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The Influence of Rib Spacing and Borehole Diameter on the Axial Response of Fully Cemented Rebar Rock Bolts Using Distributed Fiber Optic Sensors

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ABSTRACT

Rock bolts are often utilized to provide support to excavations. To better understand bond performance numerous investigations have been conducted. Due to practical and technological limitations, an in-depth investigation (at the geo-mechanical micro scale) of the load transfer and continuous stress distribution along a fully grouted rock bolt has been challenging. The advent and application of Distributed Fiber Optic Sensors (DOS) has led to a methodology (developed by the authors) capable of providing a continuous strain profile for structural members. This paper summarizes the innovative methodology that has been employed for a series of laboratory axial pullout tests in order to determine the effects of rib spacing and borehole diameter on the geo-mechanical response of fully cement grouted rebar rock bolts within simulated rock masses. The results of the research will augment the current body of literature, while also improving rock bolt development, design and implementation.

RÉSUMÉ

Les boulons d'ancrage (BDA) sont souvent utilisés pour soutenir les fouilles. Pour mieux comprendre la performance des obligations d'armature, de nombreuses enquêtes ont été menées. En raison des limites pratiques et technologiques, une étude approfondie la mécanique du BDA entièrement jointoyé était difficile. L'innovation récente dans l'application des capteurs à fiber optique distribuée (DOS) a mené à une méthodologie (développée par les auteurs) capable de fournir un profil de déformation continue pour les éléments de structure. Cet article résume la méthodologie innovatrice qui a été employée pour une série de tests en laboratoire de traction axiale afin de déterminer les effets de l'espacement des nervures et du diamètre du trou de forage sur la réponse géomécanique des BDA contenant des barres d'armature entièrement cimentés dans des masses rocheuses simulées. Les résultats de la recherche augmenteront la littérature actuelle tout en améliorant le développement, la conception et la mise en œuvre des BDA.

1 INTRODUCTION

The art of underground excavation has been an important engineering capability since ancient times. Early Roman civilizations often utilized underground aqueducts for transportation of water (Castellani and Dragoni 1997). Since then, underground excavation has been used to support engineering endeavours such as transportation, military and resource acquisitions. Across all applications and situations, challenging support requirements push not only the need for engineering designed support measures but also the real requirement to optimize such designs based on their true performance. The demand for these support requirements are increasing over time as there is a greater prevalence of operations conducted in less favourable conditions, in both hard and soft rock applications, due to necessity. To combat this, creative and innovative technologies are being applied to the construction, support methodology, monitoring, and design of underground excavations. One commonly used ground support technology, which has potential for optimization, is the fully grouted rock bolt (FGRB).

Rock bolts have various uses depending on the ground conditions. One of the most basic design principles is that the bolt carries load from an unstable to stable rock. Another common design principle is the artificial arch. Both of these design principles can be seen in Figure 1. Rock bolts come in many different variants consisting of different connection methodologies and different bolt materials. FGRB, the system selected for investigation, is a continuous mechanically coupled reinforcing system (Windsor 1996). Load is transferred from the bolt to the grout and finally to the rock, this along with the testing setup can be seen in Figure *2*. The design of the system must consider not only the three main elements (four if the external fixture is to be taken into account) but also the interfaces between them, featuring various load transfer mechanisms. This makes understanding the complex geo-mechanics, and behaviour of the system and its elements, non-trivial. In order to successfully optimize FGRB bolt design, monitoring, and implementation methodology, a better understanding at the millimeter level must be achieved.

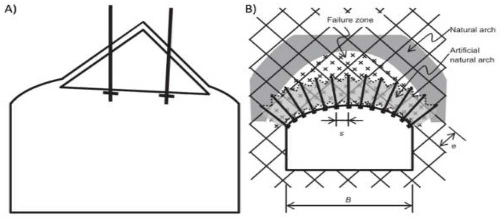

Figure 1: Examples of the use of rock bolts, A) suspension, B) creation of an artificial arch. (Li 2017)

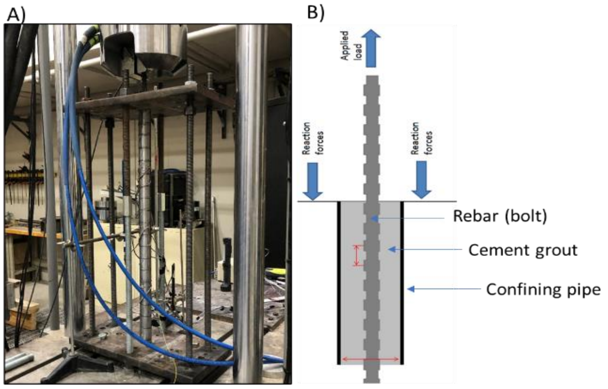

Figure 2: A) Loading during testing (O'Connor et al. 2019), B) Schematic of loading and components, red arrows show the two factors under investigation

Since the 1940s, research on the bond performance of rebar bolts has been conducted analytically, numerically, and experimentally; in-situ and in the laboratory. This research has aimed to understand the load transfer mechanics and behaviour of the rock bolt system both in entirety and through the investigation of specific factors. However, due to technological limitations, this has not been achieved because of a lack of spatial resolution in experimental testing. With the aim of creating a deep understanding, the following factors for investigation and methodology have been proposed. This paper will detail the existing methodology developed by the authors, its background, and recently proposed improvements. These lessons learned and methodology are not limited to the specific application discussed herein and could be applied in other fields. In addition, this paper will also provide context and the planned testing scheme for the selected variable of investigation.

2 BACKGROUND

To address the technological limitation discussed above which has hampered the understanding of ground support, a research program headed by Dr. Vlachopoulos (Vlachopoulos et al. 2014, Vlachopoulos and Diederichs 2014, Forbes et al. 2017, Vlachopoulos et al. 2018a) with support from research associates, graduate students and industrial partners, has developed an innovative monitoring methodology that provides unprecedented spatial resolution for ground support elements. Since its inception in 2014, development and implementation has occurred across a spectrum of scales, in laboratory and in-situ, and with varied purposes. This methodology has leveraged ROFDR technique as they are found to be superior for this application (Vlachopoulos et al. 2017). With the aim of advancing the state of the art, research has been conducted to understand behaviours and the effects of various parameters of support elements in a controlled manner. This data can be compared with in-situ monitoring to construct a better understanding of both the development of ground support methods and ground movement / geo-mechanical responses. This effort is coupled with the group's advanced ground characterization research through the use of LiDAR, amongst other complimentary technologies, and advanced numerical modelling. The synergized effects of these endeavors have a symbiotic relationship resulting in a novel understanding of the geo-mechanics associated with support elements. Recently, one of the major objectives of the group has been to determine the geo-mechanical response and behaviour of the FGRB. To this end, the fiber optics monitoring solution can truly aid in such an objective. Thus far, the research team has investigated the performance of FGRB in a variety of confining materials (including the investigation of specific material properties), embedment lengths, and resin/cement grout. This research aims to expand this investigation to include the effects of rib spacing and borehole diameter to the performance of the FGRB system.

3 METHODOLOGY

In order to further the understanding of geo-mechanics of FGRB, specifically, the impact of selected variables, a series of pull-out tests will be conducted. The methodology as presented in papers (Hyett et al. 2013, Vlachopoulos et al. 2014, Forbes 2015, Cruz 2017, Vlachopoulos et al. 2018b, O'Connor et al. 2019) produced by the authors and the rest of the research group for specimen preparation and testing procedure will be summarized herein. This innovative methodology is the result of an iterative development process. Following this, areas of weakness will be highlighted, and the proposed improvement will be provided.

3.1 Summary of Current Methodology

The selected rebar is cut to the desired length. Consideration for the sizing of the loading apparatus must be taken into account in order to ensure sufficient length for loading application and monitoring of free-end movement, in addition to the embedment length. To bond and protect the DOS, two or three sets of grooves were made along the length. Examples of the groove(s) can be seen in Figure *4*. Depending on the application, protective return loops are also machined into the rebar. Typically, the grooves are located in the transverse ribs. Sizing for the grooves are made as small as possible, minimizing their impact on testing but not limiting the installation procedure. Sizes such as 2.5mm x 2.5mm have been used previously. After the grooves have been deburred and cleaned, in-place DOS was installed. The DOS is created by installing a single-mode fiber onto the sample, the terminal is created and spliced to the sensor, along with the LC connector. This technique is summarized in Forbes (2015, and 2019) and

Vlachopoulos et al. (2018) and will not be repeated herein. Areas of potential weakness are protected with heat shrink and metal bonding adhesive. This adhesive not only protects but bonds the DOS to the rebar. The adhesive is typically applied well beyond the embedment length in both directions.

Depending on the confining material selected, different processes are followed. When pipes are utilized as confining material the process is as follows. Pipes are cut slightly larger than the required embedment length for ease of grouting purposes. The outer surfaces are also prepared for bonding of DOS. Bonding is achieved with a different adhesive than the one used on the rebar. Note, the selected adhesive in both cases has been determined through investigation in numerous applications. Once the sample is grouted, a series of DOS 'rings' were installed on the members, as seen below Figure *3* . Depending on the length and the desired resolution, different numbers of rings were used. These are outlined in O'Connor (O'Connor 2020).

Figure 3: DOS rings shown in red (O'Connor et al. 2019)

Differences in procedure also exist for different embedment lengths, material types, and grout types. After trialing various methods, selected processes have proven to be most effective in the laboratory setting, based on DOS and post-test analysis (Vlachopoulos et al. 2018c). For lengths of 750mm in pipe with cement grout, grouting from the bottom through a brass fitting was found to minimize air pockets. The pipe was capped with plumber's putty and pipe caps at both ends. Cylinders of concrete are also poured for the purpose of testing to ensure consistency, to explore differences between rounds of testing, and aid in numerical modelling.

Once samples have cured for 28 days, they are tested using a Material testing system (MTS). Monitoring of the applied load, displacement of the rebar's loading and free ends, along with the movement of the plate are captured in addition to strain from the two DOS. This is conducted through the use of internal and external Linear Voltage Differential Transforms (LVDTs) and load cells. Loading occurs in a controlled fashion until failure of the rebar or grout-rebar interface occurs. After testing has been completed, samples are cut diametrically for the purpose of quality assurance, confirmation of failure mechanics, and crack propagation.

3.2 Proposed Changes

After a review of the most recent research endeavours (Vlachopoulos et al. 2018b, O'Connor et al. 2019, O'Connor 2020), proposed improvements have been developed. These proposed improvements are featured on the current rounds of testing. Improvements presented herein will focus on the innovative application of DOS. Minor adjustments and considerations to other elements of the methodology will not be included. Lessons learned from this innovative process could be utilized in other monitoring applications which feature DOS. The proposed improvements consist of location and number of grooves, decoupling of DOS near the loading end, and layout variations of DOS on the confining medium.

The research group has used both three and two sets of grooves. Although three grooves allow for a complete 3D understanding of loading applied to a bolt as well as determining the bending direction, strain (bending and co-axial), in the application of 1D loading it is not required (Forbes et al. 2017, O'Connor et al. 2019). By placing DOS along the length at diametrically opposing grooves within the bolt, any bending that occurs as a result of the bar being loaded axially can be averaged out or will not be captured depending on the orientation. This allows for purely axial strain results to be collected. The selection of three grooves is also problematic as it requires the removal of sections of the transverse ribs. This is important as the transverse ribs are critical in the load transfer of an FGRB. Load transfer occurs primarily through three means, adhesion, friction, and mechanical interlock; the latter being the most significant (Li and Stillborg 1999). In the design of a monitoring plan, it is paramount to ensure the method of observation does not influence the behaviour occurring. This is known as conformance and is an uncertainty of instrumentation. In order to minimize this uncertainty, a new location of grooves is proposed. By placing the grooves within the longitudinal ribs, there is minimal impact on the mechanical interlock, while allowing for the collection of strain along the length of the bolt. This can be seen in Figure *4*. The effect on surface friction will be the same as in the 2-groove layout previously used (difference in coefficient of friction of steel vs metal bonding adhesive). This is especially significant when trying to understand the effects of mechanical interlock and how altering that geometry affects the geomechanics. The effects of the change of location on the rib will be compared to another sample of the same length, confining material, and loading rate to quantify the conformance issues of previous researchers (Cruz 2017, O'Connor 2020).

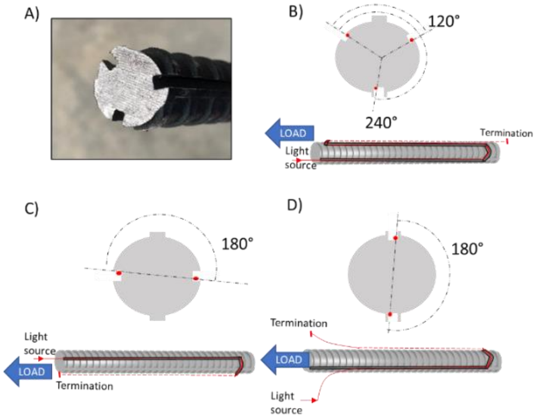

Figure 4: Layout of grooves, A) photo from previous grooving layout, B) three groove layout, C) two groove layout, D) new two groove layout featuring decoupling at loading end

One of the original reasons for mounting DOS on the outside of the pipe, in addition to understanding the radial strain of the pipe, was to observe the strain profile beyond the serviceability limits of the DOS on the bolt. In the current methodology, the DOS is bonded to the bolt, both within and in front of the embedment length. This is problematic as the bolt outside of the embedment length fails prematurely (at a maximum strain of 1.5%) compared to the rest of the system. Significant changes in stress distribution in the pipe, and thus the bolt, were observed post failure of the DOS monitoring on the bolt. This can be seen in Figure *5*. At load values of 120kN to 140kN the DOS solution adds no further, reliable insight. In order to better understand this change in behaviour, a decoupled front end is proposed. This can be achieved by having the return loop at the free-end and allowing free movement of the DOS outside the embedment length. However, during failure, grout shearing at the loaded end is typically observed. This can be seen in Figure *6*. To accommodate for this expected behaviour (due to the nature of the testing scheme), the DOS was decoupled 2.5cm into the embedment length in order to ensure protection from the unsupported loading and premature failure. This proposed methodology will hopefully provide insight into the range of behaviour outside of what has been previously observed.

As mentioned above, strain reading along the pipe offers valuable insight into the load transfer. Analytical modelling has shown that different factors which define the grout-bolt interface can affect the amount of load which is transferred radially to the pipe (Cao 2012). In a first attempt to capture strain readings on the pipe, fiber optic was installed in a series of rings along the circumference of the pipe. Results from testing show an extreme amount of variance along each ring, at 140kN for a 1000mm resin sample at the DOS ring closest to the loaded end, the standard deviation was 28% of the mean and the range was 159% to 65% of the mean. Given the geometry of the ribs on the bolts tested, this was anticipated. At locations near the load transfer points, one would expect higher values of stress; whereas stress should be lower when the sensor location is further from the load transfer points. The distancing between the ribs and the sensor changes along the circumference, due to the angle of the transverse ribs. In previous research, this has been simplified to existing analytical stress distributions, specifically, Boussinesq-Cerruti distribution, and numerical modelling supported this (Cao 2012). This rationale can be applied to the collected results with a view to capture, analyze and understand these trends, as seen in Figure *7*. The benefit of using this monitoring technology is to provide a continuous collection of stress distribution along the pipe. However, in the application in rings along the circumference, data is collected discreetly along the length. In order to better take advantage of the distributed nature, the sensor will be set along the length of the pipe. This will allow for better characterization of load transfer factors, which would not have been possible previously.

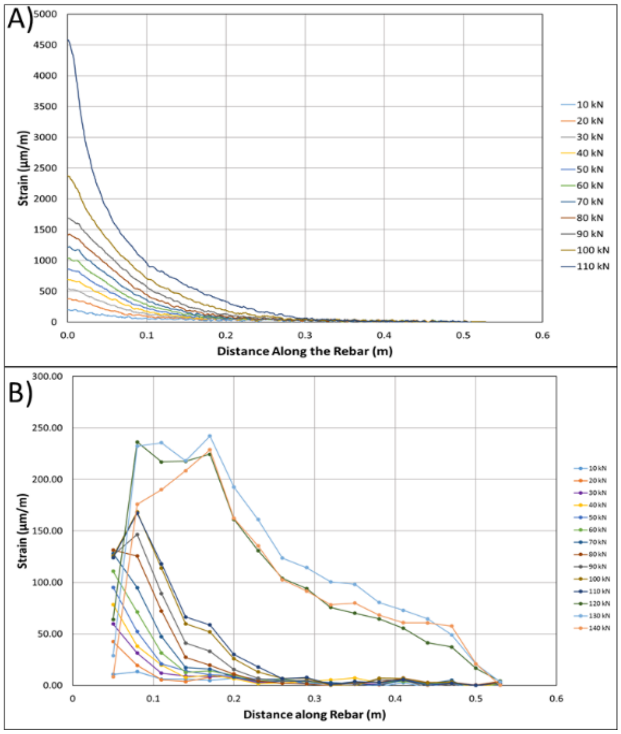

Figure 5: Strain during load as collected by, A) DOS on the rebar, B) Averaged from DOS on the pipe, from a 500mm embedded sample (O'Connor et al. 2019).

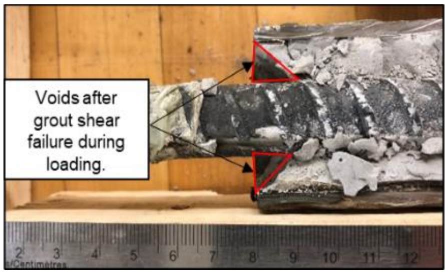

Figure 6: Example of grout shearing observed during testing (O'Connor et al. 2019)

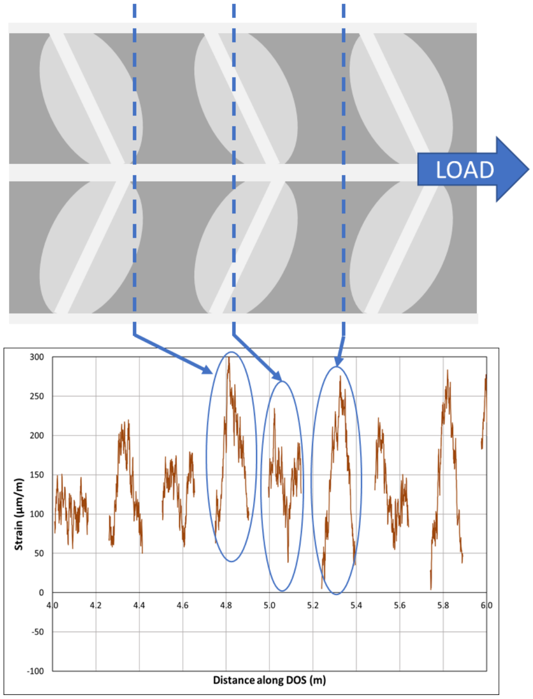

Figure 7: Demonstration of potential DOS positions resulting in different stress patterns along loops

4 TESTING SCHEME

4.1 Rib Spacing

One key factor which greatly influences the performance of the rock bolt is the geometry of the bolt-grout interface, which is defined by the bar's ribs. The importance of ribs in creating bonding through mechanical interlock is well documented, with the strength of a ribbed versus a planbar being much superior (Fabjanczyk & Tarrant, 1992 in Mark, 2000; Tadolini, 1998). Studies indicated that various geometric factors (rib spacing, rib height, rib face angle, etc.) could alter the strength and stiffness of the bolt system (Aziz and Webb 2003, Kilic et al. 2003). Later, this was analytically modelled to better understand and optimize the system (Cao 2012). Following this, studies aimed to further the understanding of this behaviour were conducted. The studies largely focused on rib spacing, under different conditions such a confining mediums/ properties (Kang et al. 2015, Wu et al. 2017, Zhao et al. 2018). This research generally supports that rib spacing could optimize bar performance by increasing spacing on typical rebars used. This behaviour has also been explored numerically and generally confirms these findings (Shang et al. 2018, Nie et al. 2019, Yokota et al. 2019).

The study of the effects of bar geometries, specifically rib spacing, has remained a relevant research topic despite the number of studies conducted. The biggest gap in the research conducted thus far is the link between the experimental results and numerical and/or analytical models. Models based on observations have predicted stress distributions, load transfer, and general system behaviour. Up until now, all experimental research has had little to no information on anything that is not displacement and load capacity of the system. Furthermore, a majority of the testing has been done in short embedment testing, which is not how FGRB is used in-situ. Testing needs to be conducted to understand the response of the bar and the other components to gain a true insight into the micro-mechanics of the system. With the use of this DOS methodology, the load transfer mechanism and the stress distribution along the rebar can be properly understood.

Results from recent axially loaded FGRB, have revealed the need to determine the effect of rib spacing (and other anomalies, i.e. manufacturer's stamp) on the bolt system performance. When rebar is purchased from manufacturers it often comes with vendor stamps. Vendor stamps consist of alphanumeric characters which replace every other rib in a select region. Typically, during testing the stamp is kept away from the loaded end (if at all) inside the embedment length. However, during a recent round of testing, one sample had these markings at the loaded end and the results were skewed due to this reason. Previous research has suggested that this spacing should have shown greater performance, however, this stamped area demonstrated poor performance (specifically decoupling). This decoupled section began to extend towards the free end while the ribs closer to the loaded end were still able to carry load. This can be seen in Figure *8*. As explained above, DOS on the pipe provides insight on the load transfer. When examining the results of the DOS on the pipe (Figure *9*) one sees an atypical response. During the initial phase of testing, the radial load transfer is matching the strain within the rebar, this is not congruent. If the rebar is completely debonded, as suggested by the constant strain in the rebar in that section, no load should be transferred radially. This pattern continues as the flat region extends further into the embedment length. However, this is not in sync with the data from the DOS on the rebar. The flat region appears larger for the 50kN to 80kN reading, whereas in the DOS on the bar the extension does not occur until 80kN. This suggests that during this phase the load transfers mechanics are changing. The stress attenuation pattern on the rebar is same, meaning the amount of load transferred is constant/ remain proportional but the stress pattern changes on the pipe, suggesting the orientation of this force vector is shifting. Due to material properties of the system this likely has to do with a failure of the resin key. Of most significance is when the applied load increases beyond 90kN, it is seen that only the first region of the embedment length transfers load radially, and the DOS on bar suggests the load is still being transferred. Such a response is indicative of friction at the end section of the bolt. An observational forensic analysis of the sample post-test (Figure *10*) largely supports the interpretation of DOS data. Loss of the resin key is evident in the 35cm to 53cm range of the bolt system, with a large crack showing resin failure at 35cm. This verifies the observation in the pipe. As mentioned above, at the final stages of testing no outward forces (DOS on the pipe) were observed. The outwards force is a result of mechanical interlock of the rebar to the resin key. If no outwards force is detected this means this interlock has failed, which is evident in the post-testing analyse. However, in the 60cm to 80cm region, the resin key is still intact, there was stress captured in the bar, however, not on the pipe. It is important to note that this sample utilized a resin grout, and problems regarding installation are common with samples of such length and configuration. These presented findings not only highlight the insight provide by the use of DOS in such a manner but also the need to conduct additional research to better understand the behaviour of such specimens.

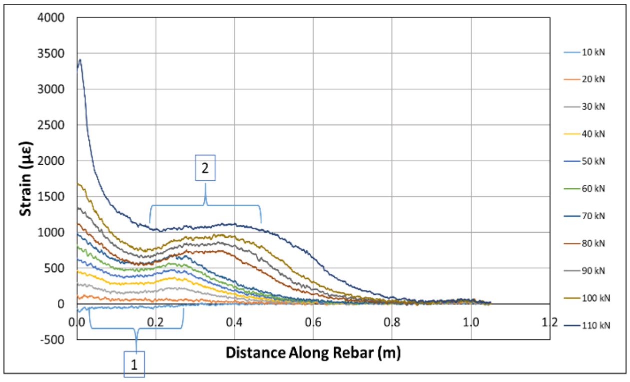

Figure 8: Strain distribution of DOS on rebar, during testing 1000mm resin sample, in steel pipe. Numbers depict the initial debonded area and larger debonded area

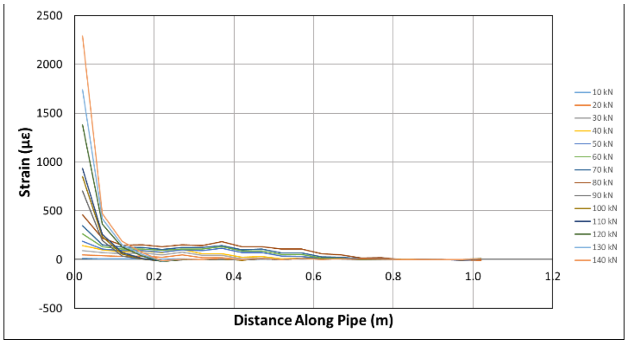

Figure 9: Averaged strain distribution of DOS on pipe along the length, during testing 1000mm resin sample, in steel pipe.

In order to address this research gap, a selection of various rib spacing has been chosen for investigation. Rib spacing of 12mm, 24mm, 36mm, 48mm, 60mm have been featured commonly in the aforementioned studies. Testing will be conducted in cement grouted steel pipe of various diameters to minimize material-based uncertainty. One pipe size will also test a variety of smooth bars for completeness. The full testing scheme can be seen below, Table *1*.

4.2 Borehole Diameter

Another factor which influences the performance of a FGRB is the borehole diameter. This factor is of interest as recent research has proposed a paradigm shift, suggesting benefits of larger sized boreholes than proposed previously. This research has also linked borehole diameter to bar geometries. The understanding of this factor is important as it has been shown to impact various properties of rock bolt performance. In research, this factor has also been described as the grout annulus, defined as the radius between the bolt and rock. Early research indicated that minimized borehole diameter (3mm), without impacting on the installation procedure was optimal from an economical and engineering stand point (Karabin and Debevec 1976, Ulrich et al. 1989, Tadolini 1998, Mark 2000, Fabjanczyk and Tarrant 1992 in Frith et al. 2018). Research largely focused on resin grouting system. Resin can either be mixed and poured, or cartridge-based. Although it was identified that some of the performance difference of borehole diameter is directly linked to selected installation system, the optimal range appeared to be 2.5mm to 7mm (depending on the conditions) (Pile et al. 2003, Weckert 2003, Aziz 2004). Conversely, in soft rock conditions larger size boreholes, simulated in laboratory by concrete, resulted in greater strength (Ghazvinian and Rashidi 2010, Cruz 2017). This testing also featured cement grouting vice resin of earlier studies. However, recent analytical modelling that focused on crack propagation of the grout, suggest large annulus between 9x and 12x rib height had greater strength (Yokota et al. 2019). This is of interest as it connects the annulus to the rib geometries.

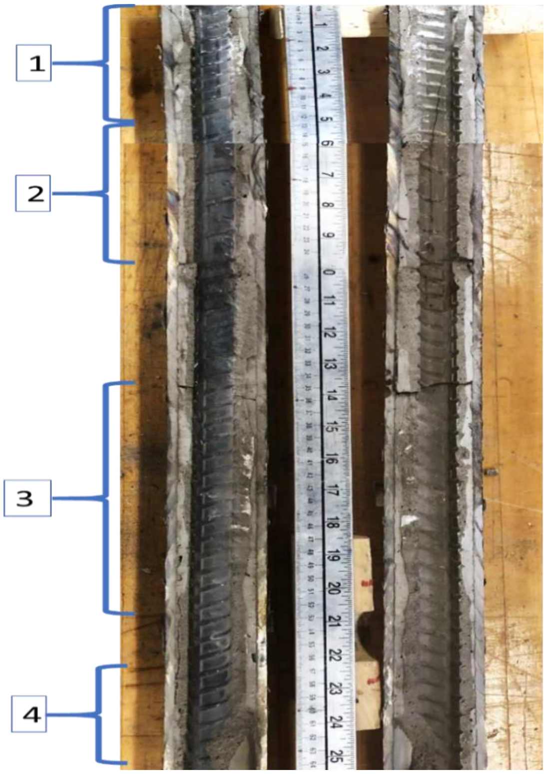

Figure 10: 1000mm resin sample, in steel pipe post test analysis. 1. Signs of grouting crushing and build up, 2. Region of bar stamp, 3. Resin key is completely flattened, 4. Resin key appears intact.

In order to obtain comparable results consideration of various pipe thickness and diameters was conducted. To reduce the difference between samples the same material was selected for all pipes and the radial stiffness was kept as close as possible with commercially available pipe options. Radially stiffness can been calculated, as explained by Hyett with thick wall cylinder theory (Hyett et al. 1992). When selecting the sample sizes the aim was to maximize the range of borehole diameter while also maintaining reasonable sizes and minimizing the difference between radial stiffnesses. This criterion, as present in Figure *11*, allowed for selection of pipe sizing.

The testing scheme, including rib spacing testing, can be seen below, Table *1*.

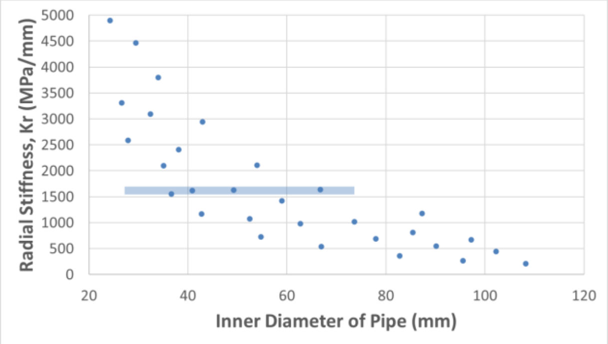

Figure 11: Inner diameter and radial stiffness of commercially available pipe. Highlighted region shows selected sizes in stiffness range

Table 1. Testing scheme

Serial[1]	Borehole Diameter (mm)	Radial Stiffness, Kr (MPa/mm)
1	36.6	1557
2	40.9	1624
3	49.3	1625
4	66.7	1636

[1] All serials will feature rib spacing of 12,24,36,48 and 60mm of 19.05mm grade 60 rebar. Serial 2 will feature additional tests of smooth bars.

5 SUMMARY

Due to the complex interaction between multiple components of a FGRB system, specifically a cemented rebar bolt, that is utilized as an underground support technique, an understanding of the load transfer, behaviour and mechanics is non-trivial. In an attempt to further develop such an understanding, the authors have established a novel technique with a view to determine the mechanisms and behaviour of FGRB systems under various scenarios. The selected results included within this paper serve to highlight not only the insight that such a methodology can provide but also improvements which can be made from lessons learned. These are in-line with an observational approach. These proposed improvements based on informed results from previous testing, feed into the next generation of testing. The testing also capitalizes on the strength of the DOS technique developed i.e. the ability to collect continuous strain readings with millimeter spatial resolution. This methodology and improvements developed by the authors will not only allow for greater in-sight in the mechanics of FGRB but can also be applied to other structural elements in a wide variety of applications.

Research conducted by this research group has included performance of FGRB with a myriad of parametric studies focusing on various factors. To expand upon this research, rib spacing and borehole diameter have been selected for further investigation. Preliminary results and proposed, further testing scheme have been presented herein. Given the insight this methodology provides, as demonstrated in the analysis of selected results, the authors will be able to provide greater understanding of the geo-mechanics and behaviour of these factors.

6 ACKOWNLEDGEMENTS

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