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Roofex® — Results of Laboratory Testing of a New Concept of Yieldable Tendon

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Abstract

To provide the mining and tunnelling industries with a rock reinforcement fixture that is better suited to mining with high stress conditions, Atlas Copco has developed a new rockbolt that can accommodate both very large displacements and high energy release in the rock mass. The design principles that guided the development of the rockbolt are presented and discussed. For one, the Roofex® was designed to offer accurate pre-set load-deformation behaviour. This first model or prototype is based on a 12.5 mm diameter steel bar because of borehole diameter limitations.

1 Introduction

This paper presents the preliminary results of a laboratory testing program aimed at assessing the impact energy dissipation capability of a new rockbolt. The laboratory program had not been completed at the time of the publication of this document. However, the results represent the most up-to-date findings at this current time. In situ field tests are still on-going and have been delayed due to issues at the various mine sites. Unfortunately, no results were available at the time writing the paper. All the dynamic tests referred to in the paper have been performed at the premises of the CANMET Mining and Mineral Sciences Laboratories (CANMET-MMSL), of Natural Resources Canada, Ottawa, Canada.

The rockbolt, named Roofex®, has been tested in the laboratory for static and dynamic loading conditions. Static loading tests have been performed at the Atlas Copco MAI laboratory, and showed energy dissipation of 800 J/cm of displacement and a capability to accommodate more than 60 cm of displacement at the rock surface with dissipation of deformation energy of more than 50 kJ. At CANMET-MMSL, impact loadings of up to 27 kJ have been applied, with the rockbolt accommodating 425 J/cm of displacement. The physical set up of the testing is discussed, and the loading curves are presented and analysed.

2 Background

Dynamic failure of rock in an underground space can generate high levels of kinetic energy and expulsion of rock from the opening surface. Rock material could reach velocities of more than 3 metres per second. In those conditions, the rock reinforcement is more than often destroyed or at least mobilised in excess of its working range. This tends to result in localised caving or a highly deformed excavation profile. An example of such behaviour is seen in Figure 1, with the result of a strain burst that destroyed the roof of an underground stope access and the installed reinforcement. Rock reinforcement used in such extreme conditions must be able to sustain the energy burst, as well as retaining the rock adequately before and after the event.

Although they do not simulate exactly the mechanics of the bursting rock mass, drop tests are still the easiest way to evaluate the suitability of a rock reinforcement fixture to be used in rockburst prone ground. It is the energy transfer to the fixture that is of interest, and using the kinetic energy of a moving mass to generate the energy released during a rockburst, is the fundamental purpose of performing a drop test over an anchored rockbolt. Laboratory tests also provide an easy way to quantitatively compare a given rockbolt capacity to any theoretical loading energy. Repeatability is an important advantage of simple laboratory tests, and their applicability is a function of our understanding of the laboratory test and the field mechanic of rockbursting.

3 Roofex® — A new rockbolt

As mining progresses towards greater depths, the rock reinforcement must provide adaptability never needed before. Reinforcement must sustain the static load necessary for immediate support of the excavation. However, with more extreme stress changes occurring around excavations, the reinforcement must also be able to adapt to large stresses and deformations and maintain its integrity, thus providing the required operational safety.

The Roofex® rockbolt, as presented in Figure 2, is a rockbolt specifically designed to provide stiff reinforcement up to the yield load of the system; when the yield load is exceeded, the bolt will provide that same load for the entire pre-determined displacement length. The bolt system consists mainly in a sliding element inside which a smooth bar is travelling, generating a constant frictional resistance. The sliding element is anchored using resin or cement grout (at this stage), and the face plate located at the collar of the borehole transfers the displacement of the rock contour into the bar via the nut.

The bolt can be installed either manually, with a stopper or jack-leg drill, or in a mechanised fashion with a bolting rig. Installation with resin cartridges is performed easily as the mixing element is specially designed to assure a proper tearing of the cartridges envelope and an adequate mixing of the catalyst. The development of the mixing element was an important phase of the rockbolt development, and its efficiency was first evaluated by mixing tests in Plexiglas and steel tubes, and afterwards with field installation tests. Laboratory and field installation tests have proven the validity of the installation method, as pull tests confirmed the good anchorage of the sliding element. Figure 3 shows tests in Plexiglas and in slotted steel tube, to verify that the system would not tend to act as a piston and push the resin out of a fractured borehole.

The bolt mechanically yields when the load on the bar exceeds a value of 75 kN. The system yield load is designed to be slightly lower than the bar yield load, enabling the bolt to keep as much as possible its original properties during the entire loading process. The ultimate load of the bar at the threads is 100 kN, while its yield load is 90 kN.

In order to assess the Roofex® capability in dynamic loading conditions, a laboratory testing program has been undertaken to quantify the performance of the new rockbolts in such loading conditions using an impact rig.

Figure 1 Strain burst on the roof of a stope access

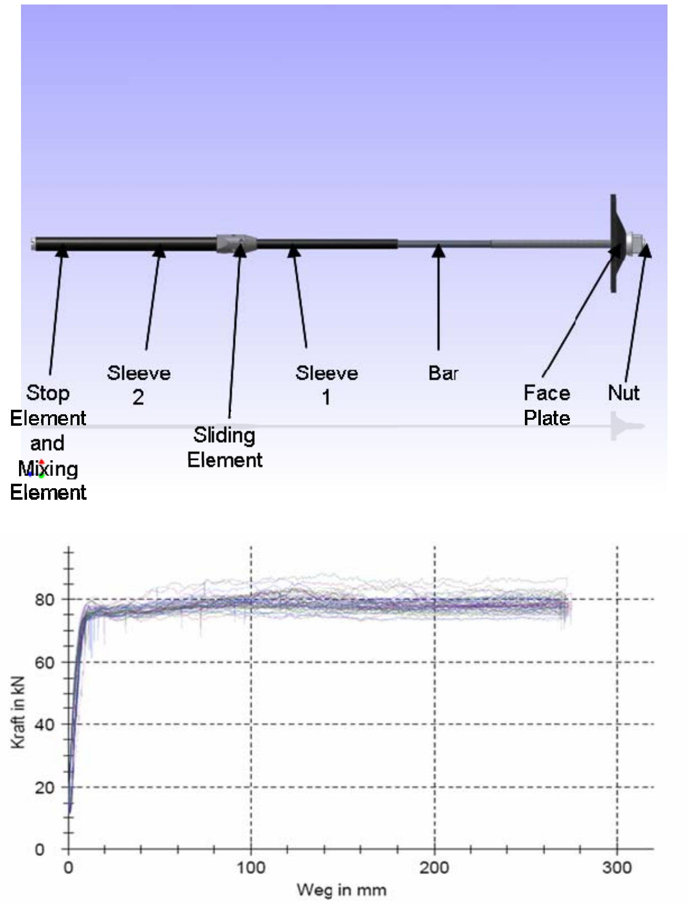


Figure 2 Description and static performance of the Roofex® rockbolt. Load – Displacement curve for a 30 cm displacement setting

a) b)

Figure 3 Mixing tests in a) plexiglas tube and in b) slotted steel tube

3.1 Testing program

The dynamic loading testing program was performed at the CANMET-MMSL facilities in Ottawa, Ontario, Canada. The equipment used was the previous Noranda Technology Centre dynamic loading testing frame, which has subsequently been upgraded mechanically and with better monitoring capabilities. In order to gain experience, a preliminary test program started with a series of impact tests at 5 kJ of impact energy. The test program then moved to increase the energy levels of 15 kJoules and more, as seen on Table 1. Figure 4 shows a schematic of the testing frame.

Table 1 Preliminary testing program for dynamic loading at CANMET-MMSL

	Energy Levels at 4.7 m/s velocity			
First impact	5 kJ	10 kJ	15 kJ	20 kJ
Second impact	5 kJ	5 kJ	15 kJ	5 kJ
Third impact	5 kJ	5 kJ		
Total energy	15 kJ	25 kJ	30 kJ	25 kJ

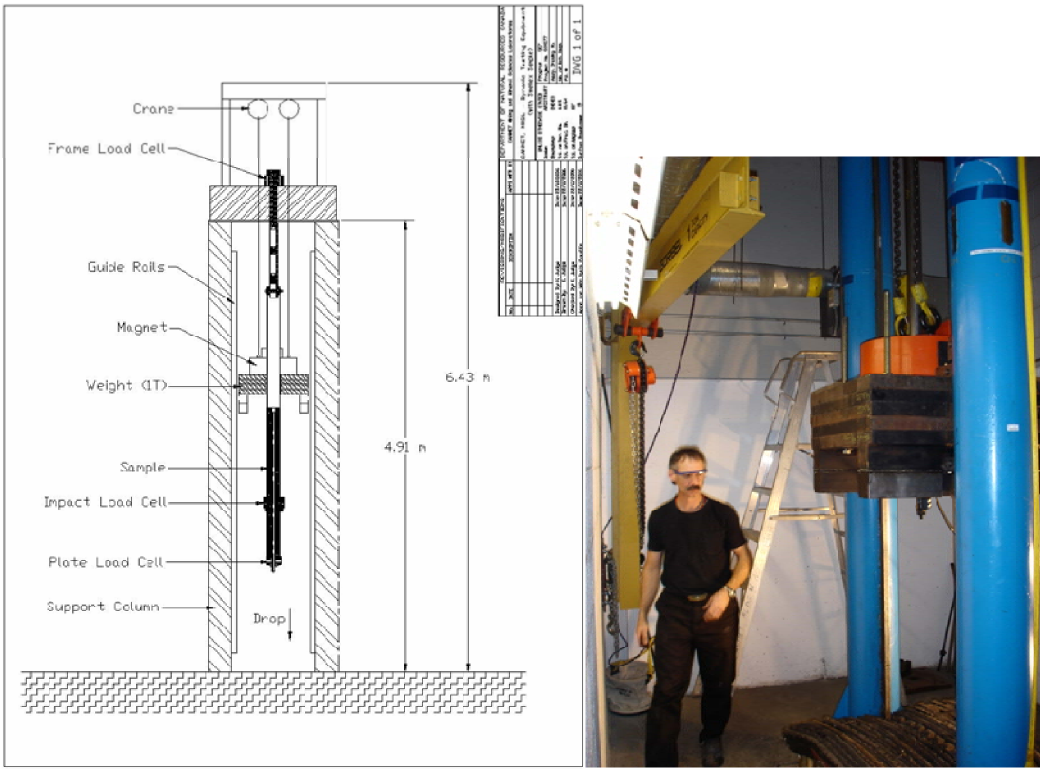


Figure 4 Testing frame located at CANMET-MMSL facilities

3.2 Testing results

3.2.1 Tests at 5 kJoules

The tests at 5 kJ were performed to get some experience with the system, and bring in design improvements at an early stage of the product development. In total, 32 drop tests have been performed at 5 kJ of kinetic energy at impact. As a result of the initial 11 tests, several modifications made to the bale, the stop element and the sleeves were implemented during the exploratory phase with the 5 kJ impact tests. At the end of the 5 kJ test program, the results were extremely similar and consistent, and 5 drop tests concluded the 5 kJ tests. Figure 5 presents the testing result for 3 of these bolts, were identified by B, C and D. These 3 drop tests were successful in capturing all load and displacement data, and the sliding system worked typically very well. In fact, the tests have shown that, if the sliding element works normally, the system is quite stable and the energy dissipation is following a very consistent pattern (see Figure 5).

A very important parameter to consider is the reaction time of the system, which is the time elapsed between the full application of the load and the beginning of the sliding of the bar inside the sliding element. From the laboratory tests, an approximate duration of 0.0003 second separates the maximum load on the bar and the beginning of the bar movement, as is seen on Figure 6. Such a short time prevents failure of the bar and allows, to a large extent, dissipation of energy without deforming the bar.

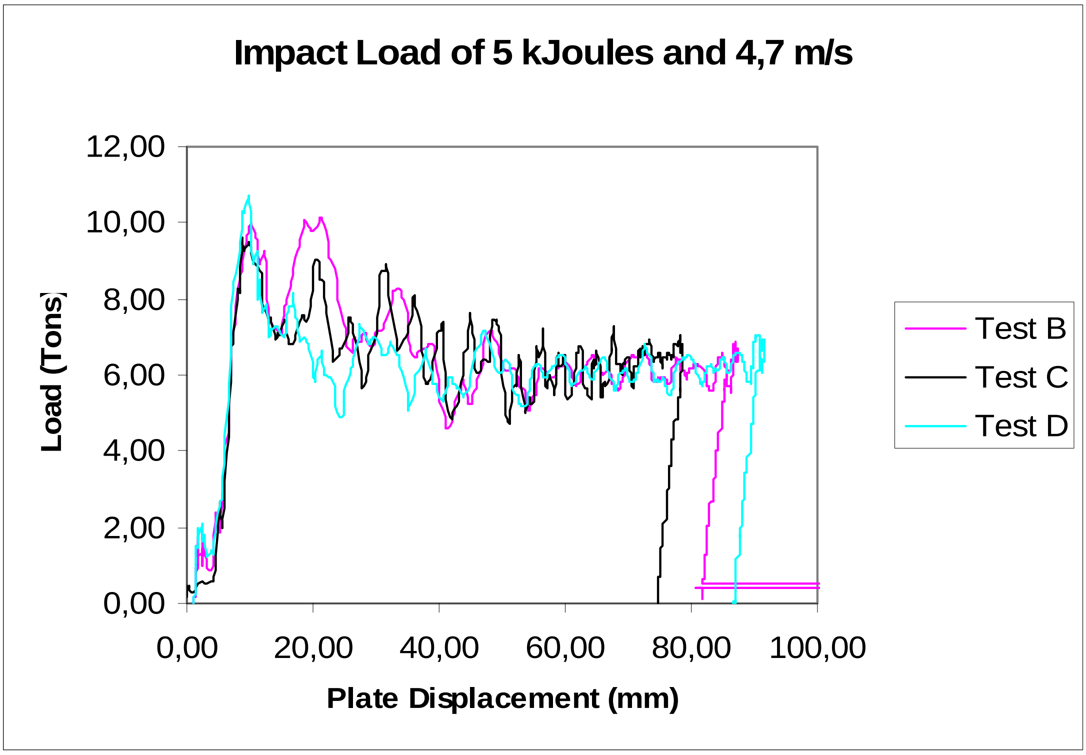


Figure 5 Typical impact tests results at 5 kJ

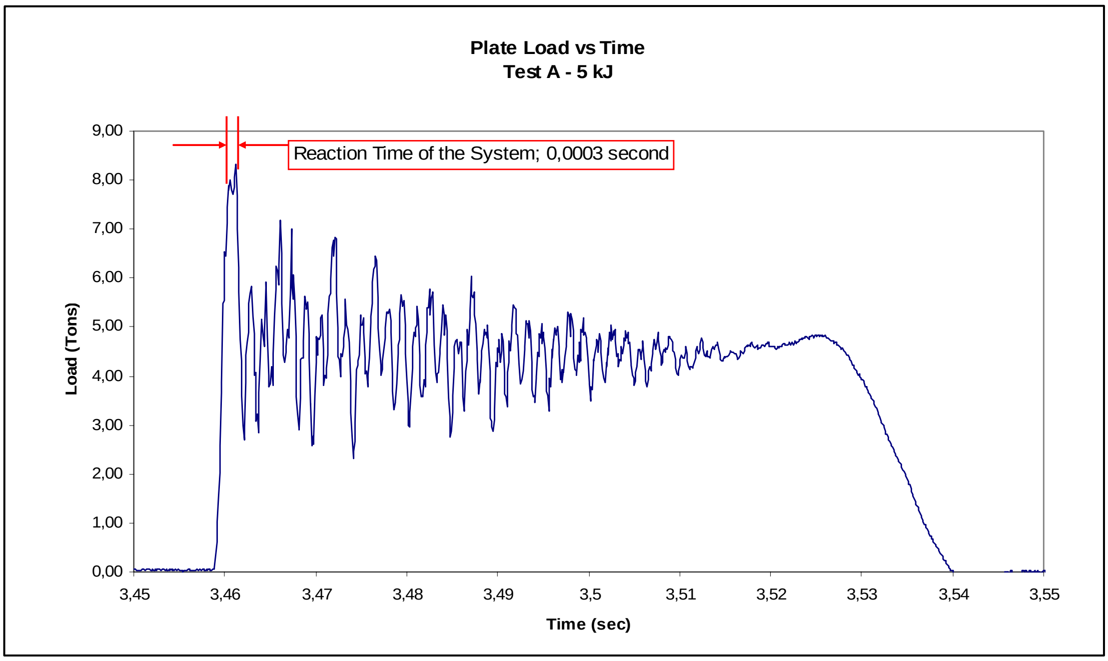


Figure 6 Typical loading of the bar versus time and reaction time of the system for 5 kJ test

3.2.2 Tests at 15 kJ and more

Following the success of the 5 kJ tests with the prototypes, it was decided to go immediately to the 15 kJ tests in order to get an idea of the maximum impact value possible. During the first tests at 15 kJ, it could be observed that the sliding cylinders or pins inside the sliding element were being damaged by the heat dissipated. After 25 cm of displacement, the resisting load was dropped by at least 30% (Figure 7). Laboratory tests in static conditions following the impact (Figure 8) showed that the residual load is similar to the end load of the dynamic test. A modification to the material type of the sliding pins was made, with testing then resuming. With the new material, very little damage of the sliding pins occurred and the friction load was very constant for displacement of up to 60 cm. Figure 9 shows a comparison of typical tests at 5 kJ, 15 kJ, 20 kJ and 27 kJ. At 27 kJ, the 60 cm system capacity is exceeded and the bolt fails. Therefore, based on 10 additional laboratory tests, it was assumed that the maximum dissipation capacity of a 60 cm set prototype Roofex® should be around 25 kJ. The 27 kJ test was not planned originally but was added during a testing session.

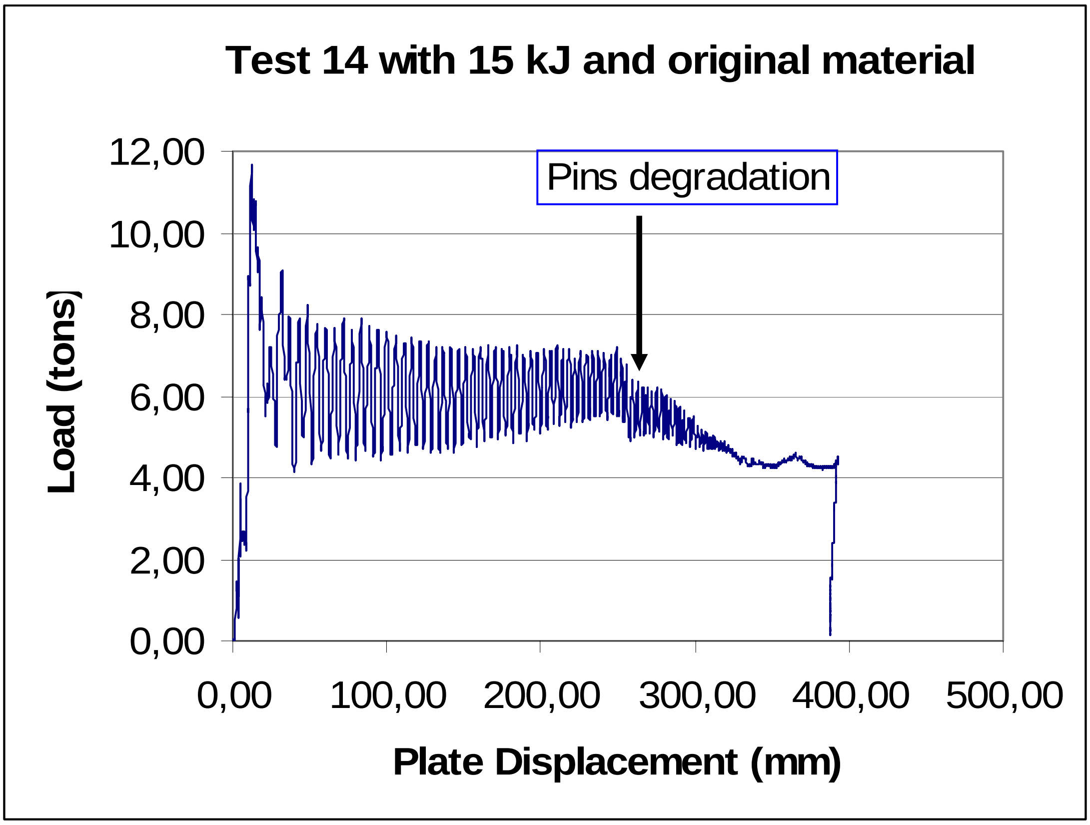


Figure 7 Typical results for 15 kJ impact

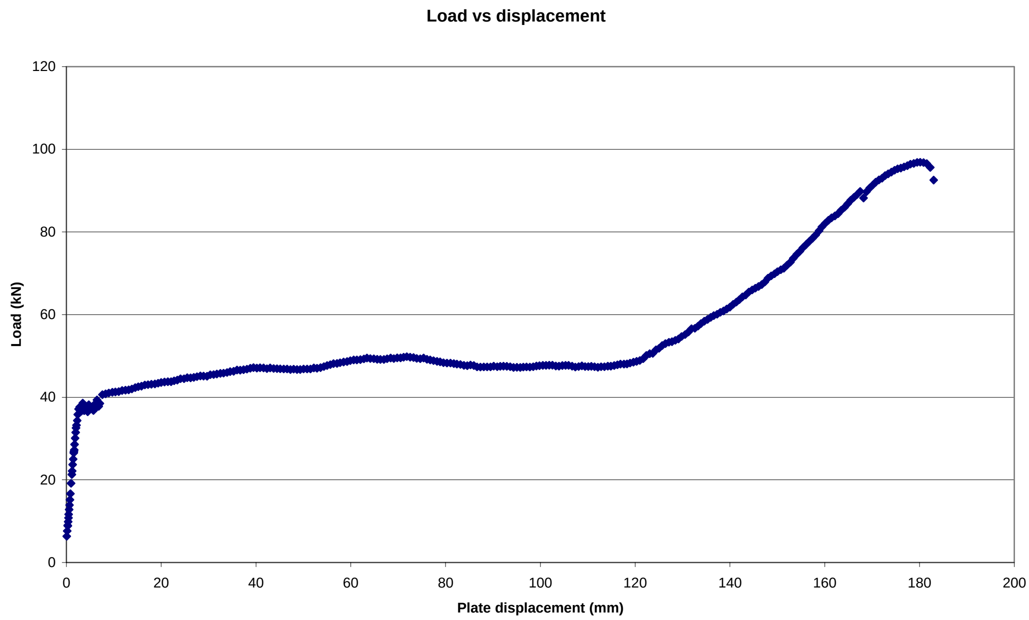


Figure 8 Static pull test performed after a 15 kJ drop test with original material

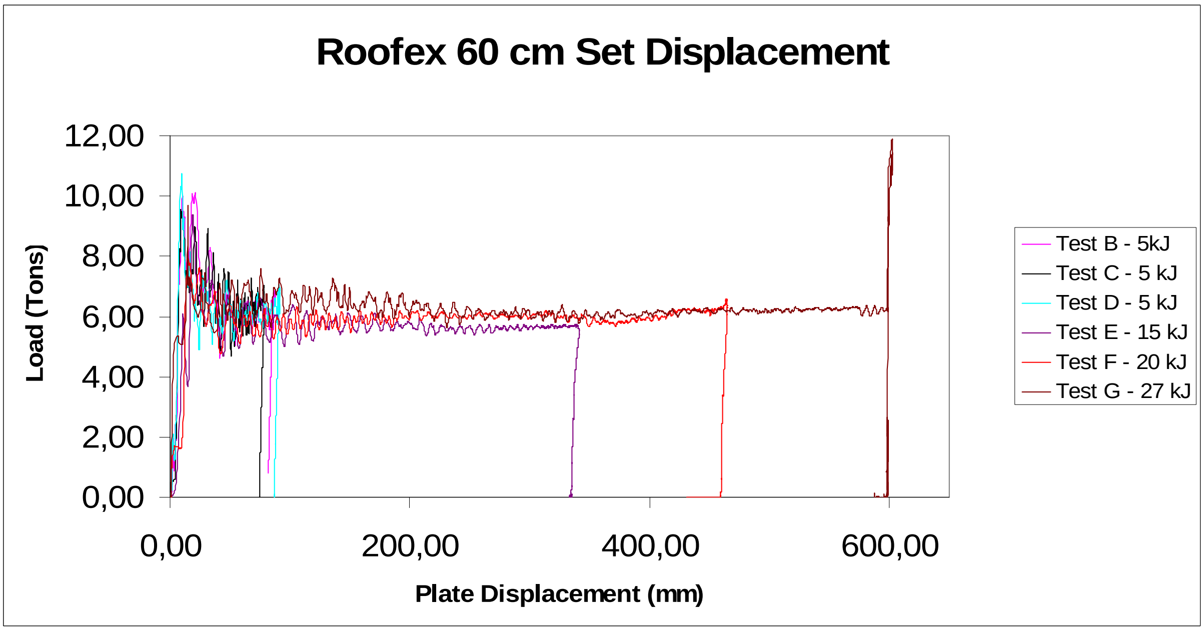


Figure 9 Comparison of drop tests at different kinetic energy level for the Roofex set at 60 cm of sliding with the new material for the sliding pins

An important factor that should be evaluated is the working condition of the rockbolt after a dynamic impact. The fixture should be able to sustain the impact, then work as a static support providing the necessary load to maintain the ground and structures in a stable state. For this to happen, the ultimate load of the rockbolt should be maintained at a reasonably high value. As seen on Figure 8, the ultimate load is in the order of 95 kN, which is slightly lower than the original ultimate load of 100 kN of static testing. However, this final load capacity is still adequate to keep most rock masses in place following a seismic event. With the new material of the sliding pins, it is expected that the static load should be in the order of 6 tons; the testing will be completed by the end of September 2007 and this critical value will be reported.

4 Discussion

The testing program was not completed at the time of preparing this paper. The complete testing program will encompass energy dissipation tests from 5 kJ up to 30 kJ, and impact velocity from 3.1 to 5.5 m/s. However, the present results at an impact velocity of 4.7 m/s provides enough data to discuss the performance of the rockbolt under laboratory impact loading. Figure 10 shows a comparison between the displacement of the stop element (end of the bolt) and the displacement of the plate; there is a difference of about 5 to 6% more displacement at the plate location, due to deformation of the bar during the loading and sliding process. The passage of the bar inside the sliding element reduces the area of the bar by approximately 5 % and Figure 10 demonstrates that the deformation of the bar due to loading in the yield strength range is around 1% of the total displacement, so the deformation energy due to yielding of the bar is negligible. This difference of area of 6% is relatively small but leads to a small reduction of the ultimate capacity of the bar in the same range (see Figure 8).

The tests from 5 kJ to 27 kJ have demonstrated that if the system reaction time is short enough, the maximum load that the rockbolt will have to endure will be within 20% above its ultimate strength but will not be sustained long enough to develop strain and failure inside the bar. This is a critical factor affecting the ability of a rockbolt to dissipate energy without failure. The sliding load is also a key factor in minimising the bulking of the rock mass and the convergence of the excavation, so a maximisation of this parameter is a development target.

Impact tests performed by way of a downward travelling weight colliding with the face plate of the rockbolt are set to replicate an event occurring at the roof of an excavation, and the energy to decelerate the moving mass and immobilise it is higher than the energy to stabilise a similar mass moving horizontally. This can be demonstrated by the Equations (1) and (4), respectively describing the energy balance of a horizontal and a vertical system.

For a horizontal impact, there is no change in potential energy, only a change in kinetic energy, deformational and sliding energy.

$$K = \tfrac{1}{2}\, m\, v^2 = U_d + U_{sl} \tag{1}$$

Where K is the kinetic energy at the position of impact, while U_d and U_{sl} are the deformational and sliding energies. The potential energy is equal to 0. For a horizontal impact, the surface under the curve should be equal to the kinetic energy of the weight immediately before impact.

The deformation energy can be calculated by:

$$U_d = \tfrac{1}{2}\, Q\, \delta_{def} \tag{2}$$

The energy dissipated by sliding inside the sliding element is given by:

$$U_{sl} = F\, \delta_{sliding} \tag{3}$$

For a vertical system, the energy can be computed using the following equation:

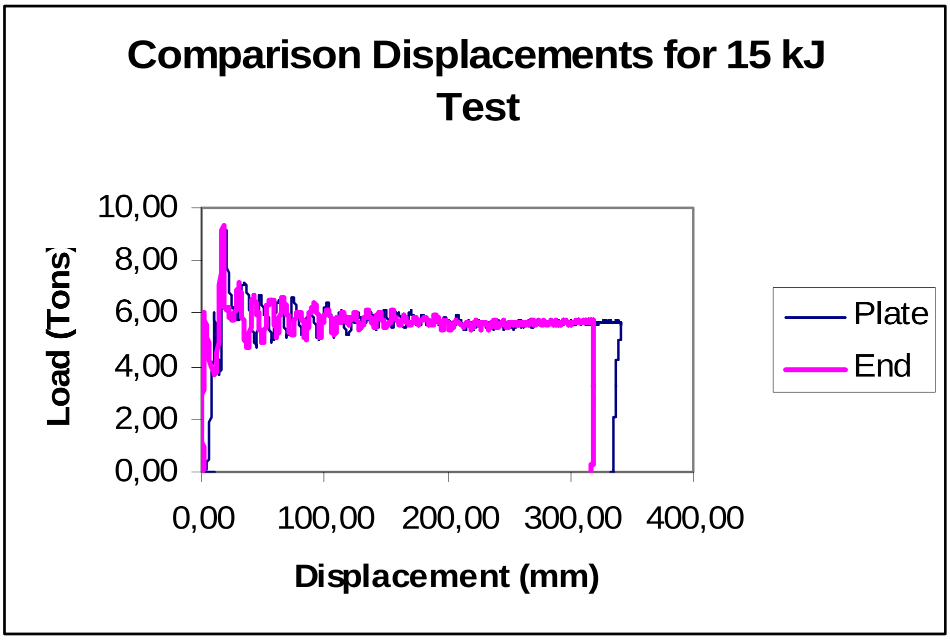
$$U_{final} + K_{final} + U_d + U_{sl} = U_{initial} + K_{initial} = Q\,(\delta_{height} + \delta def/2 + \delta_{sliding}) \tag{4}$$

Where Q is the load in N, δ_{height} is the difference in vertical position between the initial position and the impact position, δ_{def} is the bolt deformation including elastic and plastic deformations, and $\delta_{Sliding}$ is the displacement of the anchored end of the bolt inside the sliding element. For a vertical test, the impact position is an intermediate position, for which the velocity is at its maximum, but for which the remnant of potential energy is defined by the dissipation capacity of the rockbolt. Indeed, the higher the dissipation capacity, the shorter the course of the weight after the impact and the lesser the change in potential energy.

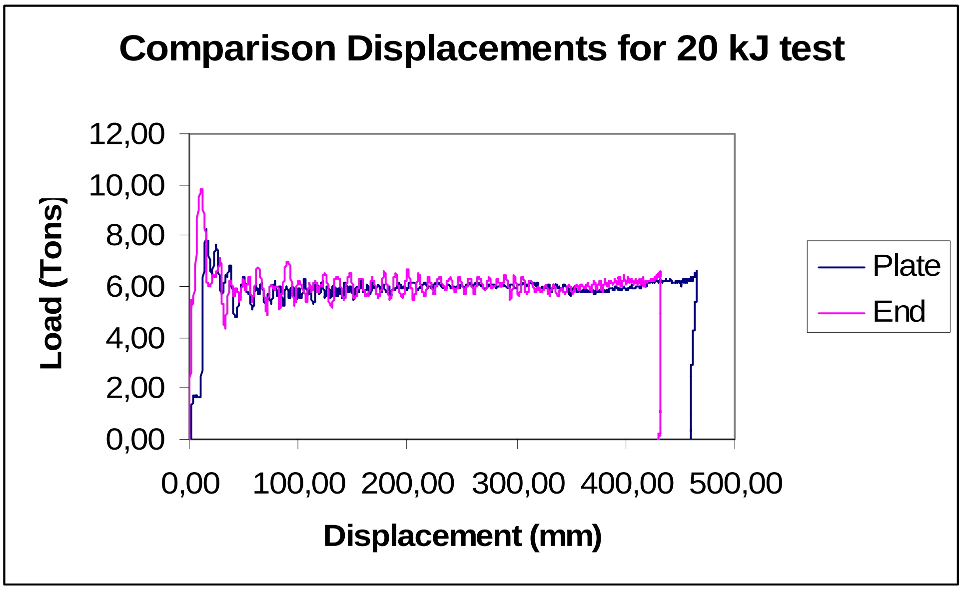
When using a vertical impact test, we introduce additional potential energy into the system, namely $Q\,(\delta def + \delta_{sliding})$, and the rockbolt has to dissipate this amount too. This is why the surface under the curve is the sum of the kinetic energy at impact, plus the added potential energy term. This dissipated energy is:

$$F_{sl}(\delta_{sliding}) + F_{ult}\,(0{,}5\,\delta def) = K_{before\ impact} + Q\,(\delta def + \delta_{sliding}) \tag{5}$$

Where F_{ult} is the load during the deformation of the bar, before sliding, and F_{sl} is the sliding load recorded during the tests. Typically, the value of F_{ult} is about 10 tons and F_{sl} is about 6 tons. However, since δdef is considered negligible, the main energy dissipation is done via sliding through the sliding element.



a) Drop test at 15 kJ energy level



b) Drop test at 20 kJ energy level

Figure 10 Comparison of displacements between the plate and the stop element, at 2 different levels of impact energy

The Roofex® rockbolt is a new rockbolt that provides a very innovative energy dissipation mechanism. Laboratory testing of this rockbolt is therefore a new operation, dealing with different parameters than conventional grouted bolts or friction bolts. The testing protocol is also different and there is still much to be done to fully compare these results with all types of rockbolts. It is also understood that laboratory testing allows for an index value of performance under dynamic conditions and are not an absolute measure of reinforcement effectiveness under yielding or rockbursting conditions, so the future work will be targeting the field efficiency in both static and seismic conditions.

5 Conclusion

The paper presented the preliminary findings from the laboratory impact testing of the Roofex® rockbolt. Energy dissipation capability was analysed in relationship with the total kinetic energy applied at a velocity of about 4.7 m/s. It was found that a sliding length setting of 60 cm can allow up to about 25 kJ of energy dissipation, but since the relationship between energy applied and displacement is quite constant, the sliding length can be adjusted to match the expected energy release level.

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