Optimisation of Roof Bolt Performance

M. Fabjanczyk¹, K. Hurt² and D. Hindmarsh²

¹Strata Control Technology
PO Box 824, Wollongong East, NSW 2520, Australia

²Rock Mechanics Technology
Breitby Business Park, Ashby Road, Stanhope Breitby
Burton on Trent, Staffordshire, DE15 OQD, UK

Abstract: The performance of any reinforcement design is limited by the efficiency of load transfer of the reinforcing members. The load transfer is the mechanism by which force is generated and sustained in the reinforcing tendon as a consequence of strata deformation. Over the past thirty years the behaviour of the load transfer system has been extensively analysed both theoretically and experimentally. A summary of the more recent experimental approaches was provided in Fabjanczyk and Tarrant 92.

In a fully grouted rock bolt, the load transfer mechanism is dependent on the shear stress sustained on the bolt/resin and resin/rock interfaces. The peak shear stress capability of the interfaces and the rate of shear stress generation (system stiffness) determines the response of the bolts to the strata behaviour.

Fabjanczyk and Tarrant summarised studies conducted over several years to optimise reinforcement technology in coal mines, investigations were conducted to determine the effect of bolt profile, hole diameter and properties of the encapsulation medium on the load transfer mechanism. The role played by the generation of confining forces during the pull out of the tendon was analysed. As well as reviewing existing techniques of load transfer determination, this paper presents a new technique of laboratory testing which allows a high level of control on variables as well as well using actual strata for the test medium.

Key words: reinforcement, tendon, bolting, testing, load transfer

Determination of Load Transfer Characteristics

To enable appropriate reinforcement design the measurement and if required optimisation of the load transfer system is an essential part of the design process.

Load transfer is determined by measurement of the peak shear stress capacity and system stiffness. The shear stress capacity is calculated by using Equation 1. Peak shear stress is the average shear stress over a given encapsulation length at the maximum applied force.
\[ \tau = \frac{F}{\pi d L} \]

where:
- \( F \) = change in force over the encapsulation length (L)
- \( d \) = bolt diameter or borehole diameter
- \( \tau \) = shear stress

The system stiffness is the rate at which the shear stresses are generated for a given displacement.

Traditionally the methods have included either field measurement or laboratory based techniques.

**Field Testing**

The following field based methods have been extensively used:

*Strain Gauged Bolts*

The complete load transfer history and performance of a roof or rib bolt can be determined by the measurement of the force profile along the bolt. This is achieved by the attachment of up to 9 pairs of diametrically opposed strain gauges along the length of the bolt.

The average shear stresses sustained between each pair of strain gauges on the bolt/resin/rock interfaces are directly calculated from the force distribution.

This peak shear stress capability is only achieved once there is sufficient strata deformation to induce the load within the bolt to a level where failure of the bond is approached. It is however the best indicator of the suitability of bit type and size, correct flushing arrangement and a measure of the quality control on the placement of the reinforcement.

*Short Encapsulation Pull Test*

A standard technique of assessing potential anchor strength is to conduct short encapsulation pull tests in the field.

The minimum cartridge length required to conduct field pull tests is 150mm (Galc and Fabjanczyk, 1987) which provides approximately 300mm of embedment. This length is required to minimise end effects from poor mixing at the top and bottom of the encapsulated length. The length of encapsulation should be as low as possible to minimise the possibility of the bolt yielding prior to bond failure occurring. A typical testing configuration is shown in Figure 1 (note that the lower section of the hole is enlarged to ensure control over the effective encapsulation length.
Fig. 1 — Typical short encapsulation pull test.

The increase in the rate of the reduction in bolt diameter, as a consequence of bolt yield, limits additional shear stress generation because of the reduction of the confining forces.

The short encapsulation length also allows the measurement of load transfer at differing horizons within the strata.

These tests are subject to significant variations from:

i) gloving of the plastic resin sheath
ii) variations in borehole characteristics
iii) potential for over or under spinning
iv) loss of resin into strata.

However, the field pull test is considered to be a valuable test for the determination of adequate bond strength under field conditions and as a check on the field placement system. The sources of error listed will result in a conservative estimation of the potential load transfer performance.
Standard Laboratory Testing

The standard techniques for determining load transfer performance include pull tests out of concrete or rock blocks and pull tests out of metal tubes.

The concrete and rock pullout tests have the same sources of error as the field pullout tests with respect to the borehole surface condition and diameter.

Pullout tests of bolts encapsulated within various thickness metal tubes have the disadvantage that the act of gripping and the variability in tube thickness modifies the confinement to the bolt/resin system. The role of confinement in the load transfer mechanism is considered to be critical and is discussed further in this paper.

Laboratory 50mm Push Test

The short encapsulation push test was developed to examine the mechanism of load transfer without the variables present in field testing. The most significant advantage of this test was the ability to examine the peak load transfer performance without the constraint of yield in the bar. The test also enabled more accurate measurement of the system stiffness compared with field testing. The push test configuration is shown in Figure 2.

![Diagram of push test configuration](image)

**Cylinder Specifications**

- **Steel Grade**: K10.40
- **Length**: 50mm ± 0.5mm
- **OD**: Standard 50mm rod machined to 46mm ± 0.1mm
- **ID**: 27mm ± 0.1mm
- **Internal Thread**: 1mm deep

![Diagram of push test configuration](image)

Fig. 2 – Push test configuration for 22mm bolt.
Confinement Controlled Tests In Actual Rock

Because of the identified problems with existing laboratory and field based techniques in providing realistic techniques for load transfer determination, a laboratory installation was constructed. The facility allows for a high level of control of identified variables, while still carrying out tests in rock.

The test facility shown in Figure 3(a) and 3(b) consists of length of 150mm diameter core contained in a biaxial cell to provide confinement to the core. The biaxial cell is fixed to a lathe bed allowing drilling and placement of the bolt using the conventional drill rods, water flushing and bits.

Fig. 3(a) – Hole drilling.

Fig. 3(b) – Pull out testing.
Repeatability of the tests is assisted by:

- Control of revolution rate and feed rate of the drill bit.
- Controlled rate of insertion and spin of the bolt into the resin cartridge.
- Controlled confinement on the rock.
- Laboratory level control of the pull out test loads and displacement measurement.
- Capability of extensive instrumentation of rock and tendon.

By using core of uniform material in either 300mm or 600mm lengths, together with extensive instrumentation of the core and tendon, a high degree of understanding of the load transfer system can be obtained.

The typical results of test program are shown in Figure 4.

**Fig. 4 – Typical output from confined sample tests.**

The results shown in Figure 4 show the load distribution along a 0.5m long bolt tested in a sandstone confined at 10MPa and compares with the results with a thick steel tube pull test. Although the load distribution is similar in appearance, the stiffness measured for the steel tube system tests was higher than the confined sandstone tests. This is almost certainly a reflection of the higher friction achieved on the threaded internal surface of the tube compared with the sandstone. Typically the ultimate bond strength in the steel tube is around twice the best achieved in the confined sandstone test.
General Factors Affecting Load Transfer

The following section summarises the general issues which will affect the results of any load transfer test.

*Bar Size Variation*

In any pull test, the outward forces act on the borehole surface and the bolt resin surface as a consequence of relative displacement between the bar and the resin as shown in Figure 5.

![Diagram of load transfer mechanism](image)

*Fig. 5 – Mechanism of load transfer.*

The magnitude of shear stress sustainable on the bolt/resin/rock interfaces is highly sensitive to the magnitude of the outward forces.

The size and frequency of deformations along the bar has been shown to significantly influence the outward force generation. However, two other factors affect the magnitude of these forces:

- The actual diameter of the bar. In all commercially available tendons the size of the bar is not a constant but varies within specific limits. The size range of the bar allowed within specifications are commonly within the order of 5% of the diameter allowing for variability of the root diameter and the size of the profile. With this level of variation the actual bar size can significantly influence the results of the pull out test. To ensure consistency of results within a series of tests and between series, the bar size should be kept constant and preferably as close to the design size rather than at the limit of its specification.

- The diameter of the bar reduces as load is developed. Whilst the deformations on the bar displace the resin, the deformations are moving away from the resin as the diameter reduces. In other words, the effective annulus will increase as load is generated. Where tests are being carried out above the yield capacity of a tendon, the variability of the bar size reduction, which is related to its elongation characteristics, may significantly affect the results.
**Elongation Characteristics**

The elongation characteristics of the bolt are considered to influence load transfer, as the bar diameter is proportional to the axial strain (Figure 6).

![Graph showing elongation characteristics](image)

**A – B**
- i) Small reduction in diameter of bolt
- ii) Bar profile displaces through resin and generates confinement to resin.

**B – C**
- i) Diameter reduces faster with increase in strain
- ii) Bar profile continues to displace through resin

**C – D**
- i) Bolt necks
- ii) Load transfer reduces to zero over necked portion of bolt

**Fig. 6 – Effect of elongation characteristics and bar profile on load transfer.**

Up to the yield point of the bolt, the relatively small level of axial strain in the bar results in a reduction in bar diameter which is not sufficient to significantly relieve the outward forces generated and load transfer increases with additional deformation.

After bolt yield (but before necking) the diameter of the bolt continues to decrease along the full length of the bolt at an increased rate. The bar profile will still continue to compress the resin, however, the confining forces will be relieving in response to the reduction in the bar diameter. The net confining force and therefore load transfer will depend on the net result of these displacements.

Once necking commences, the bar diameter reduces severely on a local scale and load transfer will rapidly decrease to zero within this area of the bolt.
Resin Mixing

The difficulties involved in both laboratory and field based tests in ensuring adequate mixing of resin and grout is fundamental to all load transfer tests. When dealing with non-standard installations such as field pull tests with 150mm cartridges much greater care must be taken to prevent either under or over resin mixing. In the confinement controlled actual rock tests, later inspection of the resin rock interface can be used to confirm appropriate mixing. Confinement controlled tests with the lathe system have reproduced 'gloving' and poor mixing typically with large resin annulus sizes.

In earlier laboratory tests the problems are further compounded with the requirement to hand mix the components in sufficient time to prepare the sample. The modified lathe method described at least provides a realistic method of mixing all standard, including fast set, resin types.

Testing Rate and time dependent effects

The role of testing rate has not been extensively investigated in the measurement of load transfer in the field or the laboratory. Data from limited field tests does however suggest that faster loading rates can give marginally higher loads however insufficient data exist to quantify this influence.

The controlled confinement lathe tests have also included measurement of creep effects. Figure 4a shows the load distribution along a 0.5m long roof bolt in sandstone loaded to 15 tonnes as well as load distribution 4 days later. The load on the bolt near collar of the hole had significantly reduced with the load distribution along the bar becoming more linear. This phenomena seems to be similar to the progressive de-bonding effect seen in pretensioned ground anchors (Barley 1997). Further investigation of this effect, which calls into question the advisability of applying very high pretension loads, is planned.

Variation in Bar Profile

As with size, the profile on a tendon, which has a proven significant effect on the performance of a tendon, is specified within a range of dimensions. The performance of a series of tendons which all are within the specified manufacturing limits can vary significantly. The profile will vary within a limit of tolerance depending on the variability of the manufacturing system. Figure 7 shows the effect of a reduction of profile height on load transfer and the associated variation in the level of confinement generation.

It is possible that the range of performance within the tolerance of one tendon type may exceed the variation between one type of tendon and another.
Fig. 7(a) — Load displacement curves for rebar with various amounts of bar deformation removed. (After Fabjaneczyk and Tarrant, 1992).

Fig. 7(b) — Load versus confinement for the different bar profiles. (After Fabjaneczyk and Tarrant, 1992).
Surface Finish of Tendon

The controlling influence of the surface finish on tendon performance has been well documented, yet no specifications are typically set for tendons to be used in load transfer measurement. The variation of performance from newly rolled through to heavily rusted tendons will again potentially affect the performance characteristics of the tendon to a high degree (Figure 8).

![Graph showing comparison between Rusted Surface and Smooth Surface](image)

Fig. 8 – Comparison of clean and rusted bolt load transfer.

Repeatability

Because of the large number of variables and factors influencing results of load transfer determinations, meticulous procedures are required to achieve useable results. Although some of the variables can be eliminated through carrying out large numbers of tests with each system, it is not possible to eliminate the affects of all of the factors influencing performance with this method.

All load transfer determinations are a function of the:

- The hole geometry and condition as well as host material strength
- The resin material properties.
- The bar profile surface condition and strength.

Each of the factors needs to be controlled to a degree before any of variables is changed and assessed.
Conclusions

This paper report has addressed a review of the current procedures regarding testing methods used for the assessment of reinforcing tendons concentrating on the issue of load transfer.

At present there is no consensus within the mining industry on test procedures, or which tests themselves should be used in the assessment of tendons. Some tests such as the push tests using grouted cylinders and the basic field pull out test are used widely, however even in these cases it is believed that with lack of quality control and understanding on some of the procedures, there is a possibility of misleading results being obtained.

The newly developed technique of testing tendon/grout systems in confined rock using the lathe method is seen as major improvement over existing methods as most of the field based variables can be controlled and analysed.

Further development of the technique and the associated development of the understanding of the load transfer mechanism will hopefully lead to a better method of reinforcement product assessment and optimisation.

To successfully appraise the performance characteristics of different resin types requires an understanding of the test procedure used and the use of common sense in the interpretation of the results.

References


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