

# Understanding the Performance of Rock Reinforcement Elements under Shear Loading through Laboratory Testing — A 30-year History.

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## Abstract

*This paper outlines the history of the developments over the last 30 years in understanding the performance of rock reinforcement elements under shear loading through laboratory testing and where the research stands today. Shear testing of rockbolts was first conducted at the Swedish Rock Mechanics Research Foundation in 1974 in hard rock reinforced by rockbolts and was followed by a series of other research attempts around the world over the last 30 years. The factors looked into included the size (length and diameter) and number of bolts, the inclination of the bolts, the relative displacements in joints, joint roughness, the effect of compression, relative strength of rock and grout and elastic modulus of rock and grout. Analytical and numerical solutions were also proposed based on these experiments.*

*The paper takes the reader through these developments and critically analyses their achievements and shortcomings. It highlights the current understanding and its shortcomings, and identifies the need for further research. It then introduces the state of the art facility being established at The Mining Research Centre at UNSW for shear testing of reinforcement elements and the anticipated outcomes from this experimentation exercise.*

## INTRODUCTION

Although the use of rockbolts can be traced as far back as the Roman Empire when slot and wedge type rockbolts were in use, the more recent use in mining and tunnelling dates back to the late nineteenth century. Up until the 1950s however, it was generally held that the purpose of rockbolts was to pin surface rock (either individual blocks or bedded strata as encountered in underground coal mining) to more stable rock some distance from the surface of the excavation.

At the time, mechanically anchored (slot and wedge or expansion shell) bolts were used. The next two decades saw the advent of chemically anchored bolts, full column grout bolts and resin bolts being used in underground mines including in Australia. By the 1980s it was accepted that the term rock bolt/rockbolting was '*generally to indicate any form of mechanical support that is inserted into the rock mass with the primary objective of increasing its stiffness and/or strength with respect to tensile and/or shear loads*', Gerard (1983). This included

the application of compression (by active or passive tensioning) to improve resistance to shear and tension (referred to as the 'friction effect' by Panek (1964)).

The difference between support and reinforcement was also understood as, support being the application of a reactive force at the face of the excavation, and reinforcement as being the improvement of the overall rock mass performance from within the rock mass by techniques such as rockbolts, cable bolts and ground anchors.

The mechanism of bolt performance in reinforcing the rock mass under field loading conditions, although widely studied, still remains to be established as a universally recognised and accepted code of practice. There is a requirement by industry (i.e. end users, consultants, educators and manufacturers) to actively identify the key parameters which govern safe and cost-effective excavation practices, including:

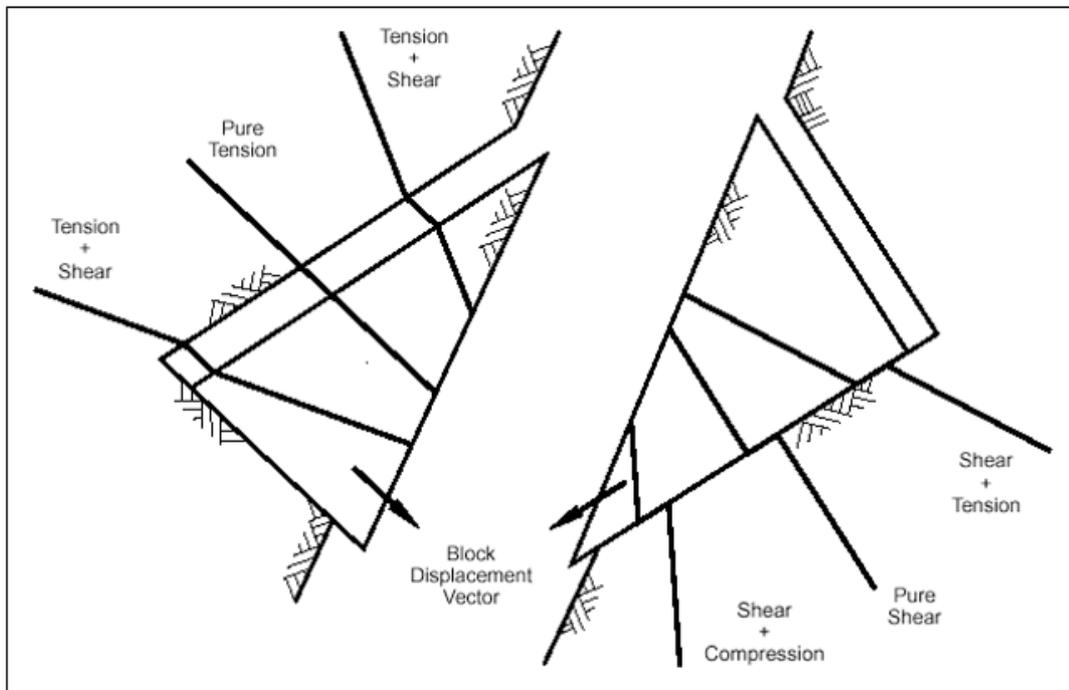
- Reinforcement installation in the form of cable bolts and splitsets in the footwall of longhole open stopes is used to prevent slide out failure on pre-existing geological structures where the reinforcement element acts as a dowel to prevent shear failure.
- In underground coalmines with roadway roofs consisting of laminated shale and sandstone, solid chemical-bonded rock reinforcement elements are the preferred method to prevent large displacements and act as shear-resistant dowels.
- Rock reinforcement elements are also used in hard rock open-cut mines with slope stability problems above ramps where large blocks are prevented from sliding out and equilibrium is established through dowel action.
- Rock reinforcement elements have been installed in roadside cuts to secure blocks of rock with potential to slide out or topple over.
- In the tunnelling community, installation of reinforcement elements is the accepted practice in stabilising the tunnels.

Statistics from the US Mine Safety and Health Administration (MSHA), show that more than 400 miners are injured in roof and rib falls annually; in the five years from 1994 to 1998, 53 miners died in such accidents (McHugh & Signer 1999).

In general, sagging of a mine roof and yielding of pillars results in vertical and horizontal stresses in a mine roof, imparting both axial and shear forces on roof bolts. Combined tensile and shear forces are at times sufficient to cause failure of the bolts.

Currently the rock reinforcement requirements for a site are estimated still based on the assumption that the bolt will pin the loose block of rock to a stronger horizon of rock. The contribution of the bolt in increasing the shear strength across the discontinuous surface (block interface, see Figure 1), although recognised, is still not quantifiable.

**Figure 1 Reinforcement actions at opening and shearing discontinuities (from Windsor & Thompson, 1992:3)**



Numerous attempts have been made at laboratory testing to determine both the tensional and shear strength contribution of bolts across joints. This research has evolved over the years and is at a stage where a final comprehensive testing exercise would reveal and state the principles involved.

## HISTORICAL REVIEW OF TESTING METHODOLOGIES

Starting from simple direct shear experiments focusing on the mechanism of shearing in a reinforced jointed rock mass, it quickly became quite apparent that the problem was a complex one and the number of parameters which could potentially influence the performance of rock reinforcement elements in a jointed rock mass subjected to shear loading was large. Thus more sophisticated ways of conducting the tests were designed. What is intriguing is the fact that over the years researchers have reported quite contradictory results with regards to some of these parameters.

### *Influencing parameters*

The influencing parameters, which have been studied through laboratory experiments thus far, may be grouped under the following sub headings:

#### 1. Rock Mass

- joint opening/aperture
- joint surface roughness
- joint strength
- dilatancy during shearing
- deformability of host rock
- rock deformability vs bolt deformability.

#### 2. The reinforcement element system

- hole size
- hole roughness
- bolt diameter
- type of grout
- thickness of grout collar
- grouted vs un-grouted bolt
- fully bonded vs point -anchored bolt
- bolt material and its strength and deformability
- bolt deformability vs rock deformability
- inclination of the bolt
- tension force in the bolt
- deformed length of the bolt.

### 3. Loading conditions

- pre-loading of bolts (tensioning and torque)
- normal stress on the shear surface
- shear displacement-induced tension
- dilatancy-induced tension during shearing
- magnitude of shear displacement
- deformed length of the bolt.

A summary of the past research results is presented below showing the chronological development in the understanding of the performance of bolted rock joints under shear loading.

### *Experimental set-up and results*

(a) The earliest traceable report of shear testing of rockbolts is by **Sten Bjurström in 1974**. He recognised the fact that the capacity of bolted joints to transfer shear forces is an important but often unknown factor when estimating stability and deformational behaviour of bolted jointed rock mass.

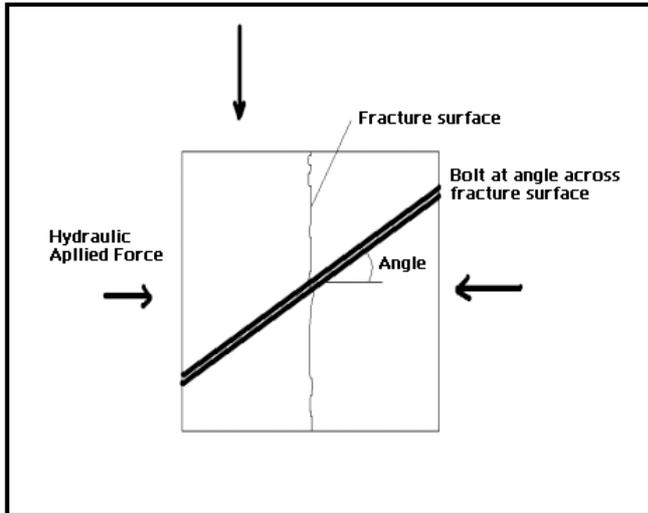
He dealt specifically with shear tests on fully cement-bonded rockbolts embedded in blocks of granite. He considered the following four aspects of the bolt effect:

- tension force in the bolt
- friction at the shear surface as a consequence of increased normal stress
- dowel effect of the bolts
- bolt inclination with respect to shear surface.

He concluded that inclining the bolts resulted in stiffening the shear and in an increase of the shear strength at smaller displacements.

(b) **Haas in 1976** conducted experiments using various bolt types and anchors in blocks of limestone and shale. He found that resistance to shear stress was increased about 3.7 times when fully grouted bolts were used to secure a natural fracture. The loading frame was orientated so that the interface between the blocks of rock was vertical. A **compressive** force was exerted normal to the plane from the right and left sides (see Figure 2).

**Figure 2 2 Schematic sketch of loading geometry showing section of rock, fracture surface, and grouted bolt (Haas 1976).**



A torque was applied to the bolts after the normal load was applied to the block. The objective of applying this torque is not clear; it appears it was used to lock in the applied normal loads. The effectiveness of this process is itself doubtful. They concluded that very low normal pressure values (of  $\sigma_n = 25$  psi) provided a significant increase in the shear resistance of a bolted rock joint. An increase in shear resistance is also noted at the higher normal pressure of 250 psi; however, the increase is small compare to corresponding shear resistance without a bolt. Haas's conclusions with regards to bolt inclination were that when the bolt is orientated between 0 and +45° (measured from normal to the shear surface and in the direction of applied shear force) the shear resistance increases significantly, whereas at -45° no shear resistance is added as the bolt lost tension at very small shear displacement.

(c) **Azuar in 1977** reported laboratory tests with resin-grouted bolts embedded in concrete (Haas et al. 1981). He concluded that:

- The maximum contribution of a rock bolt to the shear resistance of a joint is 60% to 80% of the ultimate tension load of the bolt in the case of the bolt being perpendicular to the joint, and about 90% for inclined bolts.
- The friction characteristics of the joint do not influence the contribution of the bolt.
- Perpendicular bolts do not experience considerable tension stress.
- For a given shear displacement, dilatancy increases the resistance of the bolted joint

(this is in direct contradiction to his second conclusion stated above).

(d) **Haas** repeated his earlier experiments (Haas 1981), this time applying uniform normal pressure on the shear surface. He used different types of bolts, grouts and drill holes for his experiments. His main conclusions were that:

- No positive effect of pre-tensioning could be observed.
- Bolts with full bond were much stiffer than point-anchored bolts.
- Inclined bolts were stiffer and contributed more to the shear strength of the bolted blocks than perpendicular ones.
- The normal stress on the shear surface did not influence the shear resistance of a bolt (contradicting their earlier conclusion from 1976).
- The effects of dilatancy contributed to the stiffness of the bolted joint.

(e) In **1981 Hibino and Motjima** published their results from shear tests with ungrouted bolts (both fully bonded and point-anchored) in concrete blocks. Their conclusions were:

- For given displacements the shear resistance of fully-bonded bolts was considerably higher than that of point anchored ones.
- The inclination of a bolt did not really increase its shear resistance. This conclusion was contrary to all other researchers' findings regarding the influence of bolt inclination.
- *'Pre-tensioning of the bolts reduced the shear displacements but did not influence the shear resistance.'*

(f) In **1983 Egger and Fernandez** from the Institute of Swiss Federal Institute of Technology, Lausanne, Switzerland, reported their research in this area (Egger & Pelletet, Al, 1990). They tested bolted samples of concrete blocks in a high capacity press. They found that:

- The optimum angle of bolt inclination with respect to the joint was 30° to 60°.
- Bolts perpendicular to the shear plane furnished the lowest shear resistance.
- Shear displacements at failure were minimal for bolt inclinations between 40° and 50°.

(g) In **1983 Ludvig** presented results from tests, which were conducted using the same rig as that used by Bjurström in 1976. He applied normal loads in the range of 0.2 MPa to 10 MPa. He reported that an 8 mm steel bolt installed in slate could bear up

to 18 mm of shear displacement due to the large normal stress and relatively weak rock.

Bolts were tested at 45° to the shear surfaces. The shear resistance varied between 490 MPa to 780 MPa, which is larger than the shear strength observed for bolts installed perpendicular to the shear surface. This was found to be true for fibreglass bolts as well. However, the shear displacement before failure was smaller than those observed for perpendicular installed steel bolts. All inclined steel bolts, apart from the test conducted in slate, failed after a displacement, which was smaller than the bolt diameter. His conclusions were:

- Shear strength of the rockbolts is strongly dependent on the material used for construction of the bolt and also whether the bolt is solid or hollow.
- Massive steel bolts have the largest shear strength.
- For a given diameter the shear strength of fibreglass bolts is about one half to the shear strength of steel bolts.

(h) **Dight in 1982** used various different materials including gypsum, basalt and steel and examined the shear resistance of bolted joints in them. He mainly found that:

- *'The normal stress acting on the joint had no influence on the shear resistance.'*
- *'Joints with inclined bolts were stiffer than those with perpendicular ones.'*
- *'The influence of dilatancy had the same effect as that of a bolt inclination' but did not conclude which direction angle had the same effect as dilatancy.*
- The deformed length of the bolt was related to the deformability of the rock.
- The dowel effect was defined as the difference between the shear resistance of a fully bounded bolt and that of a point-anchored bolt.

(i) **Schubert (1984)** conducted shear tests on bolted concrete and limestone blocks. The main results of his research work are:

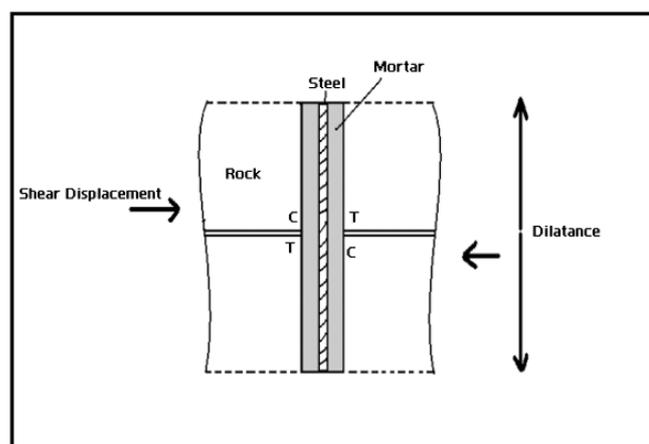
- The deformability of the surrounding rock is important for the bolt reaction.
- Bolts embedded in harder rock require smaller displacements for attaining a given resistance than those in softer rock.
- *'Soft steel improved the deformability of the bolted system in soft rock.'*

(j) **Turner (1987)** reported that appreciable opening of fractures prior to shear movements resulted in double bends and failure of rockbolts by tension (Spang & Egger 1990). Bolts across unopened fractures had been actually cut (guillotined) during rock bursts.

(k) **Spang and Egger (1990)** studied the shear resistance of different blocks reinforced with 8 mm bolts. In these tests, the deformability of the rock was shown to be one of the most important parameters for the shear resistance of bolted joints. They differentiated between elastic, yield and plastic stages of the shear stress vs shear displacement curve and pointed out that the response was softer in weaker blocks since the rock was more easily crushed near the exit point. In addition, higher reinforcement resistance was obtained in weaker blocks of rock because the cable aligned itself with the load around the crushed borehole.

The shear resistance of the bolted joint consists of its proper shear strength  $\tau = \sigma_n \cdot \tan\theta$  and of the contribution of the bolt. This latter is a result of the elastic responses of the bolt, the mortar and the rock, and depends, therefore, on the Young's moduli of these materials as well as on the dimensions of the bolt and the mortar cylinder. The stresses in the three materials are compressive on the side behind the bolt (C in Figure 3), and tensile on its front side (T in Figure 3).

**Figure 3 Initial state of a bolted joint (Spang & Egger 1990, p. 205)**



The tension stresses in the mortar and the rock disappear because of the very low adhesive strength between steel and the mortar, giving rise to a gap on the tension side. The maximum contribution of the bolt ( $T_o$ ) to the total shear strength of the joint is a function of various parameters which is shown in an empirical expression below:

$$T_o = T_u [1.55 + 0.011 \sigma_c^{1.07} \sin^2[\beta + i] \cdot \sigma_c^{0.14} (0.85 + 0.45 \tan \phi)]$$

- $T_u$  is the ultimate axial bolt load (tensile strength)
- $\beta$  is the angle between the bolt and joint surface
- $i$  is the angle of dilatancy
- $\phi$  is the angle of friction along the shear plane
- $\sigma_c$  is the compressive strength of the host rock

They further stated that one of the most important parameters is the stiffness of the rock and the mortar, which depends, to a certain degree, on the compressive strength  $\sigma_c$ .

l) **Egger and Zabuski (1991)** reported that bolts work as an additional resistance against shear failure along joints, hence the entire rock mass becomes stronger and deforms less. They used a standard apparatus for direct shear testing of rock samples. The tests were conducted without an external normal force. They explained that with no external force, the bolt was getting stressed because vertical displacements developed due to the sliding of the sample on the joint asperities. Therefore additional frictional shear resistance appears, proportional to the normal force.

Small displacements were accompanied by a great increase of the shear force. During this stage, local resisting forces were mobilised in the concrete, which limit bending of the bolt until the UCS of the concrete reached. At that moment the concrete was destroyed in those zones and the bolt was able to move more freely. The failure surface showed signs of shear and tension failure. The bolt was deformed only in the closest vicinity to the joint. Inside the sample, at a maximum depth of about 10 mm from the joint surface, there was no evidence of the bolt deformation or traces of lost contact between the steel and concrete, or of slip between them.

m) **Pellet and Egger (1996)** related theoretical and experimental analysis of rockbolt shear strength and found that '*bolts installed perpendicular to a joint plane allowed the greatest displacement along the joint before failure*', but that displacement at failure decreased rapidly as the angle between the bolt and joint plane decreased. They also found that harder rock led to bolt failure at smaller displacements.

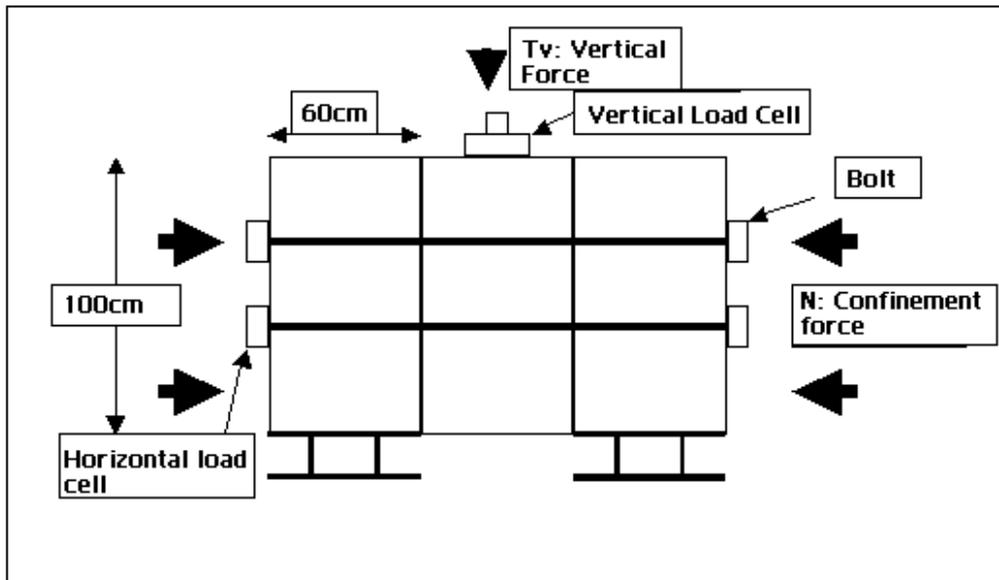
n) **Goris et al. (1996)** conducted shear tests on concrete blocks having joint surfaces ranging from rough to smooth, with and without reinforcement. Three variables were studied: smooth versus rough joint surfaces, grouted versus un-grouted cables; and small, large and oversize drill holes.

Pouring concrete around a rod and extracting it without any drilling simulated the drill holes. The increase in shear stress was attributed to shear resistance of the cable and to the fact that tensile force along the cable was transferred to the shear blocks, which resulted in an increase in the normal force on the joint.

o) **Roberts (1995)** reported shear test results for smooth bars and cone bolts and compared his results to Spang and Egger's theory. Although his results agreed with the theory he pointed out that the grout and rock have a significant contribution to the overall shear strength of the bolted rock joint and had not been included in the theoretical treatment of predicting shear resistance. He also compared results of shearing an element at two interfaces (double shear) to a single interface shear and found that the former was not simply double the latter, as true symmetry did not exist in the case of double shear. Shear failure would occur at one interface first and subsequently resulted in failure of the other interface (GAP 335 1995).

p) **McHugh and Signer (1999)** reported cases from the US of shear loading contributing significantly to failure of bolts used for rock reinforcement in coalmine roofs. They conducted a series of tests to study the behaviour of roof bolts subjected to shear loading over a range of axial bolt loads and measured the distribution of axial and bending strain along the length of the bolts.

Figure 4 Scheme of the experimental set up —three bolted blocks (60/60/100 cm) with two bolts each joint (Grasselli et al. 1999).



Their main findings included:

- That axial loading has little effect on a joint's resistance to shear loading. (Recent analytical research in the performance of pre-tensioned bolts suggests that only about 10% of the torque applied to a bolt remains as the axial tension in the bolt, the remaining 90% goes towards overcoming thread and bearing friction, (Fernando 2001).)
- Joint shear strength at yield averaged about 76% of expected actual strength of the bolt.
- The hardness of host rocks plays a role in how a bolt responds to shear loading.
- The nut and plate anchors at the ends of the test bolts ensured that grout failure would not be a factor in load and displacement profiles.

q) **Grasselli, Kharchafi and Egger (1999)** did an analysis of the results obtained from large scale (1:1) laboratory tests of bolt-reinforced rock with fully grouted rods and hollow tubes.

Apart from the influencing parameters already reported in this paper, Grasselli et al. pointed out that the 3D aspect of this system makes it hard to analyse and simulate.

An experimental set-up was developed as shown in Figure 4. The set-up simulated double shearing of one or two strain-gauged bolts installed through three large blocks. During a test, a controlled jack pushed progressively down the central block.

A numerical relation was developed giving the contribution of each bolt  $T^*$  as:

$$T^* = \frac{T_v - 2 \cdot N \cdot \text{tg} \phi_i}{2 \cdot F_{max}}$$

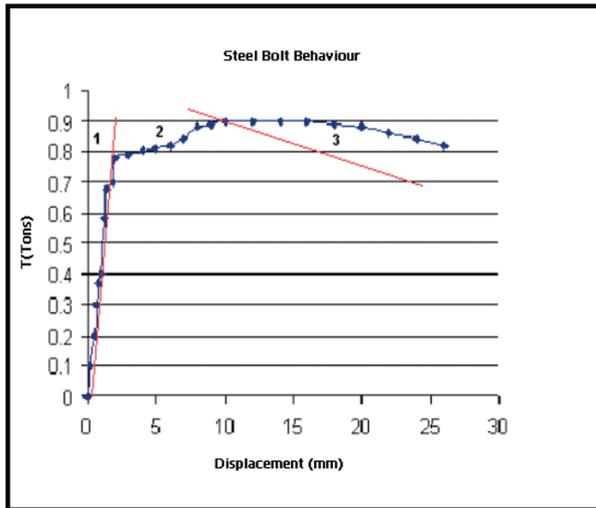
Where  $T_v$  is the vertical force applied on the central block,  $N$  is the confinement force,  $\phi_i$  is the friction angle of the block surface, and  $F_{max}$  is the ultimate tensile load of the bolt.

Figure 5 shows the load shear displacement curve for a full steel bolt.

Similar to the findings of earlier researchers, the curve exhibits:

- Linear behaviour, with small displacements and large increase of load.
- A non-linear behaviour corresponding to the plastification of the materials.
- Plastic behaviour - nearly free deformation of the bolt, until its failure.

**Figure 5 Full steel bolt Behaviour behaviour (Grasselli et al. 1999)**



According to Grasselli et al. (1999) the bolt failure is principally caused by the traction load concentrated between the two plastic hinges. A great displacement ( $\approx 8\text{mm}$ ) is associated with the formation of the plastic hinges and with the progressive breaking up of the grout around the steel rod. The resistance contribution  $T^*$  reaches its maximum value ( $\approx 0.9 F_{\text{max}}$ ). However Roberts (1995) had already reported the limitation of this testing method involving double shear and thus the results cannot be accepted as representative of performance of a bolt along a single interface.

## CURRENT UNDERSTANDING FROM PAST RESEARCH

There seems to be a general agreement among researchers and practitioners regarding the influence of some of the parameters involved, e.g. bolt inclination increases resistance and decreases shear displacements. There is a general lack in understanding of the actual reinforcement installation method and the associated loading mechanisms that may cause failure. Especially of concern is the effectiveness of pre-tensioning, torqueing, axial tensioning and/or normal loading. Experimental set-ups in the past have used one or more of these loading systems either to clamp the model or simulate the pre-tensioning practice, which is very popular in the field. Their research remains inconclusive to date. In view of the fact that pre-tensioning/torqueing is considered vital to the reinforcement methodology that has been being practiced over the last two decades, and that installation rigs have specifically been designed to incorporate this process, active research is called

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for to look exclusively at the effectiveness of this process before any more time and money is spent advancing a practice of which limited understanding exists.

In particular, the following questions still remain unanswered in our quest to understand the performance of reinforcement elements across a jointed interface:

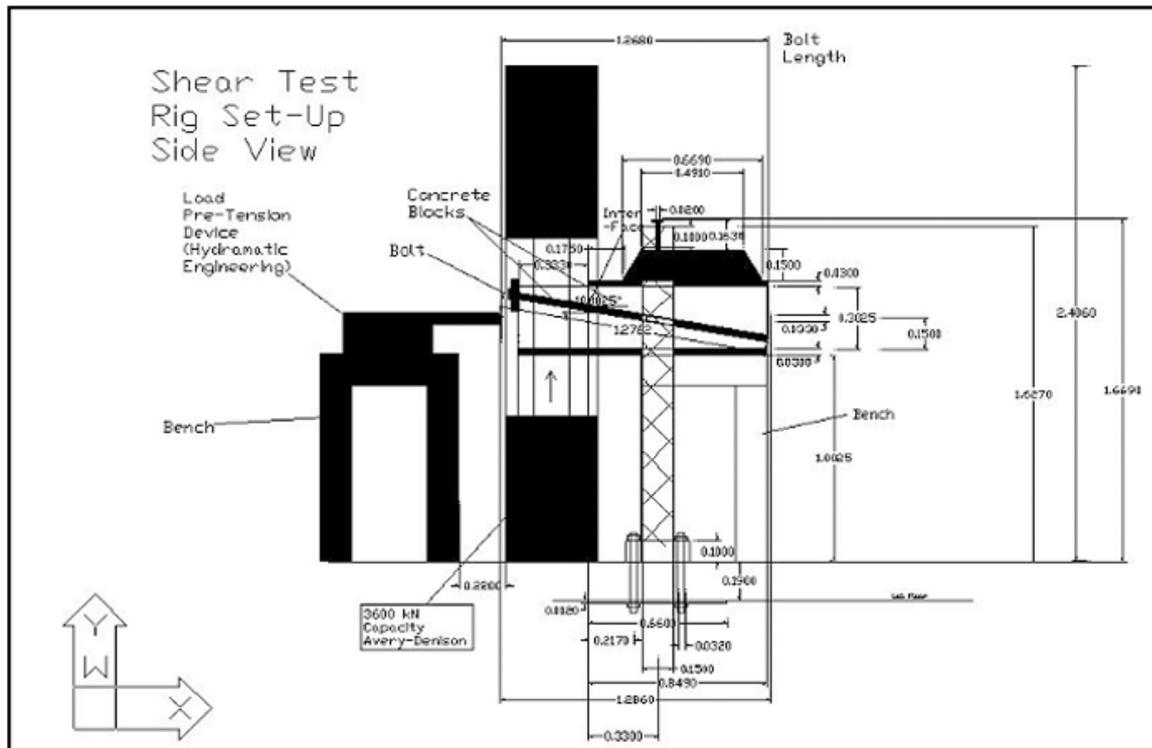
- Is pre-tensioning of the reinforcement element across a jointed surface maintained until loading of the rock mass occurs?
- Is actual torque reducing the yielding strength of a reinforcement element, and subsequently the shear resistance?
- What role does the size of the bearing plate play in the performance of the reinforcement element in shear loading?
- Will it be beneficial in upgrading the elastic moduli of grout (including resin)?
- Is the stiffness of the reinforcing element assisting or destroying the resistance to shear loading within the reinforcing system?
- What effect has shear loading on the surrounding rock mass?
- Will an Australian standard or guideline assist in proper design for expected shear loading conditions?

## NEW TESTING FACILITY BEING DEVELOPED AT THE MINING RESEARCH CENTRE, UNSW (ACARP PROJECT NO. C12010)

A laboratory test facility for full-scale testing of shear performance of installed reinforcement elements is being developed at the Mining Research Centre, School of Mining Engineering at UNSW, as part of an ACARP funded project.

A schematic diagram of the testing facility is shown in Figure 6.

Figure 6 Schematic diagram of test rig facility at Mining Research Centre, UNSW



## Objectives

The main objectives of this project include:

1. To research the current understanding of the performance of reinforcement elements in shear
2. To design and develop a testing rig which meets the need of the required testing, and
3. To conduct a series of controlled laboratory experiments using the facility, and to study the effect of the following variables on the performance of reinforcement elements in both direct shear resistance and indirect shear resistance through axial clamping:
  - borehole and element geometry
  - element orientation relative to discontinuity
  - element and grout geomechanical properties
  - geomechanical properties of test block
  - block geometry
  - element pre-tensioning
  - characteristics of discontinuity
  - discontinuity aperture.
4. To conduct parallel theoretical, mechanistic and computational studies in support of the above experimental program.
5. To prepare a set of industry guidelines for the application of reinforcement systems in

discontinuous materials, with respect to their performance in shear resistance, and comparison with axial loading performance subject to similar variables.

## Expected outcomes and benefits

- A significant improvement in the level of understanding of the performance of reinforcement elements under shear — a role that is fundamental to good roof control in Australian coal mines, open stopes, open-cut ramps, wall stability and underground tunnels.
- The availability of a controlled environment, laboratory test facility for future evaluation of different products or reinforcement concepts, under shear loading.
- The opportunity to provide a more scientific (hence efficient) basis for optimising element reinforcement designs for mines (in both primary and secondary support).
- Clear safety implications for the industry through achieving the above outcomes.
- Further training of industry geotechnical engineering specialists through this project, and the opportunity for others through similar future work.

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