Performance of Cable Bolt Anchors – An Update

Alan Thompson
Curtin University of Technology, WA School of Mines, Kalgoorlie, Western Australia

Abstract

The installation of cable bolt anchors for mining applications has been reported previously by Thompson (1992) and Thompson and Windsor (1995). Recent theoretical investigations and laboratory testing have been used to improve the understanding of the behaviour of these barrel and wedge anchors both during installation and in service. Computer generated graphical simulations have been used to relate the interference between the wedge inner teeth and the outer wires of the strand to the wedge position within the barrel.. Laboratory tests have demonstrated that corrosion may prevent the wedge sliding sufficiently within the barrel to grip the strand and results in strand slip relative to the anchor at low loads compared to the design capacity. This has significant implications for mass mining operations in which there are significant times between installation and when the cable bolt anchors may be loaded due to rock mass movements. Lubrication of the barrel/wedge interface is recommended for long term effectiveness of cable bolt anchors.

1 INTRODUCTION

The use of barrel and wedge anchors to restrain plates, straps and mesh in cable bolt reinforcing applications commenced in the early 1980s in Australian mines. At this time, the major function of the anchors was to restrain this surface hardware tightly against the rock surface and was not required to tension the strand. Also, many of these early applications were associated with cut and fill where cable bolts were installed in long lengths as pre-reinforcement (Thompson et al. 1987).

The installation of barrel and wedge anchors for the early applications was often performed using a tool on the end of an air leg or by pushing on the exposed end of the wedge using a hollow hydraulic cylinder restrained at the other end by a removable and reusable barrel and wedge anchor. While these methods of installation were crude, they were reasonably effective and reliable in the short term applications associated with cut and fill mining.

As use of cut and fill mining was reduced and long hole open stoping became the preferred mining method, more sophisticated methods of installation were sought. In particular, it was found that, in a monitoring exercise at Mount Isa Mines, the force on the strand immediately behind the anchor was only a fraction of the force being applied by the hydraulic cylinder (Windsor, personal communication 1982).

At that time, research investigations were undertaken to develop installation tools for barrel and wedge anchors on strand. These developments were reported by Thompson et al. (1987) and were the forerunners of the installation tools that are available today.

In order to more clearly understand the mechanisms of barrel and wedge anchor behaviour during and after installation, a number of theoretical and both laboratory and field testing investigations were made. The results of these investigations were published by Thompson (1992) and Thompson and Windsor (1995).

Since these investigations, barrel and wedge anchors are now being used in different applications associated with mass mining methods. These new applications may require the anchors to be functional for longer periods than in the past. The anchors may also be the only load transfer mechanism between the strand and the plate at the collar in applications in which the strand is de-bonded. De-bonding of the strand is used to enable tension to be established in the strand and to reduce the cable bolt stiffness in response to rock mass displacements. In the past, the strand was usually continuously coupled to the rock by the cement grout annulus. In these cases, the force at the collar was observed to remain at low levels despite large rock mass movements (Thompson et al. 1995).

In conjunction with these new applications, further recent theoretical and laboratory testing investigations have been undertaken by the writer and his colleagues. These new investigations attempt to more clearly quantify the behaviour of barrel and wedge anchors during installation with the different equipment that is available and to simulate the anchor performance during service, particularly after being subjected to corrosion in the underground mining environment. The following sections review the mechanisms of behaviour of barrel and wedge anchors and present the results of the recent investigations.

2 OBSERVED ANCHOR PERFORMANCE

There is visual (e.g. Figure 1) and anecdotal evidence of anchor failures in Western Australian mines. The anecdotal evidence relates to occasional observations of wedges remaining intact within anchors found on the floors of drives with no evidence of strand rupture. Anchors of similar condition were also observed by the writer after a large block failure at a Western Australian underground mine.

3 BARREL AND WEDGE ANCHORS

Barrel and wedge anchors are an important component of a cable bolt, particularly if the strand is de-bonded as shown in Figure 2.

Figure 1: Anchors with strand receded compared with original position observed in a WA mine.

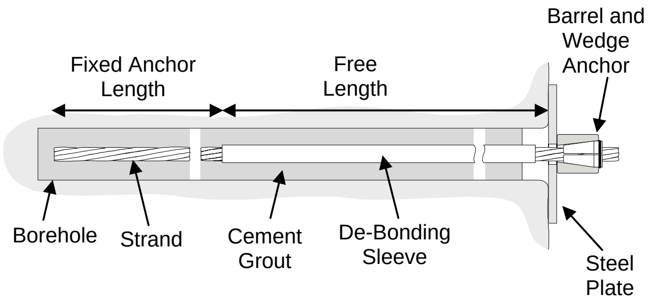


Figure 2: Schematic representation of a cable bolt.

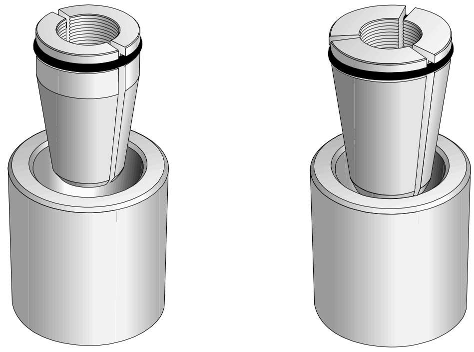


Figure 3: Schematic representation of barrel and wedge anchors with two- and three-part wedges.

3.1 Anchor components

Typical barrel and wedge anchors are shown schematically in Figure 3. The wedge may be formed into two or three parts as shown. The inner taper angle of the barrel and the outer taper angle of the wedge are approximately equal and usually can be assumed to be ~7º.

The wedge is made from hardened steel and has sharp teeth formed at the inner surface that makes contact with the strand.

3.2 Anchor installation methods

Thompson (1992, 1995) described several methods used for anchor installation. All these involve gripping and pulling on the strand and pushing on some part of the surface hardware (i.e. anchor or steel plate). These methods can be briefly summarised as follows:

- Use of a chair to enable full tensioning force to be applied to the strand.
- Application of tensioning force to wedge.
- Application of tensioning force to both barrel and wedge (either with spring to push on wedge or profiled nose assembly to suit the geometric properties of the barrel and wedge anchor.
- Application of tensioning force to barrel with secondary hydraulic cylinder to push wedges home.

Since that time, a further novel technique has been developed (Amalgamated Reinforcing 1996). This technique involves:

- Application of the tensioning force to a "shear ring" on the barrel. At a predetermined load, the ring shears, simultaneously causing the jack nose to firmly drive the wedge home.

The installation of anchors with different nose assemblies can be generalised by analysing the forces shown in Figure 4 (Thompson and Windsor 1995). The strand tension (T) is given by:

$$T = K\ P \qquad (1)$$

where:

P = force supplied by the hydraulic cylinder
K = tension reduction factor given by

$$K = 1 - \frac{P_W/P\,(1 - \tan\alpha \tan\phi_B)\tan\phi_C}{\tan\phi_B\ (1 - \tan\alpha\tan\phi_C) + \tan\alpha + \tan\phi_C} \qquad (2)$$

α = wedge taper angle
ϕ_B = friction angle between barrel and wedge
ϕ_C = friction between cable and wedge
P_W = force applied to the wedge
P_B = force applied to barrel = $P - P_W$

The initial residual tension developed in the strand after removal of the tensioning equipment depends on:

- Force applied by the tensioning equipment.
- Force applied to the wedge during tensioning.
- Barrel/wedge interface condition.
- Wedge/strand interface condition.
- The strand free length.

In all cases, the strand tension behind the plate and anchor depends on the installation method and is always less than the force applied by the tensioning equipment. Figure 5 shows the variation of wedge outstand with strand force for a particular anchor. Figure 6 shows how the strand tension may reduce due to wedge draw in after removal of the tensioning equipment. The analysis used to predict the behaviour is based on well-established principles used in both the prestressed concrete and ground anchor industry codes of practice.

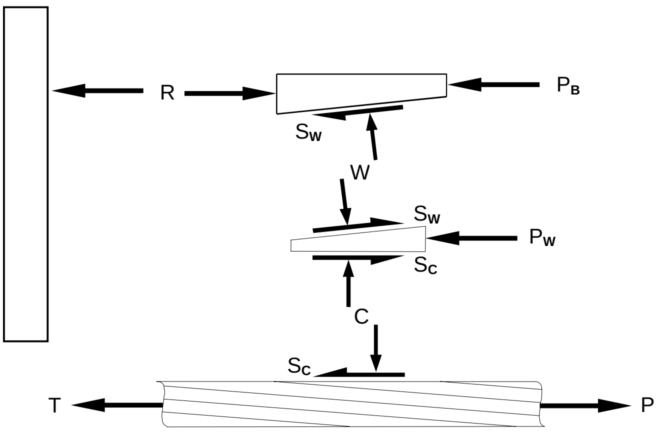


Figure 4: Forces acting on anchor during cable bolt installation.

It was generally accepted that a residual tension of ~50kN would be sufficient to ensure that the anchor was "set" on the strand and the anchor would subsequently be able to sustain forces up to the rupture force of the strand. Subsequently, as graphically demonstrated in Figure 1, this has not always be found to be the case.

3.3 Anchor mechanism and behaviour

Barrel and wedge anchors are designed to clamp the strand and embed the teeth within the outer strand wires. In order to assess under what conditions the strand will slide relative to the barrel and wedge anchor, it is necessary to analyse the interactions between the various components of the system (e.g. Thompson 1992, Chacos 1993).

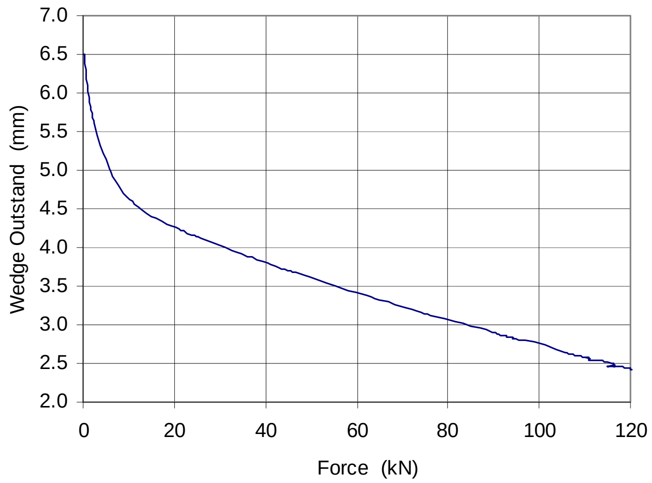


Figure 5: Typical wedge outstand from barrel versus strand force response curve.

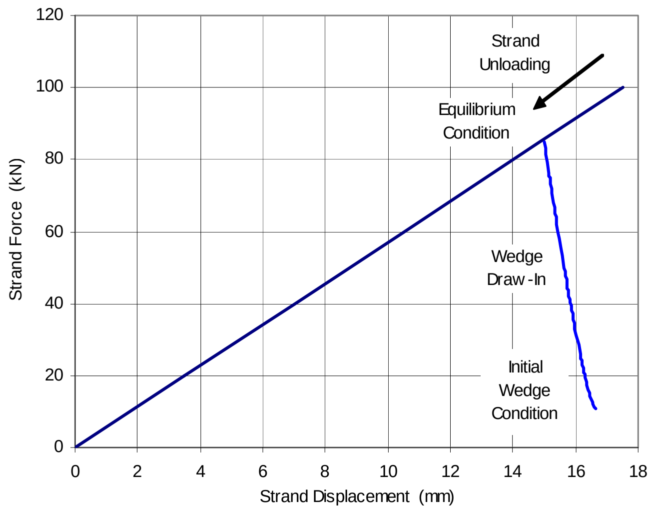


Figure 6: Theoretical prediction of strand tension loss due to wedge draw-in for 5m free strand length initially tensioned to 100kN with 10kN applied to the wedge.

Figure 7 shows the forces acting on the strand and the barrel and wedge anchor after installation and during service. In this figure:

R = force between the barrel and the plate acting against the rock/shotcrete surface

T = tension in the strand = R

W = normal force acting across the barrel/wedge interface

S_W = shear force at the barrel/wedge interface

C = normal force acting at the wedge/strand interface

S_C = shear force at the wedge/strand interface

Equilibrium of forces for the barrel requires:

$$R = S_W \cos\alpha + W \sin\alpha \tag{3}$$

and for the wedge (radially) requires:

$$C = W \cos\alpha - S_W \sin\alpha \tag{4}$$

For strand sliding to occur:

$$T \geq C \tan\phi_C \tag{5}$$

Combining equations (3), (4) and (5) results in:

$$S_W \cos\alpha + W \sin\alpha \geq \left(W \cos\alpha - S_W \sin\alpha\right) \tan\phi_C \tag{6}$$

In order to proceed from here, it is necessary to assume that sliding occurs at the barrel/wedge interface and the sliding force S_W is given by

$$S_W \geq W \tan\phi_B \tag{7}$$

Substituting for S_W, eliminating W and simplifying gives:

$$\tan\phi_C \geq \tan\left(\phi_B + \alpha\right) \qquad \text{(to prevent sliding)} \tag{8}$$

or alternatively

$$\tan\left(\phi_B + \alpha\right) \geq \tan\phi_C \qquad \text{(for sliding to occur)} \tag{9}$$

This equation means that the barrel/wedge interface friction angle must be less the wedge/strand interface friction angle by an amount more than the wedge taper angle.

Chacos (1993) suggested various values for coefficients of static friction corresponding to different surface conditions. These surface conditions and the corresponding friction angles are give in Table 1. Values were suggested by Thompson (1992) and the approximate values corresponding to the interface conditions used by Chacos are given in Table 1.

Thompson (1995) reported that the wedge/strand friction angle was measured experimentally to be ~45°. Given that the wedge taper angle can be assumed to be equal to 7°, this means that the barrel/wedge friction angle must be less than ~38° for the anchor to function properly. It can be seen that this condition is only satisfied if the interface remains new and/or lubricated.

It has also been suggested (DSI web site), that if sliding at the barrel and wedge interface is inhibited, then the wedge inner teeth will not be embedded into the strand outer wires to their full depth and may be sheared off if the strand tension increases in response to rock mass movements.

Table 1: Suggested values of friction angles for different barrel/wedge surface conditions.

Interface Condition	Chacos (1993)	Thompson (1992)
Dry, pitted, rusted, old	45°	30° to 40°
Dry, lightly rusted, new	~22°	25°
Lightly oiled, clean, new	~17°	15°
Heavily greased, clean new	~6°	~10°

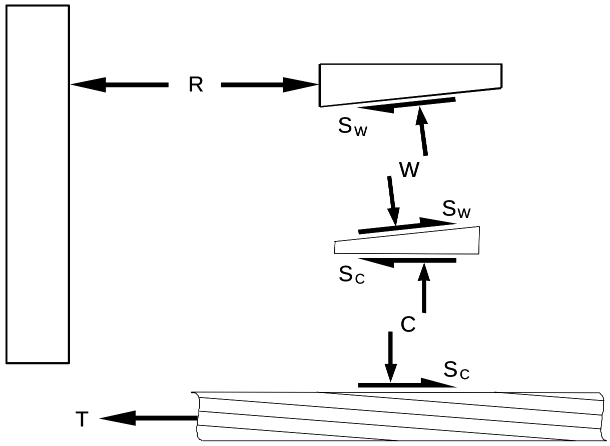


Figure 7: Component forces acting within the strand and barrel and wedge anchor system.

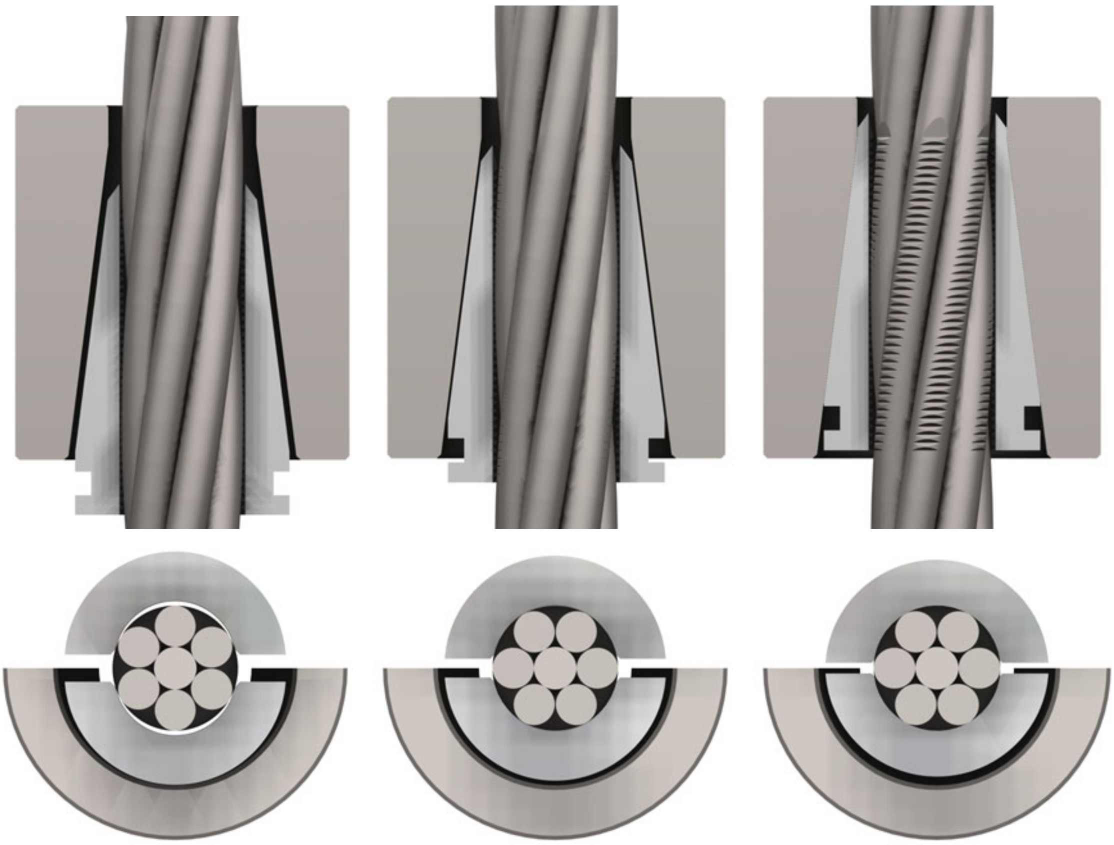
3.4 Graphical simulation of performance

In order to more fully understand the interaction between the strand and the wedge during installation and in service, a three-dimensional graphical simulation method was developed. This graphical simulation method required the accurate drawing of the actual geometries of the strand, the wedge (both two- and three-part) and the barrel. With these objects drawn, the interactions were modelled by displacing the wedge relative to the barrel to simulate loading and to then visually inspect the interaction between the wedge internal teeth and the external wires of the strand. The amount of relative displacement between the wedge and the barrel for typical strand forces was estimated from laboratory tests in which all these variables were measured (e.g. see Figure 5).

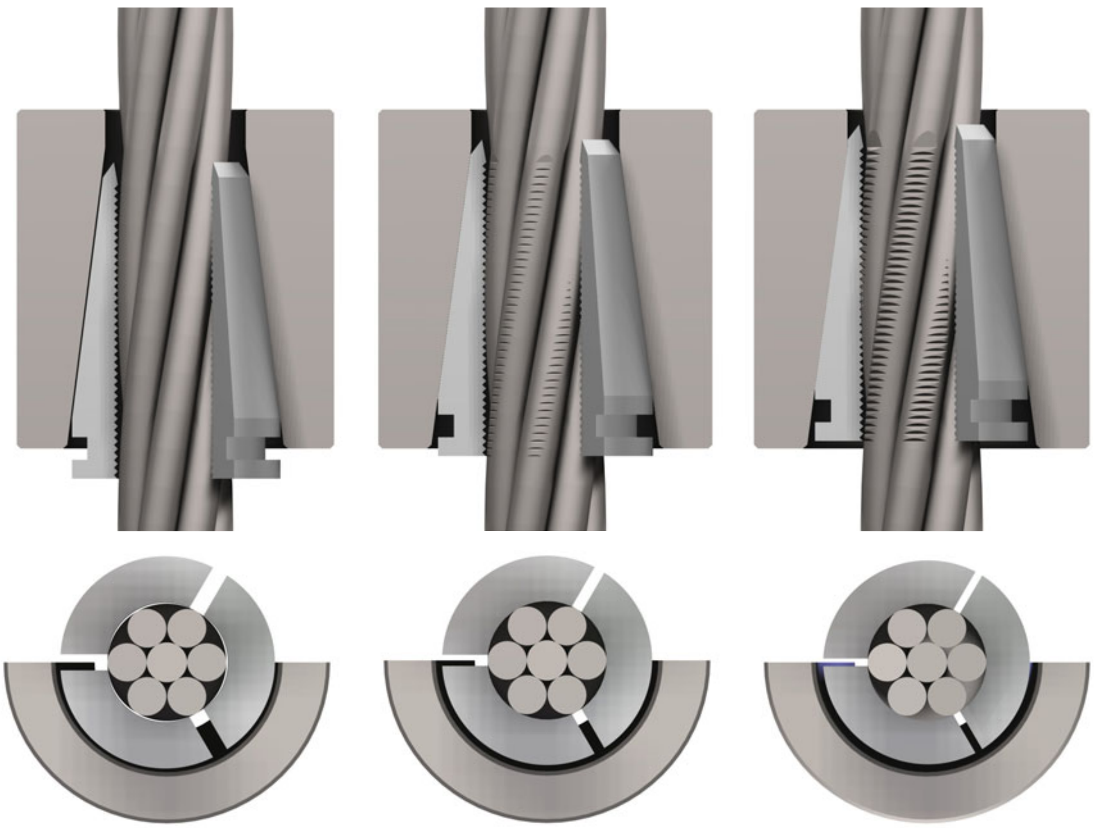
The results of these simulations for both two- and three-part wedges are given in Table 2. The interactions between the wedge and strand are clearly shown and graphically indicate qualitatively the limited amount of materials that may be available to transfer load without being supplemented by the significant clamping effect resulting from sliding at the barrel/wedge interface. The figure also shows a three-part wedge grips the wires more uniformly.

Table 2: Schematic of barrel and wedge (two-part and three-part) anchor and strand mechanism.

Manually Positioned	Low Strand Tension	Full Teeth Penetration



Two-part Wedge



Three-part Wedge

4 LABORATORY TESTING

To complement the theoretical considerations and computer simulations, a laboratory test program was designed to quantify the expected in situ performance of anchors. The test specimens were set up to simulate different methods of installation and to quantify their behaviour when subjected to loading after being allowed to corrode.

The simulated installation configuration of the test specimens and the anchor condition at the time of testing are summarised in Table 3. The surface condition of new and corroded anchors is shown in Figure 8. Corrosion was permitted to develop by keeping the anchors in humid conditions, with access to oxygen, inside a semi-sealed tube.

All the anchors were tested by pulling on the strand with a hydraulic jack. In tests 3 to 8, the wedge and strand displacements were monitored by DCDTs and were logged together with the force measured by an electronic load cell up to the point where the test needed to be reset when the hydraulic piston travel limit was reached. A second loading cycle was conducted in which only the strand displacement was measured.

Table 3: Summary of anchor specimens.

No.	Installation	Condition
1 & 2	Hand tight	New
3#	Strand pulled to 20kN	New
4#	Strand pulled to 40kN	New
5	Strand pulled to 10kN	Corroded
6	Strand pulled to 20kN	Corroded
7	Strand pulled to 40kN	Corroded
8	100kN applied to wedge*	Corroded

Barrel/wedge interface glued before load applied.

* Strand force ~36kN

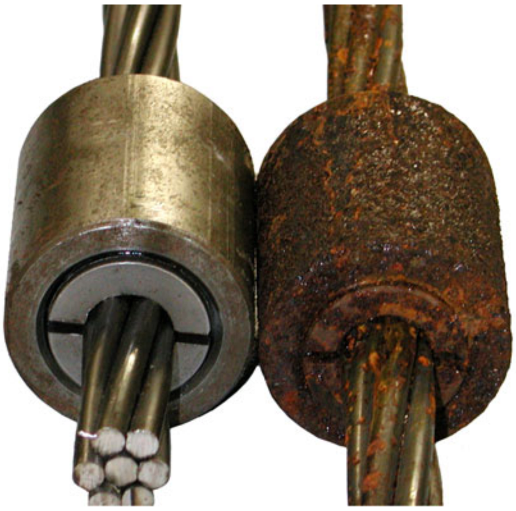


Figure 8: Comparison of new anchor with anchor subjected to 6 months exposure in a mildly corrosive artificial environment.

Table 4: Summary of anchor strengths.

No.	Peak Force (kN)	Residual Force (kN)	Failure Mode
1/2	>250	0	Rupture of one or two wires
3	~22	~10	Wedge/strand interface slip
4	~50	~13	Wedge/strand interface slip
5	~45	~20	Wedge/strand interface slip
6	~50	~25	Wedge/strand interface slip
7	~45	~20	Wedge/strand interface slip
8	~55	~30	Wedge/strand interface slip

Note: Residual force was that recorded during sliding. Actual residual force will be 0kN when strand completely pulled through wedge.

Table 4 provides a summary of the peak and residual forces measured for all the specimens tested and the failure modes. Apart from the control test specimens 1 and 2 used to confirm that anchors can mobilise the strength of the strand (but not necessarily its full elongation potential of at least ~3.5%), all the anchors failed by slipping of the strand within the anchors. This is attributed to the inability of the wedge to slide relative to the barrel.

Figure 9 shows the extent of wedge movement relative to the barrel that can be expected when anchors are loaded to cause rupture of the strand at ~250kN. Also note that the wedges protrude from the base of the barrel.

Figure 9: Appearance of new anchors (Specimens 1 & 2) after failure of one and two strand wires.

The total wedge movement relative to the barrel was measured to be ~10mm. The movement is associated initially with the teeth embedding in the outer wires of the strand and then mainly the barrel expanding radially outwards. The radial stresses in barrels and the associated radial expansion have been studied both experimentally and theoretically by Marceau et al. (2001, 2003). It is possible for barrels to expand unacceptably if the barrels are too thin or made from steel with too low yield strength. The radial forces are higher when the barrel/wedge interface is lubricated.

Figure 10 shows the appearance of anchor specimens 3 and 4 after failure by strand slip. The test for specimen 3 was stopped to show the extent of material shaved from the outer strand wires by the wedge.

All tests in which wedge/strand interface slip occurred were similar. The results for test specimens 6 and 8, shown in Figure 11 and Figure 12, are typical of the results obtained for the other specimens. Figure 13 shows the effects of sliding on the strand wires.

A summary of wedge positions before and after testing and the total wedge movement are summarised in Table 5.

Figure 10: Appearance of anchor specimens 3 and 4 after failure by wedge/strand slip.

Table 5: Summary of average wedge positions before and after testing.

No.	Initial Wedge Outstand (mm)	Final Wedge Outstand (mm)	Wedge Movement (mm)
1/2	6.5	-4.0	10
3	1.3	1.3	0
4	0.4	0.4	0
5	2.7	1.5	1.2
6	2.1	1.7	0.4
7	1.6	1.5	0.1
8	0.4	-0.1	0.5

It is of significance that, other than for test specimens 3 and 4 (shown in Figure 10) in which the barrel/wedge interface was deliberately prevented from sliding, some wedge movement occurred. This suggests that the wedge is prevented from further sliding by the corrosion products built up on the exposed wedge surface.

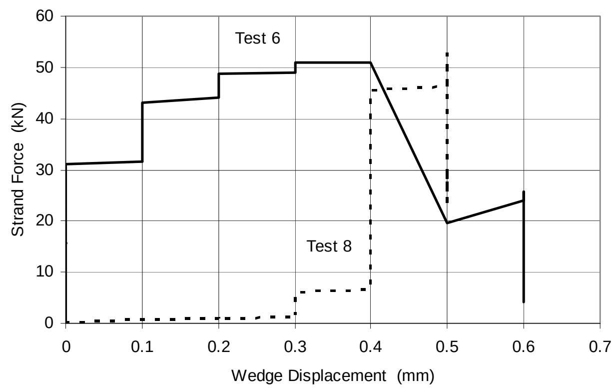


Figure 11: Typical force-wedge displacement (Test 6 and Test 8).

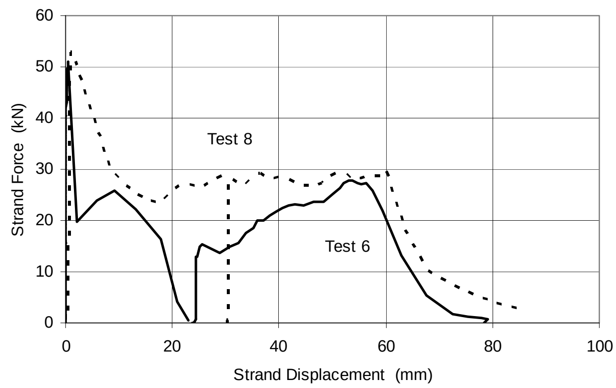


Figure 12: Typical force-strand displacement (Test 6 and Test 8).

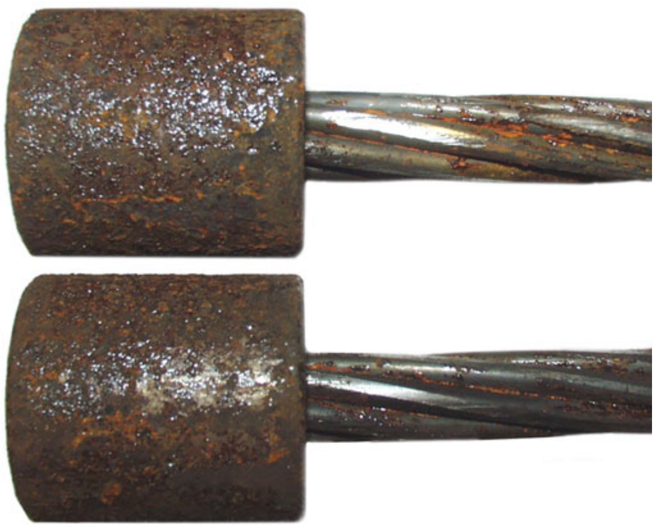


Figure 13: Anchor specimens 6 and 8 after testing (strand slip ~80mm from original position).

5 IMPLICATIONS FOR MASS MINING METHODS

The results of the theoretical and experimental investigations have significant implications for mass mining operations. Some of the factors associated with mass mining methods that impact on the performance of cable bolt anchors are:

- Potentially long lead times between anchor installation and nearby extraction.
- Changes in stress conditions cause large rock mass movements and increases in loading on reinforcement.
- The use of de-bonded strand to be compatible with expected large rock mass movements.
- The possible use of shotcrete which helps to create a humid, corrosive environment.

All these mass mining related factors lead to the requirement for longevity of the barrel/wedge sliding mechanism to ensure acceptable performance of the anchor. Current practice does not require any special preparation of sliding surfaces to inhibit corrosion and promote sliding. However, this will need to change if anchors are to perform to their design specification.

The following statement is paraphrased from DSI (2004), with changes made to be consistent with the symbols given in Figure 7.

If friction at the barrel/wedge interface increases (due to corrosion), a larger S_W *will reduce the clamping force. As* T *increases, all other forces can only increase if the wedge can seat deeper into the barrel. If the wedge is prevented from doing so (i.e. by corrosion or dirt-accumulation, the clamping force cannot increase with the pulling force causing slippage when the load on the cable bolt gradually increases during service life.*

DSI further suggests that:

To avoid slippages during use, it is important that the cable bolt is fully stressed at time of installation to a force equal to 0.5 T_{Ult} *(~125kN for a 15.2mm diameter pre-stressing strand).*

However, in mining installations, it is rarely if ever the intention to pre-stress the strand to forces of this magnitude. As a consequence, during anchor installation it must be an imperative to establish interference between the wedge inner teeth and the outer wires of the strand and to establish the barrel/wedge interface in a condition that enables it to slide and maintain this condition for the service life of the cable bolt. This requirement can only be achieved by isolating the anchor from its environment or by providing high quality and long-lived lubrication at the barrel/wedge interface.

6 CONCLUDING REMARKS

The WA School of Mines has recently set up anchor specimens with a variety of methods used to inhibit corrosion at the barrel/wedge interface. The specimens have been placed in separate corrosion chambers with controlled ambient conditions and with ground water obtained from six mine sites. It will be some time before the tests will be performed and the important results become available. In the meantime, it is recommended that some attempts are made to ensure that the barrel/wedge interface remains capable of sliding by providing lubrication or isolation from its environment.

ACKNOWLEDGEMENTS

The invaluable assistance of Mr Glynn Cadby of Fenixx Australia with modelling of the three-dimensional objects representing the barrel and wedge anchors and simulating their behaviour during loading is gratefully acknowledged. His assistance with documenting the tests and data processing is also greatly appreciated.

REFERENCES

Amalgamated Reinforcing 1996. Surelock™ Anchor Locking Device. Company brochure, 8p.

Chacos, G P, 1993. Wedge forces on post-tensioning strand anchors. PTI Technical Note 2, Post-Tensioning Institute:Phoenix, 4p.

DSI 2004. DSI Ground Support Catalogue, Dywidag Systems International:Salt Lake City, 37p

Marceau, D, Bastien, J and Fatard, M, 2001. Experimental and numerical studies of mono-strand anchorage. *Structural Engineering and Mechanics*, **12**(2), 119134.

Marceau, D, Fatard, M and Bastien, J, 2003. Constitutive law for wedge-tendon gripping interface in anchorage device – numerical modelling and parameters identification. *Structural Engineering and Mechanics*, **15**(6), 609-628.

Thompson, A G, 1992. Tensioning reinforcing cables. *Proc. Int. Symp. on Rock Support*, Sudbury, 285-291, Balkema:Rotterdam.

Thompson, A G, Matthews, S M, Windsor, C.R., Bywater, S and Tillmann V H, 1987. Innovations in rock reinforcement technology in the Australian mining industry. Proc. *6th Int. Cong. on Rock Mechanics*, Sudbury, V2, 1275-1278, Balkema:Rotterdam.

Thompson, A G and Windsor, C R, 1995. Tensioned cable bolt reinforcement – an integrated case study. *Proc. 8th Int. Cong. on Rock Mechanics*, Tokyo, V2, 679-683, Balkema:Rotterdam.

Thompson, A G, Windsor, C R, Robertson, W V and Robertson, I G, 1995. Case study of an instrumented reinforced pit slope. *Proc. 35th US Rock Mechanics Symposium*, Lake Tahoe, 381-386, Balkema:Rotterdam.