LOAD TRANSFER MECHANISMS IN REINFORCING TENDONS

By

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ABSTRACT

Cement and resin encapsulated tendons are widely used in the stabilisation of mine roadways. One of the main factors in controlling the efficiency of the reinforcement is the ability of the tendon to generate load in response to rock deformation.

The analysis of field data from instrumented reinforcing tendons complimented with extensive laboratory investigations have more accurately defined the mechanisms by which load generation occurs.

The role of reinforcing tendon profiles, hole geometry and encapsulation medium properties in controlling the reinforcement stiffness and capacity are discussed.

The results of the investigation have implications in both the design of rock reinforcing systems and the optimisation of encapsulation mediums and tendons.

1. INTRODUCTION

The performance of any reinforcement design is limited by the efficiency of load transfer. This is the mechanism by which force is generated and sustained in the reinforcing tendon as a consequence of strata deformation.

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.

The importance of good load transfer is illustrated in Figure 1. A bolt/resin system which has a limited shear stress capacity may result in reduced reinforcement provided to zones of strata deformation (Figure 1a). This is particularly important where strain zones are located near the top or bottom of the bolt. Poor load transfer may also result in high collar forces (Figure 1b) which may further reduce the effectiveness of the bolts, particularly where failure of the plate/strap system occurs.

Potentially the most important aspect of good load transfer is the utilisation of the full load capacity of the bolt. The capacity of the reinforcement system will only be utilised if the encapsulation medium can sustain the required shear stresses.

In conjunction with 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.

2. MEASUREMENT OF LOAD TRANSFER

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.

\[ \tau = \frac{\Delta F}{\pi \phi L} \]

where:

\[ \Delta F = \text{change in force over the encapsulation length} \]
\[ \phi = \text{borehole diameter} \]
\[ \tau = \text{shear stress} \]
Example 1 Poor load transfer may result in lower reinforcement across dilating strata.

Example 2 Poor load transfer may result in excessive collar forces.

Example 3 Good load transfer required to utilise potential of higher capacity systems.

Fig. 1 Comparative response of a fully grouted bolt with good versus poor load transfers.
2.1 FIELD TESTING

2.1.1 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/rock interfaces are directly calculated from the force distribution.

On the basis of numerous measurement of reinforcement performance of Australian rebars (T-Bar Profile), a peak shear stress of over 7 MPa has been positively measured.

This shear stress capability is only achieved with careful consideration of factors such as appropriate bolt type and size, correct flushing arrangement and high level of quality control on the placement of the reinforcement.

2.1.2 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 (Gale and Fabjanczyk, 1987) which provides approximately 300mm of embedment. This length is required to minimize early effects from poor mixing at the top and bottom of the encapsulated length. The length of encapsulation should be as low as possible to minimize the possibility of the bolt yielding prior to bond failure occurring.

It is considered that the reduction in bolt diameter, as a consequence of bolt yield, limits shear stress generation. 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 such as:

- hole diameter
- hole profile
- borehole surface condition
- wet or dry drilling
- cleanliness of the hole
- potential for over or under spanning
- 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.

If yield of the bolt occurs in a pull test, the peak shear stress may not necessarily have been determined because yield may result in a lowering of system performance. Pull tests on fully grouted bolts are not considered to be indicative of potential system performance.

In the experience of the authors it is common to conduct short encapsulation (300mm) field pull tests where the bolt force has exceeded the yield of the bar.

To determine the maximum shear stress capability which is not limited by bolt yield or field variables, a shorter (90mm) embedment test was developed for laboratory testing.

2.2 STANDARD LABORATORY TESTING

The standard techniques for determining load transfer performance are 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 set 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.

2.3 LABORATORY 50MM PUSH TEST

The short encapsulation push test was developed to examine the mechanism of load transfer...

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11th International Conference on Ground Control in Mining, The University of Wollongong, N.S.W., July 1982.
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 effects of hole diameter, bolt profile and resin properties on load transfer were examined.

The specifications and testing procedure for the 50mm push test is provided in Appendix 1. Briefly, a length (70mm) of rebars is encapsulated into a metal cylinder which has an internal threaded surface which prevents premature failure on the cylinder/resin interface. The rebar is pushed through the resin under strain control and the full load/displacement history is recorded.

A typical load/displacement curve is shown in Figure 2. The curve can be generally characterised as bi-linear with an initial (higher) stiffness and a working stiffness up to yield of the system.

![Figure 2](load-displacement.png)

**Fig. 2** Typical load versus displacement for 50mm push tests.

### 2.3.1 Effect of Resin Properties on Load Transfer

Figure 3(a) is a plot of peak shear stress versus resin strength (UCS) for a variety of resins and cementitious grouts. The results indicate a large scatter of points against a general background of increasing system performance with stronger encapsulation mediums.

The plot of system stiffness versus resin stiffness (E) exhibits the same degree of scatter around a trend of increasing system performance with increasing resin stiffness (Figure 3(b)).

![Figure 3](peak-stress-uc.png)

**Fig. 3(a)** Peak shear stress versus UCS of encapsulation medium.

![Figure 3](peak-stress-e.png)

**Fig. 3(b)** Peak shear stress versus Young's Modulus of encapsulation medium.

The mechanism of load transfer was only partially dependent on the unconfined properties of the resin or grout. Initial measurements of the confinement generated, within the resin annulus, were obtained by attaching strain gauges to the push test cylinder. The initial tests indicated that outward forces opposite the rebar deformations were significant and further investigations into the role of confinement on load transfer were conducted.

### 2.3.2 Effect of Confinement Within The Resin Annulus

Confinement within the annulus is the forces acting radially outward against the borehole wall as a consequence of displacement of the bar relative to the resin.

The effects of confinement generated within the resin annulus were further examined by two series of push tests.
The first series examined the effect of reducing the magnitude of confinement generated by a standard rebar after removing successively greater bar deformations. The profiles were generated by machining 1/3mm, 2/3mm and 1mm off the deformations of a standard Australian (T-Bar) profile rebar. Note that removing 1mm off rebar gives a smooth profile.

The second series examined the magnitude of confinement generated at different loads and displacements for varying encapsulation mediums.

The confinement was measured by attaching four strain gauges to the outside of the cylinder. The gauges were spaced evenly around the cylinder and orientated tangentially. Two gauges were positioned opposite the deformation ribs. The confinement values in the figures correspond to the gauges opposite the ribs and are in microstrain units.

2.3.2.1 Effect of Bar Profile on Confinement

The load/displacement curves for the four tests are shown in Figure 4 and the load generated in the bar versus confinement is shown in Figure 5 for the range of bar profiles. The same resin was used in each test.

![Figure 4: Load / displacement curves for rebar with various amounts of bar deformation removed.](image)

![Figure 5: Load versus confinement for the different bar profiles.](image)

The figure shows a linear and consistent relationship between the shear stress sustained by the resin annulus and the confinement generated. The impact of reducing the bar profile was to reduce the magnitude of confinement provided to the annulus. This reduced the shear stress sustainable by the annulus and therefore the load sustainable by the bolt.

Note also that the stiffness of the system was significantly reduced as a consequence of reducing the bar profile. The stiffness and shear stress capacity (load transfer) of the smooth bar was minimal.

2.3.2.2 Effect of Encapsulation Medium On Confinement

The second series of tests examined the confinement generated for different encapsulation mediums with a standard rebar.

Figure 6 is a 3 axis plot of load and displacement versus confinement for 2 resin types and a cementitious grout.

The graphs indicate:

1. for a given displacement the confinement generated within the cementitious annulus was over twice that for the resins,
ii) for a given displacement the confinement generated by resin No.2 was higher than No. 1 even though that resin had a lower UCS and E, and

for each encapsulation type, a higher load was sustained in the bolt for a given confinement.

This assumption is implied from the mechanism of confinement generation. Compression of resin within the annulus may result in increased particle/particle contact. The resistance against compression (confinement forces) may increase with increased particle contact or more efficient packing.

This assumption is supported by the more efficient confinement generation of cementitious grout which has a stiffer base as discussed in the previous section.

3. CONFINEMENT IMPLICATIONS

3.1 HOLE DIAMETER

The dependence of load transfer on the mechanism of confinement generation has significant implications on the optimum hole diameter for bolt installation.

A range of push tests were conducted using hole diameters from 25mm to 31mm. The results shown in Figure 7 indicate a significant reduction in shear stress capacity occurred with increasing hole size. A reduction in load transfer performance of over 20% was indicated between 27mm and 29mm hole diameters. The optimum hole size is considered to be the smallest which can be used given constraints which relate to bolt installation such as resin viscosity.

Fig. 7 Effect of hole diameter on load transfer.

11th International Conference on Ground Control in Mining, The University of Wollongong, N.S.W., July 1992.
The effect of hole size was less marked for cementitious grouts. This is considered to relate to the more efficient confinement generation and stiffness of this material type compared with resin.

The laboratory findings have been supported with field pullout tests (300mm embedment) at each colliery where comparative tests have been conducted. In soft roof strata the use of 26mm bits has been required to achieve adequate load transfer.

3.2 BOLT PROFILE AND RESIN TYPE

The generation of confinement within the annulus enhances the shear stress capacity of the system. However, the outward force may also induce tensile cracking in the medium to be reinforced. This cracking is commonly observed in pull out tests out of concrete.

The ultimate aim of the reinforcement system is to generate and sustain load in the bolt. The optimum bolt/resin/hole system should achieve this aim with the least possible radial (confinement) force generation. This implies that the optimum system is composed of:

i) an encapsulation medium which increases strength at the highest rate for a given confinement,

ii) the smallest possible annulus size,

iii) a suitable bolt profile. This would deliver the required amount of confinement for the resin to sustain the desired shear stress.

3.4 SYSTEM SELECTION

The interaction of the bolt in generating confinement and the response of the resin to that confinement makes the system one of competing effects. The confinement which enhances the resin strength is the same mechanism (bolt displacement) which causes its ultimate failure.

It is considered that selection of a bolt/resin/hole system should be conducted on the basis of testing the system rather than each individual component. The use of the short push test enables the peak performance of the system to be cheaply assessed under ideal conditions. The test should be considered complimentary to the field short encapsulation (300mm) pullout tests.

3.4.1 Diometrical Stability

It was noted that field pull tests can be limited by the yield of the bar rather than the ultimate capacity of the bar. The reduction in bar diameter associated with yield may result in a reduction in the confinement generated which may significantly reduce load transfer performance.

It is considered that assessment of new bar products should include investigation of the diometrical stability. This may be particularly important for the utilisation of high capacity systems.

4. CONCLUSIONS

Optimal load transfer is essential for the efficient performance of the reinforcement system. In higher capacity systems good load transfer is critical to utilise the full capacity of the tendon.

The role of confinement generated within the annulus is critical to the load transfer performance. The benefits of confinement generation are increased by;

i) reducing the annulus thickness

ii) using an encapsulation medium with the highest possible triaxial stress factor

iii) appropriate bit selection

iv) optimum bolt profile and bar properties

Optimising the reinforcement system requires the consideration of all factors as a SYSTEM rather than as individual components.

5. ACKNOWLEDGEMENTS

The authors wish to thank Australian Mineral Industries Research Association Limited (AMIRA) and associated sponsoring companies under which the initial investigations have been funded. The assistance of Marcia Van Lierop and Cheryl Potter in the presentation of this and the other three S.C.A. papers is gratefully acknowledged.
AFTER CURING, THE END OF THE BOLT IS MACHINED TO PERPENDICULAR WITH THE CYLINDER.

SPECIFICATIONS:

CYLINDER: STEEL, GRADE K10 40,
LENGTH - 50 mm ± 0.5 mm,
OD - STANDARD 50 mm ROD, MACHINED TO 48 mm ± 0.1 mm,
ID - 27 mm ± 0.1 mm,
INTERNAL THREAD - 1 mm DEEP.

BOLT: STANDARD BHP ROLLED EXTRA-HIGH STRENGTH BAR,
BAR SURFACE MUST NOT CONTAIN (OR HAVE CONTAINED) RUST, GREASE OR SOLVENTS.

END CAPS: TOLERANCE BETWEEN BAR OUTER DIAMETER AND DIAMETER OF END CAP LOCATING HOLE NOT TO EXCEED 0.5 mm.

App. 1: Specifications for 50mm push test.