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Evaluation of different dynamic reinforcement elements using the rate of change of energy and strain during in situ dynamic testing

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Abstract

During dynamic ground disturbances the rock mass undergoes rapid change with time, resulting in various demands imposed on installed dynamic ground support. In dynamic ground conditions, every dynamic pulse is unique, as it is the result of different source mechanisms with different transient times. The time dependent parameters of power and strain rate were investigated in this paper as additional parameters to better characterise the performance of dynamic reinforcement elements. Sandvik Mining and Construction provided data from in situ axial tests conducted by their dynamic test rig, for a total of 52 MD, 65 MDX, 11 Kinloc and 13 collar-loaded Posimix reinforcement elements, dynamically tested across eight mine sites. The test data was statistically checked to identify patterns in the data and validate the combination of data from different mines into larger datasets. Then the performance of the reinforcement elements in the dynamic tests was studied with respect to the duration of the test. The paper examines the response of the element to the test impact, via two introduced parameters: average response power, i.e. the response energy or absorbed energy per unit time, and average strain rate, i.e. the strain of the element per unit time. Clear differences were found between the different reinforcement element types. Regarding response power, the MD and Kinloc displayed similar patterns, but the MD responded with up to more than twice the power level of the Kinloc. The MDX showed a tight cluster of power values. Although the dataset is small, there is indication that the collar-loaded Posimix may be unable to survive at response power levels higher than 400 kW. Regarding strain rates, failed Kinloc elements had high strain rates, indicating the high speed with which they were pulled from the borehole once the anchor was compromised. One failed MD bolt had similarly high strain rate, but the three other failed MD bolts did not. Failed and survived MDX and collar-loaded Posimix had similar strain rates. MDX and collar-loaded Posimix reinforcement elements operated at low strain rates. This probably reflects the nature of yield of a steel bar, where there is an upper limit to strain rate that can be survived. Overall, it is found that power and strain rate analysis add additional value to describe the performance and capacity of reinforcement elements. Also, there is suggestion that it is not possible to force a particular element to accept a higher power level than it can sustain according to its design.

Keywords: *absorbed energy, power, strain rate, in situ dynamic testing, ground support*

1 Introduction

Deeper underground mining operations add more challenges in the safe extraction of mineral resources due to dynamic rock mass deformations associated with seismicity and stress. Appropriate dynamic ground support design plays a crucial role in mitigating the risk posed by seismicity. Time is one of the fundamental physical quantities and a key parameter to define the response of dynamic ground support. This paper

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encompasses data processing in terms of descriptive statistics, goodness of fit analysis, and agreement analysis to provide a holistic understanding of a range of dynamic ground support test results.

The assessment of dynamic reinforcement elements through in situ testing is considered crucial for evaluating their performance and reliability under dynamic loading conditions induced by seismic events. During dynamic ground disturbances the rock mass undergoes rapid change with time. Therefore, time sensitive parameters such as power and strain rate are investigated in this research as additional parameters to better characterise dynamic reinforcement elements. The performance of the reinforcement elements in dynamic tests is studied with respect to the duration of the test. Some reinforcement elements have capability of yielding in very short span, say in low tens of milliseconds, while others can continue to yield over a much longer period. A first hypothesis of this research paper is that power and strain rate would add additional value to describe the performance and capacity of reinforcement elements. Power and strain rate are described in this section. The hypothesis can also be expanded to surface support and other types of dynamic reinforcement elements but that is beyond the scope of this paper.

The research work evaluates dynamic in situ reinforcement element test results provided by Sandvik Mining and Construction Ltd for MD, MDX, Kinloc and Posimix reinforcement elements. All the tests were conducted using the Sandvik dynamic test rig (DTR). The work is restricted to analysis of the element only (bar, tube, anchor and collar components) and not the complete ground support system since plates and surface support are not included in the in situ dynamic tests.

It is not possible with the in situ test apparatus to test the Posimix element (or other resin-encapsulated types of bolts) in accord with their design intent. The test loads the collar of the Posimix only. However, the element is intended to be loaded in the debonded mid-section of the element, with the load transfer path passing through a resin plug a short distance inside the borehole from the collar. This arrangement diverts some loading directly into the bar and reduces the load on the collar plate. Therefore, the Posimix tests analysed in this paper are labelled as 'collar-loaded Posimix' to clarify this distinction. In underground dynamic environments, it is possible that during a seismic disturbance, for various reasons, any bolt including the Posimix could be loaded at the collar.

1.1 Input and output terminology

It is important to distinguish between input and output parameters. Input parameters are related to the disturbance imposed on the element by the in situ test apparatus and include input energy and impact velocity. Output parameters are related to response of the element to the inputs, and they include absorbed or dissipated energy, time duration of test, strain rate response, displacement response, load response, power response, and survival or failure of element.

The terms 'input' or 'response' are used in this paper to ensure clarity when discussing the various parameters. Response energy is called 'absorbed energy' in the Sandvik database. It is also called 'dissipated energy' in the literature generally, and both terms have merit. In this paper, response energy equates to the absorbed energy in the Sandvik database, and average response power equates to the average time rate of that absorbed energy.

1.2 Reinforcement element power

There exist various categories of power, including mechanical, electrical, thermal, radiant and hydraulic power. This paper specifically addresses a subset of mechanical power known as instantaneous power. Instantaneous power encompasses minimum, maximum, and average power within a given time frame. This study excludes other forms of mechanical power such as rotational power, as they do not have relevance to reinforcement elements. Power as referred to in this paper describes how fast energy leaves or comes into a system, or the energy change per unit of time. Energy is the time integral under the power curve. For a bolt experiencing a dynamic test, power is a function of both the input energy and the reinforcement element mode of response to that energy input. A higher input energy is likely to cause work on the reinforcement to be done at a higher rate. Different reinforcement types would be expected to sustain various levels of work rate (distinct levels of power). Therefore, a second hypothesis is that it is not possible to force a particular bolt to accept a higher power level than it can sustain according to its design. This paper examines this concept by analysing dynamic in situ testing data for MD, MDX, collar-loaded Posimix and Kinloc reinforcement elements.

Energy and power are closely related parameters which can be described by a simple analogy: energy can be expressed as lump sum of payment, and power can be expressed as the pay rate. Both provide useful information and one cannot replace the other. The energy stored in a fired handgun bullet is perhaps 500 J and in a triple A dry cell about 5,000 J. The bullet requires 100 ms to complete 500 J of work; on the other hand, the triple A battery may complete 5,000 J of work in 6 hours. Hence, the power of the bullet is 5 kW while that of the battery is only 0.23 W. Therefore, the performance of the dry cell and the bullet will be better described by both power and energy terms. An important observation is that the battery cannot be made to perform like the bullet and the performance of each is a function of the rate of change of energy, which is a function of their design.

1.3 Reinforcement element strain rate

The time duration of a dynamic pulse in the rock mass depends on the failure process at the source. Every dynamic pulse is unique, as it is the result of different source mechanisms, with different transient times. Therefore, ground reinforcement and support components will experience unique loading patterns over unique time intervals. The duration of strain imposed on reinforcement elements is unlikely to be the same as the duration of the event source mechanism. During a disturbance, the strain rate will vary from initially zero to a maximum and then back to zero at the end of the dynamic disturbance.

There are several rock failure mechanisms that drive the strain and strain rate imposed on reinforcement elements. Bolt response will vary depending on which mechanism activates, and more than one mechanism can be activated simultaneously. The mechanisms include:

- Bolt strained by a kinetic energy loading (an ejection mode of damage where a single rock block fixed by the bolt is impacted, gains momentum, and is thrown into the excavation).
- Bolt strained by an imposed deformation (a strainburst mode of damage creating buckling and bulking of the rock mass).
- Bolt strained by rapid differential movements (a shakedown mode of damage, where movement arises due to the inertia of a loose block fixed by the bolt to a shaking rock mass).

For each of the above, the strain versus time envelope will be different. Time is a required parameter for proper description of the strain process in each case.

2 Types of reinforcement elements dynamically tested and evaluated

2.1 MD reinforcement elements

The MD bolt is a single-pass installation mechanical friction bolt, comprising a split tube with a 20 mm central bar and a wedge anchor arrangement at the bolt toe end. Once the bolt is fully driven into the hole, the bar is rotated at the collar end to activate a set of wedges that anchor the bolt toe into the rock (Figure 1).

The wedge assembly of the MD bolt activates and develops a point anchor which can expand (as the rock mass permits, up to 52 mm) to significantly increase the static load capacity of the bolt compared to a conventional friction bolt. The split tube is welded to the collar ring. When the bolt experiences tension, radial closure of the split tube occurs which reduces friction between tube and rock mass. More of the load is then carried by the point anchor, which eventually slips in the borehole. The first MD reinforcement elements were installed and evaluated statically at Fosterville Gold Mine in Victoria in 2011 and the reinforcement elements were found to slip under about 200kN static load (Krois 2011).

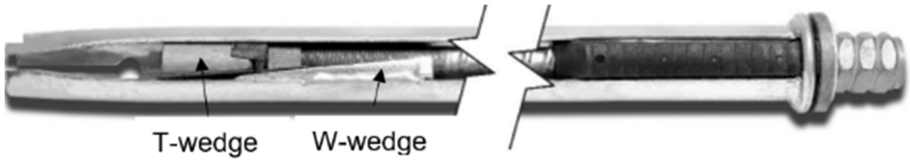

Figure 1 Sandvik MD reinforcement elements (Darlington et al. 2019)

2.2 MDX reinforcement elements

The MDX bolt is a single-pass installation bolt. The design of the MDX bolt comprises a similar friction and wedge expansion system to the MD bolt (Figure 2). The key differences between the MD and MDX reinforcement elements are the wedge assembly (which can expand up to 64 mm to enhance anchorage in softer rock) and the load transfer mechanism. The split tube is free floating and not welded to the collar ring, so it only acts as a carrier for the wedge anchor system. Under tension the load transfer is fully through the point anchor, and the split tube may potentially move into compression instead of tension, which increases its frictional resistance to movement. The MD bolt utilises both tube and rebar components to absorb load, whereas the MDX bolt relies solely on the rebar to absorb dynamic loads. The MDX bolt has high uniform elongation capacity, utilising the 2.1 m long free length of the rebar (for a 2.4 m bolt). Static tensile testing has demonstrated a 15% uniform elongation for the rebar, so over a 2.1 m free length, the bolt can elongate up to 300 mm prior to failure (Darlington et al. 2018).

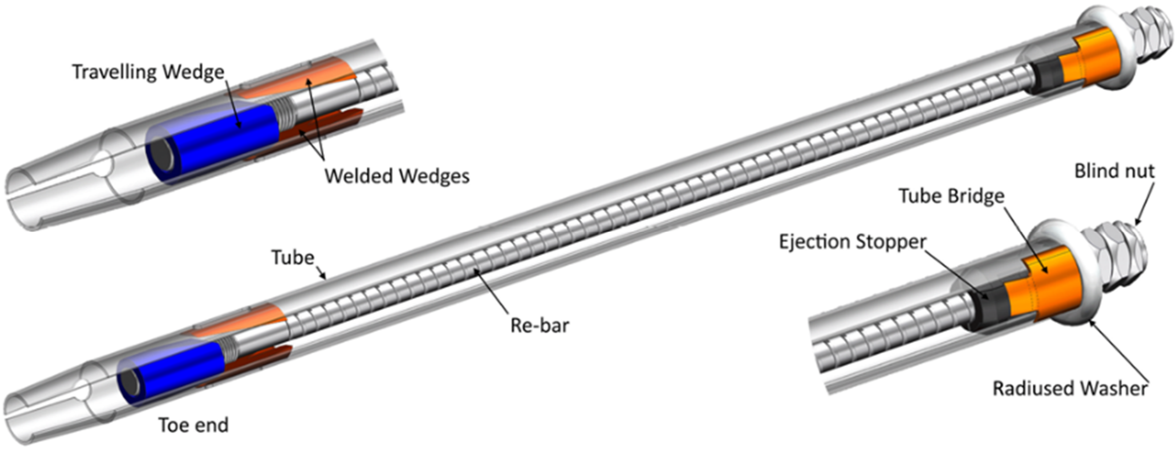

Figure 2 Sandvik MDX reinforcement elements (Darlington et al. 2023)

2.3 Posimix reinforcement elements

The Posimix bolt is a resin-anchored bolt utilising a spiral resin mixer coil around the bolt toe, and a debonding sleeve around the central portion of the bar (Figure 3). The operational challenges of this bolt include excessive loss of resin in broken ground, installation time, and quality of the installed bolt which depends heavily on the skill of the operator. The bolt is fully encapsulated with fast-set resin near the toe and slow-set resin for the remainder of the bolt (DSI Underground 2020a).

Figure 3 Posimix bolt (DSI Underground 2020a)

2.4 Kinloc reinforcement elements

The Kinloc bolt is a single-pass installation 47 mm diameter frictional mechanical point-anchored bolt installed in a 45 mm diameter borehole. It provides a toe anchorage which is limited by the small expansion that can be achieved as the cone is drawn into the split tube by the internal solid bar (Figure 4).

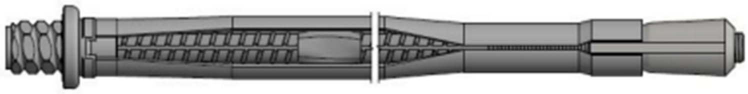

Figure 4 Kinloc bolt (DSI Underground 2020b)

3 Sandvik in situ dynamic test rig

The Sandvik in situ DTR, operational since 2013, has been subject to iterative enhancements in design and functionality (Darlington et al. 2018). Illustrated schematically in Figure 5, the rig employs the principle of free fall of a mass descending onto a plate to effect load transfer. Given the context of dynamically testing rock reinforcement elements embedded within a rock mass, a drop rod serves as the conduit for transferring dynamic loads to the test bolt. The drop mass, comprised of steel plates, can be adjusted to deliver impact energies ranging from 12 to 35 kJ (Darlington et al. 2018). Prior to testing, installed reinforcement elements are equipped with a dynamic pull collar. Reinforcement boreholes are drilled with attention to achieving near-vertical alignment.

Building upon insights collected from the initial prototype in situ dynamic testing, the Sandvik rig has made improvements in mitigating identified challenges (Darlington et al. 2019). This robust apparatus has the versatility to be mobilised to any mine site, facilitating the dynamic in situ testing of diverse reinforcement types across varied geological conditions. Certain features of this DTR have been patented.

A limitation of the DTR is the approximately axial configuration of the test loading arrangement. The in situ DTR directly measures the impact to and response of the element it is attached to. In actual seismicity, non-axial loading of the element due to various seismic loading directions and shearing within the rock mass is a common occurrence. The current DTR testing method applies load exclusively to the element collar and then evaluates the element's response. At its present stage, the DTR cannot replicate all possible seismic loading modes. Therefore, the underground dynamic test configuration should be considered a proof or index dynamic load test for an element. Additionally, the loading during testing is not instantaneous. The rate of loading varies depending on the DTR buffer configuration and the initial speed of the mass at the start of impact.

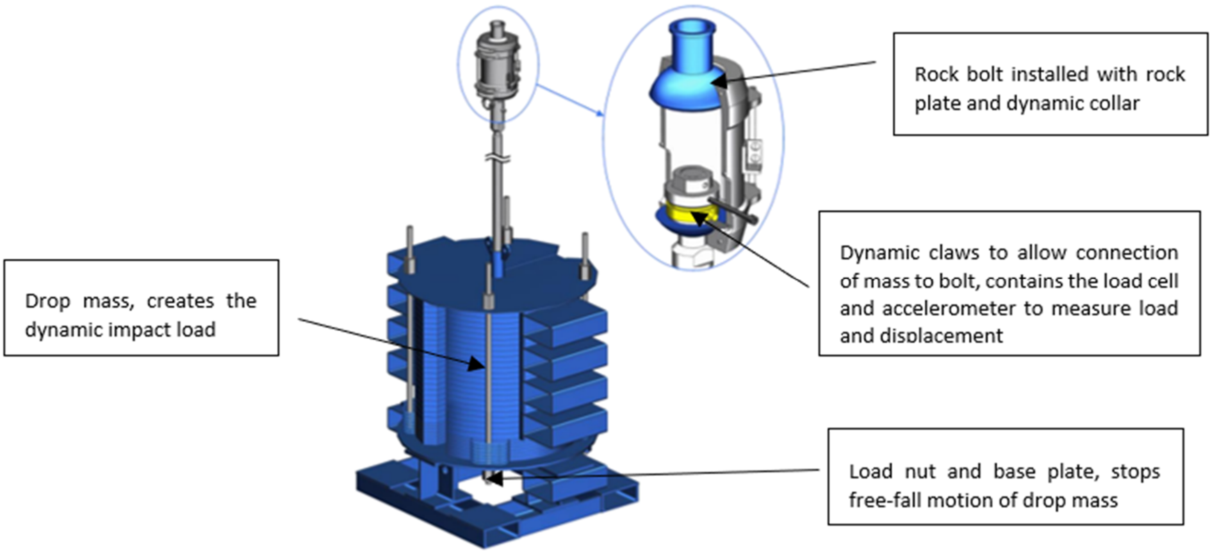

Figure 5 Sandvik in situ test rig components (Darlington et al. 2019)

4 Statistics analysis approach

4.1 Approach to dataset combination

The data provided by Sandvik originated from multiple test sessions at different mine sites and in different geomechanical conditions. Statistical analysis is required to validate the combination of data into single sets for analysis.

Combining similar datasets to establish confidence intervals, estimate values, or establish statistical distributions or goodness of fit is very attractive. Generally, larger data sets provide more information, allowing better estimates and refined values. However, this is only true if the data is consistent, of good quality, and comes from similar populations. Unfortunately concerning dynamic reinforcement elements, that is not always the case. For example, laboratory data of a dynamic reinforcement test could be combined with its corresponding in situ test data because the data may appear similar, but combining such data may not be valid, or be inefficient. It may introduce additional noise into the dataset, which increases the variance and subsequently increases the confidence interval uncertainty and size. For this reason, it is best to analyse datasets separately unless it is justified to combine them.

To justify combination of many different data sets, an exploratory data analysis of each set under consideration must be performed via tabular, graphical, and descriptive statistics to assess the data characteristics. This assessment establishes whether the population appears symmetric and unimodal or skewed. Then, prospective statistical distributions for the parent population are established, and estimates of the parameters are determined. Combining two or more datasets identifies the differences and similarities via confidence intervals and hypothesis tests for the parameters, such as the mean, variance, median, etc. Finally, in-depth statistical analyses of each dataset (such as analysis of variance, covariance, regression modelling, or goodness of fit tests) are performed to establish and quantify any statistical difference between the sets. It is proper to only combine those data sets that do not show large statistical differences between associated distributions and their parameters, and where other similarities can be established. In this study, the following are performed:

- descriptive and graphical analysis
- goodness of fit analysis via a nonparametric test
- agreement analysis via Bland–Altman Plot.

Parametric statistical procedures rely on assumptions about the shape of the distribution (i.e. assume a normal distribution) in the population and about the form or parameters (i.e. means and standard deviations). Nonparametric statistical procedures rely on no or few assumptions about the shape or parameters of the population distribution from which the sample was drawn. Table 1 gives an overview of parametric and nonparametric procedures.

Table 1 Parametric and nonparametric procedures applied to geotechnical test data

Analysis type	Parametric process	Nonparametric process
Compare means between two independent groups	Two-sample t-test	Wilcoxon rank-sum test
Compare means between three or more independent groups	Analysis of variance	Kruskal–Wallis test
Estimate association between two quantitative variables	Pearson coefficient of correlation	Spearman coefficient of correlation

In statistics, the actual test of data begins by considering two hypotheses: the null hypothesis (H0) and the alternative hypothesis (Ha). These hypotheses contain opposing viewpoints. The null hypothesis is a statement about the population that either is believed to be true or is used to make an argument, unless it can be shown to be incorrect beyond reasonable doubt. The alternative hypothesis is a claim about the population that contradicts H0 and which is concluded if that H0 is rejected.

A confidence interval is selected at which the test is performed, and this confidence interval represents a probability at which the null hypothesis is rejected. A confidence interval of 95% translates to a 95% probability that the true value lies within this range. A value outside of this range is expected to occur at a probability of 5% if sampling is random (Thomas 2013).

The significance level is denoted as α-value. Threshold of α-value set to determine the probability of rejecting the null hypothesis. The null hypothesis is rejected if the probability value (p-value) is less than the α-value; otherwise, it is accepted, while an alternative hypothesis is accepted if the p-value is less than the significance level (α-value). The p-value measures the probability of obtaining the observed results, assuming that the null hypothesis is true. The lower the p-value, the greater the statistical significance of the observed difference. A p-value of 0.05 or lower is generally considered statistically significant.

4.2 Bland–Altman statistical analysis

In many scientific and engineering problems it is necessary to display a statistical relationship between two or more sets of observations. The Bland–Altman plot (Bland & Altman 1986) is widely used to estimate how closely the values from two measurements lie, i.e. the agreement or reproducibility between measurements. In other words, the Bland-Alman analysis perceives a phenomenon but does not test it.

The Bland–Altman plot is a scatter plot of the difference between the two measurements (y axis) against the average of the two measurements (x axis); provides a graphical display of bias (mean difference between the two measurements) with 95% limits of agreement parallel to the mean difference line, as per Equation 1.

$$\text{Limits of agreement} = \text{mean observed difference} \pm 1.96 \times \text{SD of observed difference} \quad (1)$$

where SD is standard deviation.

Correlation is not synonymous with agreement. Correlation refers to a relationship between two variables, whereas agreement looks at the concordance between two measurements of the same scale. Two sets of observations, which are highly correlated, may have poor agreement; however, if the two sets of values agree, they will surely be highly correlated.

A critical issue in the Bland–Altman analysis is the need to meet the assumption of normal distribution. The continuous measurement variables need not be normally distributed, but their differences should be. If the assumption of normal distribution is not met, data may be logarithmically transformed (Giavarina 2015 and Doğan 2018). The data may be tested against the normal distribution using methods such as the Shapiro–Wilk test or Kolmogorov–Smirnov test. Also, visual evaluation of the histogram plot may not be satisfactory. Another problem arises from the sample size. Studies comparing methods of measurements should be adequately sized to conclude that the effects are universally valid, which in this paper is covered in Section 5. If the sample size is not adequate, it is possible to find a low mean bias and reduced limits of agreement by comparing two methods (e.g. Doğan 2018).

5 Statistical analysis of dynamic in situ test datasets

As the energy response, average response power and strain rate are obtained from the same in situ test, and since all three measurements for each test come from the same geological and ground condition, there exists an intrinsic relationship between them that can be studied from a statistical perspective. There could be either a negative or positive dependence between each measurement. Whatever the case, this dependence exists and cannot be neglected.

5.1 Combining data

For the statistical analysis, the data consists of strain rate, response energy and average response power. The data was obtained from eight mines numbered A to H shown in Table 2. There were insufficient data points for Kinloc or Posimix elements, so the statistical checks could only be applied to the MD and MDX elements.

In order to determine how the data from all case mines differ, the procedures mentioned in Sections 4.1 and 4.2 were adopted. First, the data of similar reinforcement elements were analysed for similarity to verify that it can be combined as a single set. Combining the data as a single set will give more information. Examination of the data showed that variations existed, and some of the group seem homogeneous while others differ.

The investigation was done by grouping data into pairs of the same measurements and analysing using the nonparametric Kruskal–Wallis method using XLSTAT software. The requirement for a combination to be valid is p-values must be greater than the respective α-values. In all cases both test p-values, obtained from the Kruskal–Wallis tests, resulted in calculations greater than $\alpha = 0.05$ meaning that combination is valid. Therefore, paired data for strain rate, response energy and average response power for each tested bolt were combined. The descriptive statistic for the combined data is summarised in Table 3.

Table 2 Dynamic in situ tests performed

Reinforcement element	Mine	Drops	Reinforcement element	Mine	Drops
MD	Mine A	10	MDX	Mine D	9
–	Mine B	9	–	Mine E	26
–	Mine C	8	–	Mine F	16
–	Mine D	11	–	Mine G	10
–	Mine E	6	–	Mine H	4
–	Mine F	8	–	–	–
Collar-loaded Posimix	Mine D	7	Kinloc	Mine D	4
–	Mine E	6	–	Mine E	7

Given that the normal distribution is restrictive and in general has several weaknesses for data not showing a normal distribution, the alternative nonparametric distribution test is employed in this study. Hence a normality test was undertaken after data were combined using the Kolmogorov-Smirnov GOF tests. In all cases the p-values obtained were less than $\alpha = 0.05$, indicating non-normal distribution. Likewise, the Akaike information criterion (AIC) (Akaike 1973) and the Bayesian Criterion (BIC) methods have been used as means of model selection of univariate distributions (e.g. Abdulai et al. 2023), although these do not constitute a formal goodness of fit test.

Table 3 Descriptive statistical analysis

Bolt type	Parameter	No. of observation	Min	Max	Median	Average	Standard deviation	Variation coefficient
MD	Strain rate (/sec)	52	0.08	5.05	0.97	1.24	0.82	66%
	Energy response (kJ)	52	10.0	23.2	17.1	16.4	3.36	20.5%
	Average response Power (kW)	52	31	823	187	237	173	73.1%
MDX	Strain rate (/sec)	65	0.57	1.58	0.74	0.78	0.16	20%
	Energy response (kJ)	65	16	29.7	25.2	24.8	2.54	10%
	Average response power (kW)	65	211	556	360	379	56	15%
Kinloc	Strain rate (/sec)	11	0.65	5.02	0.89	1.76	1.58	85.8%
	Energy response (kJ)	11	11	21	18.7	17.3	3.21	17.7%
	Average response power (kW)	11	55	346	163	186	109.1	56.1%
Collar-loaded Posimix	Strain rate (/sec)	13	0.000	5.01	0.76	1.19	1.27	121.6%
	Energy response (kJ)	13	3.3	19.5	17.1	15.7	4.60	28.2%
	Average response power (kW)	13	219	1,085	371	422	219.10	49.9%

In this study, four marginal distributions (normal, lognormal, gamma and Weibull) were adjusted to the data of statistically significant reinforcement elements to maximise their likelihood function. The suitability of each marginal distribution was compared through a goodness of fit test. The computed AIC/BIC values for all measurements and associated marginal distributions is summarised in Table 4. The bold font in the table represents the corresponding preferred distributions according to the AIC and BIC test, and their corresponding distribution curves are shown in Figure 6. The overall result is that it is valid to combine datasets from different mines.

Table 4 Akaike information criterion and Bayesian Criterion values of different marginal distributions

Bolt type	Parameter	Normal		Lognormal		Gamma		Weibull	
		AIC	BIC	AIC	BIC	AIC	BIC	AIC	BIC
MD	Strain rate (/sec)	130.2	134.1	**103.7**	**107.6**	231.3	233.2	120.1	122.1
	Energy response (kJ)	**277.7**	**281.6**	282.6	286.6	1,385.0	1,386.9	390.0	393.9
	Average response power (kW)	687.7	691.6	**668.4**	**672.3**	18,302.8	18,304.8	688.5	692.4
MDX	Strain rate (/sec)	-53.2	-48.8	**-73.3**	**-69.0**	-66.3	-61.0	-9.8	-7.6
	Energy response (kJ)	308.7	313.0	315.4	319.8	313.0	317.3	**250.3**	**254.2**
	Average response power (kW)	711.0	715.4	**707.3**	**711.6**	707.8	712.1	739.3	743.7

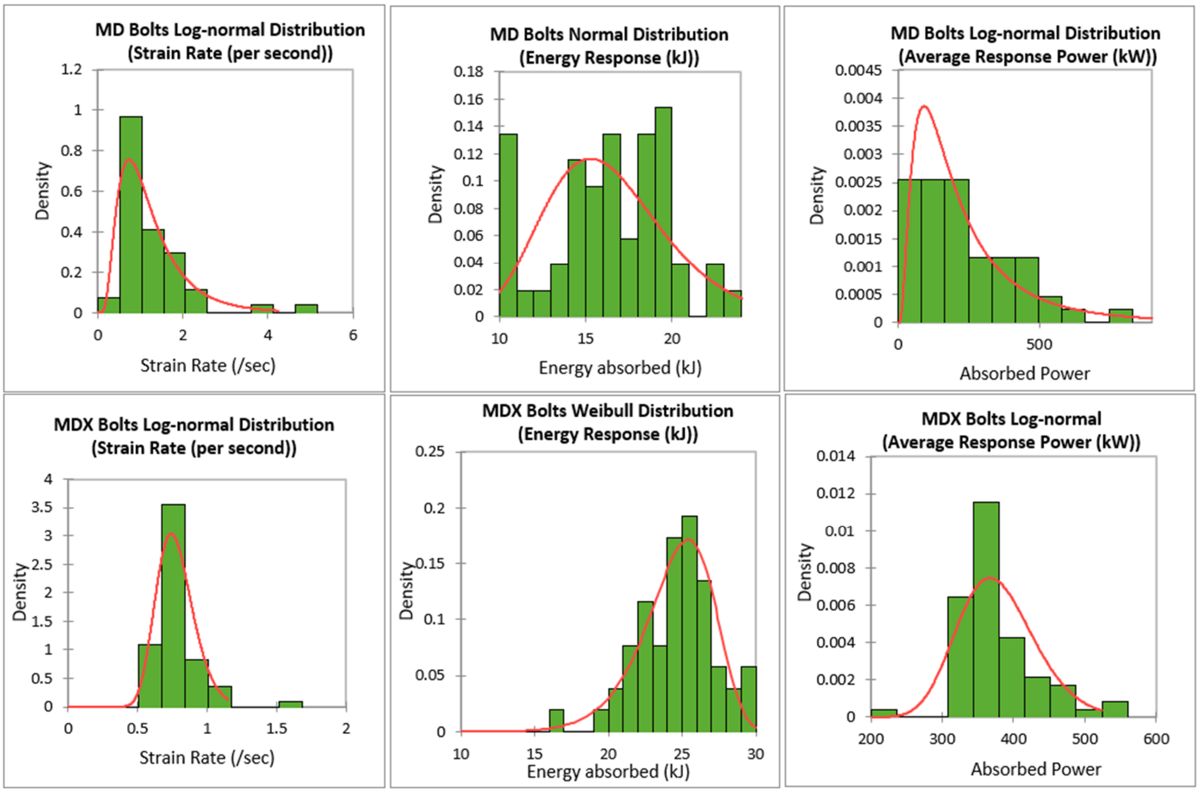

Figure 6 Probability/frequency histogram distribution of the preferred probability distribution fitting from Table 4

5.2 Bland–Altman plot

The agreement analysis perspective was examined using the Bland–Altman plot. The study comprises pairing data of similar scale from MD and MDX reinforcement elements. Descriptive statistics for the difference in strain rate, response energy and average response power for MD and MDX reinforcement elements are shown in Table 5. A study was conducted for the agreement between MDX and MD. SD was clearly smaller for MDX than for MD reinforcement elements.

Figure 7 show the classical Bland–Altman plots, supplemented by a regression line of the differences on the means. The vertical spread of the data was quite homogeneous across the measurements range (variance homogeneity), and the regression line suggested neither a positive nor a negative trend with increasing mean values.

To interpret the results, it is important to decide a priori about the level to which the error would be acceptable to the analysis. With reference to this study, less than 25% of the values lie outside the limit which indicates that there is agreement between the test results.

Table 5 Descriptive statistics for strain rate, response energy and average response power measurements of MD and MDX reinforcement elements

Parameter	N	Min	Max	Mean	SD
Strain rate (/sec) MDX	65	0.57	1.58	0.78	0.16
Strain rate (/sec) MD	52	0.08	5.05	1.24	0.82
Energy response (kJ)_MDX	65	16	29.7	24.8	2.54
Energy response (kJ)_MD	52	10	23.2	16.4	3.40
Average response power (kW) MDX	65	211	556	379	56
Average response power (kW) MD	52	31	823	237	173

In the study (Figure 7), a clear proportional bias is observed in the agreement between MD and MDX bolts. The bias plots close to zero for same strain rate, response energy and average response power values, with less than 25% of the values outside the limits. Variability is found to be proportional in all three measurements; however, the scatter plots are more random in average response power. This suggest that MD and MDX do not fully agree based on the measurements. The difference tends to be larger in response energy and average response power values than in strain rate.

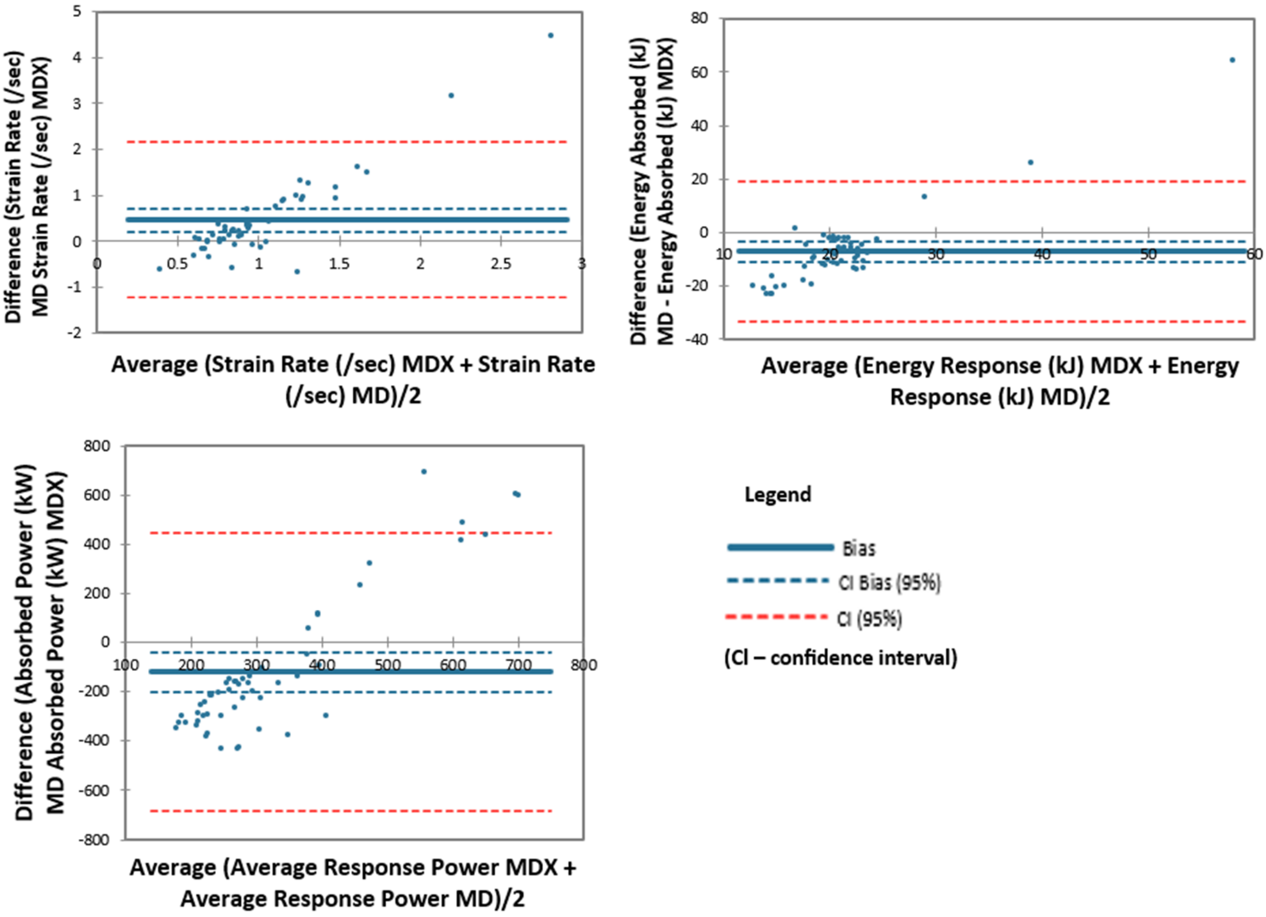

Figure 7 Classical Bland–Altman plot including the estimated limit of agreement and 95% confidence limits for MDX and MD

6 Power and strain rate study of in situ dynamic testing of MD, MDX, Kinloc and collar-loaded Posimix reinforcement elements

Response energy (absorbed energy) and displacement are two of the metrics commonly used to describe the performance of dynamically tested reinforcement elements. In this section, the time metrics of response power and strain rate are compared with response energy and displacement.

The data presented in this paper was provided by Sandvik from in situ DTR evaluations conducted on a total of 52 MD, 65 MDX, 11 Kinloc and 13 collar-loaded Posimix reinforcement elements, dynamically tested across eight distinct mine sites denoted as A to H. These tests encompassed four bolt types commonly employed within mining operations. The typical mass drop height employed during the test procedures was 1,500 mm, with variations ranging from 800 to 2,080 mm, to encompass a broader spectrum of potential loading conditions. Each test followed standardised procedures to maintain consistency. The methodologies employed in the DTR evaluations were rigorously designed to ensure robustness and validity in the assessment of the bolt performance across diverse mining environments.

6.1 Average response power and element displacement

The test time durations ranged from 10 to 515 ms. The relationship between the time taken to bring the mass to rest and the average response power exhibited an inverse correlation; as the duration increased, the average response power usually decreased as might be expected, and vice versa. Analysis in Figure 8 revealed disparities among the various bolt types, with MDX reinforcement elements demonstrating the highest correlation coefficient of 0.2596, while the other bolts showed comparatively weaker correlations. Figure 8 reveals distinct element failure characteristics among the tested reinforcement elements:

- Among MD reinforcement elements, the four elements experiencing pull-out failures all exhibited very low average response power, but response energy comparable to the majority of surviving elements. Pull-out did not correlate with response energy.
- Among MDX reinforcement elements, two experienced bar fracture at response energy of 27 kJ and 16 kJ, while one element experienced washer fracture at 24 kJ, yet these correlated well with the energy-power relationship of the survived elements. So, for the MDX reinforcement elements, bar fracture and washer fracture did correlate with response energy.
- Kinloc reinforcement elements were similar to the MD: the two elements pulled out had very low average response power.
- Among collar-loaded Posimix reinforcement elements, eight failed by bar fracture at lower response energy but similar or much higher average response power.

Power metric analysis shown in Figure 8 revealed significant average response power disparities:

- Survived MD, MDX, Kinloc and collar-loaded Posimix reinforcement elements exhibited maximum average power response of 822 kW, 556 kW, 346 kW and 390 kW.
- Failed MD, MDX, Kinloc and collar-loaded Posimix reinforcement elements exhibited maximum average response power of 50 kW, 500 kW, 50 kW and 1,085 kW. Only the MDX showed similar power levels for both survived and failed element groups.
- Wider scatter was evident for the MD and Kinloc elements, interpreted as the effect of variable frictional anchorage for these elements.
- The surviving collar-loaded Posimix elements plotted similarly to the low end of the MDX elements, interpreted as the similar yielding behaviour of the steel bar.
- The failed collar-loaded Posimix elements plotted rather different to the failed MDX elements. This is interpreted as the effect of the anchorage type. The MDX anchor is able to slip if under high load, and slip extends the test duration and reduces the test power whether or not the element survives. The Posimix collar-resin anchor cannot slip, so high load leads to rupture, a short test duration, and high power. This is because only the perhaps 200 mm collar section could stretch and absorb the dynamic load, instead of the intended 1,400 mm debonded section of the Posimix.

A total of 141 MD, MDX, Kinloc and collar-loaded Posimix reinforcement elements were dynamically tested and most of the elements were able to dissipate the imposed energy without failing; therefore, it is uncertain what might be the limiting higher response energy achievable in each case.

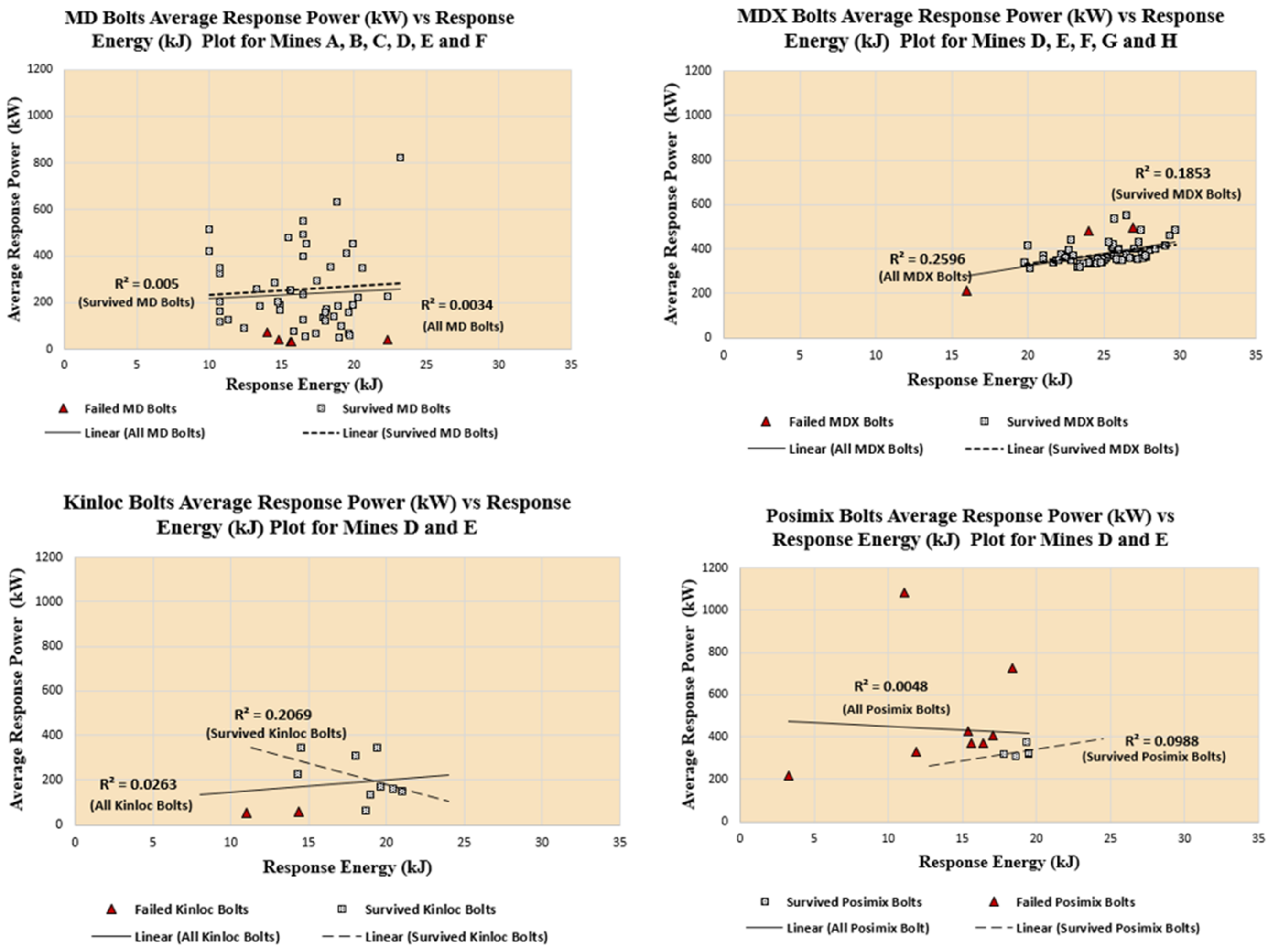

Figure 8 Average response power (kW) versus response energy (kJ) plots of MD, MDX, Kinloc and collar-loaded Posimix reinforcement elements

6.2 Average response power and an element displacement

Figure 9 shows average response power plotted against displacement for the reinforcement elements. MDX elements exhibited a tighter cluster compared to other elements, suggesting superior test repeatability. Conversely, other bolt types displayed dispersed or elongated clusters, indicating less repeatability. Figure 9 reveals the following relating to failed elements:

- Examining the failed MD and Kinloc reinforcement elements, they consistently demonstrated low average response power coupled with typical to very high displacement.
- Two of the failed MDX had typical response power compared to the survived elements. One failed MDX showcased a relatively higher displacement at failure (288 mm) yet a lower average response power of 211 kW, indicating that some anchor slip was possibly part of the element failure mode.
- Among collar-loaded Posimix reinforcement elements, the failed elements exhibited typical or higher average response power values and typical or lower displacements, with very wide scatter in both parameters. Although the dataset is small, there is indication that the collar-loaded Posimix may be unable to survive at response power levels higher than 400 kW.

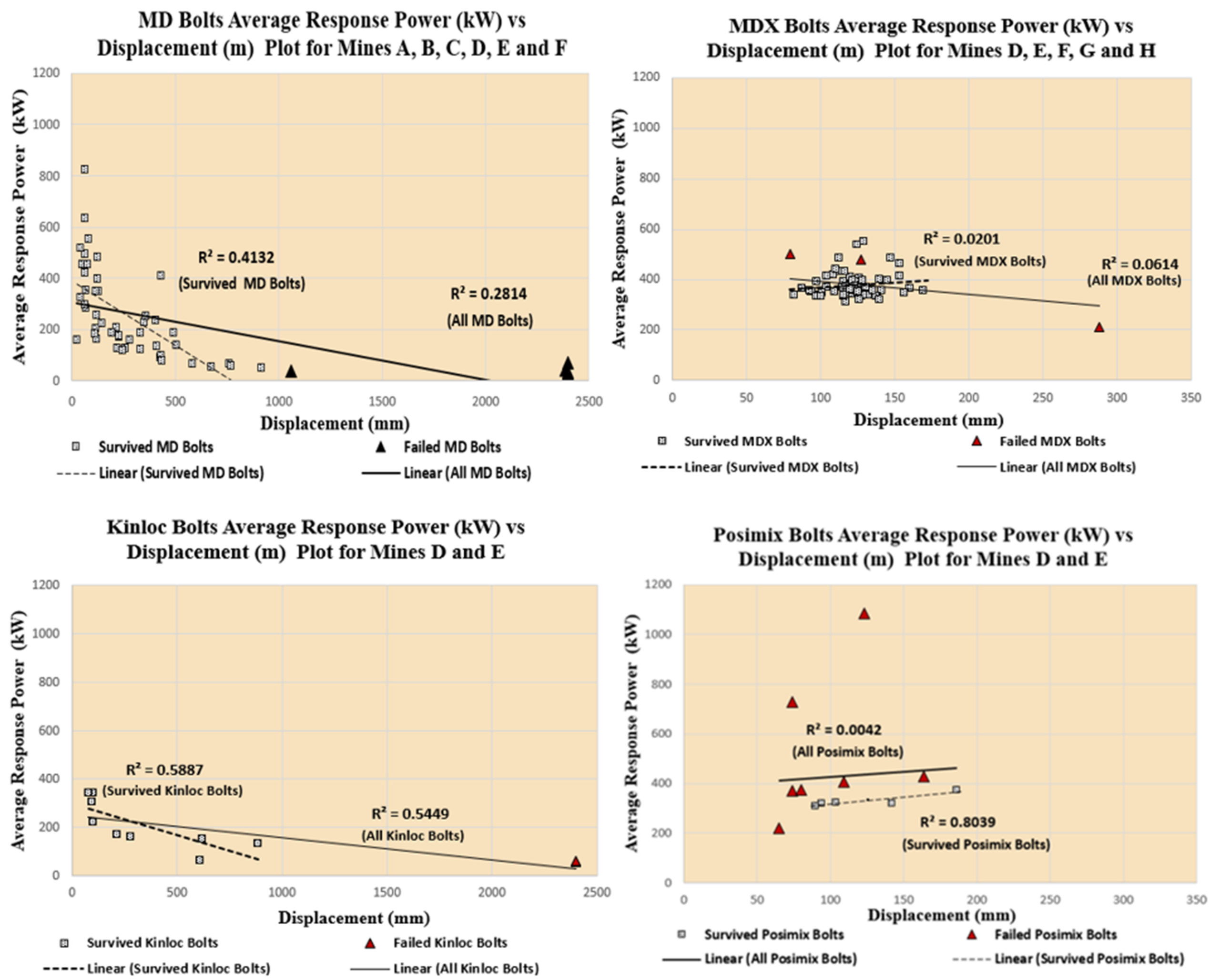

Figure 9 Average response power (kW) versus displacement (mm) plots of MD, MDX, Kinloc and collar-loaded Posimix elements. Note different displacement scales used for the MD and Kinloc elements

Regarding survived elements, Figure 9 reveals the following:

- The Kinloc did not exceed the 400 kW response power level, likely because slip in the borehole reduced the energy capacity of this element type.
- In contrast, the MD achieved more than double the power response of the Kinloc, and indeed greater power responses than the MDX or the survived collar-loaded Posimix.
- The MDX performed at a fairly consistent response power level of about 400 kW, and was the most consistent of all the element types.

6.3 Average response power and element strain rate

The strain rate, defined as the rate of elongation of a reinforcement element relative to its original length over time, serves as an additional metric in assessing performance of reinforcement elements. Several factors may influence the strain rate of tested reinforcement elements, including rock type, friction within the borehole, yielding mechanisms, and installation torque. Figure 10 reveals the following information about failed elements:

- The failed MD, MDX, Kinloc and collar-loaded Posimix reinforcement elements reached average strain rates of 2.4/sec, 1.1/sec, 4.7/sec, and 1.7/sec respectively.

- The failed Kinloc elements had high strain rates, indicating the high speed with which they were pulled from the borehole once the anchor was compromised. One failed MD bolt had similarly high strain rate, but the three other failed MD bolts did not.
- Failed MDX and collar-loaded Posimix had similar strain rates to survived elements (except for one collar-loaded Posimix that endured an extremely high strain rate).

Regarding survived elements, Figure 10 reveals the following:

- MDX reinforcement elements exhibited tighter clustering than all other tested dynamic reinforcement elements, showing reduced scatter and variability.
- The survived average strain rates were 1.1/sec, 0.8/sec, 1.1/sec and 0.9/sec for MD, MDX, Kinloc and collar-loaded Posimix reinforcement elements respectively. The MDX displayed the lowest average strain rate.
- MDX and collar-loaded Posimix reinforcement elements survived at similar lower strain rates, all less than 1.5/sec. This probably reflects the nature of yield of a steel bar, where there is an upper limit to strain rate that can be survived.

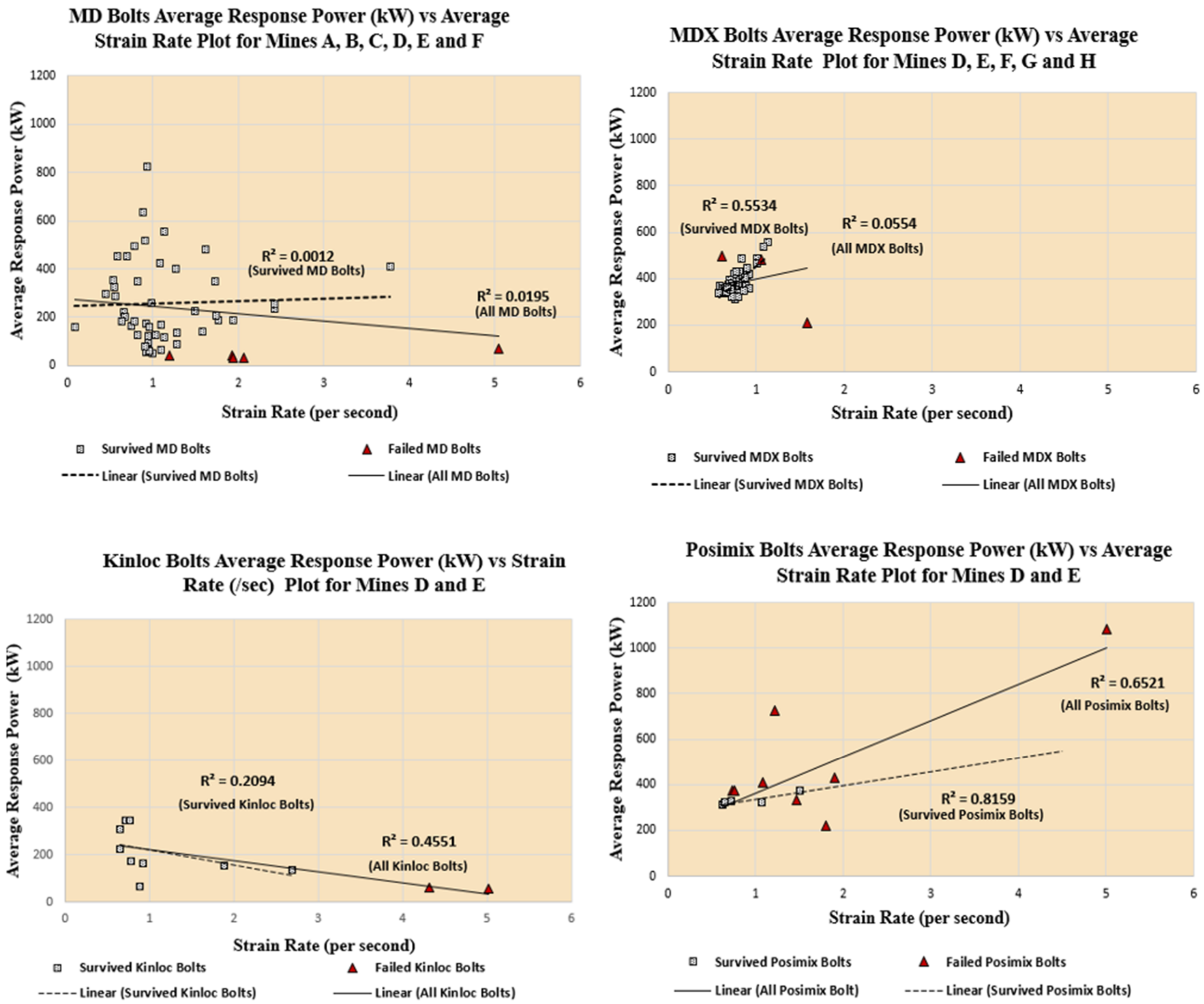

Figure 10 Average response power (kW) versus strain rate (per second) plots of MD, MDX, Kinloc and collar-loaded Posimix elements

7 Conclusion

Overall, the findings of this research show the value of the time-related parameters power and strain rate to improve understanding of dynamic reinforcement performance. The findings are of practical assistance for support selection in seismic conditions, for example:

- Clear differences exist between the different reinforcement element types examined.
- The MDX showed a tight cluster of power versus displacement values, indicating high repeatability of performance (small SD) and thus greater confidence for the practitioner in achieving that performance compared to the MD or Kinloc types.
- Anchored support types (MDX, Posimix) depending on steel stretch for yield appear to have an upper power limit they can accept, beyond which rupture occurs. The ground support system design should avoid placing high strain rate or high power expectations on those support types.
- Frictional support types (MD, Kinloc) slip easily and do not have the ability to sustain high power levels. High strain rates for these support types is an indication of pull-out failure.

Overall, the time-related parameters power and strain rate revealed additional information in terms of repeatability and performance of dynamic reinforcement elements to dynamic loading. These are additional tools to assist the site practitioner to select appropriate dynamic reinforcement for specific ground conditions.

Data was analysed from a total of 141 MD, MDX, Kinloc and collar-loaded Posimix reinforcement elements dynamically tested with the Sandvik in situ rig. Statistical analysis indicated that it was valid to combine the datasets originating from tests in different mines. The regression analysis revealed that MDX reinforcement elements exhibited the highest goodness of fit, as indicated by the coefficient of determination.

Analysis of the test data led to the following conclusions.

Hypothesis 1: Power and strain rate analysis would add additional value to describe the performance and capacity of reinforcement elements.

- The relationship between the time taken during a dynamic reinforcement test to bring the mass to rest and the average response power exhibited an inverse correlation.
- Data analysis revealed disparities among the various bolt types, with MDX reinforcement elements demonstrating the highest correlation between average response power and response energy.
- Energy analysis or power analysis on their own do not adequately differentiate among the performance of reinforcement elements, but time metric parameters enable better understanding of reinforcement element performance.
- The MD and Kinloc displayed somewhat similar power and strain rate patterns, but the MD responded with up to more than twice the power level of the Kinloc.
- The failed MD and Kinloc elements consistently demonstrated low average response power coupled with high displacement, which is a signature behaviour pattern arising from the frictional slip type of element yielding.
- Analysis of average response power versus displacement showed that MDX reinforcement elements exhibited a tighter cluster compared to other reinforcement elements, suggesting superior test repeatability. Conversely, other bolt types displayed dispersed clusters, indicating less consistency.
- Analysis of strain rate versus response power showed that MDX reinforcement elements exhibited significantly tighter clustering compared to all other tested elements.
- MDX and collar-loaded Posimix reinforcement elements operated at relatively lower average strain rates, registering 0.8/sec and 0.9/sec, respectively.

- The failed Kinloc elements had high strain rates, indicating the high speed with which they were pulled from the borehole once the anchor was compromised. One failed MD bolt had similarly high strain rate, but the three other failed MD bolts did not.
- Failed MDX and collar-loaded Posimix had similar strain rates to survived elements (except for one collar-loaded Posimix that endured an extremely high strain rate).
- MDX and collar-loaded Posimix reinforcement elements operated at similar lower strain rates. This probably reflects the nature of yield of a steel bar, where there is an upper limit to strain rate that can be survived.

Overall, evidence was found in support of this hypothesis.

Hypothesis 2: It is not possible to force a particular element to accept a higher power level than it can sustain according to its design.

- Among MDX and collar-loaded Posimix reinforcement elements, those failed or slipped exhibited much higher average response power values compared to the failed MD and Kinloc. This is related to the bar stretching type of yield mechanism.
- One MDX bolt showed mixed performance with both bar stretch and frictional slip occurring.
- Although the dataset is small, there is indication that the collar-loaded Posimix may be unable to survive at response power levels higher than 400 kW.

Overall, evidence was found in support of this hypothesis.

Acknowledgment

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