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The Significance of Mobile Machine Damage on Resin-Grouted Bolts

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Abstract

Full-column resin-grouted bolts are widely used to provide support in shallow-depth underground mines. Self-Propelled Mobile Machines (SPMMs) regularly collide with and damage these bolts in narrow reefs. Historically, mines have acted on the assumption that visible damage equates to loss of structural performance. This belief often leads to unnecessary support replacement, production delays, and additional costs. However, there is no evidence that such impacts compromise load transfer capacity. This investigation aimed to close this gap. The damage was quantified through laboratory and field studies. Bolts were grouted in suitably prepared steel pipes, and the assembly was embedded in the rock wall of a stope. Subsequently, the bolts were intentionally impacted by Load-Haul-Dump (LHD) vehicles, driving at normal, accepted speeds. The pipe assemblies were then retrieved, cut into 100 mm segments and visually examined. Each segment was subjected to push tests to measure bond strength. The results were compared to undamaged control samples. The results showed that when the annulus between the bolt and borehole wall was 4.5 mm or less, damage to the resin column did not extend beyond 100 mm from the hole collar. The bond strength in the subsequent segments remained equivalent to that of the control samples. For annuli larger than 4.5 mm, resin degradation extended up to 400 mm, driven primarily by poor mixing and gloving during installation. The findings show that visible damage does not automatically indicate functional failure, and that installation quality is the primary determinant of bond strength. The study concluded that, for the installation conditions investigated, full-column resin-grouted bolts damaged by SPMMs did not require replacement when the annulus was 4.5 mm or less and acceptable installation quality was achieved. In contrast, bolts with larger annuli should be replaced after damage.

Keywords

Full-column resin-grouted bolts, Mobile machine damage, Annulus effect, Resin bond strength, Support performance.

1 Introduction

In underground mining, safety decisions are often based on visual observations and assumptions. A bolt that is bent or severed by an SPMM collision is typically classified as “damaged support”, triggering compulsory replacement. Such replacement results in production losses and additional labour, yet no research has confirmed a loss in load-bearing functionality. This disconnect between appearance and performance forms the *functional damage paradox*: A support element may appear damaged yet still perform adequately. As a continuously mechanically coupled system, load transfer of a full column grouted resin bolt occurs along the entire encapsulated length. It is driven by shear and axial stresses. Such stresses are likely to develop within the first few centimetres of the point of impact and dissipate quickly with distance from it (Aydan et al., 1985; Holmberg, 1991; Li, 2018).

The knowledge gap that guided this research was contained in the following question: Does SPMM collision damage compromise the bond strength of a resin-grouted bolt? Laboratory and field experiments were set up to evaluate:

- the true extent of resin column damage;
- the influence of annulus on bolt behaviour;
- the post-impact bond performance; and
- under what conditions will re-installation of support not be necessary.

2 Literature review: Mechanics of resin-grouted bolts

Full-column resin-grouted bolts differ fundamentally from mechanical anchors:

- The bolt is bonded continuously to the rock via a thin resin annulus.
- Rib–resin and resin–rock interfaces mobilise shear resistance as the rock mass deforms Serbrousek and Singer (1987);
- Shear stress is highest at the point of displacement and decays exponentially with distance (Aydan et al., 1985; Holmberg, 1991; Li, 2018);
- Peak load transfer occurs within approximately 100 mm to 150 mm of the bonded length and beyond this zone, stresses dissipate exponentially; the bolt–resin system remains largely unaffected by localised damage (Li et al., 2014).

Even if a bolt is bent or sheared off at the collar, the majority of load transfer occurs near the point of damage, suggesting that overall performance may be unaffected. However, bond performance is highly sensitive to annulus thickness, mixing quality, resin encapsulation, and operator technique (Canbulat, et al., 2006). Annuli greater than ±6 mm are prone to poor mixing, resin gloving, and reduced bond strength, irrespective of mechanical damage (Hagan, 2003; Dolinar and Bhatt, 2000; Mark, 2000).

3 Experimental procedure

3.1 Pipe assemblies and installation

To assess the influence of SPMM damage on installed resin-grouted rebarbolts, steel pipes with inner diameters of 32 mm were installed into 45 mm boreholes drilled into hard-rock walls underground. The pipes were rifled for 400 mm near the collar to replicate borehole roughness in the area where most damage was expected. A faceplate was welded to the collar of each pipe to facilitate installation, with a cap welded to the distal end to contain the resin and block debris. The tests were conducted at three underground hard-rock mine sites with varying installation conditions and support practices. A total of twenty-five impacted bolts and equivalent undamaged control samples were tested. Between three and five impacted samples were prepared per test site, together with one control sample installed under the same conditions. Different bolt diameters ranging from 18 mm to 25 mm were installed into 32 mm internal diameter steel pipes, resulting in annuli ranging from approximately 3.5 mm to 7 mm. Both mechanised installations and hand-held air-leg installations were included in the investigation to evaluate the influence of operator variability and installation quality on post-impact bond performance. The resin systems and installation procedures used during the tests were identical to those employed operationally at the participating mines. The inclusion of multiple mines, varying annulus sizes,

different bolt diameters, and differing installation methods allowed the investigation to evaluate both repeatability and variability in the observed bond-strength behaviour.

3.2 Controlled SPMM impacts

After installation, the bolts were intentionally impacted using LHDs driven at normal operating speeds. The calculated impact energy was about 4.82 kJ. The damage categories resembled the three categories observed in typical operating environments: impacted, bent or severed.

3.3 Sectioning and laboratory push testing

After the SPMM impact, all pipe assemblies were recovered, and each assembly was cut into 100 mm segments. The segments were visually inspected, photographed and then subjected to axial push tests to determine the bond strength per 100 mm segment. The test results were then compared to the results of the undamaged control samples. An example of the 100 mm long assemblies is shown in Fig. 1. In total, twenty-five impacted bolts and equivalent controls were tested. The push testing method is shown in Fig. 2(Aziz et al., 2006; Aziz et al., 2014; Ma et al., 2017). The push-test results were evaluated comparatively against the corresponding undamaged control samples for each test configuration.

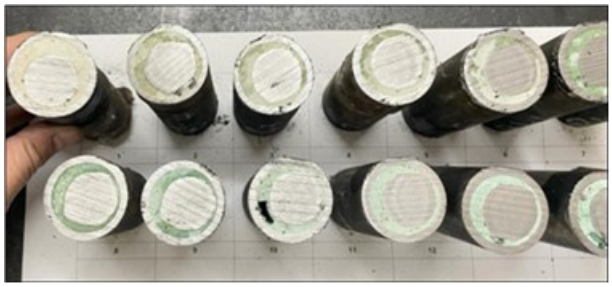


Fig. 1 Segmented pipe assemblies.

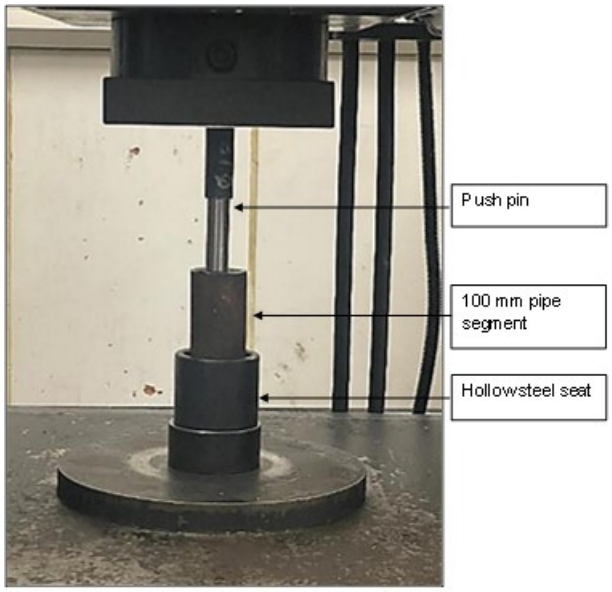


Fig. 2 Pipe push testing method.

4 Results

4.1 Installations with annuli less than 4.5 mm

For small, well-mixed annuli less than 4.5 mm, resin damage did not extend beyond 100 mm from the impact point, or roughly four to five times the bolt diameter. Visual observations found that the mixing was good throughout the samples, with no gloving, soft resin or voids. The bond strengths of deeper segments were comparable to the undamaged control samples, and no progressive debonding occurred. An example of the results is shown in

Fig. 3. The results confirmed that a bolt can appear mechanically damaged at the collar yet retain its full anchorage beyond the point of damage.

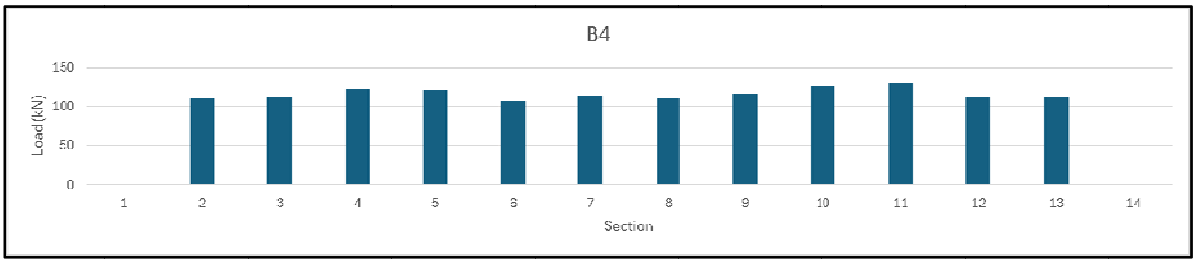


Fig. 3 Example of test results for annuli <4.5 mm.

4.2 Installations with annuli more than 4.5 mm

For annuli larger than 4.5 mm, resin degradation extended up to 400 mm from the point of impact, or roughly twenty times the bolt diameter. Inspection of the samples found that poor mixing and gloving were widespread, even in the control samples, as shown in the test results in

Fig. 4. In fact, undamaged controls showed poor bond quality in the same 400 mm zone where most impact damage was concentrated. The weakness was therefore installation-related, not necessarily impact-related. It was also found that all installations conducted using hand-held air-operated drills were of poor quality and experienced notable damage in the areas close to the hole collars.

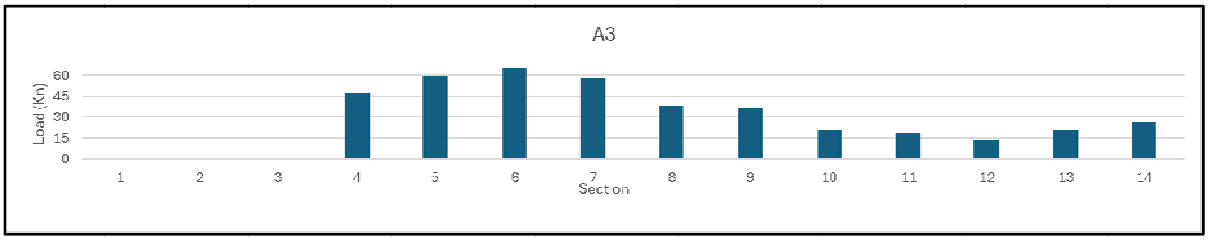


Fig. 4 Example of test results for annuli >4.5 mm.

Although the experimental programme was primarily comparative in nature, consistent trends were observed across the different test sites and installation conditions. The bond strengths of the impacted samples with annuli ≤4.5 mm remained comparable to those of their corresponding control samples beyond the first 100 mm segment. In contrast, samples with larger annuli consistently exhibited greater variability in bond strength and resin condition, irrespective of whether the samples were impacted or undamaged. The repeatability of these observations across multiple sites and installations indicates that annulus size and installation quality were the dominant variables influencing bond performance.

A statistical assessment of the results was conducted using both p-value analysis and Cohen's effect size. The calculated p-value of 0.0153 indicates that the observed difference between the two groups was statistically significant and unlikely to have occurred by chance. In addition, the calculated Cohen's d-value of 6.53 indicates an extremely large effect size, demonstrating that the difference in damage between the two groups was not only statistically significant, but also practically meaningful from an engineering perspective.

5 Discussion

The results indicate that a visibly damaged bolt does not necessarily imply functional failure of the support system. For the test conditions investigated, functional anchorage remained intact where the annulus was ≤4.5 mm and where acceptable resin mixing and encapsulation quality were achieved during installation. Under these conditions, damage to the resin column was generally confined to within approximately 100 mm of the point of impact. However, the identified 4.5 mm threshold should not be interpreted as a universal design limit. The threshold is empirical and relates specifically to the bolt diameters, hole dimensions, resin systems, and installation practices evaluated during this investigation. The results further demonstrate that installation quality remained the dominant factor controlling bond performance. Poor mixing, resin gloving, and operator-related variability resulted in reduced bond strengths even in undamaged control samples with larger annuli. The study also revealed that poor installation practices and poorly designed systems can severely compromise the strength of a support system. Across several sites, bolts that were poorly spun or incompletely mixed due to large annuli were significantly weaker than expected. This problem was worse when installations were conducted using hand-held percussive drills with air legs. The findings therefore suggest that annulus control and installation quality assurance are likely to be more important than visible mechanical damage alone when evaluating the effectiveness of resin-grouted bolts following SPMM impacts. Further work should nevertheless be conducted to evaluate whether similar threshold behaviour is observed for different bolt types, resin systems, hole diameters, and geological conditions.

6 Conclusions

Quality installation and correct equipment selection form the fundamental basis of effective ground-control management when using full-column resin-grouted bolts. Replacing damaged bolts addresses only the aesthetics. The root cause of poor support performance lies in the processes that contribute to compromised installations. Evidence indicates that impacts from Self-Propelled Mobile Machines do not inherently diminish the structural capacity of resin-grouted bolts when:

a) the annulus between the bolt and hole is ≤4.5 mm; and
b) the mixing of the grout was done properly, using the correct number of revolutions.

Under these conditions, damage is limited to the first 100 mm, and beyond this region remains equivalent to intact bolts. Annuli greater than 4.5 mm produce resin failure up to 400 mm.

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