

An empirical comparison between new and existing laboratory-based dynamic sample configurations

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Abstract

Laboratory-based dynamic testing allows rockbolt developers to apply impulses of energy to a rockbolt in order to approximate some loading aspects that the rockbolt would experience during a rockburst in an underground mine. This data can be used to compare a rockbolt's dynamic performance providing geotechnical engineers with useful information for designing their required ground support system. There are two general sample configurations commonly used in this type of dynamic testing – split-tube test and continuous-tube test. This paper summarises a proposed third configuration – a multi-split-tube test.

Keywords: *ground support, laboratory testing, rockburst, dynamic, fractured ground*

1 Introduction

There are several rockbolts designed for use in seismically active mines to absorb energy by means of steel deformation between multiple anchors. In highly fractured ground, it is possible that multiple lengths of a single rockbolt will be simultaneously loaded during a dynamic event resulting in energy being absorbed between each anchor pair by deformation of the steel (Figure 1).

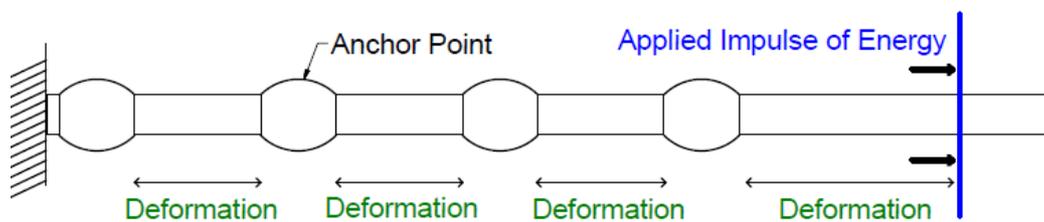


Figure 1 Illustration of a simplified rockbolt with multiple anchor points

There are currently two accepted laboratory test sample configurations – the split-tube and continuous-tube sample configurations. Each sample configuration results in an impulse of energy loading a single discrete length of the rockbolt. The recently proposed multi-split-tube sample configuration enables the simultaneous loading between each anchor pair during a single laboratory-based test. Empirical testing has shown that the multi-split-tube sample configuration results in an increase in the total energy absorbed by the rockbolt during a test, when compared to either of the currently accepted sample configurations. This has been attributed to the fact that multiple lengths of the rockbolt are loaded during the test, thereby increasing the effective loaded length (Knox & Berghorst 2018b). What remains to be established is whether the multi-split-tube sample configuration is equivalent to the summation of a number of split-tube and a continuous-tube tests.

To establish a relationship between the three test configurations, a total of nine PAR1 Resin Bolts were prepared and tested. The PAR1 Resin 25 mm diameter bolt (Figure 2) is dynamic yielding bolt designed to be pushed through or spun into resin. A pair of paddle sets provide anchor points in the medium, allowing energy absorption by deformation of steel between the anchor sets. Three samples were tested in a split-tube test, three samples tested in a continuous-tube test, and three tested in a multi-split-tube test. The research was conducted using the New Concept Mining (NCM) Dynamic Impact Tester (DIT).

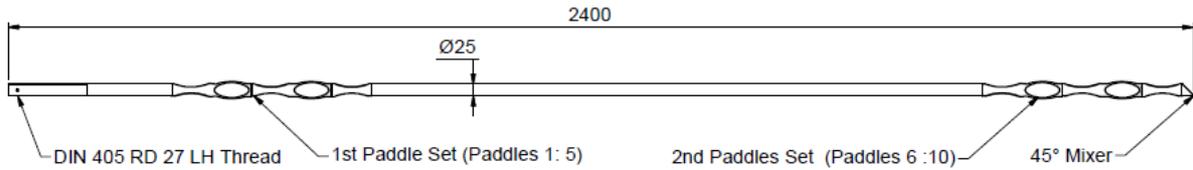


Figure 2 Sketch of the PAR1 Resin Bolt used for the testing

2 Dynamic test configuration background

In the case of a rockbolt with multiple anchor points along the length of the bolt, each of the loaded elements between anchor points should be tested. As in the case of NCM’s PAR1 style bolts shown in Figure 3, both a continuous-tube and split-tube test could be used to test each length bounded by an anchor pair along the length of the rockbolt. However, these methods test only a single loaded length at a time on the sample bolt. This means that the downfall of the two testing configurations is that it is not currently possible to test all the potential loaded lengths of a bolt in a single test. This is illustrated by the split-tube and continuous-tube simplified load paths shown below (Figures 4 and 5). The energy absorbed by the rockbolt is absorbed by deforming the steel across the loaded length.

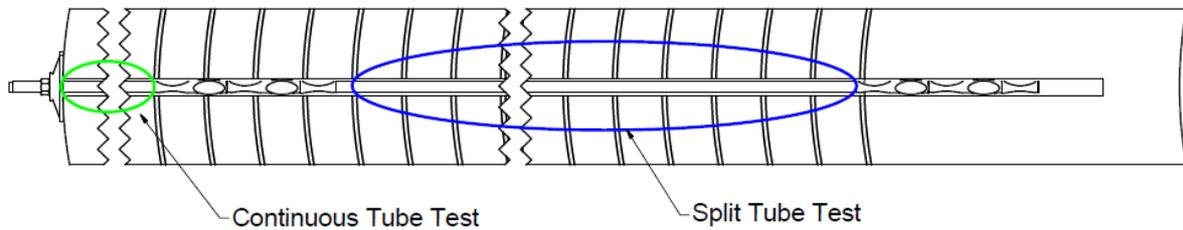


Figure 3 Illustration of discontinuity in a rock mass

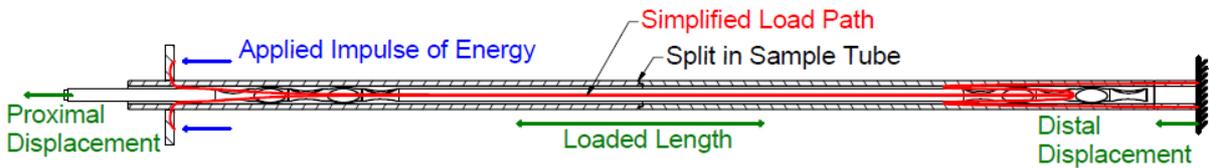


Figure 4 Dynamic split-tube test configuration; simplified load path

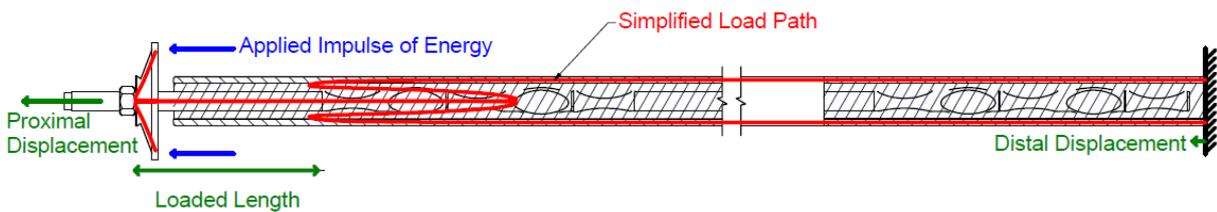


Figure 5 Dynamic continuous-tube test configuration; simplified load path

3 Multi-split-tube theory

The objective of the multi-split-tube configuration is to provide a method of testing the sample such that the rockbolt has the potential to absorb energy between each anchor pair simultaneously. Since it is understood that there is minimal deformation along the length of the anchor points of the rockbolt, both the split-tube and the continuous-tube test methods test a discrete loaded segment of the rockbolt. The multi-split-tube test configuration provides a similar loading configuration for a rockbolt with multiple anchor points, to that of a single point anchored rockbolt, in that the entire length of the bolt is loaded in a single test. It should be remembered that a single point anchored rockbolt that is anchored at the distal end, with a washer at the proximal end, can be fully tested with a continuous-tube test. The multi-split-tube test seeks to give a comparable test configuration for rockbolts with multiple anchor points along the length of the bolt. To achieve this, the impulse of energy is applied to the washer and the reaction force is provided by the distal anchor set, thereby loading the entire length of the rockbolt and fully loading the distal anchor set (Figure 6). This is achieved by adding a split in the sample tube between each anchor pair along the length of the rockbolt. The result is a method where the entire free length of the sample is loaded, isolating the distal anchor and ensuring that the loading capacity of the distal anchor is quantified. It is understood that, when correctly installed, the distal anchor should be located in a competent rock mass, and, therefore, it is critical to the performance of the bolt that the load capacity of the distal anchor within the medium is greater than the ultimate capacity of the rockbolt.

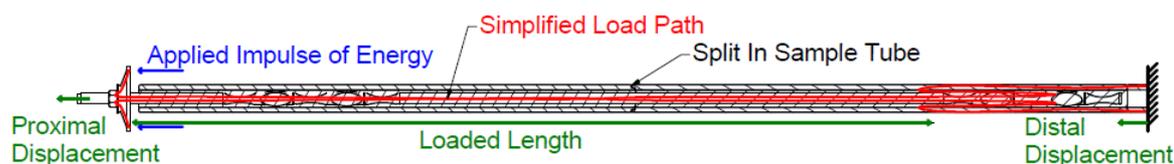


Figure 6 Dynamic multi-split-tube test; simplified load path

4 Test methodology

To perform this set of testing, NCM's PAR1 Resin Bolt was used in a $\varnothing 25$ mm by 2.4 m long configuration. The PAR1 Resin Bolt has a pair of paddle sets (anchor points), each consisting of five paddles. As a result of this design, the multi-split-tube test configuration requires only a single split positioned between the paddle sets. The splits for both the split-tube samples and the multi-split-tube samples were placed in the same relative position on the PAR1 Resin Bolt samples (Figures 7 and 9).

The samples were grouted into ST52 Hollow Bar Tubes with an internal diameter of 40 mm and an outside diameter of 63 mm, using grout with an unconfined compressive strength of 70 MPa. Once the grout had cured, the samples were prepared for dynamic testing, and the rest of the fittings were welded to the tubes to interface the sample with the DIT.

In the case of the split-tube test samples, an impact plate was welded directly to the lower portion of the sample tube, which allows for the impact to be indirectly applied to the sample (Figure 7). The impact load cell was bolted to the impact plate and a plate load cell was installed between the washer and the distal end of the Hollow Bar Tube. The Hollow Bar Tube is used to measure any load leakage through the proximal paddle set to the washer. In the case of the multi-split-tube and continuous-tube tests, the impact load cell was bolted to the impact plate secured between a washer and the distal end of the Hollow Bar Tube (Figures 8 and 9). The washer used was a square $150 \times 150 \times 8$ mm domed washer. At the completion of each multi-split-tube test impact, the length of bar protruding from the distal end of the Hollow Bar Tube was measured to determine the ratio between the deformation between the paddle sets, and between the proximal paddle set and the washer.

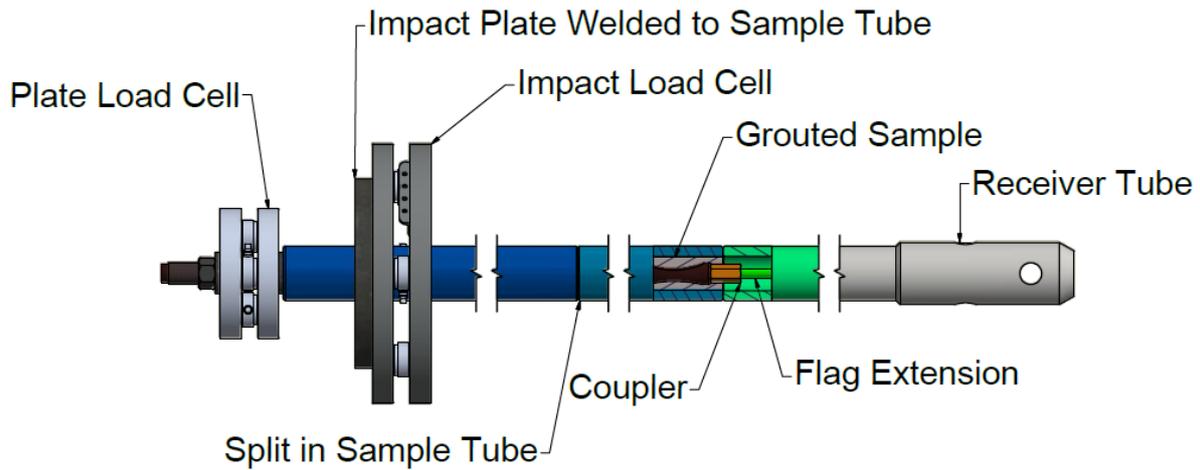


Figure 7 Split-tube sample configuration

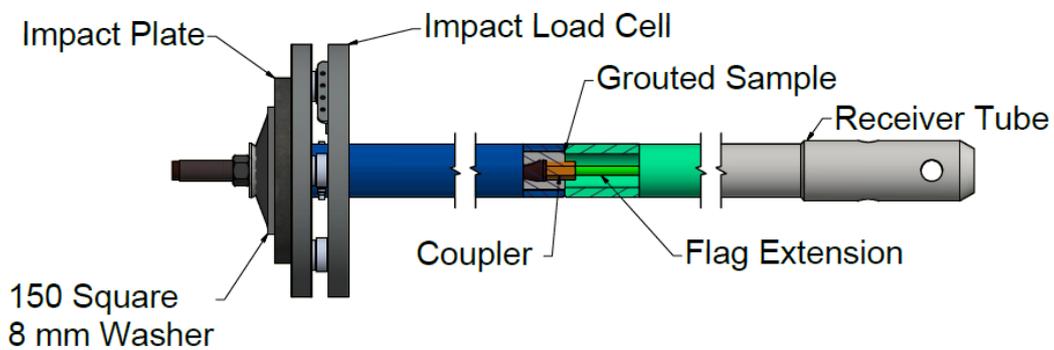


Figure 8 Continuous-tube sample configuration

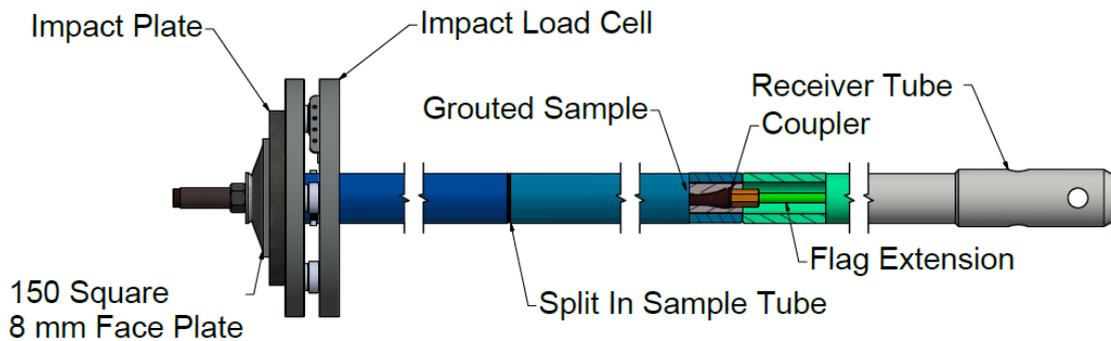


Figure 9 Multi-split-tube sample configuration

Once the samples were instrumented and installed to the DIT, the testing was performed by releasing a mass of 2,071 kg from 1.5 m above the impact load cell. This resulted in an impact energy of 30 kJ at an impact velocity of 5.4 m.s⁻¹. These input parameters were maintained for all nine tests.

To compare the relationship between the split-tube test, continuous-tube test and the multi-split-tube test configurations, the average cumulative proximal displacement and cumulative maximum absorbed energy of the split-tube test and continuous-tube test configurations were summed. The summations of the first two sets of test results were compared with the average cumulative proximal displacement and cumulative maximum absorbed energy of the multi-split-tube test results. It should be noted that the cumulative proximal displacement is compared, not the stretch in the steel, since the cumulative proximal displacement is the best indication of actual excavation closure underground. This is a critical design parameter; especially in a highly fractured rock mass.

5 Apparatus

The DIT (Figure 10) is used to transfer an impulse of energy to the test sample. The dynamic testing machine that NCM has developed has been designed in accordance with the, now obsolete, ASTM D7401-08 (ASTM International 2008). The machine is designed to perform dynamic testing on the rockbolts by raising a known mass to a known height and then releasing the mass so that the mass impacts onto the sample either indirectly (split-tube test) or directly (continuous-tube test).



Figure 10 NCM's DIT during a test

Three sets of piezoelectric load cells can be used to measure the loads applied during the tests. For all the tests, there is a load cell between the sample and DIT frame, an impact load cell attached to the sample, and then in the case of the split-tube test, there is the third load cell used to measure the load transferred to the washer, measuring leaked load. All the load measurements are recorded at 10 kHz. The displacement of the distal end and proximal end of the rockbolt are recorded by tracking rigid flags attached to the sample using a pair of Linescan cameras capturing at 10,000 lines per second. The data is compiled using a LabVIEW graphical user interface and a report is automatically generated. No filtering is performed on the reported data (Knox & Berghorst 2018a).

6 Results and discussion

6.1 Split-tube dynamic test results

A summary of the split-tube test dynamic results can be seen in Table 1, and the load–displacement curve in Figure 11. All the samples broke at approximately the midpoint between the anchor pairs, resulting in an acceptable level of deviation between the three samples. The precision of these results is seen in a total spread of only 4 kJ between the maximum and minimum cumulative maximum absorbed energy, and 12 mm on the cumulative plate displacement. There was an average of 100 kJ of cumulative maximum energy absorbed by the three samples which translates to 69 kJ/m of loaded length. Of particular interest is the low average plate load seen on all three samples; an average of 14% of the average impact load ‘leaked’ through the proximal paddle set to the washer (plate).

Table 1 Split-tube test dynamic sample summary

Sample ref.	Avg. prox. displ. (mm)	Cum. prox. displ. (mm)	Cum. toe displ. (mm)	Avg. stretch (mm)	Cum. stretch (mm)	Avg. impact load (kN)	Avg. plate load (kN)	Cum. max. absorbed energy (kJ)
ST1	75	213	2	72	210	418	89	99
ST2	74	220	13	69	205	419	38	102
ST3	77	225	3	76	222	404	47	98
Average	75	219	6	72	212	414	58	100

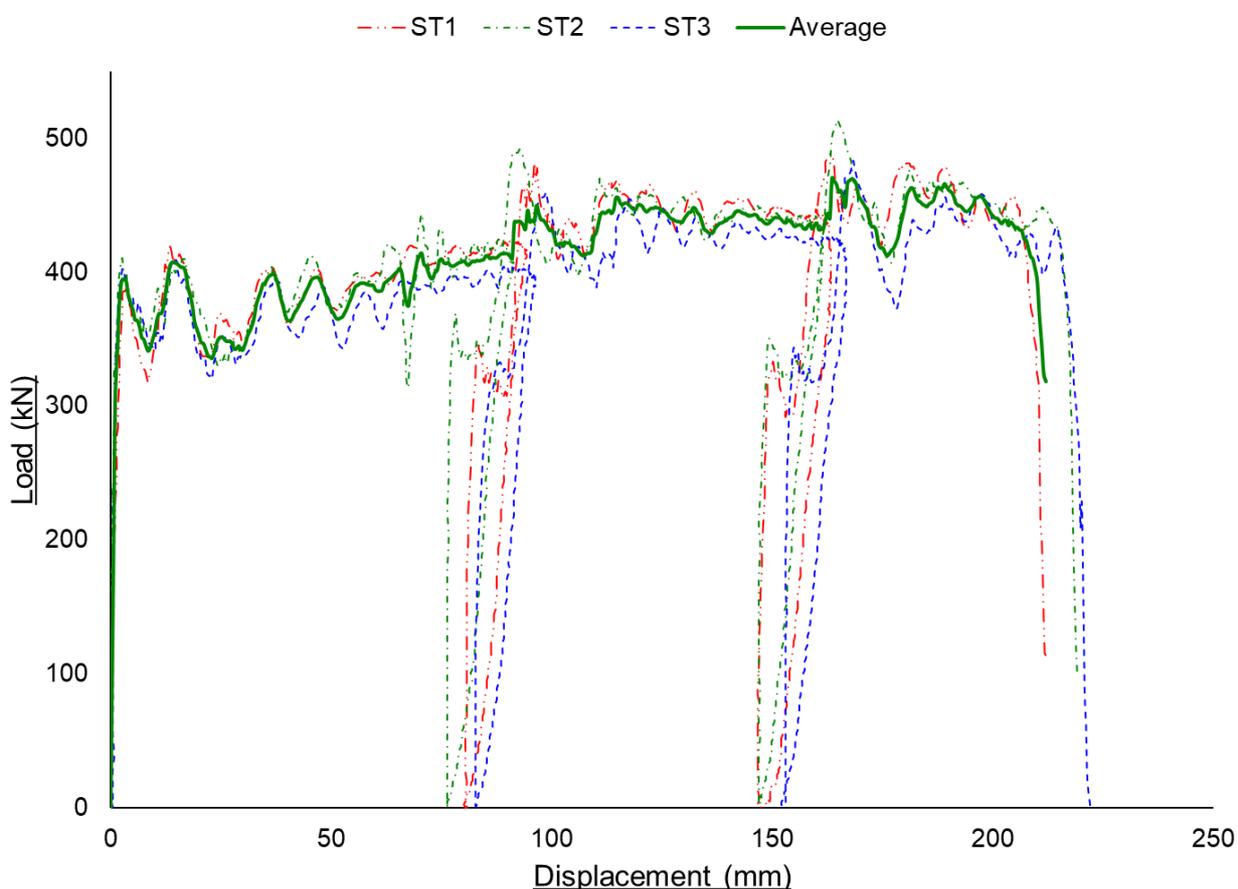


Figure 11 Split-tube sample configuration load–displacement curve

6.2 Continuous-tube dynamic test results

A summary of the continuous-tube test dynamic results can be seen in Table 2, and the load–displacement curve seen in Figure 13. The samples deformed on average 45 mm, and an average of 18 kJ of energy was absorbed by the three samples, which translates to 87 kJ/m of loaded length, where the loaded length was determined as the distance between the nut and the proximal paddle set.

The two paddle sets between the impact impulse and the distal end of the rockbolt mean that there was no measurable distal displacement by the time at which the system came to rest. The distal displacement seen during the test (Figure 12) can be accounted for in the elastic energy stored in the DIT frame during the test. There were no significant, visible damages seen on the washers during the tests, although a small deformation was noted (Figure 14). However, the washer would still be considered as perfectly functional.

Table 2 Continuous-tube dynamic test results summary

Sample ref.	Prox. displ. (mm)	Distal displ. (mm)	Stretch (mm)	Avg. impact load (kN)	Cum. max. absorbed energy (kJ)
CT1	46	0	46	403	18
CT2	45	0	45	425	18
CT3	45	0	45	414	18
Average	45	0	45	414	18

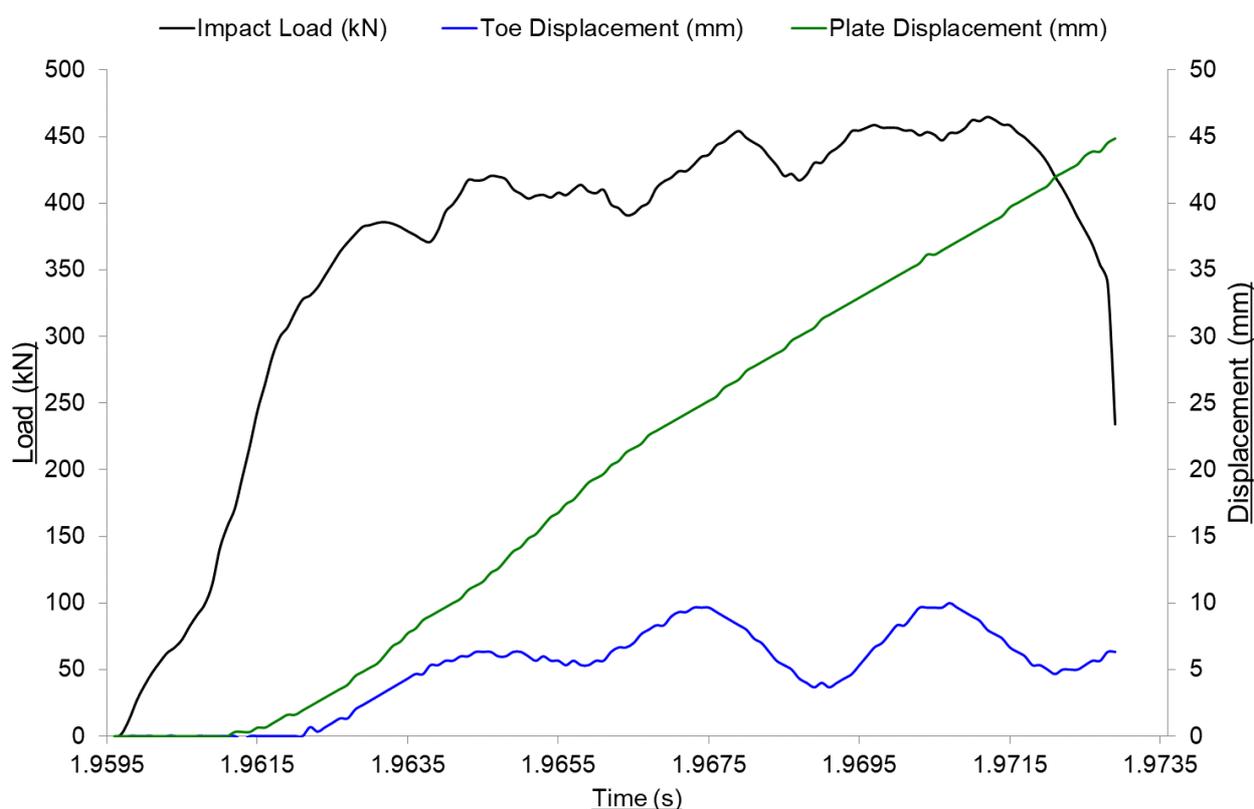


Figure 12 Sample CT2 load and displacements versus time plot

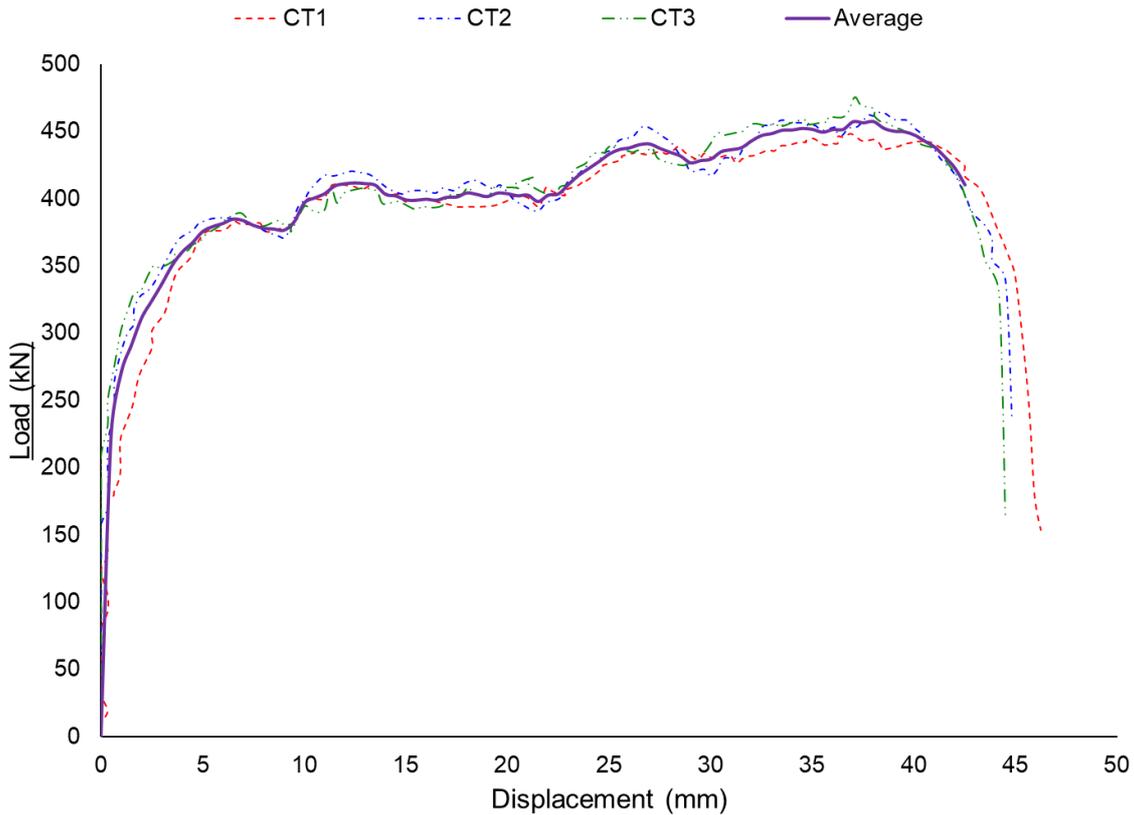


Figure 13 Continuous-tube configuration load–displacement curve



Figure 14 MS2 washer after testing

6.3 Multi-split-tube dynamic test results

A summary of the multi-split-tube test dynamic results can be seen in Table 3, and the load–displacement curve in Figure 15. Samples MS2 and MS3 failed between the paddle sets, and MS1 failed on the thread between the washer and the proximal paddle set (Figure 16). In addition, sample MS3 deformed approximately 25 mm less than samples MS1 and MS2, which skews the average results. The three samples absorbed on average 116 ± 6 kJ of cumulative maximum absorbed energy, which translates to an average of 70 kJ/m of loaded length.

Table 3 Multi-split-tube configuration dynamic results

Sample ref.	Avg. prox. displ. (mm)	Cum. prox. displ. (mm)	Avg. distal displ. (mm)	Cum. distal displ. (mm)	Avg. stretch (mm)	Cum. stretch (mm)	Average impact load (kN)	Cum. max. absorbed energy (kJ)
MS1	73	259	1	0	72	259	405	118
MS2	72	256	2	4	70	254	420	121
MS3	67	230	2	10	65	220	414	110
Average	71	248	2	5	69	244	413	116

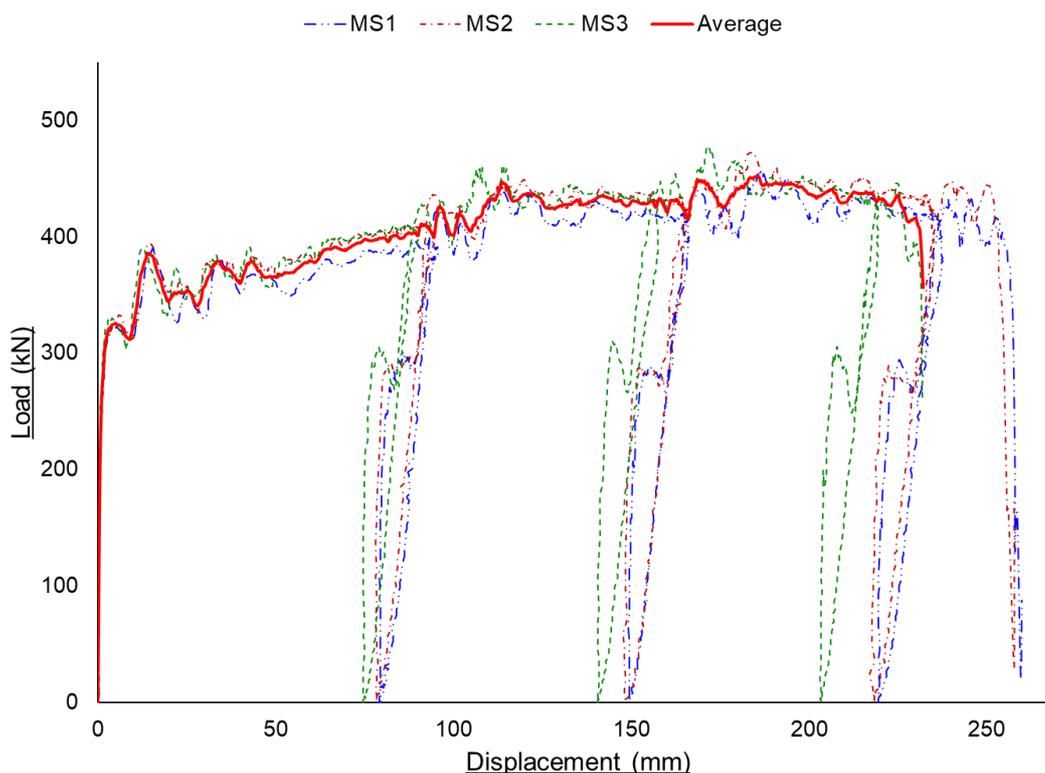


Figure 15 Multi-split-tube configuration cumulative load–displacement curve



Figure 16 Failure mode of multi-split-tube sample MS1

Before the samples were grouted and the loaded lengths were measured, the relationship of the loaded lengths was split with 87% of the loaded length between the paddle sets and 13% between the proximal paddle set and the nut and washer. When considering where the deformation occurred (Table 4), it can be seen that the deformation occurred in a similar relationship with 84% between the paddles and 16% between the washer and the proximal paddle set.

Table 4 Measurement results; location of the deformation

Sample	Length (A) (mm)	Length (A) after test (mm)	Total deformation (mm)	Deformation (C) (mm)	Deformation (D) (mm)
MS1	140	N/A	259	Sample failed on the thread	
MS2	140	180	254	40	214
MS3	140	174	220	34	186

Length (A): The length of bolt protruding from the proximal end of the sample tube.

Deformation (C): The deformation that occurred between the proximal paddle set and the nut.

Deformation (D): The deformation that occurred between the paddle sets.

7 Comparison

In order to compare the multi-split-tube test configuration to the summation of the split-tube test and continuous-tube test configuration, the minimum, maximum and average energy and displacement of the split and continuous-tube tests were summed. The result was an average cumulative maximum energy absorption of 118 ± 2 kJ compared with the 116 ± 6 kJ of the multi-split-tube configuration; a difference of less than 2%. When the cumulative proximal displacement is summed, a cumulative displacement of 264 ± 7 mm is compared with the 248 ± 18 mm of the multi-split-tube. It can be seen that there was 16 mm more displacement noted in the summation of the split-tube test and continuous-tube test configurations when compared to the multi-split-tube test configuration (Table 5). This difference is less than 6.5%, which can be viewed graphically in Figure 17, showing the comparison between the average load deformation curves for each of the sample configurations. When the entire dataset is viewed graphically (Figure 18), it can be seen that the proximal displacement per impulse (30 kJ) is in fact very similar for both the split-tube (75 mm) and the multi-split-tube configuration (71 mm).

The higher energy absorption per metre of the continuous-tube test results can be attributed to the energy absorbed in the small deformation of the washer. There is much less total energy absorbed in a continuous-tube configuration when compared to the multi-split-tube configuration. This small additional energy absorption has a greater impact on the absorbed energy per metre of the continuous-tube configuration compared to the multi-split-tube configuration. However, the energy absorbed by the washer may have resulted in the difference of 4 mm in the average proximal displacement per impulse between the split-tube and multi-split-tube configurations.

Due to the design of the PAR1 Resin Bolt, during the split-tube test the reaction force against the impact load was supplied by the distal paddle set only. This confirms that the distal paddle set can provide a sufficient anchoring by itself to break the bolt. There is a significant dispersion across the measured cumulative toes displacements ranging from 0 to 13 mm. The fact that there is an overlap of the range of distal displacements and a difference of 1 mm on average between the methods suggests that the multi-split-tube configuration can be used to verify the load capacity of the distal anchor of a rockbolt with multiple anchor points.

Table 5 A comparative summary of the average dynamic test results

Sample ref.	Prox. displ. (mm)	Distal displ. (mm)	Stretch (mm)	Avg. impact load (kN)	Absorbed energy (kJ)	Energy per metre (kJ/m)
Split-tube avg.	219	6	212	414	100	69
Continuous-tube avg.	45	0	45	414	18	89
Sum split and continuous-tube avg.	264	6	260	414	118	71
Multi-split-tube avg.	248	5	244	413	116	70

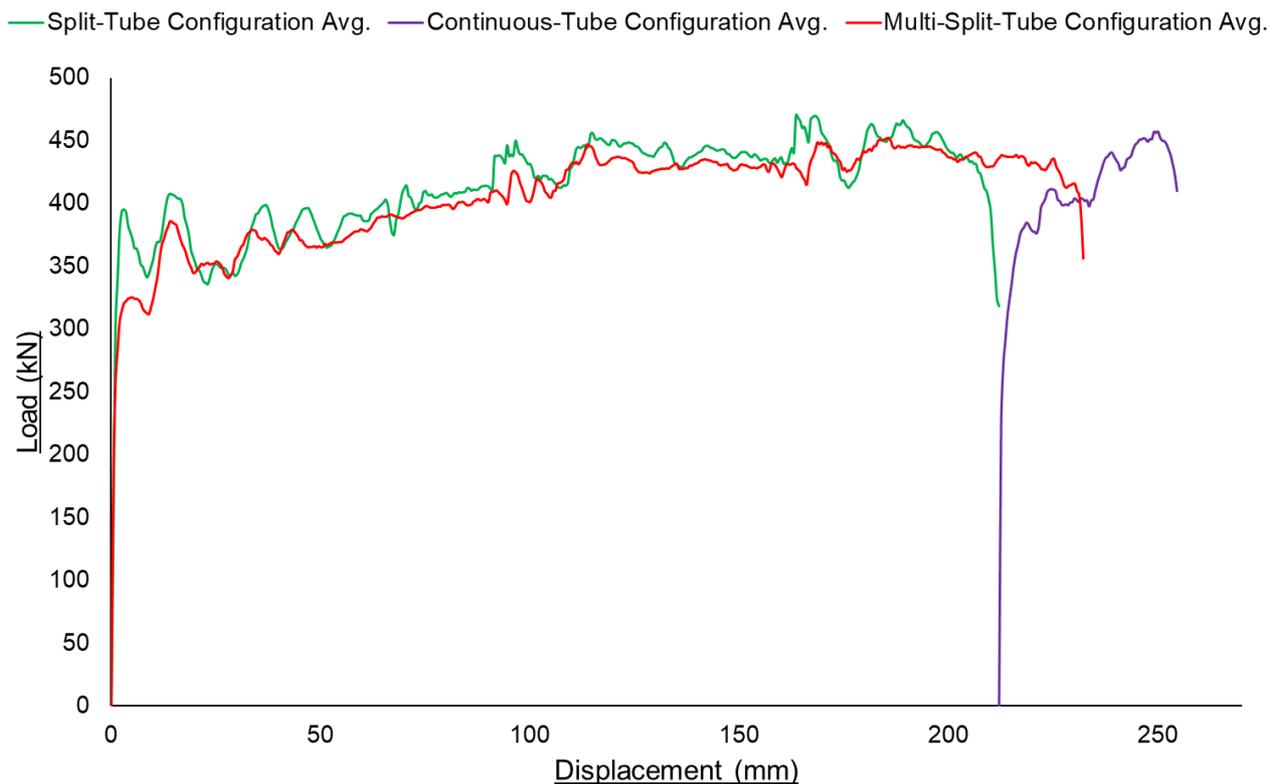


Figure 17 Average split-tube, multi-split-tube and continuous-tube configuration load–displacement curves

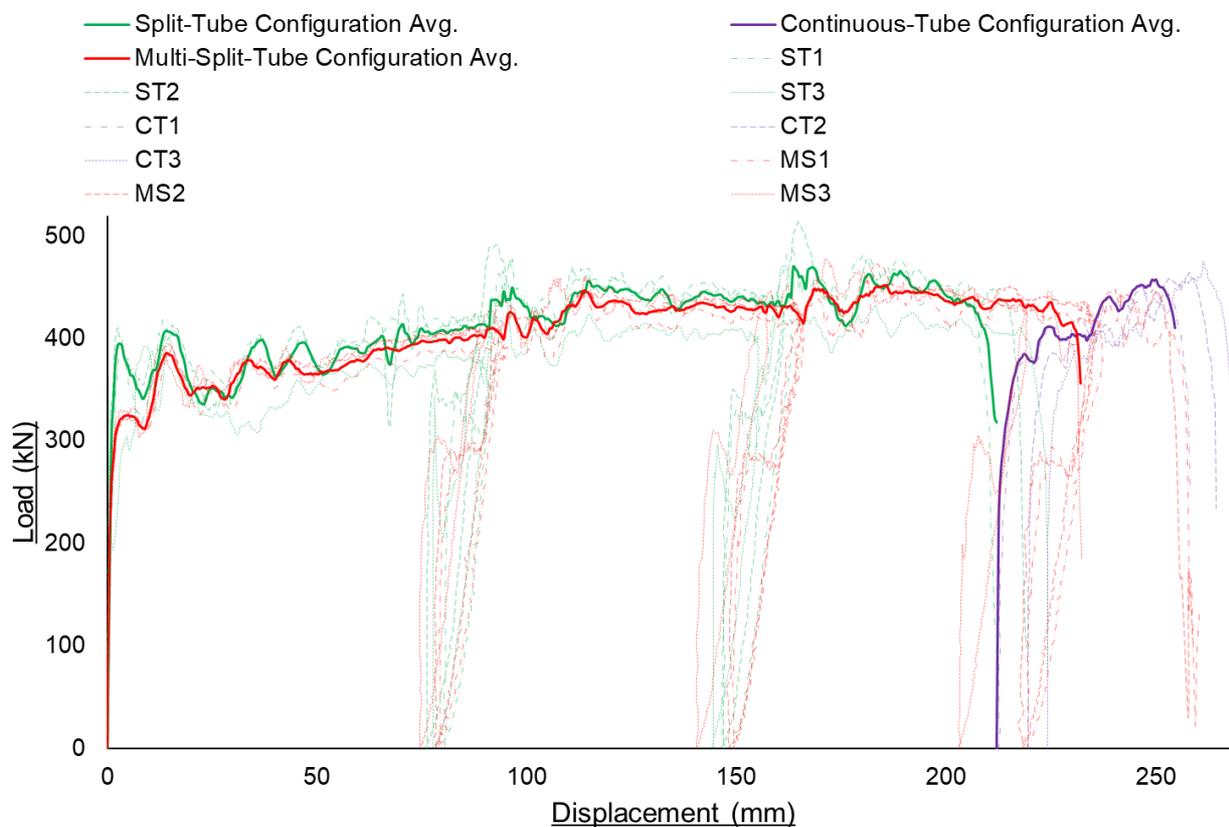


Figure 18 Measured and average split-tube, multi-split-tube and continuous-tube configuration load–displacement curves

8 Conclusion

The aim of this analysis was to determine the relationship between the split-tube test and the continuous-tube test configurations compared to the multi-split-tube test configuration. When the cumulative maximum absorbed energy is examined, it can be seen that there is a difference of less than 2%, which is less than the difference between the three samples tested using the split-tube configuration. Based on this dataset, it can be concluded that the summation of the split-tube test and continuous-tube test configurations is equivalent to the multi-split-tube test configuration. However, further testing should be conducted to conclusively establish the relationship.

The multi-split-tube test configuration allows for the entire rockbolt to be tested in a single test. Beyond this, it allows the distal end anchor set to be exposed to the full load applied during the impulse. The value of this is that in the case of a highly fractured rock mass, it is very likely that a rockbolt, with multiple paddle sets along the entire length, may require the full impact load to be carried by the distal paddle set. If a split-tube test is used, it is possible that more than one paddle set may carry this load, and this means that the test may not accurately reflect the applied loading experienced underground.

The multi-split-tube test allows for the total capacity of a rockbolt, with multiple anchor points, when exposed to multiple fractures to be tested in a single test. To achieve this result, a split in the sample tube must be placed between each anchor pair.

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