Behaviour of paddled energy-absorbing rockbolts under complex loading laboratory conditions

by G. Knox and J. Hadjigeorgiou

Affiliation:
University of Toronto, Canada

Correspondence to:
J. Hadjigeorgiou

Email:
john.hadjigeorgiou@utoronto.ca

Dates:
Received: 16 Feb. 2024
Revised: 2 Jun. 2024
Accepted: 8 Aug. 2024
Published: September 2024

How to cite:
Knox, G. and Hadjigeorgiou, J. 2024. Behaviour of paddled energy-absorbing rockbolts under complex loading laboratory conditions. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 124, no. 9. pp. 535–546

DOI ID:
http://dx.doi.org/10.17159/2411-9717/3294/2024

ORCID:
J. Hadjigeorgiou
http://orcid.org/0000-0002-6047-3964

Abstract

Since their introduction in 2010, paddled energy-absorbing rockbolts have been widely used in seismically active hard rock mines. This paper provides new data and reviews previous work to quantify the performance of paddled energy-absorbing rockbolts under controlled laboratory conditions. Of significance is the realization that the typical split location in impact tests, at the centre between two paddle anchor points can at best provide an upper limit value. This inherent variability in performance under different testing configurations should be acknowledged and taken into consideration in the design of ground support in seismic conditions.

This paper discusses the reduction in capacity of paddled rockbolts as a function of loading angle from a maximum value during axial tests (0° loading angle) to the lowest value during pure shear (loading angle of 90°). A significant reduction in displacement capacity is observed as the loading angle changes between axial (0°) and 40°. Beyond a 40° loading angle up to shear (90°) loading the reduction in displacement capacity is less significant.

Due to the variances in the capacity observed through the variance of the testing configuration: loading mechanism, direction of loading, location / presence of a discontinuity, it must be recognized that results from laboratory-based testing are not independent of the testing configuration. This should be acknowledged when extrapolating anticipated performance in the field.

Keywords

yielding ground support, paddled energy-absorbing rockbolts, impact testing configuration, combined axial shear loading

Introduction

Ground support is an integral component of risk management in all underground mining operations. A successful ground support strategy needs to meet specific design requirements and be cost effective while maintaining the stability and operability of an excavation for its anticipated service life. A successful ground support strategy matches the anticipated rock mass failure mode to the response of the ground support system. This is only possible if the rockbolt is successfully installed in what are at times adverse ground conditions.

Ground support technology has seen significant advancements in the last two decades, particularly in the introduction of energy-absorbing or yielding rockbolts. The advantages of yielding rock reinforcement elements were identified by Ortlepp and his cohorts in the 1960s. Following a review of rockbolt performance in rockbursts, Ortlepp (1969) conducted an underground blast test and demonstrated that a 'softer' system, which is able to sustain loads over a large displacement maintained the operability of the excavation.

One of the earliest energy-absorbing rockbolts was the cone bolt. Originally developed in South Africa as a cement grouted rockbolt by Jager (1992), it was not used widely at mine sites until it was modified in Canada to be used with resin. The main difference in the modified cone bolt was the addition of a blade paddle that extends ahead of the conical head that spins in the resin as the bolt is inserted in the borehole, Simser et al. (2007). Although the modified cone bolt was successfully used at several operations it was apparent from both laboratory and field observations that it did not perform well when subjected to seismic loads following considerable static deformation, (Simser et al., 2007). Although variations of the cone bolt are still used at some operations, it has been superseded by the next generation of energy-absorbing rockbolts, including the paddled energy-absorbing rockbolt.

The first paddled energy-absorbing rockbolt, the D-bolt, was developed by Li (2010) as a multi-point anchor steel bar installed in a fully grouted borehole. A series of quasi-static tests demonstrated that the paddled energy-absorbing bolt had significantly higher maximum energy-absorption than rebar bolts, (Li, 2010). The performance of the energy-absorption mechanism was also quantified through impact testing (Li and Doucet, 2012), with the rockbolt sustaining large displacements prior to rupture. These are the qualities necessary for a yielding rockbolt as advocated by Ortlepp (1969). Empirical evidence at early mining applications also demonstrated that the bolt performed well under seismic loads and is arguably the most popular energy-absorbing rockbolt used at seismically active mine sites.

Since the development of the original paddled energy-absorbing rockbolt, several reinforcement elements that use the same concept have been developed. These are now widely used as part of ground support systems for squeezing or burst-prone rock masses. A practical issue that contributed to the wide use of paddled energy-absorbing rockbolts is the use of similar installation procedures as conventional resin rebar rockbolts. The resin rebar rockbolts are typically efficient to install and offer reasonable corrosion protection when fully encapsuled within the resin.

A rockbolt is installed with the intention of maintaining the operability of an excavation for the service life. The installed capacity is determined through destructive laboratory-based testing loading the rockbolt with a singular loading mechanism. This paper provides new data on the performance of energy-absorbing paddled rockbolts as well as consolidating research into both the effect of altering the loading angle in quasi-static tests, and recognizing the influence of split location during impact tests on the performance of a paddled energy-absorbing rockbolt.

Mechanics of reinforcement

A successful rock reinforcement strategy requires a match between anticipated rock mass failure mechanisms and the desirable rock reinforcement behaviour, (Potvin and Hadjigeorgiou, 2020). This requires a good understanding of ground conditions as well as the performance of rockbolts under the anticipated loading. Where seismic or squeezing rock masses are anticipated, paddled energy-absorbing rockbolts are routinely used as part of the ground support system for both as designed and rehabilitationed excavations, as demonstrated in Figure 1.

There are challenges in determining both demand and capacity of the rockbolts, owing to the variability of the rock mass and complexity of the loading mechanisms. Li (2010) has provided several examples of rockbolt failures in high stress conditions, while Simser et al. (2007) and Stacey (2012), illustrated the complex loading mechanisms associated with seismic loads, (Figure 2). It is difficult to quantify the demand placed on the ground support system under seismic conditions. Laboratory-based testing methods, such as impact testing have improved our understanding of the capacity of a rock reinforcement element subjected to a singular loading mechanism. The main limitation of the majority of laboratory experiments is that they focus on axial loading and, to a lesser degree, on shear loads. As illustrated by Windsor and Thompson (1997), using the dislocation and rotation of a wedge, as illustrated in Figure 3, rockbolts are often subjected to a loading combination consisting of tension, shear, and torsion.

The laboratory-based testing impact testing methodologies were developed in response to the increase in demand for energy-absorbing rockbolts as part of a risk mitigation strategy in seismically active mines. The method provides a controlled environment within which capacity quantification can be conducted at a relatively low cost. A comprehensive review by Hadjigeorgiou and Potvin (2011) identified several rock reinforcement and support testing facilities that had been constructed to quantify the capacity

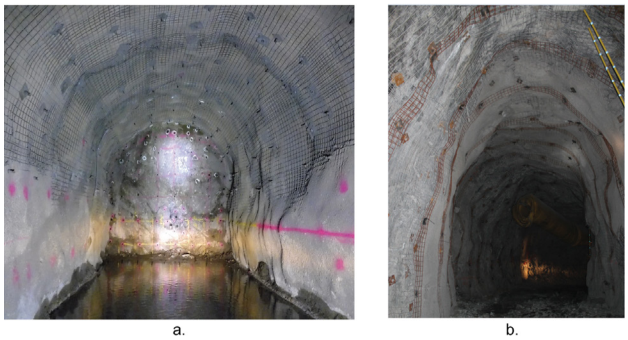

Figure 1—Application of paddled energy-absorbing rockbolts: (a) as designed excavation, (b) rehabilitated excavation (Yao et al, 2014)

Figure 2—Exposed rockbolts after a rockburst - indications of tension and shear along multiple surfaces (Stacey, 2012)

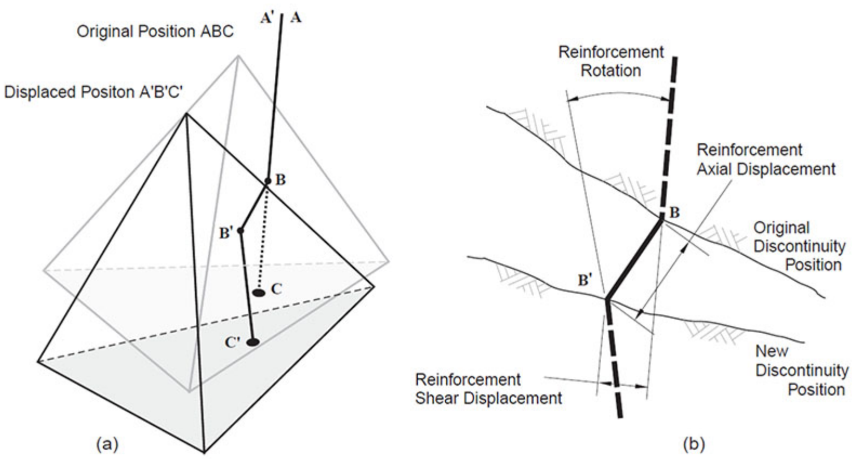

Figure 3—Rockbolt loading resulting from block displacement (Windsor & Thompson, 1997)

of rockbolts under impact loads. Only a few of those were used on a routine basis at the time. Despite the inherent limitations of impact tests, test rigs can provide repeatable results and can perform a relatively large number of tests at reasonable cost, without interfering with mining operations. Since the benchmarking study by Hadjigeorgiou and Potvin (2011), several new impact facilities have been constructed and used on a routine basis. Li et al (2021) provided a comparative case study of tests conducted at different facilities in North America, Australia, Europe, and Africa and discussed the observed variations in the reported results. This comparative study illustrated the importance of understanding the inherent biases in the machines when comparing results generated on different machines. Beyond testing rig bias, a major limitation of the laboratory drop testing methodology is that it is an axial loading case that only captures one potential mechanism in a seismic event.

The use of large-scale shear tests has provided useful data and improved understanding of the effect of shear loading on the performance of rock reinforcement (Stjern, 1995; Chen and Li, 2015; Li, 2016; Knox and Hadjigeorgiou [2023a and 2023b]). In these series of experiments the rockbolts are installed in concrete blocks, which are independently driven to generate the desired loading conditions. The inclusion of the concrete blocks into the testing configuration is an improved representation of the in-situ loading configuration due to the strength differential between the rock reinforcement element and the host rock.

Due to the composite loading resulting from the interaction between the host rock at the perimeter of the borehole, the anchoring medium and rock reinforcement element, it is accepted that the shear displacement at a joint in the rock mass will result in a combination of bending and tensile loading of the rockbolt. This is well demonstrated in a physical modelling experimental programme conducted by Moyo and Stacey (2012) to demonstrate the performance of rock reinforcement elements in blocky ground (Figure 4). Two other important considerations are highlighted in the image: the angle at which the rockbolt intersects the joint and the fact that the rockbolt intersects multiple joints. The reality of the loading cases may, however, be significantly more complex as illustrated in Figure 2.

Figure 4—Theoretical shear loading of rockbolts (Moyo & Stacey 2012)

Paddled energy-absorbing rockbolts

Paddled energy-absorbing rockbolts are widely used in underground mines as part of the ground support system when the anticipated rock mass failure will result in either squeezing or rockbursting. The base component of the rockbolt is the steel bar, into which one or more paddle sets and a threaded length are formed, as can be observed in Figure 5.

The 'free length' between the paddles sets or a paddle set, and the threaded portion is debonded from the anchoring medium (resin or cementitious grout) when a load is applied. The energy is dissipated through the plastic deformation of the steel bar between the paddle sets or threaded anchor bounding the joint or bulking rock mass. Therefore, when installed within a competent anchoring medium, the performance of the rockbolt is governed by the mechanical properties of the steel bar.

The installation procedure of a resin-anchored paddled energy-absorbing rockbolt is similar to that of a conventional resin rebar rockbolt, as illustrated in Figure 6. The resin cartridges are inserted into a pre-drilled borehole, and the rockbolt is subsequently inserted into the borehole. A rotation is applied to the rockbolt during the insertion process to facilitate the mixing of the resin by the paddle set. Thus, the purpose of the paddle set is twofold: mixing of the resin and anchoring of the tendon within the competent resin. Alternatively the rockbolt can be inserted into a borehole prefilled with cementitious grout.

Impact testing

Given that the original intent for the paddled rockbolt was to provide a high energy-absorbing rockbolt for seismically active conditions, it is not surprising that the focus was to undertake a series of impact tests to demonstrate and quantify its performance. In fact, it was often a prerequisite by several mining companies

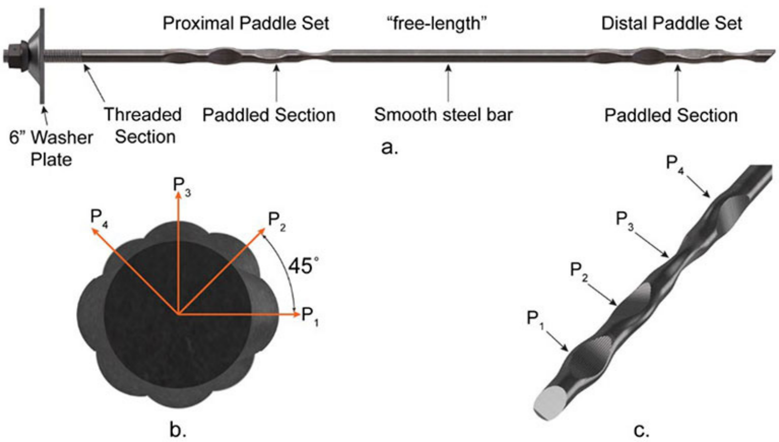

Figure 5—PAR1 bolt, an example of a paddled energy-absorbing rockbolt (Knox and Hadjigeorgiou, 2022)

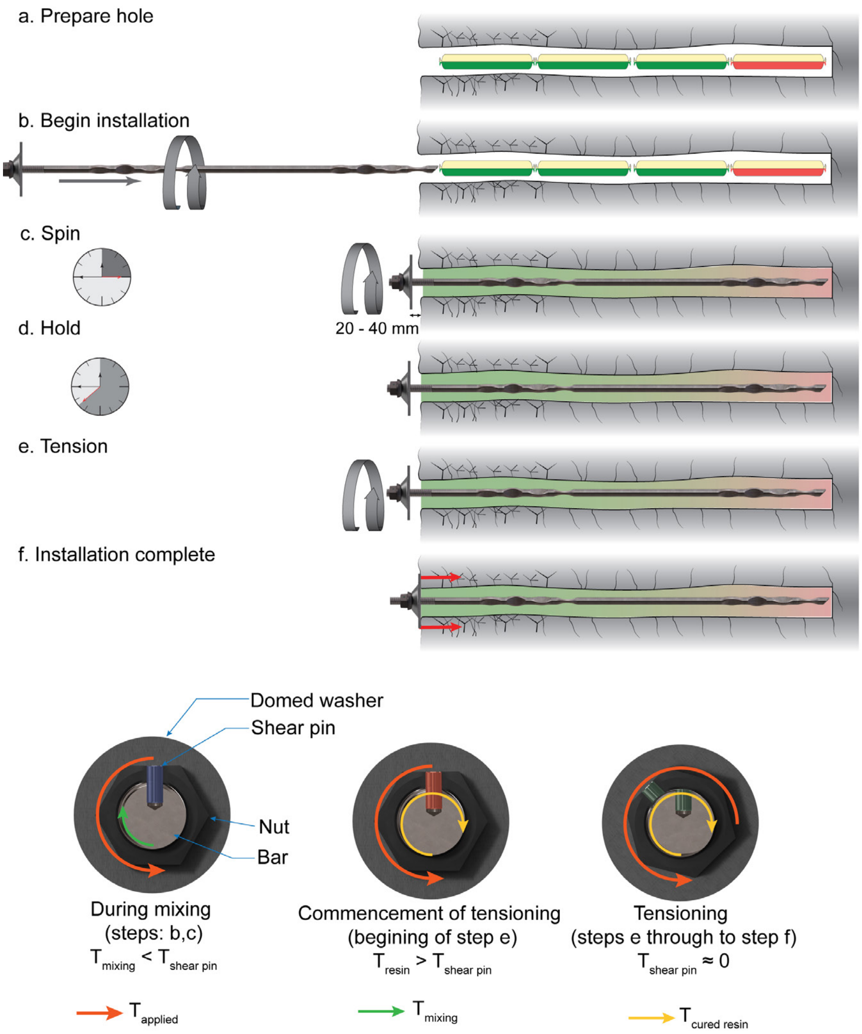

Figure 6—Installation procedure of a paddled energy-absorbing rockbolt (Knox & Hadjigeorgiou 2022)

that suppliers provide data on new rockbolts under impact loads. Examples of impact tests for rockbolts using the paddled energy-absorbing concept are provided by Li and Doucet (2012), Villaescusa et al. (2015); Bosman et al. (2018), and Knox et al. (2018).

Compilations of impact tests from multiple rigs, e.g., Potvin and Hadjigeorgiou (2020) and Villaescusa et al. (2015), clearly illustrate that paddled energy-absorbing rockbolts have greater energy-absorbing capacity than conventional rockbolts. It is now recognized, however, that there is a degree of bias in every impact testing rig, (Li et al., 2021) that may influence the results. Consequently, there are advantages in comparing the results obtained using the same rig and testing protocol.

Influence of testing configuration on the performance of paddled energy-absorbing rockbolts under impact loading

Typically, the dynamic energy capacity of a paddled energy-absorbing rockbolt is determined through an indirect impact split tube test or in combination with a direct impact continuous tube test. The continuous tube configuration simulates the situation when the impact load is directly applied onto the bolt plate, while the split-tube setup aims to reproduce a load on the bolt when a rock block is ejected by an impact thrust, (Li et al., 2021).

It was originally assumed that the performance of the rockbolts under axial impact loads would be uniform across a given free length. This was a reasonable assumption given a bolt design that facilitates the debonding or stretching of the bolt between the paddles.

Knox and Hadjigeorgiou (2022), used the Epiroc dynamic impact testing rig (DIT), illustrated in Figure 7, to conduct the only investigation into the effect of the testing configuration on the performance of the paddled energy-absorbing rockbolt. In this series of tests both the loading configuration (indirect vs direct) and the location of the split along the length of the paddled energy-absorbing rockbolt were allowed to vary. All rockbolt samples were prepared from a single batch of steel to limit variations in the mechanical properties of the steel. A total of five testing configurations were selected as shown in Figure 8, with variations of both the loading configuration and the split location. These represent different plausible loading configurations and load transfer mechanisms. The location of the rupture, total displacement at rupture, and energy dissipated at rupture were recorded following a series of 30 kJ drop tests.

The capacity of the paddled energy-absorbing rockbolt relative to the split location along the length of the rockbolt is illustrated in Figure 9. As anticipated, the direct impact continuous tube test (Figure 8a) loaded the shortest length of bar between the thread and the proximal paddle set, resulting in a significantly reduced capacity of the rockbolt. When the direct impact split tube test (Figure 8b) was used, it was anticipated that both the length of tendon between

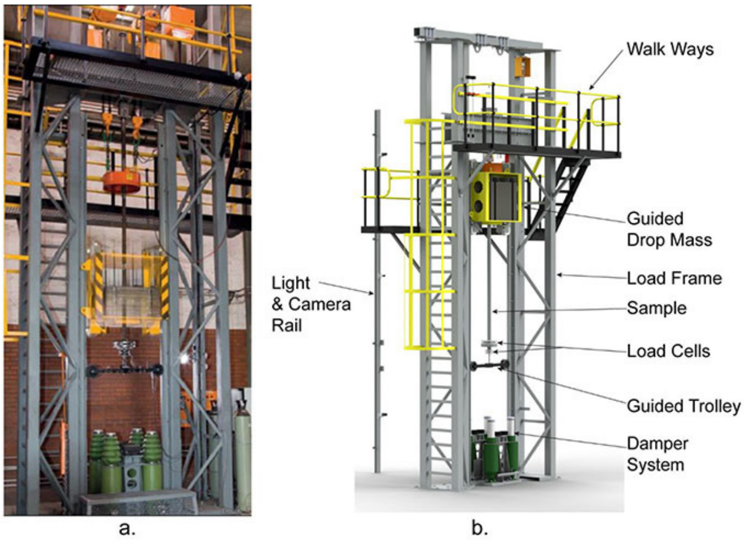

Figure 7—Epiroc dynamic impact tester (Knox and Hadjigeorgiou, 2022)

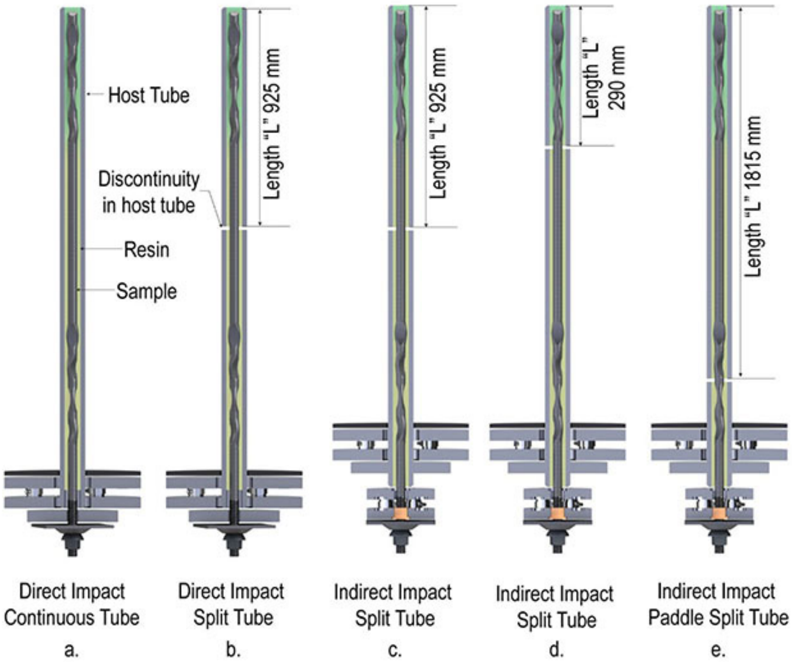

Figure 8—Paddled energy-absorbing rockbolt configurations for drop testing (Knox and Hadjigeorgiou 2022)

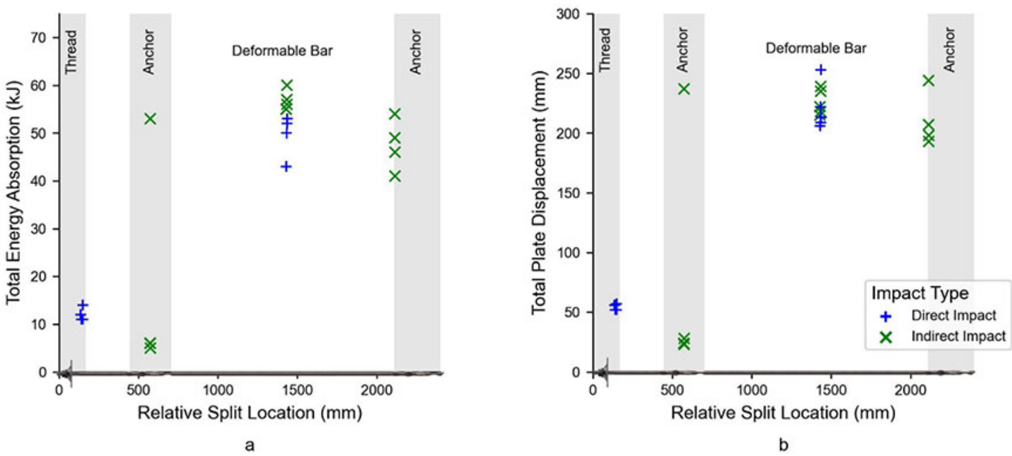

Figure 9—Capacity of the rockbolt relative to the location of the split along the length of the rockbolt: (a) total energy-absorption, (b) total plate displacement

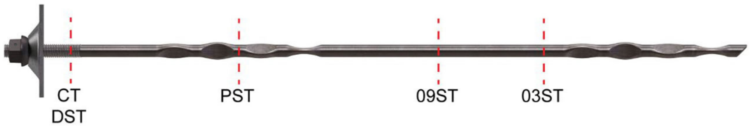

Figure 10—Typical rupture location of the rockbolt (Knox and Hadjigeorgiou 2022)

the thread and proximal paddle set and between the paddle sets would be mobilized, resulting in a higher impact capacity. However, as illustrated by the typical rupture location in Figure 10, during direct impact loading the load transfer mechanism is through the thread which has a lower capacity than the unmodified tendon. Consequently, due to the reduced capacity of the thread, it ruptures prior to the dissipation of the full plastic potential of the length between the two paddle sets. Thus, the capacity recorded when subjecting the rockbolt to a direct impact split tube test was less than the indirect impact split tube test (Figure 8a).

When the split was located within the paddle set (Figure 8e) a significant decrease in the capacity resulting from the reduced 'free length' of steel mobilized was recorded. Of interest was the effect of relocating the split: from the centre to the periphery of the deformable length between the two anchor points (Figure 8c, d). A decrease in the capacity was recorded (8.5%) when comparing the typical indirect impact split tube performance with the split centrally located (Figure 8c), to an indirect impact split tube test, which could be considered to be a short encapsulation impact test, as the split was located at the proximal end of the distal anchor set (Figure 8d). For both configurations the typical rupture locations observed was at the split location, with a length of tendon protruding from both segments as illustrated in Figure 11.

From the work presented by Knox and Hadjigeorgiou (2022), it can be concluded that the capacity of a paddled energy-absorbing rockbolt can vary significantly along the length of the rockbolt. A 90% variation in the capacity of the rockbolt was observed when the split location was changed as indicated in Figure 9 (a). The practical implication of these results is that 'typical' design values obtained from impact tests with the split located at the centre between two paddle anchor points at best provide an upper limit value. This inherent variability in performance under different testing configurations should be acknowledged and taken into consideration in the design of ground support in seismic conditions. The observed variation in performance as a function of split location can provide a plausible explanation for variations in field performance of paddled energy-absorbing rockbolts in rockburst events.

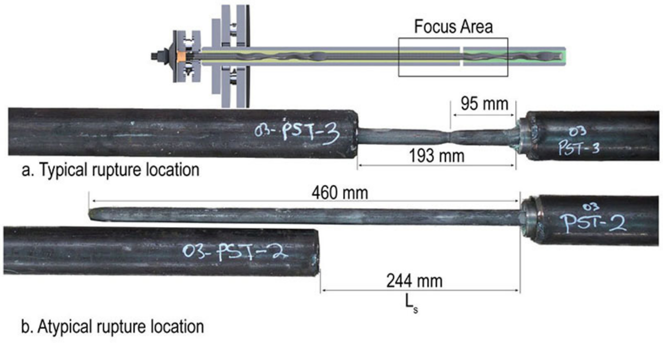

Figure 11—Typical and atypical rupture locations observed (Knox and Hadjigeorgiou, 2022)

Quasi-static tests

The advantages of conducting loading tests on rockbolts in a controlled environment are well recognized. Although there is some value in small-scale laboratory tests using a segment of a bolt, the reality is that these may not be appropriate for modified geometry such as paddled rockbolts. Arguably, the use of large-scale testing using concrete blocks is more labour-intensive, however, it can provide a more consistent testing environment as demonstrated by Stjern (1995). The investigation into the shear performance of rockbolts by Stjern (1995) was, for a long time, the most significant data on the performance of rock reinforcement elements under controlled large-scale conditions. However, it was limited to axial and shear loading applications and did not consider energy-absorbing rockbolts. At the time of that work the paddled energy-absorbing rockbolt had not been developed. Even now there are limited data sets on the performance of paddled energy-absorbing rockbolts.

Influence of loading angle in quasi-static tests

Although it is recognized that a variation in the loading angle can have a significant impact on the behaviour of rockbolts, there are limited test results of full-scale bolts under combined pull and shear loads. Chen and Li (2015) compared the performance of full encapsulated cement grouted rebar and paddle bolt under combined pull and shear loads.

Chen and Li (2015) investigated the capacity of a paddled energy-absorbing rockbolt - in this case a D-bolt, under five loading angles relative to the axis of the rockbolt (0°, 20°,40°,60°,90°), with the position of the joint located at approximately the centre of a 1.0 m free length bounded by two anchor points. The investigation was conducted using the SINTEF rockbolt pull tester, with the simulated joint being the interface between two approximately 110 MPa concrete blocks. Due to the physical constraints of the equipment, the rockbolts were 2.0 m in length. Two samples were tested for a range of loading angles.

The recorded load displacement response of each sample is shown in Figure 12. A general trend of decreasing displacement

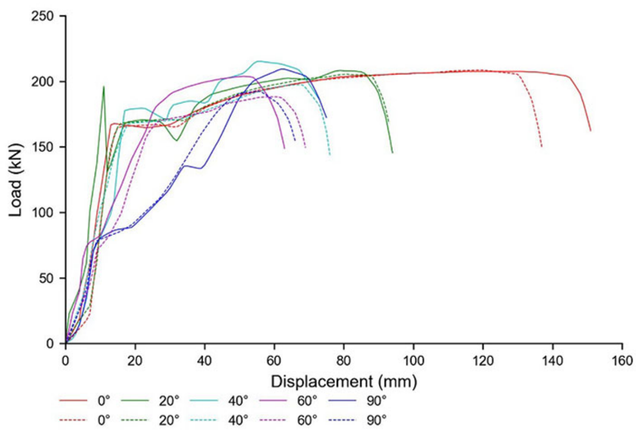

Figure 12—Combination loading performance of 2.0 m paddled energy-absorbing rockbolt (Chen and Li, 2015)

capacity is observed. For comparison purposes, the ultimate load and displacement at ultimate load were selected as the metrics to define the capacity of the paddled energy-absorbing rockbolt. This is consistent with the approach adopted by Stjern (1995). The average ultimate load and displacement at ultimate load for each loading angle are compared in Figure 13. A decrease in both the load and the displacement capacity with the increase in the loading angle is observed. A maximum reduction of 62 mm (54%) in displacement and 12 kN (6%) in load capacity were recorded at a loading angle of 60°.

From the investigation conducted by Chen and Li (2015), it can be concluded that the loading angle has a significant impact on the performance of a paddled energy-absorbing rockbolt.

Combination loading: experimental programme

The work of Chen and Li (2015) provides insight into the performance of a cement grouted paddled energy-absorbing rockbolt when subjected to a range of loading angles. Given that this was only one set of results, it was important to explore the reproducibility and limitations of these results in an independent set of tests for a paddled energy-absorbing rockbolt.

A similar experimental programme was conducted using an equivalent testing machine: the Epiroc combination shear and tensile (CST) rockbolt pull tester to investigate the performance of the PAR1 bolt (Epiroc, 2024), a paddled energy-absorbing rockbolt produced and distributed by Epiroc (Epiroc, 2024).

This was the same type of rockbolt selected for the investigation into the influence of the testing configuration on the performance of a paddled energy-absorbing rockbolt (Knox and Hadjigeorgiou, 2022). The PAR1 bolts used in the combination loading investigation were not sourced from the same batch of bolts as for the dynamic investigation, hence minor variations in the mechanical properties were present but these were not significant. The geometric properties of bar diameter (Ø20 mm), rockbolt length (2.4 m), and paddle set configurations are comparable between the two rockbolts. Figure 14 illustrates the position of the anchor points (thread and paddles sets), length of the rockbolt and length between paddle sets.

Combination shear and tensile testing

The Epiroc CST rockbolt pull tester is based on the SINTEF rockbolt pull tester (Stjern, 1995). The CST was developed with improvements to the hydraulic control system and a capacity

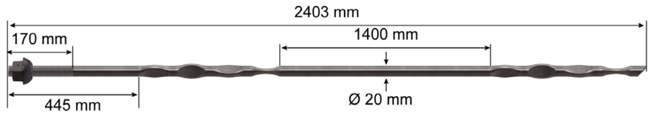

Figure 14—Illustration of the position of geometric features on the PAR1 bolt

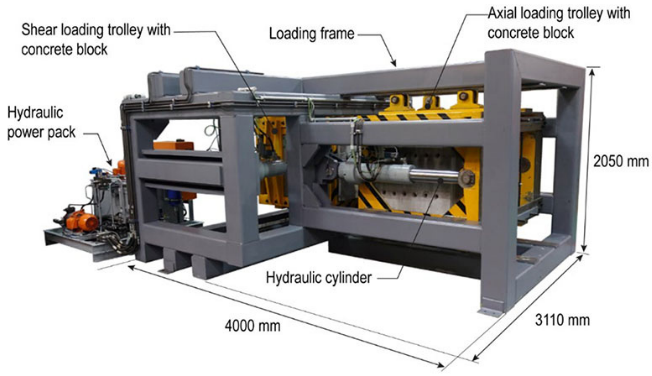

Figure 15—Layout of the Epiroc combination shear and tensile pull tester (Knox and Hadjigeorgiou 2023 b)

to accommodate rockbolts of up to 2.4 m in length (Knox and Hadjigeorgiou, 2023 a). This was achieved by increasing the dimensions of the load trollies and the concrete blocks through which the rockbolt is installed. The primary components of the machine are illustrated in Figure 15. The two loading trollies (shear and axial) are driven by two independently controlled hydraulic cylinders to achieve a desired displacement or load vector at the joint between the two concrete blocks. The displacement is monitored via linear variable displacement transducers located internally to the hydraulic cylinders and strategically placed on the interfaces between the components of the loading train to account for relative movements. The reactive force was generated by the test specimen in response to the applied displacement record using four load cells located at the interface between the hydraulic cylinders and the loading frame.

The preparation of the concrete blocks that followed the procedure is described in detail by Knox and Hadjigeorgiou (2023 a). After a curing period of 28 days, boreholes drilled with a Ø36 mm knock-off bit were prepared prior to the installation of the concrete blocks into the loading frame. The pre-drilled boreholes are aligned, and each sample of Ø20 mm 2.4 m rockbolt was individually installed through the two concrete blocks.

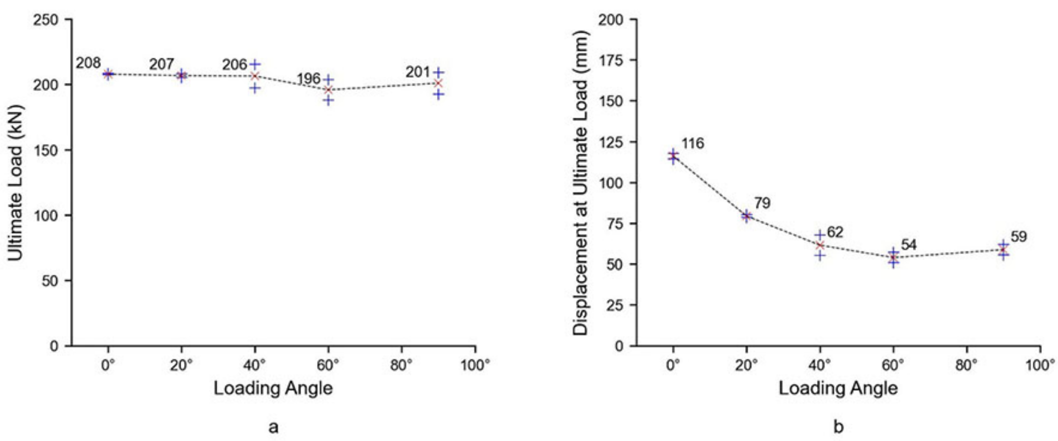

Figure 13—Summary of result (Chen and Li 2015): (a) ultimate load vs loading angle, (b) displacement at ultimate load vs loading angle

The rockbolt was subjected to one of the loading configurations illustrated in Figure 16: axial (0°) (Figure 16a), combination (30°, 60°, Figure 16b) or shear (90°, Figure 16c). The loading angle is referenced relative from the axis of the borehole as illustrated in Figure 16 d, with the constant displacement rates of the axial and shear trollies being configured to achieve a resultant displacement rate of 0.5 mm/s for all loading configurations.

Combination shear and tensile testing results

Batches of three samples of the Ø20 mm, 2.4 m PAR1 paddled energy-absorbing rockbolts were tested at each loading configuration. The load displacement responses for each loading angle are presented in Figure 17; a high degree of consistency in the response of the rockbolt is observed at each loading angle. The comparison between the ultimate load and displacement at ultimate load is presented in Figure 18. A trend of reducing load and displacement capacity is observed as the loading angle increases.

Paddled energy-absorbing rockbolt performance considerations

A paddled energy-absorbing rockbolt dissipates energy through the plastic deformation of steel. Thus, the mechanical properties of the steel, diameter of the bar and length of bar mobilized directly affect the capacity of the rockbolt. A key consideration is illustrated in the comparison between the axial loading case of the work of Chen and Li (2015) and the results presented in this paper. In the work of Chen and Li (2015), the mobilized length of steel was 1.0 m resulting in a displacement at ultimate load capacity of 116 mm (11.6 % strain). The mobilized length of steel for the work presented in this paper was 1.4 m, with a displacement at ultimate load capacity of 143 mm (10.2% strain). Consequently, the increase in mobilized length resulted in an increase in capacity. Thus, the position of the anchor points distributed along the length of the paddled energy-absorbing rockbolt (thus the potential free length of bar) should be considered when comparing the performance.

Due to the difference in mechanical properties and length of the steel between the anchor points, a relative load and relative displacement is used to compare the response of the paddled energy-absorbing rockbolt recorded by Chen and Li (2015) and the investigation presented in the paper. The relative capacity for a given loading angle is determined by normalizing the average capacity by the capacity of the rockbolt during axial (0°) loading. The relative capacity comparison between the two datasets is plotted in Figure 19.

Based on the two datasets, a trend of decreasing capacity with an increase in loading angle is observed. A minor decrease (<10%) in the load capacity is observed in the performance of the load capacity, owing to the composite loading mechanism. The shear capacity of the installed rockbolt is higher than the theoretical shear capacity of the rockbolt (50 – 60%). The failure of the chemical medium and host material at the joint, prior to the rupture of the rockbolt resulted in bending of the rockbolt allowing the bar to align with the direction of the loading. This results in a rupture, which is predominately tensile at a local scale. Both datasets recorded a change in ultimate load capacity of less than 1% at a loading angle of less than 40°. Differences were observed at 60° and 90°, with the greatest reduction (6%) in ultimate load recorded at 60° for the work presented by Chen and Li (2015). However the greatest reduction (9%) in load was recorded at a loading angle of 90°, i.e., pure shear, in this investigation.

The trend of the reduction in relative displacement observed in Figure 19 is also consistent between the two datasets, with much of the reduction (≈ 50%) in the displacement capacity resulting from the change of loading angle between axial (0°) and 40°. From 40° up to shear (90°) loading, the further reduction in displacement capacity recorded was less than 10% of the displacement capacity of the axially-loading rockbolt. Of interest is the similarity in shear (90°) displacement capacity recorded in both datasets. The length

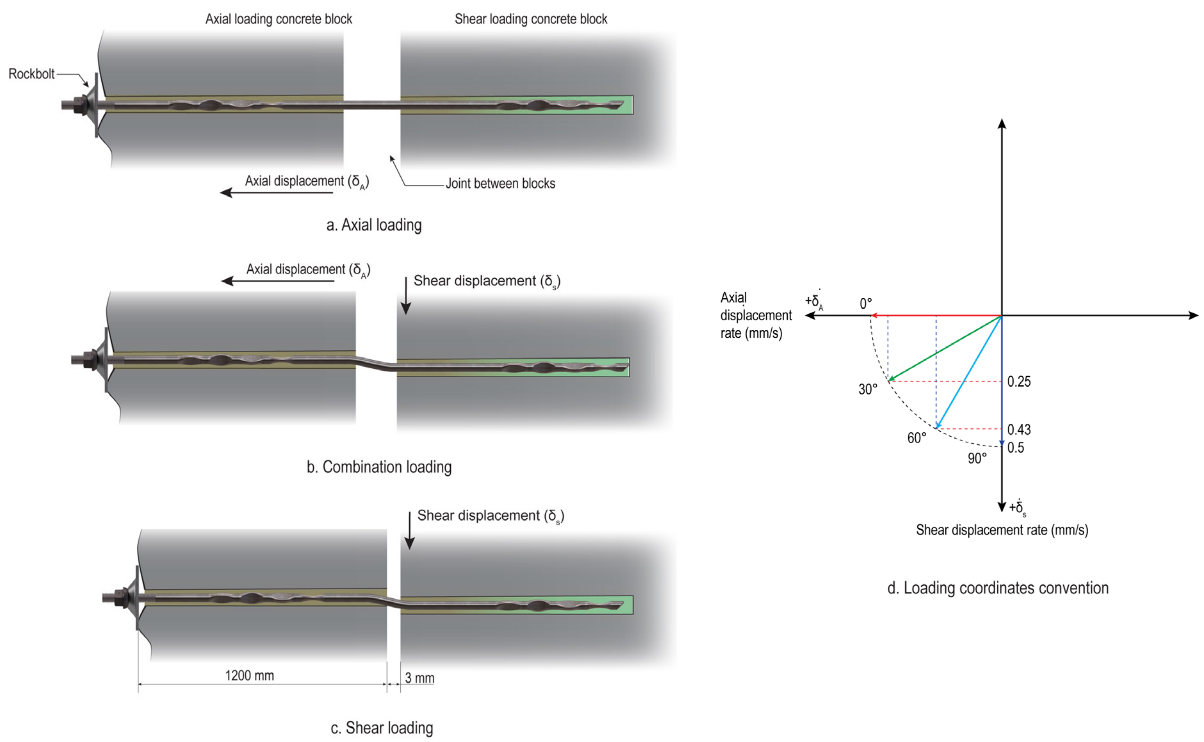

Figure 16—Illustration of loading cases: (a) tensile loading (0°), (b) combination loading (30°, 60°), (c) shear loading (90°), (d) the loading coordinates convention

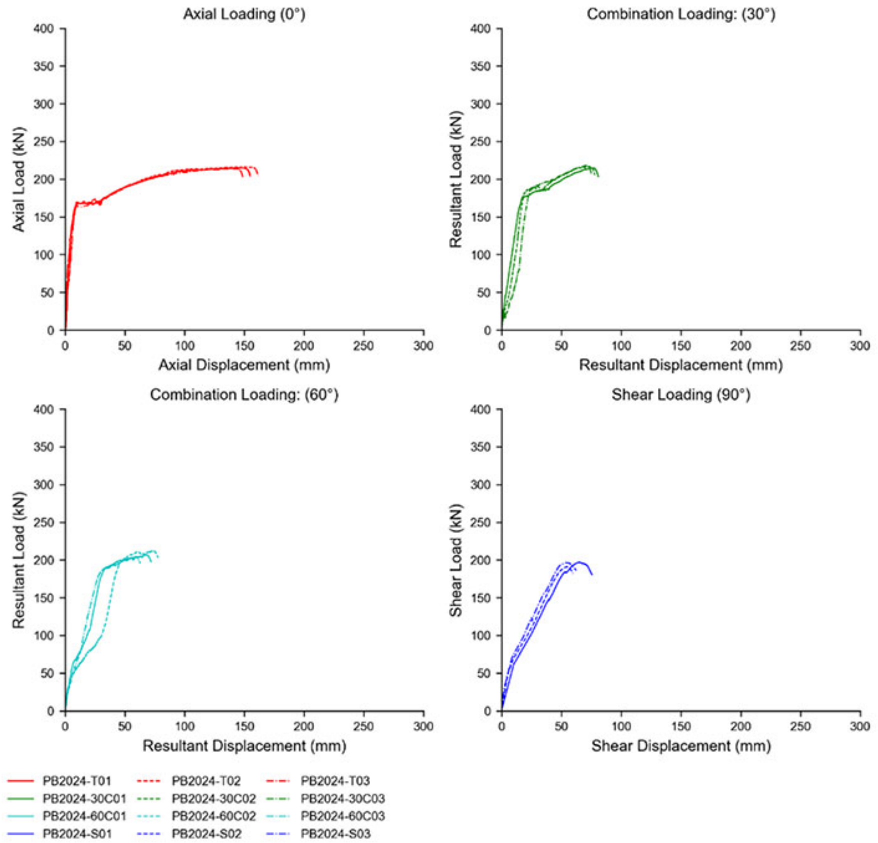

Figure 17—Combination load-displacement response for a Ø20 mm 2.4 m paddled energy-absorbing rockbolt

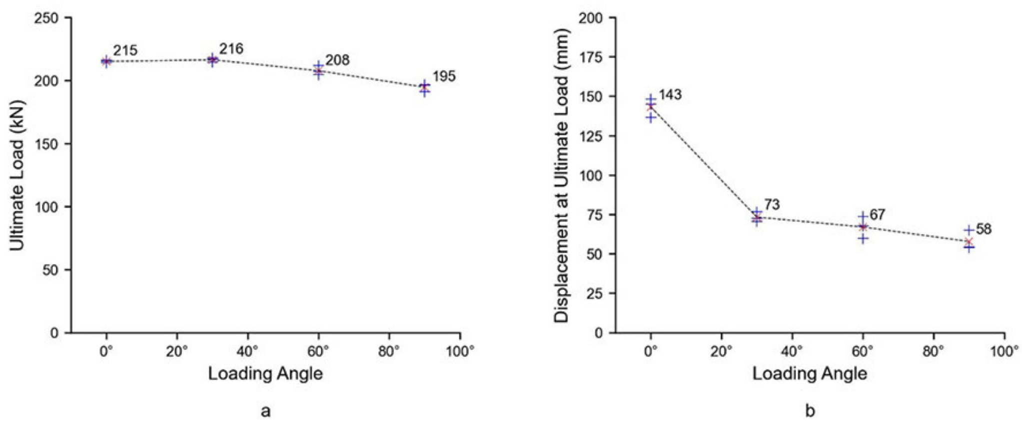

Figure 18—Summary of paddled energy-absorbing rockbolt results. (a) Ultimate load vs loading angle, (b) displacement at ultimate load vs loading angle

of smooth bar between the two anchor points varied 1.0 m (Chen and Li, 2015) and 1.4 m, thus resulting in a difference of 27 mm of average axial (0°) displacement capacity between the two data sets due to the increase in the mobilized length of steel. However, the difference in average shear (90°) displacement capacity recorded was 1 mm, suggesting that the shear capacity of a rockbolt is independent of the length of the rockbolt. The change in response of the paddled energy-absorbing rockbolt may be due to the induced bending, resulting from failure of the chemical anchor and host material at the shear interface, negating the debonding effect of the smooth bar from which the rockbolt is produced. Thus, if shear was to occur at multiple joints positioned sufficiently apart along a length between two anchor points, the joints would be loaded independently.

The influence of the loading configuration on the performance of a paddled energy-absorbing rockbolt was previously quantified by Knox and Hadjigeorgiou (2022). The investigation was conducted using the drop test methodology with the location of a joint intersected by the rockbolt. The purpose of the investigation of the joint was simulated by a discontinuity 'split' in the host tube. The two loading configurations (direct and indirect) were used in combination with the varied split location. The investigation demonstrated the following:

- ➤ The position of the split can affect the capacity of a paddled energy-absorbing rockbolt by up to 90%
- ➤ The position of the split within the length between two anchor points may affect the capacity of a paddled energy-absorbing rockbolt

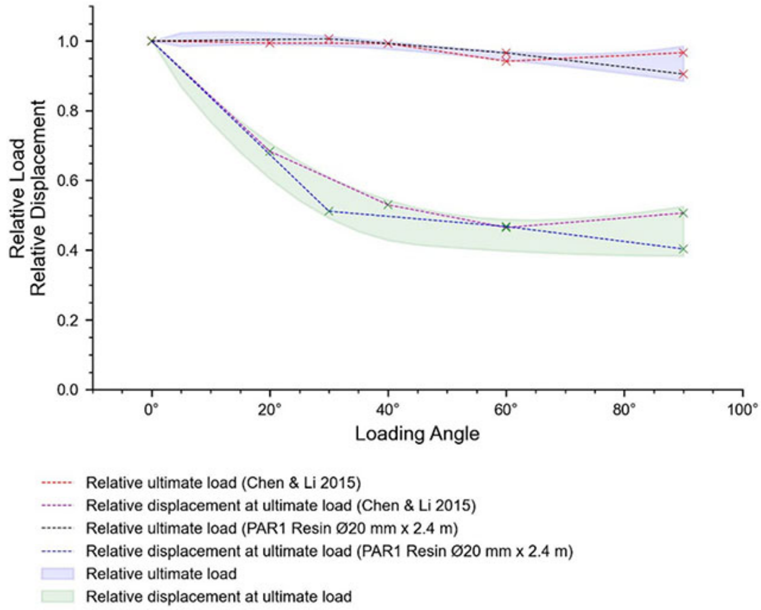

Figure 19—Relative load and displacement comparison

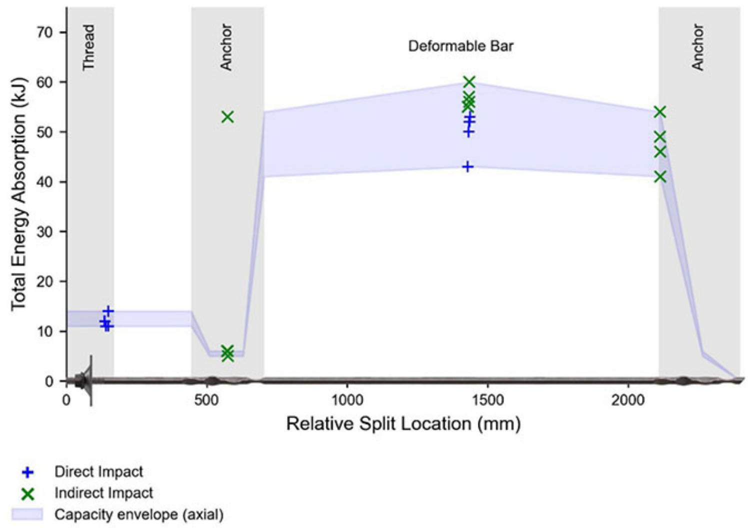

Figure 20—Influence of test configuration on the performance of a paddled energy-absorbing rockbolt

➤ The loading configuration (direct vs indirect) can affect the capacity of a paddled energy-absorbing rockbolt independent of the split location.

Based on the above observations and the data presented by Knox and Hadjigeorgiou (2022), a performance capacity envelope was developed and is illustrated in Figure 20. A linear relationship between the paddle sets was assumed.

The investigations into the effect of the loading angle on the capacity of a paddled energy-absorbing rockbolt by both Chen and Li (2015), and the investigation presented in this paper were conducted at a quasi-static loading rate, with the laboratory investigation into the influence of the testing configuration conducted through impact loading, thus at higher strain rates. Consequently, the effect of the loading rate on the result should be taken into account. It is arguable that a rockbolt will be subjected to a combination loading case during a seismic event and the possible resulting rockburst. Based on the data presented it should be taken into consideration that an anticipated combination of loading cases at higher strain rates would result in a reduction of displacement capacity.

Conclusion

It is widely accepted within the mining industry that the implementation a of yielding rock reinforcement system is a best practice when the anticipated rock mass failure mode will result in either squeezing or rockbursting. The proliferation of the use of paddled energy-absorbing rockbolts evolved based on the results of laboratory testing and field observations. In addition, the similarities in the installation procedure between rebar rockbolts and the paddled energy-absorbing rockbolt reduced the implementation complexity, as no training or equipment modification is required to facilitate incorporation into the ground support standard of a mine site installing rebar bolts.

This paper reviewed recent investigations to further understand the behaviour of paddled energy-absorbing rockbolts under complex loading mechanisms. This is necessary to provide an explanation of variations in field performance observations. Typically, two impact testing configurations exist: The direct impact continuous tube test and the indirect impact split tube test, with the split for the indirect impact test located centrally between two anchor points. However, both the position of the split and the configuration of the split locations have been demonstrated to have a significant effect (up to 90% variance) on the capacity of a paddled energy-absorbing rockbolt. Similarly, through two investigations conducted at quasi-static loading rates, the loading angle has been demonstrated to have a significant effect on the displacement capacity (up to 60% reduction) of a paddled energy-absorbing rockbolt when comparing the axial and shear capacity.

Due to the variances in the capacity observed through the variance of the testing configuration – loading mechanism, direction of loading, location/presence of a discontinuity – it must be concluded that the capacity of a rockbolt determined though laboratory-based testing is not independent of the testing configuration. When designing a ground support system as a geotechnical practitioner, careful consideration should be given to the applicability of a laboratory-based test with respect to the anticipated in situ loading to which the rockbolt will be subjected.

It is important to recognize that extrapolating from the laboratory conditions requires that the field installation is up to standard and that there is a good load transfer so that the rockbolt can attain its capacity. This necessitates the use of best QA/QC installation practice and compatibility between the surface support.

Acknowledgements

The authors acknowledge Epiroc for providing access to the testing facility, and the PAR1 bolts used in this testing campaign. The contribution of Lwazi Pambuka and his team in operating the testing facility is gratefully acknowledged, as is the support of the Natural Science Engineering Council of Canada.

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