Short-term Innovative and Exploratory Research Project

ALPHA FOUNDATION FOR THE IMPROVEMENT OF MINE SAFETY AND HEALTH

The Precise Monitoring of Rockbolt Performance Underground

Final Technical Report

1.0 COVER PAGE

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2.0 EXECUTIVE SUMMARY

Hundreds of injuries and fatalities still occur in underground coal mines across the U.S. every year due to rock related falls of ground. The falls of ground can be in the immediate roof, the intermediate roof strata or massive falls of ground. Sometimes if a fall of ground occurs, the approach to avoid a recurrence is to increase the rockbolt length or decrease the spacing without really understanding the root cause of the fall. This directly implies there is a definite lack of knowledge and understanding of roof support system performance in-situ. There is an obvious need for *improving* and *optimizing* rock support design. It is the research team's opinion that in-situ roof bolt monitoring to fully determine the rockbolt loading (tensile, shear and bending) is essential to improve, understand, visualize and optimize underground support design.

This study is focused on investigating and applying two new rock bolt instrumentation systems in the laboratory and in the field. These systems used the optical technologies Distributed Optical Sensing (DOS) and Fiber Bragg Gratings (FBG). It is the first time, a comparison of optical rock bolt technologies has ever been performed and also the first time ever to install these rock bolt instruments in an underground coal mine. Fiber Bragg Grating technology measures along the small Bragg reflectors (same size as that of the short base length resistive strain gauges) placed in a fiber at regular intervals and the DOS technology enables a continuous distributed measurement along the length of the fiber to deliver strain. The optical technologies were also compared to an older rock bolt instrumentation system (digital strain sensors) for comparison of the superiority of the optical strain monitoring systems. An illustration of strain sensors used in this research is shown in the Appendix.

Next, a rock bolt design utilizing three-slots was tested in comparison to the already applied two-slot rock bolt design. The intent of the three-slot rock bolt design allowed, for the first time, to capture the complete strain tensor applied to a rock bolt. This is essential and progressive towards understanding shear directions and magnitudes in-situ, which the research team believes are not well understood in-situ and well represented in support design. The research was carried out by recreating loading mechanisms seen in the field, in the laboratory, as well as proving the innovations through mine trials. This was important as the technologies were capable to not only measure the axial loads, but for the first time, bending and shear loads could also be reliably measured. Finally, the rock bolt instrumentations reliability over time was also determined from the in-situ trials. This is intended to help quantify the current optical instrumentation design and better assess the long term outlook of the instruments current state of the art

Overall the axial, bending and shear behavior of instrumented rock bolts can only be accurately obtained if instrumentation is placed in three slots. Two-slot instrumentation is still useful, particularly for understanding axial behavior, but cannot accurately predict the loading direction and magnitude. The FBG technology currently shows a higher probability of operation over time. The estimated number of failures per year for DOS instruments is nearly triple that of the FBG instruments based upon the current dataset. Based upon the current state of the art, the FBG's are certainly the more "field ready" optical monitoring solution. That being said the DOS technology offers much higher resolution than the FBG's.

3.0 PROBLEM STATEMENT AND INNOVATION OBJECTIVE

To date, very limited research in regards to in situ roof bolt monitoring has been conducted. This is mainly due to the lack of appropriate instrument availability and reliability, instrumentation costs, instrument strain resolution and the complexities of data processing and conceptualization.

All previous in situ rock bolt monitoring solutions to date have been implemented via two methods. The first method incorporated opposing pairs of short base length resistive strain gauges on opposing sides of a roof bolt. A more recent method uses long base length displacement strain gauges spaced at regular intervals on opposing sides of a roof bolt in a similar fashion. It has been found that these designs have significant shortcomings as neither capture the entire strain profile along the bolt which is clearly explained in the Section 5.1.1. These designs also only used two diametrically opposed slots which cannot capture a shearing direction.

These strain gauge systems, using only two slots, can misinterpret any reaction loads in the bolt depending on where the load is applied relative to the two slots. Consider that to obtain a strain tensor, three gauge rosettes are needed and for the same reasons, three orientations of strain gauges along a bolt are also needed (i.e. 3 slots).

Due to these limitations, in-situ rock-bolt interaction is still not truly understood. This lack of understanding contributes to rock related fatalities and injuries – which are all too common and still occur every year in underground mines.

This project compared the performance of long displacement gauges and two optical technologies (DOS and FBG) in both two and three slotted rock bolts (cut at 120° intervals around the bolt circumference) to better understand the tensile and shear loads applied in different positions around the circumference of the bolts in several different laboratory test scenarios. The laboratory scenario is intended to mimic the loading mechanisms occurring in-situ. In addition, a new and superior fiber optic and strain measurement technology (distributed optical sensing) developed mainly for the aircraft industry, has been modified (by YieldPoint Inc.) for rock bolt applications that promises significant potential to overcome all the present shortcomings. This technology is capable of a significant improvement of strain measurement per bolt length and shows the potential to be an easily marketable and utilized technology for the industry, which has not been the case in the past. Additionally, a competing optical fiber technology (Fiber Bragg Gratings) was also implemented to observe its advantages and disadvantages.

Significant research gaps in the area of ground control still exist, but this research will revolutionize in situ bolt monitoring. Proof of a new technology and its in-situ application will help to pioneer the way to better understanding of primary bolt rock interaction.

Through this effort a reduction of rock related falls of ground and injuries will hopefully come to fruition.

4.0 RESEARCH APPROACH

Instrumentation is the leading and most viable option for improving underground safety in coal mines. However, issues still exist, as mentioned previously, due to the lack of appropriate instrument availability and reliability, instrumentation costs, instrument strain resolution and the complexities of data processing and conceptualization.

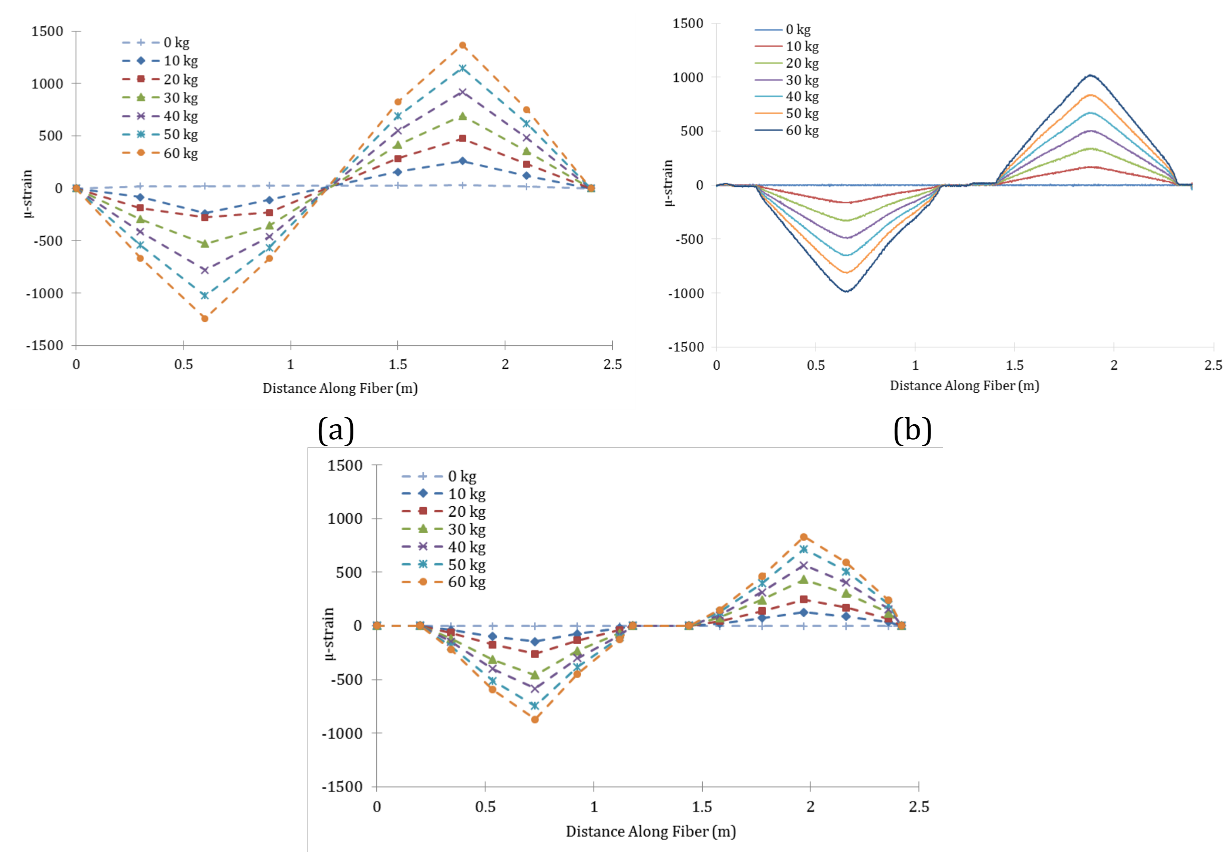
One of the most comprehensive studies involving instrumentation in coal mining is attributed to Signer in the 1980s and thereafter Spearing (2010). These studies involved diametrically opposed and two-slot resistive strain gauges for instrumentation (Signer) and diametrically opposed two-slot displacement sensors and digital instrumentation (Spearing). Both of these forms of instrumentation were expensive and offered poor strain resolution. Signer's research, was the most comprehensive as it incorporated lab, field and theoretical studies, but is dated now (over twenty years), Spearing's research conducted another comprehensive study but was mainly focused on field work and had little laboratory work related to instrumentation. Both studies also focused solely on two-slot instrumented rock bolts.

This study is different, in that, it addresses all the underlying issues in instrumentation as previously mentioned. An innovative technology - both from the cost and strain resolution point of view - for instrumented rock bolts is being applied (optical fiber technology). Additionally, this is the first study ever which incorporated rock bolt instruments with three slots – the first attempt to capture the full strain tensor. These instrumented bolts were also installed for the first time in-situ. This is the first time that multiple rock bolt instrumentation technologies have also been compared in the lab and in-situ. Other previous technologies have only focused on a single instrumentation form.

Finally, the overall reliability of the fiber optic, strain-measuring, roof bolt technologies in the field was monitored in order to quantify, for the first time, their overall performance, and therefore, offer a predictive measure to help improve the current bolt design. This enables improvements for future rock bolt instrumentation projects. The following are highlights of research conducted to validate the proposed instruments viability and design.

4.1 Optical System Performance Enhancements

One of the obvious benefits of the optical technologies is the measurement locations along the rebar. Previous technologies were capable of measuring strain at <20 points along a rebar which was also adopted in measuring strain using the FBG technology at 10 points (20 cm spacing between the sensors) along the rebar (Appendix: Figure 17) whereas the DOS technology can measure at >2000 points (Appendix: Figure 17) with comparable accuracy (+/- 10 micro-strains) as shown in Figure 1. Consequently the complete strain profile along the rebar is measured. Additionally, this optical technology allows for data acquisition immediately after installation as the technology is intrinsically safe – a feature not associated with previous technologies.



(c)

Figure 1. 3 point bend tests of (a) two slot digital bolt (b) two slot DOS bolt (c) two slot FBG bolt

4.2 Three-slot Strain Measurement Computations

The instrumented bolts were developed to measure the direction and magnitude of the bending load on installed bolts. It involves determining strains in three planes along the axis of the bolt. These 3 strains are called triads of strains and are determined at points along the three-slot rebar (Figure 2). These strain triads can be interpreted to measure bending deformations in any direction. The axial strains are determined along the bolt length from equation 1:

$$\epsilon_{(l)axial} = (\epsilon_{1(l)}+\epsilon_{2(l)}+\epsilon_{3(l)})/3 \qquad (1)$$

where $\epsilon_{1(l)}$, $\epsilon_{2(l)}$, and $\epsilon_{3(l)}$ are the strain readings on slot 1, slot 2, and slot 3, respectively, at the same point along the length of the bolt.

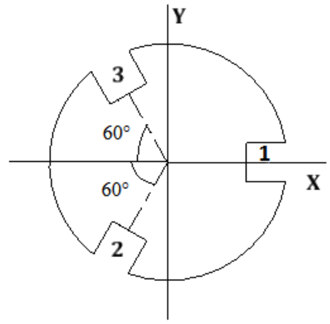


Figure 2. Cross-sectional area of three-slot rebar

The bending in the three slot rebar can be calculated individually along the x and y directions as shown in the figure 2. The corresponding bending strain is calculated with respect to slot one as:

$$\epsilon_{(l)x\text{-bend}} = (\epsilon_{(l)1} - (\epsilon_{(l)2} \cos(60°) + \epsilon_{(l)3} \cos(60°))/2 \quad (2)$$

$$\epsilon_{(l)y\text{-bend}} = (\epsilon_{(l)2} \sin(60°) - \epsilon_{(l)3} \sin(60°))/2 \quad (3)$$

$$\epsilon_{(l)total\text{-bend}} = ((\epsilon_{(l)x\text{-bend}})^2 + (\epsilon_{(l)y\text{-bend}})^2)^{1/2} \quad \text{and} \quad \varphi = \tan^{-1}(\epsilon_{(l)y\text{-bend}} / \epsilon_{(l)x\text{-bend}}) \quad (4)$$

where $\epsilon_{(l)x\text{-bend}}$ is the bending strain at length (l) along the first slot; $\epsilon_{(l)y\text{-bend}}$ is the bending strain perpendicular to the first slot at the same length (l); $\epsilon_{(l)total\text{-shear}}$ is the total bending strain at length (l) along the angle φ from slot one direction.

4.2.1 Verification of Axial and Shear Strain Magnitudes and Direction – An Applied Example

A #6 rebar (3/4" diameter) with 3-slots is subjected to a perpendicular force (i.e. in the x-direction) at the bar center similar to that of Figure 3. The force is applied to slot #1 and if we assume the remaining slots are oriented at 120° from each other the corresponding strains at the point of application of force (i.e. the same point along the rebar length) are as follows:

$\epsilon_{1(l)}$ = -853 μ-strain $\epsilon_{2(l)}$ = 426.5 μ-strain $\epsilon_{3(l)}$ = 426.5 μ-strain

$\epsilon_{(l)axial} = (\epsilon_{1(l)}+\epsilon_{2(l)}+\epsilon_{3(l)})/3$
$\epsilon_{(l)axial} = (-853 + 426.5 + 426.5)/3$
$\epsilon_{(l)axial} =$ 0 μ-strain

Therefore the rebar is undergoing zero axial strain which should be the case since it is subjected only to a bending force.

$\epsilon_{(l)x\text{-bend}} = (\epsilon_{(l)1} - (\epsilon_{(l)2} \cos(60°) + \epsilon_{(l)3} \cos(60°))/2$
$\epsilon_{(l)x\text{-bend}} = (-853 - (426.5 \cos(60°) + 426.5\cos(60°))/2$
$\epsilon_{(l)x\text{-bend}} =$ 639.5 μ-strain

$\epsilon_{(l)y\text{-}bend} = (\epsilon_{(l)2} \sin(60°) - \epsilon_{(l)3} \sin(60°))/2$
$\epsilon_{(l)y\text{-}bend} = (426.5 \sin(60°) - 426.5 \sin(60°))/2$
$\epsilon_{(l)y\text{-}bend} = 0$ μ-strain

Therefore the rebar is undergoing zero strain in the direction perpendicular to the loading vector.

$\epsilon_{(l)total\text{-}bend} = ((\epsilon_{(l)x\text{-}bend})^2 + (\epsilon_{(l)y\text{-}bend})^2)^{1/2}$
$\epsilon_{(l)total\text{-}bend} = ((639.5)^2 + (0)^2)^{1/2}$
$\epsilon_{(l)total\text{-}bend} = 639.5$ μ-strain

$\varphi = \tan^{-1}(\epsilon_{(l)y\text{-}bend} / \epsilon_{(l)x\text{-}bend})$
$\varphi = \tan^{-1}(0/639.5)$
$\varphi = 0°$ relative to slot #1

4.3 Three-slot Strain Verification Testing

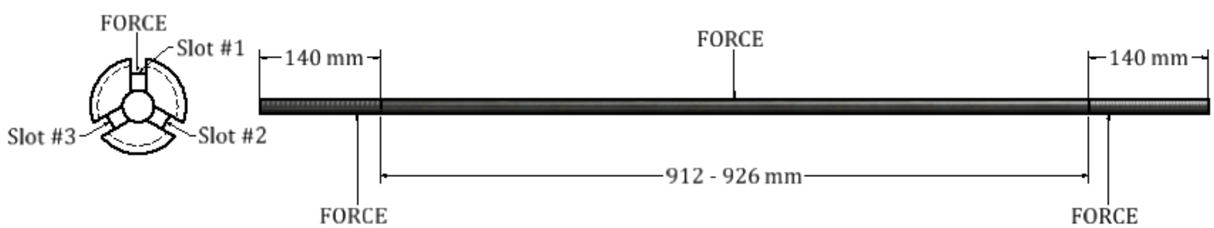
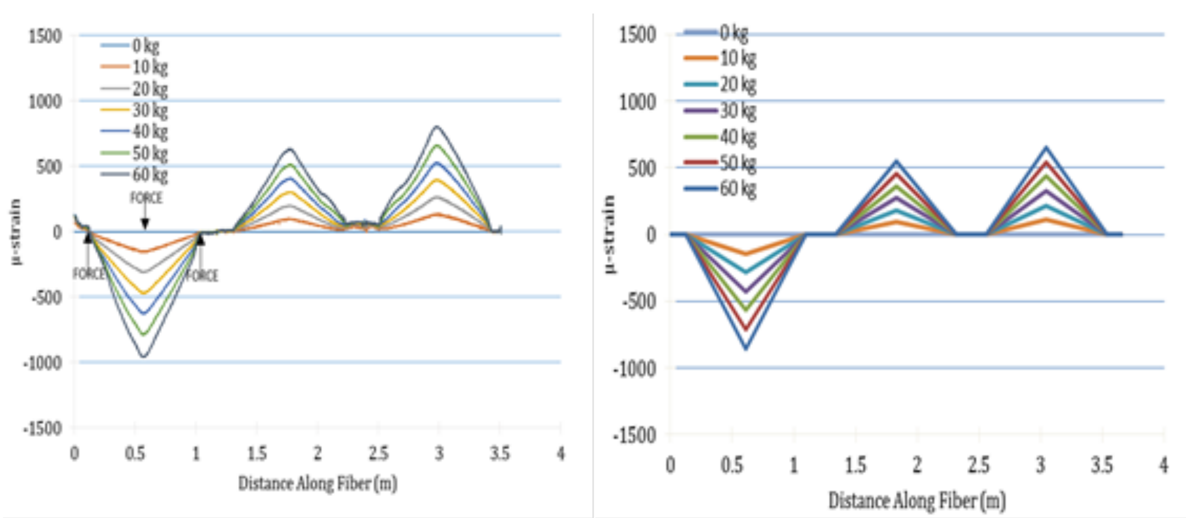


Figure 3: Example of a three point bend on a 3-slot rebar

Three point bend tests were conducted to validate the three slot instrumentation system. The force was applied at the center of the rebar and the test rig developed an equal and opposite forces on the ends to show the applicability of the optical fiber in three slots as shown in Figure 3. The total (i.e. bending and axial) strain measured by the optical fiber in all the three slots are as shown in the figure 4a. The three point beam bending test readings were within 10% of the corresponding theoretical values based on Euler Bernoulli beam theory. The shapes of the two sets of strain profiles were identical, which can be more informative than the absolute strain magnitudes (Figure 4). As the fiber is looped through the grooves on three sides of the rebar, one represents the compressive (-ve) strains and the other two tensile (+ve) strains. The results show that the DOS technology can accurately predict the bending direction of the bolts. The machining inconsistency in slot preparation can lead up to 10° error, hence this is been highlighted in unequal strain profiles in slot two and slot three.

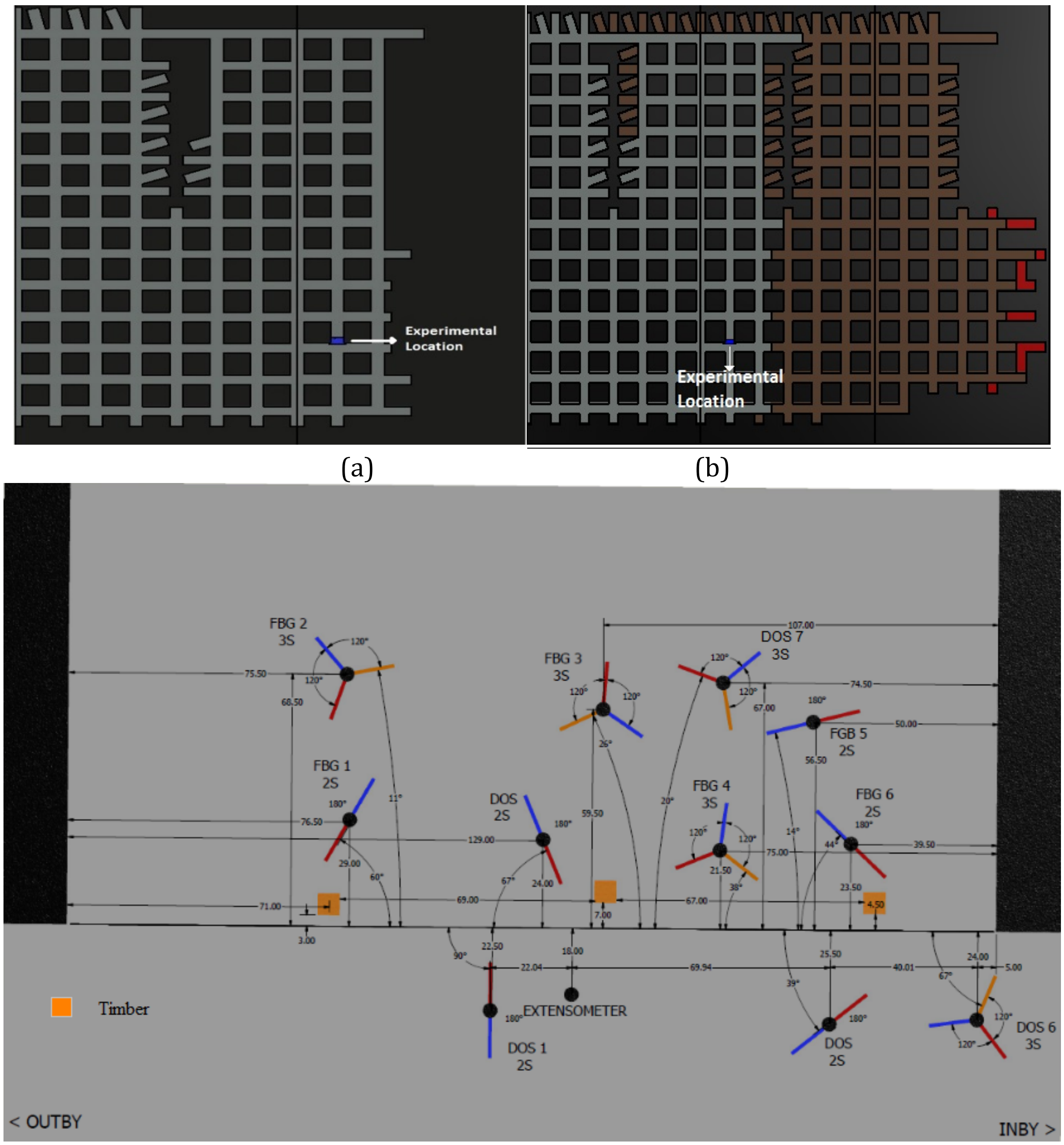


(a) (b)

Figure 4. a) Measured and b) computed strain profiles along the length of the fiber using the proposed theoretical equation for a three slot configuration.

4.4 Field Trials of Mines A and B

Field trials were conducted in a shallow (about 120 ft deep) coal mine (designated Mine A) and a deeper (630 ft) coal mine (designated Mine B). Both were room and pillar mines and extract from the Illinois Basin. For these test sites, the instrumentation included: two-eight foot long extensometers (anchored at 1,2,3,4,6 & 8 ft into the immediate strata), three two-slot DOS rockbolts, eight two-slot FBG rockbolts each, twelve three-slot DOS rockbolts and three three-slot FBG rockbolts (all rockbolts of 4 foot length). Mine plans of daily face positions, have been assembled in order to track whether any locally induced displacements, observed in the instrumented bolts, can be attributed to any path dependent exacavations of Mine A and B. Figure 5 (a & b) and 6 (a & b) showing the mine plans of the first and last day of monitoring period of Mine A and B respectively. The orientation of the bolts slots are shown in Figure 4c and 5c, and have been mapped for both test locations. The monitoring station is extensive, and is shown underground in Figure 7a. An example of a post-installed instrumented FBG bolt composed of a thicker lead wire is shown in Figure 7b.



(c)

Figure 5: Mine A - (a) panel face position at the start of the instrumentation installation (blue box shows the test site), (b) final face positions at the end of the rock bolt monitoring period (i.e. four weeks later), (c) locations and orientations of the instrumented rock bolts.

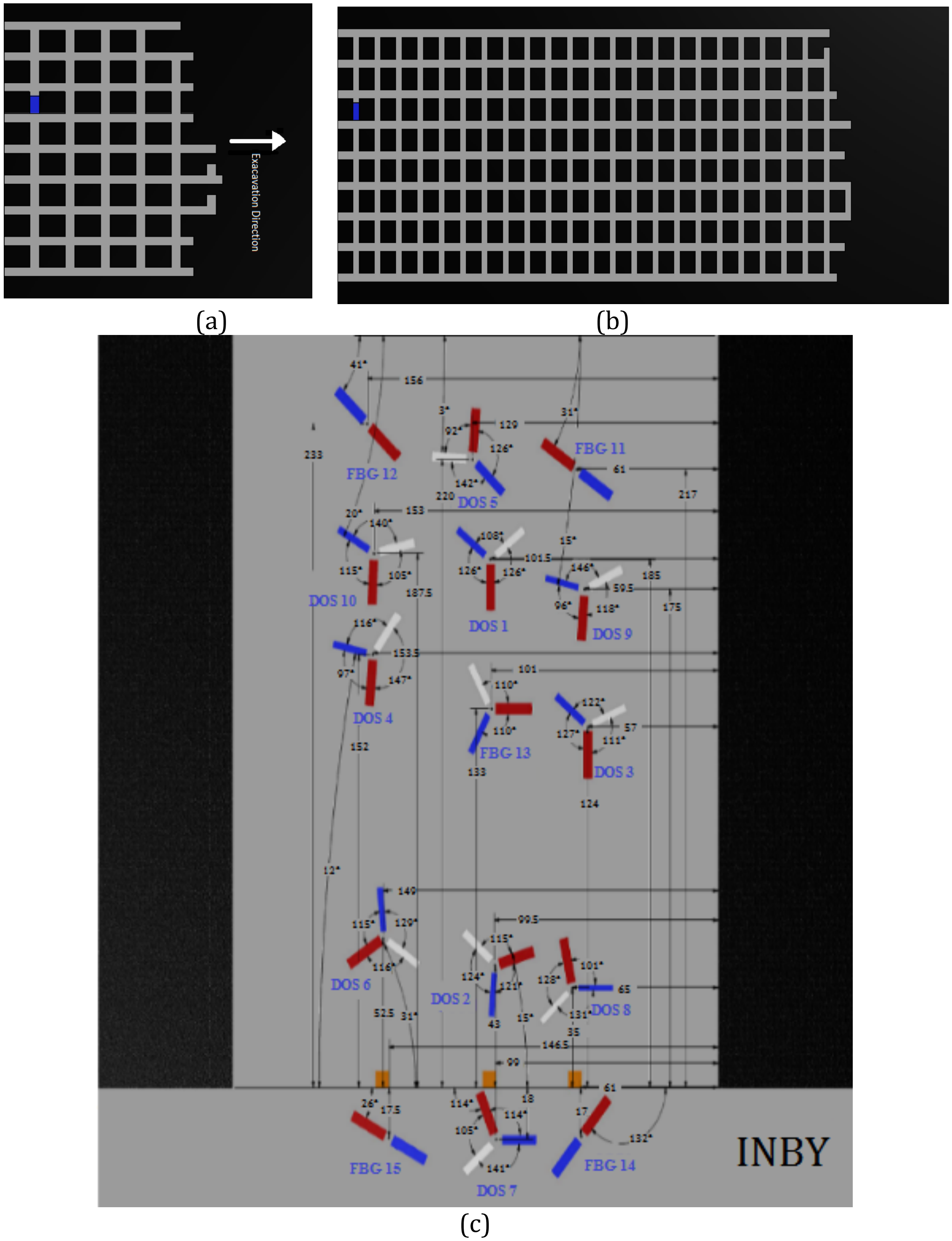


Figure 6: Mine B - (a) panel face position at the start of the instrumentation installation (blue box shows the test site), (b) final face positions at the end of the rock bolt monitoring period (i.e. four weeks later), (c) locations and orientations of the instrumented rock bolts.

(a) (b)

Figure 7: (a) The extensive monitoring equipment needed. (b) The installed instrumented rock bolts with the optical fiber leads.

The processing of the data is time consuming due to the magnitude of data generated, and a finalized method for calculating displacements, magnitudes and direction of the forces induced in fully-bonded rockbolts has been developed. A paper has been submitted and accepted for publication by the CIM Journal titled: "Measuring Roof Bolt Response to Axial and Shear Stresses: Laboratory and First In situ Analyses".

4.5 Assessment of the Instruments Reliability

The following contains excerpts from a chapter on rock bolt instrumentation, soon to be published by the research team, in an International Society of Rock Mechanics book (Spearing, Kostecki & Jessu, 2016). Some details have been omitted in order to minimize the length of this section.

Undoubtedly, failures of instruments tend to occur in situ. This is not necessarily because of a design flaw, but has more to do with the harsh environment instrumented rock bolts are subjected to over time. As a result, manufacturers and researchers must adjust to these environments and make refinements to the instrument design to improve the instruments reliability within a mining environment over time. Therefore a quantifiable measure (statistical reliability) of the FBG and DOS bolts have been determined to better assess the long term outlook of the instruments current state of the art.

Based upon past instrumentation studies, mainly by Spearing (2011), the longer the monitoring period the greater the chance of capturing significant axial and shear loadings which can play as a key indicator of a current support systems effectiveness in an entry. This is especially true for shallow mines. Therefore, it is obvious the longevity of instrumentation in-situ is critical to improving support design practices.

Therefore a *prediction* of the technologies statistical reliability, over a year was conducted based upon the current dataset. This study only monitored for twenty-four days at each instrumentation site as this was a pilot study intended to expand into a larger project and additionally the cost of the interrogator rental was high.

The following is a survival and cumulative hazard (risk) model developed based on underground testing at Mine A and B (Figure 8). This is the first time these technologies have been incorporated in an in situ scenario and the following results portray *only* the current state-of-the-art in terms of in situ mining studies. Additionally, a 95% upper and lower confidence interval was given for each model.

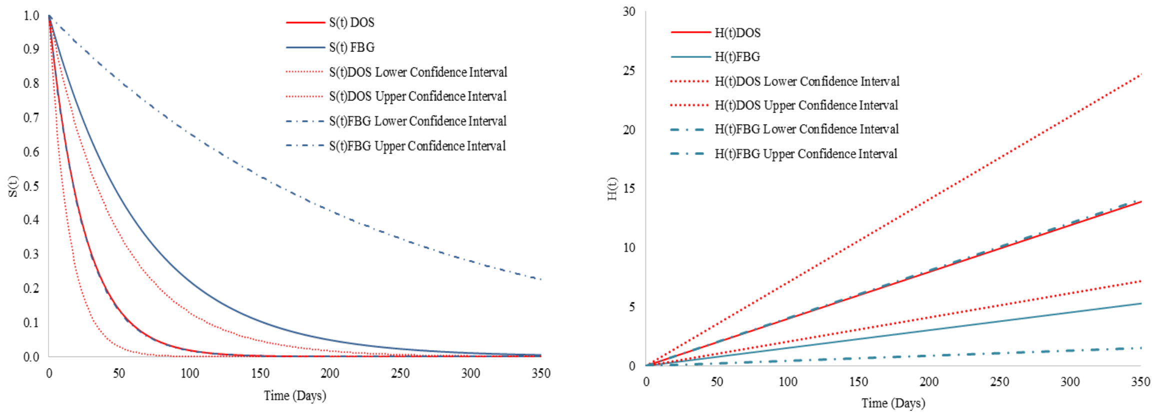
Statistically, *reliability* is defined as the probability that an item is functioning at time (t). This probability is given as a plot of a survival function S(t). Additionally, the cumulative hazard function H(t) gives the cumulative *risk* at time (t), or in this case, the number of failures that have occurred by time (t).

All the rock bolts functionality was monitored up to twenty-four days, which was the end of each of the two in situ monitoring periods. A rock bolt was considered functioning if it could be recognized by the optical interrogators and were not obviously damaged on installation. The number of failures for the DOS and FBG instrumented rock bolts were logged, and Table 1 gives the operation time in days. It should be noted that an operational time of 0 days indicates the bolt failed on installation.

Table 1: The observed operation time of the in-situ DOS and FBG instruments at Mine A and B. Note the values highlighted in the table are those installed at Mine A and those not highlighted are those for Mine B.

Operational Time (Days)																	
Bolt #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
FBG	24	24	24	24	24	24	7	0	24	24	0	-	-	-	-	-	-
DOS	6	6	0	2	0	24	24	24	24	8	24	16	9	23	24	24	14

Based upon this dataset, and shown in Figure 8, the FBG technology shows a higher probability of operation over time. In fact, the predicted lower bound of failure follows the mean survival function for the DOS technology. From the cumulative hazard function it is easy to see that, under the current installation practices and instrument design, and in terms of this particular underground coal mine study, the estimated number of failures per year, for DOS instruments (14.5) is nearly triple that of the FBG instruments (5.5). This does not indicate that the DOS technology is inferior to FBG's. Instead, based upon the current state of the art, the FBG's are certainly the more "field ready" optical monitoring solution.



(a) (b)

Figure 8: Plots of (a) the survivor function and its confidence intervals for FBG and DOS technologies and (b) the cumulative hazard function with confidence intervals for FBG and DOS technologies.

Various challenges still remain including: maintaining a clean environment underground to improve the reliability of the optical instrument long-term (i.e. dust seems to be the biggest issue), creating a more mobile workstation, finalizing the best installation method (i.e. spun with a bolter or manually grouted) and improving the instrumented head to make the bolt less suseptible to damage when spun on installation.

5.0 SUMMARY OF ACCOMPLISHMENTS AND INNOVATION HIGHLIGHTS

5.1 Accomplishments

The results to date are significant and represent a major breakthrough in rock bolt instrumentation and load determination. The following discoveries were made based on the laboratory and in situ testing to date.

5.1.1 Validity of 3-Groove and Instrumentation Rock bolt Technology

Three groove based rock bolt instrumentation clearly shows for the first time the complete bending and shear strain directions. No prior knowledge of estimated shearing direction is needed to orient the instrumented bolts. This is itself a major breakthrough – particularly for further in-situ instrumentation studies. An example of the two and three slot rock bolt design is shown in Figure 9.

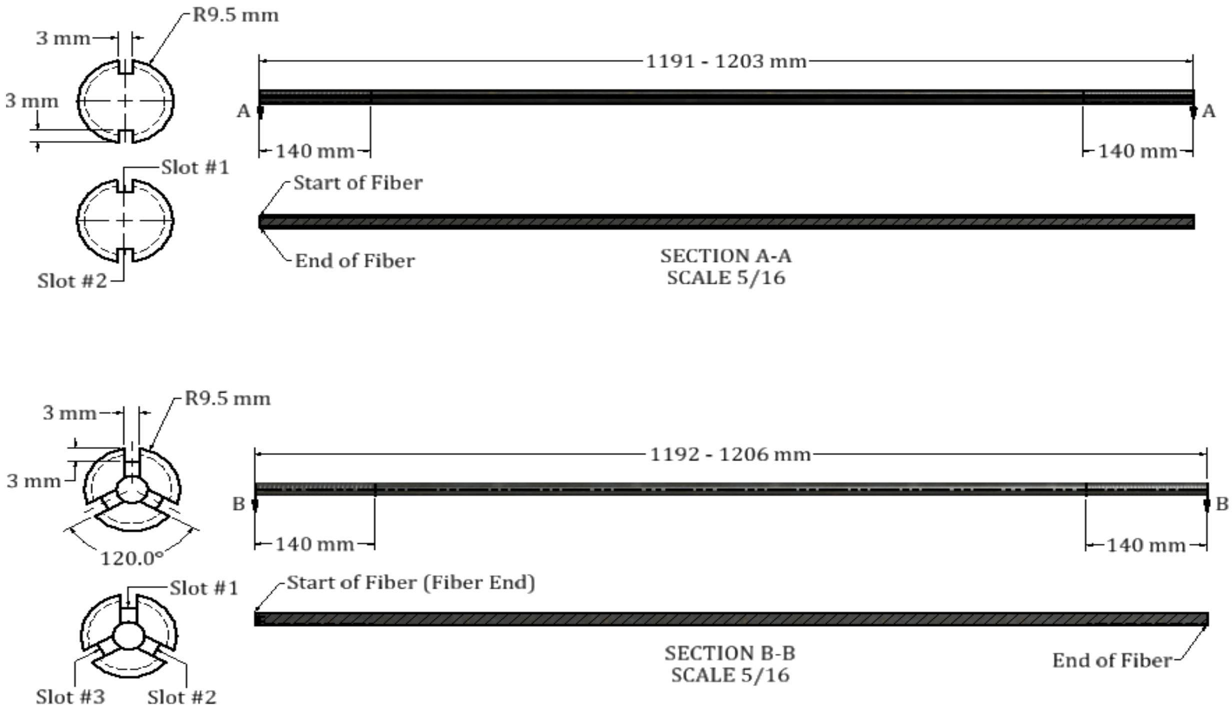
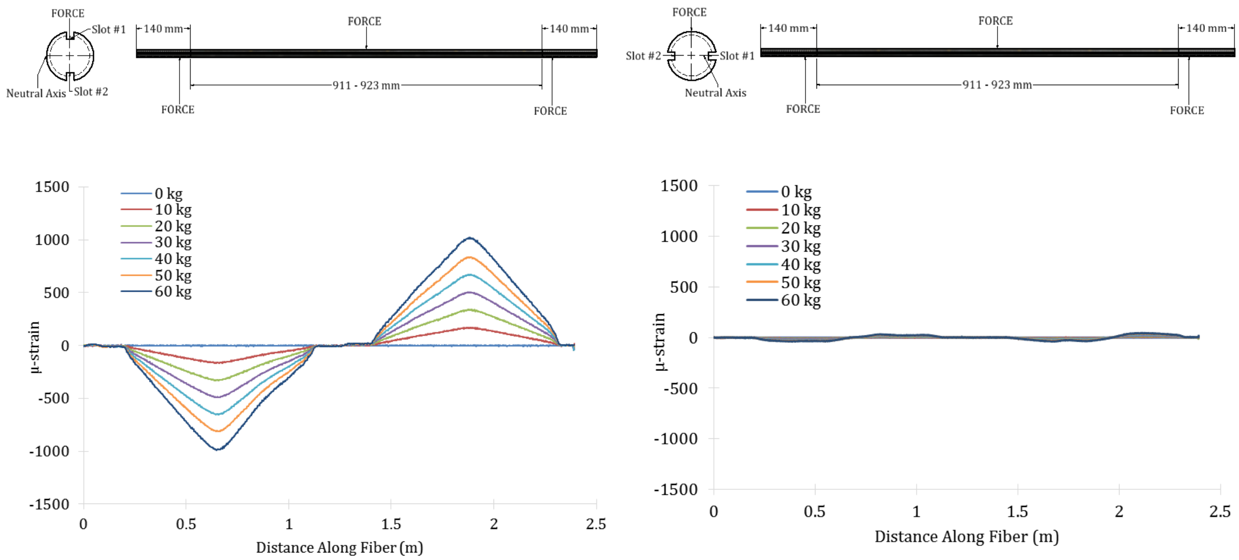


Figure 9: Two and three slot orientations utilized for the FBG and DOS technologies

As an example, a three-point bending test was conducted on two-slot and three-slot rebar to show the shortcomings of the two groove system. When a two slot rebar is loaded at an angle relative to the slots, only a component of force develops strain in the optical fiber. For example, when the rebar is loaded on the neutral axis, there is no strain development in the optic fiber and the applied force is missed entirely. An example of a two-slot DOS rebar loaded upon slot #1 is shown in Figure 10a and a two-slot DOS loaded upon the rebar's neutral axis is shown in Figure 10b. It is obvious from these results the applied force is missed entirely.

In contrast, when the three-slot rebar is loaded at an angle relative to the grooves, the components of force are redistributed along the grooves to give a bending strain profile as shown in the Figures 11a and 11b. It is obvious from these results that no matter the location of the applied force, the three-groove technology can better capture the true loading profile of the rock bolt.



(a) (b)

Figure 10. Results of a three point bending test of: a) A 2 Slot DOS Bolt Loaded Directly on Slot #1 b) A 2 Slot DOS Bolt Loaded Directly on the Neutral Axis. Note the Neutral Axis is shown in the above corresponding figures.

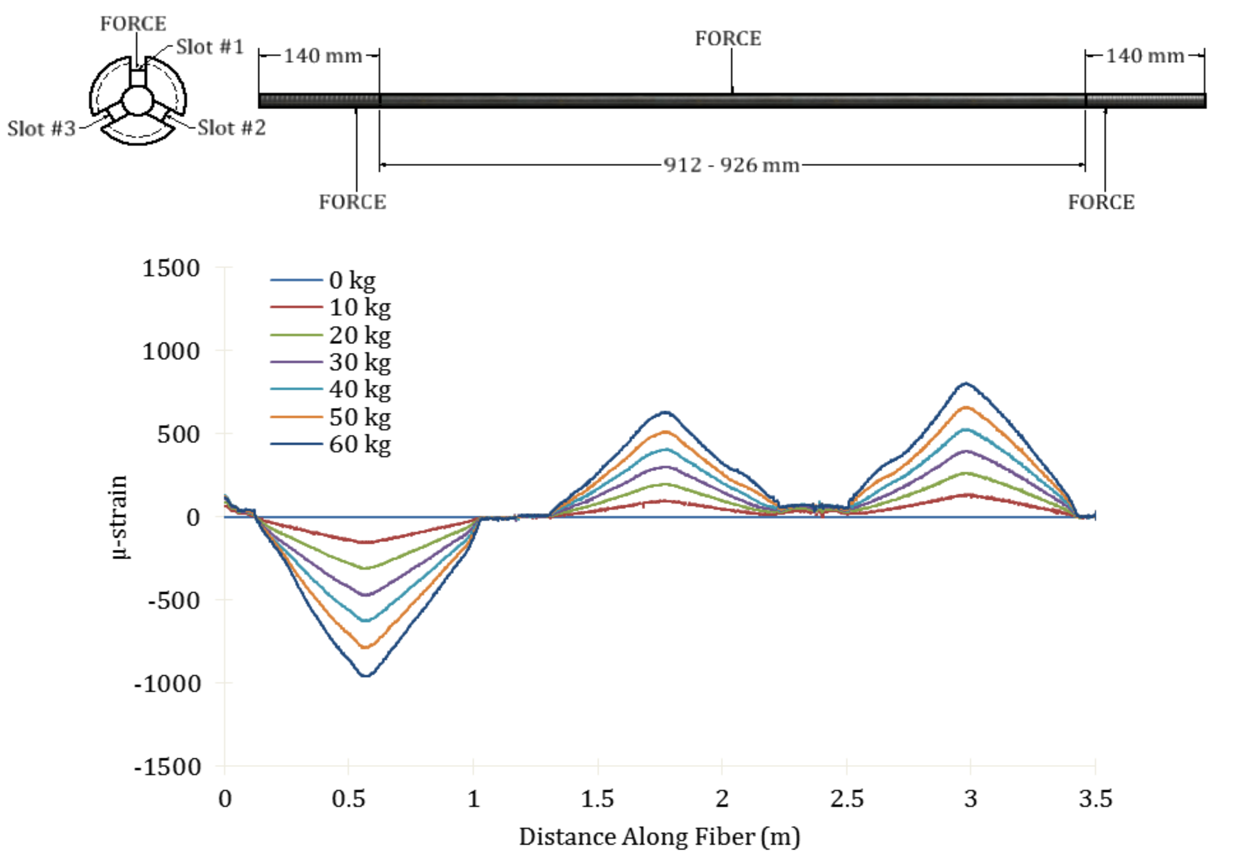


Figure 11. Results of a three point bending test of a 3 slot DOS bolt loaded directly on slot #1

For comparison of the FBG and DOS technologies, a three-point bending test of Figure 11 for a FBG three-slot instrument is shown in Figure 12. Both FBG and DOS instruments were of comparable cost so it is evident that the DOS instrument provides much higher resolution along the loading profile of the bolt than the FBG technology. Note that the dashed line between the markers on Figure 12 represents part of the loading profile that is missed entirely due to the spacing between FBG sensors.

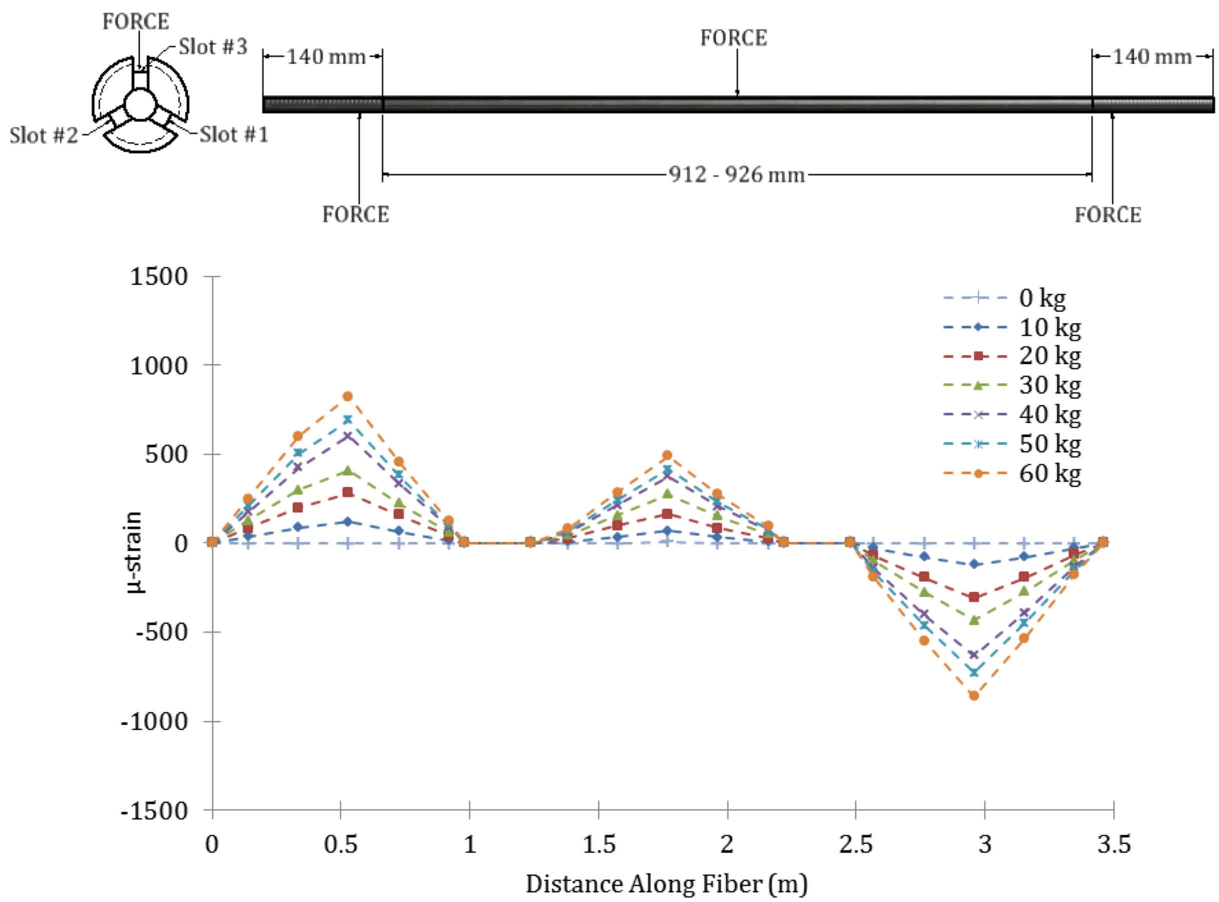


Figure 12. Results of a three point bending test of a 3 Slot FBG Bolt Loaded Directly on Slot #3

5.1.2 Accomplishments Relative to Current In-situ Support Design

Figure 13 (a) and (b) represent the setups of the double shear test and angle double shear test. The deflection in the rebar is least when the rebar is installed perpendicular to the shear planes rather when installed at an angle to the rebar. The maximum deflection of the rebar in the double and angle double shear test at 5kN force was 1.34 mm and 1.96 mm, respectively as shown in Figure 13 (c) and (d). This confirms that the concept of the perpendicularity of rebar to the bedding planes is imperative to minimizing shear displacements in underground stratified deposits.

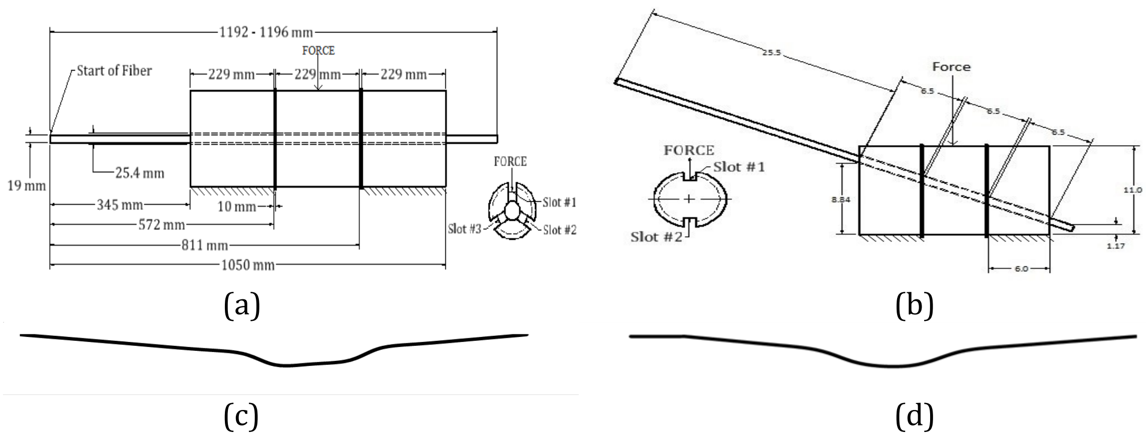


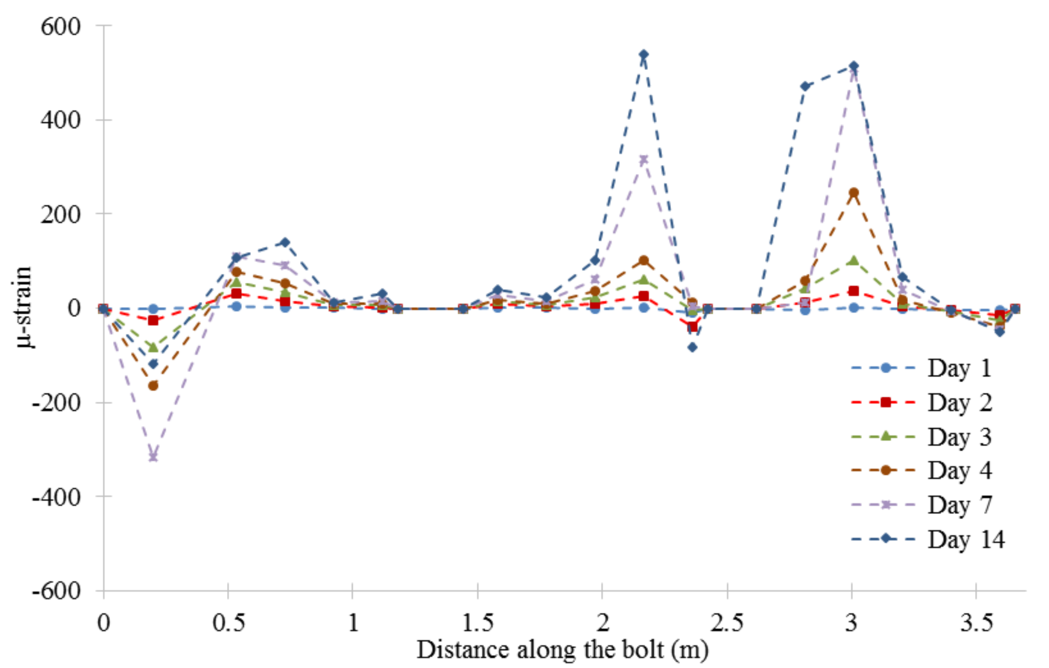
Figure 13. (a) Setup of double shear test (b) Setup of angled double shear test (c) deformed bolt shape in double shear test at 5kN (d) deformed bolt shape in angle double shear test at 5kN

5.1.3 Validation and Usefulness of 3-Groove Rockbolts In-situ

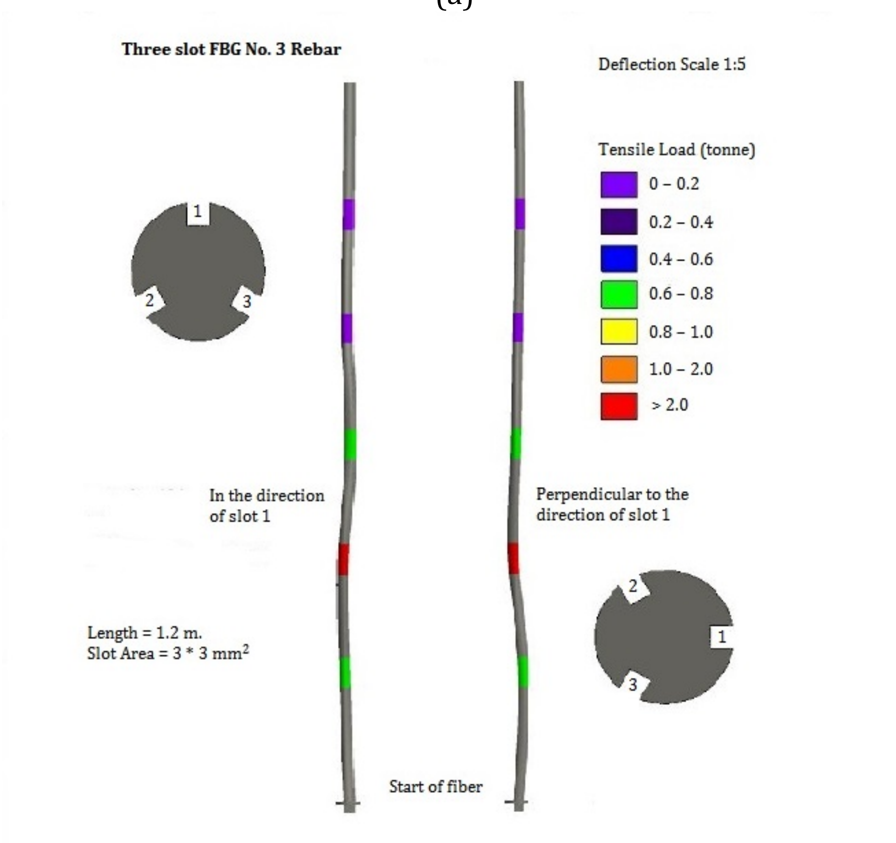
Results for an FBG bolt installed in Mine A are shown in Figures 14. The figure 14a represents the strains developed in each slot of a three-slot FBG rebar and it can be observed that the peak strains are developed in the sensors at the head of the bolt (i.e. sensor#1, sensor#8, sensor#11 and sensor#12). The research team is confident that if the strain magnitudes and locations along the bolt length, slot orientations, bolt dimensions, cross-sectional area and fiber positioning relative to the bolt dimensions are known, then the complete displacement profile of the bolt in both the directions can be rendered as shown in Figure 14b. This is instrumental to the project, as it shows, for the first time, the locally induced displacements upon a post-installed rockbolt without overcoring. The maximum tensile load of more than two tonnes was found near the head of the bolt which corelates to the peak strains observed by the sensor#8, sensor#12 and sensor#2 situated at that position.

Instrumented rockbolts were installed as the secondary support and were monitored for a period of two weeks in a shallow 40 m deep underground mine. Therefore, it can be concluded that the strains developed in the instrumented bolts are small and the maximum load was found to be little more than two tonnes which is significant enough in a shallow cover mine.

It is obvious, that with this potential, 3-groove instruments can not only give a magnitude and direction of the shear direction in-situ but has great potential at rendering a 3-dimensional visualization of an in-situ rockmass and rockbolts when subjected to axial and shear loadings. This, in the research team's opinion, could pay huge dividends at being the first indicative measure for optimizing an underground mines support design.



(a)



(b)

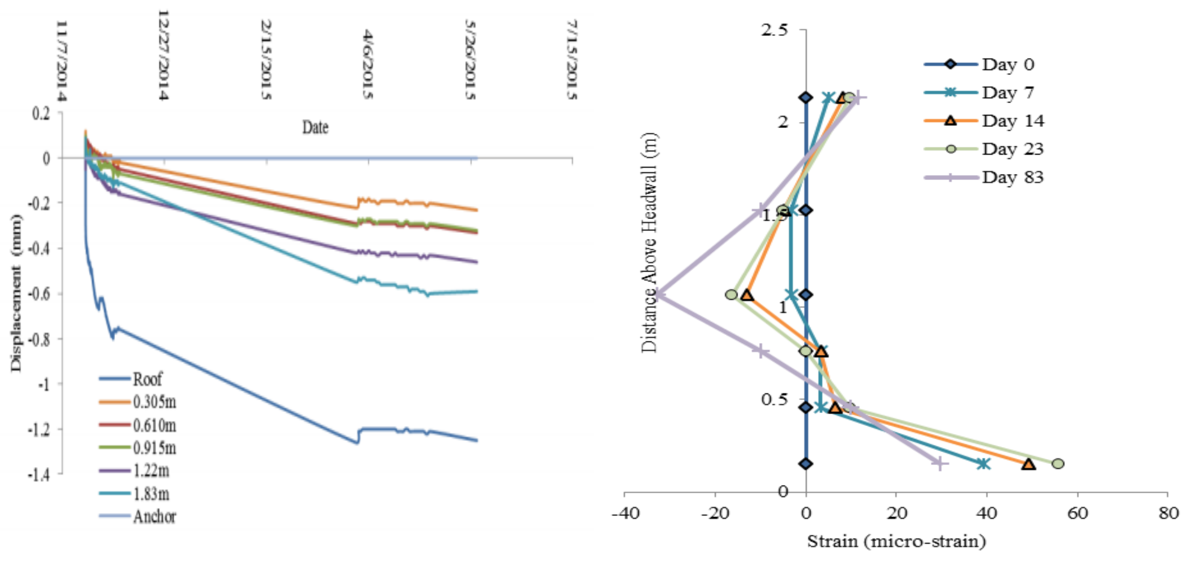
Figure 14: (a) An example of the load in a rock bolt with FBG sensors. (the markers represent the sensors on the bolt) (b) Rendering of a representation of the bending and tensile load

5.1.4 Immediate Strata Movements Overtime – Extensometers

The research team also progressively monitored the movements in the immediate roof strata over time using traditional spring-anchored extensometers at each mine site. These movements were measured over a period of six months in Mine A and three months in Mine B as shown in Figure 15.

Figure 15a shows the displacement relative to time at 0.0, 0.305, 0.61, 0.915, 1.22 and 1.83m into the immediate roof at Mine A. Figure 15b are from another spring-anchored extensometer at Mine B, however displaying the strains occurring *between* anchor points in the immediate roof. The reasoning for different charts in Figure 15a and 15b is to show a variation of extensometer results by extrapolating strains opposed to strictly time dependent movements in the immediate roof. In general, one ton (2000 lbs.) of axial load is equivalent to 153 µstrain on a #6 grade 75 .804" diameter rebar with two slots (Spearing & Gadde, 2011).

Based upon the results, there is no doubt there is a definite 'time-dependent' trend of loading within the immediate roof; however, since the magnitudes of the displacements are so small, the results tend to question the instruments resolution and accuracy, and that an optical extensometer may be more appropriate in shallow mines where small local strains are expected. This further justifies the previous observation, in that, a much longer monitoring period is needed in order to justify a shearing direction (i.e. for large strains to initiate in the immediate roof).



(a) (b)

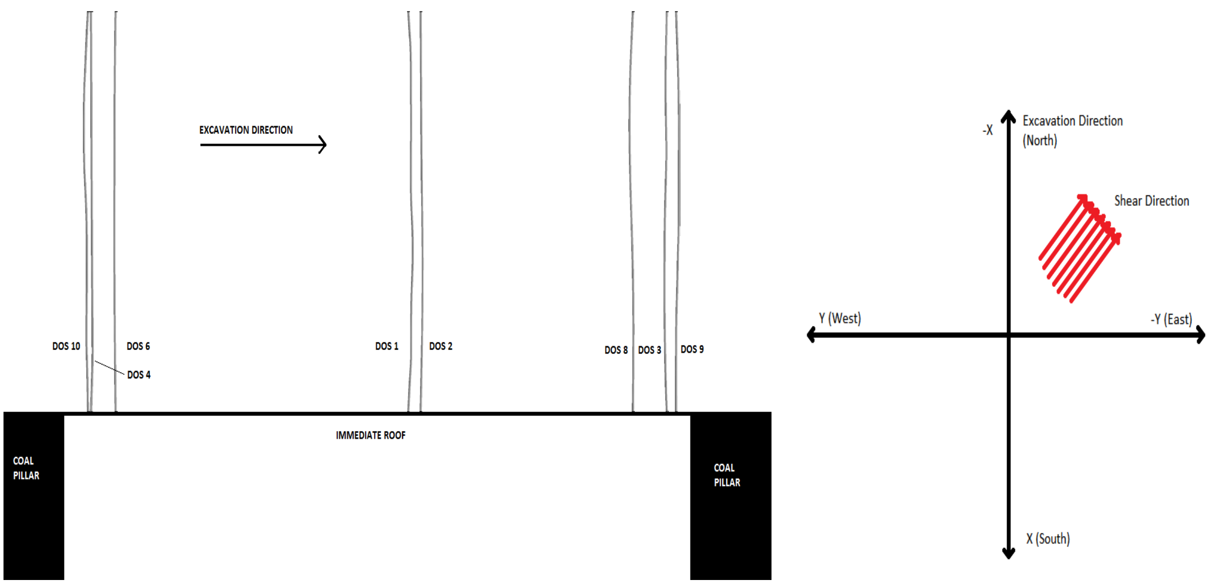
Figure 15: (a) Mine A Extensometer Results (note the increase in movement long after the mining moved significantly past the test section) (b) Mine B extensometer results

5.1.5 Immediate Strata Movements – Instrumented Rock bolts

Figure 16a shows a cross-sectional view of the displacement profiles of the eight instrumented DOS bolts installed in Mine B. This shows that only small deformations due to shear developed over the month monitoring period, and that a much long monitoring period is needed (e.g. possibly 6-8 months) especially for shallow mines.

It is not clear when and where the shearing is expected to occur (i.e. before installation, long after the monitoring has ended or above the instrumented bolt horizon). This requires extensive monitoring and geological assessment long before the instruments can be installed. Nevertheless, the resolution of the instrumentation is sensitive enough to monitor (and thereafter compute using equations 1-4), what the research team believes is, the *initiation* of shearing in the immediate roof. Shear and bending displacements were less than 2 mm and assuming excavation direction of the panel as north, the preliminary main direction appeared to be at an angle north-east to the direction of the excavation as shown in the Figure 16b. Based upon consultation with mine personnel this was their hypothesized shearing direction for Mine B.

A more definite and pronounced shearing "event" is needed to truly hone in on a shearing direction with a more precise accuracy (e.g. 45 degrees +/- 10 degrees), but at its current state, the DOS and FBG technology proves the applicability, usefulness and need for three-slot instruments.



(a) (b)

Figure 16: (a) A two dimensional depiction of bolt deformations of instrumented DOS bolts at an entry in Mine B. (b) The shear direction based on instrumented bolts in the same entry for Mine B.

Overall the optical fiber technology can be used in situ but its reliability needs further work and design improvements, but this will only take place if this research continues with the help of testing in more mine sites. The monitoring is intensive as the data logger can only be manually read, at present, so well trained operators to record and store data are still needed. The DOS instrumented rock bolts are justifiably cost effective but the data loggers are still costly. The broader analyses of data from both in situ sites is still being undertaken as it is data is enormous and never attempted to be evaluated before.

With this information it is hoped that rock bolts will in the future (after more in situ tests) be able to be more representatively modelled in computer simulations and that support systems can be better designed, optimized and rendered in such a way to only improve ground stability directly improving underground safety.

5.2 Publications

A technical paper for peer review has been prepared and accepted for publication by the Society of Mining, Metallurgy and Exploration (SME) based on the laboratory tests. Another has been submitted to the Canadian Institute of Mining (CIM) for peer review and accepted subject to some editorial changes which have been made and the paper resubmitted.

The paper details are:

- Kostecki, T, Spearing, A.J.S., Forbes, B & Hyett (2016) A. New Instrumented Method to Measure the True Loading Profile along Grouted Rockbolts – SME Transactions.
- Jessu, K.V., Kostecki, T.R. & Spearing, A.J.S. Measuring Roof Bolt Response to Axial and Shear Stresses: Laboratory and First In Situ Analyses. Publication date to be finalized – CIM Journal (publication date to be determined).

No intellectual property has been developed during the 15 month project. Some may be produced due to on-going analysis and work after the funding ended, but at the time of resubmission none exists.

The online dissemination will consist of the raw data recorded in the mines and a PowerPoint presentation. It will be available in a google drive. A person interested can email:

instrumentationoptical@gmail.com

directly to gain shared access to the files. All the files will be accessible once the request is accepted and the person is free to use the data to understand, analyze and further develop the instrumentation.

6.0 CONCLUSIONS AND INNOVATION ASSESSMENT

The following conclusions can be made:

- The axial, bending and shear behavior of instrumented bolts can be obtained if instrumentation is placed in 3 slots (not the previously used two slot configurations) preferably uniformly distributed around the longitudinal axis of the rock bolt.

- The immediate roof movement continues to move well after any mining induced movement, however a higher resolution extensometer is needed to match the capabilities of the current rock bolt state of the art.
- Monitoring of path-dependent strains upon the instrumented bolts (progressive strains which can be traced to an excavation near the instrumentation site), for these in-situ studies were not able to be correlated to the instrumented bolts.
- The FBG technology currently shows a higher probability of operation over time. The estimated number of failures per year for DOS instruments is nearly triple that of the FBG instruments based upon the current dataset.
- Based upon the current state of the art, the FBG's are certainly the more "field ready" optical monitoring solution. That being said the DOS technology offers much higher resolution than the FBG's.

This project has established an innovative and improved method to monitor rock bolt loads that should be investigated further and incorporated into future support design methodologies as shear and bending has been basically ignored in the past. Overall, the research team has not only developed an extensive and unique laboratory database of results for fully-grouted instrumented rock bolts under various axial, shear and bending conditions, but have also developed the base-line theoretical approximation for magnitude and orientation of locally induced strains for three slot rock bolts. This technology not only has the potential for use in coal mines, but can also be expanded to numerous other industries (e.g. hard rock mines, underground construction and nuclear waste repositories). A follow-up more comprehensive project is recommended to address rock bolt behavior.

7.0 REFERENCES

Jessu, K.V., Kostecki, T. & Spearing, A.J.S. Measuring Roof Bolt Response to Axial and Shear Stresses: Laboratory and First In Situ Analyses. Publication date to be finalized – CIM Journal.

Kostecki, T, Spearing, A.J.S., Forbes, B & Hyett (2016) A. New Instrumented Method to Measure the True Loading Profile along Grouted Rockbolts – SME Annual Transactions.

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8.0 APPENDICES

Figure 17 is an illustration to give an idea of the three rock bolt instrumentation systems differences in design. It is not representative of the design of the strain sensors themselves but gives a more general idea of locations of the strain sensors placements and illustrates the obvious resolution advantage of using DOS instrumentation as shown in the figure 18b over the digital and FBG sensors as shown in the figure 18a.

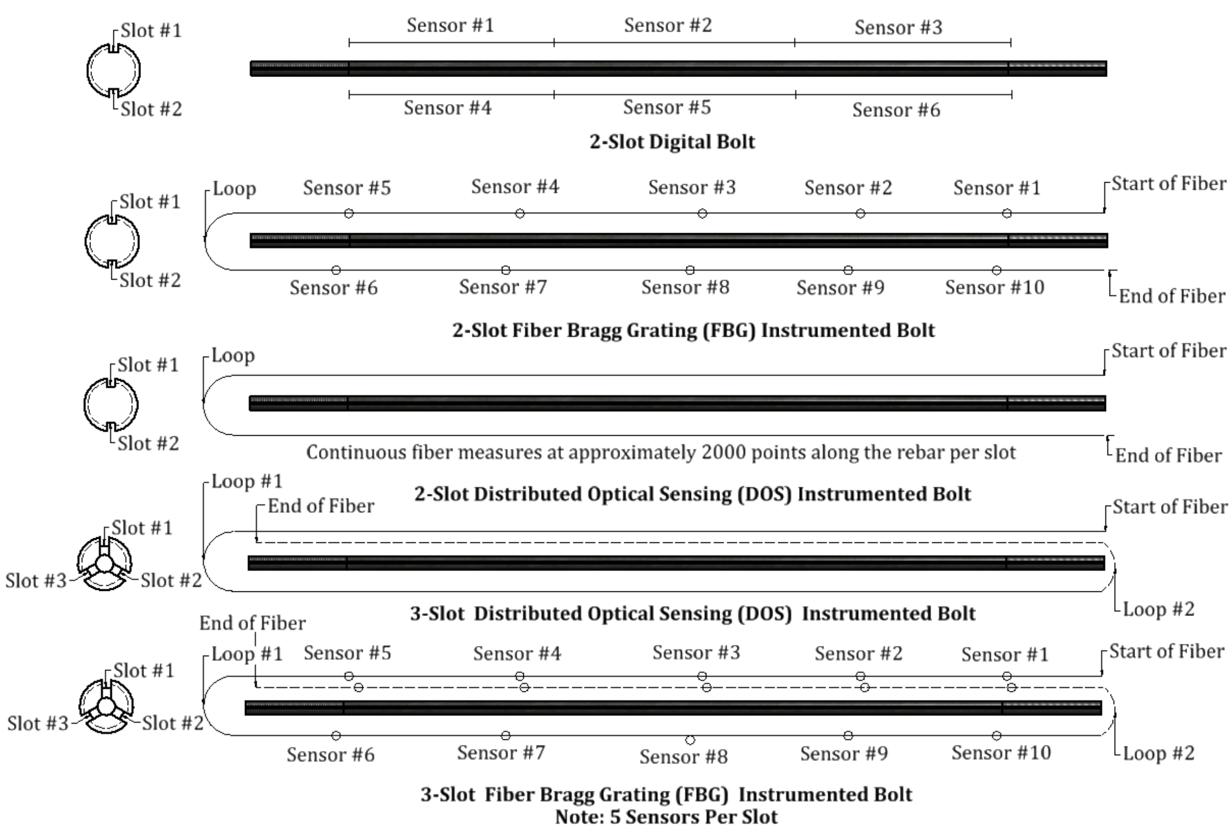

Figure 17: The three instrumented bolt technologies used in this research in a two-slot configuration.

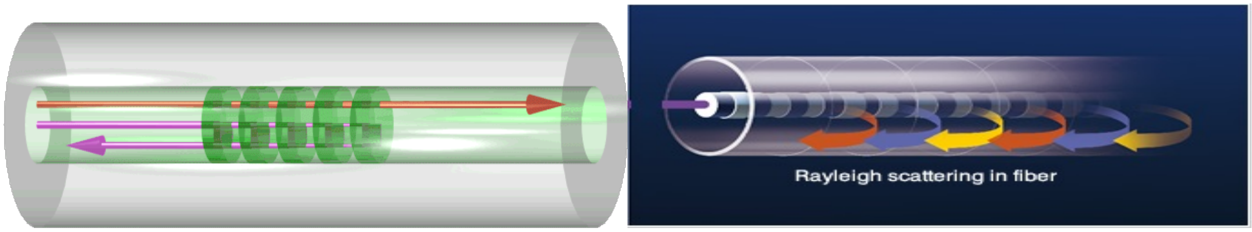

Figure 18: Instrumentation technologies a) Fiber Bragg Reflector b) Distributed Optical Sensing

9.0 ACKNOWLEDGEMENTS/DISCLAIMER

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The funding provided by the Alpha Foundation and the assistance of the two coal mines is greatly appreciated and acknowledged.

The paper provided by SME titled “New Instrumented Method to Measure the True Loading Profile along Grouted Rockbolts” is greatly appreciated. The paper is copyrighted by SME and will be published in the 2015 SME Transactions (published by the Society for Mining and Metallurgy and Exploration of Englewood Colorado).

The paper provided by CIM titled “Measuring Roof Bolt Response to Axial and Shear Stresses: Laboratory and First In situ Analyses” is greatly appreciated. The paper is copyrighted by CIM and the publishing date needs to be finalized (published by the Canadian Institute of Mining, Metallurgy and Exploration of Quebec City).