Distributed Optical Fiber Sensors for Strain and Deformation Monitoring of Pipelines and Penstocks

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ABSTRACT: Pipeline and penstock management present challenges that are quite unique. Their long length, high value, high risk and often difficult access conditions require continuous monitoring and optimizing maintenance interventions. One of the main concerns for pipeline owners involves the development of excessive strain due to external action, potentially leading to cracking or buckling. The onset of those strain hot-spots can be detected and localized using distributed fiber-optic sensors. Additionally, pipeline strain distribution and soil movement can be identified using the same technology. The aim of this review paper is to present the main technologies used for distributed strain and deformation monitoring of pipelines or penstocks and illustrate their applications through several application examples.

KEYWORDS: Distributed Sensing, Optical Fiber Sensors, Pipeline monitoring, Penstock monitoring, Deformation monitoring

1. INTRODUCTION

Pipelines and penstocks often cross hazardous environmental areas, posing natural risks such as landslides, subsidence and earthquake faults; these structures experience additional risks from the point of view of third party interference either accidental or intentional. These hazards can significantly affect the performance and durability of the flowline, producing excessive strain and deformations that can lead to damage, strain-corrosion and eventually to leaks and failure with serious economic and environmental consequences.

Permanent structural and functional monitoring can significantly improve the pipeline management and safety. Providing regularly with parameters related to the structural and functional condition of the flowline, monitoring can help to prevent issues by detecting and localizing early indicators of impending failure and allowing the owner to undertake preventive and remedial actions such as maintenance and repair activities in due time. Thus the safety is increased, maintenance cost optimized and economic losses decreased. Typical parameters to be monitored are pipeline strain and curvature, ground movement, temperature distribution, leakage locations and third-party intrusions. In this paper we will focus on structural monitoring of the pipeline or penstock itself and therefore concentrate on pipeline strain and deformation. Since flowlines are usually tubular structures with kilometric lengths, structural monitoring of their full extent is an issue in itself. Since the location of failures is not precisely known beforehand, the use of the discrete sensors installed at predefined locations is impractical, because it either requires installation of thousands of sensors and very complex cabling and data acquisition systems, or will allow only a partial coverage of the potential risk areas. Therefore, the applicability of the discrete sensors is rather limited to some chosen cross-sections or segments of flowline, but not extended to full length monitoring.

Recent developments of distributed optical fiber strain and temperature sensing techniques based on Brillouin scattering effect now provide a cost-effective tools allowing full-length monitoring over kilometric distances. Thus, using a limited number of very long sensors it is possible to monitor the structural behavior of the whole flowline with a high spatial and time resolution at a reasonable cost.

2. DISTRIBUTES STRAIN SENSING

An optical distributed sensing system is a device with a linear measurement basis, which is sensitive to measurand (in our case strain and temperature) at any point along its lengths (Tanimola and Hill 2009; Kechavarzi et al.2016). A single distributed fiber optic sensor could therefore replace thousands of discrete (point) sensors. The low fiber attenuation allows a monitoring over extremely long distances (up to 50 kilometers), which represent an impressive number of measuring points. This makes distributed sensing technique a very attractive solution when the monitoring of an extended length of pipe is required. Efforts are undergoing to introduce standard practices for the use of those types of sensors (Habel et al 2015.; Iten et al. 2015).

Such a sensing system is composed of three main parts: a sensing cable installed on the flowline, a data acquisition system and software for data management and analysis.

2.1 Strain sensing cables

Traditional fiber optic cable design aims to the best possible protection of the fiber from any external influence. In particular it is necessary to shield the optical fiber from external humidity, side pressures, crushing and longitudinal strain applied to the cable. These designs have proven effectiveness guaranteeing the longevity of optical fibers used for communication and can be used as sensing elements for monitoring temperatures.

On the other hand, the strain sensing requires a completely opposite approach: in this case, the cable must faithfully transfer the structural strain to the optical fiber.

When sensing distributed strain it is necessary to simultaneously measure temperature to separate the two components. This is usually obtained by installing a strain and a temperature sensing cables in parallel. It is therefore desirable to combine the two functions into a single packaging.

Several cable designs specifically targeted at strain monitoring have been developed (Inaudi, D., & Glisic, B. 2006) to enable easy handling, durability and accuracy in the strain and temperature measurements. Examples are shown in Figure 1 and Figure 2.

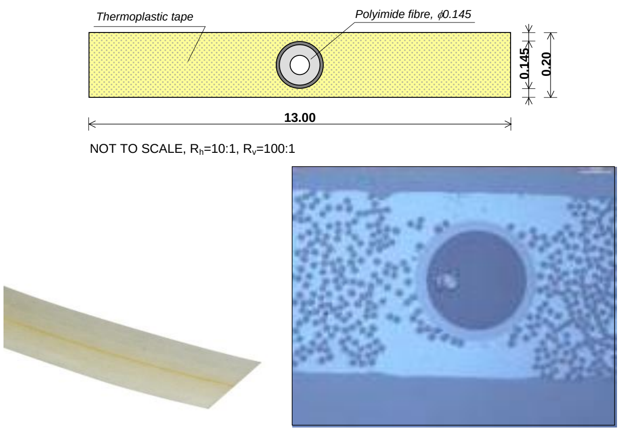

Figure 1 Cross-section, picture and micrograph of a strain sensing tape

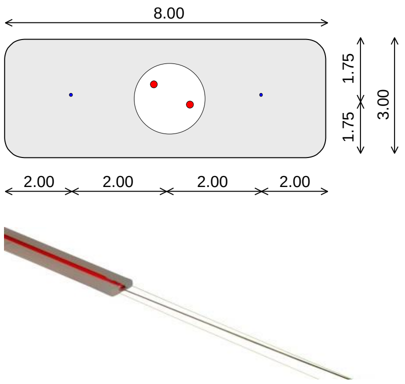

Figure 2 Cross-section and picture of a combined strain and temperature sensing cable

2.2 Measurement system

Fiber optics distributed sensing systems rely on the use of intrinsic scattering properties of the light travelling within the fiber and its dependence on the strain and temperature condition of the fiber itself. Strain sensing is based on Stimulated Brillouin Scattering (Fellay, A. et al. 1997). This scattering process is an intrinsic property of the propagation of light in the silica material from which the sensing fiber is made.

The Brillouin interaction results in the generation of scattered light which experiences a frequency shift through the scattering process. This frequency shift depends linearly on the fiber strain and temperature. As a consequence, the scattered light has a slightly different wavelength than the original light and the departure from the original wavelength is directly proportional to the local strain and temperature of the fiber.

The Brillouin readout unit is connected to the proximal end of the sensing cable and can be placed remotely from the sensing area, since a section of optical fiber cable can be used to link the reading unit to the sensor itself without any performance degradation. The other sensor end is brought back through a second fiber and connected to the reading unit to form a loop. Some systems can also work in single-ended configuration with degraded performance. This is useful in case of damage to the fiber. An example of a Brillouin readout unit is presented in Figure 3 and typical performances in Table 1.

Figure 3 Brillouin readout unit

Table 1 Performance of Distributed Brillouin readout unit

Measurement range	50 km
Number of channels	2 (standard), up to 60 (with channel switch)
Spatial resolution	1 m
Temperature resolution	0.1°C
Strain resolution	2 $\mu\varepsilon$ (0.002 mm/m)
Acquisition time (typical)	1-5 minutes

2.3 Data management software

The main functions of the data management software are aimed to measure and analyze distributed sensors automatically. The operator can view in real time the sensor's measurement history in graphical form (see Figure 4). Software is also able to trigger alerts and show warnings on the display. Warnings can be generated for different types of events such as a high strain or an extreme/low temperature. The software is able to combine measurements from different sensing cable, to obtain complex results, such as temperature compensated strains. It can also combine strain readings from several sensors installed at different positions around the pipeline to estimate pipeline deformations.

An additional module is dedicated to the detection of leaks form pipelines, dikes, reservoirs and other similar structures, by identification of local temperature anomalies (Inaudi et al. 2008). Another optional module is devoted to the detection of cracks from distributed strain data (Ravet et al. 2009).

The software stores all information into a single data-base structure. All data can be easily exported to third-party software or transmitted to an industrial control system, e.g. via a SCADA connection.

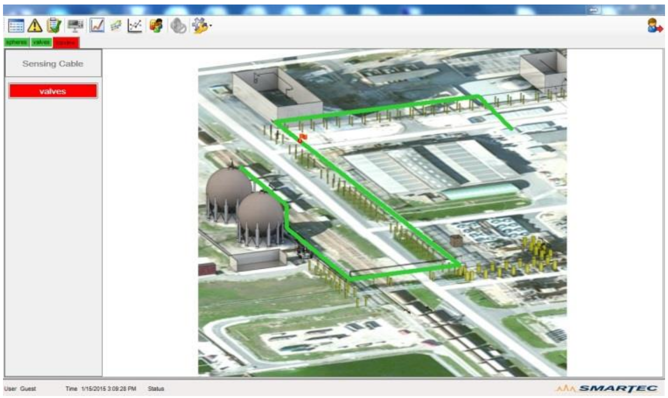

Figure 4 Distributed Data Management Software Screenshot (DiView)

3. PIPELINE AND PENSTOCK STRAIN MONITORING

Pipelines and penstocks subject to ground deformations can develop different types of deformations:

- Tension: potentially leading to cracks if tensile stress exceeds the material strength. Tension can be global if it is produced e.g. by a landslide in the direction of the pipe or local if it is produced e.g. by a crack in the rock around a penstock. Temperature changes can also induce pipeline elongation.
- Compression: potentially leading to local or global buckling.
- Bending: potentially leading to local buckling on the compression side and cracks on the tension side. Bending can be the result of a shear action in the ground due to a fault or to any other non-uniform ground deformation, such as localized subsidence. Temperature gradients can also induce bending.
- Torsion: less common, but potentially leading to buckling and cracks.
- Hoop strain: typically due to changes in internal (or external) pressure.
- Localized strain, due to local application of forces, such as a stone pushing against the pipe wall or damage from 3rd party intrusion such as a digger hitting the pipe.

Different sensor configurations are recommended to capture those effects.

3.1 Sensor configuration

Distributed sensor cables are easily installed along the length of the pipe. It is possible to install multiple lines at different positions around the pipe. If a single cable is installed (e.g. at the 12 o'clock position), it will be able to sense the tension or compression strain at that location. If the pipe is only subject to tensile and compressive strains a single cable will be sufficient to capture both. If the pipe is subject to unidirectional bending, two sensor lines are required. If the expected bending is horizontal, two cable lines at 3 o'clock and at 9 o'clock position (Figure 5) will provide both longitudinal strain (obtained by averaging the two readings) and bending strain (obtained by subtracting the two strain readings).

If two-dimensional bending is expected a minimum of three cables are required (Glisic & Inaudi 2008). Those could be installed at 12, 4 and 8 o'clock positions.

Figure 5 Sensor layout for capturing two-dimensional bending and longitudinal strain

Capturing hoop strain requires the installation of sensors around the circumference of the pipe. This increases the installation complexity significantly and is typically performed only at a few locations.

Finally, to evaluate torsion it is required to install distributed sensing cables helicoidally. This is very complex in practice and is mostly limited to cases where the sensing cable can be embedded in the pipe during fabrication (see paragraph 4.5 for an example).

3.2 Installation techniques

To sense strain the cable must be attached to the pipeline along its entire length.

Installation techniques include the following methods:

- Gluing: the cable is glued to the pipe using an appropriate adhesive such as epoxy. Also possible inside large-diameter pipes and penstocks (see application example below).
- Taping: the cable is attached to the pipe using bi-adhesive tape and/or sealing adhesive tape.
- Strapping: the cable is pre-tensioned and strapped to the pipeline at regular intervals using metallic or plastic bands.
- Combined techniques: adding straps at the ends of the sensing region is a good practice.

In most cases the installation can be carried out on top of the corrosion protection layer (polymer or HDPE layer).

For sections of up to several hundreds of meters, manual installation is feasible and cost-effective. For longer lengths automated installation robots crawling along the pipeline have been developed for special projects, such as the one depicted in Figure 6.

Figure 6 Automated sensor installation machine (curtesy of Laser Solutions, Russia)

It is also possible to install a strain sensing cable directly into the ground along the pipe. This allows the localization of areas showing movement, but does not allow a quantification of the real stain experienced by the pipe, since the interaction between soil and pipe is very complex.

4. APPLICATION EXAMPLES

The following application examples illustrate how distributed sensing technology can be effectively used to address different monitoring tasks associated with the management of oil and gas pipelines and water penstock.

4.1 Gas Pipeline in landslide area (Italy)

About 500 meters of a buried, 35 years old gas pipeline, located in Italy, lie in an unstable area. The landslide progresses with time and introduces strain to the pipeline. When the strain is estimated to be excessive, the affected section must be excavated to release the strain, typically every 10 years. Three symmetrically disposed vibrating wires were installed in several sections at a distance typically of 50/100 m chosen as the most stressed ones according to a preliminary engineering evaluation. These sensors were very helpful, but could not fully cover the length of the pipeline and only provide local measurements. Thus, there is a risk that other sections of pipe are experiencing higher strains but are not equipped with sensors. Distributed strain monitoring was selected in order to improve the vibrating wire strain gauges monitoring system, already used at the site, by extending coverage to the whole length.

Different types of distributed sensors were used: a tape sensor (SMARTape) and a temperature sensing cable. Three parallel lines constituted of five segments of SMARTape sensor were installed over the whole concerned length of the pipeline (see Figure 7). The lengths of segments ranged from 71 m to 132 m, and the position of the sensors with respect to the pipeline axis were at 0°, 120° and –120° approximately. The strain resolution of the SMARTape is 20 micro-strains, with spatial resolution of 1 m (and an acquisition step of 0.25 m) and provides the monitoring of average strains, average curvatures and deformed shape of the pipeline. The temperature sensing cable was installed onto the upper line (0°) of the pipeline in order to compensate the strain measurements for temperature variations that can occur between the seasons.

Figure 7 SMARTape on the gas pipeline

The temperature resolution of the sensor is 1°C with the same spatial resolution and acquisition of the SMARTape. All the sensors are connected to a central measurement point by means of extension optical cables and connection boxes. They are periodically read from this point using a single reading unit (DiTeSt). Since the landslide process is slow, and the measurements sessions were performed manually once a month. All the measurements obtained with the distributed system are correlated with the measurements obtained with vibrating wires.

During the excavation the pipe was laid on the soil supports every 20 – 30 m. Therefore, its static system can be considered as a continuous girder. After the burring, the pipe was loaded with soil and deformed. The pipe cross-sections located on the supports have been subject to negative bending (tension at the top) and the section between the supports to positive bending (tension at the bottom). The diagram showing the strain distribution over the length of the pipeline after the burring measured by distributed sensing is presented in Figure 8. The normal cross-sectional strain distribution as well as the curvature distribution in horizontal and vertical planes are calculated from the measurements and presented in Figure 9. It can be observed that the main impact to the pipe is vertical bending (curvature) that is due to the temporary supports.

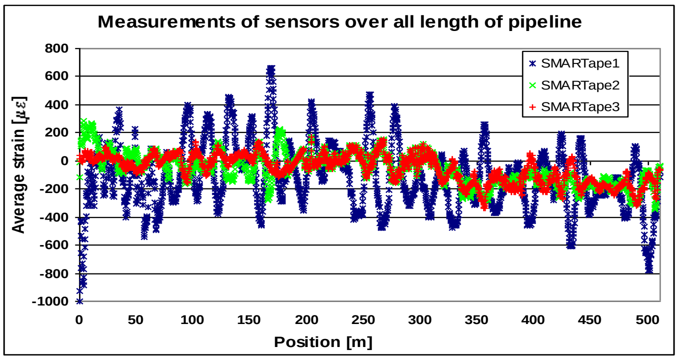

Figure 8 Strain distribution over the monitored part of the pipeline

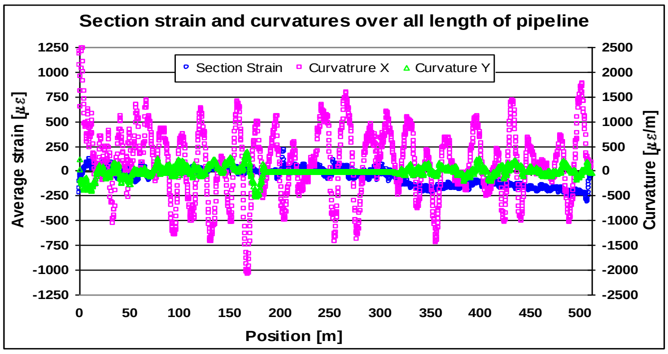

Figure 9 Cross-section strain and curvatures distribution calculated from the strain measurements

The sensors have been measuring for a period of two years, providing interesting information on the deformation induced by burying and by the landslide progression (Inaudi et al. 2007). A gas leakage simulation was also performed with success using the temperature sensing cable.

4.2 Water Pipeline crossing fault zone (USA)

A very similar application was carried out in Alameda country, California, USA, on a water pipeline crossed a tectonic fault. Several construction techniques were used to minimize the strain that the pipeline would experience in case of a fault movement following an earthquake. A distributed optical fiber strain monitoring system was installed along this section to verify the level of experienced strain after such a seismic event (Figure 10).

4.3 Penstock in fractured rock (Switzerland)

During a normal inspection, one expert detected a crack in a penstock located in the Swiss Alps. This crack was located in a horizontal armored section of an underground penstock. This started a complete non-destructive test of the 200m long section which revealed that no welds were 100% free of micro-cracks. This can be explained by a landslide that occurred in the surrounding land at a speed of about 0.5 mm/year. It was therefore decided to seal all welds with an elastic strip made of rubber and capable of up to 300% elongation. These rubber strips have been glued on each weld, including those with no cracks.

Figure 10 Water pipeline section crossing tectonic fault and instrumented with distributed strain sensors (visible on top, two other lines installed at 4 and 8 o'clock)

To allow continuous monitoring of this section and of the welds it was decided to implement a monitoring system based on conventional sensors (measuring pressure and flow around the penstock), but also a distributed strain sensing system installed along the whole disturbed length. For lines of sensing cables were installed inside the penstock as visible in Figure 11. An additional sensor line was installed in a nearby inspection gallery that is also experiencing cracking.

Figure 11 Penstock equipped with four lines of longitudinal strain sensing cables. The white circumferential strips are the sealing rubber bands

The system has been in operation for three years and the resulting data is continuously assessed according to a predefined protocol to identify any new behavior that could be indicative of crack movements (Jordan and Papilloud 2015). An example of data visualization is presented in Figure 12. The vertical lines represent areas of higher strain. It can be noticed that those lines are continuous over the whole time period, indicating that no new high-strain area has appeared.

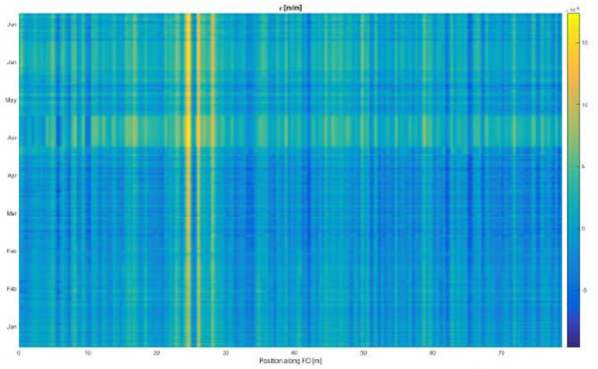

Figure 12 Pseudo color plot of strain versus time and position. Curtesy of HYDRO Exploitation SA (Jordan and Papilloud 2015)

4.4 Laboratory shear test (USA)

An interesting application of distributed sensing for monitoring underground segmental water pipelines was carried out by Princeton University at the Cornell NEES Site (Glisic & Yao 2012).

The test consisted in a large test basin in which a pipeline was assembled and tested under simulated shear movements, similar to those produced by an earthquake. The basin is a 3.40 m wide, 13.40 m long, and 2 m deep steel frame box with wooden walls. It consists of two parts: a movable part and a fixed part that can be moved relative to each other as depicted in Figure 13.

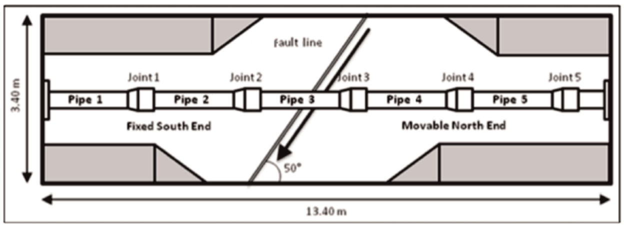

Figure 13 Schematic view of the pipeline testing facility. Curtesy of Prof. Branko Glisic (Glisic & Yao 2012)

Different types of optical fiber sensors were installed along the pipe at multiple locations around the pipeline circumference and crossing the joints between pipeline sections as shown in Figure 14.

Figure 14 Installation of sensor across a pipe joint. Curtesy of Prof. Branko Glisic (Glisic & Yao 2012)

The data recording during the test enable the identification of joints that were opening and areas that were crushing, as observed in the example of Figure 15.

4.5 Integration in composite tubing (Netherlands)

The larger hydrocarbon reservoirs in Europe are rapidly depleting. The remaining marginal fields can only be exploited commercially by the implementation of new 'intelligent' technology, such as electric Coiled Tubing drilling or Intelligent Well Completions. Steel CT with an internal electric wire line is the current standard for such operations. Steel CT suffers from corrosion and fatigue problems, which dramatically restrict the operational life. The horizontal reach of steel CT is limited due to its heavy weight. The inserted wire line results in major hydraulic power losses and is cumbersome to install. To address these issues a joint research project supported by the European Commission was started in order to develop a high-temperature, corrosion and fatigue resistant thermoplastic Power & Data Transmission Composite Coiled Tubing (PDT-COIL) for electric drilling applications. This PDT-COIL contains embedded electrical power and fiber-optics for sensing, monitoring and data transmission.

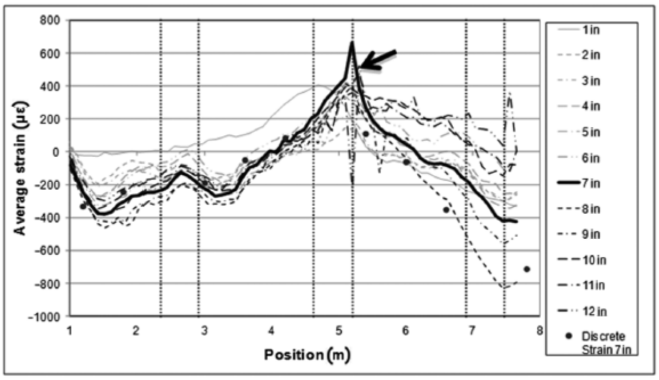

Figure 15 Detection of damage during shear test. Arrow indicates damage location. Curtesy of Prof. Branko Glisic (Glisic & Yao 2012)

The PDT-COIL consists of a functional liner containing the electrical and the optical conductors and a structural layer of carbon and glass fibers embedded in high performance thermoplastic polymers (Inaudi & Glisic 2006b). The electric conductors provide electric power for Electric Submersible Pumps or Electric Drilling Motors. A distributed fiber-optic Sensing and Monitoring System, based on the SMARTProfile design is also integrated in the liner thickness over its whole length and is used to measure relevant well parameters, monitor the structural integrity of the PDT-COIL and can be used for data transmission (see Figure 16).

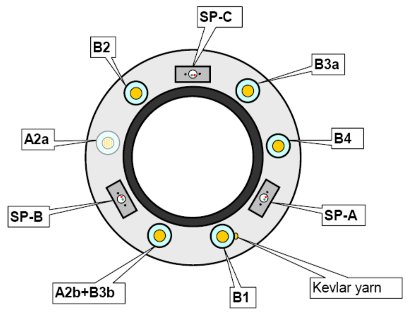

Figure 16 PDT-Coil Cross-section. The fiber optics sensing SMARTProfile are designated by SP-A, SP-B and SP-C

The embedded optical fiber system was tested for measuring strain, deformations and temperatures of the coil.

Testing of distributed strain and deformation measurements was performed on a 15m long section of polyethylene liner with integrated strain sensing fibers. The diameter of the tube was 56 millimeters. Four optical fibers were installed in a helix, with the angles of -2.5°, -5°, 5° and 10° with respect to the tube axis, in order to evaluate performance of fibers installed with different angles. Two sensors with angles of -5° and 10° were connected one after the other and a closed loop was created with the reading unit. The temperature was measured on coils with free optical fibers installed before, between and after the strain sensing sections.

The aim of this test was to verify the performance of the monitoring system and algorithms. The following tests were performed: traction test, torsion test, combined traction and torsion test, bending test, half tube bending test, double bending test and, combined bending and torsion test. As examples, the results of traction and torsion tests are presented in Figure 17 and Figure 18.

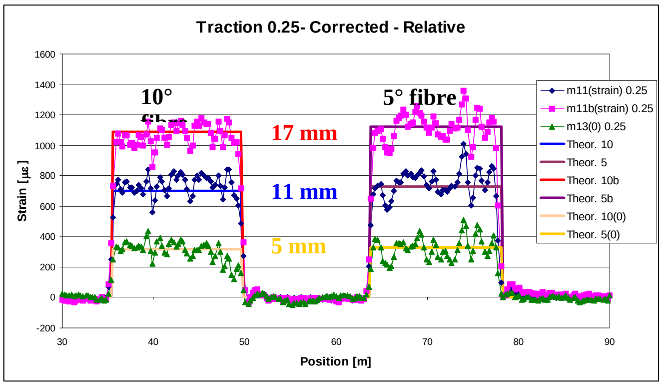

Figure 17 Results of the traction test and comparison with theoretical prediction

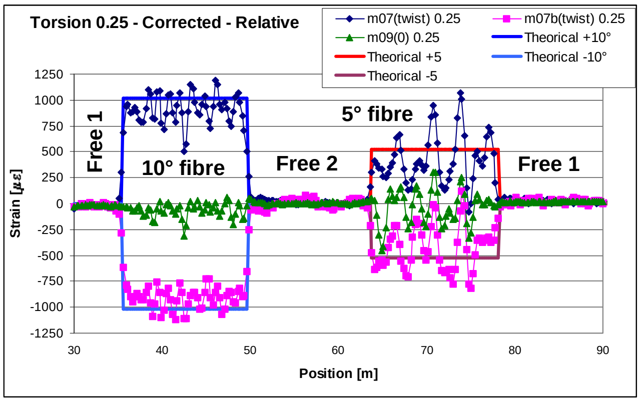

Figure 18 Results of the torsion test and comparison with theoretical predictions; higher winding angles provide more sensitivity and accuracy for torsion measurements

4.6 Other applications

Other applications of distributed strain sensing to pipeline monitoring include the following:

- Gaz de France Suez – Saint Denis La Plaine (France): oil pipeline (SMARTEC)
- Rover Pipeline LLC and Energy Transfer (USA) – natural gas pipeline (SMARTEC)
- Gas pipeline monitoring during nearby tunnel construction (Austria) (Technical University Graz and SMARTEC)
- Integrity monitoring: Sakhalin-Khabarovsk-Vladivostock transmission pipeline (Russia): oil pipeline (Omnisens and Laser Solutions)
- Pipeline integrity monitoring - Transandean route (Peru) (Omnisens)
- Smart Pipe Company – Katy TX (USA): reinforced thermoplastic pipeline (SMARTEC)

5. CONCLUSION

The use of distributed fiber optic monitoring system allows continuous monitoring and management of pipelines, increasing their safety and allowing the pipeline operator to take informed decisions on the operations and maintenance of the pipe. The presented monitoring system and the application examples shown in this paper demonstrate how it is possible to obtain information on the pipeline state and conditions. In particular a distributed fiber optic system allows continuous monitoring of strain along the pipeline. This is particularly useful at critical locations, where movements caused by earthquakes, landslides, settlements or human activities can introduce potentially dangerous strain conditions to the pipeline. Distributed strain monitoring allows the early detection of such conditions, enabling an intervention before a real damage is produced. This is a useful tool for pipeline management and for on-demand maintenance.

In general, distributed strain/deformation and temperature sensing is a useful technology that ideally complements the current monitoring and inspection activities, allowing a denser acquisition of operational and safety parameters. The measurements are performed at any point along the pipeline and not only at specific positions. Furthermore, the monitoring is continuous and does not interfere with the regular pipeline operation, contrary to e.g. pigging operations. The method can also be applied to non-piggable pipes. Recent developments in distributed fiber sensing technology allow the monitoring of 50 km of pipeline from a single instrument. To achieve the above-mentioned goals and take full advantage of the described sensing technology, it is fundamental requirement, however, to select and appropriately install adequate sensing cables, adapted to the specific sensing need. While it is generally easier to install sensing cables during the pipeline construction phases, it is also possible to retrofit existing pipelines and penstocks.

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