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Abstract

Both bolt profile shape and spacing (rib spacing) have been found to influence the bonding capacity of the grouted rock bolt. The bolt surface profile configuration has greater importance to rock bolting in strata reinforcement in mining than the steel rebar used in civil engineering construction. This is because a rock bolt in mining usually is subjected to greater dynamic loading than the steel rebar in civil engineering construction. The increased bonding capacity of a bolt is important when supported ground is either heavily fractured, faulted or the supported ground is of soft formation, typically that of coal measure rocks. Past laboratory studies have identified the bolt profile spacing as of significant relevance to bolt resin rock bonding increase, however, no attempt has been made to determine the optimum spacing between the bolt profiles spacing. Accordingly, a series of laboratory tests were carried out on 22 mm core diameter bolts, commonly used in Australian mines, installed in cylindrical steel sleeve. The study was carried out using both push and pull testing methods. The push test was carried out in 150 mm long sleeves while the pull testing was conducted in 115 mm long sleeves. Profile spacing tested include, 12.5, 25.0, 37.5, and 50 mm lengths. Additional studies undertaken include modelling the profile of the load-displacement data of pull testing. Bolts with a profile spacing of 37.5 mm were found to provide optimum load bearing capacity as compared to other tested profile spacings.

Keywords

transfer, optimisation, capacity, bolt, load, profile, configuration

Disciplines

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Bolt Profile Configuration and Load Transfer Capacity Optimisation

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ABSTRACT

Both bolt profile shape and spacing (rib spacing) have been found to influence the bonding capacity of the grouted rock bolt. The bolt surface profile configuration has greater importance to rock bolting in strata reinforcement in mining than the steel rebar used in civil engineering construction. This is because a rock bolt in mining usually is subjected to greater dynamic loading than the steel rebar in civil engineering construction. The increased bonding capacity of a bolt is important when supported ground is either heavily fractured, faulted or the supported ground is of soft formation, typically that of coal measure rocks. Past laboratory studies have identified the bolt profile spacing as of significant relevance to bolt resin rock bonding increase, however, no attempt has been made to determine the optimum spacing between the bolt profiles spacing. Accordingly, a series of laboratory tests were carried out on 22 mm core diameter bolts, commonly used in Australian mines, installed in cylindrical steel sleeve. The study was carried out using both push and pull testing methods. The push test was carried out in 150 mm long sleeves while the pull testing was conducted in 115 mm long sleeves. Profile spacing tested include, 12.5, 25.0, 37.5, and 50 mm lengths. Additional studies undertaken include modelling the profile of the load-displacement data of pull testing. Bolts with a profile spacing of 37.5 mm were found to provide optimum load bearing capacity as compared to other tested profile spacings.

INTRODUCTION

Rock bolts used for formation reinforcement differ in function from the steel ribbed rebar used in concrete reinforcement in building construction. The reinforcing effect of a grouted bolt is by the longitudinal and shear displacement in the rock mass. Thus the load transfer capacity of the bolt is governed by the shear strengths developed between the rock/grout and the grout/bolt. The bonding capacity of the bolt is in turn influenced by the bolt profile configurations. The rib shape, height, angle of wrap, and spacing or distance between the ribs, defines the profile configuration.

Blumel (1996) was the first to report on the influence of profile spacing on load transfer capacity of the bolt. Figure 1 shows the results of a test of a particular rock bolt type with different rib spacing. The tests were undertaken in a specially constructed laboratory apparatus consisting of a 500 mm long steel pipe

filled with concrete. The concrete had a central hole of diameter twice the bolt diameter. The bolt was anchored in the concrete cylinder using cementitious grout and the bolt pull-out tests were carried out with different displacement rates, applied to the bolt right from the installation. Blumel reported pull tests on different profile spacing of 13.7 mm, 27.4 mm and 54.8 mm. The pull-out tests values increased with increased rib spacing respectively, as shown in Figure 1. The tests were carried out with respect to time of loading up to 32 hours, at a pull-out displacement rate of 0.72 mm/hr. The study clearly demonstrated that the pull-out force of the bolt differed greatly by varying the rib distance. No effort was made by the researchers to investigate the optimum spacing of the profiles for optimum bolt transfer capacity. Blumel et al., 1997, reported on the final element modelling of the bolts with different profile spacing. Their study supported the experimental laboratory findings, which, as shown in Figure 2, clearly demonstrated that higher stresses with more significant peaks being developed in the case of the bolt with wider spaced ribs as compared to the small rib distance.

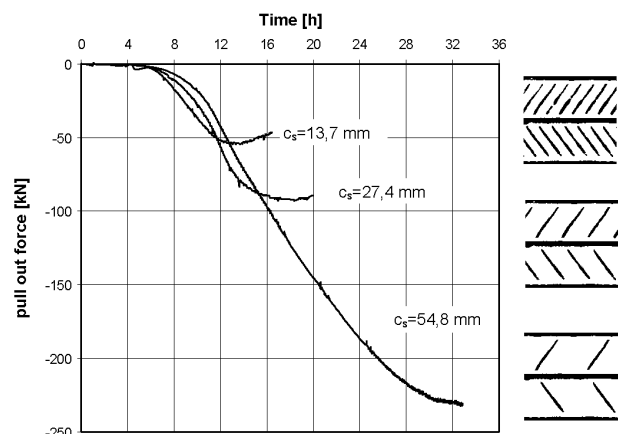


Figure 1. The pull out force results for different profile spacing on bolts.

Aziz and Day (2002) studied bolt profile spacing and load transfer conditions under constant normal stiffness (CNS)

EXPERIMENTS

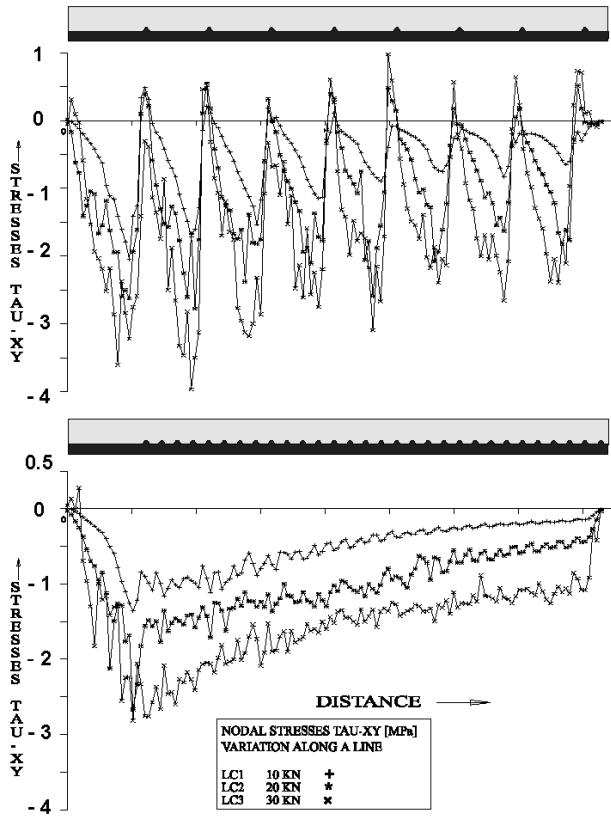


Figure 2. Numerical modelling axial stress developed on bolts of two different spaced profiles.

conditions under different confining pressures. The study confirmed the existence of changes in the load - displacement profiles with respect to the bolt surface profile configurations. Moosavi, et al., 2005, studied the profile configurations in cementitious grout, leading to similar conclusions. Aziz and Webb (2003) extended the study on profile configurations to include push testing of bolts installed in cylindrical steel tubes, 75 mm long and 17 mm in internal diameter. The tests were made using chemical resin grout instead of cement. Aziz and Jalalifar (2005 and 2006) extended this study to include both push and pull tests using longer steel sleeve lengths greater than 75 mm. The 75 mm long steel sleeves were found to be of insufficient length to provide an adequate number of profiles encapsulated within it to allow credible and meaningful test results, particularly when testing bolts with profile spacing 25 mm and greater. Aziz and Webb (2003) research concurred with the findings of the Blumel study on the effect of profile spacing on load transfer capacity of the loaded bolt.

There has been no reported attempts made to optimise the true bolt profile configurations for optimum load transfer capacity determination, and accordingly this paper represents the continuation of the work undertaken by the mining group at the University of Wollongong (UoW), and describes the laboratory testing of bolts in long steel sleeves which is aimed to address the profile spacing optimisation.

Two series of tests were carried out on bolts in cylindrical steel sleeves. In the first series of tests, bolts with different profile spacing were push tested in 150 mm steel sleeves, while the second set of tests were made under pull conditions using 115 mm steel sleeves. The procedure adopted for installing the bolt in the steel sleeves is described by Aziz and Jalalifar (2006). Each bolt was encapsulated in the sleeve, centrally located with uniform resin annulus thickness, and set axially parallel to the steel sleeve axis.

Table 1 shows a summary of the profile dimensions for all the bolt types that were tested. Wider profile spacing was achieved by grinding various profiles. Bolts with widened spacing were labeled G1, G2 and G3 with one, two and three profiles removed respectively. The respective spacings were 25 mm, 37.5 mm and 50 mm. No tests are reported for Bolts T1 and T3, because Aziz et al., 2006, reported the comparative tests previously.

Table 1. Profile configurations of various bolts.

| Bolt Type | T1 | T2 | T3 | T2 Bolt Modified | | |
|----------------------------|-------|-------|-------|------------------|-------|-------|
| | | | | G1 | G2 | G3 |
| Profile Spacing (mm) | 12.50 | 12.50 | 25.00 | 25.00 | 37.50 | 50.00 |
| Profile Height (mm) | 1.00 | 1.35 | 1.20 | 1.35 | 1.35 | 1.35 |
| Average Profile Width (mm) | 2.25 | 2.75 | 3.75 | 2.75 | 2.75 | 2.75 |
| Profile Angle (deg) | 22.5 | 22.5 | 22.5 | 22.5 | 22.5 | 22.5 |

Push test

Figure 3 shows a general view of push testing different profiled bolts in 150 mm steel sleeves. The tests were made in a 50 tonnes capacity servo-controlled Instron Testing Machine. The encapsulation medium was a reinforced polyester resin grout BPI Mix and Pour resin. The resin had a curing time of 60 minutes. The UCS strength of the resin was in the order of 70 MPa after seven days, the shear strength was 16 MPa, modulus of elasticity of 12 GPa, and stiffness value after 14 days was around 75 kN/mm.

As seen from the test result in Figure 3, the loading capacity of the bolt increased with increased profile spacing. However, the highest loading capacity was achievable with profile spacing of 37.5 mm rather than 50 mm rib profile spacing. The loading of 37.5 mm spaced bolt was halted as the un-encapsulated bolt section began to bend. For the indicated final level push load of 425.8 kN shown for 37.5 mm spaced profiled bolt (Bolt Type T2 G2) in Figure 3, this was 7% greater than the maximum load achievable with 50 mm profile spacing of Bolt Type T2 G3, and is 16% greater than that of 25 mm profile spacing (Bolt T2 G1), as shown in Table 2. The loading capacity of T2 G2 bolt was 97.5% greater than the original

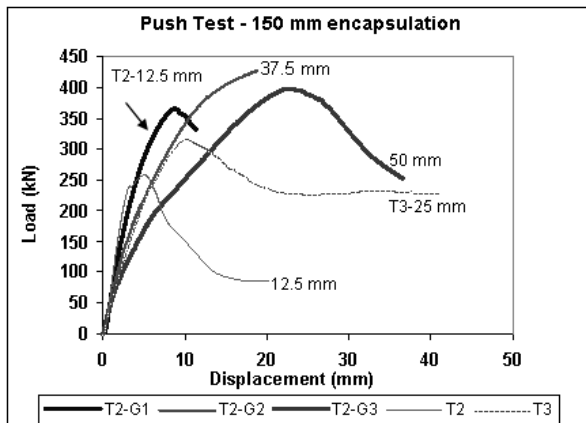


Figure 3. Push test results of bolts with different profile spacing.

Bolt Type T2, with 12.5 mm profile spacing. It should be noted that the differences between the load bearing capacity between the 25 mm profile spaced Bolt Types T2 G1 and T3 is attributed to the surface roughness of the Bolt Type T2G1, which resulted from the removal of the profile from Bolt Type T2. A bolt surface roughness effect on the load bearing capacity of a bolt was previously reported by Aziz and Webb (2003). It is also equally true that the variations between the load bearing capacity between Bolt Types T2G2 and T2G3 could have been influenced by the increased surface roughness of Bolt Type T2G3; nevertheless, the bearing capacity of Bolt Type T2G3 is significantly higher than the T2G3.

Table 2. Changes in the load capacity of different profile spaced bolts with respect to Bolt Type T2 in push testing (encapsulation length 150 mm).

| Bolt Type | Profile Spacing(mm) | Average Applied Load (kN) | Increase in Load with Respect to Bolt Type T2 (%) |
|-----------------|---------------------|---------------------------|---|
| Bolt Type T2 | 12.5 | 215.6 | - |
| Bolt Type T2 G1 | 25 | 365.9 | 69.7 |
| Bolt Type T2-G2 | 37.5 | 425.8 | 97.5 |
| Bolt Type T2-G3 | 50.0 | 398.2 | 84.9 |

Pull Test

A number of preliminary tests were made to study the bonding capacity in 150 mm sleeve encapsulations under pull-out conditions, and this was discontinued as the pull-out load exceeded the elastic limit of the steel rebar bolt. This was particularly true when testing bolts greater than 25 mm profile spacing. Noting that both Bolt Types T2-G1 and T3, with rib spacing of 25 mm, had the yield load of 250 kN and ultimate tensile strength of more 330kN.

Accordingly the next series of tests were carried out under pull testing conditions with the encapsulation length of the steel sleeve reduced to 115 mm as shown in Figure 4. Figure 5 shows the load displacement profiles for four-profile spacings of 12.5 mm, 37.5 mm and 50 mm, respectively. Also included in Figure 5 are the load displacement graphs of 50 mm profile spacing prepared from Bolt Type T3. The differences between the profile configurations of various bolts are described in Table 1.

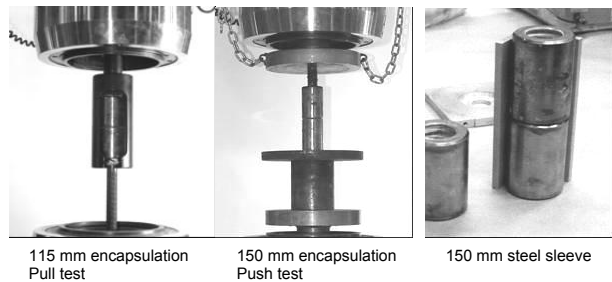


Figure 4. Pull and push testing of bolts with different encapsulation lengths of 115 and 150 mm.

As seen in Table 3, the bonding capacity or the peak load of the bolt with profile spacing 37.5 mm is, once again, greater than the 50 mm profile spacing. In this batch of tests the maximum pull out force was within the steel rebar yield load, thus there were no significant changes in bolt diameter, as would have happened in 150 mm long encapsulation pull testing, which was reported by Aziz and Jalalifar (2007).

When compared to the standard Bolt Type T2 (profile spacing 12.5 mm), all other bolts experienced an increase in the average maximum peak load capacity. The Bolt Type T3 with the modified profile spacing of 50 mm experienced an average increase of 41% in pull load of 215 kN against Bolt Type T2 load of 152.23 kN. Of more significance was the increase in loading capacity of both Bolt Types T2G2 and T2G3 respectively. The average peak load of

the T2-G2 bolts with profile spacing of 37.5 mm was 69% greater than that of the standard Bolt Type T2. Similarly for the Bolt Type T2G3, with 50.0 mm profile spacing, there was an increase of 61% with respect to Bolt Type T2.

NUMERICAL MODELLING

A FLAC model was set up to simulate a pull-out test of 115 mm grouted bolt and the results were compared with experimental output. A single rock bolt as a structural element was represented in FLAC by using a conceptual mechanical representation of fully bonded reinforcement element as shown in Figure 6. The connection to the grid in both the normal and shear directions is via coupling springs. The shear behaviour of the interface during relative displacement between the nodes and the grid is described numerically by the coupling spring shear stiffness, given by:

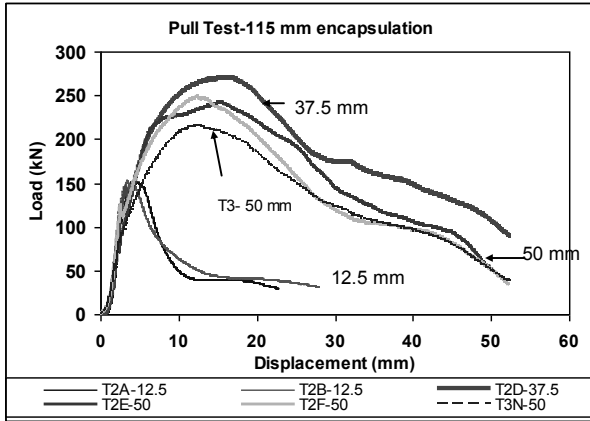


Figure 5. Displacement versus load results of different configuration bolts in pull testing.

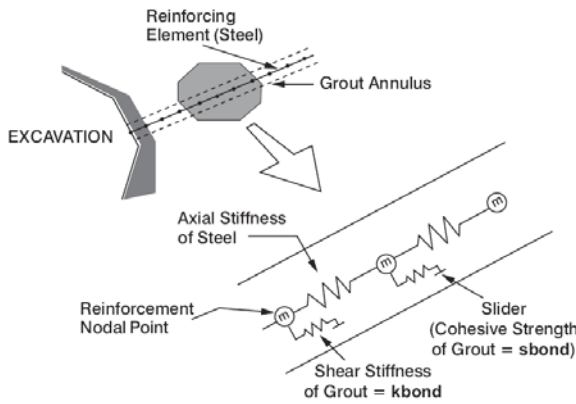


Figure 6. Rock bolt structure in FLAC (Itasca, 1999).

$$\frac{F_s}{L} = CS_{stiff} (U_p - U_m)$$

Where:

- F_s = Shear force that develops in the shear coupling spring, (i.e., along the interface between the rockbolt and the grid),
- CS_{stiff} = Coupling spring shear stiffness,
- U_p = Axial displacement of the bolt,
- U_m = Axial displacement of the rock, and
- L = Contributing element length.

The maximum shear force that can be developed along the bolt/grout interface is a function of the cohesive strength of the interface and the stress dependent frictional resistance along the interface. The following relationship determines the maximum shear force per length of the bolt.

$$\frac{F_s^{max}}{L} = CS_{scoh} + \sigma'_c \times \tan (CS_{sfri}) \times Perimeter$$

Where:

- CS_{scoh} = cohesive strength of the shear coupling spring,
- σ'_c = mean effective confining stress normal to the element
- CS_{sfri} = Friction angle of the shear coupling spring, and
- Perimeter = Exposed perimeter of the element.

The mean effective confining stress normal to the element is defined by the equation,

$$\sigma'_c = \left(\frac{\sigma_{xx} + \sigma_{zz}}{2} + P \right)$$

Where:

- P = pore pressure,
- $\sigma_{zz} = \sigma_{xx} n_1^2 + \sigma_{yy} n_2^2 + 2 \sigma_{xy} n_1 n_2$, and
- n_1 = unit vector.

Figure 7 shows the FLAC simulated load displacement profile of 12.5 mm spaced profiled bolt in 115 mm encapsulation and Figure 8 shows the simulated graph superimposed on the actual laboratory test results. The simulated load/displacement profile of the bolt include both pre and post peak loads. Different load-displacement profiles were successfully simulated for various profile spacing. The degree of the load-displacement profiles closeness with the experimental results is dependent on the uniformity of the grout encapsulation annulus thickness and the consistency of the grouts composition as well as the bolt being installed axially parallel to the encapsulation sleeve as described by Aziz and Jalalifar (2006). Optimum bolt, resin and rock mechanical properties would enhance the quality of the simulation irrespective of the encapsulation length as long as adequate numbers of the profiles are contained in the encapsulation length. Thus the correct simulation of the system will enable a better prediction of the load displacement profiles thus allowing a better understanding of the load displacement generation for future design of the bolts. This process of simulation is now further extended to the study of the profile/rib shape as well as the examination of the superimposed on the experimental test results, some variation exist between the two profiles. However, with further refinement of the model, it is possible to obtain simulated results close to the realistic data profiles. The performance of the bolt under shear conditions must be examined to gain better understanding of the effectiveness of increased profile spacing in real application.

CONCLUSIONS

It is abundantly clear from this study and that the load transfer capacity of the bolt increases with wider profile spacing. For the four different profile spacings tested, the profile spacing of 37.5 mm was found to be the optimum spacing width with the particular type of bolt tested (with given profile orientation and shape). This result supports the earlier results carried out on smaller diameter bolts reported by Blumel (1996).

The consistency and repeatability of the test results is dependent on the consistency of encapsulation preparation. The uniformity of the encapsulation annulus thickness and parallelism of the bolt axis

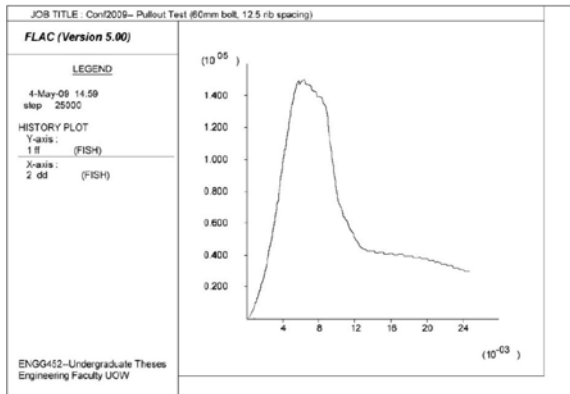


Figure 7. Displacement versus load simulation utilizing numerical model (FLAC Version 5).

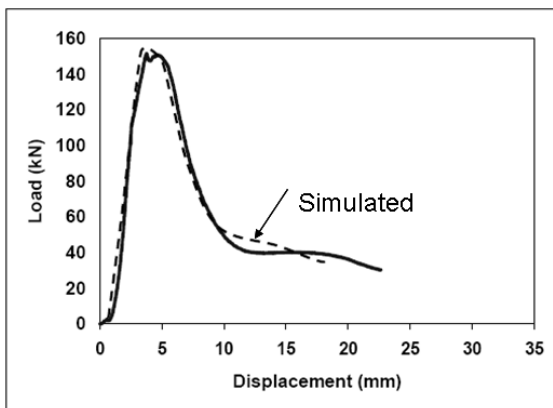


Figure 8. Simulated load and displacement profile of 12.5 mm rib spacing superimposed on a laboratory results of the same bolt type.

with the steel sleeves is essential to ensure the consistency of the tests results.

The load-displacement profiles of the bolts were successfully modelled and that modelling was extended to include bolts with different profile spacing.

For the wider spaced bolts to be assured of its performance in reality, tests must be extended to pull testing in the field as well as carrying out double shearing tests to examine the effect of latter forces in shear.

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