Caving 2022 - Y Potvin (ed.)

doi:10.36487/ACG_repo/2205_07

Dynamic testing: determining the relationship between rockbolt diameter and the residual dynamic capacity of an axially strained tendon

BR Crompton *Epiroc, Australia*

G Knox *Epiroc, South Africa*

Abstract

The specification of a tendon is stated as the capacity of the tendon in new condition on the day it was produced. Rock support tendons are discretely tested quasi-statically (replicating closure) or dynamically (replicating seismicity) depending on the conditions expected with the mine environment. Although this testing is valuable, it is likely that a tendon subjected to rapid ground movement (seismicity) would first be subjected to some level of slow closure. Previous research investigated the possible correlation between the quasi-static elongation of a rockbolt prior to dynamic loading and residual dynamic capacity. The results from this research indicated that a correlation exists between the residual dynamic capacity and the energy absorbed quasi-statically when the tendon is elongated axially. It was proposed that a conservative approach would be to consider the total energy capacity of a tendon as the energy absorbed by a tendon in pristine condition during a single dynamic impulse resulting in the rupture of the tendon. The research sample set was limited to a single rockbolt configuration of fixed length and diameter, therefore it was noted that the results should not be extrapolated to other versions of this system or other ground support systems.

This research will build on the previous work by repeating the testing regime on a larger diameter of the same configuration rockbolt. The results will be analysed to identify how the diameter of a rockbolt affects the energy and elongation capacity of the rockbolts under combined quasi-static and dynamic loading. This information will greatly assist geotechnical practitioners with support system design, product selection and decisions on when to rehabilitate an installed support system.

Keywords: *dynamic testing, ground support, pre-elongated, squeezing ground, seismicity, rockbolt, PAR1 Resin Bolt, Dynamic Impact Tester*

1 Introduction

The design of ground support systems is reliant on the performance specifications provided for the various support elements within the support system. The information contained within these specifications is derived from laboratory and field testing that is typically performed on support elements in an as new condition.

In application, ground support is subjected to various factors that degrade the system performance over time that includes installation quality, corrosion mechanical damage and changes in support demand due to ground movement. Previous research investigating several of these factors proposed a conceptual representation for the degradation of a support system over time (Hadjigeorgiou 2016).

The testing of ground support is commonly conducted at loading rates intended to simulate either quasi-static ground movement (mm/day) or dynamic (rockbursting and seismic) ground movements (m/s). The use of standardised test methodologies is suitable for comparing the performance specifications for different support products, and for use in application where ground support experiences a single loading mechanism. However, it is likely that in many rockbursting and seismic ground regimes that the support system will be subjected to a degree of slow ground movement (mm/day) and associated bulking of the rock mass prior to rapid ground movement (m/s), as indicated in Figure 1.

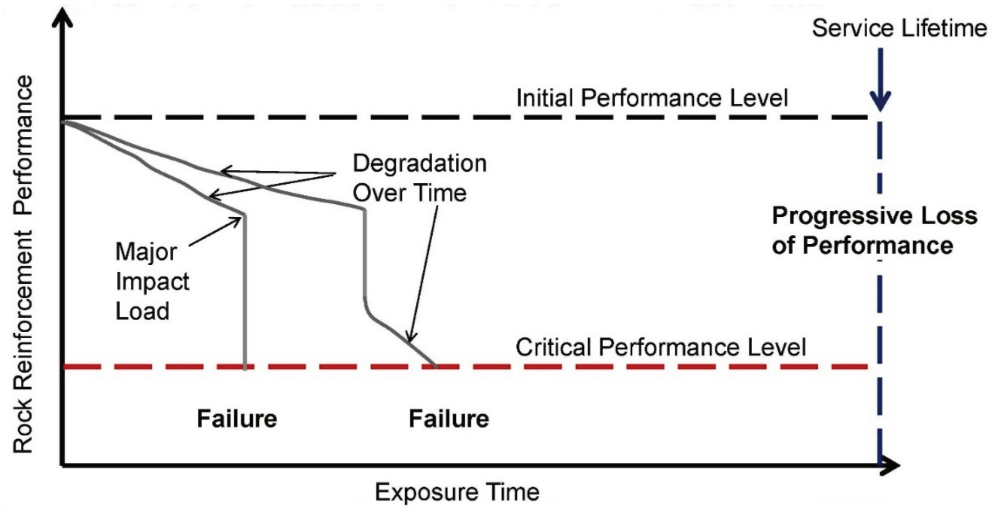

Figure 1 Degradation of a support system over time (Hadjigeorgiou 2016)

Changes in ground movement over time will continuously reduce the residual dynamic capacity of an installed support system and it is important to understand the implication of this should a dynamic loading event (rockburst or seismicity) occur.

Quasi-static and dynamic ground movement can result in any combination of tensile, shear, bending and torsional loading of a support tendon, however, current testing equipment limits the ability to dynamically test support under varying load configurations. In an attempt to better understand the effect of quasi-static ground movement on a support system prior to dynamic loading, previous research developed a new test methodology to apply axial strain to a rockbolt and to then apply a dynamic axial load to the strained tendons. The research found that, for the tendons tested, the cumulative (total) energy absorption capacity of rockbolts remained constant with varying degrees of axial strain prior to dynamic loading (Figure 2). The corollary being that the residual energy absorption capacity available at the time of dynamic loading decreases with increasing rates of quasi-static axial strain. The research also noted that there was a non-linear increase in the cumulative elongation capacity of the rockbolts with increasing quasi-static elongation prior to dynamic loading (Knox & Berghorst 2019) (Figure 3).

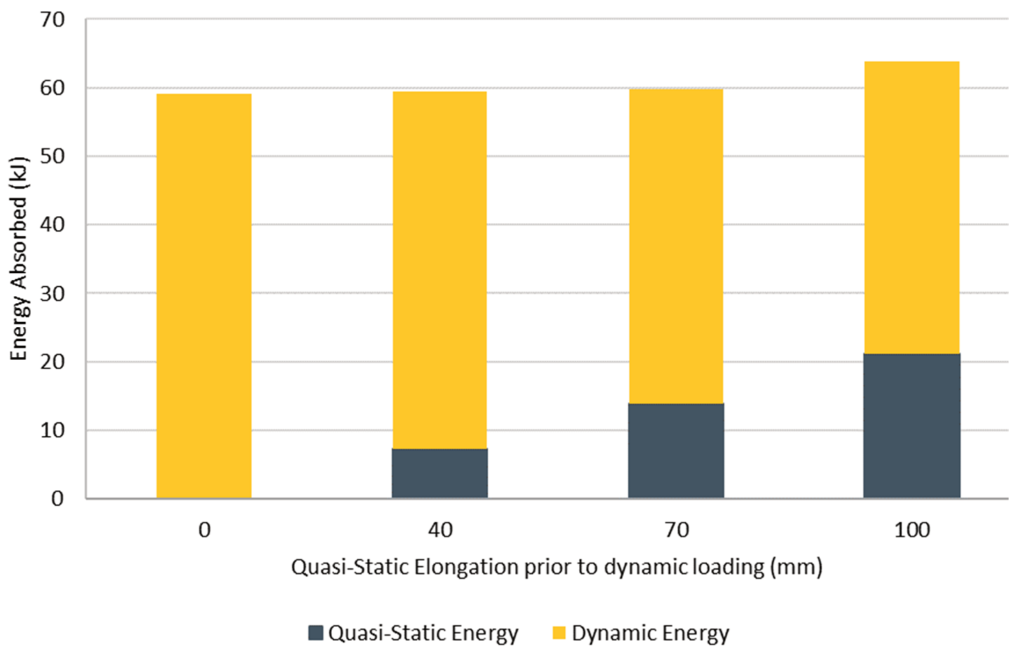

Figure 2 Average cumulative energy absorbed with varying quasi-static elongation prior to dynamic loading (Knox & Berghorst 2019)

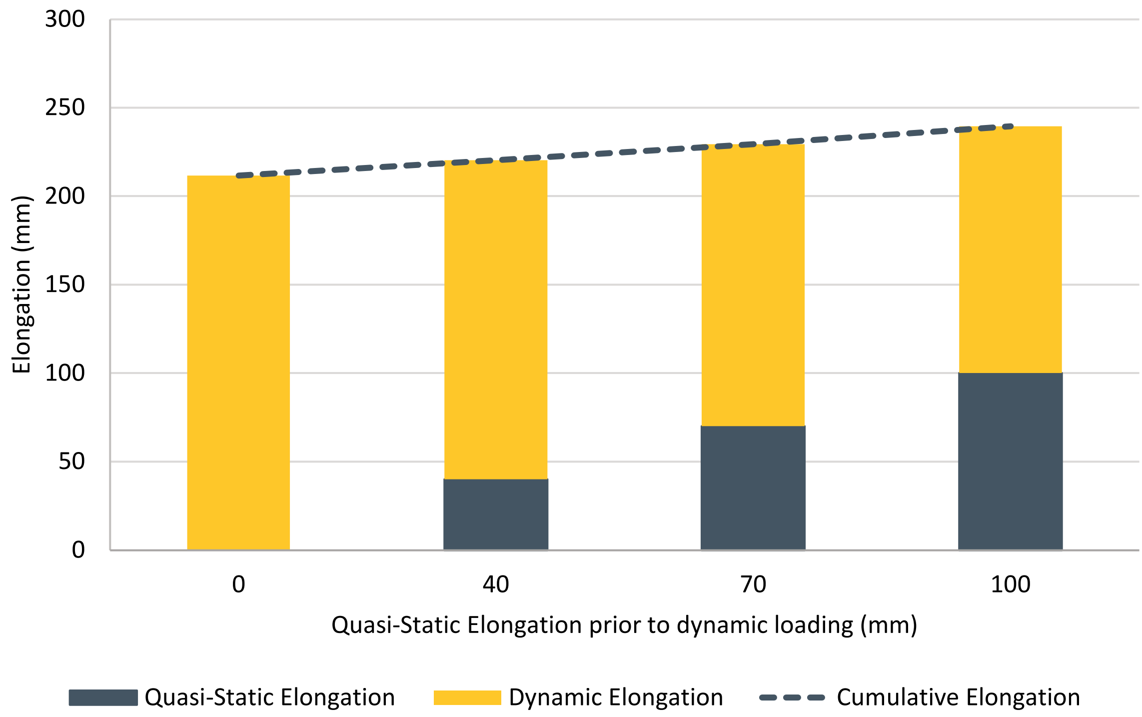

Figure 3 Average cumulative elongation with varying quasi-static elongation prior to dynamic loading (Knox & Berghorst 2019)

Whilst the research by Knox & Berghorst (2019) was limited to a single rockbolt configuration tested under purely axial loading; it broadened industry's understanding of the residual capacity of rockbolts subjected to elongation prior to dynamic loading. The aim of the research in this paper was to build on the base provided and investigate whether or not the previously observed relationship between quasi-static strain and residual dynamic capacity is consistent across different diameters of the same rockbolt.

2 Impact testing of rockbolts

The installation of energy-absorbing rockbolts is considered best practice in seismic prone and squeezing rock masses (Potvin & Hadjigeorgiou 2020). The evolution of energy-absorbing rockbolts can be traced back to the work of Ortlepp (1969) in South Africa. Subsequently a number of energy-absorbing rockbolts have been developed and made available to the market (GMA AB 2021; Epiroc 2022; Mansour Mining Technologies 2021; Normet 2022; Tonry Mining 2022). Consequently, the requirement to quantify the performance of energy-absorbing rockbolt resulted in the development of a number of laboratory testing methodologies with impact testing being the most popular (Hadjigeorgiou & Potvin 2011).

Several authors have contributed to the industries understanding of energy-absorbing rockbolts resulting in the collation of designs charts facilitating the comparison between different rockbolt types (Jager 1992; Villaescusa et al. 2004; Simser 2007; Hadjigeorgiou & Potvin 2011; Li & Doucet 2012; Louchnikov & Sandy 2017; Potvin & Hadjigeorgiou 2020). Except for the worked published by Jager (1992), all published data consists of a single loading method providing valuable insight into the performance of the rockbolts for comparison. Jager (1992) identified the need to understand the performance of a cone bolts displacement rates varied between 1×10^{-3} mm/sec to 3×10^{3} mm/sec up to a maximum displacement of 600 mm.

3 PAR1 Resin Bolt

The previous work by Knox & Berghorst (2019) was conducted using the PAR1 Resin Bolt (Figure 4), this bolt was selected as it has been extensively tested under both quasi-static and dynamic loading (Knox & Berghorst

2019) and its performance is well understood. The PAR1 Resin Bolt is a resin anchored, solid rockbolt comprising smooth steel with two sets of paddles that both mix resin during installation and anchor the PAR1 Resin Bolt within the cured resin. Energy is absorbed through elongation of the smooth steel portions of the bolt; this can occur between the faceplate and the proximal paddle set and the proximal and distal paddle sets. The design provides a highly repeatable performance under both quasi-static and dynamic elongation since this performance is defined by the properties of the steel (Knox & Berghorst 2019).

Figure 4 The PAR1 Resin Bolt

As previous research was conducted on the Ø20 mm × 2.4 m PAR1 Resin Bolt, the same configuration of PAR1 Resin Bolt was selected but with the diameter increased to Ø22 mm diameter.

4 Sample preparation

Due to the design of test facilities, it is typically not possible to quasi-statically elongate a rockbolt prior to dynamic testing. In order to achieve multi-rate loading of rockbolt samples, Knox & Berghorst (2019) developed a new sample arrangement and test methodology which separated the testing into two components: quasi-static elongation and subsequent dynamic impact testing. The modified sample tube utilised in this method ensures that the quasi-static elongation applied to each sample is maintained until the applied dynamic impulse surpasses the locked-in axial load.

To replicate the previous testing conducted on Ø20 mm PAR1 Resin Bolts a similar number of Ø22 mm samples were prepared and tested to the same parameters as before.

4.1 Installation of the PAR1 Resin Bolt

As per previous research, the sample tubes developed for this testing were configured for a split tube dynamic test (Li 2017) with a split in the host tube at approximately the midpoint between the proximal and distal anchor of the PAR1 Resin Bolt. The modified sample tube was threaded on either side of the split with a pair of threaded couplers to lock the sample tubes together across the split subsequent to quasi-static elongation. The PAR1 Resin Bolt was installed using Epiroc's resin bolt installation machine (Knox & Berghorst 2019). The machine allows the installation parameters to be set according to the resin supplier's specifications, with consistent thrust, rotation and hold parameters, as defined by Table 1. This limits any variability in installation parameters when preparing test samples.

Table 1 Installation parameters for PAR1 resin samples

Parameter	Value
Resin capsules	1 × fast, 5 × medium
Feed rate	4.0 m/min
Rate of rotation	300 rpm
Spin time	10 sec
Hold time	45 sec

4.2 Elongation of the samples

The installed PAR1 Resin Bolts were left for a minimum period of 30 minutes to allow the resin to cure, the samples were then placed into the quasi-static loading frame (Figure 5). A loading coupler and drawbar were attached to the distal end of the sample tube, and the drawbar was passed through a hollow hydraulic cylinder. The hydraulic cylinder was used to apply quasi-static load to the distal end of the sample tube sufficient for the installed PAR1 Resin Bolt to elongate plastically. Once the predefined elongation was met for each sample, the coupler was used to fix the position of the sample tubes prior to releasing the hydraulic pressure. This ensures that the elongation applied to the samples is maintained prior to dynamic testing. The sample was then removed from the load frame, and the Epiroc DIT receiver interface was attached to the distal end of the sample. During the quasi-static loading the displacement and load values were recorded to facilitate the estimation of the dissipated energy. As per the previous research (Knox & Berhorst 2019) the samples were split into four batches, three samples to be used as a benchmark for the dynamic capacity at zero initial elongation, three batches of three samples each elongated to a displacement of 40 mm, 70 mm and 100 mm. These elongations were selected as they represent elongation beyond the elastic region of the PAR1 Resin Bolt. An improvement on the previous research was the inclusion of monitoring for each sample as it was quasi-statically elongated, allowing a load deformation curve to be recorded for each sample.

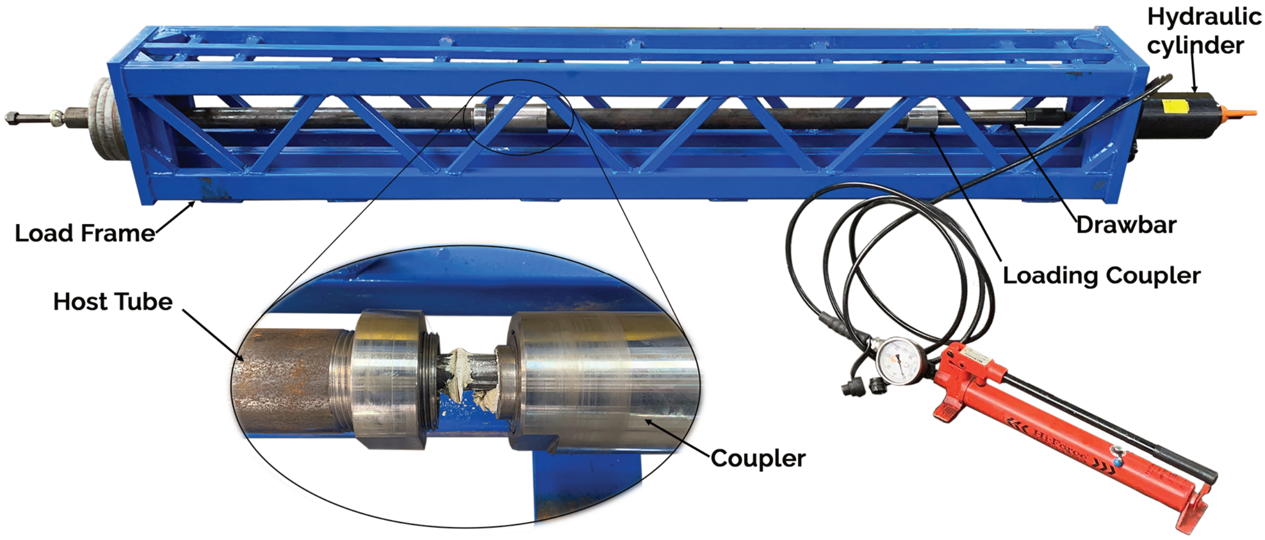

Figure 5 Equipment and sample tube used to elongate the sample rockbolt (Knox & Berghorst 2019)

5 Impact testing

Dynamic testing of the samples was conducted using the Epiroc DIT (Knox & Berghorst 2018). The system uses a free-falling mass to generate an impulse of energy imparted to the sample through an impact. The machine as described by Knox & Berghorst (2018) uses a known mass released from a known height to impart a predefined energy into the sample. During the impact, the loads and displacements are recorded at a rate of 10 kHz the energy absorbed by the tendon prior to rupture, to be calculated.

It is known that the cumulative energy capacity of a rockbolt is inversely proportional to the magnitude of the input energy during dynamic testing (Bosman et al. 2018) so to mitigate this effect Knox and Berghorst (2019) tested Ø20 mm PAR1 Resin Bolts using a single 56 kJ impulse, sufficient to cause rupture of test samples on the first impulse. The energy capacity of the Ø22 mm PAR1 Resin Bolts tested in this research have a typical energy capacity of 69 kJ (Epiroc 2022) and hence were dynamically tested using two 56 kJ impulses, applied with an initial impact velocity of 5.9 m/s, to exceed the full dynamic capacity of the samples and achieve rupture.

6 Results and interpretation

A summary of the dynamic results from this research can be seen in Table 2, these results are represented graphically in Figure 6 as a function of plate displacement. For the purposes of this research the plate displacement is considered a proxy for ground deformation in actual application, hence load, energy and deformation are used in this paper to compare the results.

Table 2 Summary of dynamic test results

Sample ref.	Quasi-static displacement (d_{QS}) (mm)	Dyn. plate displ. (d_{DYN}) (mm)	Cum. plate displ.[1] (d_{Total}) (mm)	Avg. impact load (kN)	Dyn. absorb. energy (E_{DYN}) (kJ)
P1R22-QS0-S01	0	239	239	279	66
P1R22-QS0-S02	0	241	241	283	69
P1R22-QS0-S03	0	235	235	269	63
P1R22-QS40-S01	40	181	221	275	50
P1R22-QS40-S02	40	202	242	277	56
P1R22-QS40-S03	40	197	237	270	53
P1R22-QS70-S01	70	187	257	282	54
P1R22-QS70-S02	67	182	249	250	46
P1R22-QS70-S03	70	178	248	281	50
P1R22-QS100-S01	106	154	260	273	42
P1R22-QS100-S02	99	139	238	278	39
P1R22-QS100-S03	100	148	248	284	43

[1] $d_{Total} = d_{QS} + d_{DYN}$

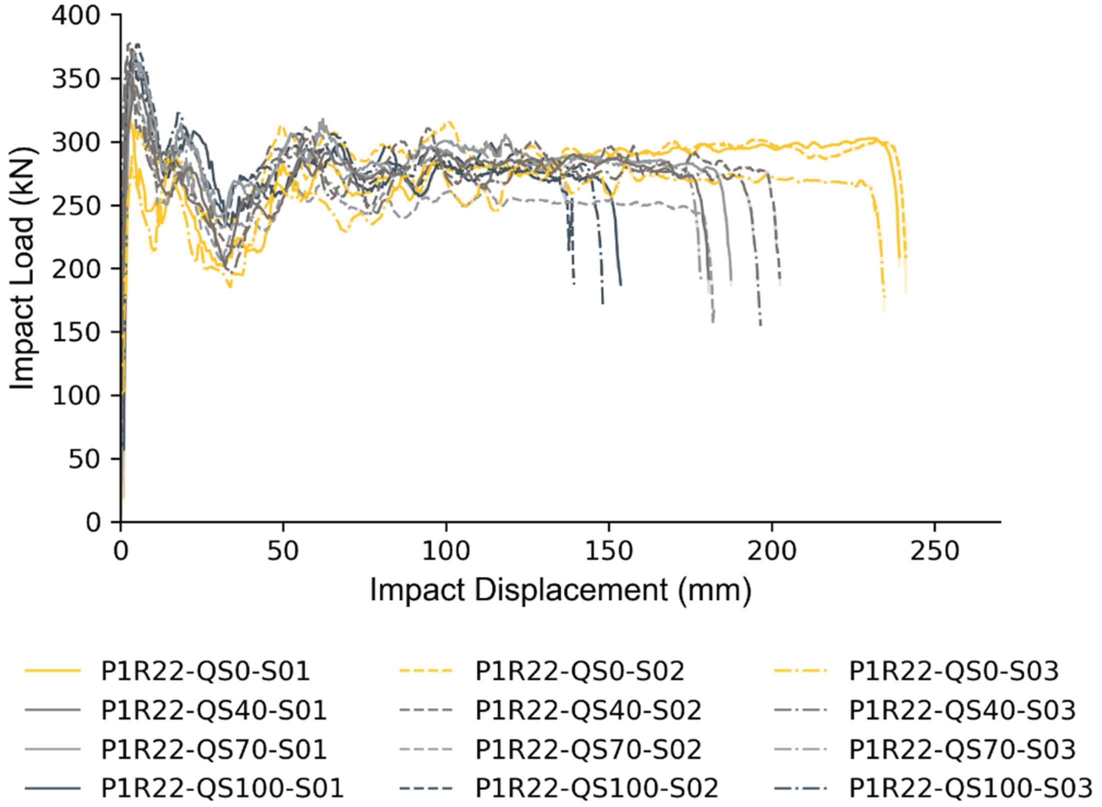

Figure 6 Average load and displacement over the impact period

The profile of the load and displacement curves in Figure 6 are consistent and show repeatability of both the test methodology and PAR1 Resin Bolt performance. What is apparent is a trend of decreasing dynamic elongation as quasi-static deformation is increased, and a comparative increase in ultimate dynamic load. These observations are consistent with the findings of Knox & Berghorst (2019).

In Figure 7 the dynamic load displacement curves are offset by the quasi-static elongation and the observed trends are represented graphically. As reflected in Table 3 and Figure 8 the average cumulative displacement increased from 238 mm for 0 mm quasi-static elongation, to 247 mm for 100 mm quasi-static elongation. The average cumulative energy absorbed remained similar at approximately 65 kJ total energy absorbed, irrespective of the degree of quasi-static elongation, Table 4, and Figure 8. These results correlate with the previous research conducted on Ø20 mm PAR1 Resin Bolt (Knox & Berghorst 2019).

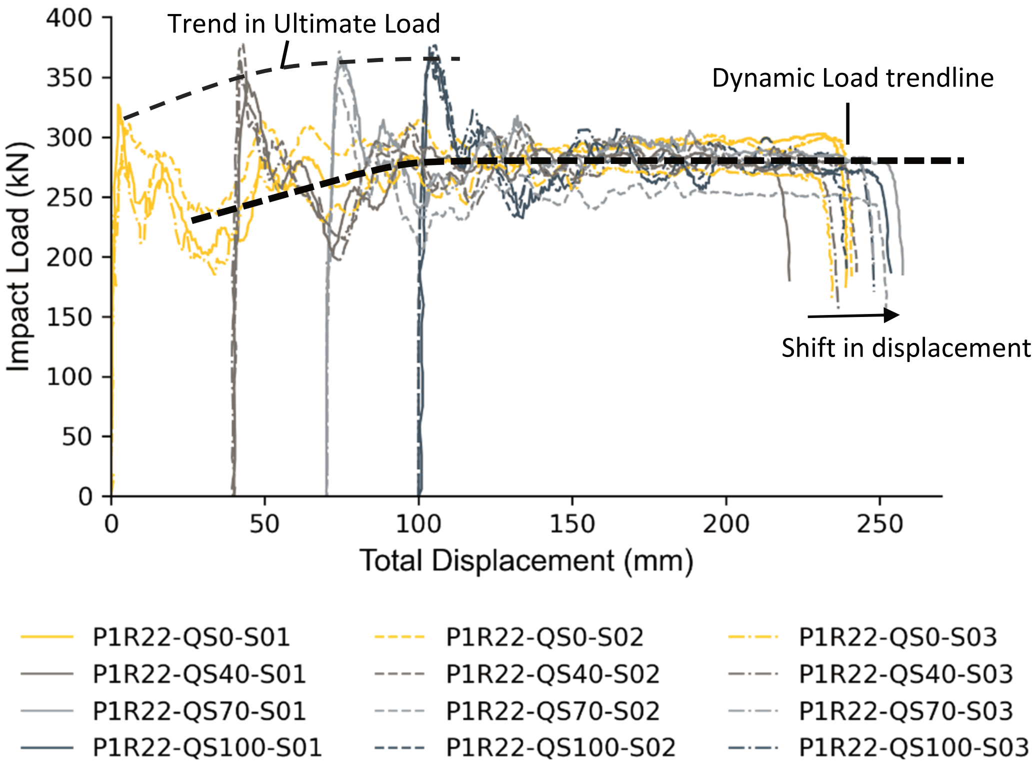

Figure 7 Graphical representation of the trends noted, dynamic displacement offset by QS elongation

Table 3 Comparison of cumulative elongation

Quasi-static elongation (d_{QS}) (mm)	Average dynamic elongation (d_{dYN}) (mm)	Average cumulative elongation (kJ)
0	238	238
40	193	233
70	182	252
100	147	247

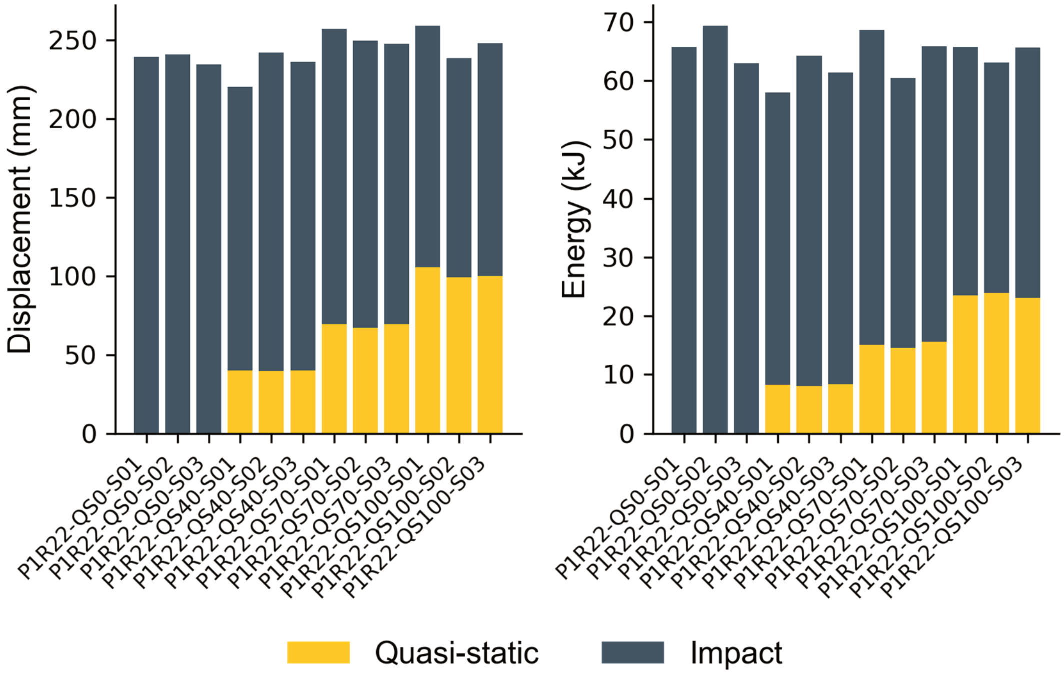

Figure 8 Total displacement and energy for each sample

Table 4 Comparison between the energies absorbed

Quasi-static elongation (d_{QS}) (mm)	Absorbed QS capacity ($E_{QS}(x)$) (kJ)	Residual dynamic capacity ($E_{DYN}(x)$) (kJ)	Total energy absorbed ($E_{QS}(x) + E_{DYN}(X)$) (kJ)
0	0	66	66
40	8	53	61
70	15	50	65
100	24	41	65

The energy absorption results from this testing on the Ø22 mm PAR1 Resin Bolt are compared in Table 5 and Figure 9 to the results of the previous research on the Ø20 mm PAR1 Resin Bolt (Knox & Berghorst 2019). This illustrates that the trends observed by Knox & Berghorst (2019) are consistent for when the diameter of the bar is increased.

Table 5 Comparison between the energies absorbed for Ø20 and Ø22 mm PAR1 Resin Bolts

Quasi-static elongation (d_{QS}) (mm)	Ø20 mm PAR1 Resin Bolt			Ø22 mm PAR1 Resin Bolt		
	Absorbed QS capacity ($E_{QS}(x)$) (kJ)	Absorbed dynamic capacity ($E_{DYN}(X)$) (kJ)	Total energy absorbed ($E_{QS}(x) + E_{DYN}(X)$) (kJ)	Absorbed QS capacity ($E_{QS}(x)$) (kJ)	Absorbed dynamic capacity ($E_{DYN}(X)$) (kJ)	Total energy absorbed ($E_{QS}(x) + E_{DYN}(X)$) (kJ)
0	0	59	59	0	66	66
40	7	52	59	8	53	61
70	14	46	60	15	50	65
100	21	43	64	24	41	65

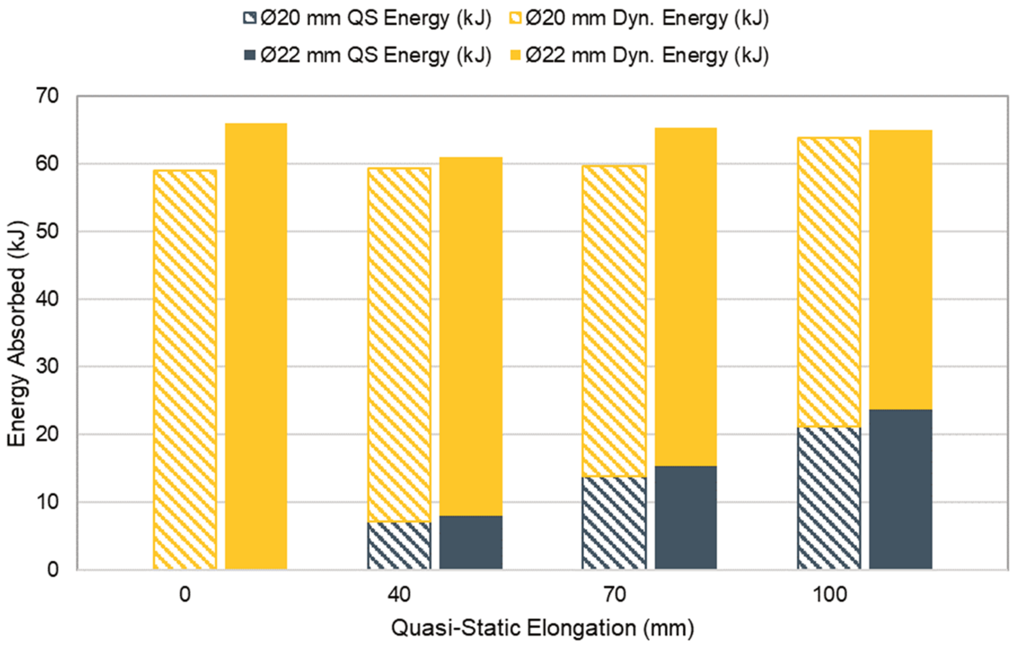

Figure 9 Representation of energy absorbed for Ø20 and Ø22 mm PAR1 Resin Bolt

7 Conclusion

From the research conducted it can be concluded that the observed trends in the results are consistent for the PAR1 Resin Bolt in different diameters. Namely, that increasing quasi-static elongation prior to dynamic loading increases the ultimate elongation capacity of the rockbolt; and, that the cumulative energy capacity of the rockbolts remains constant.

Hence, the quasi-static consumption of energy capacity results in a reduction of the residual dynamic capacity of the installed rockbolts. It is recommended that ground support designs consider the degree of quasi-static elongation applied to rockbolts, through bulking of the rock mass for example, prior to any anticipated dynamic loading of the installed tendons.

It can also be concluded that for the style of rockbolt tested, with increasing quasi-static elongation prior to impact loading the nett elongation capacity of the rockbolts increases. It is noted that the increase in cumulative elongation is not directly proportional to the degree of quasi-static elongation. This implies that for the purposes of ground support design; an elongation capacity derived from single impulse testing to failure can be considered as a conservative indication of axial elongation capacity.

Whilst the current research confirms consistent trends between two diameters of the same rockbolt system it is important to remember that the results should not be extrapolated to other ground support systems. It must also be noted that this research does not account for other factors which reduce the residual capacity of support systems such as shear, corrosion or mechanical damage.

8 Future work

The experimental programmes of both the Ø20 mm PAR1 Resin rockbolt (Knox & Berghorst 2019) and the presented investigation on the Ø22 mm PAR1 Resin rockbolt identified an increase in the cumulative elongation. The mechanism resulting in the increase cumulative deformation requires further investigation. Both investigations were conducted with a limited sample set, to improve the understanding of the relationship variation in mechanical properties of the steel will need to be investigated.

The research to date has focused on the performance of a resin anchored paddled energy absorbing rockbolt, the PAR1 Resin rockbolt, consequently future should extend to alternative anchor mechanisms. The variation of the anchor mechanism may provide valuable insight into relationships observed.

Acknowledgement

The authors acknowledge Epiroc for providing access to the testing facility, the rockbolts and resin used in this testing campaign. The contribution of Shane Koapeng and his team in the preparation of the samples and operation of the testing facility is gratefully acknowledged.

References

Bosman, K, Cawood, M & Berghorst, A 2018, 'The relationship between the magnitude of input energy per impulse and total absorbed energy', *Proceedings of the 3rd International Conference on Rock Dynamics and Applications (RocDyn-3)*, CRC Press, Trondheim, pp. 379–384.

Epiroc 2022, PAR1 Resin Bolt, Stockholm, viewed 4 May 2022, https://www.epiroc.com/en-za/products/rock-drilling-tools/ground-support/energy-absorbing-rockbolts/par1-resin-bolt

GMA AB 2021, GMA AB launches it's own dynamic rock bolt – the GE bolt, Luleå, viewed 4 May 2021, https://www.gma.se/en/gma-ab-launches-its-own-dynamic-rock-bolt-the-ge-bolt-gma-elongation-bolt/.

Hadjigeorgiou, J & Potvin Y 2011, 'A cirtical assessment of dynamic rock reinforcement and support testing facilites', *Rock mechanics and rock engineering*, vol. 44, no. 5, pp. 565–578.

Hadjigeorgiou, J 2016, 'Rock support: degradation and failure', *Proceedings of the 8th International Symposium on Ground Support in Mining and Underground Construction*, Luleå University of Technology, Luleå, pp. 1–22.

Jager, AJ 1992, 'Two New Support Units for the Control of Rockburst Damage', in PK Kaiser & DR McCreath (eds.), *Rock Support in Mining and Underground Construction*, Balkema, Rotterdam, pp. 621–631.

Knox, G & Berghorst, A 2018, 'Increased agility for the research and development of dynamic roof support products', *Proceedings of RocDyn-3*, Trondheim, Norway, pp. 373–384.

Knox, G & Berghorst, A 2019, 'Dynamic testing: determining the residual dynamic capacity of an axially strained tendon', *Proceedings of Ground Support 2019*, Australian Centre for Geomechanics, Perth, pp. 231–242.

Li, C & Doucet, C 2012, 'Performance of the D-bolt under dynamic loading conditions', *Rock mechanics and rock engineering*, vol. 45, pp. 193–204.

Li, CC 2017, *Rockbolting: Principles and Applications*, Butterworth-Heinemann, Oxford.

Louchnikov, V & Sandy, MP 2017, 'Selecting an optimal ground support system for rockbursting conditions', in J Wesseloo (ed.), *Deep Mining 2017: Proceedings of the Eighth International Conference on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 613–623, https://doi.org/10.36487/ACG_rep/1704_41_Louchnikov

Mansour Mining Technologies 2021, *Mansour Mining Technologies inc. Product Catalogue*, viewed 5 April 2022, https://www.dsiunderground.ca/fileadmin/downloads/dsi-underground-canada/MMTI_Product_Catalogue.pdf

Normet 2022, Normet D-Bolt® – Dynamic rock bolt, viewed 5 April 2021, https://www.normet.com/product/d-bolt/

Ortlepp, WD 1969, 'An Empirical Determination of the Effectiveness of Rockbolt Support under Impulse Loading', in TL Brekke & FA Jorstad (eds.) *Proceedings of the International Symposium on Large Permanent Underground Openings.* Universitats-forlaget, Oslo, pp. 197–205.

Potvin, Y & Hadjigeorgiou, J 2020, *Ground Support for underground mines*, Australian Centre for Geomechanics, Perth.

Simser, BP 2007, 'The Weakest Link – Ground Support Observations at Some Canadian Shield Hard Rock Mines', in Y Potvin (ed.), *Deep Mining 2007: Proceedings of the Fourth International Seminar on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 335–348, https://doi.org/10.36487/ACG_repo/711_25

Tonry Mining 2022, Dynamic Energy Absorbing Bolt (E-Bolt), viewed 5 April 2022, http://www.tonrymining.com/index.php?c=content&a=show&id=55&area=.

Villaescusa, E, Thompson, A & Player, J 2004, 'Dynamic Testing of Rock Reinforcement using the Momentum Transfer Method', in E Villaescusa & Y Potvin (eds) *Ground Support in Mining and Underground Construction,* CRC Press, London, pp. 237–339.