Dynamic tests of a new type of energy absorbing rock bolt – the D bolt

C.C. Li
The Norwegian University of Science and Technology (NTNU), Norway

C. Doucet
CANMET Mining and Mineral Sciences Laboratories, Ottawa, Canada

S. Carlisle
Xstrata Nickel, Sudbury, Canada

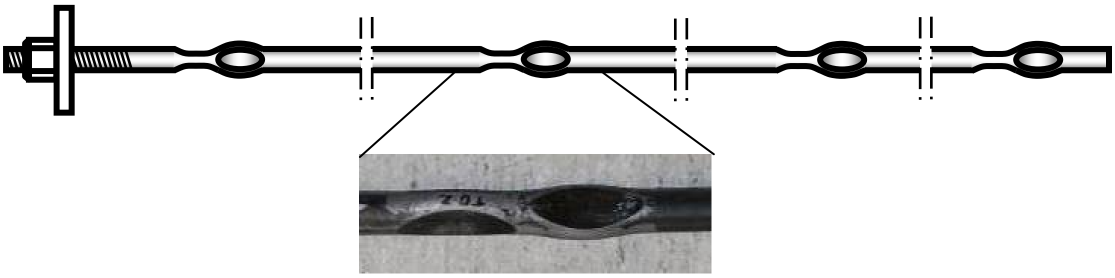
ABSTRACT: D bolt is a new energy-absorbing rock support element recently developed in Norway. The D bolt is a smooth steel bar with a number of anchors along its length. It is anchored in a borehole with either cement grout or resin. The D bolt is only fixed with the grout in the anchors' positions, while the smooth sections between the anchors can freely deform when subjected to rock dilation. The smooth sections independently provide reinforcement functions to the rock. Failure of one section would not affect the reinforcement function of other sections of the bolt. Therefore, the D bolt has a more reliable reinforcement effect than two-point anchored energy bolts. The D bolt is characterised by its large load-bearing and deformation capacities. Dynamic drop tests on D bolts were recently carried out at CANMET-MMSL's rock testing facility in Ottawa, Canada. The dynamic performance as well as the resin mixing capabilities of the D bolt will be presented in this paper. The dynamic tests (split tube) have shown that the dynamic energy absorption capacity of the 20 mm diameter D bolt is about 44 kJ/m . The impact average load was close to the ultimate load of the shank (20 tons). In the split tube configuration only a small portion of the impact load was transferred to the bolt plate. The mix tests showed the anchor paddles of the D bolt provide very reliable resin mixing.

1 INTRODUCTION

Hard rock mines face increasing ground control issues when the mining gets deeper with time. Ground support systems have to provide a satisfactory rock reinforcement as well as rock burst containment and control. The concept of ductile, or energy-absorbing, ground support has been accepted by many practitioners of ground support. Energy-absorbing elements are necessary components in a ductile ground support system. The D bolt is a new energy-absorbing rock support element recently developed in Norway. It is a multi-point steel bar anchored in a borehole with either cement grout or polyester resin. The D bolt is not only able to accommodate large rock deformations, but can also provide a load-bearing capacity as high as that of rebar bolts. Furthermore, the anchoring quality of the D bolt is similar to rebar bolts because of its multi-point anchoring design. This paper focuses on the results of the dynamic drop tests of the D bolt conducted at CANMET-MMSL (Doucet and Anderson, 2009). The contents include a brief description of the D bolt, the resin mixing capabilities of the bolt, the impact load, the plate load and the energy absorption of the bolt.

2 D BOLT

The D bolt is made of a smooth steel bar that has a number of integrated anchors evenly or unevenly spaced along the length of the bar, Figure 1. In the current design, the anchors are stronger than the shank of the bolt. The purpose for this design is to mobilise both the strength and the elongation capacity of the shank when the bolt is subjected to loading. The shank, rather than the anchors, is designed to yield, ultimately failing under extreme loading conditions. The anchors can have different shapes. The anchor shown in Figure 1 is called the paddle-anchor which is designed for polyester resin grout. Every paddle-anchor consists of two paddles that are formed by deforming the bolt shank in two orthogonal directions. The size of the paddles is only slightly larger than the bolt shank so that it can be inserted in small boreholes. D bolts use the anchor paddles to mix resin.



Paddle-anchor

Figure 1. Layout of the D bolt.

The D bolt is fully grouted in the borehole with either cement grout or polyester resin. The anchors are fixed in the grout, while the smooth bar sections between the anchors have no or very weak bonding to the grout. When rock dilation occurs between two anchors, the anchors limits the dilation so that a tensile load is induced in the bar section between the anchors. The section will elongate elastically in the beginning, but it will quickly get to yield with a small amount of elongation. Plastic elongation occurs next and continues until the ultimate strain limit. The ultimate elongation of a section is the product of the section length and the ultimate strain of the bar material. Taking the steel of rebar, i.e. B500C, as an example, its ultimate strain is between 15 – 20%. It means that a 1-m long section can elongate up to 150 – 200 mm prior to failure. The total energy absorbed by the smooth bar section is approximately equal to the product of the ultimate load and the ultimate elongation. Assuming that the bar has an ultimate load of 200 kN, which is a typical load capacity of a 20 mm diameter steel bar, the energy absorption capacity of the bolt is approximately 30 – 40 kJ/m. The D bolt fully utilises both the deformation and load capacities of the steel material. It can accommodate large rock dilation while, at the same time, bearing loads as high as a rebar bolt does.

Every section between two adjacent anchors works independently. Failure of one section or loss of one anchor only locally affects the reinforcement effect of the bolt. The other sections or the other anchors still provide reinforcement to the rock as usual. This independency is a significant improvement compared to two-point anchored energy bolts. For instance, should the anchoring function be lost at the face plate because of rock spalling behind the plate, the reinforcement function is lost only in the section of the bolt from the plate to the first anchor. For the D bolt, this section is only about 0.2 m long. The other sections are not negatively affected by the loss of the anchoring at the face plate, a common problem with conventional rock bolts.

3 D BOLT SAMPLES FOR DROP TESTS

The bolt samples for drop tests are 1.6 m long and 20 mm in diameter. Every bolt sample has three anchors each of which is comprised of two paddles that are orthogonally formed by deforming the bolt shank, Figure 2. The energy absorption capacity of the bolt section between anchors 1 and 2 will be examined by the drop tests. The nominal length of the test section is 0.8 m. The surface of the test section is either without any treatment or wrapped with a shrink film.

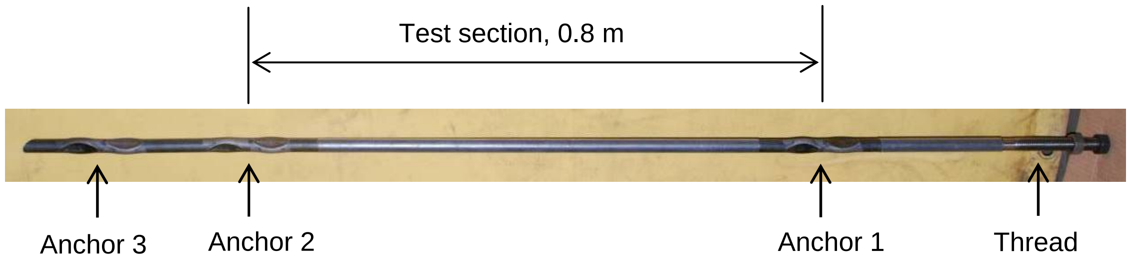


Figure 2. D bolt sample for drop tests.

4 RESIN MIXING STUDY

Mixing tests were conducted before the drop tests in order to examine the ability of the D bolt to properly mix the resin. The resin used for these tests was DSI's Ground Lok two part polyester cartridges. Boreholes are simulated by PVC pipes of the required inside diameter. The bolt is spun into the tube at a steady advancement rate and constant RPM as shown in Figure 3. Once the bolt reaches the plug at the end of the tube, the advance is stopped and the bolt is rotated for an additional 5 seconds. The insertion times in Table 1 do not include the additional 5 seconds.

Once the samples were cured, the tubes were cut open and the unmixed portions of resin were measured to determine the proportion of well mixed resin in the hole.

Figure 3. Installation set-up for the mixing study.

5 DYNAMIC DROP TESTS

5.1 *Sample Preparation*

Boreholes are simulated by a two-piece steel tube which has an internal diameter (ID) of 32 mm and a wall thickness of 12 mm. The two-piece tube is placed in a jig to align it with the drill. It has sheet metal wrapped around the joint to prevent resin from escaping. Resin cartridges are then slid to the end of the tube. The bolt is inserted in the chuck which is attached to a drill mounted on a sliding rail with an independent advance drive system. The bolt is spun into the tube at a steady advancement and constant RPM. Once the bolt reaches the plug, the advance is stopped and the bolt is rotated for an additional 5 seconds.

5.2 *Testing procedure*

Each test consists of dropping a known mass, from a known height, onto a plate connected to a tendon grouted inside a steel tube. The testing set-up for the D-bolt is presented in Figure 4. It is what is referred to as a ”split-tube” test; i.e. the bolt is installed in two (2) sections of tubes held together and the impact is not on the bolt plate but up along the tube further from the head of the bolt. The energy input is controlled by the drop height and the mass. The height of drop can be varied from 0 to 2.1 m (2.4 m if no bottom load cell is installed). The drop test rig has a present capacity of 3 Tons from a height of 2 meters.

The weight is lifted with an electromagnet, which in turn is lifted by a pair of cranes mounted in parallel on the top of the machine. By cutting the power to the magnet, the weight free falls onto the sample.

The appropriate weight is prepared by bolting together the necessary steel plates. A clevis is installed on the end of a thin-walled tube that runs up through the center of the support assembly for the tube. The clevis will attach the thin-walled tube to the end of the bolt. The end displacement is measured by a linescan camera, which monitors a target on the thin-walled tube above the frame load cell.

The bolt sample is inserted through the center of the magnet and the weight. The top of the sample tube is inserted into the receiver end of the drop test support assembly. A 25.4 mm bolt suspends the tube in place. The 25.4 mm bolt has a small hole through its middle to allow for the passage of the clevis to the tail of the bolt. The clevis is lowered onto the tail of the bolt and two machine screws are used to attach the clevis to the bolt. Then the magnet is lowered down on top of the weight. The cranes are attached directly to and lift the weights. Once lifted, a rock bolt plate, a dome washer and a thread nut are installed on the threaded end of the bolt (Figure 5). Under the threaded nut, the target for the lower linescan camera is installed.

At this time, the lights and the two linescan cameras (lower and upper) are calibrated using a specially machined black and white target. Following calibration, the weight is lowered onto the impact plate. The crane chains are moved from the weight to the magnet. The data acquisition system is started. The operator lifts the weight to a desired height. Once at the desired height and with the acquisition system ready, the operator releases the magnet.

5.3 *Instrumentation*

Instrumentation consists of plate and end displacement monitors and load cells attached to the frame above the sample and below the impact plate and below the bolt plate. The plate displacement refers to the displacement measured at the bolt plate, while the end displacement refers to the movement of the bolt end. The load cell below the impact plate measures the impact load and the load cell below the bolt plate measures the load that is transferred to the bolt plate.

6 RESULTS AND DISCUSSION

6.1 *Resin mixing study*

The capability of the bolts to properly mix the resin is a crucial parameter as it will greatly influence its behaviour under static and dynamic loading. If the resin is not properly mixed, the bolt will plough through the resin thus considerably reducing the amount of load and stretching that the bolt could withstand. Two different pipe diameters (i.e. 32 and 37 mm) were used in the course of this study. However, as the diameter required for the drop tests was 32 mm, more tests were conducted with that diameter in order to gain confidence in the mixing of the resin in that hole size.

The results obtained are presented in Table 1. All bolts used had shrink wrap between anchors 1 and 2. The results show that good mixing was obtained with the 32 mm hole. Two insertion times were used for the 32 mm hole: the first series with an average insertion time of 55 sec, corresponding to 300 revolutions, and the second series with an average insertion time of 13 sec, corresponding to 70 revolutions. The second series is closer to the actual underground installation with a mechanized bolter.

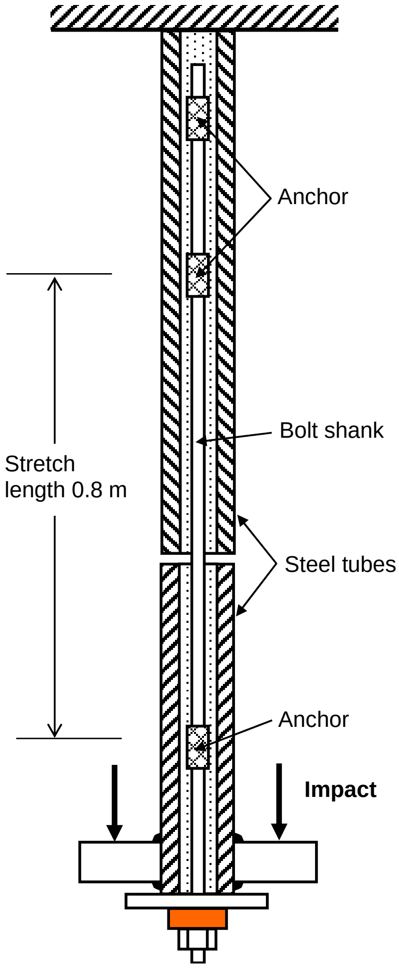


Figure 4. Dynamic test arrangement of the D bolt.

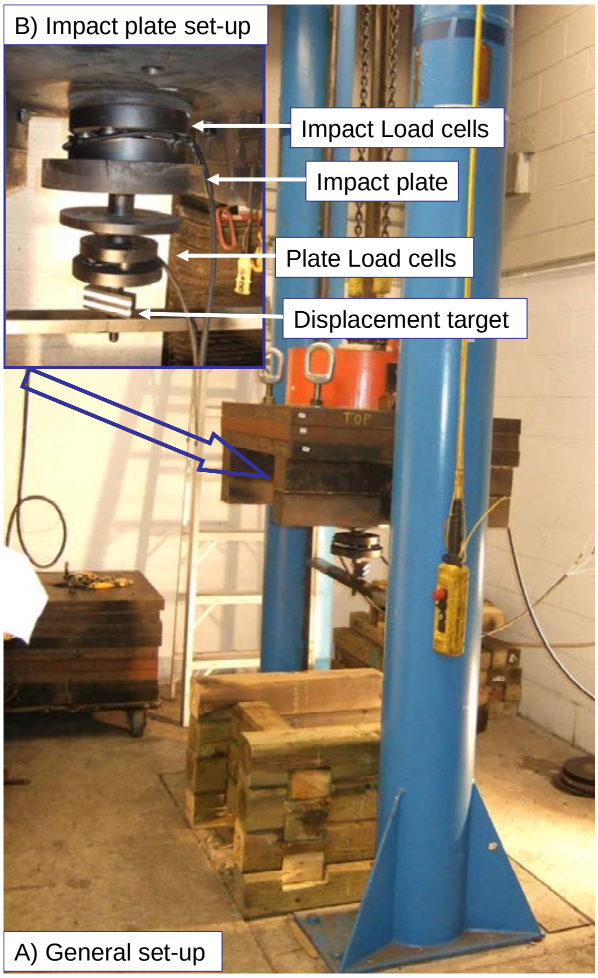


Figure 5. Dynamic drop test set-up.

Table 1. Testing parameters and results from the mixing study.

Sample	Pipe		Resin			RPM	Insert	length of	unmixed	well	Avg
	I.D.	Wall Th.	dia	Lt	Qty	measured	time	bar in pipe	length	mixed	
	(mm)	(mm)	(mm)	(mm)			(sec)	(mm)	(mm)	(%)	
1	31.50	4.85	28	457	3	350 to 270	58	1354	50	96	99
2	31.98	4.85	28	457	3	360 to 260	55	1365	0	100	
3	31.50	4.85	28	457	3	350 to 280	53	1356	0	100	
4	31.97	4.85	28	457	3	360 to 290	54	1360	0	100	
5	31.90	4.85	28	457	3	350 to 250	15	1357	20	99	96
6	31.92	4.85	28	457	3	350 to 300	12	1355	169	88	
9	31.75	4.85	28	457	3	350 to 300	12	1362	0	100	
10	31.81	4.85	28	457	3	350 to 300	12	1354	10	99	
7	36.94	5.08	30	610	2.5	360 to 300	13	1509	1000	34	
8	36.94	5.08	30	610	2.5	360 to 300	13	1506	1000	34	
11	36.77	5.08	32	305	5	330 to 260	13	1510	660	56	77
12	36.75	5.08	32	305	5	320 to 260	13	1502	30	98	

6.2 *Dynamic drop tests*

Dynamic drop tests were conducted on four D bolt samples. A total of five drop tests were actually conducted as sample D-4 failed at the first drop because of issues with the resin. This sample was therefore discarded and replaced with sample D-5. All the bolts have a measured diameter of 19.8 mm. They were all installed using the same parameters as for samples 5, 6, 9 and 10 in Table 1, which were:

- Hole diameter: 32 mm
- Resin cartridges: 28 mm in diameter
- Rotation speed: 300 – 350 RPM
- Insertion time for a length of about 1.4 m: 12 – 15 seconds.

The results of the drop tests are presented in Table 2. Figure 6 shows the typical curves of load measured below the impact plate (impact load) and below the bolt plate (plate load) during a drop. The results show that samples D1, D2 and D5 behaved similarly in the aspects of the drop number, impact load and plate load. Sample D-3 behaved differently for the first drop in that a ploughing displacement of up to 94 mm occurred with a little plastic stretch (2 mm). For the subsequent three drops, it behaved very similarly to the other three samples. It was also observed that more load was transferred to the plate for sample D-3 than for the other samples. After cutting open the steel tube of sample D-3, it was observed that the bolt slid through a patch of soft resin and then settled and started to stretch. The test results can be shortly summarised as follows:

- The impact peak load was 20 – 25 tons,
- The impact average load was 20 – 23 tons,
- The plate peak and average loads were 1 – 11 tons, except for sample D-3,
- Every drop induced a steel stretch of about 0.05 m regardless if the sample was wrapped with shrink film or not.
- All bolts failed at the joint between the two tubes, on the smooth section of the bolt.

The total stretch of the bolts was obtained by cutting open the steel tubes and measuring the distances between the anchors after the testing was completed and comparing with the initial measurements. It was found that plastic elongation only occurred in the section between anchors 1 and 2. The elongations of the stretch section for the four samples are presented in Table 3. The dynamic ultimate strain of the bolts is similar to their static ultimate strain of 15% - 20%.

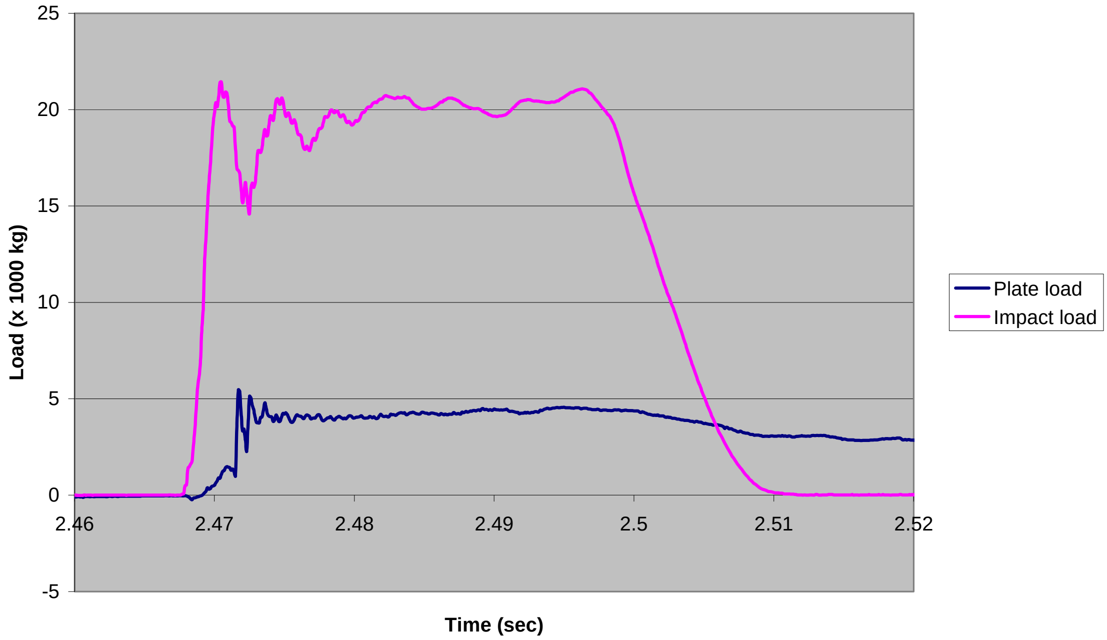


Figure 6. The impact and plate loads recorded during the first drop of sample D-1.

Table 2. Drop testing results of D bolts.

no data available

Sample D-1

Bolt type	Drop #	Drop mass (kg)	Drop height (m)	Input energy (kJ)	Impact velocity (m/s)	Plate displ. (m)		End displ. (m)		Steel stretch plastic (m)	Frame load (kg)		Impact load (kg)		Plate load (kg)	
						Incr.	Cum.	Incr.	Cum.		Peak	Avg.	Peak	Avg.	Peak	Avg
shrink wrap	1	893	1.50	13.14	5.42	0.056	0.056	0.003	0.003	0.053	24620	22500	21430	20400	5370	4000
	2	893	1.50	13.14	5.42	0.047	0.103	0.000	0.003	0.047	30380	23600	23960	20400	7450	5480
	3	893	1.50	13.14	5.42		0.103	0.000	0.003	0.000	32115	23000	22875	21460	3140	3140
shrink wrap	**Total**			**39.42**		**0.103**		**0.003**		**0.100**	**29038**	**23033**	**22755**	**20753**	**5320**	**4207**

Sample D-2

Bolt type	Drop #	Drop mass (kg)	Drop height (m)	Input energy (kJ)	Impact velocity (m/s)	Plate displ. (m)		End displ. (m)		Steel stretch plastic (m)	Frame load (kg)		Impact load (kg)		Plate load (kg)	
						Incr.	Cum.	Incr.	Cum.		Peak	Avg.	Peak	Avg.	Peak	Avg
shrink wrap	1	893	1.50	13.14	5.42	0.056	0.056	0.006	0.006	0.050	29950	22900	22490	21660	6000	7000
	2	893	1.50	13.14	5.42	0.049	0.105	0.001	0.007	0.048	32560	23400	22015	22130	12320	11075
	3	893	1.50	13.14	5.42		0.105	0.000	0.007	0.000	29550	23930	20520	22790	12105	10750
	Total			**39.42**		**0.105**		**0.007**		**0.098**	**30687**	**23410**	**21675**	**22193**	**10142**	**9308**

Sample D-3

Bolt type	Drop #	Drop mass (kg)	Drop height (m)	Input energy (kJ)	Impact velocity (m/s)	Plate displ. (m)		End displ. (m)		Steel stretch plastic (m)	Frame load (kg)		Impact load (kg)		Plate load (kg)	
						Incr.	Cum.	Incr.	Cum.		Peak	Avg.	Peak	Avg.	Peak	Avg
no shrink wrap	1	893	1.50	13.14	5.42	0.096	0.096	0.094	0.094	0.002	22950	18750	23040	17900	19280	19650
	2	893	1.50	13.14	5.42	0.057	0.153	0.000	0.094	0.057	26930	22890	25150	21760	22270	21300
	3	893	1.50	13.14	5.42	0.048	0.201	0.002	0.096	0.046	31050	23100	25510	22090	23370	21700
	4	893	1.50	13.14	5.42		0.201	0.000	0.096	0.000	30260	23650	23310	22170	22870	21970
	Total			**52.56**		**0.201**		**0.096**		**0.105**	**27773**	**22098**	**24253**	**20980**	**21948**	**21155**

Sample D-5

Bolt type	Drop #	Drop mass (kg)	Drop height (m)	Input energy (kJ)	Impact velocity (m/s)	Plate displ. (m)		End displ. (m)		Steel stretch plastic (m)	Frame load (kg)		Impact load (kg)		Plate load (kg)	
						Incr.	Cum.	Incr.	Cum.		Peak	Avg.	Peak	Avg.	Peak	Avg
no shrink wrap	1	893	1.50	13.14	5.42	0.056	0.056	0.003	0.003	0.053	26080	22900	26590	21710	10120	5700
	2	893	1.50	13.14	5.42	0.051	0.107	0.002	0.005	0.049	31010	22930	24580	22050	2220	1000
	3	893	1.50	13.14	5.42		0.107	0.000	0.005	0.000	0	0	18000	23000	500	700
	Total			**39.42**		**0.107**		**0.005**		**0.102**	**19030**	**15277**	**23057**	**22253**	**4280**	**2467**

Table 3 Elongation and strain results.

Sample	D-1	D-2	D-3	D-5
Elongation	0.141 m	0.143 m	0.133 m	0.113 m
Ultimate strain	18%	18%	17%	14%
* The measured length of the stretch section is 0.795 m.				

The input energy (13.14 kJ) was not completely absorbed by the bolt during the last drop. The portion of energy absorbed has to be estimated based on the stretch increment for the last drop by referring to the stretch increments for the previous drops of the sample. The stretch increments and energy dissipated for all drops are presented in Table 4. Notice that the energy dissipated for the last drop in the table is estimated based on the stretch increment. The total energy dissipated for steel stretching is similar for samples D-1 and D-2, while it is slightly smaller for D-3 and D-5. The average energy absorption capacity of all four samples is 35 kJ for a stretch section of 0.8 m, or 44 kJ per metre of bolt.

Table 4. Dynamic energy absorption of the D bolt samples.

Sample	Drop #	Input energy (kJ)	Plastic steel stretch (m)	Energy dissipated for steel stretch (kJ)
D-1 shrink wrap	1	13.14	0.053	13.14
	2	13.14	0.047	13.14
	3	13.14	0.041[(2)]	10.78[(3)]
	Total:		**0.141**[(1)]	**37.05**
D-2 shrink wrap	1	13.14	0.050	13.14
	2	13.14	0.048	13.14
	3	13.14	0.045[(2)]	12.07[(3)]
	Total:		**0.143**[(1)]	**38.35**
D-3 no shrink wrap	1	13.14	0.002	0.51
	2	13.14	0.057	13.14
	3	13.14	0.046	13.14
	4	13.14	0.030[(2)]	5.61[(3)]
	Total:		**0.133**[(1)]	**34.44**
D-5 no shrink wrap	1	13.14	0.053	13.14
	2	13.14	0.049	13.14
	3	13.14	0.011[(2)]	2.83[(3)]
	Total:		**0.113**[(1)]	**29.11**

Notes:

(1) Total stretch measured after failure.
(2) Calculated by subtracting the stretch increments of the other drops from the total stretch.
(3) Calculated on the basis of the stretch increment for the last drop.

7 CONCLUDING REMARKS

- The D bolt is a multi-point anchor steel bar installed in a fully grouted borehole. Loss of one anchoring point would not result in a total loss of the reinforcement performance of the bolt. Every section between adjacent anchors works independently to restrain rock dilation. Loss of one section would not affect the functionality of the other ones.
- The D bolt absorbs the deformation energy of rock by fully mobilising the strength and the deformation capacity of the bolt material (steel). Therefore, provided that the bolt has well mixed the resin during installation, its performance under dynamic conditions should be repeatable and predictable.
- The D bolt is equally loaded in every section between two adjacent anchors. Opening of individual fractures will load the whole section, which prevents the bolt from premature failure due to local stress concentration.
- A total of four (4) samples were tested under dynamic loading conditions at the CANMET-MMSL's laboratory and twelve (12) samples were used to determine the mixing ability of the D-bolt. From these tests, the following observations can be made:
    - The mixing study shows that the paddles of the 20 mm D-bolt can reliably mix cartridge resin in a 32 mm hole.
    - The average energy absorption capacity obtained is about 44 kJ per metre of bolt length for the 20 mm D bolts tested.
    - The average impact load is about 20 tons which is close to the steel's static ultimate strength.
    - Only a small portion of the impact load was transferred to the plate. This seems to indicate that the anchor closest to the bolt plate provides protection to the threaded portion of the bolt, generally considered the weakest link.
    - The effect of shrink wrap on the behaviour of the bolt seems to be minimal.

ACKNOWLEDGEMENT

The authors would like to thank Dr. Graham Swan for his initiation of the project and his engagement in the course of testing.

REFERENCE

Doucet, C. and Anderson, T 2009. Dynamic testing of D bolts. CANMET-MMSL. 27p.