School of Mining Engineering

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

THE SIGNIFICANCE OF MOBILE MACHINE DAMAGE ON THE EFFECTIVENESS OF FULL-COLUMN RESIN-GROUTED BOLTS

Andréas Esterhuizen

Student Number: 749604

I declare that this research report is my own unaided work. It is being submitted for the degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other university.

Johannesburg, 2025

DECLARATION

I have familiarised myself with the University of the Witwatersrand Student Academic Misconduct Policy (SAMP). I hereby declare that the work I am submitting for assessment is my original work. I affirm that I have not plagiarised, misrepresented, or colluded with any other person or source. I have properly acknowledged, cited, and referenced all the sources that I have used in my work. I also declare that I have used artificial intelligence (AI) tools only as a means of guidance. The ideas and arguments presented in my work are my original thoughts and interpretations. I acknowledge that any academic misconduct, such as plagiarism or collusion will result in serious consequences. These consequences may include a reduced grade, a fail mark, or disciplinary action according to the SAMP. The School of Mining Engineering has my consent to investigate any potential academic misconduct in my work. This investigation may include the use of similarity and AI detection software to check the originality of my work. I undertake to abide by the decision of any such investigation.

____

Andréas P Esterhuizen

18th day of September 2025

“When you know what you don’t know, half the battle is won.”

J.D. Bosman

ABSTRACT

This research study was undertaken to gain an understanding of the extent of the damage caused to full-column grouted resin bolts by collisions with Self-Propelled Mobile Machines (SPMMs). The primary purpose of the study was to determine whether damaged bolts must be replaced. The research consisted of push tests conducted on damaged bolts. To accurately reconstruct the extent of the damage caused by SPMM collisions, pipes were installed into the rock. Full-column grouted resin bolts were then installed into the pipes. After the resin was cured, the bolts were damaged using load-haul dump trucks. The pipes were then recovered and cut into 100 mm segments. Each segment was visually inspected to assess the extent of the damage to the resin column. Thereafter, the resin bond strength of each segment was assessed through push tests. The test results from each batch of tests were compared to a similar, undamaged control sample. The results show that, if the annulus between the bolt and the side of the hole was 4.5 mm or less, the resin damage did not extend beyond 100 mm, or roughly four times the diameter of the bolt, from the point of damage. For samples with an annulus of more than 4.5 mm, the quality of the resin column was compromised up to a depth of 400 mm, or approximately 20 times the bolt diameter. In the undamaged large annulus control samples, it was found that the lower 400 mm (from the hole collar) were poorly mixed. These samples achieved low push-out strengths as compared to the middle sections of the holes. The resin in the middle and upper portions of the holes also showed no detectable SPMM damage. The research concluded that the replacement of damaged full-column grouted resin bolts is only necessary if the annulus between the bolt and the hole is greater than 4.5 mm.

ACKNOWLEDGMENTS

I wish to thank the following institutions for their generous contributions to this research project:

- Open House Management Solutions
- New Concept Mining
- RSC Ekusasa Mining
- Rockbolt Technologies

I would furthermore like to express my sincere gratitude to the following individuals for their involvement and contributions to this research project and the testing work performed:

- Professor Bryan Watson
- Koos Bosman
- Dr. Greig Knox
- Ofentse Rakuba
- Noah Mafokane
- Gunther Betz
- Petrie Wessels

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviation	Description
CMC	Continuously mechanically coupled bolt.
CFC	Continuously frictionally coupled bolt.
DMFC	Discretely mechanically or frictionally coupled.
DMRE	Department of Mineral Resources and Energy.
LHD	Load-Haul-Dump truck.
m.	metre – SI base unit of length
SPMM	Self-Propelled Mobile Machinery.
Active support	"Active" refers to the support's ability to apply an immediate force upon installation, thereby increasing the frictional resistance along geological structures and fractures.
Debonded	A breakdown or deterioration of the bond at an interface.
Decoupled	When the bond is completely broken, with no contact between the interfaces and no frictional resistance is supplied.
Hand-held installations	Support drilled and installed using conventional rock drills with airlegs.
Hangingwall	The roof, or crown, of an underground excavation.
Inspectors	Refers to government institution inspectors, such as mining inspectors.
Roof bolts	Various types of steel tendons are used as ground support, including resin bolts, mechanical bolts and friction stabilisers.
Stiff support	"Stiff" implies that little deformation is allowed per unit of loading.
Trackless Mine	A mine in which no track-bound equipment is used. The transport of employees, material and ore is done using vehicles and equipment with rubber tyres.

1 INTRODUCTION

1.1 Research Background and Context

Resin bolts are widely used as ground support in mines and are designed to enhance the stability of rockmass through artificial reinforcement. A full-column grouted resin bolt refers to a steel rebar that is encapsulated in a borehole, along its entire length, with resin as a bonding agent. The bolts are continuously mechanically coupled (CMC) to the rockmass through short diagonal ribs along the length of the bolt and the full encapsulation resin. Figure 1-1 shows a typical resin bolt rib pattern.

Figure 1-1: Typical resin bolt rib pattern. (DSI Underground, 2024)

Each bolt is supplied with a nut, bearing plate and load indicator as its main accessories (Figure 1.2). These accessories protrude from the hole after installation, typically between 50 mm and 100 mm, depending on the quality of installation. The nut is manufactured with a flange, which allows for the spinning of the bolt to mix the resin. After the resin sets, the flange is broken, and the nut is used to pretension the bolt along the threaded end. The bearing plate allows the force produced by the resin bolt to be spread over a surface area at the collar of the hole. It also adds to the pretensioning of the bolt by supplying a surface against which the load can be applied. The load indicator is a domed, collapsible washer located between the nut and the bearing plate (Figure 1.2). The washer collapses at loads between 30 kN and 50 kN, indicating that the bolt is correctly installed and sufficiently pretensioned. Figure 1-3 shows resin bolts installed in an underground excavation.

Figure 1-2: Resin bolt accessories.

Figure 1-3: Resin bolts installed underground.

Resin bolts are installed by first inserting resin capsules into the drilled hole. Each capsule has two compartments, one containing a resin mastic and the other a catalyst. Typically, each installation consists of two capsules, a fast-setting resin capsule that sets within 60 seconds and a slow-setting resin capsule which sets within 5.0 to 10 minutes. The fast-setting capsule is inserted into the hole first and then pushed to the end of the hole, followed by the slow-setting capsule (Minova International Limited, 2006). Depending on the length and diameter of the borehole and the diameter of the bolt used, more than one of each capsule may be required. The resin may only be spun (for mixing) for a set time (gel time). Over-spinning of the bolt will cause damage to the resin as it sets. After the gel time, a set time is required for the resin to reach approximately 80% of its ultimate strength. Set times of the resin may vary, depending on operational requirements (Minova International Limited, 2006).

Once the resin capsules are inserted, the steel bolt is pushed through the resin capsules, rupturing them. Spinning of the bolt allows mixing of the resin and the catalyst, and the resin rapidly hardens as it sets. Once the fast-setting capsule at the end of the hole has set, the bolt is tensioned until the load indicator collapses (Li, 2018). This fast-setting resin is now the anchor point for the support system. Since the slow-setting resin sets at a slower rate, the pretension applied to the bolt between the fast-setting resin and the faceplate at the collar of the hole is locked in between the ribs on the surface of the bolt and the slow setting resin. Figure 1-4 illustrates the installation procedure of a resin bolt.

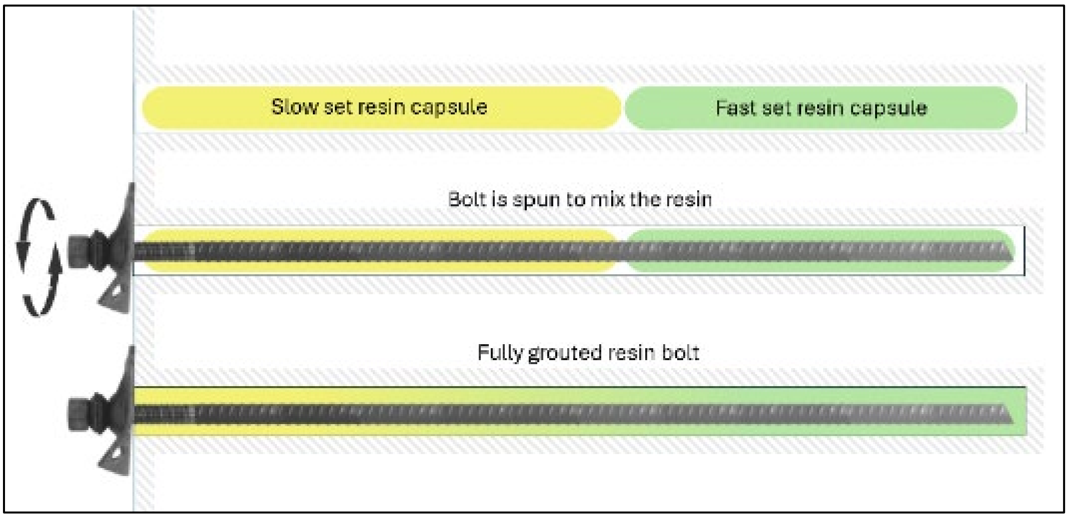


Figure 1-4: Resin bolt installation process.

Through observation on various mines across South Africa, it was identified that trackless mines often receive instructions from inspectors from the Department of Mineral Resources and Energy (DRME) to replace full column grouted resin bolts, damaged by Self-Propelled Mobile Machines (SPMMs). This particular issue is also clearly illustrated by the questionnaire conducted as part of this project, as detailed under heading 3.3.1. The results of the questionnaire indicate that 52.94% of participating mines have received DMRE stoppages due to damaged support. SPMMs in this scenario refer to equipment used in underground mining that can move freely on rubber tyres, without being bound by external power sources, tracks or rails. A Load-Haul-Dump truck (LHD) is an example of such machinery. Most mines operating at working heights less than 2.2 m now incorporate daily replacement of damaged bolts as part of their support standards. This process has a significant financial implication and results in a loss of production time. Figure 1-5 illustrates an example of a bolt replacement following SPMM damage to the original bolt.

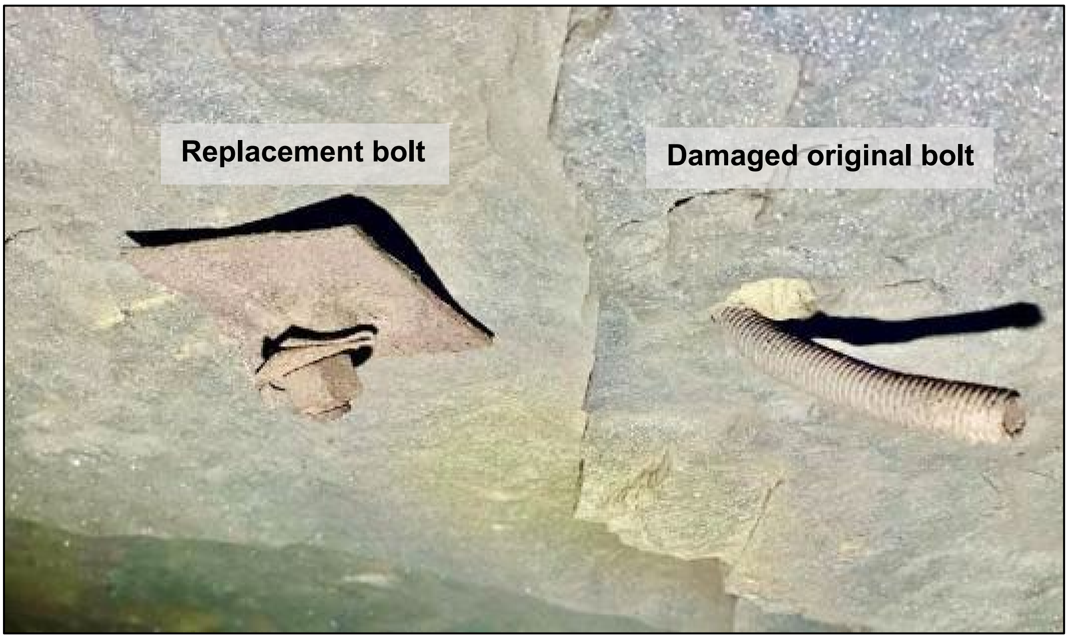


Figure 1-5: Replacement of an SPMM-damaged bolt.

It is widely assumed by miners that the pretension of a full-column grouted bolt is locked into the support system when the resin cures. It is also known that full-column grouted bolts are considerably stiffer than non-grouted bolts, and that very good load transfer occurs between the rockmass and the bolt in fully resin-grouted systems. This means that high stresses are rapidly generated along the bolt under minimal strain (Springer, 1990). Damage to protruding parts of the bolt may therefore not be significant if the resin along the remaining length of the bolt is still intact. Should the nut and faceplate be removed by SPMM collision after installation, any displacement along the bolt will still generate shear resistance between the resin and the ribs on the bolt's surface, and between the resin and the rifled borehole surface.

Inspectors argue that it is the mines' responsibility to prove the integrity of the damaged support system, and that, in the absence of such proof, a more conservative approach is warranted. Currently, no published research considers the effectiveness of full-column grouted bolts once damaged by SPMMs.

1.2 Problem Statement

Field stresses in shallow mining environments are low. Vertical stresses are transferred to the pillars from mined-out areas, whilst the horizontal stresses act to clamp the hangingwall into a self-supporting beam (Jager & Ryder, 1999). In shallow mining environments, these horizontal clamping stresses in the roof may be insufficient to stabilise large keyblocks, and keyblock failure may occur under gravitational loading. In such cases, artificial support is required to reinforce and stabilise the hangingwall (Hoek, 2000). The installed artificial support in low-stress mining environments, with minimal dilation, must be stiff enough to develop adequate resisting forces with very little deformation (Jager & Ryder, 1999).

Damage to the bolt and resin column may result in the inability of sufficient load transfer to occur between the rock and the bolt, potentially reducing the stiffness and strength of the support system. This may lead to unexpected deformation of mining excavations or a FOG. Since most of the bolt is anchored within and obscured by the rockmass, extensive damage to the resin column and bolt may not be apparent to the observer. It is surmised that damaged bolts may pose a potential safety hazard for mine personnel. After being damaged, the support may fail to meet the specified load-bearing capacity outlined in the design specifications. In addition, mine personnel may unknowingly be exposed to unstable conditions.

Due to the nature of the typical drill and blast mining process, excavation profiles and stoping heights are irregular. Damage to the protruding parts of installed bolts by an SPMM is often unavoidable. The proactive replacement of damaged support is justified, considering the lack of evidence to prove the effectiveness of the damaged bolts. This research was undertaken to determine the extent of the damage caused by SPMM collisions with installed bolts. The effectiveness of damaged bolts needed to be established.

1.3 Justification for Research

1.3.1 Safety of Underground Mine Personnel

Despite pressure from inspectors and revised mine standards, damaged bolts are often not replaced due to various reasons. These reasons include the unavailability of the necessary services in the roadways far from the active mining fronts, machine breakdowns, production pressure, cost and discipline. When this lack of replacements is identified by the mining inspectors, stoppage of the section, or in some cases, even the mine, has resulted, as indicated by the questionnaire results under heading 3.3.1. This adds a further financial implication and time constraint to mine production. Currently, there exists no definitive proof that these damaged bolts are still effective. By not replacing the damaged bolts, mine personnel may be exposed to defective support systems and an increased FOG risk.

1.3.2 Financial Implications

A 2018 benchmark study was conducted by the Author at a well-established mine in the Eastern Bushveld mining 300 000 tonnes per month on average. This mine has a planned support density of 0.44 bolts per m^2 and a planned monthly support cost of R43.89 per m^2. The study found that the actual monthly support density averages 0.64 bolts per m^2, with an average monthly cost of R64.84 per m^2. It is estimated that at least half of the 45% additional installations are replacements due to SPMM damage. If this research proves that damaged bolts are still effective, it will result in significantly fewer bolt replacements with associated support cost savings and optimised use of shift time and equipment.

1.4 Research Objectives

The primary objective of this experimental research project was to determine the extent of damage inflicted on installed full-column grouted bolts by SPMM collisions. The effectiveness of these damaged bolts was evaluated using the push test method and compared to undamaged control samples. All aspects of the research were conducted on hard rock mines.

1.5 Research Methods

The research objectives were achieved using a detailed investigative methodology. It was conducted through qualitative and quantitative research methods.

1.5.1 Qualitative research

Questionnaire

A short, fifteen-question questionnaire was distributed throughout the industry. The main objective was to gain insight into the type of bolt damage observed, and how this damage affected the bolt efficiency.

Underground Observations

Underground observations were conducted at three participating mines to inspect the condition of the installed support and SPMM damage experienced. The site visits were conducted as part of the underground tests and were aimed at determining the following aspects:

a) Individual mines' support design criteria (do mines consider pretensioning and system stiffness as essential parts of the design criteria).

b) The different types of damage observed to installed bolts; and

c) The extent of the problem (how often bolts are damaged).

Literature review

Although no research has been conducted on the effects of SPMM damage, a comprehensive body of related literature has been published over the past fifty years. These publications were reviewed to gain insight into the functional mechanics of roof bolts. Although this research project is focused on hard rock mines, literature from coal mining and civil engineering fields has also been used as supplementary material.

The following aspects of support design were researched through a literature review to establish a clear definition of “effective” support:

- the function of roof bolts;
- resin bolt load transfer mechanisms;
- pretensioning of roof bolts;
- roof bolt stiffness; and
- resin bolt failure mechanisms.

1.5.2 Quantitative research

This experimental research was conducted to achieve to following objectives:

- to visually examine the extent of damage caused to the resin column by SPMM collisions; and
- to conduct comparative laboratory tests to determine the degree of damage to the bond strength of the support system.

Tests were conducted simultaneously with the qualitative research to accomplish the objectives. The laboratory push test method was used to determine the strength of the damaged bolts (Aziz et al., 2006; Aziz et al., 2014; Ma et al., 2017).

1.6 Structure of the Research Report

This research report consists of six chapters. Chapter 1 introduces the research topic, with a brief description of the background and context of the study. It dealt with the problem statement and explained the research objectives and methods of analysis.

Chapter 2 consists of the literature survey, based on the research objectives. An overview of the research topic is provided as an introduction. This is followed by a brief review of related historical developments, the theoretical framework and key concepts. Examples and pertinent findings of the chosen methodology are presented. Key debates and controversies are discussed to the extent that they are relevant to this research topic, followed by a review of recent studies and gaps in published literature.

The research strategy and design are detailed in Chapter 3, with an explanation of how data were collected, validated and analysed. Photographs of the test samples and testing equipment are provided. The chapter details the problems encountered and the variations tested.

Chapter 4 presents the recorded data from the various research methods and test methods employed, with Chapter 5 detailing the data analysis. Chapter 6 provides the relevant conclusions and recommendations. Possible future research and limitations of the findings of the current research are also provided in this chapter.

2 LITERATURE REVIEW

2.1 Historical Development

The earliest reports of rock bolting in a quarry were in 1872 in the United Kingdom. The use of bolts as artificial ground support was first reported in a colliery in Germany in 1918. Mechanical rock bolts were used in the United States by 1927. In the 1940s, Norway began developing rock bolts for economic purposes. (Jalalifar, 2006).

After World War II, the use of rock bolting increased significantly, driven by the increase in the mechanisation of the mining sector at that time. In 1947, rock bolting technology was advanced to an industrial scale. This advancement occurred because the United States Bureau of Mines introduced rock bolts as support to combat the growing accident rates due to FOGs (Minova International Limited, 2006; Jalalifar, 2006). The use of rock bolts accelerated around 1949 after the steel shortages caused by the war had reduced. Dolinar and Bhatt (2000) write that at least 430 collieries were using rock bolts by the end of 1949. Thomas et al., (1949) note that, although some mines were already experimenting with mechanical shelled anchors at this time, most bolts in use were slot and wedge anchored. The slot and wedge bolt consisted of a 130 mm long split section on the distal end, fitted with a wedge. When the bolt was hammered into the hole, the wedge was driven into the slot, thereby anchoring the bolt inside the hole.

By 1952, mechanical end-anchored bolts had replaced slot and wedge-type bolts as the preferred support type due to improved anchorage and reliability, and annual usage increased to 25 million. Due to the poor anchorage of the mechanical end-anchored bolts in weak rock, implementation was not as successful in the United Kingdom at the time. It was identified that, in weak strata, the shell of the mechanical end-anchored bolts would slip, thereby loosening and becoming ineffective. It was identified that full-column grouting improved bolt anchorage and shear resistance (Thomas, 1954). This finding initiated research into the possibility of placing the bolt into a material to aid anchorage and prevent slippage of the mechanical anchor. In 1956, injectable epoxy resin was first introduced in the United States (Minova International Limited, 2006). Development of a system to fully embed the bolt in a material that would set shortly after installation was initiated. The first resin capsule system was produced in Germany in 1959, which contained a resin cartridge made of glass that broke as the bolt was installed. Due to its high production cost, the use of resin as an anchoring mechanism remained limited until 1980, when the plastic film capsule was developed.

The coal industry started using fully grouted bolts in the late 1960s, and by the 1970's fully grouted dowels were being used in Europe. Mechanical end-anchored bolts, or point anchor bolts, require the bolt to be tensioned upon installation to induce friction and increase shear resistance along strata layers. Full-column grouted bolts, on the other hand, provided higher lateral stiffness and could resist shear movement with or without being tensioned. (Minova International Limited, 2006).

Today, full-column grouted resin bolts are the predominant support type used in underground mines. Since the introduction of the New Austrian Tunnelling Method (NATM) in the 1960s, significant research has been conducted to understand the functional mechanism of full-column resin grouted bolts, which led to their relevant advances. NATM is a tunnel construction technique that promotes using the inherent strength of the rockmass to support itself, as opposed to the use of installed support such as steel sets. In the next section, some of this research will be reviewed to gain an understanding of the key concepts and theories of full-column resin grouted bolts.

2.2 Key Concepts, Theories and Studies

2.2.1 The functional mechanics of full-column resin-grouted bolts

A basic understanding of how rock masses fail is required to understand how rock bolts work. At shallow depth. rock around underground mine tunnels typically fails in shear along structures. In deep-level mines, the prevailing stress concentrations around tunnels and stopes cause the rock mass to fail. If the stresses around the excavation are higher than the strength of the rock, extension failure of the rock will occur with lateral dilation. In shallow mining conditions, where there is typically a lack of high horizontal forces acting on the excavation roof, a relatively large tensile zone is created above the immediate roof. Under these conditions, shear displacement may be caused by sliding along joint planes or sagging of roof beams under gravity.

The rock mass is generally much weaker in tension and, in shear, where there are discontinuities. These properties can be strengthened by bolting. Bieniawski (1984) stated that “the principle of rock reinforcement is to make greater use of inherent rock mass strength to enable the rock to support itself”. Rock bolts are installed as reinforcement into the rock mass, in a similar manner to installing steel rebar reinforcement in a reinforced concrete structure. The rock bolts strengthen the rock mass from within, so that the rock itself becomes part of the supporting structure.

Windsor (1997) classified rock bolts according to their anchoring mechanisms as continuously mechanically coupled (CMC), continuously frictionally coupled (CFC), or discretely mechanically or frictionally coupled (DMFC). A friction stabiliser, or Spit Set, is an example of a CFC bolt and will not be discussed in this report.

Mechanical end-anchored roof bolts and all energy-absorbing bolts are DMFC bolts since they are anchored in the hole at one or more discrete anchor points. An ungrouted end-anchored rock bolt is typically anchored in a borehole by an expansion shell. The bolt must be tensioned by rotating the nut, which runs up the threaded portion of the bolt and presses against a bearing plate. By doing this, an axial load is generated along the length of the bolt between the mechanical anchor at the toe and the bearing plate at the collar of the hole. During axial loading, the rock bolt experiences identical elongation along the length of the bolt. The axial load is constant and is equal to the applied load along the full length of the bolt. The end-anchored bolt only experiences shear stress at the anchor, since it is debonded along its length, as shown in Figure 2-1 (Li, 2018).

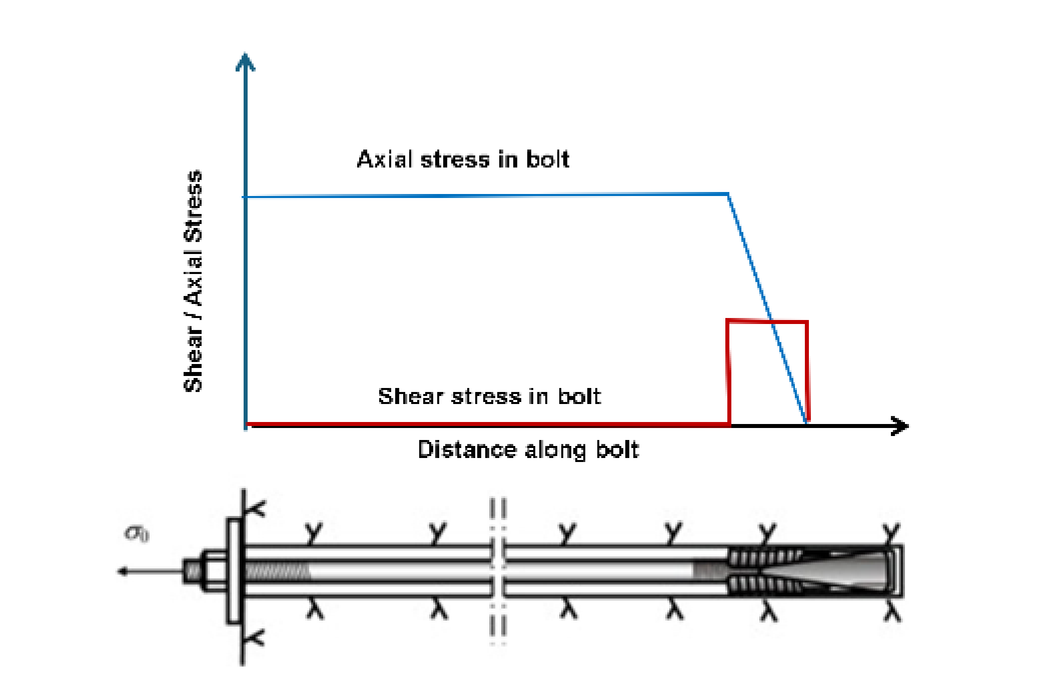


Figure 2-1: Stresses along a point anchored mechanical bolt (Li, 2018)

The load-bearing capacity of the mechanically end-anchored bolt is correlated to the mechanical anchor, since anchorage is only achieved through frictional resistance between the mechanical shell and the borehole surface. Failure of the system is dictated by its weakest link, i.e. the maximum frictional resistance supplied by the mechanical anchor, the strength of the bearing plate, and the tensile strength of the bolt thread. The yield load of the bolt thread is typically 70% - 80% of the yield strength of the bolt (Li, 2018). Mechanical expansion shells work well if anchored in hard rock but are prone to slippage in softer rock (Thomas, 1954; Jalalifar, 2006). These bolts are prone to loosen due to blasting vibrations or stress relaxation, in which case the anchorage is lost, and the bolt becomes wholly ineffective. Frequent re-tensioning of these bolts is necessary to ensure their ongoing effectiveness (Li, 2018; Minova International Limited, 2006).

Fully encapsulating a resin bolt within a resin or grout medium ensures that the bolt is continuously mechanically coupled to the rock mass by the resin, making it a CMC bolt. The surface of the resin bolt is studded with short ribs to increase the shear strength of the assembly. Drilling the hole in the rock with a button drill bit ensures that the surface of the hole is rifled for the same purpose of increasing the shear strength between the resin and the rock. The result is a substantial interlock between the resin and the surface irregularities along the bolt and borehole wall, as shown in Figure 2-2. This mechanical interlock provides the anchorage for the bolt.

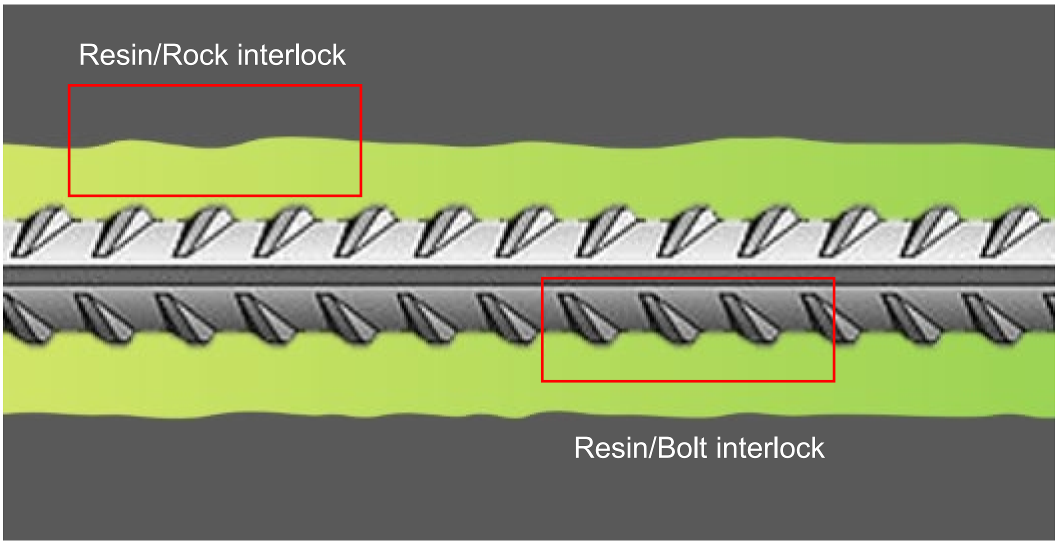


Figure 2-2: Diagram showing the interlock between resin, bolt and rock surfaces.

When movement occurs within the rockmass, be it dilation due to fracturing, separation along bedding planes or shear movement across geological structures, the load is transferred from the rock to the bolt and back into the rock, via the resin. Serbrousek and Singer (1987) found that this is possible because the mechanical interlocking between the irregular surfaces generates high shear resistance under shear and axial loading. As a result, even a small rock movement will increase the axial stress and shear resistance along the fully grouted bolt.

When the full-column grouted resin bolt is loaded, longitudinal displacement occurs along both the grout and the rock but exponentially decays away from the discontinuity during elastic deformation (Aydan et al., 1985; Holmberg, 1991; Li, 2018). This distribution is shown in Figure 2-3. In the figure, d_0 represents the diameter of the rock in which the longitudinal displacement is zero, and x is the distance from the loaded end of the bolt (typically at the collar of the borehole) into the rock mass.

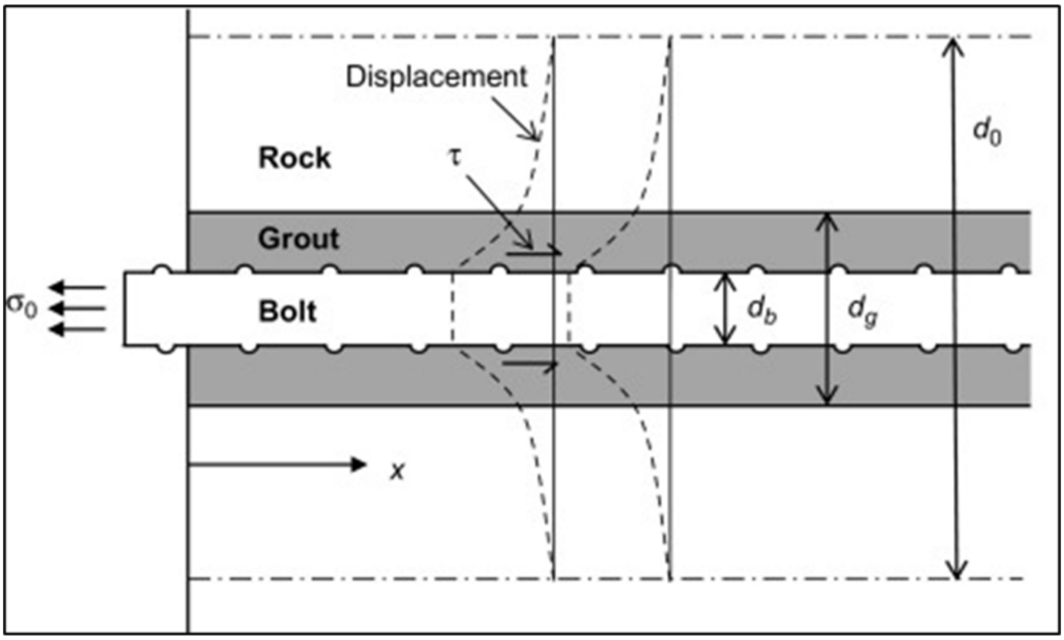


Figure 2-3: Longitudinal displacement distribution of the rock, grout and bolt (Li, 2018).

Elastic deformation refers to the stage before any bond failure occurs between the rock and the resin, or between the resin and the bolt. During this stage, axial stresses decrease exponentially away from the loading point because of the increase of shear stresses acting along the interfaces, as shown in Figure 2-4. If the applied load is sufficiently high, bond failure will occur at the point of loading and will propagate toward the nearest end of the bolt if the applied load increases. Li et al. (2014) state that laboratory tests concluded that at tensile failure of the bolt shank, the debonded portion within cement grouted bolts was approximately 150 mm. The shear stresses acting axially along the bolt are determined by the degree and extent of the bond failure. The shear stress is lowest at the loading point since this region is debonded and will increase with distance away from the loading position as the bond becomes more competent. The peak shear stress is concentrated at the end of the debonded position, where interlock is still achieved. The axial tensile stress is highest at the loading position and linearly decreases until the end of the debonded region, and then follows an exponential decrease. In Figure 2-4, S_p indicates the peak shear strength, S_r indicates the residual shear strength in the debonded section, and X_2 indicates the end of the debonded section. Figure 2-5 is a conceptual model by New Concept Mining, showing the rapid decay of the shear stresses along the bolt from the point of loading.

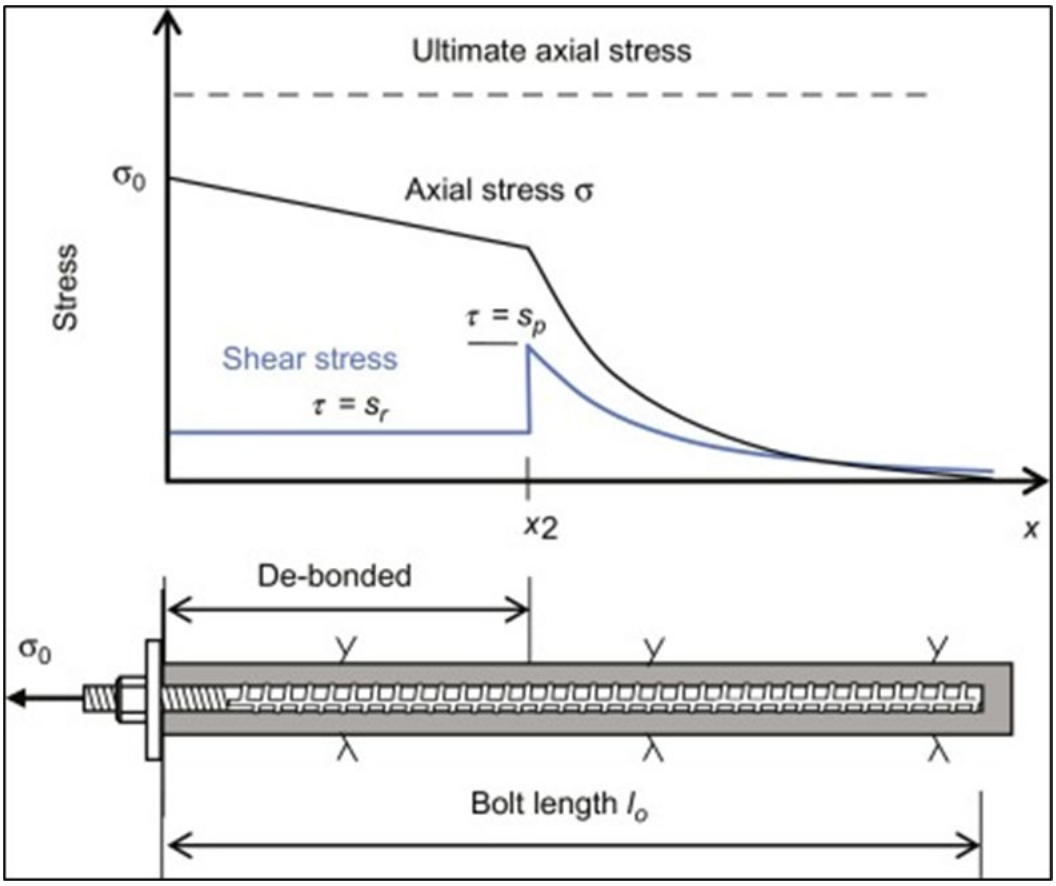


Figure 2-4: Stresses along a fully grouted bolt subjected to load increase at the bolt head (Li, 2018).

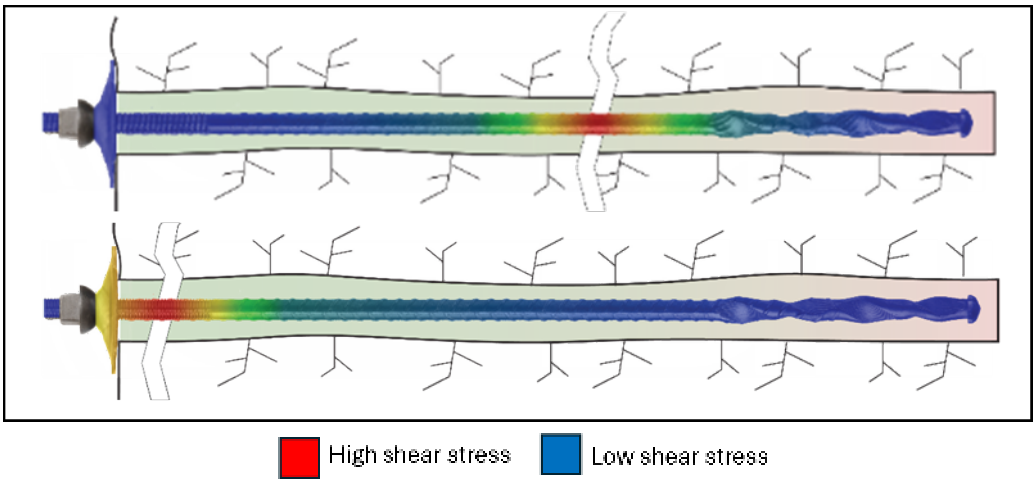


Figure 2-5: Conceptual model illustrating rapid decay of shear stress along the full column grouted bolt from the point of loading (New Concept Mining, 2024).

This rapid strain and shear stress decay, as shown in Figures 2-3 and 2-4, was also described by Forbes (2020) using distributed optical fibre strain sensing during in-situ pull tests on bolts with varying encapsulation lengths. Forbes (2020) noted that a uniform strain was recorded between the bolt head and the encapsulated section. This agrees with the findings of Li et al. (2014) as shown in Figure 2-1. The strain exponentially decreased from the point of encapsulation. Forbes (2020) was also able to show the rapid decay of the shear stress along the bolt past the point of encapsulation. His strain and shear stress results are provided in Figures 2-6 and 2-7.

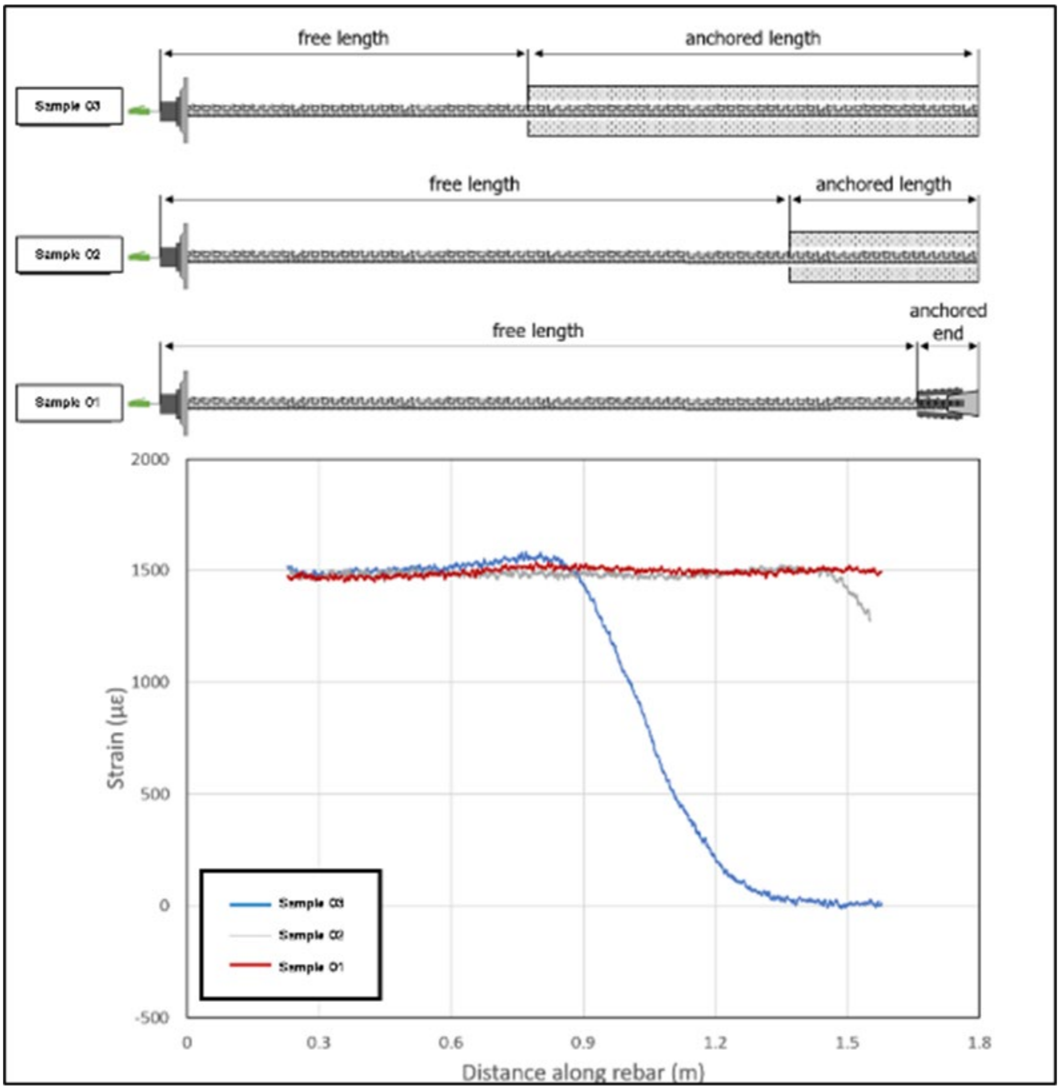


Figure 2-6: Strain distribution comparisons between three different encapsulation lengths (Forbes, 2020)

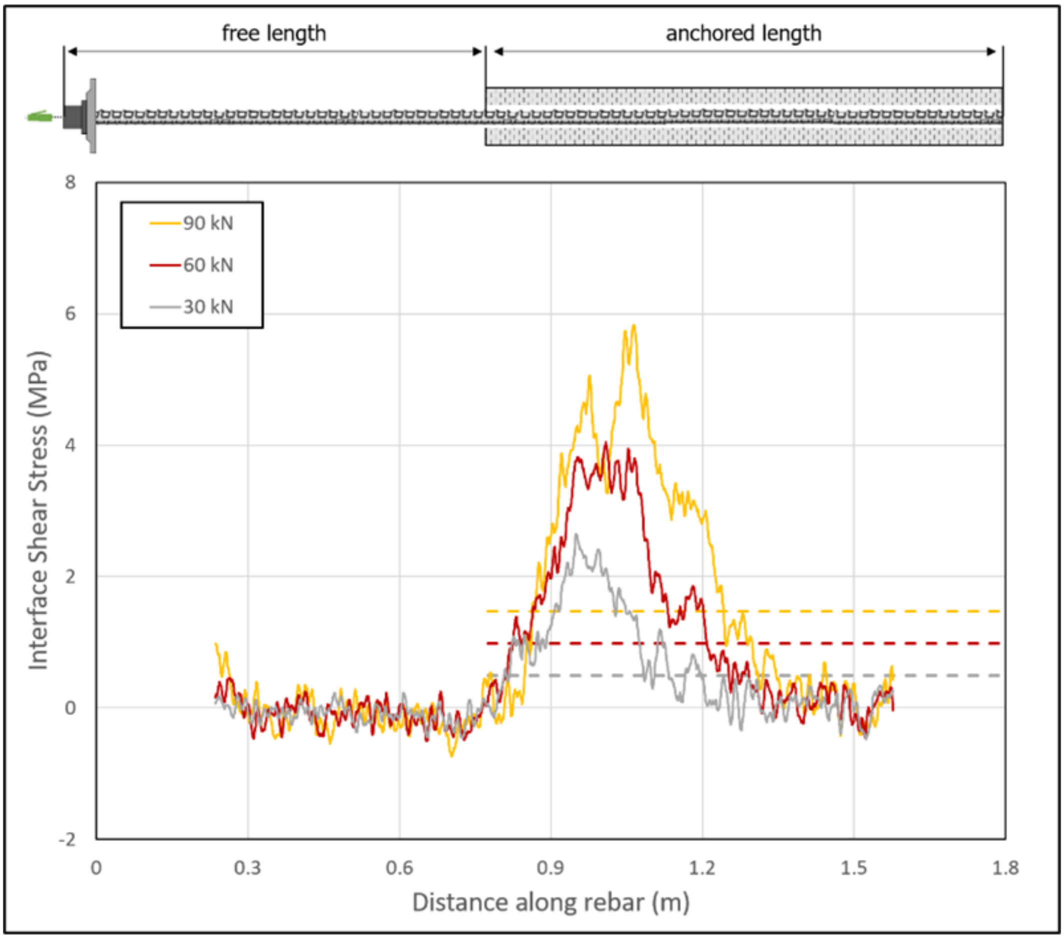


Figure 2-7: Shear stress distributions along a bolt with partial encapsulation (Forbes, 2020)

The ability of the fully grouted system to transfer load as described above is dependent on the resin annulus, the resin shear strength, the rebar surface profile and mechanical properties, and the roughness and strength of the rock wall (Serbrousek and Singer, 1987; Kilic, 1999; Aziz, 2004; Jalalifar, 2011). The actual adhesion of the resin to the bolt is very weak. Jalalifar (2011) notes that successful bonding between the bolt, the resin and the rock is dependent on several factors, including the adhesion of the resin, friction between the bolt/resin and resin/rock interfaces, and the mechanical interlocking provided by the surface irregularities. Aziz (2002) assessed the performance of various bolt profiles with regard to load transfer mechanisms in a laboratory under Constant Normal Stiffness (CNS) conditions. The study concluded that, under the normal confining stress range of 0.1 MPa to 7.5 MPa, the shear strengths of the bolts were similar. This would indicate that resin shear resistance, rather than adhesion, plays a vital role in bolt performance. Since the bonding strength of the resin is effectively zero when normal stress is removed, it is apparent that the confining pressure produced by the shearing of the bolt ribs through the resin has a major influence on the level of friction and interlocking action at the bolt-resin interface.

Load transfer between the resin bolt and the rock occurs through suspension, shear restraint and axial restraint. In most cases, the reinforcement ability of the resin bolt is reliant on a combination of these load transfer mechanisms occurring simultaneously, in that shear and axial loading occur at the same time as a result of the same rock movement (Forbes, 2020). The suspension model considers a weak layer of rock that is suspended from, or bolted to, a stronger layer above. The load of the weak, lower layer/s is transferred to the bolt and back into the stronger rock layer above. Shear restraint considers that a bolt installed through a plane of weakness will directly oppose any shear movement across that plane. This restraint is provided through crushing of the resin and some bending of the bolt (Minova International Limited, 2006). The shear movement increases the axial stress along the bolt, which is transferred back into the rock through the resin. Axial restraint is provided by the bolt resisting axial dilation of the rock mass associated with the extensional and shear movements. Axial restraint provided by tensioning of the bolts increases the normal forces acting on the shear planes, thereby increasing the shear resistance. It can also strengthen the rock mass by providing a small confinement, enabling it to be self-supporting.

2.2.2 Bolt rib configuration

The interface shear stresses are greatly affected by the geometry of the bolt and borehole and are more important than the grouting medium. The rib orientation, size and spacing dictate the roughness of the bolt surface and therefore also the degree of interlock achieved between the bolt and the resin (Jalalifar, 2011). Aziz (2002) found that deeper, wider rib profiles generate higher normal stresses than shallow, narrow ribs, especially under low confinement and constant normal stiffness conditions. The deeper and widely spaced rib profile offers a higher shear resistance because of the increased dilation. This conclusion was supported by later work done by Aziz et al. (2009). Campbell et al. (2004) tested nine different bolt profiles and concluded that off-centred and wiggle bolts were superior in preventing gloving and unmixed resin in fully grouted rock bolts. Finger gloving, or simply gloving, is the term used when the plastic cartridge of the resin capsule partly or entirely encases a length of the resin bolt during installation (Campbell, et al., 2004).

2.2.3 Pre-tensioning of bolts

Pre-tensioning of bolts is essential when installing mechanical end-anchored bolts to ensure proper activation of the mechanical shell and anchorage of the bolts. The two-speed resin system allows for the pre-tensioning of full-column resin bolts. The achieved pretension loads, however, are small, usually only around 3 t to 5 t. The weight of the rock within a typical bolted height of 1.5 m is likely to exceed 45 t/m^2. The horizontal stress acting across the roof, even in shallow mining depths, is likely to be more than 200 t/m^2 or 2 MPa. The role of reinforcement is to strengthen the rock mass to improve its natural stability (Li, 2017). Tensioning of bolts aids in clamping bedding and natural joints, which in turn increases the shear resistance across these structures (Lang, 1961). The most effective strengthening is achieved if the bolts can be installed before inelastic deformations occur (Hoek & Brown, 1980). This improves the natural stability of the roof or wall and prevents failures at the skin of the excavation, which would reduce the natural horizontal forces acting across the excavation. If the immediate roof is allowed to unravel, these horizontal clamping forces are redistributed higher up into the roof, which allows for further FOGs where the clamping forces have been reduced.

Since a typical steel bolt is approximately fifteen times stiffer than the rock, a small amount of axial deformation can lead to a complete loss of pretension. Several studies have been conducted on the tensioning of bolts (Yassien et al., 2002; Unrug et al., 2004) and found that when fully grouted bolts are tensioned, the tensioned zone only extends to approximately 0.5 m from the nut. Ranjbarnia et al., (2014) concluded that tensioning of bolts increases their effectiveness and efficiency, but that this should be done with caution since it reduces the bolt yieldability. Canbulat et al., (2006) conducted short encapsulation tests on 25 bolts to analyse the effect of tensioning on the resin bond strength. The results indicated that non-tensioned roof bolts achieved significantly greater bond strengths and that the non-tensioned bolts were significantly stiffer than the tensioned bolts. These results may have been influenced by the short encapsulation lengths used.

Bolt stiffness is directly proportional to the area of the bolt; thus, the stiffness increases significantly with an increase in bolt diameter. With mechanical end-anchored bolts, the bolt is anchored at the top, with the remainder of the bolt being decoupled, or free length. For this reason, if the length of the bolt increases, the stiffness of the mechanical end-anchored bolt decreases. Full-column resin bolts, on the other hand, do not have a free length and become highly stressed in areas where movement occurs. The full-column resin bolt system is significantly stiffer than mechanical end-anchored bolts, for which pre-tensioning was originally used. It has been shown in this literature survey that, due to this system stiffness, the resin bolt rapidly generates high shear stress in response to rock movement in the area where movement occurs. It is therefore often claimed that pre-tensioning of resin bolts offers little advantage (Minova International Limited, 2006).

Several papers have been published that argue cases for and against the pre-tensioning of bolts. The need for mechanical end-anchored bolts to be tensioned is well-known and need not be discussed in detail. Frith and Thomas (1998), argued for the pre-tensioning of full-column resin bolts. They noted that preloads significantly reduced roof delamination in the lower 0.5 m to 0.8 m of the roof beam, and thereby dramatically altered roof behaviour. Quoting Euler's critical load or buckling theory (Timoshenko & Gere, 1961), they argued that small vertical loads applied to the beam can add sufficient mechanical advantage toward resisting high horizontal forces. Gray and Finlow-Bates (1998), on the other hand, commented that full-column grouted bolts with good load transfer ability are just as effective as pre-tensioned bolts. They argued that even at high preloads of up to 100 kN, a resulting clamping stress of approximately only 70 kN was imparted on the roof. This confining pressure is minuscule compared to the in-situ horizontal stresses acting across the roof, which are at least 100 times greater. It must also be considered that this applied load has been shown to dissipate quickly into the rock beyond the bolt head. It appears to be generally agreed that full column resin bolts do not require large preloads to be effective (Maleki, 1992; Peng, 1998; Frith and Thomas, 1998). Following laboratory tests, McHugh and Signer (1999) concluded that pre-tensioned full column grouted bolts did little to strengthen natural rock joints.

2.2.4 Installation procedure, annulus and gloving

Successful resin bolt installation is dependent on several factors. The length of the spinning cycle and the rotational speed of the installation equipment determine the number of revolutions the resin capsule will be subjected to. In South Africa, the typical required spinning speed of roof bolters is roughly 450 revolutions per minute. For a 15-second spin cycle, this produces approximately 110 revolutions per installation. When using hand-held compressed air drills, the spinning speed can be much lower with a larger standard deviation. This may result in either under- or over-spin. Under-spin implies that the resin was not spun long enough during installation and that the resin and catalyst were not sufficiently mixed, resulting in unmixed portions of resin along the bolt length, which will not harden. Over-spin occurs if the bolt is spun whilst the resin is gelling, which will cause the resin to crumble whilst hardening (Minova International Limited, 2006). Another significant factor in the performance of full column resin bolt installations is the hole size or resin annulus (Canbulat, et al., 2006). The annulus is described as half the variance between the hole and bolt diameters. Figure 2-8 is a diagram illustrating the resin annulus.

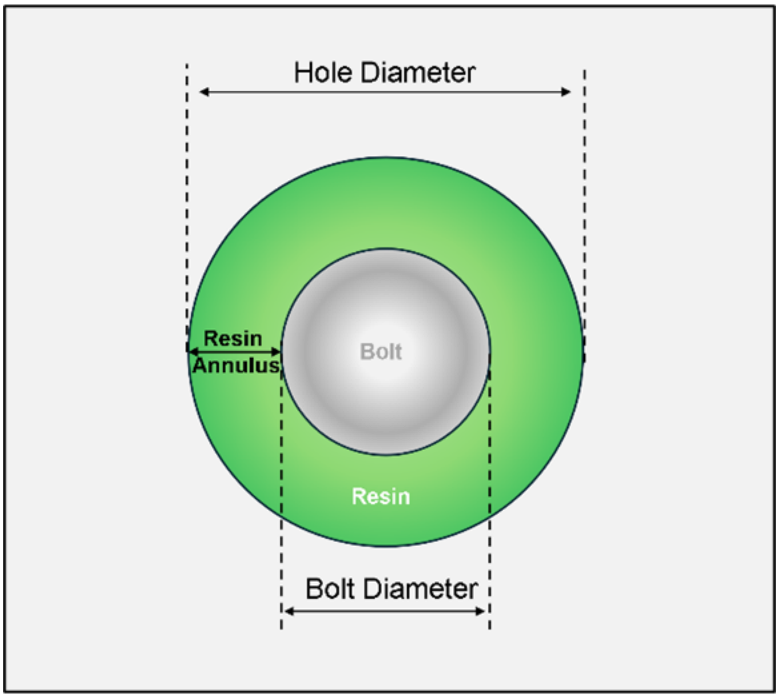


Figure 2-8: Resin annulus

Since the full-column resin bolt system works on load transfer that occurs between the bolt and the rock, the annulus, which essentially is the distance between the bolt and the rock, plays an important role in system performance and stiffness. Tests have shown that the desired annulus should be between 2 mm and 4 mm. When the annulus is lowered to below 2 mm, it harms the bond strength. An annulus of 3 mm to 5 mm is usually acceptable in hard rock operations across South Africa. Annuli larger than 6 mm are not encouraged as this yields low bond strengths and lowers system stiffness (Canbulat et al., 2006; Hagan, 2003; Dolinar and Bhatt, 2000; Mark, 2000).

Large hole annuli contribute to the occurrence of finger gloving (Dolinar & Bhatt, 2000). Gloving typically occurs due to poor installation procedures or because of large annuli. Gloving results in inadequate mixing of the resin surrounding the bolt. Campbell et al., (2004) commented that gloving is a common problem related to all resin and bolt manufacturers. It occurs in all geological conditions and happens whether the bolt is installed with hand-held or mechanised equipment. They also noted that the effects of gloved but well-mixed resin may be small, but the unmixed portions do not reinforce the roof. Gloving leads to poorly mixed resin, which is unable to harden and provide the required interlock and shear stress generation. Figure 2-9 shows the gloving of a bolt which occurred due to a large annulus.

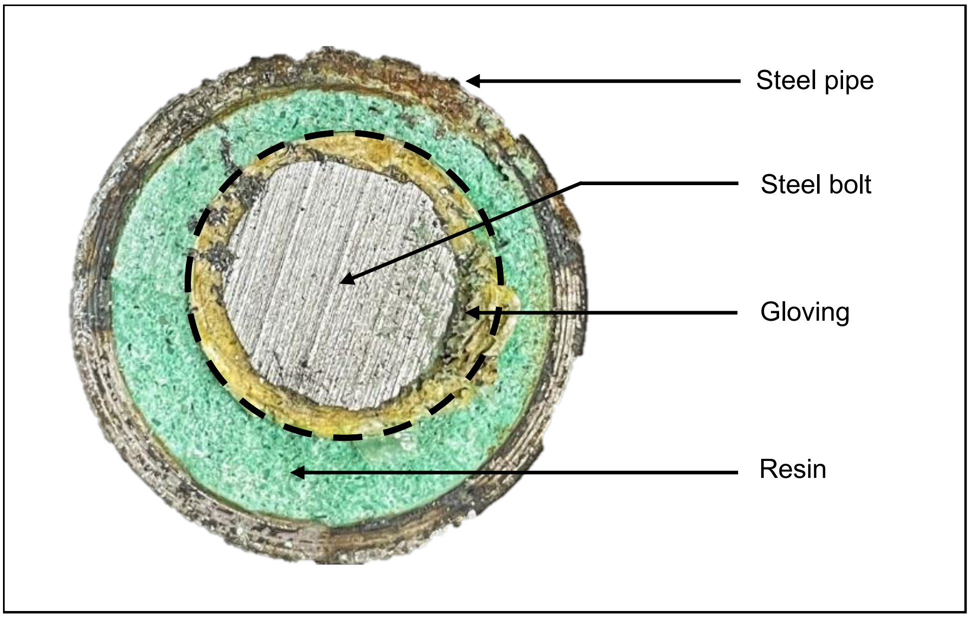


Figure 2-9: Image showing gloving in a section of pipe with poor annulus.

Campbell et al. (2004) determined that a pressure front develops inside the resin capsule ahead of the bolt being installed. They reported that the flat end of the bolt acts like a piston that is hydraulically pressurising the resin capsule. The capsule, in turn, shortens and expands radially until it meets the borehole walls. In addition, the catalyst tube within the resin cartridge also becomes flattened against the borehole wall. This allows the bolts to be spun within the cartridge without making contact or being able to shred the catalyst or cartridge. The result is a combination of mixed and unmixed resin. The larger the annulus, the more room the capsule has to expand and the higher the probability of gloving.

2.3 Resin bolt failure mechanisms

Using the tensile strength of the bolt and the bond strength of the resin, a critical bond length can be calculated for every full-column resin system. The critical bond length is defined as the longest encapsulation length of a bolt that can be pulled out of the resin without breaking the bolt shank. More simply put, it is the length of encapsulation at which point the resin bond strength becomes equally strong, or stronger, than the bolt's tensile strength. A system in which the encapsulation, or anchorage length, is less than the critical bond length, will result in the bolt being pulled out of the borehole at loads less than the tensile strength of the bolt. If the critical bond length is achieved, failure occurs because of the failure of the bolt shank. When a full-column resin bolt is loaded by a single shear plane or in a pull test, it results in an uneven distribution of the axial stress within the bolt at the loading position. The axial stress is highest at the loading position and dissipates with distance from the loading point. If the stress is sufficient, the bolt will start to yield at the point of loading. This loading propagates away from the loading point until the bolt ultimately fails in tension at the point of loading. This is referred to as necking (Li, 2018). Stilborg (1994) has shown through laboratory tests that elongation of 20 mm to 30 mm can occur in 20 mm diameter (200 kN) full-column grouted bolts subjected to a single fracture zone, before failure. Li (2018) demonstrated that 20 mm diameter fully grouted rebar bolts experienced approximately 45 mm of displacement before failure in both tensile and shear tests.

Debonding refers to a breakdown or deterioration of the bond at an interface. When debonded, shear resistance, mechanical interlock and load transfer ability is reduced. When the shear forces exceed the interface strength, the bond is completely broken with no contact between the interfaces and no frictional resistance is supplied. The latter case is referred to as decoupling. Under laboratory conditions, failure typically occurs along the bolt/grout interface. If rock, instead of a steel tube, is used to house the installed bolt, then failure may occur along the rock/grout interface. This type of failure is dependent on the strength of the rock. If the rock is weak, failure may occur along the grout/rock interface because the mechanical interlock breaks down at low loads. In hard rock the mechanical interlock and resistance to shearing through the rock asperities would generally be greater (Aziz, et al., 2006). Due to Poisson's effect, when the bolt is loaded axially, it stretches longitudinally and contracts laterally. This contraction results in a reduction of the bolt diameter, leading to a possible decoupling of the bolt near the loading point, and an increase in debonding length, until the stress is sufficiently dissipated.

When a full-column resin bolt is loaded in shear, the bolt will bend. This bending causes crushing of the resin beneath the bolt, and as a result, the bolt may ultimately fail in tension, even though it was loaded in shear. For this reason, the tensile and shear strength of bolts are similar, as shown in Figure 2-10.

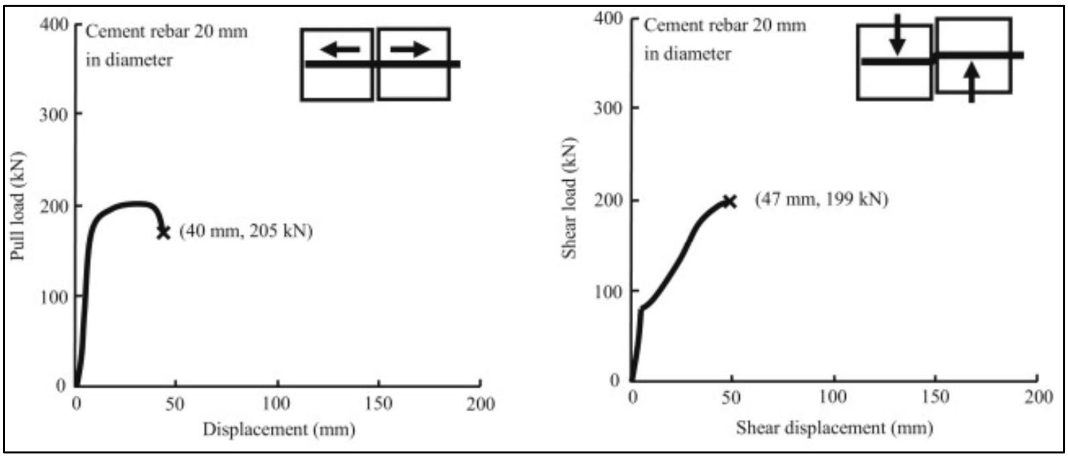


Figure 2-10: Load/displacement graphs of fully grouted rebar bolts under pull and shear testing (Li et al., (2014)).

Several push test studies conducted (Ma et al., 2017; Hillyer et al., 2013; Aziz, 2014; Aziz et al., 2006) used 100 mm segment lengths, which proved more effective than the traditional 75 mm segments by including more bolt ribs per segment.

2.4 Data Collection Methodologies

The common testing methods used for the analysis of resin and resin bolt performance include:

- in-situ pull tests (Canbulat, et al., 2006) (Aziz, et al., 2006) (Dolinar & Bhatt, 2000) (Singer, 2000);
- in-field and laboratory short encapsulation pull tests (Mark, 2000) (Bierman, et al., 2019) (Aziz, et al., 2016);
- dynamic drop testing (Knox & Berghorst, 2019);
- laboratory shear tests (Khaleghparast, et al., 2023) (Stjern, 1995), (Li, et al., 2014);
- dynamic shear tests (Khaleghparast, et al., 2023);
- double shear tests (Forbes, 2020) (Hagen, et al., 2019) (Jalalifar, et al., 2019) (Aziz & Jalalifar, 2007);
- multi-directional shear tests (Chen, 2014) (Knox & Hadjigeorgiou, 2023); and
- push tests (Hillyer, et al., 2013) (Aziz, et al., 2006) (Aziz, et al., 2009) (Ma, et al., 2017).

This literature study concluded that push tests often yield higher shear strength capacities for fully grouted rock bolts compared to pull tests (Ma, et al., 2013). This is mainly as a result of the Poisson's ratio effect in the steel rebar:

- **Push Tests:** Applying compressive force causes the bolt to expand laterally, enhancing the bond between the bolt and the grout, leading to increased load-bearing capacity; and

- **Pull Tests:** Tensile force causes the bolt to contract laterally, potentially reducing the bond strength and resulting in lower load-bearing capacity.

Since the purpose of this experimental study is to inspect the extent of damage caused to the bolt and resin column, the push test method was used. This method allowed for the cutting of the bolts into small segments so that physical examination of the resin could be conducted. The individual segment's bond strength could also be determined. The study aimed to determine the extent of damage by comparing the damaged samples' push test results to those of the undamaged control samples.

2.5 Gaps in the Literature:

Many studies have been conducted to demonstrate full-column grouted bolt behaviour in shear, double-shear, tensile and push tests. Despite 50 years of research and development of resin and resin bolts, no studies are available on the effectiveness of damaged full-column grouted bolts.

2.6 Chapter Summary

The role of resin bolt geometry, hole annulus and installation procedures has been investigated in detail during the last 50 years. This literature survey concluded that:

- Full-column resin bolts are significantly more successful in supporting roof strata than other types of bolts, where a stiff support system is required;
- The load transfer mechanism of full-column resin bolts is well-researched and well-understood;
- Load transfer, and anchorage, of the full column resin bolt occurs because of interlock between the bolt and borehole surface irregularities through the resin;
- Due to the continuous mechanical coupling, the full-column resin bolt system is very stiff as compared to other rock bolts;
- Any movement along the bolt leads to rapid increases in the resisting shear stresses along the bolt, which is focused on the point of movement. These stresses are redistributed back into the rockmass through the resin;
- The shear stress rapidly decays away from the point of movement;
- Parameters such as bolt profile, resin strength, hole annulus and rock strength influence the bolt stiffness and overall effectiveness;

- Push testing is a viable testing method for this study, but the typical 75 mm section lengths should be increased to 100 mm to ensure that enough ribs are included in each section;
- Push test results are typically higher than pull test results, due to the compression effect on the bolt and resin column. Since comparative results, rather than absolute values, are the aim of this experimental research, push testing is deemed adequate.
- According to Li et. al., (2014), the debonded length is expected to be approximately 150 mm if the load equals the bolt tensile strength; and
- Failure under lab conditions is expected to occur at the bolt/grout interface.

3 RESEARCH APPROACH

3.1 Introduction

The load transfer along bolts occurs through the shear resistance of the resin and the mechanical interlocking through the contact surfaces. It is thus important to be able to examine the full length of the encapsulated bolt to determine the extent of the SPMM impact damage on the bolt and the grout column. An important aspect of this research is the ability to test the bond strength of the resin along the length of the damaged bolt. This must be conducted to compare the results with those of undamaged bolts to determine what effect the damage has on the resin, if any, and how much of the full column length is affected by the collisions. Over-coring is expensive and challenging, with a low probability of success over the bolt length of 1.5 m or 1.8 m. Pull tests (ISRM, 1974) are also not deemed suitable, since an integral part of the study will involve bolts where the protruding portion of the installed bolt is damaged or broken off. Such damage will prevent the successful attachment of the pull test clevis and axial testing of the damaged bolts. Bending the damaged bolts back into alignment after the SPMM collisions may result in metal fatigue and violent failure of the threaded portion of the bolt during pull tests.

Various authors have published results on push testing (Aziz et al., 2014; Crompton & Sheppard, 2020; Ma et al., 2017). Pipe push testing consists of full-length bolts installed into prepared steel pipes. After the resin cures, the pipes are cut into shorter lengths of approximately 75 mm. Axial push tests are conducted on each section to determine the bond strength of the bolt. This method ensures that every part of the bolt can be physically examined. The extent of damage to the resin column can be analysed, and the individual pieces of the pipe can be tested to determine a comparative bond strength. The details of the push test method and the research design are discussed in more detail in the following section.

3.2 Research Design

3.2.1 Preparation and design

Preparation for the tests initiated with the off-site manufacturing of the steel pipes required for the installations. The pipes were turned from solid mild steel tubes with an outside diameter of 41 mm. The pipes were purchased from Barnes Tubing Industries, with a SANS 62-1 certification. A part of the test design is intended to assess the influence of the hole annulus on the extent of damage, since the annulus is known to be one of the most important factors influencing the bolt behaviour. In addition, the influence of the bolt diameter was also assessed by testing bolt diameters ranging between 18 mm and 25 mm. To satisfy the above requirements, it was decided to make use of a pipe with an inside diameter of 32 mm. The different configurations result in various annuli, as detailed in Table 3-1.

Table 3-1: Bolt annuli tested.

Hole diameter	Bolt Diameter	Annulus	Comment
32 mm	18 mm	7 mm	Poor annulus
32 mm	20 mm	6 mm	Poor annulus
32 mm	23 mm	4.5 mm	Plastic coating, annulus ranges between 2.3 mm - 2.5 mm
32 mm	25 mm	3.5 mm	Good annulus

Each pipe was rifled for 400 mm at the start of the pipe since this is the area where most damage was anticipated. Since it was planned to conduct all tests with 1.5 m long bolts, the pipes were 1.5 m long to simulate 50 mm “over-drill” as the effective length of the bolts is 1.45 m due to the 50 mm protrusion. This was done to replicate actual practice. The pipes were fitted with baseplates so that they could be fixed to the rock with 10 mm expansion bolts. Figure 3-1 shows the prepared pipes before and after installation.

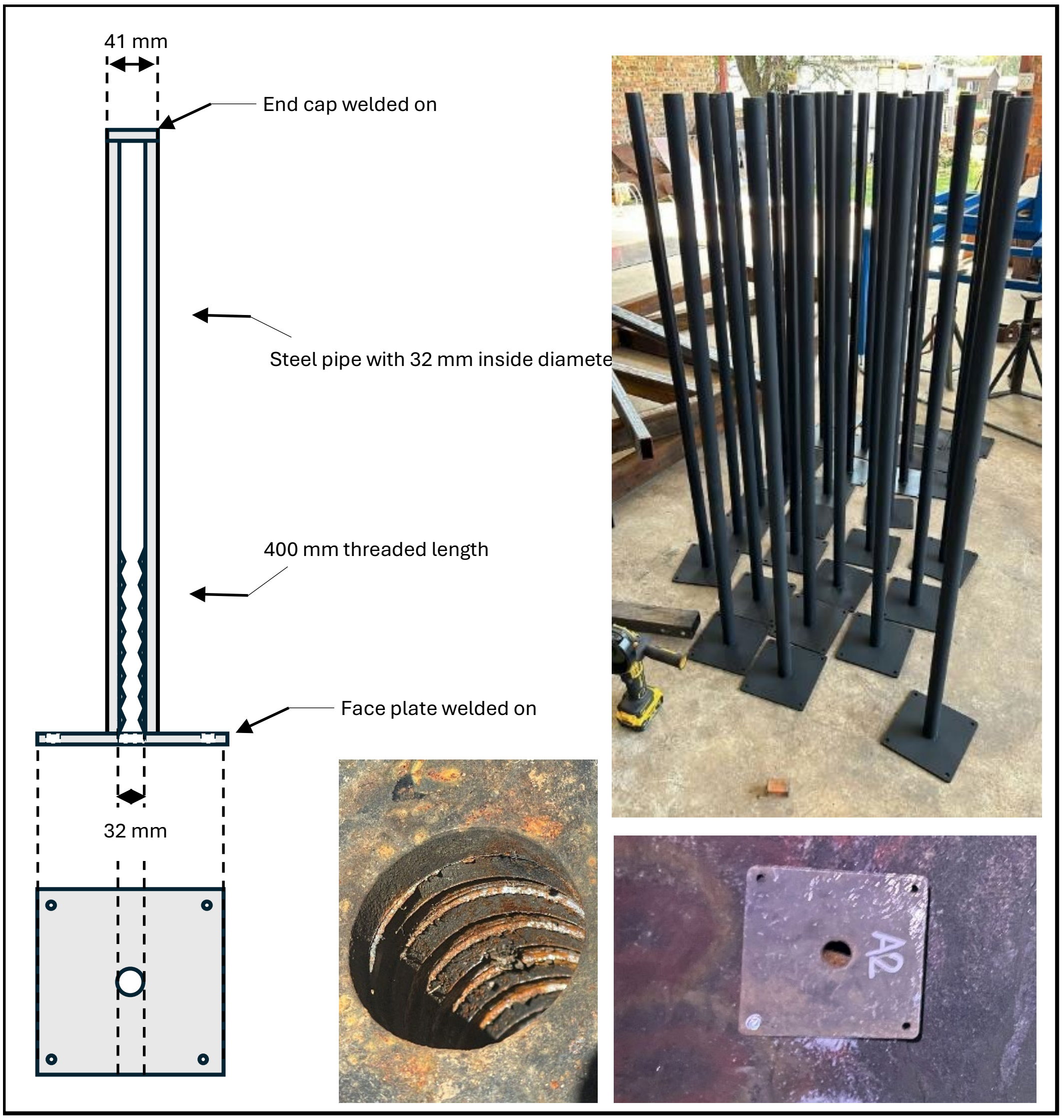
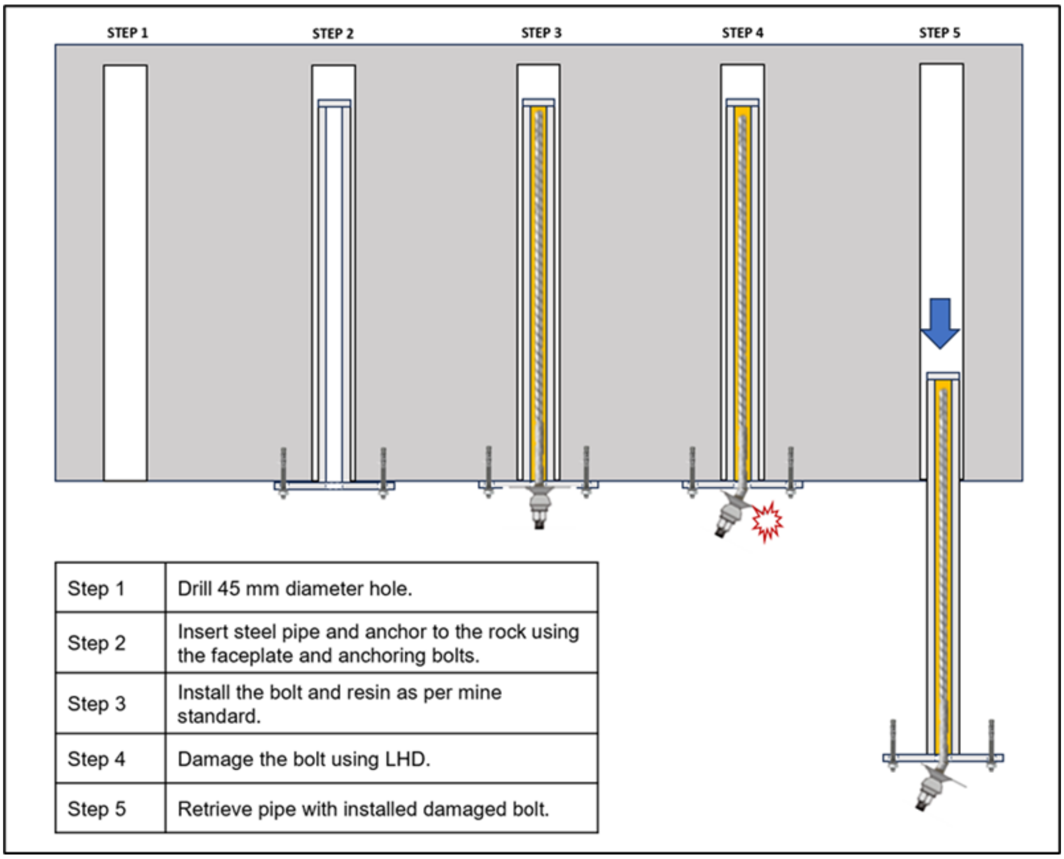


Figure 3-1: Diagram showing the pipe design and photos showing the pipes before and after installation.

The pipes were installed into 45 mm diameter holes drilled into the rock in either the hangingwall or sidewall. All tests were conducted in stoping heights between 2.2 m and 3.0 m. The resin bolts were subsequently installed into the pipes using the procedure prescribed by the resin suppliers. Two similar resin products were used from RSC (Rocloc) and Rocbolt. Both suppliers provided the standard twin components with 60 sec and 5 min to 10 min setting times (Canbulat et al., 2006). The resin from both suppliers had similar specifications. Bolts from various suppliers were used for the different mine sites.

At least one day after installation, the bolts were damaged to varying degrees using a Load-Haul-Dump Truck (LHD). Simply striking the bolts with a hammer in a laboratory setting was excluded as an option because a hammer strike cannot credibly replicate the dynamics of a moving LHD side-swiping an installed bolt. Using a 5-tonne effective impacting mass at 5 km/h, the impact energy is 4.82 kJ. By comparison, a 5 lb (2.27 kg) hammer swung at ~10 m/s delivers 113 J. Thus, the LHD side-swipe imparts approximately 43 times the energy of a hammer blow.

Six test bolts and one control sample were planned for each of the five test sites. The goal was to obtain a minimum test sample size of 30 bolts, following the Central Limit Theorem (CLT). This theory states that if the sample size is at least 30, the distribution of the mean will approach a normal distribution, regardless of the shape of the population distribution (Triola, 2018). Due to operational difficulties and other practical constraints experienced at the test sites, this planned sample size could not be achieved, and only 25 samples were tested. The test design is illustrated in Figure 3-2.



Step 1	Drill 45 mm diameter hole.
Step 2	Insert steel pipe and anchor to the rock using the faceplate and anchoring bolts.
Step 3	Install the bolt and resin as per mine standard.
Step 4	Damage the bolt using LHD.
Step 5	Retrieve pipe with installed damaged bolt.

Figure 3-2: Diagram showing the test design.

Resin curing is complete after 24 hours. Some bolts were damaged after one week due to operational difficulties. Since no further resin curing occurs after the initial 24 hours, this variance in time is not expected to have an influence on the strength of the resin during testing.

3.2.2 Extent of damage

Underground investigations found that damage to bolts due to SPMM damage falls into three distinct categories: impacted, bent and severed. Examples of each type of damage are shown in Figure 3-3.

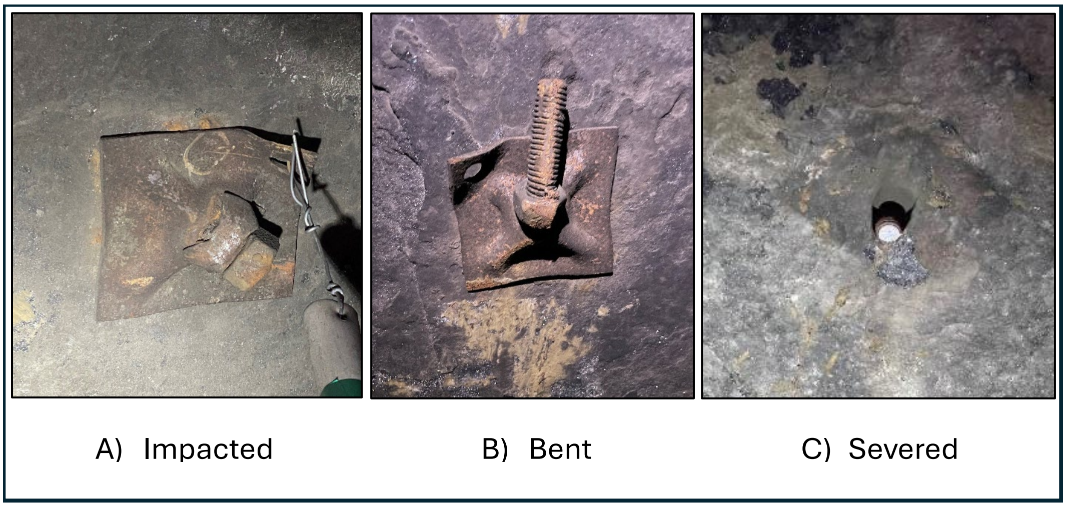


Figure 3-3: Different types of SPMM bolt damage were observed.

Following the curing of the bolts, LHDs were used to intentionally damage the installed bolts according to the three expected damage categories. The aim was to replicate the extent of damage often observed underground. Once damaged, the pipes were removed from the rock and transported to the testing facility for testing and analysis. The details of each set of tests are summarised under the specific test sites' description under Heading 3.3.2.

3.3 Data Collection Process

Data collection was conducted through three separate methods:

- Questionnaire;
- Underground inspections and test setup; and

- Push Testing of Bolts.

3.3.1 Questionnaire

Industry-wide collection of data was attempted through an electronic questionnaire using the online platform Jotform, which was distributed via email, LinkedIn, Facebook and WhatsApp. It comprised 15 concisely phrased questions, which were both multiple-choice and open-ended formats. A copy of the questionnaire is attached as Appendix A. The objective of the questionnaire was to gain insight into the following three questions:

a) What is the magnitude of the problem under investigation?

b) What, according to practising rock engineers, is the perceived impact of SPMM damage on the effectiveness of the bolts?

c) What are the main types and costs of the support used?

Unfortunately, only 17 participants completed the questionnaire, of which three mines also participated in the study. Many of the participants did not give sufficiently detailed answers or left questions unanswered. A summary of the most pertinent results, given by questions, are supplied in Table 3-2.

In general, the result of the questionnaire indicates that, from the group of participants, the most frequently used bolt diameter is 20 mm, and the most frequently used length of bolt is 1.5 m. Of the participants, 77.8% indicated that they work in mines where it is standard practice to replace damaged bolts daily. However, 66.7% of participants believe that workers do not consistently replace damaged bolts, despite it being required by the mine standards. The support designs on most mines do not specifically cater for SPMM damage, but 66.7% of participants felt that the factor of safety included in their designs sufficiently caters for the amount of bolt damage experienced. Section 54 stoppages were received from DMR inspectors by 52.9% of participants due to damaged bolts not being replaced. However, 76.5% of participants have never experienced an FOG where SPMM damage to bolts was considered a contributing factor. On average, 6% of installed bolts are replaced daily due to SPMM damage, at an average cost of

R173 per bolt. The most frequent support spacing reported is 2.25 m^2, and the average critical bond length is 300 mm.

Table 3-2: Summary of questionnaire results.

Question	Yes	No	Other
Does your mine standard stipulate that resin bolts damaged by SPMMs must be replaced?	77.78%	22.22%	
Does your support design cater for the damage to resin bolts by SPMMs through increased FOS or redundancy?	5.5%	27.78%	66.67% SPMM damage was not specifically accounted for in the design, but the achieved FOS is sufficient to cater for the amount of damage encountered.
Do workers consistently replace every resin bolt damaged by SPMMs?	33.33%	66.67%	
Have you ever received an instruction from the DMRE (Sect. 54 or 55) or a stoppage from the Safety Department due to resin bolts broken/damaged by SPMMs?	52.94%	47.06%	
Have you ever experienced a FOG where resin bolts damaged or broken by SPMMs were identified as a contributing factor?	4%	76.47%	
How many replacements of bolts damaged by SPMMs are installed per day? (Total for all shafts in your mine)			Maximum 20%, minimum 1%, **average of 6%** of installed bolts.
What is the total cost of one resin bolt installation? (Bolt, resin and labour, if possible)			Maximum R230 per bolt, Minimum R117 per bolt, average of R173 per bolt
What length and diameter resin bolts do your mine install?			Length sample mode = 1.5 m, diameter sample mode = 20 mm.
What is your resin bolt spacing?			Sample mode = 1.5 m x 1.5 m.
What is your critical bond length?			Sample mode = 300 mm
In your opinion, do bolts broken off or damaged by SPMMs pose a safety risk in terms of the effectiveness of support?	43%	57%	

3.3.2 Underground inspections and test setup

As part of the underground tests, detailed inspections were conducted at the participating mines. The aim of the inspections was to record the extent of the resin bolt damage, determine the most likely type of damage, and assess the replacement frequency and impact of the damage on the support effectiveness and the surrounding rock mass.

Mine A

General: Test A was conducted at Mine A, which is a shallow bord and pillar operation on the Eastern Bushveld. The mine uses drill rigs for face drilling and installs 1.5 m long, 18 mm diameter bolts into 29 mm diameter holes, using hand-held drills. It has been observed that, in some instances, the production crews erroneously use the 32 mm diameter drill bits to drill support, thereby increasing the annulus from 5.5 mm to 7 mm. Stopes are cleaned using LHDs, with an average stoping height of 2.2 m. The support spacing is 1.5 m x 1.5 m, installed 1.0 m from the face.

FOG history: The mine has a very good safety record, with only two recorded FOGs in the last 10 years. None of the FOGs occurred in supported areas. No FOG occurred because of SPMM damage to the support.

The extent of support damage and replacements: Roughly one out of every ten installed bolts was observed to be damaged. Most of the damaged bolts were replaced, and discipline in this regard was good. The types of damage observed consisted of impacted, bent and severed bolts. Most damaged bolts were observed at the intersections between the lateral pillar holings and strike panels.

Resin bolt installation quality: At first, visual observations indicated that all bolts are well installed and tensioned, although most bolts are installed at angles between 70 and 75 degrees. This is common in mines using hand-held drills and is typically related to the incorrect length of the air leg used. Closer inspection of the installation process found that the bolts are installed and spun in accordance with the manufacturer's instructions, but that the bolts are not always tensioned upon installation. Some installations are left untensioned and are only tensioned with a T-spanner during the next shift. No reason for this could be established other than poor discipline and supervision. As a result, the bolts are not pre-tensioned as intended, even though the nuts are driven up along the thread and the load indicators are collapsed. In essence, only the faceplate and the 10 mm to 20 mm of rock between the bolt head and the start of the resin column were tensioned. This is a significant finding since the mine has a pristine FOG record with no experience of support failures. This would then suggest that either the stiffness of the resin bolts is sufficient to reinforce the roof beam without the additional pre-tension, or that the support system is over-designed.

Test setup: The details of the test setup for Test A are given in Table 3-3. The underground installations were planned to be conducted over a series of three shifts. Due to operational difficulties and requirements, the actual installations and tests were conducted over a period of one month, where the holes were drilled during two shifts, five bolts were installed on one shift, and the remaining six bolts were installed a week later. The LHD damage was conducted only a week later. Removal of the pipes was conducted on the next shift, following the SPMM damage.

Table 3-3: Mine A test setup details.

Test A Setup						
Pipe Diameter	**Pipe Length**	**Bolt Diameter**	**Bolt Length**	**Annulus**	**Type of installation**	**Number of installations**
32 mm	1.5 m	18 mm	1.5 m	7 mm	Handheld	10 samples+1control

The incorrect resin was used for tests A8, A9 and A10, and therefore, the push test results for those bolts were not included in this study. However, the bolts were examined and tested. In general, it was found that the quality of handheld installations is heavily dependent on factors such as air legs slipping, machines falling over, loss of compressed air and/or water, operator skill and discipline. The details of the individual installations are summarised in Table 3-4. A perfect installation, as referred to in Table 3-4, implies an installation where the spin and hold times were adhered to, and the bolt could be tensioned successfully after the required holding time had lapsed. Most of the pipes became loose upon impact and were pulled out of the hole. This caused bending of the pipe along with the installed bolt, which caused additional damage to the resin column. This additional damage due to the bending of the pipe is considered the worst-case scenario, as the support column would not experience similar damage under normal circumstances. The condition of the pipes once removed from the rock is shown in Appendix B.

Table 3-4: Bolt installation details for Mine A

Bolt ID	HW/ SW	Install Method	Bolt Diam. (mm)	Resin Diam. (mm)	Capsule length (mm)	Annulus (mm)	Installation quality	Bolt Tensioned?	Type of damage	Post-damage Observations
AC	SW	Handheld	18	30	500+800	7	Perfect	Yes	None – Control Sample	Perfect condition
A1	SW	Handheld	18	30	500+800	7	Perfect	Yes	Impact, pulled and bent	Nut slightly damaged, bent pipe broke on two welds near the collar
A2	SW	Handheld	18	30	500+800	7	Perfect	Yes	Impact, pulled and bent	Nut damaged and slightly bent. Pipe bent towards the bottom third of the hole.
A3	SW	Handheld	18	30	500+800	7	Perfect	Yes	Impacted, pulled and bent	Slight nut damage. Pipe bent and broken on the first weld near the collar
A4	SW	Handheld	18	30	500+800	7	Perfect	Yes	Heavy Head-on Impact	Minimal damage visible, pipe straight and not broken
A5	SW	Handheld	18	30	500+800	7	Perfect	Yes	Heavy head-on impact	Slight nut deformation, pipe bent near collar, all welds intact.
A6	SW	Handheld	18	30	500+800	7	Perfect	Yes	Heavy side impact, pulled and bent	Slight nut damage, pipe bent and partially broken on the first weld near the collar.
A7	SW	Handheld	18	30	500+800	7	Perfect	Yes	Heavy side impact, bent protrusion	The protruding bolt is bent. Pipe is slightly bent near the collar.
A8	SW	Handheld	18	25	500+900	7	Very Poor. Airleg slipped out. The pipe broke before the test in the hole. Incorrect resin capsules and poor spin and hold times. (8/90)	No	Pulled out and bent	No visible damage. Pipe bent and broke on the first 5 welds near the collar. Unmixed resin is visible through breaks in the pipe.
A9	SW	Handheld	18	25	500+900	7	Poor. Incorrect resin capsules and poor spin and hold times. (12/50)	Yes	Side impact, pulled out and bent	Bolts are slightly bent and damaged. Pipe bent, broke on the second weld near the collar
A10	SW	Handheld	18	25	500+900	7	Poor. Incorrect resin capsules and poor spin and hold times. (10/45)	Yes	Heavy side impact, pulled out and bent	Slight damage to the nut. Pipe bent and partially broke on the first weld near the collar

Mine B

General: Tests B, C and D were conducted at Mine B, which is a shallow bord and pillar operation on the Eastern Bushveld. The mine uses drill rigs for face drilling. They install 1.8 m long, 25 mm diameter bolts into 34 mm diameter holes, using fully mechanised bolters as well as HPE drilling equipment. Both the HPE and mechanised drilling equipment use knock-off bits with S25 mm drill steel to drill holes. Stopes are cleaned using LHDs, with an average stoping height of 2.2 m to 2.8 m. The standard support spacing is 1.5 m x 1.5 m, installed 1.0 m from the advancing panel face.

FOG history: The mine has a good safety record, with a very low FOG injury rate.

The extent of support damage and replacements: Due to the mining height, support damage is rare. Approximately three out of every ten installed bolts were observed to be damaged. Almost all the damaged bolts were replaced within the supporting cycle, and discipline in this regard was good. The type of damage observed consisted of impacted, bent and severed bolts. Most damaged bolts were observed on the down-dip side of panels, where the stoping height is relatively low.

Resin bolt installation quality: Since bolting is conducted with a small annulus and using mechanical bolters, the general quality of installations was good. Where poor installations were found, these were most often attributed to poor discipline.

Test setup: The details of the test setups for Mine B are given in Table 3-5. The underground installations were planned to be conducted over a series of three shifts. Due to operational difficulties, the actual installations and tests were conducted over three weeks, and the holes were drilled during three shifts. The installations were conducted over two weeks. Difficulties concerning spinning adaptors resulted in serious delays and poor installations of the 20 mm diameter bolts. All bolt damages were inflicted during one shift, at the end of which all samples were recovered and transported to the surface.

Table 3-5: Mine B test setup details.

Test B Setup						
Pipe Diameter	**Pipe Length**	**Bolt Diameter**	**Bolt Length**	**Annulus**	**Type of installation**	**Number of installations**
32 mm	1.5 m	18 mm	1.5 m	7 mm	Bolter	4 samples + 1 control
Test C Setup						
Pipe Diameter	**Pipe Length**	**Bolt Diameter**	**Bolt Length**	**Annulus**	**Type of installation**	**Number of installations**
32 mm	1.5 m	20 mm	1.5 m	6 mm	Bolter	4 samples +1 control
Test D Setup						
Pipe Diameter	**Pipe Length**	**Bolt Diameter**	**Bolt Length**	**Annulus**	**Type of installation**	**Number of installations**
32 mm	1.5 m	25 mm	1.5 m	3.5 mm	Bolter	4 samples +1 control

The details of the individual installations are summarised in Table 3-6. The condition of the samples once removed from the rock is shown in Appendix B. In some instances, bolts were impacted more than once to achieve the visual level of damage expected.

Table 3-6: Bolt installation details for Mine B

Bolt ID	HW/ SW	Install Method	Bolt Diam. (mm)	Resin Diam. (mm)	Capsule length (mm)	Annulus (mm)	Installation quality	Bolt Tensioned?	Type of damage	Post-damage Observations
BC	SW	Bolter	25	30	500+800	3.5	Perfect	Yes	None – Control Sample	Perfect condition
B1	SW	Bolter	25	30	500+800	3.5	Perfect	Yes	Impacted, bent	Impacted, slightly bent at the collar
B2	SW	Bolter	25	30	500+800	3.5	Perfect	Yes	Impacted, bent	Impacted, slightly bent at the collar
B3	SW	Bolter	25	30	500+800	3.5	Perfect	Yes	Bent	Bent, slightly bent at the collar
B4	SW	Bolter	25	30	500+800	3.5	Perfect	Yes	Bent	Bent, slightly bent at the collar
CC	SW	Bolter	18	30	500+800	7	Perfect	Yes	None – Control Sample	Perfect condition
C1	SW	Bolter	18	30	500+800	7	Perfect	Yes	Impacted, bent	Slightly bent, bent at the collar
C2	SW	Bolter	18	30	500+800	7	Perfect	Yes	Impacted, bent	Impacted and bent, slightly bent at the collar
C3	SW	Bolter	18	30	500+800	7	Perfect	Yes	Impacted, bent	Bent, slightly bent at the collar
C4	SW	Bolter	18	30	500+800	7	Perfect	Yes	Severed	Sheared off, straight
DC	SW	Bolter	20	30	500+800	6	Poor	Yes	None – Control Sample	Perfect condition
D1	SW	Bolter	20	30	500+800	6	Poor	Yes	Impacted	Impacted, bent at the collar
D2	SW	Bolter	20	30	500+800	6	Poor	Yes	Bent	Sheared off, bent
D3	SW	Bolter	20	30	500+800	6	Poor	Yes	Bent	Impacted, bent at the collar
D4	SW	Bolter	20	30	500+800	6	Poor	Yes	Impacted	Bent, straight

Mine C

General: Test E was conducted at Mine C, which is a shallow bord and pillar operation on the Eastern Bushveld. The mine uses drill rigs for face drilling and installs 1.5 m long 18 mm diameter bolts into 28 mm diameter holes, using mechanised bolters for support installation. Stopes are cleaned using LHDs, with an average stoping height of 2.5 m. The support spacing for resin bolts is 1.0 m x 2.0 m, installed 1.0 m from the face and 2.0 m x 2.0m for Flexibolts.

FOG history: The mine has a good safety record, with only three recorded FOGs since December 2023 (11 months FOG-free at the time of this research). All three collapses were human behaviour-related, where the standard operating procedures were not adhered to.

The extent of support damage and replacements: Mining heights varied between 1.95 m and 3.2 m throughout the mine. LHDs were used to clean panels. It was found that operators often level off broken ore in the LHD buckets in order to lessen spillage en route to the tips. This levelling-off is done by scraping the loaded bucket along the hangingwall, which invariably results in damage to the protruding bolts. Damage to the resin bolts differs but ranges from being bent to severed.

Resin bolt installation quality: Support installation was generally good. Since mechanical bolters were used to drill support holes, under- or over-drilling of the hole was seldom an issue. Of concern was tensioning upon installation, not achieving full column resin in the hole and gloving. It has also been identified that bolts are spun from the point of insertion, which may result in an overspin of the resin at the bottom of the hole or an underspin of the resin at the top of the hole. This results in the bottom portion of the bolts not being full-column resin-filled, poorly mixed or damaged. All these aspects are operator errors and thus behaviour issues.

Where the hole was full-column resin-filled and struck by an LHD, the bolt was generally severed on the bolt thread. This was not regarded as detrimental to the installation or support effectiveness, as it happened post-installation and tensioning. System stiffness was not deemed to be compromised by the mine's rock engineering department. In cases where full column grout was not achieved, the likelihood of the bolt being bent, rather than severed, was greater.

Test setup: The details of the test setup for Mine C are given in Table 3-7. The underground installations were planned to be conducted over a series of three shifts. The holes were drilled in one shift, and the bolts were installed the following week during one shift. The bolts were damaged using an LHD two weeks later.

Table 3-7: Mine C test setup details.

Test E Setup						
Pipe Diameter	**Pipe Length**	**Bolt Diameter**	**Bolt Length**	**Annulus**	**Type of installation**	**Number of installations**
32 mm	1.5 m	23 mm	1.6 m	4.5 mm	Roof bolter	3 samples + 1 control

The details of the individual installations are summarised in Table 3-8. The condition of the pipes once removed from the rock after damage was inflicted is shown in Appendix B. The increased protrusion of the bolts facilitated easy severing of the exposed nuts. Based on visual inspection after the collisions, little to no damage to the visible resin column could be observed around the collars of the bolts.

Table 3-8: Bolt installation details for Mine C

Bolt ID	HW/ SW	Install Method	Bolt Diam. (mm)	Resin Diam. (mm)	Capsule length (mm)	Annulus (mm)	Installation quality	Bolt Tensioned?	Type of damage	Post-damage Observations
EC	HW	Bolter	23	30	700+700	4.5	Perfect	Yes	None – Control Sample	Perfect condition
E1	HW	Bolter	23	30	700+700	4.5	Perfect	Yes	Severed	Severed, straight, ring-welded to remove.
E2	HW	Bolter	23	30	700+700	4.5	Perfect	Yes	Severed	Severed, bent
E3	HW	Bolter	23	30	700+700	4.5	Perfect	Yes	Severed	Severed, bent

3.3.3 Push Testing of Bolts

Once the pipes with damaged bolts reached the testing facility, the pipes were measured, labelled and cut into 100 mm segments. The segments were individually inspected and logged in detail, noting the extent of damage and photographing each segment. After the inspections were complete, push testing of the segments was conducted using a constant loading rate of 30 mm per minute. The load was servo-controlled using an MTS testing machine with a capacity of 600 kN and a logging frequency of 10 Hz. The load and displacement of each sample test were electronically recorded and plotted. The tests were stopped once the sample lost its load-bearing capacity, and this value was recorded as the segment's bond strength. An example of the machine and sample setup is shown in Figure 3-4.

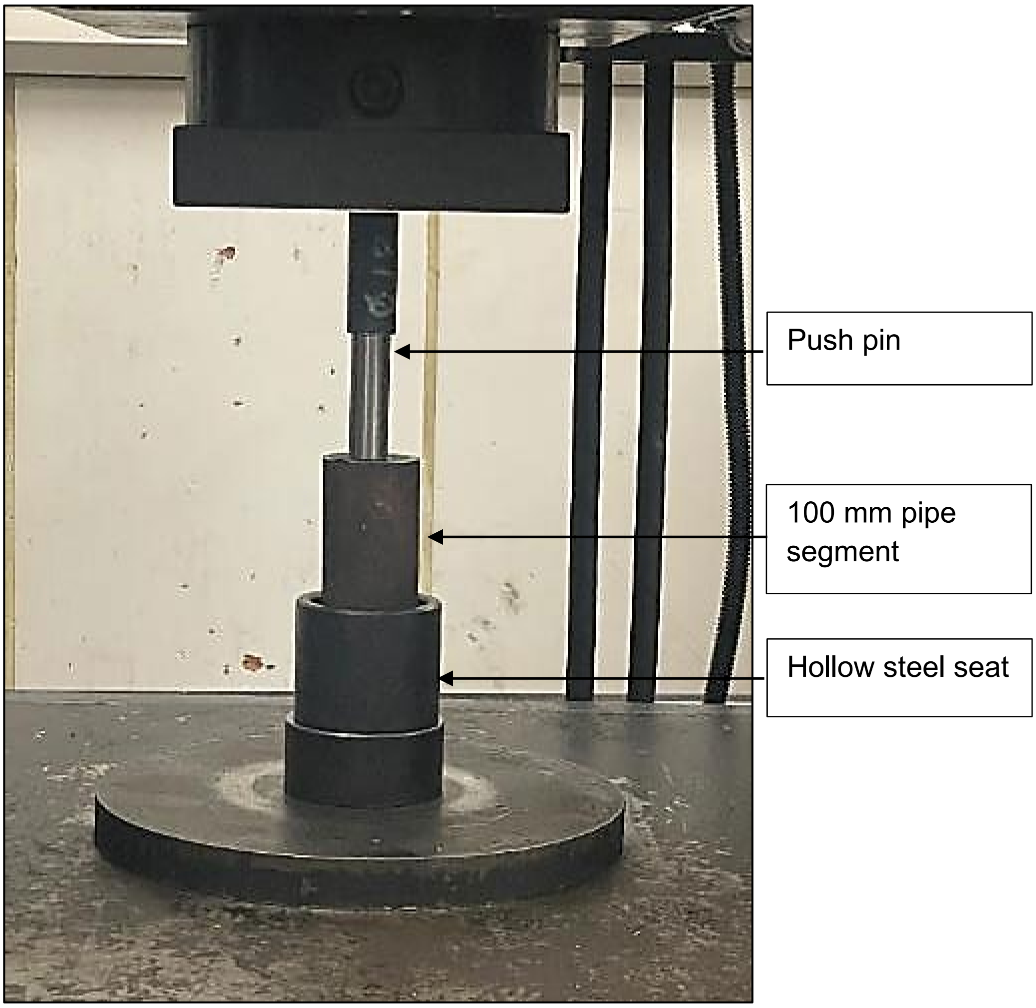


Figure 3-4: Testing machine and sample setup.

The test facility used is ISO certified. There is no ISRM or SANAS-approved procedure for push testing. The procedure used copied the procedure used in previously published tests, such as (Aziz, 2002; Jalalifar, 2011; Ma et al., 2017; Hillyer et al., 2013; Aziz, 2014; Aziz et al., 2006).

3.4 Data Validation Process

The push test results were recorded and compared to an undamaged control sample, with the same bolt annulus and bolt diameter. The test results from various mine sites were also compared to each other to determine any similarities or trends.

3.5 Data Analysis Approach

The data analysis aimed to visually and quantitatively determine the extent of damage to each sample following SPMM damage. In order to do this, the following approach was followed

3.5.1 Data Collection

From the prepared samples visual observations were conducted to determine:

- Physical condition of each segment
- Quality of installation / mixing of resin
- Observable extent of damage

From the push tests conducted, the following information was recorded:

- Applied load at failure
- Displacement at failure
- Type of failure

3.5.2 Analysis of Results

The visual observations and push test results were used to compare each sample to the undamaged control sample to determine the effect of SPMM damage on the samples.

Using the findings, a statistical analysis was conducted to determine if the results are statistically significant.

3.6 Chapter Summary

Tests for each site were kept as consistent as possible, whilst trying to improve on issues identified during the previous round of tests. Installations with various annuli and bolt diameters were tested to investigate the influence of annulus and bolt stiffness on the amount of damage experienced during SPMM collisions. Due to operational constraints at the different mines, the desired number of tests could not be conducted at each site; however, a substantial sample size was gathered.

Handheld installations proved to be problematic, even under close supervision, and consistent installations were impossible to achieve. In some instances, bolts were impacted more than once to assimilate the level of damage observed in typical underground conditions. Some pipes loosened upon impact and were pulled out of the holes, bending the pipe and bolt in the process. This additional damage may have skewed the results, as the same level of damage is not possible under normal conditions. The preparation and inspection of the individual test segments are detailed in the following chapter.

4 DATA FOR THE STUDY

4.1 Introduction

Each 100 mm long segment was visually inspected and photographed, and the information was logged on a spreadsheet for reference. Thereafter, push tests were conducted to failure on all segments. Once the segment lost load-bearing ability, the tests were stopped, and the maximum load achieved was recorded as the bond strength. The test results are summarised in this chapter according to the test site. The details of the type of damage inflicted on each sample are listed in Table 3-4.

4.2 Mine A

Samples A8, A9 and A10 were poorly installed, and visual inspections found the resin to be soft and unmixed along large sections of all three bolts. Most bolts had significant gloving, which was expected due to the large hole annulus. Figure 4-1 shows an example of the prepared samples. Gloving occurred between 600 mm to 1300 mm. Figure 4-2 shows an example of the gloving observed.

Figure 4-1: Example of prepared samples.

Figure 4-2: An example of gloving observed in samples from Mine A.

It was observed that the bolts were not centred in the holes, and that resin in the middle of the samples was mixed the best, whilst resin at the top and bottom of the samples was not consistently mixed. Where gloving occurred, soft, unmixed resin seeped out of the pipe after cutting the samples into segments. Despite the observation of poorly mixed resin at the bottom of the samples, it was consistently observed that SPMM damage did not exceed 300 mm, as shown in Figure 4-1. This depth of damage was restricted to 300 mm, even though most of the bolts were pulled out of the holes and bent during the collisions. Due to the observed poor mixing and gloving, it was anticipated that the samples from Mine A would achieve low push-out loads.

4.3 Push test results for Test A

During the tests, failure occurred at the bolt/resin interface as described in the literature survey. At the bottom of the sample, failure occurred either at the resin/pipe interface or sheared through the resin. This is due to the build-up pressure because of the push test as described in the literature review. Where gloving was encountered, failure occurred along the bolt/glove interface, as shown in Figure 4-3.

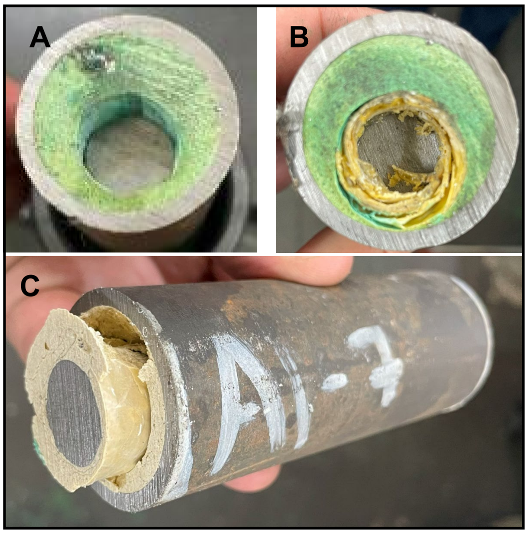
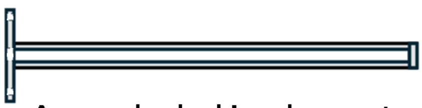


Figure 4-3: Photos showing the different failure mechanisms: A- Bolt/resin failure, B – Gloving, C – Plug failure.

The results for Test A show that the large annulus resulted in low push-out loads. Importantly, the undamaged control sample achieved poorer results than most of the damaged bolts. This is an indication of the effect of a large annulus, and how it negatively affects resin quality and bolt effectiveness. The average peak load achieved for samples A1 to A7 was 60.7 kN per 100 mm (10.74 MPa bond strength), with a standard deviation of 7 kN per 100 mm (1.31 MPa bond strength). The best consistency was achieved in the middle section of the samples, with the first 300 mm achieving poor or no results. Table 4-1 compares the control sample results to the average of the test results. The test results for the seven samples with all the segments tested per sample are shown in Appendix C.

Table 4-1: Test A results compared to the Control Sample.



Average load achieved per sector

Load (kN)	Start	Middle	End
Control	1.38	23.03	32.32
Ave of Tests	24.02	36.11	24.08

4.4 Mine B

At Mine B, three different bolt diameters and hole annuli were tested (Test B, Test C and Test D). Of the three tests, the installations of Test B with the smallest annulus (3.5mm annulus) were the most successful.

4.4.1 Test B

All bolts were well installed with better centring than Mine A, and the resin was well mixed. All samples had some portions of soft, wet resin at the distal ends of the holes, which is expected due to the planned over-drilling of 50 mm. The small annulus had a positive influence on the installation quality and limited the extent of impact damage to the resin column. Examples of the prepared segments for Test B are shown in Figure 4-4. The segments show a small void in the resin of segment 10. Inspection found that these gaps are created by the metal clamps used on the resin capsule ends.

Figure 4-4: Photo showing the prepared samples for Test B.

In all four of the test samples from Test B, the portion of the pipes at the collar of the holes deformed slightly. At the impact site, decoupling of the bolt could be observed for all four bolts with the crushing of the resin. This damage did not continue to the end of the segment except in segment B3. In this segment, debonding continued to the end of the first segment but did not continue to the next segment. In other words, the damage did not extend beyond 100 mm into the hole for any of the samples. Figure 4-5 shows the two ends of the first segment of each sample. Note the absence of damage on the distal ends of the segments. Push tests were not conducted on these first segments, as the bent pipes would result in additional resistance and skewed results.

Figure 4-5: Photo showing the damage to the first segment of each test.

4.4.2 Push test results for Test B

Failure occurred at the bolt/resin interface at the loading point and the resin/pipe interface at the distal end for all samples (Figure 5-6). No gloving was encountered, and the results were much more consistent throughout the length of the samples.

Figure 4-6: Photos showing the failure mechanisms of Test B.

The results for Test B show that the small annulus resulted in higher push-out loads, as compared to Test A. The average peak load achieved for the samples was 141 kN per 100 mm (17.97 MPa bond strength), with a standard deviation of 17.8 kN per 100 mm (2.27 MPa bond strength). The undamaged control sample results were similar to the average of the damaged samples, as shown in Table 4-2.

Table 4-2: Test B results compared to the Control Sample.

Load (kN)	Start	Middle	End
Control	110.25	113.00	102.00
Ave of Tests	113.94	115.44	101.06

Most samples show a reduction in strength toward the end of the samples, with the peak strength in most cases achieved in the centre of the sample. The test results for the samples with all the sections tested per sample are shown in Appendix C.

4.4.3 Test C

Test C consisted of 18 mm diameter bolts installed with an anulus of 7 mm. This test differs from Mine A only in that the bolts for Test C were installed by a mechanical bolter. As with Mine A, inspection of the various segments found that the resin was poorly mixed in all samples, with noticeable gloving and areas of soft, wet resin found throughout. The quality of installation with the bolter was no better than that of the hand-held installations. Mixing of the resin in the lower 400 mm of the samples was poor, with most of the resin being crushed and missing. It is assumed that the crushed resin material was lost during the cutting of the pipes for sample preparation. When examining the nuts and washers of the bolts, the extent of decoupling seems disproportional to the extent of impact damage, especially when compared to Test B. The undamaged control sample displayed similar crushed and missing resin in the first 400 mm of the sample, which indicates that the observed loss of resin in the test samples is not due to the impact damage alone. The large annulus has an obvious negative effect on the quality of installation, regardless of the installation method. The large annulus resulted in poorly mixed, weak resin at the collar of the hole, which left the bolts decoupled along the first 300 mm to 400 mm after installation. Since the bolts were decoupled before impact, the collisions only bent the decoupled portions of the bolts and caused little additional observable damage to the remaining resin column. However, the remaining resin was also soft in most samples. Figure 4-7 shows the undamaged control sample compared to one of the test samples.

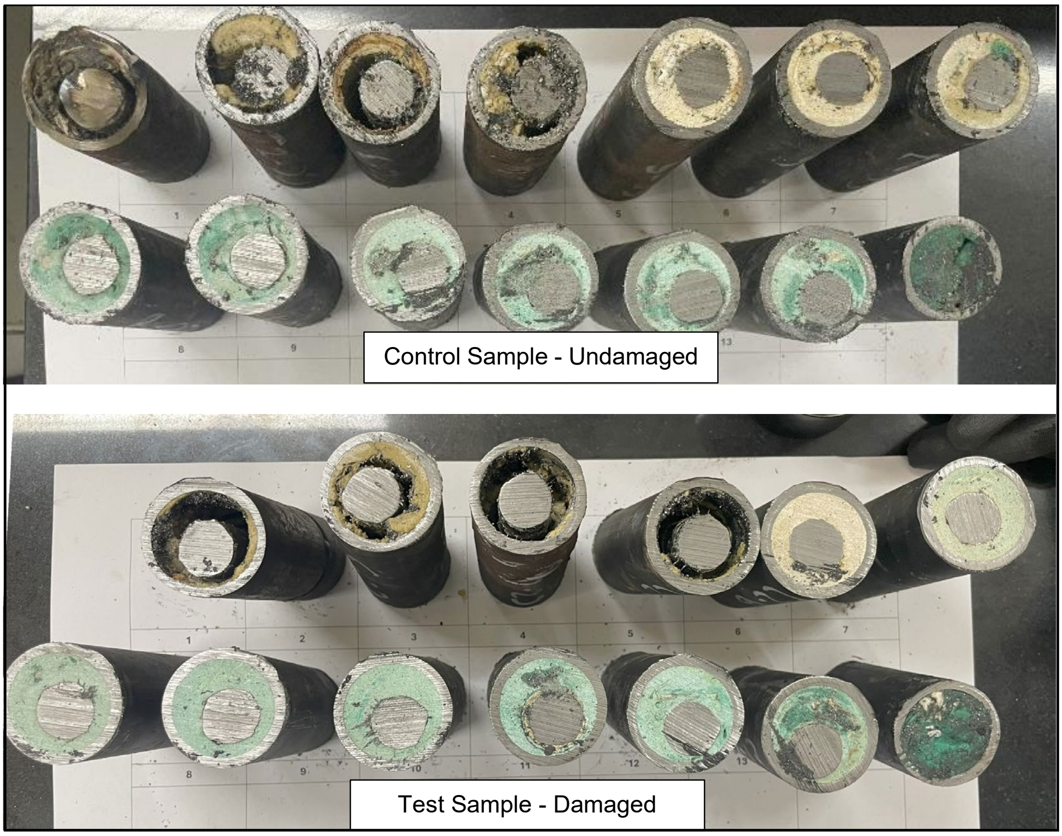


Figure 4-7: Photos showing the condition of the control sample compared to a test sample with a large annulus.

4.4.4 Push test results for Test C

Test C consisted of 18 mm diameter bolts installed in a large annulus of 7 mm. The results are comparable with those of Test A, in that the push-out loads were low, and performance was inconsistent along the length of the samples. Failure occurred at the bolt/resin interface at the loading point and along the resin/pipe interface at the bottom of the sample in every case. Where gloving was encountered, failure occurred along the bolt/glove interface. After push testing, it was observed that the resin in most segments was still wet and not mixed. Figure 4-8 shows the condition of one of the samples after testing.

Figure 4-8: Photo showing an example of the condition of Test C samples post-testing.

The results for Test C show that the large annulus led to poor mixing, weak resin, and debonding up to 500 mm. It must be noted that the debonding is not necessarily attributed to the SPMM impact damage, as the undamaged control sample shows similar debonding in the first 300 mm. This indicates that the debonding most likely occurred during transport or cutting, due to the poor quality of the resin. The average peak load achieved for the samples was 67.5 kN per 100 mm (11.93 MPa bond strength), with a standard deviation of 26.5 kN per 100 mm (4.69 MPa bond strength). The undamaged control sample results were lower than the average of the damaged samples, as shown in Table 4-3.

Table 4-3: Test C results compared to the Control Sample.

	Average load achieved per sector		
Load (kN)	**Start**	**Middle**	**End**
Control	3.59	28.45	19.03
Ave of Tests	8.43	40.21	23.36

4.4.5 Test D

Test D consisted of 20 mm diameter bolts with an annulus of 6 mm installed using a mechanical bolter. The support crew experienced difficulties with the spinning adaptor during installation, resulting in mostly poorly installed bolts. The undamaged control sample, like with Test C, exhibited poor quality mixing with resin missing up to 200 mm. Despite the problems encountered during installation, all bolts could be tensioned following the 45-second holding period and would, under normal circumstances, be considered acceptable installations. The remainder of the resin column had several soft spots, indicating inadequate mixing. All test samples exhibited poor mixing in the top and bottom portions of the samples. Figure 4-9 shows the quality of mixing of sample D4, in which dark green soft patches of resin can be seen. The damage observed along the samples ranged from 0 mm to a maximum of 300 mm.

Figure 4-9: Photo showing the extent of impact damage and poorly mixed resin of Sample D4.

4.4.6 Push test results for Test D

Test D consisted of 20 mm diameter bolts with an annulus of 6 mm. Despite the improved annulus, the bolts were poorly installed due to difficulties experienced with the spinning adaptor. The test results indicate that most segments achieved at least 50 kN push-out load at a distance of 400 mm from the collar. After testing, it was found that most segments were oily, and soft resin was pushed out of some samples, as shown in Figure 4-10.

Figure 4-10: Soft, unmixed resin pushed out of the sample, Test D.

The failure occurred at the bolt/resin interface at the loading point and along the resin/pipe interface at the bottom of the sample for all segments tested. As with Tests A and C, decoupling and small voids also occurred in the undamaged control sample, which indicates that the decoupling most likely occurred during transport or cutting, due to the poor quality of the resin in that section of the samples. The average peak load achieved for the samples was 112 kN per 100 mm (17.82 MPa bond strength), with a standard deviation of 3.6 kN per 100 mm (0.57 MPa bond strength). The undamaged control sample achieved better results than the damaged samples, particularly in the distal end of the samples, as shown in Table 4-4. The test results for the samples with all the sections tested per sample are shown in Appendix C.

Table 4-4: Test D results compared to the Control Sample.

	Average load achieved per sector		
Load (kN)	**Start**	**Middle**	**End**
Control	61.75	95.75	89.50
Ave of Tests	50.19	96.44	68.31

4.5 Mine C

Mine C was the test site for Test E. To overcome the large hole annulus problem without increasing the diameter, and thereby the stiffness of the bolt, Test E was conducted using special bolts coated in plastic. The plastic increases the diameter of the bolts to a minimum of 23 mm, thereby reducing the hole annulus to 4.5 mm. Inspection of the prepared samples found that all installations were perfect, with no unmixed resin. All nuts were severed during the impact tests. Sample E3 showed minor debonding at the collar of the hole; however, the damage was limited and did not extend to the end of the segment (i.e. less than 100 mm). Sample E2 showed no damage whatsoever. Sample E1 was stuck in the hole after the SPMM damage, and a steel ring had to be welded to the end of the sample to pull it from the rock. This damaged the resin in the first segment of the sample, and the segment was discarded. Figure 4-11 shows the condition of the various segments of Sample E3. In the photo, the black plastic coating can be seen around the bolt.

Figure 4-11: Photo showing the condition of Sample E3.

4.6 Push test results for Test E

The setup of Test E consisted of 18 mm bolts coated in plastic to increase the bolt diameter to 23 mm. This resulted in an annulus of 4.5 mm. All samples were well mixed, and no obvious soft or wet spots could be observed in the resin. There was no observable impact damage to any of the samples, except sample E3, which had minor debonding in the first 100 mm. The samples either failed on the bolt/plastic or the plastic/resin interfaces at the end where the load was applied, as shown in Figure 4-12. At the distal ends, failure either occurred on the bolt/plastic interface or as a plug failure. As shown in Table 4-5, the undamaged control sample did not perform better than the damaged test samples.

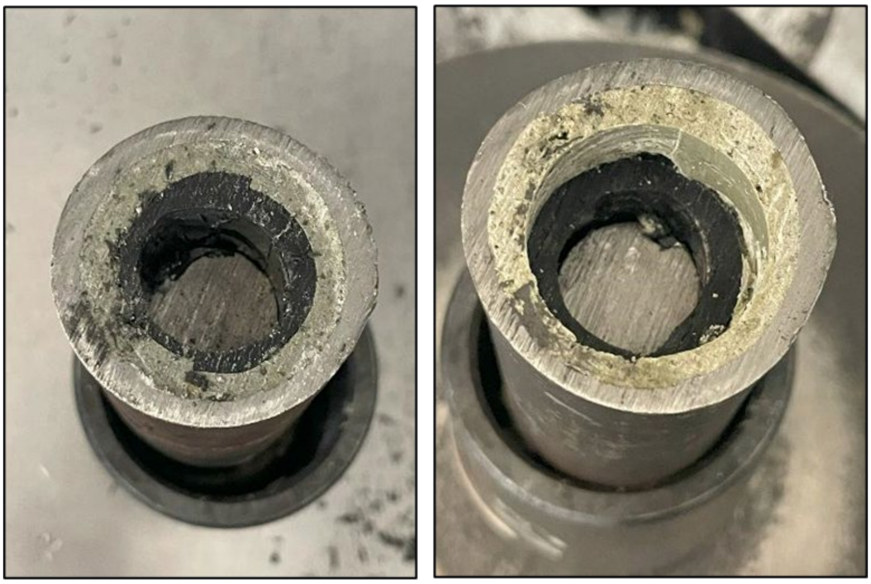


Figure 4-12: Samples failed on the bolt/plastic interface.

Table 4-5: Test E results compared to the Control Sample

Average load achieved per sector

Load (kN)	Start	Middle	End
Control	73.00	80.00	81.50
Ave of Tests	81.58	87.58	78.08

Test E performed better than Tests A and C, where 18 mm bolts were used without the plastic coating. The plastic coating adds a positive advantage to the system by significantly reducing the annulus. The influence on the frictional resistance of the resin/bolt interface was not considered for this project. The average peak load achieved for the samples was 112 kN per 100 mm (15.5 MPa bond strength), with a standard deviation of 22 kN per 100 mm (3.04 MPa bond strength). The test results for the samples with all the segments tested per sample are shown in Appendix C. The test shows good consistency between the samples with little variation.

4.7 Chapter Summary

Inspection of the samples found that the hole annulus may have a larger influence on the resin strength than SPMM impact damage. Samples with large diameters (Test A and Test C) display damage up to an average of 300 mm, or 20% of the bonded length. It is important to note that in both cases, the undamaged control samples experienced poor, crushed and missing resin up to the same depth into the hole. It is thus concluded that the 300 mm damaged portions were weak and possibly crushed, even before the SPMM impacts. The studies found that the bottom 300 mm of the installations are poor, even in undamaged samples. This is also the region in which pipe bending occurred during testing. The extent of damage caused by the bending of the pipes did not exceed the damage in the control samples. Thus, the damage caused by the bending of the pipes is considered inconsequential.

The smaller annulus samples (B, D and E) appear to have experienced significantly less damage, which contributed to the improved mixing and, thereby, quality of the resin. Where the grouting medium was homogeneous and filled the entire annulus, damage was minimal and limited to the collar of the hole. It is noteworthy that the samples in this category, even after SPMM damage, appear to be more competent than the undamaged control samples in the large annulus samples.

Where bolts were impacted or bent, the damage to the resin column appears to be more pronounced than that of bolts where the nuts were severed. Since the bolt thread typically has a tensile strength of 80% of the capacity of the steel bar, it is expected that the severing of the bolt at the thread occurs in a quick, brittle manner, without causing additional deflection of the bolt with accompanying crushing of the resin column. Figure 4-8 shows the extent of observable resin damage per sample.

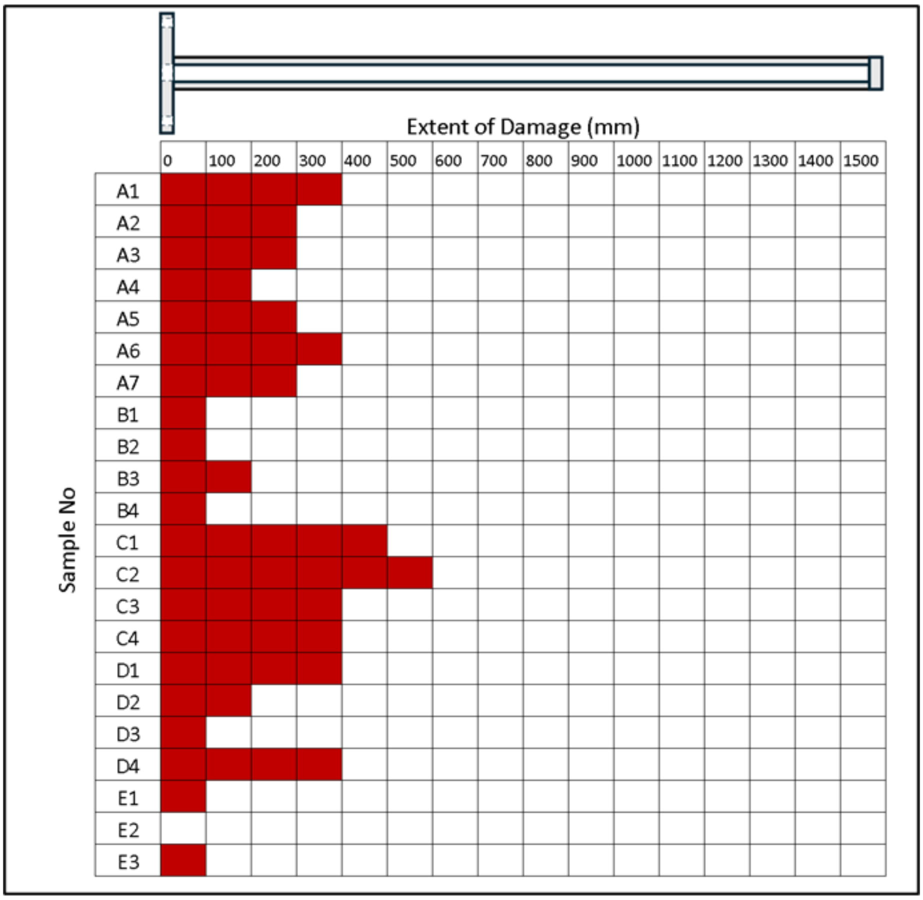


Figure 4-13: Observable damage extent per sample.

When comparing the observable resin damage to the bolt diameters, it appears to indicate that the extent of damage for installations with annuli less than 5 mm is limited to four times the bolt diameter. For installations with annuli larger than 5 mm, the damage is approximately twenty times the bolt diameter, as shown in Table 4-6. The strength results are detailed and analysed in Chapter 5.

Table 4-6: Extent of damage to bolt diameter ratio.

	Bolt Diameter (mm)	**Annulus (mm)**	**Mode Extent of Damage (mm)**	**Damage / Bolt diameter Ratio**
Test B	25	3.5	100	4
Test E	23	4.5	100	4
Test D	20	6	400	20
Test A	18	7	300	17
Test C	18	7	400	22

5 ANALYSIS AND FINDINGS

5.1 Introduction

The visual observations indicated that damage to the samples with annuli less than 4.5 mm was limited to 100 mm. Mixing of resin in these samples was good, and the resin appeared homogeneous. During push testing, the samples achieved more consistent results as compared to the samples with large annuli (>4.5 mm), and the undamaged control samples did not perform better in testing than the damaged test samples.

All samples with annuli larger than 4.5 mm showed inconsistent mixing of the resin with frequent gloving. The samples showed damage up to 400 mm from the point of impact, although the same amount of debonding was observed in the undamaged control samples. The sample tests were inconsistent with large standard deviations. The control samples did not perform better than the damaged test samples. Where gloving was observed, the results of the push tests were significantly lower than those of the segment without gloving.

5.2 Results for Test A

Figure 5-1 indicates that most bolts started generating noticeable loads past 300 mm of bolt length, which corroborates the observation that damage did not extend past the first 300 mm. Finger gloving affected most bolts and resulted in sporadic low loads achieved along the length of the bolt. It is noticeable, and of concern, that the top 500 mm, which is supposed to be the anchor point, performed poorly in most sample tests.

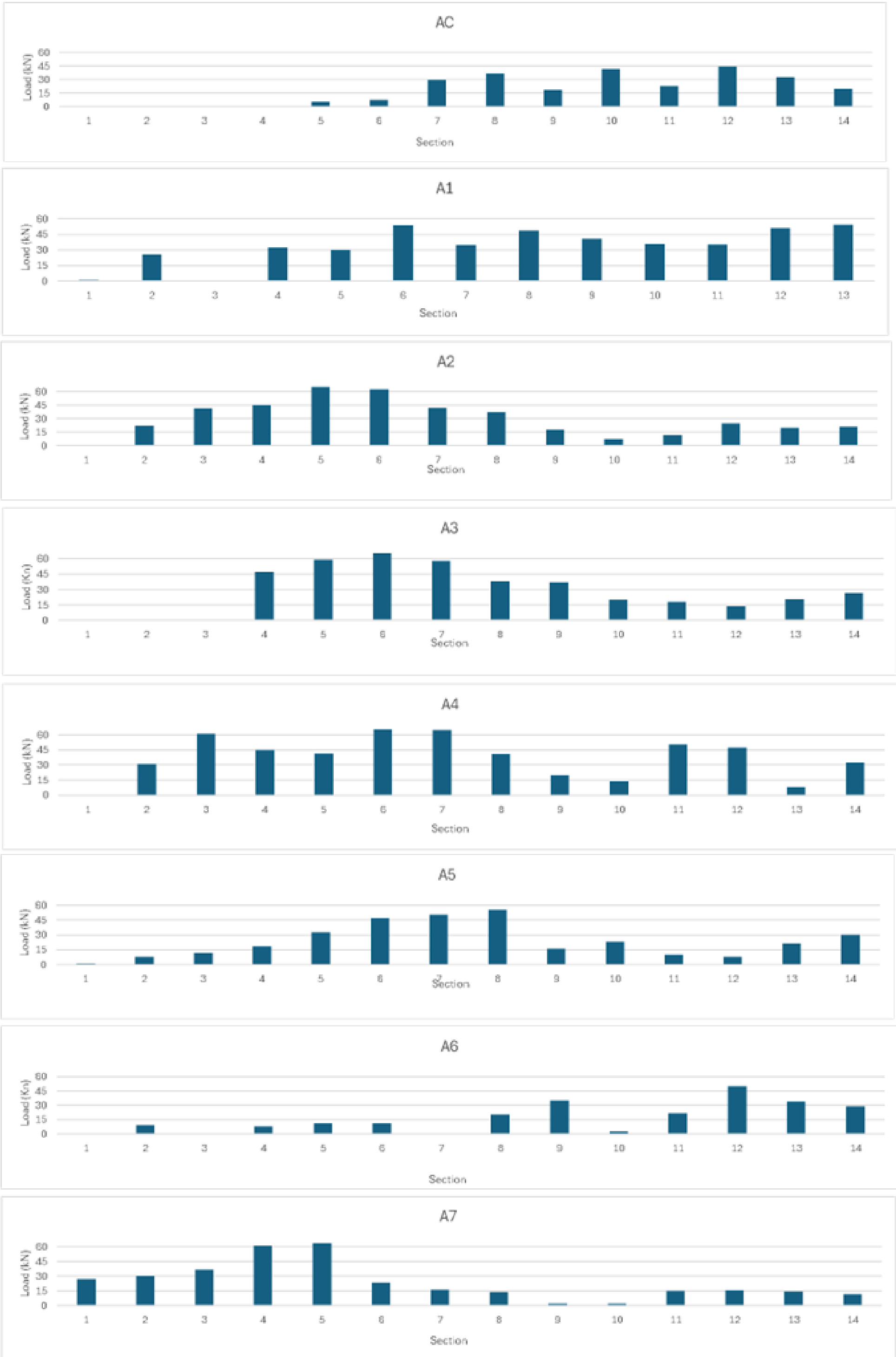


Figure 5-1: Peak load per section, Mine A

From the tests conducted, it can be concluded that large resin annuli result in sporadic poor mixing of resin and finger gloving, which detrimentally affects the effectiveness of the resin bolt system. The damage due to SPMM damage was limited to the bottom 300 mm of the holes. The undamaged control sample did not perform better than the damaged samples. The negative effects of large hole annuli outweigh the effects of SPMM damage.

5.3 Results for Test B

Sample B2 achieved poor results in segments 10, 12 and 13. Inspection of the samples before and after testing could not identify a clear cause of the poor results. Based on the overall performance of all the samples tested, it is assumed that poor mixing at the distal end of the bolt was the most likely cause of the poor results. The results obtained per sample are shown in Figure 5-2.

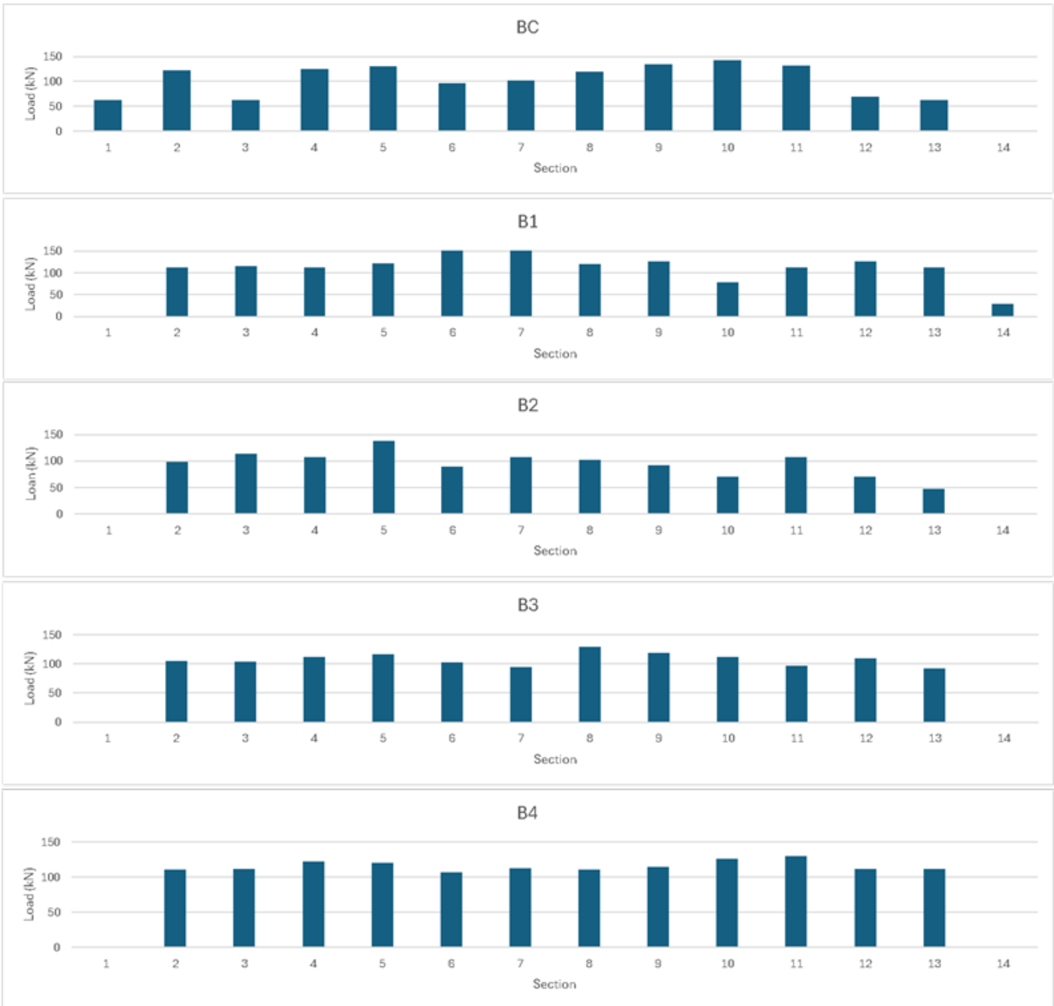


Figure 5-2: Peak load per section, Test B.

The samples showed no indication of damage because of the SPMM impact. Variations in test results were less pronounced than the Test A, where a large annulus was tested. The test samples achieved similar results to the control sample, and the reduction in annulus had a positive influence on the bond strength and amount of damage experienced by the SPMM impact.

5.4 Results for Test C

Most samples show a reduction in strength toward the end of the pipes, with the peak strength in most cases achieved in the centre of the pipe. The test results for the samples with all the sections tested per sample are shown in Figure 5-3.

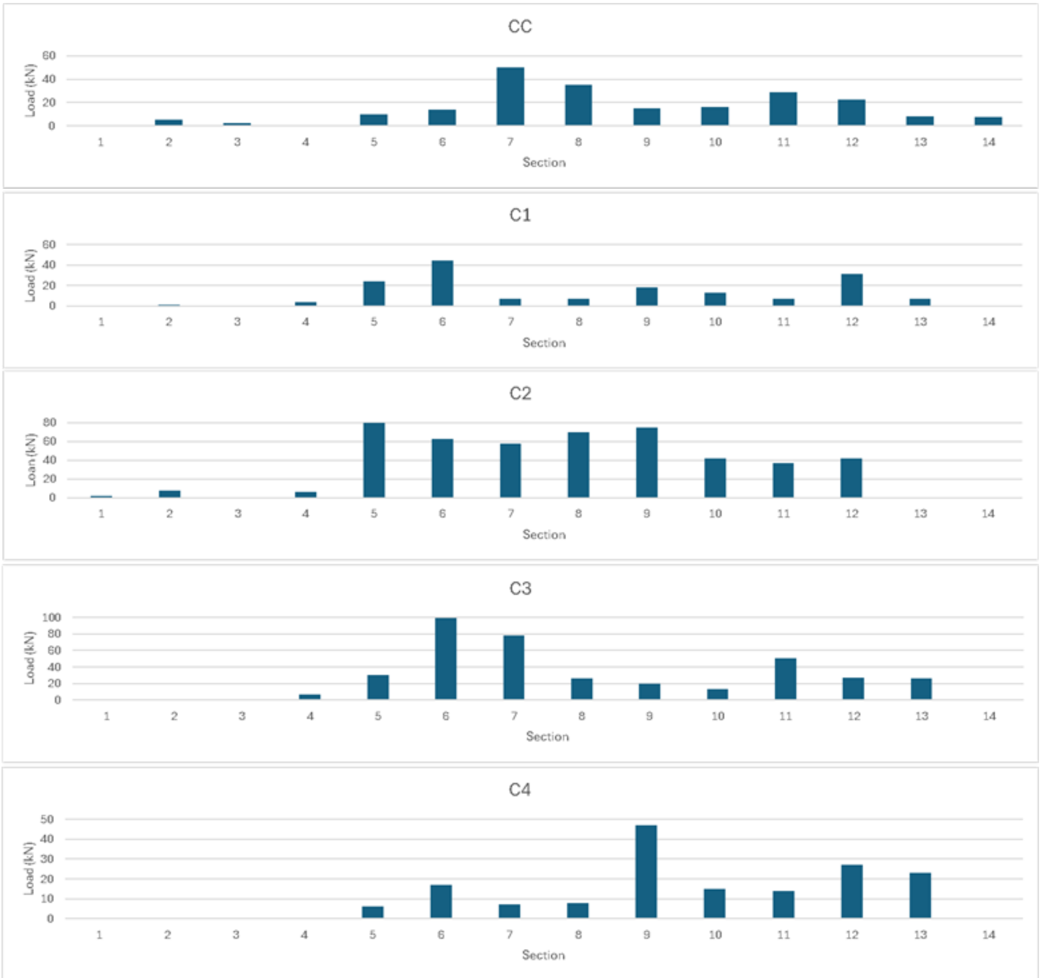


Figure 5-3: Peak loads per bolt for Test C.

Due to the poor mixing as a result of the large annulus, the bolts performed poorly under push testing. Most samples only started to generate load after 500 mm. The control sample did not perform better than the damaged samples, and the highest strengths were achieved in the centre of the samples. The extent of the decoupling should not be considered solely as a result of the SPMM damage, since the undamaged control sample shows similar decoupling in the first 500 mm. The only conclusion that can be made is that the damage incurred through SPMM damage is not more significant than the effect of poor mixing and the resultant poor resin quality at the collar of the hole before damage.

5.5 Results for Test D

Due to the improved annulus, Test D achieved more consistent results with higher peak loads than Test A and C, despite the poor resin mixing during installation. The resin at the beginning and end of all samples was poorly mixed, which led to decoupling in the first 300 mm to 400 mm of all samples, before the SPMM impact. The test results per segment for all bolts are shown in Figure 5.4.

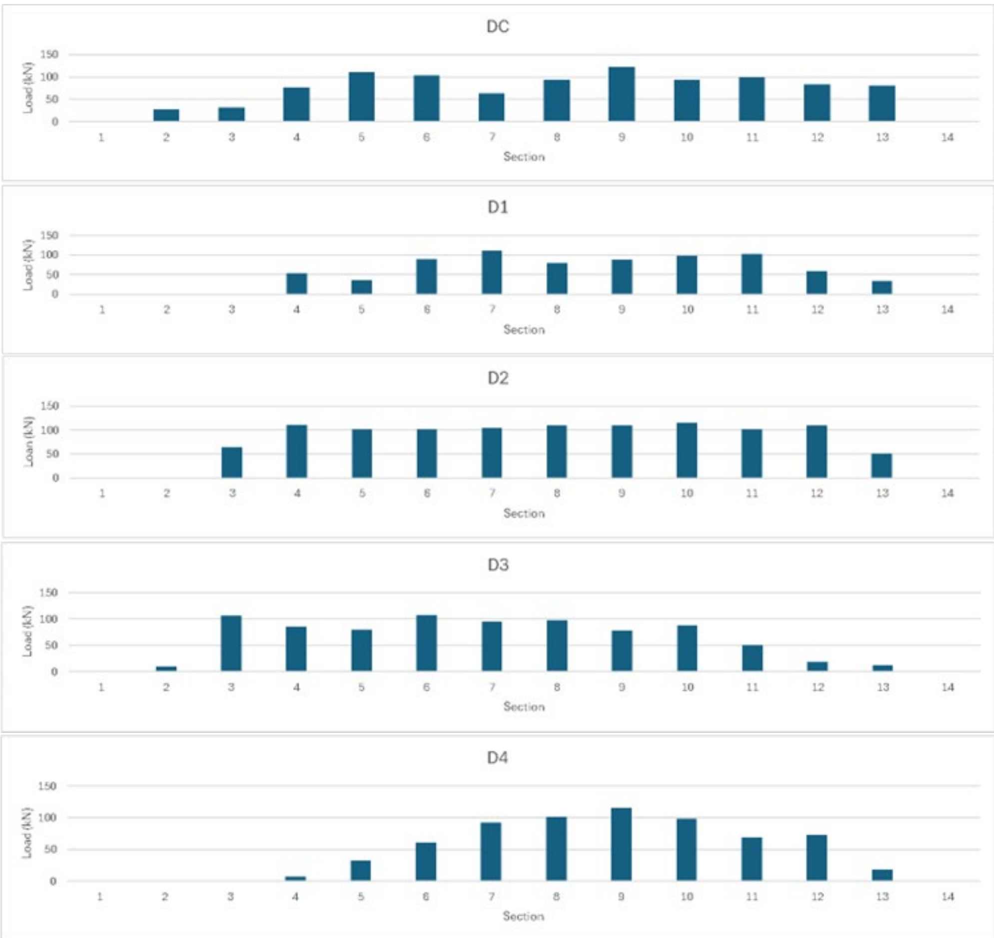


Figure 5-4: Peak loads per bolt for Test D.

The damaged test samples did not perform as well as the control sample in the segments located at the start and end of the samples, but achieved, on average, similar push-out loads in the central portions of the samples. It is concluded that poor installation of bolts results in poor mixing and poor quality of resin. The effect of the poor installation is pronounced at the start and end of the installation. The effect of the poor installations mirrors the affected lengths of SPMM damage in the first 300 mm of the installations. The effect of SPMM damage in this portion of the test samples was not noticeably worse than the effect of the poor installations alone.

5.6 Results for Test E

Test E, with a plastic coating to reduce the hole annulus, performed significantly better than Tests A and C, where 18 mm bolts were used without the plastic coating. The plastic coating adds an obvious and notable advantage to the system's performance. The resin was well mixed and homogenous, and tests show little variation in strengths. Figure 5-5 shows the load for each segment per sample.

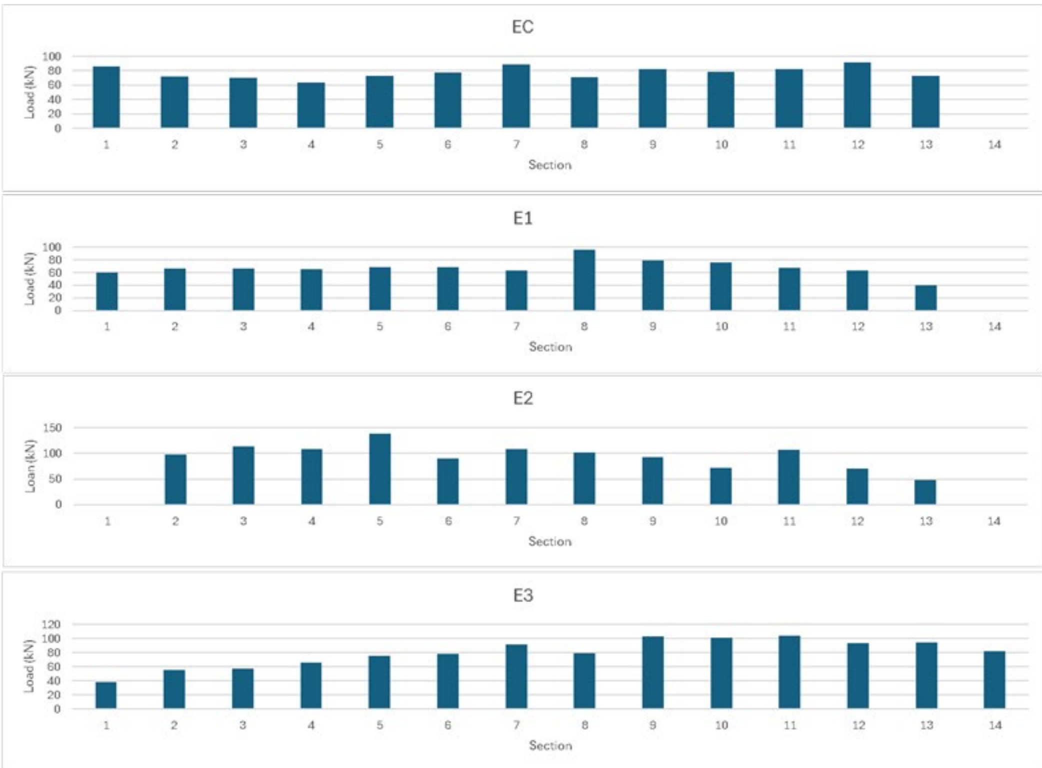


Figure 5-5: Peak loads per bolt for Test E.

5.7 Questionnaire comparative needs analysis

The results of the questionnaire revealed that 77% of contributing mines are obligated by their Standard Operating Procedures to replace bolts damaged by SPMMs. Despite this requirement, a total of 76.47% of participants indicated that they have never experienced a FOG because of bolts being damaged by SPMMs. Additionally, 57% of participants indicated an instinctive belief that such replacements are not necessary, based on their understanding of the load transfer mechanism of fully grouted bolts.

The findings of this study provide strong evidence that bolts installed with annuli of 4.5 mm or less do not require replacement (see heading 6.5 for statistical analysis of results) when damaged by SPMMs. The study results thus seem to confirm the industry experts' sentiment, which is typically informed by accumulated empirical evidence and operational experience over the lifespan of a mine.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

The study was conducted to determine the extent of damage inflicted on installed full-column grouted bolts by SPMM collisions. In order to achieve this, 25 fully encapsulated resin bolts were installed into steel pipes installed into the rock mass. After installation, the pipes were impacted using LHDs to replicate real-world damage. The bolts were then removed and cut into 100 mm long segments. Each segment was visually inspected for damage and then tested using the push test method.

Various bolt diameters and hole annuli were tested to consider the influence of bolt stiffness, installation quality and annulus on the effect of SPMM damage on full column grouted resin bolts.

6.2 Summary of Chapters

This report has presented five chapters that cover the following:

- Chapter 1 presented an introduction and background on the research topic, detailing the justification for this study

- Chapter 2: Literature review of relevant topics, such as the historical development of full column resin bolts, key concepts and suitable testing methodologies.

- Chapter 3 detailed the research approach and design.

- Chapter 4 presented the data for the study, detailing the test results and pertinent findings.

- Chapter 5 consisted of an analysis of the most important findings of the study.

6.3 Research Observations

6.3.1 Key findings and observations

The research indicates that bolts installed with annuli of 4.5 mm or less did not experience significant damage as a result of SPMM damage, and do not require replacement after damage. SPMM damage to the resin column appears to be limited to the lower 100 mm for installations with an annulus of less than 5 mm, or 4 times the bolt diameter. Installations with annuli of 4.5 mm or less showed more competent resin columns after SPMM damage than undamaged samples with annuli of more than 4.5 mm.

Importantly, the study also found that bolts installed with large annuli (>4.5 mm) not only consistently display poor resin mixing and consistency but also suffer significantly more damage when impacted by SPMMs. Damage to the resin column of installations with an annulus of more than 4.5 mm appears to be limited to the lower 400 mm, or 20 times the bolt diameter. Based on the test results, it is recommended that bolts installed with annuli of more than 4.5 mm should be replaced after SPMM damage.

Other key findings made during this research include:

- The bottom 300 to 400 mm of the resin column, near the collar of the hole, is typically poorly mixed and of weaker strength than the resin in the centre of the hole.
- The effectiveness of full column grouted resin bolts is more significantly affected by the annulus size than by SPMM damage on good quality installations with small annuli.
- Increasing the diameter, and thereby the stiffness of the bolt, did not result in less damage than the smaller diameter bolt covered in plastic to reduce the annulus.
- The extent of SPMM damage is more pronounced for bent bolts than for bolts that were severed on the thread.
- It is not recommended to install full-column grouted resin bolts with annuli of 6 mm or more.

6.4 Research Contributions

This will contribute significantly to underground mining practice, especially in mines with operating heights of less than 2.2 m, where resin bolts are often damaged by SPMM impacts. To date, no published research has been conducted in this respect to determine the effectiveness of damaged bolts.

This research indicates that, if bolts are installed with annuli of 4.5 mm or less, the extent of the impact damage is insignificant, and such bolts do not require replacement. On the other end of the spectrum, bolts installed with large annuli (> 4.5 mm) can be expected to be significantly impacted by the SPMM damage and should be replaced.

If implemented, these findings can help in the prevention of unnecessary bolt replacements on mines with support annuli of 4.5 mm or less. Survey responses from participating mines indicate that, on average, 6% of installed bolts require replacement post-installation. For a representative medium-sized operation installing ≈20 000 bolts per month, this equates to ≈1 200 replacements per month. If 50% of these replacements are attributable to SPMM-related damage, approximately 600 bolts per month are affected. At an installed cost of ~R140 per bolt, the avoidable cost is ≈R84 000 per month, or ≈R1 008 000 per annum.

Contrarywise, it can also inform mines with larger annuli that replacements of damaged bolts are required, or inform updated support design parameters as well as predictive and preventative maintenance. Additionally, this study can be used as a benchmark for future and complementary studies.

6.5 Research Limitations

The research was limited to hard rock operations, mining platinum or chromite, in the Eastern Bushveld of South Africa. The effect of installing the bolts into pipes, instead of directly into the rock, may have influenced the extent of damage in the lower portion of the bolts, at the collar of the hole. With the removable steel pipes, the samples often came out of the holes during impact testing, which resulted in the bending of the pipes. This undoubtedly increased the amount of crushing experienced in the bottom 400 mm of the samples, which could not occur if the samples were installed into the rockmass.

For this research, resin with comparable specifications was sourced from two suppliers. Resin from different suppliers should be tested to assess potential variations in strength, susceptibility to damage, and the occurrence of gloving. The test results for small annuli installations show little variation and seem to indicate that small annulus installations (<4.5 mm) experience significantly less damage than larger annulus installations (>4.5 mm). To test this conclusion, a statistical test, using the P-value and Cohen’s effect size, was conducted (Ross, 2020; Welch, 1947; Cohen, 1988)

P-Value (Significance Testing)

The p-value is used to determine whether the observed difference is statistically significant by means of the following equations:

$$p = 2 \times \left(1 - F_t\ (|t|, df)\right)$$

Where:

- t = t-statistic
- Ft = cumulative distribution function of the t-distribution
- df = degrees of freedom

Degrees of freedom were calculated using Welch's T-Test formula, which is used to compare two groups with potentially different variances.

$$t = \frac{\mu_{small} - \mu_{large}}{\sqrt{\frac{\sigma^2{}_{small}}{n_{small}}} + \frac{\sigma^2{}_{Large}}{n_{large}}}$$

Where:

- $\mu_{small} - \mu_{large}$ = mean damage for small and large annulus groups
- $\sigma_{small,}\, \sigma_{large}$ = standard deviations
- $n_{small,}\, n_{large}$ = sample sizes

And

$$df = \frac{\left(\frac{\sigma^2{}_{small}}{n_{small}} + \frac{\sigma^2{}_{large}}{n_{large}}\right)^2}{\frac{\left(\frac{\sigma^2{}_{small}}{n_{small}}\right)^2}{n_{small} - 1} + \frac{\left(\frac{\sigma^2{}_{large}}{n_{large}}\right)^2}{n_{large} - 1}}$$

A p-value of less than 0.05 indicates that the results are statistically significant. A p-value of more than 0.05 indicates that the test results are not statistically significant. The p-value of 0.0153 calculated thus indicates that the difference in results is statistically significant.

Cohen's d (Effect Size)

Cohen's d measures how large the difference is between two groups in standard deviation units:

$$d = \frac{\mu_1 - \mu_2}{\sqrt{\frac{{\sigma_1}^2 + {\sigma_2}^2}{2}}}$$

Where:

- μ_1, μ_2 = mean of the two groups
- σ_1, σ_2 = standard deviations

A Cohen's d above 2.0 typically indicates a very large effect. The Cohen's d- d-value of 6.53 indicates an extremely large effect, indicating a significant and practically meaningful difference in damage between the two groups.

6.6 Recommendations for Future Research Work

The effect of SPMM damage under normal conditions, where the bolt is installed into the rock and not into pipes, should be investigated in more detail. The effects of embedding the bolts within soft rock, such as coal or sandstone, may also have a negative effect on the resin/rock interface, which warrants more investigation. Resin from different suppliers should be tested to assess potential variations in strength, susceptibility to damage, and the occurrence of gloving

7 References

Aydan, O., Ichikawa, Y. & Kawamoto, T., 1985. *Load Bearing Capacity and Stress Distribution in/along Rockbolts with Inelastic Behaviour of Interfaces.* Nagoya, Proceedings of the 5th International Conference on Numerical Methods in Geomechanics .

Aziz, N., 2002. *A New Technique to Determine the Load Transfer Capacity of Resin Anchored Bolts, in Naj Aziz and Bob Kininmonth (eds.).* University of Wollongong, Proceedings of the 2002 Coal Operators' Conference, Mining Engineering.

Aziz, N., 2004. *Bolt surface profiles- an important parameter in load transfer capacity appraisal.* Perth, Proceedings of the fifth International conference on ground control and mining construction.

Aziz, N., 2014. *Status of Ground Support in Australian Coal Mines with Reference to the Latest Research on Rock Bolting Technology.* University of Wollongong, NSW, International Symposium on Earth Science and Technology.

Aziz, N., Craig, P., Mirzaghorbanali, A. & Nemcik, J., 2016. *Factors Influencing the Quality of Encapsulation in Rock Bolting,* Wollongong, NSW, Australia: Springer-Verlag.

Aziz, N. & Jalalifar, H., 2007. *Experimental and numerical study of double shearing of a bolt under confinement.* [Online]
Available at: https://ro.uow.edu.au/engpapers/3927
[Accessed 14 04 2024].

Aziz, N., Jalalifar, H. & Concalves, J., 2006. *Bolt surface configurations and load transfer mechanism.* Wollongong, Proceedings of the 2006 Coal Operators' Conference, Mining Engineering, University of Wollongong.

Aziz, N., Nemcik, J., Cao, C. & Jalalifar, H., 2009. *Bolt Profile Configuration and Load Transfer Capacity Optimisation.* Wollongong, University of Wollongong, Faculty of Engineering and Information Sciences - Papers: Part A. 2447.

Aziz, N., Nemcik, J., Craig, P. & Hawker, R., 2014. *Development of a New Testing Procedure for the Assessment of Resin Performance for Improved Encapsulated Roof Bolt Installation in Coal Mine,* Wollongong: ACARP Project.

Bieniawski, Z. T., 1984. *Rock Mechanics Design in Mining and Tunnelling.* 1 ed. Boston: A. A. Balkema Publishers.

Bierman, I. R., Gardner, L. & Piper, P., 2019. *An evaluation of the bond strength of multiple resin bolt and capsule combinations through laboratory testing and applied methodologies.* Mulderdrift, South Africa, The Southern African Institute of Mining and Metallurgy, Deep Mining 2019 Conference.

Campbell, R., Mould, R. & MacGregor, S., 2004. *Investigation Into the Extent and Mechanisms of Gloving and Un-mixed Resin in Fully Encapsulated Roof Bolts.* Wollongong, 2004 Coal Operators' Conference, University of Wollongong & the Australasian Institute of Mining and Metallurgy.

Canbulat, I., Wilkinson, A. & Prohaska, G., 2006. *Roof Bolting Guidelines in South African Collieries.* SIM 020205 ed. Johannesburg: Safety in Mines Research Advisory Committee.

Chen, Y., 2014. *Anchorage performance of fully encapsulated rock bolts under pull-and-shear loading, Doctoral Thesis,* Trondheim, Norway: Norwegian University of Science and Technology, Faculty of Engineering Science and Technology, Department of Geology and Mineral Resources Engineering.

Cohen, J., 1988. *Statistical Power Analysis for the Behavioural Sciences.* 2nd ed. Hillsdale, NJ: Lawrence Erlbaum Associates.

Crompton, B. & Sheppard, J., 2020. A practical design approach for an improved resin-anchored tendon. *Journal of the South African Institute of Mining and Metallurgy,* Volume 120, pp. 7-13.

Dolinar, D. R. & Bhatt, S. K., 2000. *Trends in roof bolts application.* Pittsburgh, PA., NIOSH Publications.

DSI Underground, 2024. *DSI Underground Canada.* [Online] Available at: https://www.dsiunderground.ca/products/mining/rebar-rock-bolts/rebar-rockbolts
[Accessed 9 April 2024].

Forbes, B. J., 2020. *High Spatial Resolution Measurement of Tendon Reinforcement in Underground Construction Works (PhD thesis report),* Kingston, Ontario, Canada: Queen's University.

Frith, R. & Thomas, R., 1998. The pretensioning pedigree. *Australia's Mining Monthly Supplement-Underground Equipment and Technology*, June, pp. 68-72.

Gray, P. & Finlow-Bates, P., 1998. The Pre-Tension Placebo. *Australia's Longwalls Magazine*, March, pp. 78-81.

Hagan, P., 2003. *The effect of resin annulus on anchorage performance of fully encapsulated rockbolts, in Technology roadmap for rock mechanics.* Johannesburg, Proceedings ISRM 2003 Conference.

Hagen, S. A., Larsen, T., Berghorst, A. & Knox, G., 2019. *Laboratory full-scale rock bolt testing: Analysis of recent results.* Muldersdrift, South Africa, The Southern African Institute of Mining and Metallurgy, Deep Mining 2019 Conference.

Hillyer, J., Craig, P., Ma, S. & Aziz, N., 2013. Variation in load transfer along the length of fully encapsulated rock bolts, based on the installation mixing parameters. *Tunnelling and Underground Space Technology,* 35(1), pp. 1-9.

Hoek, E., 2000. *Practical Rock Engineering.* [Online]
Available at:
https://www.rocscience.com/assets/resources/learning/hoek/Practical-Rock-Engineering-Full-Text.pdf
[Accessed 30 March 2025].

Hoek, E. & Brown, E. T., 1980. *Underground Excavations in Rock.* 1 ed. London: Institution of Mining and Metallurgy.

Holmberg, M., 1991. *The Mechanical Behaviour of Untensioned Grouted Rockbolts (Doctoral Thesis),* Stockholm, Sweden: Royal Institute of Technology.

ISRM, 1974. Suggested Methods for Rock Bolt Testing. In: R. Ulusay & J. Hudson, eds. *The Complete ISRM Suggested Methods for Rock Characterisation, Testing and Monitoring.* Ankara, Turkey: The International Society for Rock Mechanics, pp. 533-538.

Jager, A. J. & Ryder, J. A., 1999. *A Handbook on Rock Engineering Practice for Tabular Hard Rock Mines.* 1 ed. Johannesburg: The Safety in Mines Research Committee (SIMRAC).

Jalalifar, H., 2006. *A new approach to determining the load transfer mechanism in fully grouted bolts. PhD Thesis,* Wollongong: School of Civil, Mining and Environmental Engineering, University of Wollongong.

Jalalifar, H., 2011. An analytical solution to predict axial load along fully grouted bolts in an elasto-plastic rock mass. *Journal of the Southern African Institute of Mining and Metallurgy,* 111(11), pp. 809-814.

Jalalifar, H., Aziz, N. & Hadi, M., 2019. *An Assessment of Load Transfer Mechanism Using the Instrumented Bolts.* Wollongong, Proceedings of the 2006 Coal Operators' Conference, Mining Engineering, University of Wollongong.

Khaleghparast, S., Aziz, N., Remennikov, A. & Anzanpour, S., 2023. *An experimental study on shear behaviour of fully grouted rock bolt under static and dynamic loading conditions,* Amsterdam: Elsevier: Tunnelling and Underground Space Technology, Volume 132.

Kilic, A., 1999. *The effects of grout properties on the bolt capacity. Proceedings of the sixteenth Mining Congress of Turkey.* Ankara, Kozan Press.

Knox, G. & Berghorst, A., 2019. *Dynamic testing: determining the residual dynamic capacity of an axially strained tendon,* Sudbury, Canada: Ground Support 2019.

Knox, G. & Hadjigeorgiou, J., 2023. Behaviour of yielding mechanical hybrid rockbolts under complex loading conditions. *International Journal of Rock Mechanics and Mining Sciences,* 1(1), pp. 1365-1609.

Lang, T. T., 1961. Theory and Practice of Rockbolting. *Transactions of American Institute of Mining, Metallurgical, and Petroleum Engineers,* 220(1), pp. 333-348.

Li, C., 2017. Principles of rockbolting design. *Journal of Rock Mechanics and Geotechnical Engineering,* 9(1), pp. 396-414.

Li, C. C., 2018. *Rockbolting Principles and Applications.* 1 ed. Ann Arbor, MI. USA: Elsevier.

Li, C., Stjern, G. & Myrvang, A., 2014. A review of the performance of conventional and energy-absorbing rockbolts. *Journal of Rock Mechanics and Geotechnical Engineering,* 6(1), pp. 315-327.

Maleki, H., 1992. *Significance of bolt tension in ground control.* Balkema, Proceedings of the Rock Support in Mining and Underground Construction.

Mark, C., 2000. *Design of Roof Bolt Systems.* Pittsburgh, PA, Proceedings: New Technology For Coal Mine Roof Support, NIOSH.

Ma, S., Aziz, N., Nemcik, J. & Mirzaghorbanali, A., 2017. The effects of installation procedure on bond characteristics of fully grouted rock bolts. *Geotechnical Testing Journal,* 40(5), pp. 1-13.

Ma, S., Nemcik, J., Aziz, N. & Ren, T., 2013. *Experimental investigation and numerical modelling of fully grouted rock bolts subjected to pull and push loading.* [Online]
Available at: https://doi.org/10.1016/j.tust.2013.08.004
[Accessed 22 3 2025].

McHugh, E. & Singer, S. P., 1999. *Roof Bolt Response to Shear Stress: Laboratory Analysis.* Morgantown, WV, Proceedings of the 18th International Conference on Ground Control in Mining.

Minova International Limited, 2006. *The Minova guide to resin-grouted rockbolts.* 1 ed. Chipping Norton: Minova International Limited.

Peng, S., 1998. Roof bolting adds stability to weak strata. *Coal Age Magazine*, December, pp. 32-38.

Ranjbarnia, M., Fahimifar, A. & Oreste, P., 2014. Simplified Model to Study the Behavior of Pre-Tensioned Fully Grouted Bolts around Tunnels and to Analyze the More Important Influencing Parameters. *Journal of Mining Science,* 50(3), pp. 533-548.

Ross, S. M., 2020. *Introduction to Probability and Statistics for Engineering and Scientists.* 6th ed. London: Academic Press.

Serbrousek, M. O. & Singer, S. P., 1987. *Linear load-transfer mechanics of fully grouted roof bolts. Report of Investigations 9135,* Pittsburgh, PA: US Bureau of Mines.

Singer, S. P., 2000. Load Behaviour of Grouted Bolts in Sedimentary Rocks. *Proceedings: New Technology for Coal Mine Roof Support,* 1(1), pp. 73-80.

Springer, S. P., 1990. *Field verification of load transfer mechanisms of fully grouted roof bolts.* Spokane, WA, New Technology for Coal Roof Support, (NIOSH), Publication No. 2000-151.

Stillborg, B., 1994. *Professional Users Handbook for Rockbolting.* 1 ed. Clausthal-Zellerfeld: Trans Tech Publications.

Stjern, G., 1995. *Practical Performance of Rock Bolts, Doctoral Thesis,* Trondheim: University of Trondheim.

Thomas, E., 1954. *The application of rock bolting as a means of ground support is limited only by the resourcefulness and ingenuity of the mining engineer,* Washington, DC: U.S. Department of the Interior, Bureau of Mines.

Thomas, E., Barry, A. J. & Metcalfe, A., 1949. *Suspension roof support.* Washington, DC, U.S. Department of the Interior, Bureau of Mines.

Timoshenko, S. & Gere, J. M., 1961. *Theory of Elastic Stability.* 2nd ed. New York: McGraw-Hill.

Triola, M. F., 2018. *Elementary Statistics.* 13th ed. Boston: Pearson.

Unrug, K., Padgett, P. & Campolini, A., 2004. *Tensioned Versus Non-Tensioned Roof Bolt Systems.* Morgantown, USA, 23rd International Conference on Ground Control in Mining.

Welch, B. L., 1947. The generalization of "Student's" problem when several different population variances are involved. *Biometrika,* 34(1-2), pp. 28-35.

Windsor, C. R., 1997. Rock reinforcement systems. *International Journal of Rock Mechanics and Mining Sciences,* 34(6), pp. 919-951.

Yassien, A., Zhang, Y., Han, J. & Peng, S., 2002. *Comparison of some aspects of bolting mechanisms between grouted resin and tensioned bolts in underground mine entries.* Morgantown, USA, 21st International Conference on Ground Control in Mining.

APPENDIX A. QUESTIONNAIRE

Resin Bolt Replacement Questionnaire

Please take a moment to fill out this 15 question industry survey

Does your mine standard stipulate that resin bolts damaged by SPMM's must be replaced?

- ◯ Yes
- ◯ No

If not, do workers replace the damaged resin bolts regardless of the standard?

- ☐ Yes
- ☐ No
- ☐ Sometimes
- ☐ Not Applicable

Does your support design cater for the damage to resin bolts by SPMM's through increased FOS or redundancy?

- ☐ Yes
- ☐ No
- ☐ SPMM damage was not specifically accounted for in the design, but the achieved FOS is sufficient to cater for the amount of damages encountered.

Do workers consistently replace every resin bolt damaged by SPMM's?

- ☐ Yes
- ☐ No

Have you ever received an instruction from the DMRE (Sect. 54 or 55) or a stoppage from the Safety Department due to resin bolts broken/damaged by SPMM's?

- ☐ Yes
- ☐ No

Have you ever experienced a fall of ground where resin bolts damaged or broken by SPMM's were identified as a contributing factor?

- ☐ Yes
- ☐ No

How many bolts does your mine install per day? (Total for all shafts on your mine)

How many bolts does your mine install per day? (Total for all shafts on your mine)

How many replacements of bolts damaged by SPMM's are installed per day? (Total for all shafts in your mine)

What is the total cost of one resin bolt installation? (Bolt, resin and labor If possible)

What length and diameter resin bolts does your mine install?

What type and length resin capsules are used, (e.g. 1 × 300mm 15 sec and 2 × 500mm 5-10min)

What is your resin bolt spacing?

What is your critical bond length?

What is the shear strength of your resin in MPa?

In your opinion, do bolts broken off or damaged by SPMM's pose a safety risk in terms of effectiveness of support?

APPENDIX B. TEST SAMPLE PHOTOS

Mine A

Condition of the pipes following LHD damage.

Sample ID	Side view
A1	
A2	
A3	
A4	
A5	
A6	
A7	**PHOTO CORRUPTED**
A8	

A9	
A10	

Mine B

Sample ID	Side view
B1	
B2	
B3	
B4	
C1	
C2	
C3	
C4	

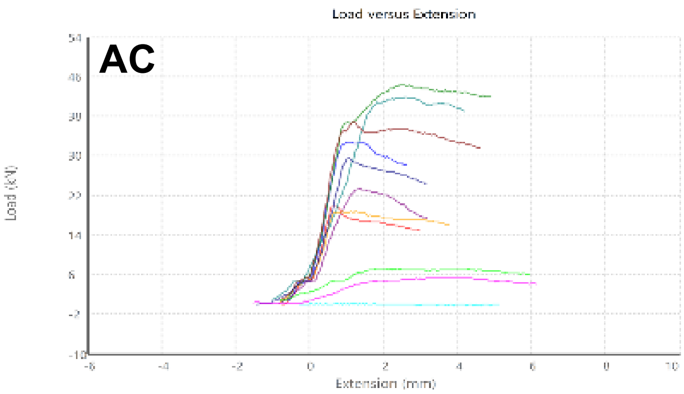
D1	
D2	
D3	
D4	

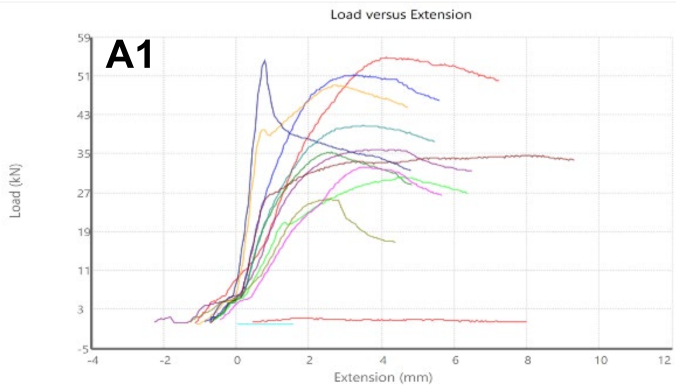
Mine C

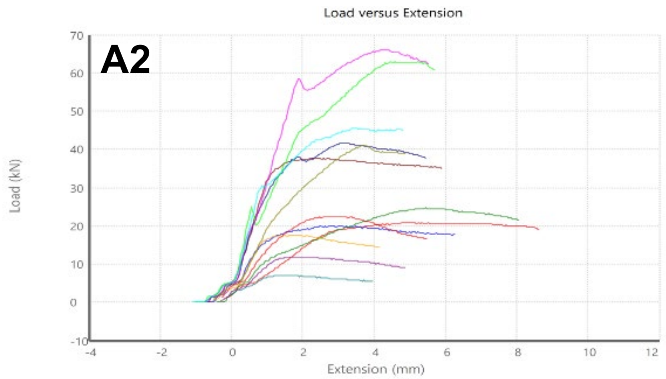
Sample ID	Side view
E1	
E2	
E3	

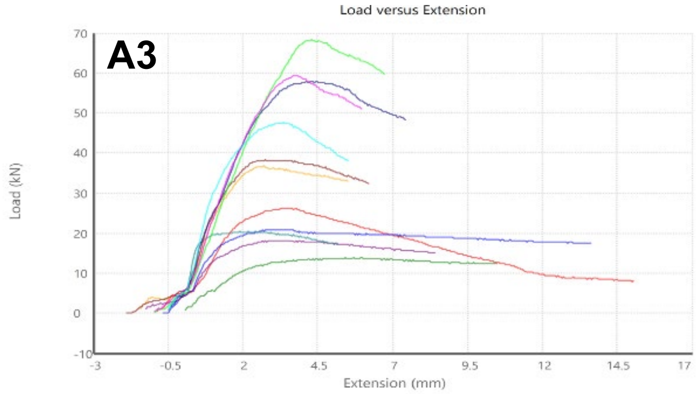
APPENDIX C. PUSH TEST RESULTS

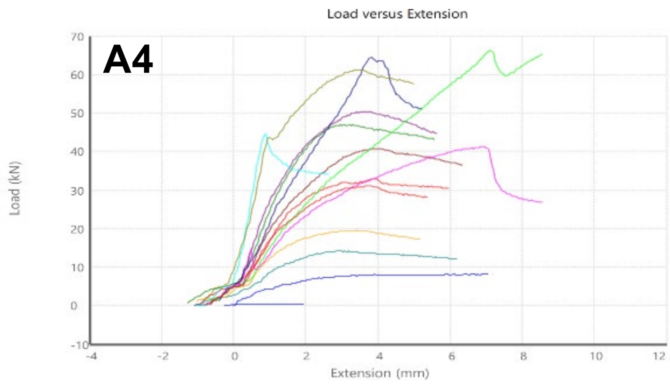
Test A Results

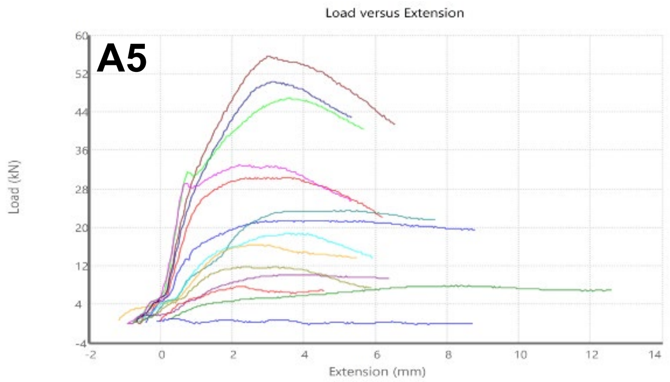


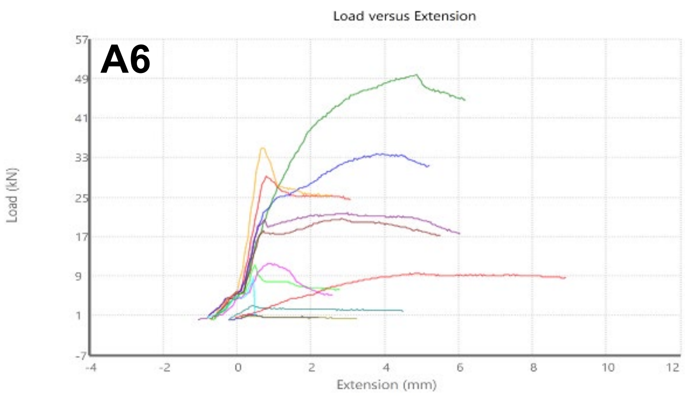


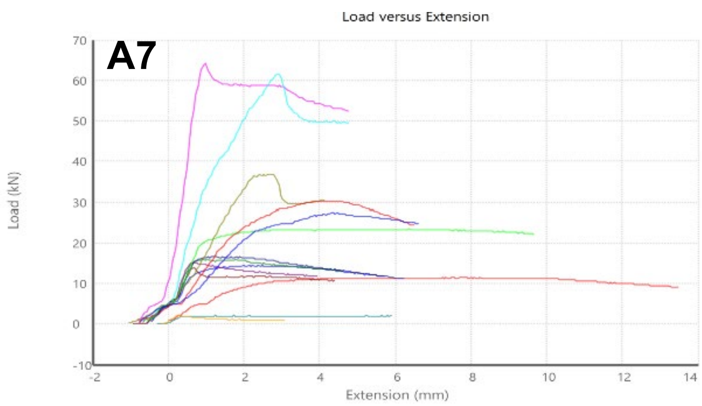




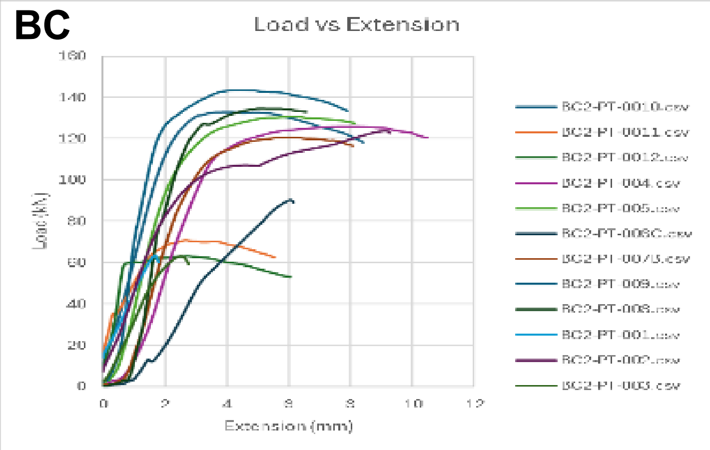


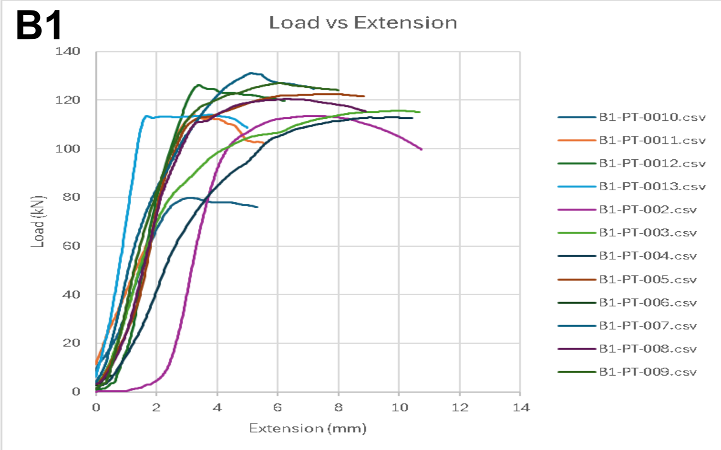


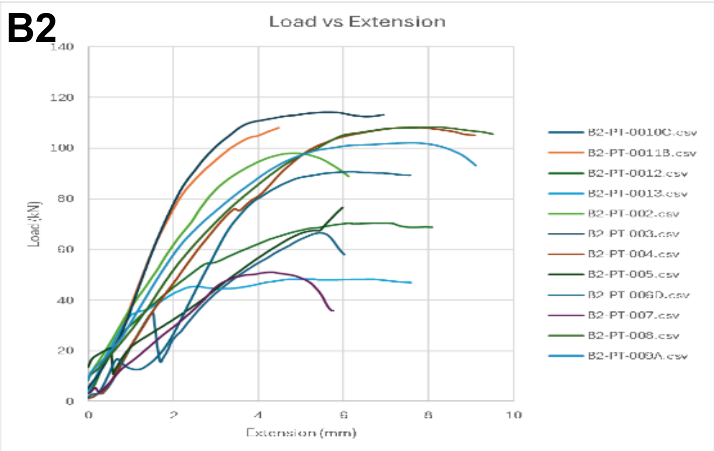


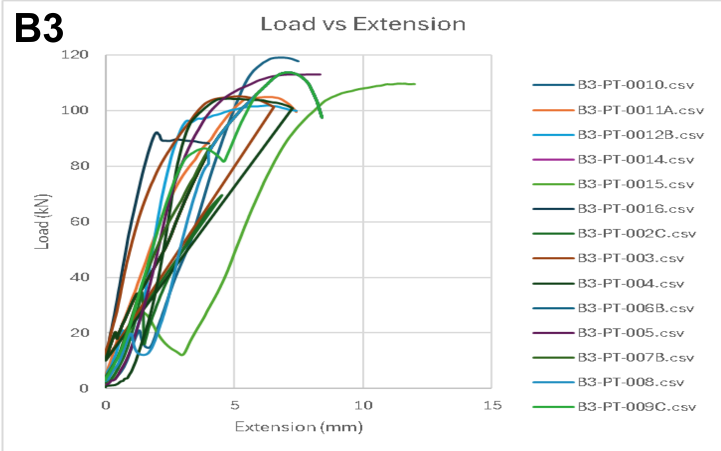


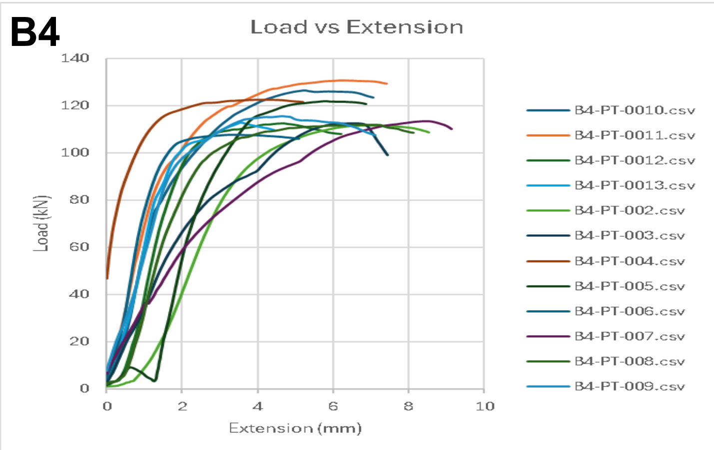
Test B Results



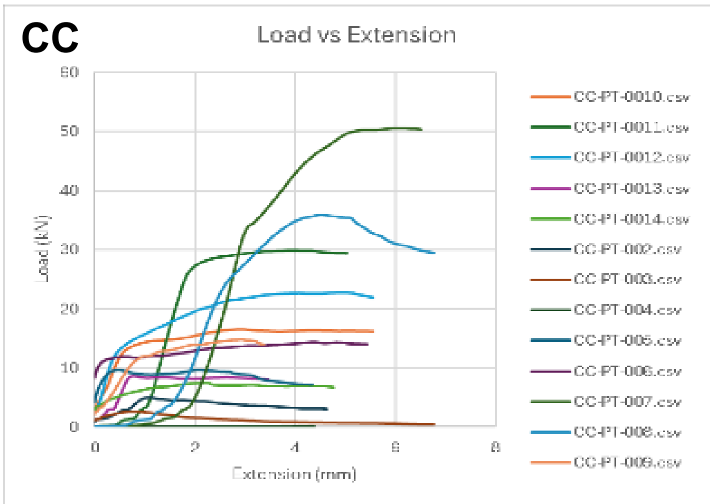


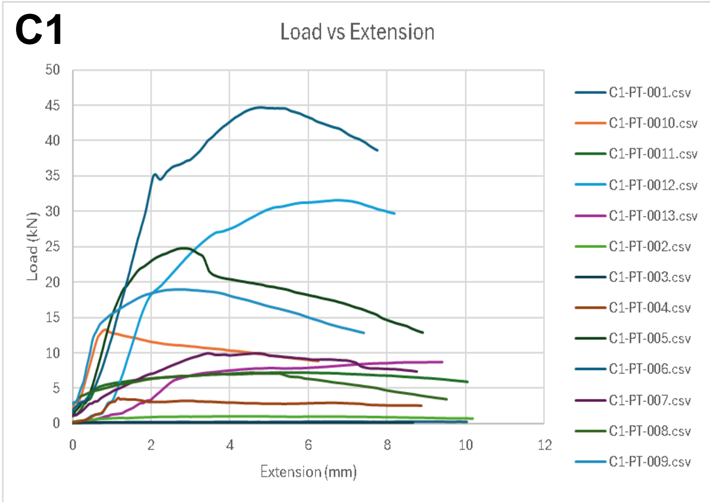


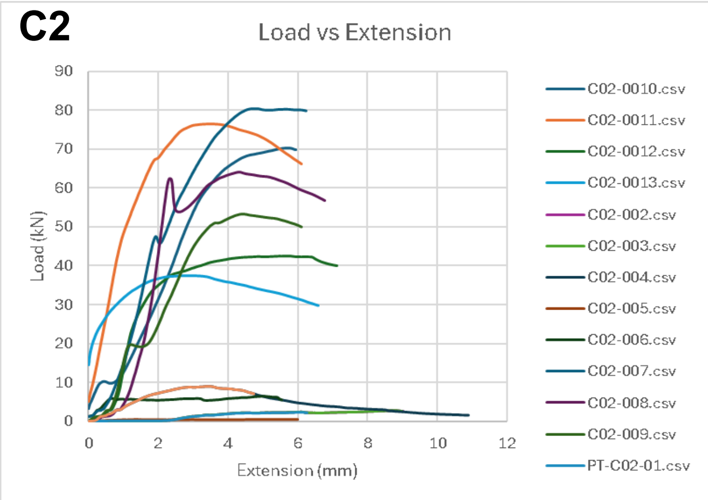


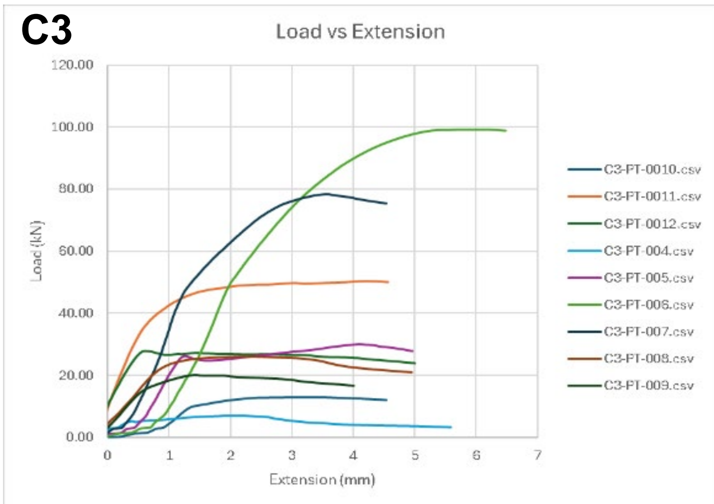


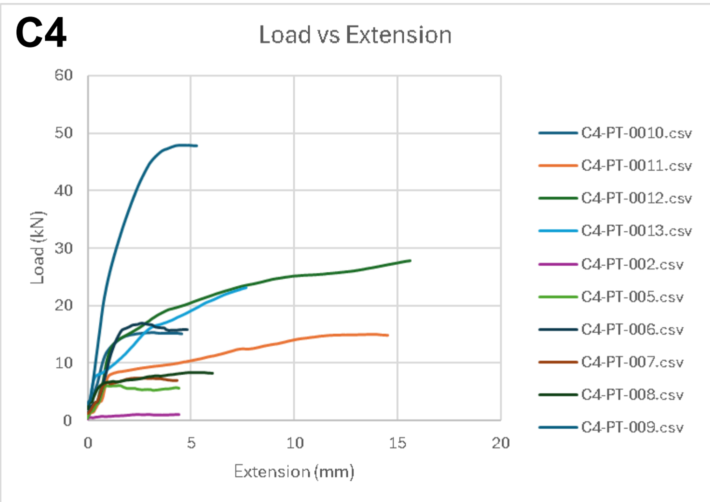
Test C Results



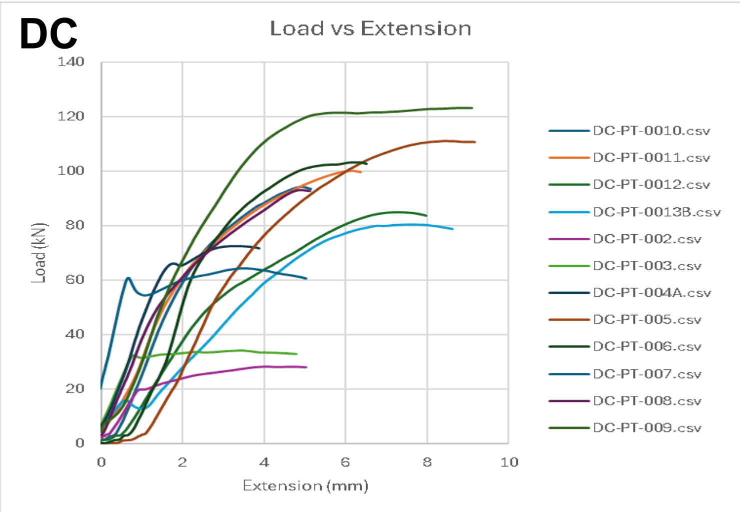


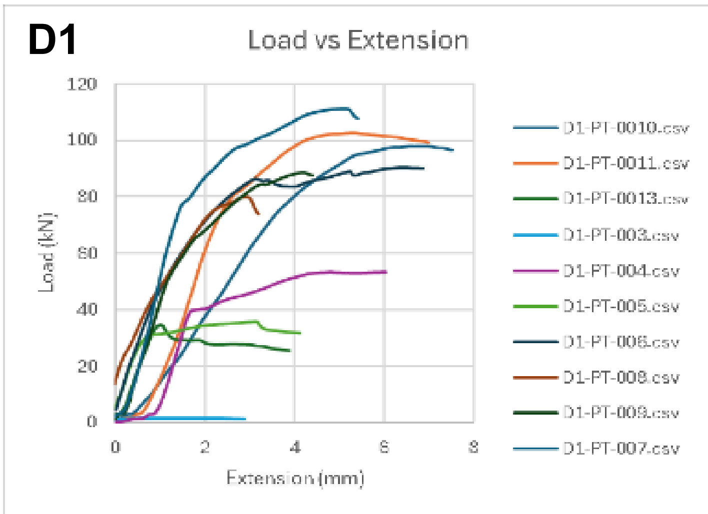


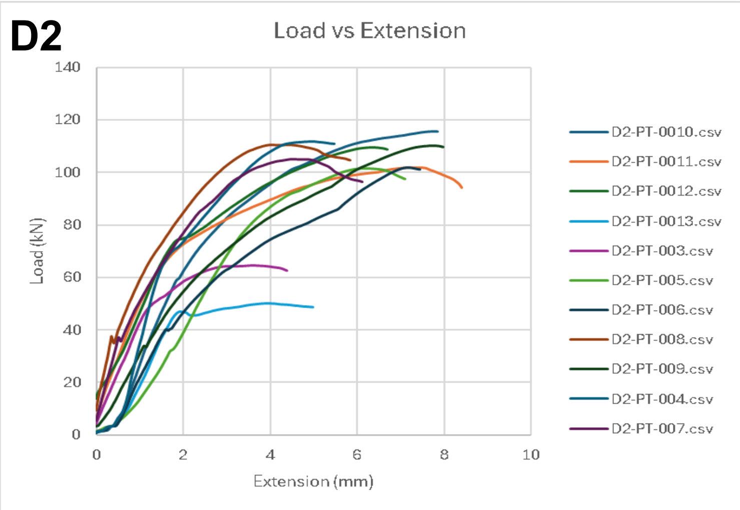


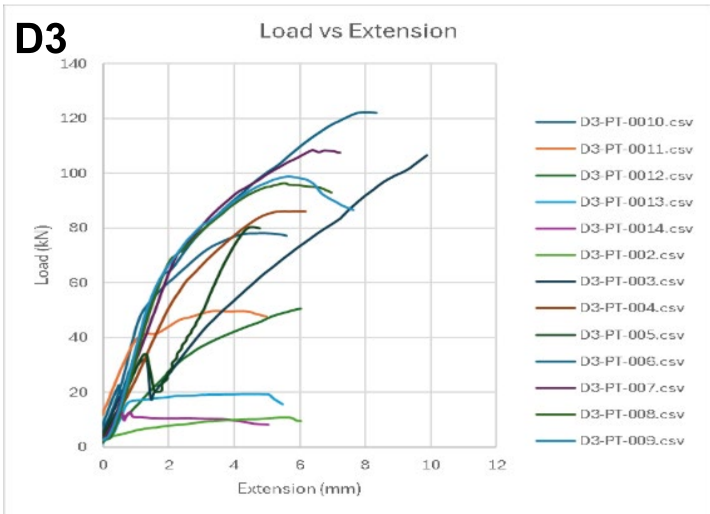


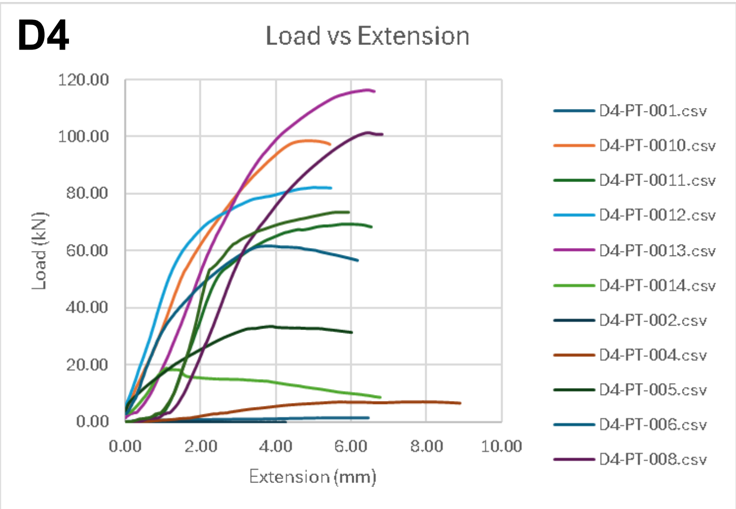
Test D Results











Test E Results