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Smart Geosynthetics Based on Distributed Fiber Optic Sensors in Geotechnical Engineering

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ABSTRACT: Smart geosynthetics with embedded optical fibers as distributed sensors provide solutions both for applications in geotechnical engineering and for cost-effective monitoring of critical infrastructures. The incorporation of glass or polymer optical fibers (GOFs or POFs) in geotextiles and geogrids allows early detection of mechanical deformations, temperature and humidity. This paper presents selected examples of smart geosynthetics based on Brillouin and Rayleigh scattering effects in incorporated fiber optic sensors for monitoring of large geotechnical structures like dikes, dams, railways, embankments or slopes. The focus of the presented work is on real field tests of measurement capability with respect to the chosen measurement principle and used fiber type.

KEYWORDS: Smart geosynthetics, Fiber optic sensor, Distributed sensing, Glass optical fiber (GOF), Polymer optical fiber (POF)

1. INTRODUCTION

The rapidly growing development of synthetic polymeric products observed in recent decades has led to long-term establishment of cost-effective geaosynthetics as modern construction materials in civil engineering. In the field of industrial applications various types of geosynthetics have been used to provide reinforcement, separation, drainage or filtration in soil and rock materials. The steadily increasing use of flexible geotextiles and stiff geogrids has initiated extensive research to enhance their functionality, e.g. to enable distributed monitoring of mechanical deformations, soil displacement, temperature and humidity. Furthermore, the integration of fiber optic sensor cables into such smart geosynthetics used as sensor carriers allows creating two- or even three-dimensional sensitive structures for large-scale monitoring in structural and civil engineering.

The fiber optic sensors based on both polymer optical fibers (POFs) and glass optical fibers (GOFs) offer substantial advantages over conventional sensors used for structural health monitoring (SHM), e.g. strain gauges, accelerometers or inclinometers. Aside from their electromagnetic immunity, electrical non-conductivity, corrosion resistance and multiplexing capability, the lightweight optical fibers can be processed like standard textile yarns due to their fibrous nature. This can in turn facilitate the straightforward integration of sensors into geosynthetics.

Depending on the applied fiber type, cable design and application, several sensor techniques based on scattering effects in the optical fiber can be used. The paper highlights the development of smart geotextiles and geogrids incorporating distributed fiber optic sensors performed in several German and European projects.

2. SENSOR-BASED GEOSYNTHETICS

The monitoring of large geotechnical structures requires sensor lengths of a minimum one hundred meters and possibly reaching even up to several kilometers. For the short distances, standard PMMA POFs can be used as distributed sensors. Their optical attenuation limits the measurement range to about 100 m (Liehr et al. 2009). Using perflourinated POFs, this distance can be increased to more than 500 m (Liehr et al. 2008a). The attenuation-related limits of measurement range can finally be overcome by using low-loss single-mode (SM) GOFs allowing extension of the measurement range up to tens of kilometers. Due to integration of GOFs into geotextiles (Figure 1) or geogrids (Figure 2) and the related occurrence of prejudicial bending effects increasing optical fiber attenuation, however, the expected distances in the range of tens of kilometers could not be achieved. Moreover, unlike POFs, due to the small core diameter, the SM GOFs are very sensitive to microbending and macrobending causing additional optical losses. The manufacturing process of GOF-integrated geosynthetics developed in several research projects was optimized to the reproducible low optical fiber attenuation of 1.5 dB/km (Wosniok and Krebber 2015). This value in turn allows measurement ranges of a few kilometers.

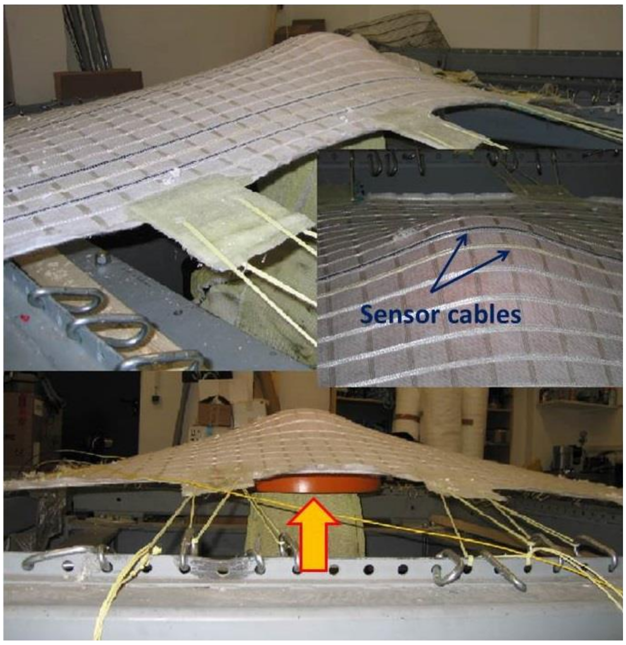

Figure 1 Smart non-woven geotextile with integrated optical fibers during mechanical load tests at STFI e.V

The development of sensor-based geosynthetics also revealed the relevance of choosing the appropriate design of fiber optic cables to be incorporated both into geotextiles (Figure 1) and geogrids (Figure 2). Due to the fragility and the low break-down strain of GOFs, the choice of suitable cable design played an important role for the use of this kind of fibers (Wosniok and Krebber 2015). Furthermore, the tests of the behavior of various cables have shown that a trade-off needs to be made between preservation of the fiber sensitivity and its mechanical protection during integration into geosynthetics and embedment at a construction site.

Figure 1 shows a stretching test on a non-woven GOF-integrated geotextile mat strained by a mushroom-shaped indenter. The test was performed at the Saxon Textile Research Institute (STFI) in Chemnitz. The gradual application of mechanical load applied to the tested mat equipped with various GOF cables resulted in design-related distinctions in the transfer of the mechanical deformation to the measured fiber strain signals. The tested GOF cables differed in thickness and number of cable coatings, tightness of the buffering and the performance of strain relief. By varying the cable design, different level of strain transmission to the measuring fiber placed in the center of the cable can be achieved. Generally, the loose buffering causes decrease of friction between the sensor fiber and the cable coating leading to slipping of the fiber when outside strain is applied to the cable. This behavior results in a blurring of the measured signals, thus causing a decrease in spatial and strain resolution. At the same time, loose buffering can lead to significant underestimation of measured strain value, compared with the true applied outside strain. On the other hand, only partial strain transfer may be advantageous for the protection of sensor fibers in applications where high deformation is expected.

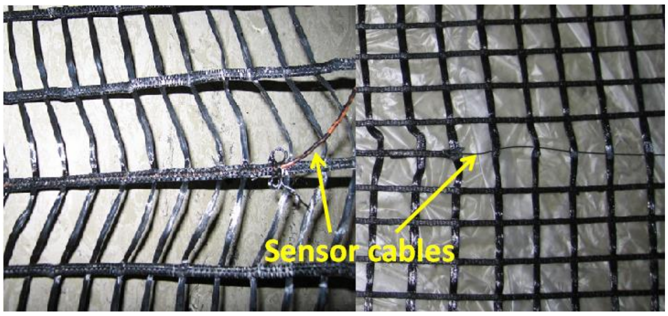

Figure 2 Uniaxial (left) and biaxial (right) sensitive geogrids containing GOFs

The functionality of the fiber-sensor-integrated geosynthetics has been proven in several installations and field tests. Figure 3 shows the embedment of a non-woven fleece mat (Wosniok et al. 2017), typically used as drainage and filter material in geotechnical engineering. In this case, the GOF sensors were applied on the surface of the geotextile using a warp-knitting technique. The embedment in the soil body of a gravity dam in Swinna Poremba, Poland, was performed by means of heavy machinery in the framework of the German project RIMAX (Risk Management of Extreme Flood Events). All fiber optic sensors have survived the installation without any damage.

Figure 3 Installation of a GOF-based non-woven geotextile in a gravity dam in Swina Poremba, Poland

3. DISTRIBUTED FIBER OPTIC SENSING

Distributed sensing provides the advantage of spatial measurements of various physical quantities along the sensor fiber. The single distributed fiber optic sensor can therefore replace a myriad of local point-wise sensors resulting in the reduction of sensor system costs. Especially in case of monitoring of large geotechnical structures like dikes, tunnels and reinforced earth structures, the costs can be reduced. The choice of suitable GOFs or POFs as distributed fiber optic sensors depends on specific application requirements.

The sensing techniques are mostly based on scattering effects in the optical fibers. The elastic Rayleigh scattering process plays the predominant role in the POF-based sensor systems. Compared to GOFs, POFs exhibit a significant Rayleigh-backscattered power dependence on strain with slight temperature and humidity cross-sensitivities (Liehr et al. 2009a; Liehr et al. 2017). The section 3.2 gives detailed information on the optical time domain reflectometry (OTDR), commonly used for POF-based distributed monitoring of large mechanical deformations. In contrast to POF-based OTDR, the methods using inelastic Brillouin scattering effects provide higher strain sensitivities as explained below. Furthermore, the GOF-based distributed Brillouin sensing is in the meantime a well-established method for combined temperature and strain measurements for SHM applications. The application fields of the Brillouin sensing can be further enhanced in the future for high-strain measurements by the prospective use of low-loss POFs.

3.1 GOF-based sensing

The most developed industrial solutions for distributed fiber optic sensing are based on Raman and Brillouin scattering in GOFs. The former physical phenomenon can be used only for temperature measurement and Raman-based systems are therefore of limited significance for real geotechnical applications where information about mechanical deformations or soil displacements is required. Because of this requirement, Brillouin-based systems represent the most suitable distributed fiber optic sensors in geotechnical engineering.

The use of all Brillouin systems is based on the distributed measurement of the Brillouin gain spectra (BGSs) along the sensor fiber. Furthermore, the BGSs can be measured by coupling a pump lightwave into the sensor fiber and by determining the amplification of a weak counter-propagating probe signal coupled into the other end of the fiber. Such a sensor technique based on stimulated Brillouin scattering in time domain (Horiguchi and Mitsuhiro 1989) as well as in frequency domain (Garus et al. 1996; Nöther 2010; Wosniok 2018) usually provides higher measurement accuracy than the Brillouin-based reflectometry methods. Figure 4 shows spatially resolved BGSs recorded by means of Brillouin optical-fiber frequency-domain analysis (BOFDA) along a 600 m long sensor section consisting of 20 m long GOF-based geogrids connected together and embedded into the soil.

In Figure 4 the frequency shift of BGSs towards higher frequencies observed at selected positions along the fiber corresponds to the increased local strain values caused by soil deformations. Furthermore, the Brillouin frequency shift (BFS) varies linearly with temperature T and applied strain ε:

$$BFS = C_{\varepsilon} \cdot \varepsilon + C_T \cdot \Delta T + f_{BO} \quad (1)$$

in which C_{ε} and C_T are the strain and the temperature coefficient, respectively. f_{BO} corresponds to the characteristic Brillouin frequency shift in an unstrained fiber at T= 20 °C.

For standard SM GOFs in the third near-infrared spectral window at around 1.55 µm the following applies:

$$C_{\varepsilon} = 490\ \mathrm{MHz}/10^4 \mu\varepsilon \quad (2)$$

$C_T = 1.1$ MHz/°C (3)

with the strain unit defined as με=μm/mm.

The distributed Brillouin sensing allows measurement accuracy of 0.5 °C and 10 με, respectively. In practice, the accuracy decreases with rising signal attenuation along the fiber. Our installation and field tests have shown that the robust embedding of sensor-based geosynthetics into the soil can result in a significant increase of fiber optical losses. In case of the field test, whose results are shown in Figure 4, the embedment of GOF-integrated geogrids into the soil has caused an increase of optical fiber attenuation from 1.5 dB/km to 5.5 dB/km. For this application, such installation-related signal deterioration has impaired the achievable measurement accuracy, i.e. up to around 1-2 °C for temperature and 20-40 με for strain measurements, respectively.

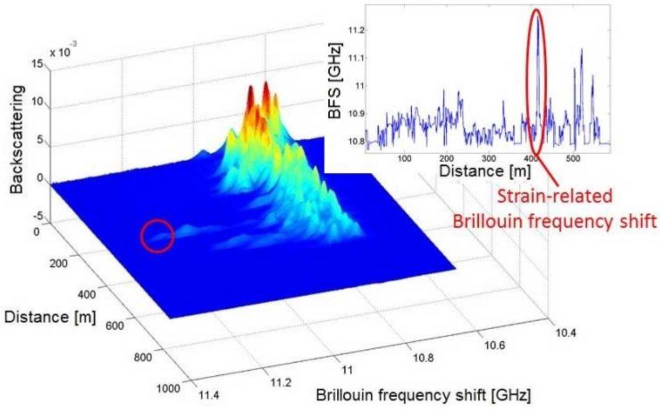

Figure 4 Measurement of the BGS distribution along a GOF integrated in a geogrid field

3.2 POF-based sensing

The potential of the POF-based distributed sensor systems can be realized in high strain measurements (even over 40%), e.g. detecting significant deformations in earthwork structures. The most established measuring technique (Lenke et al. 2007; Liehr et al. 2009a) is based on Rayleigh OTDR. This approach is commonly used in telecommunication industry for in-depth fiber characterization and fault analysis. For the past decade, the technique has been used for SHM applications as well. The Rayleigh-backscattered signal gives spatially resolved information about fiber optical losses affected by perturbations, fiber kinking or bending. The sensor signals shown in Figure 5 (Liehr et al. 2008b) reveal that also longitudinal strain can be seen as a certain type of perturbation affecting spatial distribution of backscattered traces. As shown in Figure 5, a local strain along a fiber causes an increase of backscatter intensity at the position of the strain.

The level of strain-induced increase in backscatter depends on the applied strain. The PMMA POFs can be used at high strains up to 45% (Liehr and Krebber 2016). The relaxation processes occurring in the strained fiber section lead to an asymptotic decrease of the backscattered level over time. As a result of the relaxation, the application-dependent strain resolution is in the range of 0.1-1.0% (10^3-10^4 με) (Liehr et al. 2008b).

4. MONITORING APPLICATION EXAMPLES

The safety and management of geotechnical structures require continuous monitoring and maintenance. Continuous damage detection and localization is necessary in order to quickly take actions in case of occurrence of any critical mechanical deformation. The development of geosynthetics with integrated distributed fiber optic sensors has been in the focus of extended research for many years. This section presents selected examples of applications of smart geosynthetics for distributed monitoring tasks.

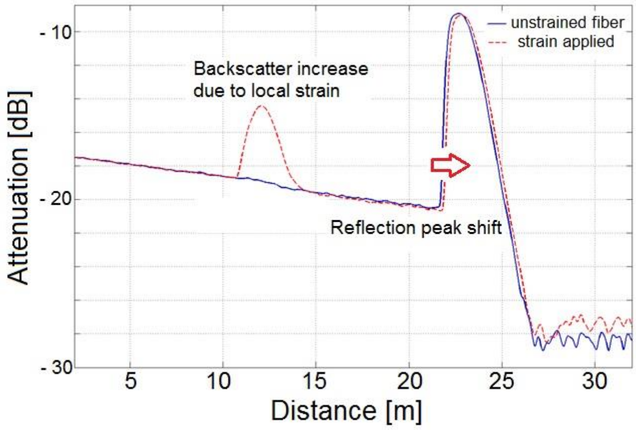

Figure 5 Spatially resolved Rayleigh scattering measurement along a POF in an unstretched condition (solid line) and after a local strain occurrence (dashed line)

4.1 Brillouin-based sensor systems

The field test shown in Figure 6 and in Figure 7 illustrates the potential of soil-embedded GOF-based geotextiles under harsh environmental conditions. The Brillouin measurement results presented in Figure 7 prove the suitability of using GOF-based sensors even when installed at a depth of 7 m in stony terrain. The embedded 140 m long non-woven mat contains a cable solution with two fibers connected to a loop. One of the fibers (Fiber 2 in Figure 7) is placed centrally in a loose tube allowing pure temperature measurements by mechanical decoupling of the fiber from the cable jacket. For the better distinction of the fiber signals, differently doped fibers have been used. This results in varying basic Brillouin frequency shift f_{BO} values for the two fibers.

Figure 7 shows installation-induced local prestraining of the sensor fibers up to 0.8% which affects the measurable strain range due to the break-down strain limit of GOFs (about 2%). The installation under harsh environmental conditions, however, has not led to a significant increase in optical losses. The sensor-based geomat has therefore proven to be suitable for measurements with accuracies in the range of 1-2 °C and 20-40 με, respectively.

Figure 6 Installation of GOF-based geosynthetics at an abandoned opencast pit at a depth of 7 m in Zimmersrode, Germany

Figure 8 shows the integration of GOF-based smart geotextile behind an earth dam in Myczkowce, Poland in 2006 performed in the framework of the RIMAX project. The goal of the field test was to detect possible geophysical activities in the dam using distributed Brillouin sensing. For this purpose, a number of on-site measurements were performed between 2009 and 2013 as shown representatively in Figure 9.

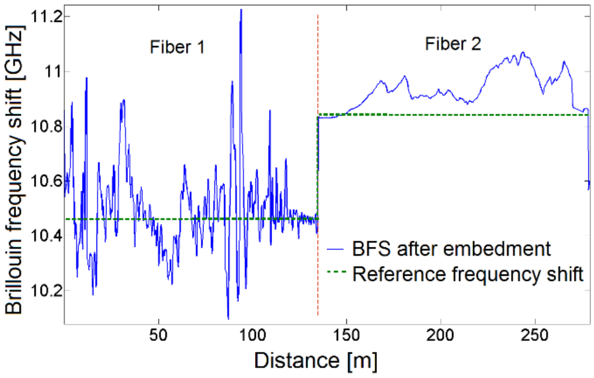

Figure 7 Distributed Brillouin frequency shift after embedment in the soil measured along the fiber loop consisting of two different fibers at an abandoned opencast pit at a depth of 7 m in Zimmersrode, Germany

Figure 8 Installation of a GOF-based non-woven mat behind an earth dam in Myczkowce, Poland

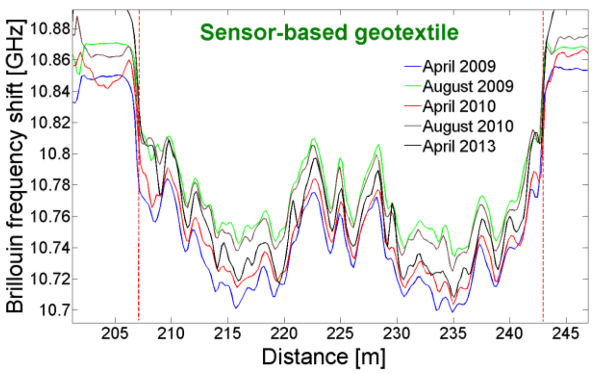

Figure 9 Distributed Brillouin frequency shift measured in steps on the fiber section embedded in the soil behind an earth dam in Myczkowce, Poland

The sensor-based geotextile embedded in the soil was located between 207 m and 243 m. The signal offset between recorded measurements corresponds to the temperature differences during the single measurements. Due to the local soil movements occurred between August 2010 and April 2013, mechanical deformations were detected at the position 209.8 m and 229.6 m resulting in the local strain about 350 με and 500 με, respectively. In addition, no aging processes in the sensor fibers were observed 7 years after the embedment of the geotextile.

4.2 Rayleigh-based sensor systems

POF-integrated geosynthetics have successfully moved from the laboratory to the field for the past decade. Accordingly, Figure 10 shows the installation of a sensor-based geogrid placed perpendicular to the tear-off edge of a creeping slope at an open brown coal pit at Belchatow, Poland.

The cleft formation predicting dangerous slope slide, observed after embedding and presented on the right side of Figure 10, was monitored in steps using OTDR technique. Here, the recorded backscatter increase shown in Figure 11 (Liehr et al. 2009c) could be converted to the strain value of more than 10% in the sensor section marked in dark blue. Such a high strain value can only be detected by using POF sensors. Their glass counterparts would have already failed at strains of about 2%.

Figure 10 Monitoring of a creeping slope at an open brown coal pit near Belchatow, Poland: Installation of POF-based geogrid (left), Final state after creeping (right)

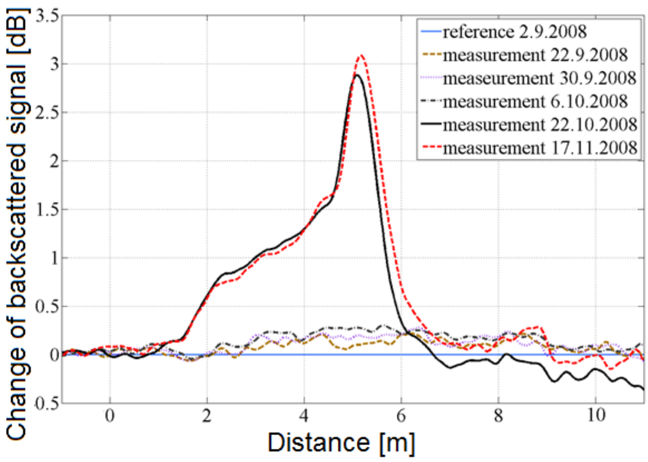

Figure 11 OTDR results of the field test at an open brown coal pit near Belchatow, Poland

The successful demonstration of POF-based OTDR sensors in the field and the huge interest of the geotechnical industry resulted in the development of the first distributed PMMA POF sensor integrated in geosynthetics, called GEDISE (GLÖTZL GmbH).

5. CONCLUSION

Monitoring systems based on geosynthetics with integrated fiber optic sensors represent a potentially new sector. POF-integrated geomats have proven to be a cost-effective solution to increase the structural safety of geotechnical structures. The high elasticity and break-down strain of POFs allow distributed sensing of large mechanical deformations in the form of longitudinal strains up to 45%. The use of GOFs integrated in geotextiles and geogrids provides potential for large-scale monitoring of geotechnical structures over a few kilometers.

6. ACKNOWLEDGMENT

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