The relationship between the magnitude of impact velocity per impulse and cumulative absorbed energy capacity of a rock bolt

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ABSTRACT

Laboratory-based dynamic testing provides an invaluable tool in the development of rock bolts for use in highly stressed, burst prone rock masses. While in most cases the laboratory-based test method is not a direct comparison to an in-situ installation due to the purely axial loading and variations in boundary conditions, it does provide an indication of the performance of the tendon system under dynamic loading. The aim of the research described in this paper is to provide an understanding of the effect of the impact velocity of the impact mass during a laboratory-based dynamic test. Understanding the effect of boundary conditions of laboratory testing will improve Geotechnical Engineers understanding of the performance in an in-situ installation. In addition, due to the limited number of dynamic test facilities, an understanding of the effects of the boundary conditions will aid in the comparison of test results for different products from different test facilities.

The research was conducted using an impact tester, whereby a known mass is raised to a known height defining the kinetic energy and velocity of the mass at the point of impact with the test sample after release. The impact velocity was varied between 2.7 m/s and 5.4 m/s, while the kinetic energy of the mass was maintained at 11.5 kJ. While a correlation between the impact velocity and strain rate of the system tested was established, due to the properties of the system tested, the range of impact velocity on which dynamic tests were conducted was insufficient to result in a considerable change in the average impact load, the cumulative proximal displacement and the cumulative maximum energy absorbed over multiple impulse. However, due to the reduction in the momentum of the impact mass the impact duration and displacement during each impulse in the series of impulses reduced.

INTRODUCTION

While the performance of products in a laboratory-based testing environment cannot be directly compared to the in-situ performance of a support system, laboratory-based testing does provide a safe, relatively cost-effective, repeatable environment under which the performance of different tendons can be compared without affecting mining operations (Hadjigeorgiou & Potvin, 2011). Laboratory-based dynamic testing of rock bolt enables rock bolt developers and Geotechnical Engineers the ability to estimate the performance of rock bolts used in highly stress burst prone conditions. As with all testing methods, it is imperative that the effects of the testing boundary conditions on the results are understood. Understanding the effect of the boundary conditions on rock bolts performance during testing allows Geotechnical Engineers to better compare the results from different products tested at different laboratories. This understanding of the boundary conditions will also aid in decreasing the disparity between laboratory-based testing and the understanding of the capacity of the tendon in-situ. In addition to the method of sample preparation, the host bore diameter, the strength of medium in which the sample is installed and the test configuration, the effect of the parameters of the dynamic event should also be understood. These are the impact energy, momentum and impact velocity which is the subject of this research. These three parameters are driven by the impact mass and drop height used during the test.

The effect of the input kinetic energy during loading on the cumulative total energy absorbed by steel has been established (Bosman, Cawood, & Berghorst, 2018). It was determined that the kinetic energy of the drop mass at impact is inversely proportional to the total energy absorption of the rock bolt when the energy absorbed during multiple impacts is cumulated. The variation of the energy was achieved by varying the drop mass and maintaining the drop height in order to achieve the desired input energy. Therefore, maintaining the impact velocity.

It is known that an increase in strain rate will increase the yield and ultimate load sustained by steel under loading, however, the properties of the steel will determine the increase in sustained load. This factor of increase is termed the Dynamic Increase Factor (DIF) (Malvar & Crawford, 1998), for this reason, Geotechnical engineers cannot rely on the information gained from the quasi-static testing when designing dynamic ground support systems for seismically active or strain burst prone environments. In addition to the increase in loading the energy absorption capacity of the bolt increases. The purpose of this research it to determine the effect of the impact velocity on the strain rate and subsequently the total energy absorption of the rock bolt. This will improve the understanding of the difference between quasi-static and dynamic test results, in addition the understanding of the effect of the impact velocity on the total energy absorption will allow for results with difference input parameters to be objectively compared. To establish the relationship between the impact velocity and the total absorbed energy a number of PAR1 Resin Bolt samples were tested in the New Concept Mining (NCM) Dynamic Impact Tester (DIT).

APPARATUS – NCM DYNAMIC IMPACT TESTER

The dynamic testing was carried out using the New Concept Mining (NCM) Dynamic Impact Tester (DIT). The DIT uses the Direct Impact Method defined by the ATSM standard for dynamic testing (ASTM, 2008), which is currently under revision. The test methodology describes the use of a known mass which is raised to a known height, before release. The falling mass impacts with the test sample transferring the kinetic energy of the mass to the sample. This method applies an almost purely axial impulse to the sample. This achieved using the structure depicted in Figure 1. Prior to loading the sample into the DIT the sample is prepared and instrumented with load cells (Fig 2), the sample is then loaded through the bore of the Trolley, mass plates and electromagnet. A receiver tube welded to the sample (Fig 2) allows for the sample to be interfaced with the DIT, fixing the distal end of the sample tube. The flags are then attached to the proximal and distal ends of the sample to record the resultant displacement during the impact. The electromagnet is then used to rise the trolley to a defined height above the impact load cell, whereupon release the trolley impacts with the sample, applying a predefined impulse of energy to the sample.

During the event, the impact load, plate load and testing frame loads are recorded at a rate of 10 kHz using three piezo-electric load cells. The displacement of the distal and proximal ends of the sample are measured using a pair of Line scan cameras to track a target at a rate of 10000 lines per second. This data is automatically processed to determine the energy absorbed by the tendon during the impulse (Knox & Berghorst, 2018).

The design of the DIT allows the applied energy (kinetic energy) and velocity of the mass at impact to be varied by altering the drop mass within the range of 551 to 3171 kg and the drop height up to 2.1 m. This results in a maximum energy input of 65 kJ at a maximum velocity of 6.4 m/s.

Definitions

When defining the performance of a rock bolt tested in the NCM DIT the following terms are used. Where Figure 3 is a reference, the illustration of the definition can be seen overlayed on a typical load time graph of a single impulse.

- *Applied Energy*; the theoretical impulse of energy applied in a drop - this is a function of the height and the weight of the mass dropped. Defined using the following relationship

  $$E_{applied} = m_{drop\ mass}\ g\ h_{drop\ height}$$

- *Cumulative Absorbed Energy – Maximum*; the summation of the maximum absorbed energy as a result of each the consecutive impulses of energy applied to the sample until failure
- *Cumulative Final Deformation*; the summation of all of the final deformations (Fig 3) resulting from the applied impulse of energy for the consecutive impulse until failure of the sample
- *Distal End*; the end of the bolt that is first introduced into the hole
- *Drop;* a single impulse of energy transferred to a sample
- *Drop Height*; the given height that determines the Impact Velocity that the Trolley will strike the Sample

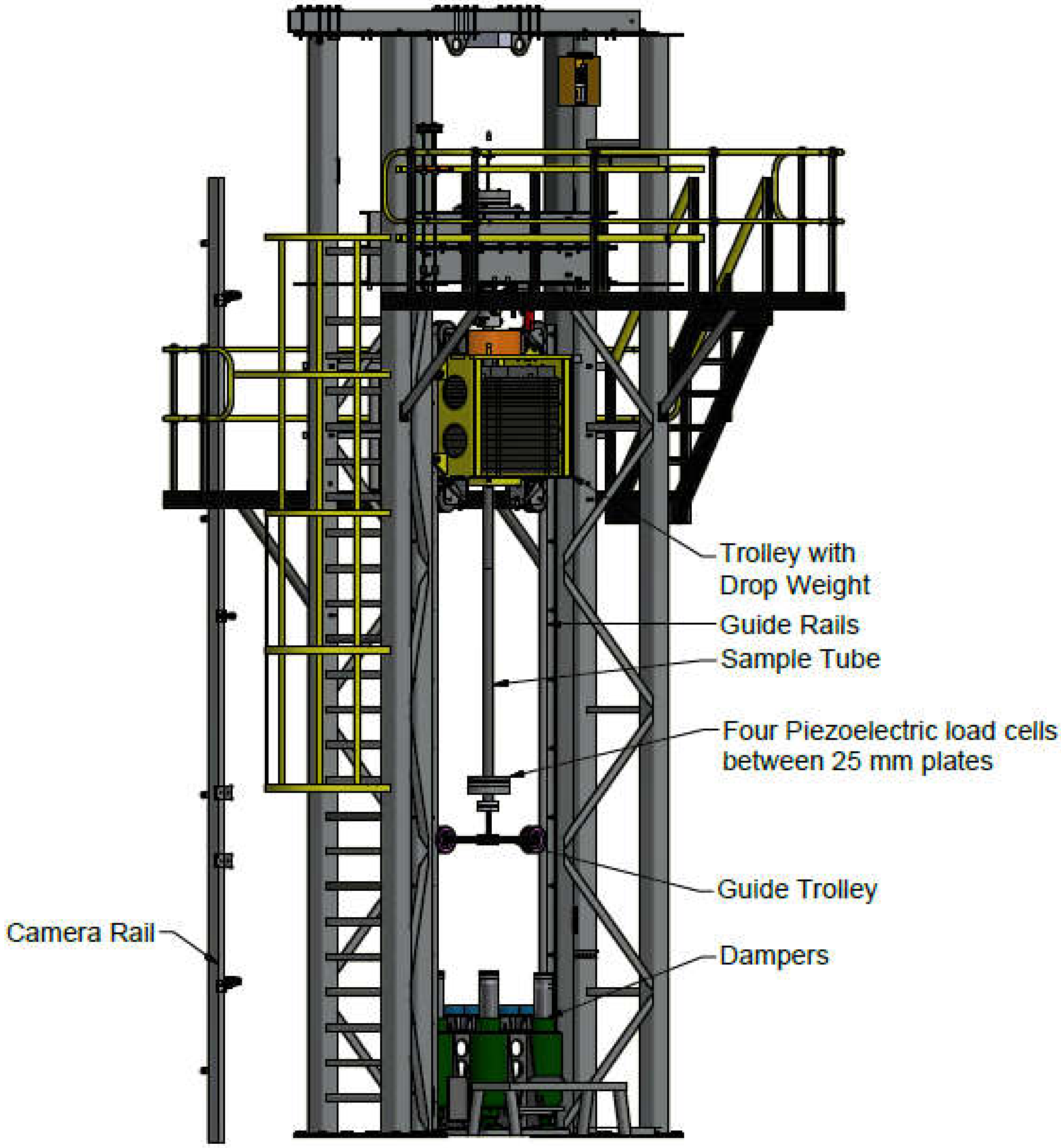

FIG 1 – Illustration of the NCM DIT

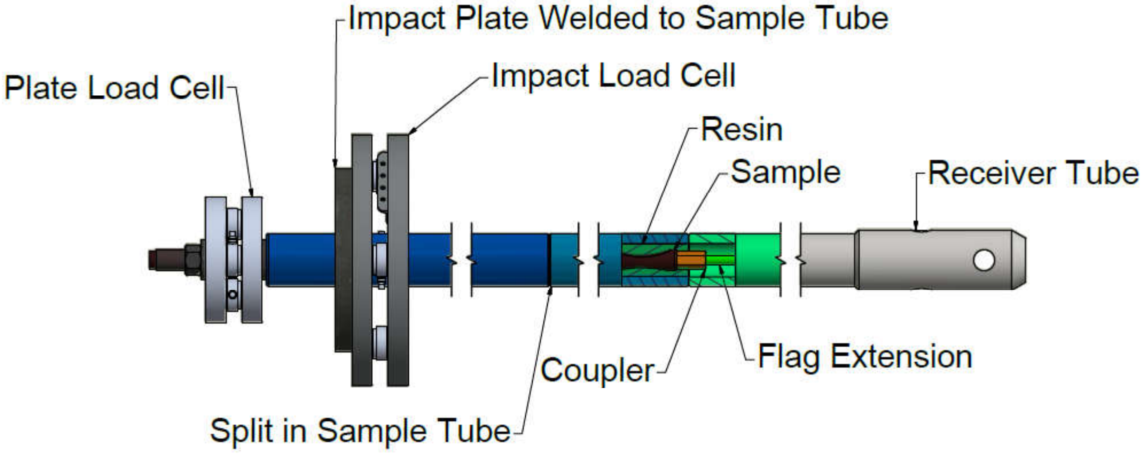

FIG 2 – A Split tube sample

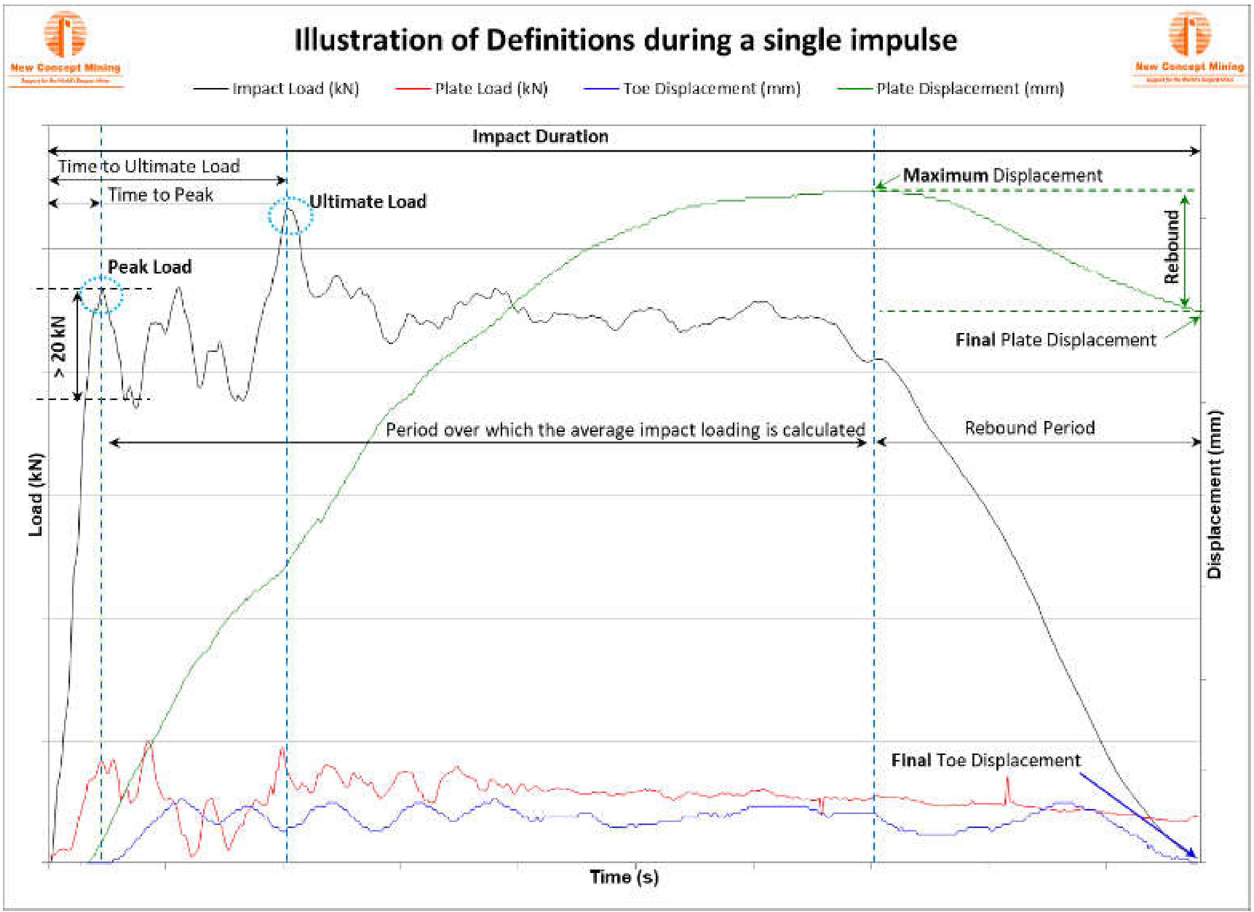

FIG 3 – Illustration of the definitions

- *Drop Mass*; the total weight of the trolley and mass plates that is released from the electromagnet to impact onto the samples
- *Final*; a value measured when the impact load returns to zero for the final time during the First Impulse (Fig 2)
- *Flag*; the black and white pattern used as a marker and tracked by the line scan camera, to determine the displacement during an impulse
- *Impact Duration*; the duration of time that the Impact Load Cell read load (Fig 3)
- *Impact Load*; the resultant load applied directly to the trolley by the sample as a result of the impact; in the case of a split tube test this is applied to the lower portion of the sample, and in the case of a continuous tube test this is applied onto the proximal end of the bolt
- *Impact Load – Average*: the average impact load measured from the peak load to maximum displacement (Fig 3)
- *Impact Velocity;* the velocity of the trolley at the point of impact with the impact load cell defined by the following equation $v_{impact} = \sqrt{2gh_{drop\ height}}$
- *Impulse;* a transfer of energy over a period which is usually in the order of tens of milliseconds
- *Plate Displacement;* the displacement in the proximal end of the sample measured for the duration of the drop
- *Plate Load*; in a split tube test, this is the load that is transferred from the impact on the sample to the plate - this is effectively the load that the washer/faceplate would have been exposed too
- *Proximal End*; the end of the bolt that will protrude from the hole

- *Toe Displacement*; the displacement in the distal end of the sample measured for the duration of the drop
- *Trolley*; the carriage that contains the masses that is dropped from the electromagnet to impact onto the sample during the test (Fig 1)

METHODOLOGY

A total of 16 samples were prepared for the testing the effect of impact velocity on the cumulative maximum energy absorbed and the cumulative displacement of a rock bolt. These two parameters were selected as the reference parameters. The measured displacement of the system during testing equates to the closure or bulking, that would be observed in an excavation around the rock bolt. As it is possible to measure the displacement of the face in an excavation, the correlation between displacement and capacity of the system allows Geotechnical engineers to estimate the remaining capacity in the system, assuming that the distal end of the rock bolt remains in competent rock and fixed in its original position. The second parameter, the cumulative energy absorbed, defines the capacity of the system to dissipate energy during a high strain rate event.

The samples tested were the Ø20 mm version of New Concept Mining's Par1 Resin Bolt with a length of 2.4 m. The Par1 Bolt absorbs energy through the elongation of the bolt under loading. These were prepared in a split-tube testing configuration (Knox, Berghorst, & De Briun, 2018). The samples, installed into an ST52 hollow bar which simulated a Ø35 mm borehole, were spun through five Ø28 mm by 400 mm resin capsules at a constant 300 rev/min at a rate of insertion of 4 m/min, using NCM's Resin Bolter. Once the samples had cured for an hour they were prepared for dynamic testing as seen in Figure 2. An impact plate, to which the impact load cell was bolted, was welded to the lower sample tube. A receiver tube welded to the upper sample tube to interface the sample with the DIT. A connector was welded the distal end of the tendon to allow for the attachment of a flag so that the displacement at the distal end of the sample could be recorded during testing.

The PAR1 Resin bolt has two sets of anchor points consisting of five paddles located at each end of the rock bolt. The paddles provide anchor points within the anchoring medium in which the sample is installed, in this case, resin with a typical ultimate compressive strength (UCS) of 30 MPa. In a split-tube testing configuration, an impulse of energy is indirectly applied to the sample. The load applied to the impact plate cell is transferred through the lower split tube through the medium to the sample. The paddle sets act as rigid anchors within the resin and the energy is absorbed through deformation of the steel between the paddle sets. The load cell located at the faceplate of each sample is used to determine the magnitude of the load which "leaks" through the proximal paddle set to the faceplate.

The samples were categorised into four batches. All samples were tested with a constant input energy of 11.5 kJ per impact and cumulative impacts were imparted to each sample until rupture at the ultimate capacity. It has previously been established that the magnitude of the impact energy does affect the cumulative maximum energy absorption of the tendon when subjected to multiple impacts (Bosman, Cawood, & Berghorst, 2018). The four test batches were tested at impact velocities of 2.7, 3.4, 4.4, and 5.4 m/s and the impact mass varied for each batch to maintain a consistent kinetic energy at impact at the different velocities. Varying the impact velocity of a dynamic test is equivalent to changing the loading rate applied to the samples. As with quasi-static testing, it is expected that the relationship between the impact velocity and the resultant strain rate of the sample is determined by the properties of the system. After each test, the cumulative proximal displacement and cumulative maximum energy absorbed by each sample was calculated.

INTERPRETATION OF RESULTS

A summary of the results of the dynamic testing can be seen in Table 1. It can be seen that no correlation can be seen between the impact velocity, proximal displacement, and the cumulative maximum energy absorption. For three of the four test batches, the average cumulative maximum energy absorption was 64 kJ, the exception being the 2.7 m/s batch of samples which absorbed on average a total of 61 kJ of energy. There was a difference between the distal displacement of the 2.7 m/s impact velocity impact and the remaining samples, however, the average of 11 mm is the average over a range of displacements ranging from between 5 and 17 mm. This is likely a result of inconsistency in the resin mixture rather than the effect of the impact velocity. The cumulative proximal displacement for the samples ranged between 202 and 210 mm with no correlation being found between the impact velocity, the displacement or average impact loads (which ranged between 259 and 275 kN). The average impact load is defined as the average load over the period between the peak load and the maximum proximal displacement (Knox & Berghorst, 2018).The only correlation between the impact velocity and the results can be seen when viewing Figure 4 and Figure 5; the increase in impact velocity resulted in an increase in the initial stiffness of the system and a reduction in the impact duration. The average stress strain curve for each batch was calculated from the summation of multiple impacts as in Figure 6.

TABLE 1 Summary of the results of the dynamic testing

Impact Velocity (m/s)	Cum Prox. Displ. (mm)	Cum. Distal Displ. (mm)	cum. Stretch (mm)	Impact Load (kN)		Avg. Plate Load (kN)	Cum. Max. Absorbed Energy (kJ)
				Ultimate	Avg.		
2.7	206	11	194	290	269	54	61
3.4	202	5	198	301	275	61	64
4.4	210	5	206	293	267	47	64
5.4	205	8	197	299	259	73	64

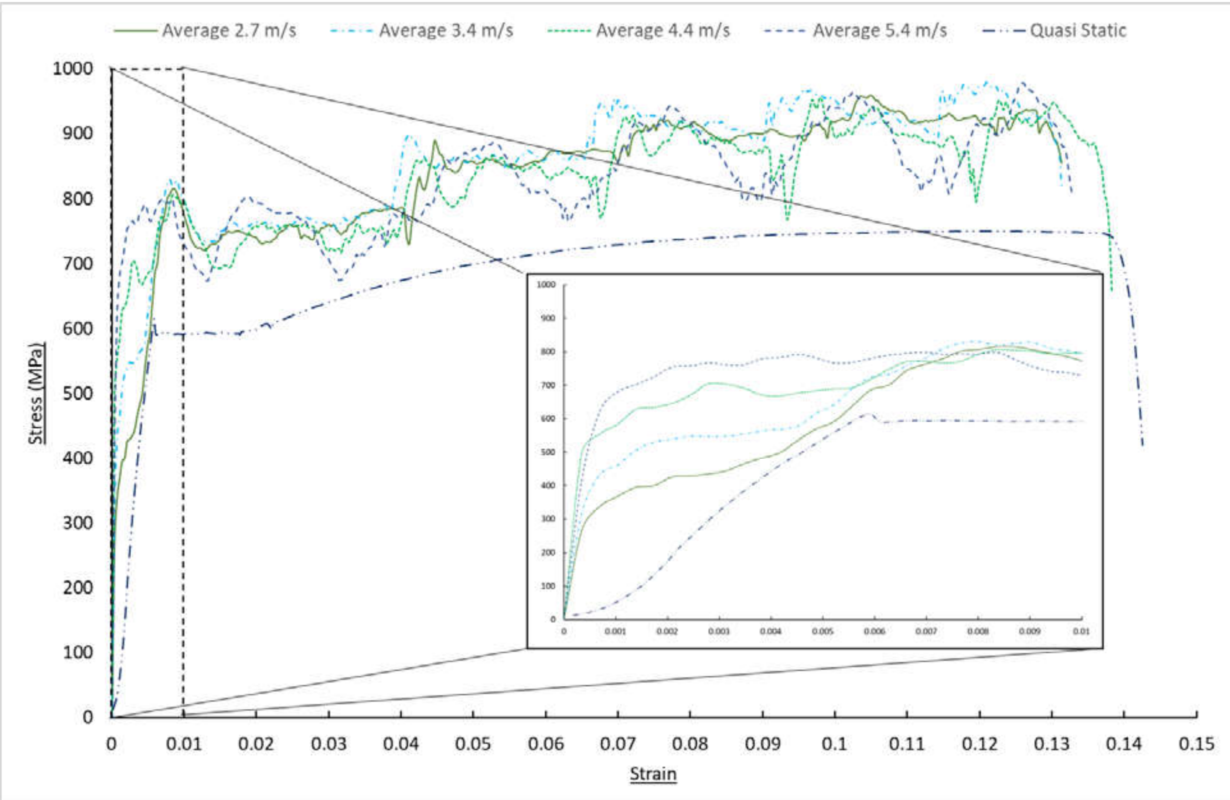

FIG 4 – Dynamic and Quasi-Static Stress Strain Curve for the PAR1 Resin Ø20 mm bolt of length 2.4 m

A further analysis was conducted on the first impulse imparted to each test sample. The first impulse was selected as the quasi-static properties of the material are known before the first impulse, however, once the first impulse has been applied to the material it can be assumed that work hardening has taken place and as a result, the quasi-static properties of the material will have been altered. A summary of the results from the first impulse for the samples can be seen in Table 2.

There are a number of considerations to note when comparing the results from the first impulse. The first being the fact that the average impact load does not appear to be related to the impact velocity just as seen when comparing the cumulative data over multiple impulses. In order to calculate the DIF (Malvar & Crawford, 1998) the strain rate was calculated using the following definition:

$$\dot{\varepsilon}_{avg} = \frac{1}{L_0}\left(\frac{\Delta L}{t_{md}}\right) \quad (1)$$

Where t_{md} is the period between the initial loading and the maximum displacement ΔL.

Two strain rates were calculated, one being the strain rate of the system where the elongation was defined as only the proximal displacement, the second being the strain rate of the steel, where the elongation was defined as the difference between the distal and proximal displacements of the sample. In both cases, the initial length L_0 was defined as the distance between the paddle sets, measured before the samples were installed. The strain rates for the system were calculated to be 0.813, 1.018, 1.167 and 1.665 1/s for the 2.7, 3.4, 4.4 and 5.4 m/s impacts respectively. The correlation between the impact velocity and the strain rate can be seen in Figure 7. A linear relationship between the impact velocity and the strain rate was determined to be:

- $\dot{\varepsilon}_{system\ avg.} = 0.30v_{impact} - 0.03$ (2)
- $\dot{\varepsilon}_{steel\ avg.} = 0.25v_{impact} - 0.01$ (3)

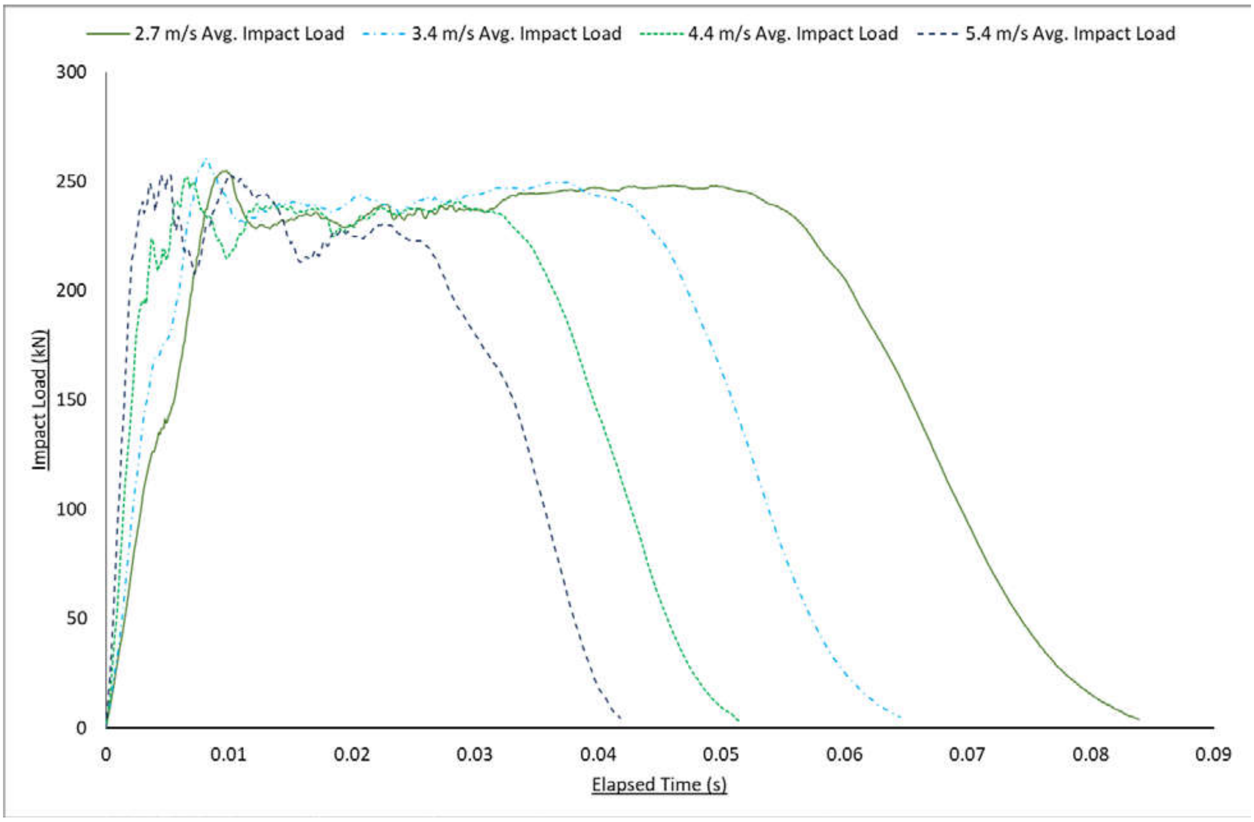

FIG 5 – Comparison of the average Impact load over the period of the impulse for the four batches

While the batch of results from the 4.4 m/s impact fell below the expected relationship, the clustering noted from the remaining three batches indicates a consistency in the relationship between the impact velocity and the strain rate. In addition, the fact that the system and the steel strain rates deviate at higher impact velocities suggests that the relationships would be dependent on the energy absorption mechanism of the system and the strength of the medium in which the sample is installed. In the case of this rock bolt design, the energy absorption mechanism is the deformation of the steel. What should be noted is that whilst the strain rate for each impulse in the series of impulses applied to the samples were similar to that of the first impulse, the strain rate of the final impulse increased as the samples softened beyond the ultimate stress, as seen during a quasi-static test.

The DIF proposed by Malvar and Crawford (Malvar & Crawford, 1998) was stated as valid for materials with a yield stress of between 290 and 710 MPa. The material being tested had a yield stress of 596 MPa, as a result, the DIF was used to calculate the dynamic yield stress using the average strain rate calculated for the sample. The resultant DIF's calculated were in the range of 1.159 to 1.173 which results in an estimated range of 3 kN across the impact velocities between 2.7 and 5.4 m/s, with the Ø20 mm samples tested. This is within the tolerance of variation between samples of the same batch, therefore the difference in yield loading would not be apparent across the batches.

It should be noted that the range of strain rates calculated during the dynamic tests conducted for this research was considerably greater than the calculated strain rate of 0.00036 1/s during the quasi-static test depicted in Figure 1. This difference between strain rates accounts for the difference between the loads recorded during a quasi-static and dynamic test.

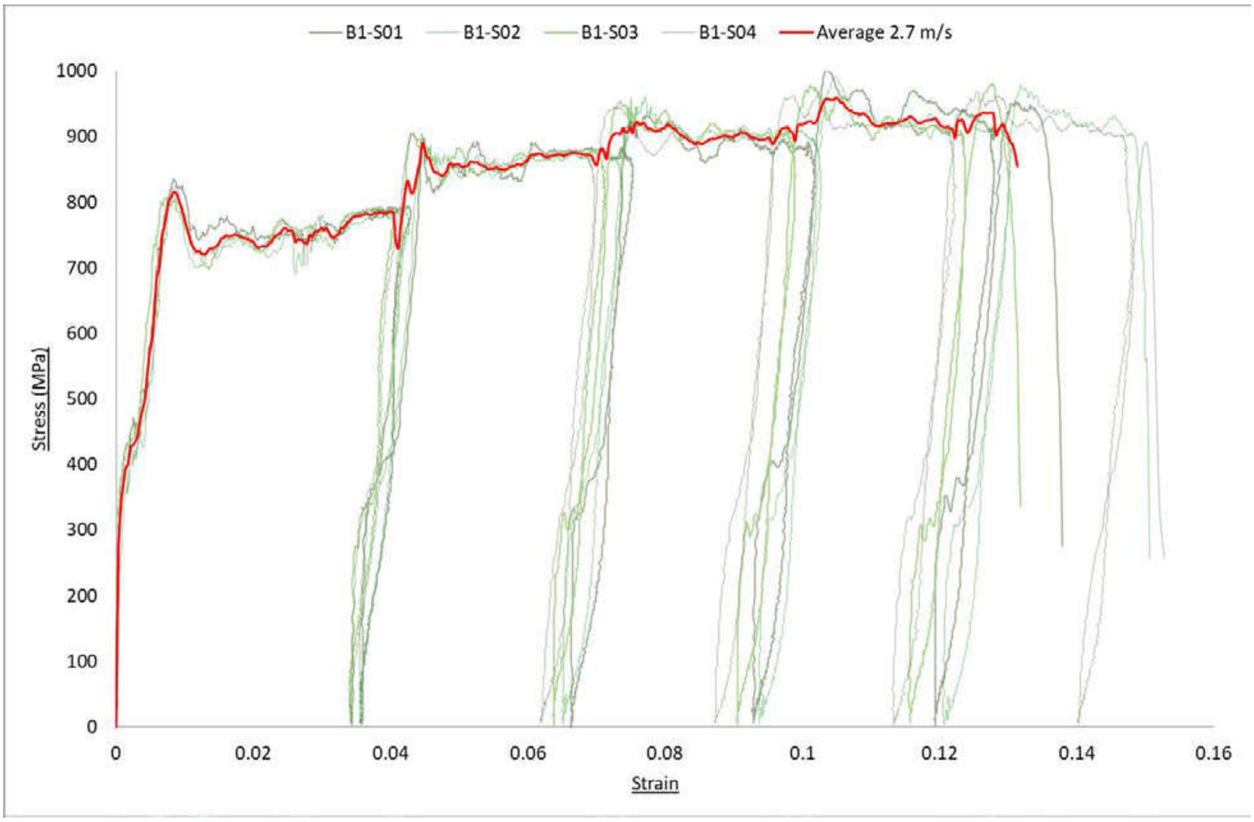

FIG 6 – Average stress strain curve for the 2.7 m/s batch

TABLE 2 Summary of the average dynamic results from the first impulse applied to each sample of across the four batches

Impact Velocity (m/s)	Momentum (kg.m/s)	Max. Prox. Displ. (mm)	Max. Distal Displ. (mm)	Stretch (mm)	Avg. Impact Load (kN)		Avg. Plate Load (kN)	Absorbed Energy (kJ)
					Ultimate	Avg.		
2.7	8543	60	8	52	257	240	48	12.6
3.4	6763	56	8	48	264	242	50	11.7
4.4	5365	55	9	46	255	234	33	11.6
5.4	4238	53	8	45	265	232	64	11.3

The second parameter to be considered during the first impulse is the reduction of the impact duration. The impact durations were on average 85, 66, 52 and 42 ms for the 2.7, 3.4, 4.4 and 5.4 m/s impact velocities. As it has been determined that the input energy per impulse does affect the total cumulative maximum energy absorbed (Bosman, Cawood, & Berghorst, 2018), the input energy was constant for all the impact velocities, as a result of this the momentum of the mass at impact, decreased from 8543 to 4238 kg.m/s across the four batches of samples. Considering the conservation of momentum, between the initial impact and the maximum displacement, where the velocity of the mass and the sample is zero the following holds true.

$$p = m_{mass}v_{mass} = F_{avg}t_{md} \quad (4)$$

$$F_{avg} = m_{total}a + m_{total}g \quad (5)$$

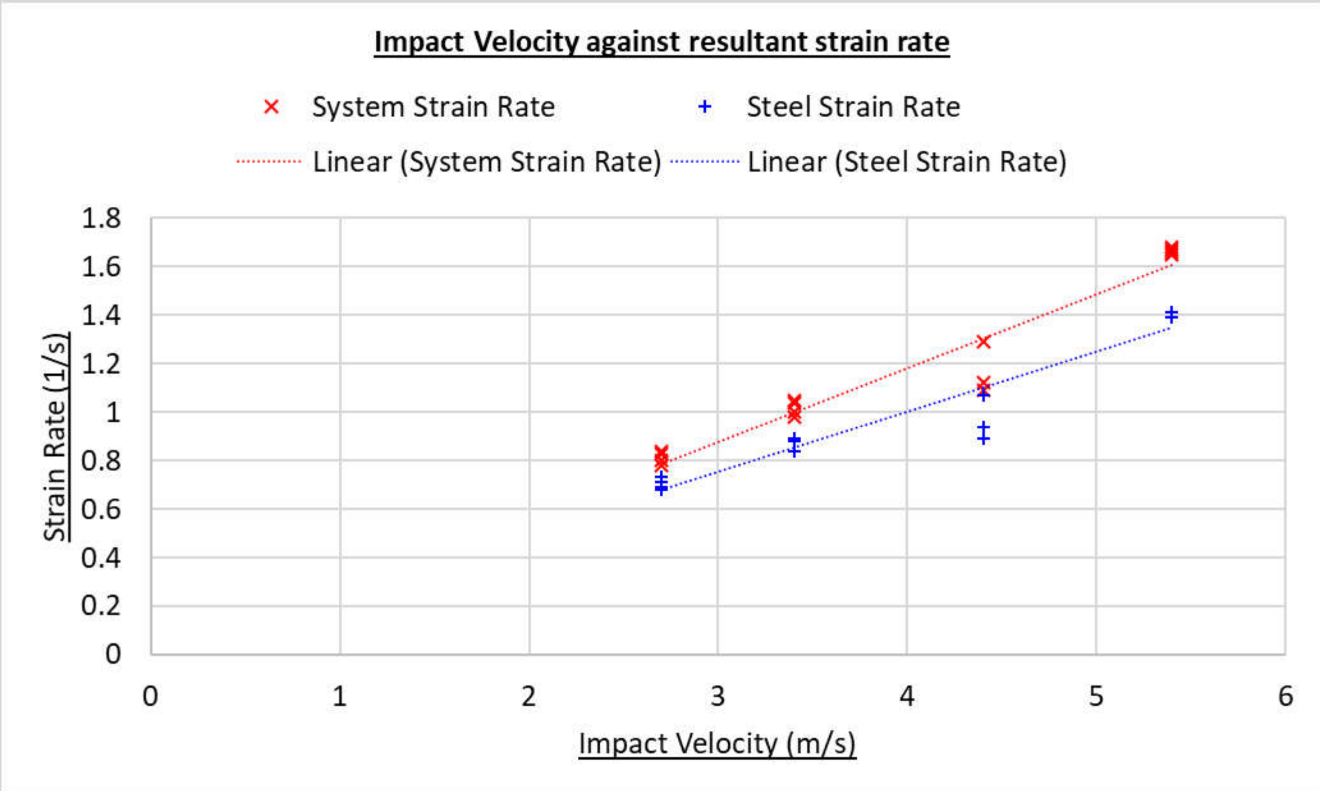

FIG 7 – The correlation between the impact velocity and the strain rate for the first impulse of each sample

The average force is driven by the test sample, across the four batches of samples it was noted that there was no considerable change in the average impact force over the period of the impulse. However, there was approximately a 50% decrease in the momentum (p) of the mass, which results in approximately a 50% decrease in the impact duration (t_{md}). Similarly, when considering the changes in proximal displacement, the reduction in displacement is accounted for by the reduction in mass of the impact mass. The weight of the mass decreases, hence a large component of the constant average impact load is applied towards decelerating the reduced mass, resulting in a reduction of the displacement.

CONCLUSIONS

Based on the results of the research the following conclusions can be drawn: within the range of impact velocities which were tested, there was no significant change in the cumulative proximal displacement or cumulative maximum energy absorbed by the rock bolts as seen in Table 1. A relationship between the impact velocity and the strain rate was established, however, it is limited to the material properties of this system. While the impact velocity did affect the average strain rate over the period of the impact, the change in strain rate resulted in an insignificant variation of the impact load. As the bar rupture is strain-based, the cumulative displacements for the samples were comparable. As a result, the total absorbed energy was consistent across a range of tested impact velocities.

There was a difference in the strain rate when calculated over the whole system or over the bolt. As a result of this, it can be concluded that while these findings are applicable to a system where the method of energy absorption is through the deformation of steel. This relationship will have to be verified for bolts which rely on either friction and or sliding as a method of energy absorption.

A reduction in impact duration was noted, which can be accounted for when the momentum of the impact mass is considered at the point of impact. This change in momentum could also account for the change in initial stiffness of the system.

FUTURE WORK

The relationship between the impact velocity and strain rate is a result of the properties of the system, the UCS of the medium in which the sample is installed and the properties of the sample. The effect of the diameter and length of the sample on the relationship between the impact velocity and the strain rate should also be considered. In addition, the parameters of the sample and the parameters of the system should be explored and the effect of increasing the strength of the medium in which the sample is installed should be investigated.

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