Designation: F3079 – 14

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[1]

1. Scope

1.1 This practice specifically addresses the means and methods for the use of distributed optical fiber sensors for monitoring ground movements during tunnel and utility construction and its impact on existing utilities.

1.2 This practice applies to the process of selecting suitable materials, design, installation, data collection, data processing and reporting of results.

1.3 This practice applies to all utilities that transport water, sewage, oil, gas, chemicals, electric power, communications and mass media content.

1.4 This practice applies to all tunnels that transport and/or store water or sewage.

1.5 This practice also applies to tunnels that carry the utilities in (1.3), water for hydropower, traffic, rail, freight, capsule transport, and those used for storage.

1.6 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

1.7 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

E2586 Practice for Calculating and Using Basic Statistics

2.2 *Other Standards:*

IEC 61753-1 Fibre Optic Interconnecting Devices and Passive Components Performance Standard—Part 1: General and Guidance for Performance Standards[3]

IEC 61757-1 Fibre Optic Sensors—Part 1: Generic Specification[3]

COST Action 299 "FIDES" Optical Fibres for New Challenges Facing the Information Society[4]

ITU-T G.652 Characteristics of a Single-mode Optical Fibre and Cable[5]

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *accuracy*—the closeness of the measured value to the true or the ideal value of the parameter being measured. Accuracy represents the difference between the measured result and the true value and is affected by both bias and precision.

3.1.2 *attenuation*—the decrease in power of a signal, or light wave, from interaction with the propagation medium. The decrease usually occurs as a result of absorption, reflection, diffusion, scattering, deflection, dispersion or resistance.

3.1.3 *attenuation budget (also called optical power dynamic range and link budget)*—the maximum cumulative one-way or two-way power loss between the interrogator and the measurement point that allows a measurement with a specified performance.

3.1.4 *bias*—the difference between the measured result after averaging and the 'true' value. The true value can be obtained either by measuring a reference standard maintained by the national standard organizations or by using a traceable measuring instrument.

3.1.5 *bofda*—Brillouin optical frequency domain analysis.

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[1] This test method is under the jurisdiction of ASTM Committee F36 on Technology and Underground Utilities and is the direct responsibility of Subcommittee F36.10 on Optical Fiber Systems within Existing Infrastructure.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from International Electrotechnical Commission (IEC), 3, rue de Varembé, P.O. Box 131, CH-1211 Geneva 20, Switzerland, http://www.iec.ch.

[4] For additional information, visit http://www.cost.eu.

[5] Available from International Telecommunication Union (ITU), Place des Nations 1211, Geneva 20, Switzerland, http://www.itu.int.

3.1.6 *bofdr*—Brillouin optical frequency domain reflectometry.

3.1.7 *botda*—Brillouin optical time domain analysis.

3.1.8 *botdr*—Brillouin optical time domain reflectometry.

3.1.9 *characteristic frequency and/or wavelength at reference temperature (Brillouin technologies)*—the wavelength that characterizes the sensor response at reference temperature as monitored by the interrogator. As Brillouin frequency varies with wavelength of the light source, this also changes the temperature and strain coefficients for various sensing fibers. Therefore, the characteristic frequency and the wavelength at a specified reference temperature and at zero strain are usually provided by the producers.

3.1.10 *cladding*—optical transparent material over the core of the fiber optic cable, with a refractive index lower than that of the core, to provide total internal reflectance.

3.1.11 *connector*—coupling device that permits a signal to pass from one optical fiber to another.

3.1.12 *connector insertion loss*—the power loss due to the insertion of a connector between two elements.

3.1.13 *contractor*—usually, the entity in charge of construction of the new tunnel or other infrastructure that may impact the utility.

3.1.14 *core*—the primary light-conducting region of an optical fiber. The refractive index of the core is higher than its cladding, the condition necessary for total internal reflection.

3.1.15 *cross-sensitivity*—the unwanted change of measured result due to the influence of physical factors other than the measured parameters.

3.1.16 *distributed optical fiber sensor system (DOFSS)*—a system using optical fiber cable as a sensor, without discrete elements such as wound mandrels or fiber Bragg gratings, that is sensitive over its entire length to deliver spatially continuous and resolvable data on the desired measured parameters.

3.1.17 *drift*—a slow change in time of the monitoring characteristics of the measurement system.

3.1.18 *durability*—a quality of a manufactured component of a measurement system or of the entire measurement system measured by how well it withstands a sustained period of specified operation.

3.1.19 *engineer*—the licensed professional engineer designated by the owner/operator of the utility or the tunnel to represent the owner's/operator's interests during the ground movement monitoring process.

3.1.20 *failure criteria of the sensor*—the measurement uncertainty due to overstressing, overheating and other factors leading to results or data that are unreliable.

3.1.21 *gauge length (GL)*—the length of the fiber that contributes to the measured output value of a single channel.

3.1.22 *life expectancy*—a period of time during which the measuring system or its components are expected to operate according to its specifications for defined conditions.

3.1.23 *limiting conditions*—the extreme conditions that a measuring instrument is required to withstand without damage, needing to switch off or degradation of specified characteristics when it is subsequently operated under its rated operating conditions.

3.1.24 *linearity*—the tolerance to which the transfer response characteristics of a measurement system (scale factor) approximates a straight line over the sensor range of the system. For Brillouin sensors, it means that the range of temperature or strain should be within the Brillouin frequency which is linearly proportional to the strain or temperature. For Optical Frequency-Domain Reflectometry (OFDR) systems it means that the wavelength or frequency shift is linearly proportional to temperature or strain over certain length.

3.1.25 *link budget (also called optical power dynamic range or attenuation budget)*—the maximum cumulative one-way or two-way power loss between the interrogator and the measurement point that allows a measurement with a specified performance.

3.1.26 *location accuracy*—the estimated location of a measurement or other system output, such as a detection report, minus the true location of the stimulus that generated the measurement or output.

3.1.27 *measurement range*—a set of values of measured parameters for which the error of a measuring instrument is intended to fall within specified limits.

3.1.28 *measuring spatial resolution*—the minimum distance over which the DOFSS is able to detect the value of the measured parameter, such as strain or temperature, averaged over this minimum distance, within the specified uncertainty.

3.1.29 *measuring time*—the required time interval needed to obtain a measurement within the specified uncertainty, the spatial resolution, and the system range, including any time required for data post-processing.

3.1.30 *noise*—the random variation in the measurement result unrelated to the measured parameter. It primarily affects the precision of measurement.

3.1.31 *operating temperature range of the measurement unit*—the range of temperatures over which, the measurement unit can collect data on the parameters of interest, without losing its capacity for performance and reliability.

3.1.32 *operator*—the firm hired by the owner to perform operation and maintenance of the tunnel or utility.

3.1.33 *optical fiber sensing cable*—cable formed using one or more strands of optical fiber to sense physical parameters and/or transmit data.

3.1.34 *optical fiber sensor*—composed of one or more optical fiber sensing cables and the associated light signal processing equipment as pertinent to DOFSS defined in 3.1.16.

3.1.35 *optical power dynamic range* (also called *link budget* and *attenuation budget)*—the maximum cumulative one-way or two-way power loss between the interrogator and the measurement point that allows measurement with a specified performance.

3.1.36 *owner*—the person(s) or a governing body charged with construction, operation and maintenance of the underground utility or tunnel system.

3.1.37 *precision*—describes how repeatable a measurement result is. Precision is measured by the estimated standard deviation of a specified series of measurements.

3.1.38 *Rayleigh cotdr*—Rayleigh coherent optical time domain reflectometry.

3.1.39 *repeatability*—the closeness of the agreement between the results of successive measurements of the same measured parameter carried out under the same conditions of measurement. This means that for every one hundred repeated strain or temperature measurements, repeatability is the measure of the highest probability associated with either the strain or the temperature.

3.1.40 *report*—the official written work product or project deliverable that contains a description of the scope of work done, data collected and presented in various forms, interpretation of the data, findings and recommendations for further action.

3.1.41 *reproducibility*—the closeness of the agreement between the results of measurements of the same measured parameter carried out under changed conditions of measurement.

3.1.42 *resolution*—the smallest change in the measured parameter that can be indicated by the measurement system. Not to be confused with precision. This is often called the "quantization interval" of the measurement system.

3.1.43 *responsivity*—the change in the response (output signal) of a complete measurement system to the corresponding change in the stimulus (input signal).

3.1.44 *scale factor*—the inverse of the ratio of a change in the stimulus to corresponding measured change.

3.1.45 *scale factor at reference conditions*—the ratio of the measured input parameter's engineering units to the output parameter's units.

3.1.46 *sensor range*—the range between the smallest and the largest allowable value of the measured parameter.

3.1.47 *spatial resolution*—the minimum distance between two step transitions of the measured parameter in time domain that can be independently observed with a specified performance.

3.1.48 *spatial sampling interval (dx)*—The spatial distance along the fiber between two adjacent outputs of the DOFSS. This is usually controlled by the high-rate temporal sampling interval of the optical detector, dt, and the speed of light in the fiber, cf, using dx = dt*cf/2. The spatial sampling interval shall be at least one-half of the spatial resolution.

3.1.49 *system distance range*—the length of fiber over which the measurement can be performed within the stated precision, or the system can achieve its stated performance (for example, probability of detection, location accuracy...).

3.1.50 *tester*—the person or the entity responsible for carrying out the evaluation of the impact of tunneling or utility construction.

3.1.51 *total internal reflection*—reflection that occurs in a medium when the incidence angle of a light ray striking a boundary of the medium is greater than the critical angle and the entire energy of the ray is reflected back into the medium.

3.1.52 *true value*—the result of a measurement that would be obtained by a perfect measurement with no precision or bias error.

3.1.53 *updating time*—the time interval between updates of the measured value of all channels of the DOFSS. This is the same as the temporal sampling interval for systems other than multi-channel or those that provide data incrementally.

3.1.54 *warm-up time*—the duration from the time power is turned on until the system performs in accordance with all specifications.

3.1.55 *wavelength*—the length of a wave measured from any point on a wave to the corresponding point on the next cycle of the wave.

3.1.56 *wavelength of operation*—the range of wavelengths of optical radiation the sensor uses to provide the required data.

NOTE 1—Every effort has been made in the above definitions to be consistent with those defined in Cost Action 299 and IEC 61757-1.

4. Summary of Practice

4.1 Distributed optical fiber sensing technology has many advantages over current methods using discrete "point" sensors for monitoring ground movements around underground utilities and tunnels. The advantages include, but are not limited to:

4.1.1 Their distributed nature means that there are no monitoring gaps, as compared to conventional point sensors, provided the distributed optical fiber sensing cable is installed over the whole length, area or volume of interest;

4.1.2 A single optical fiber sensing cable can provide tens of thousands of continuously distributed measurement points;

4.1.3 No electricity used within the optical fiber sensing cable; thus, it is immune to electromagnetic interference and does not cause electromagnetic interference (EMI), other than that generated by the electro-optical equipment—which can be shielded and controlled;

4.1.4 They are generally safe in explosive environments;

4.1.5 They can be made robust to chemical exposure through proper design and materials selection for the protective outermost sheath of the cable;

4.1.6 Cost-effective due to the ability to collect data over long distances from a single electro-optical interrogator unit; cable lengths for a single system of 60 miles (100 km) are achievable.

4.2 Successful broader adoption of this technology depends on the proper selection of most appropriate materials, design, installation, data collection, interpretation and reporting user interface design.

4.3 This practice offers the minimum standards on the essential aspects of this technology.

4.4 There are many different technologies that fall within the classification of DOFSS that can be used for measuring ground movement during tunneling or utility construction and its impact on existing utilities. The focus in this practice, however, is solely on the most widely used Brillouin scattering technologies (BOTDR / BOTDA).

4.5 The user of this practice needs to be cognizant that a companion standard covers the standard practice for leak detection in pipelines using Rayleigh Coherent Optical Time Domain Reflectometry (COTDR). That standard describes the complementary technology to Brillouin DOFSS in far more detail. Rayleigh COTDR can also be used for very precise detection of short-term ground movements. It is most applicable, however, to short-term strain events because Rayleigh methods cannot measure very low frequency strain in the presence of the background thermal variation in most environments. This practice's focus is primarily on the most widely used Brillouin technology for measuring long-term strains. The users of this practice may refer to companion standards for specific guidance on the use of other forms of optical fiber sensing technologies to meet the needs of similar or other applications.

4.6 The DOFSS technologies discussed in Section 6 of this practice measure the longitudinal strains along the optical fiber sensing cables to assess the impact of new tunnelling and utility works on existing tunnels or utilities. The conversion of the strain measurements to displacement measurements require processing of the strain data with appropriate assumptions for the boundary conditions. Therefore the resulting indirect displacement measurements are expected to yield an estimate of the in-situ displacements. As a result, the measured ground movements referred to in the text of this practice shall be used bearing this in mind. Better accuracy may be achieved, however, when procedures discussed in 9.3 and 9.5 of the practice are used.

5. Significance and Use

5.1 This practice is intended to assist engineers, contractors and owner/operators of underground utilities and tunnels with the successful implementation of distributed optical fiber sensing for monitoring ground movements prior to construction for site planning and during utility and tunnel construction and operation and the impact of such ground movements on existing utilities.

5.2 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 ground movements for the intended purpose and to have access to certain locations of the structure and the surrounding ground. It may also be necessary for the installer to have written explicit authorization from applicable jurisdictional agencies such as the Department of Transportation, the Army Corps of Engineers, the Department of Environmental Protection and other.

5.3 Engineers, contractors, and owners/operators shall also be cognizant of how the use of distributed optical fiber sensing for monitoring ground movements around utilities and tunnels 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.

5.4 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 DOFSS.

6. Instrumentation Objective, Design and Layout

6.1 *Brief Overview*—The effect of Brillouin scattering is the most widely used form of DOFSS technology which provides a monitoring technique to measure strain and temperature along the intended optical fiber route as shown in the schematic view in Fig. 1. The optical cable itself plays the role of hundreds of thousands of sensors of multiple parameters of interest for long distances. Usual telecommunication optical fiber cables are designed to protect the optical fibers from the surrounding environment. In a strain sensing cable, however, the environment causing stimuli must be efficiently transferred to the optical fiber core that transmits light or the medium in which we can measure the effects of Brillouin scattering.

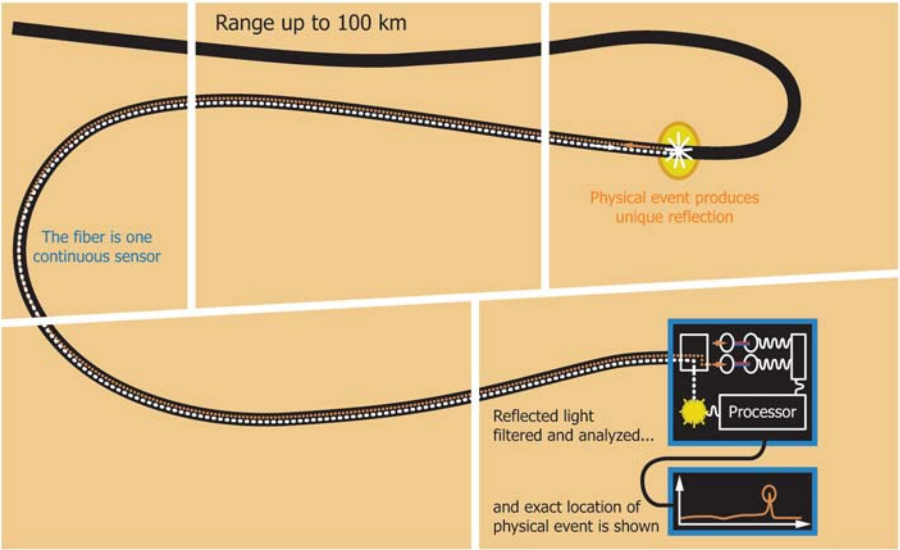


FIG. 1 Typical Layout of a DOFSS

Typical optical fiber sensing cable designs are shown in Figs. 2-4. When light travels through a transparent media such as glass, most of it goes through the core of the fiber, while a small fraction is back scattered due to the perturbation following the principle of total internal reflection illustrated in Fig. 5. Different components of the back scattered light can be identified, including the Brillouin scattering components, such as the peaks shown in Fig. 6; these are carefully analyzed and used to measure temperature or strain along the fiber. In this technology, two laser beams are injected into an optical fiber core from both its ends, as shown for BOTDA in Fig. 7. One is called the pump signal, being a pulse-modulated (for BOTDA systems) or a sinusoidally modulated (for BOFDA systems) laser beam of a unique wave profile; the other one is the continuous (CW) probe laser, sometimes referred to as the Stokes laser. The interaction of these two laser beams produces an acoustic wave through the phenomenon 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 on the right one-half of Fig. 7. Similar set up for the BOTDR technology is shown in Fig. 8. Therefore, an appropriate interrogator, like the one shown in Fig. 9, with a graphic user interface shown in Fig. 10, and the software, for example shown in Fig. 11, 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, essentially in real time. Typical results from such BOTDA and BOFDA are shown for strains in Fig. 12 and Fig. 13, respectively.

6.2 *Effect of Brillouin Scatter Facilitating Temperature and Strain Measurements*—Brillouin scatter is extremely sensitive to any changes in temperature and the deformation or the 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:

$$\nu_B = \{2\ n\ V\ a\} / \lambda o \tag{1}$$

where:

n = the effective refractive index of the propagating mode,
Va = the acoustic wave velocity in the optical fiber, and
λo = the vacuum wavelength of the incident light.

It is clear that the Brillouin frequency shift is affected by the acoustic wave velocity, which can be expressed using the theory of elasticity, for homogenous, isotropic, linearly elastic solids as:

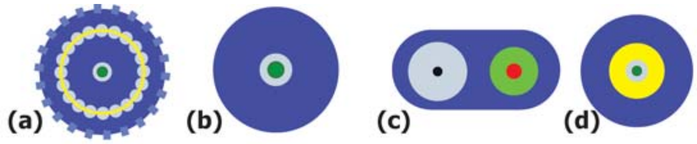
$$Va = \{K / \rho\}^{0.5} \tag{2}$$

where:

K = the bulk modulus, and
ρ = the density of the optical fiber.

The density of the optical fiber is dependent on temperature; therefore, the Brillouin peak shifts when plotted as a function of the difference in the frequency between the laser pump and the signal varying with temperature as shown in Fig. 14. Similarly, any deformation or strain in the optical fiber affects the density of the optical fiber as shown in Fig. 15. In summary, the temperature and the strain induced in the optical fiber can be measured using the effects of Brillouin scattering.

6.3 *Instrumentation Objective*—The instrumentation objective has to be clearly stated by the involved parties in terms of what problem is going to be solved (for example, detection of ground movements, quantification of axial elongation or shortening, bending, shear, stresses, strains in the utility pipes). The objective shall also include the definition of the time frame of the monitoring-during a limited time period such as when there is nearby construction, a specific season or the lifetime of the structure. The objective shall also include a clear statement on how the resulting data will be used and who will be responsible for data management and analysis. If the system is



(a) Robust, armored fiber optic strain sensing cable with metallic armoring wires and structured outer sheath for enhanced adhesion.

(b) Flexible, mini armored fiber optic strain sensing cable with hermetic metal tube.

(c) Strain sensing cable with one tight-buffer strain fiber and one integrated temperature compensation fiber in loose-tube configuration.

(d) Small, lightweight, high sensitive, metal free tight-buffer fiber optic strain sensing cable.

FIG. 2 Components of Various Optical Fiber Sensing Cables

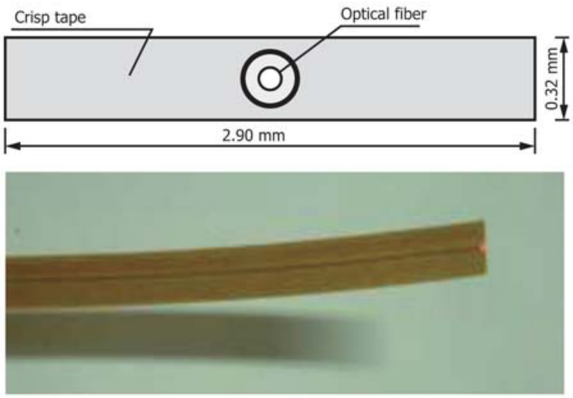


FIG. 3 Components of an Optical Fiber Strain Sensing Cable

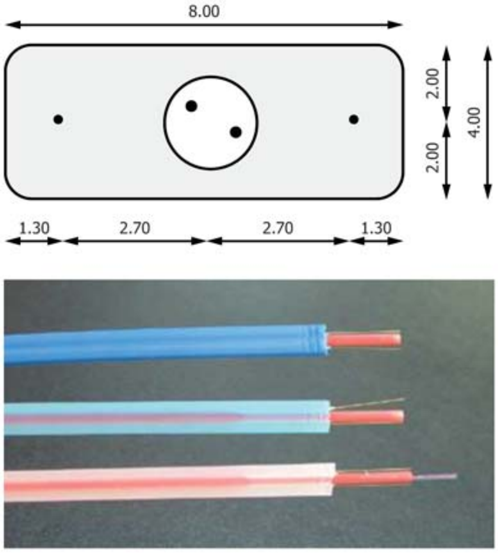


FIG. 4 Components of an Optical Fiber Strain and Temperature Sensing Cable

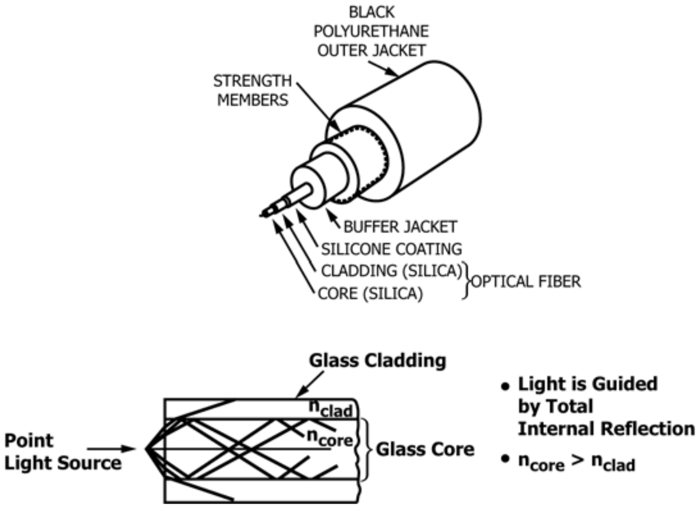


FIG. 5 Principle of Total Internal Reflection

used to generate alerts, a clear response plan to all types of possible alerts also shall be prepared.

6.4 *Instrumentation Design*—The instrumentation has to be designed in a way so that the objective can be achieved by the

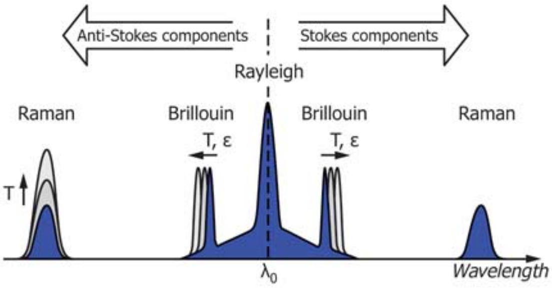


FIG. 6 Brillouin Peaks as Functions of Wavelength

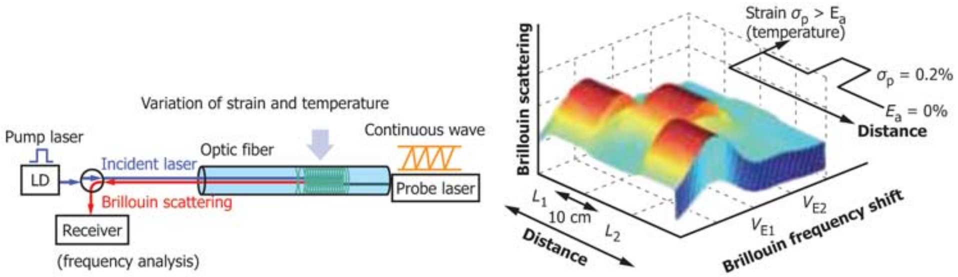


FIG. 7 Principal Components of the BOTDA System

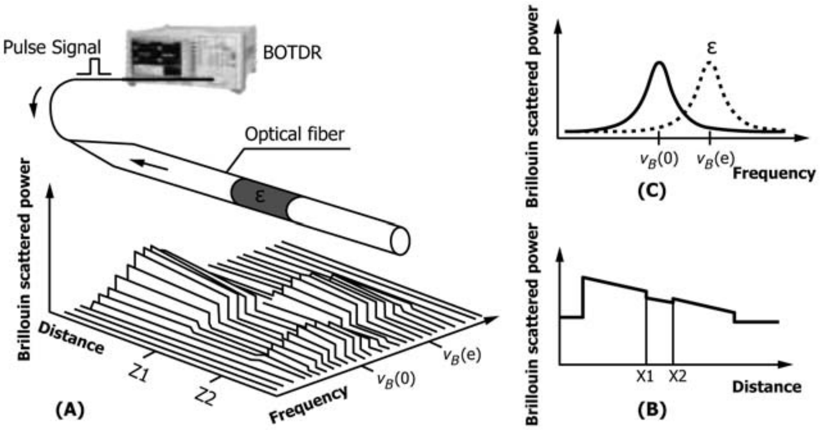


FIG. 8 Details on a BOTDR System

system components' specifications, such as the spatial resolution, the sampling interval, the accuracy and the repeatability, the system range, the strain range of the instrument and the optical fiber sensing cable, and the temperature range of the instrument and the optical fiber sensing cable. In addition, the system components and especially the cable need to be of adequate durability to survive the harsh soil environment, ground water, rodents, and other environmental forces.

6.5 *Instrumentation Layout*—The instrumentation layout specifies the details of the object to be instrumented and the project overall. It needs to be defined where, when and how the optical fiber sensing cable are to be placed, attached and protected, where the readout unit is to be placed and what services are available at that location, what the overall time frame is and whether for all construction stages, and the locations of the necessary connections and the interfaces.

7. System Components

7.1 *Specifications for the Sensing Instruments:*

7.1.1 *Spatial Resolution*—This specifies for a DOFSS by the minimum resolvable distance between two step transitions of the measured parameter of amplitude greater or equal to 20 times of the system resolution. The spatial resolution has its physical origin in the optical pulse width in time domain systems, or the equivalent pulse length in frequency domain and correlation domain systems.

7.1.2 *Spatial Sampling Interval*—This specifies the spatial distance between two sequential data points along the cable in the output of a distributed sensing system. The sampling interval is dominated by the sampling rate of a time domain system and has no direct impact on the spatial resolution. It is necessary, however, to use a sampling interval which is at least one-half as short as the spatial resolution. Sometimes it is defined as spatial accuracy or distance resolution.

FIG. 9 Typical BOTDA

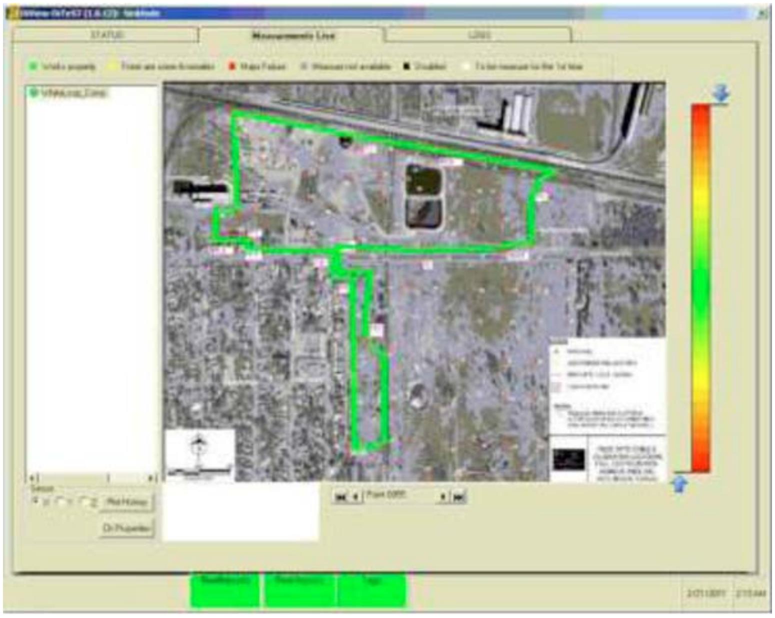


FIG. 10 Typical Graphic User Interface

7.1.3 *Measured Accuracy*—This represents the smallest change in the measured parameter, meaningfully detectable by the measurement system.

7.1.4 *Repeatability*—This is defined as the closeness of the agreement between the results of successive measurements of the same parameter carried out under the same conditions of measurement.

7.1.5 *Frequency Range*—This term only applies to Brillouin-based systems. This is the frequency range, in which a Brillouin frequency shift can be measured. The temperature and the strain sensing ranges are derived from this with the knowledge of the characteristic fiber parameters. This property changes from one fiber to another. When different sensing fibers are used, the Brillouin frequency for a known temperature and strain and their temperature and strain coefficients must be given for any measurement. Often it is for a standard room temperature of 73ºF (23ºC) and the fiber in a loose condition.

7.1.6 *Frequency Step*—This is the minimum frequency step with which the Brillouin gain profile is scanned.

7.1.7 *Data Processing-Peak Search*—When a structure is subjected to varying strain or temperature within a spatial resolution, often a few Brillouin peaks appear in the Brillouin spectrum; the peak fitting process must be imposed to consider the realistic strain or temperature condition in adjacent locations, so that a realistic strain or temperature can be obtained, corresponding either to the dominant or to the maximum strain or temperature value. Peak fitting involves the use of a higher order polynomial function for the peak in a set of data points on Brillouin gain with, for example, Lorentz' algorithm to minimize the variance. Especially for abnormal strain or temperature locations, when the disturbance is shorter than the spatial resolution, it is important to pick up the maximum strain or the temperature rather than the maximum peak associated strain or temperature for the purpose of structural health and hydraulic health monitoring of pipes.

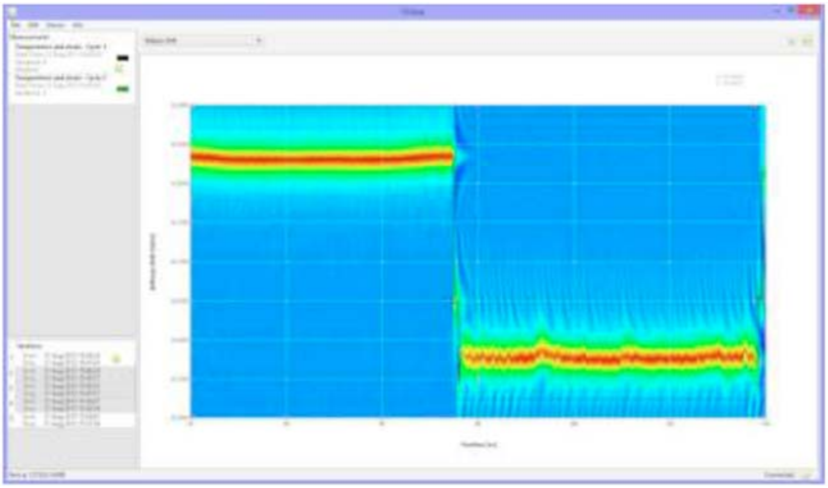


FIG. 11 Typical Screen Shot of Software of BOFDA

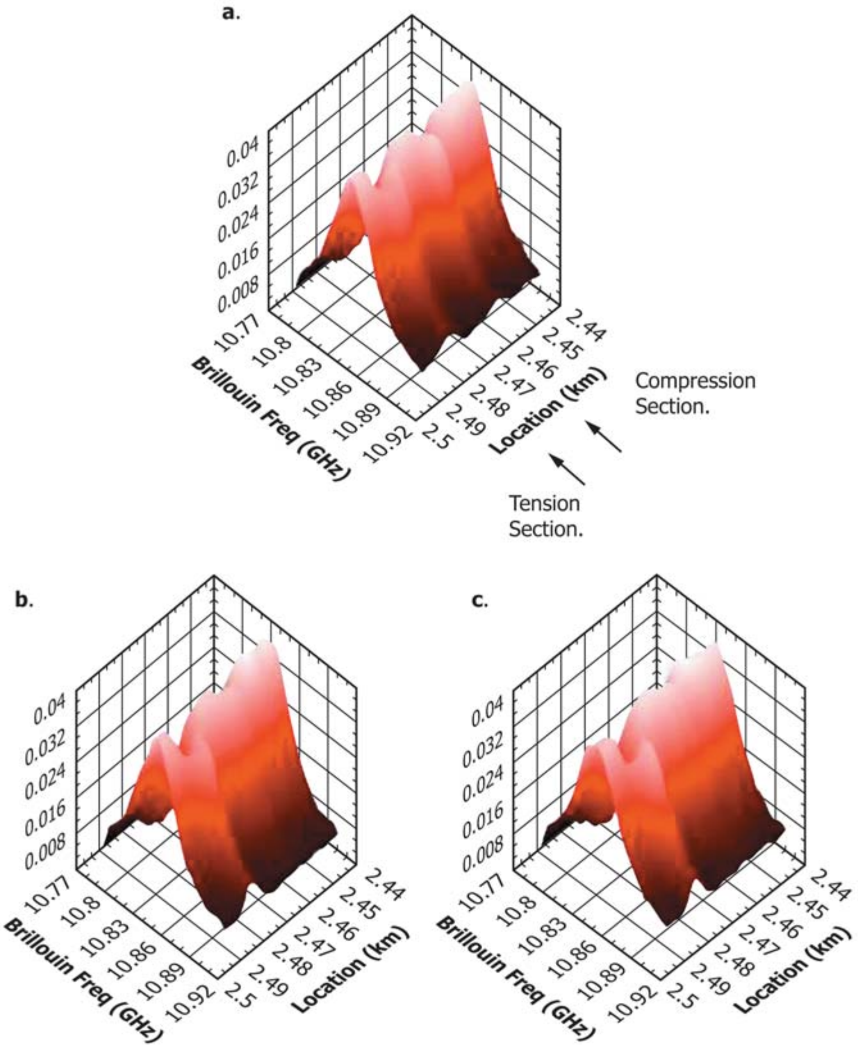


FIG. 12 Typical Results on Strain Measurements from BOTDA

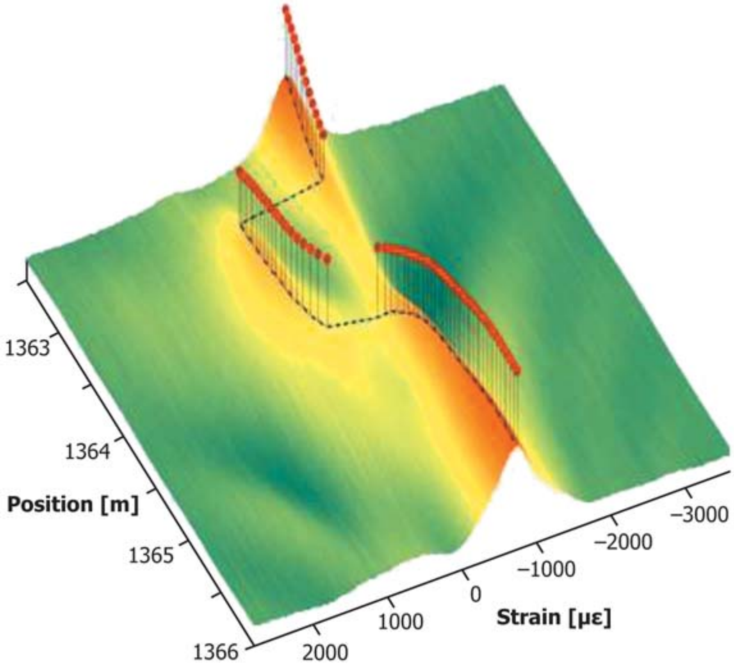


FIG. 13 Typical Results on Strain Measurements from BOFDA

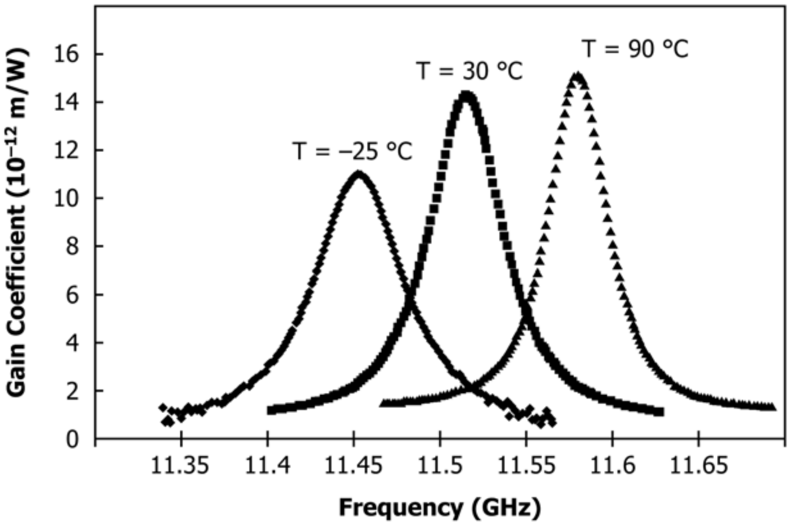


FIG. 14 Peak from Brillouin Scattering Affected by the Temperature of the Optical Fiber

Some Brillouin interrogators are able to provide multiple values for the same location, if several levels of strain or temperature are observed within the spatial resolution. It is important to recognize that the events that affect only a section much shorter than the spatial resolution or the smaller stress or temperature change than the Brillouin peak width might not be detected at all.

7.1.8 *Dynamic Range*—This specifies the ratio between the strongest and the weakest optical scattering event to be detected by the distributed sensing system within the specified performance. This is most relevant for scattering-based sensing systems.

7.1.9 *Attenuation Budget*—The maximum cumulative one-way or two-way power loss between the interrogator and the measurement point that allows a measurement with a specified performance. This is relevant for both BOTDR and BOTDA/BOFDA systems. With long sensing length, and double passage of the scattering and pump wave, the attenuation budget can envelope the entire dynamic range, although Erbium-Doped Fiber Amplifier (EDFA) and Raman amplifiers can be useful to mitigate any excessive use of the attenuation budget.

7.1.10 *Compatibility to the Type of Fiber*—This when specified can include material (silica, polymer etc.), geometry (single-mode, multi-mode, non-zero dispersion-shifted

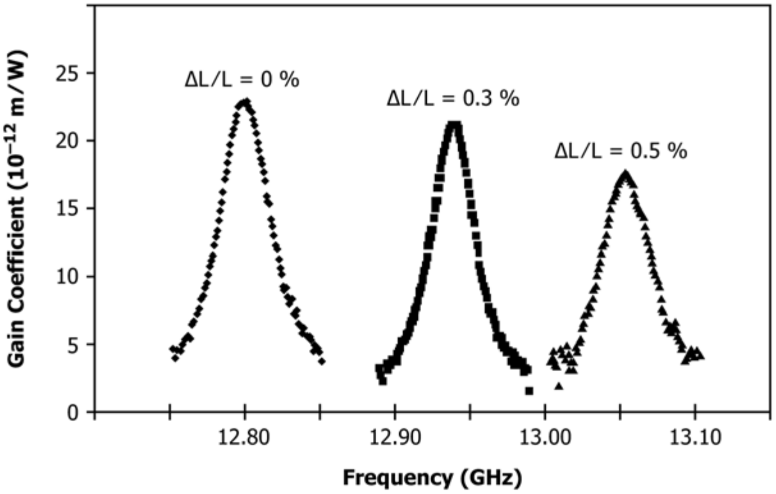


FIG. 15 Peak from Brillouin Scattering Affected by the Strain in the Optical Fiber

(NZDSF), polarization maintaining (PM), few-mode fibers, etc.), references to standards (such as ITU-T G.652.D) and others. If a special parameter is crucial for the sensing performance, this is to be specified (such as the requirement on single Brillouin peaks).

7.1.11 *General Caution*—Spatial resolution, accuracy, measuring time and attenuation budget (measurement range) strongly depend on each other. It is very difficult to define a representation that grasps all the cross-influences of these parameters in a way that is helpful to the user. The best spatial resolution is sometime not related to the best temperature or strain resolution, and associated sensing length. It is important to verify with suppliers the required performance for specific parameters will meet the expectation for the product in the specific combinations that will be used in the project.

7.2 *Distributed Optical Fiber Sensing Systems*—The contractor shall consider the following guidance and include minimum requirements on the following components and their attributes, when applicable:

7.2.1 *Optical Fiber Sensing Cable*—The optical fiber sensing cable consisting of a bundle of optical fibers protected by one or more buffer tubes and protective layers over the fibers is a critical element in the performance of the DOFSS. The optical fiber sensing cable may be composed of either one or several, for different purposes (strain and temperature) or for redundancy. Therefore, often the optical fiber sensor is formed of multiple optical fiber sensing cables and other materials. Buffering and protection coating are critical elements in the performance of the DOFSS. The sensing cable has to be designed in a way that the fiber within is able to be affected in a predictable manner by the parameter to be measured, and provide the required sensitivity needed to protect the asset. If the processing units cannot distinguish individual components or decouple co-mingled contents forming the output from the optical fiber sensing cable, cross-sensitivity of an optical fiber sensing cable has to be avoided. An example of this is the cross-sensitivity of strain and temperature in Brillouin-based systems-which are generally solved by using a cable design with a strain coupled and strain-decoupled fiber for temperature reference, or by combining Brillouin and Raman interrogators. Sensing cables are specially designed products—optimized tight buffered and loose tube cable elements. In the former, the plastic buffer tubes are bonded to the glass fiber, and the strain on the outside of the cable is very well coupled to the strain in the fiber—which is then measured by the interrogator. The disadvantage of tight buffered designs is that they are prone to micro bends, increasing the attenuation of the fiber, or even breaking it. These sensing cables are typically avoided for long cable runs because of their handling sensitivity; however, they are used in strain measurement systems that attempt to measure absolute strain down to very low frequencies, including static strain. Loose tube designs were specifically developed to protect the fiber from damage and change in optical propagation characteristics due to handling and environmental stresses. These do not communicate the static or very low frequency strain in the environment around the cable to the fiber itself, and are therefore unsuitable for measuring strain. Because the fiber is isolated from mechanical strain effects, however, the Brillouin frequency shift is only a function of local temperature changes and these cables can be used for temperature compensation when installed along the side of strain cables. The sensing cables to be used is to be chosen consciously and specifically as a function of the application requirements, cost, environment characteristics, type of sensing technology, required mechanical performance, compatibility with installation procedures; in other words, the strain sensing cables are not standard tight buffer telecom cables but those that require special manufacturing processes ensuring that all the layers are tightly bonded together.

7.2.2 *Strain Sensor*—A strain sensing optical fiber cable.

7.2.3 *Temperature Sensor*—A temperature sensing optical fiber cable.

7.2.4 *Maximum Strain*—The maximal strain (in tension and compression) an optical fiber sensing cable may experience before its functionality is affected by attenuation or mechanical failure or scale factor change (for example, slippage of the fiber within the protection layers).

7.2.5 *Strain Range*—The difference between the maximal strain in elongation and compression.

7.2.6 *Maximum and Minimum Temperature*—The maximal and minimal temperature a sensing cable may experience before its functionality is affected by attenuation or mechanical failure (for example, melting of the protection layers).

7.2.7 *Temperature Range*—The difference between the maximal and minimal allowable operational temperature of the optical fiber sensing cable.

7.2.8 *Mechanical Parameters of the Optical Fiber Sensing Cable*—Mechanical property of the optical fiber sensing cable depends both on the material composition of the jacket of the fiber and on the other sensor parts in contact with the external media.

7.2.9 *Protection Features*—The environmental demands an optical fiber sensing cable is able to resist, for example, hydrostatic pressure, chemicals, crush load, temperature. In addition to the loose-tube construction technique discussed above, armoring of the cable is commonly done to increase its resistance to environmental abuse. Cables can be of single or double armor construction—and have various armor configurations for strength and flexibility. A particularly strong type of armor is "wire armor" where the armor is constructed of a tightly wound wire covering—like a spring surrounding the cable. Rodent damage to cables is a significant threat, and armor is the first defense against it. But excessive armoring may decrease the resolution of the sensing cable, for example when detecting small strains. Optical fiber sensing cable can include other protection components, for example textile.

7.2.9.1 *Bending Performance*—The minimal radius of bending shall meet the following minimum criteria: for bend-insensitive fiber the minimum bend radius is 0.2 in. (5 mm), for normal single mode fiber the minimum bending radius is 0.8 in. (2 cm). Cables typically need a minimum bending radius of at least 10 to 20 cable diameters. These values are specified by the cable producer.

7.2.9.2 *Mechanical Coupling Between Optical Fiber Sensing Cable and the Outside Medium*—The other components of the DOFSS and the optical fiber sensing cable construction were discussed above in the section on the comparison of tight buffered and loose-tube cables, and the importance of gel fill in loose-tube cables. See also interfacing.

7.2.9.3 *Load-Elongation Relationship*—The Brillouin frequency is linearly proportional to the load. The coefficient depends on the material characteristics of the fiber jacket.

7.3 *Interfaces:*

7.3.1 *Interface Between the Optical Fiber Sensing Cable and the Sensing Instrument:*

7.3.1.1 *Optical Fiber Connectors:*

(1) An optical fiber connector terminates the end of an optical fiber, and enables quicker connection and disconnection than splicing. The connectors mechanically couple and align the cores of fibers so light can pass. Better connectors lose very little light due to reflection or misalignment of the fibers. In all, about 100 optical fiber connectors have been introduced to the market. The most common connectors used in optical fiber sensing technology are: ferrule (FC), lucent (LC) and standard (SC).

(2) A basic connector assembly consists of an adapter and two connector plugs. Due to the polishing and tuning procedures that may be incorporated into optical connector manufacturing, connectors are generally assembled onto optical fiber in a supplier's manufacturing facility. The assembly and polishing operations involved, however, can be performed in the field, for example, to make cross-connect jumpers to size. Most optical fiber connectors are spring-loaded, so the fiber faces are pressed together when the connectors are mated. The resulting glass-to-glass or plastic-to-plastic contact eliminates signal losses that would be caused by an air gap between the joined fibers.

(3) Measurements of these parameters are now defined in IEC standard 61753-1. The standard gives five grades for insertion loss from A (best) to D (worst), and M for multimode. The other parameter is return loss, with grades from 1 (best) to 5 (worst). A variety of optical fiber connectors are available, but SC and LC connectors are the most common types of connectors on the market. Typical connectors are rated for 500-1,000 mating cycles. The main differences among types of connectors are dimensions and methods of mechanical coupling. Generally, organizations will standardize on one kind of connector, depending on what equipment they commonly use.

(4) Features of good connector design include:

(a) Low insertion loss,

(b) High return loss (*low* amounts of reflection at the interface),

(c) Ease of installation,

(d) Low cost,

(e) Reliability,

(f) Low environmental sensitivity, and

(g) Ease of use.

7.3.2 *Interface Between the Optical Fiber Sensing Cable and the Structure or the Soil*—The fixation needs to assure that the optical fiber sensing cable is tightly connected to the object under investigation. If the object is a structural component, fixation may be achieved by attaching the optical fiber sensing cable to the object by screwing, welding, gluing, using magnets or any other means of fixation. The fixation can be realized over the whole length or at discrete locations. Alternatively, the optical fiber sensing cable may be embedded directly into the structure. If the object under investigation is the soil itself, a tight connection of the optical fiber sensing cable to the soil is required. This may be achieved, however, by friction between the optical fiber sensing cable and the soil or by placing micro-anchors at intervals along the optical fiber sensing cable. An alternative is to embed tightly the sensing cables onto a geotextile with high friction properties with the surrounding soil. The failure force of the fixation has to be chosen in a way that either the fixation fails before the optical fiber sensing cable fails at the force corresponding to maximum allowable strain in the optical fiber sensing cable or that the fixation force is larger than the optical fiber sensing cable force at the maximal allowable strain. It is sometimes desirable that the connection between the optical fiber sensing cable and the object under investigation loosens at high level of strain to avoid breakage of the sensing cable. This means that not all of the strain will be transferred to the cable from the surrounding medium and hence not all of the strain will be measured.

8. Details of Instrumentation

8.1 *Fixation and Installation Procedures*—Fixation and installation procedures need to be laid out in detail so that all involved personnel are able to follow these procedures to assure consistent quality of the installation. In addition, the procedures need to assure that minimal risk of optical fiber sensing cable destruction is achieved. Procedures for repairing a damaged cable shall be detailed, whenever this is possible.

8.2 *Pre-Straining*—If pre-straining is foreseen in the design, measures for the application of optical fiber sensing cable pre-straining as well as control of the actual pre-straining achieved are necessary.

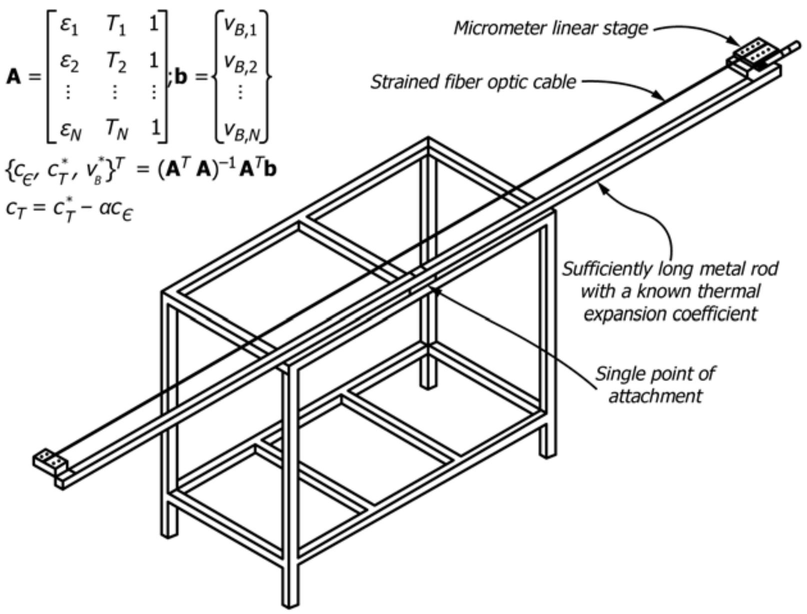
8.3 *Splices and Connections*—Maximal allowable splice loss has to be stated in accordance with IEC 61753. Connectors must be of the same type and must be compatible with the cables and the interrogator. The *link budget* of the system, the maximum allowable total attenuation over the *system range* should be specified, as well as acceptable point losses at splices or connectors, and reflection coefficients.

8.4 *Calibration and Quality Control of Optical Fiber Sensing Cables*—Calibration is primarily achieved by knowing the transfer function from the sensing cable exterior wall strain to the fiber strain as a function of frequency, and ensuring that the fixation method reliably transfers environmental strain to the cable. Calibration can be done through laboratory measurements, or *in situ* using ambient noise or an active sound/vibration source with ground true strain, displacement, or velocity optical fiber sensing cables, properly corrected for wavelength and frequency of the incident waves near the cable. Measurement of these parameters requires either knowledge of the elastic properties of the environment, or the use of an array of point sensors to estimate the spatial wave number of the incident strain. Because of their extended nature with gauge lengths typically 3.28 to 32.8 ft (1 to 10 m), DOFSS sensors are directional measuring the strain projected along their axis. Most cables are also sensitive to the acoustic pressure around them, as well as the strain, so at higher frequencies, their response is not exactly that of an ideal extended strain sensor. If the optical fiber sensing cables are used for qualitative measurements, for example, to only identify locations with high levels of strain, either a simpler calibration procedure or the use of generic calibration coefficients shall be sufficient. Calibration shall meet the minimum requirement of 1 µstrain.

8.4.1 *Simultaneous Determination of Strain and Temperature Coefficients of the Sensing Cable*—Calibration of the strain and temperature coefficients, c_ε and c_T, shall be performed according to 8.4.1.2 by the integrator in case the intended fiber optic cables (that is, sensors) were not characterized by the cable manufacturer. The process described in 8.4.1.2 can also be used for quality control of reported values by fiber manufacturers as described in 8.4.1.3. These calibration coefficients can be defined as:

$$\begin{gathered}\Delta\nu_B = \left.\frac{\partial\nu_B}{\partial\varepsilon}\right|_{T=const}\Delta\varepsilon + \left.\frac{\partial\nu_B}{\partial T}\right|_{\varepsilon=const}\Delta T \\ c_\varepsilon = \left.\frac{\partial\nu_B}{\partial\varepsilon}\right|_{T=const};c_T = \left.\frac{\partial\nu_B}{\partial T}\right|_{\varepsilon=const}\end{gathered} \tag{3}$$

8.4.1.1 *Calibration Setup*—The process shall be performed using a calibration setup which consists of the following components and configuration (schematically shown in Fig. 16): *(1)* a long metal rod with a known coefficient of linear thermal expansion, α_{rod}; alternatively, if the rod is made of invar, the rod can be considered to have almost zero thermal expansion and the value of α_{rod} can be set to zero. The length of the rod (and the gauge length) shall be at least 1.5 times greater than the spatial resolution of the considered optical interrogator. The rod shall be connected to a stable support at a single point, to ensure free thermal expansion. *(2)* A



$$\mathbf{A} = \begin{bmatrix} \varepsilon_1 & T_1 & 1 \\ \varepsilon_2 & T_2 & 1 \\ \vdots & \vdots & \vdots \\ \varepsilon_N & T_N & 1 \end{bmatrix};\mathbf{b} = \begin{Bmatrix} v_{B,1} \\ v_{B,2} \\ \vdots \\ v_{B,N} \end{Bmatrix}$$

$$\{c_\epsilon, c_T^*, v_B^*\}^T = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{b}$$

$$c_T = c_T^* - \alpha c_\epsilon$$

FIG. 16 Calibration Setup and Process

micrometer linear stage, is connected to one end of the rod. *(3)* a fixing point at the other end of the rod. The setup shall be configured such that an optical cable could be strained uniformly between the two ends of the rod.

8.4.1.2 *Calibration Process:*

(1) Using the considered optical interrogator, the Brillouin frequency shift, ν_B, shall be measured under multiple known combinations of strain and temperature. Each measurement shall be recognized by three values: $\nu_{B,i}$, T_i, and ε_i, where $\nu_{B,i}$ is the measured Brillouin frequency shift in the mid section of the strained fiber, T_i is the averaged room temperature near the fiber, and ε_i is the induced strain ($=\Delta l/l_0$, where l_0 is the nominal length between the rod fiber attachment and the micrometer, and Δl is the induced elongation). Note that the initial condition (which defines l_0) shall entail a strained fiber, such that it could also be shortened relatively. Room temperature and induced strains may be simultaneously changed from one measurement to another. It is advised to allow significant temperature change (in the range of 10°C) if the thermal coefficient is of interest. The induced strain shall be kept to levels which do not inflict damage to either the fiber or the cable (typically less than 1 %).

(2) The sensing coefficients shall be determined by a linear regression, which may be established using the following algebraic manipulations: *(1)* The measured Brillouin shift shall be arranged in the form of a vector as $\mathrm{b} = \{\nu_{B,1}, \ \nu_{B,2}, \ \ldots, \ \nu_{B,N}\}^T$ (where N is the number of measurements). *(2)* Each set of measured room temperature and induced strain (T_i and ε_i) shall compose the first and second arguments of the ith row of an N by 3 matrix as follows:

$$\mathrm{A} = \begin{bmatrix} \varepsilon_1 & T_1 & 1 \\ \varepsilon_2 & T_2 & 1 \\ \vdots & \vdots & \vdots \\ \varepsilon_N & T_N & 1 \end{bmatrix} \tag{4}$$

(3) The strain coefficient, c_ε, and the temperature coefficient, c_T, may be determined using the first and second terms of the resulting vector from the following equation using operations on matrices.

$$\{c_\varepsilon, \ c_T^*, \ \nu_B^*\}^T = (\mathrm{A}^T \mathrm{A})^{-1}\mathrm{A}^T\mathrm{b} \tag{5}$$

(4) The strain coefficient is equal to the first term, while the temperature coefficient is equal to $c_T = c_T^* - \alpha_{rod} c_\varepsilon$ (where α_{rod} is the coefficient of linear thermal expansion of the metal rod). The central Brillouin shift, at the room temperature, T_R = 73.4°F (23°C) and the prescribed initial straining condition (l_0) is equal to $\nu_0 = \nu_B^* + T_R c_T^*$. The variance of coefficients and the central shift may be evaluated as:

$$V[c_\varepsilon] = \frac{\sum_{i=1}^{N} (\nu_{B,i} - c_\varepsilon \varepsilon_i - c_T^* T_i - \nu_B^*)^2}{(N - 3)} (\mathrm{A}^T \mathrm{A})^{-1}_{11} \tag{6}$$

$$\mathrm{V}[c_\mathrm{T}] = \frac{\sum_{i=1}^{N} (\nu_{B,i} - c_\varepsilon \varepsilon_i - c_T^* T_i - \nu_B^*)^2}{(N - 3)} ((\mathrm{A}^T \mathrm{A})^{-1}_{22} + \alpha^2 (\mathrm{A}^T \mathrm{A})^{-1}_{11} - 2\alpha(\mathrm{A}^T \mathrm{A})^{-1}_{12}) \tag{7}$$

$$\mathrm{V}[\nu_0] = \frac{\sum_{i=1}^{N} (\nu_{B,i} - c_\varepsilon \varepsilon_i - c_T^* T_i - \nu_B^*)^2}{(N - 3)} ((\mathrm{A}^T \mathrm{A})^{-1}_{33} + T_R^2 (\mathrm{A}^T \mathrm{A})^{-1}_{22} + 2T_R(\mathrm{A}^T \mathrm{A})^{-1}_{23}) \tag{8}$$

(5) It is important to verify that the strain is distributed uniformly along the section being calibrated. Non uniform strain may mean that the cable is not straining evenly due to non-uniform bonding of the coatings or other defects which means that it is not suitable for strain or temperature measurement.

8.4.1.3 *Quality Control*—The quality control shall ensure that the coefficients reported by the fiber optic cable manufacturer are correct and relevant to the interrogator used by the integrator. The process is the same as that described in 8.4.1.2, except that the comparison is performed with a reference to the wavelength for the optical interrogator used by the cable manufacturer. The coefficients reported by the optic fiber cable manufacturer shall be multiplied by a factor of λ_m/λ_i for comparison with those obtained in 8.4.1.2, where λ_m is the wavelength used in the calibration process of the manufacturer, and λ_i is the wavelength associated with the interrogator used for reference during quality control. Any major discrepancy (beyond one standard deviation) with the values reported by the manufacturer shall be investigated and the problems causing such discrepancies shall be resolved before the fiber is put into use.

8.4.2 *Stress Free Cable Coefficient:*

8.4.2.1 In some field applications, such as when the temperature is to be determined by a loose section of the strain sensor (for example by placing loops inside a closed boxed free of straining), a lump coefficient $c_{T,f} = c_T + \alpha_c c_\varepsilon$, where α_c is the coefficient of linear thermal expansion of the cable coatings, can be used directly to evaluate the temperature change from Brillouin shift.

$$\begin{aligned} \Delta\nu_B &= \left.\frac{\partial \nu_B}{\partial T}\right|_{\sigma=0} \Delta \mathrm{T} \\ c_{T,f} &= \left.\frac{\partial \nu_B}{\partial T}\right|_{\sigma=0} \end{aligned} \tag{9}$$

8.4.2.2 Note that if c_T was established using 8.4.1 then the expansion coefficient of the cable can be determined. The method can also be used for loose tube fibers. In this case $c_{T,f}$ should be similar to c_T based on 8.4.1.2, since it is expected that the inner fiber is free of stress.

8.4.2.3 For calibration of $c_{T,f}$, temperature controlled thermal water tanks or baths, with a minimum accuracy of ±0.2°F (0.1°C) shall be used as follows. Cables are coiled into stress-free loops and then submerged into a water bath where water or antifreeze coolant liquid is heated in incremental stages within the range of temperature of interest. Temperature uniformity must be ensured thorough continuous mixing. The Brillouin frequency shift is recorded at each stage once the temperature has stabilized. It is also good practice to then decrease the temperature in stages to characterize potential hysteresis.

8.4.2.4 In addition, the water bath can be used to check for non-uniform cable thermal expansion at higher temperatures which could lead to permanent effects on the linearity of the frequency-temperature relationship. The range of 0 to 175-200°F (80-90°C) shall be used for such evaluation as it relates to applications where the optical fibers are embedded in concrete before curing occurs.

8.5 *Temperature Compensation:*

8.5.1 If temperature changes from the zero reading, temperature compensation must be considered in order to establish the strain value.

8.5.2 A commonly used compensation method for BOTDR, BOTDA and BOFDA consists of placing a separate loose tube temperature cable, in which the fiber is free from stresses, parallel to the strain cable. The measured Brillouin frequency shift is then used to calculate temperature variations at any point along the fiber and to compensate for thermally induced strain in the strain cable.

8.5.3 Another temperature compensation technique, mainly used with surface attachment installations, consists of using free loose sections of the strain cable which are kept free from physical movement, usually in the form of a series of small loops (Mohamad, 2012) (**1**).[6] This method is only valid if loose and strained sections have the same temperature at all times.

8.5.4 In both methods the temperature change can be obtained by the Brillouin shift and $c_{T,f}$, as: $\Delta T = \Delta \nu_B / c_{T,f}$. This temperature change can then be used to compensate for the temperature effect.

$$\Delta \varepsilon = \frac{1}{c_\varepsilon} \Delta \nu_B - \frac{c_T}{c_\varepsilon} \Delta T \tag{10}$$

8.5.5 The temperature change may also be used to calculate thermally induced stresses. For example, in concrete structures, the stress can be calculated as the superposition of the straining effect and thermally induced stressing as: $\Delta\sigma = E(\Delta \varepsilon - \alpha_{con} \Delta T)$, where E is the Young's modulus of the concrete and α_{con} is the coefficient of linear thermal expansion of the concrete (tension is positive).

8.6 *Mapping*—It is important to establish a clear relationship between the locations reported by the instrument (typically expressed as a linear distance from the instrument itself) and the physical location of the measurement points (typically expressed through GPS coordinate or other customer-specific coordinate systems). This activity is called mapping and can be performed for example by identifying length markings along the cable or by introducing a controlled stimulus (heating, stretching, and vibration) at known cable locations.

8.7 *Zero Measurements*—For zero strain measurements, for example, there shall be no contribution from the environmental effects on the structure under investigation. Therefore future measurements are typically reported as differences compared to an initial measurement, called the Zero Measurement. It is important to perform this Zero Measurement under known conditions and to document the outcome and timing for future reference. It is sometimes necessary to repeat the Zero Measurement if the cable re-installed or moved. The time between the sensor installation and the zero measurement shall be sufficient for most of the loss in pre-strain and creeping within the sensing system as well as the effects of soil consolidation, temperature and ground water on the sensor have taken place.

8.8 *Instrumentation Reporting*—The details of the instrumentation have to be included in the report, prepared by the contractor for the owner, so that other experts are able to continue using the installed system.

8.9 *Assignment of Responsibilities*—The tester is expected to work with the owner of the structure to investigate the existing conditions, assess the risk of future damage, and mitigate the risk by establishing criteria for the critical strain or temperature conditions of the structure.

9. Direct Integrity Measurement versus Indirect Evaluation of the Impact of Tunneling on Existing Pipelines

9.1 Two main approaches may be taken to evaluate the impact of tunneling on existing pipelines—the first entails direct evaluation of the developed strains of the existing pipeline and the second is by an indirect evaluation through the analysis of greenfield measurements. The first approach may be considered more suitable for large or new pipelines, in which installation of fiber cables can be applied directly to the pipeline (either from inside for large pipelines or externally for newly constructed pipelines put into service). The second approach may be considered more suitable for existing pipelines in which the owner cannot grant access for direct fibers installation on the structure of interest.

9.2 *Direct Integrity Measurement*—In the direct integrity approach, fiber optic cables are attached directly to the structure of interest, facilitating a direct evaluation of the pipeline response to tunneling. The manner in which the fiber optic cables are attached and the information is analyzed depends on the parameters of interest. Mohamad et al, (2010) (**2**) and Mohamad et al, (2012) (**3**) provide case studies on how the impact assessment can be carried out in practice.

9.2.1 *Optical Fiber Cable Installation:*

9.2.1.1 For pipelines for which longitudinal behavior can be well represented by Euler-Bernoulli beam theory, it is sufficient to install three fibers along the pipeline at different positions in the cross-section for the evaluation of the longitudinal behavior. By knowing the pipeline bending stiffness, EI, and the axial stiffness, EA, information from these three fibers will be sufficient to determine the axial force and two bending moments (along two perpendicular axes) in every cross section. It is preferable that the three fibers be installed at angles of 90 degrees (for example, along the crown and the springline of the pipeline).

9.2.1.2 In case the temperature of the pipeline varies from the zero-reading, the effect of temperature shall be compensated for in the evaluation of the axial force. This can be achieved by attaching a fourth cable, insensitive to strain (or with different sensitivity to strain and temperature compared to the other cables).

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[6] The boldface numbers in parentheses refer to the list of references at the end of this standard.

9.2.1.3 The use of a smaller number of fibers may still be valuable, but will require additional assumptions regarding the mechanical behavior of the pipeline in order to establish the complete longitudinal stress state.

9.2.1.4 It is possible that a single fiber may be sufficient for the task of monitoring, in case the expected critical point is known and the design value is defined directly as strain at this specific point (or at the section where the measurements are taken). For example, a single fiber spanning a pipeline joint would provide information relating to joint rotation or relative pullout. This approach may also be taken in case the structure is flexible to the extent its longitudinal behavior cannot be represented as an Euler-Bernoulli beam, and the measured strain cannot be used to directly evaluate the axial and bending moment forces.

9.2.1.5 The optical fiber cables shall be attached to the existing pipeline in a manner which guarantees that the fiber strain measurements represent the pipeline deformation. This may be achieved by mechanical anchoring systems or stiff adhesive materials (for example, epoxy glue), or both. The spacing between the attachments/anchoring defines the spatial resolution, limited by the optical measurement resolution.

9.2.1.6 The strain reading location from every fiber shall be identified and associated with a longitudinal axis of the pipeline, in order to allow cross-sectional interpretation of the results.

9.2.2 *Readings*—To ensure that the zero reading is not affected by the tunneling process, it shall be taken when the tunnel face is sufficiently distant from the pipeline, at least 1.5 times the depth of the tunnel.

9.2.3 *Interpretation*—Using the strain profile from the (minimum) three fibers, a plane of local deformation defining two (perpendicular) curvatures and shortening/lengthening of the neutral axis can be defined. Under the 90 degree combination, the two springline fibers can be used to define the local shortening/lengthening of the neutral axis and the horizontal bending curvature, independently of the crown fiber. Using the derived shortening/lengthening strain together with the remaining crown fiber gives the vertical bending curvature. Other fiber locations and associated frames of reference may also be used in a similar fashion.

9.3 *Indirect Evaluation of Ground Movements Induced by Tunnel or Utility Construction*—Direct integrity evaluation is generally preferable and most representative of actual pipeline response. It may not always be possible or even recommended, however, from a pipeline damage avoidance perspective (since uncovering the pipeline to attach fibers may actually cause more damage than tunneling). The indirect evaluation method entails measurement of the soil behavior at a greenfield area ahead of the pipeline location and the use of the obtained greenfield information within analytical solutions in order to predict the impact of tunneling on pipeline integrity. The advantage of the indirect evaluation method is that it allows corrective measures to be taken before the tunneling process actually affects the existing pipeline.

9.3.1 *Optical Fiber Cable Installation:*

9.3.1.1 The process involves the burial of a fiber optic cable at a shallow depth parallel to the pipeline, at an area sufficiently distant from the pipeline to allow tunneling corrective measures to be taken, if needed, before the pipeline itself is affected by the tunneling process. The fiber optic cable shall be buried in an area that is sufficiently remote from existing buildings and infrastructure such that it corresponds to a greenfield condition.

9.3.1.2 The cable shall be installed such that it guarantees that its deformation is compatible with that of the soil. This condition is satisfied as long as there is no relative pull out/slippage of the fiber, which may be evaluated by examining the gradient of the measured strain, given by $(EA_f / S)\partial\varepsilon/\partial x < \tau$, where EA_f is the axial stiffness of the cable, S is the perimeter of the cable cross-section, $\partial\varepsilon/\partial x$ is the strain gradient and τ is the pull-out shear strength (which can be estimated as $\tau \approx 0.75\ yz\ \tan\ \delta$ (where yz is the overburden vertical stress at the cable level and δ is the cable soil interface friction angle). In most cases the above inequality will hold, and no slippage will occur. Cable anchors may be used if needed. In this case $\tau \approx 0.75\ yz\ \tan\ \delta + F_A/LS$, where F_A is the anchor capacity and L is the distance between the anchors.

9.3.1.3 The cable shall be pre-strained and laid as straight as possible, preferably on a pre-compacted layer. Any variation from the perfectly horizontal condition may affect the local strain reading and hence shall be avoided. Height variation causing a gradient greater than ±10 % (1 in. per 10 in. or 10 cm per m) shall be avoided.

9.3.2 *Readings*—To ensure that the zero reading is not affected by the tunnel or tunneling process, it shall be taken when the tunnel face is distant from the cable (at least 1.5 times the depth of the tunnel). Readings throughout the tunneling process may be used to define the input greenfield values into the analytical solution, each of which associated with different relative distance between the tunnel face and the pipeline, equal to the relative distance between the tunnel face and the optical fiber cable.

9.3.3 *Interpretation:*

9.3.3.1 The spatially distributed optical fiber measurements can be used to define tunneling ground model parameters, through different types of analysis. Individual or collective continuous strain profiles can be used as target values in a fitting process of accepted 2D and 3D greenfield ground displacement models. Alternatively, specific ground displacement parameters, such as the settlement trough width and the length of a Gaussian model may be determined by specific procedures on the integrated strain and rate of strain change with advancing tunnel (for example, Klar et al. 2014) (**4**).

9.3.3.2 Determination of the settlement trough intensity (or volume loss) requires the inclusion of the focal point to which the displacement vectors point, or alternatively an additional independent measurement of the maximal vertical displacement.

9.3.3.3 The established greenfield ground displacement parameters can then be used as input parameters for analytical (linear, nonlinear, or equivalent linear) solutions of soil pipeline interaction to estimate the expected pipeline stressing (for example, Attewell et al, 1986 (**5**); Vorster et al, 2005 (**6**); Klar et al, 2008 (**7**)). A conservative evaluation, not requiring soil pipeline interaction, may be obtained by forcing the pipeline to 'follow' the greenfield soil displacements.

9.4 *Procedures for Measurements*—The field measurement procedure will be designed with coordination between the instrumentation suppliers and the user with input from the owner. Testing will be conducted covering a range of extreme conditions to verify the instrument meets the design requirements. Measurements can be performed automatically and continuously or manually at discrete time intervals. This depends on the specific project requirements and the expected evolution of the phenomena under investigation with time.

9.5 *Additional Guidance*—Although both methods of attachment, continuous or discrete, can be used as described in the above sections, the uncertainty in measurement or the limits of errors, or both, need to be determined correctly recognizing the following:

(1) Strain is the value that is associated with an infinitesimally small mathematical point, and such a mathematical point does not have dimensions; therefore, a practicing engineer does not expect to see such a point in the real world;

(2) Traditional "point" sensors, short-gauge or long-gauge (strain gauges, vibrating wires, discrete fiber optic sensors), all have physical dimensions and the strain measurement that they provide is actually an average value of the strain over the gauge length of the sensor; thus, the value of measurement is always an average value that has an error inherent to the gauge length of the sensor; this error can be estimated using the detailed procedure as given in Glisic (2011) (**8**);

(3) In its nature, the measurement performed by distributed fiber optic strain sensors is actually an average value of the strain over the length of spatial resolution. Thus, the spatial resolution can be considered as the gauge-length for every measurement point. This is independent of the manner of the installation of sensors. This leads to the following three possibilities *(4)*, *(5)* and *(6)*.

(4) If the distributed sensor is attached (bonded) continuously along the structure, in every measurement point, the result of measurement will be an average value over the spatial resolution, and the accuracy of strain measurement will depend on the spatial resolution length and strain distribution over the spatial resolution.

(5) If the distributed sensor is fixed to the structure in discrete points, and the distance between the points is not shorter than spatial resolution, then the result of measurement is ideally the average value of the strain between these fixation points. In the case that the distance between fixation points is equal to spatial resolution, then ideally the result of measurement will be the same as for sensors that is continuously attached. In the case that the distance is longer, then an additional error is introduced, and it depends on the shape of the strain distribution between the fixing points. If the strain distribution is smooth, close to linear, which is the case in most of the structures, and then the additional error is negligible Glisic (2011) (**8**).

(6) If the distributed sensor is fixed to the structure at discrete points, and the distance between the points is shorter than the spatial resolution, then important additional error could occur because the result of measurement will encompass the strain not only from the interval between the points of fixation, but also from neighboring interval(s); consequently, such an installation should be avoided.

9.5.1 If the sensor is installed by fixation at discrete points, however, then the sensor should be prestressed during the installation for a controlled value; in steel and concrete structures the prestressing value is usually 0.5 % (5000 microstrain), which covers well the range of ultimate strain in these two materials (crushing of concrete = 0.35 %, yielding of steel = 0.2 %). An example of a successful application is given in Glisic and Inaudi (2008) (**9**).

9.5.2 In most of the cases, however, the axial stiffness of the sensing cable is several orders of magnitude lower than the axial stiffness of the structure (pipe or tunnel); thus the calibration performed in laboratory provides satisfactory results. The influences of geometrical and mechanical properties of sensor on the accuracy of strain measurement are studied in detail in Calderon and Glisic (2012) (**10**) with guidelines.

9.5.3 If the on-site calibration has to be confirmed, then reliable discrete sensors with high accuracy and gauge length similar to spatial resolution of the sensing cable can be installed at several locations in immediate proximity of the sensing cable; the measurements from discrete sensor can be correlated with signals from the sensing cable and the calibration can be performed in this manner; in order to generate strain changes in the structure (for calibration purposes), either load test could be performed, the response of the structure to daily temperature variations could be used, or both methods combined.

9.5.4 The issue of strain transfer from the soil to the sensor can be solved:

(1) By embedding the sensor in geotextile that will prevent the flow of the soil around the sensor;

(2) By mounting anchoring points of a certain size along the sensor; this will ensure fixation of sensor to the soil at discrete points; Calderon and Glisic (2012) (**10**) can be used to determine the size of fixation points based on geometrical and mechanical properties of the sensor; a project similar in application (chain of long-gauge discrete sensors) is presented in Glisic and Inaudi (2008) (**9**).

10. Interfacing

10.1 *Data Transfer*—The measured data will be transferred from the storage medium of the interrogator system (which can be integrated into the interrogator unit or into a local or remote computer connected to the interrogator unit) to the user's computer or control room, for refinement and analysis, affording an opportunity to display the desired sensing information, to localize and track changes and to interpret the data in order to assess the condition of the monitored structure.

10.2 *Output Data*—The manufacturer of the interrogator shall specify the measurement data that can be retrieved from the measurement unit. For general distributed strain and temperature sensing systems, this will be strain and temperature data with the location along the optical fiber sensing cable—usually a "virtual channel" with a table mapping channel number to spatial location, in latitude-longitude, grid coordinates, or mile- or kilometer-points along the asset to be monitored (see 8.6 for additional details). Meta data such as measurement time (start/stop) and measurement settings shall be made available. For Brillouin sensing, the Brillouin frequency distribution along the optical fiber sensing cable shall be made available.

10.3 *Communication Interfaces*—The interfacing options between the interrogator system and the user's monitoring system shall be specified by the manufacturer of the interrogator system. The engineer and owner shall provide input when such interfacing options are selected to ensure that the long term use, operation and maintenance of the monitoring system by the owner and the engineer are feasible. This includes all relevant communication layers, especially the physical connection, the communication protocol, the data link and the data format.

11. Reporting

11.1 Shall include the measured strain or temperature and a detailed analysis of the condition of the structure. In addition, the owner shall be provided with the optical fiber sensing cable parameters used in the analysis and the calibration data.

12. Precision

12.1 A statement of precision allows potential users of a test method to assess in general terms the test method's usefulness with respect to variability in proposed applications. A statement of precision is not intended to exhibit values that can be exactly duplicated in every user's laboratory. Instead, the statement provides guidelines as to the magnitude of variability that can be expected between test results when the method is used in one, or in two or more, laboratories that have at least a 3-year record of having met the "standard of care" in the expertise of the subject matter. The precision of a measurement process, and hence the stated precision of the test method from which the process is generated, is a generic concept related to the closeness of agreement between test results obtained under prescribed like conditions from the measurement process being evaluated. The greater the dispersion or scatter of the test results, the poorer the precision. Measures of dispersion, usually used in statements about precision, are, in fact, direct measures of imprecision.

12.2 Although it may be stated quantitatively as the reciprocal of the standard deviation, precision is usually expressed as the standard deviation or some multiple of the standard deviation. The precision of the measurement process will depend on what sources of variability are purposely included and may also depend on the test level. An estimate of precision can be made and interpreted only if the experimental situation (prescribed conditions) under which the test results are obtained is carefully described. There is no such thing as the precision of a test method; a separate precision statement will apply to each combination of sources of variability. Additional details are given in Practice E177.

13. Bias

13.1 A statement of bias furnishes guidelines on the relationship between a set of typical test results produced by the test method under specific test conditions and a related set of accepted reference values. An alternative term for bias is trueness, which has a positive connotation, in that greater bias is associated with less favorable trueness. Trueness is the systematic component of accuracy.

13.2 The bias of a measurement process is a consistent or systematic difference between an average of a set of test results and the Accepted Reference Value for the measured property. Test method variability includes systematic as well as random components. The systematic components can be evaluated if a certified reference material with an accepted reference value of the property being measured is available.

13.3 In determining the bias, the effect of the imprecision is minimized by taking the average of a large set of test results. This average minus the accepted reference value is an estimate of the bias of the test method. The magnitude of the bias may depend on what sources of variability are included, and may also vary with the test level and the nature of the material. Additional details are given in Practice E2586.

14. Keywords

14.1 chemical; electrical cables; gas; geotechnical; ground loss; ground movement; monitoring; oil; optical fiber; optical fiber sensing cable; pipelines; pipes; power; sensing; sensors; settlement; sewage; shafts; strain; temperature; tunnels; underground; utilities; water

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