Application of Fiber Optic Sensors to Structural Monitoring

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1 Monitoring as a structure management tool

The construction and maintenance of the civil infrastructure represents between 10% and 20% of the public investment in most European countries. In the last decade we have however witnessed an increasing shift from investments in the construction of new structures to the maintenance and the lifetime extension of the existing ones. With the exception of the high-speed train lines, most of the transportation network, including highways and railway, is completed and in service. However, the steady increase of the passengers and goods circulating in the continent, amplified by the free circulation policy introduced by the European Community, is putting the civil infrastructure under a rude test. Many bridges and tunnels built a few tens of years ago need repair and in many case an extension of their bearing capacity and lifetime that exceed the original plans. Besides the direct costs associated with these interventions, the disruption to the normal use of the structures causes additional inconvenience including traffic jams and accidents that carry additional hidden costs.

The authorities managing the civil infrastructures face the challenge of maintaining the transportation network in a satisfactory state using a limited budget and with little perturbation to its normal use. This task is far more complex than that of building new structures and requires new management instruments.

Structural health monitoring is certainly one of the most powerful management tools and is therefore gaining in importance in the civil engineering community. Monitoring is often and mistakenly presented as a security tool. This is however only the case for the few structures that present a high potential danger such as nuclear power plants and dams. For most other structures the security risks are very limited and fortunately we rarely witness casualties due to a structural collapse. For all other structures, monitoring should be seen as a management tool delivering information on the state of a single structure or on a network of structures. In what we call the information age, structural health monitoring closes the gap between the seemingly inert world of structures and the frenetic one of information technology.

A typical health monitoring system is composed of a network of sensors that measure the parameters relevant to the state of the structure and its environment. For civil structures such as bridges, tunnels, dams, geostructures, power plants, high-rise buildings and historical monuments, the most relevant parameters are:

- Physical quantities: position, deformations, inclinations, strains, forces, pressures, accelerations, vibrations.
- Temperatures.
- Chemical quantities: humidity, pH, chlorine concentration.
- Environmental parameters: air temperature, wind speed and direction, irradiation, precipitation, snow accumulation, water levels and flow, pollutant concentration.

Conventional sensors based on mechanical and/or electrical transducers are able to measure most of these parameters. In the last few years, fiber optic sensors have made a slow but significant entrance in the sensor panorama. After an initial euphoric phase when optical fiber sensors seemed on the verge of invading the whole world of sensing, it now appears that this technology is only attractive in the cases where it offers superior performance compared to the more proven conventional sensors. The additional value can include an improved quality of the measurements, a better reliability, the possibility of replacing manual readings and operator judgement with automatic measurements, an easier installation and maintenance or a lower lifetime cost. The first successful industrial applications of fiber optic sensors to civil structural monitoring demonstrate that this technology is now sufficiently mature for a routine use and that it can compete as a peer with conventional instrumentation.

2 Strain vs. long-gage sensors

The monitoring of a structure can be approached either from the material or from the structural point of view. In the first case, monitoring will concentrate on the local properties of the materials used in the construction (e.g. concrete, steel, and timber) and observe their behavior under load or aging. Short base-length strain sensors are the ideal transducers for this type of monitoring approach. If a very large number of these sensors are installed at different points in the structure, it is possible to extrapolate information about the behavior of the whole structure from these local measurements. Since it is impossible to cover the whole structure with such sensors, some a-priori knowledge about the most interesting and representative locations to be analyzed is required. It will than be assumed that the rest of the structure lying between the measurement points will behave in a similar or predictable way.

In the structural approach, the structure is observed from a geometrical point of view. By using long-gage sensors with measurement bases of the same order of magnitude as the typical size of the structure (for example a few meters for a bridge), it is possible to gain information about the deformations of the structure as a whole and extrapolate on the global behavior of the construction materials. The structural monitoring approach will detect material degradation like cracking or flow only if they have an impact on the form of the structure. Since it is reasonably possible to cover the whole structure with such sensors, no a-priori knowledge about the position of the degradations to be observed (for example the exact position of a crack) is required. This approach usually requires a reduced number of sensors when compared to the material monitoring approach.

The availability of reliable strain sensors like resistance strain gages or, more recently, of fiber optic strain sensors as Fabry-Perot interferometers and Fiber Bragg Gratings has historically concentrated most research efforts in the direction of material monitoring rather than structural monitoring. This latter has usually been applied using external means like triangulation, dial gages and invar wires. Fiber optic sensors offer an interesting means of implementing structural monitoring with internal or embedded sensors.

3 Long-Fiber Optic Sensor Types

There are a great variety of fiber optic sensors [1, 2, 3, 4] for structural monitoring, developed in both the academic and the industrial areas. Unlike the USA, where most efforts seem concentrated to strain sensing, Europe is developing and producing a great variety of sensors for the most disparate types of measurement and application. In this overview we will concentrate on sensors for civil health monitoring that have reached an industrial level or are at least at the stage of advanced field trials.

The following table resumes the sensor technologies that will be discussed in the next paragraphs:

	Main Measured Parameters	Selection of active groups and companies (see text for details)
SOFO	Displacement	SMARTEC, IMAC-EPFL (Switzerland)
Microbending	Displacement	Osmos-DehaCom (France)
Bragg gratings	Strain, temperature, pressure, (displacement)	FOS&S (Belgium)
		LETI (France)
		EMPA (Switzerland)
		Naval Research Laboratory (USA)
		CiDRA (USA)
		Blue Road Research (USA)
		and many more...
Fabry-Perot	Strain	Fiso, Rocktest (Canada)
		Luna Innovations (USA)
		BAM (Germany)
Raman	Distributed temperature	SENSA/Schlumberger (UK/USA)
Brillouin	Distributed temperature and strain	Omnisens, MET-EPFL, SMARTEC (Switzerland)
		ANDO (Japan)
Hydrogel	Humidity, water ingress	Univ. of Strathclyde, Glasgow (UK)

Table 1 Selection of Fiber Optic Sensors for civil structural monitoring.

3.1 SOFO Displacement Sensors

The SOFO system is a fiber optic displacement sensor with a resolution in the micrometer range and an excellent long-term stability. It was developed at the Swiss Federal Institute of Technology in Lausanne (EPFL) and is now commercialized by SMARTEC in Switzerland [5, 6, 7].

The sensor consists of a pair of optical fibers installed in the structure to be monitored. One of the fibers, called measurement fiber, is in mechanical contact with the host structure itself, being attached to it at the two anchorage points, pre-tensioned in between and protected with a plastic pipe. The other, the reference fiber, is placed loose in the same pipe. All deformations of the structure will then result in a change of the length difference between these two fibers. To make an absolute measurement of this path unbalance, a double Michelson interferometer in is used. The first interferometer is made of the measurement and reference fibers, while the second is contained in the portable reading unit. This second interferometer can introduce, by means of a scanning mirror, a well-known path unbalance between its two arms. Because of the reduced coherence of the source used (the 1.3 micron radiation of a LED), interference fringes are detectable only when the reading interferometer exactly compensates the length difference between the fibers in the structure. If this measurement is repeated at successive times, the evolution of the deformations in the structure can be followed in time.

The precision and stability obtained by this setup have been quantified in laboratory and field tests to 2 micron (2/1000 mm), independently from the sensor length over more than five years. Even a change in the temperature of in fiber transmission properties does not affect the precision, since the displacement information is encoded in the coherence of the light and not in its intensity.

More than 2600 SOFO sensors have been successfully used to monitor more than 100 structures, including bridges, tunnels, piles, anchored walls, dams, historical monuments, nuclear power plants as well as laboratory models.

3.2 Microbend Displacement Sensors

An alternative fiber optic sensor useful for the measurement of length variations is based on the principle of microbending. In that setup, an optical fiber is twisted with one ore more other fibers or with metallic wires [8] along its

sensing length. When this fiber optic twisted pair is elongated, the fibers will induce bending in one-another and cause part of the light to escape from the fiber. By measuring the intensity of the transmitted light it is therefore possible to reconstruct the deformation undergone by the structure on which the sensor is mounted.
A system based on this principle has been marketed for some years through Sicom and more recently by Osmos Deha-Com in France. Typically obtainable resolutions are of 30 μm for short periods (below one day) and 100 μm for the long-term. Microbending sensors are conceptually simple, however temperature compensation, intensity drifts, system calibration and the inherently non-linear relationship between intensity and elongation still present some challenges. This type of sensor seems particularly appropriate for short-term and dynamic monitoring as well as for issuing alarms.

3.3 Bragg Grating Strain Sensors

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 white light 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 spectrum of the reflected light [9]. This is typically done using a tunable filter (such as a Fabry-Perot cavity) or a spectrometer. Resolutions of the order of 1 με and 0.1 °C can be achieved with the best demodulators. If strain and temperature variations are expected simultaneously, it is necessary to use a free reference grating that measures the temperature alone and 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 potential. 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 a trade-off between the number of grating and the dynamic range of the measurements on each of them.
Because of their length, fiber Bragg gratings can be used as replacement of conventional strain gages and installed by gluing them on metals and other smooth surfaces [10]. With adequate packaging they can also be used to measure strains in concrete over basis length of typically 100 mm.
A large number of research and development projects for this type of sensors are underway worldwide [11]. In north America, many research and industrial projects are underway to develop monitoring systems based on Bragg Gratings. Just to name a few, the US Naval Research Laboratory has an extensive monitoring project, CiDRA is developing a large verity of fiber optic sensors for the oil and gas intrustry, Blue Road Research is developing multi-axis sensors and insturmenting refurbished bridges in Oregon and Elecrophotonics in Canada produces Bragg-based monitoring systems.

Two European projects (STABILOS [12] and COSMUS) focussd on the application of this technology to the measurement of movements in tunnels, mines and other geostructures. In particular, an array of Bragg grating has been installed in the Mont Terri tunnel in Switzerland. The LETI group in France has also used this technology to monitored lock gates [13] and is introducing the system in the nuclear power industry [14], while EMPA (Swiss Federal Laboratories for Materials Testing and Research) has installed them in the Luzzone Dam [15] and in a cable-stayed bridge. Finally, the University of Cantabria in Spain is developing sensors for the electrical power generation industry including strain and acceleration sensors (also base on other sensing techniques) [16]. A comprehensive review by Pierre Ferdinand on the applications of Bragg gratings in Europe can be found in the references [11]

3.4 Fabry-Perot strain sensors

Extrinsic Fabry-Perot Interferometers (EFPIs) are constituted by a capillary silica tube containing two cleaved optical fibers facing each others, but leaving an air gap of a few microns or tens of microns between them. When light is launched into one of the fibers, a back-reflected interference signal is obtained. This is due to the reflection of the incoming light on the glass-to-air and on air-to-glass interfaces. This interference can be demodulated using coherent or low-coherence techniques to reconstruct the changes in the fiber spacing. Since the two fibers are attached to the capillary tube near its two extremities (with a typical spacing of 10 mm), the gap change will correspond to the average strain variation between the two attachment points [1,9].
In north America, companies like Sensa in the USA and FISO in Canada offer interesting sensors based on this

technology. Contrary to the rest of the world, Europe seems to pay relatively little attention to this interesting sensor technique. A notable exception is the group at BAM in Berlin (Germany), that is using these sensors to monitor the early-age deformations of mortars [17] and has applied them to the monitoring of a concrete bridge in Charlottenbourg [18].

3.5 Raman Distributed Sensors

Raman scattering is the result of a non-linear interaction between the light traveling in a fiber and silica. When an intense light signal is shined into the fiber, two frequency-shifted components called respectively Raman Stokes and Raman anti-Stokes, will appear in the back-scattered spectrum. The relative intensity of these two components depends on the local temperature of the fiber. If the light signal is pulsed and the back-scattered intensity is recorded as a function of the round-trip time, it becomes possible to obtain a temperature profile along the fiber [19]. A system based on Raman scattering is commercialized by Sensa-Schlumberger in the UK/USA. Typically a temperature resolution of the order of 1°C and a spatial resolution of less than 1m over a measurement range up to 10 km is obtained for multi-mode fibers. A new system based on the use of singlemode fibers should extend the range to about 30km with a spatial resolution of 8 m and a temperature resolution of 2°C.

3.6 Brillouin Distributed Sensors

Brillouin scattering sensors show an interesting potential for distributed strain and temperature monitoring [20]. Systems able to measure strain or temperature variations of fibers with length up to 50 km with spatial resolution down in the meter range are now demonstrating their potential in the first field trials. 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 diffracted 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 travelling 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 [21]. This is the result of the change the acoustic velocity according to variation in the silica density. 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 times. A commercial system based on spontaneous Brillouin scattering is available from ANDO (Japan).

Systems based on the stimulated Brillouin amplification have the advantage of working with a relatively stronger signal but 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. The MET (Metrology laboratory) group at Swiss Federal Institute of Technology in Lausanne (EPFL) proposed a more elegant approach [22]. It consists in generating both waves from a single laser source using an integrated optics modulator. This arrangement offers the advantage of eliminating the need for two lasers and intrinsically insures that the frequency difference remains stable independently from the laser drift. Omnisens and SMARTEC (Switzerland) commercialize a system based on this setup and named DiTeSt. It features a measurement range of 10 km with a spatial resolution of 1 m or a range of 25 km with a resolution of 5 m. The strain resolution is 20 $\mu\varepsilon$ and the temperature resolution 1°C. The system is portable and can be used for field applications. These values are close to the theoretical limits for a Brillouin system.

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. Similarly to the temperature case, knowing the frequency shift of the unstrained fiber will allow an absolute strain measurement.

3.7 Hydrogel Distributed Humidity Sensors

Many of the degradations that can occur to the most used structural materials: concrete and steel, have a chemical origin. It is therefore interesting to monitor the presence and the concentration of potentially harmful chemicals such as humidity, chlorine as well as the variations of pH. Chemical measurements with fiber optic sensors are much less developed than those of physical parameters and temperature. It is therefore interesting to cite the development of a distributed humidity sensor that is based on the use of a particular hydrogel capable of transforming a humidity variation in a change in its dimensions [23]. This allows the transformation of a difficult chemical measurement in a much easier strain or elongation measurement. A first sensor, developed at Strathclyde University, is based on a hydrogel that swells when wetted. The expansion of the hydrogel induces microbending losses in an optical fibers that can be detected with a standard Optical Time Domain Interferometer (OTDR). The system shows potential for measurement of water ingress and humidity in large structures and in areas that are difficult to inspect. In one of the first field demonstrations, the system was used to detect an incomplete grouting of a post-tensioning cable duct [24]. By using another type of hydrogel, it is expected that this type of sensors will be capable of measuring other chemicals and in particular the pH chances associated with carbonation in concrete.

4 Outlook

In the first decade of Fiber Optic Sensing technology, most efforts were concentrated on the different subsystems. The demodulators and the multiplexing architectures have seen important developments and many technologies are today mature for field and industrial applications. Some techniques have emerged like fiber Bragg grating sensors, low-coherence sensors and external Fabry-Perot interferometers, others are living a second youth like intensity based sensors. New technologies, like Brillouin scattering, are still in the development phase and many more will certainly emerge in the future. Portable reading units are getting smaller each year and have been successfully operated in demanding environment like those found in marine and civil engineering applications.

In these last few years, the maturity of the reading unit subsystems has driven toward the development of reliable sensors and installation techniques. Fiber optic sensors have been embedded successfully in a number of materials and structures including composites, concrete, timber and metals. Some of these efforts are leading to industrial products and this will allow the instrumentation of structures with an increasing number of sensor at reasonable prices. It can be estimated that a few thousands fiber optic sensors have been installed to date in civil structures alone. The improvement of packaging techniques and the reduction of costs will also be helped by the continuous development of fiber optic components like fibers, cables, connectors, couplers and optical switches driven by the much larger telecommunication market.

With structures equipped with hundreds or even thousands of sensors, measuring different parameters each second, the need of automatic data analysis tools will become increasingly urgent. Efforts have already been directed in this direction. Unfortunately, each type of structure and sensor needs specific processing algorithms. Vibration and modal analysis have attracted many research efforts and geometrical analysis like curvature measurements can be easily applied to different types of structures like bridges, tunnels or spatial structures. Many other concepts like neural networks, fuzzy logic, artificial intelligence, genetic algorithms and data mining tools will certainly find an increasing interest for smart processing applications.

The ubiquity of digital networks and cellular communication tools increases the flexibility of the interfacing and makes remote sensing not only possible but even economically attractive. Of course every remote sensing system has to be based on reliable components since the need of manual interventions obviously reduces the interest of such systems.

Smart structures will both demand and produce sophisticated smart sensing and processing systems. Continuous developments in actuators based on piezoelectric materials and shape memory alloys complement ideally the progress made in sensor and processing technology. Most efforts are directed towards vibration damping, noise reduction and shape control, mainly for the aeronautics and space industry. Civil engineering is also producing interesting smart structures applications in particular for seismic control and many experiments have been conducted at least on reduced scale models. Other applications like vibration and modal control of large civil structures like suspended bridges could

be potentially interesting but the forces required to achieve these results are still exceedingly high. In a first phase we can expect that smart structures will be used to increase the comfort of the users and the life-span of the structures by reducing the amplitude of its oscillations under seismic, traffic or aerodynamic loads. These systems will not have a major structural role and their failure would not lead to important structural damages. The acceptance of smart structures where the control system plays a structural role will require well-proved and reliable systems and will probably appear first in high-risk structures like fighters airplanes or space structures.
More than the developments in each of the smart sensing subsystems, it is however the successful integration of different technologies that will lead to increasingly useful applications. This integration is possible only in highly multidisciplinary teams including structural, material and sensor engineers. The necessary competencies already exist in many industries and universities but have to be brought together and adapted to each other needs.
The final judge of Fiber Optic Sensors systems will however be the market. Even well designed and perfectly functioning systems will have to prove their economic interest in order to succeed. Unfortunately the evaluation of the benefits of a sensing system is often difficult and the initial additional investments are paid back only in the long run. Furthermore it is not easy to quantify the benefits of the increased security of one structure or of a better knowledge of its aging characteristics. In many fields including civil engineering and aeronautics we are however witnessing an investment shift from the construction of new structures to the maintenance and the life-span extension of the existing ones. In these domains, smart sensing technologies have certainly an important role to play.

5 Conclusions

The monitoring of new and existing structures is one of the essential tools for a modern and efficient management of the infrastructure network. Sensors are the first building block in the monitoring chain and are responsible for the accuracy and reliability of the data. Progress in the sensing technology can therefore be produced by more accurate measurements, but also from systems that are easier to install, use and maintain. In the recent years, fiber optic sensors have moved the first steps in structural monitoring and in particular in civil engineering. Different sensing technologies have emerged and quite a few have evolved into commercial products.
It is difficult to find a common reason for the success of so diverse types of sensors, each one seems to have found a niche where it can offer performance that surpass or complement the ones of the more traditional sensors. If three characteristics of fiber optic sensors should be highlighted as the probable reason of their present and future success, I would cite the stability of the measurements, the potential long-term reliability of the fibers and the possibility of performing distributed and remote measurements. In the near future it is therefore to expect that fiber optic sensors will consolidate their presence in the structural sensing industry.

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