Full-scale dynamic tests of a ground support system using two layers of high-tensile strength chain link mesh to increase the energy dissipation at El Teniente Mine, Chile

Alejandro Muñoz1, Eduardo Rojas1, Rico Brändle2, Roberto Luis2 and Germán Fisher2
1 Codelco El Teniente, Chile
2 Geobrugg Group, Switzerland

Traditional support and reinforcement systems used in underground mining are limited in their capability against dynamic loads. Full-scale dynamic tests carried out by Codelco El Teniente, the largest underground mine of the world and the Swiss Company Geobrugg have shown that the special design, developed by the Geotechnical Department of this Division of Codelco, is highly suitable for protection and support in underground excavations. The design consists of high-tensile steel wire mesh, anchors and shotcrete. Because of the use of high-tensile steel wire and the flexibility of the chain link mesh, such a support system can be applied in areas with very high static and dynamic stress. The El Teniente Mine in Chile is facing huge challenges in terms of seismicity and have to adapt their ground support systems to high new demands in terms of energy absorption and also the way the systems are installed inside the tunnels. This innovative ground support system of high-tensile chain link mesh provides a solution for high energy demands up to 50-60 kJ. The results achieved thus far, in terms of miners’ safety and production performance improvements, are very encouraging.

INTRODUCTION

Mining is getting deeper, and rockburst damage is a growing risk in underground excavations around the world. Especially in mining tunnels, when in search of the mineral strata, tunnels are deepened more and more, until reaching depths bigger than 1,000 meters. However, these seismicity events and associated rockburst can occur, even at smaller depths. Traditionally, the support of the galleries at El Teniente mine was realized with shotcrete reinforced with mesh and bolts. This traditional solution was strong enough and rigid to control the movement of small blocks and to avoid the clearing of the rock surface; however, its capacity to absorb dynamic loads has been really limited, with capacity to absorb energy under the level of 25 kJ. To deal with the rockburst, rock bolts with better capability to dissipate energy were introduced; so it was necessary to increase the retention capacity of the reinforcement system.

The request to increasing the energy dissipation capacity in the support system designs at El Teniente mine comes from many years ago. With this final goal, systematic studies have been carried out, aiming to improve the performance of the single elements and also the complete reinforcement systems. In 2011, in the accesses of the mine “Esmeralda blocks”, a support systems were installed based on 2 layers of standard steel meshes, the first layer supported by traditional grouted bolts and the second layer by cable bolts (Design Map IM8-29581 "Fortification Access Zanja 29 and 40. Esmeralda Sur, Section Gallery 4.2 x 4.2m"). With this setup, good results were obtained in the mitigation of damages produced by the rockburst, which allowed validating the design, for its use in multiple locations.

In addition, the development of diamond shaped lightweight steel wire membranes of very high-tensile strength, in recent years has given a great turnaround to this trend. These powerful flexible solutions combined with suitable anchors have undoubtedly been a huge step towards solving situations where protection against dynamic load is imperative. This specific case is related to field trials on a large-scale (1:1), made by Codelco in collaboration with Geobrugg, to a strong and flexible system, that allow absorb high energy with less deformation. Main goals is determined the stress-
strain behavior and maximum energy values achievable under the simulation of real dynamic loads.

**HIGH-TENSILE STRENGTH STEEL WIRE MEMBRANES**

The high-tensile wire (1,770 MPa) mesh offers a surface support for most ground conditions. The mesh is made from high-tensile steel wire with a diameter of 4 and/or 3 mm. The mesh has a specifically developed, diamond shape to minimise deformations and along the edges, each spiral wire is looped and twisted back on itself (Figure 1). This enables the edge of the mesh to have the same loading capacity as the mesh (Luis Fonseca, R. et al 2009). Both mesh types are produced in rolls, which reduces the storage space, and can be manufactured in widths of up to 3.9 m and in tailor-made lengths corresponding to the tunnel surface to be meshed. Due to the use of high-tensile wire, the mesh is very light in relation to its strength (G65/4 - 3.3 kg/m², G80/4 - 2.6 kg/m² and G80/3 - 1.45 kg/m²). In terms of corrosion protection, the wires are coated with a special aluminium-zinc coating, which has a higher corrosion resistance than standard Zn galvanising. Comparison tests, based on standardised salt spray tests; show that this wire lasts at least three to four times longer under such conditions than conventional Zn galvanised wire.

The mesh geometry was designed to have a very high breaking load as well as low deformation characteristics to avoid unacceptable deformation rates and unraveling of the rock after a rockburst impact. The resistance properties of the mesh were determined in a series of laboratory tests (2002) at the University of Cantabria, Spain. The properties of the meshes are summarized in Table I.

<table>
<thead>
<tr>
<th>Material</th>
<th>G65/4</th>
<th>G80/4</th>
<th>G80/3</th>
</tr>
</thead>
<tbody>
<tr>
<td>mesh width</td>
<td>63 mm</td>
<td>80 mm</td>
<td>80 mm</td>
</tr>
<tr>
<td>diagonal</td>
<td>83 x 138 mm</td>
<td>102 x 177 mm</td>
<td>103 x 180 mm</td>
</tr>
<tr>
<td>wire diameter</td>
<td>4 mm</td>
<td>4 mm</td>
<td>3 mm</td>
</tr>
<tr>
<td>wire strength</td>
<td>1,770 MPa</td>
<td>1,770 MPa</td>
<td>1,770 MPa</td>
</tr>
<tr>
<td>breaking load of wire</td>
<td>22 kN</td>
<td>22 kN</td>
<td>12.5 kN</td>
</tr>
<tr>
<td>tensile strength</td>
<td>250 kN/m</td>
<td>190 kN/m</td>
<td>110 kN/m</td>
</tr>
<tr>
<td>weight</td>
<td>3.3 kg/m²</td>
<td>2.6 kg/m²</td>
<td>1.45 kg/m²</td>
</tr>
</tbody>
</table>

**REINFORCEMENT SYSTEM INSTALLED IN THE VENTILATION TUNNEL OF THE NUEVO NIVEL MINA, EL TENIENTE MINE**

The technical management of Codelco in the El Teniente Mine has decided to use as a reinforcement system a combination of elements. In this case, the surface support system used was applied in two steps (Figure 2b). The first layer consist of 70mm shotcrete, with a diamond mesh, type G80/4 applied over the top, anchored with solid Ø25 mm rockbolt of 4 m long. The second step consisted of a thin layer of shotcrete (30 mm) with a diamond mesh type G65/4 over the top, anchored with cable bolts (7 strands) up to 6 m long, arranged radially, as shown in Figure 2a.

This combined solution is intended for ground support under dynamic load conditions. For example, a gallery located in El Teniente Mine was collapsed by a high rockburst event, with very important consequences from the point of view of security and production. Then the main goal of this work is
the evaluation of the reinforcement system design, intended to absorb impacts up to 60 kJ, by an experimental test. The test is designed to simulate rockburst energy and evaluate the transmission of loads to the anchor points. In this paper, we show the results of the real scale tests based in the previous dynamic laboratory tests.

![Image](image1.png)

Figure 2  Surface support system used in El Teniente Mine (Codelco)

**DYNAMIC LABORATORY TESTS**

The G80/4 mesh was tested at the dynamic testing facility of WASM (Player et al. 2008) by using a momentum transfer method (Player et al. 2004; Thompson et al. 2004). The mesh panel is installed using shackles and eye-bolts in the frame and the weight is placed on top of the mesh. The full system is dropped onto buffers from different heights. When the system hits the buffers everything comes to a sudden stop, except the weight placed on the mesh that keeps decelerating and is loading the mesh dynamically. This is simulating the situation underground where the mesh is placed against the rock mass, which can eject into the surface support (mesh) under dynamic load. The dynamic test apparatus is instrumented with a high-speed video camera, load cells and accelerometers. Figure 3 shows a general view of the test setup at the WASM facility (Roth, 2013).

![Image](image2.png)

Figure 3 Dynamic test setup WASM, Kalgoorlie (Roth, 2013)

Figure 4 shows images from a camera (Figure 4a) and a high speed video camera (Figure 4b) before and after a mass of 1,000 kg (bag with mill steel balls) hits the high-tensile chain link mesh. The mesh
deforms with the applied load and transfers the forces to the boundary. The boundary conditions are fixed to have comparable and repeatable results.

![Image](image1)

**Figure 4** Photo: (a) from underneath the test arrangement before the 1,000 kg impact mass; and, (b) from the high-speed video camera after impact

It was established that the high-tensile chain link mesh G80/4 is able to absorb energies of up to 12 kJ in such a configuration (Villaescusa et al., 2012). This is equal to stopping a rock mass of 1,000 kg that was accelerated to 4.9 m/s. This value represents the energy absorption of the mesh only and does not include any absorption by the rock mass or the yielding bolts. Welded wires mesh (5.6 mm, 100 × 100 mm) showed energy absorption capacities up to 2 kJ in the same test setup.

In order to determine the distribution of loads between the anchor bolts and the surface support, tests were carried out at the Geobrugg facility in Switzerland (Bucher et al., 2013). In these tests it was found that the distribution between bolts depends on the rigidity of the rock mass. That is, for a rigid rock mass, 25% of the dynamic energy entering the system is absorbed by the mesh, with the remaining 75% being absorbed by the bolts. With a rocky soft mass, the distribution is 70/30 respectively. As both cases represent extreme conditions, the 50/50 distribution would correspond to the generality of the cases. Assuming a conservative approach, 70% of the energy could be absorbed by the surface underground support.

**ROCKBURST CODELCO LARGE-SCALE TEST**

The large-scale testing was the main part of research and development project supported by Codelco. A series of large-scale tests were conducted during September 2016 in a quarry in Walenstadt (rockfall testing facility) Switzerland described in DTC test report (Saner, A., and Murri, R., 2016). The main goals for performing large-scale tests were: increasing knowledge about the behavior and the interaction of ground and the anchored flexible support in front dynamic load and checking the reliability and validation of the dimensioning assumptions, based on test site observations and back calculations. Initial experiments of the test program allowed for observation and optimization of the test setup, testing procedure and data acquisition method. After optimization of the test setup the following experiments were conducted in a repetitive way to guarantee reliable and comparable experimental results.

The rockburst is simulated by dropping a barrel filled with steel and concrete. The impact of the barrel was in the middle of the shotcrete floor. The accelerations in the three main axes were measured on the top of the barrel. In addition, the forces acting during the test on the anchors have been detected by measurement equipment. The test was recorded with two high-speed and two real-time cameras. The deflection was determined with high-speed camera from the side.
Test arrangement

The test device is composed of a platform with two-level table of square-shaped pyramidal trunk geometry (Figure 5a), in the upper level housing the impact set consisting of 1320 kg barrel dropped from a height of 4.6 m for test S3 and S5 and from 2.3 m for test S4. The barrel is guided with 4 steel profiles. The lower level is composed of a shotcrete slab, together with the meshes layers fixed by anchors, which are attached to the upper level. The impact area surface was increased to 1 m² by a steel plate (figure 5b). A copper contact was mounted on the steel plate to determine the moment of first contact.

![Figure 5](image1.jpg)

(a) Photo: (a) frontal view of the full setup; and, (b) steel plate on shotcrete floor with the trigger contact impact

The dimensions of the first level slab are 3.6x 3.6 m (Figure 6), there the two anchoring levels simulated to the ground support, the external composed of cable bolts of 140 mm² arranged in a grid of 2.0 x 2.0m and the inner, consisting of a pattern 1.2 x 1.2m of diameter Ø25 mm rockbolt anchors.

![Figure 6](image2.jpg)

Lower level frame, top view with the shotcrete slab and the anchoring points
The previously described shotcrete slab is composed of two layers. The upper one is approx. 70 mm thick and consists of shotcrete, immediately underneath is placed a layer of high strength mesh type G65/4. The lower shotcrete layer is more thin (about 30mm) and below is placed the second mesh layer type G80/4 (see the set details on figure 7).

![Diagram of Section A-A](image)

**Figure 7** Set cross section A-A: composed of two layers of shotcrete and two of high tensile strength mesh

**Measurement and data recording**
The accelerations of the barrel were measured in the middle of the top surface using a three-axis accelerometer (2000 g). In-Dummy measuring technology was used. The data storage is done directly in the sensors (figure 8a). The sensors record the measured data completely even with interruption of the connecting cable. After the test the sensor will be reconnected with the gateway for downloading the information data. The forces were measured with four load cells at four anchors. Due to the symmetrical design, the measured forces were multiplied by two for the resultant force on all eight anchors. Measurement channels 1, 2, 3 and 4 correspond to anchors (Figure 8b).

![Measuring equipment on top of the barrel](image)

(a)

![Load measurement cells](image)

(b)

**Figure 8** (a) Measuring equipment on top of the barrel and (b) Load measurement cells

The coordinates system origin (zero-point) is in the middle of the shotcrete floor, where the barrel hits the metal plate on the shotcrete slab floor: +X (positive right), +Y (positive back) and +Z (positive upwards), see figure 9.
The measurements of the stresses are basically made by using the accelerometers placed in the barrel, which allows to obtain measurements on the axes of coordinates previously described and the forces in the anchors from load cells located in the 4 points of anchorage before indicated (figure 8b and in following table II). The measurement equipment was manually triggered.

<table>
<thead>
<tr>
<th>Measuring point</th>
<th>Size / Type sensor</th>
<th>Frequency</th>
<th>Direction</th>
<th>Video-camera filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel accelerations</td>
<td>2000g triaxial accelerometer</td>
<td>20kHz</td>
<td>x, y, z</td>
<td>CFC 180</td>
</tr>
<tr>
<td>Anchor 1</td>
<td>500 kN</td>
<td>4.8kHz</td>
<td>Pulling direction</td>
<td>CFC 180</td>
</tr>
<tr>
<td>Anchor 2</td>
<td>500 kN</td>
<td>4.8kHz</td>
<td>Pulling direction</td>
<td>CFC 180</td>
</tr>
<tr>
<td>Anchor 3</td>
<td>500 kN</td>
<td>4.8kHz</td>
<td>Pulling direction</td>
<td>CFC 180</td>
</tr>
<tr>
<td>Anchor 4</td>
<td>500 kN</td>
<td>4.8kHz</td>
<td>Pulling direction</td>
<td>CFC 180</td>
</tr>
</tbody>
</table>

Two stationary digital high-speed and two real-time cameras were used for the visual documentation of the test and to determine the deflection. The cameras were manually triggered and synchronized by LEDs. As frontal camera it use the high-speed cameras AOS technologies type X-EMA (Extended Environmental Application) is a camera used under the toughest conditions (figure 10a).

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**Test results and video analysis**

On September 28, 2016, were executed three trials, S3, S4 and S5. In all tests, the same barrel was used in the same impact area (1m²), while the release height was varied from 4.60m (S3-S5) to 2.30m in the S4 test, which evidently halved the energy in the contact moment. A sequence of frames is shown below (figure 11) during the first tests (S3). In this sequence, it was possible to see the effect of the
impact of the barrel on the distribution plate of 1m² on the shotcrete slab and the rebound effect manifested once it reaches the maximum deflection at t=100ms.

![Figure 11 Impact sequence during test S3](image)

The S3 test results are shown below, as the release height is 4.60m and the barrel weighs 1320 kg, then was thrown onto the shotcrete slab with a speed of 9.5 m/s (34.2 km/h), which corresponds to impact energy of 60 kJ (figure 12), in this case the total amount of the forces into the anchoring system is 429 kN, the maximum acceleration achieved is 70.5g (figure 13). The barrel was completely restrained by the rockburst setup with a deflection of 0.24 m, whose static value is slightly lower 0.225 m (figure 14).

![Figure 12 Test field S3 results. Sum of the forces in the load cell for anchors multiplied by two and maximum energy recorded](image)
Figure 13  Test field S3 results. Acceleration on barrel at Z direction (filter CFC 180)

Figure 14  Test field S3 results. Maximum displacement (0,24 m)

Figure 15 shows the consequences of the impact on the strong support system, the effect of the rockburst simulation, seen from above and below, where the protection level remains right. It should be noted, once again, that the residual deformation is very small and the level of high energy absorption up to 60 kl.
Once the S3 test is completed, the second impact S4 is prepared on the same surface previously affected by the S3 test impact, so that the behavior of the ground support solution can be evaluated over an area affected by more than one consecutive event, without prior repair. A sequence of frames is shown below (figure 16) during the second tests (S4).

The S4 test results are as follow: In this case the release height is the half to the previous 2.30m and the barrel weighs is the same so the impact energy is about 30 kJ. This test show that the system can absorb 30 kJ as a second impact (previously impacted with 60kJ) (figure 16), in this case the total amount of the forces into the anchoring system is 162 kN, the maximum acceleration achieved is 33.4g (figure 17) and the elongation is about 0.20 m (figure 18).
The results of the impact over strong support system are showed in Figure 19, the effect of the rockburst simulation, seen from above and below view, show that the residual deformations are very small and the energy absorption is up to 30 kJ.

The S5 (last tests performed, figure 20), it was also carried out on the same support system that the two previous ones (S3 and S4) have been done, without any maintenance work on the steel membranes or the anchoring system, the shotcrete layer present at the beginning, is already nonexistent, then all the support forces is transmitted to the anchoring system by the two layers of high tensile wire mesh 4 mm diameter and opening 65-80 mm respectively.
The S5 test results are shown below: In this case the release height is again 4.60 m and the barrel weighs is the same so the impact energy is about 60 kJ. This test show that the system can absorb 60 kJ as a third impact (previously impacted with 60 kJ and 30 kJ) (figure 21), in this case the total amount of the forces into the anchoring system is 155 kN, the maximum acceleration achieved is 32.5g (figure 22) and the elongation is about 0.60 m (figure 23).
Figure 22  Test field S5 results. Acceleration on barrel at Z direction (filter CFC 180)

Figure 23  Test field S5 results. Maximum displacement (0,60m)

**Support system safety factor**

According to the forces measurements in test S3, the maximum force values are generated in the anchors 1 and 3 (figure 24). These points correspond to the inner anchors system composed of steel bars of Ø25 mm. As can be seen, the maximum values observed in the test are in the order of 125 kN, and then if the anchor bars Ø25 mm considered, have as yield strength force 241 kN, then safety factor of the system anchors is 2.

Figure 24  Test field S3 results. Anchor Forces in Z direction (filter CFC 180)

In pictures below (figure 25) it can be seen, that the punching shear strength resistance is related to the amount of wires involved, which are located all around the plate boundary section (red circles on figure 25b) for the G65/4 mesh and the distribution load plate geometry.
The theoretical shear force capacity [1] for the mesh with the distribution plate can be calculated with the amount of wires, diameter and the tensile strength of the wire.

\[
\tau_{\text{mesh G65/4-P15}} = N \cdot \tau_{\text{wire 4mm}} \tag{1}
\]

\[
\tau_{\text{wire 4mm}} = \frac{\sqrt{3}}{2} \cdot f_y \cdot A_{\text{wire}} = 0.577 \cdot 1770 \cdot 2^2 \cdot \pi = 12.8 \text{ kN}
\]

\[
\tau_{\text{mesh G65/4-P15}} = 12 \cdot 12.8 = 154 \text{ kN}
\]

were:

- \(\tau_{\text{mesh G65/4-P15}}\) = punching shear strength resistance
- \(N\) = number of contact wire at the boundary in plate
- \(\tau_{\text{wire 4}}\) = shear resistance of the single wire 4mm high yield stretch

\[
\text{SF} = 154/125 = 1.23 \text{ (ok)} \tag{2}
\]

Then it can be concluded that after the impact of 60 kJ in which the maximum impact stresses are transmitted, the inner mesh shearing resistance remaining about 23% [2]. Additionally, the contribution of the G80/4 secondary mesh, in combination with the cable bolt 140 mm² (Figure 26) also can be evaluated.

At the same time, the contribution in safety factor [3] of this part of the layers combination can be estimated, neglecting the influence of the inner G65/4 mesh.

\[
\tau_{\text{mesh G80/4-P20}} = 16 \cdot 12.8 = 205.4 \text{ kN}
\]

\[
\text{SF} = 205/125 = 1.64 \text{ (ok)} \tag{3}
\]

Then the overall safety factor of the solution is at least 2.9, so the safety is guaranteed, for events such as those recorded in the impact tests at 60 kJ.
CONCLUSIONS

Given the characteristics of a structure that attempts to reproduce the conditions of a mine, edge conditions are generated, for example free anchors (without grout), which it cannot make a direct relation of the results obtained in the test with the results expected at the mine. However, it allows comparisons between systems / elements of fortification and helps to advance in understanding the complex problem of rockburst.

With this successful test of a reinforcement system (shotcrete with mesh, rockbolt and a second mesh with cable bolts) under dynamic conditions, we can add experimental antecedents to the theory and confirm that this type of support is suitable to be used in potential rock burst areas.

Dynamic laboratory tests contribute to the primary knowledge and establish initial parameters of comparison between different elements; however, the need to work at small scale limits the possibilities of a perfect simulation of the reality and therefore is important to understand how the test is carried out and the significant of the results.

These series of tests make a very positive contribution in the verification of the designs used at El Teniente. The elements of the measurement system (load sensors, accelerometers and high-speed video cameras) showed their suitability in obtaining data. The detailed description of each test also gives data related with acceleration and displacement of the system after impact.

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