New Approach to Study Load Transfer Mechanisms of Fully Grouted Bolts

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ABSTRACT: The load transfer mechanisms across the rock/resin/bolt interfaces are governed by the surface properties of the bolt. Although there are various bolt surface configurations available in the market, very little work is reported on die bolt/resin interface failure mechanism. This paper examines the behaviour of bolt surface roughness under constant normal stiffness conditions which is considered as being a realistic way of evaluating bolt surface roughness. To study the shear behaviour of bolt/resin interface, laboratory tests were conducted on the bolt surfaces of two most popular types currently in use in Australian coal mines, at an initial normal stress of 0.1 to 7.5 MPa. The study snowed different shearing characteristics of both bolt types under similar loading environment. Field investigations carried out in a local coal mine produced similar results as obtained from the laboratory testing.

1 INTRODUCTION

The load transfer characteristics of the bolt play an important role in the design of effective support system for stabilising rock mass in various types of excavation. The load transfer characteristics of a bolt in the field largely depend on the behaviour of its surface properties among other parameters. In the recent past, the shear stress developed at bolt-resin interface has been calculated by the strain gauged instrumented bolts (Fabjanczyk & Tarrant 1992, Fuller & Cox 1975, Gale 1986 and Signer, Cox & Johnston 1997), and the shear stress developed at any point along the bolt length could then be calculated by the following formula:

$$\Delta \tau = \frac{F_1 - F_2}{\pi d l} \qquad (1)$$

where,
$\Delta \tau$ = Shear stress at bolt-resin interface,
F_1 = Axial force acting on the bolt at strain gauge position 1, calculated from strain gauge reading,
F_2 = Axial force acting on the bolt at strain gauge position 2, calculated from strain gauge reading,
d = Bolt diameter, and
l = Distance between strain gauge position 1 and strain gauge position 2.

One of die major shortcomings of die above mediod is that, it does not consider the effect of horizontal stress or the confining pressure on the shear stress at bolt/resin interface. As the confining pressures or the horizontal stresses around the opening play an important role İn the failure mechanism of grouted rock, incorporation of the confining pressure in the above formula would result in a better approximation of the İn-situ condition. Following the installation of a bolt in the field, the relative movement, however small, between the rock and the bolt causes the load to be transferred on the bolt, and as a result the normal stress is applied on the resin/rock interface through the ribs of the bolt. The magnitude of normal stress İs dependent on the relative displacement, shape of the rib profile and the composite stiffness of the bolt/resin/rock interface. The Constant Normal Stiffness (CNS) condition thus represents a better approximation of the deformation behaviour in the field as compared to conventional Constant Normal Load (CNL) condition. The above hypothesis has been suggested by many researchers (Benmokrane *&c* Ballivy 1989, Indraratna, Haque & Aziz 1998 and Ohnishi & Dharamaratne 1990). A novel approach was, therefore, adopted to study the shear behaviour of bolt/resin interface under Constant Normal Stiffness condition.

2 BOLT SURFACE PREPARATION

A 100 mm length of a bolt was selected for the surface preparation for CNS shear testing. The

specified length of bolt was cut and then drilled through. The hollow bolt segment was then cut along the bolt axis from one side and preheated to open up into a flat surface as shown in Figure 1. The surface features of me bolt (ribs) were carefully protected while opening up the bolt surface. The flattened surface of the bolt was then welded on the bottom plate of the top shear box of the CNS testing machine. Although these flattened bolt surfaces may not ideally represent the complex behaviour of circular shaped bolt surface observed in the field, nevertheless, they still provided a simplified basis for evaluating the impact of the bolt surface geometry on the shear resistance offered by a bolt. Table 1 shows the specification of two types of bolt used in the study, known as type I and type II bolts respectively.

Figure 1. Flattened bolt surface.

Table I Specification of bolt types.

Bolt	Core Diameter (mm)	Finished Diameter (mm)	Rib Spacing (mm)	Rib Height (mm)
Type I	21.7	24.4	28.5	1.35
Typen	21.7	23 2	12.5	0.75

3 SAMPLE CASTING

The welded bolt surface on the bottom plate of the top shear box was used to print the image of bolt surface on cast resin samples. For obvious economic reasons, the samples were cast in two parts. Nearly three-fourth of the mould was cast with high strength casting plaster and the remaining one-fourth was topped up with a chemical resin commonly used for bolt installation in underground coal mines. A curing time of two weeks was allowed for all specimens before testing was carried out. The properties of the hardened resin after two weeks were, uniaxial compressive strength (σ_c) = 76.5 MPa, tensile strength (σ_t)= 13.5 MPa, and Young's

modulus (E) = 11.7 GPa. The cured plaster showed a consistent σ_c of about 20 MPa, σ_t of about 6 MPa, and E of 7.3 GPa. Such model materials were suitable to simulate the behaviour of a number of jointed or soft rocks, such as coal, friable limestone, clay shale and mudstone, and were based on the ratios of σ_c/σ_t and σ_c/E applied in similitude analysis (Indraratna, 1990). The resin sample prepared in this way matched exactly with the bolt surface, allowing a close representation of the bolt/resin interface İn practice as shown in Figure 2.
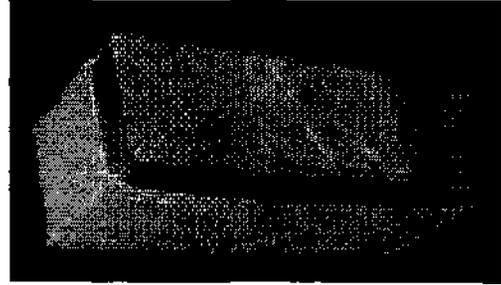
Hgure 2. A typical cast sample.

4 CNS SHEAR TESTrNG APPARATUS

Figure 3 is a general view of the CNS testing apparatus used for the study, which was a modified version of the similar equipment reported by Johnstone and Lam (1989). The equipment consisted of a set of two large shear boxes to hold the samples in position during testing. The size of the bottom shear box İs 250x75x100 mm while the top shear box is 250x75x150 mm. A set of four springs are used to simulate the normal stiffness (k,,) of the surrounding rock mass. The top box can only move in the vertical direction along which the spring stiffness is constant (8.5 kN/mm). The bottom box is fixed to a rigid base through bearings, and it can move only in the shear (horizontal) direction. The desired initial normal stress (σ_{no}) is applied by a hydraulic jack, where the applied load is measured by a calibrated load cell. The shear load is applied via a transverse hydraulic jack, which is connected to a strain-controiled unit. The applied shear load can be recorded via strain meters fitted to a load cell. The rate of horizontal displacement can be varied between 0.35 and 1.70 mm/min using an attached gear mechanism. The dilation and the shear displacement of the joint are recorded by two LVDT's, one mounted on top of the top shear box and the other is attached to the side of the bottom shear box
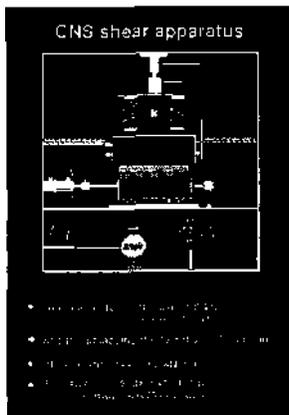
Figure 3 Line diagram of the CNS apparatus (modified after Indraratna et al., 1998).

5 TESTING OF BOLT/RESIN INTERFACE

A total of 12 samples were tested for two different types of bolt surface at initial normal stress (σ_{no}) levels ranging from 0.1 to 7.5 MPa. Each sample for bolt type I was subjected to five cycles of loading in order to observe the effect of repeated loading on the bolt/resin interface. Samples for bolt type II were subjected to only three cycles of loading, as it was found that me stress profile did not vary significantly after the third cycle of loading. The stress profile, as described above, is defined as the variation of shear (or normal) stress with shear displacement for various cycles of loading. The σ_{no} applied to the samples represented typical confining pressures, which might be expected in the field. A constant normal stiffness of 8.5 kN/mm (or 1.2 GPa/m when applied to a flattened bolt surface of 100 mm length) was applied via an assembly of four springs mounted on top of the top shear box. The simulated stiffness was found to be representative of the soft coal measure rocks. An appropriate strain rate of 0.5 mm/min was maintained for all shear tests. A sufficient gap (less than 10 mm) was allowed between the upper and lower boxes to enable unconstrained shearing of the bolt/resin interface.

6 SHEAR BEHAVIOUR OF BOLT/RESIN INTERFACE

6.1 Effect of Normal Stress on Stress Paths

Figure 4 shows the shear stress profiles of the bolt/resin interface for selected normal stress conditions for the type I bolts. The difference between stress profiles for various loading cycles was negligible at low values of σ_{no} (Figure 4a). This

was gradually increased with increasing value of σ_{no} reaching a maximum between 3 and 4.5 MPa (Figure 4b). Beyond a 4.5 MPa confining pressure, the difference between stress profiles for the loading cycles I and II decreased again (Figure 4c). A similar trend was also observed for the type II bolt surface (not shown in figure).
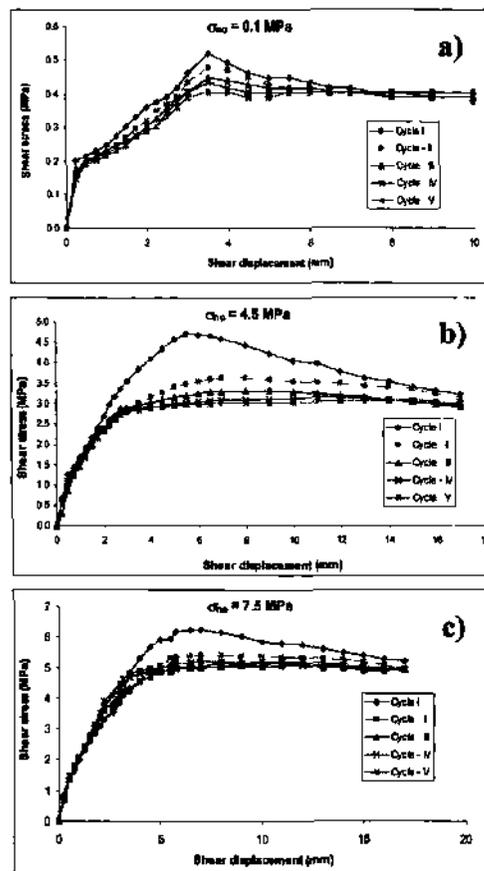
Figure 4 Shear stress profiles of the type 1 bolt from selected tests.

At low σ_{no} values, the relative movement between the bolt/resin surfaces caused an insignificant shearing and slickensiding of the resin surface, thus keeping the surface roughness almost intact. For each additional cycle of loading, the shear stresses marginally decreased, especially in the peak shear stress region. However, as the value of σ_{no} was increased, the shearing of the resin surface was also increased, and the difference in stress profiles for various cycles of loading became significant.

6.2 *Dilation Behaviour*

For the first cycle of loading, Figures 5a and 5b show the variation of dilation with shear displacement at various normal stresses for type I and type II bolts, respectively. For various values of σ_{no}, the maximum dilation occurred at a shear displacement of 17 - 18 mm and 7 - 8 mm, for type I and type II bolts, respectively {Figures 5a and 5b). The distance between the ribs for both bolt types İs shown in Table 1. Therefore, İt may be concluded that die maximum dilation occurred at a shear displacement of about 60% of the bolt rib spacing.
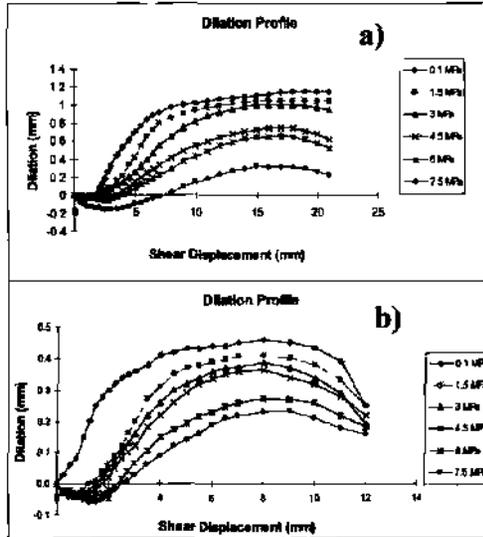
Figure 5. First loading cycle dilation profiles at various σ_{no} values., a) type I bolt, and b) type II bolt

6.3 *Effect of Normal Stress on Peak Shear*

Figures 6 and 7 show the variation of shear stress *with* shear displacement for the first cycle of loading at various normal stresses, for both type I and type II bolts, respectively. The shear displacement for peak shear stresses increased with increasing value of σ_{no} for both bolt types. This was due to the increased amount of resin surface shearing with the increasing value of σ_{no}. However, there was a gradual reduction in the différence between the peak shear stress profiles with increasing value of σ_{no}. The shear displacement required to reach the peak shear strength is a function of the applied normal stress and trie surface properties of the resin, assuming that the geometry of the bolt surface remains constant for a particular type of bolt as evident from Figures 6 and 7.

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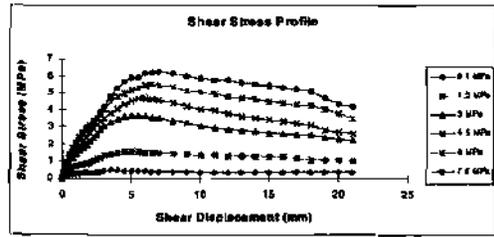
Figure 6. Shear stress profiles of type I bolt for first cycle of loading.
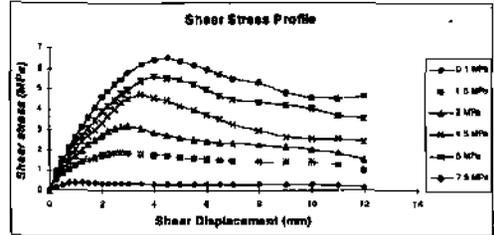
Figure 7. Shear stress profiles of type II bolt for first cycle of loading

6.4 *Effect of Cyclic Loading on Peak Shear*

Figures 8 and 9 show the variation of peak shear stress with normal stress applied for type I and type II bolts for various loading cycles. For the type I bolt surface, the graphs of cycle I through cycle III show a bi-linear trend, whereas the graphs representing cycles *TV* and V show only a linear trend. For the type II bolt surface, only cycle I shows a bi-linear trend and cycles II and III show a linear trend. At low initial normal stress, the shearing of resin surface is negligible, and hence, the rate of increase of peak shear stress with respect to normal stress is high. At higher normal stress, the degree of shearing of resin surface is greater, and some of the energy is thus utilised to shear off the resin surfaces. As a result, there is retarded rate of increase in peak shear stress with respect to the normal stress.
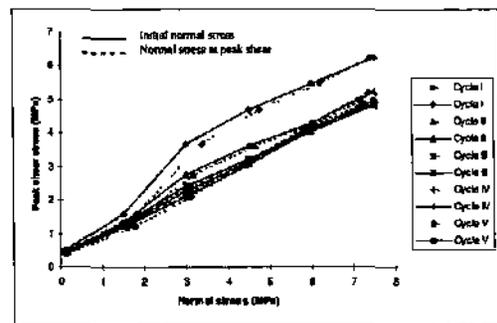
Figure 8. Variation of peak shear stress with normal stress *for* type I bolt.
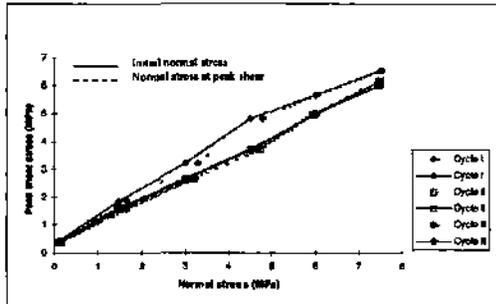
Figure 9 Variation of peak shear stress with normal stress for type [[bolt

As the samples are loaded repeatedly, the resin surfaces become smoothened reducing the surface roughness, and as a result, the rate of increase of peak shear stress is likely to remain constant with respect to the normal stress.

6.5 Overall Shear Behaviour of Type I and Type II Bolts

Figure 10 shows the shear stress profiles of both type I and type II bolts for the first cycle of loading. The following observations were noted.

- The shear stress profiles around peak were similar for both bolt types However, slightly higher stress values were recorded for the bolt type I at low normal stress levels, whereas slightly higher stress values were observed for the bolt type II at high normal stress levels, in most cases.
- Post peak shear stress values are higher for the bolt type I indicating betteT performance in the post-peak region.
- Shear displacements at peak shear are higher for the bolt type I indicating the safe allowance of more roof convergence before instability stage is reached.
- Dilation is greater in the case of bolt type I

6.6 Effect of Normal Stiffness

The laboratory experiments were carried out with spring assembly with an effective stiffness of 8.5 kN/mm. In practice, the stiffness of resin/rock system will be usually higher than the laboratory simulated stiffness. As the stiffness increases, the effective normal stress on the bolt/resin interface at any point of time will also increase, as per the following equation:

$$\sigma_n = \sigma_{no} + \frac{k_n.\delta_v}{A} \tag{3.1}$$

Where,

σ_n = effective normal stress,
σ_{no} = initial normal stress,
k_n = system stiffness,
δ_v = dilation, and
A = area of the bolt surface
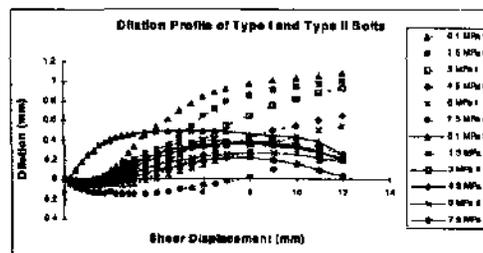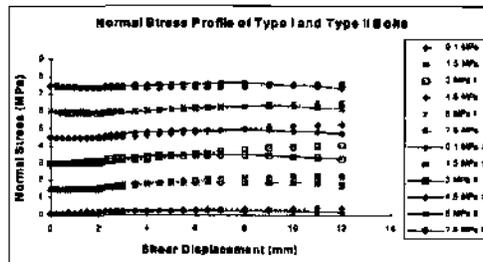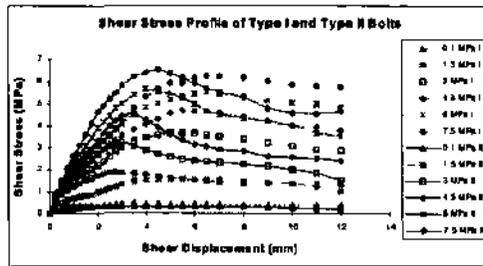
Figure10 Comparison of stress profile and dilation of type 1 and type II bolts for first cycle of loading

In general, higher values of effective normal stresses should be observed for the type I bolt as compared to the type II bolt as long as the confining pressure remains low. Higher values of effective normal stress will have a direct positive impact on the peak shear stress values and, therefore, when installed in the field, the type I bolt would outperform the type II bolt, particularly at low confining pressure conditions. However, in deep mining conditions, where the high stress conditions prevail, the reverse situation may occur because of the greater contact zone between the resin surface and the closer spaced bolt ribs in bolt type II. This increase in contact surface area would require

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greater shearing force necessary to fail, which might not he the case in wider spaced ribs in bolt type I, and that explains the reason for the stability of the bolt type II in deep mine applications.

7 FIELD INVESTIGATION

In an attempt to verify the laboratory findings, with respect to the influence of bolt surface profiles on load transfer mechanisms under different testing environments, a program of field investigation was undertaken in a local coal mine, known as Mine A. The mine is located at Douglas Park about 80 km South-West of Sydney, NSW, and mines coal from Buili seam, 3m thick, at a depth of about 480m. The mine produces around 1.5 mt of coal from a 230m longwall face and heading development operations. The Buili seam is overlain with a succession of moderately strong roof layers consisting mainly of

sandstone, mudstone, siltstone and shale. Figure 11 shows the general plan of the test site. The direction of the principal horizontal stress (σ_1=25 MPa) at the instrumented site was nearly parallel to the headings axis. However, and because of the presence of the dyke, there were some variations in the overall principal horizontal stress orientation, particularly at the outbye of the dyke as shown in Figure 11.

The Geld investigation program consisted of installing 12 instrumented, 2.4m long, strain gauged bolts in two adjacent main entries to die longwall panel as shown in Figure 12. Eighteen strain gauges were housed in each bolt in two diametrically opposite channels (6mm x 3mm). In addition to the instrumented bolts, three extensometer probes were also installed between the two rows of instrumented bolts in each gateroad. Each extensometer location housed 20 magnetic reference points above the roof. The notations adopted for the bolts and extensometer probes in Mine A is explained in Figure 12.
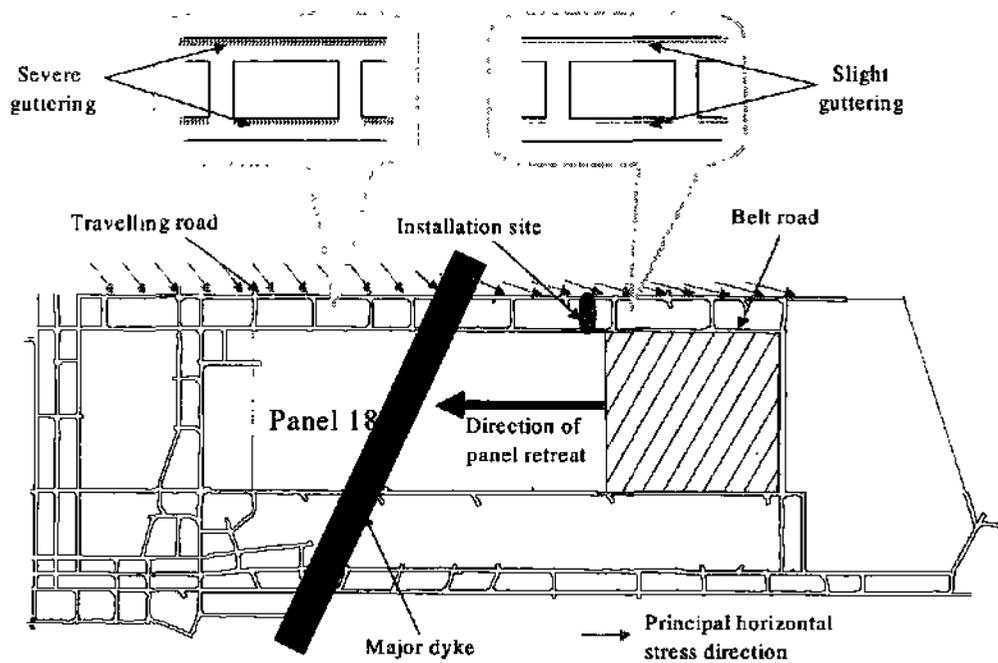
Figure 11. Detail layout of the panel under investigation at Mine A.

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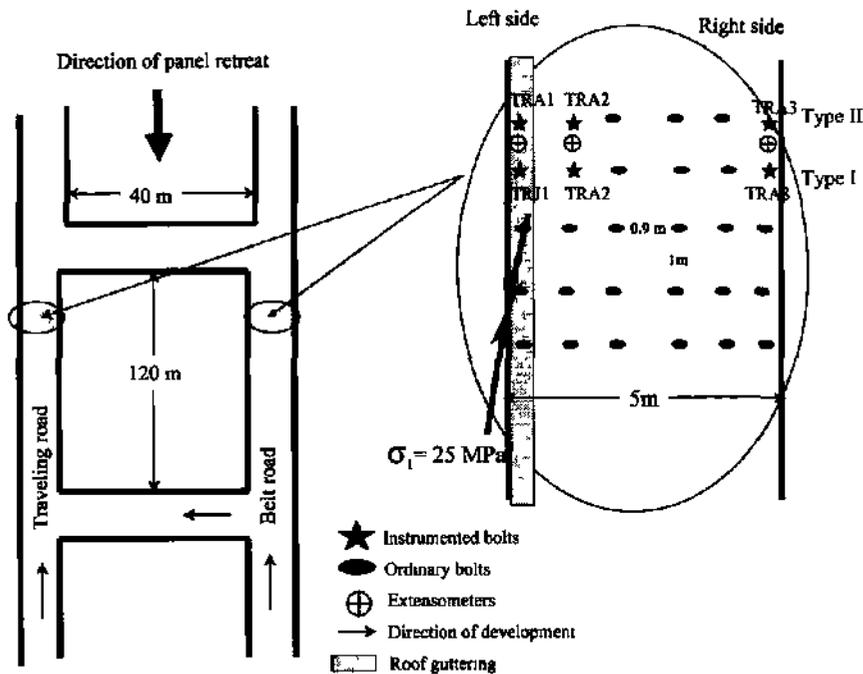
Figure 12. Detail layout of the instrumentation site at Mine A

8 RESULTS AND DISCUSSIONS

Field monitoring commenced immediately following the completion of site instrumentation, monitoring ended when the site was overrun by the retreating longwall face. The total period of site monitoring was S months.

8.1 *Load transfer during the panel development and the longwall retreating phases*

Figure 13 shows the overall load transferred on the type II bolts during panel development and subsequent longwall retreating phases, installed at the left side of the travelling road (numbered as TRA1 in Figure 13). As expected, the load transferred on the bolts during the panel development stage was relatively low as compared to the longwall retreating phase in both the travelling and belt roads. The load build up due to the front abutment pressure of retreating longwall face was, on the average, 5 to 8 times higher than that of panel development phase (see Figure 13).

The maximum load transferred to the bolt BRJ2 at a particular face position, during panel development and longwall retreating phases, is shown in Figure 14. The load transferred during the panel development stage became constant within

40m advance of development headings, away from the instrumented sites. However, the load build up due to the front abutment pressure of the approaching longwall face began to increase significantly, when the distance was 150m from the test sites.

8.2 *Load transfer m the belt and travelling road*

Figure 15 shows the maximum load transferred on to BRJ2 and TRJ2 for a particular face position, during the panel development and the longwall retreating phases. In both gateroads, the load on the bolts started to build up immediately after their installation during the panel development stage, and then became constant when the heading development face was about 50m away from the test sites (see darker lines in Figures 15a and 15b). During the longwall retreating phase, however, the impact of front abutment pressure was observed (by sharply increasing load), when the approaching longwall face was around 60m away from the test site in case of travelling road (Figure 15a). In case of belt road, the same was observed when the approaching longwall face was about 150m away from the test site (Figure 15b). Thus, the impact of longwall face movement was more prominent in case of belt road as compared to the travelling road.

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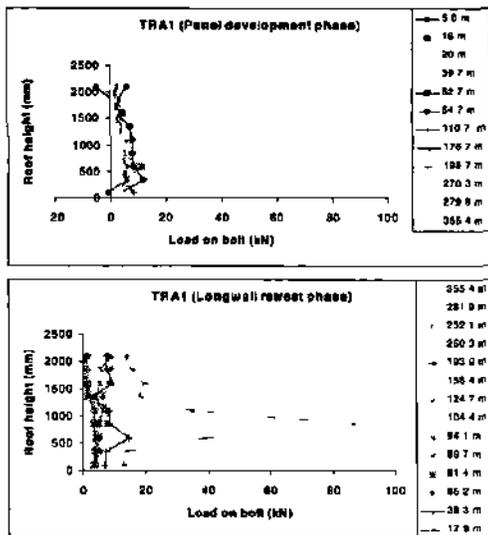
Figure 13. Load transferred on the bolt TRA1, during the panel development and longwall retreating phases, Mine A
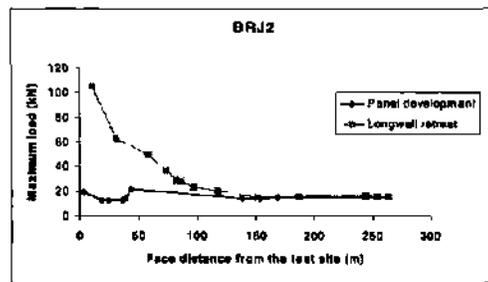
Figure 14 Maximum load transferred on the bolt BRJ2, for a particular face position, Mine A.

relatively stable, with negligible amount of strata deformation (Figure 16c). No significant strata deformation was observed at a horizon level of more than 3m from the roof level. Thus, it may be suggested that, in addition to the regular bolt pattern at Mine A, occasional use of longer secondary reinforcement units (e.g. cable bolts) may be required for effective heading stabilisation. However, İt is difficult to suggest similar strata reinforcement pattern at outbye side of the dyke, because of varying stress conditions.
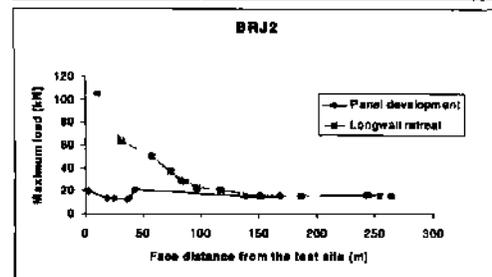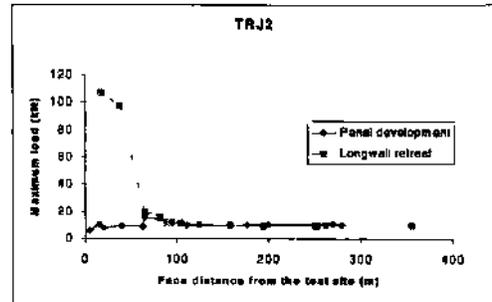
Figure 15- Maximum load transferred on bolts TRJ2 and BRJ2, for a particular face position, Mine A

8.3 Behaviour of strata deformation

Figure 16 shows the overall roof deformation recorded from the extensometry readings in the travelling road. As expected, the maximum deformation was recorded in the middle of the road (Figure 16b) because of the prevailing near parallel principal horizontal stress direction, and was aggravated by the deadweight of the separated sagging roof. The amount of roof deformation recorded at the left side of the gateroad (Figure 16a) was relatively small as compared to the middle section (Figure 16b), but was greater than that on the right side (Figure 16c) of the roadway. Also, the acute angle between the horizontal stress direction and the axis of the gateroads caused some shearing İn the immediate roof at the left side of the gateroads, while the other side of the gateroads was

8.5 Comparison of load transfer in type I and type II bolts

Figure 17 shows the load transferred on the bolts TRJ1, TRJ2 and TRJ3, installed at the left, middle and the right side of the travelling road. The maximum load recorded on the above bolts was 39 kN, 97.6 kN and 33.5 kN, respectively. The bolt at the left side was subjected to relatively higher load as compared to the bolts at the right side, which may have been due to the influence of the orientation of principal horizontal stress, striking the gateroads with an acute angle from the left side (Figure 12). When compared with other bolts, the bolt at the middle of the road recorded the maximum value because of the dominant role of excessive strata deformation in the middle of the gateroads.

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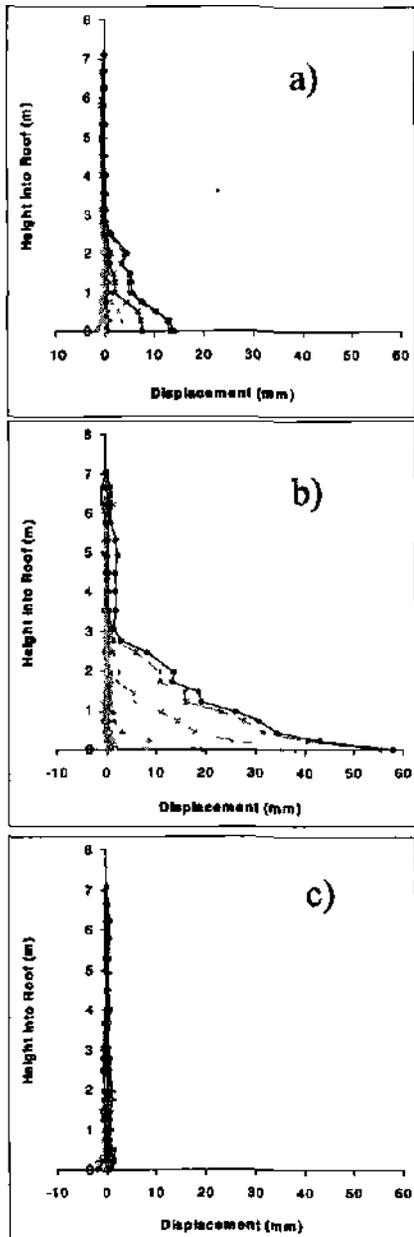
Figure 16. Strata deformation in the travelling road, a) left side (TRI), b) middle (TR2), and c) right side (TR3).

84.6 kN, respectively. The corresponding shear stress developed at the bolt/resin interface for botJi bolts is shown in Figure 19. Thus, it can be inferred that, the location of the neutral point is independent of the bolt type. The comparative values observed from the shear stress profiles of BRJ1 and BRA1 suggests that, the bolt type II offered better load transfer characteristics when subjected to higher shear loading, caused by the influence of the horizontal stress.
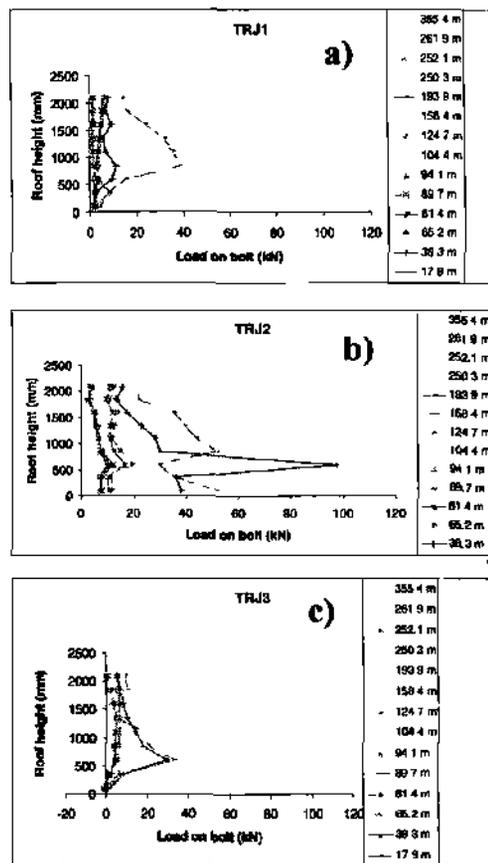
Figure 17 Load transferred on the type 1 bolts, installed *m* the travelling road. Mine A

Figure 18 shows the pattern of load transferred on the type I (BRJ1) and type II (BRA1) bolts, installed at the left side of the belt road. The load transferred on the type I bolts was relatively smaller as compared to the type E bolts. The maximum load transferred on BRJ1 and BRA1 was 41.7 kN and

Figure 20 shows the load transferred m type I (BRJ3) and type II (BRA3) bolts, installed at the right side of the belt road. As expected, the load transferred in type I bolt (38.1 kN) was relatively higher as compared to the type II bolt (18.6 kN). Because of the lower influence of the horizontal stress on the bolts, the shear stress developed at the bolt/resin interface in type I bolt was relatively higher than in type II bolt (see Figure 21), thus,

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reconfirming the superior load transfer characteristics of the type I bolts under lower levels of prevailing horizontal stress. Based on both laboratory and field study, it is clear that bolts with deeper and wider rib spacing should be used in section of the roadways subjected to the influence of low horizontal stress, whereas, bolts with shallower and narrower rib spacing should be used in areas under the influence of high horizontal stress (as evidenced by the excessive roof guttering).
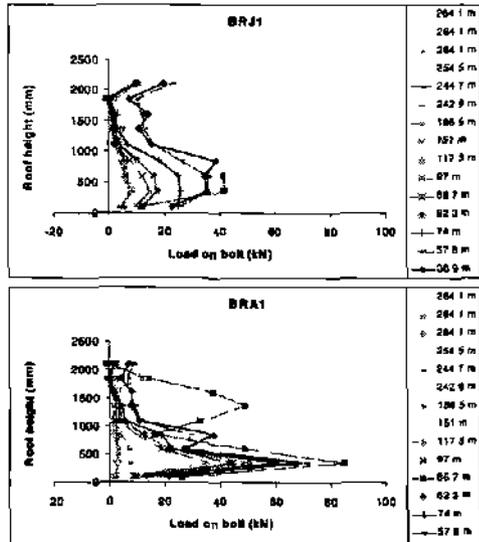
Figure 18. Load transferred on type I and type II bolts, installed at left side of the belt road, Mine A
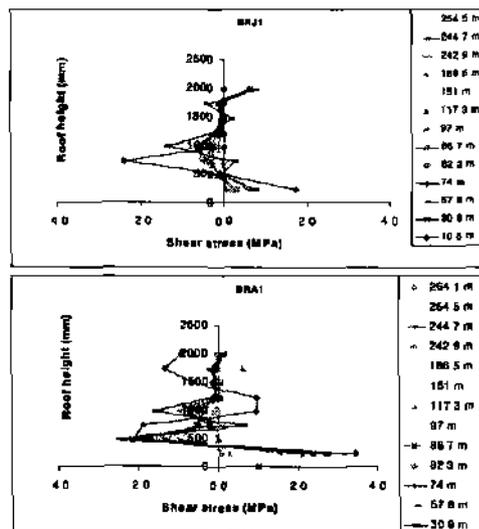
Figure 19. Shear stress developed at the bolt/resin interface of the type I and type II bolts, installed at the left side of the belt road, Mine A.
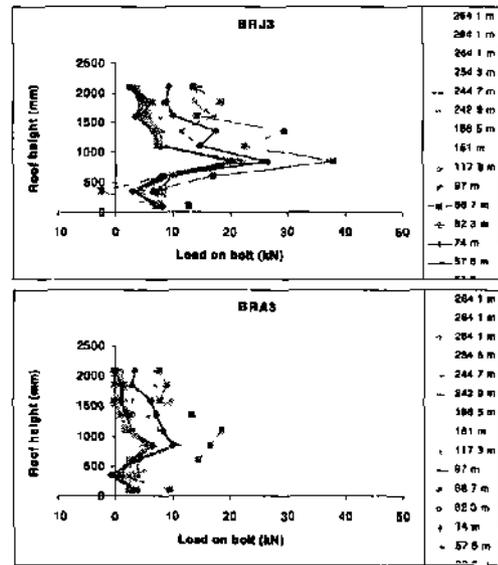
Figure 20 Load transferred on the type I and type II bolts, installed at the right side of the belt road. Mine A

9 CONCLUSIONS

It can be inferred from this study that:

- The shear behaviour of the bolt surface at various confining pressures directly affects the load transfer mechanism from the rock to the bolt.
- The type I bolt offered higher shear resistance at low confining pressure (below 6.0 MPa), whereas, the type II bolt offered greater shear resistance at high normal stress conditions exceeding 6.0 MPa. This was attributed to the surface profile configuration of the bolt i.e., the spacing and the depth of the rib.
- The bolt with deeper rib offered higher shear resistance at low normal stress conditions, while the bolt with closer rib spacing offered higher shear resistance at high normal stress conditions.
- The impact of repeated loading on the effective shear resistance of the bolt/resin interface was influenced by the magnitude of the applied normal stress, the number of loading cycles and the surface geometry of the bolt.
- The maximum dilation occurred at a shear displacement of nearly 60% of the rib spacing.
- The bolt type I showed better performance than that of bolt type If when considering the shear behaviour at low normal stress, dilational aspects, and the post-peak behaviour.
- The load transfer on the bolt was influenced by; a) the confining stress condition, b) the extent of strata deformation, and c) the surface profile roughness of the bolts.

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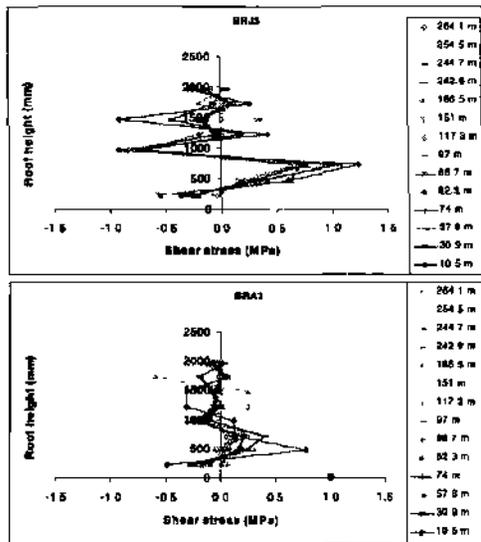
Figure 21. Shear stress developed at the bolt/resin interface of the type I and type II bolts, installed at the right side of the belt road, Mine A.

- The load transferred on the bolts, during the longwall retreating phase, was relatively greater than that of panel development phase.
- The face movement did not influence the load transferred on the bolts, when the development face moved beyond 50m away, or the approaching longwall face position was 150m away from the test sites.
- The influence of front abutment pressure build up on die gateroads appears at different face positions. The load build up on the bolts in the belt road occurs when the longwall face is less than 150m from the test site, whereas, the same build up on the travelling road starts when the face position İs less than 60m.
- The field study showed that, under the low influence of horizontal stress (both in magnitude and die direction), the type I bolt offered higher shear resistance, whereas under high influence of

horizontal stress, the type II bolt offered better shear resistance at die bolt/resin interface. Such findings were also observed in the laboratory studies as indicated before, and can provide useful guidelines for future selection of appropriate bolt type for given stress conditions.

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