

DETERMINATION OF LOAD TRANSFER CHARACTERISTICS OF GLOVED RESIN BOLTS FROM LABORATORY AND *IN SITU* FIELD TESTING

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ABSTRACT

Resin based grouts are the main form of rock bolt anchorage in the underground coal industry in Australia and New Zealand. To be effective, the system requires the mixing of the catalyst and mastic components of the resin, as well as shredding of the laminate cartridge that contains the resin.

An unknown measure is the load transfer characteristics of a bolt where the resin is well mixed but remains encased in the cartridge (gloved). Laboratory and *in situ* field investigations have been undertaken to quantify the performance loss due to mixed gloved bolts. This work showed repeatable results, indicating serious performance loss of the gloved and mixed system, with load transfer approximately 10-15% of a non-gloved system (MacGregor, 2004).

The *in situ* testing has demonstrated the relationship between the adhesion qualities of the resin and the mechanical interlock generated by radial confinement with progressively increasing tensile load. Effective load transfer is defined by the ability of the system to sustain shear stress on the bolt hole wall.

INTRODUCTION

Solid Energy New Zealand Ltd is New Zealand's leading coal mine operator with four underground operations and six open cut operations throughout the country. Figure 1 shows the Huntly East Underground Mine located 60 km south of Auckland in the North Island of New Zealand. The underground operation is located in the Huntly Coalfield of the Waikato region. Development roadways are driven 5 metres wide by 3.2 metres high in the combined Kupakupa and Renown Seams that have an overall thickness from 5 metres to 28 metres and an average thickness across the mining licence of about 15 metres. (Figure 2).

The ground conditions at East Mine are generally difficult. *In situ* stresses, low strength coal and the high density of discontinuities often results in roadways that rapidly deteriorate and often lose profile. The mine installs 10,000, 2.4 metre long, high grade bolts per month with secondary support in the form of grouted cables being installed for intersection support at the coal face.

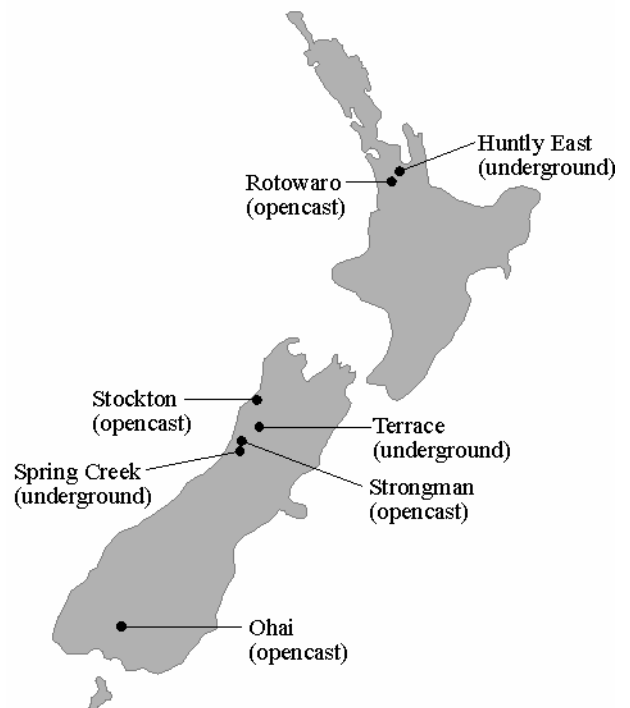


Fig 1: Location plan showing Huntly East Mine.

Overview of the Issue

The performance of any resin based reinforcement system is primarily a function of the load transfer generated by the load bearing members. Load transfer is the ability for these load bearing members to apply a resisting force with the onset of strata movement (Fabjanczyk and Tarrant, 1992). In fully resin-grouted bolts the load transfer mechanism is dependent on the shear stress levels developed on the rock - resin and resin - bolt interfaces with the peak shear stress and rate of shear stress being the ultimate force that can be applied for a reinforcement system.

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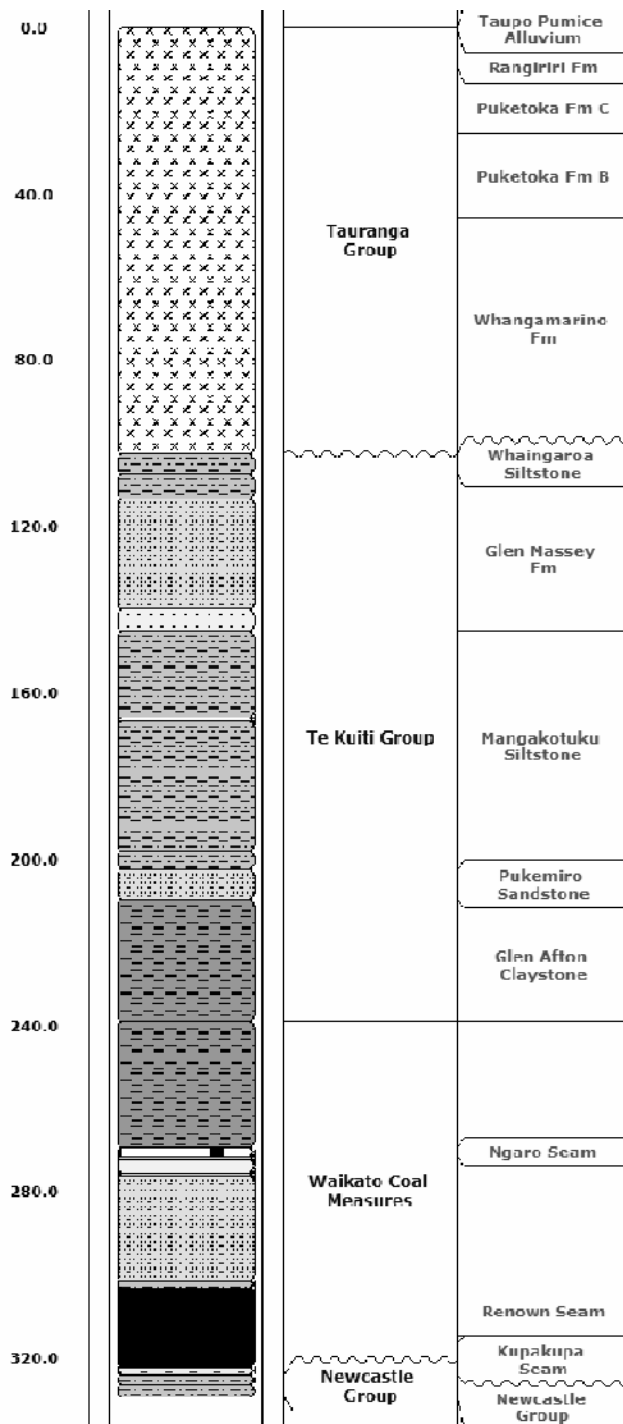


Fig 2: General stratigraphic sequence at East Mine
(Note: Typical working section is 15m thick - Kupakupa/Renown Seam).

Gloving, where the plastic tri-laminate film remains between the rock and resin interface has been identified in fully encapsulated roof bolts since the inception of resin anchor systems (Pettibone, 1987) and has been attributed to poor installation techniques related to drilling, inconsistent and poorly identified roof lithology and poor quality assurance of drilling consumables (Mould et al, 2004).

Solid Energy New Zealand Ltd periodically audits the effectiveness of primary reinforcement. The overcoring audit consists of drilling around the previously installed roof bolt using a 2.4 metre barrel and tungsten bit that allows recovery of the bolt and surrounding coal. Audits in Solid Energy's underground operations from 2002 until 2004 have shown systematic trends of poor quality bolts, notwithstanding correct procedures and consumables being used. Regardless of the roof lithology, roof bolt type and bolts installed run-of-mine or under controlled conditions, the results of the audits show on average an unacceptable proportion of gloving on the bolt length (Pastars 2003, Campbell et al 2003 and Mould et al 2004). Both hydraulic (continuous miner mounted) and hand held pneumatic (gopher/wombat) installed bolts are included in these audits with marginal variations in results.

Many different alterations to bolt profiles have been investigated by Solid Energy over the last three years with only minor improvements in reducing gloving. To understand the nature and effect of gloving on the overall performance of ground support, quantification of the compromised system performance is needed. A series of laboratory pull tests and *in situ* pull tests of induced gloved bolts were carried out by SCT Operations in December of 2004.

LABORATORY TESTING PROGRAMME

Overview and Aims

The short encapsulation pull test is an industry standard procedure for determining the shear strength and stiffness of a grouted rock bolt or tendon. A total of six tests were conducted on two combinations of resin-grouted bolts:

- control group (no gloving x 3); and
- gloved group (laminar film wrapping bolt x 3)

The aims of the laboratory testing were to:

- provide a controlled, repeatable test environment;
- develop base line performance for the control group (no gloving);
- quantify the shear strength and stiffness of the gloved bolts; and
- provide insight into the mechanisms of load transfer and the contribution of adhesion and mechanical interlock (friction).

Methodology & Testing Apparatus

The laboratory testing comprised two main components:

- preparation of the test cylinders; and
- short encapsulation pull out tests.

Preparation of Test Cylinders

Arrangement and Pouring - A decision was made to conduct the pull testing from high strength grout cylinders. In part this was due to the field site comprising a thick coal roof sequence (refer section 1) that made the recovery of suitable, large diameter core unlikely and provided potential for non repeatability of samples.

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Test cylinders were created from a high strength cementitious grout (Stratabinder from Minova Australia Pty Ltd) that was poured into pre-prepared thick wall steel cylinders. Cylinders had an internal diameter of 104mm (wall thickness of 3mm) and an overall length of 300mm. The test cylinders were poured in two batches, with grout samples taken for strength testing from each batch. Following pouring, samples were kept moist and allowed to cure for 28 days prior to preparation and testing.

Laboratory testing showed the samples to have the following material properties (at 31 days after pouring):

Sample/Batch	UCS (MPa)	E (GPa)	Poisson's Ratio
1/1	77.3	21.6	0.234
2/1	83.3	21.4	0.252
3/2	84.4	21.1	0.255

Figure 3 details the completed test cylinders prior to surfacing (to provide a flat bearing surface) and drilling of the 27mm diameter bolt hole.



Fig 3: High strength grout cylinders used for laboratory pull testing after pouring.

Drilling the Hole - The bolt hole was drilled using a standard 27mm EP tungsten carbide wing bit and 22mm hex drilling rods. To provide repeatability on each hole, a test jig was constructed for use with a commercial drill stand as shown in Figure 4. The drill stand enabled a constant drill speed (approximately 400 RPM and similar to the hand held pneumatic bolters used underground) and alignment of the cylinder and drill steel. Samples were wet flushed during drilling then thoroughly flushed with water and dried with compressed air to remove any residual cuttings.

Figure 5 details the completed test cylinders with the ends faced for final testing.

Installing the Bolt - Standard run of mine bolts as used at East Mine were supplied by DSI Australia Pty Ltd. Bolts were a high capacity CVX, with a nominal root diameter of 22mm and overall nominal diameter across the deformations of 24.7mm. Yield strength is approximately 240kN, with an ultimate strength of at least 320kN.



Fig 4: General arrangement of drill stand showing alignment jig, drill steel and 27mm ø bit.

To ensure consistency and repeatability in grout quality a mix and pour version (PB1) of the standard polyester resin used in the cartridges was supplied by Minova Australia Pty Ltd. As in the cartridge, the PB1 resin is in two parts. The catalyst and mastic were mixed together for the recommended 60 seconds prior to pouring into the pre-prepared cylinders. Nominal working time with the resin was 10 minutes.



Fig 5: Test cylinders prior to installation of bolts.

For the control group (no gloving), the following procedure was used:

- Cylinders drilled and cleaned;
- PB1 resin mixed to manufactures specification and poured into cylinder; and
- CVX bolt pushed and inserted to back of hole.

Simulation of Gloving

As noted, the phenomena to be tested in this phase of the research was the impact of having an intact resin cartridge (tri-laminate film) against the bolt hole wall - but with a mixed resin. The physical system therefore comprised:

Bolt hole wall - Tri-Laminate Film – Mixed Polyester Resin - Bolt

Blanks of the same tri-laminate film used in construction of cartridges were supplied in sheet format by Minova Australia Pty Ltd. 400mm long x 27mm diameter tri-laminate cylinders were then constructed by rolling the sheet around a template and welding the film on itself. One end of the cylinder was then sealed to prevent return of the mixed resin along the bolt hole wall during pouring.

The following procedure was then used to prepare the final sample:

- Cylinders drilled and cleaned;
- “Empty” 27mm diameter tri-laminate cylinder pushed into bolt hole and conformed to bolt hole wall by temporarily pressuring using nitrogen;
- PB1 resin mixed to manufactures specification and poured into the tri-laminate cylinder – no resin in contact with bolt hole wall;
- CVX bolt pushed into the resin and inserted to the back of the hole; and
- Cable ties used to seal off the glove cylinder and provide a nominal pressure to the grout column during setting to ensure film conforms to bolt hole wall.

Samples were then left for at least 24 hours prior to pull testing.

Pull Testing Apparatus

A conventional hollow ram hydraulic jack and pump system was used as the basis for both the laboratory and field testing. This was done primarily to take advantage of developing the same loggable displacement and load monitoring system for field and laboratory testing. Displacement was monitored using a linear potentiometer, with load monitored using an in line pressure transducer off the pump line. Transducers were interfaced with a National Instruments (NI) DAQ card in a standard laptop computer running LABVIEW (NI) to provide continuous (100Hz) real time monitoring.

A pull testing jig was constructed to ensure alignment of pull testing cylinders and the testing apparatus. Figure 6 details the general arrangement of the pull testing apparatus showing:

- Test frame;
- Test cylinder;
- Hollow ram jack (30T);
- Hydraulic pump;
- Linear Potentiometer;
- Pressure Transducer; and
- Laptop and interface.

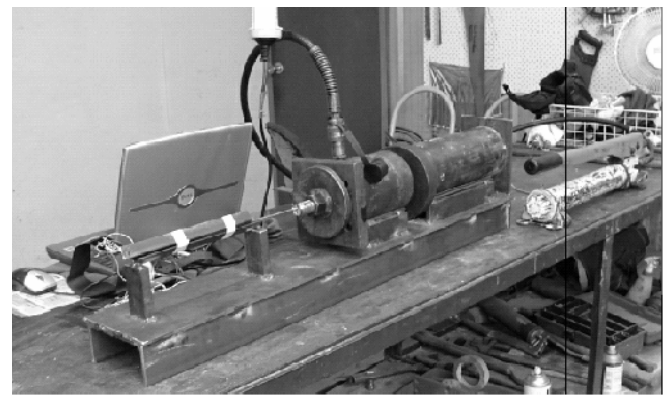


Fig 6: General arrangement of laboratory pull testing apparatus.

Samples were placed into the test frame and load applied incrementally via the hydraulic pump for a total test duration of approximately 5 minutes. As well as real time display, the process was logged to file with LABVIEW for later processing.

The pressure transducer had a safe working limit of approximately 180-200kN, which is just below the yield strength of the CVX bolt (240kN). During testing, samples were loaded to post failure of the bolt/resin/gloving system or a maximum of 180-200kN.

Results

Three control (non-gloved) bolts and three gloved bolts were subject to short encapsulation pull testing. In all cases, slip and yield of the system occurred and no physical (tensile) failure of the bolt itself occurred.

Figure 7 details the logged raw system displacement and load for each test.

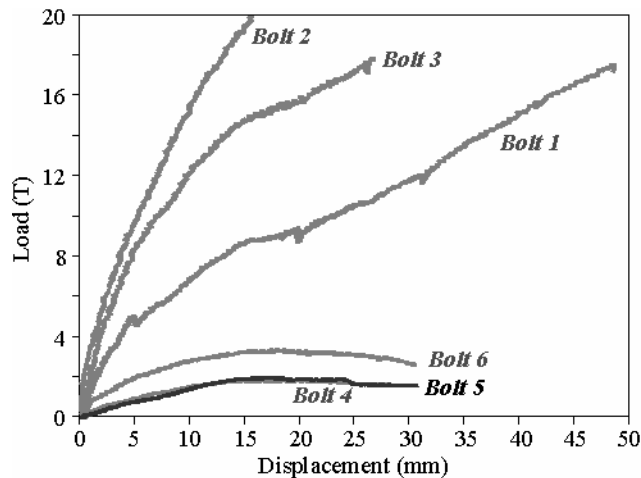


Fig 7: Load versus displacement for the six laboratory tests on 300mm encapsulation.

Control Bolts (Non Gloved)

Bolts 1 and 3 were tested to a load of 182kN and 183kN respectively, with indication of the system being near peak capacity. Failure was along the resin/grout interface. Bolt 2 was tested to a peak load of 203kN and whilst it was obviously failing along the resin/grout interface, had not reached its peak load.

Bolts 2 and 3 showed very similar system stiffness, particularly in the 0-100kN range. Bolt 1 showed a somewhat softer response, although still maintained a similar load.

Figure 8 details the six bolts following testing indicating the general mode of failure along the resin/bolt hole-wall interface.



Fig 8: Tested samples showing failure along resin/borehole wall interface.

Gloved Bolts

As shown in Figure 7, system response from all of the gloved bolts was very similar. Peak loads were: 20kN (Bolt 4), 22kN (Bolt 5), 36kN (Bolt 6). Failure on all bolts was along the tri-laminate/grout boundary. Peak load was developed at approximately 15-16mm displacement.

Discussion

The laboratory pull tests for the non-gloved bolts have shown repeatable results that are consistent with previous testing and design expectation (MacGregor, 2000). The gloved bolts provide low peak shear stress values with a low rate of shear stiffness. The laboratory exercise shows the effect of gloving in generating load transfer between gloved and non-gloved bolts. A gloved bolt provides about 10% of the load transfer generating force of a standard resin anchor non-gloved bolt.

FIELD TESTING PROGRAMME

To compliment the laboratory programme, and provide field validation of the results, a program of short (600mm) encapsulation pull tests were conducted at Solid Energy's Huntly East Mine.

Overview and Aims

Two x 600mm long (encapsulated length) gloved bolts and one x 600mm long (encapsulated length) control bolt were installed in the coal floor of a development roadway.

The aims of the field testing were to:

- Quantify performance of a gloved (mixed) system *in situ*;
- Quantify performance of a non-gloved (control) system *in situ*;
- Investigate the bolt load profile of each system through the use of strain gauged bolts; and
- Provide insight into the mechanisms of load transfer and the contribution of adhesion and mechanical interlock (friction).

Methodology & Testing Apparatus

A similar methodology was employed for the field testing as that used for the laboratory testing. The major differences being:

- The use of 600mm encapsulation length;
- Bolts were instrumented with 9 pairs of strain gauges at 60mm intervals; and
- Strain gauges were logged using a Datataker DT500 at 5 second intervals.

The 600mm encapsulation length was used for several reasons. Previous testing showed that for a 300mm sample the peak load would be in the order of 70-90kN, meaning a 600mm length would still be expected to fail the bond strength prior to reaching yield of the steel. This allowed improved spacing on the strain gauges and greater capability to monitor changes along the bolt during the pullout process.

Two gloved (mixed) bolts and one control bolt were installed successfully at the one site.

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Arrangement of Site and Installation of Bolts

Holes were drilled into the coal floor using a pneumatic hand held rotary rib borer, standard drill steels and drill bits (nominal 26.5mm) using water flushing. As water and cuttings could not be removed during drilling, each hole was blown clean using the mine air supply and a 25mm air line that was able to be pushed to the bottom of the 600mm deep hole.

The same configuration of plastic tri-laminate film and PB1 mix and pour resin as used in the laboratory testing was used here.

For the non-gloved (control bolt) the procedure was:

- Clean bolt hole using compressed air;
- Mix PB1 resin to manufacturer specification;
- Pour resin into bolt hole;
- Manually push home instrumented 600mm long CVX ensuring resin issues from collar; and
- Allow bolt to set for a minimum 1 hour prior to testing.

For the gloved (mixed) bolts the procedure was:

- Clean bolt hole using compressed air;
- Push “empty” gloving cartridge to bottom of hole;
- Inflate and conform “empty” cartridge to bolt hole wall using compressed air;
- Mix PB1 resin to manufacturer specification;
- Pour mixed PB1 into cartridge;
- Manually push home instrumented 600mm long CVX ensuring resin issues from collar;
- Tie off top of cartridge using cable ties to provide nominal pressure to resin column during setting; and
- Allow bolt to set for a minimum 1 hour prior to testing.

All three instrumented bolts had 300mm of bolt protruding from the collar of the hole to enable the pull testing apparatus to be installed.

Figure 9 details the general arrangement of the site showing the two “empty” cartridges in place awaiting resin pouring.

Following installation and curing, the pull testing apparatus was attached and the bolts tested. In addition to the same displacement and load measurement as used in the laboratory, a Datataker DT500 was used to log the nine pairs of diametrically opposed strain gauges on each bolt.

Figure 10 details the general testing arrangement with the full assembly shown. Displacement was measured using a support arm from a specifically installed standard bolt in the floor adjacent to the test bolts. The support arm was able to be rotated about several axes to ensure alignment with the test bolt.

Figure 11 details the arrangement of the strain gauged bolts relative to the overall testing setup, indicating the high density of gauges along the bonded length.

At the completion of testing, the bolts were sawn off at ground level (to minimise impact to operations) and later recovered for inspection using over-coring.

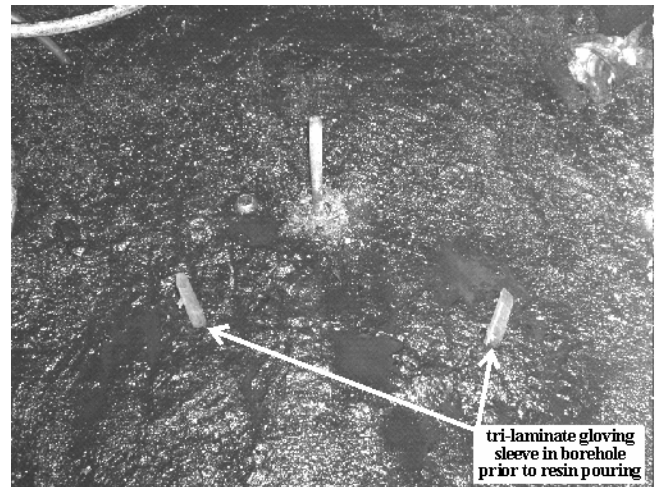


Fig 9: General arrangement of field test site showing gloving cartridges prior to resin pouring and bolt installation.

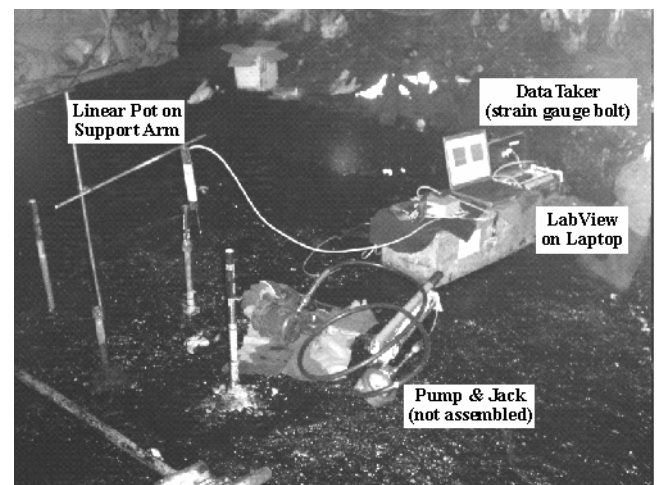


Fig 10: Arrangement of field testing apparatus with jack/pump, displacement plus load measurement and strain gauge logger.

Results

Figure 12 details the raw system displacement and jack load for each of the three tests.

Gloved Bolts

The two gloved bolts exhibited very similar, poor, performance. Peak loads were less than 20kN on both bolts and were very consistent with the laboratory results. The load was maintained at a generally consistent level throughout the testing period.

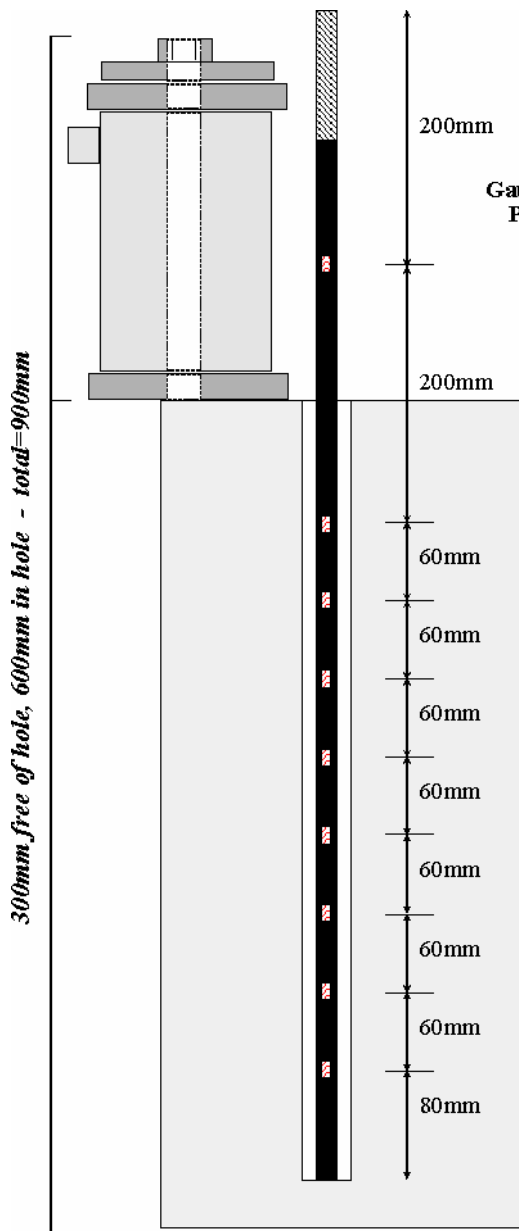


Fig 11: General arrangement of gauges on bolt relative to test set-up.

Figure 13 details the distribution and generation of bolt load along the profile for gloved Bolt 344. Note that in this configuration, the bolt is encapsulated from 300-900mm, with 0-300mm being the section proud of the collar. Figure 13 shows that load was generated along the bolt, indicating contact of the bolt system with the ground along the bolt, for most of the encapsulated length. Only the section from 760mm-820mm does not show any load transfer from the commencement of pull testing. Some other sections of the bolt showed that as load is developed, peak shear stress is achieved and no additional load can be taken over that section – this is apparent over the 520-580mm, 640-720mm and 300-360mm sections of bolt as testing progresses.

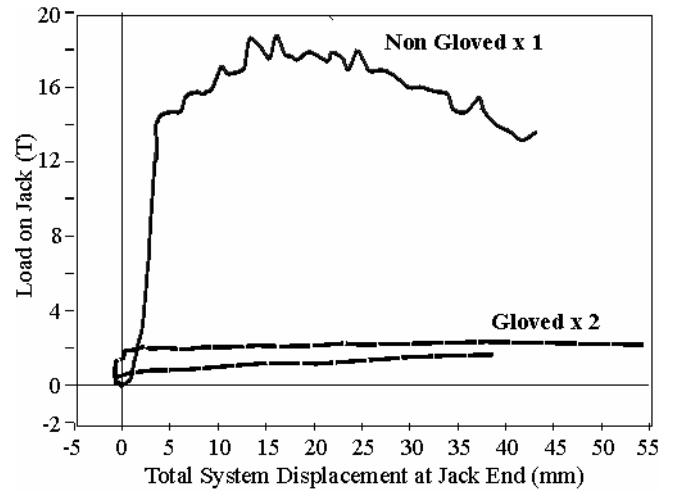


Fig 12: Load versus displacement for 3x600mm CVX bolts in coal.

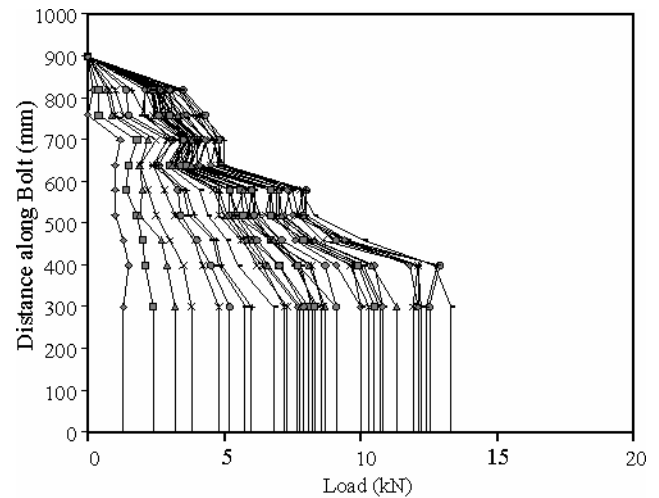


Fig 13: Bolt loading profile for gloved bolt (344) showing progression of load generation.

The encapsulated sections of overcored bolt (that were not removed when sawn off at the collar) are shown in Figure 14. The bolts exhibit very good resin mixing and setting (as would be expected with the mix and pour resin). The gloving is generally intact about the bolt and shows evidence of being displaced relative to the bolt hole wall. Measurement of the resin column diameter using a vernier calliper shows that the diameter is variable and would appear to have conformed to the hole size – again indicating contact of the tri-laminate film with the bolt hole wall. Measured resin diameters for each gloved bolt were:

Gloved Bolt ID	Measured Resin Diameter at Distance from Base of Bolt			
	100mm	200mm	300mm	400mm
342	29.0	29.4	28.4	
344	30.6	30.4	30.1	29.8



Fig 14: Overcored bolt 344 showing well mixed resin, presence of gloving on outer surface.

Non Gloved Bolt

As shown in Figure 12, the non-gloved control bolt displays the characteristic form of a standard short encapsulation pull test. Following initial stiff performance, where load reached approximately 145kN after 3mm displacement, system stiffness reduced with the peak load of 187kN developed at approximately 19mm of displacement.

The magnitude of bolt load is consistent with earlier field pull testing that showed the CVX to exhibit 70-90kN over a standard 300mm embedment length. Inspection of the failed bolt showed failure to have occurred along the resin/coal interface which is consistent with previous testing (MacGregor, 2000).

Figure 15 details the distribution of bolt load from the strain gauge results indicating the control bolt is encapsulated along its entire length.

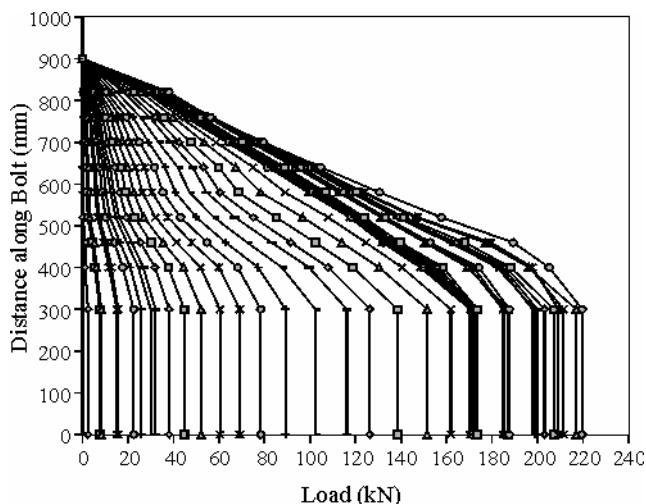


Fig 15: Bolt loading profile for non-gloved bolt (343) showing progression of load generation.

Load Generation in a Fully Encapsulated Bolt

The strain gauged control bolt provides an insight into the nature of load generation in a standard fully encapsulated bolt. To analyse the contribution of each part of the bolt, each gauge pair was reviewed to determine the amount of work done (as a measure of shear stress). Figure 16 details the calculated shear stress on the bolt hole wall versus system displacement (gauge pairs at the collar and bottom of bolt not shown due to possible end effects from free surface and bolt end).

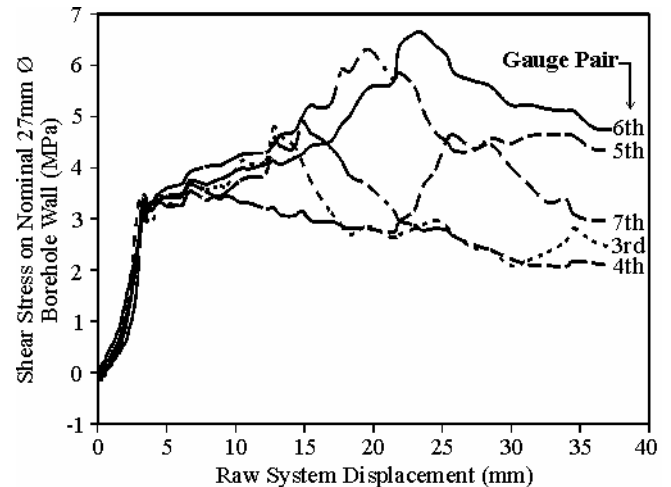


Fig 16: Calculated shear stress on borehole wall (27mm Ø) at locations along instrumented non-gloved bolt showing components of work done at different locations and time.

The results show that the style of behaviour is very consistent over the initial stiff period of load development. All gauge pairs show a similar capability to sustain load, in the order of 3MPa shear stress on a 27mm diameter bolt hole. At this stage, the peak load at the collar is approximately 140kN (refer Figure 15). After this stiff behaviour, the contribution of load at each point along the bolt is markedly different, although following a consistent trend.

The trend is one of increasing shear stress that reaches a peak sustainable load by the coal/resin interface (the weakest link in the coal/resin/bolt system) which then rolls over to a lower, sustained residual shear stress. The progression of this trend is also consistent, and migrates from the collar (area applied load) towards the back of the bolt. This is obvious in Figure 16 as a “wave” of peak shear stress passing progressively through gauge pairs 3, 4, 5, 6 and 7. At any one point in time, the load capacity of the bolt is the weighted average of the individual contributions. Therefore, whilst locally shear stresses are in the order of 7MPa, the weighted average is typically 4-4.5MPa, which is consistent with the peak loads measured.

CONCLUSIONS

The geotechnical environment at Huntly East Mine is characterised by moderate to high levels of stress. Roadways exhibit clear signs of horizontal stress, induced shear failure and guttering. The high density and persistence of structural disturbance and cleating throughout the coal and a consistently

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weak non-coal roof requires that the installed reinforcement performs as designed.

A laboratory and field testing programme to investigate the effects of gloved bolting systems on bolt system performance was successfully completed. Both the laboratory and field results show a similar loss in performance of the gloved system, being almost an order of magnitude less than a non-gloved bolt.

The ability of a bolting system to generate and maintain load is strongly controlled by the shear stress capacity at the bolt hole wall. It is this interface that is typically the point of failure for most roof bolting systems, particularly in weak roof lithologies. The introduction of a tri-laminate film at this interface, effectively debonding the bolt/resin from the bolt hole wall, significantly limits the ability of mechanical interlock to develop and results in drastically reduced system performance.

As part of Solid Energy's broader investigation into bolt quality, quantifying the effect of gloving has allowed Huntly East Mine to *pro rata* the effective system performance of the various bolt components to effectively manage the roadway conditions.

The root cause of a range of bolt quality issues, including gloving, is the generation of high resin pressures during installation (Campbell, Mould & MacGregor, 2004). Mitigating the high resin pressures will reduce the incidence of gloving, loss of resin into strata and the un-mixed resin component common to the recovered bolts from this on-going program of auditing and post-audit investigations being undertaken by Solid Energy New Zealand.

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