Performance assessment of tendon support systems submitted to dynamic loading

D. Gaudreau
Noranda Inc. Brunswick Mine, Bathurst, NB, Canada

M. Aubertin & R. Simon
École Polytechnique de Montréal, Montréal, QC, Canada

ABSTRACT: An approach is proposed in this paper to assess the performance of tendon support systems submitted to dynamic loading. The approach was developed subsequent to the quasi-static and impact pullout testing data assembled during the MCB (Modified Cone Bolt) prototype tendon support validation. It consists in the calculation of the displacement of tendon support systems when subjected to dynamic loading using experimental data from the tendon’s response to quasi-static loading. The proposed displacement evaluation method could provide a means of calculating the maximum capacity range of tendons for rockburst support design.

1 TUNNELS IN HIGHLY STRESSED GROUND

1.1 Introduction

Deep mines and underground operations with a high extraction ratio are sensitive to ground stresses. Increasing stresses in a mining area can cause the failure of rock masses around openings and convergence of rock towards the exposed surfaces of excavations. Under a combination of circumstances such as the presence of strong and brittle rock and high stresses, it is possible for the rock mass to fail violently thus causing a rockburst. Reinforcement and tunnel support techniques such as the use of rock bolts, reaction plates and mesh are well suited for gravity driven situations when the support systems are subjected to static and quasi-static loading. The performance of the systems can be at any time verified, through pull out testing of the tendon support elements and the meshing units for example. Bolting patterns and support system design can be inspired from a number of published references to meet specific performance requirements.

The design of support strategies for dynamic loading is less obvious. Published guidelines suggest adopting a tendon burden as well as an arbitrary ejection velocity. These factors can be used to calculate the energy absorption capacity requirements of a support system so that it can be compared to the work energy during a pull out test in quasi-static loading mode. In this article a different approach is proposed based on quasi-static and impact pullout testing data assembled during the MCB (Modified Cone Bolt) prototype tendon support validation. Results and observations from the testing phase were used to derive a simple displacement evaluation method for tendons submitted to impact loading. The proposed displacement evaluation method could provide a means of calculating the maximum capacity range of tendons for rockburst support design.

1.2 Background

The tendon energy absorption testing methodology presented in this paper was developed concurrently with Noranda Inc.’s Technology Centre (NTC) research project R2-9684. The project related to the design of support systems able to sustain rapid loading conditions. In 2002, a patent application (US 6,390,735 B1) has been granted for Noranda Inc. regarding a new bolt called MCB for “Modified Cone Bolt”. This new tendon can yield in its polyester resin grout matrix. The bolt’s mechanical response to rapid loading has been evaluated using an impact test rig located inside its NTC premises. Impact testing on different bolt types called for an energy absorption calculation method that could describe the tendon’s impact behaviour through time for two reasons. The first is due to limitations on the test rig’s maximum drop weight load and height. Certain types of support require more than one impact to break the tendon. Thus drop heights and impact velocities were not constant from one test to another. The second reason pertains to the purpose of the impact testing. The characteristic response of each tendon had to be summarised in such a fashion that it could be used for rockburst load simulation purposes. This paper focuses on the selected method for testing and assessing the response of different
systems to impact loading, by proposing a methodology for the verification of the MCB capabilities (Gaudreau 2004).

Tendon support is most often used with other support elements, such as wire mesh and straps, as a system for tunnel support in mines. Tendon support consists of a stiff rod of a given geometry, length and diameter installed in a borehole. Different tendon support systems are available, for example cable bolts, rock bolts, rebars and Split Sets (e.g. Hoek et al. 1995). Each type of tendon will react differently when subjected to slow or rapid loading.

Stiffer support systems can provide immediate resistance to the deformation of openings. If the deformations become too large or if the drift sustained damage, the tunnel is rehabilitated, usually by removing loose parts and installing new rock support devices. Certain support systems are better suited to carry massive deformation through time, and can avoid the rehabilitation process. By definition, a yielding tendon support system has enhanced load-time distribution properties when subjected to large displacements, while providing resistance to the movement. An example is given for clarity. A massive impact load is suffered by a supporting structure at the periphery of a tunnel, due to the violent failure of a wall. If the wall support system is stiff, it will carry the full load in a very short amount of time. Hence, the steel tendons will elongate elastically and plastically then break, leaving a large amount of energy available that may be imparted to mobile rock particles. The smaller ejected masses will likely be ejected at high velocity, the heavier ones will be found near the toe of the wall. If this wall was supported using yielding support, the impact load received by the reaction plates through strapping and screening materials will be transferred to the tendon unit. If the tendon unit can move and follow the wall displacement with some resistance, the load will be transferred to the tendon, until the wall comes to a full stop. It is near the end of the deceleration that the tendon will sustain the most damage if the dynamic load is too large. But during the controlled movement of the wall, a quantity of work energy will have been absorbed, which could decrease the damage to the opening. The load absorbed inside the tendon is a complex mechanism dependent on the characteristics of the support system and of the bonding materials inside the borehole. One can speculate that the pressure of the reaction plate and straps on the wall in reaction to the tendon displacement inside the borehole can reduce the size of the failure zone since rock is stronger when confined. The extra confinement given by the movement resistance of the tendons could change the size of the failure zone during the impact.

All support systems available commercially have limitations, and the choice of the proper one depends on factors such as the in-situ stresses, the expected rate and amount of deformation of the drift walls, the nature and quality of the rock mass, as well as the tunnel function and utilization time.

Cook and Ortlepp (1968) suggested the use of yielding support in the deep gold mines of South Africa. The concept was further developed by Jager et al. (1990), who introduced the South African Cone Bolt (Jager 1992), a groutable tendon equipped with a cone anchor. Preliminary impact testing of resin and cement grouted Cone Bolts was conducted in May of 1998 at the Noranda Inc. Technology Centre. Testing results and other industry results suggested that the Cone Bolt was not reliable when installed with cartridged polyester resin, but seemed effective for use with cement grout. This was mainly due to the bolt’s inability to mix the cartridged resin in a reproducible fashion.

1.3 Scope of work

This paper presents experimental procedures and results pertaining to the evaluation of tendon support performance in impact loading. More specifically, the experimental results and procedures will be descriptive of the validation tests for the Modified Cone Bolt (MCB) developed at Noranda Inc. Technology Centre (NTC).

Section 2 contains a literature review on seismicity in mines, load-deformation-time behavior of tendon support, and testing methods thereafter. Section 3 contains experimental procedures used to test MCB prototype tendons at various loading rates, as well as testing results and analysis. Section 4 elaborates on a proposed displacement evaluation method for tendons submitted to dynamic loading based on observations from impact testing of MCB tendons.

2 LOADING MECHANISMS AND REQUIRED PERFORMANCE OF TENDON SUPPORT

2.1 Rockbursts and seismicity in mines

In Eastern Canada rockbursts are often called “bumps”. A 1920 definition of a bump is “a sudden breaking sometimes accompanied by a setting or upheaval of the strata in the mine, accompanied by a loud report. (...) often interpreted as a sudden squeeze, or buckling of the floor or walls of the mine passage-ways. It has its origin in the shocks accompanying earth movements” (Fay 1947).

Rockbursts are violent failures of rock that result in damage to excavations (e.g. Cook 1965). Only those events that cause damage in accessible areas of the mine are called rockbursts (Gibowicz 1993). Out of thousands of bumps recorded in Canadian mine seismic networks, only a few can be considered
as rockbursts. A seismic event is a broader term referring to all occurrences that are associated with the release of kinetic energy, with the exclusion of blasting. Salamon (1974) suggested that a rockburst could be described as a seismic event that adversely affects the operation.

2.2 Rockburst source mechanisms, size and classification

A rockburst mechanism classification is suggested in Table 1. This classification was derived from Ortlepp (1992) to better reflect the relative calibration of Noranda Inc.’s mine seismic systems. The classification is illustrated in Figure 1. Note that this classification is somewhat arbitrary. Its intent is only to illustrate the relative magnitude of what could be “felt” by someone near the affected area, in terms of a fairly well known moment magnitude scale, namely the Richter scale.

As illustrated in the classification, different rockburst mechanisms have different associated “burden” on the tendon support system used in the tunnel. For example, the mechanism “face crush”, is probably the one which could have the highest individual tendon burden and impact velocity on the support system. The size of the volume of rock that violently fails and its proximity to an open face can cause a lot of damage. On the other hand, the mechanism “fault-slip”, although corresponding to the highest probable moment magnitude, is the one less likely to induce a large burden or impact velocity on the support system. Its incidence on tunnel stability is most likely to be due to shake damage or spalling of loose and poorly supported material.

Table 1. Proposed classification for rockburst source mechanisms and associated damage.

<table>
<thead>
<tr>
<th>Type of failure</th>
<th>Postulated mechanism at the source of the seismic event</th>
<th>Local Richter Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress-induced fracture</td>
<td>Energy dissipation in the rock mass by creation of new fractures</td>
<td>-3.0 to –1.0</td>
</tr>
<tr>
<td>Strain bursting</td>
<td>Superficial spalling of tunnel surface and violent ejection of rock particles.</td>
<td>-2.0 to 0.0</td>
</tr>
<tr>
<td>Buckling</td>
<td>Bending of rock slabs inwards the tunnel due to the pressure on both ends</td>
<td>0.0 to 1.5</td>
</tr>
<tr>
<td>Face crush/Pillar burst</td>
<td>Violent and deep expulsion of rock from a tunnel surface or multifaceted structure (pillar, rib, “skin” pillar, remnant)</td>
<td>1.0 to 2.5</td>
</tr>
<tr>
<td>Shear rupture</td>
<td>Violent propagation of a shear surface in a solid or healed area</td>
<td>1.0 to 3.0</td>
</tr>
<tr>
<td>Fault-slip</td>
<td>Violent slip on a pre-existing shear surface.</td>
<td>2.0 to 3.0</td>
</tr>
</tbody>
</table>

Figure 1. Tunnel damage classification (Gaudreau, 2004).
2.3 Performance requirements of yielding support

Tunnels driven into highly stressed ground typically suffer from stress-induced damage (e.g. Wagner 1984, Mühlaus 1990, Ortlepp 1992a, Dyskin & Germanovich 1993, Langille et al. 1995, Maxwell & Young 1997). Stress-induced damage can form from either creation of new fractures or reactivation of existing fractures in the rock mass. This phenomenon is depicted in Figure 1a, showing an exaggerated profile of the induced fracture lines relative to the influence of the principal stress direction.

The extent of the induced fracture zone can affect the amount of “dead load” in the back of the tunnel. Static loading performance of tunnel support in highly stressed ground must reflect this aspect. Further to this, the tunnel support must be able to tolerate relative convergence of tunnel walls, or swelling and squeezing rock conditions (Stillborg 1986). Sidewall dilations in excess of 500 mm have been recorded under both static and dynamic conditions. However, when such large movements occur, the dimensions of conventional tunnels are reduced to such an extent that the basic functions of these tunnels cannot be maintained. Wojno et al. (1987) recommended a static tendon yield force greater than 100 kN to control wall movement. Moreover, these same authors suggested that the distribution of the dilation within the fractured zone is an important factor to the design of support tendons for yielding ground. They observed average values of dilation within the fractured zone is an important factor to the design of support tendons for yielding ground. They observed average values of dilation in the range due to sidewall/hangingwall movement within 2 m of the tunnel wall, 16% between 2-3 m and 38% at depths greater than 3 m from the tunnel sidewall. They thus recommended that the yielding range due to sidewall/hangingwall movement within the supported rock thickness for non-rockburst conditions be:

- 230 mm for a tendon length of less than 2 m,
- 310 mm for a tendon length of 2 m to 3 m,
- 500 mm for a tendon longer than 3 m.

Langille et al. (1995) have set the following criteria for the selection of a one-pass support system (i.e. installed in one cycle) for use in a high stress mining environment at Creighton Mine in Sudbury:
- immediate support of loose rock blocks for protection of men and equipment at the face,
- yieldability of at least 50 mm in the short term,
- long term rigid reinforcement of the broken rock mass,
- corrosion resistance to heat, humidity, fumes, smoke and percolating mine water.

The quantity of material that could potentially be statically contained by a rockburst support package after a dynamic event will depend on the bolting pattern at the periphery of the opening, or more specifically the tendon burden. Tendon loads can easily reach the order of 100 kN. Kaiser et al. (1992) have proposed a Rock Damage Scale for which levels of displaced rock range from a few kilograms to amounts greater than 10,000 kg.

Further to quasi-static considerations pertaining to “dead load” on tendon support, one must consider dynamic effects if a tunnel is to be subjected to high stresses. Dynamic loading implies physical forces producing motion. Stress changes and blast vibrations after mining to a new stope geometry can produce dynamic loading of a nearby tunnel. The stress regime at its periphery can fluctuate rapidly.

Wojno et al. (1987) have set these guidelines for the capacity of tendons in dynamic loading:
- The amount of work to be done during yielding of the tendon must be greater than 25 kJ.
- The mean dynamic yield force must be in excess of 50 kN.
- The maximum dynamic yielding range must not exceed 500 mm of displacement.
- The dynamic strength of the tendon should exceed the static yield load of the tendon by at least 25 per cent.

Gaudreau (2000) set the design criteria for the components of a yielding support system for Noranda Inc. at:
- peak reaction load of less than 11.3 tons and greater than 6.8 tons for an impact energy of 15 kJ,
- tendon system plasticity limit at load greater than 6.8 tons,
- pull-out displacement greater than 150 mm (at maximum static capacity and at impact loading of 15 kJ),
- ability to install in cement or polyester resin grout using mechanized or non-mechanized means of installation,
- support must not creep if load below plasticity limit after initial movement of the anchor,
- better corrosion resistance than resin-rebar installation,
- support can be pre-tensioned at installation,
- support to be installed in a 38 mm hole with a 17 mm smooth bar of grade C1060.

These criteria were set to match energy absorption and wall control requirements from damage observed underground at Brunswick Mine and from other operational restrictions including compatibility with the mine’s machinery and rapidity of installation. The choice of the smooth bar was made based on two assumptions:
- it is preferable for the full rock load transfer in the steel rod from the reaction plate to the bolt’s inner end,
- there is a possibility for creating an “active” support effect, i.e., additional clamping charge transferred to the rock mass during the event of a strain burst from a tunnel face.

The latter assumption could be verified provided the demonstration that the volume of rock subjected
to failure decreases with the instantaneous clamping provided by the bolt during the burst.

The use of energetic absorption requirements in the formulation of yielding support performance requirements can be estimated by different means. For example, one can use case analysis of rockbursts, or published data pertaining to average ejection velocity (Yu 1980, Wagner 1984, Stillborg 1986, Wojno et al. 1987, Ortlepp 1993, Kaiser et al. 1996). A different, and perhaps more pro-active method could be to evaluate the ERP (Evaluation of Rockburst Potential) for the mining area and calculate (Simon et al. 1998, Simon 1999) the quantity of excess energy available after rupture using stiffness comparisons. Once the quantity of excess energy is approximated, and given a tendon support burden, one can calculate the average possible impact velocity on the support system. The importance of the proper selection of the impact velocity will be demonstrated in section 4.

2.4 Performance of yielding support

Commercially available tendons have been tested for their plausible reaction to impact loading using different methods. Tendons are often pull-tested and the load-displacement curve can be utilised to calculate the work spent during the test. Tannant & Buss (1994), Langille et al. (1995), Kaiser et al. (1996) and Hoek (2000) published pull strength parameters for tendon support and mesh. The different tendons are classified by their ability to yield. Split Sets, Swellex and Cone Bolts were classified within the best yielding tendons available on the Canadian market, thus would be better suited for use in rockburst-prone areas to prevent damage.

Tendons can also be directly tested in rapid loading. Most tendon rapid loading testing methods depicted in the literature can be classified under explosive loading or impact loading categories.

Ortlepp (1992) discussed the blast testing approach where a tunnel half-section is bolted with conventional end-anchored bolts and the other half with yielding end-anchored bolts. These trials were conducted by Ortlepp in 1969. The test was used to demonstrate the relative performance of both support systems under dynamic loading. Another widely published experiment concerns the explosive testing of the COMRO Cone Bolt, developed and manufactured by Strata Control Systems, and now manufactured by Steeldale in South Africa (see Ortlepp 1994, Stacey & Ortlepp 1994, 1999, 2000, Ortlepp & Stacey 1998). In this experiment, different sets of support tendons, namely two distinct sets of 16 mm Cone Bolts, and one set of each 16 mm rebars, 16 mm smooth bars, 25 mm rebars and 22 mm Cone Bolts were installed in a quarry. Each set was installed and grouted into bedrock through an independent concrete slab. Explosive charges were then inserted in horizontal cavities consisting of rows of PVC pipes laid on the bedrock before the casting of concrete. Each slab was tested separately and monitored using a high-speed camera and a velocity transducer consisting of a velocity of detonation electronic timer. The objective of the experiment was mainly to compare the performance of a stiff support system to a yielding one. The explosive jolt was not the same from one test to another, making it difficult to estimate the energy absorption of each set. Gases from explosive charges did not burst out from the fractured ground in exactly the same way every time, thus inducing a different energy at each test.

Tannant et al. (1992) used a different approach when a test drift, located near a large stope, was instrumented in the expectation of a large blast susceptible of triggering seismic activity. Accelerometers were set up directly on Split Sets, mechanical bolts and Swellex bolts. The performance of tendon support under these events was thus measured. The peak particle velocity measured was in the range of millimetres per second, whereas ejection velocities during a rockburst are in the order of 1 to 10 metres per second. Although this technique measures the impact of real seismic events on tendon support, it carries a disadvantage, the uncertainty of expectation. One must wait until a natural seismic event hits a particular instrumented area to get results.

Ansell (1999) and Tannant et al. (1994) have worked on an approach were the dynamic damage is simulated in a tunnel by using a blasthole drilled at a small angle to the axis of the haulage. The maximum ejection velocities were no greater than 2 metres per second, but were successful in creating damage to the haulage. The tests showed that loading by explosives close to bolts causes cracking of the surrounding rock and thereby inadequate loading of the bolts. Furthermore, it would be preferable to test support packages at velocities higher than 2 m/s for rockburst support design.

Special impact test rigs have been used to test tendons at impact velocities and loads that are comparable to theses of yielding support system requirements. Ansell (1999) grouted yielding tendon support inside a large cylindrical concrete mass. The mass, attached to an horizontal H-beam, was dropped from the ceiling of a two story high pilot plant, to a receiving structure were it was suddenly stopped. The set-up was used for fully grouted bolts and for ungrouted steel bars coupled to steel weights.

Stacey & Ortlepp (1999) used a swing-beam mechanism and a large mass to provoke the separation of a test tube where the tested tendon is installed. Maloney & Kaiser (1996) have designed the test rig that has been installed at Brunswick mine in 1997 and was later modified by Noranda Inc. The test rig was never used at the mine site due to operational difficulties.
Tendons have also been tested in shear and dynamic shear. Tendons can be loaded not only in pure traction, but also in shear or by a combination of both loading modes. This can occur during the course of induced stress fracturing (Figure 1a) and dislocation of fracture surfaces thereafter. The shear movement can be significant if combined with stress changes due to mining of excavations in proximity. Haile et al. (1995) have studied the phenomenon using two types of shear inducing apparatus to perform shear tests on tendon support. The tests were performed under both static and dynamic loading. It appears from the results that the 16 mm Cone Bolt and the 16 mm smooth bar performed equally well under dynamic shear. The 16 mm Cone Bolt showed better shear resistance in static shear than the smooth bar. The authors have recommended the Cone Bolt over the smooth bar, rebar, Split Set and twist bar in applications where shear movements in the rock are predicted. They recommended further work before using larger diameter bars for shear loading but argued that it would not be necessary to increase the diameter size of the Cone Bolt for such a use. The strength of the Cone Bolt in shear loading mode lies in its ability to alter the loading mode. In essence, the Cone Bolt installed in a dislocating wall would be loaded in a combined shear and traction mode.

Gillerstedt (1999) experimented on the ability of the 22 mm Cone Bolt to perform in mixed loading mode. The bolts were installed through two concrete blocks and loaded in shear. The resulting axial load on the tendon was measured using a load cell mounted under the bolt’s reaction plate. Electronic displacement transducers were used to measure the cone displacement in the grouted bore hole and the crack aperture. Wire potentiometers were used to monitor shear movement of the concrete block. The deformation rate was approximately 0.1 mm/s. Results indicate that the Cone Bolts did transfer some of the shear load into axial loading. One particular Cone Bolt sample broke in shear after 226 mm of shear displacement having locked in place in its encapsulating matrix. The compressive strength of the cement grout did not seem to influence the Cone Bolt’s behavior by comparing results.

3 EXPERIMENTAL PROCEDURES AND MAIN RESULTS

3.1 Quasi-static underground pull-testing of MCB tendon

Quasi-static pull testing is generally used to evaluate the in-situ reaction of tendon support. This consists in extracting pre-installed rock support from its installation site using a hydraulic ram while measuring the force given to the ram and the displacement of the tendon at the collar of the hole. A schematic of the pull testing assembly used for the prototype MCB tests is illustrated in Figure 2.

Pull testing was performed in April 2000 at Brunswick mine on MCB prototypes of 2.1m length. Displacement was measured through a potentiometer and load using an electronic pressure transducer, as illustrated in Figure 2. The polyester resin used was Fosroc 35 mm diameter cartridges. A summary of quasi-static pull test results is illustrated in Figure 3. The testing results showed good agreement with the design criteria. The bolting system was neither too stiff nor too flexible.

The instrumented pull test result consists of a load-displacement characteristic curve representing the possible performance of tendons under the same relative displacement. Such a schematic characteristic curve is illustrated in Figure 4. Typical rock tendon behavior under quasi-static loading show an elastic displacement phase and a plastic displacement phase. For the benefit of this study, the idealized tendon reaction will be said to have an elastic stiffness $K_e$ and a plastic stiffness $K_p$. Some permanent displacement is said to occur when a tendon has been pulled past its elastic displacement.
range into its plastic deformation range. The plastic stiffness $K_p$ as can be measured in a quasi-static pull tests will be used later to estimate the tendon support’s reaction to impact loading. If a pull test is done for that purpose, it is important to pull the tendon long enough to gather a significant part of the plastic deformation behavior without necessarily carrying it to failure which can be hazardous.

3.2 Impact testing

The impact testing facility located at NTC used a drop weight to induce displacement of the tested tendon at a fixed initial impact velocity. For impact testing, the rig can be set for a drop mass of a maximum of 1000 kg over a fall distance of no more than 2 m. The potential energy is thus of a maximum of 20 kJ. Figure 5 illustrates the details of the impact test rig.

The drop weight is attached to a release system located on the top part of the facility. Once released, the annular shaped impact mass slides along the test tube until it collides with the reaction plate. The latter is supported by the tendon installed in a test tube of an internal diameter of 38 mm and of 9.5 mm wall thickness. Each sample is prepared and installed as it would be underground using a stoper mounted horizontally on a track. A stoper is a hand-held mining drill that can be used to drill boreholes and install roof support.

All tests were instrumented using a load cell located on the top part of the machine, reading load on the test tube, a load cell underneath the reaction plate, reading load on the tendon, and a potentiometer attached on the tendon to read displacement of the bar. The steel mass is hoisted into position using a 5 ton capacity crane. All 1.7 m long MCB prototype samples were spun into two Fosroc 915 mm length and 35 mm diameter resin cartridges. The first cartridge has a speed index of 30 (for fast), and is of type 3591SM35. The second has a speed index of 240 (for slow), and is of type 35910LIF90. All samples were pushed through the slow setting resin, then pushed and rotated through the fast setting resin, to simulate a jackleg/stoper installation underground. Load-displacement curves generated from the tests are based on the measurements made from the superposition of load curves from the top and bottom load cells. The surface area under the load-displacement curve representing the work energy dissipated is typically calculated from the bottom load cell when available.

Data was recorded using a LeCroy 9424E Quad 350 MHz oscilloscope. Three channels were used for the test, two for the load cells, and one for the displacement transducer. The top load cell was an RST model SGA-75-1.30 of 34 ton capacity. The bottom load cell was a Sensotec model TH/1591-01 of 90 ton capacity. Each cell was connected to a Vishay P-3500 strain indicator. The amplified signal was recorded using the oscilloscope. The displacement transducer was a UniMeasure P-20A potentiometer.

Although a large number of data points were collected in little time (40,000 data points in 0.2 seconds), the waveform recorded was noisy. The source of the noise is assumed to be due to environmental electrical and magnetic disturbances whose source was generated by machines and power distribution around the pilot plant at NTC. Voltage jolts often triggered the oscilloscope, and the amplitude and frequency of the ambient noise was erratic. A wavelet filter provided the ability of rejecting the white noise and was considered well suited for the transient nature of the recorded displacement and load waveforms. The removal of noise from noisy data to obtain the unknown signal is referred to as denoising. The wavelet shrinkage method (Wolfram Research, 1996) was used to suppress the white noise.
Figure 6 illustrates one impact test result on a MCB specimen. The figure illustrates processed filtered signals from one test, in load-displacement form. Displacements and loads have been combined on the graph from which work energy can be calculated as the area under the curve. The oscillations, mostly detectable on the top frame load cell (force1), may correspond to the natural frequency of the tendon-tube-impact machine system.

Specimens were typically tested numerous times, thus using numerous cycles of loading. Permanent damage to the steel was only detectable if the load measurement at the end of each loading run exceeded the elastic limit of the steel material.

Impact tests demonstrated that the MCB prototype could absorb an impact load of 1000 kg over 1.5 m drop height, resulting in an impact speed of 5.4 m/s. Multiple impacts were imparted on each specimen. Since the specimen’s reaction plate was driven further down at each test, the impact velocity was changed at each loading cycle. Can one add the absorbed energy from each test to conclude on the energy absorption capacity of the tendon for a single impact, and to evaluate the maximum load in the tendon for a given choice of ejection velocity and tendon burden?

The ejection velocity could be derived from energetic considerations equations, given a plausible violent rock mass failure of a given depth and expected energy. The burden of the tendon, or impact mass, can be estimated from the depth of failure expected in the rock mass and the bolting pattern applied. One could evaluate if the tendon can withstand the given impact, by verifying if the axial load in the bolt exceeds its ultimate tensile strength.

An adequate model for tendon displacement submitted to impact loading is required to analyze impact test results and could ultimately be used to predict the energy absorption capacity of support systems. Cyclic impact testing was performed on the MCB bolting system. Although it would have been interesting to set the impact testing for higher impact energy, so as to break the tendon on first impact and directly evaluate its maximum energy absorption capacity, the available equipment could not be set for higher drop heights nor bigger drop weights. The relative effect of an increase of the impact velocity and/or the drop height in the testing protocol on the tendon’s response must also be assessed. For the benefit of the MCB testing program, the velocity for all tests was higher than 5 m/s, and yield point and its plastic stiffness under quasi-static loading. The method can be used to estimate the tensile load within a tendon submitted to axial impact loading. The proposed calculation method could be used to interpret the maximum energy absorption capacity of the tendon for a single impact, and to evaluate the maximum load in the tendon for a given choice of ejection velocity and tendon burden.

In this section, a displacement evaluation method is proposed for tendons submitted to impact loading, given a tendon burden, impact velocity, the tendon’s yield point and its plastic stiffness under quasi-static loading. The method can be used to estimate the tensile load within a tendon submitted to axial impact loading. The proposed calculation method could be used to interpret the maximum energy absorption capacity of the tendon for a single impact, and to evaluate the maximum load in the tendon for a given choice of ejection velocity and tendon burden.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cycles to failure</th>
<th>Energy absorption by cycle (kJ)</th>
<th>Total additive energy (kJ)</th>
<th>Load at failure (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17-3</td>
<td>4 at 1000 kg</td>
<td>16.4+17.5+ 18.3+7.4</td>
<td>59.6 Not available</td>
<td></td>
</tr>
<tr>
<td>17-11</td>
<td>4 at 1000 kg</td>
<td>17.3+17.0+ 12.7+3.2</td>
<td>50.3 19.6 thread failed</td>
<td></td>
</tr>
<tr>
<td>17-12</td>
<td>4 at 750 kg</td>
<td>11.0+12.0+ 12.3+10.6</td>
<td>45.9 23.7 nut slipped</td>
<td></td>
</tr>
<tr>
<td>17-13</td>
<td>4 at 750 kg (no failure)</td>
<td>11.6+12.1+ 12.9+14.2</td>
<td>50.8 Not applicable</td>
<td></td>
</tr>
<tr>
<td>17-14</td>
<td>5 at 750 kg</td>
<td>10.6+11.4+ 12.3+13.0+ 12.4</td>
<td>59.6 23.0 thread failed</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Tendons tested to failure and tendon load measured during last cycle of loading.
increasing at every cycle of loading for one sample since the tendon reaction plate was pushed further down with each blow. Drop loads were varied between 750 kg and 1000 kg. The impact tests on the MCB prototypes have provided valuable information useful for the selection of a calculation method for the displacement of tendon support submitted to impact loading.

The following phenomena were observed during the impact tests protocol:
- The impact load-displacement curves show an oscillatory behavior, possibly representing the exchange of load from the nut to the cone in a number of pulses through time. Ideally, the calculation method should reflect the oscillatory behavior.
- When the so-called maximum load reaches a value larger than the static yield point of the steel, the carbon coating on the steel bar flakes off, suggesting plastic deformation of the tendon. Ideally, the model should be applicable beyond the elastic range.
- There are no signs of plastic deformation on steel bars for which the initial impact peak load (see Figure 6) was larger than the static yield point of the steel.
- The bar can slide further into the test tube even at the last impact cycle on a sample, when the yield point of the steel is almost equal to the ultimate tensile strength.
- Discrepancies in yield load were observed at the onset of movement.

The discrepancies in yield load from one test to the next can be due to the adhesion of the tendon in the resin matrix. If the adhesion is strong, the load transfer from the reaction plate to the conical anchor is not completely achieved before the plastic deformation wave travels back to its origin. This would result in premature deformation near the collar of the test tube, and a higher load response than normally measured at the onset of movement. This can momentarily create uneven steel properties over the tendon length. Overall, the observed phenomena suggest that the tendon support system materials can be hardened due to plastic strain, and that the impact cycles have no apparent effect on Young’s modulus or on the ultimate tensile strength of the steel.

The proposed calculation method for the displacement evaluation of tendon support submitted to impact loading is based on critically damped harmonic motion (Engel 1978, Derrick & Grossman 1987, Thomas and Finney 1992, Van Sint Jan 1994) and incorporates a so-called “friction factor” and a yield point offset. The critically damped harmonic motion model consists in a single spring and a dashpot attached to fixed points at each distant end and to a mass at the inner end. A spring and a dashpot in series constitutes a Maxwell model (Mase 1970; Gibowicz 1993). A Maxwell substance, or an elastoviscous material, behaves differently under rapidly changing stress in contrast with slow loading. The MCB support system behavior displays this characteristic. The friction factor is a force referring to friction loss and heat dissipation during impact loading; it is not a yield point. Thus unlike a true Maxwell substance, the proposed model incorporates the combination of the so-called friction force of the tendon in the holding matrix and the action of the yield point when the tendon goes beyond the plastic range.

The proposed calculation method consists of two main steps. The first relies on a rheological model used to simulate the displacement of a tendon under impact loading. The second involves potential energy and work balanced with the friction factor imparted to the rheological model. The outcome is the approximation of the maximum tendon displacement under impact loading, or alternatively its maximum axial load for a given mass, impact velocity and characteristic plastic stiffness. The rheological model chosen to simulate the displacement of tendon support under impact loading consists of a mass attached to a slider, a spring, and a dashpot in series (Figure 7). The mass m is impacted at initial velocity and displacement $v_0$ and $x_0$. The spring has a plastic stiffness of $k_p$ to which is added a constant yield force of $F_y$ when displaced. The dashpot has a damping factor c, proportional to the plastic stiffness of the spring and to the size of the impact mass. Positive displacement $x$ is downwards.

The overall constant yield force value $F_y$ (N) consists of:

$$F_y = \text{YieldLoad} + F_f$$  \hspace{1cm} (1)

where YieldLoad is the yield load (N) of the tendon material and $F_f$ is the friction factor (N) representing all sources of friction losses.

The model should then require only input parameters that are known a priori from quasi-static pull testing results and specifics, such as the impact mass and initial velocity, the tendon support system plastic stiffness, and the yield load of the tendon material.
Solving the equilibrium of this model (e.g. Figure 7) for forces, we have:

\[
m \frac{d^2x}{dt^2} + c \frac{dx}{dt} + k_p x + F_g = 0
\]  

(2)

where \(m\) is the mass (N), \(c\) the damping factor, \(k_p\) the plastic system stiffness (N/m) as evaluated from pull testing of the tendon, and \(F_g\) the overall constant yield force (N) for the displacement of the system, calculated as the addition of the tendon material’s yield load and the friction factor (eq. 1).

Assuming a critically damped system, the solution to the second order non-homogeneous differential equation is:

\[
x_g = (C_1 \cdot t + C_2) \cdot e^{-\omega t} - \frac{F_g}{k_p}
\]  

(3)

\[
w = \sqrt{\frac{k_p}{m}}
\]  

(4)

\[
C_1 = v_0 + w \cdot (x_0 + \frac{F_g}{k_p})
\]  

(5)

\[
C_2 = x_0 + \frac{F_g}{k_p}
\]  

(6)

where \(x_g\) (m) is the model’s calculated tendon head displacement (3), \(k_p\) (N/m) the plastic stiffness of the tendon support system, \(m\) is the mass (N), \(x_0\) (m) and \(v_0\) (m/s) the initial displacement and speed respectively, \(t\) is the time (s) and \(C_1\) and \(C_2\) the particular solution constants.

The force in the tendon \(F_{\text{bar}}\) (N) can be calculated using:

\[
F_{\text{bar}} = x_g \cdot k_p
\]  

(7)

and the potential energy absorption (J) can be calculated as:

\[
E_{\text{bar}} = \frac{m \cdot v_0^2}{2} + m \cdot g \cdot \max x
\]  

(8)

where \(g\) is the gravitational constant (m/s²) and \(\max x\) (m) the maximum displacement calculated.

The work \(W\) (J) required to pull out the tendon in impact load can be calculated from the load displacement graph:

\[
W = \int F\,dx
\]  

(9)

The variables for the rheological model equations (3-6) are parameters \(m\) (N), \(x_0\) (m) and \(v_0\) (m/s) which must be defined by the user. The yield load of the tendon material, consisting of part of the overall yield force value \(F_y\) (N), as well as the plastic stiffness of the system \(k_p\) (N/m), are factors specific to the tendon support system. They can be drawn preferably from quasi-static pull testing and materials specifications, or alternatively from impact tests results. In the latter case, the plastic impact stiffness can be calculated from the end of the load displacement curve at small impact weight velocity, where the peak may appear if the impact load was sufficiently strong to deform the tendon. In normal conditions, the initial displacement is set to zero and the initial velocity corresponds to the impact velocity or block ejection velocity. The mass corresponds to the impact weight or the tendon burden.

In order to obtain the axial load in the tendon as well as the energy quantity absorbed through the tendon’s movement in impact load, one can follow the following steps (the use of a spreadsheet is recommended):

1. Define an arbitrary friction force \(F_f\) representing the friction losses and other energy dissipation sources. For the first iteration, it is suggested to use the tendon support system’s yield load measured with pull tests, if not available the yield load of the tendon material.

2. Calculate the axial displacement \(x_g\) for different time increments, typically in the order of milliseconds, using equations (1), (3), (4), (5) and (6).

3. Calculate the axial force in the tendon \(F_{\text{bar}}\) using equation (7).

4. Construct a load displacement graph for the reaction of the tendon. The graph must be set so that if the axial force in the tendon \(F_{\text{bar}}\) is not greater than the friction force \(F_f\), then the force in the tendon \(F_{\text{bar}}\) equals the friction force \(F_f\).

5. Calculate the potential energy dissipated through the tendon \(E_{\text{bar}}\) using equation (8).

6. Calculate the work done during the pull \(W\) using equation (9).

7. Repeat steps 1 to 6 until the potential energy \(E_{\text{bar}}\) is approximately equal to the work \(W\).

For modeling of the MCB system in single impact, the factor \(k_p\) can be estimated at 775 kN/m, which corresponds to the possible stiffest response calculated from the quasi-static loading tests (Gaudreau 2004). Higher values of \(k_p\) are required to calculate the MCB system’s reaction to multiple impacts. The plastic stiffness \(k_p\) as measured from impact load-displacement graphs of a number of test specimens falls within the range of 760 to 1050 kN/m. The quasi-static evaluation of \(k_p\) from test specimens is in the range of 630 to 775 kN/m. It could be argued that the stiffest potential quasi-static \(k_p\) is within the range of the impact plastic stiffness.

The steel yield load has a value of 112 kN for the 17.2 mm diameter MCB. Since the energy balance exercise is an iterative process, any value close to the tendon’s yield load is considered satisfactory as a first trial for the friction force.

Figures 8 to 10 show the tendon load evaluation result for a sample having a \(k_p\) value of 1050 kN/m, a yield load of 112 kN, and a friction force \(F_f\) of 93 kN, at an impact weight of 1000 kg and initial impact velocity of 5.7 m/s. This impact velocity corresponds to a drop height of 1.66 m and the \(k_p\) value to a tendon whose grout matrix could have stiffened
under a first large impact. The maximum load evaluated in the bar is 169 kN (see Figures 8 to 10), and the simulated impact time to the onset of elastic recovery is 70 ms (see Figure 8). On a similar set up, 163 kN was measured for maximum tendon load on sample 17-11-2 (Gaudreau 2004) and the impact duration was 61.2 ms to elastic recovery and 74 ms for the complete test. The friction force of 93 kN falls into the tested laboratory measured range of 80 to 154 kN.

Figure 9 contains a superposition of impact test results for sample number 17-11-2 and that of the proposed calculation model. Force 1 is the measured load on the top of the load frame, Force 2 is the load measured just underneath the reaction plate and Rheo_F2 is the calculated reaction from the model. The model is in good agreement with the experimental data, notably for the calculation of the maximum load in the tendon at the onset of elastic recovery (end of the loading cycle).

The proposed displacement evaluation method for tendons submitted to impact loading can be used to estimate the maximum energy absorption capacity of a given tendon submitted to impact load. The potential energy absorption of a tendon can be estimated by matching the calculated maximum load to the known ultimate tensile capacity of the tendon. The latter can be measured from cyclic impact testing or simply taken from the tendon material’s specifications.

For example, if the model is used for a plastic stiffness range corresponding to that of the quasi-static pull out testing results of the program, the calculated single impact absorption capacity of the prototype MCB ranges from 32 to 40 kJ. This result was attained by fixing the impact mass velocity at 5.4 m/s and by increasing the impact weight only to match the ultimate tensile strength of the tendon. With the same range of plastic stiffness and drop weight of 1000 kg, one can calculate the capacity range of the MCB tendon system by modifying the impact speed. The result of such an approach ranges from 29 to 35 kJ. It appears that there is no particular solution to the energy absorption capacity of a tendon. The latter depends on the combination of ejection speed and tendon burden. Further to this, one can consider that the choice of the potential ejection speed is critical to the evaluation of the level of energy absorption capacity of a tendon. For example, if an ejection velocity of 3.0 m/s is selected, comparable to that selected in the literature review as responsible for the onset of damage in headings, the minimum MCB system capacity becomes 45 kJ. By lowering the plastic stiffness of the bolting system within the range found in quasi-static testing, the bolt reacts entirely in “friction” energy dissipation and its capacity is 50 kJ. The friction energy dissipation in the proposed model equations could include energy losses due to mechanisms other than friction such as heat losses and noise. Also, more representative equations could also be used to represent the high strain rate behavior of steel (e.g. Uenishi & Teodosiu, 2004), but this aspect was deemed unnecessary at this point of our investigation.

After cyclic impact testing to the failure of the tendon, samples 17-11 and 17-14 were sawed apart to measure the amount of displacement of the cone inside the resin. These two samples were chosen because they had been tested using two different drop masses. Figure 11 and 12 illustrate the split test tube samples. Figure 11 shows the cone moved 127 mm into the resin matrix. The drop mass used for cyclic impact tests on this sample weighed 1000 kg. Figure 12 shows the cone...
moved 177 mm into the resin matrix. The mass used for these cyclic impact tests weighed 750 kg. The figures and the proposed calculation method for the tendon displacement under impact loading demonstrate that the prototype MCB both plastically elongates and “plows” through the resin at different degrees depending on the mass-ejection velocity couple.

5 DISCUSSION AND CONCLUSION

In essence, simple pull out testing of tendon support could be envisioned as a means of constructing a set of observations that can be used to approximate the reaction of tendon support in impact load given a simple calculation method such as that presented in section 4. The impact testing rig at NTC premises was quite useful in understanding controlling parameters for the performance of tendon support submitted to impact loading. Although simplified, the displacement evaluation method for tendons submitted to impact loading could be an asset to the engineer wishing to postulate on the best choice of a support system for a given failure mechanism. The model is valid for a velocity range corresponding to that of plausible rockbursts.

REFERENCES


