Fiber optic sensing in an integrated Structural Health Monitoring system

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ABSTRACT: Designing a Structural Health Monitoring (SHM) system starts by identifying the risks associated with the specific structure and their probability. The risk analysis will lead to a list of possible events and degradations that can possibly affect the structure. Example of risks and uncertainties are corrosion, loss of pre-stressing, creep, subsidence of foundations, earthquake strike, unauthorized overloads, impact, inaccuracy of Finite Elements Models, poor building material quality and poor execution. The severity and probability of each risk will be classified using the usual risk analysis procedure to produce a ranking of risks. In this context, risks that are more likely to occur simultaneously or cascading will deserve special attention. Some risks will be retained, others will be addressed by regular inspection and the remaining will be dropped because of a low impact and/or probability. The result is a ranked list of risks that must be addressed by the SHM system.

1 INTEGRATED STRUCTURAL HEALTH MONITORING SYSTEMS

1.1 *Why structural health monitoring*

Complex structures like buildings, bridges, dikes, dams, tunnels and water, chemical or oil & gas pipelines are made of multiple elements and components that are stressed and interact with one another when exposed to external actions. Structures vary widely in size, geometry, structural system, construction material, and foundation characteristics. These attributes influence how a structure performs when overcharged or when under stress of natural events.

Structural Health Monitoring allows rapid assessment of a structural state of health and such approach is becoming recognized as a proper mean to increase the safety and optimize operational and maintenance activities. The data resulting from the monitoring program are used to improve the operation, the maintenance, the repair and the replacement of the structure based on reliable and objective data. Detection of ongoing damages can be used to discriminate deviations from the design performance. Monitoring data can be integrated in structural management systems and increase the quality of decisions by providing reliable and unbiased information.

The malfunctioning of significant structures can often have serious consequences. The most severe are failures involving human victims. Even when there is no loss of life, populations suffer if the structure is partially or completely out of service. The economic impact of structural deficiency is reflected by costs of reconstruction as well as losses in the other branches of the economy.

Learning how a structure performs in real conditions will help to design better structures for the future. This can lead to cheaper, safer and more durable structures with increased reliability, performance and safety.

The life of each structure is far from being monotonous and predictable. Much like our own existence, its evolution depends on many uncertain events, both internal and external. Some uncertainties arise right during construction, creating structural behaviors that are not predictable by design and simulations. Once in use, each structure is subject to evolving patterns of loads and other actions. Often the intensity and type of solicitation are very different from the ones taken into account during its design and in many cases they are mostly unknown in both nature and magnitude. The sum of these uncertainties created during design, construction and use poses a great challenge to the engineers and institutions in charge of structural safety, maintenance and operation.

In such a multi-hazard environment one hazard might trigger another as so-called domino effects that would stress the structure dramatically. Defining service levels and prioritizing maintenance budgets relying only on models and superficial observation can lead to dangerous mistakes and inefficient use of resources. Regular inspection can certainly reduce the level of uncertainty, but still presents important limitations being limited to the observation of the structure's surface during short times spaced by long periods of inactivity.

Structural Health Monitoring aims to provide more reliable and up-to-date information on the real conditions of a structure, observe its evolution and detect the appearance of new degradations. By permanently installing a number of sensors, continuously measuring parameters relevant to the structural conditions and other important environmental parameters, it is possible to obtain a real-time picture of the structure's state and evolution.

Instrumental Monitoring is a new safety and management tool that ideally complements traditional methods like visual inspection and modelling. Monitoring enables a quick reaction after event and even allows a better planning of the inspection and maintenance activities, shifting from scheduled interventions to on-demand inspection and maintenance (Del Grosso & Inaudi 2004).

1.2 *Monitoring strategies*

Each monitoring project presents its peculiarities and although it is possible to standardize most elements of a monitoring system, each application is unique in the way they are combined.

It is however possible to classify the monitoring components according to several categories:

- Scale: Local scale, Member scale, Global scale, Network scale
- Parameter: Mechanical, Physical, Chemical, Environmental, Actions.
- Periodicity: Periodic, Semi-continuous, Continuous.
- Response: Static or Dynamic.
- Data collection: None, Manual, Off-line, On-line, Real-time.

All these types of monitoring can be mixed and combined according to the specific need of the bridge under exam. This freedom requires a rigorous design to select the appropriate approach.

1.3 *System integration*

It is of fundamental importance that a monitoring system is designed as an integrated system, with all data flowing to a single database and presented through a single user interface. The integration between the different sensing technologies that can be simultaneously installed on the structure, e.g. fibre optic sensors, vibrating wire sensors, tilt meters, weather stations and corrosion sensors, can be achieved at several levels. Different sensors can be connected to the same datalogger; otherwise several dataloggers can report to a single data management system, typically a PC, which can be installed either on site or at a remote location (cloud based). The data management system must interface to all types of dataloggers and translate the incoming data into a single format that is forwarded to the database system as shown in Figure 1.

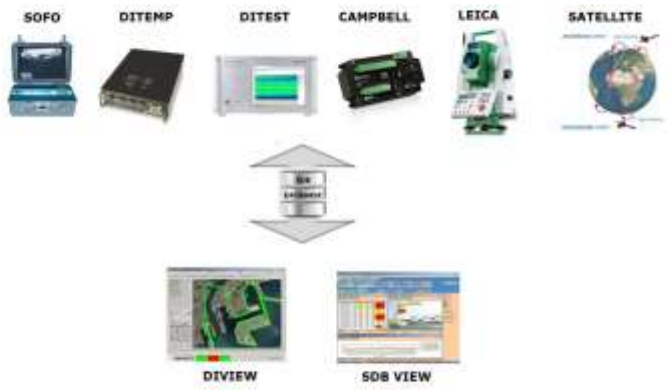

Figure 1. Integration of sensing technologies into a single database and user interface

Although many vendors of sensors and data acquisition systems provide their own software for data management and presentation, these tend to be closed system that can only handle data from their specific sensors. Since a monitoring project often requires the integration of several technologies, it is important to provide the end-user with a single integrated interface that does not require him to learn and interact with several different user interfaces.

2 IMPLEMENTATION OF SHM

2.1 *Benefits of SHM*

The benefits of having a Structural Health Monitoring system installed on a significant structure are many and depend on the specific application. Here are the more common ones:

- Monitoring reduces uncertainty
- Monitoring discovers hidden structural reserves
- Monitoring discovers deficiencies in time and increases safety
- Monitoring insures long-term quality
- Monitoring allows structural management
- Monitoring increases knowledge

2.2 *Designing and implementing an SHM system*

Designing and implementing an effective Structural Health Monitoring System is a process that must be carried out following a logical sequence of analysis steps and decisions. Too often SHM systems have been installed without a real analysis of the owner needs, often based on the desire to implement a new technology of follow a trend. These monitoring system, although perfectly working from a technical point of view, often provide data that is difficult to analyze or which cannot be used by the owner to support management decisions.

The 7-step procedure has proven over the years to deliver integrated structural health monitoring systems that respond to the needs of all parties involved in the design, construction and operation of structures of all kinds:

- Step 1: Identify structures needing monitoring
- Step 2: Risk analysis
- Step 3: Responses to degradations
- Step 4: Design SHM system and select appropriate sensors
- Step 5: Installation and Calibration
- Step 6: Data Acquisition and Management
- Step 7: Data Assessment

Unfortunately, this process is not yet formalized in the same way as for example the construction process, where codes, laws and regulations reduce the uncertainty and improve the interaction between the different actors involved in the process.

Recommendations and drafts codes for the implementation of SHM systems are however starting to appear; certainly an important step towards a mature SHM industry.

2.3 *SHM in practice*

To put the previous methodology in practice, we will now consider how it can be applied to design integrated structural health monitoring systems.

Table 1 discusses the typical expected responses and the candidate types of sensors to measure structural risks that are typically found and can be used as a starting point for a specific analysis pertaining to a given structure (Inaudi 2009).

Table 1. Design structural health monitoring system

Risk / uncertainty	Response / consequence *Sensors*
R1: Correspondence between Finite Element Model and real behavior	Strain distribution and magnitude different from model *Local strain sensors, including strain gauges, vibrating wire gauges and fiber optic sensors*
R2: Dynamic strain due to traffic, wind, earthquake, explosion…	Large strains, fatigue, cracks *Local strain sensors, including strain gauges, vibrating wire gauges and fiber optic sensors, with dynamic data acquisition systems. Distributed fiber optic crack sensors. Crack-meters*
R3: Creep, relaxation of prestress	Global deformations, bending *Long-gauge fiber optic strain sensors, settlement gauges, laser distance meters, topography*
R4: Correspondence between calculated and real vibration modes	Mode shapes and frequencies different from model *Accelerometers, long-gauge fiber optic strain sensors*
R5: Cracking of concrete or steel	Crack opening *Crack-meters: potentiometers, vibrating wire or fiber optic*
R6: Temperature changes and temperature gradients in load bearing elements	Strain redistribution, cracking *Temperature sensors: electrical fiber optic point sensors or distributed sensors*
R7: Differential settlement between foundations	Global movements, tilting, strain redistribution *Laser distance meters, topography, settlement gauges, tiltmeters*
R8: Change in water table or pore water pressure around foundations	Change in pore water pressure *Piezometers: vibrating wire or fiber optic*
R9: Change in concrete chemical environment; carbonatation, alkali-silica reaction, chlorine penetration	Corrosion of rebars *Concrete corrosion and humidity sensors*
R10: Environmental conditions	Actions on structure *Weather station, wind speed measurements*
R11: Construction schedule and specific actions	Difficulty in analyzing data *Webcam, image capture and archival*

3 APPLICATION EXAMPLES

3.1 *HDB buildings - Singapore*

The Housing and Development Board (HDB), as Singapore's public housing authority, has an impressive record of providing a high standard of public housing for Singaporeans through a comprehensive building program. As part of quality assurance of new HDB tall buildings, it was decided to perform long-term structural monitoring of a large number of new buildings. Currently more than 1’000 buildings, such as the one in Figure 2, have been instrumented and are regularly monitored. This monitoring project is considered as a pioneering project with two aims: to develop a global monitoring strategy for column-supported structures such as buildings, and to collect data related to the behavior of this buildings providing rich information concerning their behavior and health conditions. The monitoring is performed during whole lifespan of the building, from construction to the use. Thus, for the first time the sensors are used in a large scale life cycle monitoring of high-rise buildings.

Figure 2. Building from Housing and Development Board

The aims of monitoring are (1) increase of knowledge concerning the real structural behavior, (2) verify the construction process, (3) increase of safety during the service, (4) enhance maintenance activities and (5) evaluation of structural condition after risky events such as tremor (earthquake), strong wind or terrorist attack. The monitoring is performed at (1) local, column level and (2) global, structural level.

The ground columns have been selected for monitoring, being the most critical elements in the building. A total of ten long-gauge fiber optic sensors were installed by embedding in each construction block, as in Figure 3.

In Figure 4 the time-dependent evolution of the average strain in columns monitored during more than seven years with particularly important periods. 48-hours sessions allow better assessment of building performance (rheological effects) in long-term. The displayed measurement shows that the earth tremor from 2004 did not cause residual effect.

Figure 3. Long-gauge fiber optic sensor and junction box in a column before concrete pouring

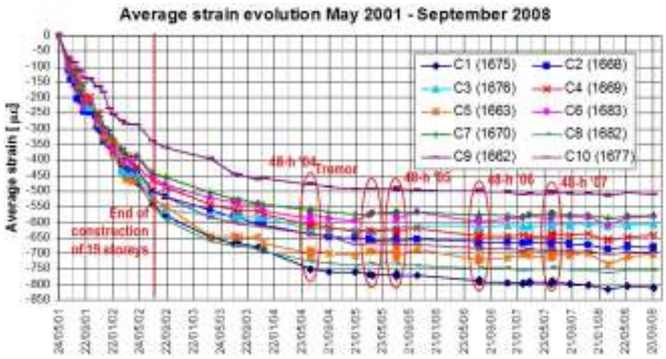

Figure 4. Average strain evolution May 2001-September 2008

3.2 *I35W Bridge in Minneapolis*

The collapse of the old I35W Bridge in Minneapolis in 2007 shook the confidence of the public in the safety of the infrastructure that we use every day. As a result, the construction of the replacement bridge (see Figure 5) must rebuild this confidence, by demonstrating that a high level of safety can not only be attained during construction, but also maintained throughout the projected 100-year life-span of the bridge (Russel, 2008).

One of the central factors contributing to this is the design and installation of a comprehensive structural health monitoring system, which incorporates many different types of sensors measuring parameters related to the bridge performance and ageing behavior.

This system continuously gathers data and allows, through appropriate analysis, to obtain actionable data on the bridge performance and health evolution. The data provided is used for operational functions, as well as for the management of ongoing bridge maintenance, complementing and targeting the information gathered with routine inspections (Inaudi & Church 2011).

Figure 5. View of the completed I35W St. Antony Falls Bridge

The monitoring system was designed and implemented through a close cooperation between the designer, the owner, the instrumentation supplier and University of Minnesota.

The main objectives of the system are to support the construction process, record the structural behavior of the bridge, and contribute to the intelligent transportation system as well as to the bridge security.

The design of the system was an integral part of the overall bridge design process allowing the SHM system to both receive and provide useful information about the bridge performance, behavior and expected lifetime evolution.

Monitoring instruments on the new St Anthony Falls Bridge measure dynamic and static parameter points to enable close behavioral monitoring during the bridge's life span. Hence, this bridge can be considered to be one of the first 'smart' bridges of this scale to be built in the United States.

The system includes a range of sensors which are capable of measuring various parameters to enable the behavior of the bridge to be monitored. Strain gauges measure local static strain, local curvature and concrete creep and shrinkage:

- Thermistors measure temperature, temperature gradient and thermal strain,
- Potentiometers measure joint movements,
- At the mid-spans, accelerometers are incorporated to measure traffic-induced vibrations and modal frequencies (eigenfrequencies).
- Corrosion sensors are installed to measure the concrete resistivity and corrosion current.
- Meanwhile there are long-gauge SOFO fiber optic sensors which measure a wide range of parameters, such as average strains, strain distribution along the main span, average curvature, deformed shape, dynamic strains, dynamic deformed shape, vertical mode shapes and dynamic damping. They also detect crack formation.

The sensors are located throughout the two bridges, the northbound and southbound lanes, and are in all spans. However, a denser instrumentation is installed in the southbound main span over the Mississippi river. This span will therefore serve as sample to observe behaviors that are considered as similar in the other girders and spans. The load test is presented in Figure 6.

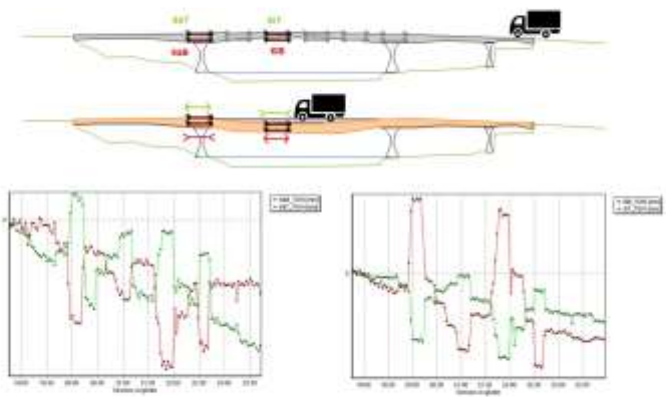

Figure 6. I35W load test with long gauge SOFO sensors

3.3 *I-Wall levee - New Orleans (US)*

The iLevees project "Intelligent Flood Protection Monitoring Warning and Response Systems", in the state of Louisiana, has the goal of providing an alerting and monitoring system capable of preventing early stage failure, both in terms of ground instability and seepage. The motivation for the monitoring system is to improve safety awareness, provide sensible information about levees' status and conditions, before, during and after floods, and to avoid the tragic events like the ones that occurred following Hurricane Katrina in 2005. The use of distributed fiber optic sensing will help in overcoming the issue of optimal sensor location allowing full structure coverage over several kilometers. The continuous long-term monitoring during the complete levee lifetime will allow for the collection of data that can improve our general knowledge of these structures, with unquestionable benefits in future levee designs, operation and maintenance.

The project had the goal to monitor the levee wall, deformation and shear, and the surrounding soil, movements and water infiltration / seepage.

The particularity of the project was the installation technique adopted for the levee wall integration. In order to provide a good transfer of the acting forces from the wall to the sensor itself a good bonding strength shall be given: to do this it was decided to “cut” a groove all along the installed section, where the sensing cable was deployed and sealed by means of specific episodic resins.

For the surrounding soil a more common ground embedding technique was chosen on the base of our previous returns of experience. Sensors are embedded between 0.5 and 1 m below the ground level, after compacting the trench, the sensors are deployed and covered with soft filling material. After this operation the trench is back-filled and compacted. Installation details are presented in Figure 7.

Figure 7. Installation of sensor in a groove, on top of the levee wall section and in a trench

An example of calculated deformation on the sensor placed on the top of the wall section I presented in Figure 8. Deformation is plotted as a function of position along the wall and as a function of time.

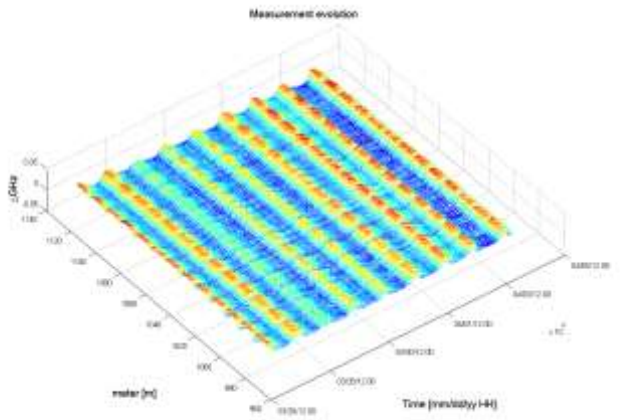

Figure 8. Recorded deformations on a levee wall as a function of position and time

In the plot it is possible to observe the daily expansion-contraction cycles of the wall due to temperature fluctuations. It is also possible to localize the expansion joints along the levee wall that shows a different behavior. In case of an event along the levee section, a localized deformation peak will appear in the visualization software and would automatically trip an alarm.

3.4 *Penstock movement monitoring project - Nendaz (CH)*

The penstock of an important mountain dam in the Swiss Alps is subject to rock mass movements that can influence its mechanical performance (Jordan & Papilloud 2015).

In order to provide a safe installation, the penstock is made of several pipe sections welded together in order to form a more flexible pipe, thus allowing a higher degree of movement.

Nevertheless a deformation monitoring system is necessary to detect any abnormal penstock deformation and penstock curvature. In addition to this, the penstock access tunnel is also affected by concrete cracking due to the water pore pressure and rock movements. A distributed strain monitoring system was selected because of its capability to monitor long lengths through a single cable, thus simplifying installation. A different installation technique is chosen for the 2 different sections: in the penstock, where precise and accurate monitoring under water is required, the sensing cable with flat profile is directly glued on the internal surface. The steel penstock is sand-blasted to offer a smooth and clean installation surface where 510 m, linear length, of sensing cable is glued along 4 different lines, as illustrated Figure 9.

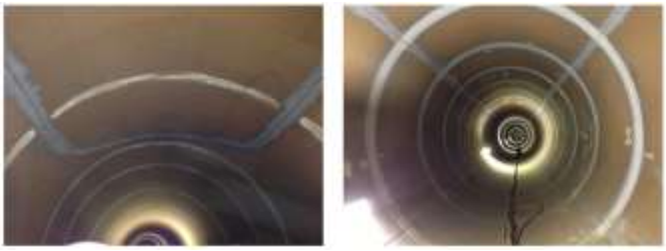

Figure 9. Strain sensing cable installation inside the penstock

On the other hand, for the access tunnel a mixed installation technique was selected: sensing cable was directly glued on concrete for most of its length, but fixed with stainless steel bracket where wide cracks were already visible and developing; this decision was taken in order to preserve sensor from breaking in case the crack keep developing, Figure.10. This installation technique allows a precise and accurate monitoring over the whole length of this tunnel of approximately 70 m.

Figure 10. Strain sensing cable installation on penstock access tunnel

After 3 years of monitoring the collected results are in line and good agreement with the mathematical predictions and other geo-matic measurements provided by additional monitoring systems installed at site.

A typical example of strain distribution measured in the penstock access tunnel clearly shows the location of open developing cracks, peaks can be seen and easily localized along the sensing cable length, Figure 11.

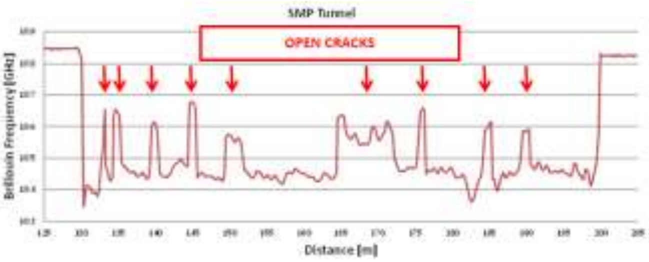

Figure 11. Strain distribution measured along the penstock access tunnel

3.5 *Gas pipeline deformation monitoring (IT)*

Flowlines laid in the areas exposed to potential landslides can be deformed by the ground movement and damaged up to be put out of service. Since many years SNAM RETE GAS, Italy, has developed a very effective technology for pipeline control in landslide areas based on the use of vibrating wire strain gauges to measure the stresses induced on the pipeline by the ground movements. Three symmetrically disposed vibrating wires are installed in sections at a distance typically of 50/100 m chosen as the most stressed ones according a preliminary engineering evaluation. These sensors were very helpful, but could not fully cover the length of the pipeline and only provide local measurements. In order to monitor the pipelines over longer lengths the distributed sensing systems is more adequate. This is why it was decided to equip a 500 m long segment of a buried gasline “La Bonina”, located near Rimini (Italy) and laying in parallel with a landslide, with a distributed strain sensing system, Figure 12.

Figure 12. Strain sensing cable installation

The strain sensing cable with flat profile is fixed to the whole monitored length of the pipe (Glisic et al. 2003). The position of sensing cable in respect to the pipeline axis is 17°, 103° and -103° approximately, Figure 13.

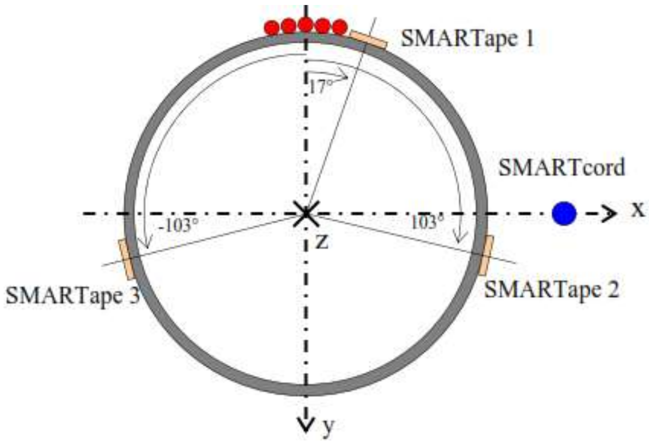

Figure 13. Position of sensors in pipe cross section

During the works 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 burying, 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 με, and maximal curvature without normal forces 5303 με/m. The diagram showing the strain distribution over all the length of the pipeline after the burying measured by SMARTapes is presented in Figure 14.

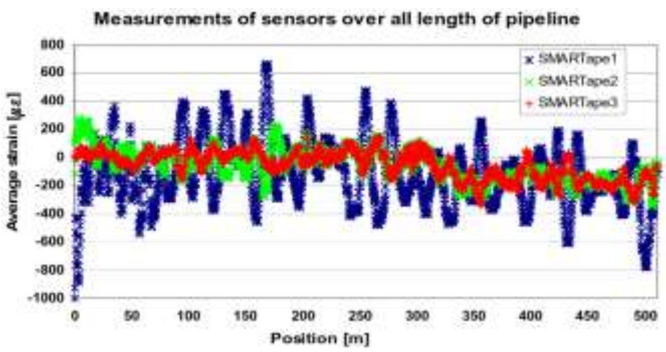

Figure 14. Strain distribution over the monitored part of the pipeline measured by SMARTape sensors

The normal cross-sectional strain distribution as well as the curvature distribution in horizontal and vertical plane are calculated from the measurements and presented in Figure 15.

The SMARTape 1, installed in the top of the cross-section, Figure 13, shows the traction at supports and compression in the mid-spans, with average amplitude varying from ±250 to ±500 με. The SMARTapes 2 and 3 installed symmetrically below the neutral axis and closer to it, Figure 13, show proportionally less strain (variations of ±120 με) and variations that have the same periods but opposite sign to the measurements of SMARTape 1.

Cross-sectional normal strain is very low, Figure 15, since the burying does not activate axial forces, except in the last 150 m where the slope of the terrain is higher. Vertical curvatures are considerable and are ranged between ±250 and ±750 με/m, exceeding ±1000 με/m in few points. Horizontal bending is very low, which is in accord with the fact that burying provokes only vertical bending.

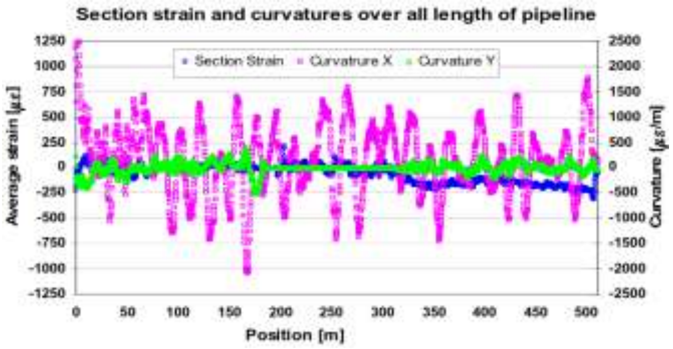

Figure 15. Cross-section strain and curvatures distribution measured by SMARTape sensors

As an example of the evolution of structural shape, the pipe curvature distribution in horizontal plane is presented for the Segment 2, Figure 16. The August session is used as reference. The length of the segment is 110 m approximately and, after the burying, only small changes are observed in the first 80 m confirming stable strain state in the pipe. However, last 30 m, close to the point where the gasline changes the direction, are subject to curvature change of 250 με/m, which corresponds to a bending moment of approximately 58 kNm. The range of the curvature change is far from the plastic domain, but the future development will be observed with attention and sources of the bending will be more examined.

The structural health monitoring system enables damage assessment of buried structures due to geohazard like earthquakes, landslides and surface subsidence result into ground movement. Monitoring design based on risk analysis will define the quantity and position of sensing cable to install. A simplified installation method is to install the sensing cable in parallel to the pipeline and directly into the ground, in order to easily cover greater length, and resulting in a lower strain sensitivity. Main advantage of distributed sensing for this application is to cover long stretches of pipe.

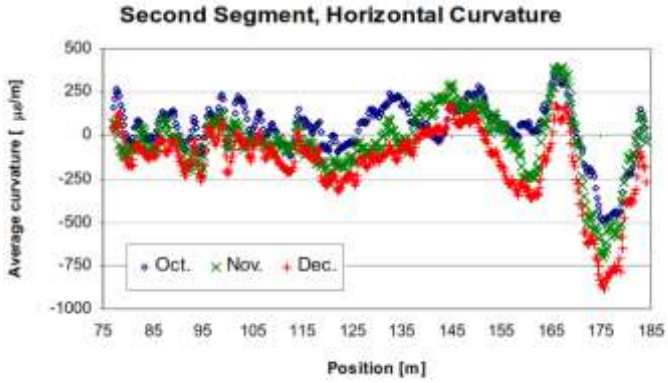

Figure 16. Evolution of horizontal curvature distribution in the Second segment of the pipe (76 – 185 m)

4 CONCLUSION

As for any engineering problem, obtaining reliable data is always the first and fundamental step towards finding a solution. Monitoring structures is our way to get quantitative data about our structures and help us in taking informed decisions about their health and destiny. This paper has presented the advantages and challenges related to the implementation of an integrated structural health monitoring system, guiding the reader in the process of analyzing the risks associated with the construction and operation of a specific structure and the design of a matching monitoring system and data analysis strategy.

5 REFERENCES

Del Grosso, A. & Inaudi, D. 2004. *European perspective on monitoring-based maintenance*, IABMAS International Association for Bridge Maintenance and Safety, Kyoto, Japan

Inaudi, D 2009. *Integrated structural health monitoring systems for buildings*, Stanford, USA

Inaudi, D. & Church, J. 2011. *Paradigm shifts in monitoring levees and earthen dams: distributed fiber optic monitoring systems*, Proceedings, 31st USSD Annual Meeting & Conference, San Diego, California, USA

Jordan, A & Papilloud E. 2015. *Penstock structural health monitoring*, Hydro 2015, Session 19 Gates and penstock, Bordeaux, France

Glisic et al. 2003. *Health monitoring of a pipeline based on distributed strain and temperature measurements.*