Increased agility for the research and development of dynamic roof support products

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ABSTRACT: **N**ew **C**oncept **M**ining (NCM) has developed the **D**ynamic **I**mpact **T**ester (DIT) capable of testing as many as 179 rock bolts in a period of six months, with no interruptions to mining operations. The limitations of the dynamic axial loading testing method are known, however, the DIT provides an efficient platform, on which a large number of tendon support systems can be compared under controlled conditions with increased agility. During the rapid development of new rock bolt products it is crucial to quantify the effects of high strain rates exerted by rock bursts on ground support systems. The DIT provides this capacity.

1 INTRODUCTION

"Increasingly, dynamic capabilities of ground support are becoming key design parameters when selecting yielding elements for highly stressed, burst-prone or high deformation environments." (Plouffe, Anderson, & Judge, 2007). As these rock burst events result in high strain rates being applied to ground support systems, it is critical to an effective design, to be able to understand the effects of such events on the ground support system. A dynamic increase factor proposed by Malvar and Crawford (Malvar & Crawford, 1998) links the dynamic properties of a steel to the strain rate and yield strength. This is indicative of the necessity for dynamic testing to understand the effect of high strain rates on a tendon and design accordingly.

Results of one of the first recorded dynamic tests performed on rock bolts were presented in 1969 by Ortlepp (Ortlepp, 1969). These tests were conducted using in-situ blasting methods. Several laboratory-based test facilities have since been established, one being at the Canadian government owned testing facility at CanMET and another at the Australian academic institution at the Western Australian School of Mines (Villaescusa, Thompson, & Player, 2004). Recently, the addition of the system tester developed by Geobrugg allows for a full system test. These existing testing facilities, although highly accredited, have limited capacity, which is a constraint to rapid development and qualification of new rock bolt products.

New **C**oncept **M**ining (Pty) Ltd (NCM) has commissioned an in-house **D**ynamic **I**mpact **T**ester (DIT) that complies with Method B of ASTM D7401-08 (ASTM, 2008) and gives NCM the ability to rapidly develop customized rock bolt products for the industry in line with customers' specific test parameters and requirements.

2 REQUIREMENTS FOR A DYNAMIC IMPACT TESTER

The limitation of a dynamic impact tester with respect to the simulation of an underground rock burst are clearly understood. However, "the main advantage of the drop test approach lies in the capacity to perform a relatively large number of tests at a reasonable cost without interfering with mining operations." (Hadjigeorgiou & Yves, 2011) Based on this, NCM commissioned the development of a drop tester capable of fulfilling the following requirements: low cost configuration, test a tendon system and capability to inducing failure in a single impulse. The low configuration cost allows for a large number of tests to be performed on the tendon system including the washer, nut and face plate. The ability to impart enough energy to induce failure in a single drop will allow the effects of the input parameters on the results of testing to be fully understood.

3 DYNAMIC IMPACT TESTER

The **D**ynamic **I**mpact **T**ester (DIT) (Fig. 1) is used to transfer an impulse of energy to the sample, that could be expected during a rock burst. The dynamic testing machine developed by NCM has been designed in accordance with ASTM D7401-08 (ASTM, 2008). The machine is designed to impart an impulse of energy to the rock bolts by raising a known mass to a known height and then releasing the mass so that the mass will impact onto the sample either directly (continuous tube test) or indirectly (split tube test). The specifications of the machine can be seen in Table 1.

Table 1: DIT Specifications

Specification	Value
Max. Impulse	65 kJ
Max. Impact Velocity	6.42 m/s
Max. Drop Mass	3171 kg
Min. Drop Mass	551 kg
Max. Drop Height	2.1 m
Max. Sample Length	3.5 m
Height of Structure	8.2 m

The designed components, which enable the machine to meet these specifications can be viewed as four main subsections: the mechanical structure, dynamic components, the instrumentation and the software.

3.1.1 *Mechanical Structure*

The main support structure of the DIT is an H-frame comprising two pairs of C-channels between two columns (Fig. 1). The receiver block with four pins allows for a quick coupling between the receiver tube welded to the sample and the frame. A pair of Guide Rails attached to the columns, on which the wheels of the Trolley travel, constrain the direction of the impact along the axis of the tendon. The final structural component, seen in Figure 1, is the camera rail. This provides a stable platform from which the measurements can be taken, improving the accuracy of the linescan imaging system.

To empirically prove the stiffness of the frame, a flag was placed on the frame load cell, located at the midpoint of the pair of C-channels. The results seen in Table 2 were recorded during four 37.4 kJ material tests. A stiffness of 121.3 kN/mm was calculated from the maximum displacement and maximum loading of the frame, which was considerably stiffer than the 1.7 kN/mm of the sample being tested, proving the limited effect of the structure on the results.

3.1.2 *Dynamic Components*

During an impact, the kinetic energy of the Trolley is imparted on to the test specimen. As the kinetic energy of the Trolley is approximately equal to the potential energy of the Trolley relative to the point of impact, when the Trolley is released, $E_k=U=mgh$. Therefore, the magnitude of this energy imparted is adjusted either by changing the combination of 190 kg and 90 kg mass plates or the height from which the Trolley is released to achieve intended energy and impact velocity. The impact velocity is calculated as follows: $v = (2 \times 9.81 \times h)^{½}$, where h is the height, relative to the impact plate from which the Trolley is released, using an electromagnet. Once released, the Trolley free falls onto the impact plate, axially loading the tendon. The forces and displacements, resulting from the impact enable the calculation of the energy transferred during the impact.

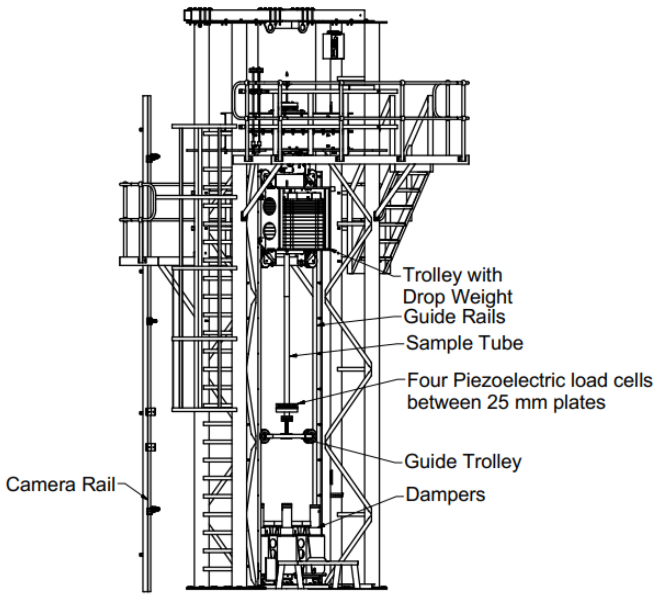

Figure 1: NCM Dynamic Impact Tester

Table 2: DIT Frame Stiffness and Deflection

Nr	Max Frame Load (kN)	Max. Frame Displacement (mm)	Stiffness K (kN/mm)	Energy Absorbed (kJ)
1	409.6	3.1	131.1	0.84
2	422.1	3.2	130.8	0.92
3	416.3	3.8	109.8	1.08
4	431.4	3.8	113.7	0.99
Avg.	419.8	3.5	121.3	0.96

3.1.3 *Instrumentation*

During each test, the drop height, impact forces and displacements are determined using the following sensors and data capturing hardware. A string pot is used to measure the drop height and calculate the theoretical kinetic energy and velocity of the Trolley at the point of impact. During the impact, the load transferred from the tendon to the Trolley is measured using four PCB205C piezoelectric load cells. The load cells are sandwiched between two 25 mm plates to evenly distribute the loading across the four cells. In addition to the impact load cell, the same configuration of piezoelectric load cells is used to determine the load transferred from the sample to the frame. In the case where the sample is indirectly loaded, the load that would be imparted to the washer attached to the tendon is measured with a third set of load cells. The signals from the load cells are fed through a pair of PCB 483C05 signal conditioners before being captured at a rate of 10 kHz.

To provide an accurate displacement measurement during the impulse, the displacements of both the distal and proximal ends of the tendon are measured. This measurement is recorded by attaching black and white striped flags to the ends of the test specimen. These flags are used as reference points to be tracked by a pair of Basler Racer GigE Line Scan cameras at a rate of 10000 lines per second. Using the width of the stripes as a reference for determining the scale, lines are processed to determine the displacements of the flags. To ensure the loading and displacement data signals are aligned, the ADC sample clock signal, from the PCIe-6434 DAQ capturing the load signals, is routed to the Line Scan cameras as a trigger line. The signals from the instrumentation are recorded for a period of 10 seconds, commencing 0.5 seconds after power is removed from the electromagnet. With the delayed collapse of the magnetic field, a minimum of 1 second is recorded prior to the impact. It is important to note that the data is not filtered by either the hardware or software.

3.1.4 *Data Processing*

Prior to data processing, all data is saved, ensuring the raw data is secure, before the automated data processing commences with the processing of the line scan data. A function that was developed using the LabVIEW vision library scans the lines tracking the pattern of the flags.

The load data is then scanned to locate the first impulse of the drop as seen in. The consecutive bounces are ignored as the majority of the plastic deformation of the tendon occurs on the first impulse. Once the region of interest has been isolated, the cumulative energy absorption, displacement and load indicators are calculated. The data is reported in the form of a Microsoft Excel Workbook. The data for the individual drops is tabulated in the form of a detailed summary seen in Table 3: the definitions are graphically demonstrated in Figure 3 and an abbreviated summary seen in Table 5.

The individual drops are graphically represented as a function of time (Fig. 7) and as a function of the plate displacement. A cumulative load-displacement curve (Figs 8,9) represents the data of multiple consecutive drops. The cumulative final plate displacement results allow for a graphic comparison between multiple samples of the same test batch.

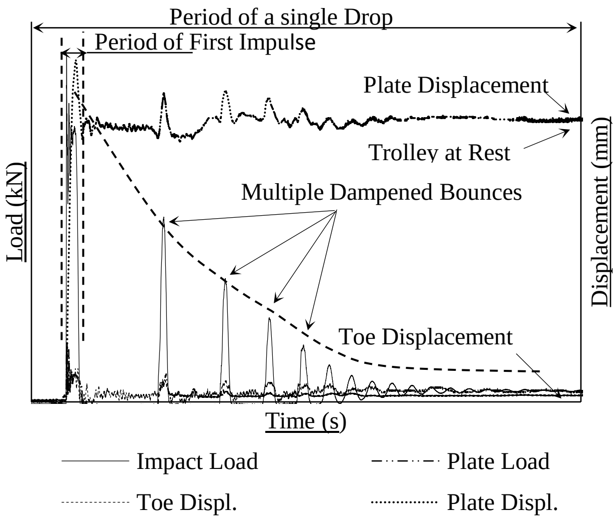

Figure 2: Typical load and displacement signals during the period of a drop

Table 3: Detailed Summary

Input Data	Drop Number
	Drop Mass (kg)
	Drop Height (mm)
	Input Kinetic Energy - Theo. (kJ)
	Input Kinetic Energy - Actual (kJ)
	Impact Velocity - Theo. (m/s)
	Impact Velocity - Actual (m/s)
Displacement	Plate Displ. - Final (mm)
	Plate Displ. (mm)
	Plate Displ. - Max. (mm)
	Toe Displ. - Final (mm)
	Toe Displ. (mm)
	Toe Displacement - Max. (mm)
	Deformation - Final (mm)
	Deformation (mm)
	Deformation - Max. (mm)
	Cumulative Deformation - Max. (mm)
Load	Frame Load - Max. (kN)
	Frame Load - Peak (kN)
	Frame Load - Avg. (kN)
	Impact Load - Max. (kN)
	Impact Load - Peak (kN)
	Impact Load - Avg. (kN)
Time	Time to Plate Displacement - Max. (mS)
	Time to Impact Load - Max. (mS)
	Impact Time (mS)
	Rebound Time (mS)
	Total Impact Duration (mS)
Strain	Peak Load Avg. Load Rate (kN/s)
	Impact Avg. Strain Rate (mm/s)
	Rebound Avg. Strain Rate (mm/s)
Energy	Absorbed Energy - Final (kJ)
	Absorbed Energy - Max. (kJ)
	Cumulative Absorbed Energy - Final (kJ)
	Cumulative Absorbed Energy - Max. (kJ)

3.1.5 *Energy Balance and Absorption Calculation*

Most of the rock bolt systems tested thus far in the DIT rely on a stretching of a loaded length of steel to absorb energy. For this reason the energy absorption calculation for the system is implemented by a trapezoidal integration of the impact load over the displacement of the plate during the first impulse.

$$W_{plate} = \int_{S_1}^{S_n} F \, d\delta = \sum_{S_1}^{S_n} \frac{F_n + F_{n-1}}{2} \times (\delta_n - \delta_{n-1}) \qquad (1)$$

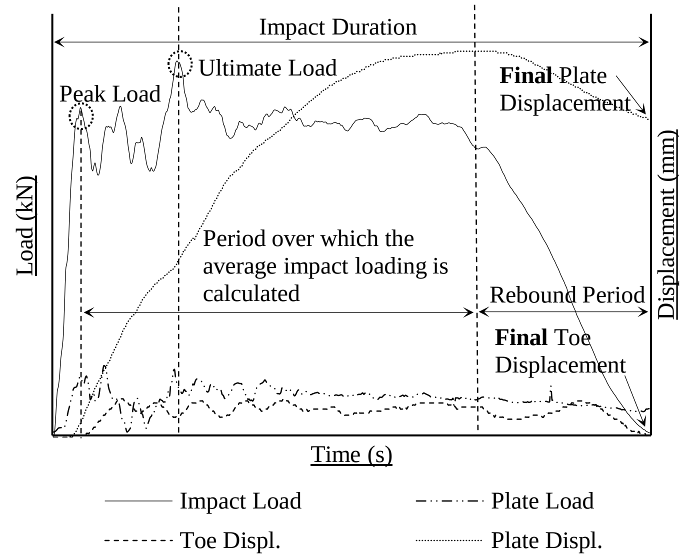

Figure 3: Illustration of definitions

where S_n is the final position of the plate and S_0 in the initial position of the plate at impact. At the point of impact, the Trolley has a theoretical kinetic energy equivalent to the potential energy calculated from the drop height. However, at the point of impact, the Trolley has a potential energy relative to its final position. Therefore, the total potential energy can be represented as follows: $U_{Total} = m_{Trolley} \times 9.8 \times (\delta_{drop\ height} + \delta_{plate})$, hence the losses during the test can be determined by calculating the difference between the total potential energy and the energy absorbed by the tendon system. In Table 4 the calculated potential energies for 20 drops were batched in the following kinetic energies at the point of impact: 8.1 kJ, 17.4 kJ, 30 kJ and 37.4 kJ. The impact velocity was kept constant at a theoretical 5.4 m/s for all the samples. The average losses per batch remain relatively constant with an average magnitude of 0.83 kJ (Table 4) and hence higher relative to the total potential energy as seen in Figure 4.

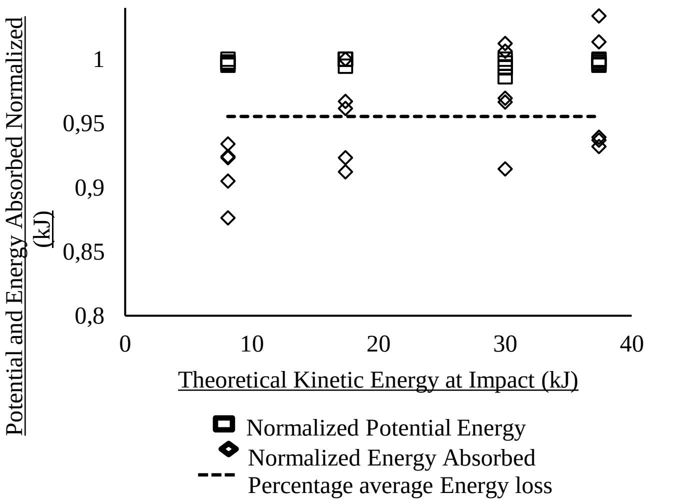

Figure 4: Normalized Potential Energy, Absorbed Energy at different impact kinetic energies

Table 4: Energy Losses in the System

Theoretical Kinetic Energy (kJ)	Avg. Loss (kJ)	Avg. Loss (%)
8.1	0.70	8.5
17.4	0.84	4.6
30.0	0.70	2.1
37.4	1.10	2.7

The system losses will be the sum of frictional losses, acoustic energy and energy absorbed by the rubber pads on the load cells used to prevent ringing and heat, as the temperature of the sample increases during the impact.

3.1.6 *Efficiency of Testing*

Currently the testing process is such that the sample preparation requires the bulk of lead time in the testing of a sample. Should all the materials be in stock at the time a test is requested, the sample preparation lead time can be as short as 3 days for a resin bolt or friction unit and 9 days for a grouted sample. Currently grouted samples are allowed to cure for 7 days. Once prepared, samples can be tested at a rate of between 3 to 6 per day dependent on the failure mode. As the data from the Line Scan camera is processed automatically, analysis of the results can begin directly after the test. In a period of 6 months 179 dynamic tests were performed, a testament to the efficiency of the DIT testing process. A summary of these results can be seen in Figure 5.

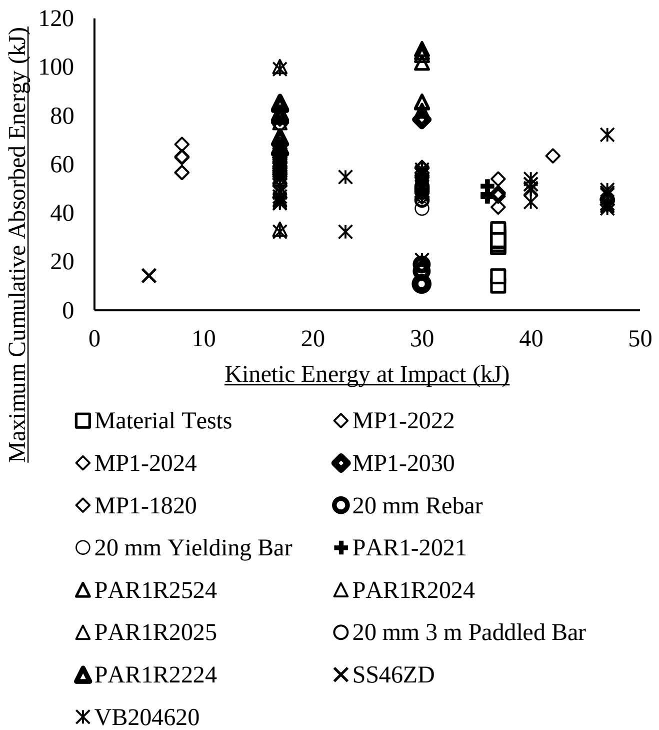

Figure 5: Representation of the last 6 months of testing

4 DISCUSSION OF RESULTS

In order to illustrate an example of the results generated by the DIT, the test results from a MP1-2024 tested with multiple impulses of a theoretical kinetic energy of 17.4 kJ, with an impact velocity of 5.4 m/s, will be discussed.

The MP1-2024 is a 2.4 m Ø20 mm yielding rock bolt. Upon insertion, the shell (see Fig. 6) at the distal end of the bolt is ejected from the grout sleeve, providing a mechanical anchor against which pretension can be applied. A grouting nozzle placed over the grout sleeve allows grout to be pumped up the internal bore of the sleeve, then back down through the bore of the hole, providing a full column. Once the grout is cured, the paddle pairs at the distal and proximal ends of the bar form anchor points between the grout and the rock bolt. During squeezing or a rock burst, the bar between the paddles de-bonds from the grout, absorbing the energy via deformation.

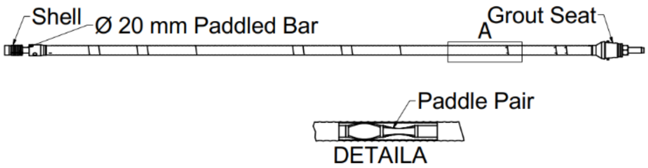

Figure 6: Illustration of the MP1-2024

The MP1-2024 was tested in a split tube configuration where the load was indirectly applied to the tendon. The load applied to the lower split tube is transferred through the grout to the proximal paddle set. Of particular significance is the low “load leakage” onto the washer measured by the plate load cell (Fig. 7). This “load leakage” is generally in the range of around 30 % of the impact load.

The effects of strain hardening which can be noted on a Quasi-static pull test can also be seen when analysing the change in loading and displacement over multiple drops: the 12 mm reduction in stretch between drops 2 to 4 and the increase in the average load of 9 kN (Table 5). This is graphically represented in Figure 8, however, it is generally more pronounced in the resin bolts as seen in Figure 9.

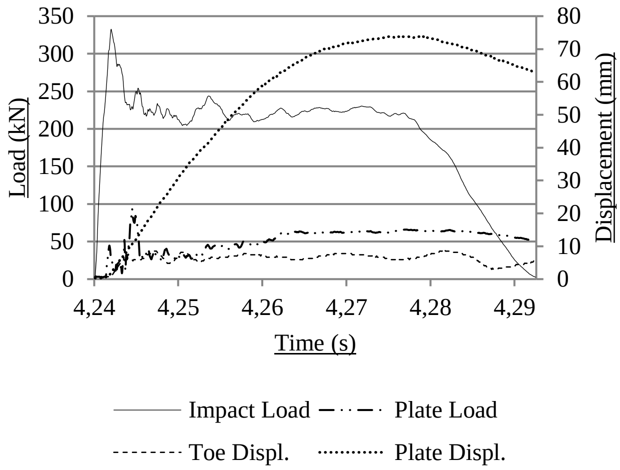

Figure 7: Load and Displacement as a function of time for the first of the 5 drops on to the MP1-2024

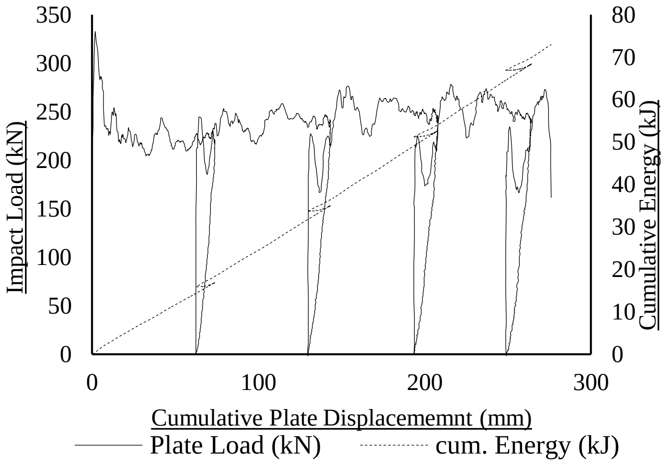

Figure 8: Cumulative Load-Displacement Curve for the MP1-2024

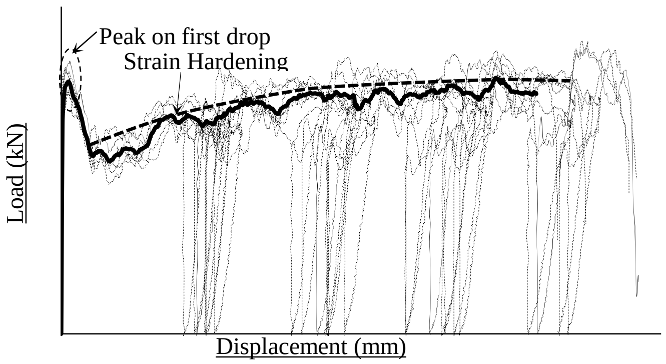

Figure 9: Typical cumulative Load-Displacement curve for a resin bolt

Table 5: Standard Results Summary for the MP1-2024

					Impact Load (kN)			Plate Load (kN)			
Drop Nr	Plate Displ. (m)	Toe Displ. (m)	Stretch (m)	cum. Stretch (m)	Peak	Ultimate	Avg.	Peak	Ultimate	Avg.	Absorbed Energy (kJ)
1	0.062	0.005	0.058	0.058	332	332	226	45	94	51	16.9
2	0.068	0.002	0.066	0.124	244	258	238	37	75	48	19.1
3	0.064	0.000	0.064	0.188	226	276	245	57	122	88	18.9
4	0.056	0.001	0.055	0.243	223	278	247	88	135	91	17.1
5	0.027	0.004	0.023	0.266	232	273	226	64	132	79	6.0

Common to both the grouted and resin bolts is the initial peak on the first impact; on the consecutive drops the initial peak is not the maximum recorded load. This is a phenomenon that is still to be investigated. It could be a result of the additional initial stiffness provided by the medium in which the sample is installed. It is, however, not noted on any of the Quasi-static results.

5 CONCLUSION

The aim was to develop an efficient system capable of dynamically testing roof support systems. The DIT developed for NCM allows for a relatively low configuration cost enabling a high volume of tests (179) to be performed in a relatively short period (6 months). Testing has revealed that the DIT has an acceptably limited influence on the result: the structural stiffness of 121 kN/mm, with a loss of approximately 0.83 kJ per impulse, indicates that an acceptably small proportion of the input energy is absorbed by the DIT, with the majority of the energy being absorbed by the tendon support system being tested.

6 FUTURE WORK

The future work consists of a number of subsections, including further development of the machine, research and expanding the capabilities of the facility.

The focus on the future work in respect of the machine, is to improve the understanding of the input parameters: the kinetic energy and the velocity at impact. Therefore, the first improvement to the machine will provide the capability to accurately measure the impact velocity of the Trolley prior to and during impact. This will be achieved by tracking the trajectory of the Trolley with an additional Line Scan camera, thus increasing the field-of-view of the lower linescan imaging system to 2.8 m. The trajectory of the Trolley will be tracked prior to the impact, allowing for the losses in the system to be accounted for and the drop height adjusted. In addition, this will allow for the rebound velocity to be calculated enabling the coefficient of restitution and the system dampening to be calculated, further improving the understanding of the impact.

Currently the standard is to calculate the impact mass based on the sum of the average value of the plates used and the mass of the Trolley. In order to improve the accuracy of the stated impact mass, a pair of load cells with be added. The impact mass will be determined as the difference in the mass measured before and after releasing the mass.

As the initial work on the machine will be focused on improving the accuracy with which the input parameters are quantified, the focus of the research will be to understand the effects of the test parameters, including the sample configuration, on the results.

Finally, additional machinery may be added to the testing facility. Currently, in addition to the DIT, the NCM Resin Bolter allows for the installation of resin bolts with accurately controlled rates of insertion, spin rates and hold times which can all be programmatically adjusted and controlled. This provides a platform on which resin bolts can be consistently installed and the effects of the installation parameters on the performance quantified. The benefits of this machine have been noted and there are plans for additional machinery to be added to the facility.

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