Rockbolts in shear

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Abstract

There is a considerable wealth of information on the behaviour of rockbolts under axial loading conditions both in situ and under controlled laboratory conditions. However, there is comparably less data on the behaviour of rockbolts in shear. Several authors have contributed to the understanding of the behaviour of conventional rockbolts' performance under shear loading. Much of this data have been gathered through experimental programmes conducted on sections of the rockbolt. Considering the continuous coupling between the rockbolt and borehole interface, the approach is justified. Due to the design premise of energy-absorbing rockbolts with discrete couplings, full scale testing is required to quantify the behaviour of the rockbolts.

This paper reviews published results obtained from two testing facilities, which are the SINTEF rockbolt pull test rig in Trondheim, Norway and the Epiroc Combinations Shear and Tensile test rig in Johannesburg, South Africa, both capable of conducting full scale testing of rockbolts. Based on this high-quality database it was possible to identify three distinct responses of rockbolts in shear. The behaviour under load is controlled by the presence or absence of an encapsulation medium (resin/cement grout), the reinforcement mechanism, and whether the rockbolt is continuously or discretely captured. As a reference the results are compared to the performance in shear of conventional grouted rockbolts.

Keywords

rockbolts, shear loading, conventional fully encapsulated, energy-absorbing, full scale laboratory testing

Introduction

Ground support is routinely used to maintain the integrity of underground excavations in rock for both mining and civil engineering applications. These include providing access to an ore deposit (mining), developing transportation routes, or storage caverns (civil). The design of an effective ground control system considers both the local ground conditions and anticipated loading conditions. In addition, it is important to ensure the compatibility between different ground support elements and aerial coverage. Recognising that there are multiple ground support options, it is convenient to design for "normal" and "challenging or extreme" ground conditions (Hadjigeorgiou, 2023).

From a design perspective it is important to quantify the capacity and demand of ground support elements both as units and as a system. The focus of this paper is on improving our understanding of the load, deformation, and energy capacity of rockbolts subjected to shear loading. In this context the location, direction, and rate of loading are considered as controlled variables.

Early work in trying to understand the behaviour of reinforcement was based on small scale experimental programmes conducted on sections of a reinforcement element (Bjurstrom, 1974; Haas, 1976; Dight, 1982; Ludvig, 1984; Spang, Egger, 1990; Ferrero, 1995; Grasselli, 2005; Jalalifar, Aziz, 2010; Li et al., 2016). Arguably, this approach can be justified for most conventional rockbolts due to the continuous coupling between the rockbolt, chemical anchor, and borehole. In the case of energy-absorbing rockbolts, used in extreme ground conditions, this is clearly inappropriate and any results from small scale partial tests can be misleading. Under these conditions a full-scale test is more appropriate due to the discrete coupling and relationship between the length of the rockbolt and its performance capacity.

Currently, there are two testing facilities, which have the capacity to conduct full scale testing of a rockbolt, that being the SINTEF rockbolt pull tester in Trondheim, Norway (Stjern, 1995) and the Epiroc Combination Shear and Tensile Tester in Johannesburg, South Africa (Knox, Hadjigeorgiou,

2022). Several contributions have been made to demonstrate the effect of both conventional and energy-absorbing rockbolts to shear loading (Stjern, 1995; Chen, Li, 2015a; Hagan et al., 2019; Knox, Hadjigeorgiou, 2022, 2023, 2024a, 2024b; Kouhia et al., 2024).

Li et al. (2014) compared the behaviour of several conventional rockbolts under shear loading. Most of the data, however, were from a single source, the experimental programme conducted by Stjern (1995). Consequently, the shear behaviour of most energy-absorbing rockbolts was not included due to the limited applications at the time of the experimental programme by Stjern (1995).

This paper presents a review of five rockbolt types, comparing the shear and tensile performance using the single shear method. Within the selected five rockbolt types two anchoring methods are represented. Three distinct rockbolt responses were identified within the sample set, providing insight into the behaviour of the rockbolts under shear loading conditions.

Rockbolts in shear

There are several examples where rockbolts are subjected to a combination of shear and tensile loading at multiple points along the length of the rockbolt both under static and dynamic loading, as illustrated in Figure 1. The observed mode of failure highlights the interaction between the rockbolt and the rock mass, resulting in bending of the rockbolt prior to rupture. This phenomenon is difficult to capture in laboratory tests without careful consideration of the boundary conditions (host medium in which the rockbolt is installed).

The interaction between the rock mass and anchoring medium can result in a complex loading mechanism, as per Figure 2. Due to the difference in the mechanical properties of the steel and grout, the shear displacement will result in localised crushing of the anchor medium and rock mass at the collar of the borehole at

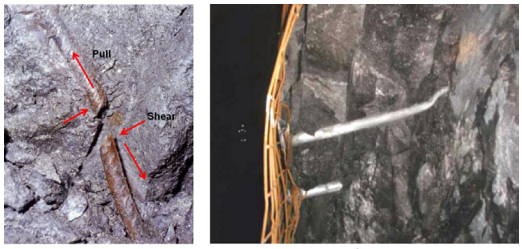

Figure 1—Examples of shear loading of rockbolts. a) conventional rebar rockbolt (Li, 2010), b) bulking of an excavation side wall leading to shearing of the rockbolts, a Ø46 mm friction rock stabiliser (Yao et al. 2014)

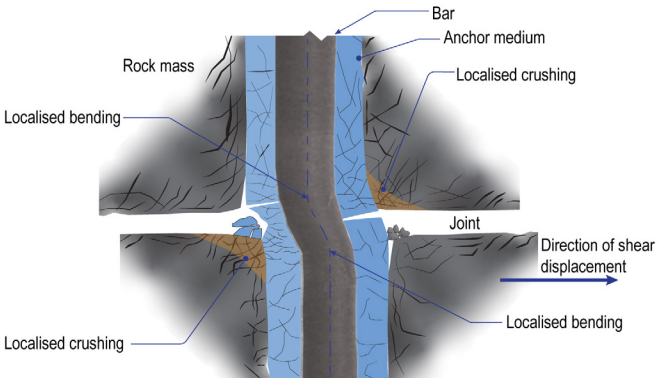

Figure 2— Illustration of the conceptual shear loading mechanism present when loading a rockbolt

the joint (shear interface). A consequence of the localised crushing is that the rockbolt bends, thus aligning the axial of the rockbolt towards the direction of the displacement and resultant loading. The bending of the rockbolt serves to isolate the section of the bar, which is loaded, resulting in the rupture of the bar at the shear interface. This phenomenon was demonstrated in the results presented by Chen and Li (2015b) where strain gauges applied to the rockbolt demonstrated a localised strain concentration of the bar.

The shear loading of rockbolts is often present in field applications. Consequently, it is necessary that laboratory tests replicate the composite loading mechanism for the results to be able to predict the in situ performance of rockbolts.

Laboratory shear loading of rockbolts

The objective of a laboratory testing campaign is to quantify the load and deformation capacity of a rockbolt. Careful consideration of the boundary conditions is required to represent the composite loading witnessed in situ. Axial laboratory load testing of rockbolts is typically conducted in either a steel host tube (chemically anchored rockbolts) or a borehole drilled into concrete core cast within a steel host tube (friction and/or mechanically anchored rockbolts); selection of the configuration is dependent on the anchor mechanism (Li, 2010; Li, 2012; Player, 2012; Bierman et al., 2019). A number of shear loading investigations have been conducted on rockbolts installed within steel host tubes (Ayres, Gardner, 2014; Dube,1995; Punkkinen, Royer, 2022). An alternative method is the method adopted by Stjern (1995), Chen and Li (2015a, 2015b), and Knox and Hadjigeorgiou (2022, 2023, 2024a, 2024b), whereby a rockbolt is installed within two concrete blocks located in a loading frame. The two testing methods were compared by Hagen et al. (2019), demonstrating that the displacement shear capacity of a rockbolt determined within a steel tube is lower than when determined by loading a rockbolt within a concrete block. The effect of the strength of the concrete block/host material was demonstrated by Spang and Egger (1990), with the results within concrete and granite being comparable. Additional displacement was recorded when the rockbolts were installed within sandstone, demonstrating the effect of the host material properties on the rockbolt performance.

There are currently two methods of conducting a shear test within concrete blocks to simulate the boundary conditions, the single shear (Haas, 1976; Spang, Egger, 1990; McHugh, Signer, 1999; Stjern, 1995) or the double shear method (Aziz et al., 2003; Grasselli, 2005). Both techniques are illustrated in Figure 4. It

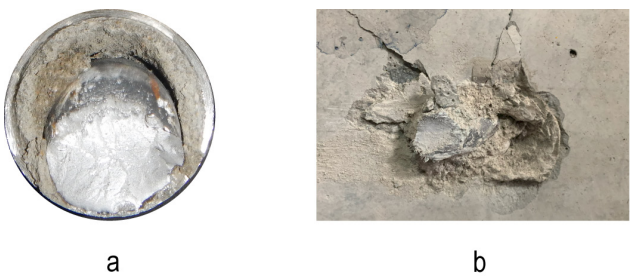

Figure 3—Comparison between the rupture interface of two of the shear loading methods. a) Within a steel host tube, b) installed within a concrete block (images curtesy of Epiroc)

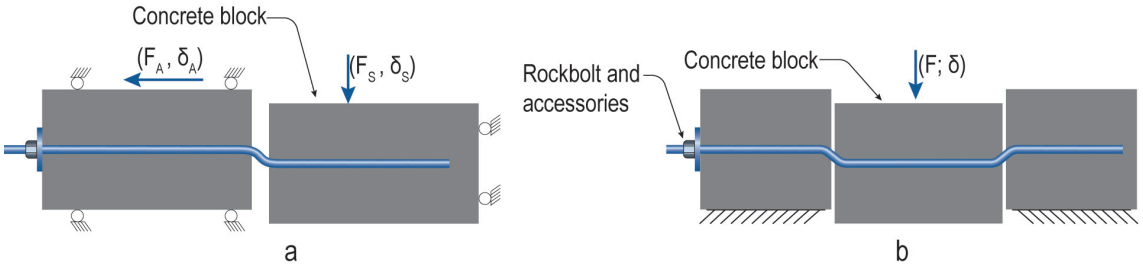

Figure 4—Laboratory-based rockbolt shear loading mechanisms: a) single shear loading, b) double shear loading

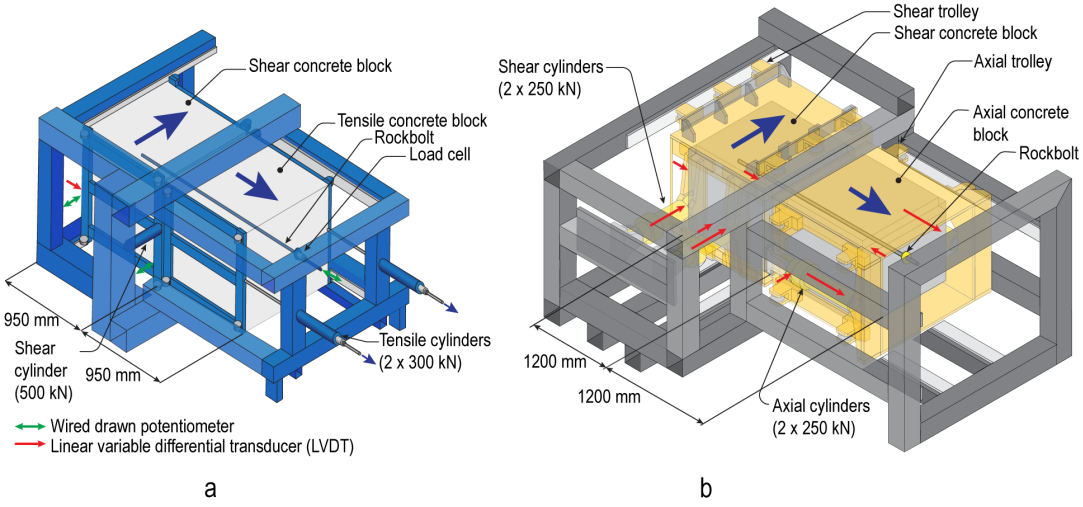

Figure 5—Laboratory testing equipment for conducting full scale shear and tensile testing. a) The SINTEF rig based in Trondheim, Norway (Stjern, 1995), b) the Epiroc Combination Shear and Tensile Tester, Johannesburg, South Africa

should be noted that when the double shear methodology is applied, the applied force is halved to determine the capacity of the loaded element.

To date the double shear method has been used to test sections of conventional rock reinforcement elements: cable bolts, fibre glass reinforced, and rebar rockbolts (Dube, 1995; Aziz et al., 2003; Grasselli, 2005; Li et al., 2016). Due to the continuous coupling between the rockbolt and the anchoring medium, this method can provide representative results for conventional rockbolts. Energy-absorbing rockbolts are discretely coupled along the length of the rockbolt, consequently, testing sections of the rockbolt does not represent the capacity of the rockbolt. Two test rigs have been developed, which can apply shear loads to full scale samples, the SINTEF rockbolt pull test rig and the Epiroc Combination Shear and Tensile (CST) test rig. The two rigs are similar in construction as the latter was developed using the same design premise with improvements to the hydraulic control system and increasing the scale to test 2.4 m long rock reinforcement elements.

The concrete blocks are prepared in moulds prior to installation in the test rig. The boreholes are then drilled into the concrete blocks, which are subsequently installed in the testing rig. A rockbolt is then installed into the borehole, with the interface between the two concrete blocks simulating a joint within the rock mass. When loaded in tension, the load is applied by the two tensile cylinders and the displacement rate is controlled. Prior to applying a shear load to an installed rockbolt, a tensile load is applied to result in a joint separation of 3 mm. This mitigates the potential for a frictional resistance between the two blocks.

Data sources

The review of the shear performance of the rockbolts was conducted on previously published results. Five different types of rockbolt were selected for comparison. Conventional rockbolts, energy-absorbing rockbolts, solid bar rockbolts, hollow bar rockbolts, and hybrid rockbolts are all represented within the dataset. All results considered were from full scale rockbolt tests conducted in approximately 100 MPa concrete blocks employing the single shear method using either the SINTEF rockbolt pull test rig or the Epiroc Combination Shear and Tensile test rig. The final criteria were that the presented result should include both a tensile and shear load and displacement curve, which were to be included in the dataset.

The dataset comprised of two conventional and three energy-absorbing rockbolts. The two conventional rockbolt bolts were the self-drilling rockbolt and the rebar rockbolt, illustrated in Figure 6. It should be noted that the results obtained for the SINTEF rig were for 1.8 m long rockbolts while the results obtained from the Epiroc rig were for rockbolt that were 2.4 m in length. The self-drilling rockbolt results included the R25 produced from a ductile material (Kouhia et al., 2024) tested by using the SINTEF rig, and an R28 self-drilling rockbolt (Knox, Hadjigeorgiou, 2023) tested by using the Epiroc rig. As for the rebar rockbolts (Chen, Li, 2015; Knox, 2022) both were Ø20 mm in diameter and sourced from the same grade of steel. This allowed for a direct comparison between the two testing rigs.

Figure 7 illustrates the paddled energy-absorbing rockbolts, a yielding mechanical hybrid rockbolt and an energy-absorbing self-drilling rockbolt. Two datasets for the paddled energy-absorbing

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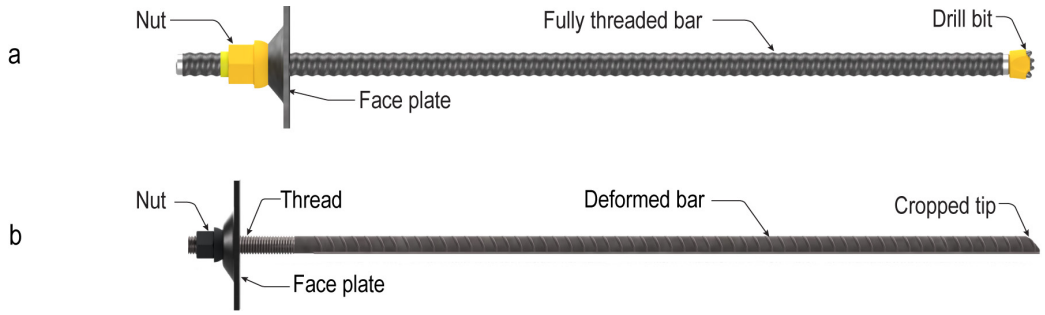

Figure 6—The two conventional rockbolts selected for the experimental programme. a) Self-drilling rockbolt, a hollow fully threaded bar, b) rebar rockbolt, a solid ribbed bar

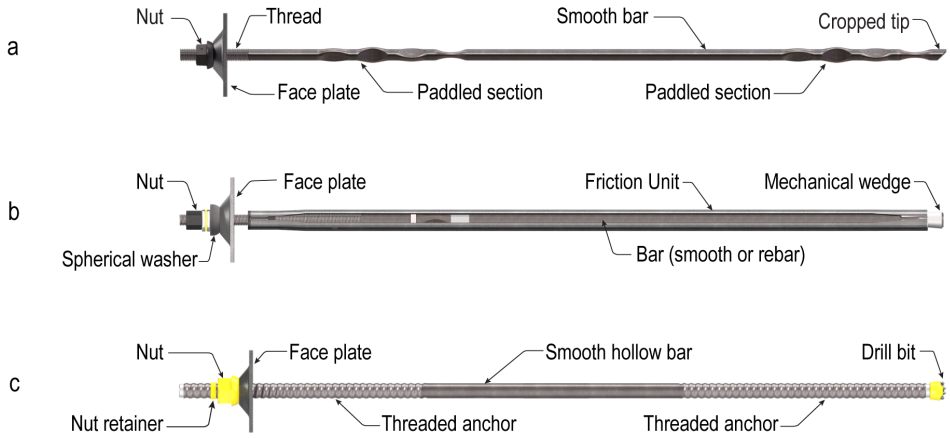

Figure 7— Three types of energy-absorbing rockbolt, which dissipate energy through the plastic deformation of the tendon. a) Paddled energy-absorbing rockbolt, b) yielding mechanical hybrid rockbolt, c) energy-absorbing self-drilling rockbolt

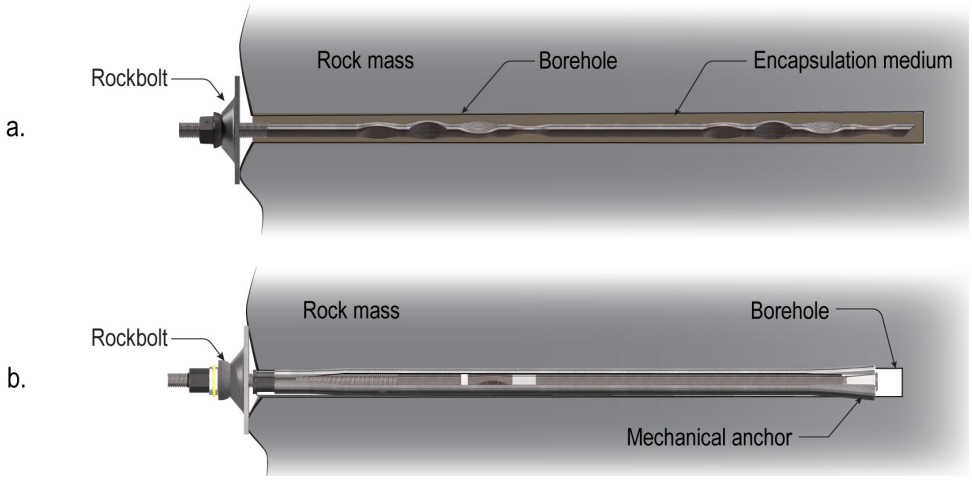

Figure 8— Rockbolt anchoring mechanisms for the experimental programme. a) fully encapsulated rockbolt, b) yielding mechanical hybrid rockbolt

rockbolt, Ø20 mm in diameter were used, however, the length of smooth bar between the paddled sections (anchor points) differed. The paddled energy-absorbing rockbolt used by Knox and Hadjigeorgiou (2024) was 2.4 m in length with a 1.4 m section between the paddled sections. The rockbolt tested by Chen and Li (2015) was 2.0 m in length with a 1.0 m smooth section between the paddled sections. The yielding mechanical hybrid rockbolt was 2.4 m in length with a Ø20 mm bar mechanically anchored within a Ø39 mm friction unit (Knox, Hadjigeorgiou, 2024). Finally, the energy-absorbing self-drilling rockbolt was an R28 variant, 2.4 m in length with a 1.2 m smooth section bounded by the two threaded anchors (Knox, Hadjigeorgiou, 2023).

The rockbolts used in the experimental programme can also be classified based on their anchoring mechanism. As illustrated in Figure 8, fully encapsulated rockbolts are installed with a chemical anchor, which fills the annulus between the rockbolt and the borehole serving as the load transfer interface. The rebar rockbolts and the paddled energy-absorbing rockbolts were installed into a

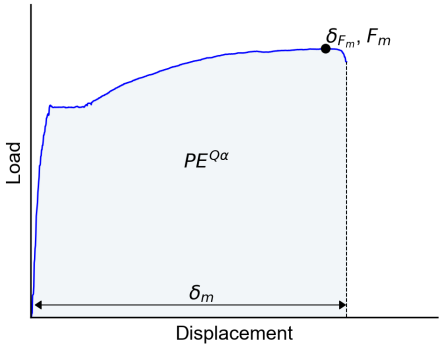

Figure 9—Representation of shear and tensile test result

pre-grouted borehole. The hollow bar rockbolts, and the self-drilling and energy-absorbing self-drilling rockbolts were both installed into the borehole and then post-grouted using a polyurea-silicate resin.

The intent of this analysis was to highlight the shear behaviour of the different rockbolt types. Consequently, all data were sourced from two testing rigs, similar in construction and employing similar shear testing procedures to reduce the risk of testing equipment bias. The similarities in the results for the rebar rockbolts demonstrated that there is limited or no equipment bias between the two testing rigs.

Representation of results

In all tests, the ultimate load (F_m) and the displacement at the ultimate load (δ_{F_m}) were recorded as originally proposed by Stjern (1995), Figure 9. This is reasonable given that beyond the ultimate load the capacity of the rockbolt diminishes to the point of rupture. Consequently, an applied load that exceeded the ultimate load capacity of the rockbolt will likely cause the rock mass strain rate to accelerate as the capacity of the rockbolt diminishes.

For the purposes of this comparative study two additional metrics were used, the displacement at rupture ($\delta\delta_{mm}$) and the total plastic energy at rupture (PE^{Q}). In this configuration the superscript 'Q' denotes that the energy capacity was determined at a quasi-static loading rate and 'α' represents the displacement loading angle. Each dataset was reprocessed to calculate the metrics for each result to facilitate a comparison between the responses of the rockbolts.

Data synthesis

The eight datasets of tensile and shear data for the five rockbolt types were collated from various sources (Chen, Li, 2015; Knox, 2022; Knox, Hadjigeorgiou, 2023; Knox, Hadjigeorgiou, 2024a; Knox, Hadjigeorgiou, 2024b; Kouhia et al., 2025). The average results when loading axially (0°) and in shear (90°) are summarised in Table 1. The response of each rockbolt can be observed in Figure 10. For all five of the rockbolt types a softer loading response is observed when loading the rockbolt in shear. This can be affected by the presence/absence and strength properties of encapsulation/anchoring medium. The installation parameters for each of the seven datasets are summarised in Table 2.

A careful review of the load deformation data for all rockbolt datasets has identified three distinct responses, as depicted in Figure 11. All four rockbolts encapsulated in a chemical anchoring medium dispalyed a reduction in load capacity (F_m) when loaded in shear. The load capacity of the yielding mechanical hybrid rockbolt, however, increased when the rockbolt was loaded in shear. The change in displacement (δ_{F_m}) when loaded in shear was different between conventional and energy absorbing rockbolts. This is illustrated in Figure 12, where results to the left of the dashed diagonal line indicate that the shear displacement capacity is greater than that of the tensile displacement capacity. While the absolute capacity of the energy-absorbing rockbolt is greater than that of the conventional rebar and self-drilling rockbolt, a significant reduction in the shear displacement capacity was recorded when compared to their axial displacement capacity.

The relative capacity of a rockbolt is a method of comparing the capacity of a rockbolt at a given loading angle to the capacity determined through axial testing. This highlights the relationship between the axial and shear response for the rockbolt. The relative capacities for the different rockbolts are summarised in Figure 13.

Table 1

Summary of quasi-static axial and shear loading results for the conventional rockbolts (Chen, Li, 2015; Knox, Hadjigeorgiou, 2023, 2024a, 2024b; Kouhia et al., 2024)

Rockbolt	Nr. samples	α	δ_{F_m}(mm)	F_m (kN)	δ_m (mm)	PE^{Q}(kJ)
Rebar rockbolt (Ø20 mm x 2.4 m)	3	0°	26	189	40	7
	3	90°	51	181	54	6
Rebar rockbolt (Ø20 mm x 1.8 m)	2	0°	21	210	40	7
	2	90°	43	197	48	6
R28 SDA	3	0°	26	273	32	7
	3	90°	44	218	45	6
R25 SDA	2	0°	28	231	35	7
	2	90°	40	215	43	6
Paddled energy-absorbing (Ø20 x 1.4 m)	3	0°	143	215	155	30
	3	90°	58	200	66	9
Paddled energy-absorbing (Ø20 x 1.0 m)	2	0°	117	208	144	26
	2	90°	59	208	71	9
Yielding mechanical hybrid rockbolt	3	0°	246	222	255	47
	5	90°	160	333	167	29
R28 energy-absorbing self- drilling rockbolt	3	0°	182	233	206	44
	3	90°	55	216	60	8

Rockbolts in shear

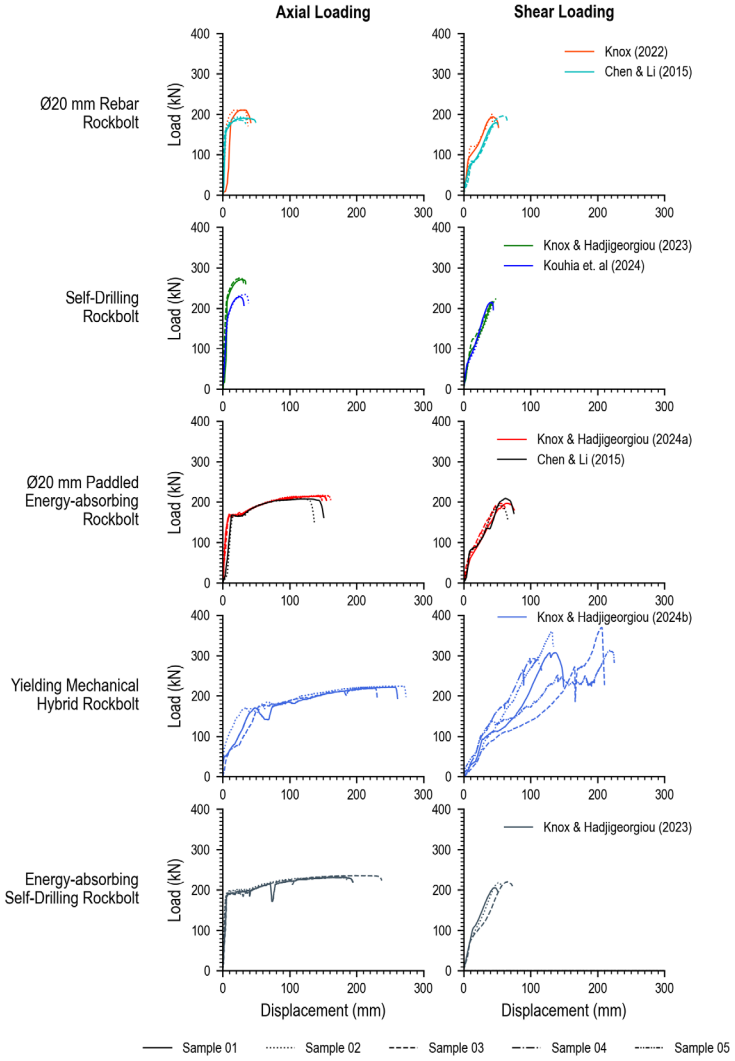

Figure 10—Summary of the load-displacement response for a number of rockbolt types under axial loading (left) and shear loading (right) (Chen, Li, 2015; Knox, Hadjigeorgiou, 2023; Knox, Hadjigeorgiou, 2024a; Knox, Hadjigeorgiou, 2024b, Kouhia et al., 2024)

Table 2

Rockbolt installation properties

Rockbolt	Borehole Ø (mm)	Anchoring Medium
Rebar rockbolt (Ø20 mm x 2.4 m)	33	Grout
Rebar rockbolt (Ø20 mm x 1.8 m)	33	Grout
R28 SDA	36	Polyurea silicate resin
R25 SDA	unknown	Polyurea silicate resin
Paddled energy-absorbing (Ø20 x 1.4 m)	36	Grout
Paddled energy-absorbing (Ø20 x 1.0 m)	33	Grout
Yielding mechanical hybrid rockbolt	38	Friction & mechanical anchor
R28 Energy-absorbing self-drilling rockbolt	36	Polyurea silicate resin

The yielding mechanical hybrid rockbolt was the only bolt to have a relative increase in the load capacity when loaded in shear. This was attributed to the mobilisation of the friction unit when loaded in shear. However, the friction unit borehole interface failed when loaded axially, resulting in the bar providing the primary load bearing and energy-dissipation mechanism (Knox, Hadjigeorgiou, 2023). The relative energy capacity (Rel. PE^{Q}) for all rockbolt types was less than 1, indicating a decrease in the capacity. The reduction in energy capacity was less than 20% across the four conventional rockbolt samples. As a consequence of the significant reduction in displacement capacity, the energy capacity of the fulling encapsulated energy-absorbing rockbolts was greater than 60%.

Of the energy-absorbing rockbolts, the yielding mechanical hybrid rockbolt appears to be the most resilient to shear loading, with an increase in the recorded load capacity and a reduction in displacement and energy capacity of less than 40%. This is due to the absence of an encapsulation medium allowing for greater displacement prior to the induction of bending and pinching of the

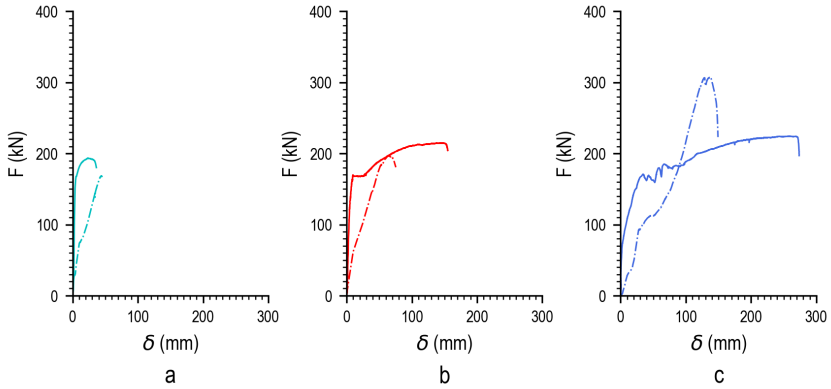

Figure 11—Three types of response observed in the results. a) Conventional encapsulated rockbolts, b) encapsulated energy-absorbing rockbolt, c) yielding mechanical hybrid rockbolt

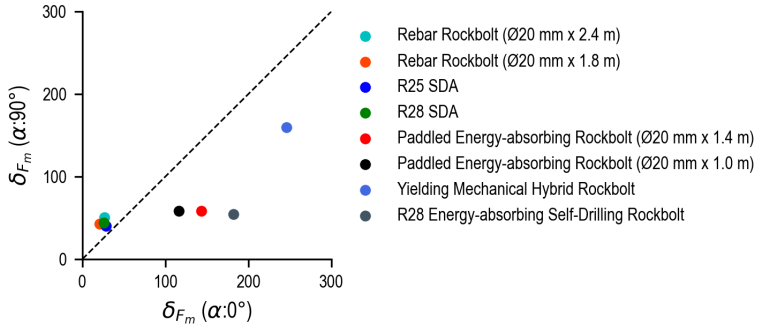

Figure 12—Comparison between the displacement at ultimate load determined through shear and tensile testing

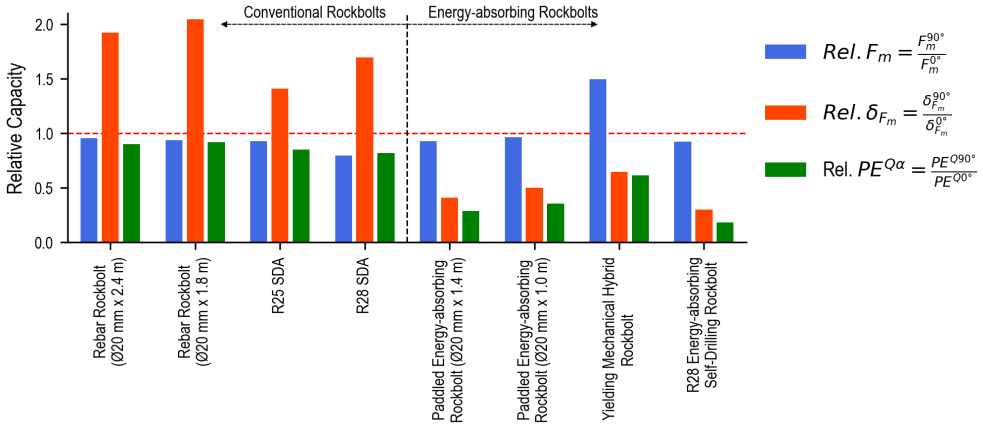

Figure 13—Relative performance capacities for the rockbolts

bar. The trade-off is a reduction in the stiffness of the response of the rockbolt, which may limit its application in certain conditions. In addition, the lack of an encapsulation medium presents a potential concern when the rockbolt is installed in highly corrosive environments for long term applications.

Conclusion

This paper presented a review of the response of five types of rockbolts, conducted using the single shear method on full scale rockbolts. Of the eight datasets included, three were undertaken using the SINTEF rockbolt pull test rig and the remaining five using the Epiroc Combination Shear and Tensile test rig. The inherent similarities in the construction and operation of these two testing rigs allowed for a direct comparison of the published results.

Three responses to shear loading were observed, differentiated by the encapsulation of the rockbolt and design premise, and conventional versus higher energy-absorbing rockbolts. The typical response was that of a decrease in the ultimate load capacity, which ranged between a 3% and a 20% reduction in load capacity, the exception being the yielding mechanical hybrid rockbolt, which recorded a 50% increase in load capacity. The displacement capacity for the conventional rockbolts all increased, however, remained less than the absolute value of the shear displacement capacity of an energy-absorbing rockbolt. This study is a contribution to an improvement in our understanding of rockbolt behaviour under controlled testing conditions.

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