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Continuous Monitoring of Mining Induced Strain in a Road Pavement Using Fiber Bragg Grating Sensors

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Abstract: This paper describes the application of fiber Bragg grating (FBG) based sensors for monitoring road pavement strains caused by mining induced ground subsidence as a result of underground longwall coal mining beneath a major highway in New South Wales, Australia. After a lengthy planning period, the risks to the highway pavement were successfully managed by the highway authority and the mining company through a technical committee. The technical committee comprised representatives of the mining company, the highway authority and specialists in the fields of pavement engineering, geotechnical engineering and subsidence. An important component of the management strategy is the installation of a total of 840 strain and temperature sensors in the highway pavement using FBG arrays encapsulated in glass-fiber composite cables. The sensors and associated demodulation equipment provide continuous strain measurements along the pavement, enabling on-going monitoring of the effects of mining subsidence on the pavement and timely implementation of planned mitigation and response measures to ensure the safety and serviceability of the highway throughout the mining period.

Keywords: Sensing, monitoring, fiber Bragg grating, pavement strain, distributed sensors

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1. Introduction

The principle behind the use of optical fiber based components as sensing elements in structural health monitoring (SHM) applications is well known. A number of different technologies have been developed over the years, and among them the fiber Bragg grating (FBG) based sensor is one of the most used in commercial applications thanks to a number of advantages over other technologies. Here a novel application is presented where FBG based sensors are being used to monitor the pavement of a major highway subject to mining induced subsidence effects. Sensing cables were developed for this application, capable of deploying many hundreds of FBGs over kilometers of highway pavement to provide continuous measurement of the subsidence-induced strain in the pavement. The

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pavement monitoring system was installed as an important component of a comprehensive management system developed and implemented by the highway authority and the mining company to manage the effects of mining subsidence on the highway and ensure the on-going safety and serviceable operation of the highway.

2. Principles of fiber Bragg grating based monitoring

A Bragg grating is defined as a periodic perturbation of the effective absorption coefficient and/or the effective refractive index of an optical waveguide. In particular, fiber Bragg gratings are periodic variations of the refractive index in an optical fiber. This variation is obtained in the fiber by exploiting the phenomenon of photosensitivity, the variation of the refractive index in the core of an optical fiber induced by an incident ultraviolet light beam [1]. By irradiating the fiber with an intensive pattern that has a periodic distribution, a corresponding index perturbation is permanently induced in the core of the waveguide. The result is an index grating that is photo-imprinted in the optical waveguide. As a result, the Bragg grating becomes a very selective spatial reflector in the core of the fiber [2]. When illuminated with a broadband light, the grating reflects a narrow bandwidth component of the spectrum. The central wavelength of the reflected component is called Bragg wavelength, λ_b, and it is a function of the spatial period of the grating Λ and of the refractive index n as per the following equation:

$$\lambda_b = 2n\Lambda.$$

Any change to the spatial period of the grating, or refractive index, causes a proportional shift in the reflected and transmitted spectrum. Strain and temperature field variations on the grating induce both period and refractive index variations, and these in turn induce a shift in the central wavelength of the reflected signal. This wavelength shift is a linear function of both the applied strain and the temperature variation according to the following formulas:

Strain-wavelength shift relation:

$$\frac{\Delta\lambda}{\lambda} = \left[1 - \frac{n^2}{2}\left[P_{12} - v\left(P_{11} + P_{12}\right)\right]\right]\varepsilon_1$$

where ε_1 is the longitudinal strain component, v is the Poisson ratio, n is the unstrained refractive index, and P_{11} and P_{12} are components of the elasto-optic tensor [3]. As v, n, P_{11} and P_{12} are constant characteristics of the material used in the fiber, the above equation indicates a linear relation between the strain and wavelength shift.

Temperature-wavelength shift relation:

$$\frac{1}{\lambda}\frac{\Delta\lambda}{\Delta T} = f\left(\alpha, \xi\right)$$

where α is the thermal expansion coefficient of the fiber, and ξ is the thermo-optic coefficient relating the change of refractive index to the temperature. As both these coefficients are constant, the equation again indicates a linear relation between the temperature and wavelength shift.

The linearity of the above relations makes the FBGs ideal strain and temperature transducers. A number of demodulation schemes have been developed and implemented in commercial instruments that allow the detection of reflected wavelength shifts with great accuracy.

FBGs show a number of advantages over conventional electrical sensors and other fiber optics sensors for the use in sensing and in long term monitoring systems, which make them the best choice for most structural monitoring applications:

(1) Accuracy and range: typically a commercial instrument is today capable of measuring wavelength shifts of 1 pm–2 pm, that for most FBG can be translated in strain accuracies of 1.5 με–3 με and in temperature accuracies of 0.1 ℃–0.2 ℃. The maximum range for an FBG based strain sensor varies from 5,000 με to 50,000 με depending on the FBG manufacturing process while temperature based sensors can be specially manufactured to achieve a maximum operating temperature over 600 ℃.

(2) Small size: as the FBGs commonly used in sensing applications have a length of 5 mm–10 mm, they can be considered point sensors in most applications. As the diameter is the same of the host optical fiber (typically 150 μm–250μm), the sensors can be easily embedded in composite materials and used as part of small size mechanisms.

(3) Self-referencing: as λ_b in the unstrained state is a function of the manufacturing parameters, FBGs provide at any moment an absolute strain measurement, provided that the temperature effects are compensated for. Thanks to the extremely high stability of FBGs structural properties, FBGs do not suffer from drift and do not require recalibration over the years.

(4) Multiplexing: as each FBG reflects a very narrow bandwidth signal centered on λ_b and this is a function of its design parameters, FBGs can be employed in high numbers on a single optical fiber (in-series multiplexing). This is a unique feature of the FBG. The use of standard fiber optics couplers and switches and the use of multi-channel interrogation equipment allow a number of different fibers to be connected to a single interrogation unit (parallel multiplexing). This allows the creation of large and sophisticated networks. The low attenuation of the light signals in optical fibers allow these networks to span over distances of several km. Moreover, as each FBG sensor converts the measurand into a wavelength shift, sensors for different measurands can be interrogated by the same unit without the need for dedicated conditioning modules typical of other electric sensors.

(5) Electro magnetic (EM) noise immunity: FBG sensors and optical fiber cables are passive (spark-free) devices that are immune to electromagnetic interference and do not require any signal pre-amplification. As the fiber carries light, this is not affected by any electromagnetic source. This allows the installation of sensing networks in structures subject to heavy EM noise, such as antennas or power distribution stations. This also allows the cables carrying the signals to be routed through existing electric cables conduits. Fiber optics (FO) sensors also do not emit EM noise and therefore do not affect any EM sensitive equipment that might be located in proximity of the sensing network.

(6) Passive spark free operation: Thanks to the very low attenuation typical of optical fibers, FBG sensors can be installed at long distances from the interrogation unit without the need to supply electrical power to each sensing location. This is also a significant advantage in retro fit situations or in locations where power is not easily available, e.g. highways and bridges. The sensors and the connection cables are totally spark free and can therefore be safely employed in underwater applications or in chemical plants or anywhere electric sensors can cause hazards. The spark free nature of these sensors also makes them very robust in case of lightning strike.

(7) While FBGs can be used immediately to replace electrical strain gauges and thermocouples in strain measurement and temperature measurement respectively, the use of unpackaged FBGs is not practical when field measurements are required. As a consequence, a number of different designs have been developed to allow an easier installation of FBGs. Sensors aimed at measurands different from strain and temperature have also been developed. In this case, the sensor packaging includes mechanisms capable of converting the measurand in a strain on the FBG.

3. Fiber Bragg grating sensors in structural monitoring

As shown above, FBGs are ideal strain and temperature transducers, and their potential has been exploited in the monitoring of different types of structures. Aerospace structures were the first to see experimental use of FBG based sensors as the small size of optical fibers made them a perfect candidate for embedment in composite materials to manufacture so-called smart materials. While the interest of the aerospace community is still high, the application areas that have benefited most from the use of FBG sensors are the oil and gas and the monitoring of civil structures. In the monitoring of civil structures in particular, a number of companies have operated with success, and FBG based monitoring can now be considered a mature technology.

Among the types of structures that have been instrumented with FBG based sensors, bridges are the most common. Bridges are generally monitored periodically using conventional strain gauges and other electric sensors, but as a result of a number of catastrophic structural failures the relevant authorities are now expressing a growing concern about the state of structural health of the existing structures. This has led to a wider need for continuous automatic monitoring, a type of monitoring for which optical fiber sensors in general and FBG sensors in particular are very well suited. An example of the monitoring of a bridge with FBG based sensors is the monitoring of the historic Hampden bridge in Kangaroo valley (Fig. 1), started by Monitor Optics Systems Ltd. (MOS) in 2004.

Opened in 1898, this suspension bridge was an outstanding engineering achievement for its time. Over one hundred years on however, the effects of a far greater traffic loading than that for which it was originally designed were considered a potential cause for damage, and it was decided to install an automatic monitoring system based on the use of FBG strain sensors on a number of suspension rods and other key structural elements. Traffic induced dynamic strain data measured by the sensors were automatically acquired, classified and transmitted to a web-based database for management and visualization. An example of the dynamic strain data relative to a heavy vehicle is shown in Fig. 2. The monitoring system provided the customer with useful information not only on the structural behavior of the bridge, but also on the traffic patterns. Through the use of the on-line data management system DaMins, it was possible to verify the number of heavy vehicles engaging the bridge and confirm the suspect that overweight trucks were routinely using the bridge despite the weight limitations in place.

Fig. 1 Hampden bridge in Kangaroo valley.

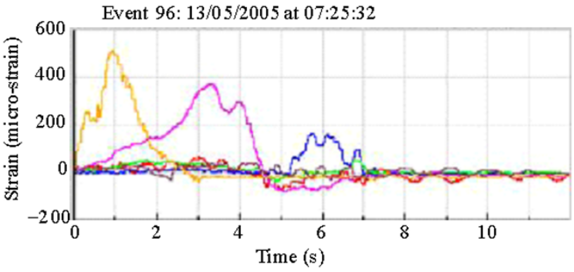


Fig. 2 Dynamic strain data acquired using FBG sensors.

FBG sensors have also been applied in tunnels, retaining walls, cultural heritage buildings, foundations, and gas tanks. While most sensors are designed to be externally mounted on the structures, others have been designed to be embedded in concrete and other materials, allowing the monitoring of structural parameters directly inside the structural components. A similar approach has been used to monitor a highway subject to mining induced subsidence phenomena.

4. Effect of mine subsidence on road pavements

When underground coal is extracted using the longwall mining method, the ground immediately above the coal seam is allowed to collapse into the void that is created as extraction proceeds, resulting in subsidence of the ground surface.

The highway was constructed in the 1970's with a composite pavement structure comprising asphaltic surfacing, slag road base and stabilized (bound) sandstone sub-base. Experience from mining beneath pavements of similar stiffness found that subsidence induced damage typically consisted of cracking of the pavement and drainage structures. However, of concern were observations of shear/compression steps, up to 40 mm to 80 mm high, at two locations. Both steps occurred where irregular subsidence was observed in the form of elevated compressive ground strain. From trenches excavated through the pavement at the impact sites, it was established that the stiff shallow base course layer had sheared due to compressive ground strain, as shown in Fig. 3.

Fig. 3 Example of "stepping" in a road pavement caused by mining induced compressive strain.

This mode of failure was considered one of the major risks associated with mining beneath the highway. The technical committee proposed and investigated options for mitigating this risk. Based on the results of numerical modelling, the preferred option was to install slots into the existing pavement prior to mining to allow compressive stresses in the pavement to be dissipated into the slots. Figure 4(a) shows the slot being cut in the pavement sub-base following removal of the asphaltic top layer and slag base course. The slots were installed at night to minimize disruption to road users. Figure 4(b) shows the completed transverse slot following replacement of the asphaltic top layer.

(a)

(b)

Fig. 4 Cut of strain-relieve slots: (a) cutting a subsidence strain relieving slot in the pavement prior to mining commencement and (b) finished transverse pavement slot with the top asphaltic layer replaced.

In addition, the technical committee recognized the need to make provision for locally high compressive stresses in the pavement caused by irregular subsidence movements. The location and magnitude of these localized irregularities could not be identified prior to mining, but were generally associated with geological or topographical structures. It was determined that additional slots could be installed proactively during mining provided extensive, real-time monitoring could be exploited to identify the development of localized irregular subsidence profiles with sufficient warning to allow additional slots to be installed. After extensive trials in a nearby pavement subject to mining effects, surface embedded FBG-based sensing cables produced by MOS were identified as being very effective in meeting this critical monitoring requirement [4].

Comprehensive risk management strategies were then developed and implemented before permission was granted to undermine the highway. Risk management measures included the installation of slots prior to mining at predetermined locations, implementation of extensive monitoring and inspection measures including the FBG-based monitoring system and planned response measures that could be undertaken if triggered from the observed monitoring data [5].

5. Direct continuous monitoring of pavement strains

An important element of the management system was to monitor changes in pavement strain (and inferred stress) during mining. This allowed the technical committee to detect early changes in pavement condition and respond if required before the stiff layer in the pavement sheared in compression.

5.1 Technology selection

Optical fiber sensing systems are ideal for accurate, autonomous, long-term monitoring in the field [6]. Optical sensors based on FBG transducers do not suffer from drift, do not require electrical power for signal transduction or transmission and are immune to electro-magnetic interference. They can be multiplexed in series and in parallel with negligible optical loss [7].

Two commercially available optical fiber sensing techniques were assessed, namely the FBG and stimulated Brillouin scattering (SBS). While it was concluded that either technique could in principle be applied for monitoring mining induced strains in road pavements, the FBG technology was selected based on its relative affordability, proven performance for structural health monitoring and the relatively short lead-time required to develop and deploy a complete monitoring solution including data management. The challenge remained however to develop a practicable method for deploying hundreds of FBG strain and temperature sensors over kilometers of highway pavement.

5.2 Distributed sensing using FBG sensors

The embedment of a large number of FBGs within a host material is a technique that is commonly employed using FBG arrays on a standard diameter optical fiber. A number of examples can be found in the literature, and several commercial applications make use of this technique. The use of the non-protected optical fiber is however difficult and potentially unreliable in harsh environments due to the risk of fiber breakage. One reason for this is that when FBG arrays are produced, the fiber is typically stripped of its protective coating and then recoated after the writing process is complete, thereby introducing microscopic defects in the glass [8]. Moreover, when the desire is to embed the sensing fiber in a coarse matrix such as asphalt or other construction material, even a virgin optical fiber will be prone to breakage during onsite handling and embedment.

MOS has developed its own proprietary method of embedding one or more optical fibers into a glass fiber reinforced composite (GFRC) sensing cable, of up to kilometers in length. The mechanical properties of the sensing cable can be tuned to optimize strain transfer from the structure to the sensing fiber, while maintaining a very high level of protection for the optical fiber. This sensing cable design and construction are suitable for a number of different optical sensing techniques, including the FBG and SBS. The GFRC cable is compatible with most epoxy resin based adhesives. This enables the effective surface bonding and embedment of the sensing cables. The material properties ensure the survival of the cables when installed in environments such as concrete, asphalt, salt water, and composite materials. The strain sensing cables can also be cast into concrete or asphalt matrices thanks to their durability and good temperature resistance (up to 200 ℃). If required, the cables can be surface treated or coated with polymers for added protection.

The sensing cables can be stored on reels for storage and transport, as shown in Fig. 5, and are readily deployed and installed in the field, realizing considerable savings in time and cost.

The chemical properties of the resin used in the GFRP ensure optimum adhesion between the cable and the polyimide coating of the FBGs embedded in it, thereby ensuring a very reliable strain transfer. The diameter of the cable (typically from 1 mm to 10 mm) is selected to suit the particular monitoring application. For pavement strain measurement, a 1-mm cable diameter was selected to maximize the physical robustness of the cable while maintaining the flexibility required for the sensing cables to be easily coiled on a reel for transport and installation and to avoid the sensing cable acting as a local reinforcement in the host pavement.

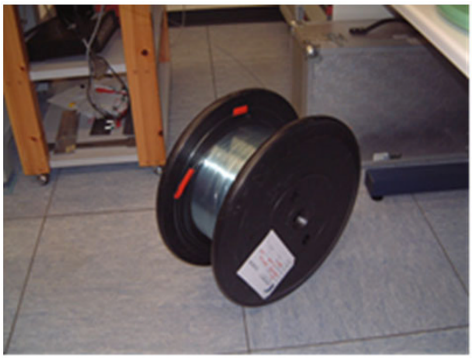


Fig. 5 MOS distributed sensing cable of 100-m length stored on a reel.

The use of FBGs as strain transducers is affected by their sensitivity to temperature variations [9]. Temperature fluctuations in the vicinity of a strain sensing fiber can indicate an apparent strain, and vice versa. The most common approach to avoid cross-sensitivity problems is to measure strain and temperature in parallel, using two separate sensing fibers. One of these fibers is packaged in order to decouple it mechanically from its environment so that it senses only temperature, while the other fiber is deployed to measure both temperature and strain. A simple algorithm can then be used to process the measurement data in order to actively compensate for temperature effects and arrive at pure strain data.

The MOS temperature sensing cable is based on an FBG array encapsulated in a composite GFRP pultruded cable which is loosely enclosed in a polymer tube. The polymer tube allows the unrestrained thermal expansion of the GFRP cable and isolates the sensing cable from the strain field of the host structure. These sensors can also be employed independently as temperature sensors if desired.

5.3 Testing undertaken by the technical committee

While the ability of the FBG technology to detect strains in general was well understood, its application to detect changes in strain of an asphaltic road pavement was new and unproven. The MOS system was therefore rigorously researched and tested by the technical committee prior to endorsing its use for detecting mining-induced pavement strains in the highway. These included:

(1) Review of the effectiveness of the system by the University of New South Wales.

(2) Laboratory testing by the highway authority of concrete beams incorporating surface embedded FBG sensor cables and surface mounted electric strain gauges. The results demonstrated good correlation between the FBG data and the electric strain gauge data.

(3) Trialing the system in a local road pavement subject to subsidence. The results demonstrated good correlation between FBG strains in the pavement and strains in the ground adjacent to the pavement.

(4) Testing of the FBG system in response to wheel loading, to see if resulting spikes in strain might exceed trigger levels and therefore raise an excessive number of false alarms. The trial determined that the FBG sensors did not register changes in strain unless the wheel load was directly above the sensor. While spikes from some sensing locations were sufficient to exceed trigger levels, the

probability of a wheel resting directly above an FBG sensor was considered to be very low, particularly as the sensors were to be installed in the shoulder of the pavement and not within the travel lanes.

6. Embeddment methodology

The flexible asphaltic concrete (AC) surface layer was approximately 100 mm thick. The sensing cables were embedded in this surface layer at a depth of 30 mm–40 mm.

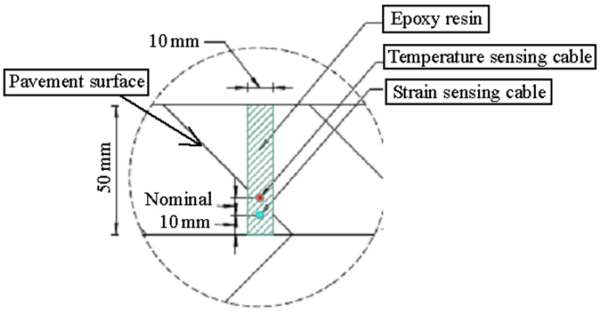


Fig. 6 Strain and temperature sensing cables embedded in the asphaltic top layer of the pavement.

A commercially available 2-component epoxy resin adhesive was selected by the technical committee to bond the sensing cables to the pavement. A number of alternative epoxy resins were considered for this purpose, and the final selection was based on ease of installation, curing time, stiffness, creep and adhesion properties both to the GFRP sensing cable and the AC pavement layer. Test installations were conducted to assist in epoxy resin selection. The selected epoxy resin was used by the highway authority for other in-pavement sensor applications and in the airline industry for runway lighting. The epoxy resin is resistant to physical damage and is black in color. Sensing cable embedment is illustrated in Fig. 6.

The embedment process comprises the following steps which are shown in Fig. 7:

(1) Saw cut a slot along the pavement; clean the slot using an air blast.

(2) Prepare the epoxy resin and pour a bed of the resin into the base of the slot.

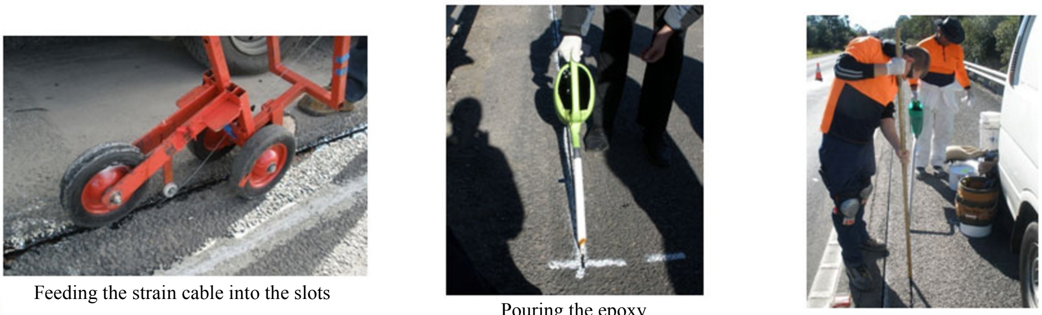
(3) Install the strain sensing cable; cover the sensing cable with a first layer of epoxy resin.

(4) Install the temperature sensors and fill the slot with epoxy resin.

Marking out the site

Saw cutting the slots

Unspooling the temp cable



Feeding the strain cable into the slots

Pouring the epoxy

Using a gauge stick to ensure the cable is embedded at the correct depth

Fig. 7 Sensor cable embedment process.

(5) Terminate the sensing cable ends. The ends of the cables are carried off the pavement in buried conduits leading to in-ground pits similar to those used for telecom cabling applications. Both ends of each sensing cable are terminated with standard fiber connectors for serial multiplexing or connection to signal transmission cables.

7. Monitoring system

7.1 System specifications

Maximum tensile and compressive strains due to systematic mining subsidence were predicted to be in the order of +/- 1000 με equating to approximately +/- 1 nm of the FBG central wavelength shift. The maximum temperature range was expected to be approximately 60 ℃ equating to approximately 0.8 nm of the FBG central wavelength shift. To ensure that an adequate separation between FBG central wavelengths was maintained at all times, the central wavelength spacing of 4 nm was specified for the strain sensors.

As variations in topography and shading result in variations in pavement temperature along the highway, it was determined that an FBG temperature sensor should be co-located with each FBG strain sensor to ensure accurate temperature compensation of the FBG strain sensor and accurate determination of the pavement’s diurnal behavior.

From an assessment of the predicted strain profile, a minimum resolution and accuracy of the monitoring system of at least 10 με was required. The maximum rate of an increase in strain due to systematic subsidence was predicted to be in the order of 10 με/day, while that due to non-systematic ground movement was predicted to be up to 100 με/day. On this basis, an FBG interrogator with a resolution and accuracy of 1 με – 2 με and an acquisition rate of 1 Hz – 4 Hz was selected. The interrogator had a bandwidth of 80 nm, allowing for up to 20 FBGs per channel at 4-nm spacing. With the capacity to switch over 16 channels, a total of 320 FBGs could be supported by one interrogator.

The technical committee decided that FBG sensors should be spaced at 10-m intervals along the hard shoulder of both carriageways over the extent of the subsidence effected region to ensure that, as well as measuring systematic subsidence strain, the FBG sensors would detect the development of localized non-systematic strain and/or cracking or stepping at any location along the pavement. Data were logged every 15 minutes.

7.2 FBG sensor network

The monitoring system network has been installed in stages in line with the progression of the longwall mining panels. The system has been fully operational since February 2009. Since that time, it has been expanded twice, from an initial network of 120 FBG sensors to the present network comprising 840 FBG sensors, 420 of which used to measure strain and another 420 used to measure temperature, distributed over a 2.5-km stretch of both northbound and southbound carriageways.

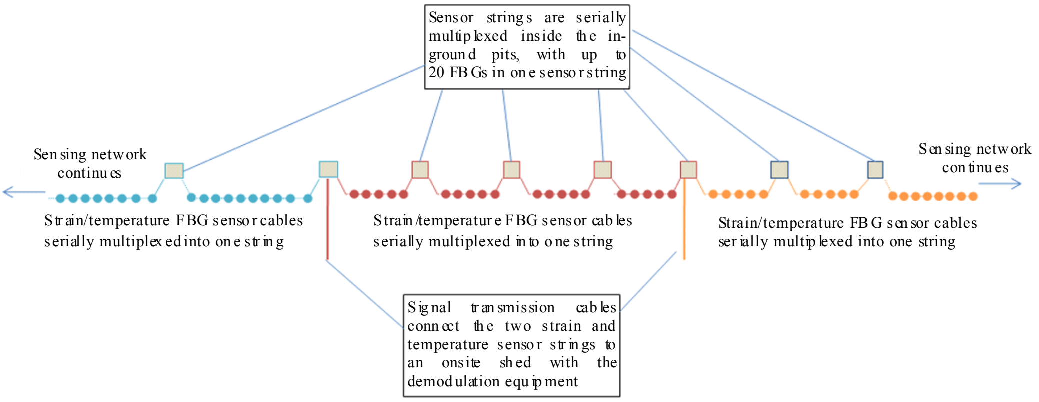


Fig. 8 FBG sensing cables are serially multiplexed and connected to signal transmission cables for demodulation.

The FBG sensing cables vary in the length and hence number of FBGs per cable, depending on the spacing between transverse pavement slots. To efficiently interrogate the FBG sensors, the sensing cables were serially multiplexed into strings of up to 20 FBGs inside in-ground pits located between each sensor cable. Signal transmission cables connected the ends of each sensor string to an onsite demountable building with the demodulation equipment. A diagram of this is illustrated in Fig. 6. One end of each sensing string was connected to the demodulation system while the other was kept available for redundancy in the event of the introduction of a new transverse pavement slot, which would split the sensor string into two.

7.3 Demodulation system

Signal transmission cables were used to connect the FBG sensor strings to a dedicated demodulation system located in an onsite demountable building. The modular demodulation system was progressively expanded as the sensor network expanded, with a total of four modules installed to date. Each module consists of:

(1) A Micron Optics Inc. (www.micronoptics.com) sm125 interrogator with an acquisition frequency of 1 Hz.

(2) A dedicated Micron Optics Inc. sm041 optical multiplexer to increase the interrogator channels from 4 to 16.

(3) A Micron Optics Inc. sp125 processor to process the FBG data.

The modular demodulation system is illustrated in Fig. 9.

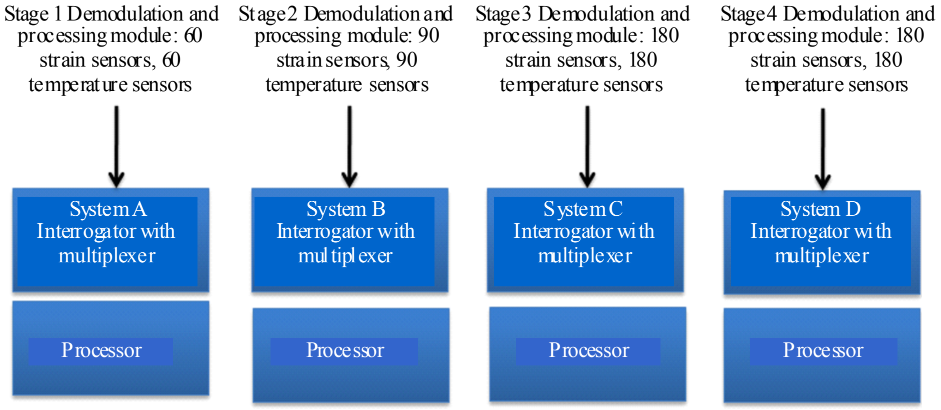


Fig. 9 FBG modular demodulation system.

7.4 Quality assurance

A comprehensive quality assurance system was employed by MOS from manufacture to installation. As a final quality assurance check, the entire in-pavement sensor network was successfully tested by driving a truck with a wheel directly loading each sensor in sequence.

7.5 Data acquisition and processing

FBG central wavelengths were acquired by each interrogator every 4 seconds and converted to relative strain and temperature measurements on the local processor. Custom utility software located on System A processor captured the strain and temperature data at 15-minute intervals and generated the mining strain data sets which were copied to the master control computer. The strains measured by the FBG monitoring system were sent to an overall master control system. The master control system consolidated data from all real-time monitoring systems for the project, displayed the results on a website in real time, compared the mining strain values to pre-set thresholds, and if thresholds were exceeded, sent an alert to the key personnel using short text messaging (SMS) protocol. The strain and temperature data were also uploaded to the MOS secure, web-hosted database every 24 hours. This custom data management and information system provided visualization, post-processing and report generation functionality and was accessed online by the authorized personnel. The pavement monitoring system data acquisition and processing cycle is illustrated in Fig. 10.

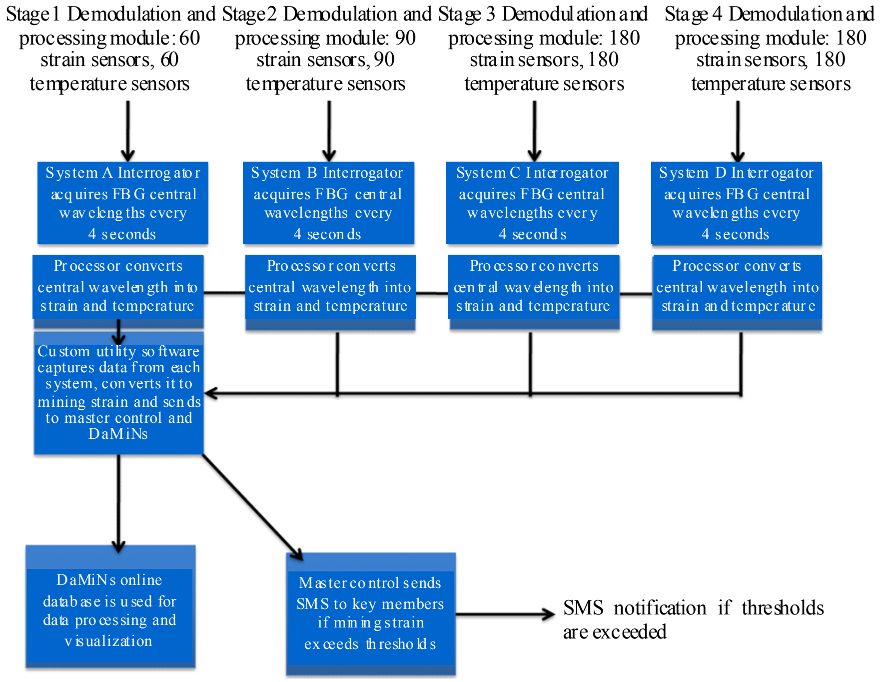


Fig. 10 Data acquisition and processing cycle.

8. Results

8.1 General system performance

The system has operated continuously over a period of 3 years and has proven to be extremely reliable and robust. Triggering of alarms and initiation of associated response actions were predicated on the FBG strain sensor data. The most recent mining phase (active subsidence) spanned a period of 11 months, from July 2010 to June 2011. Over this period, five transverse pavement slots were cut at locations of high compressive strain as measured by the FBG sensors. The ability to interrogate a sensing cable from either end was exploited to good effect, allowing the slot to be cut through the signal cable without loss of the signal from any of the FBG sensors. In effect, the cutting of a slot converted a single sensing cable into two shorter sensing cables. This same feature was exploited to overcome loss of the sensor signal on the one occasion where a sensor cable broke within the pavement due to subsidence induced cracking. Another significant advantage of optical networks was highlighted when a lightning strike damaged a number of the electrical slot displacement transducers but did not detrimentally affect the MOS monitoring system.

In light of its primacy, it was critical that interruptions to data acquisition and transmission were minimized. The system was programmed to send automatic real-time email alerts in the event of:

(1) Loss of detection of one or more individual FBG signals.

(2) Loss of data transmission from one or more interrogation modules.

(3) Loss of data transmission from the MOS control computer to the master control computer.

Response protocols were implemented during the mining phase to ensure that acquisition interruptions were addressed within one hour of an alert being transmitted.

During the mining phase, over 18 million data points were logged and processed. Throughout the same period, a total of approximately 40 thousand data points were not transmitted, approximately 80% of which were due to external impacts, such loss of power or external communication. These results equated to a system reliability of 99.95% in terms of data acquisition.

8.2 Detection of mining-induced pavement strains

Strains due to diurnal temperature fluctuations are ever-present in the pavement. FBG sensors were embedded in the pavement at least 6 months in advance of the commencement of mining to enable the accumulation of sufficient baseline data to derive the strain-temperature relationship for the pavement at each FBG location. The consistency of the strain-temperature relationship allowed the mining-induced pavement strain to be determined by compensating for the temperature related pavement strains.

Over 70% of the FBGs exhibited a linear pavement behavior, with a Pearson's product moment correlation coefficient, $r > 0.9$ or $r < -0.9$, facilitating direct calculation of the slope of the strain-temperature relationship. Of the remaining FBGs, a majority exhibited a non-linear pavement behavior requiring curve fitting and the creation of lookup tables. The technical committee considered that non-linear behavior could be expected from a stiff pavement containing cracks. Examples of linear and non-linear behaviors are shown in Fig. 11.

The ability of the FBG system to detect mining-induced pavements strains is shown in Fig. 12. In this case, five 60-meter-length monitoring strings are shown. Three strings consisted of ground survey pegs spaced 20 meters apart. Two strings consisted of FBG sensors spaced 10 meters apart in the pavement. Each string was located in the same location relative to the side of the extracted longwall. The longwall was extracted over time from right to left across the image, so each string experienced mining-induced changes at different time as mining progressed. It can be seen, however, that a consistent pattern emerged when comparing monitoring data if it was plotted relative to the position of the longwall for each survey epoch, which was measured weekly to three times weekly for ground surveys and every 15 minutes for FBGs. The change in the length of the pavement was estimated by averaging FBG data over the 60-meter length and multiplying the average strain by 60 meters.

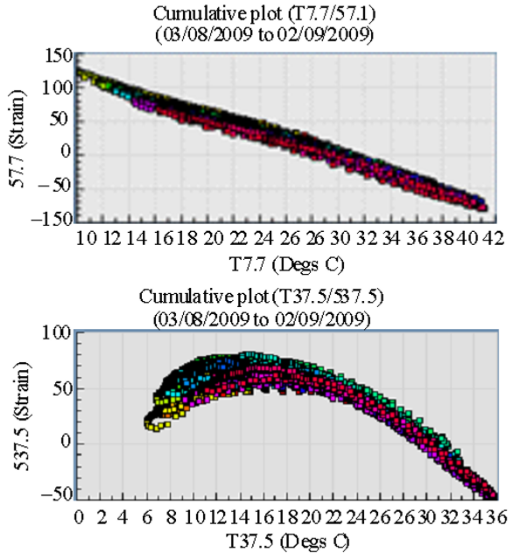


Fig. 11 Examples of linear and non-linear pavement strains-temperature relationships.

It can be seen from Fig. 12 that there is very good correlation between ground survey and FBG strain results at each stage of mining. The small differences between each string are broadly attributable to the changes in ground response to subsidence at each monitoring string.

The accuracy of the FBG system was also tested during mining by comparing changes in the length of the pavement as indicated by the FBG data with changes in the length of the pavement as measured by traditional survey of pins located in the pavement. Figure 13 shows the correlation between the surveyed pavement strains, i.e. the change in the horizontal distance between survey pins and the equivalent pavement strains derived from the FBG data. The correlation was strong over regions where the pavement was subject to compressive strains and behaving homogenously. In regions where the pavement was subject to tensile strains, the FBGs were found to be sensitive to localized regions of high tensile strains such as in the vicinity of cracks. For these regions, averaging the FBG strains does not correlate well with the survey pin measurements. For the purposes of this project, however, compressive strains are of key concern.

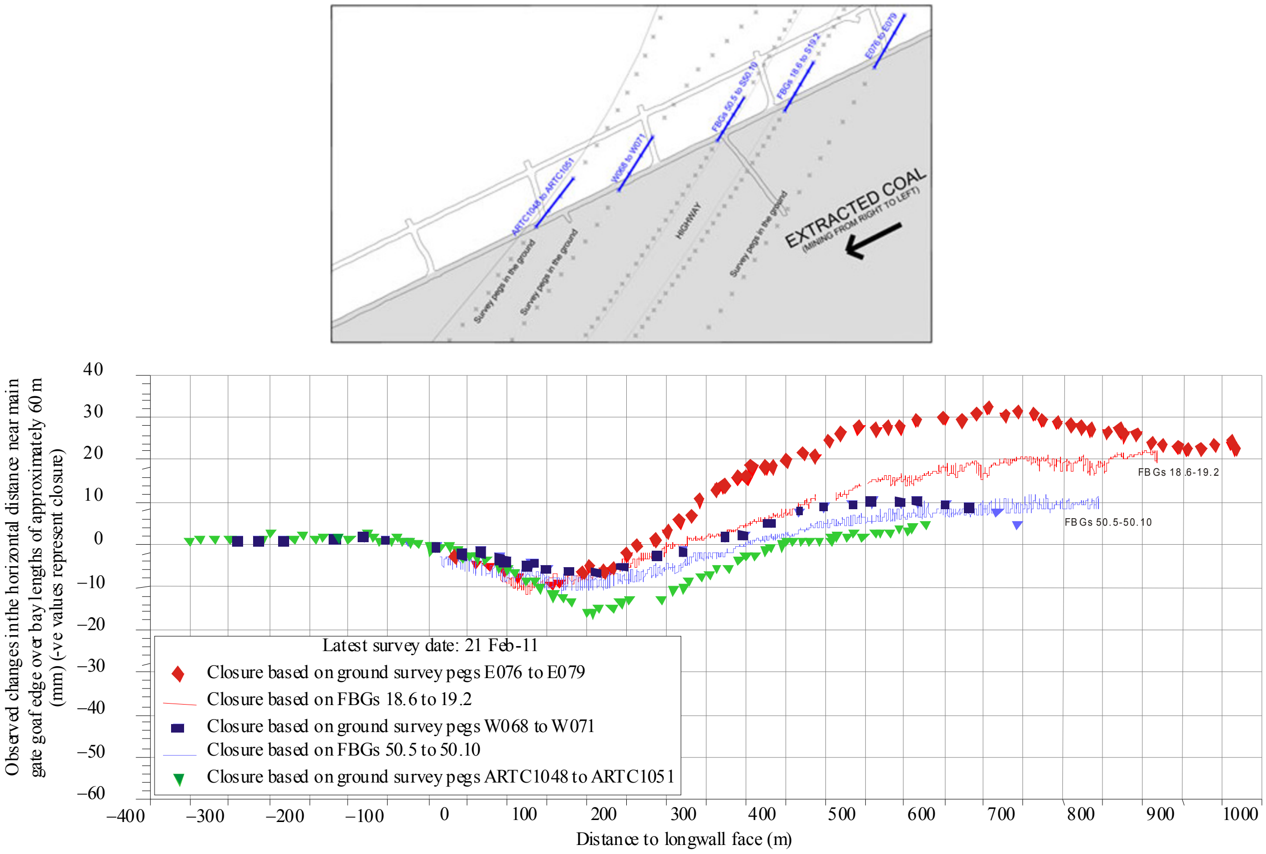


Fig. 12 Observed changes in horizontal distance over 60m bay lengths near edge of longwall.

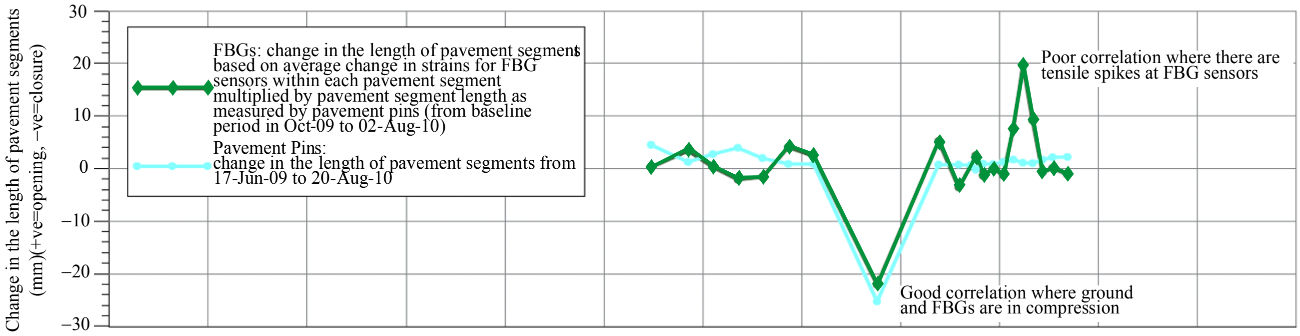


Fig. 13 Comparison between survey pin and FBG strain measurements in the pavement.

8.3 Detection of relief of pavement strain due to construction of additional transverse slots in the pavement

Additional transverse slots were installed proactively in the pavement during mining at locations of increasing compressive strain as detected by the FBG sensors. FBG data were acquired and logged at an acquisition frequency of 0.25 Hz during the installation of additional transverse slots to assess its efficacy as a strain relieving measure. Figure 14 shows the change in compressive strain levels recorder during the cutting of two new transverse slots which bisected a sensor cable at the midpoint between FBG sensors labelled S5.6 and S5.7 and between S6.3 and S6.4, respectively. The stepped response recorded by the FBGs demonstrates the instantaneous strain relieving effect of the pavement slot in the adjacent regions of the pavement. The more distant FBGs measured smaller reductions in the compressive strain as a result of the slot cutting. Figure 14 also demonstrates the good correlation between FBG data and measured changes in the pavement length after the slots were cut by traditional survey of pins in the pavement and measuring of the closure of the pavement on either side of the strain relieving slot by steel tape.

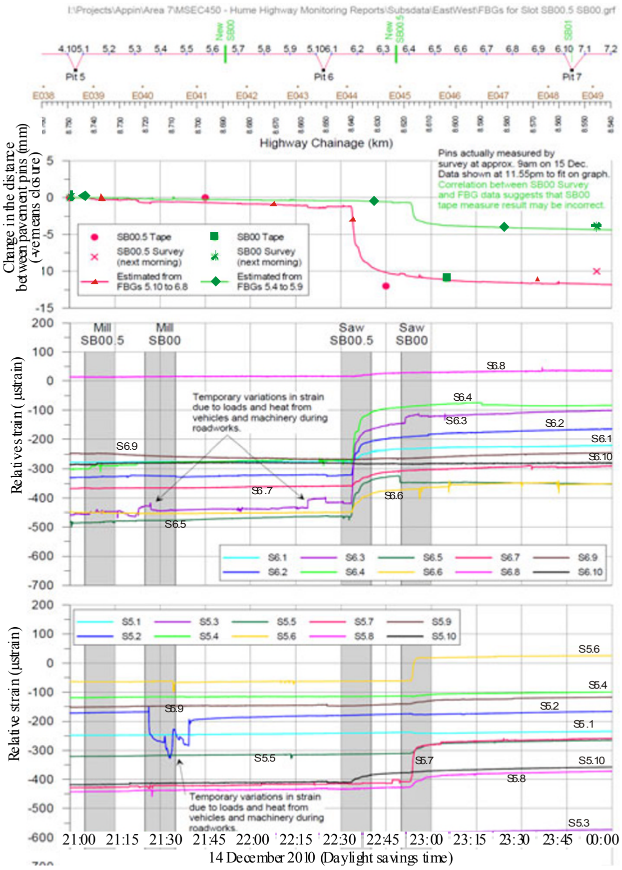


Fig. 14 Reduction in compressive pavement strains recorded during the cutting of a transverse slot.

9. Conclusions

An optical fiber sensing system comprising many hundreds of FBG sensors distributed over many kilometers is being used to monitor the condition of the pavement of a major highway subject to mining induced subsidence effects. Following a lengthy testing and validation process, the system was installed and is currently in its third year of continuous operation. It is a critical component of the comprehensive management system developed and implemented by the highway authority and the mining company to control the effects of mining subsidence on the highway and ensure its on-going safety and serviceability.

The system used robust, easy-to-handle distributed FBG sensing cables developed by Monitor Optics Systems Ltd. which were embedded in the top asphaltic layer of the pavement. The system has proven to be extremely robust and reliable and is highly effective for both the detection of mining induced compressive strains in the pavement and the verification of the effectiveness of mitigation measures. The transmission of alarms and initiation of response actions was predicated on the system data. It is intended that the monitoring system will be expanded over time to facilitate the continued exploitation of high-value coal resources under the highway.

The success of this application points to the suitability of the MOS distributed FBG sensing cables for other ground movement monitoring applications, such as monitoring of landslide-prone regions, railway embankments, excavations and foundations; an immediate development was the use of the sensing cables to monitor strains in airport runways. In this application, the speed of installation of the sensors was considered ideal because any activity on a runway could only be performed during the limited available hours of night closure. The cables have been embedded successfully in both concrete and asphalt covered runways.

These sensing cables are currently employed in studies aimed at overcoming some limitations of conventional vertical and horizontal inclinometers. For this reason, a number of special coatings have been developed to allow the cables to survive in extremely harsh environments and also in soils characterized by the presence of coarse aggregates or gravel.

Acknowledgement

The on-going success of the project relies upon the valuable contributions of a large and diverse team of specialists in pavement design and maintenance, geotechnical and subsidence engineering, systems design, and construction and project management, acting under the auspices of the Roads and Traffic Authority of NSW and the mining company.

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