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Analysis of Rock Bolt Behaviour under Shear and Combined Load and an Improved Rock Bolt Design Methodology

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where acknowledgement has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any other university.

Signed:

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Abstract

Rock bolts are subjected to different loads along their length, such as axial, bending, shear and a combination of loads, which can cause unexpected failure if not considered in the design. The common existing rock bolt design methodologies do not, however, consider the actual loading of the rock bolts and assume it is only axial or shear. The purpose of this study was to understand the rock bolt failure mechanism and response to combined load conditions and suggest improvements in the rock bolt design considering the existing loading conditions in situ such as combined load. A series of laboratory tests were conducted using un-grouted rock bolts under combined and shear load conditions. The first set of tests were conducted to evaluate the steel mechanical performance under combined loads using rock bolts for hard rock and coal. For the combined load conditions applied to the rock bolt, two loading regimes were evaluated: the effect of initial shear displacement on axial load capacity and displacement, and the effect of initial axial displacement on the shear load capacity and displacement. The first regime was also conducted for shear with a gap when there is a spacing between the shear interfaces. From the results, it was evident that the combined load decreased the rock bolt capacity significantly for both rock bolt types. These findings showed the need to consider the effect of combined load conditions in the rock bolt capacity. A hybrid failure criterion was developed to calculate the decrease in load capacity of the rock bolt under combined load conditions. Based on the results of the failure criterion developed, a simplified methodology was suggested to determine the rock capacity to be considered in the rock bolt design. This methodology suggests to always reduce the rock bolt capacity by 50% since combined load is a common condition in situ. Alternatively, a detailed assessment of the ground conditions of the mine can be done to validate this approach.

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Author’s Peer Reviewed Papers

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Chapter 1
Introduction

1.1 Introduction

The ground reinforcement in underground mines is the primary defence against unplanned falls of ground that can cause injury, equipment damage and loss of production. Having adequate ground reinforcement design can increase safety and operation reliability. Rock bolts are commonly used as part of the ground reinforcement system and are typically installed as primary support (i.e. in the development cycle). Studies have been completed to understand the rock bolt performance under the varied load conditions in situ (Li, 2010). These studies have shown that the rock bolts are typically subjected to a combination of loads in situ: mainly shear, axial, and bending. In the conventional rock bolt design, however, the rock bolt capacity is generally defined only by its axial (tensile) capacity. This study aims to understand the effect of combined load on the rock bolt capacity and consider it in the support design method.

1.1.1 Ground Support Overview and Safety Aspects

In Western Australia, rockfalls and rockbursts were the primary cause of fatalities between 1980s-90s. (Department of Mines and Petroleum, 2014). From 1993 to 2001, fall of ground was estimated to have caused 25% of all lost-time injuries and 40% of all fatal incidents in Western Australian underground mines (Potvin et al., 2001). Procedures such as Ground Control Management Plan (GCMP) have been implemented to help reduce injuries and fatalities related to the failure of the ground support. This seems to have had some success, as between 2000 and 2012, three rockfall fatalities occurred. Between 2012 and 2017, two more fatalities occurred due to fall of ground, representing again the primary cause of fatalities. In 2016-2017, in Western Australia, rockfall represented 5% of lost time injuries cause for gold underground operations (Figure 1.1).

Falls of ground can be related to a series of factors. The main causes identified by the Queensland Government (2004) Mines Safety Bulletin no. 45 include, but are not limited to:

- Corrosion of ground support,
- Incorrect installation,
- Incorrect design or incorrect implementation of ground control system,
- Further mining activities,
- Alteration of faults movement or stress condition,
- Surface support damage from equipment, and
- Lack of specific knowledge of ground control.

This study focused on the rock bolt design and how it can be improved to consider the varied load conditions in situ due to mining after installation. Due to the complexity and variability of the rock mass, the rockfall failure mechanisms are often complex. It is, therefore, necessary to understand the interaction between the immediate rock mass around an excavation, the stresses, and how they change over time and how the installed support reacts.

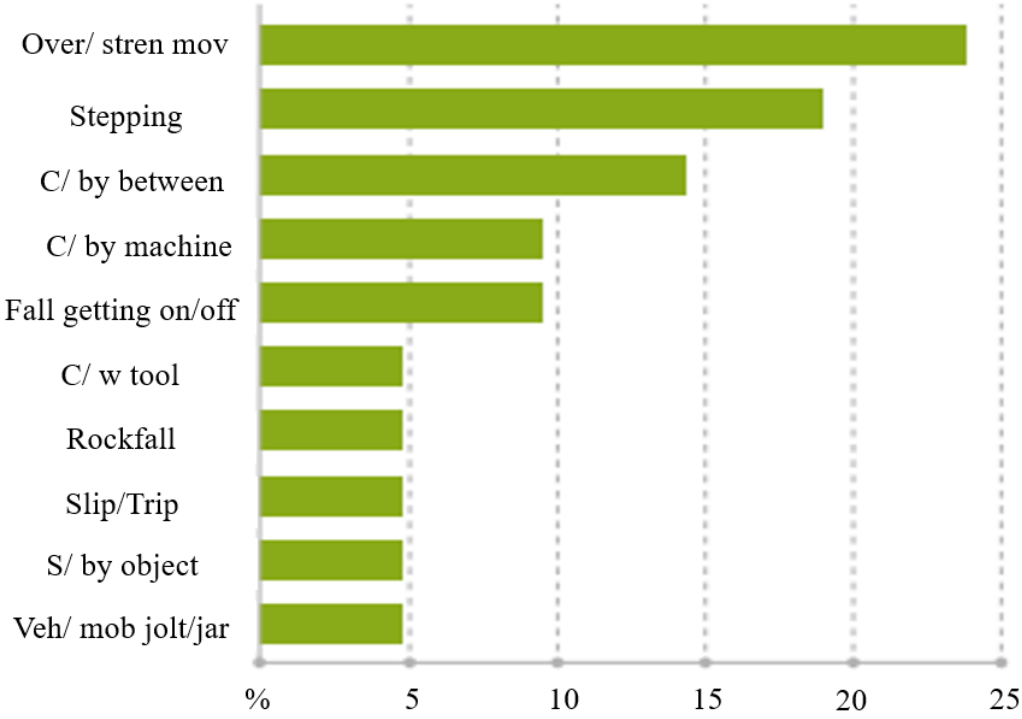

Figure 1.1 – Lost time injuries for gold mines underground injuries 2016-2017. (Safety Performance, 2018)

The loads acting on the rock bolts varies with the changing in situ condition. Under low in situ stress conditions, the rock bolt should generally only resist the deadweight generated by the loose "key" blocks. In this case, the rock bolt capacity has an important effect on the rock bolt design, and the safety factor is defined by the rock bolt strength and weight of the block. Under high-stress conditions, the rock bolt failure is driven by stress causing significant rock movement. In soft rock, it can cause convergence of the ground (Figure 1.2a) and rockburst in hard rock (Figure 1.2b). In this load conditions, the rock bolt is responsible for preventing the rock disintegration (Li, 2010; Li, 2017). The ground condition will determine which rock bolt type is more suitable (Table 1.1).

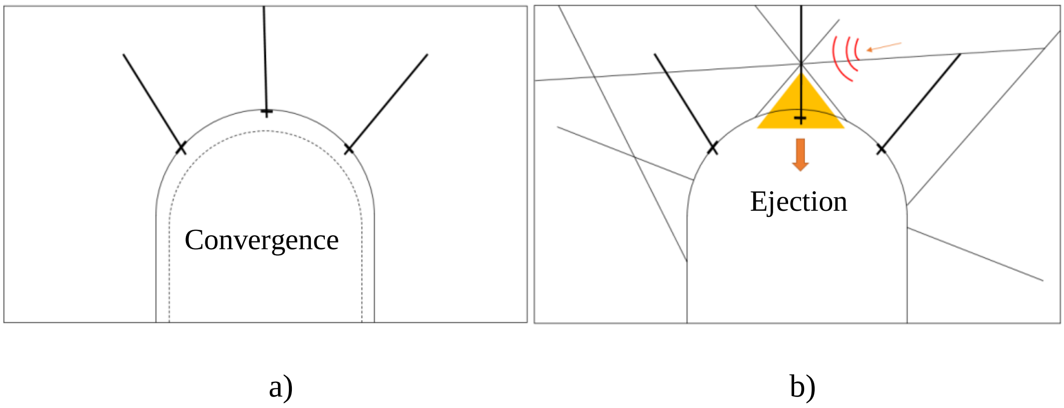

Figure 1.2 – High in situ stress conditions: a) convergence, and b) rockburst.

Table 1.1 – Load conditions and suitable rock bolt types

Load Condition In Situ	**Rock Bolt Type Suggested**
Load-controlled conditions	Fully grouted rock bolts (Figure 1.3), threadbar bolts, and cable bolts (Figure 1.4).
Overstressed weak rock (squeezing conditions)	Split sets (Figure 1.5) can be used with surface elements such as mesh to assist in retaining the rocks.
Rockburst conditions	Energy-absorbing bolts. (Figure 1.6)

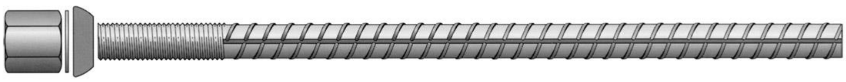

Figure 1.3 – Rebar Rock Bolt (Rock Bolts – Solid Bar, n.d.)

Figure 1.4 – Cable Bolt (Rock Bolts – Cable Bolt, n.d.)

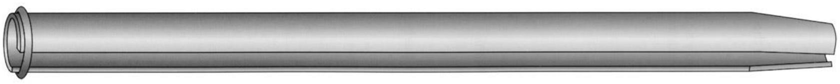

Figure 1.5 – Split set (Rock Bolts – Friction Bolt, n.d.)

Figure 1. 6 – Garfors dynamic solid bolt (Garford Dynamic Solid Bolt, n.d.)

The loads acting along the rock bolt length can also be identified in the rock bolt reinforcement mechanism theory that divides the ground reinforcement into three types (Mark, 2000): key block, beam building, and suspension.

Key Block Mechanism

The key block mechanism is used to support a rock mass with discontinuities that form discrete blocks that can cause mainly gravity-induced block collapses into the excavations. Peng (1984) presented a method to calculate the rock bolt minimum axial stress provided for this condition. However, in this case, the rock bolt is not only subjected to axial load but also shear (Figure 1.7).

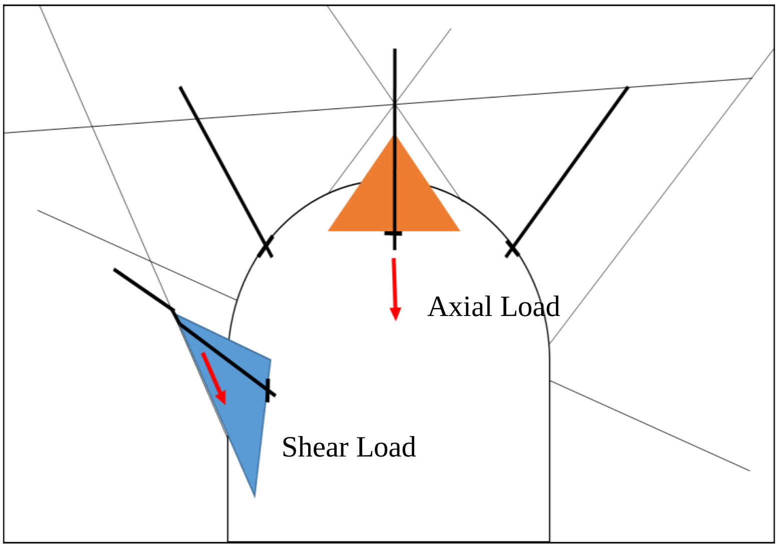

Figure 1.7 – Key block reinforcement mechanism.

Beam Building Mechanism

The beam building mechanism is used when the roof is bedded, and the rock bolts are used to tie the beams together forming one “laminated” beam. Xiu (1990) stated that this mechanism increases bending strength and bending stiffness of the beam formed. However, depending on the condition, the increase in bending stiffness can cause extra load. In this case, the beam could fail in shear instead of tension. Even though shear and combined load are load conditions identified in this mechanism (Figure 1.8), it is not considered to determine the rock bolt load capacity.

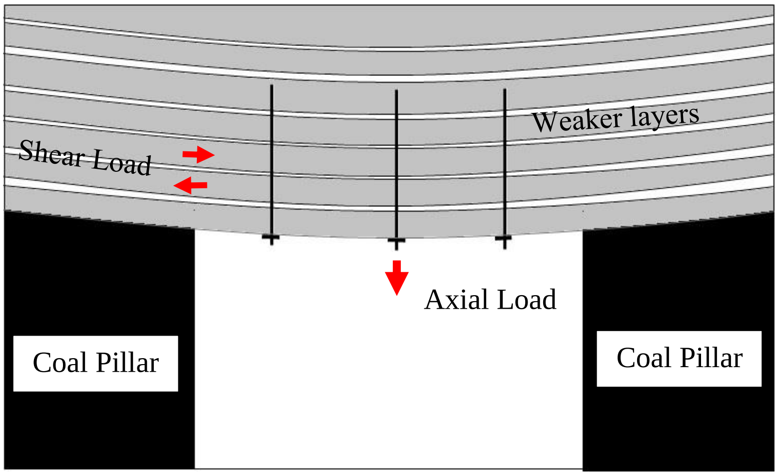

Figure 1.8 – Beam building reinforcement mechanism. (Modified from, Mark (2000))

Suspension Mechanism

For the suspension mechanism, when the immediate layered roof is weak and cannot bear it is own weight, the roof is suspended to the stronger rock located above these weak beds by the ground reinforcement. The reinforcement design aims to hold the deadweight generated by the weak layers in the strong rock. Obert and Duval (1967) presented an equation to calculate the required capacity for each bolt. Later, Unal (1984) proposed a modified equation using the Rock Mass Rating (RMR) classification method. In this method, the rock bolts are generally subjected to axial, shear, bending and/or combined loads, as shown in Figure 1.9. Only axial load is however mentioned in the analysis of the required load capacity of the rock bolt.

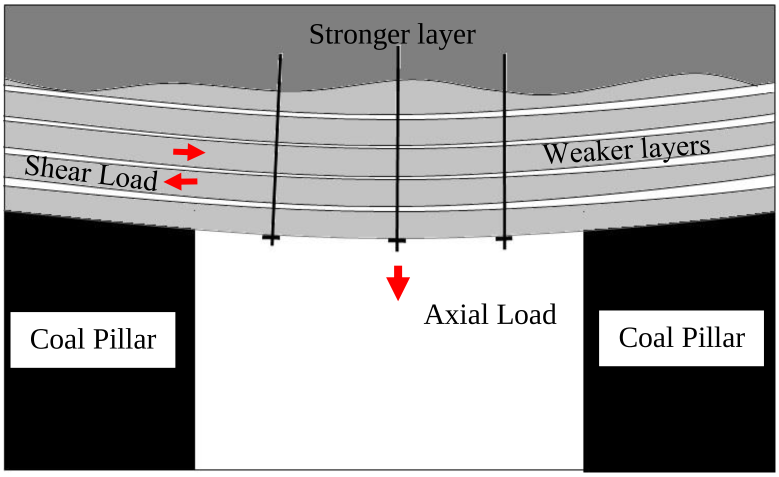

Figure 1.9 – Suspension reinforcement mechanism. (Modified from, Mark (2000))

1.1.2 Current Rock Bolt Design Considerations and Limitations

Different methodologies have been developed to design rock bolts as they are a key contributor to mine safety. The conventional methodologies used traditionally in the rock reinforcement design are:

- Experiential Methods
- Empirical Methods (such as Rock Mass Rating (RMR))
- Analytical Methods
- Physical Methods
- Numerical Methods (including Finite Element Methods, Discrete Element Methods, and Boundary Element Methods)

The issue in designing an adequate support system is also related to the complex load conditions the rock bolt is subjected to in situ, mainly for fully grouted bolts, which are subjected to combined load (shear and axial). There is however not a standard methodology for rock bolt design, and the existing ones do not generally consider complex load conditions. The only international standard on rock bolt testing (ASTM F432) only mentions tensile capacity, for example. An understanding of the effects of complex load conditions and the interaction with the surrounding rock strata on rock bolt performance is essential.

Each of the main methodologies mentioned is presented in details as following:

Experiential

Laboratory tests have been developed to replicate the load conditions in situ in the laboratory to understand the rock bolt performance under varied load conditions. The most common tests conducted in laboratories are pull testing (Figure 1.10), single shear and double shear testing (Figure 1.11a and b). Tests are conducted using instrumented and non-instrumented rock bolt to evaluate the rock bolt performance under varied load conditions. Even though it is challenging to replicate in situ conditions in the laboratory, the experiential tests are the first stage to understand the rock bolt behaviour. Details of this methodology are given in the review chapter of this thesis.

Figure 1.10 – Pull testing set up using an Instron machine at Minova, Nowra, NSW. (Pinazzi et al., 2020)

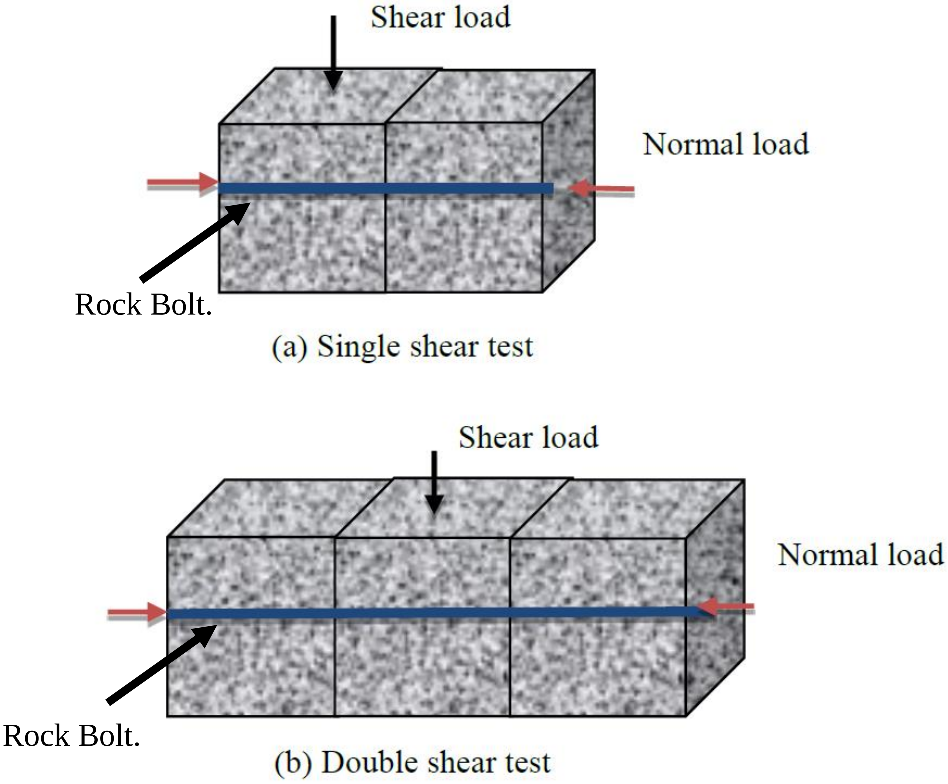

Figure 1.11– Single and double shear tests layout. (Li, 2016)

Empirical

The use of an empirical model for rock bolt design was presented first by Terzaghi (1946). He developed a descriptive methodology to estimate rock loads. After his work, other methodologies were developed and have been used in the rock bolt design. The main methodologies are listed as follows:

- Rock Quality Designation (RQD) – (Deere, 1964)

- Rock Mass Rating (RMR) – (Bieniawski, 1973)
- Q-system – (Barton et al., 1974)
- Coal Mine Roof Rating (CMRR) – (Molinda and Mark, 1994)

These methodologies are commonly used to better understand the rock mass and the support needed. However, it relies on the user's perception and experience. Thus, the same condition being evaluated by two different people might give significantly different results. It is also qualitative and based on a particular database; thus, they should not be used outside the conditions used in the database.

Analytical Methods

The oldest and most common rock bolt design methodology is the dead-weight suspension (Obert and Duvall, 1967). The equation is given by:

$$P = \left[\frac{U * t * R * W_e}{n+1} \right] SF \quad (1)$$

Where,

P = required bolt capacity;

U = unit weight of the rock;

t = thickness of suspended rock;

n = number of bolts per row;

W_e = entry width;

R = row spacing; and

SF = safety factor.

It can be used to determine the rock bolt required capacity for varied conditions, for low-stress environments (Mark, 2000).

Peng (1984) presented another equation to calculate the load required for each bolt considering different parameters:

$$P = \frac{w * t * B * L}{(n_1+1)(n_2+1)} \quad (2)$$

Where,

P = Required bolt capacity;

w = Unit weight of the immediate roof;

t = Thickness of the immediate roof;

B = Roof span (i.e. entry width);

L = Length of immediate roof;

n_1 = Number of rows of bolts in length L;

n_2 = Number of bolts per row.

Signer et al. (1993) tested the dead-weight methodology comparing measurements of the rock bolt loads to the load given by dead-weight design and figured out that the load measured can be twice the amount estimated by the methodology. It shows that using this methodology could overestimate the rock bolt capacity.

Physical Modeling

Physical models are used to evaluate rock bolt performance under different load conditions. However, due to the complexity to replicate the rock mass condition in the model, assumptions such as homogenous conditions are assumed (Panek, 1964; Fairhurst and Singh, 1974; Mark, 1982). It is also complicated to replicate or be consistent in the ratio of geometry and material properties (Yassien, 2003). Other shortcomings of this method are the time consuming and costs. Figure 1.12 shows a physical model created to evaluate the rock bolt and rock massif interaction.

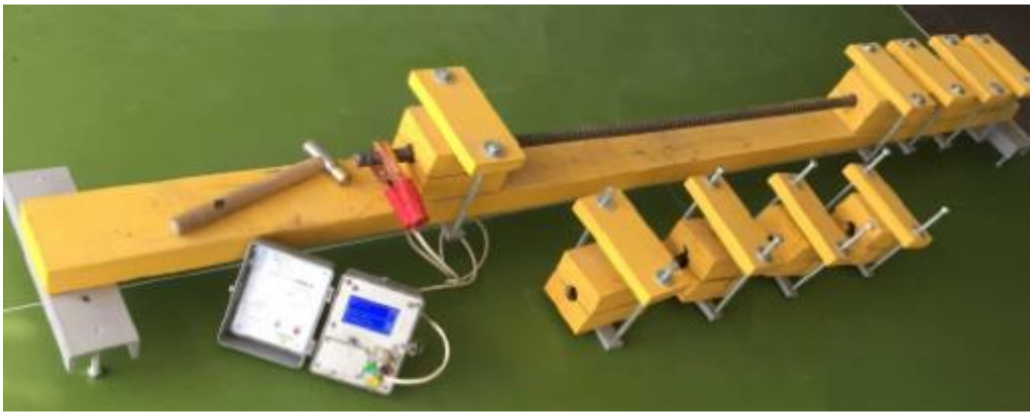

Figure 1.12 – Physical modelling - rock bolt and rock massif interaction. (Skipochka et al., 2019)

Computer Modeling

The numerical model analysis is a useful source to evaluate rock bolt performance under varied properties and stress conditions, which makes them potentially very valuable as design tools. Numerical modelling analysis was developed to replicate axial pull testing in laboratory (Serbousek and Signer, 1987), other simulations used to simulate shear testing (Spang and Egger, 1990). Numerical modeling was also calibrated with laboratory (Jalalifar, 2006) and in situ tests (Spearing and Hyett, 2014). However, none of these studies mentioned combined load conditions. The numerical modeling limitations are related to the difficulty to replicate the rock mass behaviour, to incorporate detailed and representative rock property and in-situ stress. Moreover, it is seldom adequately calibrated with field data.

1.2 Problem Statement

Falls of ground are still a too common event in underground operations that can cause injury, equipment damage and production loss. There is, therefore, a need to understand the complex and combined (hybrid) load conditions and their effect on the rock bolt performance. To date, there is not a methodology that considers shear and combined load in the rock bolt design.

1.3 Research Objectives

There is still a need to understand the rock bolt behaviour under complex loads that is a common condition in situ. In the conventional methodologies, the rock bolt capacity is given by its tensile capacity. Being able to understand the rock bolt behaviour under combined load condition is an essential step to develop a potentially more reliable methodology to effectively design ground support. The main objectives of this research study are:

- Understand the rock bolt behaviour subjected to pure axial, pure and gapped shear, and combinations of both (combined load).
- Determine an approach to consider combined load conditions in the rock bolt design.
- Suggest improvements to the current rock bolt design methods.

1.4 Thesis Content and Layout

This work focuses on presenting the relevance of considering shear and combined load in the rock bolt design. To improve the rock bolt design, the effect of loads acting along the rock bolt needs to be well understood as well as the failure mechanisms. Therefore, this thesis is structured to first present how shear and combined load effect the rock bolt performance (Chapter 3), being able to evaluate and quantify the rock bolt decrease in capacity under these loading mechanisms (Chapter 4), and evaluate the failure mechanism under each load conditions and consider it in the design (Chapter 5). The following diagram (Figure 1.13) presents a summary of the thesis structure.

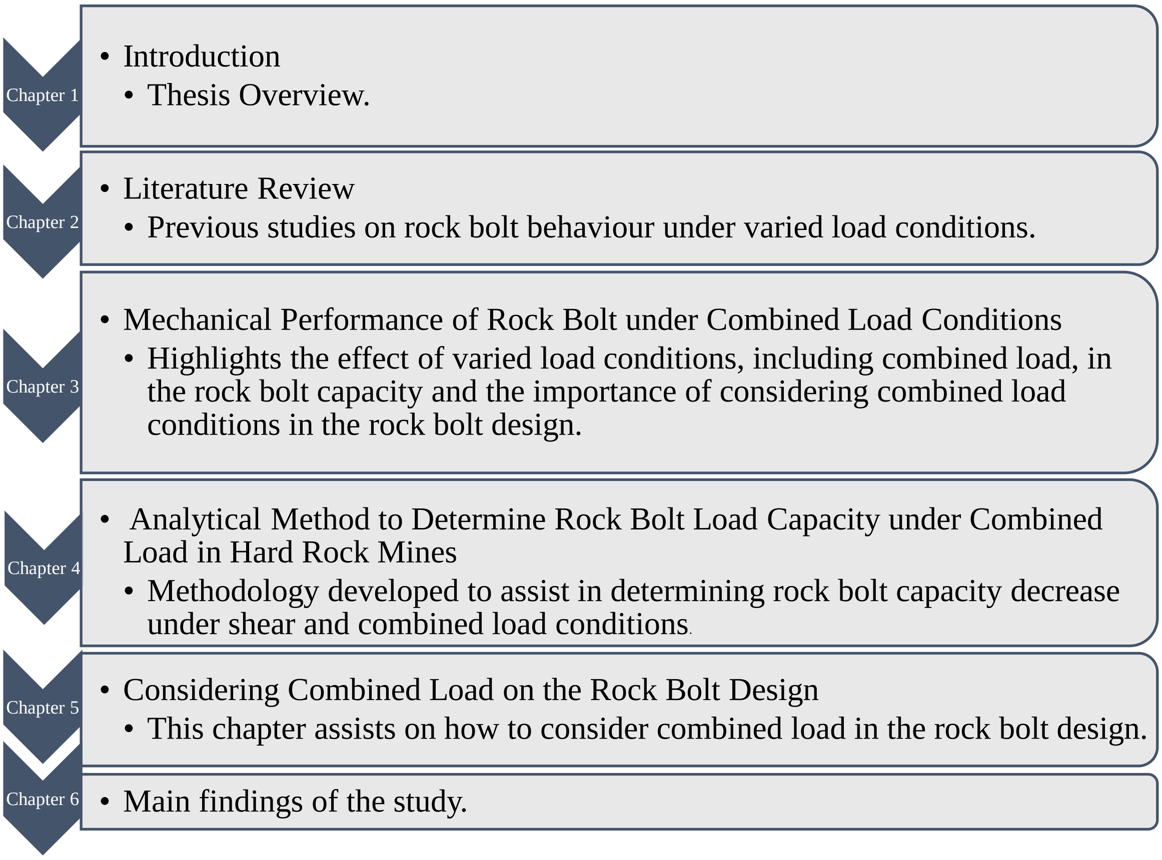

Figure 1.13 – Thesis structure summary.

This thesis is laid out as follows:

Chapter 1: **Introduction**

This Chapter includes an overview of the topic and the problem statement.

Chapter 2: **Literature Review**

This includes the background and previous studies related to shear and combined load.

Chapter 3: **Mechanical Performance of Rock Bolts under Combined Load Conditions**

Paper under review: Pinazzi, P.C., Spearing, A.J.S., Jessu, K.V., Singh, P., & Hawker, R. (2020). Mechanical performance of rock bolts under combined load conditions. *International Journal of Mining Science and Technology*. https://doi.org/10.1016/j.ijmst.2020.01.004

Considering combined load in the rock bolt design requires an understanding of the effect of combined loading on the rock bolt performance. Thus, a new laboratory test set up was developed to test ungrouted rock bolts under axial, shear and combined loads. The tests conducted consist of applying shear load only with and without a gap, and combined load, i.e. shear and axial loads.

In this thesis, the single load (shear or axial) and combined load conditions were applied to the rock bolt. The combined load condition stands for when more than one load mechanism is acting on the rock bolt at its failure. The combined load condition is applied to the rock bolt using two methods: applying a shear load with a gap (between the shearing surfaces) and applying two different load mechanisms to the bar.

In one of the tests regime conducted, the shear load is applied to the bar with a gap, which is the spacing between the shear interface/discontinuity. Due to the spacing/gap, the bar undergoes shear and axial load, where the axial load is created by the bending mechanism. In the other procedure, the combined load was applied to the bar by applying two types of load, both loads being kept to the bar until failure. In this case, two regimes of load were applied to the bar: axial displacement and then shear load to failure, and shear displacement and then axial load to failure.

Chapter 4: **Combined Load Failure Criterion for Rock Bolts in Hard Rock Mines**

Paper under review: Pinazzi, P.C., Spearing, A.J.S., Jessu, K.V., Singh, P., & Hawker, R. (2019). Combined Load Failure Criterion for Rock Bolts in Hard Rock Mines. Manuscript submitted for publication.

This Chapter presents the failure criterion for combined load, considering each load mechanism applied to the rock bolt and also a hybrid failure criterion that can be used because it is impossible to determine which loads are applied when and generally along the rock bolt, shear and tensile loads are applied simultaneously.

The failure criterion was developed to predict the failure of the rock bolt under hybrid loading conditions. Chesoon et al. (1965) had previously developed a failure criterion for structural bolts under combined load. However, it does not apply to this study because it only considers that the bar undergoes shear and axial load, it does not include bending. Developing a failure criterion helps to improve the reliability of rock bolt designs

Chapter 5: **Considering Combined Load on the Rock Bolt Design**

Chapter 5 discusses the effect of the combined load and how it can be taken into consideration for rock bolt design. It presents a qualitative analysis of the rock bolt failure mechanism that can be used to help estimate the loads acting on the rock bolt in situ. It also shows how to use the hybrid failure criterion presented in Chapter 4 on the rock bolt design.

Chapter 6: **Summary of Findings and Conclusions**

Chapter 6 presents the study findings and its contribution to the field. It presents a summary of the main findings in this study and how to use the approached developed to consider the combined load on the rock bolt design.

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Chapter 2
Literature Review

2.1 Literature Review

Rock bolts are used internationally to reinforce unstable rocks around excavations. The rock bolts reinforce and mobilize the inherent strength of the rock mass (Deb, 2012). Support has an important role in the mines' safety as they help to control or stop rock falls. Laboratory and in situ tests using instrumented and un-instrumented rock bolts have been developed in the past decades to being able to improve the design of the rock bolt to better meet the in situ conditions, and subsequent changes due to on-going mining.

Even though many studies have determined that the rock bolts are subjected to varied load conditions such as axial, shear and/or bending, the international standard on rock bolt testing American Society for Testing and Materials (ASTM F432) only mention tensile loading. The combined load is only mentioned on the testing standard for structural bolts in the ASTM and American Institute of Steel Construction (AISC). However, it does not apply to the load conditions presented in this study.

This chapter provides a background on for the content of this thesis and presents the previous research develop to understand the rock bolt performance under varies load conditions (shear, axial, and/or bending loads).

2.2 Key Rock Bolt Research Findings from the Past 50 years

In the early 70s, most of the research focused on investigating axial load. Later, other studies were also developed to understand the rock bolt under shear load. These studies have evaluated a series of parameters that affect the rock bolt performance and its failure mechanism (Dulacska 1972; Bjurstrom 1974; Fuller and Cox 1978; Dight 1983; Egger and Fernandes 1983; Spang and Egger 1990; Ferrero 1995; Pellet et al. 1995; Kharchafi et al. 1999; Grasselli 2005; Haas 1976; Jalalifar 2006). However, most of the studies developed to understand the rock bolt performance until now focused on a single load condition, axial or shear, because it is less complex to evaluate the effect of one load rather than a combination of loads.

In the conventional rock bolt design, its capacity is given as the axial capacity. In a discontinuous rock mass, the load is influenced by the number of discontinuities that intercept the bolt and cause varying tension and shear stresses along the bolt. The rock bolts are also subjected to shear in high horizontal stress conditions and in fractured/bedded rocks. Thus, studies have also been conducted to evaluate shear and the rock bolt contribution at joints.

2.2.1 Overview of Rock Bolts Performance under a Single Load Condition

One of the first shear test was conducted by Bjurstrom (1974), who applied direct shear to the rock bolt using fully cement grouted bolts. He evaluated the tension loads in the bolt, friction at the shear interface, dowel effect, and bolt inclination. The main findings were the rock bolts failure characteristics depended on the inclination angle between the rock bolt and joints. He also found that for angles smaller than 40 degrees, the rock bolt failed by a combination of shear and tension loads.

Farmer (1975) conducted tensile tests using instrumented rock bolts to evaluate the shear stress distribution along the rock bolt length. His study showed that the shear stress at the bolt-grout interface would reduce from the loading point to the far end of the bolt before decoupling occurs. The limitation of his theory is that it was only applied when the rock bolt was subjected to low axial load.

Haas (1976) studied the shear resistance of the rock bolts along the shear interface under high and low normal pressure and evaluated the shear mechanism under each condition. He found out that the shear resistance increased significantly along fracture or bedding plane when the average normal compressive stress on the plane was 25 psi (172 kPa).

Freeman (1978) used strain gauges to measure strains along fully grouted bolt length and developed a concept that divided the bolts into sections under axial load: neutral point, pickup length, and the anchor length. The neutral point is the point where the rock and the bolt displace the same and shear stress within the resin annulus is zero. The pickup length is the rock bolt length where the rock displaces more than the bolt and it is located close to the excavation and the anchor length is the length where the bolt displaces more than the rock and shear forces are in opposite sense. Figure 2.1 is representing the difference of axial displacement when using faceplate or not. In fact, in theory, when using a faceplate, the neutral point moves to the surface, but in reality, the neutral point is located somewhere between the two situations shown in Figure 2.1 (Modified by Hyett et al., 2013).

Dight (1982) conducted an analysis to evaluate grouted rock bolt performance. He assumed that the rock bolt contribution to the joint shear strength was due to tensile force and the dowel effect. The dowel effect is a localised shear deformation as presented in Figure 2.2. The main findings of his study were the bolts were subjected to a combination of loads shear and tension, bolts with an inclination showed to be stiffer compared to when installed perpendicular to the joint, and the rock bolt deformability is related to the rock properties.

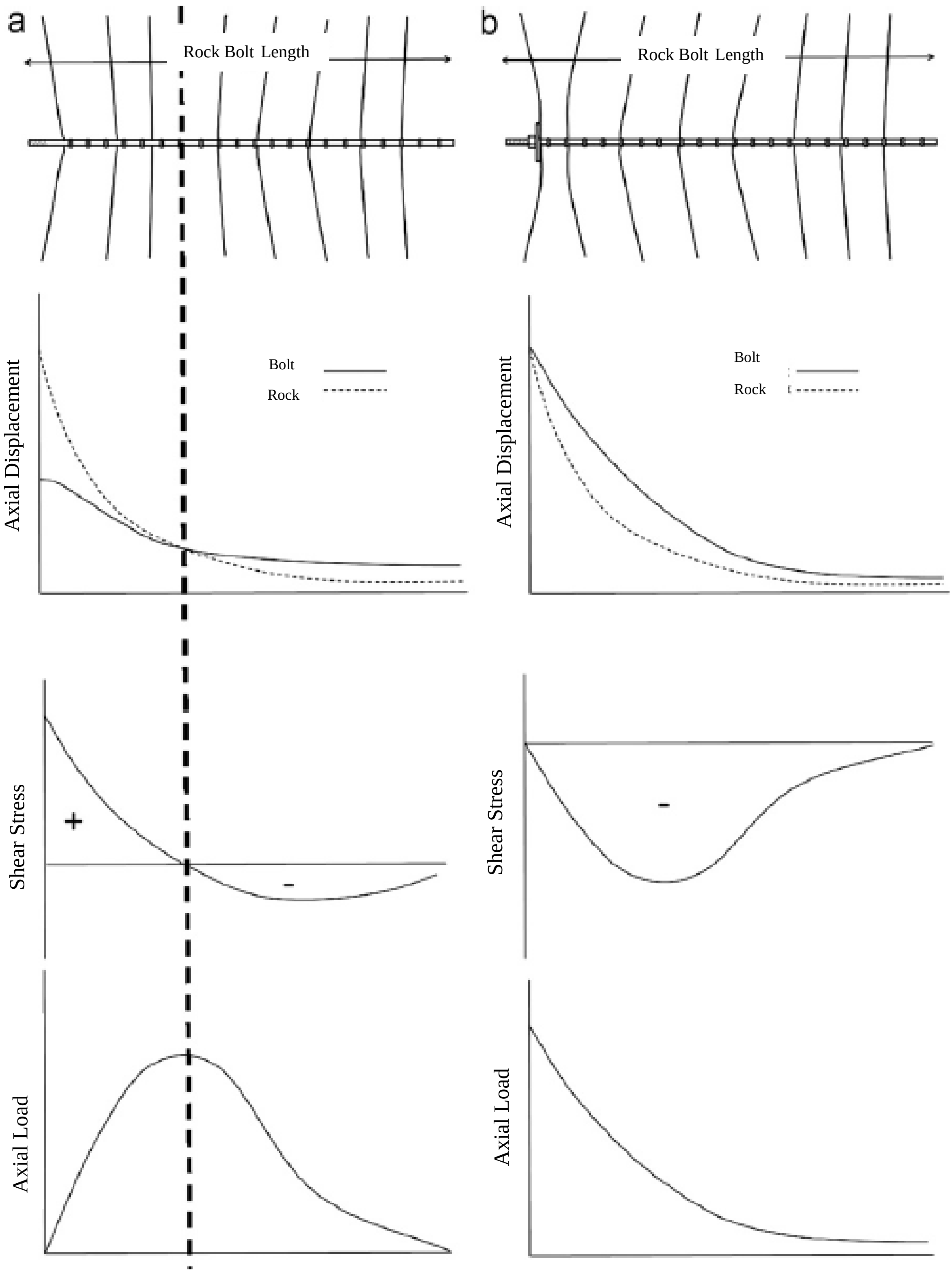


Figure 2.1 – Behaviour of rock bolt with and without the faceplate. (Freeman (1978) modified by Hyett et al., 2013)

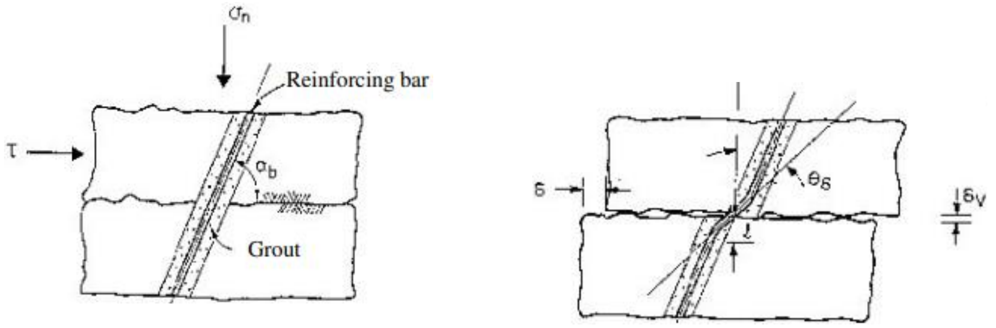


Figure 2.2 – Example of deformation for a dowel in shear. (Jalalifar, 2006)

Spang and Egger (1990) conducted laboratory, in situ and numerical analysis to evaluate the grouted rock bolt contribution to the joint shear strength. The main parameters evaluated were: bolt diameter, friction angle along joint, rock deformability, bolt inclination, joint dilatancy, and normal stress. The main findings of this study were that the contribution of fully cement-grouted bolts to the shear resistance of joints depends strongly on joint friction, inclination, dilatancy and deformability of rock and ground with lesser influence. The limitation of this analysis was that the tests were conducted using cement grout in a borehole of twice the bolt diameter.

Signer et al. (1997) proposed design criteria that considered axial load and maximum bending stress to determine rock bolt spacing in coal mines. However, it did not consider shear loads, only axial and bending.

Instrumentation has been an important tool helping to understand the loading mechanism acting along the rock bolt length resulting from ground movement. Most of the experiments conducted until 2013 used two opposite slots to place short-length resistive strain gauges. Spearing et al. (2013) pointed out the ineffectiveness of instrumented rock bolts using short-length resistive strain gauges in which no more than 10% of the bolt length was monitored. Increasing the number of strain gauges would also raise the costs making it unaffordable since the strain gauges are expensive. Furthermore, a two-slot instrumented bolt can only measure the shear direction if the slots are oriented in the direction of shear. The most recent monitoring technology, Distributed Optical Sensing (DOS) and Fiber-Bragg Grating (FBG), which uses the optical fibre technology, were compared to understand the rock bolt load conditions (Hyett et al., (2013); Kostecki et al., (2015)) (Figure 2.3).

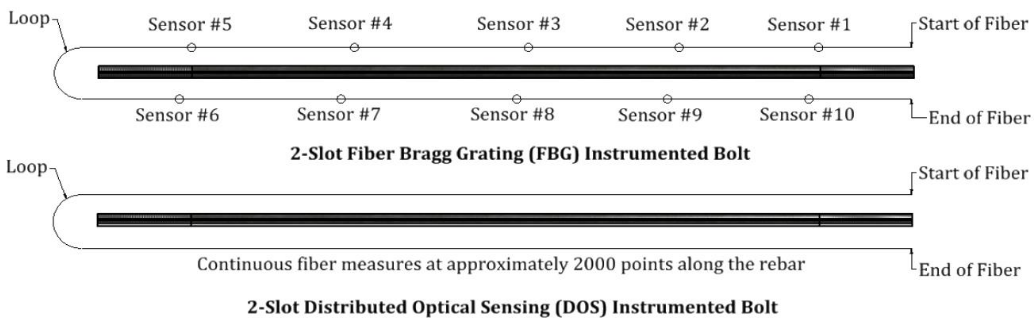


Figure 2.3 – Example of DOS and FBG technology placed in the rock bolt. (Kostecki et al., 2015)

2.2.2 Combined Load Condition Concept

The first study conducted to evaluate the combined load's effect on bolts date 1965. Chesson et al., (1965) were the first to develop a failure criterion for structural bolts under combined load. Frisher and Struik (1974) used the approach to also evaluate structural bolts performance under combined load. Dight (1985) used the concept to explain how combined load affects the rock bolt performance as shear is applied at different angles. After Dight (1985), other studies were conducted mainly to evaluate the effect of combined load with focus on the bolt contribution to joint shear strength (Has, 1981; Ferrero 1995; Pellet and Egger, 1996; Jalalifar, 2006; Li et al., 2016).

The most recent failure criterion to predict the load at failure or the ultimate load of a bolt in combined shear and tension is based on normal stress and maximum shear given as follow (Steeve and Wingate (2012)):

$$\sigma_{max} = \frac{\sigma}{2} + \sqrt{\frac{\sigma^2}{2} + \tau^2} \tag{3}$$

and

$$\tau_{max} = \sqrt{\frac{\sigma^2}{2} + \tau^2} \tag{4}$$

If the maximum allowable load can be given as σ_{ult} and τ_{ult} , then $R_s = \tau/ \tau_{ult}$, $R_t = \sigma/\sigma_{ult}$, and $k= \tau_{ult}/ \sigma_{ult}$, the equations 1 and 2 can be written as follows:

$$1 = \frac{R_t}{2} + \sqrt{\left(\frac{R_t}{2}\right)^2 + (kR_s)^2} \tag{5}$$

and

$$1 = \sqrt{\left(\frac{R_t}{2k}\right)^2 + (R_s)^2} \quad (6)$$

In structural engineering, it is convenient to use Tresca failure criterion, which considers k=0.5. This simplifies the equation 5 to the following:

$${R_s}^2 + {R_t}^2 = 1 \quad (7)$$

This failure criterion is used when the rock bolt failure interface is subjected to a combination of shear and axial loads. The limitation of this failure criterion is that it can only be applied when there is no bending moment or bending moment is considered minimum. It also does not apply when k is ≠ 0.5. In this situation, a more complex analysis is required.

After Chesson et al., (1965) and Frisher and Struik (1974) studies, the combined load condition was often mentioned in the rock bolt research studies developed to understand the rock bolt behaviour under shear load. However, the combined load mentioned previously (ie. axial, shear, and/or bending) is a resultant of shear being applied to the bar.

Dight (1982) conducted an analysis to evaluate grouted rock bolt performance. He assumed that the rock bolt contribution to the joint shear strength was due to tensile force and the dowel effect. The dowel effect is a localised shear deformation as presented in Figure 2.4. The main findings of his study were the bolts were subjected to a combination of loads shear and tension, bolts with an inclination showed to be stiffer compared to when installed perpendicular to the joint, and the rock bolt deformability is related to the rock properties.

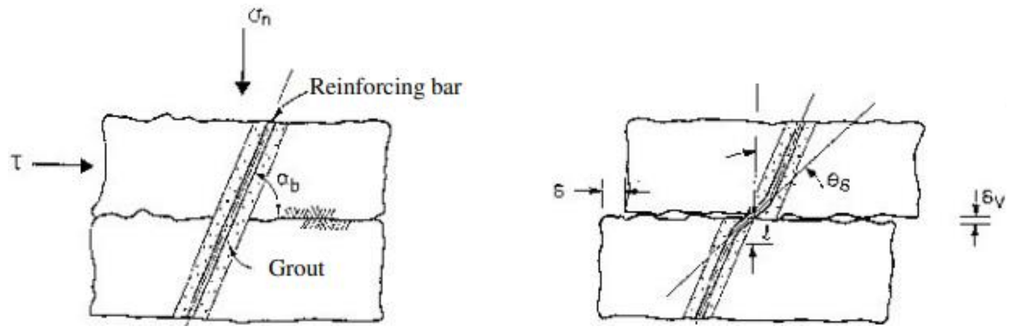


Figure 2.4 – Example of deformation for a dowel in shear. (Jalalifar, 2006)

Ferrero (1995) conducted laboratory tests using strain gauges to evaluate shear strength contribution to rock joints. From the laboratory results and numerical analysis, he determined two different failure mechanisms for hard and weaker rock. For hard rock, he observed that the rock bolt failed by a combination of shear and tensile stresses, and for weaker rock, he pointed out that it failed by tensile stresses and bending moment. From the results obtained, an analytical model was developed. However, it was limited to rock bolts installed perpendicular to the joint interface in bedded strata.

Pellet and Egger (1996) have also developed an analytical model for rock bolt mechanical behaviour of rock bolts subjected to shear load at joints taking account the interaction of shear and axial load and also large plastic displacement of the bolt. Their theory was applied to rock bolts installed in an angle less than 90 degrees. However, it was not applied if perpendicular to the joint. Although all these studies mention axial, shear, bending, and combined load, the combined load is created as a result of shear load being applied to the rock bolt. It only considers the combined load condition at the rock bolt failure interface as shown in Figure 2.5.

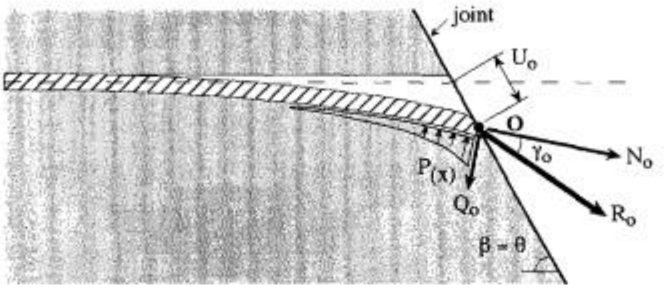


Figure 2.5 – Bolted joint subjected to shearing, No = axial force and Qo = shear force. (Pellet and Egger, 1996)

Li et al. (2016) conducted laboratory tests to evaluate the behaviour of different rock bolt under shear load. The tests were conducted under shear load and compression to evaluate the bolt contribution to the joint shear strength. The different rock bolt types presented different failure mechanism varying between a single load failure mechanism such as shear or axial, or combined load mechanism such as shear and tension. The main findings were that the angle between the shear interface and bolt installation, rock mass strength, and joint friction angle, influence the contribution to the rock bolt to the joint subjected to shear. Figure 2.6 shows the rock bolt failure mechanism for each rock bolt type tested.

Snell et al. (2017) conducted double shear tests to evaluate the performance of fully grouted bolts with different gap sizes between the joints. The resin grouted rock bolts were installed in three sections of steel pipes, and the load was applied in the middle section of the steel pipe (Figure 2.7). He found that as the gap size increases the capacity of the rock bolt and its resistance to shear decreases. The rebar stiffness, yield and ultimate strength were reduced as the gap increases. His study did not mention the combined load acting at the rock bolt shear interface at failure.

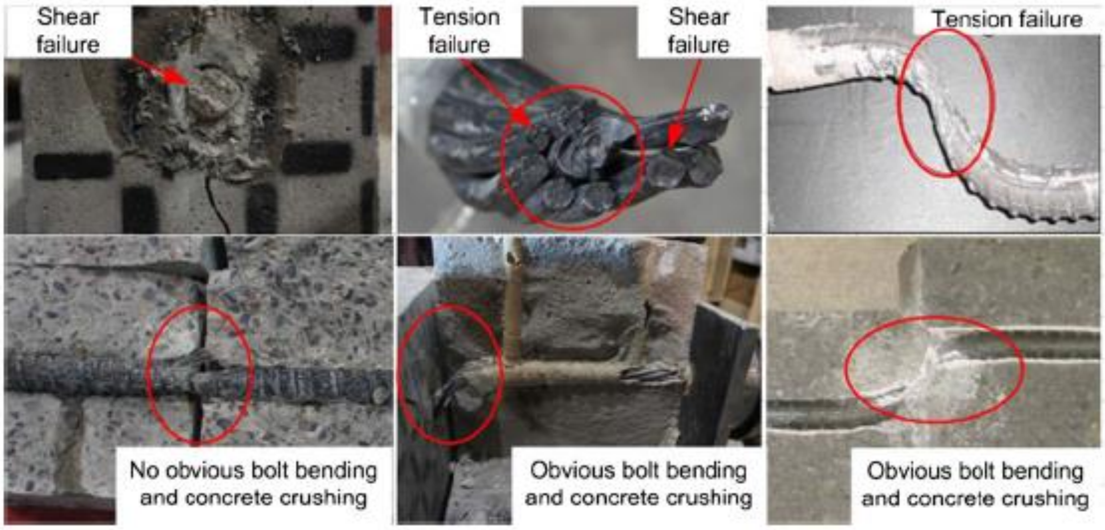


Figure 2.6 – Failure mechanism of different rock bolt types. (Li et al., 2016)

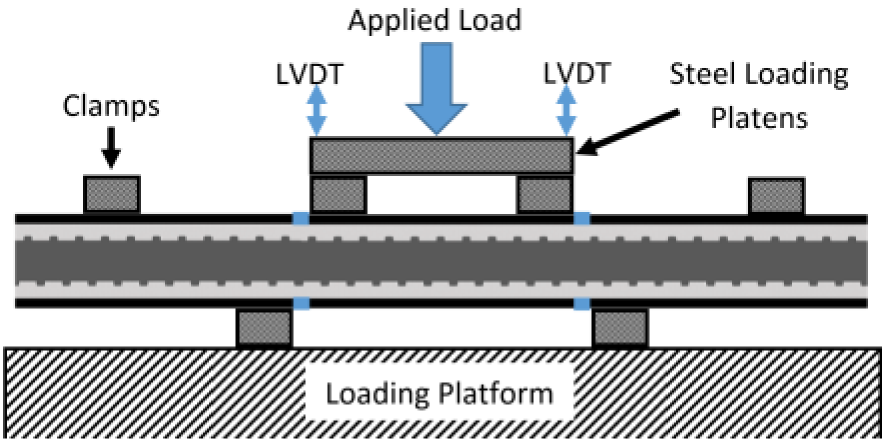


Figure 2.7 – Double shear test set up. (Snell, 2017)

Even though most of the studies have considered that the rock bolt fails by combined load when subjected by shear load, Li (2010) studies have shown that the rock bolt is subjected by more than one load in situ and not only shear or axial loads. He stated that the rock bolt failure mechanism has a direct impact on the rock bolt design. His study was conducted in a cut-and-fill mine at the advance face of the mine stopes. In Figure 2.8, it is possible to identify that the rock bolt is being subjected by a combination of loads, axial, shear, and also bending.

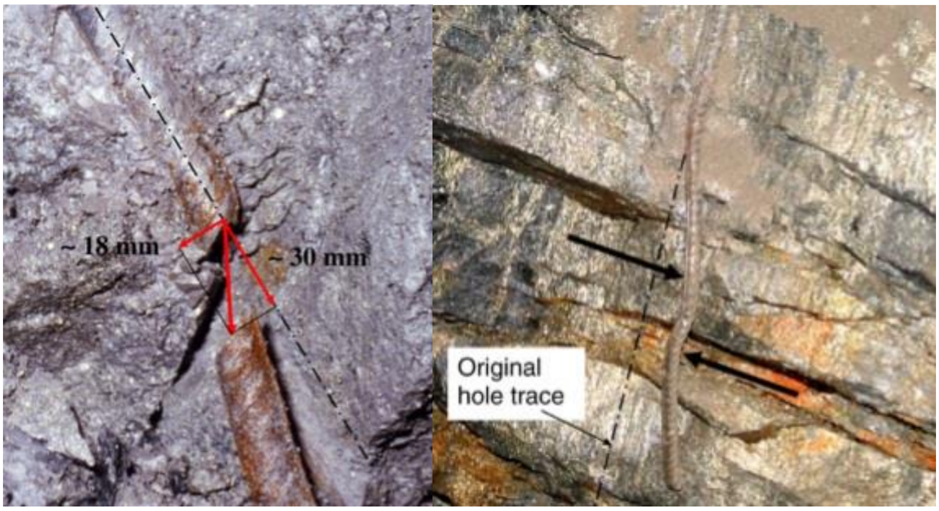


Figure 2.8 – Field analysis of rock bolt under shear and tensile loads. (Li, 2010)

Chen (2014) conducted a study that evaluated the effect of combined load in the rock bolt performance. He developed a new test setup for pull-and-shear loading conditions (Figure 2.9a). The rock bolt performance was evaluated varying the displacing angle, gap size, and rock mass strength (concrete strength). The displacing angle (α) (Figure 2.9b), which is the resultant force of combined load angle, showed to have a major influence in the displacement capacity. As the displacing angle applied increased, the displacement capacity of the rock bolt decreased. On the other hand, the load capacity was not significantly affected. These findings agreed with the findings of this thesis. However, the influence of shear load in axial load and vice-versa was not quantified by previous research, and no suggestion has been made on how to consider combined load condition in the rock bolt design.

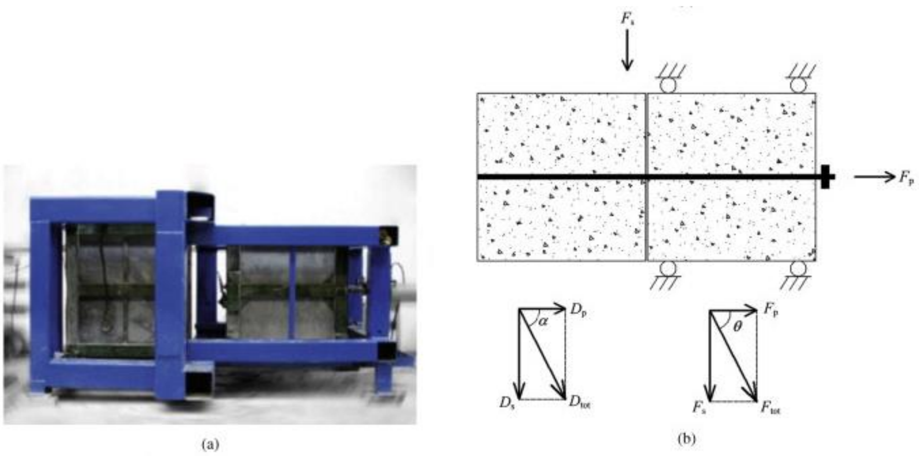
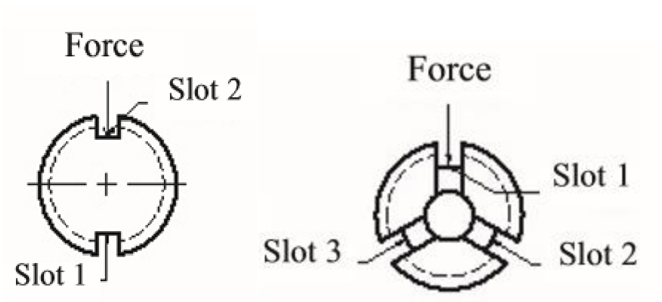


Figure 2.9 – a) Laboratory test rig and b) view sketch. (Chen, 2014)

The instrumentation technology has also been developed to be able to identify combined load conditions. Kostecki et al. (2015) and Jessu et al. (2016) conducted laboratory experiments using DOS and FBG in a two and three slots configuration in the rock bolt. They found that using two slots configuration, the sensors must be oriented in the direction of the maximum shear vector as it cannot account for shear perpendicular to the slots. The direction of maximum shear stress is often however unknown and changes due to on-going mining. Using three slots configuration both studies could generate the strain profile without knowing the shear direction. However, machining 3 slots at 120° to each other is difficult because the load can bend the bolt in different directions if the slots are not symmetrically placed (Figure 2.10). Thus, the number of slots and also its geometry can interfere with the measurements and generate inaccurate data. Jessu et al. (2016) mentioned that instrumented rock bolts using these technologies can measure a combination of shear and axial loads.



a) b)

Figure 2.10 – a) Two slots configuration and b) three slots configurations. (Jessu et al., 2016)

Most of the previous research developed to understand rock bolts has focused on single load conditions. However, in situ observations have also shown that the rock bolt is subjected by a combination of loads. These combined (hybrid) load conditions are still not considered in the rock bolt design.

2.3 Summary of Literature Review

The literature review presented in this chapter has shown that there is a need to understand the rock bolt performance under combined load conditions and to consider it in the design. The main gaps identified in the existing research from the literature were:

- Most of the previous research focused on the rock bolt axial or shear behaviour as a single load condition.
- There is no standard methodology to test rock bolts under shear and combined load conditions.
- The effect of combined load in the rock bolt performance has not yet been quantified.

- There is not a methodology or guideline to consider combined load in the rock bolt design.
- The rock bolt capacity is still given by its axial capacity, although the rock bolt is usually subjected to a combination of loads and not only axial.

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Chapter 3
Mechanical Performance of Rock Bolts under Combined Load Conditions

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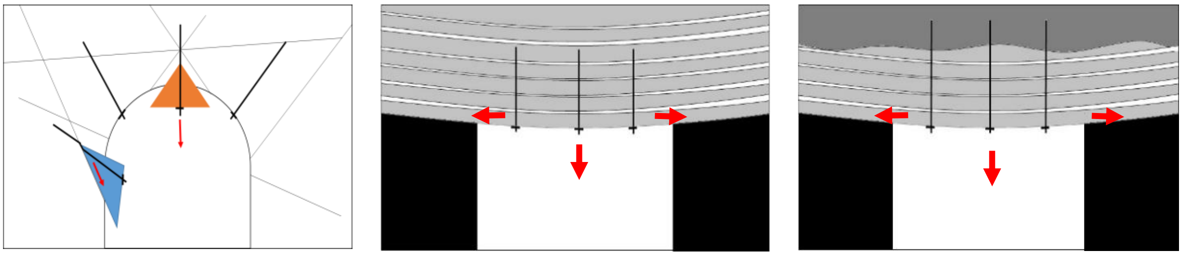
Pinazzi, P.C., Spearing, A.J.S., Jessu, K.V., Singh, P., & Hawker, R. (2020). Mechanical performance of rock bolts under combined load conditions. *International Journal of Mining Science and Technology*. https://doi.org/10.1016/j.ijmst.2020.01.004

Abstract: Rock bolts are subjected to different loading conditions along their lengths such as axial, bending, and/or shear forces, which can cause failure at lower loads than those considered for design purposes. The common existing methodologies do not consider the actual loading of the rock bolts and assume it is only pure axial or pure shear. This study was conducted to investigate the un-grouted rock bolt performance under combined load conditions. Two loading regimes were evaluated: the effect of initial shear displacement on axial load capacity and displacement, and the effect of axial displacement on the shear load capacity. The first regime was also conducted for shear with a gap, when there is a spacing between the shear interfaces. The results of this study showed that the rock bolt can resist higher axial loads than shear under pure or combined load conditions. Under combined load conditions, the rock bolt capacity decreased significantly for both regimes. However, when applying the shear load with a gap, the rock bolt load capacity was not affected significantly. Also, the total bar deformation was improved for shear and axial. The findings of this study show the need to improve the rock bolt design considering the complex loading conditions in situ with/without a gap.
Keywords: Rock bolt, Combined load, Gap test, Failure mechanism, Axial load, Shear load, Strain

3.1 Introduction

Rock bolts are used worldwide to reinforce potentially unstable rocks around excavations. The excavation reinforcement and support system play an important role in mine safety since it is directly correlated to the fall of ground. Potvin and Nedin conducted a study that pointed out the risks and causes of rock fall focused during 1998-2003 period; according to their study, mining areas away from the working face are considered as “low risk” of injury [1]. However, when analyzing the fatalities, the data showed that most of them happened away from the faces under reinforced and supported grounds. In this case, the causes were pointed out to be due to, in order of relevance, corrosion, bolts too short, broken bolts, incorrect installation and bolt spacing too wide. In 2015, the fall of ground was the major cause of fatalities in mines around the world; it counted for 29% of the International Council on Mining and Metals report’s statistical samples of 2016 [2]. These facts show the need for improvements of the conventional rock bolt design methodologies. Even though there are many methodologies used for the reinforcement design, none of them are considered to be accurate [3]. It is still a challenge to understand the complexity of the load in situ, mainly to replicate these loads on numerical modeling or laboratory analysis. Although there were studies conducted to understand the rock bolt behaviour under axial and shear load, only a few attempts were made to investigate the effect of complex loading conditions (i.e. shear, axial, and bending) on the rock bolt performance.

The loading conditions in situ can vary from mine to mine, and they require different reinforcement mechanisms. Tunnel support requirements depend on: the stress regime around the tunnel, stresses change during its lifetime, the shape and size of excavation and geological features [4]. For each existing reinforcement mechanism (i.e. the key block, beam building, and suspension), the load conditions on the support will change and the occurrence of combined load conditions can be observed in these mentioned basic support conditions [3]. Figure 3.1a represents the key block loading mechanism, which the rock bolts hold the dead-weight generated by the block. Depending on the rock bolt's location (i.e. roof or wall) and the distribution and orientation of discontinuities, the loading acting on the rock bolt will change. The beam building mechanism is used when the roof is bedded, so the rock bolts will tie the beams together to form one "laminated" beam (Figure 3.1b). In the rock bolt located at the center of the excavation, the load is typically only axial, but the other rock bolts are subjected to a combination of axial, shear and bending. For the suspension mechanism, the loading mechanism is similar to the beam building mechanism; however, in this case, weak rock beds are suspended from a thicker and stronger rock layer (Figure 3.1c). Therefore, the loads that the rock bolt undergoes vary from each in-situ condition.



(a) Key block (b) Suspension (c) Beam building

Figure 3.1 – Support mechanisms (after [3]).

Studies have been conducted to understand the rock bolt response of each possible load condition. Freeman was the first to investigate axial loadings along the rock bolt length using strain gauges [5]. Numerous studies were also conducted to understand the effect of axial load and also shear load on the rock bolt performance [6-14]. Most of these studies were conducted to evaluate the mechanical properties of rock bolts, grout and installation procedure. Recent studies focused on the contribution of bolts to the joints reinforcement. In this case, the combined load is a result of shear and bending/axial load. In this paper, however, the combined load had two sources of loads: in the shear tests with a gap (Figure 3.2), when shear load is applied and axial load is also generated as a result of bending moment and as a result of more than one load being applied to the rock bolt.

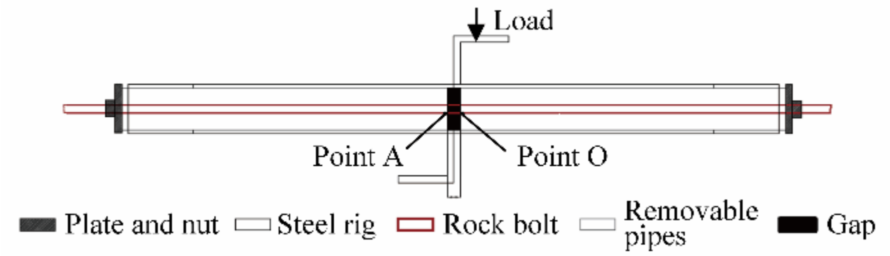


Figure 3.2 – Shear tests with a gap (between the shear platens).

3.1.1 Shear loads at discontinuities

In situ observations in hard rock have pointed out the rock mass condition and discontinuities characteristics in shallow and deep mines. Li observed that at deep conditions, the rock mass presented a higher quality because the induced stresses are higher [15]. Thus, the discontinuities were closed. At shallow/intermediate conditions, the discontinuities were open (i.e. gap) because the stresses conditions are less. Therefore, the shear load with open discontinuities/gap is a common condition in shallow, hard rock mines.

The gap conditions can also occur in rock with no spacing between the discontinuities, in both shallow and deep mines, when the rock strength is low, as in coal mines. In this condition, as the rock bolt deforms, the rock at the discontinuity interface will break generating a spacing/gap [11]. Although this condition has been identified in situ, this load condition is not well understood, and there are only a few studies in the literature that consider the effect of the gap on the rock bolt performance [14,16].

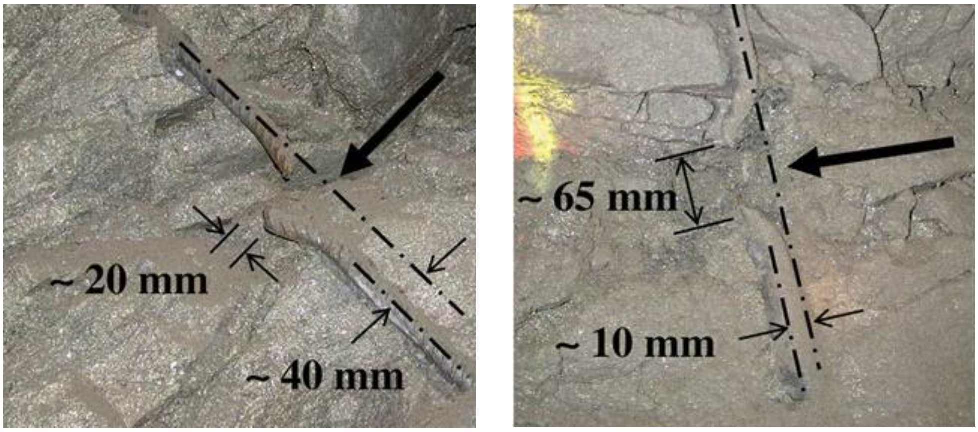
The effect of a gap between discontinuities was first considered by Stimpson to evaluate the rock bolt performance; his study was conducted to develop an analytical method to better understand the rock bolt performance considering the bolt inclination, hole and bolt diameter, grout, Young's modulus of rock and spacing of the discontinuities [16]. However, it did not focus on the gap effect on the rock bolt capacity. Snell et al. conducted shear tests to evaluate the performance of fully grouted bolts with different gap sizes between the joints; it was found that as the gap size increases, the shear ultimate load capacity of the rock bolt decreases, and its resistance to displacement increases [14]. Even though in shear tests with a gap the only load applied is shear, the rock bolt fails by a combination of shear and axial loads. The gap allows the bar to bend before failure and the bending moment results in an axial force.

Pellet and Egger applied the beam theory to understand the shear behaviour of the rock bolt across discontinuities and determined that the two endpoints of the gap (points A and O in

Figure 3.2) influence the failure mechanism of the rock bolt [8]. In this study, shear load was applied at point O, where the rock bolt failed under shear and axial. In this case, point A undergoes a maximum bending moment. According to the above-mentioned studies, when the rock bolt reaches the plastic stage, the bending stiffness drops and the bolt behaves as a truss, and only axial forces grow. This justifies why the rock bolt failed by a combination of shear and axial loads.

3.1.2 Combined load

In situ observations have shown the effect of combined load on the rock bolt performance as identified in the basic support mechanisms (i.e. key block, beam building, and suspension). Li conducted in situ observations of ground support in high-stress conditions at advance faces of cut-and-fill mining; his findings evidenced a combination of load mechanisms in situ as presented in Figures 3.3a and b, where it is possible to identify that both rock bolts in Figures 3.3a and b were subjected to axial, bending and shear before failure [17].



(a) Shear load is bigger than axial load (b) Axial load is bigger than shear load

Figure 3.3 – In situ combined load conditions (after [17]).

Few studies have been conducted to understand the effect of combined load on the rock bolt mechanical properties in which shear and axial loads are applied at the same time to the rock bolt with/without a gap [18]. The purpose of this study was to understand the complexity of the failure mechanism and the rock bolt response to combined load conditions, at an early stage, and progress to be able to suggest improvements in the rock bolt design considering the existing complex loading conditions in situ.

3.2 Materials and methods

Tests were conducted to evaluate the rock bolt steel performance under combined load. The first set of tests were conducted using single loading conditions: pure tensile and pure shear. The pure conditions were used as a reference for applying complex load conditions as shear tests with a gap and combined load conditions. In total, 131 tests were conducted using three different steel types (Table 3.1): Australian (AUS) R27, South African (SA) R27 and South African (SA) M24.

Table 3.1 – Rock bolt types and specifications.

Property	AUS R27	SA R27	SA M24
Rock bolt diameter (mm)	27.0	27.0	23.2
Typical application	Hard rock mines	Hard rock mines	Coal

Figure 3.4 shows the Instron machine used for all the tests at the Minova facility in Nowra, New South Wales, Australia. The rock bolt was held by the two sets of jaws and tested to destruction. Throughout all the tests, the movement of the hydraulic platen was set at 5 mm/min unless otherwise stated.

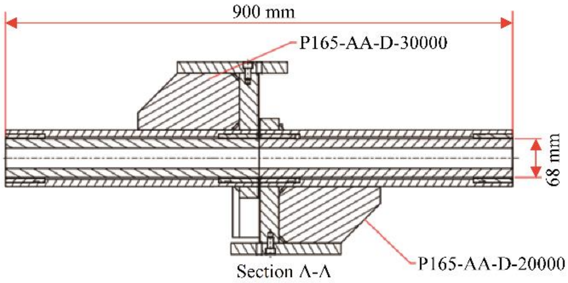
Figure 3.4 – Tensile test machine.

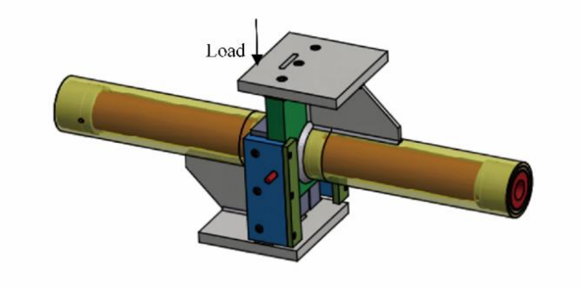
3.2.1 Tensile tests

Tensile tests were performed to evaluate the properties and behaviour of a material under a uniaxial load condition. In these tests, tensile loads against displacement were recorded.

3.2.2 Shear tests

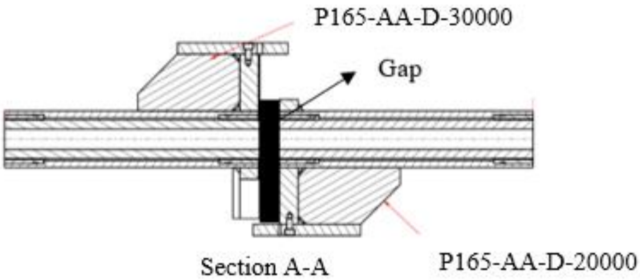
Pure shear/guillotine tests and shear tests with a gap were conducted using the apparatus shown in Figures 3.5 and 3.6. The shear rig test is composed by a fixed side and a removable side. In the internal part, it is composed of removable pipes (Figure 3.5a), where the rock bolt (Figure 3.5b) is placed. For the guillotine tests, the rock bolt was inserted into the steel pipes, and a load was applied in one side of the steel pipe until the rock bolt failure. In the tests conducted with a gap, the rock bolt was inserted into the steel rig, and the removable steel pipes inside the rig were adjusted to the spacing required for the tests (5, 10, 15 and 20 mm), as represented in the Figures 3.6a and b. For the gap tests, a nut and a plate were hand tighten on each side to avoid the bolt movement as the load was applied.





(a) Steel pipes (b) Rock bolt

Figure 3.5 – Schematic steel rig setup used for shear tests.



(a) Gap (b) Actual setup

Figure 3.6 – Shear test with a gap schematic figure and the actual setup.

3.2.3 Combined load tests

A new laboratory test was designed to evaluate the effect of combined load on the rock bolt performance. Two regimes were conducted to evaluate the effect of shear displacement on axial load capacity and the effect of axial displacement on shear load capacity.

The Instron machine was used to apply the shear load to the rock bolt placed inside the shear test rig as shown in Figure 3.7. The tensile load was applied to the bar using a 6×10^4 kg capacity Enerpac hydraulic cylinder (RCH 606). Figure 3.8 represents each part of the test set up and also the position of the hydraulic cylinder. For pure shear tests, the rock bolts were not tightened. Under combined load, AUS R27 and SA M24 steel rock bolts were tested.

Figure 3.7 – Combined Load set up test.

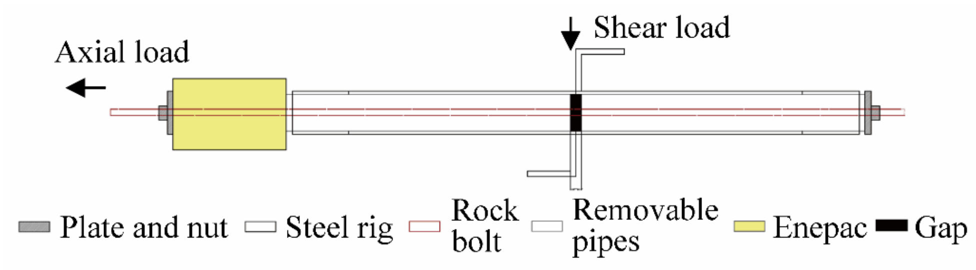


Figure 3.8 – Schematic set up of combined load tests.

Two regimes of combined load were conducted as follows.

3.2.4 Axial Displacement Effect on Shear Load

Axial displacement was applied to the rock bolt, using the hydraulic cylinder. The axial displacement was kept, and the shear load was applied to failure. The axial displacement applied to the bar varied according to the maximum displacement the bar can undergo under pure loading conditions. The percentages of displacements applied compared to the bar maximum displacement capacity are given in parentheses. Two steel types were evaluated on this regime: (1) for AUS R27, axial displacements applied were 20 mm (16%), 30 mm (25%), 40 mm (33%), 45 mm (37%), 50 mm (41%), 60 mm (49%), 70 mm (58%), 80 mm (66%) and 100 mm (82%); and (2) for SA M24, axial displacements applied were 20 mm (12%), 30 mm (17%), 40 mm (23%), 50 mm (26%), and 60 mm (33%).

3.2.5 Shear Displacement Effect on Axial Load

Shear displacement was applied to the rock bolt by the Instron machine. The load was kept to the bar, and the axial load was applied to failure, using the hydraulic cylinder. The percentages of the shear displacements applied compared to the maximum shear displacement the bar can undergo are given in parentheses. For this condition, only AUS R27 was used since SA M24 was failing at the threads. In addition to the tests with pure shear displacement, some tests were conducted with a gap. For AUS A27, shear displacements applied were 2 mm (20%), 4 mm (39%), 6 mm (59%), 7.5 mm (74%), and 9 mm (88%). This method was also conducted for shear with a 5 or 10 mm gap. The shear displacements applied were 7 mm (65%) and 9 mm (86%) for 5 mm gap and 9 mm (50%) and 12.5 mm (69%) shear displacements for 10 mm gap.

3.2.6 Calibration of hydraulic cylinder

Two different types of equipment were used to apply axial load to the rock bolt: Instron machine and Enerpac hydraulic cylinder using hand pump and foot pump. Thus, the hydraulic cylinder used for combined load tests was calibrated with the Instron machine for the accuracy. The calibration curve is shown in Figure 3.9.

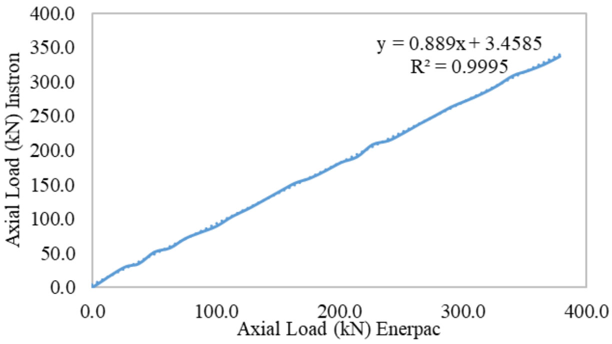


Figure 3.9 – Calibration Curve between the Instron and the Enerpac.

3.3 Results and discussion

3.3.1 Tensile and shear (guillotine) tests

The first set of tests were conducted under only axial or only shear loading to benchmark the two extremes of the loading. These results were then used as a reference to compare rock bolt performance under combined load mechanisms (axial then shear to failure and shear then axial to failure). Table 3.2 shows the mechanical properties of each rock bolt type.

Table 3.2 – Properties of the three rock bolts steels tested.

Property	AUS R27		SA R27		SA M24	
	Mean	σ	Mean	σ	Mean	σ
Shear ultimate load (kN)	217	4	257	6	225	9
Shear ultimate strength (MPa)	482	9	565	20	501	19
Displacement (mm)	10.2	0.3	9.6	2.1	8.1	0.2
No. of shear tests	3		5		5	
Tensile ultimate load (kN)	299	3.6	354	1.2	336	5
Tensile ultimate strength (MPa)	664	8	786	3	747	10
Displacement (mm)	76.6	1.1	94.0	0.5	80.1	1.7
Length between grips (mm)	680		685		546	
No. of tensile tests	3		3		3	
Elongation (%)	11		14		15	
Ratio of shear load to axial load	0.73		0.73		0.67	

Based on the ultimate load, the ratio of shear load to tension was found to be: (1) 0.73 for AUS R27 hard rock; (2) 0.73 for SA R27 hard rock; (3) 0.67 for SA M24 coal.

Figures 3.10 and 3.11 show that the axial load capacity of the rock bolt is superior to shear load capacity. However, the percentage in elongation is higher in shear.

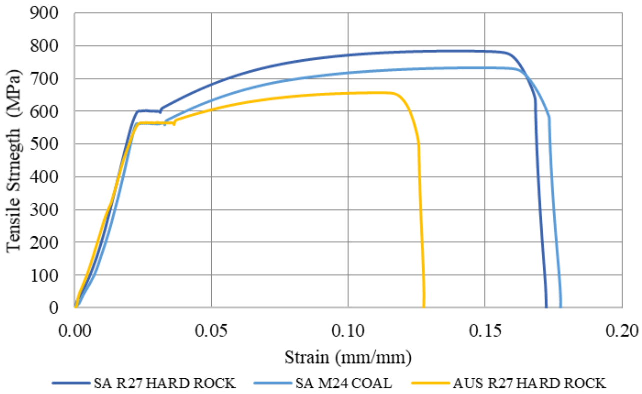


Figure 3.10 – Ultimate tensile strength for all the rock bolts tested.

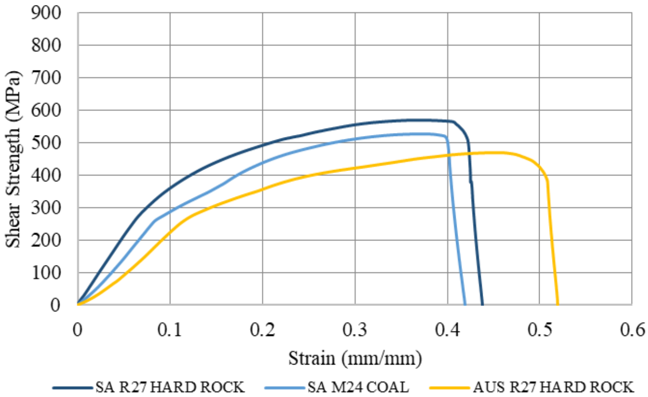


Figure 3.11 – Ultimate shear strength for all the rock bolts tested.

Failure mechanisms in pure shear and pure tension are represented in Figure 3.12a and Figure 3.12b, respectively. In Figure 3.12b, the necking before failure can be easily seen.

(a) Shear tests failure profile (b) Tensile tests failure profile

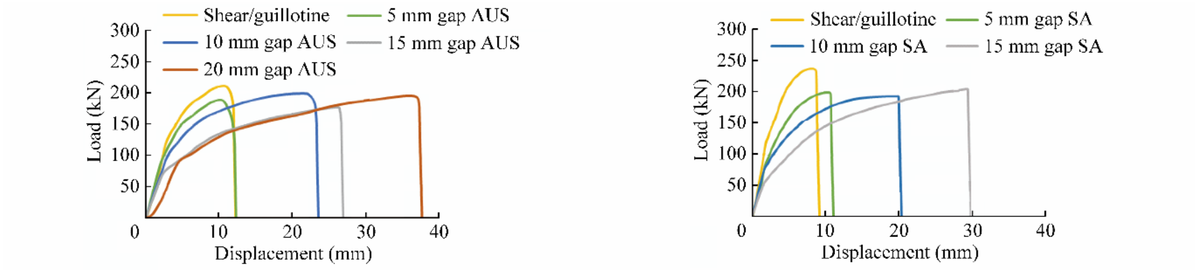
Figure 3.12 – Pure tests.

3.3.2 Rock bolt performance under combined load

3.3.2.1 Shear Tests with a Gap Analysis

Gap shear tests were conducted to evaluate the rock bolt performance of two rock bolt types, AUS R27, and SA M24. 26 tests were conducted in which 16 tests were on AUS R27, and 10 were on SA M24. The AUS R27 and SA M24 shear capacity was evaluated under different gap sizes, 5, 10, and 15 mm gap for both steels and 20 mm gap for AUS R27. The tests conducted with 20 mm gap were not repeated because as the rock bolt deformation increased for this gap size, the bar started to touch the steel rig at point A (Figure 3.2) and to shear at the contact point.

The load and displacement capacity were evaluated under shear load varying the gap size. The increase in gap size resulted in a decrease of shear capacity and an increase in total displacement (Figures 3.13a and b). The variance in load is not yet well understood. However, the increase in total displacement is caused by the failure mechanism, which is a combination of localized shear, axial, and bending, which is not presented in the pure shear tests.



(a) AUS R27 (b) SA M24

Figure 3.13 – Shear capacity under a gap.

In the shear tests with a gap, the displacement capacity was the most affected. The displacement needed to reach the maximum shear capacity of the rock bolt increased with gap size (Figures 3.13a and b). This displacement measured by the Instron unit is the total displacement (vertical displacement), which is the combination of the bending, axial, and shear as described by Pellet and Egger [8]. The total displacement was used to calculate the combined displacement as shown in Figure 3.14. The combined displacement was defined by Pythagorean Theorem (Eq. (1)). From this analysis, the resultant force (combined load) angle (α) was calculated from Eq. (2). For pure shear, the bar breaks in 90° to the bar and for pure axial load, the bar break at 0° to the bar. Under combined load mechanism, the angle will vary between 0° and 90°. The total displacement, combined displacement, and α for each gap size are presented in Table 3.3.

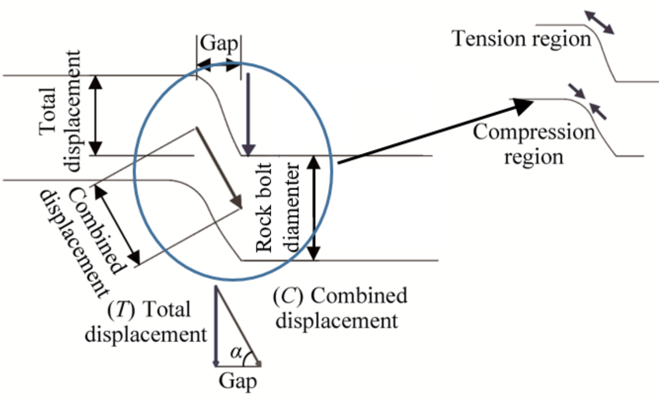


Figure 3.14 – Shear tests with gap loading mechanisms.

$$C = \sqrt{T^2 + Gap^2} \quad (8)$$

$$\alpha = tan^{-1}\frac{T}{Gap} \quad (9)$$

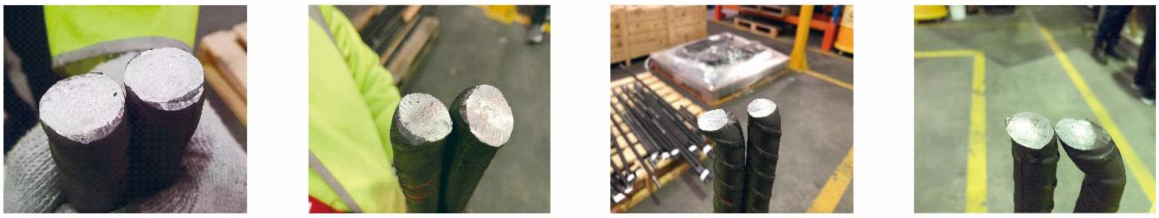
where C is the combined displacement (axial, bending, and shear displacements); T the total displacement, given by the Instron; Gap the spacing between shear interfaces; and α the angle of combined load acting on the bolt.

The combined load condition in the gap tests can be identified in the bar failure mechanism from Figures 3.15b-e. When shear is applied with a gap, the rock bolt will bend before failure, and at the failure interface, the rock bolt will fail by shear and axial load. Moreover, as the gap increased the bending effect also increased. The same behaviour was seen on the SA M24 rock bolts failure. The M24 failures are represented in Figures 3.16a-d. For both steels, the effect of 5 mm gap was minimum. The failure mechanism at this gap size is similar to the shear failure in pure condition; however, it can be observed that there was less bending. For the other gap sizes, as the gap increases the effect of bending and shear also increases at the failed interface.

(a) Pure shear (b) 5 mm (c) 10 mm (d) 15 mm (e) 20 mm

Figure 3.15 – Failure mechanism of rock bolts with/without a gap.

Due to the steel composition difference (i.e. content of C, P, Mn, Si, S, Ni, Cr, Mo, etc.) between SA M24 and AUS R27 (Figures 3.15 and 3.16), the failure characteristic was found to be slightly different. However, the total and combined displacement with the varied gap sizes were similar (Table 3.3).



(a) Pure shear (b) 5 mm (c) 10 mm (d) 15 mm

Figure 3.16 - Failure mechanism of rock bolts with/without a gap.

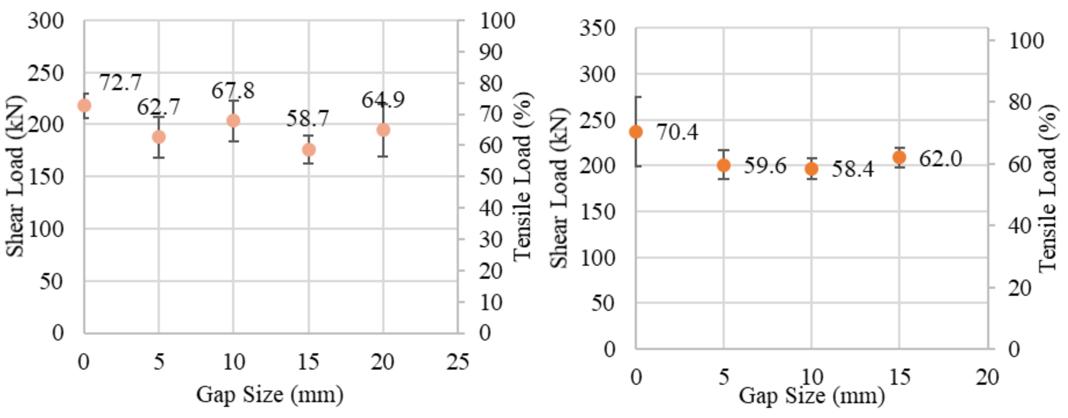
Table 3.3 – Total, combined, shear and axial displacement for AUS R27 and SA M24 shear tests with a gap.

Parameter	Steel type							
	AUS R27				SA M24			
Gap size (mm)	5	10	15	20	5	10	15	20
Total displacement (mm)	10.8	18.0	25.1	35.8	10.5	18.2	28.0	N/A
Shear displacement (mm)	10.2	10.2	10.2	10.2	8.1	8.1	8.1	N/A
Combined displacement (mm)	11.9	20.6	29.2	41.0	11.6	20.8	31.8	N/A
Axial and bending (mm)	1.7	10.4	19.0	30.8	3.5	12.7	23.7	N/A
α (°)	65.2	60.9	59.1	60.8	64.5	61.2	61.8	N/A

For both steel types, AUS R27 and SA M24, the shear displacement at failure did not vary as the gap size increased. However, the total displacement increased because as the gap increased, the bar underwent bending and axial, compression and tension (on different sides of the bolt as it bends, Figure 3.14). The total displacement was found to be proportional to the gap size. From Table 3.3, it can be observed that the total displacement is almost twice the gap size. Although, the composition of both steels is different, and the nominal diameters are 23.5 and 22 mm for AUS R27 and SA M24, respectively, the combined displacement and resultant force angle showed to be similar for both steels.

Evidence of combined load acting on the bar has also been given by the angle α (Eq. (2)), which is the angle of the resultant forces acting on the rock bolt. The angle α varied from 59° to 65° for all gap size conditions. For same gap sizes, α showed to be similar even though the steels have different mechanical properties. This similarity shows that the effect of gap on the rock bolt performance depends on the gap size, and not as much on the rock the bolt properties.

These results found in the gap tests also illustrate the effect of the gap on the ratio of shear load to axial load. The AUS R27 shear load to axial load ratio dropped from 0.73 to 0.59 (Figure 3.17a), and for SA M24, it dropped from 0.70 to 0.58 (Figure 3.17b) with the varying gap sizes.



a) AUS R27 for hard rock b) SA M24 for coal

Figure 3.17 – Effect of gap on the correlation between tensile and shear load capacity.

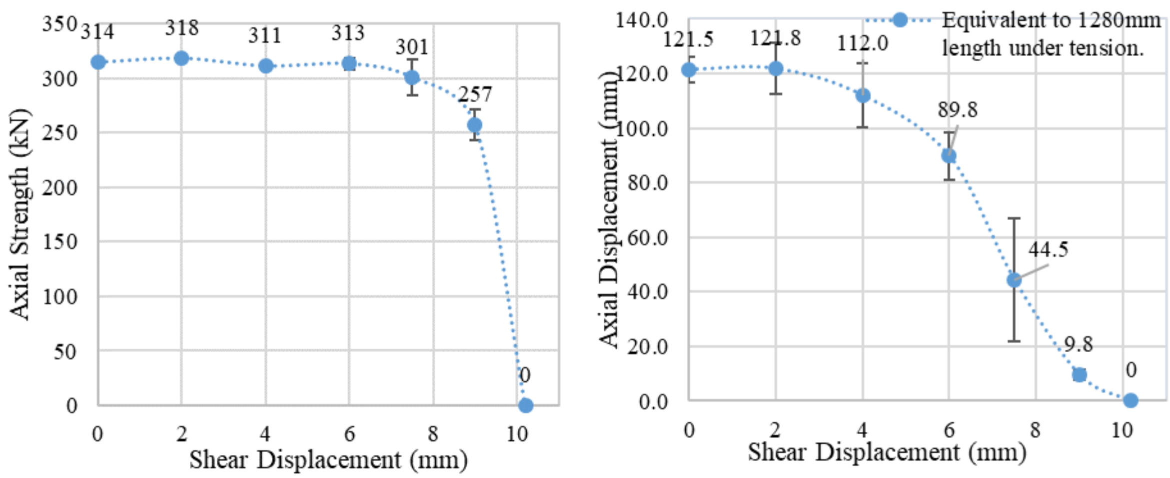
From the anova statistical analysis, it was found that there is a significant difference in the ultimate loads between the guillotine shear test and gapped test. Thus, the gap had a significant influence on the rock bolt performance. Overall, the SA M24 performance was more affected by the gap in load comparing to the rock bolt AUS R27.

3.3.2.2 Combined Load Tests Analysis

The Effect of Shear Displacement in the Axial Load and Displacement Performance for Australian Steel R27 for Hard Rock with and without a gap

In total, 29 tests were conducted to understand the influence of a shear displacement on the tensile strength. Figure 3.18 shows the tensile strength and displacement of the rock bolts when subjected to shear displacements of 0 mm, 2 mm (20%), 4 mm (39%), 6 mm (59%), 7.5 mm (74%), and 9 mm (88%).

Applying a shear displacement first from 2 to 6 mm had a minimal effect on the ultimate tensile capacity but it had a major effect on the displacement capacity of the bar. However, as the shear displacement increased, the tensile capacity and displacement were affected. Applying a shear displacement of 9 mm (88% of the ultimate shear displacement), the axial elongation decreased by 92%, which shows that the shearing of the rock bolt significantly decreases the ability to elongate axially. This behaviour is explained because when the bar is under shear, the load will concentrate at the weakest point, which is the shear interface for 9 mm shear displacement. Thus, when applying tensile load, the load will be distributed on half of the bar, from the source of axial load to the shear interface. As a consequence, the total bar displacement will be most affected as it is affected by the decrease in bar length under tension.



a) Ultimate Load b) Displacement

Figure 3.18 – Influence of shear load on tensile strength.

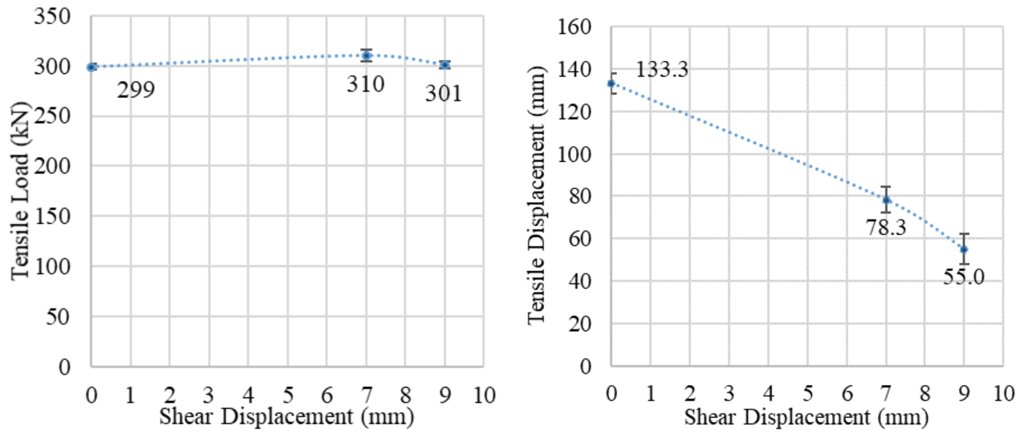
The failure mechanism for each scenario varied as shown in Figures19a-e. At lower shear displacement, from 2 to 6 mm, the predominant failure mechanism was axial load, and the bar broke between the nut and the shear interface. When the shear displacement is increased to 7.5 mm, the major failure mechanism was tensile load, and the bar broke at the shear interface. At 6 mm shear displacement, the bar broke at the threads for the three tests performed with 1.5 m bar length. In this study, threads failure was considered to give erroneous results because at the threads the load capacity is decreased since the rock bolt diameter is decreased by the threading procedure. Increasing the shear displacement to 9 mm, the tensile performance of the bar decreased and the major load mechanism identified was shear. In this last scenario, the rock bolt underwent 88% of its total shear displacement before failure, which justifies the failure response.

(a) 2 mm (b) 4 mm (c) 6 mm (d) 7.5 mm (e) 9 mm

Figure 3.19 – Failure mechanism on the combined load: applying shear displacement and then axial load.

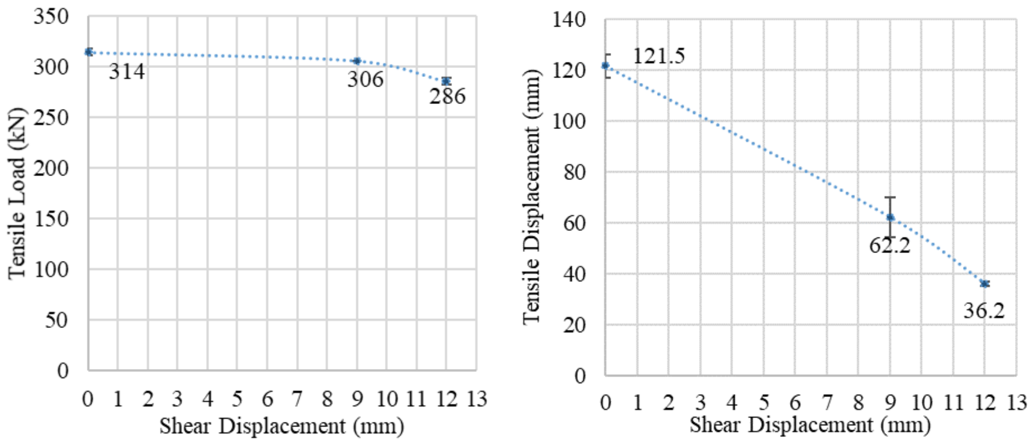
13 tests were therefore conducted to try and understand the influence of shear with 5 and 10 mm gap on tensile strength for AUS R27. In the tests with a 5 mm gap, the shear displacements of 7.5 mm (69%) and 9 mm (86%) were applied and with 10 mm gap, 9 mm (50%) and 12 mm (66%) shear displacements were applied, as the rock bolt can undergo more shear displacement with the increase in gap. Tensile load and displacement at failure are shown in Figures 3.20 and 3.21 for 5 and 10 mm gap tests, respectively.

The shear displacement over a gap had a minimal effect on the tensile capacity of the bolt, while the elongation needed to achieve the tensile capacity decreased significantly. For 5 mm gap, in one of the tests with 7.5 mm shear displacement, the bar broke at the threads and in the other tests it broke at the shear interface. For 10 mm gap, the bar broke at the shear interface for all the tests. Shear tests with the gap, in combined load condition, allows the bar to deform more before breaking. They resulted in failure at the threads at higher shear displacement (7.5 mm) compared to the condition without a gap (6.0 mm).



a) Ultimate Load b) Displacement

Figure 3.20 – Influence of shear load with 5 mm gap on tensile strength.

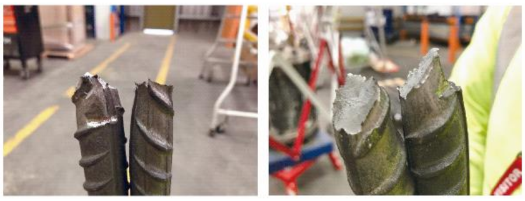


a) Ultimate Load b) Displacement

Figure 3.21 – Influence of shear load with 10 mm gap on tensile strength.

To understand the effect of shear load with a gap on the axial capacity, the tensile capacity and the displacement were compared at 9 mm shear displacement with gap of 0, 5 and 10 mm. The ultimate tensile capacity for pure tensile load condition was found to be 314 kN and total displacement 121.5 mm (1280 mm bar length) when using the hand pump. When using the foot pump, the tensile capacity was found to be 299 kN and displacement 133.3 mm (1297 mm bar length). These values were calibrated with those from the Instron machine. The tests conducted with 0 and 10 mm gap were conducted with the hand pump, and for 5 mm gap, the foot pump was used. Thus, the pure tests are the reference values for these findings. The findings for axial performance with 9 mm of shear displacement were: (a) with no gap: the tensile capacity dropped to 30%, and displacement decreased by 91%; (b) for 5 mm gap, the load capacity increased by 0.67% and decreased by 59% in displacement; (c) for 10 mm gap, it decreased in load capacity by 3% and displacement by 49%.

Applying a combined load with a gap means that two combined load mechanisms are acting on the rock bolt (Figures 3.22 and 3.23). When shear is applied with a gap as the first load, the rock bolt can undergo more axial deformation as well as bending compared to the guillotine condition. The initial gap length is deformed by bending, and as the shear deformation grows the bar will also deform by axial load. Therefore, the bar failure mechanism will be a combination of both shear and axial loads. For the same total displacement applied to the bar, the smallest the gap size is, the sooner the bar will start to deform axially compared to bigger gaps. It explains the difference of the axial displacement the bars underwent when applying axial load to failure and using the hydraulic cylinder after applying shear with a gap. Therefore, with increase in gap, the axial deformation of the rock bolt improved under combined load.



(a) 7.5 mm (b) 9 mm

Figure 3.22 – Combined load tests with 7.5 and 9 mm shear displacements with 5 mm gap.

(a) 9 mm (b) 12.5 mm

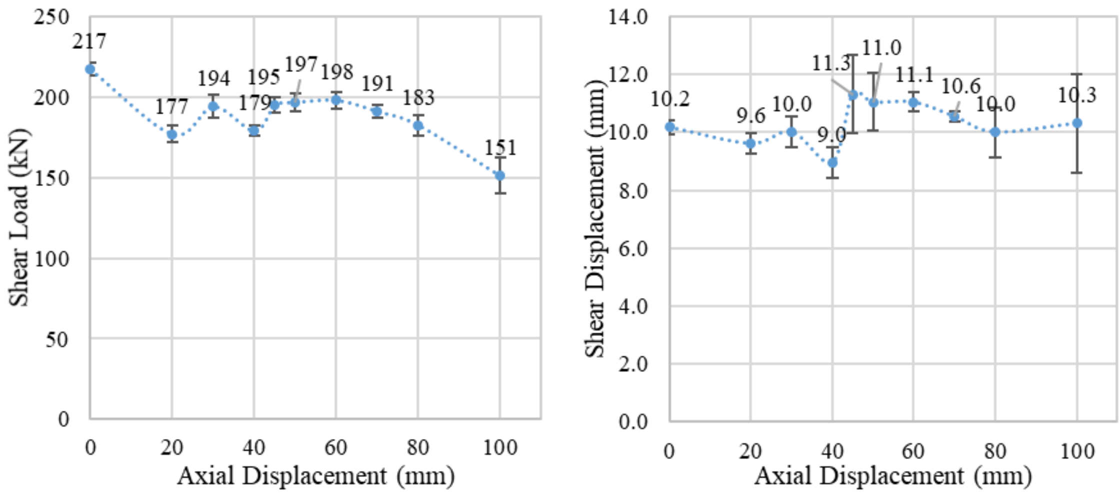
Figure 3.23 – Combined load tests with 9 and 12.5 mm shear displacements with 10 mm gap.

The Effect of Axial Displacement on the Shear Load and Displacement Performance for AUS R27 and SA M24

In total, 47 tests were conducted under initial axial displacement to investigate the rock bolt shear performance for AUS R27 and SA M24. 32 tests were conducted to understand the influence of axial on shear capacity of AUS R27. The axial displacements applied to the steel were 20 mm (16%), 30 mm (25%), 40 mm (33%), 45 mm (37%), 50 mm (41%), 60 mm (49%), 70 mm (58%), 80 mm (66%), and 100 mm (82%). Figure 3.24 shows the effect of tension on shear capacity and displacement. There was a gradual decrease in shear capacity with the increase in the axial displacement while the shear displacement was found to be about 10% higher than the shear displacement at pure shear conditions.

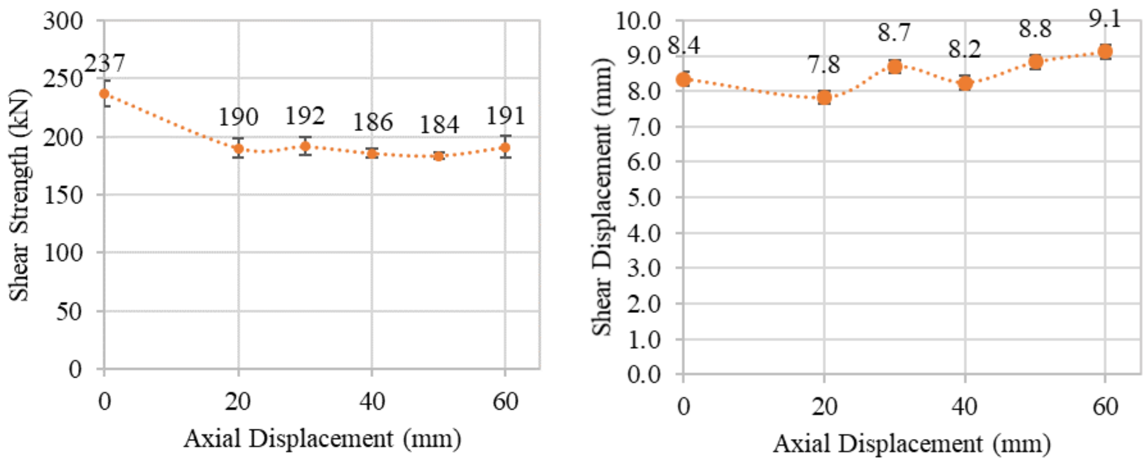
The SA M24 was also evaluated for this combined load condition. 15 tests were conducted using SA M24 to investigate its shear capacity under tension. The rock bolt was subjected to

20 mm (12%), 30 mm (17%), 40 mm (23%), 50 mm (26%), and 60 mm (33%) axial displacement. The higher axial displacements were not tested as the rock bolt failed on threads at 80 mm axial displacement. The shear capacity decreased as the axial displacement increased from 20 to 60 mm axial displacement (Figure 3.25a). Both rock bolt types presented to have the shear capacity and displacement affected by axial displacement.



a) Ultimate Load b) Displacement

Figure 3.24 – Influence of axial load on shear strength for AUS R27.



a) Ultimate Load b) Displacement

Figure 3.25 – Influence of axial load on shear strength for SA M24.

The rock bolts AUS R27 and SA M24 bars have presented similar behaviour under combined load (Figures 3.24 and 3.25). The load variation is a result of combined load acting on the bar, but more research is needed to understand it fully. The variation in displacement or its increase is a result of this combined load mechanism acting on both rock bolts type. Figures 3.26 and 3.27 present the failure mechanisms for both AUS R27 and SA M24. The failure mechanism suggests that the rock bolt underwent bending, and axial deformation as it was the load being applied before failing by shear load.

As a result of these findings, the load capacity and also displacement was affected by a combination of loads. Thus, the total displacement recorded by the Instron machine was a sum of the combined load (shear and axial/bending) being applied to the rock bolt. The increase in displacement by the Instron is explained by this combination of loads acting on the bar. Similarly to what happens when applying shear with a gap, before failing by shear the bar bends increasing the total displacement. Comparing AUS R27 and SA M24, the AUS bar deformed slightly more, when applying axial load then shear to failure, compared to the SA. (Figures 3.24b and 3.25b). The total displacement increased: (a) for AUS R27, at maximum 1.1 mm compared to the displacement at pure shear, which is 10.2 mm; (b) for M24, at maximum 0.7 mm compared to its total capacity, which is 8.4 mm.

These results showed that both rock bolts underwent a similar failure mechanism, shear or axial/ bending. However, on the SA M24, a structural failure was identified due to its difference in composition and mechanical properties as presented in the previous method.

Figures 3.26 and 3.27 show the rockbolt surfaces after failure. It can be noticed that at lower axial displacement, the failure mechanism is predominantly shear load, e.g. at 20 mm axial displacement. As the axial displacement applied increases, the bar underwent more axial load as can be seen at 100 and 60 mm axial displacement for AUS R27 and SA M24, respectively.

(a) 20 mm (b) 30 mm (c) 40 mm (d) 50 mm

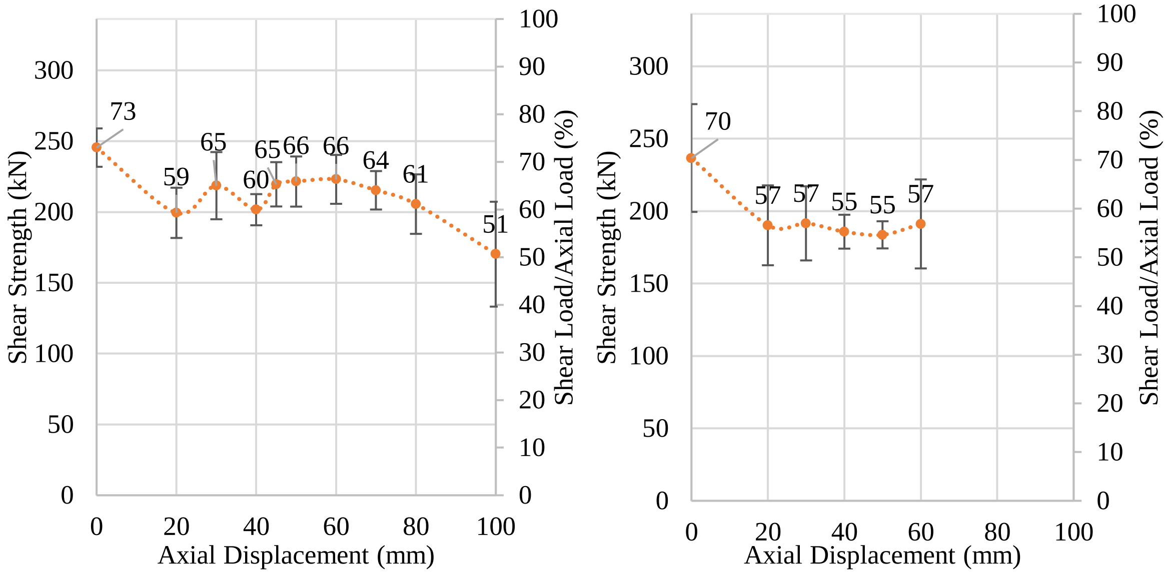
(e) 60 mm (f) 70 mm (g) 80 mm (h) 100 mm

Figure 3.26 – Rockbolt surfaces after failures for AUS R27.

(a) 20 mm (b) 30 mm (c) 40 mm (d) 50 mm (e) 60 mm

Figure 3.27 – Rockbolt surfaces after failures for SA M24.

The effect of the axial displacement on the shear load has also affected the ratio of shear load to axial load (Figure 3.28). The main reason is that the tensile capacity is considered as the weakest link in the main rock bolt design methodologies. In fact, under this condition, for SA M24 the shear load capacity can almost reach half of the axial load capacity.



a) AUS R27 b) SA M24

Figure 3.28 – Effect of combined load on the correlation between shear and tensile load.

3.4 Rock bolt design

The load conditions in situ play an important role when designing ground support. This study has shown that in-situ load conditions such as shear with a gap and combined load have a major effect on the rock bolt capacity. Moreover, the rock bolt shear capacity has presented to be lower than axial capacity in every regime evaluated in this study (i.e. pure, with a gap and combined). In pure conditions, the ratio of shear load to axial load was found to be around 0.7, in conditions with a gap it dropped up to 0.58, and in combined load conditions (axial load then shear to failure), it dropped up to 0.55. Considering that the rock bolt capacity is based on the axial capacity, in a situation where the rock bolt capacity required is calculated to be 100 kN and a safety factor of 2 is used, a rock bolt of 200 kN capacity will be chosen. However, if the rock bolt is subjected to shear, the safety factor can be decreased to 1.4, considering the shear load to axial load ratio of 0.7. Under combined load conditions, this ratio can decrease up to

0.55. Thus, the safety factor can decrease up to 1.1. Considering the axial capacity in the support design could lead to an underestimation of loads to which the rock bolt can be subjected in situ.

Under combined load conditions with a gap, the gap has also shown to have a significant influence on the rock bolt performance. In the combined regime, without a gap, load capacity and displacement decreased. Nevertheless, when applying shear with a gap and then axial load to failure, the rock bolt axial displacement increased as the gap increased. The findings of this study have suggested that in a gap and combined load conditions with a gap, which are common situations in situ, the rock bolt undergoes more deformation before failure. Then, when identifying these loads conditions, a rock bolt that can undergo more deformation should be considered in the support design.

These results show evidence of the need in creating a support design capable of considering the impact of shear as well as combined load conditions and conditions with a gap. It is necessary to implement the laboratory-based combined load studies into the reinforcement design to increase the safety and optimize the ground support design.

3.5 Conclusions

Rock bolts have shown to be subjected to complex loading conditions, e.g. combined load. The early stage of this study was developed to understand the complexity of failure mechanism of the rock bolt and its response to complex loading conditions. Laboratory tests were conducted using un-grouted rock bolts steels because they are useful to help understand the response of rock bolt under different loading conditions. Every combined load test performed showed an influence on the rock bolts performance differently. However, different steel types have shown to perform similarly under the same load conditions.

Based on the research and the lab tests to date, the following conclusions can be made:

(1) Current rock bolt support design methodologies consider only the axial capacity.

(2) For typical rock bolt steel in Australia, the shear capacity is about 70% of the axial (tensile) capacity.

(3) Most of the rock bolts are loaded along their length under varying combinations of axial, shear, and bending.

(4) Under both shear and combined load with a gap condition, a low-stiff bar is suggested in the design since it can undergo more displacement.

(5) Combined load conditions are still not considered in the rock bolt design; however, it could decrease the rock bolt shear and axial capacity by 30% and 18%, respectively.

To suggest improvements on the rock bolt design, further investigations will be undertaken to evaluate the effect of combined load on the system (i.e. rock bolt, grout, and cement block) with/without instrumentations.

Acknowledgments
The authors would like to thank Mining3, Minerals Research Institute of Western Australia, Curtin University and Peabody Energy for funding this research project. They also wish to thank Minova Global and its personnel who assisted in completing all the tests conducted at their facility in Nowra, NSW and for providing the rock bolts for testing.

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Chapter 4
Combined Load Failure Criterion for Rock Bolts in Hard Rock Mines

This chapter is under review for publication.

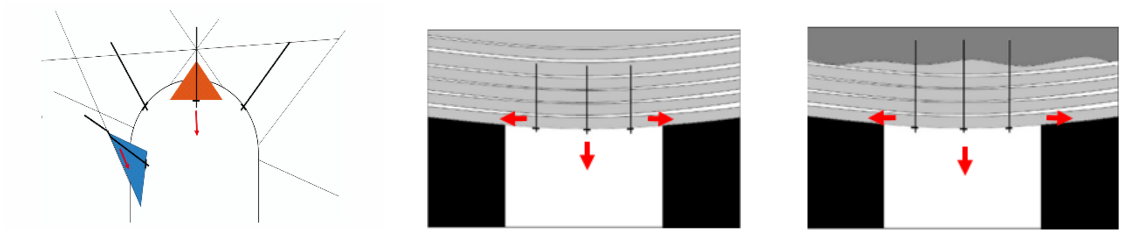
Pinazzi, P.C., Spearing, A.J.S., Jessu, K.V., Singh, P., & Hawker, R. (2019). Combined Load Failure Criterion for Rock Bolts in Hard Rock Mines.

Abstract
Rock bolts are highly important underground to prevent falls of ground and thus ensure safety. In situ, the ground reinforcement is subjected to a combination of loads; such as shear, axial/tensile, and/or bending loads. Studies have been conducted to evaluate the effect of either shear, axial/tensile, or bending loads on the ground support. However, only a few studies have been done to evaluate the effect of combined load on the rock bolt performance. In situ, the load's order acting on the bar cannot be predicted, and more than one load can be acting on the bar at the same time. Thus, a hybrid failure criterion was developed that covered all combined loading conditions. Fifty-eight un-grouted laboratory rock bolt tests were conducted in total, under two load conditions: applying shear displacement to the rock bolt and then axial load to failure and applying axial displacement to the rock bolt and then shear load to failure. From the tests result, the failure criterion was developed based on regression analysis. A non-linear relationship was determined for the loading condition variations. The failure criterion presented in this paper can be used as a guide in the rock bolt capacity design under all loading conditions.

Key-words: Axial Load, Shear Load, Bending Load, Combined Load, Failure Criterion, Rock Bolt Design

4.1 Introduction

Rock bolts are the primary ground reinforcement used to prevent fall of ground in situ. Every mine presents different conditions related mainly to geology, hydrology, and mining characteristics and conditions. These characteristics directly impact the loads generated along a rock bolt. In situ, the rock bolt can be subjected to a combination of loads such as shear, axial/tensile, and bending. These loads can be identified in the current ground reinforcement mechanism. It confirms that the rock bolts are subjected to a combination of loads, Figure 4.1 ([10], modified by [11]). Even though combined load have been evaluated in previous research [1], no attempt has been done yet to consider its effect on the rock bolt capacity that should be used in the support design process.



(a) Key block (b) Suspension (c) Beam building

Figure 4.1 – Support mechanisms: a) Key Block, b) Suspension, and c) Beam Building. [11]

Chesson et al. [2] and Frisher and Struik [7] developed a failure criterion for structural bolts under combined load. Even though the failure criterion has been used to evaluate the effect of combined load on rock bolts, the results obtained in this study do not comply with this failure criterion because the load condition applied to the structural bolts was different from the one applied in this study. Dight [3] used Chesson et al. [2] and Frisher and Struik [7] concept to explain how combined load affects the rock bolt performance as shear is applied to the bolts at different angles. After Dight [3], other studies were conducted mainly to evaluate the effect of combined load with focus on the bolt contribution to joint shear strength [4-6, 9, 12]. In these studies, however, the combined load is generated by applying shear at a discontinuity and as a side effect, the rock bolt bends resulting in axial load. As a result, the bar fails in both loading mechanisms shear and axial loads.

In this paper, the combined load is defined as applying two independent loads to the bar, shear load and axial load, and not as a result of shear load. A failure criterion was developed for the load conditions applied to this study, which the rock bolt is subject to loads simultaneously. This study presents the failure criterion for combined load conditions applied for rock bolts in hard rock mines.

4.2 Tests Methodology

A new laboratory test set up was developed to apply combined load conditions to rock bolts (Figure 4.2 and 4.3). Two regimes of combined load (shear then tension to failure, and tension then shear to failure) were applied to the bar; the details of the methodology can be found in Pinazzi et al. [11]. For both load conditions, the loads applied to the bar were kept until its failure.

Table 4.1 is showing the number of tests and displacement variation for each load condition applied. The percentage of the displacement applied compared to the maximum displacement the bar can undergo is given in parentheses.

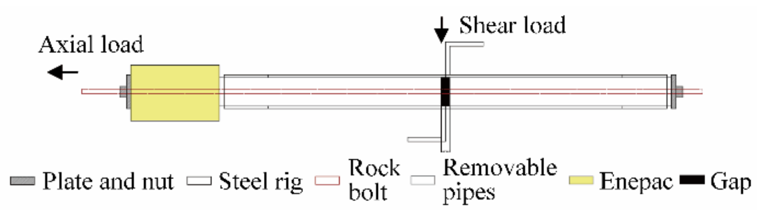


Figure 4. 2 – Schematic set up of combined load tests. [11]

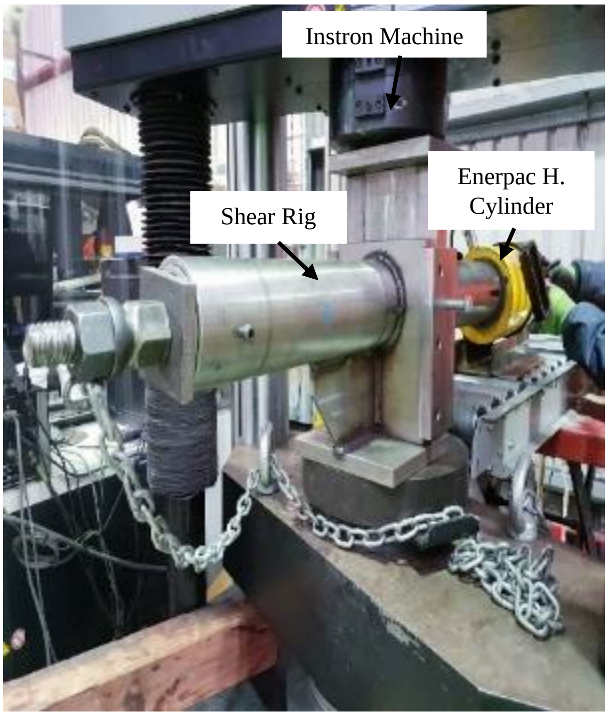


Figure 4.3 – Combined Load test set up. (Length between grips 1280mm) [11]

Table 4.1 – Load conditions applied to R27.

<table>
<tr><th colspan="2">Load Conditions Pure</th><th>N. of Tests</th></tr>
<tr><td colspan="2">Pure Shear Load / Guillotine</td><td>3</td></tr>
<tr><td colspan="2">Pure Axial Load using Enerpac Hydraulic Cylinder (60 ton.)</td><td>4</td></tr>
<tr><th colspan="3">Combined Load Conditions</th></tr>
<tr><td rowspan="9">Axial displacement and then shear load to failure</td><td>20mm (16%)[1]</td><td>3</td></tr>
<tr><td>30mm (25%)[1]</td><td>3</td></tr>
<tr><td>40mm (33%)[1]</td><td>3</td></tr>
<tr><td>45mm (37%)[1]</td><td>3</td></tr>
<tr><td>50mm (41%)[1]</td><td>4</td></tr>
<tr><td>60mm (49%)[1]</td><td>3</td></tr>
<tr><td>70mm (58%)[1]</td><td>3</td></tr>
<tr><td>80mm (66%)[1]</td><td>3</td></tr>
<tr><td>100mm (82%)[1]</td><td>4</td></tr>
<tr><td rowspan="5">Shear displacement then axial load to failure</td><td>2mm (20%)[2]</td><td>3</td></tr>
<tr><td>4mm (39%)[2]</td><td>3</td></tr>
<tr><td>6mm (59%)[2]</td><td>6</td></tr>
<tr><td>7.5mm (74%)[2]</td><td>4</td></tr>
<tr><td>9mm (88%)[2]</td><td>6</td></tr>
</table>

[1] Axial displacement applied to the bar in the combined load condition 1.

[2] Shear displacement applied to the bar in the combined load condition 2.

In total, fifty-eight tests results were used to determine the failure criterion, for each load combination applied to the rock bolt. The tests results presented in this paper were conducted using the Australian rock bolt for hard rock, R27. The mechanical properties of R27 can be found in Table 4.2.

Table 4.2 – R27 mechanical properties.

Properties	Mean	σ (Standard Deviation)
Shear Ultimate Load (kN)	217	4
Ultimate Shear Displacement (mm)	10.2	0.5
Tensile Ultimate Load using Enerpac	314	3
Ultimate Tensile Displacement (mm)	121.5	4.7
Rock Bolt Diameter (mm)	27	

4.3 Failure Criterion for Rock Bolt under Combined Load

The approach used in this paper to predict the rock bolt failure is based on a regression analysis of the data. A nonlinear relationship is established for each load condition applied to the rock bolt using the data generated in the laboratory tests. In in situ conditions, it is impractical to predict which load mechanism will act on the rock bolt first, or even if both shear and axial could be acting on the bar at the same time somewhere along its length. Thus, a hybrid failure criterion was developed for combined load conditions.

The analysis for each combined load mechanism applied is presented by plotting the amount of displacement applied to the bar and its load at failure. For the hybrid failure criterion, the load at failure is plotted versus a percentage of the bar displacement compared to its displacement capacity (Displacement Percentage). Figure 4.4 represents a summary of the approach used to evaluate each load condition applied, and the hybrid failure criterion.

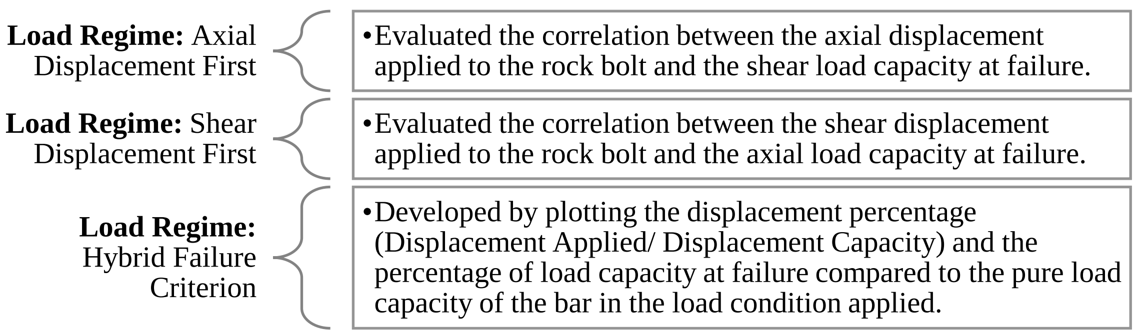


Figure 4.4 – Approach used for each failure criterion presented.

4.3.1 Load Regime: Axial Displacement then Shear Load to Failure

Tests were conducted to evaluate the axial displacement effect on the shear load performance of the rock bolt. At pure load conditions, the value of k=shear ultimate load / axial ultimate load is 0.7. However, when applying axial displacement and then shear load to failure, k dropped up to 0.48, reducing significantly the ratio shear load/axial load.

The failure criterion found for this load condition, applying axial displacement and then shear load to failure, is given by Equation 10. Figure 4.5 is representing the data set used to determine the correlation, which is given by the axial displacement applied to the rock bolt and the shear load capacity under the condition applied. A nonlinear relationship is given by a third degree polynomial equation that was found to have the best fit for the data collected, as it gave a concise coefficient of determination of 0.98. The combined load data is represented in the chart of Figure 4.5.

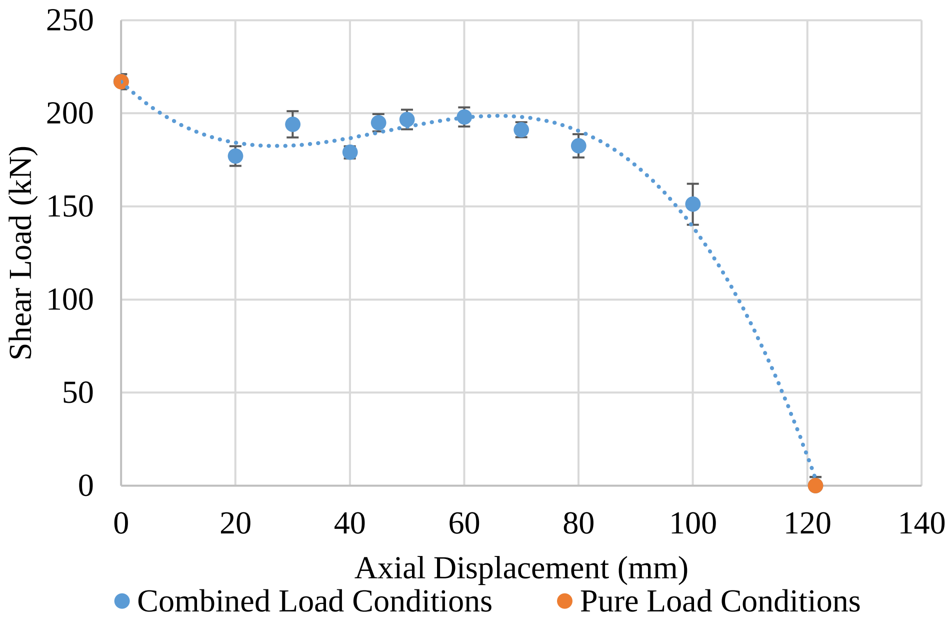


Figure 4.5 – Failure criterion for combined load, regime: axial displacement then shear load to failure.

$$S_l = -0.0006A_d^{3} + 0.0772A_d^{2} - 2.9589A_d + 217 \quad (10)$$
$$R^2 = 0.984$$

Where:

S_l = Shear Load at Failure (kN)

A_d = Axial Displacement Applied (mm)

R^2 = Coefficient of Determination

4.3.2 Rock Bolt Axial Load Performance after Applying Shear Displacement

Tests were conducted to evaluate the combined load effect on the rock bolt where the shear displacement is applied first to the bar and then axial load to failure. For this loading condition, the failure criterion was also given by nonlinear regression. Figure 4.6 is presenting the data used to determine the failure criterion. It was given by the shear displacement applied to the bar (y-axis) and the axial load capacity for the applied load condition. It presented a better coefficient of determination of 0.92.

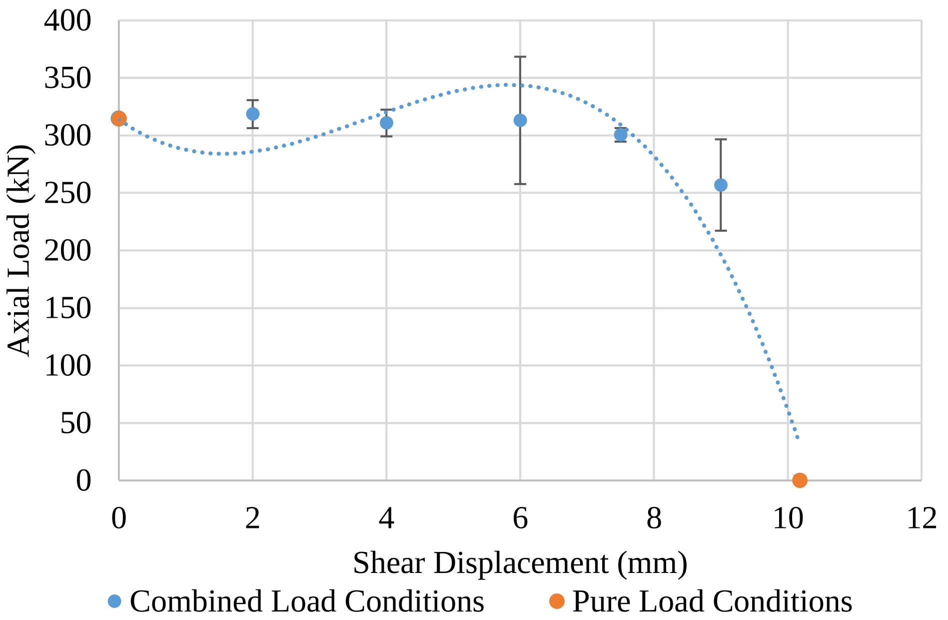


Figure 4.6 – Failure criterion for combined load, regime: shear displacement then axial load to failure.

$$A_l = -1.5371S_d^{\,3} + 17.048S_d^{\,2} - 42.024S_d + 314.00 \quad (11)$$

$$R^2 = 0.917$$

Where:

A_l = Axial Load at Failure (kN)

S_d = Shear Displacement Applied (mm)

R^2 = Coefficient of Determination

4.4 Hybrid Failure Criterion for Combined Load Conditions

The rock bolt can be subjected to shear load or axial load first, or even both load types at the same time. Thus, a hybrid relationship was established to predict the amount of load capacity decrease, for shear or axial, compared to the percentage of the displacement applied to the bar and the bar displacement capacity.

The hybrid relationship is presented in Figure 4.7. From the correlation, it is possible to determine how much the load capacity of the rock bolt, in shear or axial, is going to be adversely affected under combined load based on the amount of displacement the bar will or is predicted to undergo. In Figure 4.7, the green area shows that in a big range of displacement being applied to the bar under combined load, the bar load capacity will decrease up to 18%. If the displacement percentage is bigger than 80%, the rock bolt is almost reaching its displacement capacity. Thus, its load capacity is affected the most, and the bar is imminent to failure. The hybrid failure criterion is given by equation 12. It is represented by a polynomial regression of order 5. The coefficient of determination has shown that the correlation is accurate, and the standard error of regression shows that it is valid. However, it has limitations.

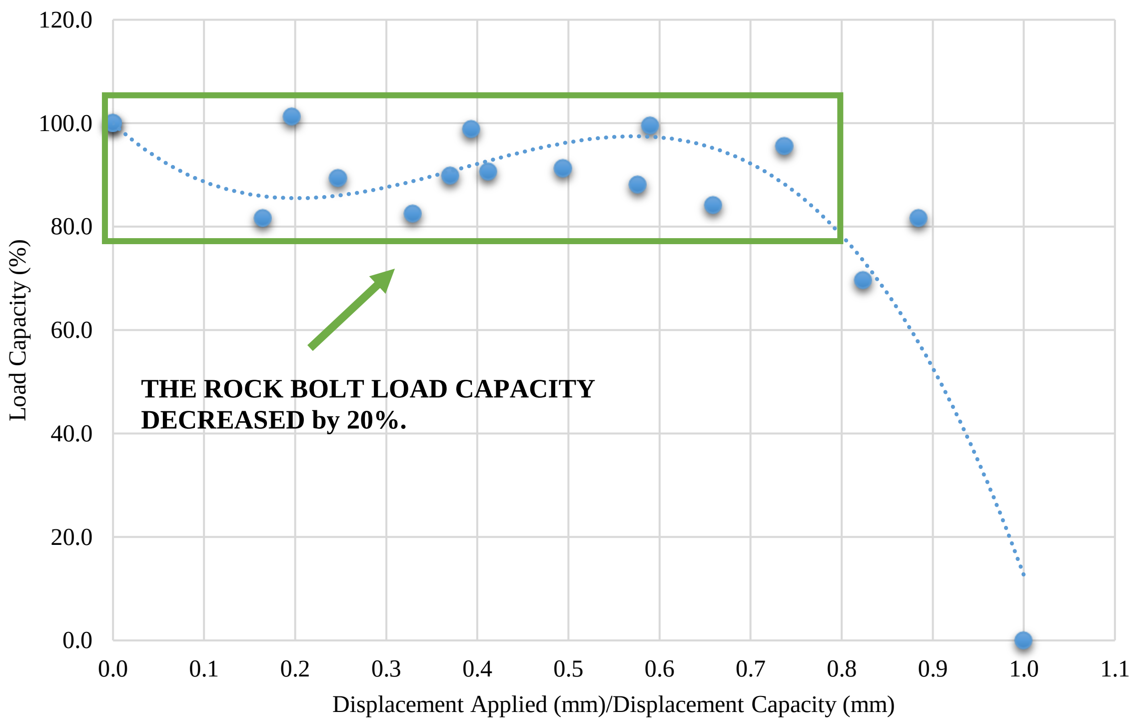


Figure 4.7 – Hybrid Failure Criterion for a Rock Bolt under Combined Load Conditions.

$$L_{\%} = -471.07\, D_{ac\%}{}^{3} + 546.55\, D_{ac\%}{}^{2} - 162.91 + 100.00 \quad (12)$$

$$R^2 = 0.839$$

$$S = 10.411$$

$L_{\%}$ = Percentage of load capacity under combined load condition compared to pure load condition.

$D_{ac\%}$ = Percentage of displacement applied to the bar compared to its displacement capacity.

S = Standard Error of Regression

4.5 Rock Bolt Design for Combined Load Conditions

The combined load condition is not considered when determining the rock bolt capacity in the common rock bolt design methodologies. The conventional design considers the rock bolt capacity to be its axial load capacity. However, under pure load conditions, the rock bolt shear load capacity represents 70% of its axial capacity. Moreover, the present study has shown that the rock bolt axial and shear load capacity can be decreased up to 18% and 30%, respectively, under combined load conditions. The failure criterion presented for the load conditions applied in this study can be used to predict the reduction in axial or shear load capacity of the rock bolt.

The hybrid criteria can be used for the example given by Figure 4.8 from Li [8]. In the condition presented in the picture, the bar underwent a combination of 10mm in shear displacement and 65mm in axial displacement. Knowing the displacement capacity of the bar, the displacement percentage can be determined and applied to the hybrid failure criterion to estimate the decrease in load capacity of the rock bolt. This information can be used for rock bolt capacity design for new mine headings.

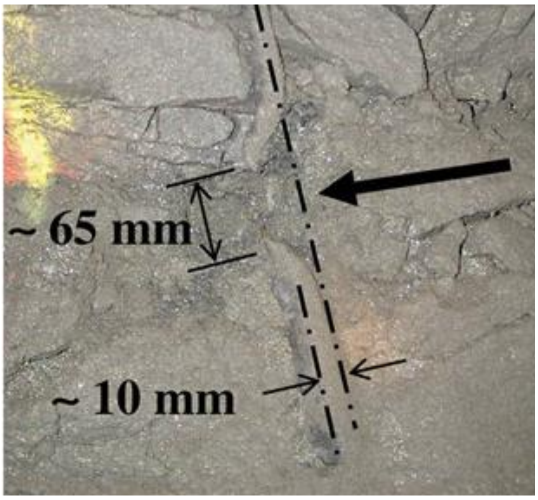


Figure 4.8 – Combined load conditions in situ. [8]

4.6 Conclusions

Based on the results obtained from the combined load tests conducted, the following conclusions can be made for rock bolt capacity design:

- The current rock bolt design methodologies are not applicable to most mines, where combined load conditions are present.
- Under combined load conditions:
  - 80% of the rock bolt axial load capacity should be assumed for the rock bolt design.

- Under combined load conditions with large shear identified:
  - 50% of the rock bolt axial load capacity should be assumed (18% from being under combined load and another 30% should be decreased due to the shear capacity of the rock bolt being 70% of its axial capacity) in the design.
- For both conditions, if the displacement percentage is higher than 80% the rock bolt selection should be reconsidered (i.e. Low-stiffness bar).
- The failure criterion developed in this study has shown to contribute for a better design of the rock bolt capacity, considering the combined load conditions in situ.

Acknowledgments

The authors wish to thank Mining3, Minerals Research Institute of Western Australia, Curtin University and Peabody Energy for funding this research project. They also would like to thank Minova Global and its personnel who assisted in completing all the tests conducted at their facility in Nowra, NSW and for providing the rock bolts for testing.

Compliance with Ethical Standards

Conflict of Interest The authors declare that there is no conflict of interest.

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Chapter 5
Considerations on Rock Bolt Design under Combined Load Conditions

5.1 Rock Bolt Design

There are different rock bolt design methodologies available such as Experiential, Physical, Empirical, Analytical and Numerical Methods. The limitations of these methods are related to the varied conditions in situ, which is not the same for every mine site. There is not a standard reinforcement design methodology that can be used for all the mines. The recommendations given by the Western Australian Department of Industry and Resources (1997) are that the design of ground support and reinforcement should be based on understanding: considering the geological structure, rock stress levels and stress changes, rock strength, groundwater, the potential for mining-induced seismicity, and behaviour of the rock support reinforcement system under load. This chapter is focused on the last research area, identifying the failure mechanism of rock bolt, under combined load, understanding and considering these effects on the performance of the rock bolt and the design of rock bolt systems.

Understanding the mechanical behaviour of the rock bolt under different loading conditions can assist when designing the rock bolt capacity. The rock bolt failure mechanism can be used as a visual tool for identifying the loads being applied to the rock bolt in situ (Li, 2010). In this study, the failure mechanisms were identified by testing the rock bolts under different loading conditions in the laboratory. The failure mechanism for each scenario is presented and evaluated individually. This approach can be used, when there is a rock bolt failure underground, to visually identify the possible loading mechanism acting on the rock bolt and consider it in the rock bolt design to avoid a similar recurrence. The rock bolt design should take into consideration the load in which the rock bolt will be subjected. Being able to identify the load mechanisms acting on the rock bolt underground is also essential for a reliable and safe rock bolt design. An alternate and safer approach is to assume a "worst case scenario" which is a combined shear and tensile load on the rock bolt and design using those conditions. Most rock bolts are loaded in this manner so it is an acceptable assumption.

In current rock bolt designs, the rock bolt load capacity is often given by its axial load capacity. Rock bolt suppliers rarely mention shear load capacity in the specifications. Studies, however, have shown the rock bolt in situ can undergo not just axial loading but also shear loading and also commonly by a combination of axial and shear loading conditions. Chapters 3 and 4 have presented how the rock bolt capacity is affected by shear and also combined loads. In this Chapter, the results found are used to consider the effect of shear and combined load on the rock bolt capacity design based on the hybrid failure criterion from Pinazzi et al., (2020) and the analysis developed in this study.

The load conditions in situ have a considerable impact on the rock bolt mechanical performance. It is essential to develop methodologies to be able to identify these loads in situ and consider it in the rock bolt design. This chapter is divided into two sections, to determine the failure mechanism of the rock bolt under shear and combined load, and how to consider the effect of combined load in the rock bolt design. The effects of corrosion, especially stress corrosion failure is also an important consideration but is beyond the scope of this research study.

5.2 Methodology

Two methodologies are presented in this Chapter. The first one is an analysis of the rock bolt failure mechanism for each load condition applied in this study (Table 5.1). The second is a qualitative analysis to consider shear and combined load on the rock bolt design.

5.2.1 Analysis of Rock Bolt Failure Mechanism

There are many ways of identifying the load in situ, for example, using instrumentation or even evaluating rock bolts failure mechanism after a fall of ground. Visual observations of the rock bolt failure mechanism can be used to identify the loads it was subjected to at failure. The rock bolt failure mechanism for each load condition applied in this study is presented in photographs, and the load is evaluated. The photographs for each load mechanisms are presented in Appendix A. Table 5.1 is showing the load conditions applied to each rock bolt type tested. Details of the methodology for the load conditions applied to the rock bolt can be found in Chapter 3.

Table 5.1 – Load condition applied for each rock bolt type tested in the laboratory.

Load Condition	Rock Bolt (Rebar)Type		
	AUS R27 (Hard Rock)	SA R27 (Hard Rock)	SA M24 (Coal)
Pure Axial Load	✓	✓	✓
Pure Shear Load	✓	✓	✓
Shear Load with a Gap	✓		✓
Shear Displacement + Axial Load to Failure	✓		
Shear Displacement(Gap) + Axial Load to Failure	✓		
Axial Displacement + Shear Load to Failure	✓		✓

5.2.2 Analysis to Consider Shear and Combined Load in the Rock Bolt Design

In situ, there is a high probability that the rock bolt will be subjected to axial and shear load at the same time at different locations along the rock bolt (combined load). As mining activities progress, the loads acting along the rock bolt can change dramatically over time. Thus, a failure criterion was developed to consider combined load condition in the rock bolt design. The method to consider combined load in the rock bolt design, the so-called hybrid failure criterion can be applied to consider combined load. Hybrid failure criterion can be used to identify the decrease in load capacity under combined load. The details of the hybrid failure criterion methodology can be found in Chapter 4.

Using the hybrid failure criterion, a simplified approach is presented to consider shear and combined load in the design. This approach assumes that the rock bolt will always undergo a combination of loads. Considering that the rock bolt capacity is given by its axial load capacity, the axial capacity is decreased based on the specific conditions assumed (i.e. pure shear load conditions, combined load conditions, combined load conditions with large shear.).

5.3 Analysis of Rock Bolt Failure Mechanism under Combined Load Conditions for Different Rock Bolt Types

The response of rock bolt behaviour under varied load conditions is part of understanding the rock bolt performance in situ. As stated, the rock bolt can fail under axial, shear, bending, or a combination of loads. Being able to identify the loads in which the rock bolt was subjected to can help in the rock bolt design. A series of photographs were taken of each rock bolt tested in this study under varied load conditions, pure and combined. These photographs were evaluated to identify the predominant mechanism acting on the rock bolt at its failure. Each of these pictures is discussed and presented for each load condition applied to different rock bolt types.

5.3.1 Rock Bolt Failure Mechanism under Pure Load

The failure mechanism of the rock bolt under a single load, axial and shear (Table A.1), is presented as a reference to identify the predominant load at failure for each mechanism applied to the rock bolt under combined conditions. The different rock bolt types tested show a similar failure mechanism under pure load conditions when applying shear or axial. The loading mechanism at failure is easily identified for all rock bolts tested.

5.3.2 Rock Bolt Failure Mechanism under Shear Load with a Gap

The shear load applied with a gap results in a combined load failure mechanism, as discussed in Chapter 3. Table A.2 shows the failure mechanism when applying shear load with a gap for Australian R27 (Hard Rock) and South African M24 (Coal). At 5 mm gap, it is possible to identify that the dominant failure mechanism is shear. For both rock bolt types, the bar bent slightly mainly for SA M24. For the AUS R27, it is easier to identify all the load mechanisms. A similar condition can be observed when applying shear with 15 mm gap, for both rock bolts type, shear and bending can be easily identified. However, the axial load can be identified only for AUS R27, for SA M24 the rock bolt presented to have a brittle failure, and it is harder to identify axial load.

5.3.3 Applying Shear Load and Then Axial Load to Failure

The failure mechanism for this load condition, applying shear load then axial load to failure, has shown that at lower shear displacement applied to the bar (2mm to 6mm), the bar failed purely under axial load. It also did not fail where the shear load was applied. At this condition, the bar load capacity was not significantly affected, but the displacement capacity was. However, when applying 9mm shear displacement, the bar axial load and displacement capacity were significantly affected. As the shear displacement increases, the bar shows to undergo a combination of shear, axial and also bending (Table A.3).

Applying shear load with a gap and then axial load, the failure mechanism presented more bending than without a gap. When applying the combined load with a gap, the bar undergoes more axial displacement because the total shear displacement applied with a gap is smaller than the shear displacement applied without a gap, as discussed in Chapter 3. Also, as the gap increases, the axial capacity of the bar is less affected since it can undergo more axial deformation before failure. The significant difference between applying this combined load condition with a gap compared to without a gap is the amount of bending the bar undergoes.

Table A.3 shows the failure mechanism for each load condition applied to the rock bolt. The visual identification column was divided into two. The first one is showing where the shear load was applied, and the second the failure mechanism. For the first three load conditions applied, the bar did not fail where the shear load was applied as presented.

5.3.4 Applying Axial Load and Then Shear Load to Failure

Similar to the previous combined load conditions, when applying axial displacement and then shear load to failure; as the axial displacement applied increases almost reaching the bar axial displacement capacity, the axial load becomes the predominant failure mechanism. At 20mm of axial displacement, the bar fails predominantly under shear load, the effect of the axial load is barely noticeable. It is possible, however, to identify bending for both all conditions applied for AUS R27 and SA M24. For AUS R27, applying 100 mm axial displacement to the bar, it also fails by a combination of shear, bending, and axial. However, the axial load is predominant. Applying this condition to the SA M24, the failure mechanism was different from the other tests. It showed a different structural failure, consistent for all three samples tested. This difference in failure mechanism can be justified by the difference in steel compositions.

For the AUS R27 (Table A.4), from 20 to 70mm of axial displacement, it is hardly possible to tell that the bar underwent shear as well as axial load. However, if comparing the failure interface to when applying the only pure shear, for this combined load condition, the failure can be identified and also it is possible to notice that the bar underwent bending, which does not happen under pure load conditions.

For SA M24, the rock bolt presented a different failure mechanism compared to AUS R27 (Table A.5). At 20mm axial load, the predominant failure mechanism is shear and bending, axial load is identified as minimum. From 30mm to 60mm axial displacement, the failure mechanism is a combination of loads shear, bending, and axial. However, the axial failure mechanism is located at the centre of the rock bolt, as shown by the red arrow in the photographs in Table A.5. The failure is very different from the pure load condition. It also seems that the rock bolt failed in a brittle behaviour.

5.3.5 Rock Bolt Failure Mechanism Consideration on Rock Bolt Support Design

The analysis developed to identify the predominant rock bolt failure mechanism can be used as a reference to classify the rock bolt failures in situ, and consider it in the rock bolt design. A summary of the rock bolt failure mechanisms analysis presented in this section is presented in Appendix A, Table A.6.

5.4 Analysis of Laboratory Tests Results to Consider The effect of Combined Load on the Rock Bolt Capacity Design

The results presented in Chapter 3 and 4 have shown that even though the rock bolt capacity is typically given by its axial load capacity, the shear and combined load capacity are significantly lower than the bar's axial capacity. For the three rock bolts tested, Australian R27 (Hard Rock), South African R27 (Hard Rock), and Coal M24 (Coal) the shear load capacity is around 70% of the bar axial load capacity. Moreover, when shear load is applied with a gap/discontinuity, the load capacity variation can represent 58% of the rock bolt axial capacity. Under combined load, the rock bolt capacity can be decreased by 18% of the rock bolt axial capacity, and 30% of its load capacity. The findings from these Chapters, the understanding of combined load in the rock bolt performance and the development of hybrid failure criterion to consider combined load in the rock bolt design, were used to develop an approach to consider shear and combined load in the rock bolt design.

Mining operations are dynamic. The stress and load conditions acting on the rock bolt changes as the mine progresses. A simplified approach was developed to design the rock bolt system without having to access detailed information as it might also change. In this approach, the only assumption is that the rock bolt will always be subjected to combined load conditions. In this study, the rock bolt shear capacity presented to be 70% of the rock bolt axial capacity. In addition, as presented in Figure 5.1, at a wide range of shear displacement applied to the bar under combined load, the rock bolt capacity decreased by 20%. As a sum of both effects, combined load and shear, and considering that the rock bolt capacity is given by its axial capacity, 50% of the rock bolt axial load capacity should be considered as the rock bolt capacity in the design.

This suggested methodology can be validated through an investigation of the ground conditions in situ. A summary guideline for this investigation is presented in Figure A. 2. As a first stage, the geological conditions in situ need to be well understood based on data collection. Geological mapping and rock deformation can give relevant information about the rock mass condition and also the possible loads and displacement in which the rock bolt will be subjected. In situ observations and evaluation of previous fall of ground can also validate the design. After identifying the load condition, i.e. combined load, large shear displacement, or combined load plus large shear displacement, the displacement percentage (displacement applied/displacement capacity) should be determined. It can be used in the hybrid failure criterion (Figure 5.1) to define the decrease in load capacity of the rock bolt. Using the guideline suggested the methodology presented to consider combined load in the rock bolt design can be validated.

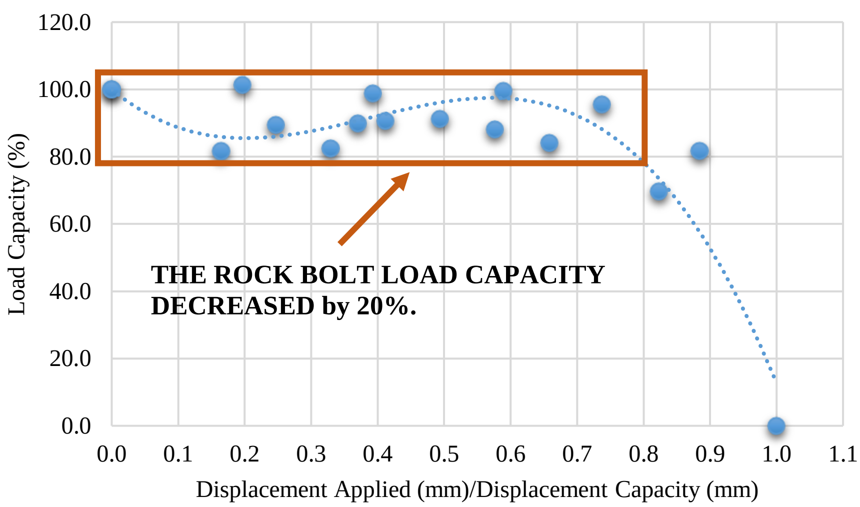

Figure 5.1 – Combined Load Effect on the Rock Bolt Load Capacity. (Pinazzi et al., 2020)

5.5 Shear Load with a Gap

The load condition of shear with a gap is a form of combined load. When shear is applied with a gap/discontinuity, the bar bends before failure, and axial load is created. Thus, the bar fails by a combination of shear and axial load. In the tests conducted applying shear load with a gap, the rock bolt shear capacity represented around 58% of the axial load capacity for both rock bolts tested. In the suggested method to consider combined load in the rock bolt support design, the displacement expected to be applied to the rock bolt is already being considered by the displacement percentage. However, it is known that if the rock bolt is subjected by the load with a gap, the bar will deform significantly more than if there is no gap. Thus, if a gap/discontinuity condition is potential underground, a low-stiffness rock bolt should be considered as it can undergo more deformation before failure.

5.6 Conclusions

The following conclusions can be drawn from the analysis developed in this Chapter:

- The failure mechanism guide presented in Appendix A can be used as a guide to identify the predominant failure mechanism of the rock bolt. The failure mechanism analysis of the rock bolts tested in this study can be used as a reference to identify the rock bolt failure mechanism in situ. This information can assist to help design a more realistic rock bolt design for the next heading of the mines.
- The hybrid failure criterion can be used to predict the decrease in load capacity when the rock bolt is subjected to combined load conditions.

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Li, C. C. (2010). Field observations of rock bolts in high stress rock masses. *Rock Mechanics and Rock Engineering, 43(4),* 491-496.

Pinazzi, P.C., Spearing, A.J.S., Jessu, K.V., Singh, P., & Hawker, R. (2020). Mechanical performance of rock bolts under combined load conditions. *International Journal of Mining Science and Technology*. https://doi.org/10.1016/j.ijmst.2020.01.004

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Chapter 6
Summary of Findings and Conclusions

6.1 Rock Bolt Performance under Combined Load Conditions

The results obtained in this study have shown that the load capacity and displacement of rock bolts are adversely affected under combined load conditions. The summary and findings for each load condition combination and the effect on the bolts performance are as follows:

- Rock bolts are generally subjected to a combination of shear, axial, and/ bending loads in situ.
- The rock bolt shear load capacity is generally only typically 70% of its axial load capacity.
- Table 6.1 is presenting a summary for each load conditions applied to the different rock bolt types. The decrease in load capacity presented in percentage is compared to the rock bolt shear or axial load or displacement capacity under pure load conditions.

Table 6.1 – Rock bolts performance under varied load conditions.

<table>
<tr><th colspan="7">Load Conditions and Rock Bolts Performance Summary</th></tr>
<tr><th>Rock Bolt Type</th><th colspan="2">Load Condition</th><th>Change in Load Capacity (%)</th><th>Average (%)</th><th>Change in Displacement Capacity (%)</th><th>Average (%)</th></tr>
<tr><td colspan="7">Applying Shear with a Gap</td></tr>
<tr><td>R27</td><td colspan="2">Shear with a Gap: 5, 10, 15, 20 (mm)</td><td>↓Decreased 7% - 19%</td><td>-13%</td><td colspan="2">↑ Increased (Bar bent and elongated before failure)</td></tr>
<tr><td>M24</td><td colspan="2">Shear with a Gap: 5, 10, 15 (mm)</td><td>↓ Decreased 16% - 21%</td><td>-18%</td><td colspan="2">↑ Increased (Bar bent and elongated before failure)</td></tr>
<tr><td colspan="7">Applying Shear Displacement then Axial Load to failure</td></tr>
<tr><td rowspan="3">R27</td><td rowspan="3">9mm Shear Displacement Then Axial Load to Failure</td><td>No Gap</td><td>↓ Decreased 1% - 35%</td><td>-18%</td><td>↓ Decreased 90% - 94%</td><td>-92%</td></tr>
<tr><td>5mm Gap</td><td colspan="2">No Significant Change</td><td>↓ Decreased 51% - 63%</td><td>-59%</td></tr>
<tr><td>10mm Gap</td><td colspan="2">No Significant Change</td><td>↓ Decreased 39% - 56%</td><td>-49%</td></tr>
<tr><td colspan="7">Applying Axial Displacement then Shear Load to failure</td></tr>
<tr><td>R27</td><td colspan="2" rowspan="2">Axial Displacement then Shear Load</td><td colspan="2">↓ Decreased 9% - 30%</td><td colspan="2">↑ Increased (Bar bent and elongated before failure)</td></tr>
<tr><td>M24</td><td colspan="2">↓ Decreased 19% - 22%</td><td colspan="2">↑ Increased (Bar bent and elongated before failure)</td></tr>
</table>

6.2 Approach to Consider Combined Load Conditions in the Rock Bolt Design

In this study, two types of load conditions were evaluated. The one to determine the effect of shear displacement on the axial capacity of the rock bolt, and the other to investigate the effect of axial displacement on the shear capacity of the rock bolt. In-situ, it is not possible to define which load type comes first and in reality, the different forces probably load at the same time. Moreover, as the mining continues, the load conditions on the rock bolts changes. Chapter 4 presented the combined (hybrid) failure criterion and shows that at a wide range of displacement applied to the rock bolt under combined load conditions, the rock bolt capacity decreases by 20% or less.

As a simplified approach, the following considerations should be addressed in the rock bolt design, using the axial capacity as the rock bolt load capacity:

- Decrease the axial capacity by 50%. As presented in Figure 6.1, under the combined load conditions, the rock bolt capacity decreases by 20% at a wide range of displacement being applied to the bar. If large shear displacement is assumed, another 30% should be decreased to consider the effect of shear in the rock bolt capacity. In the previous sections of this study, the shear capacity of the rock bolt represented 70% of its axial capacity.

6.3 Main Finding

The only assumption to be considered in the presented approach is that the rock bolt will always undergo combined load conditions. Perhaps this uncertainty of the actual load conditions is the reason why traditionally a high factor of safety has been used in the rock bolt design.

Therefore, the main finding of this study is that to consider every possible load conditions the rock bolt might be subjected, the rock bolt capacity should be considered as being half of the tensile load capacity supplied by the suppliers.

6.4 Limitations and Future Work

The following limitations and improvements can be addressed in the future:

- The tests conducted in this research for the varied load conditions tested can be conducted using different rock bolt types, application (i.e. soft or hard rock, underground or surface operation, civil, etc.) and rock bolt mechanical properties such as capacity, diameter, stiffness, etc.
- Instrumentation can be used to help in identifying the change in loads along the rock bolt length and investigate load conditions change in situ. It should be noted that there is already ongoing research on this being done under the same Instrumented Rock Bolt Project which also funded the work done in this thesis.

Appendix A
Rock Bolt Failure Mechanisms and Guideline Summary to Validate Methodology to Consider Combined Load in the Rock Bolt Design

Table A.1 – Pure Load Conditions.

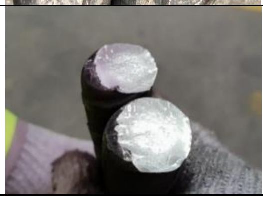
Pure Load Failure Mechanisms		
Rock Bolt Type	Load Applied	Failure Mechanism
AUS R27	Axial	
	Shear	
SA R27	Axial	
	Shear	
SA M24	Axial	
	Shear	

Table A.2 – Shear Load with a Gap.

Shear Load with a Gap Failure Mechanisms			
Rock Bolt Type	Load Applied	Picture	**Identifying this failure mechanism in situ:**
AUS R27	Shear Load w/ 5mm Gap		A significant bending at the rock bolt shear interface means that the bar underwent deformation at a discontinuity or the rock broke at the shear interface allowing the rock bolt to deform. Figure A.1(Li, 2009, in situ observations) shows that the rock bolt bent before breaking in situ. The failure mechanism in Figure A.1 is comparable with the rock bolt failure mechanism observed in this study. Identifying similar failure in situ is an indication that the rock bolts installed at the rockfall area are possibly under a shear load with gap/spacing. Thus, it requires a rock bolt capable of undergoing more deformation before breaking.
	Shear Load w/ 10mm Gap		
	Shear Load w/ 15mm Gap		
	Shear Load w/ 20mm Gap		
SA M24	Shear Load w/ 5mm Gap		
	Shear Load w/ 10mm Gap		
	Shear Load w/ 15mm Gap		

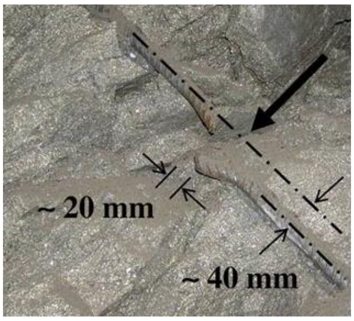


Figure A.1 – Combined load failure mechanism in situ. (Li, 2010)

Table A.3 – Combined load failure mechanism: applying shear displacement then axial load to failure for AUS R27.

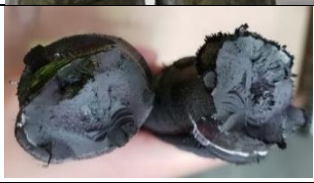
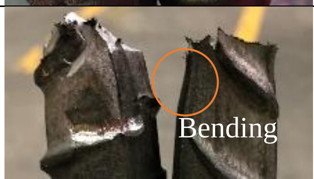
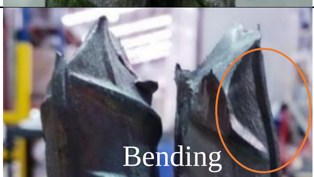
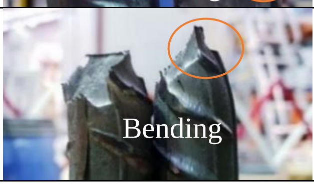
Combined Load Failure Mechanisms – Applying Shear Displacement and then Axial Load to Failure for AUS R27			
Load Applied	Visual Identification of Loads		**Identifying this failure mechanism in situ:**
2mm shear load then axial load to failure			Under this load condition, as the shear displacement increases, shear load seems to be the predominant failure mechanism. The bar also presents to bend before failure. For a shear condition with a gap, the rock bolt presented more bending moment than without a gap. Thus, if shear and axial load are identified means the bar failed under combined load. Also, when a significant bending moment is identified, there is a high possibility that the load was applied in a gap/discontinuity, as mentioned previously.
4mm shear load then axial load to failure			
6mm shear load then axial load to failure			
7.5mm shear load then axial load to failure			
9mm shear load then axial load to failure			
7.5mm shear load then axial load to failure with 5mm gap			
9mm shear load then axial load to failure with 5mm gap			
9mm shear load then axial load to failure with 10mm gap			
12.5mm shear load then axial load to failure with 10mm gap			

Table A.4 – Combined load failure mechanism: applying axial displacement then shear load to failure for AUS R27.

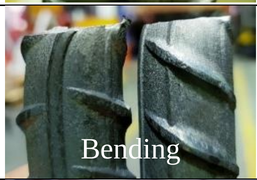
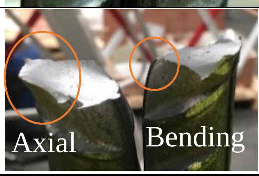
Combined Load Failure Mechanisms – Applying Axial Displacement and then Shear Load to Failure for AUS R27			
Load Applied	Visual Identification of Loads		**Identifying this failure mechanism in situ:**
20mm axial load then shear to failure			The major difference of this failure mechanism to pure conditions is that applying less axial load, the bar bends before failure. Shear might be the first failure mechanism identified, but if bending is also noticed, there is a chance that the rock bolt also underwent axial load. As the bar is almost reaching its axial displacement capacity, the predominant mechanism is axial load. However, it also shows bending, indicating that the bar also underwent a combination of loads. In this case, a significant amount of axial load and being able to identify bending, evidence the combined load conditions.
30mm axial load then shear to failure			
40mm axial load then shear to failure			
50mm axial load then shear to failure			
60mm axial load then shear to failure			
70mm axial load then shear to failure			
80mm axial load then shear to failure			
100mm axial load then shear to failure			

Table A.5 – Combined load failure mechanism: applying axial displacement then shear load to failure for SA M24.

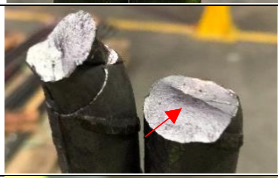
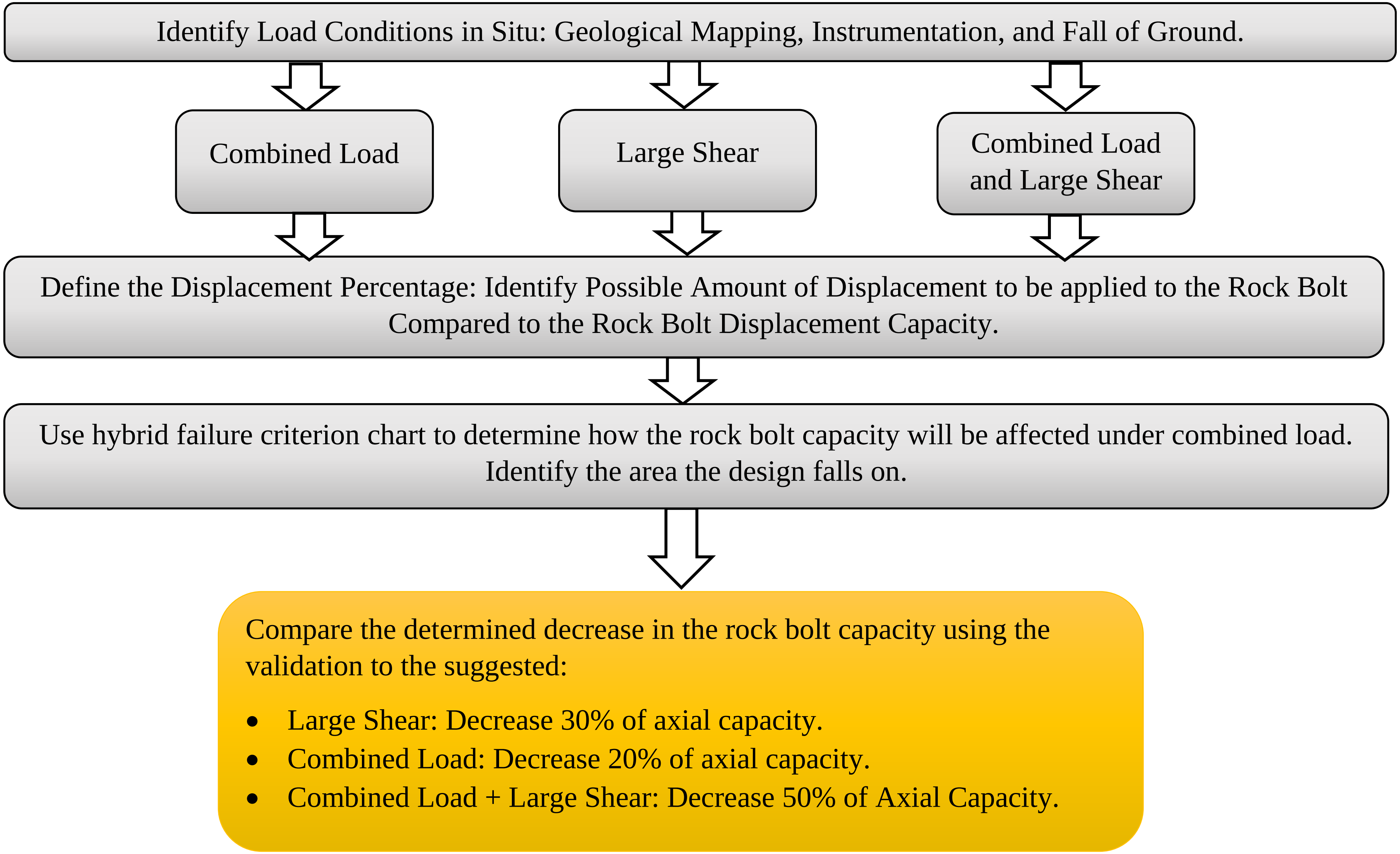
Combined Load Failure Mechanisms – Applying Axial Displacement and then Shear Load to Failure for SA M24			
Load Applied	Visual Identification of Loads		**Identifying this failure mechanism in situ:**
20mm axial load then shear to failure			For M24, under axial displacement then shear load to failure, the rock bolt fails by a combination of load shear, bending, and/or axial. The failure presents to have a brittle behaviour and the bar breaks at axial load at the centre as shown in the figure, while shear and bending are also present.
30mm axial load then shear to failure			
40mm axial load then shear to failure			
50mm axial load then shear to failure			
60mm axial load then shear to failure			

Table A.6 – Summary analysis of the rock bolt failure mechanism.

	Visual Identification of Load Conditions Check				
	Shear Load	Axial Load	Bending	Significant Bending	Failure Appearance
Shear Load	✓				
Axial Load	✓				
Shear Load with a Gap	✓	✓		✓	
Axial Displacement then Shear Load to Failure	✓	✓	✓		  
Shear Displacement then Axial Load to Failure	✓	✓	✓		 
Shear Displacement with a gap then Axial Load to Failure	✓	✓		✓	 

Figure A.2 – Guideline to validate the methodology to consider combined load in the rock bolt design.



Appendix B
Declaration of Authorship

DECLARATION OF AUTHORSHIP

I Pammela Caroline Pinazzi da Silva Ribeiro, contributed:

- 80% of design and data analysis of the paper entitled "Mechanical Performance of Rock Bolts under Combined Load Conditions". Anthony Spearing assisted with the tests design, data analysis, supervised the work and reviewed the paper. Prasoon Singh and Kashi Jessu assisted with the laboratory work and review of the paper. Robert Hawker assisted with the review of the study.
- 75% of design and data analysis of the paper entitled "Combined Load Failure Criteria for Rock Bolts in Hard Rock Mines". Anthony Spearing assisted with the data analysis, supervised the work, and reviewed the paper. Kashi Jessu, Prasoon Singh, and Robert Hawker assisted with the review of the paper.

Pammela Caroline Pinazzi da Silva Ribeiro

Date: 21/08/2019

I endorse that the level of contribution stated above by the candidate is appropriate.

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Appendix C
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