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THE LOAD TRANSFER MECHANISM OF FULLY GROUTED CABLE BOLTS UNDER LABORATORY TESTS

Paul Hagan, Jianhang Chen and Serkan Saydam

ABSTRACT: The load transfer mechanism of fully grouted cable bolts plays an important role in the performance of cable reinforcement systems. In order to better understand this behaviour, researchers have utilised a number of approaches including theoretical analysis, laboratory tests and numerical simulation. However, laboratory experiments are more often used because it offers a more direct and relatively accurate way to understand the physical and mechanical behaviour of cable bolts. This paper outlines the major developments and evolution in understanding the load transfer mechanism of fully grouted cable bolts under axial loading conditions through laboratory testing. The advantages and some of the shortcomings arising from previous tests are also presented. The major influencing factors that have been studied include embedment length, cable surface geometry and confinement of surrounding rock. A number of theoretical equations have been proposed based on these experiments. In conclusion, a roadmap for future research has been outlined that is necessary to better understand and improve the performance of cable bolts in stablising underground excavations.

INTRODUCTION

A cable bolt is a flexible tendon consisting of a quantity of wound wires that are grouted in boreholes at certain spacings in order to provide ground reinforcement of excavations (Hutchinson and Diederichs, 1996). They were first introduced into the mining industry in the 1960s (Thorne and Muller, 1964) and since the early 1970s have been used in both hard rock and coal mining operations. Over time, cable bolts have become the dominant form of ground support particularly in highly stressed ground conditions.

Originally, cables were only used as a temporay reinforcement element. This was due to the fact that many earlier cables were made from discarded steel ropes which had very poor load transfer properties as a consequence of their smooth surface profile. Over subsequent years a number of modifications have been made to the basic plain strand cable such as buttoned strand (Schmuck, 1979), double plane strand (Matthews, *et al*., 1983), epoxy-coated strand (Dorsten, *et al*., 1984), Fiberglass Cable Bolt (FCB) (Mah, 1990), birdcaged strand (Hutchins, *et al*., 1990), bulbed strand (Garford, 1990), and nutcaged strand cable bolts (Hyett and Bawden, 1993). These changes to the cable surface geometry have been undertaken in an effort to improve the load transfer efficiency and anchorage capacity that has resulting in the more widespread use of cable bolts for permanent reinforcement.

Despite these development in design, failure of cable reinforcement systems still occur. Rupture of the cable strands rarely occurs as it requires the shear resistance between the cable strand and the grouted surface of the strand being larger than the cable's maximum tensile capacity (Mitri and Rajaie, 1992). Potvin *et al*. (1989) stated that it is more likely for a cable bolt to fail at either of the cable/grout or grout/rock interfaces but more likely the cable/grout interface which is a function of the load transfer between the cable bolt and rock mass.

In order to evaluate load transfer efficiency, both peak shear stress capacity and system stiffness need to be determined. Although values for these can be estimated, most researchers tend to use the load versus displacement curves obtained from laboratory tests to study and compare the load transfer characteristics of cable bolts. More recently Thomas (2012) proposed the Load Transfer Index to evaluate the cable load transfer efficiency.

Hartman and Hebblewhite (2003) stated there are three sets of factors that have an impact on the cable load transfer, including the reinforcing element, rock mass and loading conditions. The following sections outline results of the effect of relevant parameters on cable load transfer together with the evolution in design of testing facilities showing the development in understanding the load transfer mechanism of cable bolts with respect to axial loading.

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LOAD TRANSFER BEHAVIOUR OF CABLE BOLTS UNDER AXIAL LOADING

"Split-pull/push" tests

The earliest "split-pull" testing equipment as shown in Figure 1 was designed by Fuller and Cox (1975) and used in a study of the load transfer mechanism of cable bolts. In this design, steel split pipes were used to represent the rock mass and provide confinement to the grouting material surrounding the cable bolt. Within this facility, although the rotating behaviour of cables was constrained, the steel tube provided a level of confinement that was markedly different from that of a rock mass as evident by the stress-strain relationship. The consequence of this was very high peak loads being achieved, much greater than was achieved in field measurements.

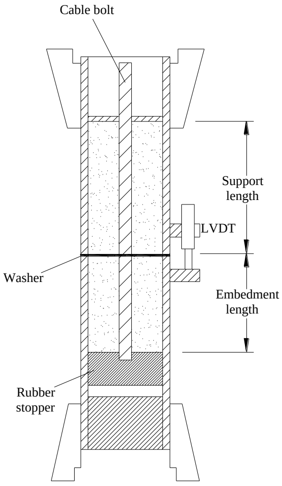

Figure 1 - Split-pulling rig (after Fuller and Cox, 1975)

The facility was used to evaluate the effect of surface geometry on the performance of cables and they found the shape and conditions of the cable had a critical impact on the load transfer. Any protrusion such as surface rust on the wire strands improved the load transfer whereby the location of each protrusion would influence the characteristic of the residual load but it had little impact on the peak load. Following that, the effect of wire indentations on the performance of cables was reported by Cox and Fuller (1977). They found that the indentations have a positive effect on load transfer for mill-finished wires. However, for rusted wires, indentations reduced the effective rusted surface area and thereby the change in load transfer capacity. Thus, it was suggested, the wire surface should be slightly rusted and non-indented. They also showed that high grout strength had a positive impact on load transfer.

Goris and Conway (1987) went on to use a similar test rig design to investigate the impact of epoxy coating, showing that epoxy-coated cables had a larger bearing capacity compared with conventional cables. In addition with respect to the position of steel buttons along the cable bolt in a grout column they found that an increase in the distance between the button and joint significantly enhanced the performance of the cable bolts. Finally the impact of birdcage node location with respect to rock fractures was investigated. Here if the node was located at the pipe discontinuity, the bearing capacity of cables was nearly 31% higher than that of strands in which the anti-node was located at the discontinuity, indicating the birdcage node if located near a rock joint would degrade, the load transfer efficiency. However, this effect is only suitable for single birdcage cables whereas double birdcage cables were less sensitive to the location of nodes or antinodes with respect to rock joints (Goris, 1991). Comprehensive experiments were carried out by Goris (1990) to investigate the axial performance of cable bolts. The ultimate bearing capacity of plain cables improved linearly with embedment length from 203.2 to 812.8 mm. The bearing capacity was also found to increase with the presence of two wound cables, high curing temperatures, low water-cement ratios and sand-cement grouts. Furthermore the load transfer of cables was not influenced by breather tube size and the existence of a breather tube so long as the breather tube was fully filled with grout.

Strata Control (1990) paid particular attention to the effect of bulb density of twin strand Garford bulb cables. A linear relation was found between the cable bearing capacity and bulb density with bulb density frequency ranging from 3.9 to 6 bulbs per strand per metre, indicating load transfer increased with the bulb frequency and number.
Although the “split-pull” test provided much useful information on the different kinds of cable bolts, the design was defective in the extra confinement created near the pulling threads given by the the screw gripping assembly that tended to over-estimate the measured pull-out load. In order to overcome this issue, Reichert (1991) designed the “split-push” test, which was a modification of the traditional pulling test. In this arrangement, the grout column and pipe were pushed off from the cable as indicated on the right in Figure 2, rather than being ‘pulled’ as in the conventional sense shown on the left.

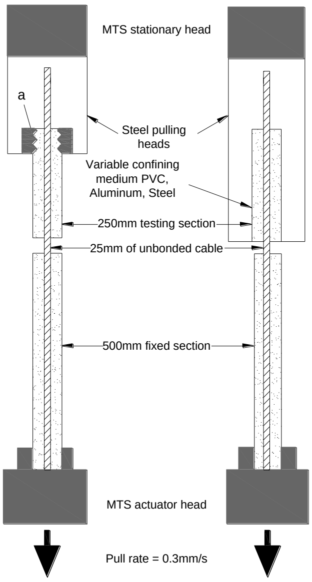

Figure 2 - Comparison of conventional and modified test (after Reichert, *et al.*, 1992)

Using this test arrangement aluminium, PVC and steel pipes were used to model the effect of different radial confinements or stiffness. It was reported that larger capacities were achieved with higher radial confinement. Also bearing capacity of cables increased with embedment length though not in direct proportion. Finally, cable capacity increased by 50% to 75% when using stiffer grouts having low water-cement ratios of less than 0.40.

With this “split-push” test equipment, Hyett and Bawden conducted tests on various kinds of modified cable bolts. In 1993, the impact of nutcase geometry was evaluated and they found that the nutcase cables were less sensitive to high water to cement ratios and lower confinement. As for the nutcase size the larger the nutcase, the larger the nutcase cable stiffness (Hyett and Bawden, 1993). In later follow-up work 1994, they also studied the impact of low radial confinement and low water: cement ratio on 25 mm Garford bulb cables. In this case, radial confining pressure had little impact on the load transfer capacity of this cable. As for the effect of water to cement ratio, it was found that the load carrying capacity remained largely unchanged even at a high water to cement ratio of 0.5 (Hyett and Bawden, 1994).

Further improvements to the design were made by Macsporran (1993) when he pointed out that previous research on the performance of cable bolts was based on constant normal stiffness conditions. This was as a consequence of the use of metal pipes, concrete blocks or actual rock to provide confinement to the cable. However, load transfer under constant normal pressure conditions had not been studied. To this end he incorporated a Modified Hoek Cell (MHC) to apply constant radial pressure as shown in Figure 3.

The MHC was integrated into the “split-push” testing rig. Using this design, the effect of confining pressure and water to cement ratio on cable performance was studied. A direct link was reported between the carrying capacity of the cable bolt and confining pressure whereby carrying capacity increased with confinement. As for the impact of water to cement ratio, a low ratio resulted in larger bond capacity.

Single embedment pull test

Stillborg (1984) had taken a different approach using concrete blocks to represent the rock mass and provide confinement to the cable bolt, carrying out both short and long single embedment length pull-out tests. This approach has several advantages, firstly concrete blocks more closely model the properties of a rock mass compared to metal tubes. Furthermore, both the borehole roughness and radial stiffness of concrete blocks better simulate that of boreholes within a rock mass. It was found that bearing capacity of the cable was not directly related to embedment length. Also the surface properties of the cable bolt, curing conditions and grout type all influenced load transfer to a large extent. But the design had the disadvantage in that a length of cable was left free which allowed rotation or unravelling of the cable bolt under load.

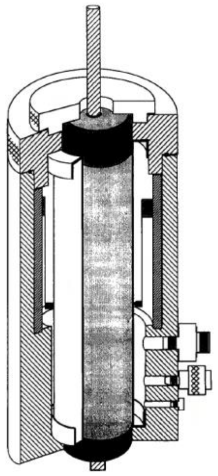

Figure 3 - Cutaway section of a modified Hoek cell (after Macsporran, 1993)

Farah and Aref (1986) used a similar method to study axial behaviour of cables using a fast loading rate to simulate dynamic loading environments. They compared the effects of a mortar mix of sand, water and cement as the grout material against a concrete mix of mortar plus an aggregate. They found the cable bolts grouted with concrete had a larger ultimate bonding strength and ductility as well as higher load at bonding failure compared to mortar-based grouts. These being desirable properties in dynamic loading environments.

Hassani and Rajaie (1990) conducted tests to study the effect of shotcrete as aggregate on load transfer of cables, finding that when using grouts having shotcrete, the peak strength of cables was larger than that of cables with traditional grout materials. Furthermore, large residual bonding strength could be attained. However, the bearing capacity and bonding stiffness decreased.

Mah (1990) just used Schedule 80 pipe to confine the grouted FCB strand and conducted tests to understand the performance of FCB used in hard rock mines. After the experiment, the author indicated that three parameters including hand-mix time, embedment length as well as water to cement ratio were the most important for FCB performance.

Similar single embedment tests were reported by Hassani *et al.* (1992). In their research, PVC and steel pipes were used to represent rock mass with different stiffness. They found that rock mass with larger stiffness tended to generate more confinement, enhancing the cable load transfer capacity.

Benmokrane *et al.* (1992) used a concrete cylinder having a diameter of 200 mm to represent the rock mass and conducted tests on two kinds of reinforcing tendons including a seven-wire cable and a deformed bar, which is shown in Figure 4.

They studied the effect of grout type on bond stress-slip relationship, using six kinds of grouts. It was found that there was a difference in the load transfer mechanism between the steel bars and cable bolts, which was later verified by Ito *et al.* (2001). Further work by Benmokrane *et al.* (1995), based on a theoretical analysis approach, developed a model for the behaviour of the rock tendons the results of which are shown in Figure 5.

This model is tri-linear in nature and can be represented by Equation 1:

$$\tau = ms + n \tag{1}$$

Where,

τ: shear stress on the tendon-grout interface;

s: slip between the tendon and grouts;

The coefficients of m and n for three phases in the bond stress *vs*. slip curve were depicted as:

In the case when $0 \le s \le s_1$

$$m = m_1 = \frac{\tau_1}{s_1} \text{ and } n = 0 \tag{2}$$

When $s_1 \le s \le s_2$

$$m = m_2 = \frac{\tau_1 - \tau_2}{s_1 - s_2} \text{ and } n = \frac{\tau_2 s_1 - \tau_1 s_2}{s_1 - s_2} \tag{3}$$

Finally when $s_2 \le s$

$$m = 0 \text{ and } n = \tau_2 \tag{4}$$

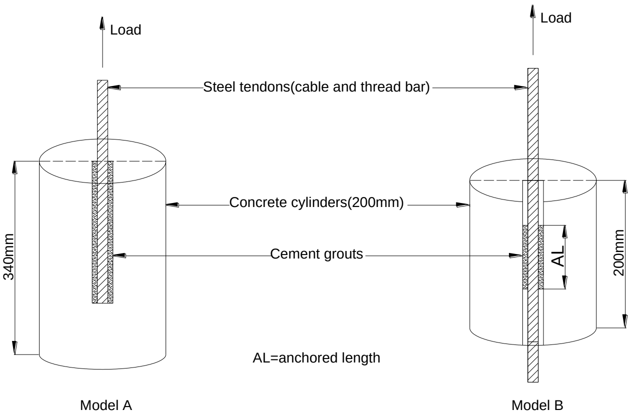

Figure 4 - Concrete cylinders reinforced with two different tendons (after Benmokrane, *et al.*, 1992)

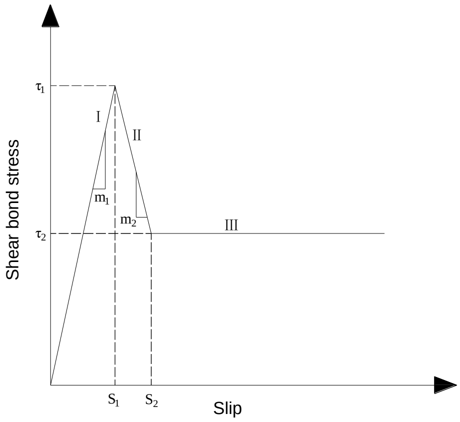

Figure 5 - Tri-linear bond stress-slippage model (after Benmokrane, *et al.*, 1995)

During the first phase of loading (indicated as I in Figure 5), there is a linear relation between the bonding stress and slip. Immediately following the ultimate load (II), debonding takes place resulting in a reduction in stress. In the third and final phase (III) some level of residual stress was achieved due to interface friction.

Thompson and Windsor (1995) studied the impact of pretension on load transfer in an axial direction, finding that pretension did not seem to improve load transfer performance. This finding was later confirmed by Mirabile *et al.* (2010).

Martin *et al.* (1996) carried out tests using resin-grouted cable bolts to study the effect of surface buttons on load transfer. It was found that those cables that had buttons had a much greater stiffness. The effect of borehole size on Garford bulb cables was also evaluated. When the borehole diameter was within the range of 25.4 to 35 mm, there was little change in load transfer efficiency. However when testing from 42 to 106 mm there was a degradation in performance. Similar findings were reported by Mosse-Robinson and Sharrock (2010) who found that smaller borehole diameter resulted in larger load transfer capacity for bulb cables.

Hyett and Bawden (1996) conducted 75 pull-out tests to study the effect of bulb spacing on performance of Garford bulb cables. According to their research, at shorter bulb spacing and longer embedment length as well as higher radial stiffness of the confining medium, axial load increased as did bond stiffness, which is illustrated in the graph in Figure 6.

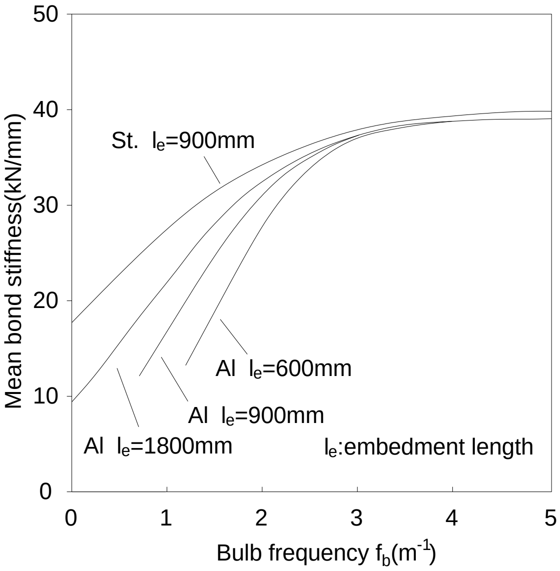

Figure 6 - Effect of bulb spacing on bonding stiffness (after Hyett and Bawden, 1996)

The effect of stress change on axial performance of plain and bulb cables in hard and soft rock mass was studied by Prasad (1997). He reported that the load transfer capacity of the plain cables in weaker rock was found to be more sensitive to both isotropic and anisotropic stress change compared with stronger rock. However, the effect of stress change on the bearing capacity of Garford bulb cables was negligible.

Tadolini *et al.* (2012) studied the indentation geometry impact on the behaviour of PC strands, finding the indentations had an important effect on cable load transfer whereby both cable bearing capacity and stiffness increased with indentation depth. They concluded that indentations on cable wires enhanced the mechanical interlock at the interface between the cables and grouts, which in turn improved load transfer efficiency.

Double embedment pull test

The double embedment pulling test illustrated in Figure 7 was initially proposed by Hutchins *et al.* (1990) to investigate the load transfer features of birdcage cable bolts. This newly devised testing method differed from previous pull test methods in that it enabled the study of the effect of embedment lengths on either side of the discontinuity. However, this type of test could not properly simulate underground conditions, particularly the grout/rock interface since the tube used in the test was specially threaded internally to prevent failing along this interface.

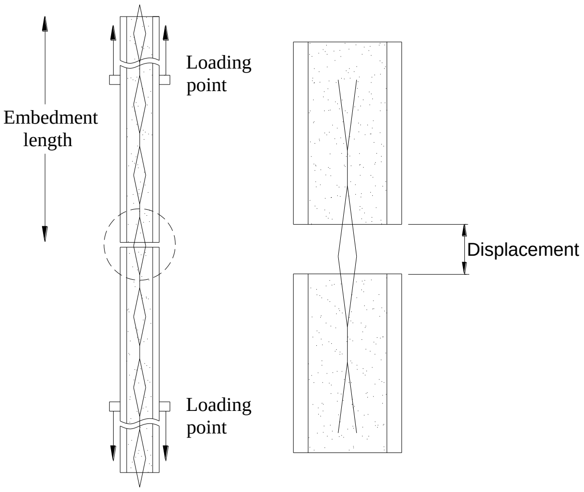

Figure 7 - Double embedment length test set up (after Hutchins, *et al.*, 1990)

The effect of debonding was studied whereby parts of the surface of the cable were painted. In the case of standard cables, the ultimate pull-out load decreased significantly, which was also verified by Satola (1999). This reduction in load was not repeated with birdcage cables although there was a reduction in system stiffness. There was also little effect of node location relative to the discontinuity on load transfer. Later, Satola and Aromaa (2004) designed a new double pipe test system to investigate the impact of epoxy and zinc coatings on the performance of cable bolts. In this arrangement, the embedment length was increased nearly ten-fold to 2.0 m. It was found that the corrosion protection mechanisms of epoxy coating and zinc galvanising on the cable surface increased the cable ultimate load capacity and stiffness to a large extent.

Laboratory short encapsulation pull test

Thomas (2012) reported on a modified Laboratory Short Encapsulation Pull Test (LSEPT) as originally reported by Clifford *et al.* (2001) and shown in Figure 8. Here a thick-walled steel cylinder is used to provide confinement to a sandstone core in which the cable bolt is grouted. Incorporated between the two halves of the test cell is an anti-rotation device that prevents the cable bolt from rotating or unravelling during a test.

A total of 14 different types of grouted cable bolts were tested with the aim of evaluating the effect of cable design and borehole diameter on load transfer,. As expected, there was a marked difference in load transfer with the different cable designs. The impact of borehole diameter on cables was not consistent. For bulbed and nutcaged cables, the load transfer efficiency increased with borehole diameter from 45 to 71 mm. Whereas for plain-strand cables, the load transfer efficiency decreased as borehole diameter increased from 28.5 to 61 mm.

DISCUSSION

Previous studies found that load transfer mainly relies on the shear resistance at the cable/grout interface and this resistance is provided by three basic mechanisms: chemical adhesion, mechanical interlock and friction (Gambarova, 1981). However, the influence of chemical adhesion is only temporary since a small displacement of approximately 0.2 mm can damage this adhesive bond (Fuller and Cox, 1975). Hence in most instances the latter two mechanisms dominate (Stillborg, 1984). Mechanical interlock can be enhanced by the relative movement between the cable bolt and cement grout, compressing the grout within the borehole and generating extra normal pressure at the cable/grout interface. As for friction, it occurs along the cable/grout interface as a result of shear resistance, preventing the cable from slipping, which is the most important part in determining the load transfer behaviour. This also explains the reason why the load transfer efficiency of modified cable bolts is much greater than that of conventional cables. In the case of modified cable bolt designs, structures such as the bulb on the strand, especially when they are filled with grout, increases the geometric mismatch and normal pressure at the cable/grout interface, resulting in the much higher load transfer capacity.

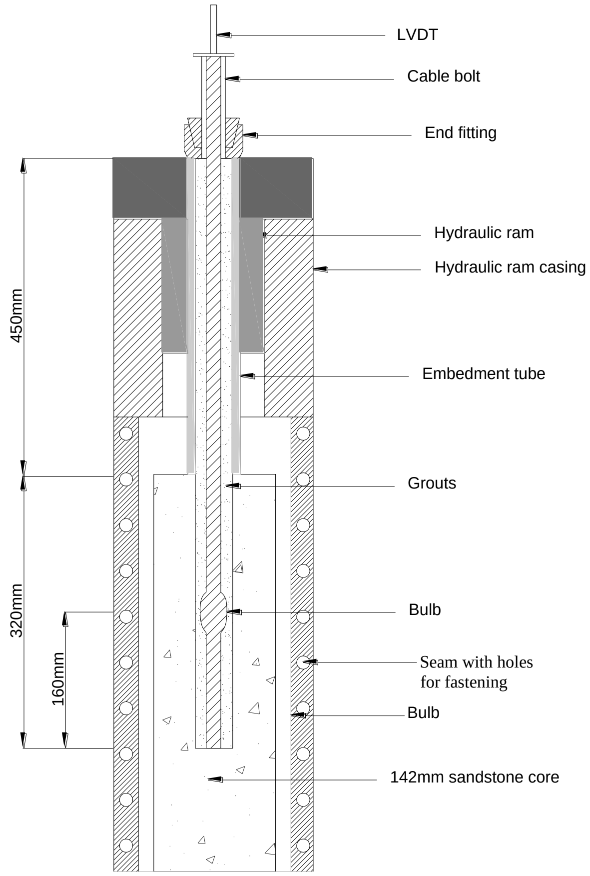

Figure 8 - Schematic diagram of modified LSEPT (after Thomas, 2012)

CONCLUSIONS AND RECOMMENDATIONS

It has been found that over the past years, many different testing procedures and equipment have been developed and used to determine the influence of a wide range of parameters on the load transfer behaviour of fully grouted cable bolts in the axial direction. Based on previous research, the impacts of critical parameters including the rock mass confinement, the cable surface geometry, water: cement ratio, embedment length and so forth on the axial strength of cables are well understood. However, there is a lack of knowledge on the load transfer behaviour of the wide range of cable bolts currently available for use in ground control particularly based on a common testing methodology. A project is underway with support of the Australia Coal Association through their research funding organisation, ACARP (the Australian Coal Association Research Program) to devise a testing facility. This project focuses on studying the axial performance of some particular types of cable bolts and assessing the impacts of corresponding factors on them. The design of the new testing facility which is shown in Figure 9 is based on the recommendation design principles outlined in the British Standard with modifications that accommodate the requirements of the wider range of cable bolt designs used in Australia.

The main objectives of this project mainly include the following aspects:

1) To design and establish a robust axial test rig for kinds of fully grouted cable bolts;
2) To evaluate the behaviour of cables including the twin-strand, PC strand, indented PC strand, Sumo bolt and TG bolt.
3) To assess the effects of soft and medium rock confinement on those types of cable bolts.
4) To study the impacts of normal and larger boreholes on corresponding cable bolts.
5) To investigate the influences of normal and higher grout strength on the load transfer of cable bolts.

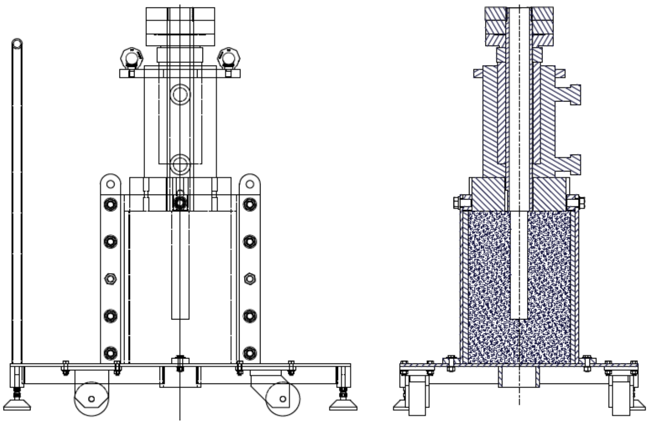

Figure 9 - Schematic of the design of proposed new LSEPT test facility

REFERENCES

Benmokrane, B, Chennouf, A and Ballivy, G, 1992. Study of bond strength behaviour of steel cables and bars anchored with different cement grouts, in Proceedings Rock Support in Mining and Underground Construction (ed: Kaiser, P K and McCreath, D R), pp 293-301 (A. A. Balkema: Rotterdam).

Benmokrane, B, Chennouf, A and Mitri, H S, 1995. Laboratory evaluation of cement-based grouts and grouted rock anchors, *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts,* 32(7):633-642.

Clifford, B, Kent, L, Altounyan, P and Bigby, D, 2001. Systems used in coal mining development in long tendon reinforcement, in *Proceedings 20th International Conference on Ground Control in Mining Proceedings*, pp 235-241 (CSM: Morganton).

Cox, R H T and Fuller, P G, 1977. *Load transfer behaviour between steel reinforcement and cement based grout*, pp 1-12 (Division of Applied Geomechanics, CSIRO: Australia).

Dorsten, V, Frederick, F H and Preston, H K, 1984. Epoxy coated seven-wire strand for prestressed concrete, *Prestressed Concrete Institute,* 29(4):1-11.

Farah, A and Aref, K, 1986. An investigation of the dynamic characteristics of cable bolts, in *Proceedings 27th U.S. Symposium on Rock Mechanics*, pp 423-428 (American Rock Mechanics Association: Tuscaloosa).

Fuller, P G and Cox, R H T, 1975. Mechanics of load transfer from steel tendons to cement based grout, in *Proceedings Fifth Australasian Conference on the Mechanics of Structures and Materials* (ed: Grundy, P and Stevens, L K), pp 189-203 (Melbourne).

Gambarova, P, 1981. *On aggregate interlock mechanism in reinforced concrete plates with extensive cracking*, pp 105-134.

Garford, 1990. *An improved, economical method for rock stabilisation*, pp 1-4 (Garford, Pty Ltd: Perth).

Goris, J M, 1990. *Laboratory evaluation of cable bolt supports (in Two Parts) 1. Evaluation of supports using conventional cables*, pp 1-23 (Uited States Bureau of Mines: America).

Goris, J M, 1991. *Laboratory evaluation of cable bolt supports (in Two Parts) 2. Evaluation of supports using conventional cables with steel buttons, birdcage cables, and epoxy-coated cables*, pp 1-14 (United States Bureau of Mines: America).

Goris, J M and Conway, J P, 1987. Grouted flexible tendons and scaling investigations, in *Proceedings 13 World Mining Congress*, pp 783-792 (Stockholm).

Hartman, W and Hebblewhite, B, 2003. Understanding the performance of rock reinforcement elements under shear loading through laboratory testing-A 30-year history, in *Proceedings 1st Australian Ground Control in Mining Conference*, pp 151-160 (Australasian Mining Rock Mechanics Society: Sydney).

Hassani, F P, Mitri, H S, Khan, U H and Rajaie, H, 1992. Experimental and numerical studies of the cable bolt support systems, in *Proceedings Rock Support in Mining and Undergound Construction* (ed: Kaiser, P K and McCreath, D R), pp 411-417 (A. A. Balkema: Rotterdam).

Hassani, F P and Rajaie, H, 1990. Investigation into the optimization of a shotcrete cable bolt support system, in *Proceedings 14th Congress of the Council of Mining and Metallurgical Institution*, pp 119-129 (Edinburgh).

Hutchins, W R, Bywater, S, Thompson, A G and Windsor, C R, 1990. A versatile grouted cable dowel reinforcing system for rock, in *Proceedings The Australasian Institute of Mining and Metallurgy Proceedings*, pp 25-29.

Hutchinson, D J and Diederichs, M S, 1996. *Cablebolting in underground mines*, pp 1-2 (BiTech Publishers Ltd.: Richmond).

Hyett, A J and Bawden, W F, 1993. The nutcase cable bolt, in *Proceedings Innovative Mine Deisgn for the 21st Century: Proceedings of the International Congress on Mine Design* (ed: Bawden, W F and Archibald, J F), pp 409-419 (Ontario).

Hyett, A J and Bawden, W F, 1994. *The 25mm Garford bulb anchor for cable bolt reinforcement Part 1: laboratory results*, pp 1-16 (Garford Pty. Ltd.: Perth).

Hyett, A J and Bawden, W F, 1996. *The effect of bulb frequency on the behaviour of fully grouted Garford bulb cable bolts*, pp 1-54 (Garford Pty Ltd: Canada).

Ito, F, Nakahara, F, Kawano, R, Kang, S-S and Obara, Y, 2001. Visualization of failure in a pull-out test of cable bolts using X-ray CT, *Construction and Building Materials,* 15(5-6):263-270.

Macsporran, G R, 1993. An empirical investigation into the effects of mine induced stress change on standard cable bolt capacity, Master thesis(Published), Queen's University, Kingston.

Mah, G P, 1990. The development of a fibreglass cable bolt, Master thesis(Published), The University of British Columbia, Vancouver.

Martin, L, Girard, J M and Curtin, R, 1996. Laboratory pull tests of resin-grouted cable bolts, in *Proceedings 15th International Conference on Ground Control in Mining Proceedings*, pp 455-468 (CSM: Golden).

Matthews, S M, Tillmann, V H and Worotnicki, G, 1983. A modified cable bolt system for the support of underground openings, in *Proceedings AusIMM annual conference*, pp 243-255 (Australasian Institution of Mining and Metallurgy: Melbourne).

Mirabile, B, Poland, R and Campoli, A, 2010. Application of tensioned cable bolts for supplemental support, in *Proceedings 29th International Conference on Ground Control in Mining*, pp 128-133 (West Virginia University: Morgantown).

Mitri, H S and Rajaie, H, 1992. Shear bond stress along cable bolts, in *Proceedings International conference on ground control in mining*, pp 90-95 (CSM: Morgantown).

Mosse-Robinson, S and Sharrock, G, 2010. Laboratory experiments of quantify the pull-out strength of single strand cable bolts for large boreholes, in *Proceedings Second Australasian Ground Control in Mining Conference* (ed: Hagan, P and Saydam, S), pp 201-209 (Australasian Institution of Mining and Metallurgy: Sydney).

Potvin, Y, Hudyma, M and Miller, H D S, 1989. Design guidelines for open stope support, *CIM bulletin*):53-62.

Prasad, K, 1997. Effect of isotropic and anisotropic stress changes on the capacity of fully grouted cable bolts, Master thesis(Published), Queen's University, Kingston.

Reichert, R D, 1991. A laboratory and field investigation of the major factors influencing bond capacity of grouted cable bolt, Master thesis(Published), Queen's University, Kingston.

Reichert, R D, Bawden, W F and Hyett, A J, 1992. Evaluation of design bond strength for fully grouted cables, *CIM Bulletin,* 85(962):110-118.

Satola, I S, 1999. Testing of the yielding cable bolt achieved by debonding, in *Proceedings 9th Congress of the International Society for Rock Mechanics* (ed: Vouille, G and Berest, P), pp 1467-1470 (International Society for Rock Mechanics: Paris).

Satola, I S and Aromaa, J, 2004. The corrosion of rock bolts and cable bolts, in *Proceedings Ground Support in Mining and Underground Construction* (ed: Villaescusa and Potvin), pp 521-528 (London).

Schmuck, C H, 1979. Cable bolting at the Homestake gold mine, *Mining Engineering,* 31(12):1677-1681.

Stillborg, B, 1984. Experimental investigation of steel cables for rock reinforcement in hard rock, PhD thesis(Published), Högskolan i Luleå University, Kiruna.

Strata Control, 1990. *Testing of Garford bulb tendons*, pp 1-5 (Strata Control Technology Pty. Ltd.: Australia).

Tadolini, S C, Tinsley, J and McDonnell, J P, 2012. The next generation of cable bolts for improved ground support, in *Proceedings 31st International Conference on Ground Control in Mining*, pp 1-7 (CSM: Morganton).

Thomas, R, 2012. The load transfer properties of post-groutable cable bolts used in the Australian coal industry in *Proceedings 31st International Conference on Ground Control in Mining*, pp 1-10 (CSM: Morganton).

Thompson, A G and Windsor, C R, 1995. Tensioned cable bolt reinforcement-An integrated case study, in *Proceedings 8th ISRM Congress* (ed: Balkema, A A), pp 679-682 (International Society for Rock Mechanics: Tokyo).

Thorne, L J and Muller, D S, 1964. Prestressed roof support in underground engine chambers at Free Geduld Mines Ltd., pp 411-428.