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Laboratory-based drop testing of rock reinforcement

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Abstract

The requirement for resources has resulted in mining activities moving into more challenging conditions, from conventional, gravity driven ground conditions to highly stressed rock mass. In highly stressed, burst-prone rock masses, mining-induced seismicity presents a challenge to most ground support systems. The capacity of conventional rock reinforcement elements such as grouted rebar rockbolts and friction rockbolts is often found to be inadequate when subjected to large deformations resulting from mining-induced seismicity. The requirement to sustain large loads over large deformations has led to the development of several energy-absorbing rock reinforcement elements. The performance of an energy-absorbing element is typically determined through a laboratory-based drop test. During a laboratory-based test, the kinetic energy of a known mass, released from a known height, is transferred to the rock reinforcement element installed in a steel tube. There are two primary drop test methods, impact testing and momentum transfer. Although there are arguably differences between the two methods, both share common limitations. This paper provides a summary of recent investigations conducted to understand the effect of the test parameters on the performance of rock reinforcement elements determined through laboratory-based drop testing. The purpose is to provide a high-level overview rather a detailed review.

Keywords: *drop testing, impact testing, momentum transfer, rock reinforcement elements*

1 Introduction

As mining resources accessed through surface and low stress mining environments are consumed, miners are accessing ore bodies located in increasingly more challenging conditions. Consequently, mining methods, mine design philosophies, and ground support elements have evolved to allow for the safe and efficient extraction of ore in these challenging, extreme conditions. In severe stress conditions, the resultant failure of the rock mass manifests as sudden and violent releases of energy in burst-prone rock masses. It was observed that conventional rock reinforcement elements lacked the capacity to maintain the confining forces in these conditions. To ensure the excavations remain operational for the anticipated service life, the application of energy-absorbing rock reinforcement elements, such as paddled energy-absorbing rockbolts, has become a best practice (Potvin & Hadjigeorgiou 2020). Consequently, the requirement for a method of quantifying the performance of energy-absorbing rockbolts prior to the implementation of a field trial was sought.

Ortlepp (1969) and his collaborators observed that a system comprising of ductile rock reinforcement elements was able maintain the confinement of the rock mass; first during blast testing, illustrated in Figure 1, and secondly during in situ applications. The success was attributed to the elements' capacity to sustain large loads over large displacements, hence the principal concept of an energy-absorbing rockbolt was formed. Energy-absorbing rockbolts are now considered as a best practice in burst-prone ground conditions (Cai & Kaizer 2018; Potvin & Hadjigeorgiou 2020).

Early blast testing trials conducted by Ortlepp (1969) successfully demonstrated that an energy-absorbing rock reinforcement element was a potential solution to the support challenges encountered in burst-prone rock masses. The test was a comparative test with one half of the tunnel supported with conventional support and the other half with yielding rock reinforcement elements. The tests were successful; however, it was clear an alternative method with a higher degree of control was required to suitably quantify the capacity of the rock reinforcement. The blast tests were both costly and subject to the site-specific variables. Repeatability through the control of the sample configuration and installation parameters is a valuable feature offered in laboratory-based testing that cannot be attained with in situ blast testing. In addition, laboratory-based tests can be conducted at reasonable cost without affecting mining activities (Hadjigeorgiou & Potvin 2011). The adoption of laboratory-based drop testing has facilitated the development of energy-absorbing technologies such as the paddled energy-absorbing rockbolt (Li 2010) which have become widely accepted for use in burst-prone conditions.

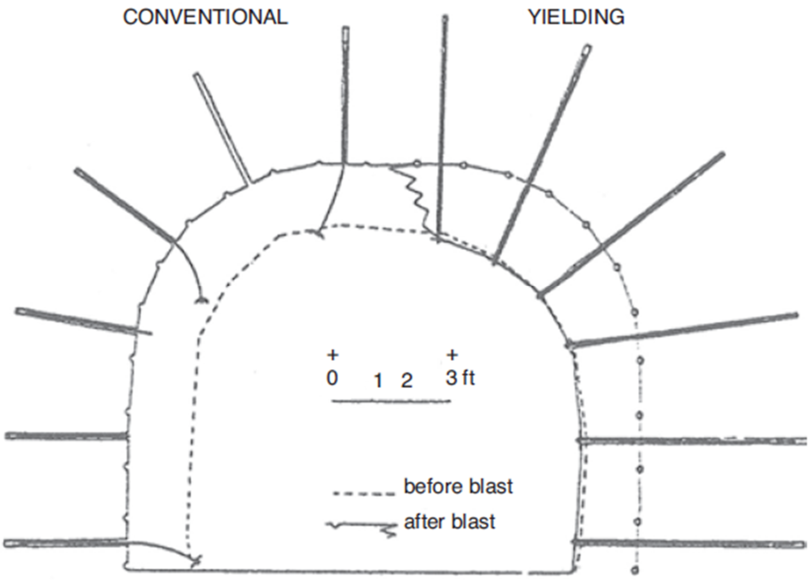


Figure 1 Tunnel profile after the second blast test conducted by Ortlepp (1969)

Current laboratory-based drop tests employ a mass free fall method. An impulse of energy is generated by raising a quantified mass to a specific height. The mass is then released to free fall until arrested by the rock reinforcement element coupled to the frame of the test rig. There are two methods of performing a drop test: the impact test method and the momentum transfer method. It is arguable that momentum is transferred in both methods, however, this convention has been adopted by the broader industry.

The Noranda test rig, as shown in Figure 2, was one of the early designs of a drop test rig which is now known as the impact test method. The Noranda test rig was transferred to Canmet and the instrumentation upgraded (Hadjigeorgiou & Potvin 2011). The design has since been adopted by the developers of both the Dynamic Impact Tester (DIT) (Knox & Berghorst 2018) and Dynamic Testing Services (DTS) (Potvin & Hadjigeorgiou 2020). The impact test method predates the momentum transfer method developed at the Western Australian School of Mines (WASM) by Player et al. (2004). There are arguable differences between the two methods; however, when the body of knowledge is examined, some similarities can be observed in the results when the variations in instrumentation and data processing are accounted for. The primary limitation of both methods is the fact that the loading applied is axial. Consequently, it does not represent complex loading which could include tensile, shear, bending and torsional loading (Thompson et al. 2012). This complex loading can result in failures illustrated by Stacey (2012) (Figure 3).

Figure 2 Noranda impact test rig (Simser 2007)

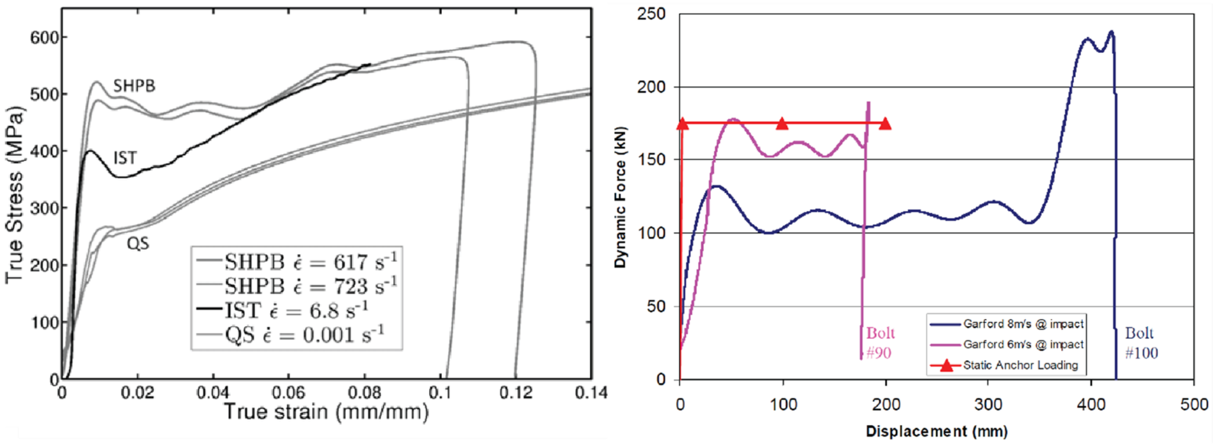
Figure 3 Complex loading of rock reinforcement elements captured by WD Ortlepp (Stacey 2012)

This paper servers to collate the current understand of laboratory-based drop testing from multiple research programs. The scope of the paper will be limited to laboratory-based drop test method for rock reinforcement methods and is therefore not an exhaustive review of all drop test methods.

2 Requirement for high strain rate testing

The change in response of materials to an increase in loading rate has been well-documented for both steel (Cloete & Stander 2012**;** Malvar & Crawford 2008) and rock (Ryder & Jager 2002). The work of Cloete & Stander (2012), shown in Figure 4, illustrates the increase in both yield and ultimate strength of a material as the strain rate is increased. These tests were conducted on a series of homogeneous material which repeatably demonstrate the relationship between an increase in strength related to an increase in strain rate.

Energy-absorbing rock reinforcement elements absorb energy through three primary mechanisms: plastic deformation, slip, and extrusion. Typically, the principle of increased yield and ultimate strength can be applied to rock reinforcement elements which rely on a method of plastic deformation as demonstrated by Knox et al. (2018a) when comparing the impact load response to the quasi-static load response of a paddled energy-absorbing rockbolt (Ø20 mm PAR1 Resin bolt). The converse, a decrease in the resisting force, was recorded by Player (2012), when a test was conducted on the Garford Dynamic Solid Bolt at the WASM test facility. The Garford Dynamic Solid Bolt relies on an extrusion mechanism to absorb energy. An increase in the strain rate resulted in a decrease of the resisting load resulting from change in the dynamic friction, as illustrated in the load response shown in Figure 4.



(a) (b)

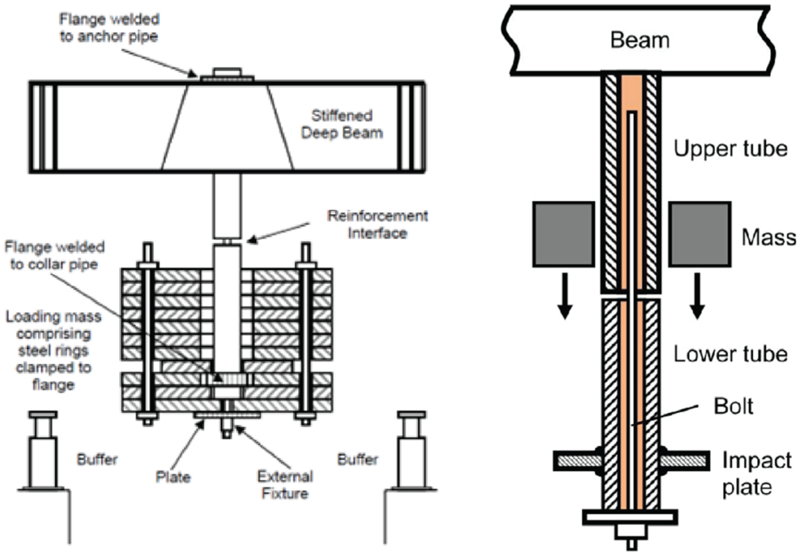
Figure 4 Effect of strain rate on the materials. (a) Change in response of annealed mild steel to varied strain rates (Cloete & Stander 2012); (b) Effect of loading rate on the response of a Garford Dynamic Solid Bolt (Player 2012)

3 Drop testing

There are two methods of performing high strain rate testing on full-scale rock reinforcement elements within a laboratory: impact testing and momentum transfer. Both methods rely on a free-falling mass to generate an impulse of energy which is dissipated through plastic deformation of the sample, hence the common name of drop tests. The sample is defined as the rock reinforcement element installed within a host tube. While there are arguable differences between the two methods, neither replicates the complex loading cases to which a rock reinforcement element is subjected in situ (Stacey 2012). Consequently, both should be considered as a comparative test method as opposed to a comprehensive simulation of what is observed in the field.

The primary difference between the two high strain rate testing methods is the following:

- During an impact test (Figure 5b), the drop mass is released and impacts with a stationary impact plate affixed to the proximal end of the samples. The distal end of the sample is coupled to the rigid frame of the impact test rig. Consequently, the impact energy is dissipated as plastic deformation of the sample.
- During a momentum transfer test (Figure 5a), the mass is coupled to the proximal end of the rock reinforcement element. The distal end of the sample is coupled to a loading beam, with the entire loading train (loading beam, sample installed within the host tube and drop mass) being released from a known height. The loading beam impacts with a pair of dampers which control the rate of deceleration as the momentum of the mass is transferred to the sample. The kinetic energy of the loading train at impact is dissipated through a combination of the dampers and plastic deformation of the sample.



(a) (b)

Figure 5 Simplified illustrations of drop test methods. (a) Momentum transfer method (Player 2012); (b) Impact test method (Li et al. 2021)

Both methods rely on potential energy generated by raising a known mass to a known height. For simplicity, the potential energy (E_p), or input energy, is considered to be the energy imparted to the sample. In practice, system efficiencies result in a loss of energy and consequently, the kinetic energy (E_k) of the drop mass (impact testing) or loading train (momentum transfer) is less than E_p at the point of impact. Assuming that the free-falling mass is arrested during the test, the primary component of the kinetic energy is dissipated through the plastic deformation of the sample. Minor components of the energy are dissipated through a combination of thermal energy, acoustic energy and frictional energy losses between the guide rails and mass. For practical purposes, the minor components of the energy dissipated are considered as a singular component known as the 'system losses' which can vary significantly between different test rigs.

During the period over which energy of the free-falling mass is dissipated, the displacement and resistive load generated by the rock reinforcement element are recorded. The period of the impact is isolated, and the energy dissipated (E_d) is calculated through the integral of force (F) and displacement (δ) (Equation 1). This is determined by calculating the area under the load–displacement curve using trapezoidal integration (Equation 2). The area is discretised using the width of the trapezoid defined by the displacement occurring during a single sampling interval. What is frequently observed in impact tests is that the calculated dissipated energy is greater than the input energy. This is because the input energy does not represent the total change in potential energy of the mass, but merely the potential energy of the mass relative to the impact location. The total potential energy of the sample mass is relative to the location at which the mass is arrested, which is unknown at the initiation of the test. Hence, the total potential energy (Equation 3) is calculated using the final location (drop height (H) + deformation (δ)) which includes the additional deformation which occurs during the dissipation of the energy. This phenomenon is not observed in the momentum transfer method, as a component of the potential energy is consumed by the buffer system.

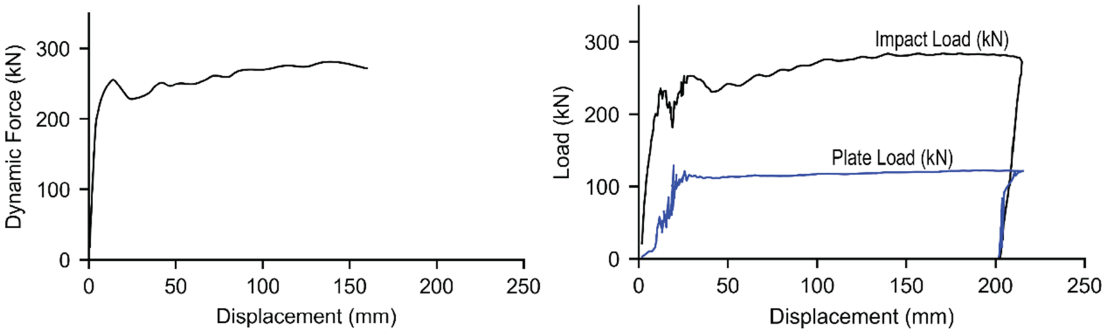
$$W = E_d = \int_0^{\delta_f} F \, d\delta \tag{1}$$

$$E_d = \sum_0^n 0.5(F_n + F_{n-1})(\delta_n - \delta_{n-1}) \tag{2}$$

$$E_{p_{total}} = m \times g \times (H + \delta) \tag{3}$$

The load–displacement response and resultant energy dissipated is calculated from the data recorded by the load and displacement sensors. Consequently, to ensure reliable results, significant effort is directed to the selection, maintenance, and verification of both the load and displacement sensing systems. The violent nature of the drop test and subsequent impact which occurs after the rupture of the sample increases the probability of damage to the instrumentation. Therefore, a robust QA/QC verification program is required to maintain the integrity of the results. For the same reason, optical displacement measurement systems are typically employed at most testing rigs.

Due to a number of reasons, including complexity of testing and differences in data processing, the two systems cannot be fully compared. In addition, there are few instances where the same rockbolt have been tested using both methods with similar sample preparations and input parameters. One example is the results of a Ø22 mm D-Bolt testing at both WASM (Villaescusa et al. 2015) and at Canmet (Li & Doucet 2012). The load–displacement responses of the rockbolt are shown in Figure 6. It should be noted that the length of the loaded segment was 1.2 m for the sample tested at WASM and 1.5 m for the sample tested at Canmet. Both samples arrested the drop mass and neither test represented the ultimate displacement capacity. During the data processing and analysis, a filter was applied to the data recorded at WASM, whereas the raw data is presented by Li & Doucet (2012).



(a) (b)

Figure 6 Drop test results for a Ø22 mm D-Bolt. (a) Momentum transfer method (WASM) after Villaescusa et al. (2015); (b) Impact test method (Canmet) after Li & Doucet (2012)

3.1 Drop testing rigs

Globally, there are currently six laboratory-based rock reinforcement drop testing rigs and a single instrumented field testing rig. Figure 7 illustrates the locations of the rockbolt testing laboratories. Four of the laboratory testing rigs are owned by a government or educational institute: Canmet (1) (Plouffe et al. 2008), WASM (2) (Player et al. 2004), SWERIM (5) (Vallati et al. 2022) and the GIG (6) (Pytlik 2020) which provide testing services to the industry. The remaining two laboratory-based drop testing rigs, DIT (3) (Knox & Berghorst 2018a) and DTS (4) (Potvin & Hadjigeorgiou 2020) are privately owned by rockbolt producers. Consequently, many of the tests are conducted on the respective companies' products. In-field testing is conducted using the Sandvik in situ rig enabling testing to be conducted at a mine site, as described by Darlington et al. (2018, 2019). As the rig is privately owned, much of the data published to date is on a mechanical hybrid rockbolt, the Sandvik MDX bolt.

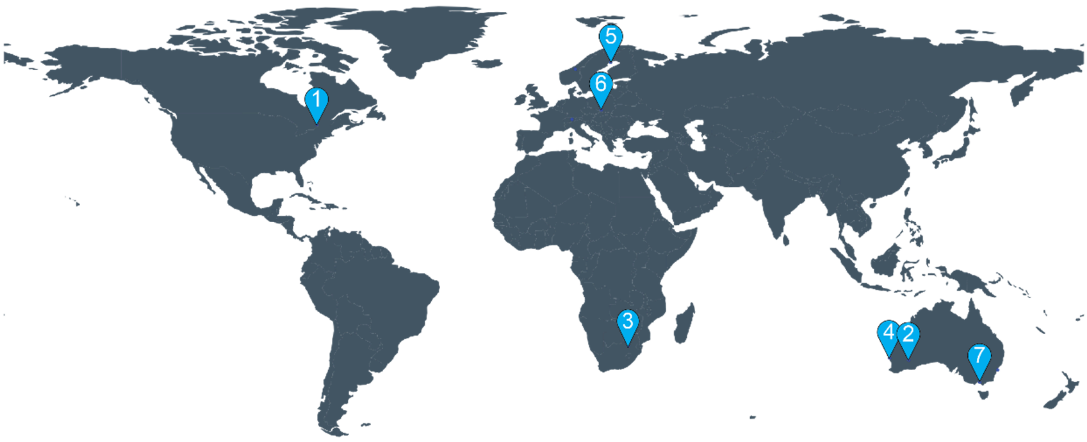
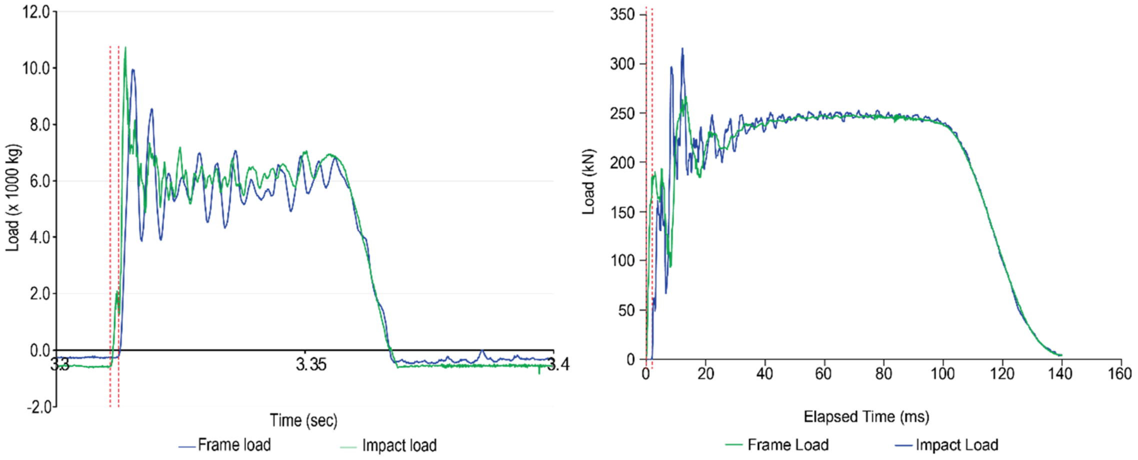


Figure 7 Location of rock reinforcement drop testing facilities

3.2 Drop test rig instrumentation

Due to the nature of the drop test methodology, a robust instrumentation and data acquisition design is critical to the integrity of the results. The energy of the free-falling mass is typically dissipated over a period of 30–160 ms and consequently, the frequency response (bandwidth), resolution of the acquisition system and location of the load sensors affect the recorded result.

There are two primary instruments to a drop test rig: the impact load cell and the displacement measurement system. Due to the upper frequency limit of 50 kHz, piezo-electric load cells are commonly applied (Plouffe et al. 2008; Player et al. 2004; Knox & Berghorst 2018a; Darlington et al. 2018; Vallati et al. 2022). Frequency response of the load cell allows for the impulse to be accurately captured. The location/placement of the load cells is of equal importance. This is demonstrated by Charrette & Plouffe (2008) and Li et al. (2022). In both instances, impact test rigs were instrumented with two sets of load cells; the lower located at the impact plate and the upper located at the coupling between the sample and the frame of the test rig. A delay in the response of the upper load cell is observed in Figure 8 and attributed to the inertia of the sample.



(a) (b)

Figure 8 Delay in impulse propagation recorded between the frame and impact loads. (a) 4.9 kJ impact on a Roofex rockbolt (Charrette & Plouffe 2008); (b) The difference in response between the frame and impact load for an unspecificed impact on an unspecificed bolt tested in Rig 3 (Li et al. 2021)

The second parameter recorded during the impact is the displacement. The initial design of the Noranda test rig included a linear displacement transducer used to record the deformation that occurred during the impulse (Gaudreau 2004). This has subsequently been changed to an optical displacement sensor which has improved the durability of the sensor. The use of line scan and high-speed cameras facilitates a contactless displacement measurement system capable of sub-millimetre accuracy once the lens distortion is accounted for. The importance of synchronising the load and displacement acquisition systems is highlighted in Figure 9. It can be observed that during the initial loading phase, no displacement is recorded, and only after the first peak is reached does displacement occur. The inertia of the sample is affected by the mass of the sample. Consequently, the delay between the load cell location (Figure 8) and the time elapsed between applying a load and displacement occurring (Figure 9) will vary between testing rigs and sample configurations. As the line scan camera is a digital system and the load cells an analog system, it is critical to ensure the two acquisition systems share a common timing as post-processing data alignment will be incapable of correctly representing the delay.

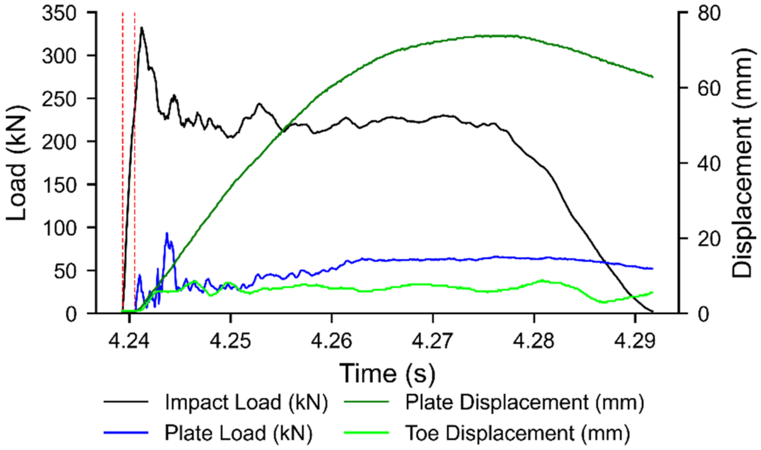


Figure 9 A load–displacement versus time plot for an impact test after Knox & Berghorst (2018)

A third consideration when reviewing the result of a drop test is the filtering applied to the data during processing and analyses. Figure 10 illustrates results for an MP1 rockbolt subjected to a 47 kJ impact (Bosman et al. 2018). A second order 150 kHz low pass Butterworth filter was applied to these data. The result is a significant decrease in the magnitude of the first peak. In effect, when applying a filter, a delay is introduced into the peak loading.

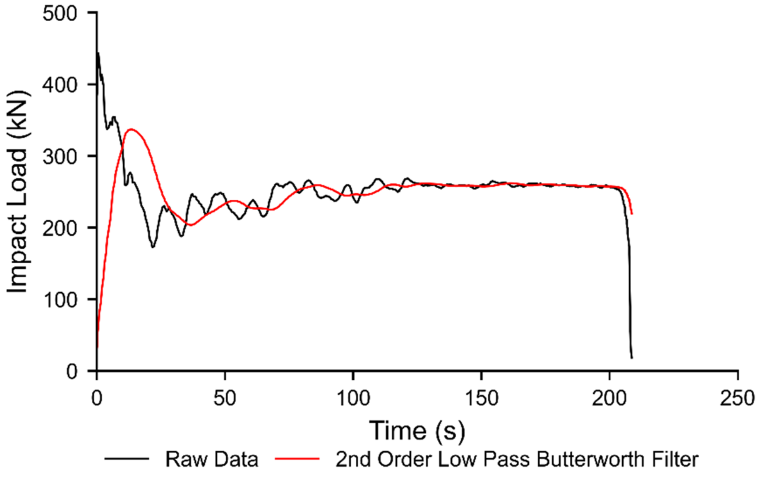


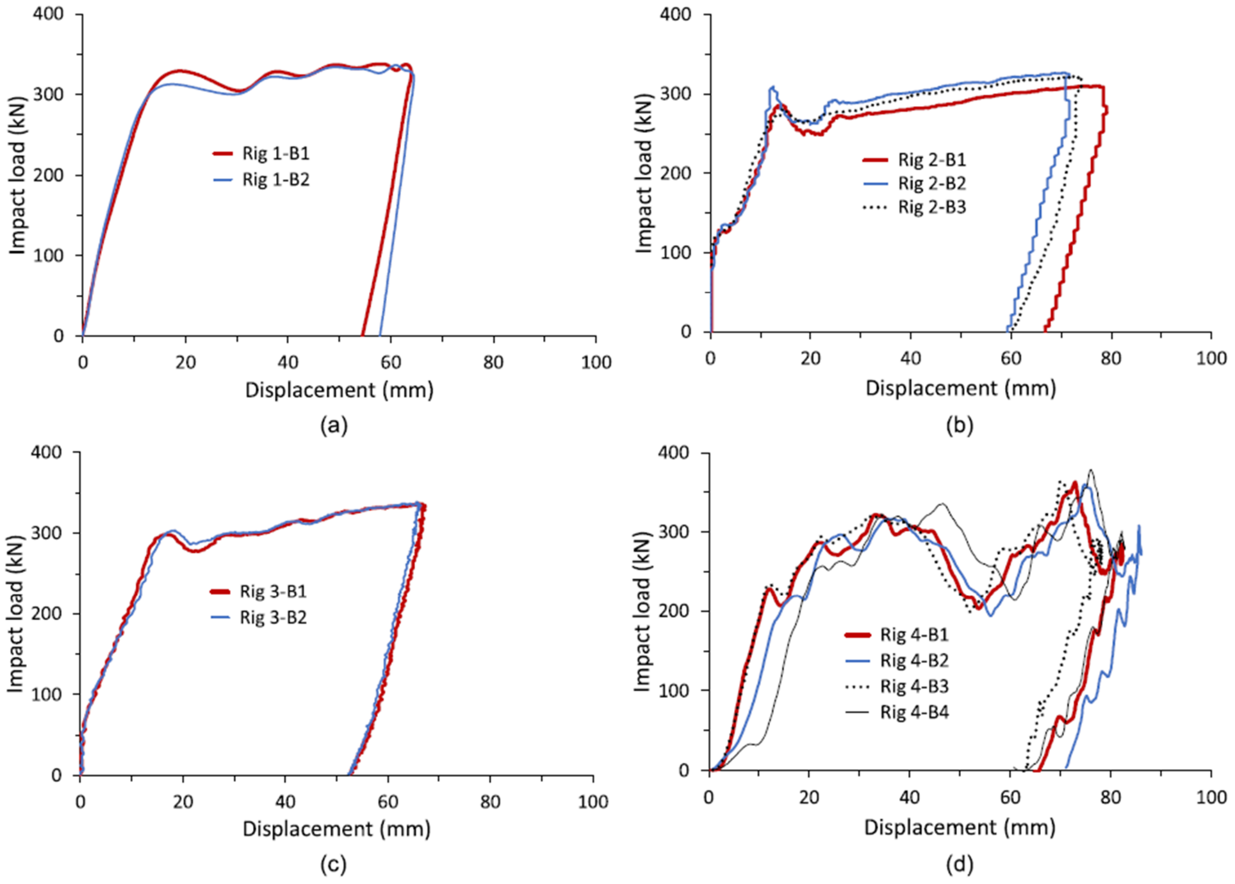
Figure 10 Effect of the application of a filter to an impact test result

3.3 Performance comparison between testing rigs

Due to the geolocation of the rigs, cost of testing and variations in construction and ownership, comparative testing between rigs has historically been challenging. In 2018, at the 3rd Annual Rock Dynamics Conference, Professor Charlie Li engaged multiple stakeholders to establish a framework for comparing the impact test rigs. While some rigs declined to participate in the comparative testing campaign, the program was able to successfully perform the same test on four test rigs: Canmet, GiG, Sandvik in situ and DIT. Three of the four rigs employed the impact test methodology, while the fourth, the Sandvik in situ test rig, is designed around a modified impact methodology. The piezo-electric load cell and accelerometer are located in the coupling between the bar upon which the mass impacts and the proximal end of the rockbolt.

Li et al. (2021) reported the results of this comparative study between the participating rigs. In summary, a fully threaded Ø22 mm bar supplied from a single batch of material was shipped to the laboratories and tested using an identical test set up (direct impact), input energies (≈20 kJ) and impact velocity (4.4 m/s). The load–displacement responses are reproduced in Figure 11. There are clear similarities between rigs 1, 2 and 3, but the difference in the construction and instrumentation is clearly highlighted by the difference of the profile of the response recorded for rig 4. A variance in between the results recorded on the same rig is also evident for rigs 1, 2 and 4.

The investigation demonstrated that there is a need for a standardised test method, however, due to the differences in construction of the rigs, there is also a requirement for a universal calibration method. Consequently, due to the bias of each rig, it is arguably impractical to compare the results of different rigs without accounting for these differences.



(a) (b) (c) (d)

Figure 11 Results generated off of the individual rigs for impact testing (Li et al. 2021)

4 Considerations when reviewing results

Of equal importance to the result is the sample preparation, configuration and finally the input parameters. It is recognised that it is important to have a good understanding not only of what was tested, but how it was tested.

Two test configurations are typically employed: a direct impact continuous tube test and an indirect impact split tube test. When configured for direct impact continuous tube test, the loading is applied directly to the rock reinforcement element at the proximal end. The loading configuration can be likened to a strainburst event (Li et al. 2021). As the loading is applied directly to the rock reinforcement element, it is of critical importance that the ancillaries are correctly configured. This was highlighted by Simser (2007), where it was observed that the plate–nut or plate–washer interface was failing prior to the tendon. The profile of the nut can be clearly seen in the plate recovered after the test in Figure 12. Similarly, Player (2012) observed the failure of thread–nut interface when testing fully threaded bars at WASM. Consequently, due to the failure of the fixture accessories, the full capacity of the tendon was not mobilised. In contrast, Li & Doucet (2012) observed that the loads applied to the accessories of multipoint anchored rockbolts was lower than the impact load during indirect impact split tube tests.

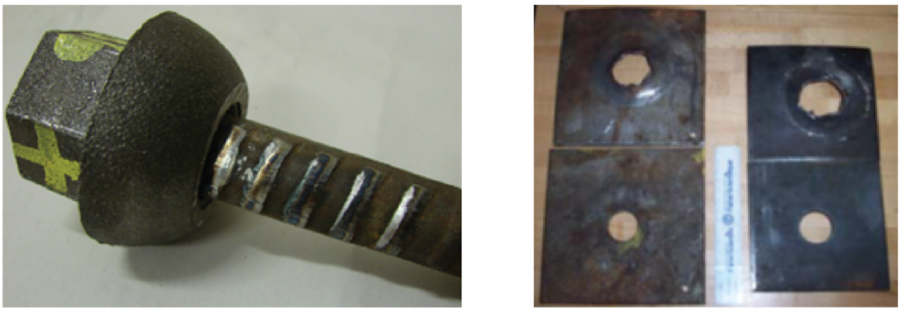

(a) (b)

Figure 12 Failure of accessories during direct loading. (a) Thread–nut interface stripping (Player 2012); (b) Nut–plate interface failure (Simser 2007)

When configured for an indirect impact split tube test, the loading configuration is considered to represent a block thrust ejection (Li et al. 2021). The location of the split is typically located at the approximate midpoint between the two anchors points. This is a common test methodology for determining the performance of a paddled, energy-absorbing rockbolt. In both cases (continuous tube and split tube), the loading is limited to a single section bounded by an anchor pair. For point anchored rockbolts, the continuous tube test represents the capacity of the rockbolt. However, for multipoint anchor rockbolts, the split tube or continuous tube test represents the capacity of a single section of the rockbolt bounded by two anchors. For this reason, the direct impact split tube test was developed by Knox et al. (2018b). A discontinuity in the host tube is placed between each anchor pair and consequently, the entire length of the rockbolt is loaded and the load is transferred through the distal anchor.

The effect of these loading configurations on the performance of a rockbolt was demonstrated by Knox & Hadjigeorgiou (2022), where the position of the split location and the configuration of the instrumentation were adjusted, as illustrated in Figure 13. While this investigation highlighted the effect of the split location on the performance of a paddled, energy-absorbing rockbolt, the program suggested that the performance of a rockbolt may vary along the length of the rockbolt. A variance of 90% was recorded between a sample with the split located in the centre of the proximal paddle set and a split located between the two distal anchor points. Typical results for each testing configuration are compared in Figure 14. These tests were conducted using a rockbolt which dissipates energy through the plastic deformation of steel. The capacity of the distal anchor is best captured by placing the split location at the distal paddle set. The capacity of the anchor was sufficient to result in rupture of the bar without significant movement within the resin. The location of the split is an important consideration when comparing the performance of a plastic deformation and slip for energy-absorbing rockbolts. The location of the split relative to the anchor will define the maximum displacement capacity for an energy-absorbing rockbolt employing the slip or 'ploughing' method to dissipate energy.

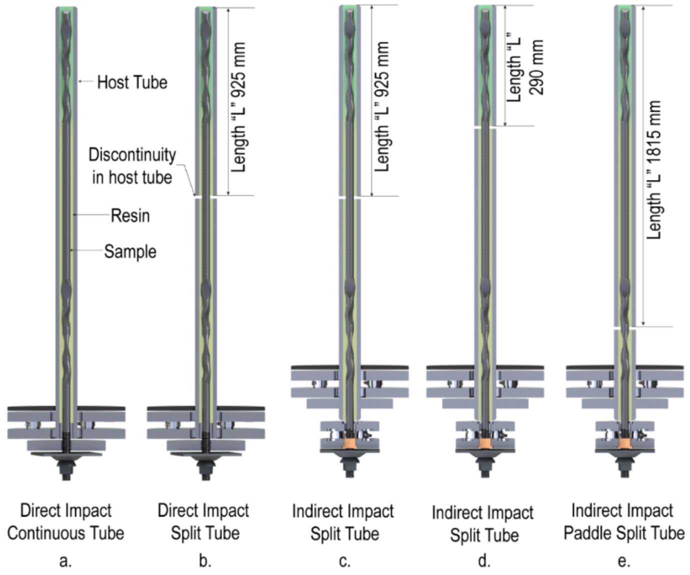


Figure 13 Sample configuration (Knox & Hadjigeorgiou 2022)

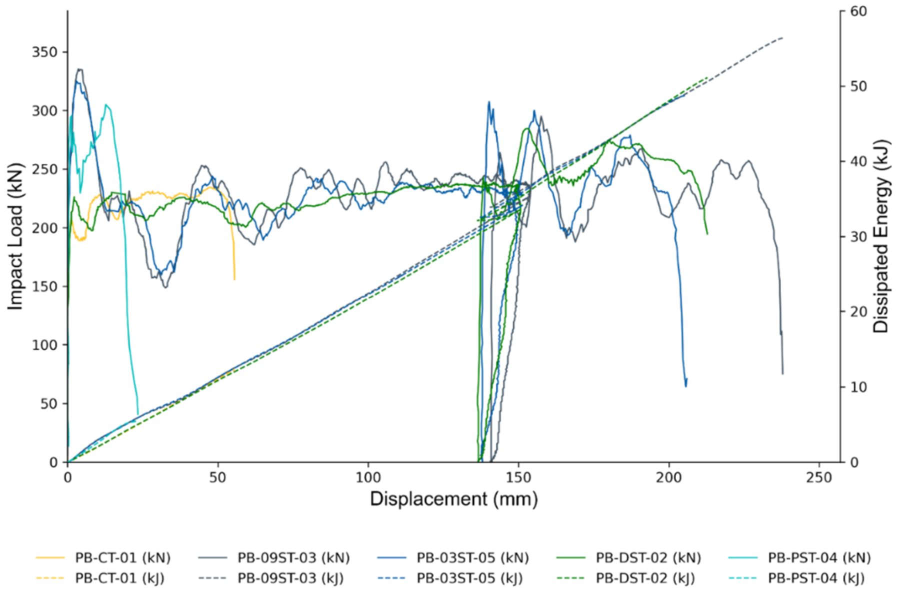
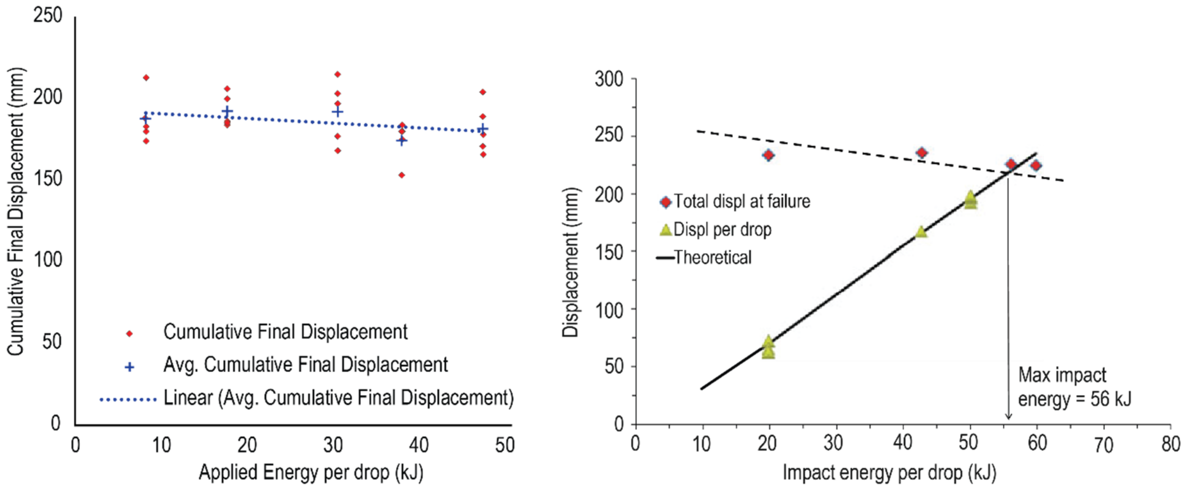


Figure 14 Effect of split location and loading configuration on the performance of a paddled energy-absorbing rockbolt (Knox & Hadjigeorgiou 2022)

The input testing parameters are the drop mass and the height from which the mass is released (dropped). From these two variables, the theoretical velocity at impact and impact energy are calculated. The indirect relationship between the input energy and the cumulative total energy absorbed has been observed by Li & Doucet (2012) when testing the D-Bolt, by Player (2012) for the Garford Dynamic Solid Bolt, and Bosman et al. (2018) when testing the MP1 Bolt. The D-Bolt and MP1 rockbolts are both designed to dissipate energy through the plastic deformation of the steel tendon from which it is produced. Consequently, as shown in Figure 15, the total cumulative displacement decreased with the increase in the magnitude of the impact energy, while the average impact force remained constant. This resulted in a reduction in the cumulative absorbed energy (Figure 16). The Garford Dynamic Solid Bolt, however, dissipates energy through an extrusion mechanism. While a reduction in the cumulative absorbed energy was recorded (65–70 kJ down to 53 kJ) with the increase in impact energy, a reduction in the resistive force was observed. The reduction in the resistive force is illustrated in Figure 4b.



(a) (b)

Figure 15 Effect of impact energy on total displacement. (a) Effect on a Ø20 mm MP1 rockbolt (Bosman et al. 2018); (b) Effect on a Ø22 mm D-bolt (Li & Doucet 2012)

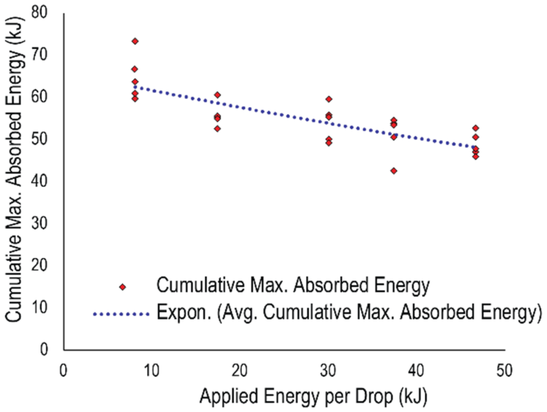


Figure 16 Effect of input energy per drop on cumulative maximum absorbed energy

In their investigations, both Player (2012) and Li & Doucet (2012) varied the impact velocity and impact energy, however, Bosman et al. (2018) maintained the impact velocity and modified the impact mass. To demonstrate the effect of the impact velocity on the performance of a rockbolt under impact loading, Knox et al. (2018a) conducted a series of impact tests on a PAR1 Resin paddled energy-absorbing rockbolt. During the investigation the impact energy was maintained and the impact velocity of the mass was varied. Within the range of velocities tested the velocity was found to have a negligible effect on the cumulative absorbed energy. The difference between the observations of Player (2012) and Knox et al. (2018a) can be explained when the variation in the employed rockbolts energy absorption method is accounted for (plastic deformation versus extrusion).

5 Future considerations

Drop tests provide valuable insights into the performance of rock reinforcement systems during high strain rate events. In the past, significant emphasis has been directed at understanding the effect of the input parameters, sample configuration and components included in the sample on the performance of the rock reinforcement element. However, the effect of variances within a single grade of steel on the performance of a rock reinforcement element have not received the same level of attention. An example of reporting the full traceability for a testing program has been provided by Knox & Hadjigeorgiou (2022).

Several testing campaigns have demonstrated the performance of a rock reinforcement element produced from a singular batch of steel. This represents the performance of a variant of the rockbolt design. The approach does not capture the range of the anticipated responses from the rockbolt design when the variances in the mechanical properties of a steel are considered. It is reasonable to consider steel as a homogenous material. Consequently, maintaining production of a rockbolt from a singular grade of a material mitigates the risk of large variations in performance. However, the range of mechanical properties of a given material is magnified due to the dynamic increase factor (Malvar & Crawford 1998), therefore an increase in the variability of the performance at high strain rate is expected. It is arguably not practical to perform destructive testing on every batch of material from which a rockbolt is produced. However, a well-documented annual QA testing would facilitate the generation of sufficient data to perform a statistical analysis on the results. Due to the lack of a global standardisation of the testing programs and demonstrated differences in the test rigs employing the same method, these tests should be conducted on a single drop test rig.

The focus of this paper was directed at laboratory-based drop testing of rock reinforcement elements. These test facilities have assisted in the accelerated development of innovative rock reinforcement elements; however, attention to the interface between the rock reinforcement element and the surface support is lacking. Some insights have been provided by Villaescusa et al. (2015) and Brandle et al. (2019); however, it can be argued that the boundary conditions applied to the mesh do not accurately reflect an in situ installation. The ability to test the interface between the surface support and the rock reinforcement elements is a limitation of the current laboratory-based drop testing facilities.

Practically, an in situ rock reinforcement element will be subjected to a series of quasi-static and dynamic displacements during its service life, as opposed to a singular loading to rupture experienced during a laboratory-based test. Knox & Berghorst (2019) and Crompton & Knox (2022) explored the effect of first applying a quasi-static loading to a rockbolt followed by a destructive impact test. The investigation illustrated the negative effects of the quasi-static displacement on the energy capacity during an impact test. These investigations demonstrated an increase in the total displacement to rupture, an observation which will require further investigation. This demonstrates the need to further explore alternative loading configurations.

6 Conclusions

There are two methods of performing laboratory-based drop tests: the impact test method, and the momentum transfer test method. Although there are differences between the two methods in construction and operation, both require a free-falling mass to generate an impulse of energy. Both approaches employ impact and a transfer of moment. Even in the best documented comparative testing campaign by Li et al. (2021), all participating rigs employed a variation of the impact method. Therefore, comparisons between the two methods are limited. Due to the cost of operation and geolocation of the testing facilities, there are few published results of identical rock reinforcement elements tested using both methods. It is important to further explore how differences in data processing can influence testing data obtained by different drop test methods.

In the past, significant emphasis has been directed at understanding the effect of the input parameters, sample configuration and components included in the sample on the performance of the rock reinforcement element. Several of these tests have been conducted on paddled energy-absorbing rockbolts which rely on the plastic deformation of steel (Li 2012; Bosman et al. 2018; Knox et al. 2018a). The work of Player (2012) demonstrated the challenge in interpretation of results from rock reinforcement elements which employ alternative energy absorption mechanisms such as the extrusion method. However, it can be concluded irrespective of the drop testing method that the cumulative absorbed energy is indirectly proportional to the impact energy.

Laboratory-based drop tests provide an opportunity to conduct comparative testing under controlled conditions and a relatively acceptable cost. The primary limitation is the fact that the test is an axial loading case and consequently does not account for the complex loading to which a rock reinforcement element is subjected to in situ. Acknowledging this limitation, laboratory-based drop testing is a powerful tool for performing quality assurance testing and verifying the performance of a new technology prior to a field trial. When reviewing the result of a drop test, careful consideration should be given to the effect of the sample configuration and test parameters as these have been demonstrated to have a dramatic effect on the performance of the rock reinforcement element being tested.

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