Long-Range Pipeline Monitoring by Distributed Fiber Optic Sensing

Daniele Inaudi
e-mail: inaudi@smartec.ch

Branko Glisic

SMARTEC SA,
Via Pobiette 11,
Manno,
Ticino 6900, Switzerland

Distributed fiber optic sensing presents unique features that have no match in conventional sensing techniques. The ability to measure temperatures and strain at thousands of points along a single fiber is particularly interesting for the monitoring of elongated structures such as pipelines, flow lines, oil wells, and coiled tubing. Sensing systems based on Brillouin and Raman scattering are used, for example, to detect pipeline leakages, to verify pipeline operational parameters and to prevent failure of pipelines installed in landslide areas, to optimize oil production from wells, and to detect hot spots in high-power cables. Recent developments in distributed fiber sensing technology allow the monitoring of 60 km of pipeline from a single instrument and of up to 300 km with the use of optical amplifiers. New application opportunities have demonstrated that the design and production of sensing cables are a critical element for the success of any distributed sensing instrumentation project. Although some telecommunication cables can be effectively used for sensing ordinary temperatures, monitoring high and low temperatures or distributed strain presents unique challenges that require specific cable designs. This contribution presents advances in long-range distributed sensing and in novel sensing cable designs for distributed temperature and strain sensing. This paper also reports a number of significant field application examples of this technology, including leakage detection on brine and gas pipelines, strain monitoring on gas pipelines and combined strain and temperature monitoring on composite flow lines, and composite coiled tubing pipes. [DOI: 10.1115/1.3062942]

1 Introduction

Flowlines, pipelines, or gas lines often cross hazardous environmental areas from the point of view of natural exposures, such as landslides and earthquakes, and from the point of view of third-party influences such as vandalism or obstruction. These hazards can significantly change the original structural functioning of the flowline, leading to damage, leakage, and failure with serious economic and ecologic consequences. Furthermore, the operational conditions of the pipeline itself can induce additional wearing or even damage.

The structural and functional monitoring can significantly improve the pipeline management and safety. Providing regularly with parameters featuring the structural and functional conditions of the flowline, monitoring can help (1) prevent the failure, (2) detect the problem and its position in time, and (3) undertake maintenance and repair activities in time. Thus the safety is increased, maintenance cost is optimized, and economic losses are decreased. Typical structural parameters to be monitored are strain and curvature, while the most interesting functional parameters are temperature distribution, leakage, and third-party intrusion. Since the flowlines are usually tubular structures with kilometric lengths, structural monitoring in full extent is an issue itself. The use of the discrete sensors, short- or long-gauge, is practically impossible because it requires the installation of thousands of sensors and very complex cabling and data acquisition systems raising the monitoring costs. Therefore, the applicability of the discrete sensors is rather limited to some chosen cross sections or segments of the flowline, but not extended to full length monitoring. Other current monitoring methods include flow measurements at the beginning and end of the pipeline, offering an indication of the presence of a leak, but no information on its location.

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

Even if the development of Brillouin scattering based sensing techniques, as well as their application in temperature and leakage monitoring, is presently well advanced, there is a comparatively modest advancement in the development of the distributed strain sensors and their installation techniques.

The aim of this paper is to present on-site applications of an innovative distributed sensing system called the distributed temperature and strain (DiTeSt) monitoring system [1].

2 DiTeSt Monitoring System

2.1 Basics on Distributed Sensing. A distributed sensor is, conventionally, a device with a linear measurement basis, which is sensitive to the measurand at any of its points. Optical fiber distributed sensors consist of a single optical fiber sensitive over its entire length. A single distributed fiber optic sensor could therefore replace thousands of discrete (point) sensors. The low fiber attenuation allows monitoring over extremely long distances (up to 25 km), which represent an impressive number of measuring points. This makes the distributed sensing technique a very attractive solution when monitoring of a large number of locations is required.

2.2 DiTeSt Reading Unit. The development of a fiber optics distributed sensor system relies on using a known and reproducible method by which the measurand can interact with the light traveling within the fiber. The DiTeSt monitoring system is based on a detection scheme using a nonlinear optical effect named

---

Contributed by the Pressure Vessel and Piping Division of ASME for publication in the JOURNAL OF PRESSURE VESSEL TECHNOLOGY. Manuscript received January 31, 2007; final manuscript received September 26, 2008; published online December 9, 2009. Review conducted by Shawn Kenny. Paper presented at the 2006 International Pipeline Conference (IPC2006), Calgary, AB, Canada, September 25–29, 2006.

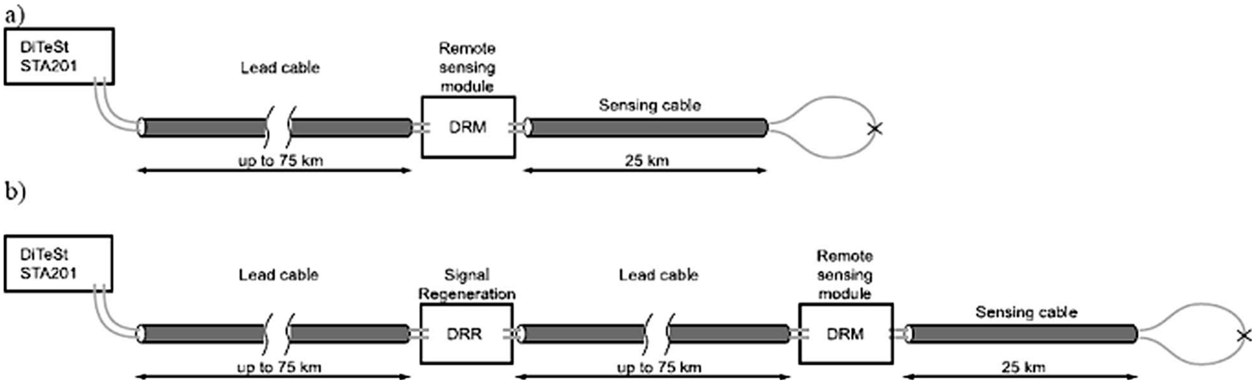


Fig. 1 Range extender configurations, allowing the monitoring of long pipeline sections with a single instrument

stimulated Brillouin scattering [1]. 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 scattering effect exhibits a well-known and reproducible response to external measurands such as temperature and strain.

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 dependent on the strain and temperature of the fiber. A system based on the analysis of the Brillouin scattered light in optical fibers is naturally devoted to perform strain and temperature measurement.

The main components of the DiTeSt system are the reading unit and the sensor cable. The reading unit is connected to the proximal end of the sensor and can be placed remotely from the sensing area, since a section of optical fiber cable could be used to link the reading unit to the sensor itself without any performance degradation. The other sensor-end can be either connected to the sensor termination module (single-end configuration), which could be placed remotely from the sensor area as well, or brought back and connected to the reading unit (loop configuration). The selection of the configuration (single-end or loop) depends on the application. The use of optical amplifier modules (range extenders) allows the monitoring of up to 300 km of pipeline from a single instrument (see Fig. 1) [2]. A scheme of the DiTeSt system is given in Fig. 2 and typical performances are given in Table 1.

2.3 Sensing Cable Design. Traditional fiber optic cable design aims to give the best possible protection to the fiber itself from any external influence. In particular it is necessary to shield the optical fiber from external humidity, side pressures, and crushing and longitudinal strains applied to the cable. These designs have proven to be effective in guaranteeing the longevity of optical fibers used for communication and can be used as sensing elements for monitoring temperatures in the −20°C to +60°C range, in conjunction with Brillouin or Raman monitoring systems.

Sensing distributed temperature below −20°C or above 60°C requires a specific cable design, especially for Brillouin scattering systems, where it is important to guarantee that the optical fiber does not experience any strain that could be misinterpreted as a temperature change due to the cross-sensitivity between strain and temperature.

On the other hand, the strain sensitivity of Brillouin scattering prompts to the use of such systems for distributed strain sensing, in particular, to monitor local deformations of large structures such as pipelines, landslides, or dams. In these cases, the cable must faithfully transfer the structural strain to the optical fiber, a goal contradicting all experiences from telecommunication cable design where the exact opposite is required.

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

2.4 Extreme Temperature Sensing Cable. The extreme temperature sensing cables are designed for distributed temperature monitoring over long distances. They consist of up to four single mode or multimode optical fibers contained in a stainless steel loose tube, protected with stainless steel armoring wires and optionally a polymer sheath. These components can be differently combined in order to adapt the cable to the required performance and application. The use of appropriate optical fiber coating (polyimide or carbon/polyimide) allows the operation over large temperature ranges; the stainless steel protection provides high mechanical and additional chemical resistance while the polymer

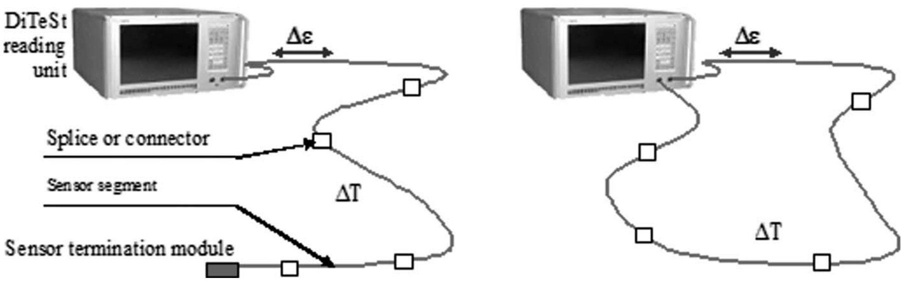


Fig. 2 Schema of DiTeSt® system configurations, left: single-end configuration; right: loop configuration

Table 1 Performances of DiTeSt system

Measurement range	30 km (standard) 150 km (extended)
No. of channels	2 (standard) max. 60 (with channel switch)
Spatial resolution	1 m over 5 km 2 m over 25 km
Temperature resolution	0.1°C
Temperature range (depends on type of sensing cable)	−270°C to +500°C
Strain resolution	2 $\mu\varepsilon$ (0.002 mm/m)
Strain range (typical)	−1.25 to +1.25%
Acquisition time (typical)	2 min

sheath guarantees corrosion protection. The carbon coating offers improved resistance to hydrogen darkening. The overlength of the optical fibers is selected in such a way that the fiber is never pulled or compressed, despite the difference in thermal expansion coefficients between glass and steel. The total cable diameter is only 3.8 mm (see Fig. 3).

These cables can be used in a wide range of applications that require distributed temperature sensing, such as temperature monitoring of concrete in massive structures, waste disposal sites, onshore, off-shore and downhole sites in gas and oil industry, hot spots, cold spots, leakage detection of flow lines and reservoirs, fire detection in tunnels, and mapping of cryogenic temperatures, just to name a few.

2.5 Strain Sensing Tape: SMARTape. When strain sensing is required, the optical fiber must be bonded to the host material over the whole length [3]. The transfer of strain is to be complete, with no losses due to sliding. Therefore an excellent bonding between the strain optical fiber and the host structure is to be guaranteed. To allow such a good bonding, it has been recommended to integrate the optical fiber within a tape in the similar manner as the reinforcing fibers are integrated in composite materials. To produce such a tape, we selected a glass fiber reinforced thermoplastic with polyphenylene sulfide (PPS) matrix. This material has excellent mechanical and chemical resistance properties. Since its production involves heating to high temperatures (in order to melt the matrix of the composite material) it is necessary for the fiber to withstand this temperature without damage. In addition, the bonding between the optical fiber coating and the matrix has to be guaranteed. Polyimide-coated optical fibers fit these requirements and were therefore selected for this design.

The typical cross-sectional width of the thermoplastic composite tape that is used for manufacturing composite structures is in the range of 10–20 mm and therefore not critical for optical fiber integration. The thickness of the tape can be as low as 0.2 mm, and this dimension is more critical since the external diameter of polyimide-coated optical fiber is approximately 0.145 mm. Hence, only less than 0.03 mm of the tape material remains on top or bottom of the optical fiber, with the risk that the optical fiber will emerge from the tape. The scheme of the sensing tape cross section, with typical dimensions, is presented in Fig. 4.

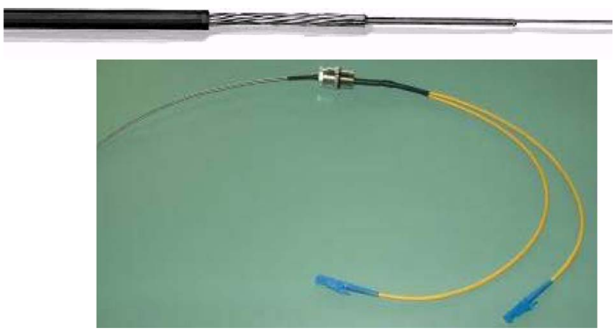


Fig. 3 Extreme temperature sensing cable design and termination

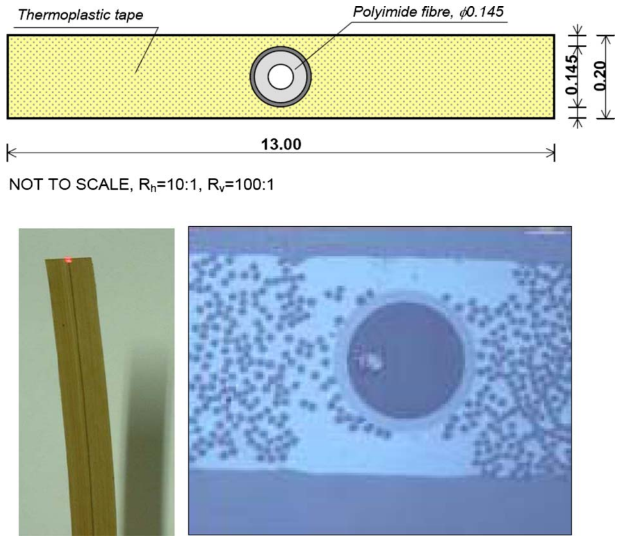


Fig. 4 Cross section picture and micrograph of the sensing tape (SMARTape)

The use of such sensing tape (called SMARTape) is twofold: it can be used externally, attached to the structure, or embedded between the composite laminates, having also a structural role.

2.6 Combined Strain and Temperature Sensing: SMARTprofile. The SMARTprofile sensor design combines strain and temperature sensors in a single package.

This sensor consists of two bonded and two free single mode optical fibers embedded in a polyethylene thermoplastic profile. The bonded fibers are used for strain monitoring, while the free fibers are used for temperature measurements and for compensating temperature effects on the bonded fibers. For redundancy, two fibers are included for both strain and temperature monitoring. The profile itself provides good mechanical, chemical, and temperature resistance. The size of the profile makes the sensor easy to transport and install by fusing, gluing, or clamping. The SMARTprofile (see Fig. 5) sensor is designed for use in environments often found in civil, geotechnical, and oil and gas applications. However, this sensor cannot be used in extreme temperature environments or environments with high chemical pollution. It is not recommended for installation under permanent UV radiation (e.g., sunshine).

3 Pipeline Monitoring Applications

In Secs. 3.1–3.4 we will introduce application examples showing how different pipeline monitoring tasks can be addressed with the presented system.

3.1 Leakage Detection in a Brine Pipeline. In 2002 the construction of a natural gas storage facility some 1500 m under the ground surface was started in the area of Berlin in Germany. Using mining technology the building of underground caverns for gas storage in large rock-salt formation requires hot water and produces large quantities of water saturated with salt, the so-called brine. In most cases the brine cannot be processed on-site and must be transported by a pipeline to the location where it can either be used for chemical processes, or injected back safely into the ground. Because the brine can be harmful for the environment, the pipeline shall be monitored by a leakage detection system.

In the Berlin project a 55 km pipeline was built and the company GESO was selected for the development and the installation

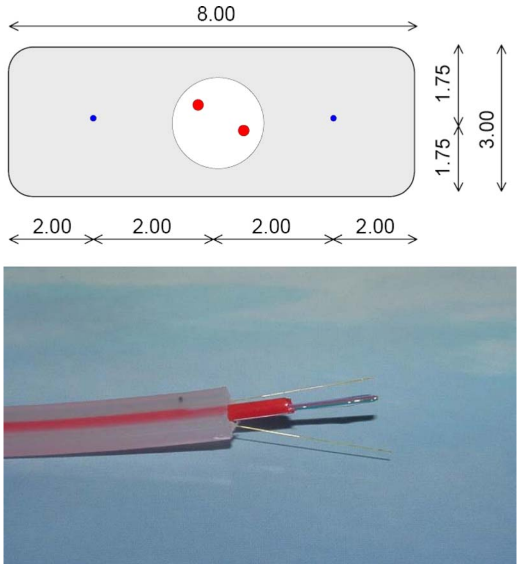


Fig. 5 SMARTprofile cross section and sample. The red tube contains the free fibers.

Fig. 6 Construction phase of a buried brine pipeline in the north-east area of Berlin. The fiber optics cable is placed in the sand at the 6 o'clock position about 10 cm underneath the pipeline [4].

of the leakage detection system [4]. In order to cover the whole pipeline distance, it was decided to use two DiTeSt analyzers, although one instrument would have been theoretically able to cover the whole distance with its two channels. However the installation of the fiber cable required some 60 splices (that correspond to an additional loss of up to 3 dB), which reduces the distance range of the instrument accordingly and justifies the use of two instruments, since the range extender technology was not yet available.

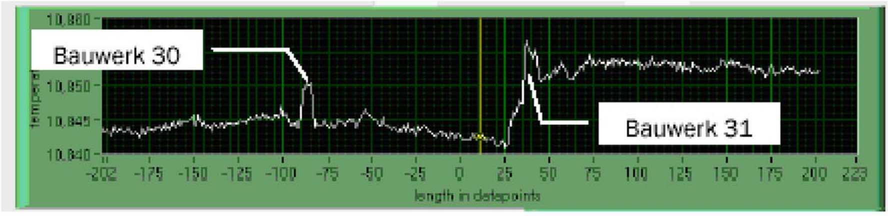
During the construction phase the temperature sensing was first placed in the trench and buried in the sand some 10 cm underneath the pipeline. The pictures in Fig. 6 show the construction of the pipeline before and after the pipeline was put in the trench.

The temperature profiles measured by both DiTeSt instruments are transferred every 30 min to a central PC and further processed for leakage detection. A dedicated software performs the leakage detection through a comparison between recorded temperature profiles, looking at abnormal temperature evolutions and generating alarm in the case of the detection of a leakage. The system is able to automatically transmit alarms, to generate reports, to periodically reset and restart measurements, and requires virtually no maintenance.

The pipeline construction phase was completed in November 2002, and the pipeline was put into operation in January 2003. In July 2003, a first leakage was detected by the monitoring system. It was later found that the leakage was accidentally caused by excavation work in the vicinity of the pipeline. Figure 7 shows the occurrence of the leakage and its effect on the temperature profiles showing a local temperature increase of 8°C. An alarm was immediately and automatically triggered and the flow was eventually stopped.

3.2 Gas Pipeline Monitoring. About 500 m of a buried 35 year old gas pipeline, located in Italy, lie in an unstable area. Distributed strain monitoring could be useful in order to improve vibrating wire strain gauges monitoring actually used in the site. The landslide progresses with time and could damage pipelines up to be put out of service. Three symmetrically disposed vibrating wires were installed in several sections at a distance of typically 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 could only provide local measurements.

Temperature profile before leakage



Temperature profile when the leakage is detected

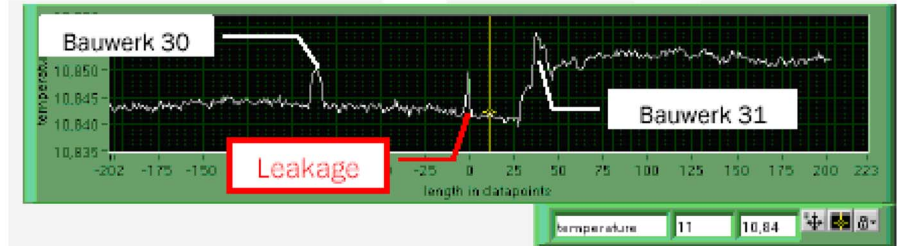


Fig. 7 Measured profiles before and after the leakage [3]

Fig. 8 SMARTape on the gas pipeline

Different types of distributed sensors were used: SMARTape and temperature sensing cable. Three parallel lines, constituted of five segments of the SMARTape sensor, were installed over the whole concerned length of the pipeline (see Fig. 8). 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 deg, 120 deg, and −120 deg, approximately. The strain resolution of the SMARTape is 20 microstrains, with a spatial resolution of 1.5 m (and an acquisition range 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 on the upper line (0 deg) of the pipeline in order to compensate for the strain measurements for temperature. The temperature resolution of the sensor is 1 °C with the same 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 read from this point using a single DiTeSt reading unit. Since the landslide process is slow, the measurements sessions are performed manually once a month. In case of an earthquake a session of measurements is performed immediately after the event. All the measurements obtained with the DiTeSt system are correlated with the measurements obtained with vibrating wires. At present stage, the sensors have been measured for a period of 2 years, providing interesting information on the deformation induced by

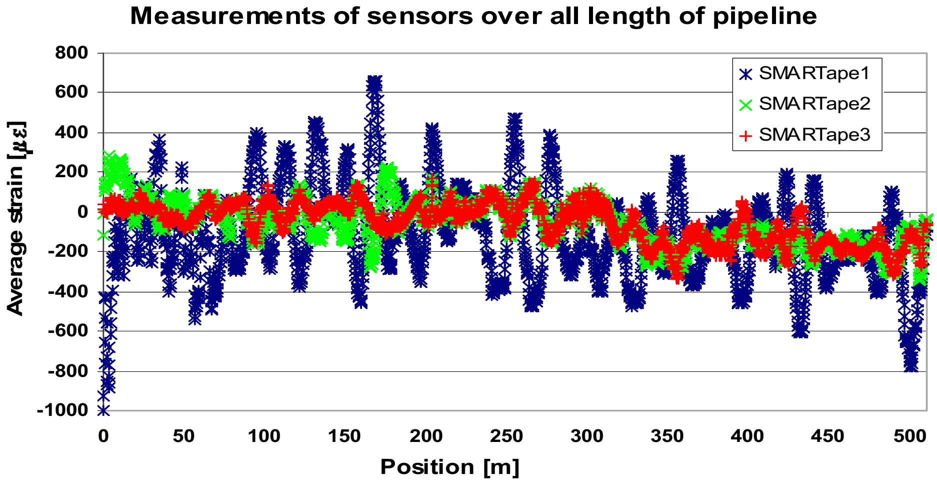


Fig. 9 Strain distribution over the monitored part of the pipeline measured by SMARTape sensors

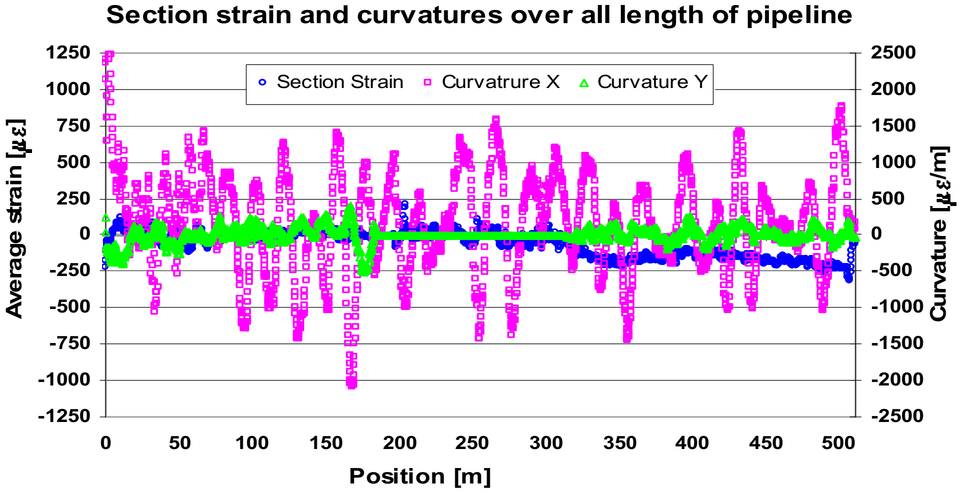


Fig. 10 Cross-sectional strain and curvature distributions measured by SMARTape sensors

Fig. 11 Leakage simulation test

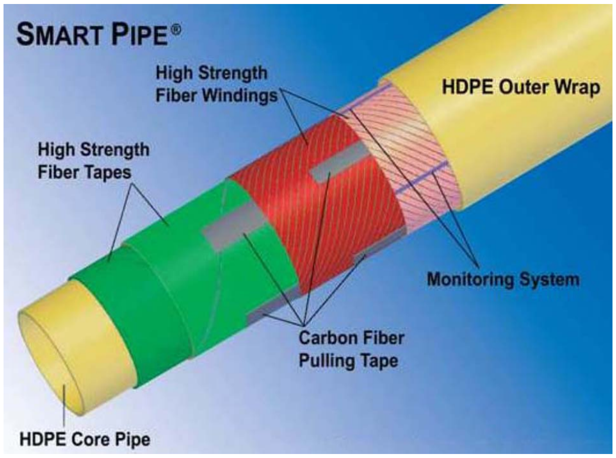


Fig. 13 SmartPipe design, including SMARTprofile monitoring system

burying and by the landslide progression. A gas leakage simulation was also performed with success using the temperature sensing cable.

During the work, 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 therefore deformed. The pipe cross sections located on the supports have been subject to negative bending (traction at the top part), and the section between the supports to positive bending (traction at the bottom part). The maximal allowed strain in the elastic domain is 1750 $\mu\varepsilon$, and maximal curvature without normal forces 5303 $\mu\varepsilon/\mathrm{m}$. The diagram showing the strain distribution over the entire length of the pipeline after the burring measured by SMARTapes is presented in Fig. 9. The normal cross-sectional strain distribution and the curvature distribution in the horizontal and vertical planes are calculated from the measurements and are presented in Fig. 10.

During the placement of the sensors and the burring of the pipe, an empty plastic tube was installed connecting the upper part of the pipe with the surface, 50 m from the beginning of the first monitored segment. This tube was used to simulate a leakage of the gas. Carbon dioxide was inserted into the tube, cooling down the pipe end due to pressure relaxation, and making the thermal conditions surrounding the contact between the pipe and the tube similar to conditions expected in case of leakage. This process is presented in Fig. 11.

A reference measurement was performed before the tube was cooled down. After the carbon dioxide was inserted, the temperature measurements were performed every 2–10 min and compared with the reference measurement. The results of the test are presented in Fig. 12. The test was successful and the point of simulated leakage was clearly observed in diagrams (encircled area in Fig. 12).

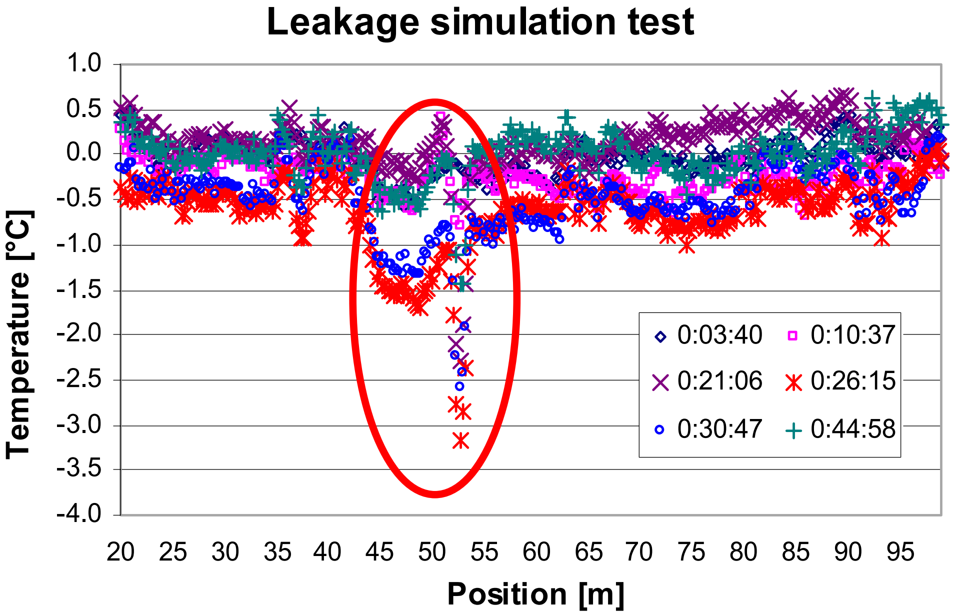


Fig. 12 Results of leakage test; leakage is detected as temperature change

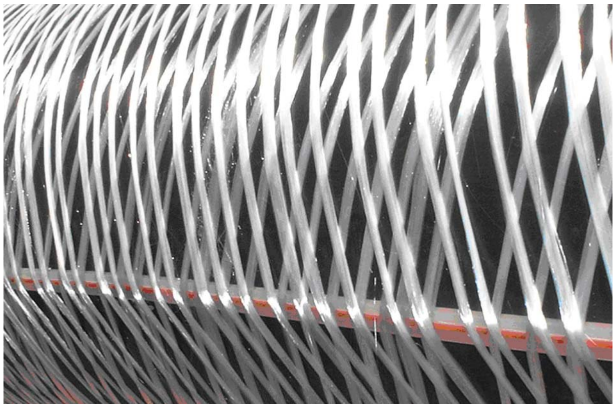


Fig. 14 SMARTprofile integration with high-strength fiber windings

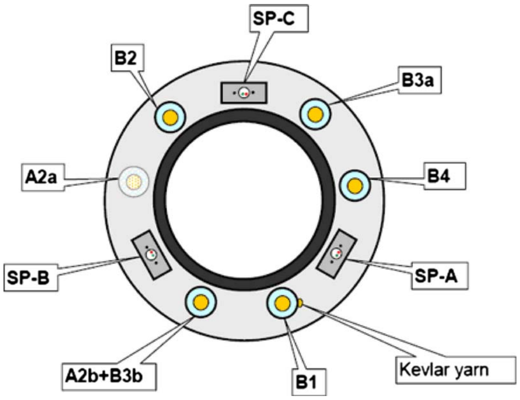


Fig. 15 PDT-coil cross section. The fiber optics sensing SMARTprofiles are designated by SP-A, SP-B, and SP-C.

3.3 Composite High-Pressure Pipe Monitoring: Smart Pipe. Smart Pipe is a high-strength light weight monitored reinforced thermoplastic pipe that can be used for the rehabilitation of an existing pipeline, or as a stand alone replacement. The key feature of the technology that underlies Smart Pipe is the use of ultrahigh-strength fibers that are wrapped onto a high density polyethylene core pipe (see Fig. 13). Through the selection of the fibers, the lay angles, and their sizes, Smart Pipe can be specially tailored for any given condition in terms of design pressure, pull-in length (for a rehabilitation), and safe operating duration.

In urban and environmentally sensitive areas, it delivers significant savings in the costs of access to and permitting for difficult locations using its trenchless installation methods. It is simultaneously manufactured and installed as a tight fit liner in up to 50,000 ft of an underground pipeline without any disruption of the surface areas covering the pipeline (except for a small opening at the entry and exit points of the pipeline section being lined). It can restore the subject pipeline to its full pressure service rating, renewing the projected service life of the subject pipeline to like new or better than new condition, and in most cases does so without reducing the flow rates through the line despite the nominal reduction in the inside diameter of the pipeline that occurs due to the presence of the liner.

The integrated SMARTprofile sensors (see Fig. 14) provide the operator of the pipeline with continuous monitoring and inspection features to assure safe operation of the line throughout the renewed operating life of the pipeline and to provide compliance with the regulations now emerging under the various pipeline safety acts.

3.4 Composite Coiled Tubing Monitoring. 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 the year 2000.

The project aims to solve these problems by researching and developing a high-temperature, corrosion, and fatigue resistant thermoplastic power and 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.

The PDT-coil consists of a functional liner containing the elec-

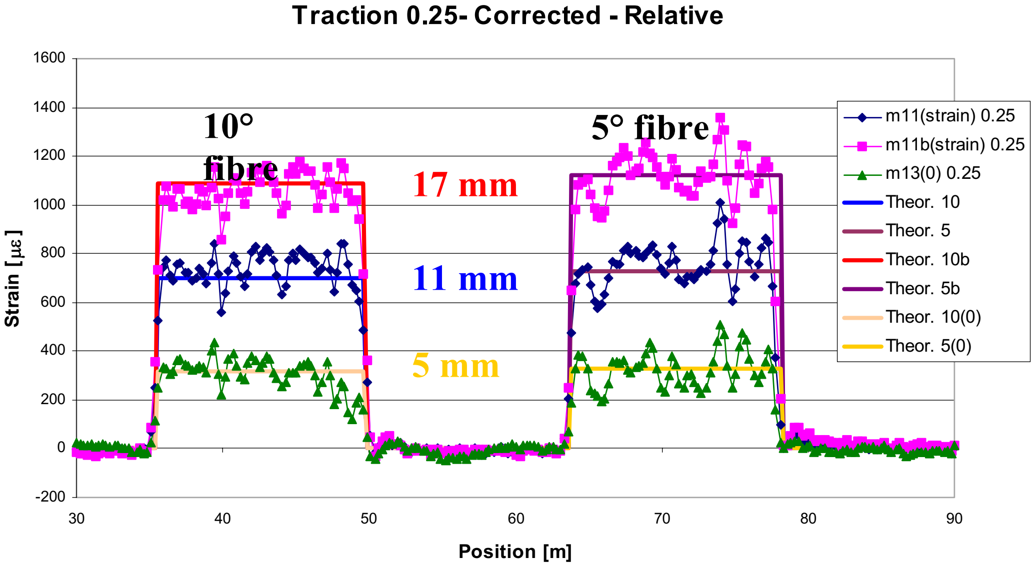


Fig. 16 Results of the traction test and comparison with theoretical prediction

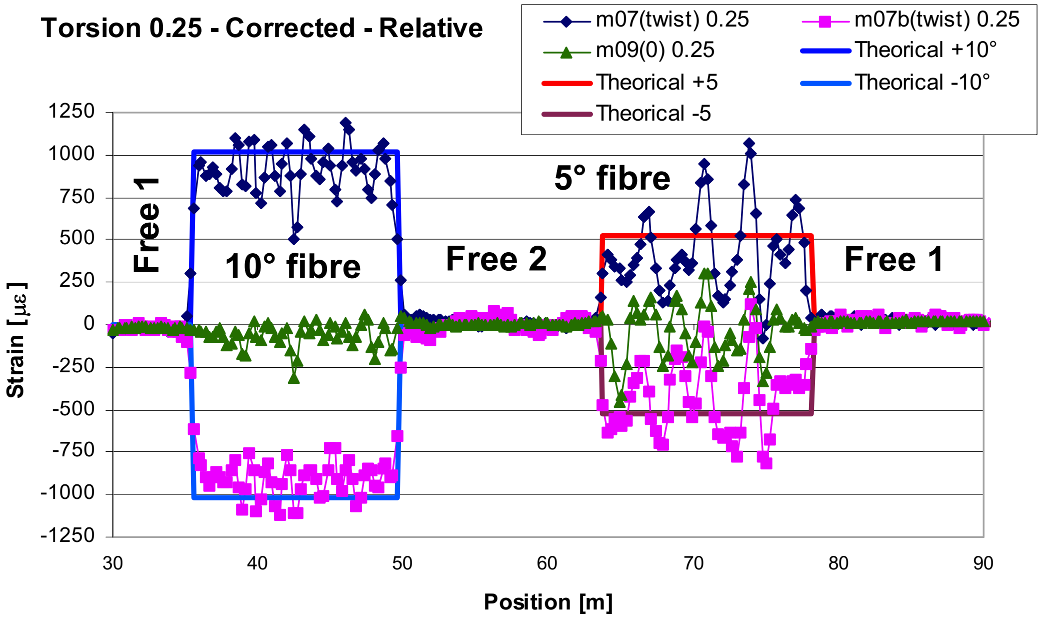


Fig. 17 Results of the torsion test and comparison with theoretical predictions; higher winding angles provide more sensitivity and accuracy for torsion measurements

trical and the optical conductors and a structural layer of carbon and glass fibers embedded in high performance thermoplastic polymers. The electric conductors provide electric power for electric submersible pumps or electric drilling motors. A 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 and to monitor the structural integrity of the PDT-coil, and can be used for data transmission (see Fig. 15).

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 15 m long section of polyethylene liner with integrated strain sensing fibers. The diameter of the tube was 56 mm. Four optical fibers were installed with the angles of -2.5 deg, -5 deg, 5 deg, and 10 deg with respect to the tube axis, in order to evaluate the performance of fibers installed with different angles. Two sensors with angles of -5 deg and 10 deg 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.

The results of this test confirmed the excellent performance of the DiTeSt reading unit, providing a resolution compatible with the requirements (better than $\pm 30\ \mu\varepsilon$) and a short measurement time (better than 5 min). Resolution of temperature was better than 1°C. As examples, the results of traction and torsion tests are presented in Figs. 16 and 17.

To test the temperature sensing capabilities of the PDT-coil sensing system, a 150 m section of integrated liner was heated by injecting different levels of current in the electrical conductors, as shown in Fig. 18.

Figure 19 shows the recorded temperature profile for different current levels. It can be noticed that the temperature is not constant along the liner, since one part of the liner was in direct contact with the metallic winding drum that acted as a heat sink, while further sections were wound on a second layer that was essentially surrounded by air and therefore thermally insulated. In real applications the PDT-coil tubing would be cooled by the fluids circulating inside and outside the pipe [5].

4 Conclusions

The use of distributed fiber optic monitoring system allows continuous monitoring and management of pipelines, increasing

Fig. 18 Liner heating test by electrical current injection

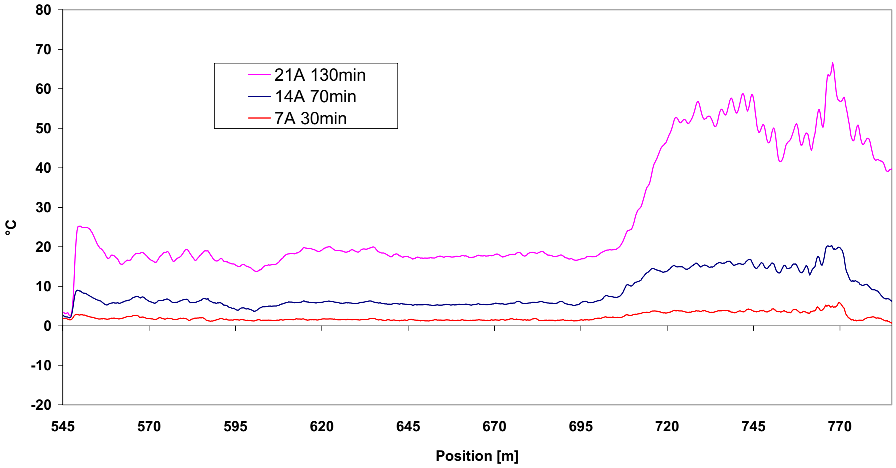


Fig. 19 Liner temperature changes for different current levels and heating times. The first 545 m of the optical fiber are not integrated into the liner and not shown.

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 different types of information on the pipeline state and conditions. In particular a distributed fiber optic system allows the following monitoring tasks.

Distributed temperature monitoring. Allows the measurement of the temperature profile along the pipe and therefore of the temperature changes in the transported fluid. This information can be used for optimizing operational parameters and for identifying and locating the hydrate, ice, and wax accumulations. These may be detected by sensing changes in temperature on either side of the accumulation.

Leakage detection. Through the identification of temperature anomalies, it is possible to detect and localize leakages of small entity, which cannot be detected by conventional volumetric techniques. Furthermore, the ability to pinpoint the exact location of the leak allows an immediate reaction at the event location, minimizing downtime and ecological consequences.

Intrusion detection. Based on a similar approach, focusing on localized strain and temperature changes, the presence and location of an accidental or intentional intrusion can be detected. This enables preventive action before the intruder can damage the pipeline.

Distributed strain and deformation monitoring. Provides information on the strain evolution 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, allowing an intervention before a real damage is produced. This is a useful tool for pipeline management and for on-demand maintenance. Distributed strain monitoring also has the potential of detecting wall-thickness changes along the pipe, resulting from corrosion or abrasion.

In general, distributed strain/deformation and temperature sensing is a useful tool that ideally complements the current monitoring and inspection activities, allowing a more dense acquisition of operational and safety parameters. The measurements are performed at any point along the pipeline and not at specific positions only. 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 nonpiggable pipes.

Recent developments in distributed fiber sensing technology allow the monitoring of 60 km of pipeline from a single instrument and of up to 300 km with the use of optical amplifiers. To achieve the above-mentioned goals and take full advantage of the described sensing technology, it is however fundamental 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. In some cases it is even possible to use existing fiber optic telecommunication lines installed along a pipeline for temperature monitoring and leakage detection.

Acknowledgment

The authors would like to thank Dr. Grosswig at GESO, Germany, Mr. Milani at SNAM Rete Gas, Italy, Mr. Catha and Mr. Stringfellow at Smart Pipe, and the PDT-coil project partners (Airborne, Netherlands; SHELL, Netherlands; Swiss Federal Institute of Technology, Zurich, High Voltage Laboratory; and University of Leuven, MTM Department, Belgium) for their significant contribution to the results presented in this paper.

They would also like to extend their gratitude to the personnel at Omnisens for their help and support in the use of the DiTeSt system and at Smart Pipe for the effective cooperation.

References

[1] Thévenaz, L., Niklès, M., Fellay, A., Facchini, M., and Robert, Ph., 1998, "Truly Distributed Strain and Temperature Sensing Using Embedded Optical Fibers," SPIE Conference on Smart Structures and Materials, Vol. 3330, pp. 301–314.

[2] Niklès, M., Briffod, F., Burke, R., and Lyons, G., 2005, "Greatly Extended Distance Pipeline Monitoring Using Fibre Optics," *Proceedings of OMAE05, 24th International Conference on Offshore Mechanics and Arctic Engineering*, Halkidiki, Greece, Jun. 12–17.

[3] Glisic, B., and Inaudi, D., 2003, "Sensing Tape for Easy Integration of Optical Fiber Sensors in Composite Structures," 16th International Conference on Optical Fiber Sensors, Nara, Japan, Oct. 13–17, Vol. 1, pp. 291–298.

[4] Niklès, M., Vogel, B., Briffod, F., Grosswig, S., Sauser, F., Luebbecke, S., Bals, A., and Pfeiffer, T., 2004, "Leakage Detection Using Fiber Optics Distributed Temperature Monitoring," 11th SPIE Annual International Symposium on Smart Structures and Materials, San Diego, CA, Mar. 14–18.

[5] Thévenaz, L., Facchini, M., Fellay, A., Robert, Ph., Inaudi, D., and Dardel, B., 1999, "Monitoring of Large Structure Using Distributed Brillouin Fiber Sensing," *13th International Conference on Optical Fiber Sensors*, Kyongju, Korea, Vol. 3746, pp. 345–348.