Monitoring of Sprayed Concrete Lined Tunnels Using Fibre Bragg Grating Sensors

M Brunton, J Preston, BE Whelan
Monitor Optics Systems Pty. Ltd.

ABSTRACT

This paper outlines the use of Monitor Optics Systems' (MOS) Fibre Bragg Grating (FBG) sensor cables for convergence monitoring in tunnels made from sprayed concrete lining (SCL). The Crossrail project is currently installing the new Elizabeth line into the London rail network, and at Farringdon Station, the line will connect to both the London Underground and the Thameslink lines. Due to several of the new tunnels being in close proximity, as well as existing infrastructure and challenging geotechnical conditions, the decision was made to monitor the critical "RTE2" tunnel to ensure it was performing as designed. Pressure sensors and survey prisms were initially selected to monitor the tunnel's critical locations. However, as pressure sensors had a reputation for unreliable results due to difficulties with their installation, an additional method was sought out to validate the pressure and surveyed results. Following their successful use in a tunnel at Bond Street Station, MOS sensor cables were selected to monitor the tunnel in conjunction with the pressure sensors and survey prisms.

MOS sensor cables that incorporate a nylon coating are designed to survive direct embedment into the SCL of a tunnel and can provide real time monitoring of the lining immediately after embedment. Sensor cables with five FBGs were installed at two locations in the RTE2 tunnel, along with corresponding temperature sensor cables. The FBGs were monitored using an optical interrogator located outside of the installation area through the use of fibre optic signal cables. Data was available for visualisation and manipulation through the MOS web hosting site DaMiNs.

FBGs, survey prisms, and pressure sensors were located at the same locations, and the FBG results generally showed good agreement with the surveyed results. The majority of the pressure sensors were unable to capture reliable results but were also in good agreement with the FBG results where reliable data was captured. The monitoring results validated the tunnel design and allowed additional tunnel construction to continue without additional unnecessary concrete linings.

1 INTRODUCTION

Construction for the new Elizabeth line commenced in 2009 and will link London's east to London's west through the city, adding 10 new stations and upgrading 30 existing stations. Farringdon Station is one of the stations being upgraded and it will be the only link between the Elizabeth line and both the London Underground and the Thameslink lines.

The upgrade to Farringdon Station will include two large ticket halls and two new platform tunnels, as well as smaller linking tunnels, escalator inclines and escape shafts. The rail tunnels are being constructed using tunnel boring machines (TBM), which continue into where the new platforms are located to create "pilot tunnels" for the platforms. These pilot tunnels are then enlarged using sprayed concrete lining (SCL).

To allow for the simultaneous development of the underground tunnels and the adjoining ticket hall, the Main Contractor proposed abandoning the TBMs in the ground permanently following the excavation of the pilot tunnels instead of retrieving it through the ticket hall shaft. This "turn and bury" solution would allow the construction of the ticket hall to proceed unimpeded, reducing cost, time and risk. However, the simultaneous construction of the underground tunnels and the ticket hall shaft would pose several geotechnical challenges.

Figure 1 shows a plan view of the Farringdon tunnel network. Once the TBM was buried and backfilled with foam concrete, the "RTE2" tunnel was to be excavated from the "PL4" headwall to the "ETH" (Eastern Ticket Hall) shaft. Following the excavation of RTE2, the concourse "CH2" tunnel was to be excavated from the pilot tunnel to the ETH shaft while RTE2 SCL work was being completed. The CH2 construction was to end at a temporary headwall only 25mm from the extrados of RTE2. Finally, the escalator shaft "ES2" was to be excavated from the ETH shaft to the CH2 tunnel, with a "bench and invert" enlargement, and the lining of the ES2 tunnel almost coming within millimetres of the lining of the RTE2 tunnel. The secondary lining of RTE2 was to be installed during the construction of ES2.

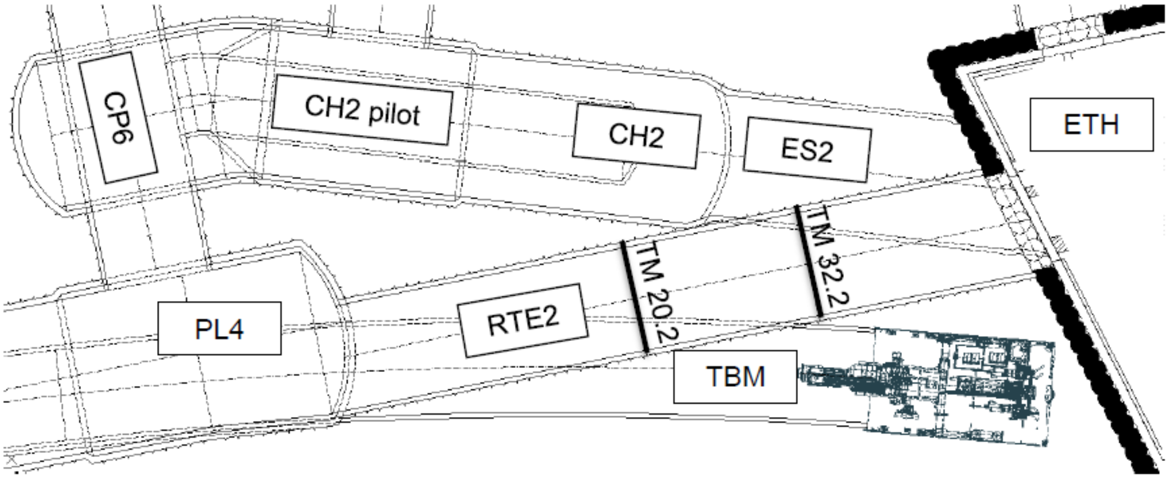

Figure 1: Plan view of Underground Tunnel Excavations

Further complicating the geotechnical conditions was a Listed Railway structure, the Lindsey Street Bridge (LSB), located directly above ES2, and 5 pre-existing major geological faults in the area.

A 3D Finite Element Analysis (FEA) was carried out to assess any ground movements and expected stresses and displacements in the tunnel network. From this, concerns were raised about the integrity of RTE2 with the construction of CH2 and ES2, and it was suggested that the secondary lining for RTE2 be installed prior to the excavation of ES2. This would have caused issues with the Contractor's program, so monitoring of RTE2 was proposed instead, with an overall increase in the thickness of the sprayed concrete lining of RTE2 in critical areas as well.

Survey prisms were considered adequate to monitor for changes in displacements for the majority of the tunnel, but a more direct and accurate method was sought to monitor the stress in the lining itself at key locations. Hydraulic concrete pressure (or stress) cells were suggested, but the Contractor had experienced difficulties with the installation and reading processes, causing many of the cells to yield incorrect or unreliable results. Embedded sensor cables were also suggested following a successful trial at Bond Street Station where Monitor Optics Systems (MOS) embedded their glass fibre reinforced composite (GFRC) sensor cables with Fibre Bragg Gratings (FBGs) into the SCL to measure strain. A compromise was reached to install all three systems at the key locations.

2 MONITORING OF SPRAYED CONCRETE LINING

Prior to the application of fibre optic sensor cables to monitor sprayed concrete linings, survey prisms and pressure cells were the common methods used to understand stress within the concrete linings. However, each of these methods had drawbacks. Survey prisms are only accurate to within a few millimetres, and the displacement results need to be converted to strain and then to stress, which is sensitive to any errors in the surveying measurements. Pressure cells measure pressure (and hence stress) directly from behind the concrete lining, so are ideal in this regard, but there are difficulties associated with their installation and data collection. The pressure cell needs to be set correctly against a mortar pad with good contact with the earth, which can be difficult to achieve, and the crimping (pressurisation) of the cells require a lot of precision and care from highly experienced personnel. Additionally, the results require complicated conversion formulae, making readouts difficult without software.

Embedded FBG sensors are well suited for tunnel monitoring. FBGs are periodic perturbations of an optical fibre that results in the reflection of a narrow bandwidth of light when illuminated by a broadband light. The reflected central peak wavelength is a function of both the grating's period and the refractive index of the fibre's core. If strain is applied to the grating, the grating period changes, changing the reflected wavelength as a linear function to the strain applied. If the fibre undergoes a temperature change, the refractive index of the fibre will change, which also changes the reflected wavelength as a linear function of temperature. This linear response makes FBGs ideal strain and temperature transducers. Some benefits include:

- They are passive and spark free, and are not influenced by EM noise
- They are self-referencing and experience zero drift, so no recalibration is ever required
- They have no moving parts and are of low impact, so they will not affect the structure
- They are highly resistant to the elements, allowing them to survive indefinitely in harsh environments
- They have high resolution and accuracy (typical 1-2με for strain, 0.1°C for temperature)

However, fibre optic FBG arrays are generally too delicate to survive the harsh sprayed concrete process when they are directly embedded. MOS's sensor cable consists of an optical fibre that is pultruded into a glass fibre reinforced composite cable (GFRC) which protects the fibre optic array while maintaining excellent strain transfer. A nylon coating can also be applied for further robustness.

MOS FBG Sensor cables were first tested with sprayed concrete at Cambridge University, and then installed at Bond Street Station in a full trial.

2.1 DIRECT EMBEDMENT OF SENSOR CABLES USING SPRAYED CONCRETE

Sprayed concrete is the process of projecting wet concrete through a nozzle with compressed air. This technique is often used for the containment and reinforcement of earth works in tunnels and underground structures. The sprayed concrete process is aggressive and can be damaging to sensitive instruments that are embedded using this technique.

In 2012, MOS carried out tests embedding their GFRC sensor cables in sprayed concrete at the University of Cambridge. The purpose of the this was to test the survivability of the MOS sensor cables under the harsh sprayed concrete process, and to demonstrate the capability of the embedded FBG sensor cables to accurately measure strains inside the concrete structure.

Three different sensor cables were installed into the framework of the concrete beam; one with one FBG, another with two FBGs and the last with three FBGs. This setup is shown in figure 2. Sensor cables with a protective nylon coating and no FBGs were also installed for validation purposes using OTDR. Sprayed concrete was then applied to the beam.

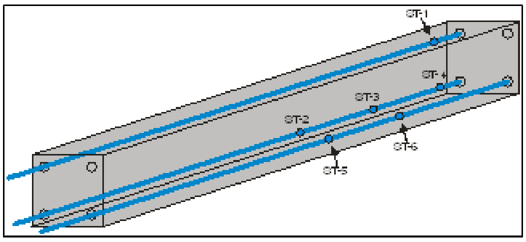

Figure 2: Sensor Cables Installed into Beam

The sensor cables survived the embedment process, with some losses to the FBG reflection levels, but the nylon coated sensor cables proved to be very robust during the installation process, with no losses. The sprayed concrete process is shown in figure 3. Load cells and vibrating wire sensors were then installed onto the beam for comparison to the FBG results.

Figure 3: Sprayed Concrete Applied to Beam

The beam was subject to a four-point bending load until failure. The FBGs results compared well with the other sensors attached to the outside of the beam as well as numerical simulations.

2.2 BOND STREET STATION INSTALLATION

Following the successful embedment tests, a trial installation of nylon coated sensor cables was carried out at the upgrade to Bond Street Station in 2013. Nylon coated sensor cables were selected because of their excellent performance at the University trials, and they were installed in two different locations. Each strain sensing cable had five FBGs, with all FBG positions corresponding to a desired position in the tunnel lining (as shown in figure 4). MOS temperature sensor cables with one FBG were installed alongside the strain cables to compensate for temperature induced changes to the strain values and to provide information on the temperature variance during the curing process.

All sensor cables survived the sprayed concrete application and provided information on the curing process. All results were set to zero at the conclusion of the spraying process, and the results for one of the installations can be seen in Figure 5. All FBGs showed tension in the lining which gradually turned compressive as the concrete cured. Additional compression was also noted at subsequent stages of tunnelling, most pronounced during the top heading excavation that occurred 21 and a half hours after the lining installation. This increase in compression is due to the lining taking the load from the surrounding London Clay.

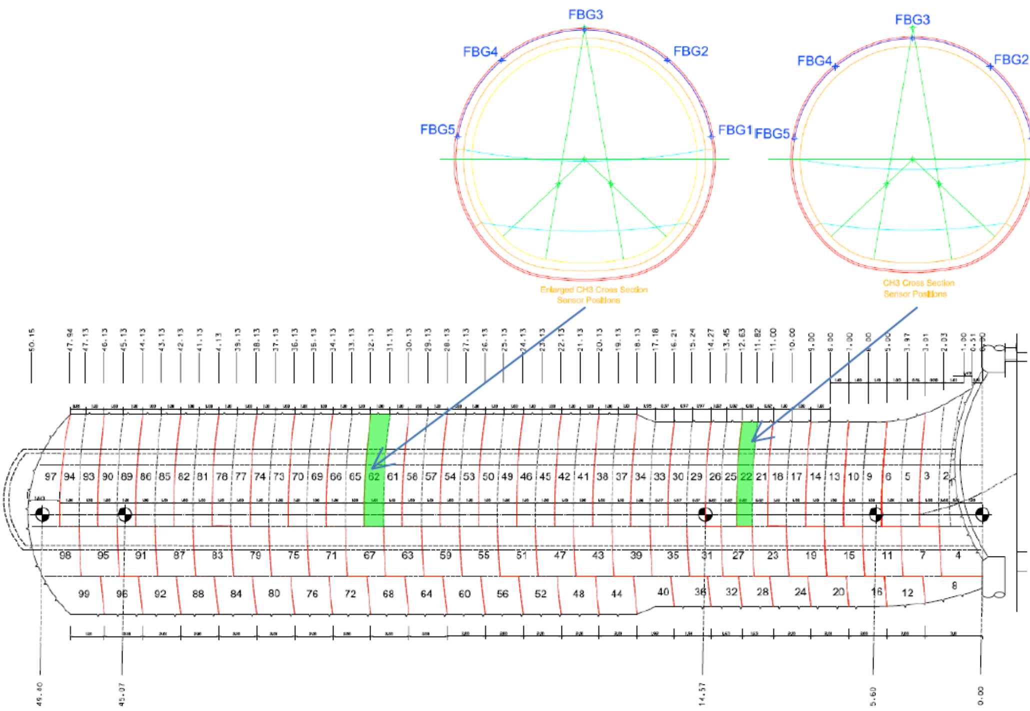

Figure 4: Section of Tunnel Monitoring Locations

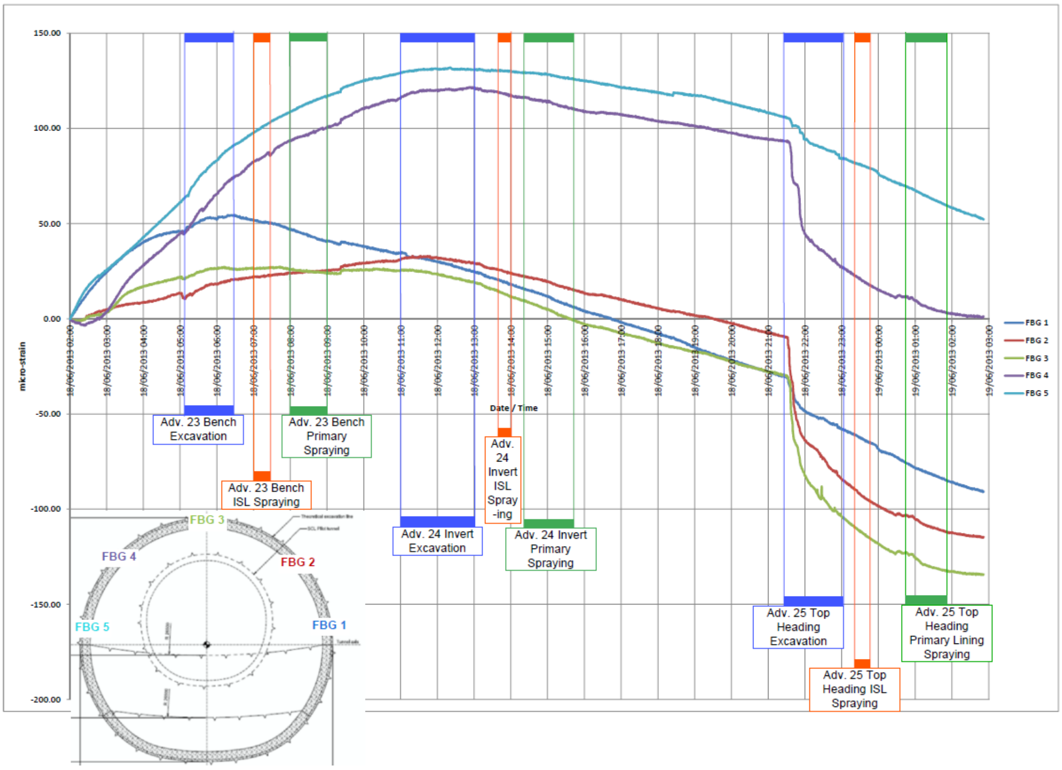

Figure 5: Results of Sprayed Concrete Lining Installation

3 FARRINGDON STATION INSTALLATION

The installation of all three monitoring systems occurred in late 2014.

3.1 FBG SENSOR INSTALLATION

FBG strain sensor cables with nylon coatings were installed at two tunnel locations, "TM20.2" and "TM32.2". The strain sensor cables were paired with temperature sensor cables for temperature compensation. Following the initial boring of the tunnel, an initial sealing layer was applied for safety reasons, and once it had reached an appropriate strength, the sensor cables were installed.

The sensor cables were attached around the circumference of the tunnel using steel staples from an elevated work platform, with the identified FBGs positioned at their design location. A typical monitoring section is shown in figure 6. The FBG sensor cables had pigtails at each end of the cable, allowing redundancy in the event it became damaged. The pigtails were drawn back to the previous advance in conduit and protected using junction boxes. The sensor cable pigtail was connected to a signal cable that connected to a Micron Optics, Inc. sm130 dynamic interrogator located outside of the tunnel area in an office.

Data was automatically uploaded to MOS's dedicated web server DaMiNs for visualisation and manipulation of data.

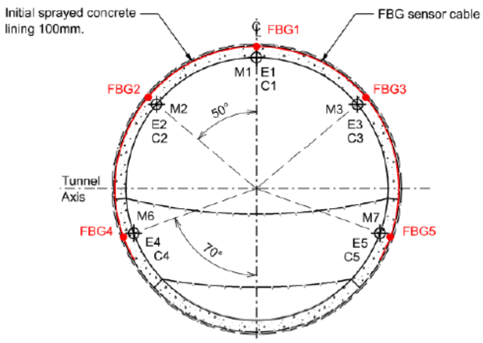

Figure 6: Section of Typical Instrumentation of RTE2

3.2 PRESSURE CELL INSTALLATION

The Contractor's in-house surveying team carried out the installation of the earth and concrete pressure cells. The team had experience with the installation of pressure cells and care was taken to install them correctly. The pressure cell mortar pads had to be fixed to the earth of the tunnel wall, meaning a suitable gap needed to be made from the sealing layer. The pressure cells were installed adjacent to the FBGs also using an elevated work platform and were pressurised according to the manufacturer's instructions. The pressure cells are also represented in figure 6 as C1 to C5 (concrete cells) and E1 to E5 (earth cells). A data logger was on hand to monitor the cells.

3.3 SURVEY PRISMS

The Contractor's in-house surveying team also carried out the installation of the prisms. A threaded rod that the survey prisms are attached to was installed following the sealing layer installation at the same location of the FBGs and pressure cells (M1 – M3 and M6 – M7 in figure 6). The primary lining was then applied, and the targets were installed onto the threaded rods after the lining had cured enough for safe access. Monitoring of these were then carried out by surveyors, relying on line of sight from the station setup to the target. The station was benchmarked against a static point in the tunnel away from the tunnel operations.

4 RESULTS

The FBG results generally compared well with the vertical displacement results. An example of the results is shown in figure 7. These results show point M2 of TM 32.2, which exhibited the largest changes in strain and displacement throughout the construction of CH2 and ES2.

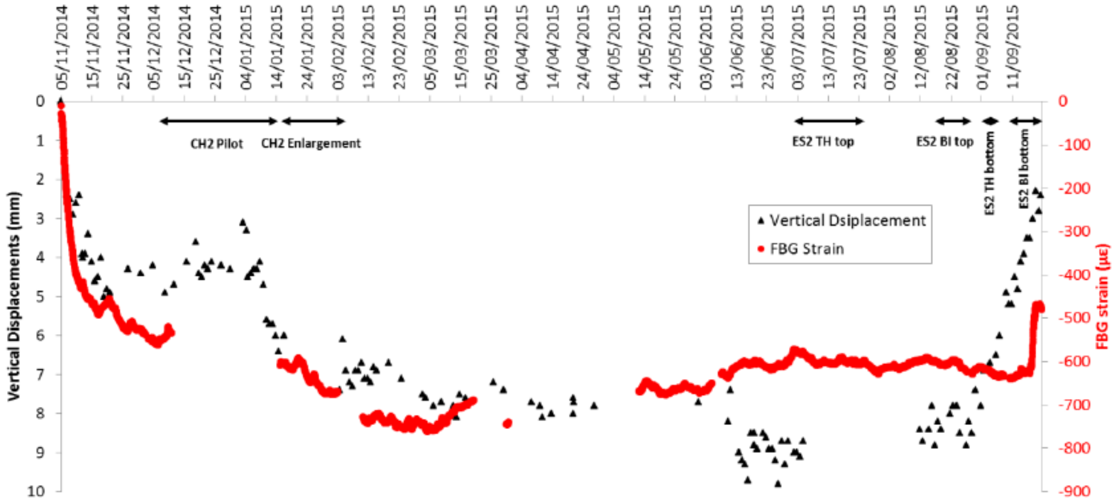

Figure 7: Vertical Displacement Vs FBG Strain Results at Point M2 of TM 32.2

In most cases the pressure cells were unable to capture reliable stress readings for the soil or concrete, but at M2 of TM 32.2, the data compared well between the first readings and steady state conditions. This is illustrated in Figure 8.

Figures 9 and 10 show FBG results for TM 20.2 and TM 32.2. Compression was observed for all FBG sensors during the initial stage, with additional compressive strains observed during the construction of CH2 and ES2.

The FBG results compared well with the FEA results, as shown in Table 1.

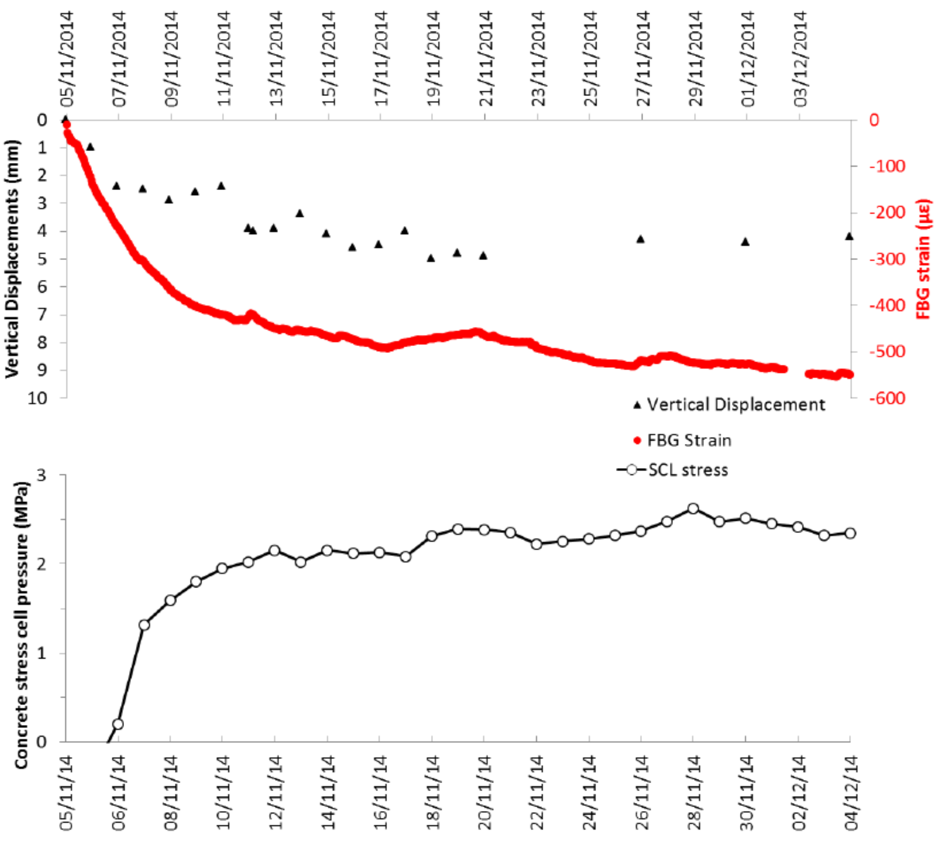

Figure 8: Agreement of Measurements between all sensors at M2 TM 32.2

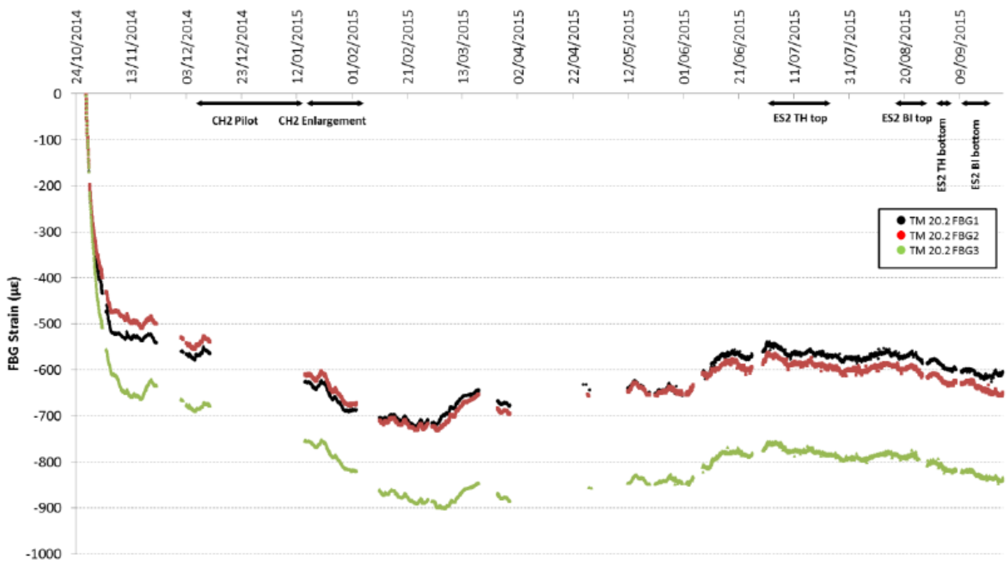

Figure 9: FBG Results at TM 20.2

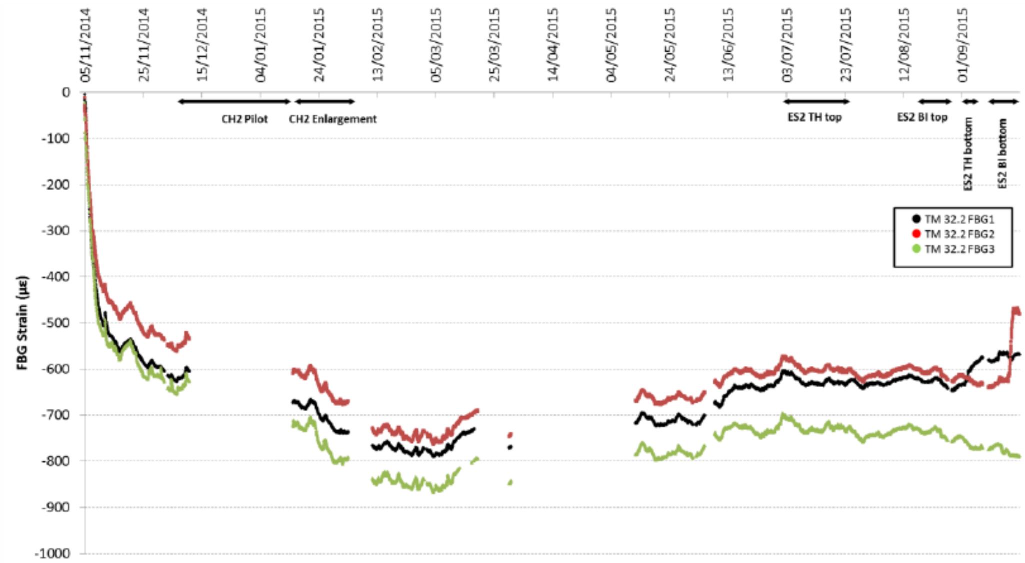

Figure 10: FBG Results at TM 32.2

Table 1: FEA VS FBG Results

		Radial Strains (με)					
		M1		M2		M3	
		FEA	FBG	FEA	FBG	FEA	FBG
TM 20.2	CH2 Pilot	-50	-65	-100	-75	-50	-80
	CH2 Enlargement	-100	-80	-150	-105	-50	-115
	CH2 Total	**-150**	**-145**	**-250**	**-180**	**-100**	**-195**
TM 32.2	CH2 Pilot	-20	-70	-50	-75	-20	-95
	CH2 Enlargement	-50	-100	-70	-125	-20	-120
	CH2 Total	**-70**	**-170**	**-120**	**-200**	**-40**	**-215**
	ES2 from Ticket Hall	50	60	150	-15	20	-10
	ES2 B&E Enlargement	50	5	250	160	30	-20
	ES2 Total	**100**	**65**	**400**	**145**	**50**	**-30**

5 COMPARISON BETWEEN SENSING METHODS

The Contractors made comparisons between each system, noting their strengths and weaknesses.

Aside from being a cost-effective option, the survey prisms were easy and safe to install, as this was done once the primary SCL had cured. Also, damaged prisms were easy to replace without any loss of data. However, the survey prisms are not autonomous, requiring manual labour for each reading, and they are limited by line of sight, need a static point away from tunnel operations, and require regular cleaning due to the large amount of dust in the tunnel.

The pressure cells were generally regarded as the weakest system as they are difficult to install and maintain, particularly with the crimping process, and many did not yield credible or reliable data.

The FBG system was considered safe and easy to install, and provided high precision, accurate and reliable data. All ten sensors remained functional throughout the monitoring period, and continuous access was provided by MOS's web-server DaMiNs. Their main weakness was considered to be the signal cables that ran between the sensors and the interrogator, as these were susceptible to damage from tunnelling machinery. However, damaged cables could easily be replaced, minimising data down-time.

Table 2 shows a summary of the pros and cons of each system according to the Contractor.

Table 2: Pros and Cons of Each Monitoring System

	Pros	Cons
Survey Prisms	• Cheapest system • Fast, easy and safe to install • Easily replaced if damaged without loss of data	• Limited by line of sight • Results depend on accuracy of levelling and control points • Manual operation • Targets get dirty and easily damaged • Least accurate system and can be affected by creep
Pressure Cells	• Most direct way to measure stress • Mid-range price • Very durable and robust once embedded • No maintenance required aside from crimping • Good accuracy (when installed correctly)	• No remote connection • Manual readings • Crimping process difficult • Difficult to obtain good contact with earth • Least safe option as it requires exposing earth • Slowest installation option • Signal cable can be frail and cannot be replaced • Complicated conversion formulae (although can be overcome with software) • Unreliable data
FBGs	• Reasonably fast, easy and safe to install • Very durable and robust when embedded • Signal cable can be replaced if damaged • DaMiNS provided easy and immediate access to data • Highest accuracy of each system • Reliable real-time data • Automated system	• Most expensive system • Signal cables can be frail

6 CONCLUSION

FBG sensor cables with nylon coatings were embedded into the SCL of the new RTE2 tunnel in Farringdon Station alongside survey prisms and pressure cells. Each monitoring system was installed in late 2014, and were used to monitor for changes to the SCL caused by the construction of adjacent tunnels CH2 and ES2.

The FBG sensors compared well with FEA models completed prior to the construction and to the data obtained by the survey prisms. The pressure cells were unable to yield reliable or credible data for the majority of cases, but the FBGs were in agreement with their results when reliable data was captured.

The Contractor concluded that FBGs are an effective tool to measure stress within concrete linings where survey prisms are not deemed accurate enough, and that it validated the design of RTE2.

7 ACKNOWLEDGEMENT

The authors would like to express their thanks to the members of Crossrail and the University of Cambridge that allowed these trials and eventual full installation to proceed.

8 REFERENCES

Masanari, N., Hammer, A.L., Thewes, M., Elshafie, M. Soga, K. (2015). Mechanical Behaviour of a Sprayed Concrete Lining Isolated by a Sprayed Waterproofing Membrane. *Tunnelling and Underground Space Technology 47*, 143-152.

Nosenzo, G., Whelan, B.E., Brunton, M., Kay, D., Buys, H. (2012). Continuous Monitoring of Mining Induced Strain in a Road Pavement Using Fiber Bragg Grating Sensors. *Photonic Sensors*, DOI: 10.1007/s13320-012-0077-0

O'Donnell, J., Nosenzo, G., Preston, J. And Sturman, T (2013). Installation of Optical Fibre based Sensors within Sprayed Concrete Lined Tunnels to measure Strain and Temperature *Crossrail Annual Technical Papers Competion,* London, U.K 2013

Salak, P., Gakis, A. and St.John, A. (2015). Taking the strain, coping with pressure or shooting targets? An objective comparison between monitoring solutions within sprayed concrete lined tunnels at Crossrail Farringdon Station, London. *Crossrail Technical Papers 2015*