THE *25mm* GARFORD BULB ANCHOR FOR CABLE BOLT REINFORCEMENT
PART 1: LABORATORY RESULTS

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ABSTRACT

The Garford bulb anchor is a modified cable geometry developed and patented by Garford Pty of Australia, and which has recently become widely available in Canada. It is produced by simply deforming the 7 wires (including the central *kingwire)* of a standard cable into a bulb[1] (see Figure 1). Laboratory cable pull tests indicate that the bond capacity of the *25mm* Garford bulb anchor is comparable to the *nutcase* cable, in excess of the *birdcage* cable, and significantly higher than standard 7-wire strand. Its comparative advantage over the latter is most significant for tests at low radial confinement and high water:cement ratio grout, which corresponds to operational conditions of low quality rock (ie: weak, highly fractured rock masses, foliated hanging walls, failed ground etc.) and poor installation quality control (perhaps the most common explanation for cable bolt failures). It is under such conditions that cable bolting is often ineffective. The most impressive result is that for a reduction of the effective rock mass modulus by a factor of five, the Garford bulb cable capacity remains virtually unchanged. For tests conducted at a 0.4 *w:c* ratio grout the dominant failure mechanism involved rupture of the strand (tensile strength of the strand = 250kN) and as such the capacity of Garford Bulb Anchor was independent of the effective rock mass confinement. Field test results will be presented in a companion paper.

1 As a matter of terminology, this ungrouted configuration is called a *bulb*, and the grouted configuration a *bulb structure.*

1. INTRODUCTION

Perhaps the most important development in recent cable bolt research has been to highlight the limitations of conventional 7-wire strand. Both laboratory and underground tests have demonstrated that cable bolt failure occurs primarily due to slip at the cable-grout interface, and that the bond strength is associated with frictional-dilational rather than adhesional resistance. Cable pull tests conducted at constant radial pressure in a Modified Hoek cell (Hyett *et al.,* 1994) indicated that the radial dilations induced during bond failure, which are responsible for the frictional strength of 7-wire strand are minuscule: 10-20μm for higher radial confining pressures. Herein lies both the advantage and disadvantage of conventional 7-wire strand. In very good quality rock masses, under favourable mining conditions, it represents an effective yielding support system, mobilizing around 60-80% of the strength of the steel for a 10"(250mm) embedment length. However, in poor quality ground, or where the rock mass is destressed or has failed - namely in cases where cable support is often of critical importance - excessive borehole deformation or mining induced borehole relaxation may result in very low capacities. Such incidences may lead some engineers to falsely conclude that cable bolting is always ineffective. In such circumstances, modified cable geometries, which force much higher radial dilations, will guarantee higher bond strengths which are less sensitive to installation quality control, rock mass characteristics and mining induced effects (ie: stress redistribution around openings).

The Garford Bulb Anchor is a modified cable geometry developed and patented by Garford Pty Ltd in Australia. It is produced by simply deforming the 7 wires (including the central *kingwire*) of a standard cable into a bulb[1] (see Figure 1). This can be done without reducing the tensile strength of the strand. The versatility of the manufacturing process allows both the bulb diameter and the bulb spacing to be readily varied. Preliminary laboratory test results by CSIRO and Strata Control Technologies indicated that the bond strength of the Garford bulb cable may be significantly higher than standard cable and *birdcage* cable. The objective of the laboratory test programme presented in this paper, was to determine the bond strength of the Garford bulb anchor under different radial confinements, different water:cement ratio grouts, and, in particular, to evaluate its prospective behaviour under adverse conditions of low radial confinement (ie: in low quality, failed or destressed rock masses) and high water:cement ratio grouts (poor operator quality control) that are all too common in many mines worldwide. In a companion paper, Part 2, results from a field test programme will be presented.

[1] As a matter of terminology, this ungrouted configuration is called a *bulb*, and the grouted configuration a *bulb structure.*

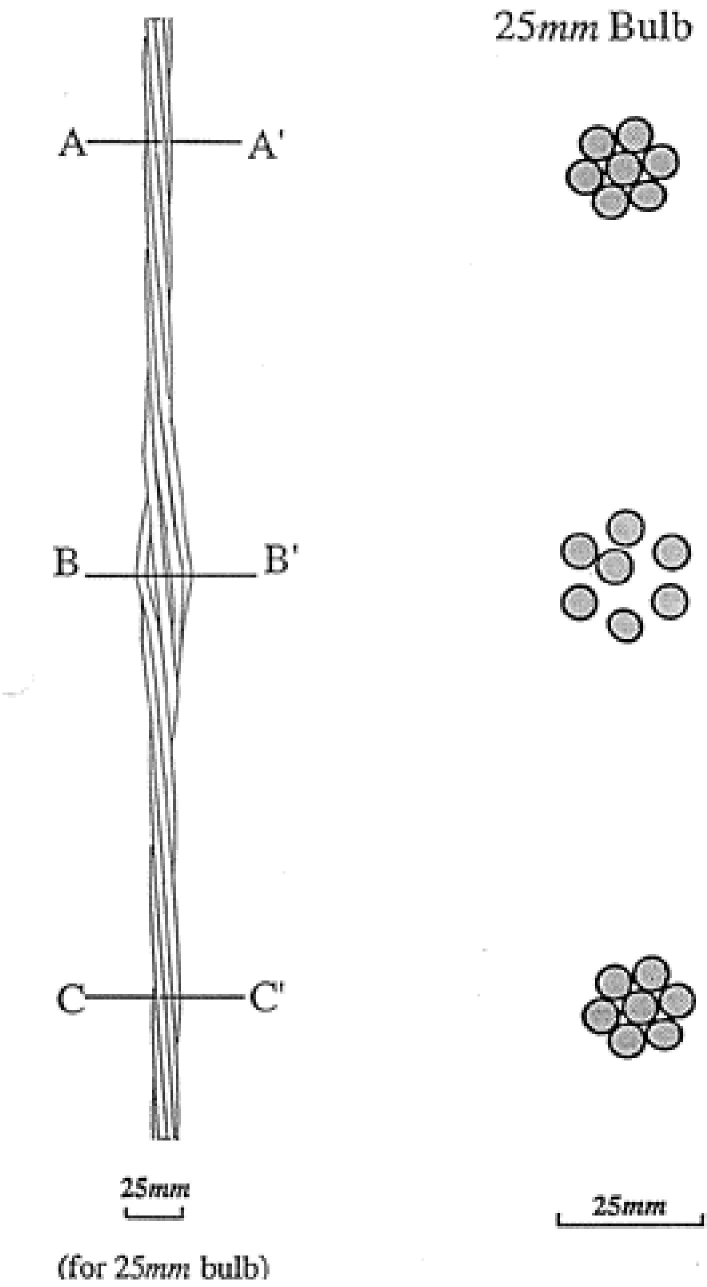

Figure 1. The Garford Bulb Anchor geometry

2. THE LABORATORY TEST PROGRAMME

The experimental setup is shown in Figure 2c, and is contrasted with the standard laboratory pull test setup used by previous workers (Fuller and Cox, 1975; Goris, 1990) (Figure 2b). All tests were conducted with a 300*mm* embedment length, the bulb being located at the midpoint before testing. The pull rate was maintained constant at 0.3 *mm/s* with a servo-controlled MTS testing frame.

From an operational perspective, the test programme was intended to evaluate the bond capacity of the Garford bulb anchor under various conditions of installation quality control and rock mass quality. Therefore, as outlined in Table 1, two experimental parameters were varied:

(i) the *w:c* ratio of the grout (see Table 2 for details and compare with Hyett *et al.*, 1992b)); and,

(ii) the radial stiffness of the confining pipe (see Table 3 for details).

The purpose of using confining pipes of different radial stiffness was to simulate different *in situ* rock mass conditions. A correlation between laboratory and field test was demonstrated by Hyett *et al*. (1992a).

Twelve tests were conducted for the 25*mm* Garford bulb (see Table 1), as well as twelve additional tests for the larger 40*mm* bulb. These included tests at a 0.5 *w:c* ratio (poor grout quality control), and using Sch. 40 Aluminum pipe (very low radial confinement ie: low rock mass quality).

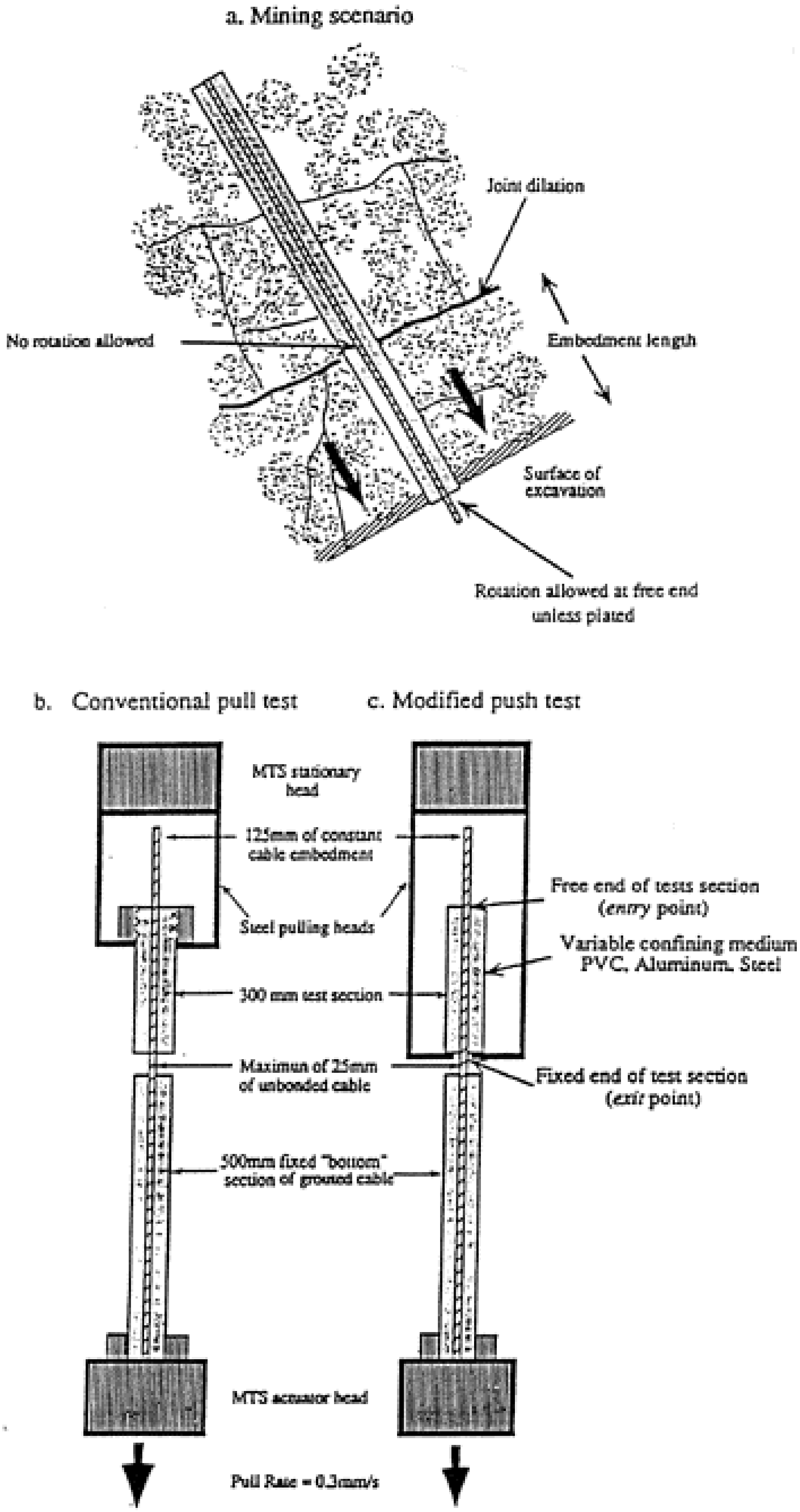

Figure 2. *(a)* Mining scenario and the laboratory pull test setups intended to simulate it: *(b)* the conventional pull test and *(c)* the modified push test used in this study.

Test #	w:c ratio	Confinement	Embed. Length
1 (A-D)	0.4	Sch 80 - Alum	300mm
2 (A-D)	0.4	Sch 80 - Steel	300mm
3 (A-B)	0.4	Sch 40 - Alum	300mm
4 (A-B)	0.5	Sch 80 - Alum	300mm

Table 1. The 25mm bulb test programme. In addition these tests were duplicated for the 40mm bulb.

w:c ratio	P_d (28 day) (g/cm3)	UCS (MPa)	E (GPa)	V
0.40	1.96-1.99	58 - 69	11.5-12.7	0.18
0.50	1.85 - 1.81	42-51	8.9 - 9.7	0.18

Table 2. Properties of the Type 10 portland cement grout. P_d is the bulk density after 28 day cure: UCS - Uniaxial compressive strength according to ASTM C39-84. E - Young's modulus. v - Poissons ratio.

Pipe Spec.	I.D. (mm)	O.D (mm) .	Kr (MPa/mm)	Equiv Rock Mass Modulus (GPa)
Sch. 80 - Steel	49.30	60.13	1604.2	49.7
Sch. 80 - Alum	49.02	60.45	599.5	17.7
Sch 40 - Alum	52.22	60.38	332.5	10.3

Table 3. Dimensions and radial stiffnesses of the pipes used to provide radial confinement K_r is the radial stiffness of the pipe, which may be thought of as the pressure in MPa required to induce 1*mm* of radial deformation. The number on the RHS provides an indication of the equivalent rock mass Young's modulus. A value of 49.7 represents a relatively good quality rock mass (Q' = 10-25) at surface, or a fair/good quality rock mass (Q' = 5-15) at depth, 10.3 represents a fair (Q'=1-5) quality rock mass at surface, or a poor (Q'=0.5-1) rock mass at depth.

3. LABORATORY TEST RESULTS AND INTERPRETATION

The full load displacement plots are presented in Figure 3. Comparable results for a standard cable are presented by Hyett *et al*. (1992a). Failure always occurred in the test ("top") section and never in the anchor ("bottom") section (refer to Figure 2). Using the results of calibration tests, all deformations associated with the bottom section and the test frame have been subtracted, so that the displacement along the abscissae of the plots in Figure 3 are exactly those at the *exit* point of the cable (see Figure 2). A comprehensive summary of the results is presented in Table 4.

Test #	Peak Load	Failure Mechanism	Broken Cable?
1A	254	#1	N
1B	258	#1	Y
1C	260	#1	Y
1D	247	#1	N
2A	253	#1	N
2B	259	#1	Y
2C	262	#1	N
2D	-	-	-
3A	252	#1	Y
3B	237	#1	N
4A	191	#1	N
4B	231	#1	N

Table 5. Comprehensive summary of the results.

Failure Mechanisms

Below 25*mm* of axial displacement, failure involved axial displacement of the bulb structure through the surrounding cement annulus by the mechanism illustrated in Figure 4. Thereafter, for specific tests the bond strength at the cable-grout interface was sufficient to exceed the tensile strength (250 kN) of the 7-wire strand. For tests in the lowest confinement (Sch. 40 Aluminum), rupture of the cable did not occur, and a noticeable hardening was observed, which may correspond to an increase in the *wedging* action of the bulb as it was progressively displaced through the grout annulus. After 25*mm* of axial displacement failure was unstable, either due to (i) the rupture of individual strands, or (ii) stick-slip displacement of the bulb through the cement annulus. For tests in the lowest confinement (Sch. 40 Aluminum), rupture of the cable did not occur, though a noticeable bulging of the pipe was observed, and in one case the pipe actually split (Figure 5). This clearly indicates the potential dilatancy that can be induced during bond failure of the Garford Bulb Anchor. Figure 6 shows successive sections through failed samples. Although the grout within the bulb structure is highly fractured, there was no evidence that the bulb was able to collapse.

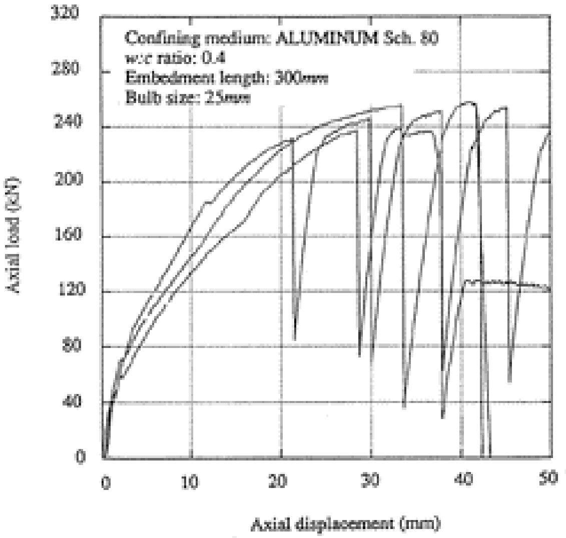

FIGURE 3a. Test GB1.

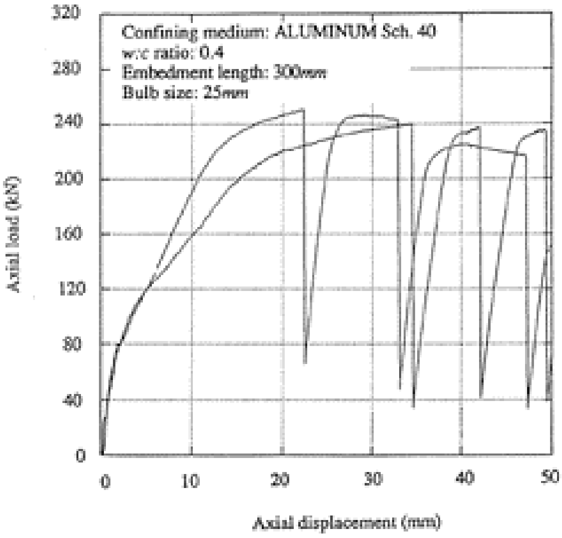

FIGURE 3c. Test GB3.

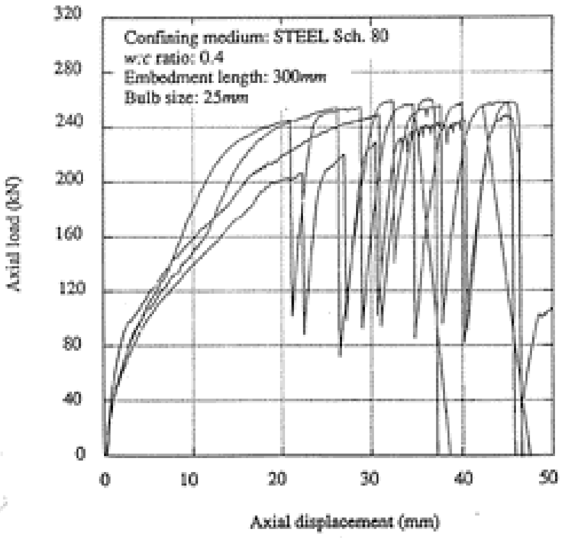

FIGURE 3b. Test GB2.

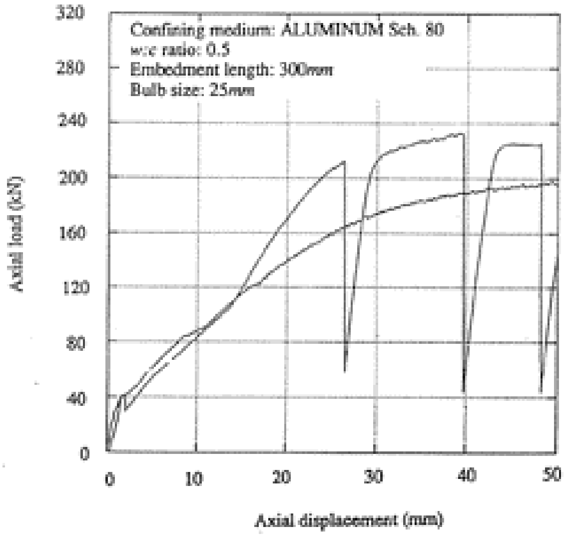

FIGURE 3d. Test GB4.

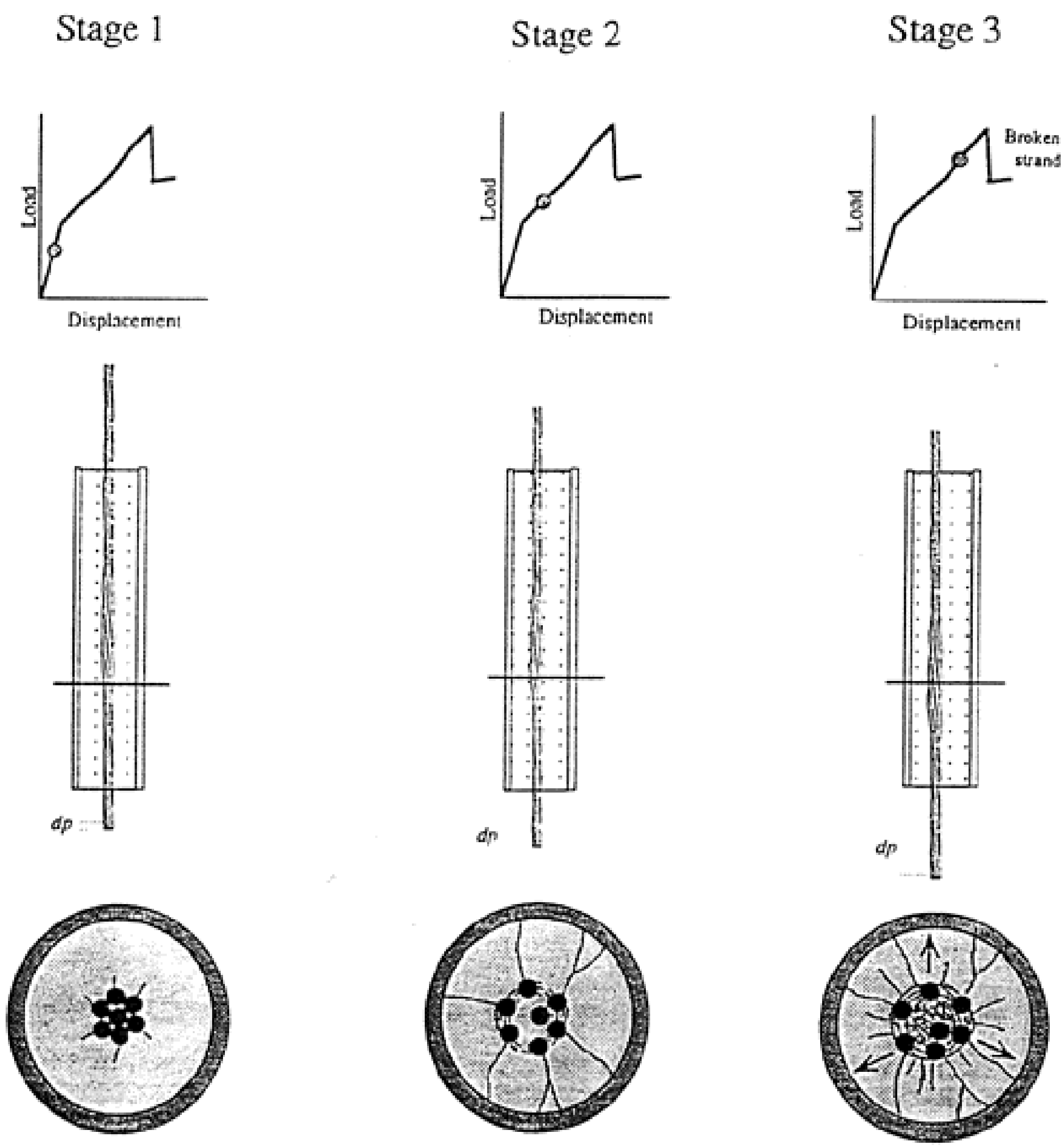

Figure 4. The progressive sequence of failure

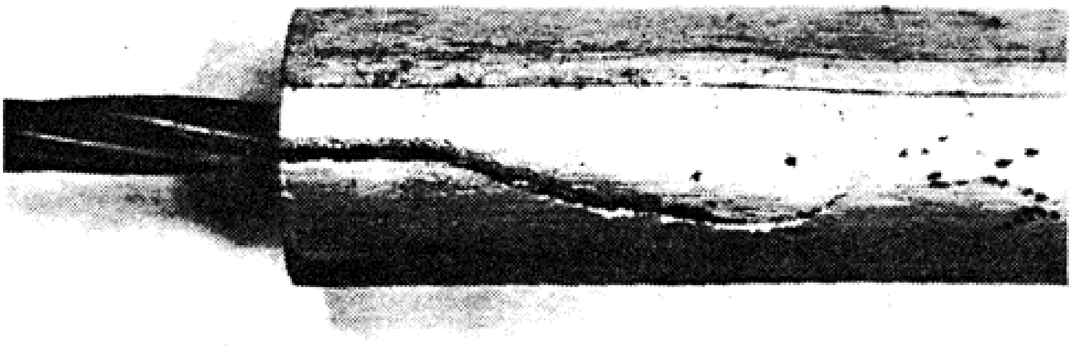

Figure 5. Specimen 3B: the aliminium Svh. 40 pipe redially split.

The effect that each of the two experimental parameters had on the bond capacity of the Garford bulb anchor will be discussed below.

Effect of radial confinement

A comparison between Figures 3a, 3b and 3c indicates that radial confinement had almost no effect on the bond capacity of the 25*mm* Garford bulb. A peak load of 240kN was obtained even at very low radial confinement (Sch. 40 Aluminum). The distinct bulge of the confining pipe for the Sch. 40 Aluminum, and to a lesser degree the Sch. 80 Aluminum, indicates the much higher potential for radial dilation induced during failure of the Garford bulb than a standard 7-wire strand. Consequently, the confining pressures generated in response to radial dilation and the corresponding bond capacity attained are relatively independent of the radial stiffness of the confinement.

Effect of grout water:cement ratio

Even for a 0.5 *w:c* ratio grout (Figure 3d) high bond capacities (190kN and 230kN) were attained. Again, this emphasizes that the potential for radial dilation during bond failure, which induces high radial confining pressures, is able to compensate for the lower strengths, lower Young's modulae, and higher shrinkage strains associated with higher water:cement ratio grout.

Effect of Bulb Size

Intuitively one would expect an increase in bond strength corresponding with larger bulb diameters, because of the greater mechanical interlock between the grout and the cable. However, whereas the 25*mm* bulb resulted in capacities close to the tensile strength of the strand and in many cases failure involved rupture of the steel[1], for the 40*mm* bulb bond failure occurred at lower loads (150 - 210 kN).

[1] Rupture occurred wire by wire, either at the exit point or internally within the test section, presumably within the bulb.

In view of this unexpected result, following testing to failure, several of the specimens were sectioned (ie: cut perpendicular to the cable axis) for visual observation. This categorically established that the grout had fully penetrated the bulb structure, but more importantly revealed that a different failure mechanism had operated for the 40*mm* bulb. In contrast to the behaviour for the 25*mm* Garford bulb described above, this involved slip and twist of the individual wires through the bulb structure, so that, although the cable had been pulled in excess of 50*mm*, the centre of the bulb structure remained in its original position (Figure 7). The *unscrewing* characteristic of this failure mechanism can be reconciled with the observation of cable "splaying" at the *entry* point (ie: free end) of the test section. The corresponding bond capacities were lower and considerably more scattered than for those for the 25*mm*. Therefore, for underground applications, it is recommended that the bulb size should be restricted to 25*mm*.

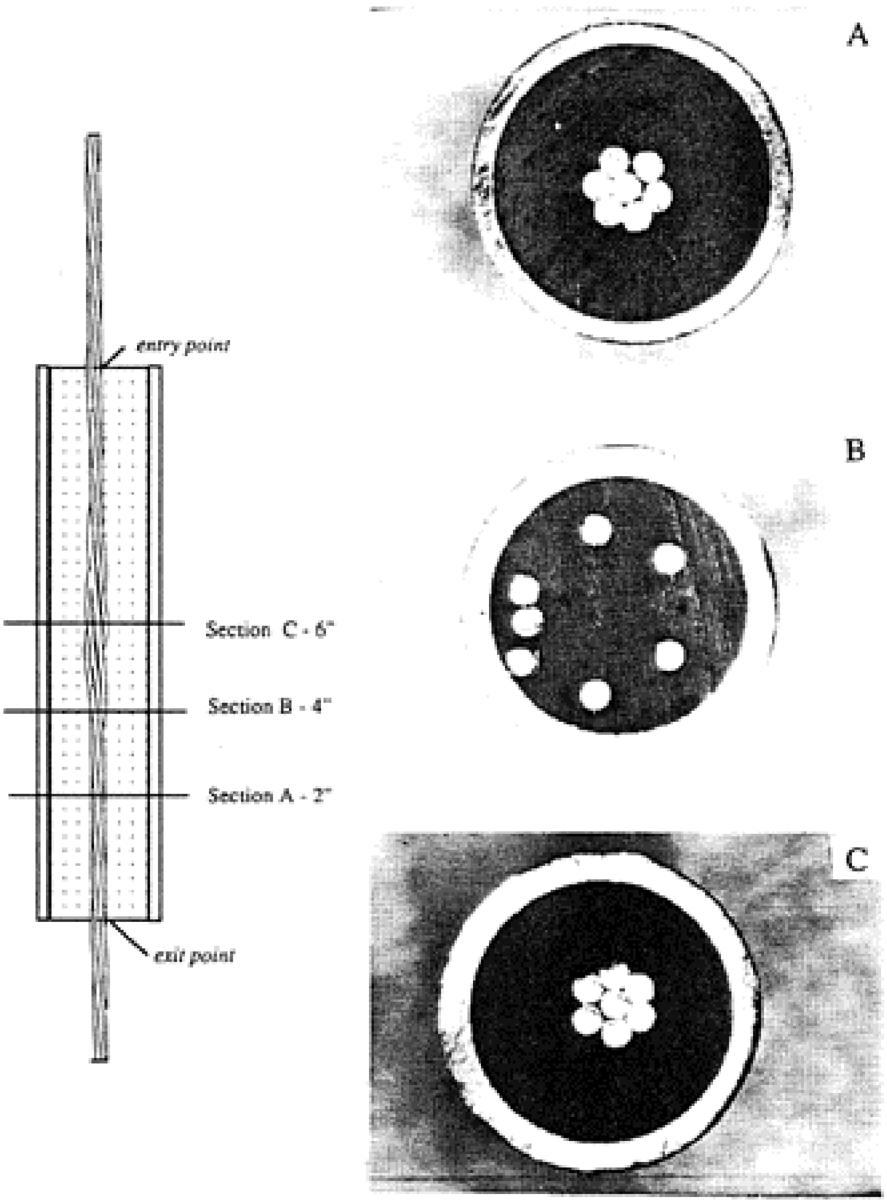

Figure 7 Sections through a 40mm specimen following failure

DISCUSSION AND CONCLUSIONS

Comparison with other types of cable bolt

In Table 5, the results presented in Table 4 have been averaged and normalized with respect to the bond capacity (or predicted bond capacity) for standard cable (*Hyett et al.*, 1992a). Note the marked comparative advantage of the Garford Bulb cable under conditions of low radial confinement and high water:cement ratio (weak) grout. It is interesting to note that, for the Garford bulb, a reduction of the effective rock mass confinement by a factor of five, (Test Series GB1, GB2 and GB3), had minimal effect on cable bolt capacity. Reduction of the grout from 0.4 *w:c* to 0.5 *w:c* (GB4) had a more significant effect, albeit less than the equivalent test for a standard 7-wire strand. This indicates that the operator should strive for optimal grout quality control irrespective of the type of cable being used. Conventional strand will, however, be much more sensitive to poor grout quality control than will the Garford bulb anchor. The use of a 0.35 - 0.4 *w:c* grout is recommended with the Garford bulb cable in order to ensure penetration into the bulb structure; in other words slightly thinner than the 0.35 *w:c* ratio recommended for the installation of standard 7-wire strand. Pumping a grout in this range should be routinely possible using most grout pumping systems, and will remain in upholes without the use of plugs.

Table 6 provides a comparison between laboratory determined cable capacity for the 25*mm* Garford bulb anchor cable and the nutcase cable (Hyett *et al*., 1993) for identical confinement and grout quality test conditions. The geometric similarity between the two types of cable is reflected in almost identical bond strengths and failure mechanisms. The nutcase cable has already proven extremely effective during field tests and is currently being used in several Canadian mines. At present no field tests have been conducted for the bulb cable, although, based on the results in this report, its prospects are considered to be excellent.

Confinement			
Water:cement ratio	Sch. 80 Steel	Sch. 80 A1	Sch. 40 A1
0.4	2.5	3.33	4.0
0.5		3.5	

Table 5. The comparative advantage of a 25*mm* Garford bulb over standard cable based on 300*mm* embedment length tests of a single bulb. A factor of 4 means the Garford Bulb has four times the peak load of single cable.

Confinement		
w:c ratio	Sch. 80 A1.	Sch. 40 A1.
0.4	0.94	1.03

Table 6. A comparison of mobilized capacity for 25*mm* Garford bulb to a comparable nutcase cable. A factor of 1.03 means the Garford bulb anchor has 1.03 times the peak load capacity of the nutcase cable.

Implications for cable bolt design

From a design perspective, based on the results presented above, it is expected that failure of cable bolted ground reinforced using the 25*mm* Garford bulb cable will most likely involve rupture of the cables rather than bond failure. In such cases, the mining engineer knows the capacity of his cable bolt system (250kN or 25 *tonnes* per cable) and is able to modify his design, either by using twin Garford bulb cables or changing the cable bolt spacing, based on this value. In contrast, for failures of cable bolted ground involving bond failure of conventional cables, the only possible effective action is to improve grout quality, and even then, the quality of the ground and the mining induced stress changes may dictate that no engineering solution exists. Furthermore the engineer doesn't know whether the bond capacity is 10 *tonnes* or 20 *tonnes.*

In summary, the most important advantages of the Garford bulb include the following:

(1) High bond capacity: the Garford bulb anchor and most modified cable geometries, offers distinct advantage over conventional cable under the following conditions:

- highly fractured, weak rock masses
- yielded (ie: failed) ground
- conditions where significant mine induced stress change (reduction) occurs normal to the cable axis.

The above are typical of many mining conditions (eg: destressing of stope hanging walls; yielding of stope backs and pillars etc).

In addition, although increasing the *w:c* ratio of the grout decreases the capacity of both the Garford bulb anchor and standard strand, the decrease in capacity is much less critical for the Garford Bulb Anchor. At 0.5 *w:c* ratio grout the Garford Bulb Anchor attained more than three times the capacity of standard strand.

(2) Replace surface fixtures: It is believed by the authors that modified geometry cables can largely replace the need for surface cable fixtures (ie: plates and/or straps) as the bulb closest to the hole collar should act as an effective surface fixture. This suggests that recessed cables and/or cable bolts placed from remote access (ie: hanging wall cable bolt drifts) should prove much more effective with modified cable than they have in the past with conventional strand. It is also important to recognise that conditions of high stresses and competent, high quality rock often result in stress slabbing of the excavation periphery. This reduces the effective cable embedment length and the increased capacity of the bulb anchor may be critical in maintaining such highly fractured rock in place.

(3) Design flexibility: The versatility of the manufacturing process, and in particular the fact that the bulb spacing can be varied, will offer a definite advantage with respect to specific design problems. Under specific conditions of very competent rock and very high stress the stiffness of modified geometry cables may be a concern (note: depending on the characteristics of the rock mass, Garford Bulb Anchor cables are roughly twice as stiff as conventional strand under high confining conditions). With the Garford bulb anchor such concerns can be addressed through appropriate design modifications. Bulb anchors can be strategically located while other sections of cable are then debonded in order to allow required rock mass movement. Alternatively, it may be sufficient to simply vary the bulb anchor spacing.

5. REFERENCES

Fuller, P.G., & Cox, R.H.T., Mechanics of load transfer from steel tendons to cement based grout. *Proc. 5th Aust. Conf. on the Mechanics of Structures and Materials*, Melborne, pp. 189-203, 1975.

Goris, J.M., Laboratory Evaluation of Cable Bolt Supports. *92nd Annual General Meeting of the CIM*, Ottawa, May, 1990.

Hyett, A.J., Bawden, W.F. and Reichert, R.D., The effect of rock mass confinement on the bond strength of fully grouted cable bolts. *Int. J. Rock Mech. & Min. Sci. & Geomech. Abstr.* 29(5), pp. 503-524, 1992a.

Hyett, A.J., Bawden, W.F. and Coulson, A.L. 1992. Physical and mechanical properties of normal Portland cement pertaining to fully grouted cable bolts. In: *Rock Support in Mining and Underground Construction*, Kaiser, P.K., and McCreath, D.R. (eds.), 1992b.

Hyett, A.J., Bawden, W.F., Powers, R. and Rocque, P. The nutcase cable bolt. In: *Innovative mine design for the 21st century eds.* W.F. Bawden and J.F. Archibald, 1993.

Hyett, A.J., Bawden, W.F. and MacSporran, G.R. In prep. to be submitted to the *Int. J. Rock Mech. & Min. Sci. & Geomech. Abstr.*, 1994.