Deployment of an optical sensing system for monitoring an underground water supply pipeline

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ABSTRACT: The present study concerns a fibre Bragg grating (FBG) based structural monitoring system installed on a water supply pipeline in Sydney, Australia. This paper presents the details of the implemented monitoring system including hardware and software. It discusses the use of FBG optical technology, that was chosen due to its advantages in the water-filled pressurized environment and the requirement for rapid installation. It also documents the transducer solution that was developed, the architecture of the optical sensing network, the data handling process from measurement to the real-time visualization, and the challenging installation performed during the shutdown window. Most significantly, this project demonstrates the feasibility of deploying such a system and provides relevant insights from two years of monitoring including opportunities for improvement.

KEY WORDS: fibre Bragg Grating, Structural Health Monitoring, pipeline monitoring, displacement measurement, optical strain sensor, optical temperature sensor.

1 INTRODUCTION

The present study concerns a fibre Bragg grating (FBG) based structural monitoring system installed on a water supply pipeline in Sydney, Australia. The pipeline is a mortar lined steel, lead-jointed underground structure with 2.5m diameter, which was laid in 1935 and is located in a back-filled tunnel embedded in sandstone ~115m below Sydney. The pipeline is a critical asset, as it is currently supplying water to nearly 1.3 million Sydney citizens.

A road tunnel and a rail tunnel were planned for construction in the vicinity of this pipeline at the inner west of Sydney. The road tunnel was anticipated to approach within 5m of the pipeline and the smaller rail tunnel within approximately 3m of the pipeline.

A risk assessment identified the possibility of serious impact on the pipeline structure from these infrastructure projects, which could cause in joint movements and consequent pressure loss and/or contamination of the water supply. Therefore, the asset owner investigated the risk implications of the planned construction using geotechnical modelling strategies. A small relaxation (10mm) in the sandstone supporting the pipeline was predicted with minimal risk to the structural integrity of the pipeline.

As the pipeline is a critical asset, the owner contracted EngAnalysis to verify the modelling predictions with live measurement at the pipe joints along critical areas of the pipeline to monitor movements during the adjacent tunnelling and construction works. In this way, the monitoring system would be able to detect and alert for potential damage and unexpected movement in the pipe adjacent due to the tunnelling operation. This monitoring plan was a vital control measure, not only to guarantee the integrity of the tunnel but also the continuous water supply. Such a monitoring system was particularly important due to the age and design uncertainties of the structure that increased the chance of unpredictable behaviour. The required monitoring system raised challenges in several fronts:

- The system should quantify the sub-mm displacements (ideally micron) between pipe segments in 3 dimensions (longitudinal displacement, tilt and yaw) in a water filled pipe embedded in sandstone beneath Sydney with the nearest portal around 1.4km from the area of interest.
- The equipment was required to meet potable water quality standards.
- The pipeline shutdown window was short considering that it was a main supply pipeline, which impacted the installation time and reduced the time for definition and design of the complete solution, and it was the first attempt to install this type of monitoring system in a pressurized pipeline.

This paper presents the details of the FBG based monitoring system implemented. It discusses the use of FBG optical technology as a suitable option for a monitoring system, which was chosen due to its advantages facing such an environment and the reduced installation time available. It also documents the transducer solution that was developed, the architecture of the optical sensing network and the challenging installation performed during the shutdown window.

1.1 The pipeline

The pipeline has a difficult history with the original tunnel housing the pipeline dug by pick shovel drills and explosives through the sandstone of the Sydney Basin in the late 1920's. The original design intent was to use the unlined tunnel as the water conduit. This was unsuccessful and the rock tunnel was lined with a steel pipe constructed from 12' sections each joined with lead lagging. The tunnel was then back-filled with concrete with a drain cavity immediately above the pipe to reduce the probability of pipe crushing during construction and later inspection.

The water pipe was originally finished internally with a bituminous anti-corrosive compound that resulted in poor tasting water. The bituminous lining was replaced with concrete render in the late 1930's. The numerous aspects of re-work and the late delivery of the project were probed by a royal commission shortly after completion.

Visual inspection of the pipeline occurs every 15 – 20 years and involves the draining of the groundwater surrounding the pipe, the dewatering of the pipeline and visual inspection. At each 12' pipe section there is a noticeable crack in the concrete render lining indicating that minor settlement is accommodated by small amounts of differential movement between the pipe sections

2 SENSING STRATEGY

2.1 Pipe displacement sensing strategy

The project team decided to monitor the displacement of every joint within the area of influence of the construction works. Each joint was to be monitored at 3 locations along the pipe perimeter (circumferentially at 0°, 120° and 240°) which allowed to determine thrust, tilt and yaw. The radial locations are illustrated in Figure 1. The design focused on the joints rather than on the pipe segment (between the joints), as the joints represent a bending and axial discontinuity, expected joint motion was much larger than that of the pipe segments.

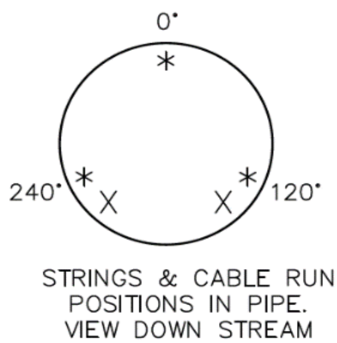

Figure 1. Optical sensors and cable run positions in pipe.

2.2 Network type

The sensing network called for the instrumentation of 127 sensors inside the water pipeline, within the distance of 2km from the surface portal structures.

The combination of water filled asset, the large distances to the surface and the serial communication between sensor strings made an optical sensing network the most reasonable option. Among other advantages such as FBG optical sensors multiplexing abilities, sensor robustness, easy integration, lightweight, small size, passive nature, and resistance to electromagnetic interference (EMI), water ingress, durability, and corrosion [1, 4].

2.3 Sensor type

To measure displacement, custom made sensors using FGB strain gauges from HBK FiberSensing (HBK FS) were a natural choice for this application. However, the application called for displacement rather than strain. Therefore, the selected HBK FS optical sensors were the FS62WSS – weldable strain sensor and the FS63WTS – weldable temperature sensor, which were welded onto a quasi-omega shape bracket as shown in Figure 2. This allowed to develop a system that measured accurate and repeatable displacements in a range of ±7mm at a resolution of 5μm and, that could be easily mounted at each side of the joints.

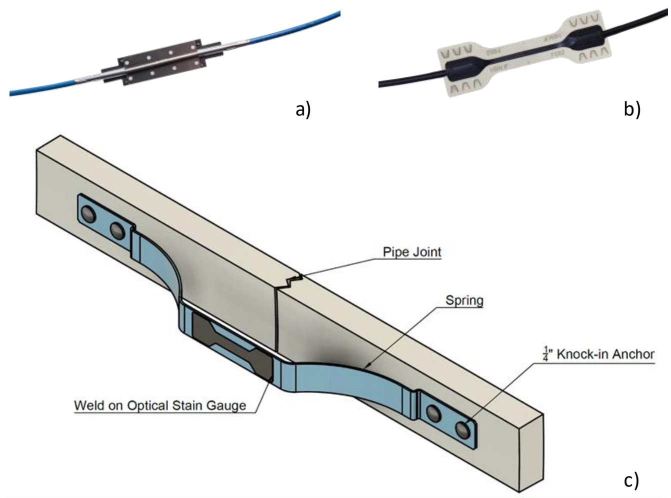

Figure 2. a) FS62WSS sensor; b) FS63WTS sensor; c) Sensor assembly.

2.4 FBG technology

An FBG sensor is an optical element commonly used in sensing. It is a reliable and precise fibre optic sensor. The FBG consists of a periodic perturbation of the refractive index of an optical fibre's core. This periodic perturbation can be imprinted in the core using different techniques. In this case, the UV phase mask technique was used. This structure acts as a mirror, reflecting a specific wavelength. The working principle follows the *Bragg* condition which relates the *Bragg* wavelength (reflected wavelength), λ_B, with the effective refractive index, n_{eff} and the grating period, Λ:

$$\lambda_B = 2n_{eff}\Lambda \quad (1)$$

As the FBG sensor is strained, the grating period is changed, and this strain is measured by the change in reflected wavelength – referred to as a wavelength shift. Any external influence in the system can cause a perturbation on the grating period and/or the effective refractive index, thereby changing its performance, in particular the *Bragg* wavelength. The structure is naturally sensitive to strain and temperature effects, and to measure strain the temperature effect must be compensated. The recommendation is to have a temperature sensor per strain sensor preventing any impact of temperature fluctuation in the strain measurements [5].

Given the technology advantages, FBG technology is a fitting option for SHM projects, delivering durable, accurate and user-friendly monitoring systems as well as easy and relatively fast installation procedures [6,7].

2.5 *Calibration procedure: Wavelength to displacement*

To convert wavelength shift to displacement, a specific calibration procedure was developed by means of a custom semi-automated test rig shown in Figure 3, and associated software for extracting calibration factors from the measurement data.

With this test rig each transducer was calibrated for displacements of ±10mm. The sensors were also calibrated for pressure and temperature effects allowing for a wavelength shift correction of these two factors. While the effect of temperature was significant, the temperature relationship for each sensor was similar and repeatable, allowing for corrections to be applied.

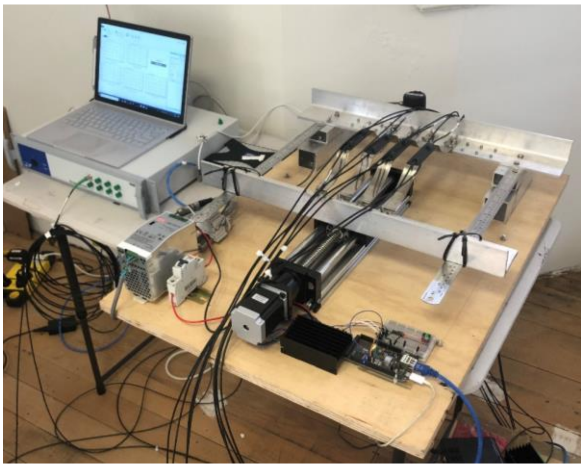

Figure 3. Custom test rig with four sensors installed for calibration.

2.6 *Array layouts and acquisition system*

The optical sensing network consisted of optical arrays with 9 or 10 strain sensors connected in series through splice connections produced and protected from factory. The arrays could be interrogated from both ends for each circumferential location; an example of this configuration is shown in Figure 4. This allows a better approach in terms of sensing network, since it takes advantage of technology's redundancy feature.

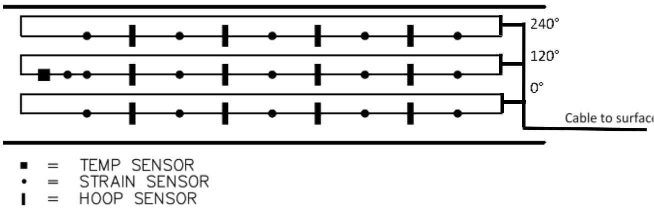

Figure 4. Optical sensing network – example of one array of sensors.

In order to compensate the temperature effect, and because a constant temperature profile was expected in the pipe, only 6 optical temperature sensors were included in the optical arrays (rather than in each string or 1 optical temperature sensor per optical strain sensor).

The data acquisition system consisted of 4 optical interrogators – FS22 BraggMETER SI – with 8 and 4 optical channels and an acquisition rate of 1 sample/s. The FS22 BraggMETER units were mounted on a rack as shown in Figure 5.

Figure 5. Server rack.

2.7 *System assembly and pre-deployment works*

Since there was no access to site prior to the pipeline shutdown period and the system was to be installed within the 5 days that were available within the scheduled shutdown of the pipe, all the optical cables and arrays had to be spliced and assembled in advance (from the factory).

The documented length between joints was 2.7m so sensors were placed 3m apart. Three optical arrays were connected at each end to a single multi core fibre cable that ran to the surface. The nine cable assemblies were brought to site pre-assembled.

As illustrated in Figure 6, the process joining the optical arrays to the cable was:

1. Fusion splice optical fibres
2. Heat shrink splice protection, with stainless steel shank
3. Encapsulate the 6 fibre connections in an aluminium channel. The encapsulant is Episet XL
4. Coat the connection with waterproof membrane paint (potable water approved).

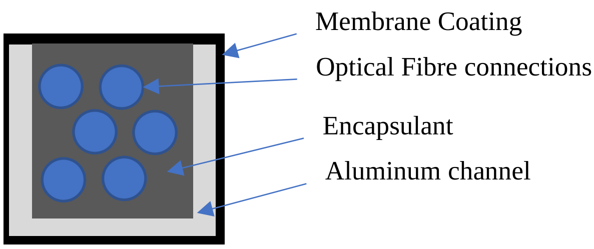

Figure 6. Potting diagram of string to cable connection.

The splices were potted for waterproofing and the cables and sensors were bundled in boxes ready for deployment. To meet the delivery timeframe, all aspects of hardware and software development were occurring in parallel. The assembly and calibration process are illustrated in Figure 7. The optical cables selected for the system are AFL Global multi-core tactical cable.

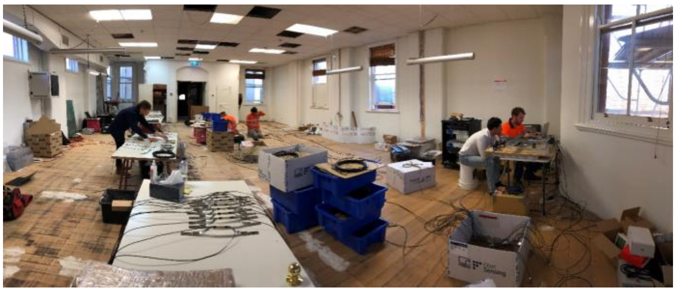

Figure 7. System assembly works.

2.8 *Deployment*

To install and protect the sensing network described the pipe had to be drained and the surrounding cavity was dewatered, this process took much longer than anticipated. After upstream sources were closed and the pipe drained, a lot of ground water had to be also pumped out for accessing the tunnel. This process delayed the installation for almost a week.

The first thing noticed on the first inspection was that the distance between joints was 3.6m rather than documented 2.7m. Since the distance between sensors was 3m and there was no time for re-splicing, it was decided to repurpose every second sensor to measure hoop strain. Fortunately, the original area that was intended to be covered had enough clearance at the sides of the expected excavation area. One side effect of this modification was that there was extra cable that had to be coiled and supported for sensor as seen in Figure 8.

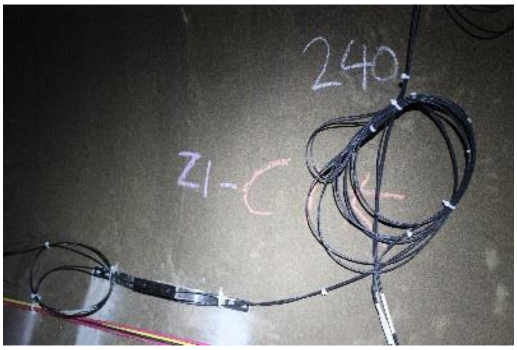

Figure 8. Coiled optical cable before and after sensor positioning.

After 5 days, a team of five engineers plus confined space tradesmen were able to install all sensors. An example of the installation environment is presented in Figure 9. All the sensors were checked and confirmed to be operational when the access to the pipeline was closed and the pipe filling commenced.

Figure 9. Installation site

3 RESULTS

It was anticipated that an initial displacement at the joints would be observed during the pipe-filling process. The dramatic increase in pressure experienced by the pipe did not create a sudden change in joint displacement, as indicated in Figure 10.

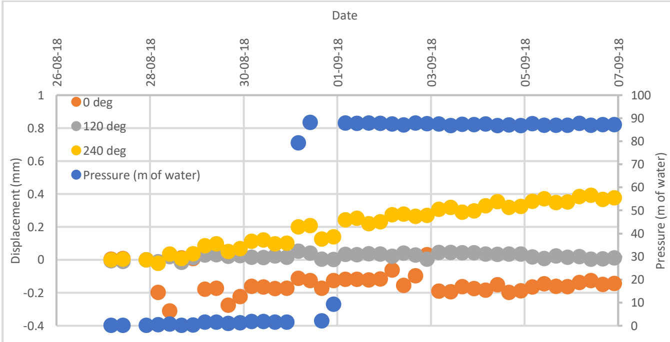

Figure 10. Pipe displacements during refill.

As indicated in Figure 11, the joints started to expand with the water entering the pipeline. Pipe settlement took much longer than expected, between 2 weeks to 3 months after the ground water was replenished (note this was a period of unseasonably low rainfall and drought in New South Wales). The typical movement of the pipe joints observed to be approximately 1mm.

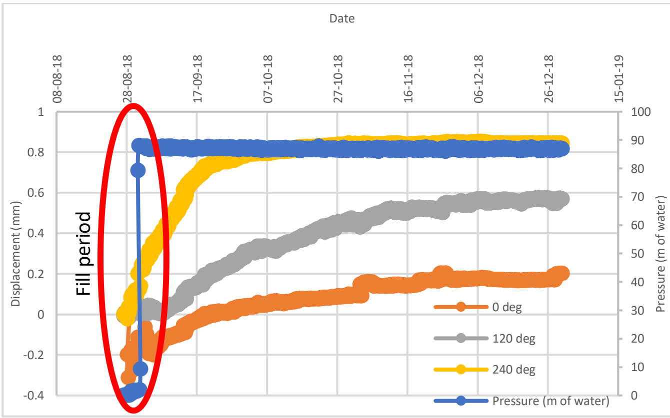

Figure 11. Pipe settlement after refill.

Once the system was fully submerged, the signal from some sensors started to vanish from the optical spectrum. Being an optical array with multiple sensors on a single cable, occasionally whole strings of sensors started to fail. The installation process had connected both ends of the strings to the surface and some of the sensors were recovered by means of interrogating from the other end of a cable string. This feature is possible due to redundancy inherent to the reflective wavelength detection technology. As seen in Figure 12, after a significant loss of sensors experienced during the first months, the system levelled out after 6 months. After two years of operation, approximately 65% of the sensors are active and reliable. Without being able to access the site it is unclear the cause of the failure, but it is believed that the in-factory splices and the coiled cables are the most likely cause of the failures. For future projects, it is highly recommended that the factory splices are further reinforced with potting strategies as outlined in Section 2.7.

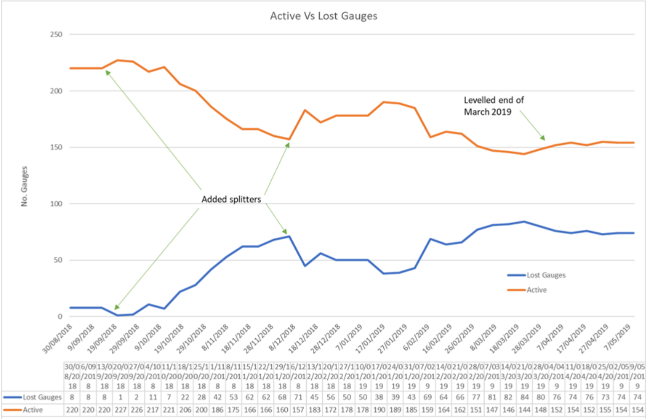

Figure 12. Active and inactive optical sensors for the first 9 months of operation.

The tunnelling of one of the sites occurred after about a year of operation and the system detected no significant motion of the pipe observed during that process.

After a year of operation, the overhead (0°) sensors started to record low frequency periodic oscillation occurring at regular times of the day on both joints and hoop sensors. It was found that the asset owner was injecting supplementary water from a desalination plant to supplement the reservoir water during the peak demand periods as indicated in Figure 13. The desalination plant derived water is warmer than the reservoir derived water. The desalination plant point of injection was more than 2km upstream of the measurement point and it was concluded that the relatively low water flow rate allowed thermal stratification within the water column. The upper sensors were consequently responding to the warmer water and not physical displacement.

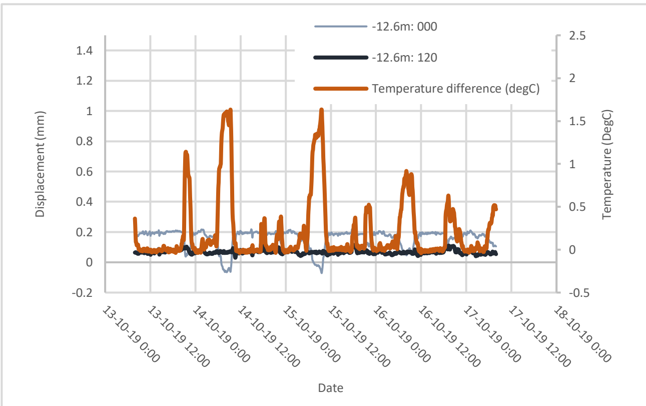

Figure 13. Calculated temperature difference between top and bottom sensors.

In the design phase it had been assumed that the water column would be well mixed and the temperature reference for each regional area was located in the lower section of the pipeline. This observation highlights the susceptible to the influence of thermoclines in the water column differentially effecting the sensor output. These observations provided evidence of water-source stratification and may explain why some distribution lines are more susceptible to alteration in water temperature, hardness and taste when the desalination system is utilized.

These observations have implications for measurements of water quality and the assumption of mixing when multiple water sources are injected to a single supply.

4 CONCLUSIONS

The project illustrates the feasibility to develop, design and install a monitoring system in a water-filled pipe underground subject to 80m of pressure within a timeframe of 3 months. It is possible to deploy an optical FBG based sensing network with 175 displacement sensors within 5 days.

However, both the FBG sensors and the interrogators are relatively high cost per unit of measurement and sensitive to temperature. While relatively low-cost connections exist for optical fibre cables in relatively dry environments, robust spliced connections are costly as is tactical grade multi-core cables. Due to the inherent sensitivity of the optical fibre to temperature, the accuracy of temperature measurement is critically important to any FBG based instrumentation array. It is highly recommended that at least one temperature sensor is placed in each aggregated location and on each sensor string.

The serial communication of FBG sensors on a single fibre makes this system vulnerable to multiple sensor loss due to the damage of a single fibre. If additional interrogator channels are available, shorter optical arrays with 5 or 6 sensors each would allow for additional redundancy when both ends of the fibre are returned to the interrogator. The single-point sensitivity of this system should be considered reduced risk of significant loss of sensors.

The optical sensor array and measurement system has been and is continuing to be an effective method of risk management during the tunnel construction. Despite sensor losses and differences between the installation site and documented pipe dimensions that the system design was based on, the built-in redundancies in both fibre cable length and interrogation techniques have allowed the system to continue with successful operation in providing the required deliverables of the monitoring system. This is allowing the asset owner and construction teams to quantify underground heave and proceed with confidence in the pipeline structural integrity.

REFERENCES

[1] B. Glišić and D. Inaudi, "*Fiber Optic Systems for structural health monitoring*", John Wiley & Sons Ltd. West Sussex, UK, 2007.

[2] D. Inaudi, R. Walder and R. Bulatao, "*Fabry-Perot Fiber Optic Sensors for Civil and Geotechnical Monitoring of Large Structures*", Structural Health Monitoring 2019, 2019.

[3] J. Braunfelds, U. Senkans, P. Skels, R. Janeliukstis, T. Salgals, D. Redka, I. Lyashuk, J. Porins, S. Spolitis, V. Haritonovs and V. Bobrovs, "*FBG-Based Sensing for Structural Health Monitoring of Road Infrastructure*", Journal of Sensors, vol. 2021, Article ID 8850368, 2021.

[4] M. Maheshwari, S. C. Tjin, W. W. Ching and A. Asundi, *"FBG and FOPS for local and global structural health monitoring on a single fiber"*, Smart Materials Structures, vol. 24, 2015.

[5] A. D. Kersey et al., *"Fibre grating sensors"*, Journal of Lightwave Technology, vol. 15, no. 8, pp. 1442-1463, Aug. 1997.

[6] I. Talebinejad, C. Fischer and F. Ansari, *"A hybrid approach for safety assessment of the double span masonry vaults of the Brooklyn Bridge"*, Journal of Civil Structural Health Monitoring 1, 3-15, 2011.

[7] C. Barbosa, R. Martins, C. Alves and P. Faro, *"Monitoring and control of the longest suspension bridge in Brazil during its complex rehabilitation process"*, Fifth Conference on Smart Monitoring Assessment and Rehabilitation of Civil Structures, 2019.