A new approach in determining the load transfer mechanism in fully grouted bolts

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CHAPTER TEN

CONCLUSIONS AND RECOMMENDATIONS
The load transfer mechanism and reinforcement system of bolts have been investigated during this research study. The thesis has presented methods and results of experimental testing of bolts under axial and lateral loading. The experimental study included tests conducted in the laboratory and underground. Analytical and numerical studies were undertaken to complement the experimental studies, therefore the aim was (i) to evaluate the shear mechanism of bolt - grout and grout - rock interfaces experimentally, numerically, and in the field for different Types of bolt, thickness of resin and type of concrete, (ii) the effect of pre-tension loading a bolt, bolt profile and re-bar specifications on the shear and load transfer mechanism of bolt, resin, and concrete, and (iii) numerical and analytical analyses of bolt - joint - concrete and contact elements under axial and lateral loading.

A number of important parameters that affected the load transfer mechanism and bolt subjected to axial and lateral loading conditions were identified. The following sections describe the main conclusions drawn from this research.
10.1. EXPERIMENTAL INVESTIGATIONS

10.1.1. Axial loading conditions

Both short encapsulation push and pull tests demonstrated that the methodology of testing influenced the level of shearing forces on interface installed steel sleeves. It was found that;

- Irrespective of bolt type, the shearing force in a short encapsulation test was higher by pushing than pulling. There was an average reduction between 8 - 11% in peak load between push and pull tests.

- Bolt profile configuration was an important parameter in its capacity to transfer load. High profiles increased the load transfer capacity of the bolt and profile spacing dictated the level of peak load displacement. Wider spaced profiles (ex. Bolt Type T3) accommodated relatively larger shear displacement. Post peak load was also higher and tapered off gradually compared to narrow spaced, low profile bolts (ex. Bolt Type T1). Accordingly, higher profile and wider spaced bolts would be suitable for installation in softer formations such as coal measure rocks.

- Yielding and necking is unlikely to occur in bolts tested in 75 mm long steel sleeves as the peak shear load was around 40% of the maximum tensile strength of the steel.

- Increased annulus encapsulation resin thickness reduces the performance of bolt anchorages. In particular, there was a reduction of almost 50% in maximum peak load when the resin increased from 2.5 mm thick in a 27 mm diameter hole to 11.5 mm in a 45 mm hole.
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10.1.2. Lateral loading conditions

- The double shear system represented a better method because a symmetrical study of bolt shearing analysis can be carried out.
- The maximum contribution of the bolts depends on the strength of the concrete and pre-tension load on the bolt.
- Under the same test conditions, the bolt contribution increased by around 15% with resin grout encapsulation compared to a situation with no grout.
- The physical and mechanical properties of the bolt types affected the bolt joint contribution.
- The axial and shear loads are at their maximum at the bolt-joint intersection.
- In 100 MPa concrete the maximum bolt joint contribution at failure was about 120% of the maximum tensile strength of the bolt.
- In Bolt Type T1 the value of the bolt contribution at the yield point in 20, 40 and 100 MPa concrete, varied between 24%, 30% and 52%, of the maximum tensile strength of the bolt.
- Increasing the strength of the concrete significantly reduced joint shear displacement and contributed to increased shear stiffness.
- Under lateral loading conditions the effect of resin and concrete strength was more significant than the thickness of the resin.
- The hinge point distance reduced with an increase in resin annulus thickness, particularly when the surrounding material was weaker than the resin.
- An extensive stress and strain was developed on the resin - concrete interface in soft concrete during bolt bending.
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- In all bending situations axial fractures occurred along the concrete blocks after the elastic yield point.
- The shear load in softer concrete was lower than in harder concrete because of excessive deformation.
- The dowel effect in harder concrete was higher due to higher shear resistance. As a result bolts snapped much more readily than the bolts installed in softer concrete.
- Bolt Type T2 displayed consistent shear load displacement profiles at all three levels of pre-tension loads (20, 50, and 80 kN), particularly in 40 MPa. This consistency was relatively less in 20 MPa concrete and remained less scattered than Bolt Types T1 and T2.
- The level of initial confining axial load (pre-tension load) applied to the bolts had a profound influence on the position of LMFBS. The higher the initial tension load the greater the positioning at the LMFBS.
- The formation of two plastic hinge points in the bolt located symmetrically opposite to either side of the sheared joint plane was determined by the strain measurements.
- Bolts fitted with strain gauges exhibited a higher strain 30 mm from either side of the shear joint plane.

10.2. NUMERICAL AND ANALYTICAL STUDIES

- The yield limit of the bolt begins from the hinge points at both sides of the shear joint.
- Further increase in the shear force beyond the yield point has no apparent influence on stress in the hinges.
• The distance between the hinge points reduced with an increase in the strength of the concrete.

• During shearing the tension and compression stresses and strains were generated in the upper and lower fibre of the bolt near the shear joint.

• Bolt profile in the vicinity of the bolt joint intersection experienced maximum shear stress, and there was an exponential relationship between the shear stress and distance from the shear joint.

• The shear stress did not exceed beyond the yield point during further loading but the bolt failed under combination of induced tensile and shear stress at the bolt joint intersection.

• Increasing the pre-tension load of the bolt decreased the shear stress, which was seen in different strength concrete.

• The value of strain along the concrete and grout was reduced by increasing the pre-tension load.

• The induced stresses exceeded the uniaxial compressive strength of the grout and concrete near the bolt joint intersection, causing them to be crushed.

• The average shear stress capacity of a bolt in a push test was greater than in a pull test, as investigated by numerical simulations.

• Failure of the bolt - resin interface occurred by shearing the grout at the tip of the profile in contact with the resin.

• In case of bolt free ends in analytical method, the maximum axial load appeared in middle of the 2.1 m bolt. However, increasing the length of a bolt meant that the peak position moved towards the surface excavation and reached closer to it.

• Numerical simulation provided an opportunity to better understand the stresses and strains generated as a result of shearing the bolt resin interface.
10.3. FIELD INVESTIGATIONS

- The field instrumentation study demonstrated the significance of the surface profile configuration influencing load transfer at the bolt - resin interface.
- The instrumented site position with respect to the longwall face position was an important factor, which influenced the level of load transferred along the bolt. The load generation in Appin (belt road) was four times greater than Metropolitan loads (travelling road). This was due to flanking stresses affecting the roof of the adjacent main gate roadway more than that over the travelling roadway.
- Bolts with higher and wider profile spacing contributed a higher load transfer capacity of bolt resin rock interaction than those with a closer spacing and lower profile.
- The vicinity of dyke to instrumented site affects the levels of load transfer.
- Cable bolt affects the load developed on the bolts located close by.

10.4. SUGGESTIONS FOR FURTHER RESEARCH

This research provides a comprehensive understanding of some of the significant factors that affect load transfer mechanism such as bolt profile, mechanical and physical property, different strengths of surrounding concrete and thicknesses of resin, and various pre-tension loads. However more research in this field is required.

- Double shearing system (DSS) gives a better understanding of bolt joint interaction but the size of the double shearing apparatus should be doubled for effective results, in particular for bigger diameters. The design of the new shear
box is completed and the apparatus is under construction for future research (Figure 10.1).

- To better understand resin thickness subjected to lateral loading, more tests need to be undertaken in different strength concrete.
- Further studies on hard concrete (more than 100 MPa) are recommended to obtain a better understanding of load transfer in hard rock. Such tests should be conducted in rock.
- To find the actual load transfer mechanism in high profile spacing in different bolt types, a longer steel sleeve should be used.
- Investigation of bolt, grout, and concrete modulus of elasticity in different strength concrete and thickness of resin in non-linear conditions by numerical simulation is recommended.
- Double shearing tests should be carried out with inclined bolts under different pre-tension loads, rock strength, and bolt profile configurations.

Figure 10.1. Large scale of double shear box (dimensions are mm)