Ground Support 2023 – J Wesseloo (ed.)
© 2023 Australian Centre for Geomechanics, Perth, ISBN 978-0-6450938-5-8
doi:10.36487/ACG_repo/2325_25

A review of ground support mesh testing around the world

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Abstract

As mines around the world get deeper and the stresses around the excavations increase, the occurrence of large damaging seismic events (often called rockbursts) become more commonplace. One of the most favoured controls used in the industry to reduce damage from large seismic events is the implementation of a ground support system. Such a system typically comprises bolts or cables and surface support, such as shotcrete, mesh or screen, and straps.

It is important to test all components of a dynamic ground support system, but there is a lack of useful testing done for surface support. Reviews and discussions of test results sourced from different test facilities show a wide scatter of energy absorption and deformation capacity. This, on top of concerns with testing setups, makes the consideration of surface support in support designs very difficult.

In this paper, we discuss the current surface support testing results for mesh, and comment on whether current testing practices are producing useful metrics for geotechnical design.

Keywords: *ground support, surface support, mesh, screen, testing, dynamic testing, capacity*

1 Introduction

In mining, excavation stability is critical. Damage to any excavation is costly, but the consequences greatly increase when underground personnel are present when such damage happens. Therefore, risk management plans are critical to ensure that controls and systems are put in place but also managed as mining progresses. An example of a seismic risk management plan is discussed by Potvin et al. (2019) for a typical metalliferous mine. Importantly, ground support is only one component of such a management plan, and several other controls and systems are necessary for geotechnical risks to be managed successfully.

Most of the geotechnical controls available to the geotechnical engineer aim to minimise the impact of mining on the surrounding rock mass. This enhances excavation stability, and failure is less likely. However, failure still happens, and ground support is the final ‘line of defence’ when this occurs. It is for this reason that adequate ground support design is a critical part of any geotechnical risk management plan.

Most ground support systems typically consist of two components, surface support and rock/cable bolts. The rock/cable bolt units are used to pin the surface support. The aim of using surface support is to ensure that any rocks between the rock/cable bolts cannot dislodge and fall to the ground. Second, it resists the forces because of rock mass failure; this is typically done by effective load transfer to the rock/cable bolts (typically the stronger component in the design). Third, it proactively provides confinement to oppose bulking and assist the rock mass to support itself.

It is widely experienced that surface support is the weakest component in the ground support system, and therefore it is critical that surface support is designed to perform adequately; this includes dynamic failure (rockburst) of the rock mass in high-stress conditions. For this reason, surface support testing (quasi-static and dynamic) is critical to the design process since it quantifies the capacity of the surface support.

This paper concerns only mesh (also called screen) testing and does not extend to composite schemes such as mesh embedded in shotcrete. The aim of this paper is to review several surface support testing methods which are widely used in ground support system designs. We discuss how 'fit-for-purpose' these methods are for providing design data for underground mining and suggest improvements to current methods to ensure 'closer to reality' type testing methodologies.

Our experience, as consultants and practitioners, is predominantly focused on underground mining in Australia. Therefore, the papers and facilities we mention here are chosen based on what we see being used in the operations we are involved in. We have also seen many of these practices used in other countries.

Therefore, we acknowledge that this paper cannot and does not capture all mesh testing conducted across the world. It is possible that some facilities are doing testing, which is more relevant to our industry and the design methods we implement. However, if this is the case, these results are not used in any of the mines we are involved with and are not widely referenced by the mine geotechnical community in Australia.

2 Quasi-static versus dynamic conditions

It is important to discuss the difference between quasi-static and dynamic conditions in mining. Ground support design approaches are very different based on the conditions. In underground mining, quasi-static conditions are typically associated with rocks falling from rest (e.g. wedge failure and shakedown) or squeezing ground conditions (slow rock mass deformation due to stress conditions). Dynamic conditions are associated with high-stress mining, where the rock mass can store strain and release it over a very short time period (less than a second) through rock mass deformation. Although there are ideas on the rock mass failure mechanism (e.g. Kaiser 2014), these ideas are still in their infancy and have not been outright accepted by the industry. This is an important aspect of dynamic design since this limitation in understanding will lead to a limitation in the testing of ground support. It is therefore widely accepted that dynamic ground support testing produces index tests for each facility, and only allows for the comparison of results, and should not be confused with an exact support capacity value.

2.1 Quasi-static conditions

For testing, quasi-static conditions are assumed to occur over a timescale where the load transfer along the surface support is slow enough to ensure that the load (or force) at any point along the load transfer path is the same. Therefore, there are no concerns regarding the impact wave load, because of rock mass failure, affecting the mesh performance. All forces (both axial and shearing) can be adequately replicated by a conventional hydraulic system.

From an operational perspective, damaging quasi-static behaviour is easier to manage with ground support since adequate time is available to intervene and replace ground support in areas of concern. Failure, in most cases, is geologically driven, and therefore a good geological understanding of the rock mass leads to ground support designs that have a very low probability of failure.

2.2 Dynamic conditions

For testing, dynamic conditions are assumed to exist while the load is not equal along the load transfer path. In these conditions, the relationship between load (force) and strain is complex (depends on many parameters, e.g. strain rate, temperature), and the quasi-static relationship does not hold. It is a well-established fact that faster loading rate increases yield and tensile strengths in steels; see Manjoine (1944) and John et al. (1996). Further to this, both the inertial forces and wave effects also affect the sample performance. The combination of these physical processes, as well as the additional complexity of mesh geometry (this includes the influence of the bolt pattern), makes the theoretical modelling of mesh performance challenging.

It is a certainty that quasi-static testing results will not apply to dynamic conditions. Testing under dynamic conditions is critical for ensuring testing results are useful for dynamic ground support design. Dynamic (seismically active) conditions underground also result in ground support systems being exposed to multiple rock mass deformations. There is uncertainty regarding the mesh performance after a significant 'hit' has occurred.

It must be acknowledged that the failure probability of dynamic systems is higher than for the quasi-static case. This is, in part, driven by knowledge deficiencies regarding the mechanisms of failure, the stochastic nature of seismicity, and the lack of suitable testing results available to the industry.

3 Laboratory and in situ testing

The testing of ground support plays a critical role in determining capacity data that can be used in ground support design. Current testing is predominantly focused on lab testing for which tests are highly repeatable, and input parameters can be adjusted to gain an insight into how different parameters impact the capacity for single samples, e.g. Knox et al. (2018), Knox & Berghorst (2019), Crompton & Knox (2022), Knox & Hadjigeorgiou (2022), and Abreu & Knox (2022). It is not possible to replicate certain underground conditions in the lab (installation quality etc.), and tests should be viewed as producing a 'best-case' result. Unfortunately, the underground conditions which cannot be replicated in the lab lead to performance downgrades.

However, laboratories must aim to replicate all other conditions as much as possible. Where this cannot be achieved, it should be shown that the testing setup adequately simulates ideal conditions. An example of a typical concern with the setup in labs is the size of the mesh sheet used, where the test sample size is much smaller than what is installed underground; we could not find justification for such a discrepancy other than constraint imposed by the design of the test rig.

Several papers (discussed in the following sections) are available with results of in situ mesh testing. Unfortunately, these tests are sparse regarding load and deformation data, because of practical limitations. The tests also describe only a handful of products compared to the wide range covered by lab testing. These tests are, however, discussed here as they add insight into mesh performance in underground conditions.

There are numerous facilities worldwide involved in the testing of surface support related to geotechnical engineering. There are even more facilities conducting testing of the tensile behaviour of metal strands used for mesh fabrication.

3.1 Quasi-static testing

Quasi-static testing is the predominant test type done for the industry, mainly by research institutes and some surface support companies. These tests are easier to set up since a simple hydraulic press can reach the required loads. Although the results are not commonly used for dynamic ground support design in the industry, they do, however, form the basis for much of the approach used by the dynamic testing facilities. Therefore, a conceptual understanding of the data is valuable.

Quality control static testing of components is routinely performed, but that is outside the scope of the review presented in this paper.

3.1.1 Laboratory testing

Three testing facilities have produced testing results that are widely used (for static ground support design) and referenced in the industry. This section aims to summarise these current facility setups and methodologies.

3.1.1.1 Western Australia School of Mines static facility

Curtin University Western Australia School of Mines (WASM) is located in Australia and is a highly reputable facility, which has historically produced many ground support testing results (Villaescusa et al. 2013a). The static facility is still in operation and still produces testing results for the industry.

Figure 1 is the WASM static testing setup for static mesh testing. This rig design implemented fixed boundary restraint conditions. This methodology differed to what was done previously in the industry, since the widely used setup at the time (e.g. Tannant et al. 1997) had bolts and plates installed at the corners of the test sheet, similar to what is installed in underground conditions. From published documents (see Villaescusa et al. 2013b), WASM considered there was a need for consistent boundary conditions that could be replicated in both their static and dynamic test setups. They reasoned that full size mesh panels were too large to test in their laboratory setup, and that the cut down panels which could be tested needed some restraint beyond just the four bolts at the corners. They chose the fully fixed boundary setup, to support better comparison between different mesh types, and repeatable testing results.

The setup panel is a 1.3 × 1.3 m sheet, restrained in a stiff frame through numerous D shackles and eyebolts passing through the frame. The load is driven at a constant rate (4 mm/s) in the middle of the sheet. Load transfer onto the mesh is done through a 300 mm square dished plate (35 mm thick) and load is measured by a loadcell.

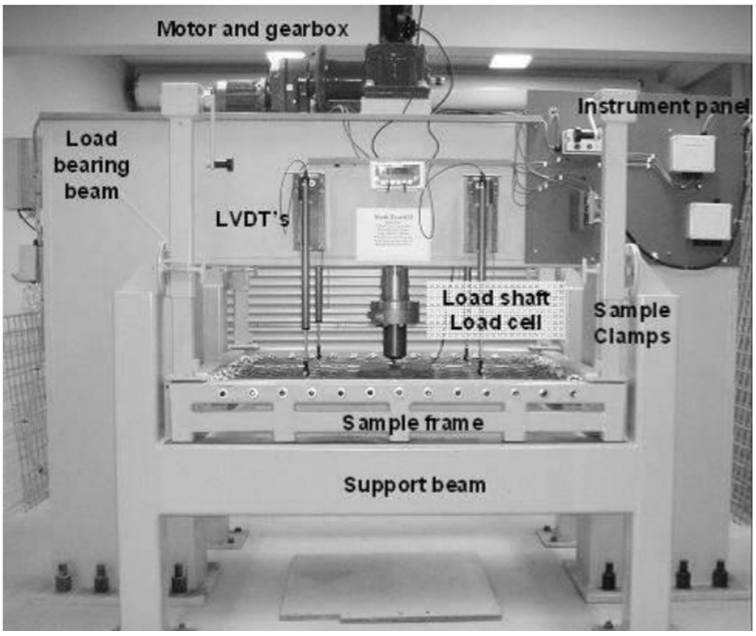


Figure 1 Western Australia School of Mines static mesh testing setup (Villaescusa et al. 2013b)

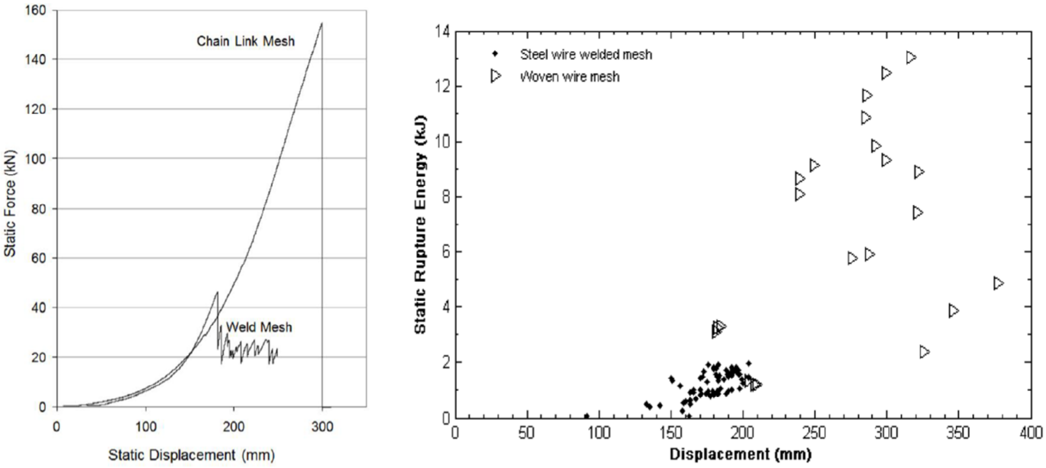
The typical testing results produced are shown in Figure 2a (the force [load] versus displacement [deformation] plots for two mesh samples), and Figure 2b (the static rupture energy and displacement recorded at first rupture for multiple tests of those two mesh types). The displacement measured here is the maximum 'vertical' displacement on the mesh (i.e. parallel to the load path and perpendicular to the mesh sheet surface).

Although these plots are the most typical produced, a much more in-depth analysis was conducted by Morton (2009) for the WASM facility, which contains many more charts that give insight into the behaviour of different mesh types. However, this work is not as widely recognised as the papers which have been produced by WASM.

Morton (2009) (Chapter 4.7) discusses the details of the different boundary conditions which were considered for the WASM facility and acknowledges that boundary conditions 'can have a large impact' on the results derived. WASM trialled three different boundary conditions:

- Clamping – the mesh was clamped between two stiff frames.
- Lacing – the mesh was bound to the frame with wire ropes.
- Fixed boundary – the mesh was connected to the frame with D shackles.

Although the results for each boundary condition were discussed, we could not find any discussion regarding the applicability of such a setup to underground conditions.



(a) (b)

Figure 2 Static test results produced from the WASM facility (Villaescusa et al. 2013b). (a) The force–displacement plot for chain link mesh and weld mesh; (b) The static rupture energy and displacements for each mesh types at first rupture

Several other interesting and useful findings were also discussed by Morton (2009), but these findings were not communicated in subsequent papers and are therefore not well known in the industry:

- Mesh orientation in the test frame affected results. The loading plate in contact with cross (short) wire strand dimension achieved higher load at larger displacements than mesh turned with the long wire strand on loading plate (i.e. a softer but higher capacity system).
- Mesh overlaps lead to a reduced mesh performance with higher displacement and reduced load transfer across overlap due to sheet separation.
- Chain link mesh configuration impacts load transfer. Symmetrical diamond shape mesh apertures result in the force transferred uniformly around the mesh. Asymmetrical shape aperture resulted in most of the forces being transferred in the long direction of the diamonds (orthogonal to wire strand alignment).
- The installation of embedded weld mesh within fibrecrete changes performance characteristics. Embedded mesh panels display different strain behaviour to fibre-reinforced panels with substantially higher load and displacement achieved.

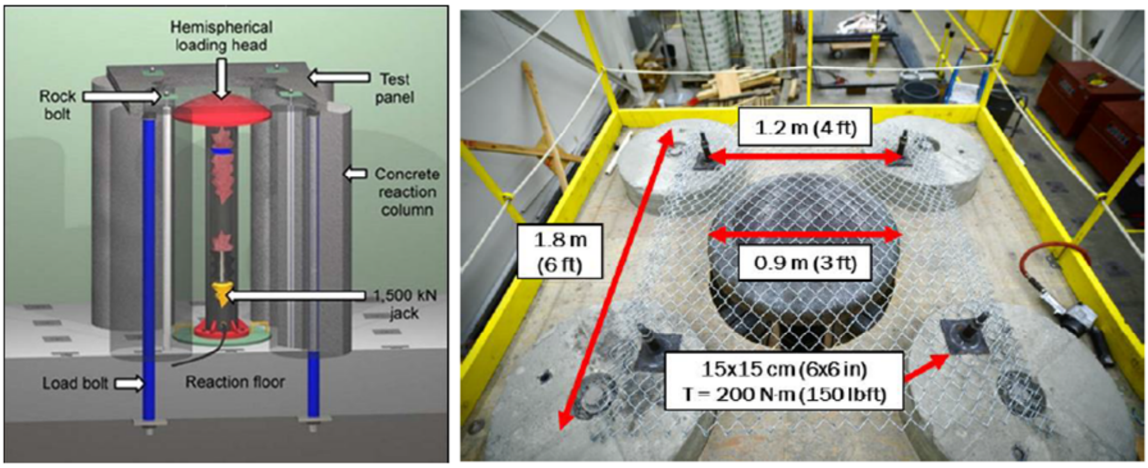
3.1.1.2 National Institute for Occupational Safety and Health

National Institute for Occupational Safety and Health (NIOSH) is in the USA and is widely recognised as a high-quality research facility. The Spokane Mining Research Division (SMRD) facility is not widely known in Australia but in recent years has produced useful testing results. It is also one of the few facilities that is focused on the geotechnical interpretation of mesh testing results.

The SMRD setup is different to the WASM facility, which allows for further insight into surface support performance. The SMRD setup (Figure 3) employs a hydraulic press to produce an upward force onto the mesh sheet, which is secured with four bolts. Bolt patterns of up to 1.2 × 1.8 m can be tested. The loading mechanism used is a hemispherical loading ram, which was used to 'avoid an unrealistic punching type failure that often occurs if a point loading is applied to test specimens' (Benton et al. 2022).

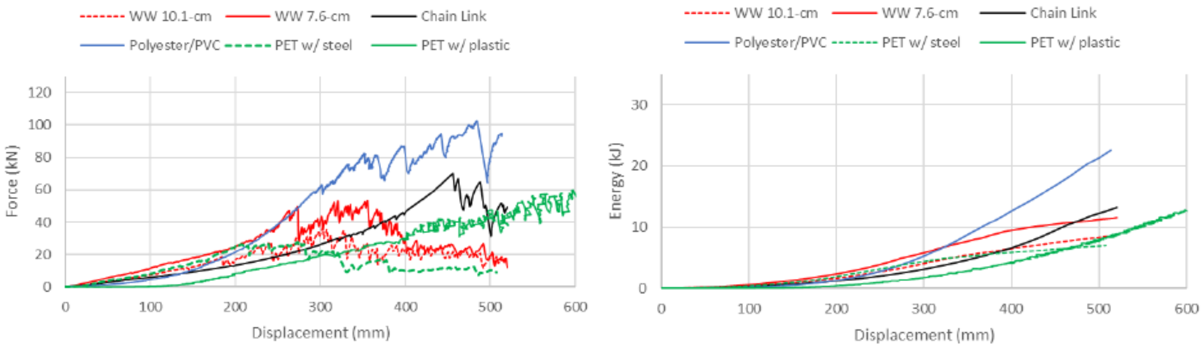
Test results for a 1.2 × 1.8 m bolt pattern with six different surface support meshes are compared in Figure 4. Figure 4a results are in a similar format to the WASM results and are therefore comparable.

Unfortunately, the mesh tested is not the same as that tested at WASM so quantitative comparison is not possible. It must be mentioned that the NIOSH difference between the welded mesh and chain link mesh is much smaller than what is seen from the WASM results. This could be because of the difference in mesh diameters and steel properties, the size of mesh sheet tested, and the different mesh boundary conditions.



(a) (b)

Figure 3 SMRD-NIOSH facility testing rig setup (from Benton et al. 2022). (a) Schematic of the high-energy high-deformation panel test machine; (b) Testing setup with the dimensions of the bolt pattern



(a) (b)

Figure 4 Results produced by the SMRD-NIOSH facility (Benton et al. 2022). (a) Force (load) versus displacement (deformation) plot of all the test results; (b) Energy versus displacement (deformation) plot of all the test results. WW refers to welded wire

3.1.1.3 Colorado School of Mines

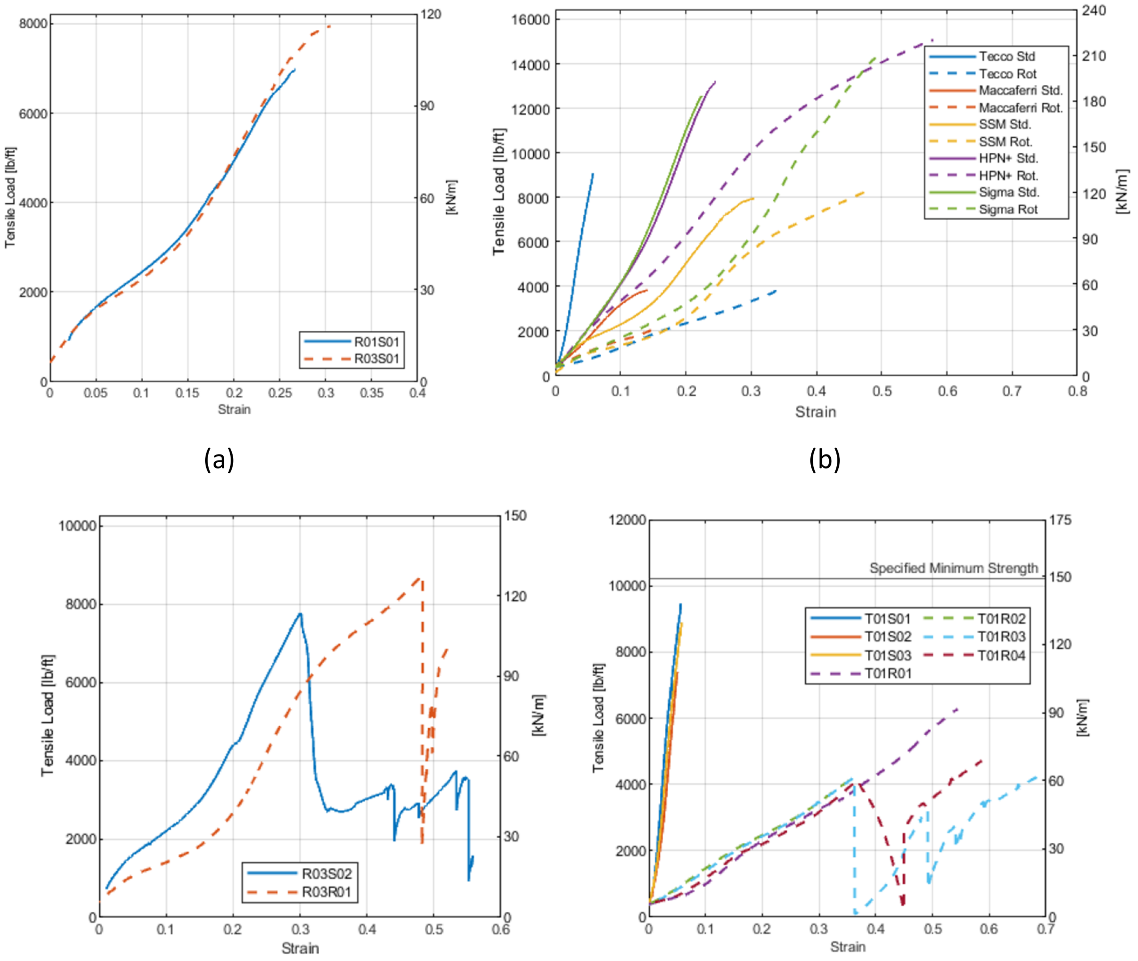
The Colorado School of Mines (CSM) facility in the USA is not well known in Australia. However, a recent report on the mechanical properties of wire mesh materials gives an interesting alternative method for how quasi-static mesh testing can be performed; see Anderson & Wham (2019).

The CSM employs a relatively simple method to test mesh performance (Figure 5). This setup allows for easy and consistent tensile testing of a small piece of mesh sheet. The test setup could also be easily repeated by other facilities. The method also allows for directional testing of the mesh since the mesh can be rotated in the setup.

The test results are not comparable to those from the other facilities since the data is plotted in terms of uniform in-plane strain (Figure 6) and not off-plane deflection. This is a stiff fixed boundary setup that is more similar to that used by the WASM facility. By plotting the results in terms of strain, the bolt pattern/test dimensions are removed from results. The method allows practitioners to understand the impact of the number of cells between testing arms (Figure 6a) and the directionality of the mesh deformation (Figures 6c and d). A summary of published mesh test results is shown in Figure 6b.

(a) (b)

Figure 5 **Tension test assembly (from Anderson & Wham 2019). (a) Standard orientation testing setup for chain link mesh; (b) Rotated orientation testing setup for chain link mesh**



(a) (b)

(c) (d)

Figure 6 **Result plots from CSM testing (Anderson & Wham 2019). (a) Tensile load versus strain plot for a mesh with a single cell (R01S01) and three cells (R03S01) exposed between the testing frame arms; (b) Tensile load versus strain plot for all the mesh results (both standard and rotated setups); (c) Tensile load versus strain comparison plot for a standard and rotated setup; (d) Tensile load versus strain results for several Geobrugg Tecco (G65) mesh tests**

The load for these tests is normalised to a dimension (load per metre) which removes the dimensionality or scale of testing. It is not possible to directly compare these results with other facilities reporting on relatively discrete or point loads applied to different mesh test dimensions.

Although the results from this testing facility are likely to play a critical role as input parameters for numerical modelling of mesh under load, it cannot replicate bolt–mesh interaction. It also requires some form of modelling to generate a load–deformation curve for ground support design. However, the testing is by design meant to investigate fundamental relationships., and the results produced are therefore much more robust and useful for the design of any rockbolt pattern.

3.1.2 In situ testing

In situ static testing of surface support presents significant logistic challenges and the non-standard test methods make comparison of results from different test configurations difficult (Hadjigeorgiou & Stacey 2018).

Whiting (2017) showed in situ static testing improves the understanding of surface support loading mechanisms by several means:

- The use of mine scale mesh geometry and bolt density which does not achieve geometrically perfect or equal bolt spacing. While this adds complexity or non-uniformity to the results, it is consistent with real world installation and hence considered acceptable and relevant.
- Installation location within a drive profile and unevenness of the rock surface. Mesh installed in the concave shoulder of a drive will accommodate greater displacements to achieve a similar load, compared to a wall installation. The rock mass in the shoulder location receives less confinement from surface support than that in wall or convex locations because of the internal curve of the mesh system.
- Installed load of rockbolts. Rockbolt bearing plate loads are individually tensioned at the discretion of a miner. There will be a range of torque or tension loads applied to bolts, as distinct from a lab environment where uniform loading is typically applied. Different tension values influence behaviour of the mesh during tests.
- Boundary conditions and interaction with adjacent mesh sheets and overlaps. Loading location on the sheet relative to the nearest edge replicates the real world ‘degrees of freedom’ in terms of mesh confinement beyond the sheet boundaries; a configuration which laboratory test methods rarely attempt to replicate.

However, the limitations on logistics and measurement of in situ tests require large effort to overcome. These tests generally suffer from unrealistic loading mechanisms and a shortage of instrumentation. They provide important observational results which improve the understating of interaction between support elements and mechanisms. Without measurement of multiple performance criteria, the data cannot be directly applied to calculate or forecast system response to changes in load.

Villaescusa (2004) stated it is virtually impossible in a field test to measure the overall response of a reinforcement system. Perhaps for this reason, in situ tests are sparsely documented in published literature, and controlled laboratory conditions dominate the focus of quasi-static testing.

Lab testing in controlled conditions allows rigorous determination of material properties and unit behaviour of individual surface support elements. Yet, there is poor correlation between real world performance and simulated, calculated, or extrapolated performance of surface support based on precise measurements derived from laboratory conditions.

Neither laboratory tests nor in situ tests can reproduce the complex loading mechanisms that mesh is subjected to in underground field conditions. Perhaps simulation of real world loading conditions should not be the goal of a single test method. Rather, it requires a combination of methods which investigate all important in situ mechanisms in a repeatable and comparable manner.

3.2 Dynamic testing

Dynamic testing of mesh is not widely done. Only a handful of research facilities are currently conducting these tests, with Geobrugg the only ground support company involved in the testing. These tests are more challenging to conduct and require significantly more resources to complete. Challenges for testing are related to several factors: the size of the facility required; the instrumentation, since mesh loading happens over ~200 ms, which is more difficult to capture (i.e. choice of instrumentation and test setup can significantly affect the quality of results); the cost per test is also significant, and therefore, without industry funding, these tests will not be widely conducted.

3.2.1 Laboratory testing

In this section, we discuss the setup and methodology of three testing facilities, which have produced testing results that are widely used and referenced in the industry.

3.2.1.1 Council of Scientific and Industrial Research drop test facility

This facility in South Africa was described by Stacey & Ortlepp (2001). The mesh sample was 1.6 × 1.6 m, attached by wire ropes to a steel frame at eight points: the four corners and the middle of each side. Loading was via a 10 t mass impacting a simulated rock mass layer overlaying the test sample (see Figure 7). The configuration was intended to simulate a dynamic loading of a fractured hanging wall of a stope.

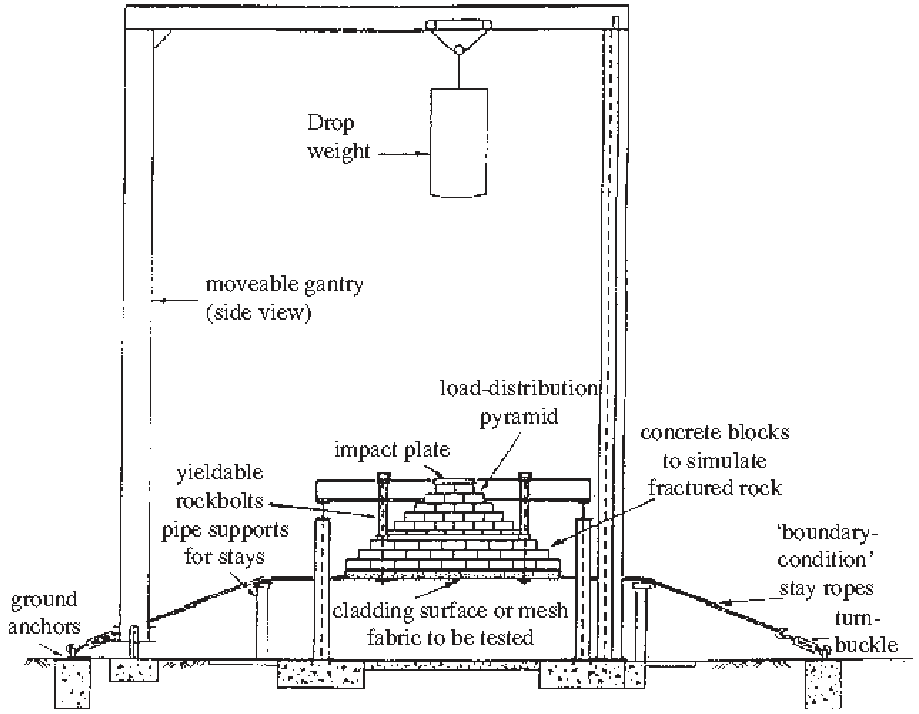


Figure 7 Dynamic mesh testing setup for the Council of Scientific and Industrial Research facility in South Africa (Stacey & Ortlepp 2001)

The results from the facility are simplistic, with each test producing a single data point (Figure 8). There is not much insight into the evolution of the stress transfer process, and a detailed energy–displacement plot is not possible. The method does, however, allow for comparison of multiple test setups, and allows practitioners to decide on an appropriate system based on its 'index' ranking. Further to this, the kinetic energy is not normalised for test sample size, and the energy loss because of the load–distribution pyramid is also not easily quantifiable.

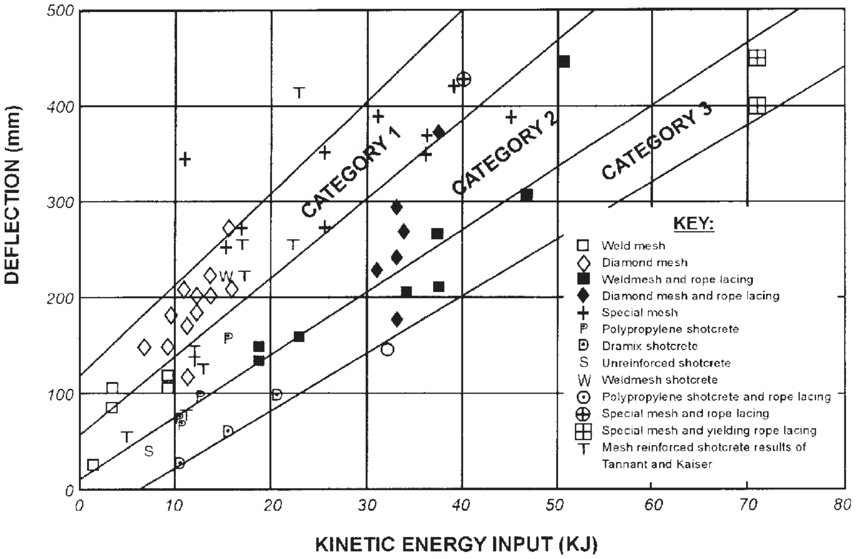


Figure 8 Testing results from Stacey & Ortlepp (2001). The system is categorised as Index 1, 2 or 3 based on its performance

It is important to recognise that this facility aimed to ensure that load transfer to the mesh was not through a point source (or small zone) but was rather transferred over a wide area. New ideas regarding dynamic rock mass failure (e.g. Kaiser 2014) suggest that failure is deformation driven and therefore, a 'point load' test setup cannot replicate rockbursting.

3.2.1.2 Western Australia School of Mines dynamic facility

The WASM dynamic facility uses a similar setup to the WASM static facility (Figure 1) but with a drop weight that transfers the load onto the mesh (Figure 9). Loading is done via a 0.5 or 1.0 t bag of steel balls with a 0.65 × 0.65m contact area to the mesh, delivering 3.8 to 16.1 kJ input energy to the central 25% area of the mesh sheet (Villaescusa et al. 2013b). The mesh panel size (1.3 × 1.3 m) and rigid mesh boundary (fixed via shackles to the frame) are the same as used for the static configuration.

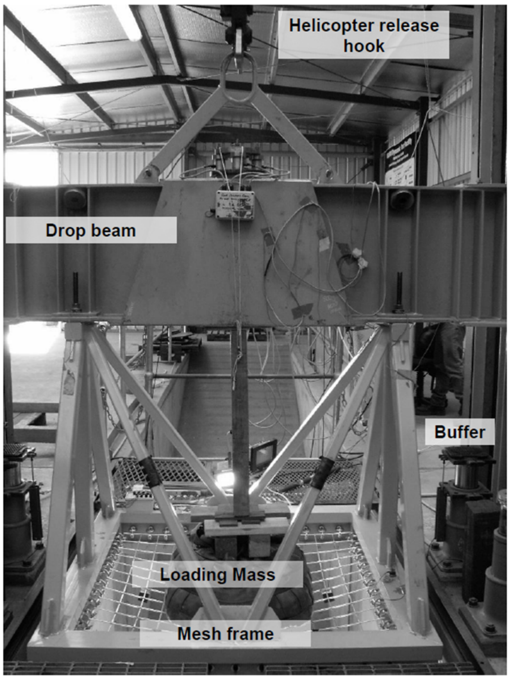
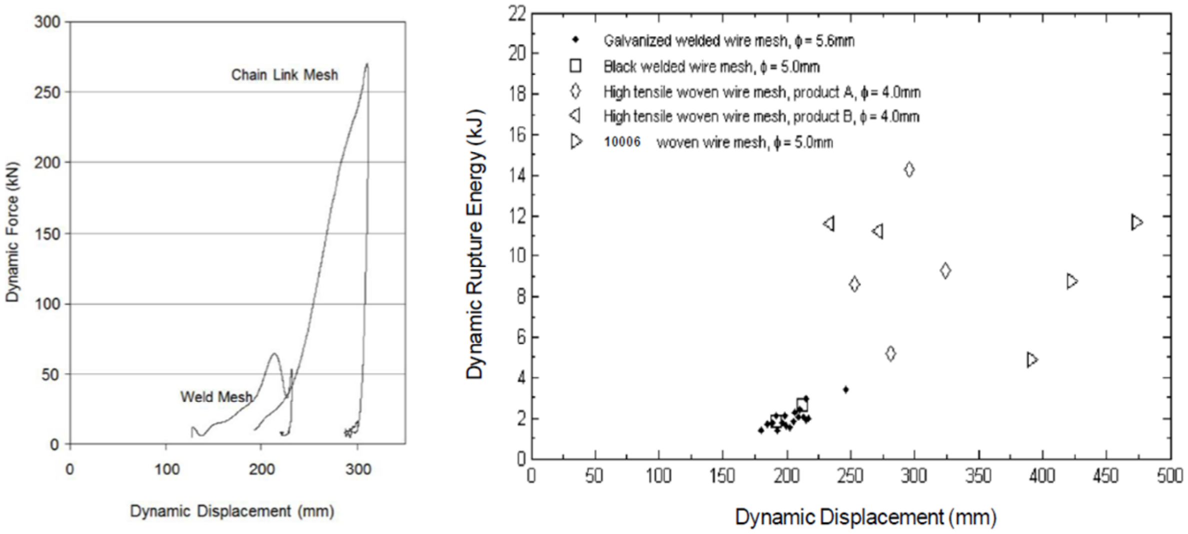


Figure 9 WASM dynamic mesh test facility (Villaescusa et al. 2013b)

The WASM facility also conducted several tests of combined bolt and mesh configurations, see Villaescusa et al. (2015). These comprised either weld mesh or chain link mesh configurations, similar to the setup in Figure 9, but with a single bolt element (threaded bar bolt or Posimix decoupled bolt) at the centre of the mesh panel. The bolt drop mass also effectively performs the role of the mesh impactor. Upon impact, the downward displacement of the bolt element generates matching maximum displacement of the central area of the mesh panel, reducing to a minimum displacement at the mesh edges. The bolt collar transfers load to the mesh. However, this is inverted compared to the usual underground observation, in which the mesh displacement at the bolt collar/plate is the minimum, not the maximum, for the mesh sheet, and the mesh transfers load to the bolt collar.

The dynamic results produced by the facility are presented similarly to the static version of the test and comprise a force versus displacement plot and a summary plot of the rupture energy versus displacement (Figure 10). These results allow for more insight than what was provided in the Council of Scientific and Industrial Research facility. However, this comes at a cost since load is transferred through a small area, and the setup cannot consider bolt patterns as it is by design a fixed boundary constraint.



(a) (b)

Figure 10 Dynamic test results produced from the WASM facility (Villaescusa et al. 2013b). (a) The dynamic force–dynamic displacement plot for chain link mesh and weld mesh; (b) The dynamic rupture energy and dynamic displacements for each mesh type

3.2.1.3 Geobrugg Walenstadt facility

This facility in Switzerland is operated by a ground support supplier (Geobrugg). Various high energy tests have been done at this facility over many years, with results widely published. A variety of dynamic anchors and patterns were tested, including cable bolts on a 2.0 × 2.0 m pattern, and rockbolts on a 1.0 × 1.0m or a 1.2 × 1.2 m pattern. Most tests used a single impact drop mass, but 2019 testing included twin drop masses, the second drop mass impacting the support 130 ms after the first, for a total nominal input energy of 245 kJ. The instrumentation installed at the Geobrugg facility allows for detailed plots of the important parameters force, displacement and energy, which allows practitioners to gain insight into the evolution of load, displacement and energy as the impact force affects the system.

Figure 11 shows a schematic of a test facility setup used by Bucher et al. (2013) for testing a 3.6 × 3.6 m chain link mesh restrained by four dynamic anchors. Loading was via a 6.28 t mass dropped onto an impact transfer structure that loaded a simulated rock mass layer, that loaded the mesh and bolts. A steel plate was installed above a rock block simulated rock mass layer to ensure the load was distributed. The mesh was connected to the frame by lacing wire rope through mesh and frame, but it was not clear if these connections were made all along the frame or at selected points. Stiffness of the simulated rock mass layer in the test was varied, to study the effect on load–distribution between mesh and bolts. The assumption was that:

> *'During dynamic loading of a surface support scheme, the surface support is loaded by a part of the fractured mass. The resulting force in the surface support will then be transferred to the connection element, e.g. plate, and then on to the reinforcement, with the other part of the load going directly to the reinforcement.'* (Bucher et al. 2013)

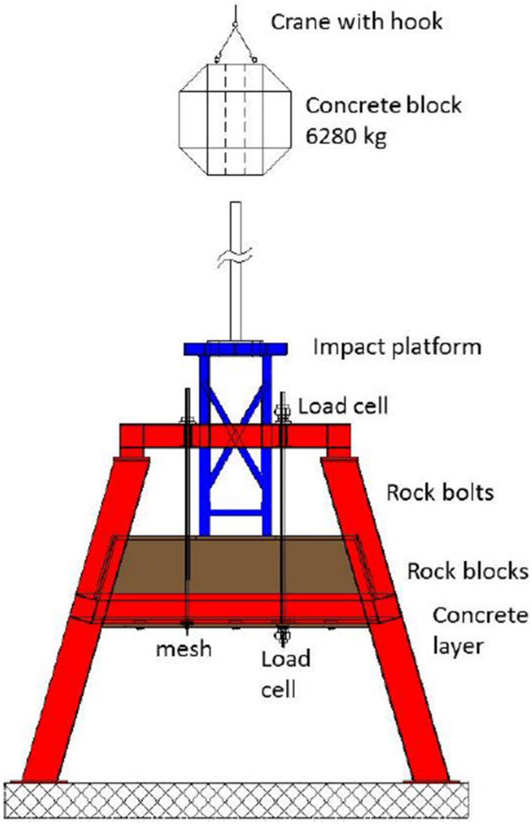
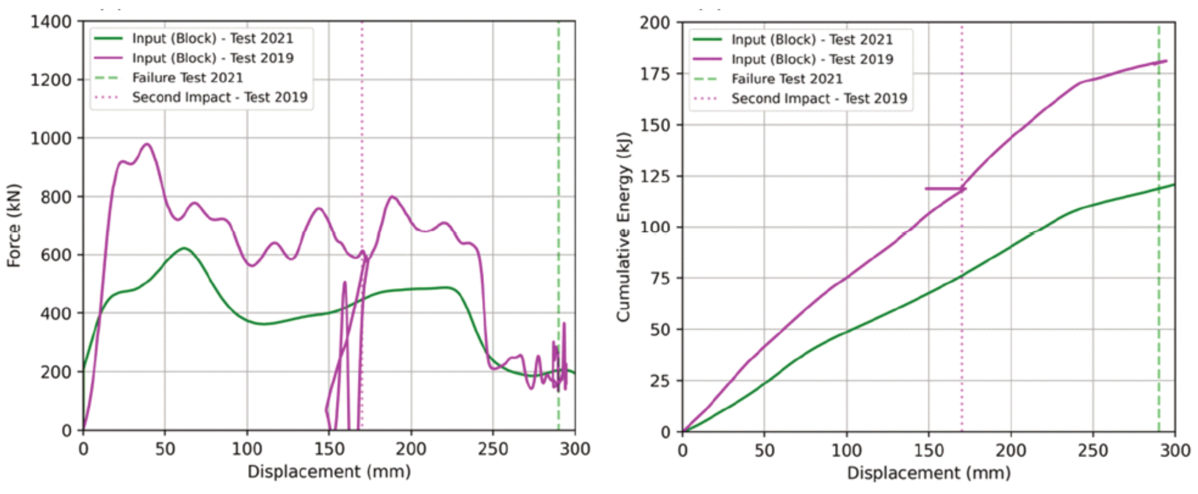


Figure 11 Geobrugg test setup (Bucher et al. 2013)

A third set of tests used the configuration of embedded and/or outer chain link meshes restrained by a pattern of five bolts and four cables (Brändle & Fonseca 2019) or nine bolts (Brändle et al. 2022). A 9.64 t mass impacted directly onto the central bolt in the pattern. Having a drop mass which impacts onto a central bolt skews the results, as the bolt would absorb most of the energy, and the load transfer via the mesh to the other bolts will be limited. An example of the force, displacement and energy plots is shown in Figure 12. The central bolt in one test recorded up to 470 kN load, as shown in Figure 13, while the others registered 80 kN or less. Such high values are not widely seen in rockbolt testing and therefore, the reliability of the data is in question. This perhaps explains the sizeable difference in energy compared with WASM data.

The analysis interpreted the falling mass input energy relative to the quite small impact area, but we are not aware of a justification for that approach. Unfortunately, this facility does not normalise the load, deformation or energy to parameters such as test area size or bolt number, which makes comparison between tests and between facilities difficult.

Geobrugg impact energies across their tests ranged from 30 to 463 kJ, much more than WASM, but only a small portion of that energy would have been absorbed by the mesh. The result curves from the Geobrugg facility differ significantly from what was seen at WASM. This reduces the confidence in the test results from either facility since many test configuration parameters were different. The difference in energy alone is about 10 times, which is significant.



(a)

(b)

Figure 12 Plots of the testing results for the Geobrugg facility (Brändle et al. 2022). (a) Force versus deformation curves for the tests; (b) Cumulative energy versus displacement curves for the tests

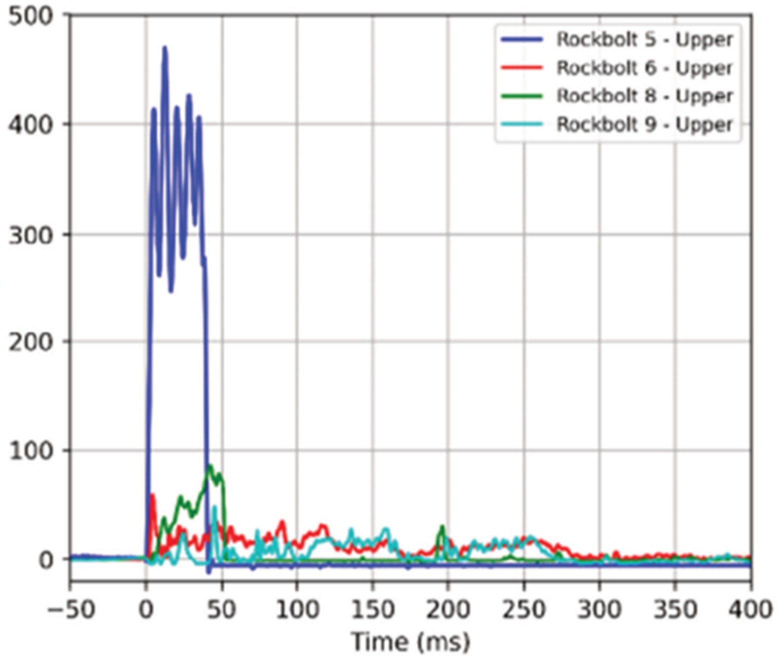


Figure 13 Measured load capacity for the four bolts used in the testing (Brändle et al. 2022)

3.2.2 In situ dynamic testing

Some in situ tests have been conducted by practitioners, but these tests are few and the data captured is limited; similar to what was seen for quasi-static in situ tests.

In situ dynamic testing was conducted by Darlington et al. (2022) on a series of mesh straps and W-straps. The test improved understanding of interaction between bolts, strap and a point load applied orthogonal to the excavation surface. Testing applied point load impact energy from 5.1 to 15.3 kJ and produced displacements of 0.35 and 0.50 m for mesh and W-straps, respectively, but the single point loading is not typical of underground conditions.

Doran et al. (2023) and Whiting (2010) completed similar in situ testing of mesh sheets over vertical raisebore openings. Testing comprised a series of vertical drops of a projectile with known mass onto the installed mesh sheets. Test conditions replicated real world underground conditions exactly with the use of production raisebore sites and mesh installation (Figure 14). Each study tested either woven mesh or weldmesh configurations and results were directly applicable to operational loading conditions.

However, test results are limited to performance observations only and do not give absolute values of energy or displacement due to no measurement apparatus installed.

Figure 14 In situ testing of Geobrugg MINAX G65/4 mesh over a raisebore hole (Doran et al. 2023)

In situ test results at this stage do not meet the instrumentation requirements required to generate results comparable to lab testing. It is important to recognise that in situ testing is vital when investigating the impact of ground conditions and quality of installation on the performance of surface support.

3.2.3 Simulated rockburst testing

Several blast tests have been conducted in South Africa and Australia to replicate rockbursts. However, at this stage, these tests have had a limited impact on the choice of ground support systems apart from comparative studies.

Simulated rockburst testing via underground blasting behind installed support was conducted in the early 1960s to understand the impact of rockbursting on the excavation support. There are several studies and published papers on this topic (see Ortlepp 1969; Tannant et al. 1994; Hagan et al. 2001; Haile & Le Bron 2001; Hildyard & Milev 2001a, 2001b; Milev et al. 2001; Reddy & Spottiswoode 2001). For Australia, the most well-known study is from the work done at the Australian Centre for Geomechanics (ACG) and is predominantly described by Heal et al. (2005, 2006).

The papers are focused on peak particle velocity (PPV) and damage to both the rock mass and the ground support. Typical results are given in 2D plots (Figure 15), but comparison plots of PPV, energy demand (based on PPV) and damage scales are also common.

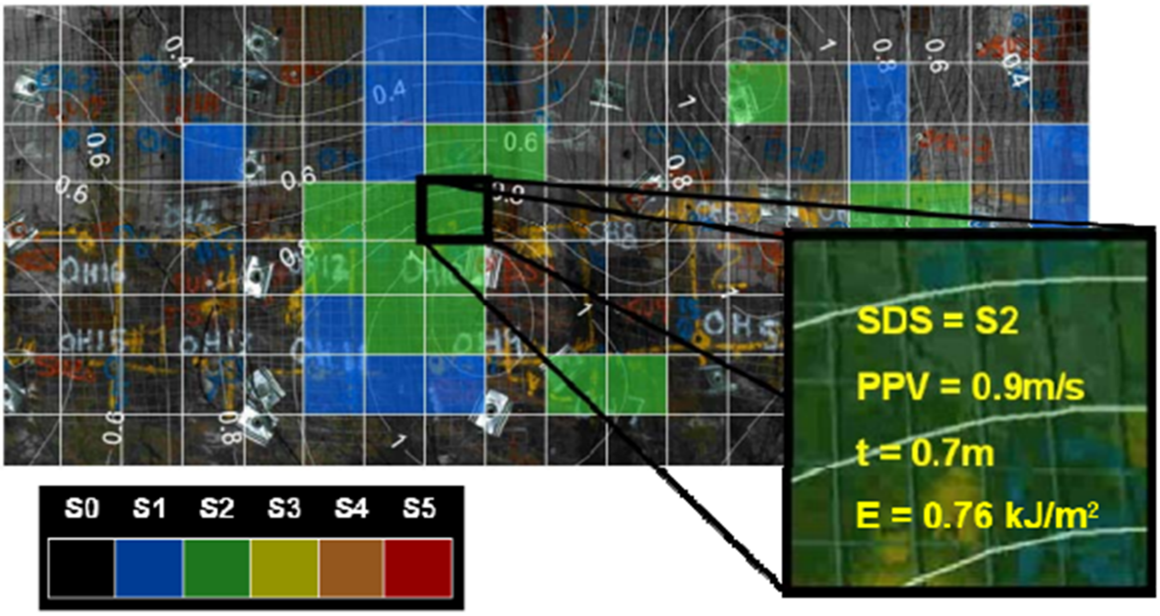


Figure 15 An example plot of PPV contours and damage scale after a simulated rockburst (Heal et al. 2005)

These tests are very expensive and therefore, published data is limited. The cost is predominantly related to the time and cost of developing or providing a drive for doing the tests. It is recognised that these types of tests are, from a mechanism perspective, most likely to be comparable to the mechanism of rockbursting. There are, however, some questions regarding the blasting configuration; specifically, regarding the proximity of the blast to the test panel and the choice of the percussion and gas components used to break up the rock. Also, the tests are not repeatable.

The instrumentation for these tests should be improved since the data collected here cannot be correlated to existing lab testing setups. Simple details such as bolt capacity, load versus deformation plots of the bolt performance, and mesh displacement curves are not recorded. The cost of implementing these additions with current technology is small compared to the cost of developing the sacrificial drive.

Further to this, the focus on PPV parameters is also not ideal as current understanding of rockbursting is leaning towards a deformation driven process, and PPV does not capture this.

4 Underground observations

Underground observations and investigations of failures play a critical role in providing confidence in the results produced by testing. If testing can produce similar failure mechanisms and surface support behaviour to what is seen underground, practitioners will have more confidence in the testing results. There are, however, limited papers on the topic. Many of the failures seen by us are not reproduced during testing. In this section, we discuss some typical mesh failures we have seen during our investigations. Differences between the observed and lab failure mechanisms will help provide context for the changes required in our testing facilities and methods.

The examples presented below must be considered knowing that historically, welded wire mesh was the dominant surface support used in mines. It is only in recent times (~3–5 years) that chain link mesh has become more widely used in Australia, but there are instances of this mesh being introduced from as early as 2015 in the Kalgoorlie area.

4.1 Mesh tearing at the bolt–mesh interface

Mesh tearing at the bolt–mesh interface is seen in many underground failures, both small and large (Figure 16). This type of failure is identified by the broken strands on the sides of the mesh, specifically where a bolt was installed. We have commonly seen these failures occur with welded mesh. Welded mesh with reinforced strands on the edges tends to not fail in this manner. At this stage, we have witnessed at least one such failure with chain link mesh.

Figure 16 Examples of mesh tearing at the bolt–mesh interface

4.2 Bolt pushing/punching through mesh

Bolt punching refers to ground support system failure, where the bolt pushes or pulls through the mesh. In Figure 17, two examples are shown. The first example shows the bolt pulled/punched into the mesh (with fibrecrete) and the second example shows the bolt pulled through the mesh.

We have seen some examples of this with welded mesh, but it is uncommon because the mesh tears first. The number of examples where this mechanism is observed for chain link mesh is endless. The reason for this is that chain link is a softer surface support (compared to welded mesh) and therefore deforms much more easily around the bolt and plate, rather than pulling off the plate. The concern here is that the load transfer from the chain link mesh to the bolts is limited because of the stiffness difference between the bolts and the mesh. A similar result was seen for the Geobrugg dynamic testing of a soft system (see Bucher et al. 2013).

We should investigate if the strongest part of the ground support system (rockbolts/cables) is too stiff compared to the mesh, which leads to a large majority of the energy being absorbed by the surface support. This concern is not a new one, since deep South African mines historically used chain link mesh in their development drives but installed lacing through the rockbolts across the mesh to stiffen up the surface support and allow for more effective load transfer onto the rockbolts.

It might be possible to improve the load transfer between the mesh and the bolt by considering the improvement a plate can have on the load transfer.

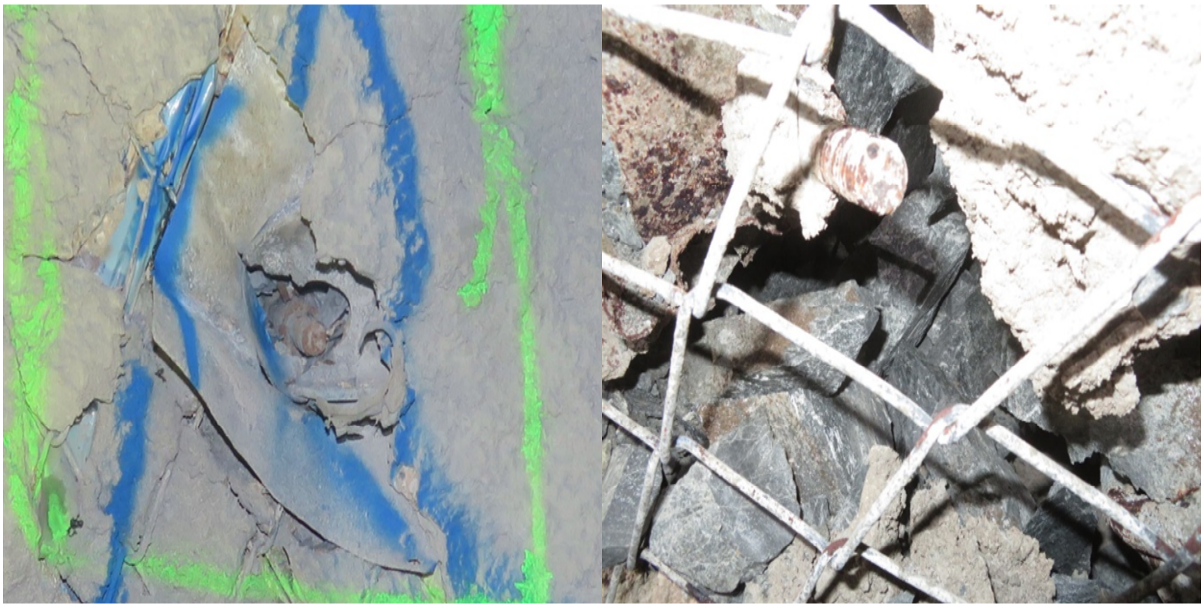


Figure 17 Examples of bolt punching into or through the mesh

4.3 Failure on the overlap

Overlap failure (Figure 18) is probably the most common historical failure mechanism seen in Australian mines. We have only observed this type of failure for welded mesh; this failure is also associated with failure of the bolt–mesh interface as discussed earlier. This type of failure mechanism is associated with both small and large failures, as is clear from the examples in Figure 18.

The occurrence of this type of failure for chain link mesh is not typical but is known. It is unclear if this is because of the short historical time span available for these failures, or if the much stronger Tecco mesh tends to not fail at the bolt–mesh interface in this manner.

Figure 18 Examples of mesh overlap failure

4.4 Excessive mesh deformation

For this specific failure mechanism, the chain link mesh absorbed the energy of the rock mass deformation. However, the deformation is excessive and large areas with bagging are observed. Examples of such failure are shown in Figure 19.

In-depth investigation of this type of failure is challenging, as the work required to rehabilitate such an area damages the rockbolts, and observations regarding the performance of the bolts cannot be made. We have heard of examples where the failure depth is so deep that there are concerns about the embedment of the bolts. It is unclear if dynamic failure leading to such large volume changes will lead to unravelling around rockbolts. We have, however, observed that many bolts in these areas of excessive deformation have either punched/pulled through the mesh or sit on the surface of the damage (both examples in Figure 19). This would likely indicate that the bolt has not performed well. This is in contrast with cables (installed at deeper depths) where a clear indent is seen in the mesh bulking. The green arrows in Figure 19 show two lines of cables and their impact on the mesh bulking.

Usually, the bolts cannot be investigated since the risk posed by bagging does not allow for access to the area. Removal of the ground support in the damage area is difficult with operational risks. There is also a risk associated with this type of rehabilitation (because of the fracture depth and strength of the mesh). This is not usually the case for welded mesh.

Figure 19 Examples of excessive deformation and bagging

4.5 Mesh strand failure

Mesh strand failure refers to failure of the mesh strands in the inner areas of the mesh. Figure 20 shows examples of mesh strand failure. This is predominantly seen for the stiffer welded mesh. This mesh breaks when it gets excessively bent, which can occur when the rock mass shears and the mesh is folded (Figure 20 top right and bottom left). There are also instances where the mesh breaks because of shearing or because of failure on a weak welding point (Figure 20 top left).

Failure like this for chain link mesh has not been observed. It is unclear if this is because of the short time span available for these failures (since chain link mesh integration is relatively new), or if the much stronger Tecco mesh tends to not fail in this way.

17/03/2022

Figure 20 Examples of mesh wire/strand failure

4.6 Localised bulking

Localised bulking refers to bulking in the mesh zone between bolts. This is typically seen for welded mesh, as is clear from the examples in Figure 21, where localised bulking can exceed 0.5 m. However, there are examples of chain link mesh performing similarly. These types of failure are probably nearest to what most test facilities are able to reproduce.

Figure 21 Examples of localised mesh bulking/nesting

5 Discussion

Surface support, specifically mesh, is a vital component in any ground support system. There are challenges with the design of ground support systems because of the uncertainties and complexities associated with rock mass failure, specifically when it is dynamic. It is accepted that the surface support is often the weakest component for most ground support systems and therefore, it is the most vital component to test and have an understanding of its limitations.

Quasi-static usefulness. Our systematic review of both quasi-static and dynamic testing facility methods gives practitioners an overview of the current practices of testing. The primary concern here is the dynamic performance of surface support, but many of the outcomes from quasi-static facilities translate well to the dynamic realm. Quasi-static facility results are, however, easier to understand and to replicate between facilities because of the relative ease of setup and instrumentation. Some of the properties related to mesh performance in quasi-static conditions transfer to the dynamic domain (e.g. directionality of mesh deformation).

Simulated rockburst disconnect. There is a large disconnect between simulated rockburst experiments and lab testing. The parameters recorded in the simulated rockbursting do not transfer to lab testing and vice versa. Since lab testing cannot reproduce the damage or PPVs, the onus is on leaders conducting simulated blast testing to install instruments which can produce similar charts to what is currently generated in lab testing. This will allow an improved understanding of the failure mechanisms, especially considering that simulated rockburst testing is the only method likely to produce a deformation driven failure process.

Differences across facilities. There is concern regarding the inconsistencies between the results of different facilities. Consistency in results ensures confidence in using test results from different facilities in the same designs. As a parallel example for bolt dynamic tests, Li et al. (2021) discussed the difference in results between four rockbolt dynamic testing facilities. Some practitioners are not comfortable with a difference in results of even less than 10% among the plastic energy values of those four rockbolt testing facilities, arguing that the test facility design configuration does have significant impact on results. For surface support, these differences are likely much higher, and results are presented in a format which makes comparisons challenging or impossible. There is a genuine need for collaboration under a recognised committee to standardise testing and specify adjustments to testing methods as new knowledge and insight is gained.

Testing overlaps. We also recognise that all testing facilities test what are considered best-case scenarios: deformation applied to the middle of the mesh sheet. Observations from underground failures suggest that failure on overlaps is the most common uncontrolled point of failure and therefore, testing should prioritise loading applied on overlaps.

Energy calculation. We have also noticed that the calculation of energy terms is inconsistent across facilities. It can be unclear how the energy is determined; sometimes the energy is the input energy (the kinetic energy from the drop mass) and in other cases the energy is calculated from load–displacement (at the load point) plots. When energy is calculated based on load–displacement curves, it seems these calculations are done similarly to rockbolt plastic/absorbed energy calculations. This is flawed. Rockbolt testing is conducted along an axis and therefore is a one-dimensional problem. A simple integration of the load–deformation curve will yield realistic energy results. For mesh however, this is not the case. In its simplest form, mesh performance calculation is a two-dimensional problem, and a double integration is required. In simplistic terms, a load–deformation integration must be done across a grid of points on the mesh and added together. This value should then be normalised to a unit area of 1 m^2. Using the maximum displacement is vastly overestimating the energy absorption capacity of the mesh.

Boundary conditions. Using fixed boundary restraint conditions results in performance curves that do not replicate in situ conditions, so cannot be used directly for in situ ground support design in mines. These types of results (WASM and CSM) should rather be used as input parameters for numerical models designed to determine expected ground system performance. Of specific concern is the WASM setup, where all sides of the mesh are rigidly connected to the frame, and limited load measurements are taken on these connections. Our review found that results are strongly dependent on boundary conditions. This rigid test setup leads to results which cannot easily be translated by practitioners to in situ conditions.

A good example of this would be the easily identifiable directionality of the chain link mesh deformability seen in the CSM results (Figure 6d), which either was not identified by WASM personnel, or if this was done, the complexities of removing the boundary effect made it difficult to communicate to the industry. A simple, practical application of the impact of mesh directionality is that practitioners should ensure the stiffer side of their mesh is located on the mesh overlaps.

We suggest that all test facilities which aim to create results for practical ground support system designs should use a bolt pattern and configuration similar to what is done at NIOSH. We would like to see more research to quantify the complexities of mesh boundary conditions and give clear guidance to industry practitioners.

New facility design. The size or configuration of new testing facilities should be selected to enable reproduction of the failure mechanisms seen underground. The current test sizes cannot produce the excessive deformation observed for chain link mesh, or even weldmesh in some instances. The complex interaction between bolt–mesh interfaces is also unlikely to be effectively reproduced in small frames. Bigger frames would also allow for testing of different bolt patterns, and knowledge can be gained on the impact of patterns on the ground support system performance.

Drop test onto central bolt. The practice of the drop mass falling onto a central bolt should be discontinued. Figure 22a illustrates the mesh bulking seen when dynamic failure occurs underground, versus the mesh profile produced in the dynamic laboratories (Figure 22b). This setup does not produce useful insight/guidance for ground support system performance. It achieves the opposite and hides viable concerns regarding the ability of the surface support to transfer loads effectively to the rockbolts. For example, it cannot reproduce the situation of mesh tearing off the plate.

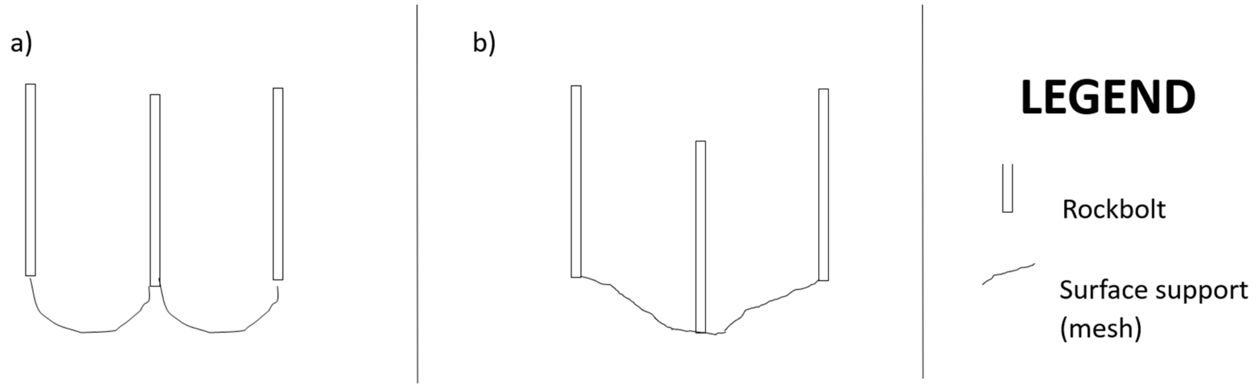


Figure 22 (a) Typical mesh bulking seen with underground dynamic failure; (b) The mesh profile produced by testing facilities where the mass is dropped on a central bolt

Distributed loading. Using 'point load' testing setups should be reconsidered. We recognise that this will be challenging, but the test setup from Stacey & Ortlepp (2001) is likely to produce results closer to reality, specifically when considering the growing support for a deformation-based model for strainburst. Some thought will have to be given to how to measure deformation and load across the surface of the mesh; new technology and improvements to old technologies (photogrammetry and LiDAR) are likely to be useful here.

Strain along mesh surface. We suggest that testing results should also be given in terms of strain along the mesh surface, as this would allow practitioners to take into consideration the tightness of their bolt pattern. Wider bolt spacings will lead to softer mesh responses, while tight spacing will stiffen up the mesh response. It is important to assist practitioners to conceptually understand this to avoid use of mesh performance curves similar to how rockbolt curves are used.

Excessive deformation concern. There are significant concerns regarding the excessive in situ deformation and excessive volumes of fractured bulked rock seen for systems employing chain link mesh. We cannot confirm that bolts are working at the desired capacity (i.e. with maximum anchorage strength) when such a large volume of rock is fractured. We urge numerical modellers to spend time on this problem in order to develop surety on the matter. We suggest for now that practitioners limit or cap their energy capacity calculations to a point at which a certain tolerable mesh bulking deformation is reached.

6 Conclusion and recommendations

Current testing of surface support is not adequate for the needs of the industry. We suggest the industry make the following changes as a matter of urgency:

1. Leaders involved with simulated rockburst experiments should push to install instruments which would allow for producing similar plots to what is done in lab testing.
2. Currently, mesh testing results are not comparable across facilities, and literature reviews indicate that there are sizeable differences in results between facilities. There is a genuine need for collaboration under a recognised committee to standardise testing and deploy adjustments to testing methods as new knowledge and insight is gained.
3. Ensure that testing is done on mesh overlaps, since this is the weakest link for surface support.
4. Ensure that boundary conditions are based on rockbolt patterns, and that stiff fixed boundary constraints are removed.
5. The size of testing facilities should be increased to enable reproduction of the failure mechanisms seen underground.
6. The configuration of the drop mass falling onto a central bolt in a mesh pattern should be discontinued.

7. Current testing is dominantly reliant on transferring the load onto a relatively small area of the mesh. Research should be conducted to transfer the load more uniformly across the surface of the mesh.
8. Facilities should ensure that mesh test results are plotted against strain in the plane of the mesh (as well as displacement). This ensures that results can be interpreted to suit any rockbolt pattern.

Other concerns are:

1. The calculation of the energy absorbed by mesh based on the load (usually a 'point load') and displacement (maximum displacement perpendicular to the mesh sheet) is incorrect. A double integral across the mesh surface is required. Current methods are greatly overestimating the energy absorbed.
2. We suggest current practitioners limit or cap the energy capacity calculations to a level at which an acceptable deformation value is reached.
3. We cannot confirm that bolts are working at the desired capacity when a large volume of rock is fractured. We urge numerical modellers to spend time on this problem in order to develop surety on the matter.

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