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IN SITU BOND STRENGTH TESTING OF AUSTRALIAN CABLE BOLTS

Peter Craig and Matthew Holden

ABSTRACT: Testing of axial load transfer of various Australian cable bolts has been conducted in overseas laboratories within the last two years (Thomas, 2012). The comparative laboratory testing determined that nutcaged cables and indented wire cables provide stiffer and higher capacity bond strength compared to plain cable. Laboratory studies have limitations in terms of rock strength and installation practice but have the benefit of controlling the type of load applied during the test. *In situ* cable bolt tests were conducted underground using common installation equipment, resin capsules instead of cementitious grout where relevant, and in a typical coal mine roof. *In situ* testing methods included anti-twist methodology similar to that used in laboratory tests.

INTRODUCTION

Research conducted by Thomas (2012) on the anchorage performance of 14 cable bolts available in Australia at the time determined that the aggressive profile of indented wire cables and modified geometry cable configurations have the potential to provide higher bond strengths. The results from the Laboratory Short Encapsulation Pull Test (LSEPT) found peak loads were up to 400% higher for nutcaged or bulbed cable designs in comparison to plain strand designs. The constant stiffness confinement conditions implemented during the LSEPT included grouting a sandstone core into a two-part steel casing to simulate a relatively strong *in* situ ground environment. Typically the weakest load transfer point in a cable bolt system, installed into competent rock, is the cable/grout interface, with slip initiating along this surface prior to degradation of the surrounding rock and/or grout. However, weaker and more variable rock masses can significantly alter the effective cable bolt strength as the load transfer between the rock/grout interface and through the strata is correspondingly weaker. *In situ* pull testing can overcome the idealised confinement conditions implemented in the laboratory and more accurately compare the performance of different cable bolt designs in typical installation conditions.

Hutchinson and Diederichs (1996) identified that constrained and unconstrained pull tests tend to give upper and lower bond strengths of cable bolts. LSEPT's by Hyett *et al.* (1995) identified that the failure mechanism of a 15.2mm diameter plain wire strand in cement was both shearing of the grout flutes and unscrewing of the cable from the cement annulus, and that the helical form of a cable bolt creates a different mechanical behaviour compared to solid deformed bar. A cable bolt will undergo torsional rotation of the wires along a free length, and the interaction of a free length adjacent to a bonded length in a SEPT would not represent the failure mechanism of a fully grouted cable bolt in service.

LSEPT typically utilise constrained methods, such as anti-rotation devices, when assessing the performance of fully encapsulated cable bolts. However, the increase in complexity between constrained and unconstrained pull test methodologies, particularly with regards to setting up anti-rotation devices, is largely prohibitive for *in situ* testing. The need for comparative testing of cable bolt performance in rock weaker than that used in LSEPTs, led to a program of *in situ* experimentation using different apparatus and methods. An anti-twist testing arrangement was subsequently developed and adapted to the common reamed hole SEPT. A selection of different diameter plain and nutcaged cable bolts were comparatively tested using the new method in moderate strength mudstone at Baal Bone Colliery to test the practicality and repeatability of the method.

DEVELOPMENT OF THE UNDERGROUND *IN SITU* TEST METHOD

Embedment length

A common SEPT method used for rebar rock bolts involves reaming of the hole below the target bond length to allow for excess resin to fall out of the top 27-28 mm diameter drill hole section, effectively de-bonding a free length of bolt and guaranteeing a specific bond length. This technique for solid rebar

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rock bolts is described by Mark *et al.* (2008). This test typically uses a short 300 mm embedment length and an initial set of *in situ* testing was conducted using this method on 22 mm Indented and plain wire SuperStrand cable bolts. These results were compared to rebar rock bolts pull tested using the same method with 300 mm embedment length.

The length of wire lay is defined as the distance along the axial length of the cable corresponding to a full spiral rotation of an individual wire (Hutchinson and Diederichs, 1996), as depicted in Figure 1. It was surmised that an embedment length with an entire length of lay within the bond would incorporate the effect of the helical structure of the strands. The typical range of lay lengths for 22 mm SuperStrand and 28 mm hollow strand cable wires are 300-350 mm and 400-450 mm, respectively. Bigby and Reynold (2005) used 450 mm embedment length for cable bolt LSEPT and the resulting bond strength on non-modified geometry cable did not exceed the yield strength of the ~60t cable. The LSEPT method described by Thomas (2012) used 320 mm embedment length in a strong sandstone rock core. *In situ* SEPT of 28 mm Hollow strand cable by Craig and Murnane (2013) successfully used 400 mm embedment length in a weak coal roof. As a result of considering the length of cable lay, previous LSEPT embedment lengths used and that the *in situ* tests would be conducted in moderate strength mudstone; the 400 mm embedment length was adopted for the remainder of the study as opposed to the first tests using the shorter 300 mm encapsulation. It should also be noted that most Australian post groutable cables have a nutcage at 500 mm centres down the fully grouted portion of the cable bolt. The true comparison of non-modified geometry cables against nutcage cables would need to be in a bond length equivalent to the nutcage spacing.

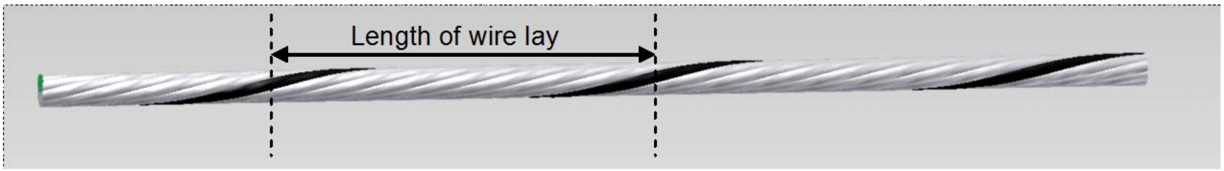


Figure 1 - Length of lay for an individual wire

Bonding agent

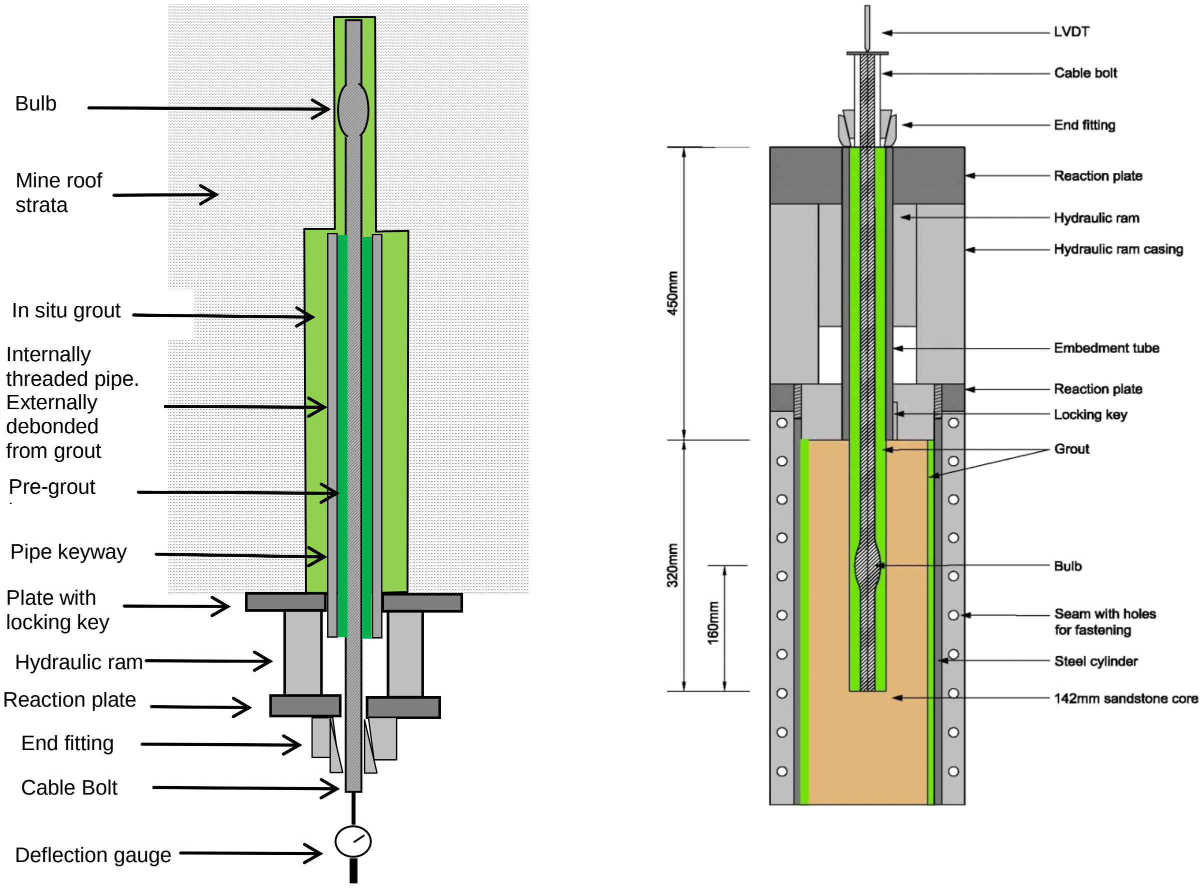
The Australia coal mining industry utilises 22 mm diameter cable bolts in 28 mm drill holes exclusively with resin capsules, and it was noted that Thomas utilised non-shrink cementitious grout for all comparative laboratory tests including those in 28 mm drill holes. The benefit of *in situ* test methods is the use of normal installation equipment used in service, which allowed the use of resin capsules for the cables in 28 mm drill holes and Australian made top-down thixotropic cementitious grout for the hollow post groutable cables in 42 mm drill holes. The initial *in situ* tests aimed at developing the method used resin capsules for immediate results and to provide in service performance information. The test program using the final developed pull test method included cementitious grout in 28 mm drill holes to compare against earlier results with resin.

The top-down pumped high strength thixotropic grout used for the *in situ* testing has a typical UniaxialUCS of 30 MPa at 1 d, 55 MPa at 7 d and 70 MPa at 28 d. The grout cure time before pull testing was six days due to mine access requirements, which gave an estimated grout UCS strength of 50 MPa. The resin capsules used in the study have a typically UCS strength of 70 MPa

Anti-twist method

Research into load transfer of Australian cable bolts conducted by Thomas (2012), using a LSEPT methodology, utilised an anti-twist mechanism to restrict the rotation of the free length of the cable. Cable rotation was restricted during testing by grouting the free length of cable in a steel pipe which is secured by a locking key that prohibits rotation, as shown in Figure 2(b).

Axial loading of a fully grouted cable *in situ* caused by simple roof dilation would naturally have no twisting of the rock mass, so design of the *in situ* test to represent in-service cable bolt loading was sought after. A similar anti-twist concept was adopted for the *in situ* pull testing investigation, the set-up illustrated in Figure 2(a). Preparation included grouting the middle section of the 1.4 m cable into a 600 mm long thick-walled steel pipe with an exterior profile which matches the key hole in a 25 mm thick steel loading plate. The steel plate remained fixed during loading, as it was compressed against the seam roof, which in turn locked the profiled pipe as it attempted to rotate. The steel pipe within the reamed out section of the borehole below the embedment length was covered in two layers of lubricant and plastic film to prevent excess installation grout from adhering to the pipe, which had the potential to provide additional strength to the system during loading.



(a) **(b)**

Figure 2 - (a) Anti-twist *in situ* method developed, (b) Anti-twist laboratory pull test method (Thomas, 2012)

The final pull test arrangement developed for *in situ* testing at Baal Bone Colliery, as illustrated in Figure 2(a), was an adaptation of the reamed hole SEPTusing 400 mm embedment length and included the anti-twist grouted pipe apparatus

Final *in situ* test program

The cable test pieces were installed 0.9 m into the mudstone roof of the Baal Bone mine. The pull test horizon location, with respect to the Lithgow coal seam, can be seen in the stratigraphy in Figure 3. The UCS of the mudstone horizon is known to be approximately 35 MPa.

Four types of cable were selected for the final test program: 1) Indented 22 mm SuperStrand; 2) Indented TG cable 28 mm hollow strand; 3) Indented SUMO 28 mm hollow strand with a 35 mm diameter nutcage; and 4) Plain wire SUMO 28 mm hollow strand with a 35 mm diameter nutcage.

The SuperStrand is a 19 wire cable with a capacity of 60 t. All three 28 mm cable configurations consist of 9 wires wound around a central hollow strand with a capacity of 63 t. The two modified geometry cables had the nutcage located half-way along the 400 mm embedment length. The 28 mm hollow strand cables were installed into holes drilled with a standard 42 mm twin-wing drill bit, while the 22 mm SuperStrand were installed using a 28 mm drill diameter.

The aim of the final larger set of tests was to ensure the pull test method gave repeatable results and that it was practical for future studies within the restrictions of underground coal mine testing.

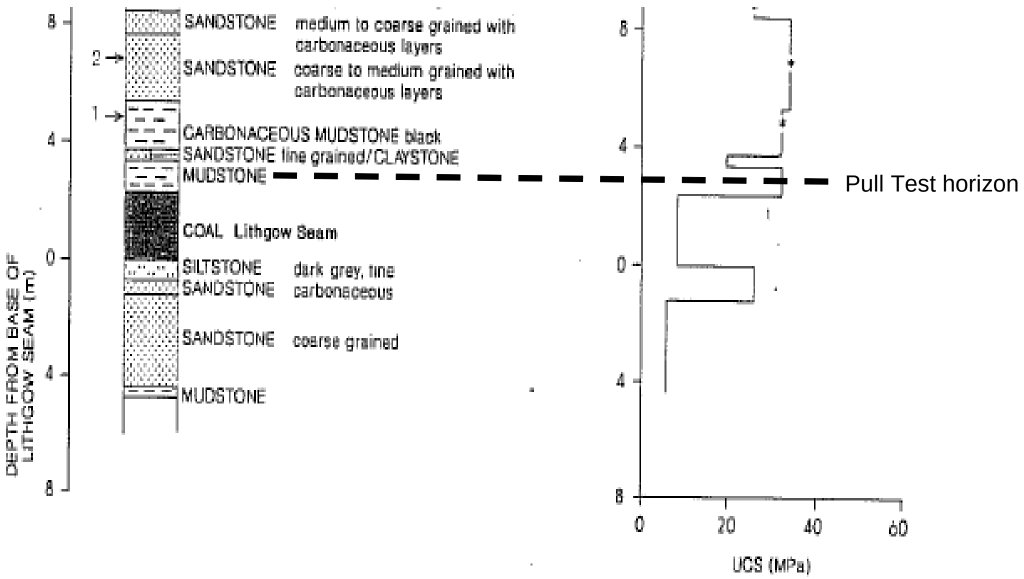


Figure 3 - Stratigraphy referenced to pull test horizon (SCT, 1997)

RESULTS AND DISCUSSIONS

Common reamed hole 300 mm SEPT

The load displacement results from the common reamed hole SEPT conducted on indented and plain wire 22 mm SuperStrand using resin capsules, compared to 22 mm rebar rock bolts can be seen in Figure 4(a). These tests did not include a pre-grouted pipe with anti-twist mechanism, therefore the free length of cable was able to stretch and twist. The tests did utilise a hydraulic ram with a key between the piston and body of the cylinder. The raw displacement measurements were corrected for theoretical cable stretch using the Young's modulus for the 22mm cable bolt.

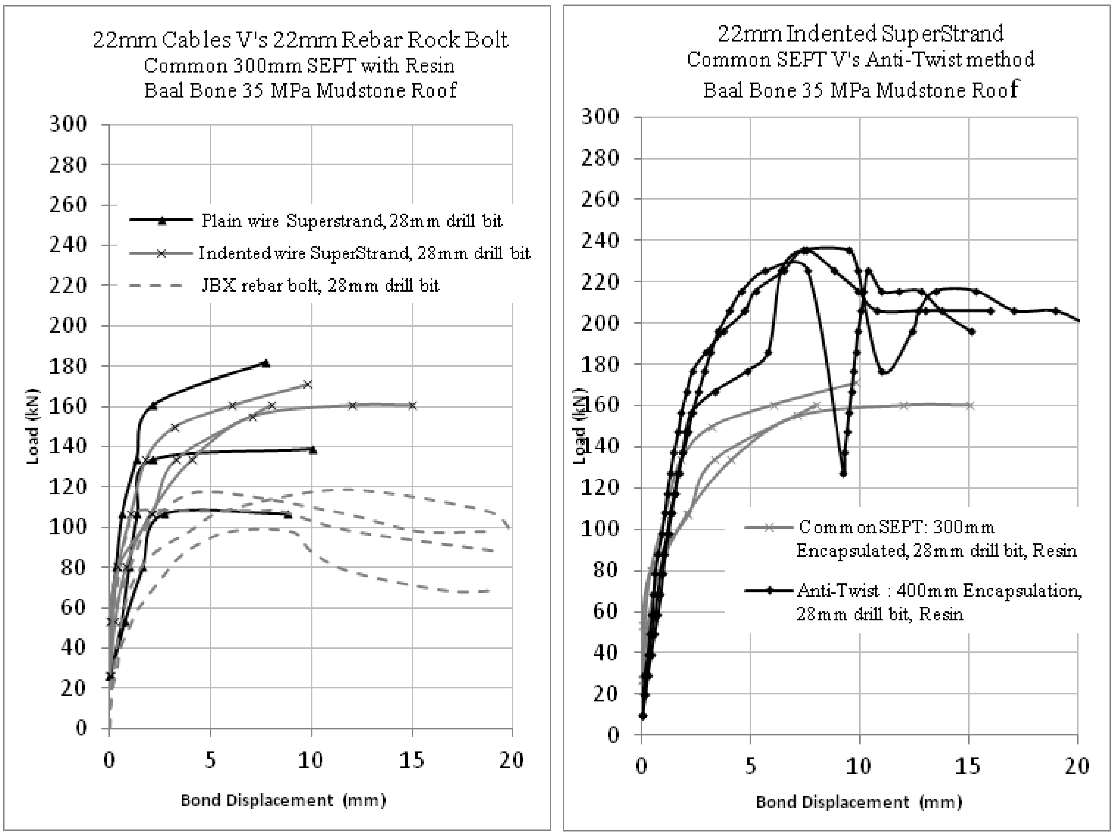
The results for the plain wire cable were variable in comparison to the indented wire cable. This could be due to the indented wire offering resistance to the cable unscrewing from the resin annulus, and shear failure of the resin flutes possibly being the main failure mechanism. The plain strands are more likely to suffer unscrewing from the resin preventing shearing of the flutes and giving a variable result. The comparison of the 22mm diameter cables to a rebar rock bolt gave a higher bond strength for the cables. The reason for such results would require further investigation and should include effects of resin mixing between cables and rebar bolts.

Anti-twist reamed hole 400 mm SEPT with resin

The indented SuperStrand was pull tested using the longer 400 mm embedment length and anti-twist method. The results plotted alongside the previous common 300mm SEPT are shown in Figure 4(b). The bond strength for the common SEPT averaged 11 t per 300 mm, while the anti-twist bond strength averaged 18 t per 400 mm bond length. Although two different bond lengths were implemented in each test method the bond strength per unit length can still be compared. Assuming a linear extrapolation for bond strength, the common 300 mm SEPT without anti-twist equates to 15 t per 400 mm bond length.

The lower bond strength of the common SEPT method is probablydue to the strands of the cable unwinding along the helical grout channels that encapsulate the outer surface of the cable strands. Restricting cable bolt rotation can eradicate this unwinding effect by forcing the strands of the cable to ride up and over the grout ridges, as opposed to following the channels. This mechanism of failure induces higher radial dilation pressures in the grout which in turn increases shear resistance to axial movement along the cable length and overall bond strength (Hutchinson and Diederichs, 1996). This effect could be magnified by the length of wire lay within the bond. The 400 mm embedment length encapsulates an entire length of wire lay, creating grout channels that restrict the movement of a single wire around the entire circumference of the drill hole. This could increase resistance to cable rotation within the bond length to a greater extent, when coupled with an anti-twist device, and consequently generate even higher dilation pressures during loading.

Under such assumptions it can be reasoned that the anti-twist device, with an entire wire lay length within the bond, has the potential to increase the bond strength of the system by up to 20%. It is therefore imperative these two parameters are either controlled or understood within pull testing methodologies as the effect on bond performance can be significant.



(a) **(b)**

Figure 4 - Reamed hole SEPT results with resin

Anti-twist reamed hole SEPT with grout

The nine various configurations of 28 mm hollow strand cable bolts were installed by pumping grout through the central hollow strand to achieve full encapsulation along the 400 mm testing length. The three Indented SuperStrand cables, on the other hand, were installed using a grout and insert method (Hutchinson and Diederichs, 1996) as the diameter of the hole was too small to accommodate both cable and grouting tube. Unfortunately, complications arose during installation of one indented nutcaged cable that resulted in inadequate encapsulation of the cable. The failure load measured for this cable was significantly lower than the other samples, and as such was disregarded.

The twelve grouted cable bolts were pull tested 6d after installation using a 60 t hydraulic cylinder. The displacement measurements were corrected to account for cable elongation of the 300 mm free length between the barrel and wedge and the base of the grouted steel pipe. It was assumed that the elongation along the grouted cable in the heavy walled pipe section was negligible. In accordance with the British Standard (2007), bond strength of the cables was determined when the stiffness fell below 20 kN/mm.

The results summary for the *in situ* pull tests are contained in Table 1. The load versus displacement curves for each test are shown in Figure 5, with the nutcaged and non-modified geometry bolt results plotted on separate graphs. The plain wire SUMO cable bolt stiffness decreased rapidly after the bond strength was exceeded, displacing comparably more than all other indented cables at peak bond loads. This suggests the aggressive profile of the indented wire cables generates significantly more resistance to cable/grout slip, most likely due to interlocking along the irregular wire surface.

Comparing the bond strengths of the 28 mm nutcaged indented and plain wire cables, averaging 35 t and 34 t per 400 mm bond length respectively, revealed little difference in bond strength due to the indentations. The indented nutcaged cables had higher bond stiffness shown by the gradient of the curves which should be attributed to the indentations. A similar mode of failure was found for all bulbed cables with a sudden drop in load corresponding to a loud pop before cable reloading. Craig and Murnane (2013) reported similar types of failure during *in situ* pull tests conducted on 28 mm hollow strand cable using injected polyurethane and cementitious grout. The sudden bond slip was suggested to have occurred at the rock/grout boundary or through the rock mass. A problem with *in situ* testing is the inability to view the failure mechanism.

Table 1 - Summary of *in situ* pull test results

Test No.	Cable Type	Bond Strength (kN)	Av. Bond Strength (kN)	Range of Results (max – min)
1	Plain wire SUMO	334	350	68kN (19%)
2		392		
3		324		
4	Indented wire SUMO	373	344	59kN (17%)
5		314		
6	Indented wire TG	265	288	49kN (17%)
7		314		
8		284		
9	Indented SuperStrand (grout)	157	147	20kN (14%)
10		147		
11		137		
a	Indented SuperStrand (resin)	157	180	49 (27%)
b		177		
c		206		

The load displacements graphs for the indented 28 mm TG and 22 mm SuperStrand cables, shown in Figure 5, have average bond strengths of 29 t and 15 t per 400 mm bond length, respectively. In comparison, laboratory pull tests conducted by Thomas (2012) found that plain strand 28 mm TG and 22 mm SuperStrand embedded 320 mm into sandstone cores had bond strengths of 21 t per 320 mm and 6 t per 320 mm bond length, respectively. Linearly extrapolating these results to an equivalent 400 mm bond length gives 26 t and 7.5 t bond strengths suggesting that either the indentations or test method created a significant difference in performance between the two different diameter non-modified geometry cables. Also included in Figure 5 are SuperStrand results from the investigation using resin encapsulation under the same testing configuration. The resin anchored cables had a 20% higher bond strength than the top-down high strength thixotropic grout at 6 d cure; this is most likely due to the stronger 70 MPa UCS of the resin, compared to 50 MPa for the grout.

Comparing the 28 mm nutcaged cable configurations to non-modified geometry indented 28 mm cables reveals a 20% increase in the bond strength with nutcaged cables. The percentage margin was larger between 22 mm Indented SuperStrand and nutcaged 28 mm cables at approximately 135%.

The only cable tested *in situ* which had also been tested using the same laboratory method described by Thomas (2012), was the plain wire SUMO cable. The plain wire SUMO was tested in the Golders UK laboratory and reported independently to Jennmar Australia Pty Ltd. The results from the Laboratory test plotted against the *in situ* tests are shown in Figure 6, with a summary shown in Table 2.

The average bond strength from the LSEPT was 30 t per 320 mm bond length. This extrapolates to a 37.6 t per 400 mm bond length which is comparatively higher than the *in situ* pull tests at 35 t per 400 mm bond length. This discrepancy is not considered excessive and could be attributed to the difference in rock or grout strength between the laboratory and *in situ* tests, with the former grout strength reaching an average UCS of 94 MPa at 58 d and the latter an approximate UCS of 50 MPa at 6d.

The Golder UK laboratory reported that failure occurred predominantly due to slip along the cable/grout interface and is shown in Figure 7. The corresponding load displacement curves in Figure 6 have gradual reloading characteristics, following the debonding load, which are indicative of such types of failure. This differs from the *in situ* pull test failure which possibly occurred along the rock/grout interface or through the rock mass. This difference can be attributed to the confinement conditions of the LSEP tests which incorporate a sandstone core and steel cylinder, representing a strong rock mass, while the *in situ* pull length was located in a weaker mudstone horizon. The strength of the grout could also have contributed to such a difference in failure modes.

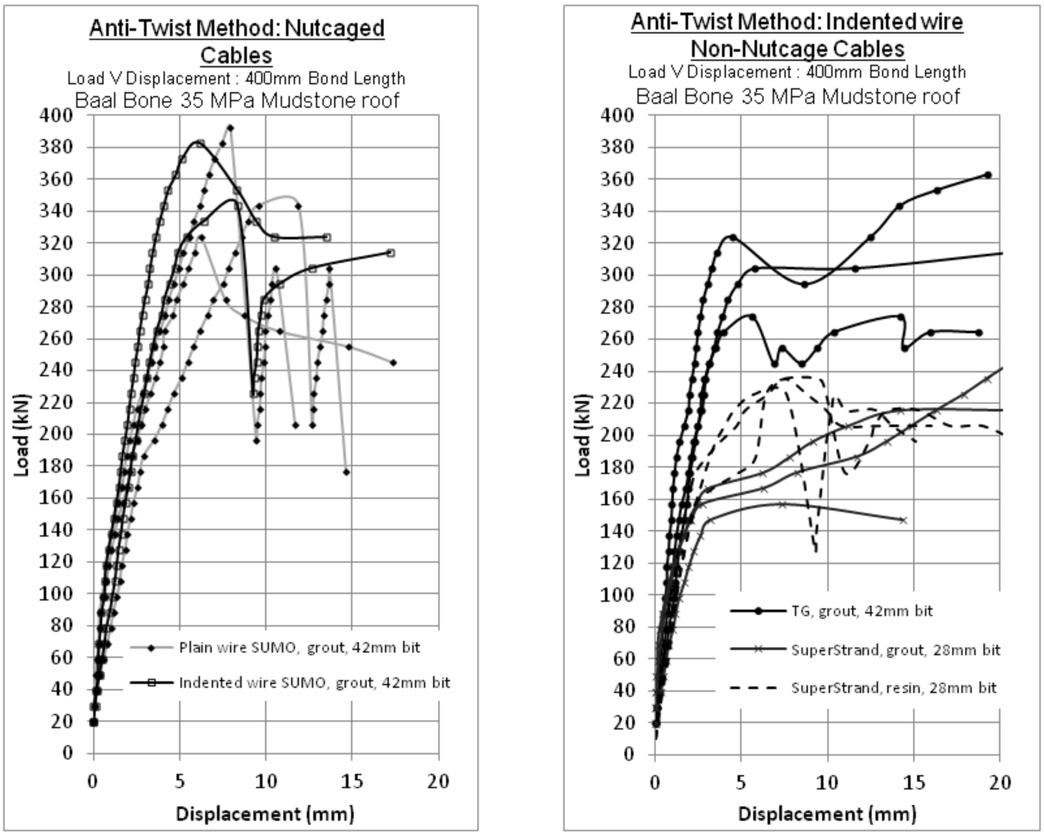


Figure 5 - *In situ* load transfer results

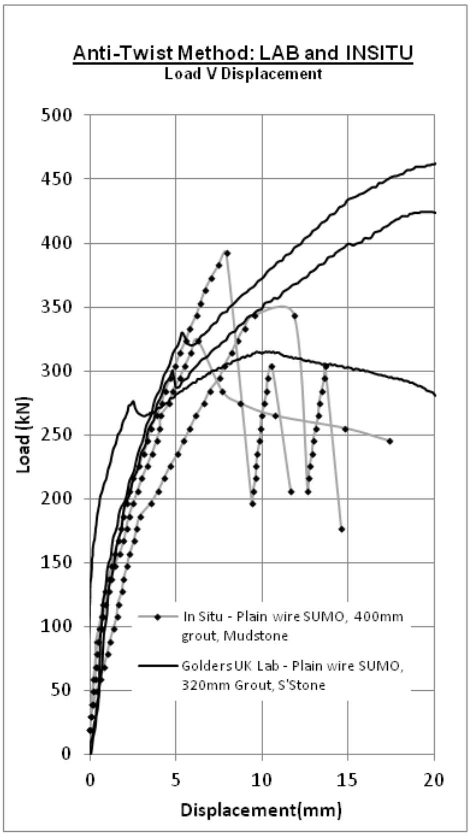


Figure 6 - Comparison of laboratory and *in situ* results

Table 2 - Summary of laboratory pull test results

Cable Type	Bond Strength (kN)	Av. Bond Strength (kN)	Range of Results (max – min)
Plain wire SUMO	276	301	54kN (18%)
	330		
	298		

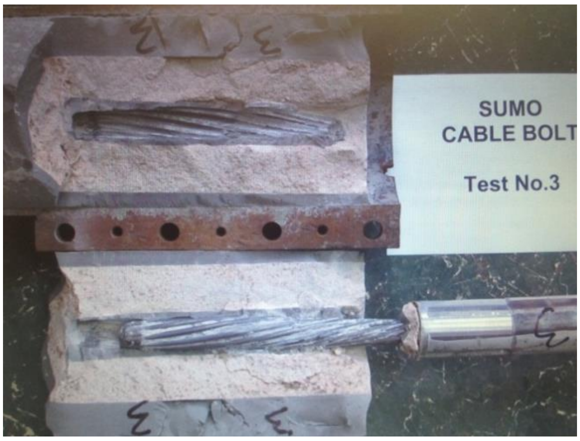


Figure 7 - Test sample after pull test and splitting of the core (Golders UK)

CONCLUSIONS

The development of an *in situ* pull testing methodology that incorporates an anti-twist device into the commonly reamed hole short encapsulation pull test was found to increase cable bolt anchorage test results by 20%. It was also found that the embedment length may have contributed to this increase as an entire length of wire lay was encapsulated within the bond length. It is recommended that these two parameters be controlled during *in situ* pull testing as they also best represent in service loading mechanisms of fully grouted cables. The anti-twist *in situ* method proved practical and as accurate as the LSEPT with the range between identical tests less than 20%.

The 28 mm hollow strand nutcaged cable bolts had comparatively higher bond performance than both types of indented wire non-modified geometry cable bolts. Within the 35 MPa mudstone rock, the average nutcage 28 mm cable bond strength was 25% higher than the indented wire 28 mm TG cable bolt and 135% higher than the Indented wire 22 mm SuperStrand cable bolt.

In the mudstone rock, the indented strands provide little benefits to the bond strength of nutcaged cable designs, which is more likely attributed to the non-collapsible bulb as opposed to the profile of the wire. The indentations, however, increased the stiffness of the system as loads approached the ultimate bond strength, with the plain strand cable displacing 50% more on average. Golders UK lab pull tests on the 28 mm plain wire SUMO cables were comparatively similar to the *in situ* test method developed.

The *in situ* test method developed is envisaged to allow further research into the parameters of embedment length and bonding material to eventually provide accurate comparative test results between different cables in the more common weak to moderate rocks found in roof strata requiring high density cable bolting.

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