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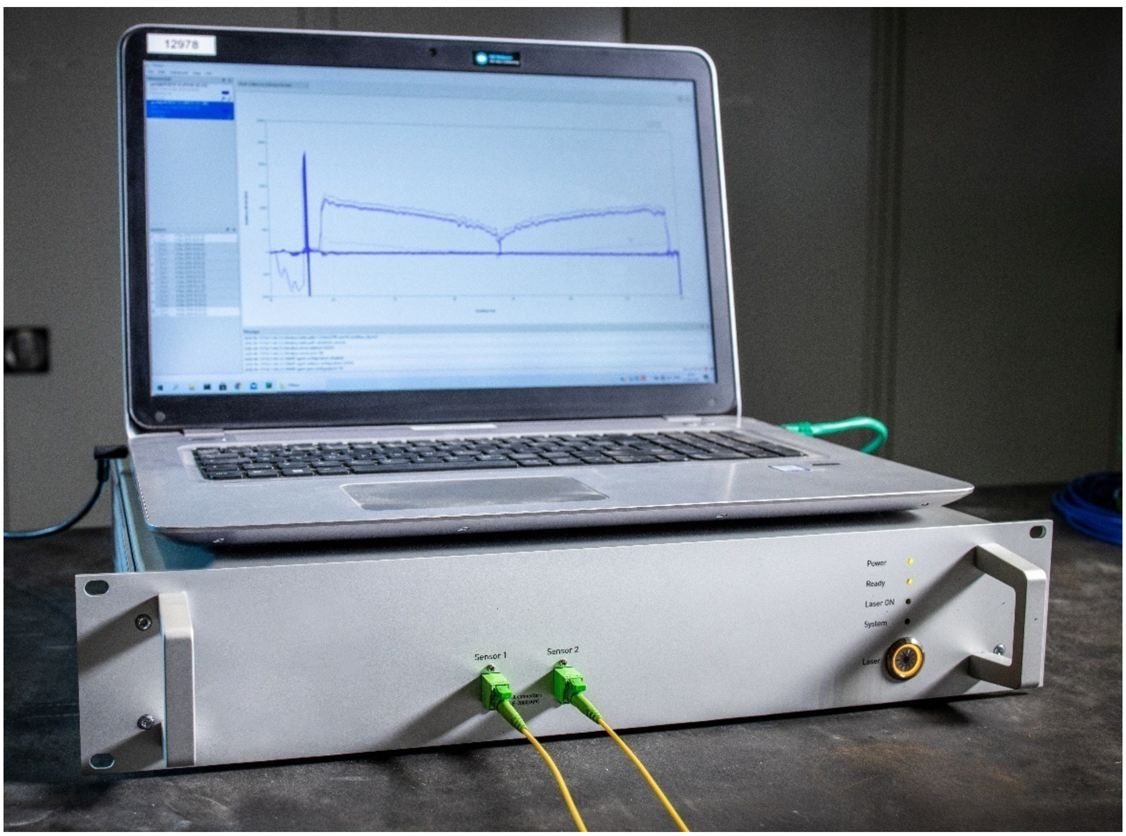
MONITORING OF STRUCTURES AND ELEMENTS WITH FIBER OPTICS

– QUICK START GUIDE –



FLANDERS INNOVATION & ENTREPRENEURSHIP

Flanders State of the Art

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1 Introduction

1.1 Some background

This quick start guide attempts to provide a compact guide for those who are new to the world of optical fiber technology. As the performance of optical fiber technology has continuously improved during the last decades and the cost has significantly decreased, the application of optical fiber sensing technologies is growing fast. However, this growth is slowed down by a lack of knowledge and some mistrust of the technology. Nevertheless, there is no doubt about the benefits of monitoring in general and the potential of monitoring with optical fibers.

This document has been written with the aim of lowering the threshold to apply or prescribe optical fiber sensing technology by summarizing the current state of the art. For more detailed information, the reader is referred to the handbook that has been elaborated within the same project (COOCK project HBC.2019.2505 'Monitoring of structures and elements with fiber optics' funded by the Flemish Agency for Innovation (VLAIO)). The latest version of this handbook can be downloaded from https://ovmonitoring.be/handbook/.

1.2 Optical fibers

An optical fiber consists of a very thin glass (silica) core with a diameter of about 9 µm (single-mode fiber or SMF) to 50 or 62.5 µm (multimode fiber or MMF), which transmits light. This glass core is surrounded by a cladding with a diameter of about 125 µm, which confines the light to the core (Figure 1). The core and the cladding are protected by a coating and optionally additional strength members and jackets. These layers may consist of plastics, metallic sheathings, GFRP material, etc. and typically have diameters of less than a millimetre to several centimetres, depending on the application and required robustness.

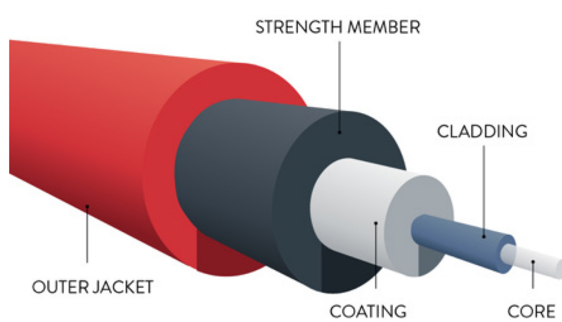

Figure 1. Typical fiber optic cable layout consisting of a glass core with a diameter of 8 to 62.5 µm, a cladding (diameter of 125 µm), a coating and optional strength members and outer jackets. Image source: https://www.ofsoptics.com/optical-fiber-coatings/.

1.3 Advantages of optical fiber sensing

Fiber optic sensing (FOS) offers several advantages in comparison to other measurement techniques, such as:

- **Reliability**: long term sensor stability, lifetime and robustness, in general no offset between disconnection and reconnection (as is often the case with other measuring techniques)
- **Performance**:

- High sensor density with very compact wiring. The fiber acts as sensor and data carrier. With distributed sensing technologies deformation/temperature/… can be monitored along the full length of the cable.
- High accuracy and precision possible (highly depends on the applied technology)

- **Inert and robust**:
    - Applicable in harsh environments, immune to corrosion
    - No electromagnetic (EM) or radio frequency (RF) interference
    - Resistant to high voltage and not subject to short circuit
    - Resistant to high temperatures
    - Explosion proof
- **Light weight and small size**
- **Geometric versatility**, over **long distances** (depending on the applied technique) and multiplexing capabilities (i.e. the ability of connecting different sensors or sensor cables in series to a single cable/connector allowing for a very compact wiring, see the example in Figure 2).

Figure 2. (left) 96 conventional temperature sensors connected to a data acquisition (DAQ) system. (right) 3 sensor arrays connected to a FBG interrogator. Each array contains up to 30 sensors.

1.4 Benefits of monitoring

New and existing structures (amongst others wind turbines, quay walls, dikes, bridges and tunnels) are increasingly being monitored over a short or longer period of time. The objectives are at least one of the following purposes:

- Assessment of the **long-term performance** of the structure or element (in terms of stability as well as durability).
- **Extension of the lifetime** of the structure, by continuous condition monitoring.
- Optimization of the **inspection and maintenance** strategy, resulting in a reduction of the inspection, maintenance and operational costs.
- Establishment of a **risk management or early warning system** to reduce/prevent hazards.
- Verification of the **structural design and optimization** of future design challenges by refining design models. The measurements might take place during the construction phase and/or after the commissioning of the structure (e.g. during excavation and after commissioning of a quay wall).

Extensive monitoring during **preliminary test campaigns** is also a valuable and powerful tool (e.g. real scale load tests). In addition to this, monitoring offers many possibilities in the area of **quality control** of the execution during construction or manufacturing. This includes **integrity testing** but also evaluating **(innovative) implementation techniques**.

All this leads to less uncertainty, greater efficiency, optimization, etc. This has not only economic advantages, but also ecological ones (reduced CO_2 emissions, more efficient use of materials and resources), among others.

2 Fiber optic sensing (FOS) technologies

A large variety of optical fiber sensing technologies is currently available on the market. The reader is referred to the handbook for a more detailed explanation on all different sensing technologies. Figure 3 presents a simplified schematic overview, classified by (1) point or multipoint sensors and (2) distributed sensors:

1. **Point or multipoint sensors**: the optical fiber contains one or more sensors at discrete locations along the fiber length. The most common multipoint sensor technology is Fiber Bragg Grating (FBG). Other point sensing technologies are based on e.g. micro-bending (Osmos) and low-coherence interferometry (SOFO).
2. **Distributed sensors**: the optical fiber acts as a sensing element over its entire length. The distributed technologies are based on three types of back-scattering of light (Brillouin scattering, Rayleigh scattering and Raman scattering). The spatial resolution and spatial accuracy highly depend on the distributed technology.

In Table 1, an overview of the most common optical fiber technologies and their characteristics is presented.

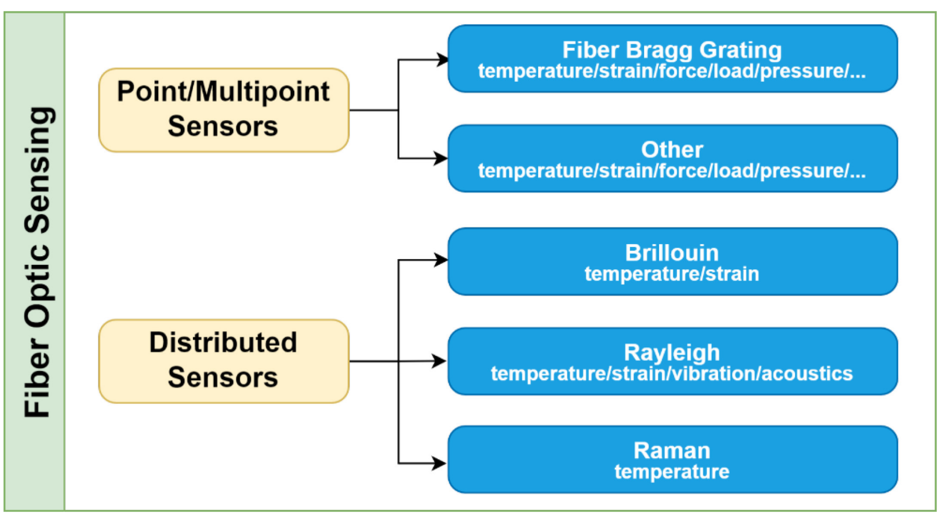

Figure 3. Simplified schematic overview of most commonly used fiber optic sensing technologies.

Table 1. Overview of the most common optical fiber technologies (based on own experience, completed with data from [1], [2], [3] and [4]). Measurement performance often depends on cable length, measurement time, etc. SMF single mode fiber, MMF = multimode fiber.

	Optical fiber technique	Strain [µstr]	Temperature [°C]	Measurement type	Cost	
		[accuracy]			DAQ	Sensor
Point sensing and/or Multi-point Sensing	**FBG**	Yes < 1	Yes 0.1 °C	Multi-point (SMF) Single ended Spatial res.: >2mm (grating length) Range: several kilometres Max. frequency: >1kHz	-/+-	+
	Other (Osmos, SOFO, …)	Yes 1	?	Single point Single-ended Large number of channels on DAQ Wireless solutions as well (Osmos) Range: several kilometres Up to 100Hz (Osmos)	-	-/+-
Distributed Sensing	**Brillouin Scattering (BOTDR/ BOFDR)**	Yes > 20	Yes > 1.0	Single ended (SMF) Spatial res.: >1.0m Range: up to 100km Typ. meas. duration: 3-60min.	+-/+	-
	Brillouin Scattering (BOTDA/ BOFDA)	Yes > 2	Yes 0.1-1.0	Double ended (SMF) Spatial res.: 0.2-1.0m Range: up to 80km Typ. meas. duration: 3-60min.	+-/+	-
	Raman Scattering (OTDR)	No /	Yes 0.1	Single and double ended (MMF) Spatial res.: 0.01-1.0m (typical 0.5m) Range: up to 10-15km Typ. meas. duration: about 5 minutes	+-	-
	Rayleigh Scattering (OFDR)	Yes < 1 µstr	Yes 0.1-0.4	Single ended (SMF) Spatial res.: <10mm up to 1mm Range: up to 70m Typ. meas. duration: < 10 seconds	+	-
	Rayleigh Scattering (TW-COTDR)	Yes < 0.5		Single ended (SMF) Spatial res.: 2-20cm Range: 20km Typ. meas. duration: < 10 minutes	++	-
	Rayleigh Scattering (DAS)	Vibration, sound, temperature variation		Single ended (SMF) Spatial res.: > 0.5-5m Range: 1-200km >1kHz	+	-

3 Guidelines to set up a monitoring project with optical fibers

3.1 Definition of the monitoring campaign

Before selecting a FOS system, one should clearly define the **objective(s) of the monitoring campaign** and what **parameters and phenomena** are to be monitored at which locations. The 'ultimate' FOS system not only depends on what phenomena should be captured by the system, on how many locations and at which frequency, but also on the material characteristics. Moreover, the expected range of strain/temperature/… should be defined. Finally, the data processing and data analysis should be kept in mind already in this stage (see Section 4).

3.2 Selection of the (D)FOS technology and sensors/sensing cables

Even if the monitoring project has been clearly defined, the selection of the appropriate (D)FOS technology for a specific application is not always straightforward. After all, each technology has its own pros and cons in terms of cost of the data acquisition system and the sensor cables, accuracy, spatial resolution and sensor density, maximum frequency, etc. (see Table 1 for a summary of all these characteristics).

In addition to the selection of the (D)FOS technology and data acquisition unit, the choice of the type of sensors and/or sensing cables and the mounting method is at least as important. The following guidelines should be taken into account when making these choices:

- **The desired measurement base.** This is the length of the sensor (e.g., in case of FBGs) or the spatial resolution/accuracy of the DFOS system (in combination with the cable type). For instance, FBG sensors typically have a length of about 10 mm. By releasing the fiber around the sensor over a larger distance, the deformation is measured over a larger length.
- **The type of material.** When interested in the global behaviour of a heterogeneous material and/or elements with a variable cross section, e.g., cast in-situ foundation piles, it is often desirable to measure over a larger measurement base.
- **The phenomena that are to be captured.** Especially when local phenomena are to be captured, the choice of the (D)FOS system and sensor or cable type is very important. For instance, in case of (multi)point technologies, the sensor has to be at the right position to detect local cracks. (D)FOS technologies are more flexible, but the spatial accuracy and spatial resolution have to be sufficient and the sensing cable has to capture this local deformation in an appropriate way. In fact, strain transfer to the cable is an important concern if local phenomena are to be measured. Refer to the handbook for more details on these topics.
- **The expected strain/temperature/… range.** Of course, the selected sensors and sensing cables should be compliant with the expected deformation or temperature ranges.
- **The conditions of installation and operation and monitoring duration.** When rough conditions are expected during installation (e.g., concreting or other construction works), a more robust sensor or sensing cable should be chosen. One should keep in mind that every additional coating layer can influence the strain transfer to the sensing fiber. The operational conditions and the planned duration of the monitoring also have to be taken into account. It is obvious that long-term monitoring applications require more robust cable types, appropriate fixation methods and additional protective measures (coatings, mechanical protection, etc.). The same applies to underwater applications or applications in specific environments (e.g., saline, high temperature).

Various manufacturers offer optical fiber sensing DAQ units and optical fiber sensors and sensing cables for all kind of optical fiber sensing technologies. Refer to the handbook for more information on this topic.

3.3 Other considerations

Apart from defining the monitoring project in detail and selecting the FOS system and sensors/sensor cables, the following elements are also important and should be kept in mind as early as possible in the project:

- **Sensor architecture**, more specifically:
    - The wiring to connect all sensors and sensor cables to each other and to the DAQ unit(s). Using connectors and couplers, splices, splitters, switches, etc., keeping in mind that the optical losses must be limited and thus the use of these tools as well.
    - Redundancy, i.e. designing the sensor wiring in a such a way that all or as much sensors as possible can be recovered in case of a damaged cable at a specific location. Possible measures are to provide one or more backup cables to the DAQ unit at the fibre extremities, to split the sensors over two or more separate arrays or to use two different FOS technologies.
    - Note that some DFOS technologies need double ended wiring, meaning that both cable extremities have to be connected to the DAQ unit. The cable must therefore be installed in a loop.
- **Sensor mounting**: local measurement or as an extensometer over a larger measurement base, glued on the surface or embedded in the surface (e.g., by grinding a narrow and shallow groove offering additional protection), poured in concrete, …
- **(!) Temperature compensation of strain measurements.** Most (D)FOS technologies are affected by both strain and temperature changes, except from the Raman technology that is only susceptible to temperature changes. When the aim is absolute strain monitoring, it is therefore mandatory to compensate the readings for the temperature effect on the fiber. The strain and temperature compensation coefficients depend on the technology and the cable type used. Temperature measurements can be performed with dedicated optical fiber temperature sensing cables or sensors. These cables or sensors are designed to transmit as little strain as possible to the sensor or sensing fiber.

4 Analysis of the monitoring data

4.1 To keep in mind from the start

It sounds logical but **data processing and data analysis** should be considered from the very beginning of a monitoring project. Taking this into account from the start of the process will also help to further optimise the monitoring strategy and sensor architecture. The big picture has to be considered so that everything fits together coherently:

- Which parameters (strain, temperature, acceleration,…) will be monitored and at which locations?
- Can the number of locations be optimized?
- How will all sensors and sensor cables be connected to the DAQ unit (sensor architecture)?
- What is the expected measurement range of all parameters? Is this in accordance with the chosen sensors and sensor cables?

- What temperature variations are expected? Is temperature compensation required and can the number of temperature sensors be optimized/minimized?
- Is there a need for a continuous monitor system? Note that it is easier to interpret continuous monitoring data rather than periodic measurements. Shifts in data can be easier understood and linked to specific events. The effect of cyclic events (like temperature or tidal variations) on the measurements will also be clearer.
- How will the data be interpret? Is there a need for advanced analysis techniques (Machine Learning (ML), operational modal analysis (OMA), …). Are there specific thresholds that can be defined? And what happens if a threshold is exceeded? One should also be aware of the fact that sometimes a certain data history has to be gathered to fully understand and exploit the monitoring.

4.2 Temperature compensation

As mentioned before, optical fiber sensing technologies are also susceptible to temperature changes. Strain measurements, for instance, have to be corrected for the effect of temperature on the fiber and the sensor.

After this correction has been performed, the resulting deformation corresponds to the real deformation of the structure or element. Note that this differs from many traditional strain sensors that measure the restrained deformation in the material, which corresponds to the stresses in the material. When restrained deformations (and stresses in the material or structure) are of interest, one should apply an additional correction for the thermal dilation of the element. Refer to the handbook for a more information on how to perform this correction.

4.3 Baseline or reference measurement

For some applications it can be very important to have an accurate **baseline or reference measurement**. Especially if the temperature of the element between the reference situation and the further operational conditions is different, sufficient attention should be paid to these measurement(s). Ideally, the external conditions are stable during such reference measurements (stable temperature, no sunlight, a variable cloud cover should be avoided). In some applications, the reliability of the reference measurement can be enhanced by performing the measurement before and after rotating the element by 180 degrees. Both measurements are then averaged.

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