

Geotechnical and Structural Applications of Fiber-Optic Sensing

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Abstract. Fiber-optic (FO) strain sensors are offering new monitoring possibilities. By integrating FO sensors into soil or structure, an unprecedented amount of accurate, (and spatially resolved in case of distributed sensors) data can be obtained. In the early twenties of the 20th century, two important types of light scattering were discovered: Raman scatter (Raman 1928) and Brillouin scatter (Brillouin 1922). The Raman scatter is often used in distributed temperature sensing (DTS) whereas the Brillouin scatter forms the basis of most current FO distributed strain measurement techniques. These discoveries opened up the possibilities of current optical sensor technology. Only with the development of laser technology, combined with fast signal processing, this has resulted in the rise of optical sensor applications from the late nineties of the 20th century. Supplemented with the Fiber Bragg Grating (FBG) technology (Hill et al. 1978), which allows for extremely accurate and fast strain measurement acquisition, most imaginable strain and temperature measurement configurations have become possible. The development and application in projects was expected to rise as measurement equipment was expected to become more affordable (Spruit et al. 2003). Due to logical market restraints (low demand due to high equipment pricing resulted in low production volume which kept the prices up), the improvement of affordability of the measurement equipment has taken longer than expected in the beginning of the 21st century. Looking at current long-term monitoring projects and papers published on these subjects, the application of optical sensor technology is really starting to take off now. Current commercially available technology allows for strain measurements in the microstrain ($\mu\epsilon$) range (0.0001%) with a spatial resolution of 1 m along a 30 km long fiber. In this paper a description of geotechnical and structural FO applications in the laboratory and field of the last 15 years are given. These range from preliminary test, through pilots and long term structural health monitoring. This paper will show some pilot monitoring projects in civil

engineering from the start of the 21st century. More extensively, a recent example of monitoring a bridge will be discussed.

Keywords: Monitoring · Fiber-optic sensors · Geotechnics · Bridge deck

1 Introduction

Fiber-optic (FO) strain sensors are offering new monitoring possibilities. By integrating FO sensors into soil or structure, an unprecedented amount of accurate, (and spatially resolved in case of distributed sensors) data can be obtained.

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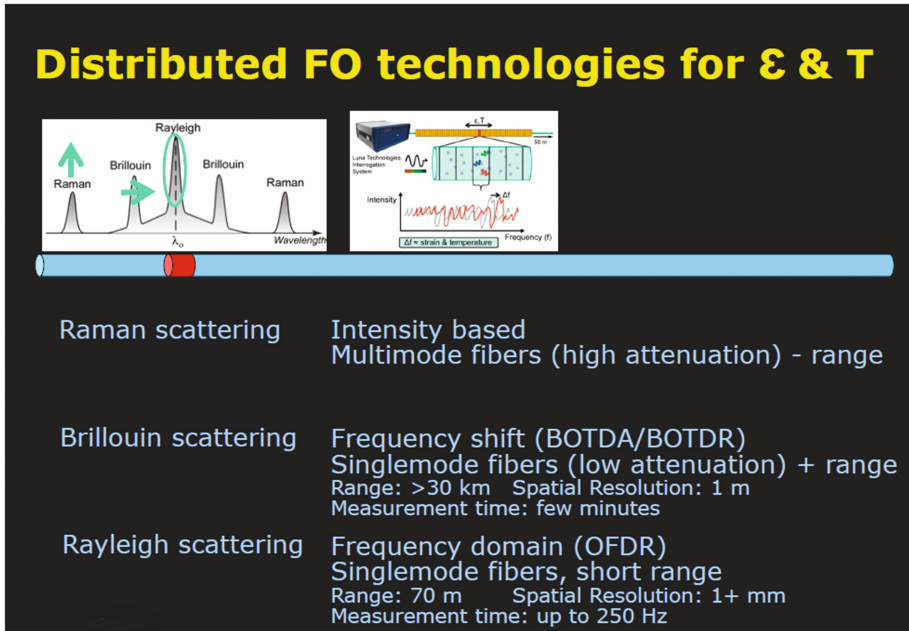
Current commercially available technology allows for strain measurements in the microstrain ($\mu\epsilon$) range (0.0001%) with a spatial resolution of 1 m along a 30 km long fiber. In this paper a description of geotechnical and structural FO applications in the laboratory and field of the last 15 years are given. These range from preliminary test, through pilots and long term structural health monitoring.

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2 Distributed Strain Measurement Technology

Continuous strain can be measured along optical fibers by several techniques based on the Brillouin scattering effect: spontaneous Brillouin Optical Time Domain Reflectometry (BOTDR) occurs when a light pulse guided through a silica fiber is

backscattered by a nonlinear interaction with thermally excited acoustic waves. In the more refined Brillouin Optical Time Domain Analysis (BOTDA), two counter-propagating light waves (pump and probe) at different frequencies interact via stimulated acoustic waves. The scattered light undergoes a frequency shift, which is directly related to the strain and temperature in the medium.



Thus, in addition to the strained FO cable, a loose fiber must be placed for temperature compensation. The backscatter is recorded in the time domain to obtain information of the scattering location along the fiber and the frequency shift of the signal is analysed and converted into strain and temperature data. The strain measured is the average value over the spatial resolution (typically >1 m), which corresponds directly to the length of the light pulse sent down the fiber. Remote control and automatic measurement mode is possible. Recently, a significant breakthrough was achieved in narrowing the spatial resolution down to 5 cm with extremely short pulse durations in the Brillouin Echo Distributed Sensing (BEDS) setup. The BEDS concept is based on observing a “negative” gain created by a very short-time phase shift applied on the pump that interferes destructively with the reflected light. BEDS is not commercially available yet, but first testing in soil has shown its potential for future applications. Table 1 gives an overview of the listed technologies (see also Thévenaz, 2010).

As can be seen from Table 1, the BOTDR family keeps developing towards better strain resolution as well as better spatial resolution.

Table 1. Comparison of distributed FO strain sensing technologies, according to the manufacturer information

	BOTDR (Brillouin Optical Time Domain Reflectometry)	BOTDA (Brillouin Optical Time Domain Analysis)	BEDS (Brillouin Echo Distributed Sensing)
Measurement accuracy	20 $\mu\epsilon$ to 40 $\mu\epsilon$	2 $\mu\epsilon$ to 10 $\mu\epsilon$	10 $\mu\epsilon$ to 20 $\mu\epsilon$
Spatial resolution	1 m	1 m	0.05 m
Max. distance	30 km	30 km	More than 5 km
Availability	Commercially	Commercially	Lab prototype
Comment	Single fiber	Loop required	Loop required

2.1 Distributed Temperature Sensing

The local temperature in a FO sensor can be determined with analyses of the Raman scatter (Raman optical time domain reflectometry R-OTDR) or Brillouin scatter (see before). Because R-OTDR requires less expensive equipment and the measurements are not influenced by the local strain, for DTS acquisition the Raman scatter is used more often than the B-OTDR. Typically, the local temperature can be determined 0, 1 degree accurate with a spatial resolution of about 1 m. The measurement principle is similar to B-OTDR in that a laser pulse is fed into the FO sensor. The backscattered light is analyzed in the time domain.

2.2 Local Strain Measurements

The Fiber Bragg Grating (FBG) technology allows for very accurate strain measurements on a predefined location in the fiber. This predefined location is treated with lasers to alter the structure. As a result, that location will only reflect a single wavelength. Local strain is linearly proportional to the change in reflected light frequency. The main advantage of this technique is the possibility of very high frequency read-out of the sensors (kHz order) as opposed to the previously mentioned OTDR method that requires several seconds to minutes interpolation time for a proper reading. Also the ability to measure strain very locally can sometimes be an advantage.

2.3 Pilot Project A: Pipe Bending Demonstration (FBG)

The engineering department of the city of Rotterdam started to look into optical sensor technology in 1999. At the InfraTech 2001 exhibition, the Rotterdam Engineering department showed a scale based on a single FBG sensor glued to the bottom of a 300 mm diameter PVC tube, placed on two supports 3 m apart. By stepping onto the middle of the tube (in between the supports), the flexing of the tube, measured with the FBG sensor, was expressed in kg on a laptop screen.

2.4 Pilot Project B: Underground Pipe Monitoring (FBG and B-OTDR)

In 2002, a water transport tube was instrumented with FBG and B-OTDR (Brioullin Optical Time Domain Reflectometry) sensors at the 4 quadrants of the cross-section. The intended monitoring goal was to monitor the tube's deformations in 3 dimensions (Spruit et al. 2003). The test was a success, providing useful practical experience, especially on sensor glueing and essential data on reliability and repeatability of the measurements resulting in confidence for future projects (Fig. 1).



Fig. 1. Instrumented water transport pipeline

2.5 Pilot Project C: Long Term Strain Monitoring in Geogrids (FBG)

In 2003 FBG sensors on geogrids were installed intended for long term strain measurements. The geogrids were used to stabilize a soil cover on top of a 1:1 high density polyethylene capping structure covering municipal waste incineration ashes. Because no proper validated models for designing the grids in this specific application, the grids were designed with unfavorable assumptions, leading to over dimensioned grid. To improve on future design, the long term monitoring supplied the actual strain in the grids during construction and during actual use of the anchored soil cover.

2.6 Pilot Project D: Load Distribution Along a Driven Anchor During Trial Loading (B-OTDR)

During construction of a quay wall in the Rotterdam harbor in 2006, the rebar cages of the diaphragm walls were instrumented with B-OTDR sensors to allow for deformation measurements during construction and use of the quay wall. Also the with grout injection driven steel MV (Mueller Verfahren) piles (45° inclination) that provide horizontal anchoring of the quay wall, were instrumented with B-OTDR sensors (Fig. 2).



Fig. 2. Anchor pile trial load test setup

Each sensor was attached to a 10 mm diameter rebar and pushed into a grout tubes while the grout was still fluid, immediately after completion of the pile driving. During trial loading of the anchors, the strain distribution along the pile and thus the function showing the load distribution to several soil layers could be monitored. A comparison with electrical strain gauges at several levels and the known applied load at the pile head showed good correlation.

The sequence of trial loading steps clearly shows a pre-tensioning of the pile due to soil resistance as the load on the pile is reduced 1000 kN after the 7963 kN and 9100 kN loading steps (1000 kN (2) and 1000 kN (3) respectively) (Fig. 3).

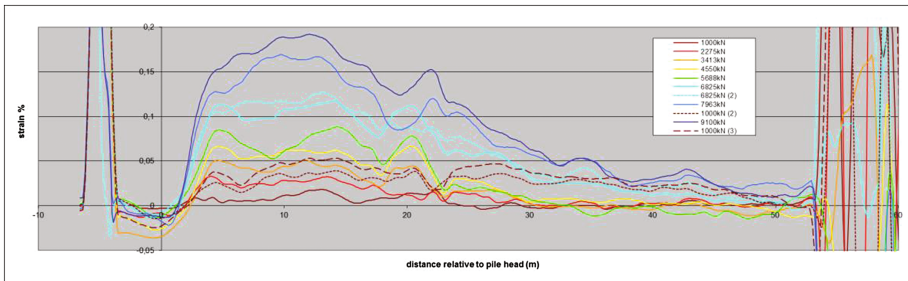


Fig. 3. Strain distribution along the anchor pile during trial loading steps

The strain sensors in the diaphragm walls clearly showed the tidal influence in the strain resulting from the varying bending moments.

2.7 Pilot Project E: Concrete Level Monitoring During Diaphragm Wall Casting (R-OTDR)

In 2009, DTS (Distributed Temperature Sensing) measurements were executed during concrete casting in slurry walls, showing the possibility of tracking the casting process, even between the trench wall and the rebar cage and in the furthest extremities of the trench (Spruit et al. 2011, Spruit 2015). The concrete levels could be derived from the DTS measurements because the concrete had a higher temperature than the bentonite slurry in the trench. The DTS derived levels correlated well with the manual depth registration performed near trench center (Fig. 4).

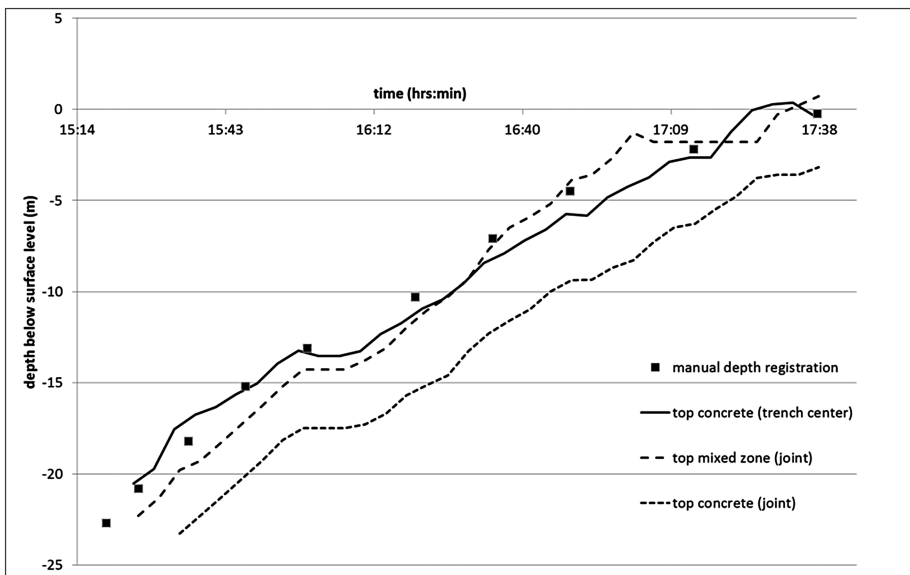


Fig. 4. Concrete level recordings with DTS and manually

2.8 Pilot Project F: Reactivation of Old Inclinometer Casings

Inclinometer casings that became unusable due to extreme deformations can be re-used by installing a FO sensor and filling the casing with cement-bentonite grout. The current sliding surface can then be identified and displacements on this surface back-calculated. Installation of such a system on site in 2008 allowed for the sliding surface to be detected within three months.

2.9 Pilot Project G: Extensometer

Similar to the previously described application, a vertically installed FO cable can be used to measure soil settlement or heave as a function of depth. This can become an economical and more refined alternative to traditional extensometers in which typically up to 4 anchor levels in the soil can be incorporated. The FO based extensometer would render a continuous vertical profile and would be consuming much less space.

3 Application of Short Fibers of a Bridge Deck

The Doesburg bridge over the river IJssel had to be renovated as fast as possible to minimize traffic disturbance. The bridge is the main access to work and school for many people in the surroundings. Near the bridge a transport company has its distribution center also relying on this bridge for business access (Fig. 5).



Fig. 5. Bridge across river IJssel near Doesburg (NL)

The bridge itself consists of a steel frame with concrete decks for two main lanes for motorized vehicles and secondary lanes for cyclists and pedestrians. It is a bridge with one main span and 2 side spans. The bridge is built in 1950 and requires an extensive renovation by coating the steel frame and by replacing of the concrete bridge deck. Also the lanes for cyclists need to be widened without adding to the weight of the bridge. This requirement has been met by building the decks for the cyclists using fiber reinforced polymers (FRP) supported but he existing steel consoles. Doing so will even reduce the overall weight of the bridge and therefor reserving some extra capacity for future increasing traffic load. A cross section of the cyclist lane can be seen in Fig. 6.



Fig. 6. Sideview cyclist path with sensor locations on the steel consoles and FRP composite bridgedeck

Monitoring System. By temporarily allowing public transport busses on the cyclist lane the disturbance for the people can be reduced. The transport busses have to reduce their velocity during bridge crossing. Also cyclists may still use this lane. The intermittent use is regulated with traffic lights. To monitor the effect of the load of the busses on the structure of the bridge, a monitoring system has been installed on the bottom of the FRP bridge deck as well as on the steel consoles. In total 4 arrays consisting of five short optical sensors were installed. Every array consists of two longitudinal sensors and two transverse sensors on the bridge deck and one sensor at the console. In transverse direction the sensors are located close to the edge of the deck and in the middle of the bridge deck, in longitudinal direction the sensors are located at mid-span of the panel length and at a quarter length of the panel (Fig. 7). Based on the reduced speed of the public transport to 24 km/h and the read-out frequency of the optical sensors of 100 Hz, a 7 cm or 0.01 s accuracy is achieved. Every half hour the sensor data will be sent to the data server, from which it can be downloaded by the users. This file counts 10 MB, so after one month adding up to a serious 15 GB of sensor data.

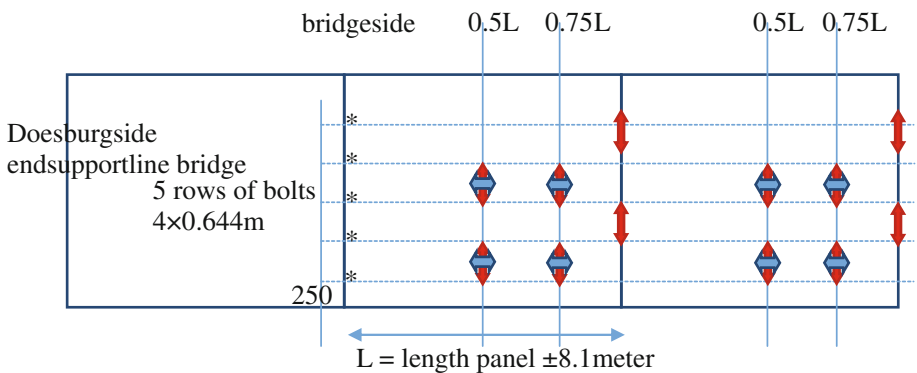


Fig. 7. Locations optical sensors (upper view)

4 Results of Measurements Traffic Passages

First of all an overview of only one sensor data over 30 min in time collected can be shown in Fig. 8. More in detail a specific passage of a bus is shown in Fig. 9. Figure 8 shows the large strains and some minor strains, which are belonging to the crane of the contractor who is moving from east to west side of the bridge.

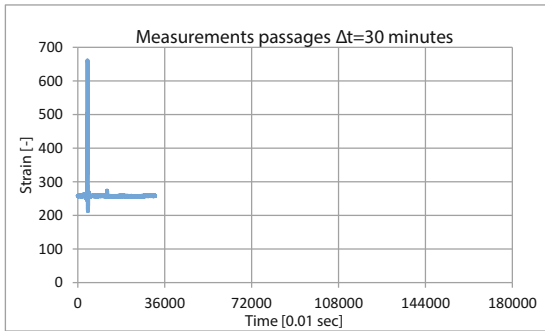


Fig. 8. Data one sensor $\Delta t = 30$ min

Figure 9 shows the strain result at a passage of a bus belonging to one longitudinal sensor. Both axles of the bus show a different strain, the front axle causes a lower strain than the rear axle. The difference in time passage gives an indication of the speed of the vehicle. Similar to this longitudinal sensor all other sensors can be shown. Validating the sensor data is done by measuring the axle loads of a similar bustype at a nearby weigh in motion location and some passages of this bustype at the Doesburg bridge.

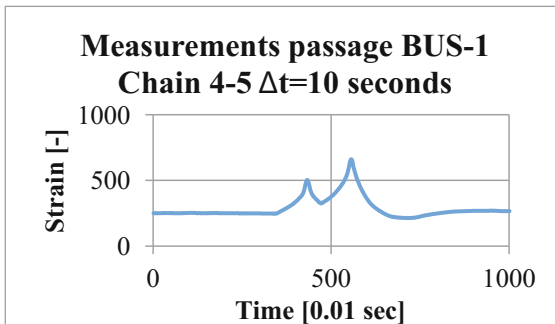


Fig. 9. Data passage public bus $\Delta t = 10$ s

Meanwhile, there is also a reinforced concrete slab field (N + way local road), and a reinforced concrete deck (N-way) measured. Recently, we have measured the fourth bridge in Hasselt, a prestressed concrete plate field, commissioned by the Province of Overijssel.

5 Conclusions and Outlook

Fiber optical sensor technology can be ideal for long term structural health monitoring because of the very high stability characteristics of the FO sensors. The application of FO sensor technology in geotechnical monitoring applications is not yet very common. However, their ability to provide enormous amounts of data at low cost per reading (in spite of the relatively expensive measurement units) is a convincing fact. The issues that have to be handled with care are (a) FO cable selection, (b) FO cable integration and (c) data interpretation. FO cables of a broad range of stiffness and protection are now available. The FO cable integration is project-specific. The data interpretation requires background knowledge of FO technology and knowledge application setting. For structural health monitoring a high level of understanding of the structure, substantiated with numerical analyses of the structure are essential. For FO sensor in geotechnical application, thorough knowledge of geotechnical engineering and high level numerical modelling are required. Sensor connection to the soil is more difficult than in structural monitoring because of the low stiffness and creep sensitive properties of soil. The authors are convinced that for the applications described in this article, FO technology is a valuable alternative to conventional methods.

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