* installation in the inspection gallery (right).

One of the dam inspection galleries coincides with a system of three bitumen joints that connects two separate blocks of the dam. Due to the abrasion produced by the water, the joints lose bitumen and a redistribution of loads in the concrete arms appears. Since the structure is now nearly 40 years old, the structural condition of the concrete could be compromised due to ageing. Thus, the redistribution of loads could provoke a damage of the concrete arm and consequently, the flooding of the gallery. In order to increase the safety and enhance the management activities, it was decided to monitor the average strain in the concrete arm next to the joints. The *DiTeSt* system with *SMARTape* deformation sensor and *Temperature Sensing Cables* from *SMARTEC* were used for this application (see right photo of Fig. 5). The sensors were installed by the company *VND2* with the support of *SMARTEC* and configured remotely from the *SMARTEC* office in Switzerland. Threshold detection software with open-ground modules was installed in order to send automatically the pre-warnings and warnings from the *DiTeSt* instrument to the Control Office.

4.3 Gas Pipeline Monitoring

About 500 meters of a 35 years-old buried gas pipeline, located near Rimini, Italy, lie in an unstable soil. Distributed strain monitoring could be useful in order to improve vibrating wire strain gauges monitoring system, currently used on the site. The landslide has progressed in time and could deform the pipelines up to the point requiring putting them out of service. Three symmetrically disposed vibrating wires were installed in several sections spaced typically by 50-100 m, in the most stressed regions according to a preliminary engineering evaluation. These sensors were very helpful, but could not fully cover the length of the pipeline and they could only provide local measurements.

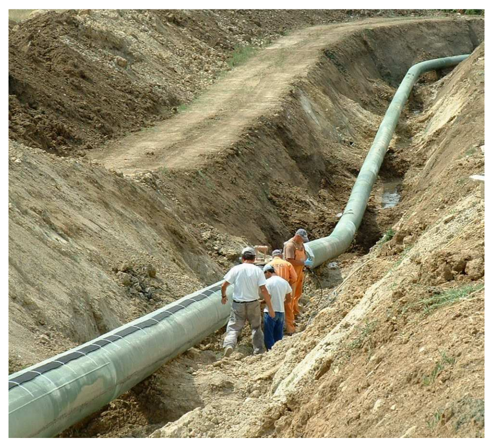

Fig. 6. *SMARTape* installed on the gas pipeline.

To dramatically increase the density of the strain reading, different types of distributed sensors were installed by *SMARTEC*: *SMARTape* and *Temperature Sensing Cable*. Three parallel lines built of five segments of *SMARTape* sensor were installed over the entire monitored length of the pipeline (see Fig. 6). The lengths of each segment were ranged from 71 m to 132 m, and the position of the sensors with respect to the pipeline axis were at 0°, 120° and –120° approximately.

The strain resolution of the *SMARTape* is 20 $\mu\varepsilon$, with spatial resolution of 1.5 m (and an acquisition range of 0.25 m) and provides the monitoring of average strains, average curvatures and deformed shape of the pipeline. The *Temperature Sensing Cable* was installed onto the upper line (0°) of the pipeline in order to compensate the strain measurements for temperature. The temperature resolution of the sensor is 1°C, with the same spatial and acquisition resolution than the

SMARTape. All the sensors are connected to a central measurement point by means of extension optical cables and connection boxes. A single *DiTeSt* reading unit is interrogating all the sensors from this point. Since the landslide process is slow, the measurement sessions are performed manually once a month. In case of an earthquake, an additional session of measurement is performed immediately after the event. All the measurements obtained with the *DiTeSt* system are correlated with the measurements obtained with vibrating wires. At present stage, the sensors have been measured for a period of two years, providing interesting information on the deformation induced by burying and by the landslide progression. A gas leakage simulation was also performed successfully using the *Temperature Sensing Cable* to detect the rapid cooling associated with a gas leak.

5. CONCLUSIONS

Fiber-optic sensors can be reliable tools for health monitoring in a variety of applications ranging from the human body to civil structures or works. Although both worlds seem to address very different realities, they both benefit from the intrinsic unique advantages of OFS, which are reviewed in this paper. Obviously, each class of applications has its own approaches. For medical applications, miniature size and total immunity to EMI are probably the most important advantages of OFS over other existing technologies. For civil structures applications, long-term reliability in all weathering conditions including lightning strokes and the possibility of having distributed sensors without any power supply along a single optical fiber spanning several kilometers, make this technology so attractive.

Thanks to different available technologies offering single-point, long gage, quasi-distributed or distributed sensors, the most appropriate ones could often be selected from commercially available solutions[37]. However, since adapted sensors solutions responding to application and market oriented specific needs are usually required, many products often require custom design. This is usually not a big challenge when the optical sensing core technology already exists commercially. Most of the customization often targets mainly sensors' packaging, system deployment, data acquisition management and data processing. This bundle of expertise and long-time experience from the *Roctest Group*, currently the largest supplier of OFS systems worldwide, will help to expand this high-tech market.

With the proliferation of fiber-optic sensors that have now started to be mass-produced in order to respond to the medical and civil engineering market needs, OFS technologies will become more and more accessible for an increasing number of applications. Definitely, the broad range of health monitoring is probably the most promising one. Now that products and technologies are more recognized and better accepted by the end-users communities, OFS will further expand in markets in which their theoretical and technical advantages over other competitive sensing technologies are already apparent.

REFERENCES

1. E. Udd *in* "Fiber optic sensors: an introduction for engineers and scientists", John Wiley & Sons, Wiley-Interscience (1991).
2. D.A. Krohn *in* "Fiber optic sensors, fundamentals and applications, 2nd Edition", Instrument Society of America, Research Triangle Park, NC (1992).
3. D. Inaudi "Fiber optic smart sensing" *in* "Optical Measurement techniques and applications", P. K. Rastogi editor, Artech House, pp. 255-275 (1997).
4. E. Udd *in* "Fiber optic smart structures", John Wiley & Sons, Wiley-Interscience, New-York (1995).
5. D. Inaudi "Photonic sensing technology in civil engineering applications" *in* "Handbook of optical fibre sensing technology", J. M. Lopez-Higuera editor, Wiley (2002).
6. D. Inaudi and B. Glišić "Integration of distributed strain and temperature sensors in composite coiled tubing", *SPIE Smart Struct. and Mat. Conf.* (San Diego, Ca, USA), Feb. 27th-March 2nd (2006).
7. T. Bae *et al.* "Interferometric fiber-optic sensor embedded in spark plug for in-cylinder pressure measurement in engines", *Appl. Opt.*, **Vol. 42 (6)**, pp. 1003-1007 (2003).
8. C. Hamel and É. Pinet "Temperature and pressure fiber-optic sensors applied to minimally invasive diagnostics and therapies", *Proc. SPIE BiOS* (San Jose, Ca, USA) paper #6083-5 (2006).
9. N. Uchida and N. Uesugi "Infrared optical loss increase in silica fibers due to hydrogen", *J. Lightw. Techn.*, **Vol. LT-4 (8)**, pp. 1132-1138 (1986).
10. A. Iino *et al.* "Mechanisms of hydrogen-induced losses in silica-based optical fibers", *J. Lightw. Techn.*, **Vol. 8 (11)**, pp. 1675-1678 (1990).

11. J. Wallace "Carbon coating reduces darkening", *Laser Focus World*, December 1, pp 15-16 (2004).
12. D. Inaudi and B. Glišić "Long-range pipeline monitoring by distributed fiber optic sensing", *Proc. IPC2006, 6th Int. Pipeline Conf.* (Calgary, Al, Canada), Sept. 25th-29th (2006).
13. C. Belleville and G, Duplain "Fabry-Perot optical sensing device for measuring a physical parameter", *US Patents* #5,202,939 (1993) & #5,392,117 (1995).
14. Pinet É. *et al.* "Miniature fiber-optic pressure sensor for medical applications: an opportunity for intra-aortic balloon pumping (IABP) therapy", *Proc. of SPIE*, **Vol. 5855**, pp. 234-237 (2005).
15. W. Habel and D. Hofmann "Determination of structural parameters concerning load capacity based on fiber Fabry-Perot-interferometers", *Proc. SPIE*, **Vol. 2361**, pp. 176-179 (1994).
16. P. Ferdinand *et al.* "Application of Bragg grating sensors in Europe", *12th Int. conf. on OFS '97- Optical Fiber Sensors*, Williamsbourg, OSA Technical Digest Series, **Vol. 16**, pp. 14-19 (1997).
17. D. Inaudi "Field testing and application of fiber optic displacement sensors in civil structures", *12th Int. conf. on OFS '97- Optical Fiber Sensors*, Williamsbourg, OSA Technical Digest Series, **Vol. 16**, pp. 596-599 (1997).
18. D. Inaudi *et al.* "Embedded and surface mounted fiber optic sensors for civil structural monitoring", *Smart Struct. & Mat. Conf.*, San Diego, SPIE **Vol. 3044**, pp. 236-243 (1997).
19. L. Thévenaz *et al.* "Monitoring of large structure using distributed Brillouin fiber sensing", *SPIE 13th Int. Conf. on Opt. Fiber Sens OFS-13.*, Kyongju, Korea, **Vol. 3746**, pp. 345-348 (1999).
20. M. Niklès *et al.* "Simple Distributed temperature sensor based on Brillouin gain spectrum analysis", SPIE OFS-10, *10th Int. Conf. on Opt. Fiber Sens.*, Glasgow, UK, **Vol. 2360**, pp. 138-141 (1994).
21. J. Geng *et al.* "An improved model for the fully distributed temperature single-mode fibre optic sensor based on Raman optical frequency-domain reflectometry", *J. Opt. A: Pure Appl. Opt.*, **Vol. 6 (10)**, pp. 932-936 (2004).
22. J. Park *et al.* "Sensors - Raman-based distributed temperature sensor with Simplex coding and link optimization", *IEEE Photon. Technol. Lett.*, **Vol. 18 (17-20)**, pp. 1879-1881 (2006).
23. A. Kantrowitz *et al.* "Initial clinical experience with intra-aortic balloon pumping in cardiogenic shock", *J. Am. Med. Assoc.*, **Vol. 203(2)**, pp. 135-140 (1968).
24. G. A. Maccioli *et al.* "The intra-aortic balloon pump: a review", *J. Cardiothoracic Anesthesia*, **Vol. 2(3)**, pp. 365-373 (1988).
25. D. F. Torchiana *et al* "Intraaortic balloon pumping for cardiac support: trends in practice and outcome, 1968 to 1995", *J. Thor. Cardio. Surg.*, **Vol. 113(4)**, pp. 758-769 (1997).
26. R. M. Gardner "Direct blood pressure measurement – Dynamic response requirements", *Anesthesiology*, **Vol. 54**, pp 227-236 (1981).
27. P. Reilly and R. Bullock *in* "Head Injury, Pathophysiology and Management", (Reilly P. & Bullock R. Eds.) ISBN10 0-340-80724-5 (2005).
28. J. D. Miller *et al.* "Significance of intracranial hypertension in severe head injury", *J. Neurosurg.*, **Vol. 47**, pp. 503-516 (1977).
29. L. F. Marshall *et al.* "The outcome with aggressive treatment in severe head injuries. Part II: Acute and chronic barbiturate administration in the management of head injury", *J. Neurosurg.*, **Vol. 50**, pp. 26-30 (1979).
30. T. W. Langfitt *et al.* "Transmission of increased intracranial pressure: I. Within the craniospinal axis", *J. Neurosurg.*, **Vol. 21**, pp. 989-997 (1964).
31. J. D. Miller *et al.* "Inaccurate pressure readings for subarachnoid bolts", *Neurosurg.*, **Vol. 19**, pp. 253–255 (1986).
32. A. D. Mendelow *et al.* "A clinical comparison of subdural screw pressure measurements with ventricular pressure", *J. Neurosurg.*, **Vol. 58**, pp. 45–50 (1983).
33. B. North and P. Reilly P. "Comparison among three methods of intracranial pressure recording", *Neurosurg.*, **Vol. 18**, pp. 730–732 (1986).
34. G. Gambardella *et al.* "Monitoring of brain tissue pressure with a fiberoptic device", *Neurosurg.*, **Vol. 31**, pp. 918-922 (1992).
35. A. Marmarou *et al.* "Multicenter clinical evaluation of a new ICP device", *in* "Intracranial Pressure IX", (Nagai H., Kamiya K. & Ishii S. Eds.), Springer-Verlag, Berlin, pp. 18–19, (1994).
36. M. Yoshihara *et al.* "A fiberoptic device suitable for subdural pressure measurement", *in* "Intracranial pressure VIII", (Avezaat C. J. J., Van Eijndhoven J. H. M. & Maas A. I. R., Eds.), Springer-Verlag, Berlin, pp. 20-24 (1993).
37. *FISO Technologies Inc.*: www.fiso.com, *SMARTEC S.A.*: www.smartec.ch or *Roctest Ltd.*: www.roctest.com; Those companies are all members of the *Roctest Group*.