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## Selected geotechnical applications of deformation sensing by fibre optics and problems with gathered data evaluation

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### ABSTRACT

The paper presents the basic principles of the application of two optic fibre methods for deformation measurement in geotechnics - Brillouin Optical Time Domain Analysis (BOTDA) and Fibre Bragg Gratings (FBG).

It briefly describes the possible and tested utilization of these methods (concerning both laboratory testing and on site applications) and in more details it deals with several issues and problems concerning specific adjustments of sensors, data interpretation and evaluation.

**Keywords:** geotechnical monitoring, BOTDA, FBG, fibre optics

### 1. INTRODUCTION

Geotechnical monitoring in the soil / rock massive should give reliable information of deformation development as a product of long-term natural processes and human construction activities. High accuracy, detailed distribution of at least deformation within the area of interest and long-term stability of measurement and warning system are often required. Fibre optics can be good alternative to electric sensors using cheap telecommunication cables for connection in several kilometres distances to the analyzer to cover large areas. The functioning of optical fibres depends on basic principles of optics and the interaction of light with matter.

From a physical point of view, light can be seen either as electromagnetic waves or as photons (quanta of electromagnetic energy). Both possibilities are valid and equal, but the most useful viewpoint for optics is to consider light as rays travelling in straight lines between optical elements, which can reflect or refract (bend) them.

The paper presents two methods working on different sensing principles. The first one is based on Fibre Bragg Gratings (FBG) and could replace standard local electric or other sensors. The second one uses Brillouin Time Domain Analysis (BOTDA), which offers new possibilities in strain sensing. These methods were initially studied and tested within two research projects in 2011 – 2013 and their research continues to this day.

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## 2. BRILLOUIN OPTICAL TIME DOMAIN ANALYSIS

Sensing methods based on the effect of Brillouin scattering utilize the fact, that continuous distributed information of time and spatial domain can be measured simultaneously by running an optical fibre to each location. Brillouin scattered light is caused by non-linear interaction between the incident light and photons that are thermally excited within the light propagation medium (Zhang et al. 2008). BOTDA instruments can measure temperature and mechanical strain distribution along the fibre length.

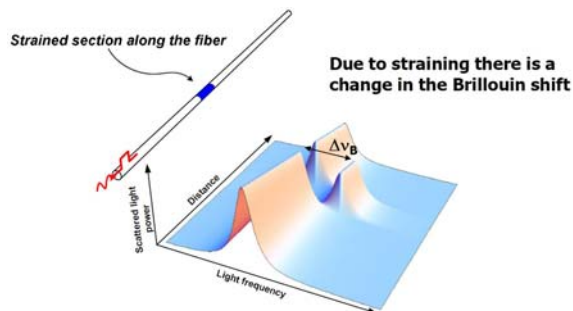


Figure 1. Brillouin light frequency shift due to change of strain and temperature, after (Klar et al. 2010)

The Brillouin Optical Time Domain Analysis (BOTDA) utilizes the effect of stimulated Brillouin scattering, which arises from the interaction of glass fibre molecules and transmitted light. The shift of Brillouin frequency corresponds to the deformation or temperature change (Figure 1). The location of the frequency change along the optical fibre is calculated from the travel time of the backscattered light; therefore the strain / temperature change value and the position of the change can be determined by this method.

Laboratory testing of BOTDA technology started in 2011 and included testing with several test beams, which had been developed by the research team. All the test beams are made of steel, have measurement interval of 1m or 2m length and vary in the number of measuring intervals. The tested BOTDA sensing cables are attached on both sides of L-shaped cantilevers, the distance between

those cantilevers can be adjusted and the elongation / shortening of the measuring base is therefore obtained (Figure 2). The principles and construction of test beams are described in more detail for example in (Záleský et al. 2015).

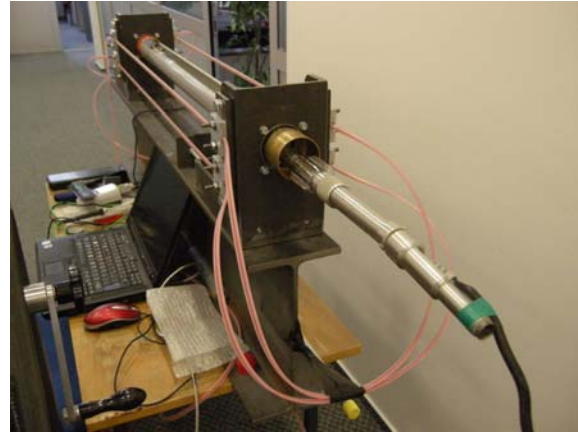


Figure 2. BOTDA test beam with one 1m long measuring interval, after (Čápková 2012)

Independent measurements of deformation were provided in two different ways in order to have comparative / control information about deformation to the fibre optic method. The first comparative method was utilization of high resolution potentiometric displacement transducers in connection to data-logger and the other was measurement by sliding micrometer (Solexperts AG, Switzerland), which is commonly used for geotechnical monitoring (measurement of axial deformations in instrumented borehole).

### 2.1. Laboratory testing – problem with splice connection

First sets of laboratory measurements included measurements of changes of length of measurement base and stability of measurement in time, then the development of optimal system of fixing of sensing cables to monitored structure followed. The sensing cable was attached to the short test beam in four 1m long measuring sections, the strain sensing fibres were connected by splice connection into a close loop (measured deformation distribution is therefore mirrored along the point of splice).

At Figure 3 an example of the output from the analyzing unit is presented. Each

sensing cable includes two sensing fibres; there is a splice connection in the middle of the measuring line (the fibre goes through four measuring parts, then is spliced and goes through the same four measuring parts in the opposite direction). In Figure 3 there are clearly visible four strained parts with almost constant strain distribution. Due to the defect in the splice connection, the other four strained parts with non-constant strain distribution appear.

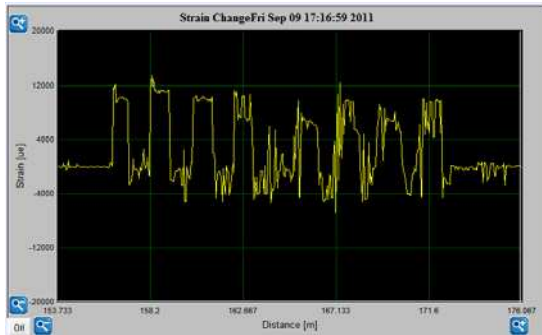


Figure 3. Screenshot of strain distribution during laboratory testing with BOTDA analyzer – poorly provided splice connection

A new set of tests was provided on a new test beam in the lab. The new test beam is very similar to the previous one, but the measuring section (base) is 2m long. The issue that need to be solved was the poorly provided splice connection of the fibres. Therefore the execution of the splice connection was extremely careful and the results showed that the effects of a poor splice were suppressed quite well, see Figure 4 (the figure presents the zero measurement of an unloaded fibre, so called baseline).

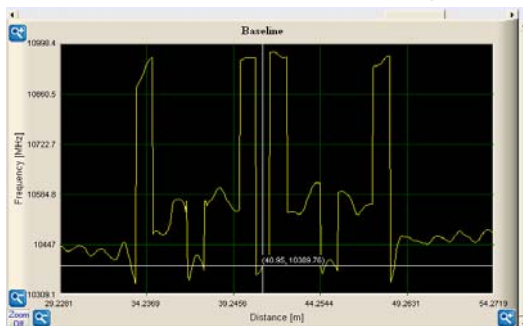


Figure 4. Screenshot of strain distribution during new laboratory testing – precisely provided splice connection

## 2.2. Attachment system of BOTDA

The sensing cable is attached to the test beam between two duralumin plates (50x50x5mm), which are screwed to L profiles on the upper flange of the IPE beam, see Figure 2.

At Figure 3 there are visible unexpected peaks both in strained and unstrained parts. These peaks were formed due to the attachment system and related large sudden changes of strain applied to the sensing cable; the sensing cable may be too much tight between duralumin plates.

These effects are quite severe; they occur not only during laboratory testing, but also in field instrumentation (see chapter 2.3). As already mentioned, they are expected to be caused by the local cable compression at the attachment points. These effects were further investigated and tested on a laboratory model of an instrumented borehole and also on a test beam. These tests resulted in careful cable coverage by thick plastic tape in the area of duralumin plates before fixing of clamps using controlled torque moment. The effects were partly reduced using this procedure (see Figure 4). Nevertheless, this solution is functional, but it is not perfect – the issue needs to be analyzed in more detail.

## 2.3. Borehole measurement

In the area observed by one member of the research team (Rabenov, Czech Republic) there is a borehole used for monitoring of 3D subsoil deformations. The monitoring in this borehole (VB01) indicated shear deformations in the depth of 14-15m below the ground level and also showed activity, which kept slowly developing since 2006. This had been the reason for providing the locality by a new borehole (VB01A) in the vicinity of VB01. The new borehole has been instrumented by combined casing for measurement by sliding deformer and inclinometer and also by BOTDA sensing cables. Optical sensing cables have been attached to the measuring casing in 1m distances – the strain is measured along this length. The results of BOTDA measurements are

presented in Figure 5 and the results of control measurements by sliding deformer in Figure 6, both BOTDA and control measurements were carried out on the same dates.

The strain was measured along 1m base using a couple of sensing cables labelled as 1-2 and 3-4. Each cable consists of two sensing fibres in closed loops (1 and 2, 3 and 4) which are spliced at the toe of the measuring casing. The resulting figure is a plot of calculated strain from sensing fibres 1 and 4 along the whole depth of the borehole, because of a disturbing phenomenon of poorly provided splice connection – only a half of each sensing cable has been used for calculation of axial strain distribution.

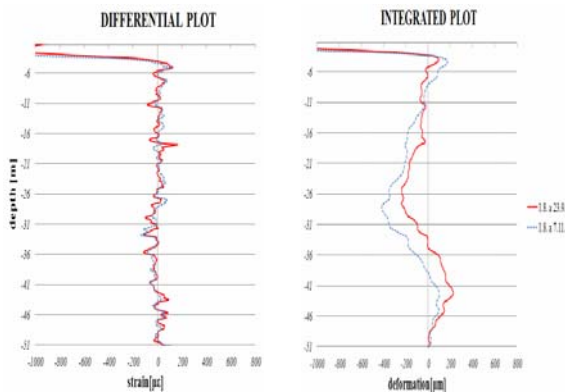


Figure 5. BOTDA measurement in VB01A – left: differential plot, right: integrated plot

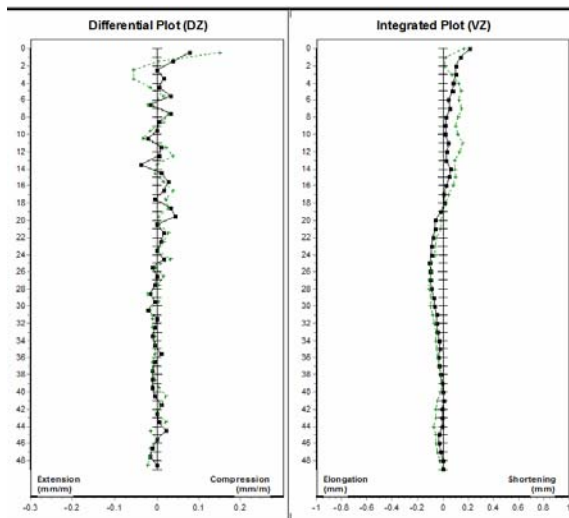


Figure 6. Sliding deformer measurement in VB01A – left: differential plot, right: integrated plot

At Figure 5 high values of strain near the ground level are clearly visible; these

values are expected to be caused by temperature changes at the ground level and they do not characterize the development of deformations. The results of the BOTDA measurements give us in points of attachment larger values of developed strain than the control measurement, nevertheless the shapes (trends) of both plots are similar. The effect of strain increase at the attachment points is discussed in chapter 2.2. and is probably caused by too high compression of the cable by the attachment system. The solution of the problem is described in the chapter 2.2. as well. It is also necessary to provide more deep analysis of the comparison of BOTDA and control measurements together with the development and laboratory testing of a new attachment system. The rest of the plot demonstrates overall stability; on the other hand several major issues occur there and need to be tested and studied more deeply.

#### 2.4. Analysis of the measured data

In several measurements, particularly in the borehole monitoring, there are unexpected increases of strain not related to the attachment system issues (too much tight cable in the attachment system). These measurements are provided with four sensing fibres at the same time, but the strain increases occur only at some of them. These effects may be caused by some defect in the sensing cable or fibres. Therefore it is necessary to provide a consistent check of any sensing cable prior to its instrumentation.



Figure 7. Brillouin scattering with Gaussian distribution, after (Čáková 2016)



Figure 8. Brillouin scattering with non-Gaussian distribution, after (Čápvá 2016)

The measuring / analysing unit used for the basic BOTDA data evaluation enables more deep analysis of the measured data at each point of the measurement. It can calculate and display a plot of the Brillouin scattering in comparison with the Gaussian distribution. This analysis was provided in several cases and the example of Gaussian and non-Gaussian distributions are presented in Figure 7 and Figure 8 (Čápvá 2016). According to this analysis it also seems that the problem is accentuated with strain increase.

### 3. FIBRE BRAGG GRATINGS

The Fibre Bragg Gratings (FBG) strain sensors are able to measure the average value of strain which has been developed on the optical fibre. The fibre needs to be provided with the Bragg grating (Figure 9) and also has to be attached between two fixed points. In order to keep the sensor in operation, it is necessary to keep the fibre tight during the whole measurement.

The measurement of reflected wavelengths is provided by the measuring unit; all the results presented in this article have been obtained by measurement with the unit FBGuard (developed by the Safibra, Ltd. within the R&D project).

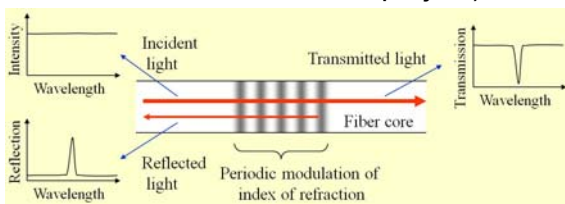


Figure 9. Principle of Bragg Grating, after (Sugimoto)

Every measuring unit operates only in specific range of the optical spectrum, for example 1510 – 1590nm, therefore it is necessary to design in advance Bragg wavelengths of specific sensors considering assumed strain changes. The FBGuard unit allows to measure on up to four channels (four optical fibres provided by FGB sensors) in the wavelength range around 1550nm. The calculations provided by (Vopička 2012) show that less the strain change, higher the maximum number of sensors per one channel.

#### 3.1. Interrogation unit FBGuard 1550

The interrogation unit FBGuard 1550 which is used for all the FBG laboratory and in-situ measurements performed and presented by the research team has been developed by the company Safibra, Ltd. within the research project. The unit is described in details in (Záleský, M. et al. 2013).

The unit is fully industrial and can perform static and dynamic measurements of FBG sensors with high accuracy. The measuring system contains a broadband light source in the range of 1550nm and performs spectral analysis by means of a linear CCD-array spectrometer platform. The monitored input channel can be selected by an optical switch; it is also possible to adjust scan frequency and number of channels.

FBGuard unit is fully controlled by an internal embedded PC and is independent on external devices and control procedures. All the measured data are stored in the internal SSD memory. The unit is designed for permanent operation using Linux system. The configuration of the interrogation unit, alarms, scan rate (frequency of measurements), events and data logging is possible via SSH and web interface, because FBGuard 1550 is designed as a web server.

#### 3.2. Borehole monitoring by FBG strain sensors

From the analysis of the local investigations, the area, where active movements are expected and the

instrumentation may help to complete the knowledge about the mechanism of slope movements, has been chosen for the instrumentation of FBG sensors into a borehole. Geological conditions and previous geotechnical monitoring of the area (Rabenov, Czech Republic) is described in more details in (Čáповá et al. 2014) or (Záleský et al. 2014)

Considerations about the most appropriate sensor lengths, as well as their deployment in the borehole cross-section were supported by parametric studies using geometric models of measuring casing deformed in a shear zone by the sliding soil mass. The aim was the determination of the maximal horizontal deformation, which can be measured, when the limit strain in the optical fibres is reached. Further, the appropriate lengths of the FBG deformation sensors had to be stated with respect to awaited horizontal deformation. The shape of deformed measuring casing was estimated as two small circular sections connected by their mutual non-horizontal tangent line, Figure 10. The parametric study was carried out for several assumed heights of the shear zone together with selected radii of the couple of circular parts on deformed casing. The presented results are based on analyses published in (Čáповá 2012).

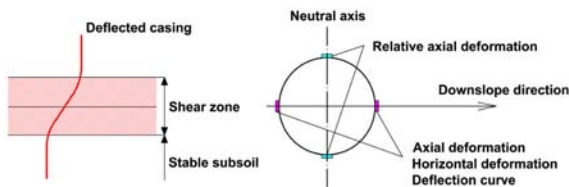


Figure 10. Scheme of deformed measurement casing (left) and schematic cross-section through instrumented borehole with FBG sensors (right), after (Čáповá 2012)

For sensor lengths of 1000mm, the maximal calculated horizontal deformation is about 200mm/1m and in case of 3m long sensors, the limit deformation is more than 600mm. This is more than satisfactory for the intended slope deformation monitoring. There are two possible ways of FBG sensors attachment to the measuring casing in the monitoring

borehole, Figure 10. In both cases, the fibres are attached along both sides of measuring casing. In the first case, the fibres are fixed in the neutral axis plane (perpendicular to the assumed slope movement direction).

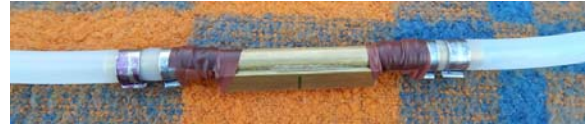


Figure 11. Detail of a chain with a cylindrical clamp of the FBG sensor in GFRP tube connected to protective plastic tube, after (Čáповá et al. 2014)

This arrangement provides the measurement of the relative axial deformation only and indicates the location of the slip surface in the borehole with the development of slope movements. One fibre is fixed at 1.0m distances to ensure sensitivity of instrumentation and the second fibre attached at 3.0m distances provides longer instrumentation lifetime in case of large displacements. The second way of optical fibres fixing is in the slope direction, so that deflection curve of the casing can be calculated together with values of horizontal and vertical deformations. Both arrangements are described in more detail for example in (Záleský, J. et al. 2013).

This instrumentation emphasized detailed resolution of the location of shear deformation; therefore the distance between FBG strain sensors has been designed as 1.0m. The strain resolution in this case can be up to 1µm/m.



Figure 12. Left – part of 3D measuring casing with uncoiled FBG chains, center – lower end of the chain fitted to the casing, right – connection of two FBG chains, after (Záleský et al. 2014)

The FBG sensors chains are in this case placed into thin protective tubes made of Glass Fibre Reinforced Polymer

(GFRP). Attachment of GFRP tubes is provided by gluing them into grooves in brass cylinders, Figure 11. Chains are attached to measuring casing which is used for geotechnical 3-D monitoring; the casing is placed in a borehole which is injected by cement-bentonite mixture, Figure 12.

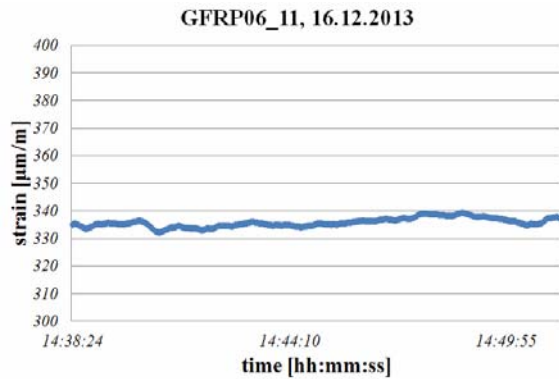


Figure 13. Example of stable reference measurement of FBG - GFRP, after (Záleský et al. 2015)

The reference set of measurements was performed in December 2013; the example of results of this measurement is presented in Figure 13. FBG sensors demonstrated sufficient overall level of stability during measurements, although in several cases there were observed unexpected increases of mechanical strain. The sensors in those cases were not subjected to real loading; the instability of the measurement probably occurred either due to defect in the sensor (fault during its production) or due to faulty optical fibre used for the manufacturing of the sensor.

### 3.3. FBG laboratory testing

New laboratory testing has been performed since 2015 due to observed unexpected instabilities during measurements with FBG sensors. Therefore the decision had been made to test two new different glues used for FBG sensor manufacturing – glue “UV” and “UHU”. The first kind of glue needs to be penetrated by the UV light to work. The UHU glue does not need that because it is a mixture of two different substances in order to allow chemical reactions which make the light penetration not necessary.

Each FBG chain had two sensors and each of these had its own Bragg Wavelength, one was 1536nm and the other 1560nm. The two sensors of the two chains were placed between two L-consoles, Figure 14. The control independent deformation measurement was performed by the displacement transducers with data-logger; the transducers measure displacement in the range of 0-25mm with  $\pm 1\mu\text{m/m}$  resolution.



Figure 14. L-consoles with displacement transducer and tested optical FBG fibres

The test consisted of a sequence of steps of console displacements. The fibres were loaded and unloaded with a series of cycles in order to check the change in its properties / behaviour. After each enforcing of displacement, a time interval of 24h had to pass in order to let the wavelengths stabilize and to apply the temperature compensation.

The temperature of the air in the lab was measured and it changed periodically. For this reason the temperature compensation was carried out fixing the instants where the temperature of the air was the same, so that only wavelengths measured in these instants were considered.

The test consisted of 3 kinds of cycles. For the first cycle four loading - unloading steps were done (enforced displacement of 0.05mm); the aim of the first kind of cycle is checking the fibres durability. The second kind of cycle consisted of five loading – unloading steps (enforced displacement of 0.1mm); this kind of cycle is useful to test the stability of anchor

system and especially of glue. The third cycle is still in progress and it consists of loading - unloading steps which last more than 24h to check the durability of glues in time.

The first cycle proved that the fibre chain with UHU glue became stable more quickly than UV fibre chain. Moreover both kinds of fibre chains showed a plastic behaviour probably because of the mechanical properties of both glues (the modulus of elasticity of the glue may be much higher than the modulus of elasticity of the fibre itself; when the fibre is elongated, there may be significant strain distribution along the glued part).

In the second cycle the fibre with UHU glue showed a minor relaxation after the sequence of loading and unloading steps (Figure 15); therefore the UHU fibre improved its behaviour. On the other hand, the UV fibre did not – it could not be fixed well to anchor and this can cause fibre sliding. The reason of that could be the fact that the glue needed to be penetrated by the UV light to work but entering into fibre is difficult for the light because the space where the glue is not protected by the anchor is too narrow. The UHU glue does not need to be penetrated by any light because it is a mixture of two different substances in order to allow chemical reactions which make the light penetration not necessary.

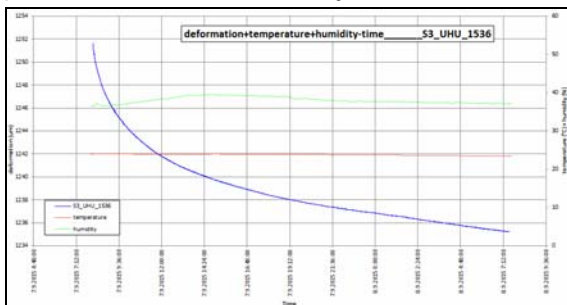


Figure 15. Example of one step of UHU testing; blue – deformation, left vertical axis,  $\mu\text{m}$ ; red – temperature, right vertical axis,  $^{\circ}\text{C}$ ; green – humidity, right vertical axis, %; horizontal axis - time

All the testing steps showed also some relevant differences between displacements recorded by the two sensors of fibres with the same glue which

were probably caused by some irregularity between glues of two sensors. Finally, both fibre chains seemed significantly influenced by sudden temperature and especially humidity changes – the fibres have to be well protected against humidity penetration and this aspect should not be underestimated.

#### 4. CONCLUSIONS

BOTDA analyzer is able to recognize locations of active strain development on the sensing cable without any prior estimation. The sensing cable is very sensitive to break on larger cracks or fissured zones and in specific cases it needs arrangements (in order to spread deformation to longer base). BOTDA sensing cables are extremely sensitive during instrumentation in boreholes, therefore some centralizers or spacers shall be used to keep optic cables in reasonable clearance to borehole casings and the injection grouting should be provided in two stages by injection tubes with sleeves (cuffs) minimizing uplift impact.

The issue concerning strain increases in the vicinity of attachment points was partly solved by careful cable coverage by thick plastic tape before fixing of clamps using controlled torque moment. Nevertheless, this solution is functional, but it is not perfect – this issue needs to be analyzed in more detail. The unexpected increase of measured strain during borehole measurements showed in several cases a relationship with the non-Gaussian distribution of Brillouin scattering. This issue may be caused by some defects in the sensing cable / fibre, but it is necessary to provide further research into the problem. It is also necessary to provide more deep analysis of the comparison of BOTDA and control measurements together with the development and laboratory testing of a new attachment system. Once well deployed, fibre optic sensing can offer long-term stable service more safe than contact electro-mechanical monitoring.

The Bragg grating sensors are in principle point-wise and they can be used in series. If they are deployed in chains, the reliable assessment of magnitudes of deformation shall be provided in advance. More Bragg gratings on one channel are sensitive to overlapping when expected range of deformation is exceeded even in case of a single grating. This results in the loss of information. In that case it is not possible to clearly automatically evaluate deformations measured these gratings.

Concerning test beam results, the first cycle proved that the fibre chain with UHU glue became stable more quickly than UV fibre chain. Moreover, both kinds of fibre chains showed a plastic behaviour probably because of the mechanic characteristics of the glue. Maybe its modulus of elasticity  $E$  is much higher than the modulus of elasticity of the fibre and when the fibre is elongated, a strain distribution along the anchor is made. The recommendation to cure plastic behaviour is to carry out a series of loading and unloading cycles in order to decrease the difference between the two modules. In this way the behaviour of the anchor system could improve because the strain distribution would not be made into anchor and the plastic behaviour could be minimized. After that finding the most fitting kind of glue, as the glue which shows the minor plastic behaviour, would be useful. When the behaviour of the glue is elastic, doing a calibration of results using a fitting simple function will be possible.

The second cycle tested, that the fibre with UHU glue showed a minor relaxation after the sequence of loading and unloading steps. The fibre with UV glue could not be fixed well to anchor and this can cause fibre sliding. The reason of that could be the fact, that the glue needs to be penetrated by the UV light to work but entering into fibre is difficult for the light because the space where the glue is not protected by the anchor is too narrow. On the other hand, UHU glue does not need to be penetrated by any light because it is a mixture of two different substances in

order to allow chemical reactions which make the light penetration not necessary. So the UHU fibre could be preferred because it is fixed better showing to be more rigid than UV fibre.

The other thing to note is that all steps showed some relevant differences between displacements recorded by the two sensors of fibres with the same glue which were probably caused by some irregularity between glues of two sensors. Finally both chain fibres look significantly influenced by sudden temperature and humidity changes. Temperature compensation is possible to adjust results but humidity compensation is not. So in this case the recommendation is to make the fibre more protected against humidity (for example using another protective tube).

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