Structural Health Monitoring Fiber Optic Sensors

K. Loupos and A. Amditis

Abstract Following the modern technological needs requiring highly increased safety and standards in structures (especially civil) located in densely populated areas with increased seismic activity or other safety critical perturbations, various technologies have been developed, aiming towards improved monitoring requirements, needs for structural performance evaluation and increased safety in general. Fibre-optic technologies provide a lot in the field of structural monitoring as a basis for condition assessment before, during or after a random (e.g. earthquake), human-imposed (e.g. blast) or other operational (e.g. increased load) event. This chapter provides an overview of the structural health monitoring concept and particular requirements per application area, the monitoring systems currently available on the market and a thorough analysis of the fibre optic technologies available today. The chapter starts with the definition of structural health monitoring in terms of the specific industrial needs for monitoring and sensing. It then presents a detailed analysis of the fibre-based monitoring solutions available, their concept of operation and operational (measuring) characteristics and capabilities and closes with a presentation of typical fibre optic installation examples where fibre optics are installed for structural health monitoring.

1 Introduction

1.1 Structural Health Monitoring

By structural health monitoring (SHM) we usually refer to any process or activity relating to damage detection and classification in any engineering structure (civil, energy, aerospace, mechanical etc.). SHM is widely used nowadays as it proves of primal importance for engineers to improve safety and maintainability of critical structures. SHM involves various sensing and/or monitoring technologies and

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usually embedded systems able to capture, store and analyse measuring data straight from the structure being monitored. This way the health, operational capability and performance of structures can be assessed through damage classification. Structural health monitoring is usually very associated with damage classification of the structure of interest. This is usually a process following the monitoring task and refers to the determination of damage in the structure that will be used to characterise the whole building regarding its overall operational performance. This also includes safety classification which is in turn used to drive maintenance or safety teams' decision such as the initiation of maintenance activities, the shutdown of the particular section/building etc. recently SHM activities are also closely linked to life-safety and economic benefits that can be enhanced in this aspect [1].

In this framework, the term "damage" is perceived as changes to the physical (geometric) properties of the structures and/or it constituting materials that if modified might affect the overall system stability and thus safety and structural integrity.

Considering civil structure health monitoring, currently we are lacking of quantifiable methods to determine the status of structures after major earthquake or other event that could cause damages to the structure itself. SHM methodologies can be used to determine the status of the structure and thus minimize uncertainties regarding post-event damage assessment. Further to this, SHM methodologies and technologies have a lot to offer in structures undergoing ageing effects. Therefore the ability of monitoring and investigating a structure's health at any time has become extremely important and this is expected to increase more and more over time [1].

SHM activities are implemented on a vast variety of applications, usually critical structures with high safety and reliability requirements.

1.2 Structural Health Monitoring Requirements

Structural health monitoring includes various modules or structural system parts with different monitoring requirements that may depend on operational or other characteristics of the structures themselves. The inspection and maintenance technique that will be used (and is allowed to be used) over such structures depends on the type, performance, safety criticality and ownership while may sometimes be imposed even by law. The largest challenge over real-time monitoring systems is that all these infrastructures are in general unique so per case solutions often need to be investigated [2].

Some of the reasons often leading to the need for structural health monitoring are the following:

- Physical or other alterations to current structure or its parts;
- Structures affected by external or surrounding works or demolitions;

- Critical structures monitoring to ensure flawless operation and performance;
- Monitoring of structural material degradation;
- Structural system assessment after hazardous events;
- Assessment of structure fatigue and system performance;
- Other effects that may question the integrity of the structure.

Some typical applications of SHM are presented in the following table divided per application field (Fig. 1, Table 1).

The selection of the most appropriate sensing technology requires a close investigation of the following parameters required by each industrial application:

- **Measuring scale**: this would require defining the minimum and maximum stress or strain that needs to be measured and would significantly direct towards the available sensing devices, elements and systems.
- **Measuring accuracy**: that defines the accuracy that the monitoring system should have. This is usually expressed in μStrain.
- **Measuring speed**: that defines the time lapse of the monitoring samples that the sensing system will acquire from the structure.
- **Spatial Resolution**: that defines the density of the sensing points on the actual structure. Some monitoring requirements may pose for dense or more spatial separated sensing positions.
- **Hazard-ness of monitoring structure**: a possible hazardous environment would reject some types of monitoring that are not qualified for use in such environments (most of the times due to EMC reasons).

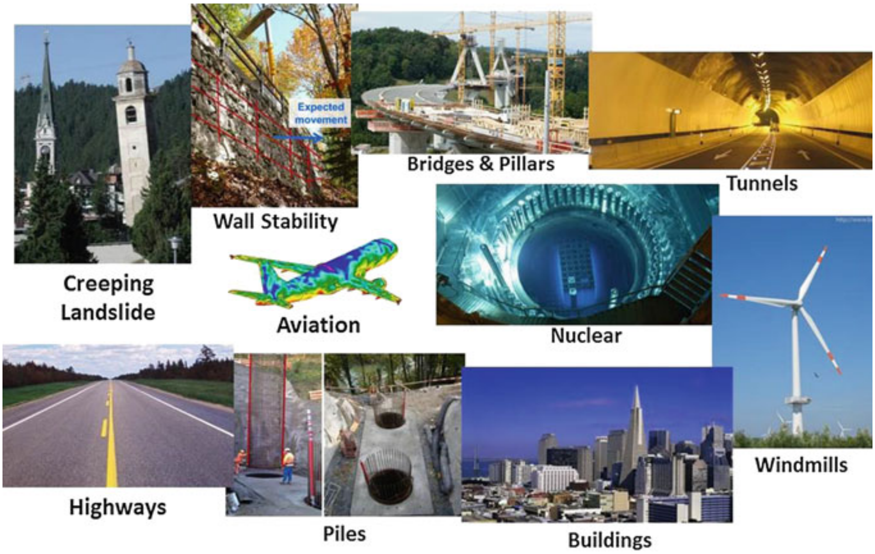

Fig. 1 Applications of structural health monitoring

Table 1 Indicative SHM applications

Application domain	Structure types
Civil infrastructure	• Critical civil buildings • Stadiums • Dams • Ports • Hospitals • Historical structures
Road transport	• Bridges • Tunnels • Highway fragments
Aerospace	• Airports • Aircraft structures (wings etc.)
Energy	• Wind turbines • Oil/gas platforms • Power plants
Mining	• Mining Shovels
Life line	• Water plants • Pipelines
Earth	• Land monitoring • Shores • Other terrestial
Marine	• Port/shores • Ships/yachts • Cargo vessels
Other industry	• Large Machinery • Other equipment

- **Power consumption**: this might also restrict monitoring options defined by the presence of electricity (and types) at the monitoring site.
- **Portability of sensing system**: this would again define the portability (e.g. hand held etc.) of the monitoring system.
- **Installation restrictions**: that would be defined from the ability and restrictions that we may have for the installation of the monitoring system on-site (e.g. space available, connectivity etc.).
- **Cost**: cost considerations for the purchase of the monitoring system, sensors, accompanied software and maintenance should be considered here.

2 Structural Health Monitoring Systems

2.1 Structure-Installed Monitoring Systems

By the term "site-specific" we consider the monitoring systems that are embodied on the structure of interest. Usually they are supported by some interrogation instruments installed locally or remotely but the difference of these sensors is that they are physically located at the positions of interest on the actual monitored structure. A summary of the existing systems has been included below.

2.1.1 Strain Gauges and Accelerometers

Strain gauges (or strain gages) are devices used very widely in SHM applications. Their most common configuration consists of a metallic foil pattern fixed on some insulating flexible backing. The gauge is usually glued on the position of interest and follows its deformation. As the gauge is deformed, its resistivity changes and thus we are able to correlate this change of resistivity to actual spatial deformation. The resistance is usually measured using a Wheatstone bridge. Strain gauges are used very widely as the sensing elements for structural health monitoring due to their low cost, ease of installation but also high sensitivity in detecting structural deformations of civil or other structures. Strain gauges are most of the times connected with wired or wireless systems increasing their total cost and sometimes restricting their operational (measuring) performance [1]. The combination of strain gauges with acceleration sensors has proved beneficial for SHM applications where the overall structure assessment is of interest.

2.1.2 Fibre Optics Systems

The principle of operation of Fibre Optic (FO) systems used for SHM applications relies in the measurement of deformation of simple (and cheap) telecommunication fibre optic cables. FO systems are currently widely used due to their ease of installation, low price (for installation and maintenance) as well as being often associated to long-time monitoring capabilities. FO sensors are also more durable, stable to sensitivity and insensitive to outside perturbations (EMC etc.). FO systems can be divided into point and distributed sensing, the latter making the system more attractive for spatial monitoring of structures (i.e. measurements along their whole cable length) that has opened a new dimension into structural monitoring. The technology is based on Raman and Brillouin light scattering that make use of the non-linear relation between the light that is passed through the FO cable and the surrounding silica material. By passing light of known wavelength through a FO cable and measuring the scattered light (wavelength difference from initial pulse) we are able to acquire the physical properties of the fibre itself and thus correlate this to structural deformation [3].

2.1.3 Micro-Electro-Mechanical Systems (MEMS) Sensors

Micro-electro-mechanical systems (MEMS) are assimilated devices or systems that integrate electrical and mechanical components for sensing as well as controlling, movement, actuating etc. MEMS can be forming various sensing components such as accelerometers, gyroscopes, strain gages, pressure or flow sensors and many more. Their concept of operation relies in the piezo-resistive effects of silicon and germanium [4]. MEMS sensors are usually quite smaller in size while can be found in low price and are generally low power and easily integrated.

2.1.4 RIFD Tags

Radio-frequency identification (RFID) tags are quite often used for structural health monitoring applications. To solve power requirement issues usually passive RFIDs are being used. However due to the fact that RFIDs can only drive imperceptible power devices (temp sensors etc.) they are not being directly used to sense deformation but are used to accurately localise particular positions of the structure and thus provide feedback on the relative positions of particular structure sections or positions of interest. There are recent works that have combined RFID tags with measuring sensors (similar to gauge) but these types are considered of low technology readiness and are rarely used in application specific case.

2.2 Site-Installed Monitoring Systems

With on-site monitoring systems we consider the monitoring systems that are used at the structure during the inspection time and require measuring apparatus to be present. This includes laser, radar, acoustic sensing and infrared spectroscopic techniques. A summary of each system has been included below.

2.2.1 Laser Systems

Non-contact laser systems are being also very extensively used in SHM applications whenever Non-Destructive-Testing (NDT) is required. Such laser systems operate via an excitation using pulse and continuous laser and their sensing capabilities are based on laser interferometry and/or Laser Doppler Vibrometers (LDV). Such systems are usually used for applications where no actual surface contact is possible (or not allowed) but are usually more expensive systems and their operation is most of the times prohibited for applications with high safety standards (e.g. nuclear reactors, gas/oil tanks etc.). These systems are often supported with some user interface that represents to the user the measurement results in simple form or can be parts of assessment interfaces that also create 3D representations of the structure.

2.2.2 Microwave Radar and Ground-Penetrating Radar (GPR)

Ground Penetrating Radar systems are also often used in SHM applications. GPR techniques involve the emission of electromagnetic emission (EM) towards the structure surface and analysis of the reflected signal (timing, strength, phase etc.) that can define the structure characteristics and properties. This usually involves a variety of waver forms (e.g. pulses, sine-waves etc.) and frequencies (1–10 GHz) depending on the structure material and depth of interest, known also as Ultra-Wide-band (UWB) technologies. The primal advantage of this technique is that they can provide information inside the structure (endoscopic SHM). A major disadvantage of such technologies is that due to electromagnetic emission they usage is prohibited in hazardous environments (nuclear plants, oil/gas tanks etc.).

2.2.3 Acoustic Emissions

Acoustic emission systems are used quite widely in SHM applications. Their operation relies on the discovery of discontinuities in structure release energy as a result of exercise of load (or stress). This energy is transmitted into high-frequency waves (vibrations) that are captured by transducers for processing. This is based on the usage of piezoelectric sensors of the range 20 kHz–1 MHz to measure responses in all directions. This methodology can offer information on the origin of these discontinuities as well as the development of flaws when continuous loads/testing are applied. This methodology can also be applied to inspection of larger areas in order to detect cracks and defects, however it is not appropriate for locating multiple damage positions. It is also affected by surrounding noise that can interfere with the measurements. Therefore these technologies are often combined with other SHM technologies to localise and measure the defective areas (and damage).

2.2.4 Imaging Type (X-Ray, Gamma Ray, Nuclear Magnetic Resonance (NMR), Ultrasonic etc.)

Imaging methods such as X-ray radiographic, Gamma Ray and Nuclear Magnetic Resonance (NMR) are also being used in cases that require damage identification in depth. Such technologies use high-frequency rays as the above and identify the damage based on their absorption and reflection. These systems can be used to quickly check larger surfaces but are very costly are much less sensitive and accurate and are usually prohibited in high safety areas.

2.3 Distant-Sensing Systems

2.3.1 Photogrammetric

Photogrammetric or optical imagery methodologies use camera images to create accurate 3D measurements of complex structures or objects. This methodology can prove very flexible especially when quick and inexpensive solution is seeked while can also deal with long-term monitoring tasks and can be fully automated. In such applications the accuracy and precision of the detected and reconstructed 3D images highly depends on the visual capabilities of the camera systems being used. It has been proved that for high accuracy higher quality lenses and more detailed (in terms of megapixels) images are needed [5].

2.3.2 Infrared Thermography

Infrared thermography is a technology that detects infrared energy transmitted from objects capturing the temperature distribution along the whole excitation surface. Such techniques for SHM are performed in distance to the structure surface and can be used to detect thermal phenomena associated to the structural deformation of structures. They are also widely used to detect leakages or other defects related to SHM. Infrared thermographic techniques allow for comparison of the surface distribution of temperature over wide areas and are considered as generally easy methodologies. However they are not directly linked to structural health monitoring rather than the thermal/temp effects of the structure deformations. This is why such technologies are often used in comparison with other SHM methodologies.

2.4 Fibre Optics Compared to Conventional Monitoring Techniques

Fibre optics technologies can be regarded as the ideal sensing elements for structural health monitoring especially of civil infrastructures. Fibre optics offer immunity to electromagnetic interference, can measure spatial deformations of structures while can also measure point deformations, can combine temp and strain/stress at any point in length of the installed cable and can provide their monitoring services with cables up to 30 km. In comparison to gauge type sensors that can provide only point measurements and can be subject to electromagnetic interference issues they have proved to be a robust and precise solution. Overall it can be said that fibre optics sensing can provide significant value due to improved quality of measurements, increased reliability and can most of the times replace

Table 2 Pros and cons of sensing technologies

Sensing technology	Advantages	Limitations
Gauge type	• Point measurement • High precision • Low price • Low power	• Not immune to electromagnetic interference • Only point measurements
Fiber optics	• Immune to electromagnetic interference • Can measure spatial deformations • Combine temp and strain/stress at any point in length of cable • Cables up to 30 km can be used • Low signal transmission losses • Corrosion free	• Lower precision of measurement • No point measurement • Can break in larger deformations (>10 %) • Communication is lost after breaking point • Decoding of signal/data required
MEMS	• Smaller size • Low power • Highly integrated • Low price • Very small size • Non-contact communication	• Sometimes not immune to electromagnetic interference
RFID tags	• Can be very low power • Passive operation • High location accuracy	• Do not usually measure stress or strain directly
Imaging	• Can see structure in depth	• High cost • No onboard use
Laser	• No sensor placement • No baseline data required • Less vulnerable to false alarms • Non-intrusive • Easily deployable • Less maintenance needed	• Limited sensitivity • Expensive • Considered hazardous for safety critical cases • Limited operation in harsh surfaces • Larger spatial resolution (can be improved)
Ground penetrating radar	• Investigation in depth • Material type detection • Quick for larger areas	• Prohibited in hazardous environments • Lower precision and accuracy
Acoustic emission	• Can identify severity of damage • Measurement accuracy	• Not suitable for large area detections • Usually combined with other SHM for damage localization • Not immune to noise • Difficult repeatability of measurements
Imagery	• Fast defects detection • Can be very accurate • No contact with structure needed	• High accuracy requires longer inspection • Might require training

Table 3 Comparison of sensing/monitoring technologies

	Gauge	MEMS	FBG	Brillouin	Laser	Photo-Grametry
E/M interference	Very sensitive	Very sensitive	Not sensitive	Not sensitive	Not sensitive	Not sensitive
Spatial resolution	Point	Point, non-linear	Point	1 m (usually reduced)	0.2 mm (could be reduced)	1 mm
Max strain	~6000 με	~10–15000 με	~10–15000με	~10–15000 με	Converted from distance	Converted from distance
Cost/sensor	Cheap	Cheap	Cheap	Cheap	60–150 k€	10 k€
Interrogation/acquisition cost	2–5 k€	2–5 k€	10–20 k€	**200** k€ (slower acq.)	–	–
Acquisition time	Instant	Instant	Instant	Near-instant (in high length)	Slow, post-processing needed	Fast, post-processing needed
Data size	Very small	Very small	Small	Large	Huge	Huge
Installation	In contact, rust prone, difficult post-inst.	In contact, rust prone, Difficult post-inst.	In contact, difficult post-inst.	In contact, difficult post-inst.	Visual (surface measurement)	Visual (surface measurement)
Special needs	Need amplification/buffer	Need amplification/buffer	Sensitive, difficult to glue	Sensitive, difficult to glue	Quite slow (20 min per cm slice)	Needs proper lighting

other types of sensors (gauge etc.) [6]. When FO sensors are supported by high-power tunable laser systems, they can provide measurements over very large distances with very little signal loss. On top of this, each interrogator channel can measure dozens of FBG sensors (through multiplexing) reducing the size and complexity of the measuring system.

What follows is a comparison of the available sensing technologies that can be used for structural health monitoring (Table 2).

Optical sensing can be an ideal sensing solution especially for cases when other sensing devices (gauges, piezoelectric etc.) prove not appropriate or ineffective. Good examples are limitations due to environmental conditions, long distance measurements, electromagnetic interference etc. What follows is a summary table comparison of the currently available sensing technologies, their technical specifications and operational characteristics (Table 3).

3 Fibre Optic Monitoring Systems

Cost reduction in the telecommunication wires has significantly paved the way for stronger and wider usage of fibre optic monitoring systems. This is enhanced by the higher demands of current structures for precise and real-time technologies and inspection/monitoring methodologies and configurations. This technology can be ideal for the constructions sector directly improving current structural monitoring systems or being applied as a stand-alone, real-time monitoring technology.

The concept of operation of Fibre Optics, as monitoring technologies, relies on the light intensity inside the fibre that decreases in cases when the fibre is stretched or compressed. This, following signal processing and decoding, is translated into deformation that informs for elongation or shortening of the attached structural piece. This has to follow a temperature calibration so that the deformation (and light change) can be compared to the one found in an uncompressed fibre (at the same temperature).

To make the monitoring (measuring) possible, special instruments such as the Optical Time-Domain-Reflectometer (OTDR) are being used to characterise the optical fibres. These metering instruments induce a pulse series into the measuring fibre and compute the back scattered (Rayleigh backscatter) light that is reflected from the fibre.

What follows is an OTDR measurement indicating the power loss across the fiber length. OTDR reveals that the fiber length has been optimized with respect to the reflections occurring at connectors, thus minimizing the power losses [7] (Fig. 2).

The correctness and dependability of OTDR equipment replies on the instrument accuracy, range that it can measure, resolving and measuring capability of closely spaced occurrences, speed of measurement and their ability to operate under harsh

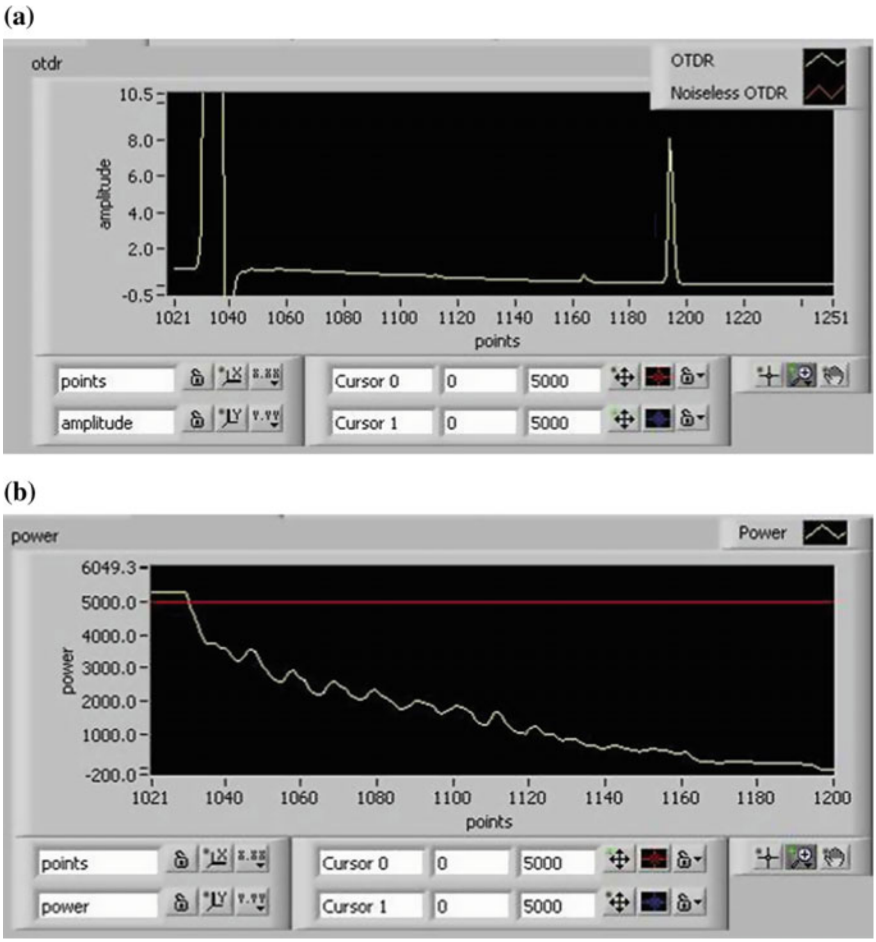

Fig. 2 **a** OTRD measurement **b** optical power versus fiber length [MONICO (FP7) EC co-funded research project] [7]

conditions. In terms of accuracy we define the difference between the real (actual) value and the measured value. By measuring range we define the maximum attenuation of the transmitted signal between the measuring point and the (pulsing) instrument (this should be inside acceptable accuracy limits so the measurement is valid). By instrument resolution we define the minimum distance that two measurements could have and still being considered and analysed as two distinct measurements.

Fibre optic systems can be distinguished between FBG (Fibre Brag Grating) and BRILLOUIN as the two relevant but still different technologies and concept of operation as presented in the paragraphs that follow.

3.1 Brag Grating Fibre Sensors

Fibre Brag Grating are produced by exposing the core of the fibre cable to extreme ultra-violet light that causes the material to increase its refractive index and thus create a fixed index modulation that is called grating. The grating (used as a refractive index) has been created in such a way so that only particular wavelengths are reflected while the rest of the light wavelengths are passing through the grating without attenuation (brag condition). This enables only particular wavelengths to be fully reflected backwards and measured by the OTDR instrument (Fig. 3).

FBG sensing technologies are used in a large variety of sensing applications that include monitoring of civil structures (highways, bridges, buildings, dams, etc.), smart manufacturing and non-destructive testing (composites, laminates, etc.), remote sensing (oil wells, power cables, pipelines, etc.), smart structures (airplane wings, ship hulls, buildings, sports equipment, etc.), as well as traditional strain, pressure and temperature sensing. The advantage of FBGs is that these devices perform a direct transformation of the sensed parameter to optical wavelength, independent of light levels, connector or fiber losses, or other FBGs at different wavelengths [8].

Typical applications of FBG sensors range in a very large spanning in structural assets monitoring starting from civil engineering, marine, airspace up to health applications. The strain range of typical FBG sensors range in ±15000 με (μStrain) with an approximate resolution of 1 με. FBG sensors can also be used a temperature monitoring sensors with a maximum temperature range of −50–120 °C and a resolution of 0.1 °C.

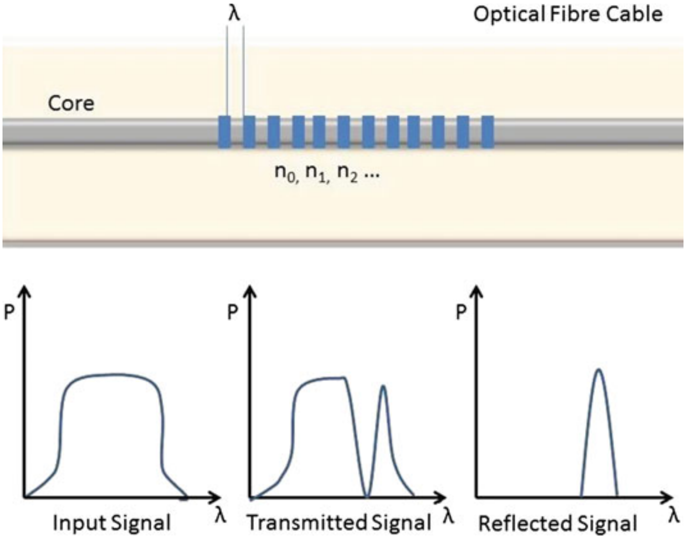

Fig. 3 Fiber brag grating and refraction signals

Table 4 Indicative FBG vendors

Vendor	Equipment	Country
Micron optics	FBG sensors, packagings, glueing, mounting, software	USA
FBGS	High-stength FBG sensors, packagings, glueing, mounting, software	Belgium
AOS-Fiber	FBG sensors, interrogation systems, software	Germany
Proximion	FBG sensors, monitoring systems, analysis software	Sweden

There are noumerous manufactures and vendors of FBG fibre optics sensors and sensing systems (interrogators, analysis software etc.). Some indicative vendors have been included below. This has been added for reference and completeness purposes only (Table 4).

Some typical characteristics of FBG sensors are included (Table 5).

The installation of FBG sensors is usually done on the structure surface while it can also be done on the structure rebars (for civil structures) as shown in the figure below. The positions of the FBG sensors can be recognised by the white coating. What is importance in this installation is to ensure that there is no slippage of the sensor and the sensor coating (if present) follows the structure deformation (Fig. 4).

Table 5 FBG sensor specifications

Max strain	±15000 με (μStrain)
Accuracy	1με (μStrain)
Operational temperature	−50–120 °C
Temperature resolution	0.1 °C
Other	Point sensing

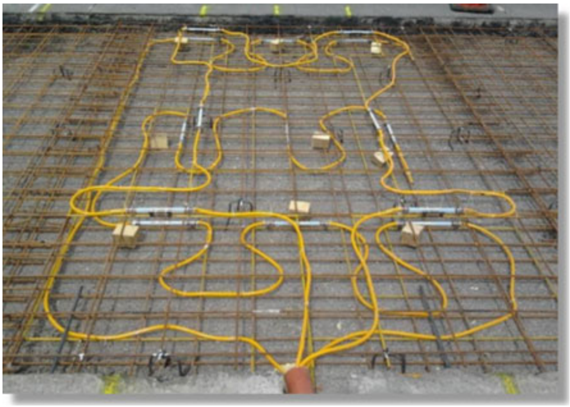

Fig. 4 FBG sensors mounted on civil structure rebars

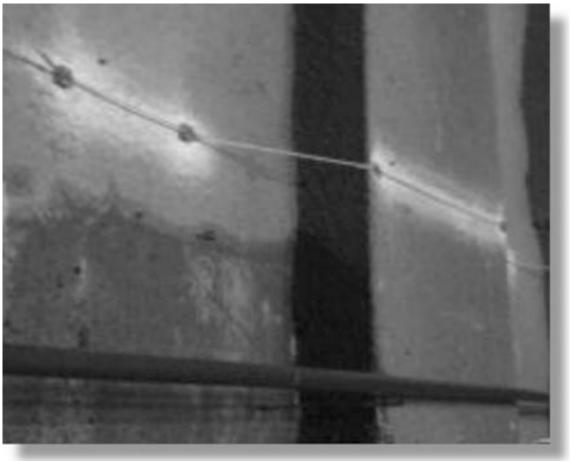

Fig. 5 Distributed sensing cable installed on tunnel wall [SMARTEC, Switzerland]

3.2 *Distributed Fibre Sensors*

In difference to point sensing technologies (Gauge, FBG, etc.), distributed sensing offers unique characteristics in being able to measure physical parameters along their whole length with a single transducer [3]. The two most complete technologies related to this methodology are the Raman and the Brillouin scattering. The concept of operation of both systems relies on the back scattering of light through the fibre optic medium and its change in wavelength and power in comparison to the original signal transmitted. This enables the interrogation system to provide information on the local properties of the fibre like exercised strain and temperature.

The figure that follows shows the distributed fibre sensing cable as installed on a tunnel wall in Spain (Fig. 5).

3.2.1 Brillouin-Type Distributed Sensors

By the Brillouin optical time domain reflectometry (BOTDR) we consider the most frequently used distributed sensing technique for strain and temperature along arbitrary regions of the optical fibre. With Brillouin scattering we consider a fundamental process of inelastic light scattering occurring due to interaction of light with acoustic waves inside the optical medium. The back-scattering property of light during the Brillouin process is shifted from the frequency of the incident light in proportion to the strain and temperature at the particular point. The Brillouin system requires a suitable interrogation unit to excite the fibre and collect back-scattered light. This is a sophisticated detection device able to measure these frequencies arising from the detuning of the incident and backscattered light.

Table 6 Brillouin sensor specifications

Max strain	±15000 με (μStrain)
Accuracy	1με (μStrain)
Range	Up to 50 km
Sampling rate	~1 Hz
Spatial resolution	1 m
Operational temperature	−50–120 °C
Temperature resolution	0.1 °C
Other	Distributed sensing

Through this frequency shift the system extracts the magnitude of strain and temperature. The location of the strain is calculated from the round-trip time of light (Table 6).

The graph below includes a typical measurement of a Brillouin system. This graph indicates a varying stress on the fibre length (represented in seconds—x axis) at seven points. As can be seen different strains are measured at multiple positions of the fibre. Different strains in the range of −2000–5000 μStrain can be seen (y-axis) (Fig. 6).

As mentioned above, the spatial resolution of the Brillouin system is of 1 m. There are several methodologies to reduce this resolution for cases that lower resolution is needed. One of the most common workarounds has to do with rolling of the optical fibre into parts to reduce the part of the fibre over a particular (smaller) section and thus be able to shrink the mean measurement in smaller parts of the structure. What can be seen below is this solution applied to a test tunnel perimeter

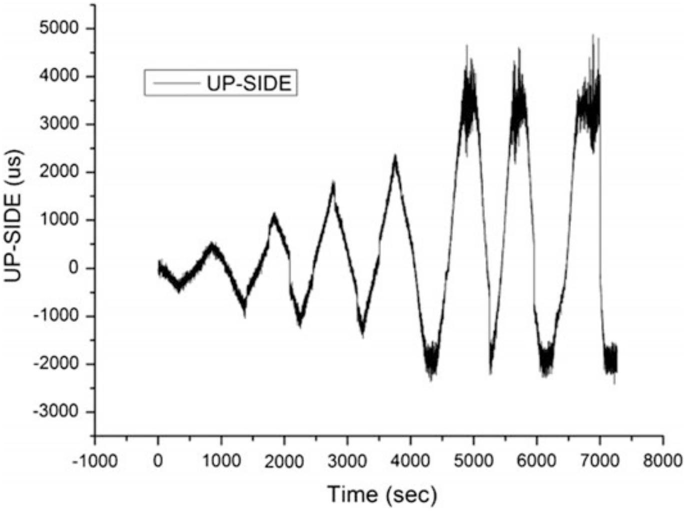

Fig. 6 Measurements of 7 Brilloun sensors as installed at experimental tunnel perimeter in the framework of the MONICO (FP7) EC co-funded research project [7]

Fig. 7 Brillouin Sensors installed at test tunnel perimeter. MONICO (FP7) EC co-funded research project [7]

Table 7 Raman sensor specifications

Range	Up to 8 km
Spatial resolution	1 m
Operational temperature	−50–120 °C
Temperature resolution	0.1 °C
Other	Distributed sensing

that was constructed, sensorised, deformed and measured at the MONICO (FP7) EC co-funded research project (Fig. 7).

3.2.2 Raman-Type Distributed Sensors

Raman sensing systems are slightly different technology systems for distributed temperature sensing. This technology is based on the Raman scattering as a non-linear interaction between the light in the fibre and the fibre surrounding coating [3]. In such systems, the intensity of the light is calculated and defines the local temperature of the fibre. Systems based on Raman scattering are currently commercialized by SMARTEC (Switzerland), Sensornet and Sensa (UK) [3] (Table 7).

4 Application Examples of Structural Health Monitoring Sensors

In this chapter we present some examples of gauge, FBG and Brillouin sensors installed at various structures in research and industrial levels. Details on the peculiarities of each system are also discussed per case.

4.1 Installation of Gauge-Type Sensors on Building Piers

In the figures below, we can see the installation of gauge-type sensors as installed on the piers of a civil building. This work has involved the development and evaluation of strain sensors in an actual newly constructed building in the framework of the MEMSCON [212004-FP7-NMP], 2009–2012, research project that was coordinated by the Institute of Communication and Computer Systems (Greece). In this particular installation, strain sensing of the rebars of the building was required. The installation included surface cleaning of the rebars and gluing of the gauge sensor on each rebar (lower parts). The sensors were connected to a monitoring embedded system that was able to collect the data from each sensor and transmit all measurements to a consolidation Decision Support System for post-processing (Fig. 8).

4.2 Installation of FBG and BRILLOUIN Sensors on Tunnel Test Ring

In the research work presented below, two evaluated and combined fibre optics technologies (i) Bragg grating, (ii) BOTDR principle for continuous tunnel monitoring were installed, tested and evaluated. The MONICO project was an EC FP7 co-funded "Specific Targeted Research Project" (STREP) under the capacity "Research for the benefit of SMEs". The project was active from October 2008 until March 2011 and was coordinated by the Institute of Communication and Computer Systems (Greece). In MONICO, a large scale specimen was developed with an outer diameter of 483 cm; inner diameter of 443 cm and thickness of 20 cm to simulate the section of a tunnel. In order to simulate representing seismic forces on

Fig. 8 Gauge-type sensors installed on civil structure pier. Work executed in the framework of the EC co-funded project "MEMSCON" [FP7-NMP]

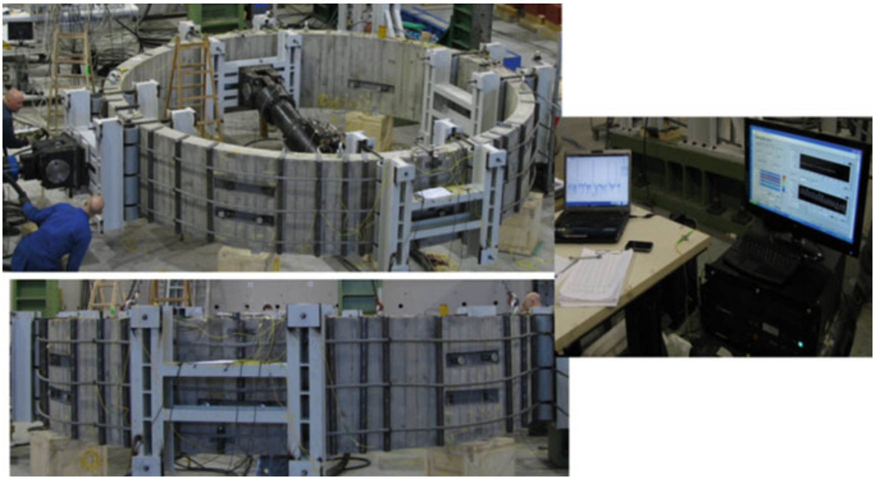

Fig. 9 FBG and BRILLOUIN sensors installed on test tunnel ring [9]

the tunnel, two actuators placed vertical to each other, were used. ECCS procedures of 1986 were used for the cyclic tests and the loading protocol was proportional to a conventional displacement δy which represents the elastic-plastic transition of the cross section. The two technologies were evaluated, validated and tuned on the tunnel circumference in 8 points. This sums to a total of 48 fibre sensors installed (32 FBG, 16 BRILLOUIN) in the outer and inner tunnel surface. In Fig. 3 we can see the tunnel ring before and after the casting. In the figures below the test tunnel ring is presented with both systems installed and simultaneously monitoring the ring deformations [9] (Fig. 9).

In the diagram below we can see the 6 cycles of the dynamic loading in the section-8 of the tunnel ring. At time 7500 s we can observe the concrete failure. As we can see above, there is a very good correlation of both technologies results, monitoring the tunnel ring behaviour. The Brillouin technology can directly be compared to the FBG but provided high noise levels at high strains (Fig. 10).

4.3 Installation of Fibre Optic Sensors for Large Structures' Real-Time Monitoring

The application of fibre optic monitoring systems can prove ideal for cases when monitoring of large infrastructures is required. In the particular case below, the Donghai Bridge—Shanghai/Yangshan, China is monitored. The bridge has a total length of 32 km, a navigation height of 40 m and navigation capacity of 5kt. In this particular case, due to the scale of the structure, the limited spatial resolution (1 m) of the Brillouin system used was not of great importance (Fig. 11).

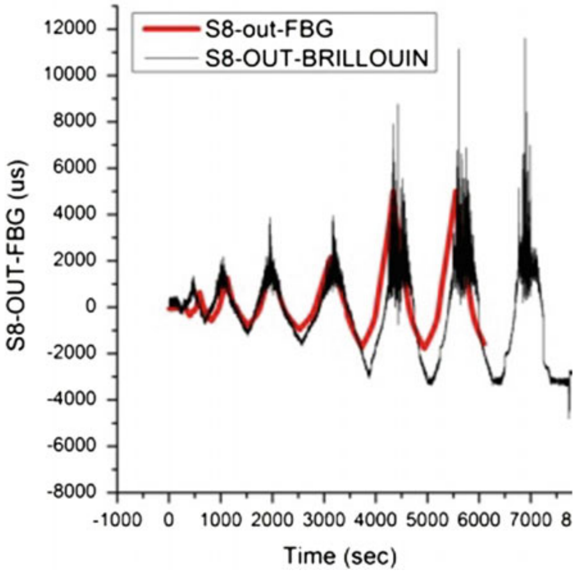

Fig. 10 FBG and BRILLOUIN Measurements for the whole experiment [9]

Fig. 11 Donghai Bridge—Shanghai/Yangshan, China

In this example the monitoring needs included monitoring of the bridge due too: temperature changes, high winds, erosion of the Chloride ion, waves, deformations due to loads, stresses (expected and not), structure dynamics (due to operational loads), lengthy cable tensions as well as displacements of dampers.

5 Conclusions

There is a high need for advanced monitoring of critical structures with increasing safety requirements. This has paved the way for the development and application of technologies that can perform seamless monitoring of these structures and either reporting periodically to an integrated decision support system or being used per case.

The usage of fibre optics as sensing elements for SHM has proved to be a very reliable methodology for a wide range of applications and physical scales. The nature of installation of these sensors proves their application even in difficult to access sections by conventional measurement tools. A good summary indicating the attractiveness of the fibre optics for SHM is their functionality serving as telecom means as well as strain and temperature measurement elements, their reliability (not being affected by weather and electromagnetic turbulences) and their passive nature (need only interrogation at one side (end) of the cable) not forgetting the capability of fibre optics to also operate as point sensors.

Currently the most appropriate sensing/monitoring solution is being selected from a large pool of available technologies depending on the particular peculiarities of the structural application. These can be point, spatial or distributed sensing solutions but they in any case depend on the nature of the structure under monitoring needs and the magnitude of monitoring desired/required.

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