Benefits of Standards for Fiber-Optic Sensors in Soil-Structure Interaction

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ABSTRACT: Measurement and data recording systems are important parts of a holistic Soil-Structure Interaction Health Monitoring (SSIHM) system. New sensor technologies such as fiber-optic sensors (FOS) are regarded at times as experimental despite the strong track record; standards or at least guidelines not being widely available internationally has always been an impediment. This lack in standardization makes the acceptance of FOS technologies in SSIHM systems more difficult. Some success has been made in publishing first standards to fill this gap over the past decade. Much more effort is needed in this area and this paper gives an overview of what has been accomplished, what is in progress, and what obstacles were along the way. A case is made for a truly independent standard writing platform that can govern itself for the fiber-optic sensing industry composed of its sellers, buyers and subject matter experts.

KEYWORDS: Fiber-optic sensor, distributed sensor, standard, temperature, strain, monitoring

1. INTRODUCTION

Fiber-optic sensors offer a great potential in different industrial and engineering projects. They are preferred even more if special conditions require the avoidance of the application of conventional electrical sensors. It is generally known that conventional electrical sensors have long-term failure rates or stability issues mainly due to corrosion, chemical interaction or creep effects of materials used, electronic drift, and disturbance affected by EM interaction. In contrast, a pure silica optical fiber is inert and stable over the long term as proven by telecom cables, which have a design lives of 20 to 30 or more years. In case of strained glass fibers, no significant creep or damage effects are known if the protective coating layer is not impaired during installation.

The scientific and technological background for optical fiber sensors is well developed; however, there are sometimes few barriers for industrial users. One barrier can be the price for the whole system; another barrier could be the lack of standards or inappropriate specifications from manufacturers of sensor components. On the other hand, application procedures are not always well validated due to a lack of understanding the mechanical, physical or chemical issues in the interface zone between the sensor and the object that is being measured.

Users therefore need standardized description of the sensor system performance, recommendations what aspects must be considered for reliable application and operation of sensors, and finally how to handle the application of sensors under possibly harsh environmental conditions. Technical rules must be provided. A few guidelines for the appropriate specification and use of fiber-optic sensors have been published. Several European and international activities have been launched to encourage the development of additional standards for special applications. This paper informs about successful standardization activities. Relevant guideline activities worldwide are also presented.

Mostly, the weakest point is the sensor itself, and its use under real measurement conditions. Therefore, several essential technical details must be considered when selecting sensor type, application method and materials. Examples are:

- Thermal stress loading on sensing element during application
- Sensor reaction to mechanical or thermal impacts (shocks) during operation
- Sensor behavior/aging under maintained vibration
- Sensor behavior (including cabling) under wet conditions
- Creep of applied sensor depending on temperature
- Drift of the sensor signal depending on temperature and other Influences
- Durability of materials under thermal, chemical, mechanical conditions.

The quality of a measurement system is generally represented by the reliable use of system components. Especially in geotechnical applications, sensor properties such as spatial and temporal resolution, extended measurement range, accuracy and repeatability under harsh environmental conditions are of importance. When users are going to pursue a measurement task, they need a comprehensive overview on the basic characteristics of the sensor system components, their performance as well as basic rules on how to use the measurement system practically. This use generally includes the selection of appropriate system components, the selection of appropriate and long-term reliable installation components such as fixing elements, adhesives, and covering materials. Finally, established application procedures must be used to eliminate weaknesses and avoid failure of installed sensor components.

A major deficiency often seen concerns the performance description of the system components. The non-availability of standardized testing methods to prove the performance of fiber-optic sensors often causes problems. For example, there was a long way to come to standards for resistance strain gauges and corresponding devices. Today, many standards, guidelines and certified application procedures, including training programs to get a certificate, are available to enable users to get reliable measurement results from applied resistive strain sensors.

In the same way, the established use of fiber-optic sensor systems on-site requires standards and guidelines. No underground railway company for example will integrate fiber-optic measurement systems in their tunnels without having gotten any standards that describe and define important parameters and procedures. At least, hand-outs or company-related guidelines, which are not yet bona fide standards, generally summarizing the essential data for design, application and operation of fiber-optic sensor systems must be available. The design work for a sensor system and the choice of an appropriate application procedure must follow specific demands according to the measurement task. In the past few years, several activities have come into play to make available more standards and guidelines for fiber-optic sensors.

Because of mostly large extensions of geotechnical areas to be monitored, distributed fiber-optic sensors are regarded in many cases as the only monitoring technology because there are no alternative sensor systems. This is the motivation to focus preferably on distributed fiber-optic sensors systems in this paper; other local sensor technologies such as Fiber Bragg grating or Fabry-Perot sensors are briefly mentioned; more details can be found in the reference list.

2. PIONEERING EFFORTS IN STANDARDS AND GUIDES

Development of standards and guidelines for fiber-optic sensor's performance specification, and relevant testing procedures have been discussed in the scientific community as well as in the industry since the mid-nineties of the last century. There are many standards for description, evaluation and use of fiber-optic components in data communication and telecommunication. Guidelines or standards for fiber-optic sensors were still an exception. The first standard draft on generic specification of fiber-optic sensors - IEC 61757 - was published in 1995; the first Working Draft P952/D24 for a specific type of a fiber sensor - the fiber-optic gyroscope was published in December 1996.

The IEC generic fiber-optic sensor standard 61757 has been revised in 2010 and 2011 and was eventually published in early 2012. A recent revision enabled to include some improvements; the new version was published on 25 January 2018 as IEC 61757:2018 Fiber-optic Sensors – Generic Specification.

The most important prerequisite when a new measurement technology is to be launched is the availability of a consistent" standardized" terminology. Not only different users make use of non-consistent terms and descriptions for the fiber-optic sensor technology, but not even all the fiber sensor experts carry the same meaning on what specific terms associated with characterization, validation and application of sensing systems do convey. It is worthwhile to notice that standards for fiber-optic sensors have also to cover characteristic details related to the respective physical sensor mechanism, to the sensor response to different measurands, to application, and finally to specific perturbing influences coming from environmental stimulants. These sensor-specific issues mark other aspects in fiber-optic sensor technology, and need to be in the scope of standardization step-by-step.

Different types of fiber-optic sensors based on glass or polymeric fibers are used to evaluate material behavior or to monitor the integrity and long-term stability of load-bearing structure components. Fiber-optic sensors have been established as a new and innovative measurement technology in very different fields, such as material science, civil engineering, light-weight structures, geotechnical areas as well as chemical and high-voltage substations. Very often, mechanical quantities such as deformation, strain or vibration are requested. Measurement of chemical quantities in materials and structure components, such as pH value in steel reinforced concrete members, however, also provides information about the integrity of concrete structures. A special fiber-optic chemical sensor for monitoring the alkaline state (pH value) of the cementitious matrix in steel-reinforced concrete structures with the purpose of early detection of corrosion-initiating factors is desired. Based on a color (wavelength) change of a pH-sensitive membrane embedded in the cementitious matrix of concrete, the sensor enables to observe the pH value of the concrete matrix. It decreases due to deterioration of the calcium hydroxide layer on the steel surface, corrosion occurs, Dantan, Habel, Wolfbeis (2005).

There are a number of applications of non-distributed fiber-optic sensor technologies in geotechnical engineering. One example concerns the use of highly dynamic concrete-embeddable fiber Fabry-Perot sensors that can be embedded in concrete for the assessment of the bearing behavior and integrity of large concrete piles in existing foundations or during and after their installation, Schallert, Hofmann, Habel (2008).

Another example concerns fiber Bragg grating (FBG) sensors attached to anchor steels (micro piles) to measure the strain distribution in loaded soil anchors**,** Habel, Krebber (2011). Polymer optical fibers (POF) can be — because of their high elasticity and high ultimate strain – well integrated into textiles to monitor their deformation behavior. Such "intelligent" textiles are capable of monitoring displacement of soil or slopes, critical mechanical deformation in geotechnical structures (dikes, dams, and embankments) as well as in masonry structures during and after earthquakes, Habel, Krebber (2011).

To understand the soil-structure interaction system's overall behavior, or to enhance the operating efficiency of aged structures, sensors are applied to components or even embedded into their material. Such sensors must work appropriately to provide safe information about the soil-structure's behavior under load conditions as well as in case of sudden damage or deteriorating processes. The first presumption to get appropriately working sensor systems is to use sensors validated according to standards. Another challenge is to install them without losing their calibration or their overall performance. The most major challenge for sensor experts is to reduce application-related influences. Guidelines should therefore define validation procedures for sensors, and recommend methods to test and evaluate the behavior of applied sensors. Description of the performance of sensors comprises many aspects: sensor characteristics (sensitivity), functional parameters (measurement accuracy, stability), interface definitions and interchangeability, environmental protection, characteristic features of the interrogation system used, measures enabling cost reduction, application and service and maintenance aspects.

In the past decade, many small and medium companies have provided sensor components or complete fiber-optic measurement systems for strain, temperature or other quantities. Despite of clear advantages of fiber-optic sensors for many measurement tasks, missing standards on how to characterize, specify, design and use fiber-optic sensor systems have made the dissemination and/or the use of excellent technical solutions difficult. Missing a clear performance specification makes the comparison of products provided by different manufacturers difficult. Not only characterization and specification of a fiber-optic sensor system, however, is important but also its right selection and application. Standards should also provide users, consultants, and technical staff on-site a survey of all technical aspects that are intrinsically tied to application and installation of sensing components. Especially in selected fields with specific challenges, e.g. geotechnical areas, structural engineering, offshore environment, it is necessary to translate generic statements of IEC or ISO standards into specific requirements. Companies, user communities or international societies usually do this. For example, members of the International Society for Structural Health Monitoring of Intelligent Infrastructure (ISHMII) - a non-profit organization of leading structural health monitoring institutions and experts, deal with development of standards for establishing new sensor and monitoring technologies. They do this translation work in their specific fields of use.

3. STANDARDIZATION OF FOS IN THE IEC

3.1 Completed projects; newly established IEC standards

A few FOS standard projects have already been completed. The first bilingual guideline focused on FBG-based strain sensors was the German VDI/VDE 2660 Guideline: 'Experimental Stress Analysis - Optical Strain Sensor based on fiber Bragg grating; Basics, Characteristics and its Testing' published in July 2010. The next international generic FOS standard was published in 2012: the IEC 61757-1 standard on "Fiber-optic Sensors". The new version was published on 25 January 2018 as IEC 61757:2018 Fiber-optic Sensors – Generic Specification. This standard encouraged the development of a fiber-optic standard family (see Figures 1 and 2). In order to have a structure in numbering FOS IEC-Standards, numbering code as shown in Table 1 was defined.

In the meantime, another two components of this IEC standard family are completed. Based on the German VDI/VDE 2660 Guideline, the IEC 61757-1-1 standard on "Strain measurement - Strain sensors based on fiber Bragg gratings" was developed in the IEC Subcommittee 86C, Working Group 2 and published in

February 2016. In the same way, the IEC 61757-2-2 standard on "Temperature measurement - Distributed sensing" based on the SEAFOM document SEAFOM-MSP-01 "Measurement Specification for Distributed Temperature Sensing (DTS)" originally published in March 2010 by the SEAFOM Measurement Specification Working Group, which is an official liaison partner of IEC SC 86C WG2, was revised and published in May 2016. Figures 1 and 2 show the structure of the IEC FOS standard family; Figure 1 shows the specification detailed for strain measurements, Figure 2 shows the same one detailed for temperature measurements. An extended description of the content of these standards can be found in Habel et al. (2007, 2009, 2011, 2012, 2013, 2014, 2015), Habel and Krebber (2011), and Habel, Krebber and Daum (2015).

Table 1 Numbering code for IEC standards on Fiber-optic Sensors (CD - Committee Draft, PNW – New Work Item Proposal)

IEC 61757 Fibre optic sensors – Generic specification				
Technology (T) Architecture / Measurand (M)	IEC 61757-M-1 Fibre Bragg grating	IEC 61757-M-2 Distributed sensing	IEC 61757-M-3 Faraday effect	IEC x-M-T
Strain measurement	IEC 61757-1-1 Strain sensors based on fibre Bragg gratings	PNW IEC 61757-1-2 Distributed sensing		
Temperature measurement	CD IEC 61757-2-1 Temperature sensors based on fibre Bragg gratings	IEC 61757-2-2 Distributed sensing		
Acoustic sensing		PNW IEC 61757-3-2 Distributed acoustic sensing		
Current measurement			PNW IEC 61757-4-3 Optical current sensors based on polarimetric method	

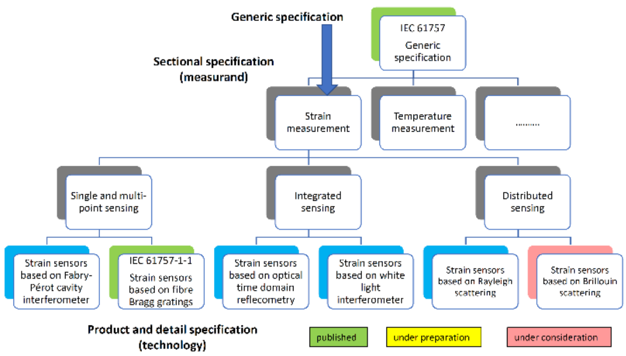

Figure 1 Structure of IEC fiber-optic sensor standards related to strain measurements

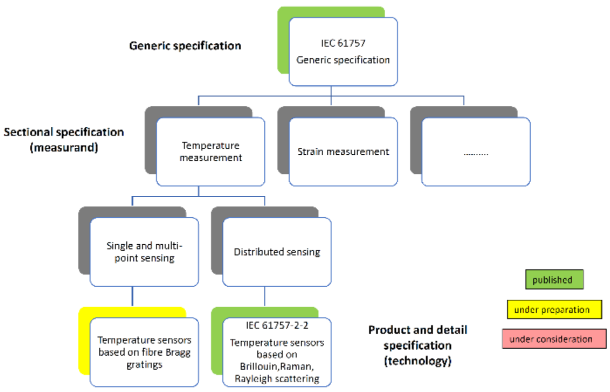

Figure 2 Structure of fiber-optic sensors standards related to temperature measurements

3.2 New projects

In October 2015, Subcommittee 86C decided to start the development of a standard document for the use of temperature sensors based on fibre Bragg gratings. This work has been proceeding within the German VDI Committee 2.17 from December 2015; the first draft for discussion in the IEC SC86C was presented at the IEC WG 2 meeting immediately before the EWOFS in Limerick, Ireland on May 30-31, 2016; in November 2016 it was approved to develop a Committee Draft. It was again intended to go the same way as in the past: to collaborate with the development of a VDI guideline draft and in the SC 86C of IEC. Currently, the draft of IEC 61757-2-1: Fiber-optic Sensors-Temperature measurement - Temperature sensors based on fiber Bragg gratings is under development and a first publication for experts' discussion is expected in early 2019.

3.3 Projects planned

Because of wide use of distributed fiber-optic strain sensors based on stimulated Brillouin backscattering, and with respect to the increasing use of distributed fiber-optic acoustic sensor solutions, two new projects have been proposed in the IEC subcommittee 86C: IEC 61757-1-2: Fibre Optic Sensors - Part 1-2: Strain measurement - Distributed sensing, and 61757-3-2: Fibre Optic Sensors - Part 3-2: Distributed acoustic sensing.

4. FOS STANDARDIZATION ACTIVITIES IN THE ASTM

Whereas the IEC standards cover rather basic aspects for preparation, testing, validation and description of sensors and sensor systems, more application-related standards or guidelines are needed to handle different fiber-optic sensor systems on-site. The Global Optical Fiber Sensing System (OFSS) Task group of the ASTM Technical Committee F36 "Technology and Underground Utilities", especially Subcommittee F36.10 "Optical Fiber Systems within Existing Infrastructure" focused its work - as a standardization body - on such practical aspects.

When the second author served as a consultant to Washington DC Clean Rivers Project tunnels, the amplitude of the ground movements measured was in fractions of an inch while the noise in the traditional instrumentation systems used was even higher, Jeyapalan et al. (2014, 2015). Therefore, the predictions made per Attewell et al. (1986) did not have a way to be compared with field observations. This led the team to consider OFSS methods, but ultimately, they were not implemented. The lack of consensus standards for OFSS methods was a contributory consideration in the client's decision. This market need was the primary driver for the birth of the ASTM F36 Global OFSS Task group (Iten et al. 2015).

Some of the significant publications which demonstrated the advantages of using OFSS in civil infrastructure include Vorster et al (2005) on assessing the impact of ground movements due to construction activities nearby on buried pipelines, Briançon et al. (2004) and Nancey et al. (2007) on a composite fiber-optic sensor-enabled geotextile for soil strain assessment using the Fiber Bragg Grating technology, Calderon and Glisic (2012) and Glisic (2011) on field observations using OFSS and the accuracy of embedded long-gauge optical fiber strain sensors, Glisic and Inaudi (2008) on the use of OFSS for structural health monitoring, Klar et al (2008) on analysis and field monitoring, Mohamad et al. (2014) on temperature and strain sensing using Brillouin Optical Time Domain Reflectometry (BOTDR), Mohamad et al. (2010) and Mohamad et al. (2012) on tunnel induced response of old brick tunnels and new tunnels, Schwamb et al. (2014) on monitoring of an excavation, Pelecanos et al. (2017) on monitoring of a pile test, and Gue et al. (2017) on tunnel monitoring. Artières et al. (2010) showed also the use of OFSS to monitor hydraulic structures. Iten (2011) and Iten et al. (2011) demonstrated the effective use of optical fiber sensing systems to a wide range of geotechnical applications. Krebber et al

(2008), Krebber et al (2010), and Liehr et al (2009) and their research group at BAM have demonstrated many of the above applications using Polymer Optical Fibers. Given that the distributed optical fiber sensing systems (DOFSS) are the type that are most widely used on soil-structure interaction monitoring projects, for example Monsberger et al (2017), to provide a basic working knowledge on DOFSS to the readers of this paper, who are geotechnical engineers, more details on this form of FOS are discussed in the next few sections with the reasonable success achieved in writing pertinent standards for the Brillouin scattering based strain and temperature measurement.

5. RAYLEIGH, RAMAN AND BRILLOUIN SYSTEMS

There are different physical effects, which can be used in optical fibers for distributed monitoring. All effects in optical fibers are based on interactions of the launched light (laser) beam with the constituent atoms and molecules of the fiber material. Because the optical fiber is an inhomogeneous medium, these interactions generate light scattering and part of the light is reflected back (backscattering). Depending on the type of interaction, different backscattering mechanisms are used for distributed sensing. Distributed sensing focusses on extended measurement areas; therefore glass fibers, which enable gauge lengths of hundreds of meters or even tens of kilometers, have to be used. If geotechnical areas of limited extensions e.g. few hundred meters have to be monitored, the use of polymer optical fibers is an efficient alternative. Polymer optical fibers are more elastic and can be stretched by about 20 % without losing their elasticity. Such fibers are usually known in mining areas to be monitored with deformation rate in the mm-range per few days or weeks, Liehr, Lenke, Krywult et al. (2009). Following, examples are given for applied glass fibers and polymer optical fiber sensors are given.

If the optical beam only interacts with local macroscopic or microscopic density fluctuations in the glass fiber, the scattered light is sent back with the wavelength of the incident light, so called elastic scattering. In this case, no energy is transferred to the glass. This effect is called **Rayleigh scattering**. Figure 3 shows the Rayleigh backscattering signal at the frequency λ_0 of the incident light.

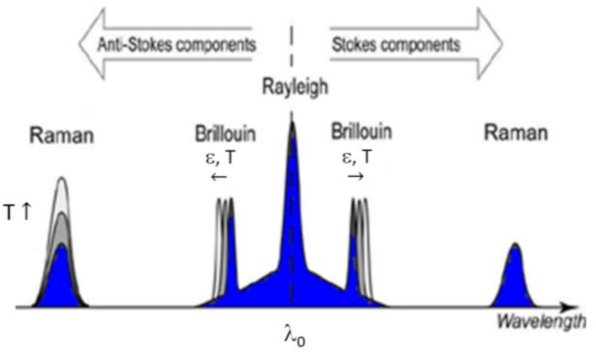

Figure 3 Typical spontaneous scattering spectrum from an optical glass fiber

An unaffected optical fiber shows a definite attenuation profile according to the transmission loss of the fiber material. If the fiber is locally strained, a change in the attenuation profile can be measured (see Figure 4).

In order to read out these changes, two methods are commonly used: the time-domain based backscattering (OTDR) or the frequency-domain based method (OFDR) as shown in Figures 4 & 5 respectively. The optical pulse launched into the sensor fiber is elastically scattered which leads to a decrease of the optical signal (tilted dotted line in Figure 4). If any deformation along the sensor fiber occurs, a change in the optical power can be measured (peaks at crack 1 and crack 2). Depending on the intensity of the defect (crack, strain, fiber deformation), the intensity of the peak varies.

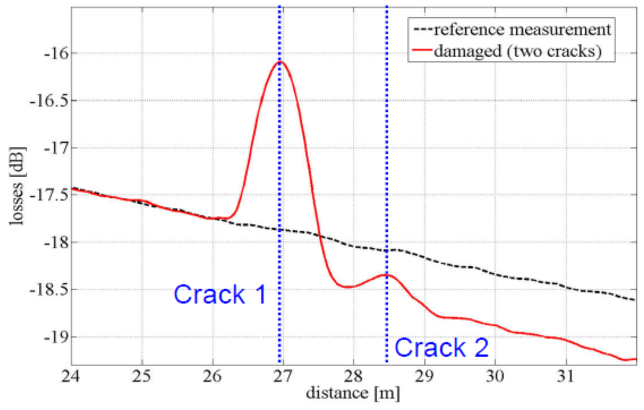

Figure 4 Typical attenuation change of a crack-induced strained polymer optical fiber recorded by the Rayleigh backscattered signal (OTDR), S. Liehr, P. Lenke, K. Krebber et al., 2008

Rayleigh OTDR is the classical backscattering method developed for fault detection in telecommunication cables. It has been used later for damage detection in sensor fibers and finally to quantify strain changes along the sensor fiber. A Rayleigh backscattering-based temperature sensing is principally possible; however, the temperature dependence is very weak. Distributed temperature sensing is therefore, preferably, based on Raman scattering (see below).

One essential part of a sensor system making distributed measurements is a reflectometer to provide spatial resolution. In many cases, Raman and Brillouin systems work with an optical time domain reflectometer, in which the monitoring unit transmits a short light pulse and uses the time of flight of the back- scattered light to determine the location of the reflection. For the Rayleigh sensor technology, a significantly higher resolution is required than can be achieved with an OTDR. This is attained using a coherent optical frequency domain reflectometer, c-OFDR. In c-OFDR systems, the beam of a variable frequency CW laser is coupled into a fibre- optic Mach-Zehnder interferometer. One fiber represents the reference arm with a fixed path length, while the second arm is formed by the sensing fiber. The light scattered back from the sensing fiber interferes with the light from the reference arm at the output coupler. Varying the frequency of the laser wavelength creates a periodic signal at the detector, the frequency of which depends on the location of the respective fiber segment scattering the light back. The further the segment is away from the detector, the greater the frequency of the interference signal. As the detector receives the backscatter signals from all the segments simultaneously, the total signal must be split into its frequency components using a Fourier transform technique.

When a commercially available glass fiber is scanned using OFDR, a fluctuating intensity profile of the Rayleigh scattering along the glass fiber will be detected. This profile is stable when the measurement is repeated under unaltered external conditions, such that it represents a characteristic “fingerprint” for a specific fiber segment. The reason for this lies in the characteristics of the Rayleigh scattering. It is caused by the elastic scattering process at local defects, refractive index variations or distortions of the waveguide geometry, which although it varies from segment to segment, is still stable. If you now change the temperature or strain conditions of the fiber, the finger- print is spatially stretched or compressed. This phenomenon is the basis for the Rayleigh sensor technology as the changes to the local Rayleigh pattern can be converted into local temperature or strain values.

Higher performance in Rayleigh-based distributed strain sensing can be reached by using OFDR. Because monochromatic light is used and interference effects are exploited, high resolution of induced mechanical or thermal changes in the fiber material can be resolved. The spatial resolution of the position of influence is better than from OTDR measurement systems.

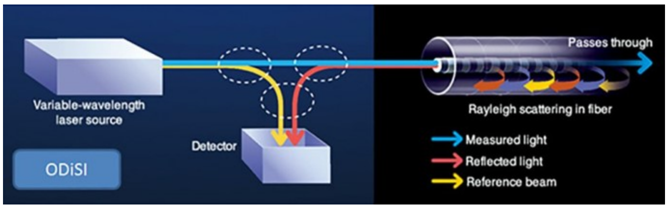

Figure 5 Simplified principle of OFDR (Source: Luna)

Typical applications are therefore detection of local strain changes, e.g. to prove ground anchor fixation or to detect strain profiles in anchors, Habel, Krebber (2011). Figure 6 shows sensor signals back reflected from measurement points along heavy rock anchors (on the order of 4,500 kN) of a gravity dam. Based on the anchor length of 70 m, deformations at the measurement points of 20 µm can be detected.

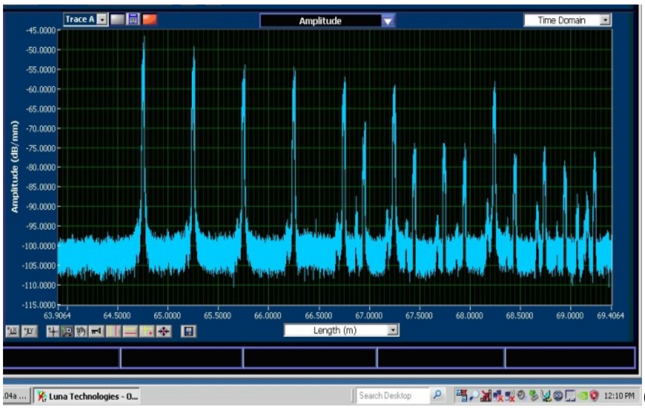

Figure 6 Evaluation of force distribution in 4,500 kN rock anchors installed in a gravity dam via strain measurement along the anchor steel

The peaks represent the position of measurement points in the fixed anchor area. Horizontal shift of the peaks shows deformation of the anchor steel from which a possible loss of the anchor fixing can be concluded. This method allows proving the integrity or the effectiveness of anchor fixation.

If the vibration of the molecules in the optical material increases due to a temperature increase of this material, photons are scattered by the effect of vibrational and rotational transitions in the bonds between first-order neighboring atoms. The light wave interaction with the matter leads to an energy exchange; this spontaneous backscattering effect is an inelastic type, called **Raman backscattering**. Inelastic scattering is associated with frequency shift of the back-reflected light. Two lines left and right of the wavelength of the incident light are formed (see Fig. 3). The downshifted so called anti-stokes wavelength line in clearly temperature dependent is used in distributed fiber-optic temperature sensor systems.

Inelastic scattering can also be stimulated by mechanical excitation of the matter, e.g. by a strong laser pulse. A strong laser pulse launched into the end of one fiber called pump beam induces acoustic vibrations (so called phonons) in the material. Such sound waves can be considered as periodic, mechanical density fluctuations in the fiber. These acoustic waves meet the scattered low-intensity optical wave (photons). The backscattered signal is recorded; the physical effect is called Stimulated **Brillouin Scattering**. Due to superposition of the electric fields of high-energy pump and the scattered optical wave, a beat with the frequency $\Delta\nu/2$, propagating with the velocity $v_a = c/n \bullet \Delta\nu/\nu_0$, where ν_0 is the mean frequency of light waves is and c/n is the speed of light in the waveguide. Maximum backscattering signal with a defined frequency (called Brillouin frequency) occurs, if v_a of the generated beat corresponds to the propagation speed of the acoustic wave in the fiber. Figure 7 shows this mechanism schematically.

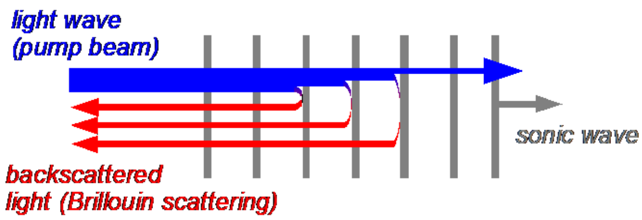

Figure 7 Principle of stimulated Brillouin scattering (Courtesy: Dr. Katerina Krebber, BAM)

If there is any mechanical (or thermal) change in the fiber material, e.g. caused by compression, tension, shear or any deformation changes, the Brillouin frequency will change and can be recorded. This enables to detect any mechanical change along the fiber with a certain uncertainty in its position (spatial resolution). Applications are mentioned in the following section.

6. DESCRIPTION OF HOW THE MOST WIDELY USED DOFSS WORKS

When a light pulse travels through the optical fiber core, most of it is transmitted from one end to the other (assuming no breakages or kinks in between) following the principle of total internal reflection. A small fraction of the transmitted light is always backscattered in the direction of the source due to the tiny imperfections in the density of the core along the cable. Different components of the back-scattered light can be identified (see Figure 3) and carefully analyzed to measure changes in temperature or strain along the fiber. Therefore, the optical fiber cable itself plays the central role of an almost infinite number of strain and temperature sensors ("distributed sensor") for long distances.

The effect of distributed Brillouin scattering is the most widely used form of OFS technology, which provides a monitoring technique to measure strain and temperature along the optical fiber cable. There are different systems on the market with varying specifications. The choice of the single system depends on the requirement with respect to sensitivity, spatial resolution of the measurement of the occurring event, cable length, dynamic range, and of course, available budget.

One is called the pump signal, being a pulse-modulated (for BOTDA systems) or a sinusoidally modulated laser signal. For Brillouin Optical Frequency Domain Analysis (BOFDA) systems a second laser beam of a unique wave profile is used which is is the continuous wave (CW) probe laser, sometimes also referred to as the Stokes laser. The interaction of these two laser beams produces an acoustic wave called "electrostriction." The pump signal is backscattered by the phonons, and the energy is transferred between the pump signal and the CW probe light.

The Brillouin Loss Spectrum (BLS) or Brillouin Gain Spectrum (BGS), as the function of frequency difference between the two laser beams, is measured by scanning the frequency of the CW probe light. The value of the strain or the temperature can be estimated using the shift of the peak frequency of BLS/BGS (Brillouin frequency), whilst its position calculated from the light round-trip time as shown in Figure 8.

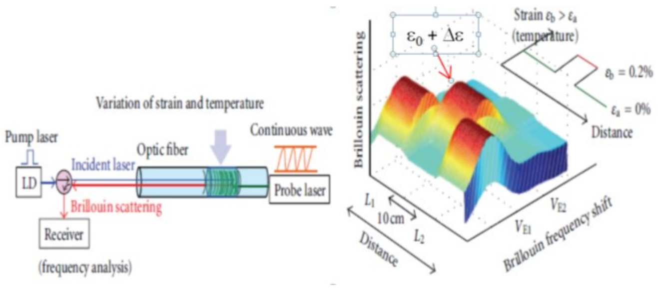

Figure 8 Principal components of the BOTDA system, right: visualized deformation change in an optical fiber (ASTM, 2014)

Similar set up for the Brillouin Optical Time Domain Reflectometry (BOTDR) technology which requires sending the light pulse from one end of the core and hence negating the need for a closed loop (see Figure 9). Therefore, an appropriate interrogator, with a graphic user interface, and the software, can acquire and keep track of the position and the magnitude of the strain or temperature at hundreds of thousands of locations along the route of the optical fiber cable, essentially in almost real time. Results from such BOFDA systems are shown for strains in Figures 10 and 11, respectively.

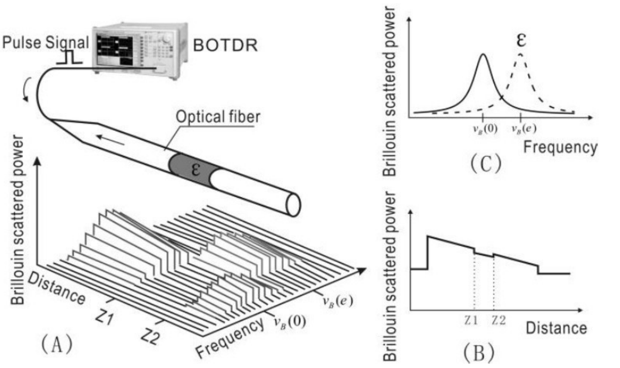

Figure 9 Details on a BOTDR system (ASTM, 2014)

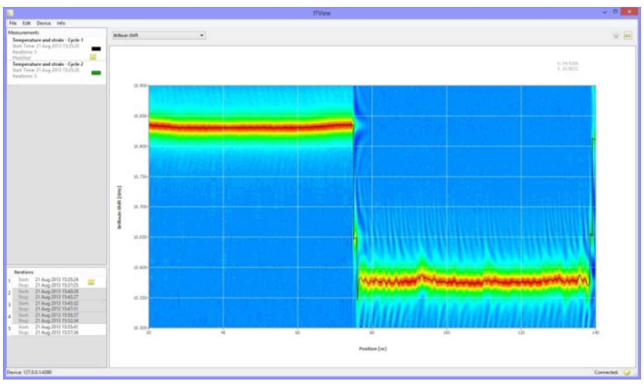

Figure 10 Typical screen shot of software of BOFDA that depicts variation of strains measured temporally and spatially (provided by Dr. Noether, fibrisTerre)

7. DISTRIBUTED FIBER-OPTIC SENSOR EXAMPLES

A standard telecommunication optical fiber cable designed to protect the optical fibers from the surrounding environment can serve as temperature or strain sensors. In case of such sensing cables, however, the measurand (strain, temperature) must

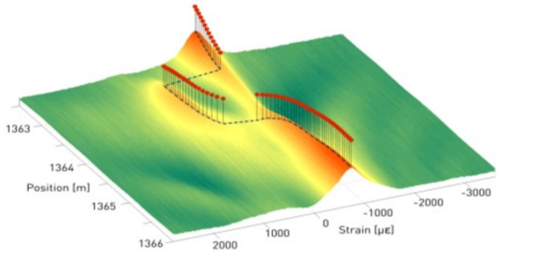

Figure 11 Typical results on strain measurements temporally and spatially from BOFDA (provided by Dr. Noether of fibrisTerre)

efficiently be transferred through the fiber coating to the optical fiber core. The measurand is then detected and measured by using backscattering technology. Strain and temperature cables of various complexities in there design are described in detail in Kechavarzi et al 2016.

In order to enable easy installation and excellent durability, other more specialists optical fiber sensing cables are in some way prefabricated and provided to ensure an optimum transfer of strain and temperature between the object that is being monitored and the sensing fiber(s) as well as to avoid any damage during installation. A common design is a sticking tape-like sensing component as shown in Figures 12 to 14.

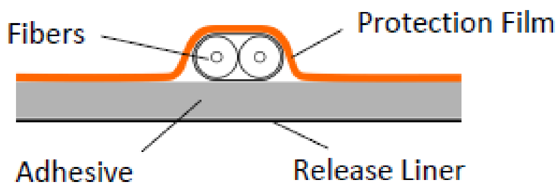

Figure 12 FN-SSL-3 tape sensing fiber consisting of two standard SM fibers on single tape; designed for temperature and/or strain measurements. (courtesy of Neubrex Co., Ltd., Japan)

Figure 13 Application of a tape sensing fiber spirally adhered to a steel pipe for detecting strain (courtesy of Neubrex)

Figure 14 Different configurations of DiTeSt SMARTxxx sensors for civil and geotechnical strain measurement and integrity monitoring (SMARTEC SA, Switzerland)

Other optical fiber cables designed to be embedded in geotextile to enhance transfer of soil movement to the fiber are shown in Figure 15.

Figure 15 Sensor-enabled geotextile with integrated strain and temperature cables (provided by Dr. Artieres of Tencate Geosynthetics)

8. EFFECT OF BRILLOUIN SCATTER FACILITATING TEMPERATURE AND STRAIN MEASUREMENTS

Brillouin scatter is extremely sensitive to any changes in temperature and strain experienced by the optical fiber; in this regard, most environmental stimuli the optical fiber is exposed to can be correlated to temperature and strain, and measurements can be made on the effects of such environmental stimuli on the serviceability of a buried pipeline or the ground responding to the impact of tunneling or new utility construction. The frequency shift, ν_B, can be calculated using:

$$\nu_B = \{2n\, \nu_a\} / \lambda_0 \quad (1)$$

in which, n is the effective refractive index of the propagating mode, ν_a is the acoustic wave velocity in the optical fiber and λ_0 is the vacuum wavelength of the incident light. The Brillouin frequency shift is affected by the acoustic wave velocity, which can be expressed for homogenous, isotropic, linearly elastic solids as

$$\nu_a = \{K / \rho\}^{0.5} \quad (2)$$

where, K is the bulk modulus and ρ is the density of the optical fiber, respectively. The density of the optical fiber is dependent on temperature; therefore, the Brillouin peak shifts can be plotted as a function of the difference in the frequency between the laser pump and the signal varying with temperature. Similarly, any deformation or strain in the sensing fiber can be tracked. In summary, the temperature and the strain induced in the optical fiber can be measured using the effects of Brillouin scattering.

9. SCOPE OF THE STANDARDS ASTM F3079 AND F3092

The F3079 Standard specifically addresses the standard practice for the use of distributed optical fiber sensor systems (DOFSS) for monitoring ground movements during tunnel and utility construction and its impact on existing utilities. It applies to the process of selecting suitable materials, design, installation, data collection, data processing and reporting of results. This standard practice applies to all utilities that transport water, sewage, oil, gas, chemicals, electric power, communications and mass media content. This practice applies to all tunnels that transport and/or store water or sewage and to tunnels for hydropower, traffic, rail, freight, capsule transport, and those used for dry storage. The second standard F3092 is companion to the first in that it includes more than 400 terms commonly used in optical fiber sensing systems, utilities and tunnels.

10. SIGNIFICANCE AND USE

This practice (F3079) is intended to assist engineers, contractors and owner/operators of underground utilities and tunnels with the successful implementation of distributed optical fiber sensing. F3079 includes DOFSS applications for monitoring ground movements prior to construction for site planning and during new utility and tunnel construction and operation, as well as the impact of such ground movements on existing utilities. Before the installation of distributed optical fiber sensing begins, the contractor shall secure written explicit authorization from the owner/operator of the new tunnel/utility and the existing utilities allowing an evaluation to be conducted for the feasibility of distributed optical fiber sensing for monitoring the impact of the ground movements on their assets and to have access to certain locations of the asset and the surrounding ground space.

It may also be necessary for the installer to have written explicit authorization from applicable jurisdictional agencies. Engineers, contractors, and owners/operators shall also be cognizant of how the use of distributed optical fiber might interfere with the use of certain equipment or tools near the installed optical fiber sensing cable in some special situations. For example, repair activities may have to temporarily remove, relocate, or avoid the optical fiber cable. Engineers, contractors, and owners/operators should be cognizant of how installation techniques and optical fiber (OF) cable location and protection can affect the performance of OFSS.

The F3079-14 Standard: "Standard Practice for Use of Distributed Optical Fiber Sensing Systems for Monitoring the Impact of Ground Movements during Tunnel and Utility Construction on Existing Underground Utilities" was developed for the evaluation of geotechnical structures, and is available. It applies to all important practical aspects such as selection of suitable materials, design, installation, data collection and processing as well as reporting of results. Thus, it assists engineers, contractors and owners/operators of underground utilities and tunnels with the successful implementation of distributed optical fiber sensing for monitoring ground movements prior to construction. To ensure that sensor experts and experts from civil and ground engineering societies speak the same technical language, the document F3092-14 "Standard Terminology Relating to Optical Fiber Sensing Systems" was created. It explains more than 400 terms commonly used in optical fiber sensing systems, utilities and tunnels. Following new standards were made available in 2002 and have been renewed: F2233-03 "Standard Guide for Safety, Access Rights, Construction, Liability, and Risk Management for Optical Fiber Networks in Existing Sewers", F2303-03 "Standard Practice for Selection of Gravity Sewers Suitable for Installation of Optical Fiber Cable and Conduits" and F2462-05 "Standard Practice for Operation and Maintenance of Sewers with Optical Fiber Systems".

11. SHM STANDARDIZATION ACTIVITIES IN THE ISHMII

ISHMII as a non-profit organization of leading (mostly civil) structural health monitoring (SHM) institutions and individuals focusses also on development of standards to adjust international SHM activities. SHM activities are not only related to development and use of sensors and whole measurement systems but substantially on the development of SHM strategies, optimization of damage detection technologies and improvement of methodologies to achieve sophisticated concepts for risk assessment and management by online monitoring of all interactions of the structure components during their life cycle. An important objective of SHM guidelines and codes is to provide all necessary (sensor) information about the behavior of the structure to estimate the remaining life and to develop optimal maintenance strategies and scheduling based on a critical lifecycle cost-benefit-analysis. Documents which combine and harmonize existing approaches for integrated management systems with those of new sensor standards are currently developed. There was established a task force "Standardization" under the leadership of Zhischen Wu (Ibaraki University, Japan), co-chaired by Yi-Qing Ni (The Hong Kong Polytechnic University, Kowloon – Kong Kong). The first survey and ISHMII state-of-the-art report on SHM standardization activities from different countries and regions was presented in a Special Session on Standardization at the SHMII-7 Conference in Turin/Italy in July 2015.

The ISHMII code series consists of three parts (levels):

Level 1: General principles, definitions and approaches.

Level 2 addresses different major structures and major sensing technologies, such as design guidelines for different structures, and a guideline for fiber-optic sensors based SHM for Civil Infrastructures.

Level 3 will consider different countries or regions. The fiber-optic sensor part is an important part of this set of standards, because this sensor technology has huge advantages in civil, geotechnical and structural engineering.

Co-operating countries and regions are Austria, Canada, China (Mainland, Hong Kong), Germany, Japan, South Korea and USA. The ISHMII Task Force members have close and cooperative relations with the committees of IEC, SAE and others. More about ISHMII activities can be found in Habel and Wenzel (2015).

12. BEST PRACTICES GUIDES FROM THE UNIVERSITY OF CAMBRIDGE CENTER FOR SMART INFRASTRUCTURE AND CONSTRUCTION (CSIC)

CSIC has published a series of best practices guides and one of these cover the subject of DOFSS (Kechavarzi et al., 2016). Given the clout of the University of Cambridge around the globe and the high productivity of the CSIC, it is reasonable to conclude that additional guides are likely to be available from CSIC in the coming years.

13. FUTURE FOR THE OFSS GLOBAL TASK GROUP

The following projects were started in 2015 and work has been on hold until a suitable platform is found to continue all the way to publishing the following work items into global standards:

1) Standard practice for the **Installation of optical fiber cables along pipelines for leak detection using distributed vibration, strain, and thermal sensing: Lead Author Dr. Greg Duckworth (Raytheon BBN, US)**

Scope: The purpose of this guidance note is to address the means and methods for the use of distributed optical fibre sensors for detection and localisation of leaks in buried terrestrial pipelines that transport or contain oil, gas, chemicals, water, slurries, and sewage. Selection of suitable materials, design, installation, data collection, data processing, and reporting of results will be detailed. It is the responsibility of each operator to adopt these recommendations according to their needs and to the specific site conditions of installation and environment.

Objective: To prepare and disseminate an authoritative document that contains good practices on how to design and install an optical fibre distributed acoustic, strain, or thermal monitoring system for reliable detection and localization of leaks along terrestrial pipelines.

The need for and anticipated benefits: Pipelines leaking products such as oil, gas, chemicals, water, slurries, and sewage particularly in highly populated urban areas cause damage to the environment and human health with significant potential for catastrophic and costly pipeline failure. Optical fibre distributed sensors have the capability to monitor changes in the strain, optical path, index of refraction, and temperature along a cable. This data can be translated into precise detection of leaks spatially and temporally, offering tools for better management of such pipelines to allow for rapid leak detection and intervention. Despite the wide spread use of terrestrial pipelines to transport fluids of such types for thousands of kilometres around the world in just about every country, no standards on good practices exist. There is a dire need for this standard and anticipated benefits to the public of the proposed standard are improvement in safety and protection of human health.

2) Standard practice **for the Use of optical fiber distributed temperature sensing to detect leaks in above-ground ammonia, ethylene and LNG pipelines - Lead author: Dr Daniele Inaudi (Smartec, Switzerland)**

Scope: The purpose of this guidance document is to describe the optical fiber leak detection system on ammonia, ethylene or LNG above-ground (Liquefied Natural Gas) pipelines, to detail its efficiency, and to propose good installation, usage and maintenance practices for these systems. It is the responsibility of each operator to adopt these recommendations according to their needs and to the specific site conditions of installation and environment.

Objective: To prepare and disseminate an authoritative document that contains good practices on how to detect and localize as fast and precisely as possible any liquid ammonia leak, using distributed optical fiber temperature sensors that can be advantageously deployed on ammonia pipelines. The functionality of this optical fiber sensing system is based on a physical principle called "Raman scattering," and on the possibility of measuring the temperature of each meter of the sensing cable from the analysis of the optical signal reflected by the fiber.

The need for and anticipated benefits: Pipelines leaking products such as ammonia, ethylene, and LNG particularly in highly populated urban areas cause damage to the environment and human health. Given the capability of optical fiber DTS to monitor minute temperature changes and translate such data into precise detection of leaks spatially and temporally offer tools for better management of such pipelines. Despite the wide spread use of above ground pipelines to transport fluids of such types for thousands of kilometres around the world in just about every country, no standards on good practices exist. There is a dire need for this standard and anticipated benefits to the public of the proposed standard are improvement in safety and protection of human health.

3) Standard Practice for the **Use of optical Fiber Bragg Grating for civil engineering system monitoring; Lead authors: Prof An-Bin Huang (National Chiao Tung University, Taiwan), Dr Ying Huang (North Dakota State University, US), Dr Hui Li (Harbin Institute of Technology, China), Prof Sun Tong (City University, UK)**

Scope: This guide addresses the use of optical fiber Bragg grating (FBG) as the sensitive element for strain and/or temperature measurement for the monitored material or as a part of a transducer for other types of physical or chemical quantity measurement, e.g. through careful layout of FBG(s) or effective coating of material on the surface of an FBG. This standard applies to all FBGs made in an optical fiber. This standard refers to the FBG based measurements in a range of frequencies for structural, geotechnical, hydrological, transportation, environmental monitoring and other purposes related to civil engineering systems.

Objective: To provide a guideline that contains important characteristics of FBG based sensors and their readout units (i.e., the interrogators), good practices for field sensor installation and procedures for data interpretation.

The need for and anticipated benefits: Because of the unique capabilities of the FBG sensor, its application in civil engineering system is expanding rapidly. The FBG sensors have been installed in various types of structures such as buildings, power plants, bridges, wind turbines, and tunnels for safety monitoring. The technology has also been used for ensuring slope stability and monitoring ground subsidence using FBG based displacement and pore water pressure transducers. FBG sensors have been developed and deployed for air humidity monitoring and toxic gas detection as well. Despite the wide use of FBG around the world, no standards on good practices exist yet. There is a need for this standard leading to anticipated benefits to the longevity of civil engineering systems and safety of our environment.

4) New Standard practice for **the Use of distributed optical fibre sensing systems for strain monitoring of reinforced concrete pile foundations during static load testing *Lead authors*: Dr Nicholas de Battista (University of Cambridge, UK), Dr Cedric Kechavarzi (University of Cambridge, UK), Dr Hisham Mohamad (Institute of Technology Petronas, Malaysia)**

Scope: This standard describes the use of distributed optical fiber sensing systems (DOFSS) for measuring changes in strain within a reinforced concrete pile foundation, during controlled static load testing of the pile. This standard will address the selection of suitable sensor system technology and components, installation methods, data acquisition parameters, data processing procedures, and reporting of results.

Objective of the standard: To prepare and disseminate an authoritative document that contains good practices on how to design, prepare, install and operate a DOFSS embedded in a reinforced concrete pile foundation, and on how to acquire, analyze and report the data from such a system in order to provide reliable information about the structural behavior of the instrumented pile.

The need for and anticipated benefits of the proposed standard: The performance of reinforced concrete pile foundations is highly dependent on the way they are constructed and on the geological composition of the ground. It is common practice to carry out controlled load tests on one or more instrumented sacrificial pile(s) in a construction site in order to estimate the geotechnical properties of the ground, prior to foundation design. Traditional instrumentation embedded within these reinforced concrete piles consist of various electrical point sensors that measure strain, temperature and relative displacement. Such sensors can only measure changes in the pile's physical parameters at discrete locations and therefore cannot provide a complete profile of the test pile's behavior over its entire depth. On the other hand, due to their distributed nature, DOFSS embedded within piles can provide a large amount of information, with unrivalled spatial resolution, from a pair of optical fibers. Despite the steady increase in the use of DOFSS for monitoring reinforced concrete piles over the past few years, no standard on good practice exists for this technique. There is a need for this standard to disseminate the knowledge gained and lessons learnt by practitioners in order to guide the Civil Engineering community. Such a standard will lead to the correct use of DOFSS for the reliable assessment of reinforced concrete pile foundations during preliminary load testing.

5) New Practice for S**patial and measurand resolution and accuracy definitions in distributed fiber-optic temperature and strain sensing data Lead Authors: Nils Nöther (fibrisTerre Systems GmbH, Germany), Avi Zadok (Bar-Ilan University, Israel), Xiaoyi Bao (University of Ottawa, Canada), …**

1. Scope:

With the increasing number of industrial applications for distributed fiber-optic strain and temperature sensing technologies, there is a growing demand for comparable performance data of the sensing instruments. A comprehensive set of clear definitions for the resolution and accuracy characteristics – taking the unconventional nature of distributed sensing data into account – shall help industrial and academic users to evaluate the technology and introduce its benefits into new applications.

This Best Practice Guidance Note shall address the need for clear definitions for the performance characteristics of distributed fiber-optic temperature and strain sensing systems (DTSS), especially for the terms of resolution and accuracy of the spatially resolved data. Distributed data is often interpreted as a chain of point-sensors, delivering independent data from defined points along the sensing fiber at fixed spatial intervals, which is often defined as the spatial resolution. In many sensing applications, this interpretation doesn't reflect the true nature of distributed sensing data for the following reasons:

a. The data points of a measurement trace of a truly distributed fiber sensor are not independent from each other; they rather correspond to nodes along a curve that represent the physical (and therefore continuous) strain / temperature distribution. This difference to a chain of spatially fixed-point sensors is important when comparing different sets of data from one sensor to another over time, especially while using automated algorithms for data processing.
b. The term "spatial resolution" does not necessarily correspond to the spacing of the data points. Spatial oversampling allows to increase the density of spatial information, while the classic definition of spatial resolution might not be affected.

The terms "accuracy", "repeatability", "reproducibility", "cross-sensitivity" and "sensor calibration" need to be handled with respect to the substantial differences between distributed sensing technologies and point-wise or quasi-distributed sensing technologies, but also to the variations among different distributed sensing principles (Brillouin DTSS, Raman DTS, Rayleigh OTDR / OBR etc.)

6) **Best Practice Guidance for the Use of distributed fiber-optic temperature sensing for locating illicit connections on sewers - Leading authors: Dr Cedric Kechavarzi and Phil Keenan (University of Cambridge, UK), and Olga Brzezinska (Atkins, UK)**

Scope: This guide describes the use of distributed fiber-optic sensing for measuring temperature inside separate sewer systems to detect illicit discharges of storm water to foul sewers and of foul sewage to storm sewers. This standard does not deal with the operation of combined sewer systems. This standard will address the installation methods of optical fiber sensing cables into sewers and the data analysis and interpretation processes required to identify potential anomalous connections.

Objective: To introduce an innovative, efficient and cost-effective method to detect illicit connections using distributed optical fiber sensing and to disseminate good practices on how to design, install and operate such a system to obtain meaningful outcomes.

The need for and anticipated benefits: Illicit connections, most often unintended, of storm water to foul sewers and of foul sewage to storm sewers, are a major problem associated with separate sewer systems. Storm water infiltration into a foul sewer can lead to the exceedance of the sewer and treatment plant design capacity and potentially local flooding and over spilling of foul sewage. On the other hand, foul sewage flow into storm sewer can result in the release of untreated sewage in surface water and the environment. The efficient removal of illicit connections is therefore of a large benefit to the public both in sanitary and economical terms. The removal of these connections, however, requires precise knowledge of their location. In addition, illicit discharges are intermittent. Hence the detection of these connection requires monitoring systems with good spatial and temporal resolution that can be deployed over kilometers of sewer networks. Distributed temperature sensing based on Raman scattering provides such a monitoring system. By detecting the sudden changes in temperature of the sewer liquid due to the difference in foul and storm water temperature at any given time and distance along an optical fiber the system can help to accurately pinpoint anomalies in operation. This standard will help disseminate the knowledge and know-how gained by researchers and practitioners and provide guidance to the end user to ensure the correct use of distributed temperature sensing and the reliable assessment of sewer performance.

Impact and value:

- this good practice guide will demonstrate the utility of distributed fiber-optic temperature sensing in detecting sewer operation and malfunction;
- data visualization sewer tools introduced in this guide will showcase the operation patterns indicative of certain sewer events (illicit discharge, domestic sewer operational patterns, sewer blockages, manhole overflow events) of value to asset owners and managers;
- this guide will illustrate how a network of fiber-optic sensors can provide asset managers with a real-time view of the condition of their critical assets;
- this innovative monitoring technology provides ample data that informs sewer planning departments to ensure asset integrity is maintained, and prevents the interruption of service due to failure.

14. SUMMARIZING THE SITUATION

Benefits of global standards

Well respected standard writing platforms offer inclusive forums and the benefits from the development, publication and distribution of its standards around the globe help the optical fiber sensing industry and its users significantly. Given many of these being the oldest standard writing bodies in the world that has stood the test of time for many years brings instant recognition and credibility in front of those doubting the usefulness of OFSS. These standards reduce the amount of time it takes engineers to write bidding documents and technical specifications. The standards bring an added degree of comfort for the engineers, contractors and the users knowing that the thorough vetting process built as part of the consensus building within these platforms based on the balanced representation of consumers, users, producers and those of general interest. Standards help to form contracts between buyers and sellers.

In case of disagreements or disputes, standards form the backbone of establishing the "standard of care" in our judicial system. In a way, the buyers and sellers have the standards provide a preview of what case law is likely to be written and help them become aware of how to avoid errors and omissions. The biggest benefit of global standards is that these consensus documents pave the way to new technologies to become more widely accepted in the market place. Given the above benefits, writing standards is a worthy pursuit for all those who are willing to set aside their own personal interests and wish to give back to mankind more than what they have taken.

Conclusions

Standardization activities to provide fiber-optic sensors for their use in SHM system have strongly been pushed in the last decade. The generic IEC FOS standard and first basic sensor standards as well as application guidelines are available. Several groups and committees are increasingly active; however, communication between participants of these groups is very important to avoid parallel activities or uncoordinated terminology use or concurrent recommendations. Continued close cooperation between experts from IEC, ISHMII, SAE, IEEE, CSIC and the Global OFSS Task Group and other standardization and guideline groups should be encouraged.

Where do we go from here?

Much work on writing standards and guides remains to be done. No single group can meet the growing demands for standards like those completed but unfilled needs in the other forms of technology and their application. Each group shall continue to contribute using their strengths in certain focused areas of FOS. Given the serious problems experienced within ASTM F36 by the Global OFSS Task Group, the most rewarding option could be that it forms its own publishing body like the geotextile industry has done. This business model of writing and publishing their own guidelines through GSI (Geosynthetic Institute) seem to have proved to be most beneficial to all members of this industry to fuel its growth. The fiber-optic sensor industry too can follow this model toward prosperity.

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