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Performance testing of various dynamic bolting element designs

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Abstract

The ability of ground support elements to take the demands of sudden and severe service loads continues as an increasing requirement for geotechnical application within the underground hard rock mining industry. Large amounts of energy can suddenly be released through the rock mass as stresses are redistributed – and at times violent ground movement can occur. Based upon the need to address such geotechnical demands, dynamic ground support remains an important area of continued study and research. While geotechnical design is the overarching discipline, the mechanical response of ground reinforcements is equally critical to understand and apply within this field.

The requirement for this unique area of research is fundamentally driven by differences in mechanical performance that are observed under varying loading rates and scenarios. The mechanical response of ground support elements under rapid loading typically differs from the results of test work that is conducted at low loading rates. As such, performance assumptions that are based on low-speed mechanical test work may not be completely relevant within the context of a dynamic event.

This paper provides an overview of a recently developed test rig for the dynamic testing of hard rock bolting elements. This rig has been used to explore the dynamic performance of a number of different classes of bolting elements and, further to this, to evaluate the performance of the anchoring and embedment media that is utilised in association with the bolting element. An overall summary of the test work is provided, covering mechanically anchored bolts, resin anchored bolts and cementitious grouted bolts. This appraisal clearly shows that bolt installations must operate as a complete system: the mechanical response of the bolting element is only proportionate to the anchoring strength of the embedment media.

Keywords: *dynamic testing, drop test, rockburst, dynamic rock bolts*

This paper is a newly revised form of an original publication by the same author within the proceedings of the Ausrock Conference 2022, Melbourne, Australia (Evans 2022). Reproduced content from the author is with the permission of the AusIMM. An updated dataset including more recent test work is now provided.

1 Introduction

The requirement to develop in-house capability for the dynamic testing of rock bolt elements has been driven by the increased demand for performance data that is directly related to the mechanical design, anchoring media and geotechnical application of the bolt element. This increasing demand for performance data directly aligns with the need to increase the speed of product development activity for dynamic rock bolt elements; without this critical performance feedback, product development cycles become constrained. Against this background, a project was commenced to develop a test rig design which provides provisional in-house capability to test rock bolt elements under dynamic loading conditions on reinforcement elements used in ground control.

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Alignment with existing test methods was seen as an important consideration in the positioning of this project. Two predominant methods are well documented: the 'momentum transfer method' (Thompson et al. 2004; Player 2012) and the 'direct impact method' (ASTM International 2008; Li et al. 2021). In both methods the rock bolt element to be tested is installed within a test pipe housing, seeking to simulate the conditions of an underground bolt installation. Both methods utilise test masses falling through a pre-determined height to apply dynamic loads under gravitational acceleration and subsequent impact. Given the momentary time frames involved with the test, high-speed data-capture systems are also used, at varying degrees of complexity, to measure event parameters and ultimately permit energy calculations of the bolts' performance.

For the momentum transfer method, the test pipe housing, test beam and test mass are structurally linked and are released as a combined assembly under gravity. The combined assembly falls until the test beam strikes impact buffers, with momentum from the test mass subsequently loading up the test piece. For the direct impact method, the test pipe housing is held stationary and the test mass, upon release, falls along the length of the test element, striking impact plates attached to the base of the test element. A comprehensive reference for this method (provided by Li et al. 2021) details work on calibrating dynamic test rigs between laboratories and encourages effort towards the standardisation of test methods. While it is important to understand that two test methods exist, and that there are structural differences between these two methods, it is not within the scope of this paper to provide a detailed and critical evaluation of them.

For data cross-validation purposes, advantages were seen in aligning the design of the new test unit with the momentum transfer method and to also utilise the 'split pipe' technique. Fundamentally, greater potential existed to crossmatch test data in common with tests conducted by the Western Australian School of Mines (WASM), an important consideration for the project. Further to this, a new design concept arose that permitted the development of a simplified, flexible and cost-effective test rig which also aligned with the momentum transfer method. WASM's recognition as a testing authority in this field of research further consolidated alignment decisions and this direction was subsequently taken for the project.

The overall goals of the project were to:

- provide a drop test mechanism to enable dynamic loads to be induced onto a bolt element
- permit high-speed data capture for both force and displacement
- permit dissipated energy to be calculated
- provide digital analysis and associated reporting of the test
- permit physical inspection of post-test specimens
- to provide such facilities in a relatively flexible and low-cost capital solution.

The new rig was to permit provisional testing for product development work while maintaining test work relationships with independent test facilities.

2 New dynamic test rig design

2.1 Structural overview

The design for the new dynamic test rig is shown in Figure 1. The entire assembly consists of:

- an external structural frame predominantly featuring four vertical columns and a base in the form of a circular annulus
- the steel test pipe, which is grouted internally, cured and then drilled to house the installed rock bolt element. The steel wall of the test pipe is circumferentially cut around the mid-point, defining an upper test pipe and a lower test pipe. This circumferential cut simulates a geological fault or discontinuity where the mid-portion of the bolt will be subjected to dynamic loads during the test

- the test mass, connected to the lower test pipe and with its profile guided under a generous clearance within vertical channels attached inside the external frame.

The entire structure is approximately 3.8 m in height and 1.9 m in diameter, and weighs 2.1 t, excluding the weight of the test mass. On conducting a test the entire assembly is raised vertically by the upper lift point to a pre-determined height above a levelled sand bed. The assembly is then released using an electronically triggered quick release mechanism and falls under gravitational acceleration. The annular base of the test frame impacts the sand bed which buffers and arrests the fall, rapidly decelerating the test frame and upper test pipe. The lower test pipe takes loads under the continued forward momentum of the test mass. These opposed forces from the impact subsequently act at the mid-point discontinuity in the test pipe, bringing dynamic loads directly onto the installed rock bolt.

The structure has been designed to take test loads up to at least 500 kN (notionally 50 t). A finite element analysis (FEA) of the structure was conducted under static loading scenarios at 500 kN and the peak deflection of the structure was shown to be in the order of 0.7 mm at this load. Rigidity or stiffness of the structure is certainly an important consideration, particularly given the high-speed force oscillations that will occur during dynamic impact. However, this static FEA analysis is a reasonable indicator of the load-bearing performance of the test frame structure. It should also be noted that dynamic test loads for typical rock bolting elements are more in the order of 300 kN, so this adds further headroom within this loading and deflection scenario.

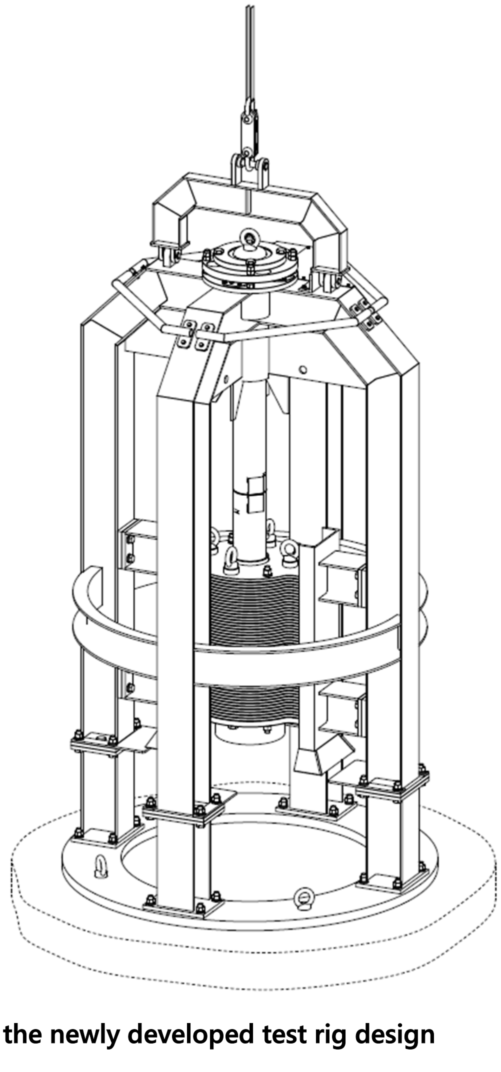

Figure 1 A perspective view of the newly developed test rig design

2.2 Test mass weight, drop height and impact velocities

The test mass weighs approximately 2,003 kg, with the total weight being further amended to include the weight of the lower test pipe assembly. With the test mass being held constant, the selected drop height is used to vary the amount of input energy under gravity. The drop height is measured using a laser distance gauge accurate to the order of 1 mm. Drop heights typically range between 2.0 and 3.5 m, meaning that theoretical impact velocities vary between 6.3 and 8.3 ms^{-1}. While impact velocities subsequently become a secondary variable, it is of worthwhile note that the linearity of test results does not appear to be affected by increasing energy input through increased drop height (refer to the data summary section of this paper).

2.3 Test mass total displacement and theoretical energy

The theoretical energy input is determined by the total displacement that the test mass moves through during the test. The total displacement is the sum of the drop height, the post-test gap at the test pipe discontinuity and the embedment depth of the test frame footing into the sandpit. The theoretical input energy is then simply calculated as:

$$E = m \times g \times h \tag{1}$$

where:

E = theoretical energy input (J).

m = mass (kg).

g = gravitational acceleration (ms^{-2}).

h = test mass total displacement (m).

2.4 High-speed measurement, analysis and reporting system

Two primary parameters are measured during the dynamic test event:

1. the force acting on the rock bolt element (kN)
2. the associated displacement at the discontinuity in the pipe (mm).

Both force and displacement are measured in line with event time, recorded to an accuracy of 0.02 milliseconds (msec). Force is measured using a load cell array positioned between the upper part of the test frame and the upper test pipe. Displacement is measured using a high-speed digital camera and image processor, digitally recording two targets that are positioned at the pipe discontinuity (above and below the split). From the test data a force versus displacement curve is produced. This curve is subsequently utilised to calculate the captured energy (kJ) which equates to the area under the curve, or the integral of force with respect to displacement.

Rates of data capture are at 50 kHz for the load cells and at 7 kHz for the high-speed camera from which displacement measurement is provided. The load cell readings, being captured at higher rates, are then compiled into averaged data packets that meet the frequency of the camera speed. This correctly matches the force versus displacement data relative to the event time.

An example test curve from the new test facility is shown in Figure 2. Upon processing the captured data, two force versus displacement curves are produced: the first shows the raw dataset and the second charts a smoothed curve derived from the raw dataset. The data smoothing ‘moving average’ is separately adjustable for both the force dataset and the displacement dataset. The moving average values remain associated against a common event time before being brought together in a final smoothed force versus displacement curve. A third curve, for cumulative energy, is also produced using the trapezoidal method to progressively calculate the area under the smoothed force versus the displacement data curve. The use of the smoothed dataset here subsequently provides a slightly conservative calculated energy value. These three test curves are all mapped together, relative to the event time and in sequence with the high-speed video footage.

Note that if the displacement reverses at the end of the test due to spring back of the bolt element, the energy calculation ends at the point of the reversal. Any further data measurement is subsequently excluded from the energy result.

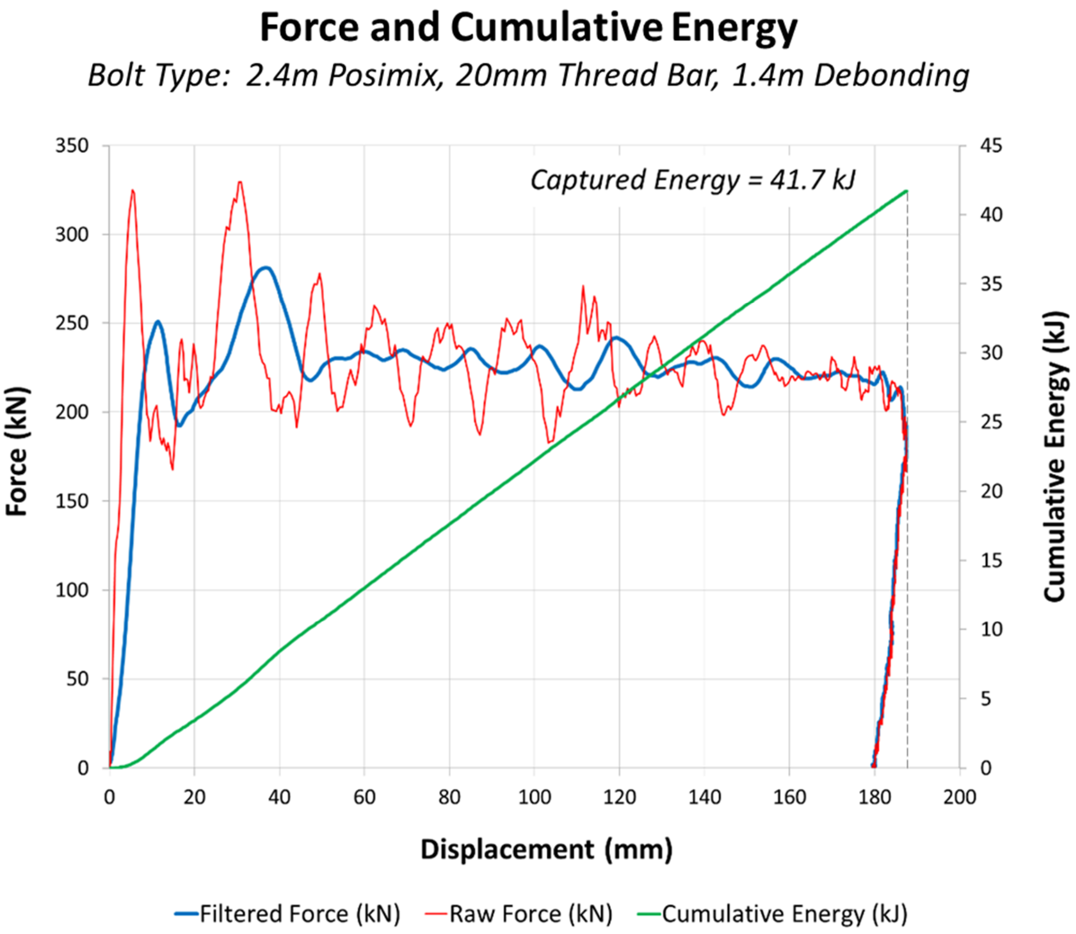

Figure 2 **An example test curve from the new drop test facility showing the captured energy at the point of peak displacement**

2.5 Energy capture and external losses

The test rig is currently capable of capturing up to 77 kJ of measured energy from the rock bolt element in a single test event, with a corresponding displacement of 295 mm. The captured energy from the test is then compared against the theoretical energy input as a percentage of energy capture efficiency. It is known that energy is lost out of the system during the test in the forms of vibration, noise and heat. However, it is highly complex to directly measure these losses and an intentional decision was made to exclude this aspect from the project scope. Of further note is that the rock bolt element is typically pre-tensioned during installation into the test pipe, as per the underground installation methods used for these bolt types. Subsequently a small portion of the energy capacity of the rock bolt element will be taken up under applied pre-tension.

2.6 Instrument calibration

Calibration checks of the system are conducted to ensure measurement accuracy is maintained. The load cell array is periodically cross-checked using a calibrated universal test machine to apply static compressive loads, ensuring that the load cell outputs remain both linear and accurate across their full rated capacity. Within the history of this project there has been no observable drift. It is noted that discussion exists about the performance of load cell strain gauge technology versus piezoelectric technology regarding high-speed signal processing (Li et al. 2021; ASTM International 2008). While acknowledging that different perspectives exist concerning this matter (Tacuna Systems 2022), the strain gauge technology that is employed within the new test rig design appears to provide repeatable high-speed data capture. A simple advantage of strain gauge technology is that static loads are witnessed and measured both before and after the dynamic test loads have been captured. Note that during free fall the mechanical design of the new test rig permits the load cells to return to zero prior to impact.

The accuracy of displacement measurements from the high-speed video camera are of equal importance. The video system will capture around 1,400 individual still images through the course of a typical test. In post-event data processing, digital recognition software is used to identify the two displacement targets in each image, then to further locate calibrated measurements embedded within the targets and use these calibrated measurements to determine the axial distance between the two targets. This digital recognition process is repeated in turn, image by image – identify, calibrate and measure – so that no single image can fall out of calibration and return an incorrect result. This digital recognition technique also negates any concerns with offset movement, bounce or vibration during the test as every displacement measurement is based on a calibrated still image. The results returned via this digital method provide very fluid displacement versus time curves, a further indication of repeatability and accuracy.

2.7 Deceleration on impact (buffering)

The sand pit is used as the method of deceleration for the test frame on impact. While this may initially be perceived as a rudimentary method, a number of considerations are taken into account to ensure repeatability and adequate buffering response. The sand is kept dry and clean from any form of contaminant to ensure that the sand properties remain consistent and homogeneous. The sand is also maintained to a constant depth within the pit and is levelled prior to every test, which further provides a levelled reference point from which to measure the drop height. The geometric shape and surface area of the base of the test frame is never modified or adjusted, so that immediate contact pressures between the frame footing and the sand buffer are consistent. Following each test, embedment depths of the frame footing into the sand are also measured to provide a physical check of repeatability relative to the drop height.

While buffering pressures through the sand are not directly measurable, the associated response from the high-speed test data is readily captured and measured. The primary measurement relating to buffering performance is the time duration (msec), taken from the initial impact or onset of load through to the first peak in force (kN) and measured from the force versus time test data. From test curves given in Li et al. (2021) the time to first peak force is shown to be in the order of 5 to 10 msec. By comparison, the new rig and sand buffer has generated time to first peak values in the order of 4 to 9 msec. While methods and bolt types differ, the time to the first peak in force falls within a similar range. Based on the physical conditions that are maintained within the sand buffer, as well as test data from the time to first peak in force, there is strong indication that the sand pit provides a suitable buffering response and time-based onset of load.

2.8 Rock bolt element mechanical response

A further reference measurement is the initial gradient (kN/mm) to the first peak in the force versus the displacement test curve. This is an indicator of the stiffness of response of the bolt sample and has been designated as the value ‘K’ (Li et al. 2021). K values are influenced by both the bolt type and installation conditions. For example, the embedment media used applied pre-tensioning and any mechanical take up in the installation. Higher K values indicate a stiffer response or an increased onset of load with respect to displacement. K values in the order of 11.4 to 22.0 MN/m across four different test rigs, using the same bar type and with each rig using the direct impact method, were reported by Li et al. (2021). By comparison, the new drop test method into the sand buffer has returned K values in the order of 13.2 to 53.2 kN/mm across a number of different rock bolt types. Note that MN/m as a unit of measurement directly equates to values reported in kN/mm. A comparison of reported K values across test rigs provides a good indication that the stiffness of the onset of load provided by the sand buffer induces a mechanical response in the rock bolt element of a similar order.

3 Dynamic test results

3.1 In-house test work – overview

Using the new test rig design a series of test work has been conducted across five different rock bolt types. Note that additional data is now contained in this updated report, supplementing previous publications (Evans 2022).

The primary purpose of this test work has been to gain a level of statistical confidence in the capability of the new rig design, including its accuracy, and also to supplement previous publications. The performance of each bolt type has also been evaluated and, as an extension to this work, where test results were held in common with WASM, a comparison of relevant test data was of interest to further evaluate the new test rig system.

A brief description of each bolt type is provided below:

- Bolt type 1 – a solid threadbar bolt design (20 mm Dynamic Posimix) installed using a polyester resin cartridge as the encapsulation media. The bolt was 2.4 m in length and had a 1.4 m-long mid-region debonding tube. Typical mechanical properties for the bar material are 725 MPa tensile strength and 21% elongation at fracture. Five tests were conducted on this bolt design.
- Bolt type 2 – a mechanical point anchored friction bolt (Kinloc Indie) having no encapsulation media. The point anchored friction bolt was 2.4 m in length. Typical mechanical properties for the bar material are 680 MPa tensile strength and 20% elongation at fracture. Twenty tests were conducted on this bolt according to a first design (denoted as Mk1).
- Bolt type 3 – following revisions to the mechanical point anchored friction bolt design (Kinloc Indie) a further 10 tests were conducted according to this second design (denoted as Mk2), also 2.4 m in length. Typical mechanical properties for the bar material are 680 MPa tensile strength and 20% elongation at fracture.
- Bolt type 4 – a solid roundbar bolt design (Dynamix) installed using a polyester resin cartridge as the encapsulation media. The bolt was 2.4 m in length, includes mixing wires as well as upper and lower anchoring deformations, and has a 1.4 m-long decoupled mid-region of smooth roundbar. Typical mechanical properties for the bar material are 680 MPa tensile strength and 22% elongation at fracture. Nine tests were conducted on this bolt design.
- Bolt type 5 – a solid threadbar bolt design installed using cementitious grout as the encapsulation media. This threadbar had a nominal 28 mm diameter and was 2.7 m in length, with a 1.0 m-long mid-region debonding tube. Mechanical properties for the bar material are estimated at 500 MPa tensile strength and 26% elongation at fracture, however, these values are based on a limited dataset. Based on this less certain position the associated subset of dynamic test data has been excluded from the linear regression shown in Figure 3. Three dynamic tests were conducted on this bolt design, with results that remain of interest to the overall program.

Being for in-house test work purposes, the bolts were all supplied by DSI Underground Australia. Across all five product types, 47 tests were conducted in total.

3.2 In-house test work: discussion of results

The results of the test work for each individual bolt type are discussed below, in reference to an overall summary chart provided in Figure 3. This chart denotes each individual test result and is further grouped by bolt type. The individual test results report the dissipated energy (kJ) at the point of peak displacement of the pipe discontinuity (mm), as represented by the example of Figure 2. The captured energy is the energy measured by the high-speed data capture system and is not simply the theoretical gravitational energy from the drop height. All reported results are from a single impact event and there are no ‘cumulative’ or ‘multiple repeated drops’ on the same bar element.

For further clarity, note that 'stable' results are classified as tests where there was no failure or rupture of the bolt element or dislodgement of the anchoring system. 'Bar rupture' results are classified as tests where the bolt installation was anchored and loaded to the point of fracture of the steel bolt element. In this instance the captured energy and displacements are measured right at the point of bar rupture.

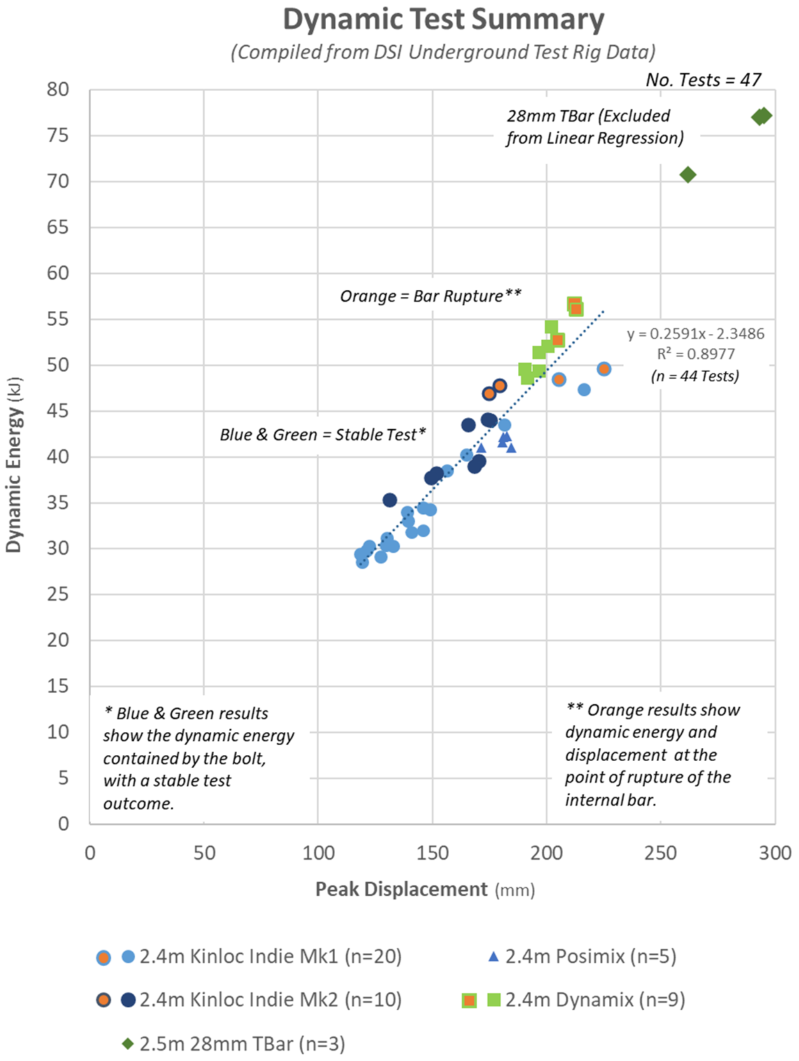

Figure 3 Summary of results from the newly developed test rig

3.2.1 Bolt type 1 results

The 20 mm Dynamic Posimix design has had five tests conducted in total, with this subset of data being denoted as a mid-blue triangle shown within Figure 3. This sub-program of test work was conducted comparatively early in the overall program, and with the five tests being intentionally released from the same drop height to best maintain all test variables as being constant. The captured energy results ranged from 41.06 to 42.25 kJ, with peak displacements at the pipe discontinuity ranging from 171 to 182 mm and all results being stable. This tight cluster of data clearly indicated a highly repeatable outcome very early in the overall program.

3.2.2 Bolt type 2 results

The Kinloc Indie (Mk 1 design) has had 20 tests conducted in total, with this subset of data being denoted as a light blue circle shown within Figure 3. Initial results from a first series of test work returned captured energy results from 28.52 to 31.10 kJ, with peak displacements at the pipe discontinuity ranging from 118 to 132 mm and this initial test work revealing a tight cluster of stable results. Further test campaigns were subsequently conducted with the input energy being progressively increased in order to test the performance limits of the bolt. A linear trend in the captured energy results became apparent, with a peak stable result being ultimately returned at 47.36 kJ/216 mm. Bar ruptures were observed at 48.50 kJ/205 mm as well as at 49.61 kJ/225 mm, with these two results being indicated as an orange and light blue circle in Figure 3. Upon post-test sectioning and examination of the test pieces there was no observable evidence of slippage of the anchoring elements, further supporting the linearity of results across this sub-program of test work. Summarily it indicated that the performance limit of the bolt conservatively resides in the range of 40 to 45 kJ, but with an additional factor of safety to be applied in practical application.

3.2.3 Bolt type 3 results

The Kinloc Indie (Mk 2 design) has had 10 tests conducted in total, with this subset of data being denoted as a dark blue circle shown within Figure 3. Stable results from this test work ranged from 35.39 kJ/131 mm through to peaks of 44.07 kJ/174 mm and 44.00 kJ/175 mm. Bar ruptures were recorded at 47.80 kJ/179 mm and 46.94 kJ/175 mm, with these two results being indicated as an orange and dark blue circle in Figure 3. A strong linear trend is again shown in the dataset but with slightly reduced displacements for this specific test program. Upon post-test sectioning and examination of the test pieces there was no observable evidence of slippage of the anchoring elements, further supporting the linearity of results across this sub-program of test work. It is to be noted that this specific test program was conducted during the Australian mid-winter, with the results potentially being influenced in part by cooler ambient temperatures at 5° Celsius. This aspect will be investigated within future work. Note that the same bar material grade and free length were used in both the Mk1 and Mk 2 designs so the two datasets are comparable in this regard.

3.2.4 Bolt type 4 results

The Dynamix bolt has had nine tests conducted in total, with this subset of data being denoted as a light green square shown within Figure 3. This dataset has six stable results at up to 54.18 kJ/202 mm and three bar ruptures at 52.75 kJ/205 mm, 56.67 kJ/212 mm and 56.10 kJ/213 mm; these being indicated as an orange and light green square in Figure 3. Upon post-test sectioning and examination of the test pieces there was no observable evidence of slippage of the anchoring elements. This subset of data is also tightly linear and displays a trend towards the upper performance limit of the bar.

3.2.5 Bolt type 5 results

The 28 mm threadbar bolt design has had three tests conducted in total, with this subset of data being denoted as a dark green diamond shown within Figure 3. While this is a limited dataset there are three stable results within a data cluster at 70.76 kJ/262 mm, 77.19 kJ/295 mm and 77.00 kJ/293 mm. This sub-program of test work effectively reached the upper limit for displacement at the pipe discontinuity of 295 mm due to travel constraints of the test mass above the sand buffer caused by the slightly longer bolt format, being 2.7 m rather than 2.4 m. Due to this constraint the upper limit of this bolt design could not actually be determined. Of particular note, however, was that the new rig showed its capability to capture up to 77kJ of energy.

3.3 In-house test work – data summary

Results from the 47 tests were graphically compiled into a summary chart as provided in Figure 3. This chart shows the relationship between the captured dynamic energy (kJ) of the rock bolt relative to the peak displacement (mm) measured at the pipe discontinuity during the dynamic event. Subsequently each individual test is represented as a single data point on this summary chart. The five different bolt types are denoted as different data series, overlayed together as indicated in the chart legend. The results are further classified as either ‘stable’ or ‘bar rupture’ as described in section 3.2, with orange data points used to indicate bar rupture.

For bolt types 1, 2, 3 and 4, a linear regression analysis was conducted across 44 tests, returning an R^2 value of 89.77%. This indicates a strong statistical relationship between the individual test points and the calculated line of best fit, and fundamentally expresses a strong linear trend in the test results. While this dataset incorporates four different bolt types it is of note that the steel grades used within these four bolt types are each of similar base mechanical properties. While bolt type five remains of interest it is excluded from this statistical analysis, given the limited base mechanical data.

To produce a linear trend of this nature across the tests, the instrumentation involved must return both repeatable and accurate values. If force and displacement measurements are unreliable this will produce a greater scatter and misalignment between comparison data. Subsequently the dataset indicates high levels of repeatability in both the bolt type and the anchoring media performance, as well as in the measurement capability of the new dynamic test rig design, providing high confidence in the measured results.

3.4 Corresponding Western Australian School of Mines' results

Dynamic test work for two rock bolt designs is held in common with WASM. The first is the solid bolt design referenced above (Dynamic Posimix), having a 2.4 m length and 1.4 m debonding tube, and anchored with a polyester resin cartridge. Three tests of this specific bolt format (Villaescusa et al. 2023, p. 152) were conducted by WASM. The second is the mechanical point anchored friction bolt (Kinloc Indie Mk1), having a 2.4 m length, with five tests in total of this specific bolt format being conducted by WASM (Villaescusa et al. 2023, p. 137). All rock bolt parameters are identical between the in-house test program and WASM's test work to ensure that the cross-correlation of data provides a true and direct comparison.

Results from the eight WASM dynamic tests are compiled into a summary chart provided in Figure 4. This chart shows the relationship between the captured dynamic energy (kJ) of the rock bolt relative to the peak displacement (mm) measured during the dynamic event, with each individual test being represented as a single data point on the chart. A linear regression analysis was conducted across the eight tests, returning an R^2 value of 87.11%. While this is a smaller dataset by comparison, the WASM data still exhibits a strong statistical relationship between the individual test points and the calculated line of best fit.

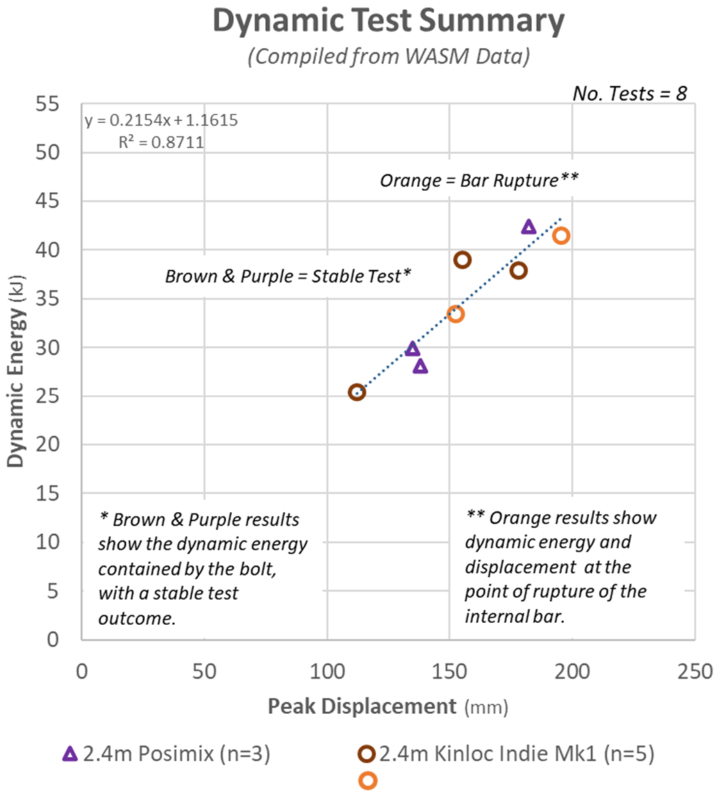

Figure 4 Summary of corresponding results from the Western Australian School of Mines

3.5 Data correlation: in-house test results and the Western Australian School of Mines

Where a test comparison existed for identical bolt types, specifically for 2.4 m Posimix and 2.4 m Kinloc Indie Mk1, 25 dynamic test results from the in-house test program were overlayed with eight dynamic test results from WASM testing. These are compiled into a final summary shown in Figure 5, with each of the 33 individual tests being represented as a single data point on this chart. A linear regression analysis was conducted across all 33 tests, returning an R^2 value of 93.13%. While the in-house test program represents the greater portion of the dataset influencing the R^2 value, the WASM data remains statistically significant in this combined analysis. Within this context the WASM test results correlate well with the in-house test work, and a clear linear relationship is visibly shown between the two datasets.

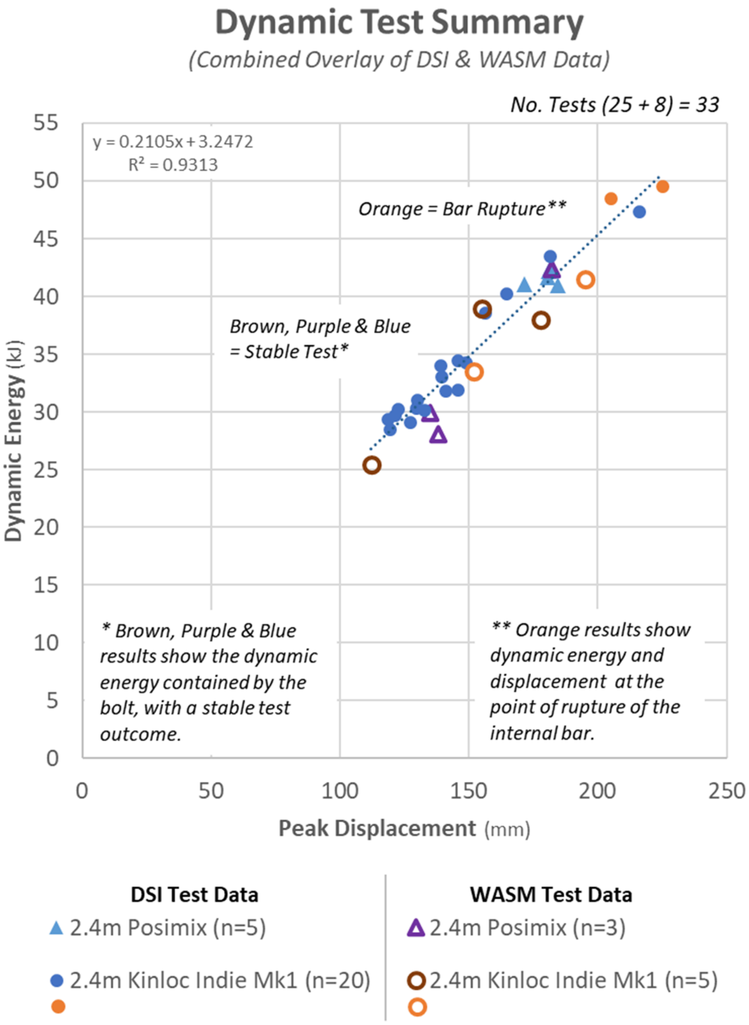

Figure 5 Combined overlay of corresponding data between the new test rig and the Western Australian School of Mines

4 Conclusion

Across 44 tests and four different rock bolt designs a statistical analysis of results strongly indicates that the new dynamic test rig design provides a highly repeatable method for the dynamic testing of rock bolts. A further three tests of a fifth bolt design are of relevance but require additional data. Cross-correlation of test data against an external source, conducted using eight available WASM data points associated with two of these rock bolt designs, provides a strong indicator of the accuracy of the new high-speed data capture system for both force and displacement measurement, as well as final energy calculation methods. Subsequently the new test rig design is increasingly seen to provide a valid method for provisional in-house dynamic testing of rock bolts, working in line with the methods of WASM (a globally recognised dynamic test facility).

Evaluation of all five different rock bolt types shows repeatable linear performance under increasing dynamic energy. In three cases this is taken through to the upper limit of the bolt, being the point of ultimate loading and rupture of the bar element. The bar's mechanical properties are the fundamental mechanism that deliver this dynamic performance, requiring rapid take up of initial loads followed by prolonged elongation at elevated loads. The mechanical response of the bolt is clearly co-dependent on load transfer through the anchoring media to the borehole. For the installed system to work the anchoring media must fundamentally be stronger than the bolt material itself. The linear trend line on the energy versus displacement chart provides a strong indicator of the repeatability of the bolt performance, the anchoring method and also the method of dynamic testing.

References

ASTM International 2008, *Standard Test Methods for Laboratory Determination of Rock Anchor Capacities by Pull and Drop Tests (ASTM D7401-08)*, ASTM International, West Conshohocken.

Evans, D 2022, 'Data cross validation for a newly commissioned dynamic drop test facility', in I Canbulat (ed.), *Ausrock Conference 2022: Proceedings of the Australian Ground Control Conference and an ISRM Regional Symposium*, The Australian Institute of Mining and Metallurgy, Melbourne, pp. 320–328.

Li, CC, Hadjigerorgiou, J, Mikula, P, Know, G, Darlington, B, Royer, R, Pytlik, A & Hosp, M 2021. 'Performance of identical rockbolts tested on four dynamic testing rigs employing the direct impact method', *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 13, no. 4, pp. 745–754.

Player, J 2012, *Dynamic Testing of Rock Reinforcement Systems*, PhD thesis, Curtin University, Perth.

Tacuna Systems 2022, *Comparing Strain Gauges to Piezoelectric Sensors*, viewed 17 June 2022, https://tacunasystems.com/knowledge-base/comparing-strain-gauges-to-piezoelectric-sensors

Thompson, AG, Player, JR & Villaescusa, E 2004, 'Simulation and analysis of dynamically loaded reinforcement systems', in E Villaescusa and Y Potvin (eds), *Proceedings of the 5th International Symposium on Ground Support, Ground Support in Mining and Underground Construction*, Perth, pp. 341–355.

Villaescusa, E, Thompson, AG, Windsor, CR & Player, JR 2023, *Ground Support Technology for Highly Stressed Excavations*, CRC Press, Boca Raton.