Fiberoptic Strain Measurements for Levy Monitoring: An FBG based system for thousands of sensing points

Johannes Singer, Devrez Karabacak, Murat Ozmen
Fugro Technology BV, The Netherlands

1 Introduction

Fugro is a worldwide operating Geotechnical, Survey and asset monitoring company head-quartered in The Netherlands. Over 50 years we have pioneered the geotechnical industry with groundbreaking technical inventions, starting from the cone penetrometer which led to the start of Fugro ("Foundation- and Ground Mechanics"). In the current presentation we will introduce a Fugro developed fiberoptic measurement system, based on the use of discrete Fiber Bragg Gratings and some aspects of its performance, as well as a case study of the application of this system with over 700 sensors using a single fiberoptic interrogator system.

2 Principle

Optical Fibers are natural strain gauges and temperature sensors: A heating of a fiber as well as a stretching causes a change of the optical response. The industry uses various flavors of fiberoptic systems, which generally classify into two groups: So-called continuous measurement systems like DTS and DAS, where a conventional single-mode fiber is used, and where in a quasi-continuous mode can be measured (with drawbacks on sensitivity of the systems, as well as increased complexity of the interrogation technology), and discrete FO systems using Fiber Bragg Gratings (FBGs). The FBG approach allows discrete sensing points with usually higher sensitivity, but in conventional systems so far, the number of sensing points was rather limited.

In our contribution we describe the FBG based system Fugro has built, its technical specs, and a case study where a single interrogator uses over 700 sensing points in a levy monitoring application in the North of Holland. We have extended the conventional FBG technology to a very fast scanning laser-based system, with an integrated optical switching mechanism, therefore creating a 64-channel system with 30 sensors per channel. This concept allows a simple system with thousands of sensors, with all the technical advantages of high accuracy, high-spatial; resolution strain measurements.

The case study describes the instrumentation of a levy construction experiment for a Dutch water management consortium, the design of ultra-wide range strain gauges required for it, as well as the installation of the system and the results obtained with it. The same principle is applicable to all kinds of other strain measurement situations (with strain being a core physical property to be measured in asset monitoring and geotechnics), but we extended it to a whole portfolio of other sensing cases by designing a set of transducers, e.g. for pressure, acceleration, inclination, load, etc. The most sophisticated sensor designed by Fugro is a purely fiberoptic cone penetrometer (CPT) of measurement class 1+ (ultrasoft soil conditions). This CPT is directionally sensitive (3 sets of differential FBGs for the cone and the sleeve), measures its inclination, temperature, and cone pore pressure.

3 The FUGRO/FAZ fiberoptic measurement system

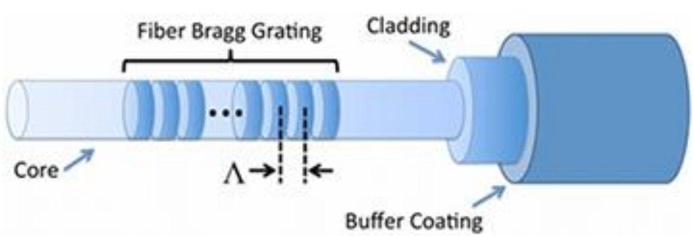

Fig.1 Principle of a Fiber Bragg Grating. A periodic change of the refractive index of the fiber is introduced. The Bragg condition based on the periodicity gives the selectively reflected wavelength. A change of the grating dimension/periodicity changes the reflected wavelength. Therefore, the FBG becomes a natural strain and temperature sensor.

Fugro developed its own fiberoptic sensing system, marketed under the brand name FAZ Technology (A Dublin-based Fugro company). The 4-channel system is based on a solid-state tunable laser operating in the C-band, with a wavelength window of 40nm. This system is quite different from typical fiberoptic FBG systems, as it operates in a rather narrow wavelength window, but in contrast to the competing systems on the market it allows rather high interrogation frequencies (up to 8kHz), the use of extremely narrow FBGs (which use a tiny optical wavelength space), and it has a extremely large dynamic range (up to 130dB) with an extremely high accuracy (better than 0.5pm) and precision (better than 0.035pm) (see www.faztechnology.com for details). This allows not only the use of a relatively large

FAZ I4 Interrogator, optics (left) and electronics (right) boards

Fig.2: Fugro/FAZ Technology Fiberoptic Interrogator (Model I4G).

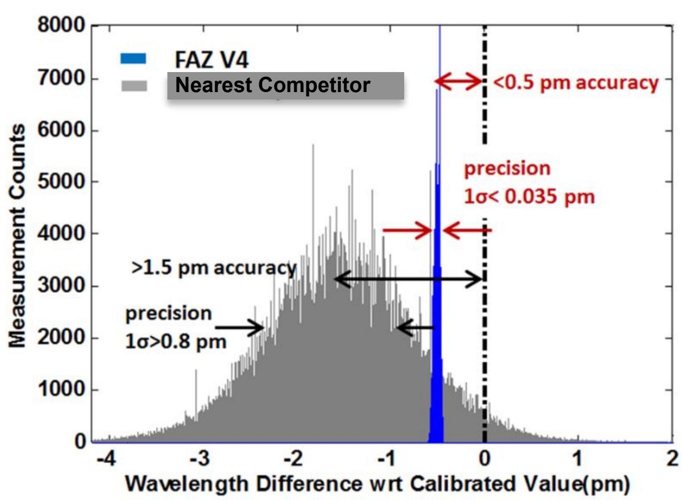

Fig. 3: FAZ I4, precision and accuracy compared to the nearest competitor ([redacted] system). A single FBG under controlled conditions is measured for a long time, the individual measurements are sampled into a distribution. The deviation from the "true" measurement is defined as precision, the width of the distribution (the scatter) is defined accuracy.

number of sensors on the generic 4-channel system (up to 120), but with the inclusion of an optical multiplexer we have a 64-channel system allowing the interrogation of close to 2000 sensors per interrogator (in combination with the narrow-wavelength sensors). For most strain measurement applications this allows a completely new approach: Suddenly very fine spatial dynamic strain sampling is possible, which allows a completely new way of observing a structure (bridge, road surface, building etc.). It is possible to “see” the motion

Fig. 4: FAZ 64 channel interrogator, using an optical multiplexer system.

and deformation of an object live and in fine grained resolution. An example is given in Fig. 5, where we show an application from road monitoring: 30 horizontal strain gauges over 3m of road width are interrogated at 2kHz sampling rate. This allows a dynamic fine-grained monitoring of the tarmac (and underground) as vehicles move over it, the tarmac layer shows

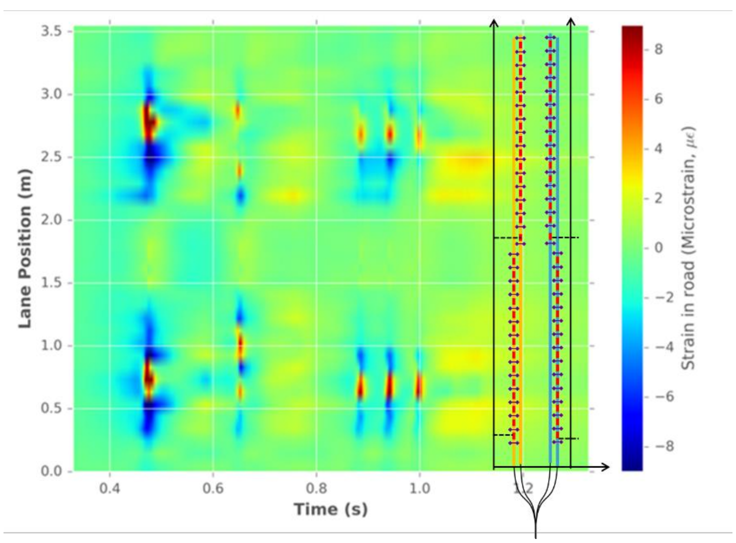

Fig. 5: Road monitoring example: Horizontal strain (color map) as a function of sensor position (vertical axis) and time for a truck passing a FO strainline buried into a tarmac layer.

its behavior like a viscoelastic membrane covering the underconstruction. At the position of a wheel we record an imprint which under the wheel is positive, but around the wheel creates a negative (bulging up) ring (very much like an inverted Mexican hat). Not only is it possible to “see” this statically, but we can monitor this fully dynamically in real time (short times: to monitor the impact of traffic, long times: to monitor the permanent (viscous) deformation of the asphalt layer because of traffic (“rutting”)).

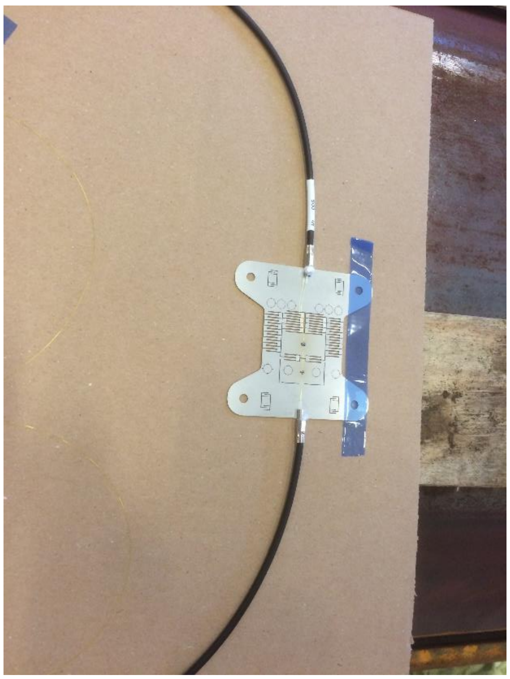

Fig. 6: Fugro Strain sensor, basic sensing element without cover and protection. The combination of optical fiber and spring “multiplier” is clearly visible, the fiber runs between the two black cable ends across the spring structure and is mounted using mineral glass solder. The round “spots” are the markers for the actual welding points to the to be monitored structure.

4 Strain Measurements: Sheet Pile Case Study

Here we want to introduce another geotechnical example: Monitoring of the deformation / bending of sheet piles, as they are used in many construction applications. In our case, these sheet piles are used to reinforce the core of a levy in the Dutch water management system. A series of sheet piles had to be instrumented to record their deformation and bending under various external influences, up the breaking of these sheet piles. The requirement was mount a total of 700 strain gauges with a range of -20000 to 20000μσ. With any kind of conventional strain measurement system this would be extremely difficult, if not impossible (at least, it would be cost-prohibitive). Even conventional fiberoptic strain sensors would not allow this unless a very large number of optical interrogators is used, as these sensors use a rather large optical wavelength range (examples: www.sylex.com, 12nm per sensor for ±5000μσ, www.micronoptics.com, 8nm per sensor for ±2500μσ). To achieve the

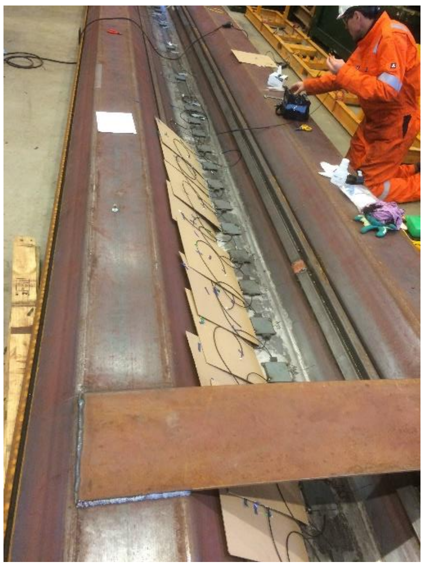

Fig. 7: Installation of the sensors on a sheetpile. The sensing elements are covered with an individual protective cover which does not interfere with their function as strain sensors.

Fig. 8: Covered and waterproofed strain sensor line ready for field deployment.

goal, we designed a new type of strain gauge, which uses a combination of optical fiber and a spring system, which acts as a load multiplier (see Fig. 6). Doing this, we could achieve a strain gauge with a measurement range of ±10000μσ while using only 2.4nm of wavelength per gauge.

In combination with the 64-channel system, this allows an easy recording of all 700 gauges (plus a series of temperature sensors) using one interrogator, with the required sampling frequency of 1Hz. Given the high precision and accuracy of the Fugro system, the resolution is equal to competing systems, while minimizing the cost and logistic effort for this installation. The sensors are weldable, screw-able or glue-able (with gluing being only recommended for short term applications as typical glues are not long-term stable). The sensing elements can be covered with a protective housing (including a waterproof system), and since they are very thin and weldable, they even survive the extreme forces during the sheet pile hammering into the ground. Equally well, an inverse mechanism could be applied, where an amplifier would be combined parallel to the fiber, allowing an extremely sensitive (even sub-microstrain) strain element.

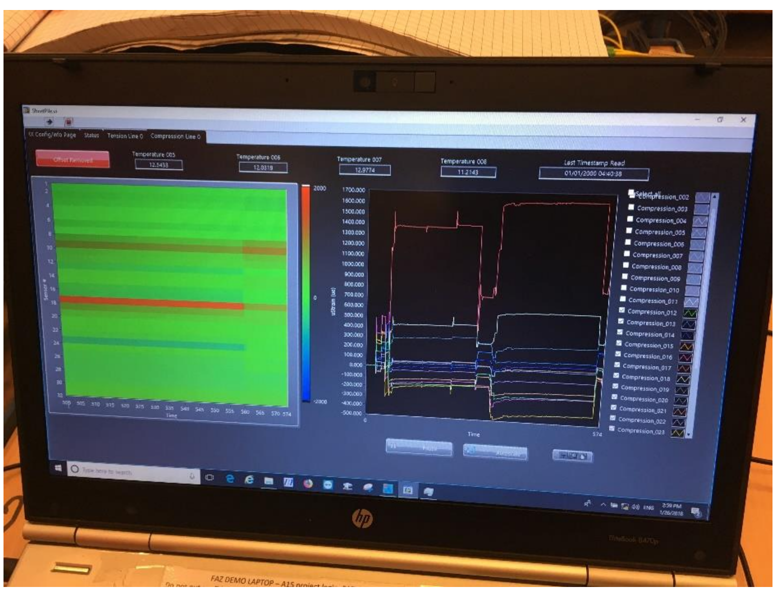

Fig.9: Display of the FO Strain measurement system during Factory Acceptance Test. The left panel displays a complete pile as strain color map, the right panel gives conventional strain versus time display for a group of sensors.

5 Summary and Conclusion

We have given an insight in the Fugro fiberoptic sensing system and its properties which distinguish it from competing systems. It has proven extremely useful in a whole series of geotechnical and asset management tasks, onshore and offshore: This includes road and traffic monitoring including weigh in motion application, foundation monitoring, windfarm monopile observation, levy projects, wall monitoring, intrusion detection, tank monitoring, and many more. Fiberoptic systems are extremely useful if large numbers of sensors are used at the same time, allowing a completely new spatial and temporal resolution. The FO sensing system allows the combination of many different sensors on one single fiber (strain, temperature, acceleration, etc.), and even complex transducers like a CPT cone can be built (with enormous improvements in sensitivity). They are not competitive if a single electric sensor is to be replaced. The system (interrogators and sensors) are built to be stable: mechanically, electrically and optically.

Authors

Dr. Johannes M Singer	j.singer@fugro.com
Dr. Devrez Karabacak	d.karabacak@fugro.com
Murat Ozmen	m.ozmen@fugro.com

Fugro Technology BV, Veurse Achterweg 10, 2264SG Leidschendam, The Netherlands, Tel. +31 6 23969738