A NEW ROCK BOLT CONCEPT FOR UNDERGROUND EXCAVATIONS UNDER HIGH STRESS CONDITIONS

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Abstract

This paper presents the preliminary results of a laboratory testing program aimed at assessing the impact energy dissipation capability of a new rock bolt. 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 (MMSL), of Natural Resources Canada, Ottawa, Canada.

The rock bolt, 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 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 rock bolt accommodating these impacts. The physical set up of the testing is discussed, and the loading curves are presented and analysed.

1 Background

High stress conditions cause stability problems in most mining operations. The severity of the situation depends on the ability of the support system to cope with deformations, either slow or violent. Very often, existing support systems are not always capable of providing a reliable controlled performance every time as their working concept is intrinsically related to the linked anchorage mechanism of the rock bolt and the rock mass properties.

In relatively weak rock masses or where highly-foliated anisotropic ground is subjected to stress levels exceeding the rock mass strength, deformations experienced by the openings can take excessive proportions (Figure 1). Anchorage capacities vary largely from one area to another as the rock mass properties influence the unit anchorage capacity value, and therefore so does the support pressure applied onto the rock mass. As the engineer tries to design a support system based on support pressure, it is often a case of trial and error before the right combination can be found. The absence of exact engineering behaviour for the loaded support is a common reason for poor performance of the support system.

At the other end of the rock mass spectrum, very hard and massive rock masses are prone to stress accumulation, leading to violent energy release events. When required conditions are satisfied, the rock mass will fail in an extreme brittle way, releasing very high amounts of energy and causing the failure of the rock and the rock reinforcement (Figure 2). High velocities and bulking are difficult to contain with fully grouted stiff rock reinforcement.
High stress conditions, either in weak ground or in massive and brittle rock masses, are always difficult to handle with existing rock reinforcement fixtures and methods, and loads and deformations of the reinforcement are not accurately controlled. Failure of the rock mass can be either ductile or brittle, or a combination of both. To offer a better controlled type of rock support, a new yielding bolt concept, issued from theoretical and practical considerations, was investigated. Field installations and laboratory testing led to a first generation of a rock bolt fixture, called Roofex, designed to control roof and pillars excessive convergence and stresses. A program of laboratory dynamic tests was then implemented in order to define the dynamic properties of the Roofex rock bolt.

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 can reach velocities of more than 3 meters per second, and in a mining environment with low local mine stiffness and very brittle rock, the released stored energy associated with rock failure and bulking can combine with rock ejection by a seismic wave to generate velocities of more than 10 m/s (Kaiser et al., 1996b). In those conditions, the rock reinforcement is more often than not destroyed or at least mobilized in excess of its working range. This tends to result in localised caving or a highly deformed excavation profile.

Drop tests are used in many locations around the world to evaluate the performance of reinforcement and support during a rock burst. 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 ground prone to rock bursts and seismic events. It is the energy transfer to the fixture through a given ejection velocity that can be studied and compared during these tests, using the kinetic energy of a moving mass to generate the energy released during a rock burst. Laboratory tests also provide an easy way to quantitatively compare a given rock bolt 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 mechanics of rock bursting.

Drop tests are most similar to an ejection of rock material at the roof of an excavation. According to Kaiser and al. (1996b), the influence of gravity adds potential energy to rocks ejected from the back, and reduces energy of a block ejected from the floor. The total kinetic energy contained within an ejected block of mass \( m \) that has travelled a distance \( d \) at a final velocity \( v \) is:

\[
E = 0.5 m v^2 + qmgd \quad \text{(Kaiser et al., 1996)} \quad (1)
\]

where \( q = 1, 0, -1 \) for ejection from the back, wall, and floor respectively,
\[
g = 9.81 \text{ m/s}^2.
\]

So the total energy that a rock bolt has to dissipate is a function of the displacement following the impact and the weight of the rock mass that is moved during the ejection.
Figure 1. Yielding ground conditions. Figure 2. Dynamic failure of back and rock bolts.

2 Roofex as an alternative

Through acquisition and research and development, Atlas Copco MAI identified a strategic concept that has the potential of providing safe and efficient rock reinforcement in extreme conditions. As a result, a new rock bolt fixture was developed, and tested in static and dynamic conditions.

The Roofex® rock bolt, as presented in Figure 3, is a rock bolt 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 cartridge envelope and an adequate mixing of the catalyst.

The bolt yields mechanically 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 retain 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 rock bolts in such loading conditions using an impact rig.
3 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 from 5 kJ to 15 kJ of impact energy (Charette and Plouffe, 2007). As improvements were made to the original design, the final phase of testing was performed and is the subject of the present paper. Impact levels of the final phase of testing varied from 5 kJ to 27 kJ, with velocity varying from 3 to over 5 m/s, and an impacting mass from 670 kg to 2898 kg. Figure 4 shows a schematic of the testing frame.

![Schematic of the testing frame](image)

Figure 3. Description and static performance of the Roofex® rock bolt. Load – Displacement curve for a 30 cm displacement setting – 50 tests.
Figure 4. Description of the drop tests apparatus at the CANMET-MMSL facilities in Ottawa, Canada

The data measured during the tests were the loads at the plate and on the frame of the testing unit, the displacement of the plate, the displacement of the free end of the rock bolt and the time. All data were synchronized with the time values. Typical tests results are seen on Figure 5. Following the test, an autopsy was performed on a large number of tested samples (see example on Figure 6), in order to assess the performance of the anchorage or to analyse a non typical behaviour for defects of material or installation.
4 Results

Table 1 summarizes the last phase of testing and the measurement data. The figures 7 to 11 summarize the basic results obtained during the second phase of testing the Roofex through drop tests. The peak load, the average sliding load and the resulting plate displacement are the most interesting parameters measured during the tests. The peak load defines the limit of deformation of the bar material, and is a critical value to control as it should not exceed some threshold value dictated by the ultimate strength of the steel bar. The average load is the main parameter defining the performance of a damping type of rock bolt as the Roofex, and it is necessary to maximize its value while preserving the integrity of the steel material. Finally, the displacement of the plate is the result obviously visible in an underground excavation as it defines the allowable convergence of the bolt. For the analysis described in this paper, only the load at the frame has been used as some measurement uncertainties were detected on some plate load measurements.
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Figure 6. Autopsy of a drop test on Roofex

Sliding element

Mixing element
The peak load measured at the frame (Figures 7 and 8) exhibits a linear relationship with the weight of the moving mass and with the kinetic energy, but no obvious relationship was determined when the peak load was compared to the velocity at impact (Figure 9). The proposed functions to relate the Peak Load to the weight or the energy of the moving mass are:

\begin{align*}
F_{ult} &= 1,8848 \, M + 7566 \\
F_{ult} &= 279,05 \, K + 6244
\end{align*}

(2a)

![Graph of Peak Load vs Mass Weight](image)

Figure 7. Variation of peak load as a function of the weight of the moving mass

The average sliding load, measured as the average load during the sliding process, can also be described as a linear function of the kinetic energy applied onto the rock bolt (Figure 10), and a proposed relationship for the function is:

\[ F_{sl} = 22,9 \, K + 5276 \]

(3)

![Graph of Peak Load vs Impact Energy](image)

Figure 8. Variation of peak load as a function of the weight of the impact energy
The relationship is relatively well defined, with little variations on the average load values, if one considers the first drop only or the average value of cumulative drops. The average sliding load does not change significantly with a second drop, as can be seen on Figure 11, where 5 tests comprised 2 drops and for which very little difference is observed.

![Peak Load at Frame vs Impact Velocity](image)

**Figure 9.** Variation of peak load as a function of the velocity of the moving mass

![Average Sliding Load vs Kinetic Energy Applied](image)

**Figure 10.** Variation of the sliding load measured as a function of the impact energy for the first drop

Finally, the plate displacement for the first drop was plotted against the applied kinetic energy, on Figure 12. It can be seen that the relationship is quite linear when a more or less constant impact velocity is present, at approximately 4.7 m/s. For the tests 41-1 and 43-1, the impact velocity was about 3 m/s, and the measured displacements are quite different from the trend shown by the tests at 4.7 m/s. Since the displacements were higher for a lesser impact velocity, it is reasonable to assume that another parameter, like the weight of the impacting mass, could play an important role into the variation.
Figure 11. Variation of the sliding load measured as a function of the impact energy for cumulative drops (maximum 2).

Figure 12. Measured plate displacement as a function of the impact energy (kinetic energy of the moving mass)

5 Discussion

Drop tests are a relatively easy and reproducible way of analysing the performance of a specific rock bolt to rock ejection events. Velocity and mass can be controlled in order to reproduce the ejection parameters as well as possible. Drop tests are also similar to an ejection at the back of an excavation and the analysis of the tests results should prove similar to the result of Equation 1.

The typical load-displacement curve for a drop test is shown on Figure 13. It can be seen that two different phases of loading are occurring successively, the first being a load initiation phase where the system accepts the load from the impact and transfers a certain amount of
energy as load on the bolt. Then the system reacts fast to transfer the momentum energy into the sliding element of the rock bolt, creating a circumferential deformation of the bar as well as a linear deformation. Geometrical analysis and laboratory tests have shown that, through the sliding element, the deformed bar has 5% less area than the original bar.

The load initiation phase can be approximated by a linear relationship, while the sliding phase load function can be approximated by a power function or more simply, by a linear function calculated as the average load after the load levels off (around 15 to 30 mm of displacement). Figure 14 shows the fitted curve for the test 25-1.

![Graph](image)

Figure 13. Typical Load – Displacement curve from drop test on Roofex

![Graph](image)

Figure 14. Typical Load – Displacement curve from drop test on Roofex

Impact tests performed by way of a downward travelling weight colliding with the face plate of the rock bolt are set to replicate an event occurring at the roof of an excavation, and the energy to decelerate the moving mass and immobilize it is higher than the energy to stabilize...
a similar mass moving horizontally. This is demonstrated by the Equations (1). For a horizontal impact, there is no change in potential energy, only a change in kinetic energy, deformational and sliding energy:

\[ K = \frac{1}{2} m v^2 = U_d + U_{sl} \]  \hspace{1cm} (4)

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.

For a vertical system, the energy conservation law can be expressed as:

\[ U_{final} + K_{final} + U_d + U_{sl} = U_{initial} + K_{initial} \]  \hspace{1cm} (5)

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 rock bolt. Indeed, the higher the dissipation capacity, the shorter the course of the weight after the impact and the lesser the change in potential energy.

As mentioned previously, the total deformation of the bar consists in the portion \( \delta_{def2} \) caused by the reshaping of the bar (5% of plate displacement) and the elastic-plastic deformation \( \delta_{def1} \) caused by the ultimate load. The total amount of deformation from the tests results is around 8% of the end displacement values.

\[ \delta_{def} = \delta_{def1} + \delta_{def2} = 0.1 \delta_{sliding \ bar} \]  \hspace{1cm} (6)

The deformation energy from the elastic-plastic deformation caused by the ultimate load on the bar, can be calculated by:

\[ U_{d1} = \frac{1}{2} F_{ult} \delta_{def1} \]  \hspace{1cm} (7)

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

\[ U_{sl} = F_{sl \ bar} \delta_{sliding \ bar} + F_{sl \ bar} \delta_{def2} \]  \hspace{1cm} (8)

When using a vertical impact test, we introduce additional potential energy into the system, namely \( U_{d1} + Q \delta_{sliding} \), and the rock bolt has to dissipate this amount too. This is why the surface under the load-displacement curve is the sum of the kinetic energy at impact, plus the added potential energy term. Calculated from the load-displacement graph, this dissipated energy is:

\[ F_{sl \ bar} ( \delta_{sliding} ) + F_{sl \ bar} \delta_{def2} + \frac{1}{2} F_{ult} \delta_{def1} = K_{before \ impact} + Mg ( \delta_{def1} + \delta_{sliding \ bar} ) \]  \hspace{1cm} (9)

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. The value of \( F_{ult} \) can be measured (Table 1) or predicted using the relationship shown on Figure 7, and \( F_{sl} \) can be measured or predicted from Figure 10.
It is a reasonable approximation to take the deformation $\delta_{\text{def1}}$ as about 5% of the end displacement and $\delta_{\text{def2}}$ also as about 3% of the end displacement. The equation (7) can be rewritten as:

$$F_{\text{sl bar}} \ (\delta_{\text{sliding bar}}) + F_{\text{sl bar}} \ (0.05 \ \delta_{\text{sliding bar}}) + F_{\text{ult}} \ (0.025 \ \delta_{\text{sliding bar}}) = K_{\text{before impact}} + Mg \ (0.1 \ \delta_{\text{sliding bar}} + \delta_{\text{sliding bar}}) \ (10)$$

or also

$$\delta_{\text{sliding bar}} \ (1.05 \ F_{\text{sl bar}} + 0.025 \ F_{\text{ult}} - 1.1 \ Mg) = K_{\text{before impact}} \ (11)$$

and then the sliding distance through the sliding element can be computed by:

$$\delta_{\text{sliding bar}} = K_{\text{before impact}} \ (1.05 \ F_{\text{sl bar}} + 0.025 \ F_{\text{ult}} - 1.1 \ Mg) \ (12)$$

and the total plate displacement by:

$$\text{Displacement Plate} = 1.08 \ \delta_{\text{sliding bar}} \ (13)$$

Combining Equations (13), (2) and (3), the displacement inside the sliding element ($\delta_{\text{sliding bar}}$) can be computed. Figures 15 and 16 present the predicted values of displacements at the sliding element and at the plate against the measured values. The results for the plate displacements show a better fit than the sliding through the sliding element but it is probably caused by the fact that measurements of the displacement at the end of the rock bolt were less accurate than the plate displacements, as the bolt end was located inside the steel tube holding the rock bolt.

The significance of being able to predict the displacement needed for a given dynamic event based on the energy and the expected area/mass involved is that a preventive design can be performed and the free damping length can be chosen to match expected requirements. From the laboratory tests, it appeared that the damping system of the Roofex is not sensitive to velocities between 3.0 and 5.0 m/s. If fact, the real implication of the particle velocity is to determine if the system will react fast enough to still slide, when velocity reaches around 10 m/s. This situation has not been studied yet.
6 Conclusion

A new rockbolt for dynamic conditions has been studied using a direct drop test procedure. The results have shown that the rock bolt can accept dynamic impacts in excess of 25 kJ when the damping length is chosen adequately. The sliding/damping load is slightly affected by the impact energy and is very consistent. The peak load is also easily predictable and shows little variations. The system offers predictable performances that can be used to design the damping length adequately for a given dynamic event. The tests have also shown that the system performs consistently for consecutive impacts. More analysis is to be done in order to
better define the velocity limit. The Roofex rock bolt will be also submitted to proximity blasting tests in order to better complete the support system, as other parameters affect field performance.

7 References


