Comparative Study of Distributed Sensors for Strain Monitoring of Pipelines

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ABSTRACT: Natural calamities such as landslides, sinkholes, and earthquakes, as well as man-induced events such as vandalism and terrorist acts, can cause significant deformation and damage to pipelines with potentially devastating humanitarian, social, economic, and ecologic consequences. Therefore, a real-time assessment of the condition of pipelines during and after such events is crucial. Distributed fibre optic technologies are ideal candidates for monitoring pipelines, due to their large spatial range, and relatively small spatial resolution. Nevertheless, practical manufacturing and implementation of distributed strain sensors, as well as their response to various actions is not yet fully understood. The aim of this paper is to compare performances of different distributed fibre optic strain sensors in terms of strain transfer quality, costs, and implementation approaches. Comparison is made qualitatively, based on experience, and quantitatively, through large-scale testing, by simultaneously exposing different sensors bonded on the pipeline wall and embedded in the soil in its proximity, to various levels of artificially induced permanent ground movement.

KEYWORDS: Distributed fibre optic strain sensors, Pipeline monitoring, Strain and deformation monitoring, Strain transfer, Large-scale testing

1. INTRODUCTION

Distributed sensor (frequently referred to as sensing cable) can be described as a single cable containing one or more sensing optical fibres which are sensitive at every point along the length of the cable. Hence, in terms of measurement capability, one distributed sensor can replace large number of discrete sensors. Important advantage of distributed sensor over the discrete ones is that former can continuously cover entire length of a structure or part of the structure, thus offering reliable, direct damage detection (Yao and Glisic, 2012). In addition, distributed sensor requires single connection cable to communicate with the reading unit, instead of a large number of individual connecting cables required in case of wired discrete sensors. For monitoring of large structures distributed sensors could be less difficult and more economic to install and operate. Finally, optical fibre is chemically inert, i.e., insensitive to corrosion and ageing, but also electrically passive (only light is transmitted), which makes is particularly suitable for applications that require durable, long-term stable, and intrinsically safe sensing (e.g., applications in oil and gas industry).

In the domain of fibre optic sensors (FOS), three main principles that enable distributed sensing are: Rayleigh scattering (e.g. Posey et al., 2000), Raman scattering (e.g. Kikuchi et al., 1988) and Brillouin scattering (e.g. Kurashima et al., 1990). Raman scattering allows only temperature monitoring, while Rayleigh and Brillouin scattering enable both strain and temperature monitoring. Both spontaneous (Wait and Hartog, 2001) and stimulated (e.g., Nikles et al., 1997) Brillouin scattering can be used for sensing purposes. Stimulated Brillouin scattering is particularly advantageous as it tolerates high cumulative optical losses that may occur in sensing optical fibres due to manufacturing and installation of distributed sensors, which allows for monitoring of exceptionally large lengths (e.g., Thevenaz et al., 1999).

While there is a lot of research going on in terms of reading unit capabilities (e.g., Lopez-Gil et al., 2016, Preter et al., 2017, etc.) and applications (e.g., Inaudi and Glisic, 2010, Feng et al., 2016, Maraval et al., 2017, etc.), there is considerably less publications that target development and assessment of distributed sensors. Consequently, manufacturing and implementation implications of distributed strain sensors, are frequently not fully understood. The aim of this paper is to identify and compare characteristic performances of different distributed fibre optic strain sensors, as they pertain to pipeline applications. Identification and comparison are made qualitatively, based on manufacturing and implementation properties, and quantitatively, through large-scale laboratory testing of sensors installed on real-size pipeline and embedded in neighbouring soil. Three types of available distributed strain sensors properties were evaluated and compared. While the tested set of sensor is certainly not exhaustive, it reflects well the typical properties of distributed sensors that have to be assessed in order to understand and interpret the measurement of distributed sensors in general.

2. QUALITATIVE ASSESSMENT OF DISTRIBUTED SENSORS

2.1 General

Basic sensing element of distributed sensor is optical fibre. Due to fragility, it would not be practical to install optical fibre directly to the structure in large-scale applications and real-life conditions. To enable safe handling, installation, and long-term protection, optical fibre is commonly embedded or inserted in a special packaging (e.g., Inaudi and Glisic, 2006). Examples of distributed sensors with different packaging that are evaluated in this paper are given in Figure 1: thermoplastic glass-fibre reinforced composite tape (Tape sensor), polyethylene profile with embedded loose tube (Profile sensor), and co-axial plastic loose tubes with tight spacing (Cord sensor).

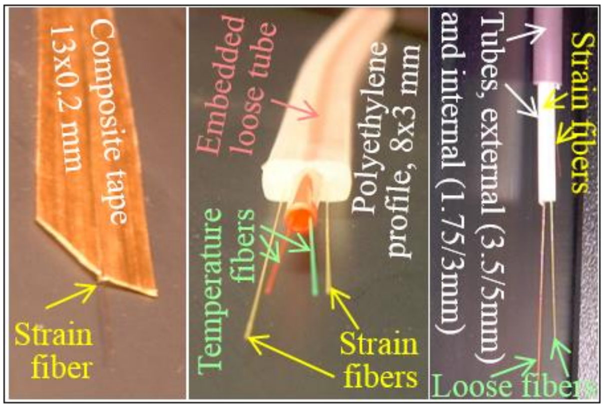

Figure 1 From left to right: Tape, Profile and Cord sensors

By adding the packaging, the strain measurement performance of distributed sensor is adversely affected in several ways, and trade-offs have to be made, depending on project requirements. The effects of packaging are presented in the next subsections.

2.2 Strain transfer / survival of damage

2.2.1 Strain transfer

The accuracy in strain measurement of packaged distributed sensors depends on the quality of the strain transfer from the structure to the strain sensing optical fibre. Several works in the past addressed this issue analytically and experimentally (e.g., Ansari and Libo, 1998, Calderon and Glisic, 2012, Her and Huang, 2016, etc.). Figure 2 schematically summarizes the challenges in strain transfer.

Figure 2 shows that the strain is transferred from the structure either through adhesive (for sensors installed externally) or by friction, with or without mechanical interlocking (for sensors embedded in material, e.g., concrete or soil). In the former case, the material of packaging has to be chosen so that an adhesive compatible with both this packaging and the material of host structure could be identified. In the latter case, material of packaging should have very high friction coefficient with respect to the host material, or the geometry of packaging should be made so that it enables good interlocking with host material.

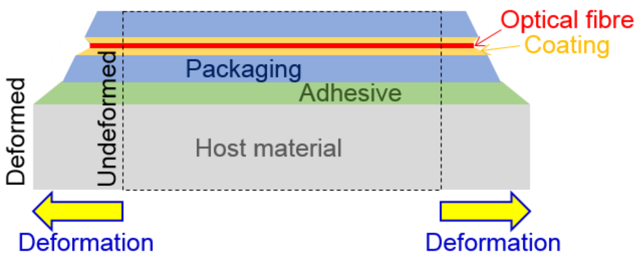

Figure 2 Schematic representation of strain transfer from host material to optical fibre for bonded sensors (not to scale)

Once the strain is transferred from the host material to the packaging, it "travels" through the layers of the packaging until it is transmitted to the coating of optical fibre. This implies that thickness and stiffness of the packaging play important roles. In general, thin and stiff packaging (e.g., Tape sensor in Figure 1) is preferable compared to thick and soft packaging (e.g., Profile sensor in Figure 1). Stiffness of the packaging should not be excessively high because this may affect the strain field in host material.

Finally, strain is transferred from the packaging to the optical fibre through the optical fibre coating. Two main types of coating found on the market are made of acrylate and polyimide. Polyimide is proven to better transmit the strain than acrylate (Glisic and Inaudi, 2007), and that is why polyimide-coated optical fibres are recommended for the best strain transfer. The disadvantage of the polyimide-coated optical fibres is in laborious splicing procedure due to difficult removal of coating and about order of magnitude higher market cost compared to acrylate-coated optical fibre, which makes sensors containing polyimide-coated optical fibres more expensive to manufacture and repair.

Tape sensor consists of polyimide coated optical fibre with external diameter of 0.145 mm embedded in thermoplastic glass-fibre reinforced composite tape with rectangular cross-section of 13x0.2 mm (Glisic and Inaudi, 2003). The process of embedding guarantee an excellent bond between the composite tape and optical fibre, i.e., excellent strain transfer from the packaging to the fibre. The thickness of the tape only slightly exceeds the diameter of optical fibre, which minimize the "travel path" of the strain from the host structure to the optical fibre and sustain good strain transfer. In addition, Tape sensor is stiff due to glass-fibre reinforcement of composite packaging, which also sustains good strain transfer. In conclusion, Tape sensor is expected to ensure high quality of strain transfer; however, the Tape sensor is relatively expensive due to use of polyimide coated fibres and demanding manufacturing process. In addition, manufacturing process introduces micro-bending in optical fibre, which results in high cumulative optical losses.

Profile sensors consists of two polyimide coated optical fibre with an external diameter of 0.145 mm embedded in polyethylene profile with rectangular cross-section of 8x3 mm (Inaudi and Glisic, 2006). The process of embedding guarantees a good bond between the profile and the optical fibre, however, due to low frictional properties of polyethylene, the strain transfer is not perfect, i.e., it is less good than in the case of Tape sensor. This is particularly the case for higher levels of strain, where fibre might slide within the profile. A loose tube containing two strain-free fibres is embedded within the profile (see Figure 1). These two fibres can be used for temperature monitoring or as guides of optical signal. Profile sensor is expected to be less good in strain transfer than Tape sensor; however, it still features moderately good strain transfer which is sufficient for most applications (e.g., see Figure 3), contains two strain fibres (i.e., redundancy), and contains two strain-free fibres. In addition, it is less expensive per fibre and manufacturing process results in significantly less cumulative losses generated in strain fibres.

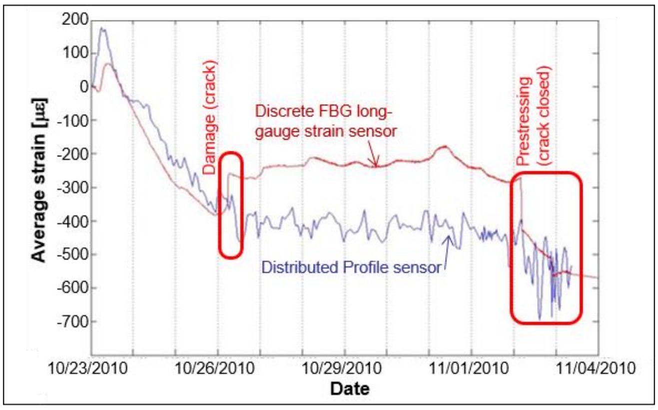

Figure 3 Comparison between measurements of Profile sensor and embedded Fibre Bragg-Grating long-gauge strain sensor at location of cracking in concrete deck of a real bridge (both sensors are embedded)

The Cord sensor (Glisic and Yao 2012) consists of two plastic tubes, the inner and the outer, each containing two optical fibres (see Figure 1). The inner tube contains two strain-free fibres having the same purpose as in the case of Profile sensor. The two other acrylate-coated optical fibres are placed between the inner and the outer tube, and are in mechanical contact with both tubes (they are practically "squeezed" between the tubes). Hence, if the strain is transferred from the host structure to the outer tube, the latter will transmit the strain to the fibres by friction. Once the friction resistance is exceeded, the fibres will slide between the tubes, and re-engage after the sliding. Thus, the strain transfer is less good than in the case of the Profile sensor. The use of acrylate-coated fibres as well as simple manufacturing process makes this type of sensor inexpensive, with negligible cumulative optical losses. Two strain fibres and two strain-free fibres provides redundancy and possibility of temperature monitoring.

2.2.2 Survival of damage to structure

While an excellent strain transfer from the host structure to sensing optical fibre is desired for accurate strain measurements in a relatively large strain range, excessive localized strain in the fibre (higher than 1 to 1.5%) due to damage to structure (e.g., cracking of concrete, permanent ground movement of soil, etc.) can actually damage the fibre and consequently, partially or completely disable the sensor. Four main approaches could be considered to mitigate the risk of damaging the strain sensing optical fibre, and combinations of these solutions can be used on-site, depending on project requirements.

For surface installation of sensors, which requires the use of adhesive (see Figure 2), two solutions are possible, depending on the type of packaging. First solution involves the sensors with stiff packaging (e.g., Tape sensor, see Figure 1). In that case the adhesive for sensor installation should be chosen so that it guarantees good strain transfer to sensor, yet its shear bonding strength is weakenough to enable sensor to delaminate from the surface of the monitored structure over limited length (e.g., 10-20 cm) in case of localized damage (e.g., cracking). This delamination enables localized strain in optical fibre to redistribute over longer (delaminated) length, which lowers the maximal strain in fibre, and in turn enables the fibre to survive the damage to structure. This principle was proven in real-life settings (e.g., Glisic et al., 2007).

In the case of soft-packaged sensor (e.g., Profile and Cord sensors, see Figure 1), the above described principle would not function; in these cases it is recommended to use strong but soft (flexible) adhesive. The drawback of using soft adhesive is that the quality of strain transfer will be lower; however, due to lower quality of strain transfer the localized strain (e.g., due to cracking of monitored structure) will be redistributed thought the thickness of adhesive, which will "shield" the packaging and the strain sensing fibre from exposure to high localized strain and enable its survival. Damage survival tests performed using soft glue to bond electrical sensors with soft polyimide packaging confirmed viability of this approach (e.g., Gerber and Glisic, 2017). Note, that stiff adhesive can still be used, if packaging enables redistribution of the high strain through its thickness or by release of bonding with strain sensing fibre, as explained in the paragraph below.

For embedded sensors, mitigation strategy depends on the host material, i.e., of the magnitude of excessive strain that can occur due to damage. In case of concrete, internal cracking will result in high localized strain, but redistribution of this strain over relatively short length would solve the problem. There are several strategies on how this redistribution can be made: (i) by release of friction between the sensor packaging and host material, (ii) by redistribution through the thickness of the packaging (e.g., in the case of Profile sensor), (iii) by release of bonding between the strain sensing optical fibre and the packaging (e.g., in the case of Profile and Cord sensors, see Figure 1), or by combination of two or three of above strategies. For example, in the case of embedded Profile sensor, given that its body is thick and made of soft polyethylene, it will sustain the strategy (ii) above. In addition, polyethylene is in general low-friction material, so it has potential to sustain strategies (i) and (iii). In fact, Figure 3 shows that an embedded Profile sensor survived internal cracking of concrete by combination of the strategies (i)-(iii). Measurements performed by discrete Fibre Bragg-Grating long-gauge strain sensor and Profile sensor at location of cracking are shown in the figure. More details regarding this comparison is given in the literature (Glisic et al., 2011).

Finally, if the damage of monitored structures produces very large strain (e.g., permanent ground movement of soil), none of the above presented methods would be sufficient to ensure survival of the sensing optical fibre in the packaging with moderate to high quality of strain transfer, such as Tape and Profile sensors. In the case of Cord sensor, strain fibres can survive much higher strain, and in addition loose fibres can be used as qualitative strain indicators, as shown in Figure 4.

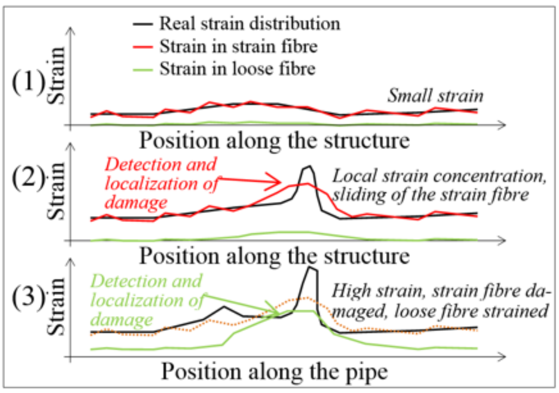

Figure 4 Schematic representation of the principle of functioning of Cord sensor

For Cord sensor, the strain from host structure will be transferred to optical fibres as follows. Small strain, up to certain limit, is transferred to the strain fibres by friction between the outer tube and the fibres, as long as there is no sliding between the tube and the fibres; "small" strain will not affect loose fibres. When the strain locally exceeds the frictional limit, the sliding will occur between the strain fibres and the outer tube, the strain transfer will not be fully guaranteed and the strain measurement will be locally inaccurate; however, detection and localization of damage, i.e., identification of the point where the excessive strain occurred will be possible, while the sliding prevents the strain fibres from damaging. In addition, for very high strain, the strain fibres may be damaged, but then the extra length of strain-free fibres will be exhausted, and they will take the role of (qualitative) strain fibres.

2.3 Redundancy / temperature measurements

Depending on the type of reading unit (which depends on the physical principle used), distributed sensors can be measured in single-ended or loop configuration. Single-ended configuration might or might not require mirror at the end of the fibre. These three configurations are schematically represented in Figure 5. For example, reading unit based on Brillouin Optical Time Domain Analysis (BOTDA) requires loop configuration or single-ended configuration with a mirror, while the reading unit based on Brillouin Optical Time Domain Reflectometry (BOTDR) or Rayleigh backscattering would require single-end configuration without a mirror.

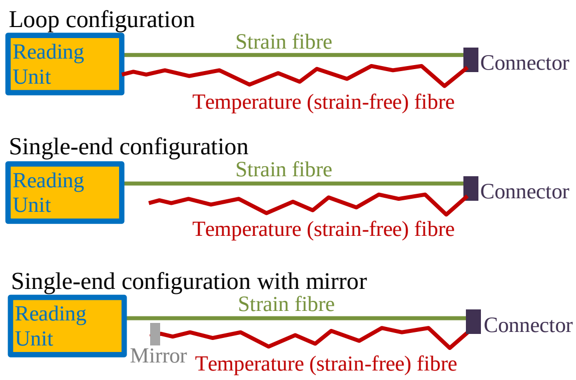

Figure 5 Schematic representation of the fibre configurations in distributed sensing; the two fibres can be integrated in the same physical sensor (e.g., Profile and Cord sensor) or in two different physical sensors (e.g., Tape sensor and additional temperature sensor)

Temperature changes affect both the properties of optical fibres as well as the strain in the host structure. Therefore, they must be monitored to compensate the influence on optical fibre and determine thermal strain in the host structure. Temperature is usually monitored using strain-free fibres, i.e., optical fibres that are, with certain over-length, placed into a tube that ensures their mechanical uncoupling with the structure. Depending on the inner diameter, the tube can store only limited over-length of the lose fibre. Thus, very large strains and deformations can extend or contract the tube so that the strain-free fibres become tensioned or compressed.

Tape sensor contains only one strain fibre and if that fibre is damaged the sensor will become partially or completely non-functional, depending on the sensor configuration. Hence, Tape sensor has no redundancy. In addition, a supplementary sensor is needed for temperature monitoring purposes, which requires additional costs in terms of material and installation. Given that the temperature sensor has to be separately provided, the inner diameter of the tube with strain-free fibres could be chosen so that it satisfy project requirements.

Profile and Cord sensors each contains two strain fibres which provides redundancy. In addition, each contains tube with strain-free fibres for temperature monitoring which simplifies and lowers the costs of installation. In addition, for large strain and deformation monitoring, strain-free fibres could be used for damage detection in extended strain range, as per Figure 4. The limitation of these two sensors in terms of temperature monitoring is pre-defined size of inner diameter of tube with strain-free fibres, which limits the over-length of stored fibres, and limits the range of measurable temperature.

2.4 Handling / ease of installation

The packaging of the sensor should enable simple and easy handling, deploying, installing, and repairing of the sensor. Due to long length, sensors are usually delivered on spools, and thus they have to be unspooled before installation. This may lead to excessive tensioning or twisting (torsion) of the sensor, which in turn can result in damage or malfunction of sensor. Tape sensor is very strong axially due to glass-reinforcing fibres in its packaging, and thus excessive tension would not damage it; however, due to very thin cross-section which barely covers the sensing optical fibre, it is less resistant to twisting, which can result in delamination of optical fibre from the packaging and failure of the fibre. Profile sensor is somewhat opposite of Tape sensor: lack of reinforcement makes it less strong in tension, but its thick cross-section provides it with good twisting resistance. Finally, Cord sensor has a good resistivity to both excessive tension and twisting, mostly due to the fact that the strain fibres can slide between tubes.

From the point of view of installation, all three sensors can be bonded (glued) to structure of interest. Tape and Profile sensor have particularly advantageous shape of the cross-section (rectangular), which provide larger contact surface and requires less glue between the sensor and the structure. This results in potentially better strain transfer than for sensors with round cross-section. In addition, rectangular cross-section guarantees that no residual twisting is present in the sensor at time of installation.

In addition to installation by bonding, sensors can be embedded in soil or concrete. To enable this, the packaging must be able to protect the sensing optical fibre from burying / pouring works and to guarantee good strain transfer to the fibre. Hence, Tape sensor might not be appropriate for this type of installation. Its weakness in twisting may lead to damage during burying / pouring works, while its high axial stiffness may resist good strain transfer, especially if embedded in soil, whose stiffness is orders of magnitudes lower than that of the sensor.

In the case of both bonding and embedding, the sensors must be slightly pre-tensioned in order to get desired shape. However, it is important to note that excessively tensioning the sensors, besides the damage to sensors discussed above, may put in tension temperature fibres e.g., for Profile and Cord sensors. If the temperature fibres are put in tension, they will not be strain-free and thus, they will not measure temperature accurately.

From the point of view of repair, easiness of repair depends on easiness of extraction of optical fibre from the packaging and type of coating of the optical fibre. All three types of sensors are relatively easy to extract from packaging; however, Tape and Profile sensors have polyimide coated strain fibres which makes them challenging to splice on site, while Cord sensor contains acrylate coated fibres that are relatively easy to splice on site.

Examples of sensors bonded to the concrete pipeline and being embedded in soil are shown in Figure 6.

2.5 Cumulative optical losses / spatial range of sensor

Commercial optical fibres have low losses, typically ranged between 0.1 and 0.5 dB/km, mostly depending on their type (single-mode or multimode), wavelength of light, chemical composition, and type of coating. Regardless the physical principle or manufacturer, the reading units for distributed sensors have limited "budget" of

Figure 6 Example of sensors bonded to pipeline (left and middle) and being embedded in soil (right)

tolerated cumulative losses, and this budget determines the spatial range of the sensor. For example, if the losses in pristine optical fibre are 0.4 dB/km and that budget of the reading unit is 20 dB, the max. spatial range of sensor using unaltered fibre would be 50 km.

By manufacturing sensors, the optical fibre does not remain unaltered – integrating fibre in Tape or Profile packaging involves bending and micro-bending of the fibre, which in turn increases distributed losses. In general, better strain transfer requires better mechanical contact between the packaging and the fibre and this leads to higher losses. For example average losses in Tape sensor are around 50 dB/km, which reduces the range of sensor to 400 m. Losses in Profile sensor are around 5 dB/km resulting in the range of sensor of 4 km. Cord sensor has losses that are slightly worse than pristine fibre so its range can reach 15-20 km.

In addition to distributed losses in optical fibres, isolated points of the sensor can have significant localized losses. Losses of a typical splice are in the range between 0.1 dB to 1 dB. Similar losses are introduced by fibre optic connectors. The fusion splice has losses rather around value of 0.1 dB, and is therefore better suited for the applications that are on the limit of the optical budget of the reading unit. For applications that are well within the optical budget, connectors could be better solution despite higher losses, as splicing on-site could be challenging and time consuming. A sharp angle of sensor geometry or point pressure to sensor introduce additional localized losses. All these localized losses combine with distributed losses in sensor and affect the spatial range of sensor. Hence, all sources of losses should be well accounted when selecting monitoring system and planning the installation of sensors, and monitored for quality purposes using Optical Time Domain Reflectometer (OTDR) during and after installation.

2.6 Cost

The cost of the distributed sensors is in general correlated with the quality of strain transfer and cost of packaging. Higher quality strain transfer requires polyimide coated strain fibres and more elaborate packaging, and hence the cost is higher per strain sensing fibre. In the case of three sensors analysed in this paper, Tape sensor is the most expensive per fibre (it has only one fibre), then follows Profile sensor, which is more expensive than Tape sensor in terms of length of the sensor, but it is less expensive per fibre, as it contain four fibres (two strain and two temperature fibres). Containing only one strain fibre, Tape sensor usually needs an additional temperature sensor to be installed in parallel for thermal compensation purposes, which would additionally increase the overall cost of material and installation. Cord sensor is the least expensive – its strain transfer quality is the lowest and packaging very simple to make.

3. ASSESSMENT OF DISTRIBUTED SENSORS THROUGH TESTS

3.1 Test description

The assessment of distributed sensors was performed within a project that researched methods for damage detection of buried concrete pipelines exposed to permanent ground movement. More detail on the broader scope of that project is found in (Glisic and Yao, 2012, Pour-Ghaz et al., 2018). Large-scale testing involving real-size pipeline was carried out at The Cornell Large-Scale Lifelines Testing Facility, the NEES site at Cornell University (Cornell NEES Site).

The testing site included a test basin in which a real-sized pipeline can be buried and exposed to controlled permanent ground movement. The basin width, depth and length were 3.4 m, 2.0 m, and 13.4 m, respectively. Approximately half of the basin was fixed, while the other half was mobile, and could be displaced using hydraulic jacks. The joint between the fixed and movable end enabled a transverse relative movement between the two ends oriented 50 degree relative to the longitudinal length of the basin. View to testing basin before and after the test is shown in Figure 7.

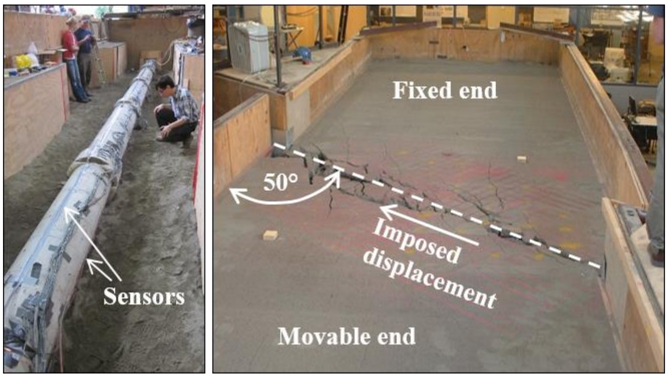

Figure 7 View to testing basin with pipeline before burying (left) and after the test is completed (right)

Two tests were performed. In each test a segmented concrete pipeline specimen consisting of five 2.4-m (8-ft) long segments were assembled using bell-and-spigot joints sealed by grout. Tape, Profile, and Cord sensors were bonded along the pipeline, while additional Profile and Cord sensors were embedded in soil parallel to the pipeline. View to sensors being bonded onto the pipeline and being embedded in the soil is given in Figure 6. Schematic view to the pipeline and the testing basin is given in Figure 7. General layouts of all sensors were similar in both tests, and they followed parallel topology scheme shown in Figure 8. Multiple sensors were installed on the pipeline with cross-sectional locations at 0°, 90°, and 270°, and multiple sensors embedded in soil at 0°, and 90° (see Figures 7 and 8).

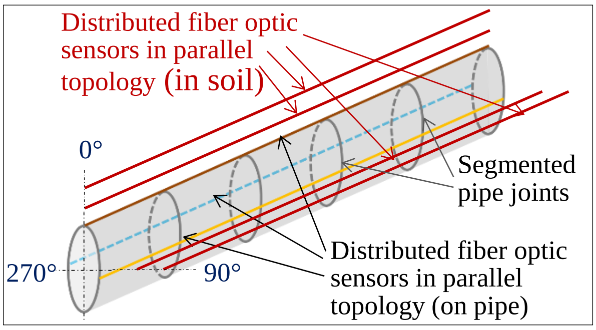

Figure 8 General layout of all sensors installed onto the pipeline

Once the sensors were bonded on the pipeline at desired locations, the basin was filled with soil to the half-depth of the pipeline's cross-section. Then the Profile and Cord sensors were laid and covered with soil. This procedure was repeated for sensors embedded at different depth. Once the burying of sensors and the pipeline was finished, the set-up was ready for tests.

The tests consisted of the basin's movable end being displaced in increments of 2.54 cm (1 in) until 30.8 cm (1 ft) was reached. Each increment of displacement simulated permanent ground movement and measurements were taken after each increment of movement was applied. The reading unit was based on BOTDA, spatial resolution was set to 1 m, sampling interval to 0.1 m and estimated resolution of strain measurement was 20 με (με=10^{-6}m/m).

The main aim of the tests was to assess the ability of distributed sensors to monitor deformed shape and detect the damage to pipeline due to permanent ground movement. Damage to segmented pipeline was expected to happen at the joints, as they are structurally the weakest part of the structure. Examples of crushed joints due to permanent ground movement are shown in Figure 9.

Figure 9 Examples of pipeline joints crushed during the first test

Detailed analysis of the tests is beyond the scope of this paper but is in available literature (Glisic and Yao, 2012, Pour-Ghaz et al., 2018). Thus, only results relevant for the topic of this paper are discussed. Measurements presented in the next subsection were not compensated for temperature as the tests were performed over short periods of time (approximately two hours per test) in laboratory with controlled (constant) temperature.

3.2 Typical test results for Tape sensor bonded to pipeline

Tape sensor was expected to have the best quality of strain transfer which was confirmed by the test. Tape sensor at location of 90° was able to monitor strain change in the pipeline due to bending. Quality of strain transfer was confirmed by comparison with strain-gauges installed along the pipeline approximately at the same cross-sectional position. Figure 10 shows the results of the measurements taken after the first movement increment of 2.54 cm (1 in) was applied. Gauge factor for Tape sensor in the figure is 0.001 GHz = 20 με (measurements non-compensated for temperature, calibrated by manufacturer).

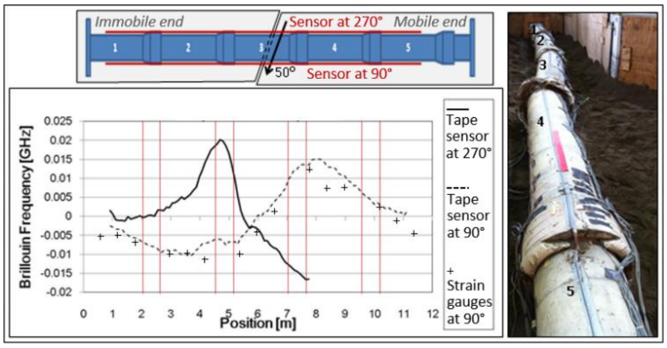

Figure 10 Measurements of Tape sensors at locations 270° and 90°, strain-gauge measurements at 90°, and their correlation with the deformed shape of the pipeline (second test; strain-gauge data available by curtesy of Prof. Jerome Lynch, University of Michigan, Ann Arbor, MI, USA).

The combination of Tape sensors installed at locations 270° and 90° provides the information about structural behaviour of the pipeline under the soil movement:

- Overall axial deformation of the pipeline is contraction;
- Bending is detected in the horizontal plane and deflected shape is qualitatively similar to deformed sinusoidal line;
- The inflection point (curvature change the sign) is approximately at the shear plane.

Tape sensor at location 270° measured tension left of shear plane and compression right of shear plane, while the sensor at location 90° had an opposite behaviour. The ability of Tape sensors installed in parallel topology to capture deformed shape of the pipeline was confirmed by the strain-gauges and visual inspection of the deformed shape after the excavation of the pipeline. This ability is due to high quality strain transfer enabled by Tape sensor packaging and the use of appropriate adhesive.

In addition to the ability to accurately monitor structural behaviour of the pipeline, Tape sensor was also able to detect the damage. Figure 10 shows the measurements taken during the first movement increment, and the peaks in measurements indicate two joints that are subjected to largest internal forces. By adding the movement increment, stresses at these two joints increased, and damage occurred at seventh increment (17.78 cm = 7 in). The damage was successfully detected as shown in Figure 11.

While Tape sensor demonstrated an excellent measurement performance, the tests showed room for improvements. Frequently, the sensor could not survive the initial damage to pipeline, as only one out of six sensors survived all 12 applied movement increments (including both tests). In many real-life applications survival of sensor after substantial damage to pipeline is not of importance as the pipeline is out of order and has to be repaired anyhow. Nevertheless, if damage is small, it is of interest to have sensor survived it, so that the progression of damage can be monitored. Hence, future research is needed to address this challenge.

3.3 Typical test results for Profile sensor bonded to pipeline

Profile sensor contains two strain fibres, but to simplify the presentation only measurements taken with one fibre are presented. For Profile sensor installed at 270° in the second test, the first fibre functioned properly until the 7th increment of the ground movement was applied, i.e., until the damage was generated. The second fibre functioned only through 6th increment. The results of measurement of the first fibre are given in Figure 11 along with measurements of Tape sensor installed next to Profile sensors (see Figure 6). Gauge factor for Profile sensors was the same as for Tape sensor, i.e., 0.001 GHz = 20 με (measurements non-compensated for temperature, calibrated by manufacturer).

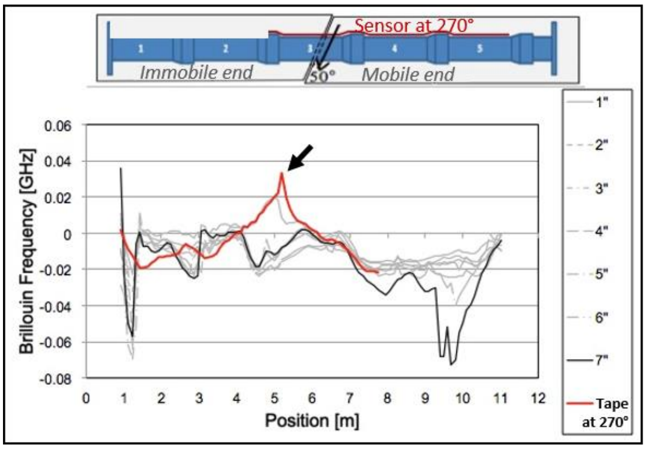

Figure 11 Measurement results of Profile sensor (for seven increments of ground movement) and Tape sensor (for seventh increment only) installed at location 270° (second test)

The first fibre of Profile sensor indicates strain changes at the location of joints #1 and #2 and qualitatively captures the overall structural behaviour of the pipeline. There is a general disagreement with the Tape sensor and strain-gauges installed at the same location. This indicates moderate strain transfer from the pipeline to the strain fibre of Profile sensor. Finally, this fibre which functioned properly during the damaging of the joint #2 did not actually detect the damage. Damage was successfully detected by the Tape sensor (shown with the arrow).

The second strain fibre of Profile sensor had a similar behaviour as the first one, however it got damaged before damage to pipeline due to installation issues. Since both strain fibres were placed at approximately the same location (belong to the same packaging), they were expected to measure very similar values, which was not the case for all points along the pipeline. Thus, the Profile sensor performance was not satisfactory and further improvements of this sensor are needed, both to improve strain transfer and survival after installation. In general, no Profile sensor survived all 12 increments of load in any of two tests (two sensors, four strain fibres in total).

3.4 Typical test results for Profile sensor embedded in soil

The strain fibres of Profile sensor installed in soil at location 270° survived all 12 increments of the applied ground movement. The measurement results are shown in Figure 12 for the first strain fibre (Glisic and Yao 2012).

Profile sensor successfully detected and localized failure of soil as pointed with black arrow in Figure 12. Noise in measurements was observed due to sliding of the sensor within the soil. The sliding resulted in stressing of the sensor at the extremity of the pipeline, due to sharp change in sensor geometry (pointed with grey arrow in Figure 12). Hence, the measurements have to be considered as indicative and their quantitative interpretation is challenging. The tests showed that the soil movement can be detected and localized using single measurement of Profile sensor; nevertheless, to avoid ambiguity, it is recommended to confirm the detection and localization by analysing time series of measurements instead of single measurement. All Profile sensors embedded in soil survived all 12 increments of imposed ground movement, indicating that, in overall, Profile sensor has very good performance for monitoring soil failure.

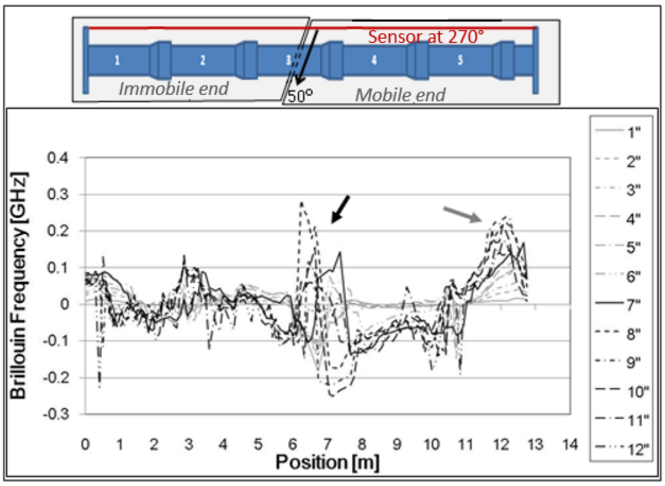

Figure 12 Profile sensor measurements at location 270° (in the soil) with detected failure of soil (second test)

3.5 Typical test results for Cord sensor bonded to pipeline

Cord sensor installed on the pipeline at location 0° (second test) survived all 12 increments of ground movement. The measurement results are shown in Figure 13. Four high strain areas were identified close to four pipe joints, as pointed with black arrows in Figure 13. Since the Cord sensor was installed on top of the pipeline, i.e., practically located at the neutral axis (for horizontal ground movement) it was not expected to be affected by the bending. The four high strain areas indicated in the figure are present practically since the first step of load, i.e. before the damage occurred. A potential explanation for this behaviour of the sensor is in the manner of installation: the sensor was left free at joints due to sharp change in geometry of the latter; therefore, it is possible that the soil movement locally influenced these areas and as a result, the four high strain zones are visible at the joints. This result is ambiguous and thus the manner of installation of Cord sensor onto the pipeline has to be improved. Its capability to detect the damage to pipeline was however confirmed in the first test, where the sensor was installed at 90° (Glisic and Yao 2012); however, the damage detection could not be inferred by observing single measurement, but rather time series of measurements had to be observed. This phenomenon is explained in detail in the next subsection.

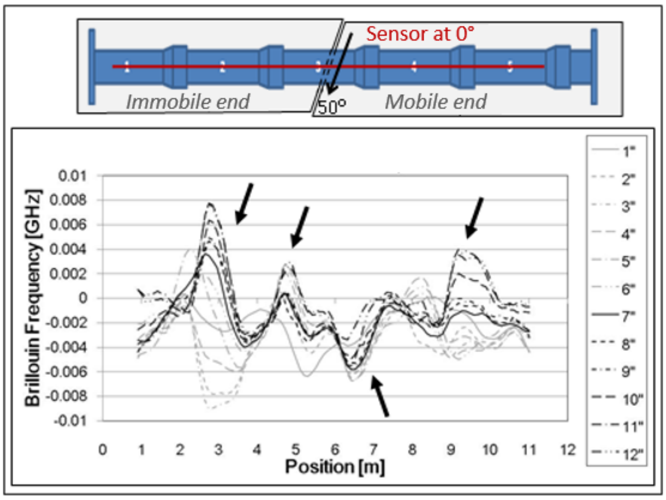

Figure 13 Cord sensor measurements at location 0°

3.6 Typical test results for Cord sensor embedded in soil

The Cord sensor embedded in the soil at location 270° survived all 12 increments of the imposed soil movement. The measurements are given in Figure 14. The figure shows that Cord sensor was able to detect and localize soil movements, as shown with black arrows. The behaviour of Cord sensor embedded in soil requires detailed explanations in order to be able to correctly interpret the data.

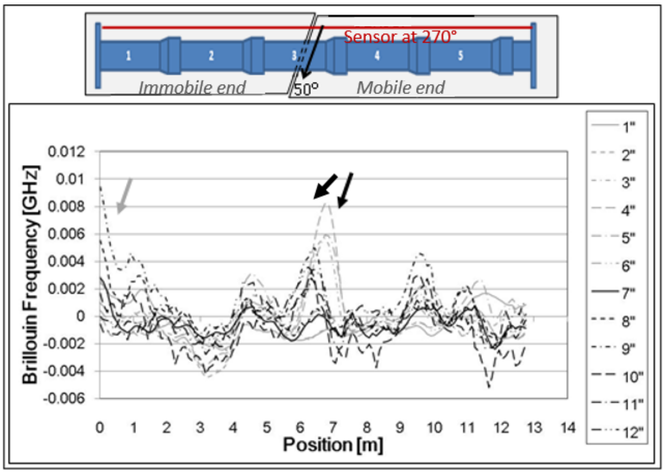

Figure 14 Cord sensor measurement at location 270° with detected soil failure

Cord sensor, by construction, has low quality of strain transfer. Once the maximal frictional force between strain fibres and inner and outer tube is exceeded, the strain fibres will slide between the tubes, and the measurement will show apparent relaxation of strain which is not true for the monitored soil. In addition, Cord sensor itself can slide within the soil. This, sliding created tensions at extremities of the Pipeline, as pointed with grey arrow. Due to both sliding of the fibres within the packaging and sliding of the entire sensor with respect to the soil, individual measurements are somewhat difficult to interpret. Hence, reliable detection and localization of the damage was possible only for higher values of ground displacement and by analysing the time series of the measurements (and not single measurement).

4. CONCLUSIONS

Distributed sensors have a unique capability of monitoring one-dimensional strain fields. These sensors can be installed along entire structure or along parts of a structure and to provide reliable direct damage detection and localization.

Three different distributed sensors, Tape, Profile, and Cord sensor were evaluated qualitatively and quantitatively. While the set of tested sensors was not exhaustive, it can be considered as representative as it included sensors with different strain-transfer qualities, mechanical robustness, and strain range.

Qualitative assessment was performed from the point of view of sensor components and included considerations regarding strain-transfer and damage-to-structure survival, redundancy and temperature measurement, handling and ease of installation, cumulative optical losses and spatial range of sensor, and cost.

Quantitative assessment focused on capability of sensors to describe structural behaviour of monitored structure and to detect and localize the damage. Two different materials and structures were monitored, segmented concrete pipeline and soil.

Analysis has shown that each sensor has advantages and limitations, and which sensor should be used depends on the application. As an example for accurate monitoring and damage detection of concrete pipelines, Tape sensors show the best performance, but it is the most expensive sensor. For soil monitoring both Profile and Cord sensor show good performance. Profile is more expensive, but damage detection can be inferred form a single measurement. Cord sensor is less expensive, but is not as reliable as Profile sensor and thus series of measurements have to be analysed to reliably detect the damage.

Given that all tested sensors have some advantages and limitations, combination of sensor could be suitable solution for specific projects, budget permitting. In addition, identified limitations of the sensors could be addressed in future research, which will lead to even more economic monitoring solutions.

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