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In situ quasi-static capacity testing and failure behaviour of weldmesh and chainlink mesh under field boundary conditions at a hard rock mine in Western Australia

Peter Mikula [a,*], Simon Bruce [b], Ganesh Sasi [b], Tharindu Dissanayake [b], William Power [b], Farhan Hafeez [b]

[a] *Mikula Geotechnics, Australia*

[b] *Evolution, Australia*

Abstract

In situ quasi-static testing was conducted at an underground mine to measure performance of weldmesh and chainlink mesh installed in typical configurations used in Australian hard rock mining. The motive for the testing was to compare mesh (or screen) products for use in seismic environments, providing engineers with mesh performance data relevant to actual field boundary conditions. A series of 22 in situ tests were conducted to determine the capacity and failure behaviour of the meshes. Laboratory testing indicates a wide range of energy capacities depending on the test method and configuration, making it difficult to confidently appraise a mesh based on laboratory data alone. The field test used a hydraulic ram to tug the mesh away from the rock surface. Test configurations included baseline mesh sheets or rolls bolted on a 1.1 × 1.4 m pattern, with variations comprising deliberately cut wires, loading at centre of sheet or at mesh overlap positions, and with fibrecrete overspray of boundaries to emulate laboratory locked-perimeter test configurations. Results showed stiffness, displacement capacity, reaction pressure and rupture vulnerability were sensitive to mesh type, test configuration and boundary conditions. Weldmesh energy capacity in most configurations was higher than for chainlink mesh to the limit of the test equipment. Beyond about 0.6 m displacement, chainlink mesh energy capacity in some configurations equalled that of weldmesh, and with further displacement it likely would be superior to weldmesh, but that was not able to be assessed in these tests. Chainlink mesh was observed to be substantially compromised by unravelling if a cut wire was present. Only one test configuration, with fibrecrete spray to lock the perimeters of the test panel, came close to the high load and energy capacities at small displacements reported in some locked-perimeter laboratory tests. Overall the testing provides guidance to assist engineers evaluate likely performance of mesh configurations in their mines.

Keywords: *weldmesh, chainlink mesh, in situ testing, energy capacity, surface support, seismicity, strainburst*

1 Introduction

Currently, different mesh alternatives are adopted in dynamic conditions across the industry. This can be taken to indicate that no alternative is universally recognised as superior, i.e. no existing mesh is ideal for seismic damage scenarios. Weldmesh (5.6 mm wires, 100 × 100 mm grid) and chainlink mesh (Geobrugg Minax 80/4.6), also called woven or roll mesh, are the 2 most common meshes adopted in Western Australian mines. The meshes have different benefits. Weldmesh, being stiffer than chainlink mesh, can locally contribute more containment pressure, which should assist in reducing rock mass bulking and the eventual final mesh displacement distance. Weldmesh carries high loads at lesser displacements than chainlink mesh, but with the result that it ruptures sooner. Chainlink mesh can locally accommodate larger displacements due to the greater flexibility of the mesh, which by design does not include weld points.

* Corresponding author. Email address: pm@MikulaGeotechnics.com.au

The scope of the testing was firstly to measure actual capacity performance and failure behaviour of weldmesh and chainlink mesh installed in typical configurations used in the Australian hard rock mining industry, and secondly to explore the effect of the different stiffness of the 2 mesh types. Chainlink meshes in some surface applications mitigate high energy rockfalls by providing very extensive deformation capacity to absorb the energy of a rockfall without rupturing the mesh. In underground mining seismicity, the situation is different. Seismic damage ejecta or bulking should preferably be brought to equilibrium in a short distance – 0.3 m and 0.4 m target distances are noted among practitioners (the greater the distance, the greater the risk of compromise via bolt rupture, the ground breaking away from under the bolt collar, and the depth of failure compromising the anchorage). A stiffer mesh should more strongly oppose the acceleration of rock being ejected and provide more containment pressure opposing bulking, but it also has greater risk of mesh rupture.

This data was necessary to provide guidance for engineers in selecting mesh capacity that is appropriate for the particular installation boundary conditions in their mines. Echoing the comments by Whiting (2017), this test work was intended to compliment, not dispute or replace, high-quality laboratory data. The different loading mechanisms and real-world geometries of the in situ test provide insight into in situ loading mechanics. The test method does not use geometrically perfect configurations, which adds complexity and non-uniformity to the results, but it is consistent with real-world installation and hence considered acceptable and relevant.

Site experience at this mine is that chainlink mesh contains very large seismic displacements (over 1 m) but appears to supply less restraint against those large displacements occurring. The mesh distorts and expands to accommodate the broken rock. Some mesh wires may still be loose after the damage, i.e. without load, indicating the mesh load transfer process is very variable. Chainlink mesh has greater capacity than weldmesh to change shape elastically (straighten out) where that will reduce forces in wires, so the forces in the wires increase more slowly with deformation compared to weldmesh. Chainlink mesh cells enjoy ease of stretch in one direction and shrinkage in the other direction, and prevention of this action would require the mesh to be quite densely pinned along all its boundaries. Villaescusa & Kusui (2018) stated that

> "*The biggest advantage of woven mesh is that it can locally accommodate large deformations compared with weld mesh … this is due to the greater flexibility of the mesh, which is not permanently fixed by a weld point."*

Static testing was undertaken to develop a database and compare with similar tests in other mines. While conducting dynamic tests would be preferable, that was considered highly challenging and not cost attractive. Steel wires in mesh in dynamic conditions are estimated to experience strain rates of about 0.1–1/sec. For that strain rate, the dynamic increase factor (DIF) (i.e. increase in strength of steel compared to the static condition) is estimated to be about 1.1 based on discussion in the literature (Manjoine 1944; John et al. 1996; Malvar & Crawford 1998; Galvez et al. 2011; Xing et al. 2021; Pytlik & Szot 2023). It is a certainty that quasi-static testing results will differ from dynamic results, but a DIF factor increase of about 10% does not appear so much as to invalidate static mesh testing. A review of relevant static versus dynamic data for the same meshes from Villaescusa et al. (2023) indicates that dynamic tests had some increases over static in all the conventional capacity metrics. This suggests that the results of the in situ static tests are likely conservative, and the meshes would perform somewhat better in dynamic conditions.

2 Previous testing for comparison

Weldmesh and chainlink mesh have been assigned different typical energy capacities by different research groups. Mesh testing is reported in the literature, and some test methods and results were reviewed by Morkel et al. (2023). The in situ data in this report is compared with the following 3 literature mesh quasi-static test catalogues.

1. Whiting (2017) conducted in situ static testing of installed weldmesh at the independence long nickel mine, showing that weldmesh reached peak loads up to 60 kN at displacements that can be greater than 400 mm, with energy capacity 2.8–12.5 kJ for the nominal 1.1 × 1.3 m bolt spacing test

panel. The loading response for all configurations was sensitive to factors including location of installation in the drive profile, bolt spacing, and interaction and overlap with other sheets.

2. Benton et al. (2022) describe National Institute for Occupational Safety and Health (NIOSH), USA, work. The test method employs a hydraulic press to produce a quasi-static force on a mesh sheet secured with 4 bolts on a 1.2 × 1.8 m bolt pattern. Six different surface support meshes were compared. The meshes tested were weaker than those used in Australia. The findings included for weldmesh, 8–11 kJ at 510–520 mm displacement, and for chainlink mesh, 13 kJ energy dissipation at 520 mm displacement.
3. Villaescusa et al. (2023) reported comprehensively on Western Australian School of Mines (WASM) static and dynamic mesh testing, considering a few mesh variants and boundary configurations. The static test data included the same products as used in the in situ tests reported in this paper.

The WASM test configuration differed from the methods used by some other industry researchers. The approximate 1.3 × 1.3 m test panel size was selected as the largest able to be fitted in the dynamic test machine, and later a static mesh test rig was built to test the same size panels. Morton et al. (2007) explain that after exploring some boundary options, WASM adopted a shackled system (every perimeter cell locked to the frame using D-shackles) to provide a hard or locked-perimeter boundary. In this configuration, the mesh under load had some initial displacement and then became very stiff. This provided the desired high consistency and reproducibility of static and dynamic test results, facilitating comparisons of performance for different mesh types. Villaescusa et al. (2023, Section 9.3.1) discuss this aspect, noting that their chosen hard perimeter consistently achieved “a boundary condition that simulates the continuation of the material beyond a limited sample area.” However, this is difficult to accept as it seems instead to simulate the continuation of an extremely high stiffness material beyond the sample area. This boundary condition differed from typical in situ practice, where mesh is restrained only by bolts, and as shown in this paper, the locked-perimeter configuration disproportionately enhances the performance of a less-stiff (chainlink) mesh type over a stiff (welded) type.

3 Test methodology

For the testing reported in this paper, the mine was able to secure the exact same ‘Meshmaster 1000’ hydraulic ram equipment that was used by Whiting (2017), and used the same procedures, making these results directly comparable to those reported by Whiting (2017). Test equipment details are available in Whiting (2017). The test method comprised positioning a pulling plate under the mesh at the time of mesh installation, and then using a hydraulic ram pushing against the rock surface to tug the plate away from the rock surface. Approximate quasi-static rates were displacement 1 mm/s, and load 0.1 kN/s. The system used a pulling plate (comprising a 150 × 150 × 6 mm bearing plate welded to a 300 × 280 × 1 mm backing plate) to apply an approximate point load to the mesh.

Most tests included 2 or 3 hysteresis loops, i.e. slightly different unloading and reloading cycles, whenever the ram was released so that longer displacement extension pieces could be fitted.

Force (load) was computed from the ram pressure gauge with appropriate conversion. Indicative containment pressure was the ram force normalised to the 1.54 m^2 area of the mesh sample.

Displacement was defined as the movement of the mesh surface in the direction perpendicular to the rock surface. Displacement is properly a distribution of values across the mesh surface, but in these tests only the peak displacement was measured. Displacement was measured using a tape measure stretched across the drive, attached at one end to the mesh at the loading plate, and configured to measure the reducing distance from the loading plate to the other side of the drive as the test progressed.

Energy input was computed as the area under the ram load–displacement curve, corrected to remove hysteresis while changing hydraulic ram extension pieces, and is considered equivalent to the dissipated energy for the static test.

This in situ testing was subject to a number of test limitations:

- Test equipment load limit was 100 kN and displacement limit 0.7 m. Only some tests resulted in mesh yield, while other tests of both meshes reached 0.7 m displacement without mesh failure.
- The system applied an approximate point load to the mesh, which differs from the more distributed force of a strainburst. However, the pulling plate was identical to those typically used in WA mines to secure mesh at every bolt collar, and the plate perimeter folded during the test, allowing the mesh to load against the plate very realistically.
- Applied force was often but not always directed close to perpendicular to the rock surface. In some cases, the push rod crept along the surface as load increased.
- In one case, the rock surface under the tip of the push rod cracked and failed under the load, leading to premature test termination.
- For the chainlink mesh fibrecrete boundary configurations, the limited patch dimensions proved to be a weakness, unable to provide the full desired boundary fixity for these tests. In hindsight, it would have been preferable to test using the regular roll-form chainlink mesh.
- Four tests were discarded due to equipment or configuration malfunction issues. The final test catalogue was small (22 valid tests) and results quite variable, so data is not considered to be statistically representative.

4 Test configurations

A total of 26 tests were conducted; however, 4 were discarded due to equipment or configuration malfunction issues, leaving 10 weldmesh and 12 chainlink mesh usable tests.

The test configurations (listed in Table 1 and shown in Figures 1 and 2) included:

- ‘Centre’: in this baseline configuration, the pulling plate was positioned near the centroid of 4 bolts. Due to limited sheet dimensions, one sheet edge always was about 1 m distant from the pulling plate. This was tested for 6 weldmesh and 5 chainlink mesh cases.
- ‘Bolted overlap’: pulling plate located midway between 2 bolts along an overlapped mesh edge. The only practicable position for the pulling plate was through both mesh sheets, i.e. the pulling plate locked the sheets, preventing lateral separation. Bolt spacing along the overlap was about 1.1 m.
- ‘Centre’ combined with a deliberately cut wire.
- ‘Centre’ with fibrecrete overspray on one perimeter side.
- ‘Centre’ with fibrecrete overspray on all 4 sides. The intent was to emulate WASM laboratory static tests with all 4 mesh edges locked. For a similar in situ test, a very stiff boundary fixing of the mesh had to be provided, and after some consideration, fibrecrete spray was adopted as the means of providing that locked boundary. Logistically the adopted procedure was to install the mesh with the pulling plate in position, attach a piece of vent bag to cover the section defined by the 4 bolts, fibrecrete spray around the section (Figure 2), and cut away the vent bag to access the loading point. In practice, spray covered some of the vent bag over the test panel leaving about a 1 × 1 m opening, but the mesh under the vent bag was still free to move.

Mesh mechanical data:

- Weldmesh: 5.6 mm diameter wires on 100 mm apertures. Sheet size 4.5 × 2.4 m. Minimum wire tensile breaking strength 9.4 kN and weld shear strength 8.0 kN.
- Chainlink mesh roll: Minax G80/4.6, 4.2 × 15.5 m, 4.6 mm strand, tensile breaking strength 29.4 kN.

- Chainlink ‘mesh patch’ panel: a 1.8 × 1.8 m section of Minax G80/4.6 supported on a 2 × 2 m light-weight weldmesh frame with 200 mm aperture cells (Figure 2), used for the CF-2 and CF-4 chainlink mesh tests resulting in 0.3 m wide fibrecrete perimeters. Unfortunately, the limited patch dimensions proved to be a weakness of these test configurations, unable to provide the full desired fixity for these 2 tests. In hindsight it would have been preferable to test using the regular roll-form chainlink mesh.
- Mesh was installed with the typical 1.4 × 1.1 m bolt pattern used in this mine.

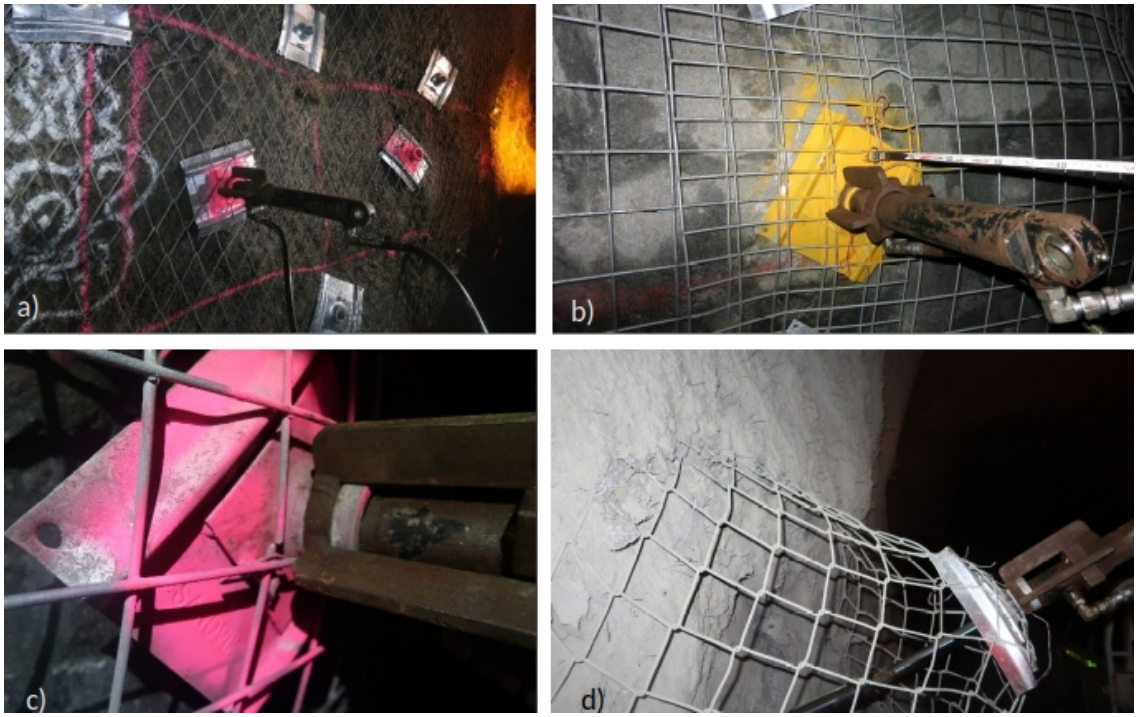


Figure 1 Test configurations. (a) Centre: weldmesh and chainlink mesh; (b) Bolted overlap (W6); (c) Cut wire (W9); (d) Fibrecrete one-edge (C1)

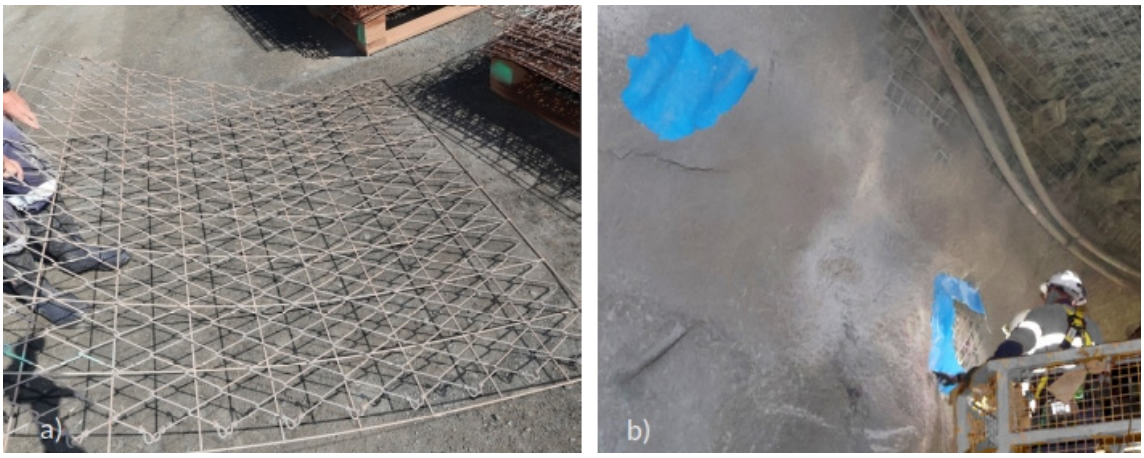


Figure 2 (a) The ‘mesh patch’ panel; (b) Test with fibrecrete on all edges of the blue ventilation bag. The bag then cut away to access the pulling plates. In this photo, CF-3 is on the left and CF-4 is on the right

Table 1 In situ mesh test configurations

ID	Configuration	Angle of ram force (°)	Test limitations	Failure mode
Weldmesh				
W1	Centre baseline	90	Terminated early	Wire snap at weld near puller
W2	Centre baseline	No data	Max ram extension	None
W3	Centre baseline	No data	Hydraulic leak	None
W4	Centre baseline	80	None	5 mid-wire snap, 1 wire snap at weld, all adjacent to puller
W5	Centre baseline	80	Rock cracked, terminated	None
W10	Centre baseline	90	Equipment malfunction	None
W7	Bolted overlap	60	None	None
W8	Bolted overlap	75	None	3 wires snapped in each sheet adjacent puller, 6 wires total
W9	Centre, cut wire	90	Max ram extension	None
WF-3	Centre, 4 f/c edges	80	None	4 wires snapped adjacent puller
Chainlink mesh				
C2	Centre baseline	45	Max ram extension	One snapped wire at bottom edge of sheet at end test
C3	Centre baseline	90	Max ram extension	None
C4	Centre baseline	No data	Max ram extension	None
C9	Centre baseline	65	Max ram extension	None
C12	Centre baseline	82	None	Mesh tore apart at puller, 2 snapped wires unravelled
C1	Centre, one f/c edge	55	Max ram extension	None
C5	Centre, one f/c edge	80	None	Mesh tore apart at puller
C6	Centre, one f/c edge	83	Max ram extension	None
C7	Bolted overlap	No data	Max ram extension	None
C8	Centre, cut wire	90	None	Mesh tore apart at puller, cut wire unravelled, large hole
CF-2	Centre, 4 f/c edges	80	None	3 wires snapped in quick succession at puller
CF-4	Centre, 4 f/c edges	90	Ram load limit reached	None

Naming codes: W = weldmesh; C = chainlink mesh

5 Test results

Results identified significant configuration-dependent behaviour: capacities were found to be sensitive to boundary conditions. Engineers using this data for guidance are cautioned to review the mesh boundary conditions applicable to particular results, and review the test limitations noted earlier.

Results are summarised in Tables 2 and 3. Only some tests resulted in mesh yield while other tests of both meshes reached 0.7 m displacement without mesh failure. Some tests were terminated when maximum equipment load or displacement capability was reached, or if equipment malfunctioned. In such cases the capacities are indicated, e.g. 67+ kN, to indicate that a truncated peak was measured, and the actual peak value would be higher than that obtained. Load, displacement and energy capacities all are important descriptors of ground support performance, and all are included in the Tables.

Mesh deflection stiffness was defined as the force imposed in a direction normal to the mesh surface, divided by the resulting displacement of the mesh at the point where the force is applied. A modified secant stiffness was calculated from the 10 kN load point to the peak load, as a measure of average stiffness after the mesh is tight enough to interact with any rock mass failure.

Table 2 Weldmesh in situ test summary performance data (numbers with + suffix indicate truncated peak values)

ID	Load at 0.4 m displacement (kN)	Peak test load (kN)	Displacement at peak test load (m)	Energy input at 0.4 m displacement (kJ)	Energy input at peak test load (kJ)	Mesh deflection stiffness (kN/m)	Was ultimate capacity identified?
Weldmesh ‘centre’							
W1	n/a	36.6+	0.25+	n/a	4.6+	149	no
W2	40	48.7+	0.47+	6.1	8.9+	126	no
W3	47	47.4+	0.38+	6.9	6.9+	143	no
W4	35	60.9	0.61	4.5	16.1	132	yes
W5	40	54.2	0.53	6.1	12.1	122	yes
W10	62	65.0+	0.43+	9.2	11.0+	219	no
AVG	*45.0*	*52.1+*	*0.45+*	*6.6*	*9.9+*	*149*	
Weldmesh ‘bolted overlap’							
W7	45	49.4	0.33	11.7	10.8	233	yes
W8	n/a	43.3	0.14	n/a	4.6	268	yes
AVG	*45*	*46.4*	*0.28*	*11.7*	*7.7*	*251*	
Weldmesh ‘centre, cut wire’							
W9	30	66.7+	0.49+	7.5	11.2+	136	no
Weldmesh ‘centre, fibrecrete 4 edges’							
WF-3	n/a	54.2	0.14	n/a	4.0	406	yes

Table 3 Chainlink mesh in situ test summary performance data (numbers with + suffix indicate truncated peak values)

ID	Load at 0.4 m displacement (kN)	Peak test load (kN)	Displacement at peak test load (m)	Energy input at 0.4 m displacement (kJ)	Energy input at peak test load (kJ)	Mesh deflection stiffness (kN/m)	Was ultimate capacity identified?
Chainlink mesh 'centre'							
C2	16	22.3+	0.53+	3.6	5.8+	36	no
C3	18	45.4+	0.67+	2.1	11.1+	100	no
C4	19	45.4+	0.70+	2.7	12.4+	98	no
C9	35	50.8+	0.54+	5.0	10.9+	118	no
C12	27	40.6	0.49	4.2	7.1	118	yes
AVG	*23.0*	*40.9+*	*0.59+*	*3.5*	*9.5+*	*94*	
Chainlink mesh 'centre, fibrecrete one-edge'							
C1	14	33.2+	0.61+	1.5	6.2+	89	no
C5	n/a	41.0	0.35	n/a	6.7	137	yes
C6	21	69.7+	0.59+	2.8	11.3+	211	no
AVG	*17.5*	*47.9+*	*0.52+*	*2.2*	*8.1+*	*146*	
Chainlink mesh 'bolted overlap'							
C7	31	66.3+	0.46+	5.6	8.1+	194	no
Chainlink mesh 'centre, cut wire'							
C8	15	33.0+	0.57+	2.1	6.0+	99	yes
Chainlink mesh 'centre, fibrecrete 4 edges'							
CF-2	n/a	29.0	0.30	n/a	2.5	199	yes
CF-4	n/a	94.8+	0.26+	n/a	7.2+	564	no
AVG	*n/a*	*62.9+*	*0.28+*	*n/a*	*4.9+*	*382*	

5.1 Baseline 'centre' configuration performance

Baseline centre configuration test results are shown in Figures 3 and 4, and indicated:

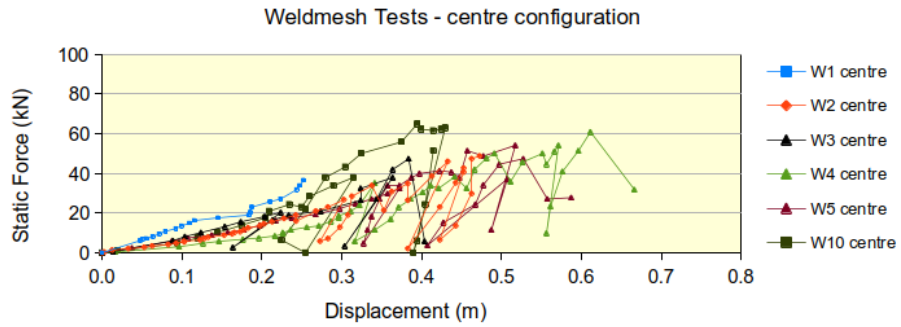
- Weldmesh average working capacities were load 52+ kN and displacement 0.45+ m.
- Chainlink mesh average working capacities were load 41+ kN and displacement 0.59+ m, i.e. chainlink mesh needed substantially more displacement than weldmesh to achieve its load capacity.

Baseline centre energy dissipation capacities were calculated for 2 displacements:

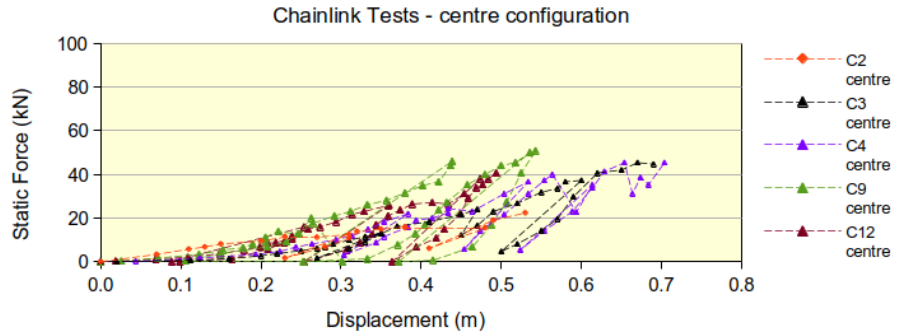
- At 0.4 m displacement (a target limit adopted by many practitioners):
  - weldmesh 'centre': 6.6 kJ
  - chainlink mesh 'centre': 3.5 kJ.
- At end of test displacement (i.e. at typically 0.45+ m weldmesh and 0.59+ m chainlink mesh):

- weldmesh ‘centre’: 9.9+ kJ
- chainlink mesh ‘centre’: 9.5+ kJ.

Weldmesh energy capacity was higher than that for chainlink mesh, to the limit of the test equipment. Chainlink mesh capacity would likely exceed that of weldmesh at higher displacements, because since energy is the integrated product of force times displacement, high displacement will boost energy capacity numbers.



(a)



(b)

Figure 3 Baseline centre configuration test results. Force versus displacement for (a) 6 weldmesh and (b) 5 chainlink mesh tests

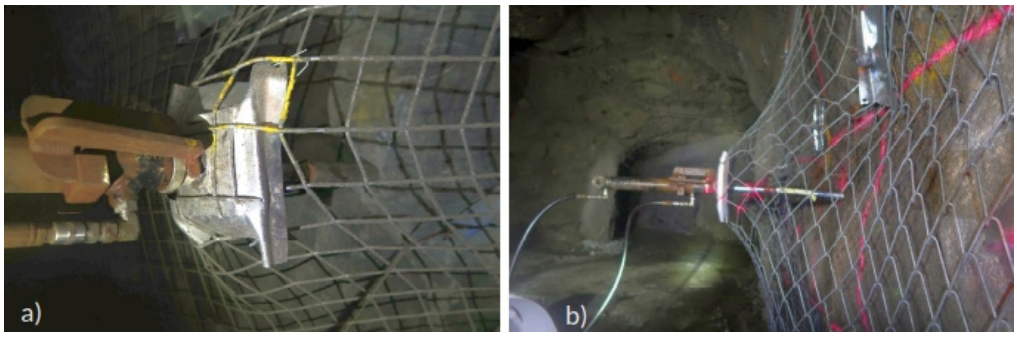


Figure 4 Baseline centre configuration. (a) W4 ruptured wires end of test; (b) C3 in progress

5.2 Bolted overlap performance

Overlap testing appears not widely reported in the literature, other than by Whiting (2017), which is perhaps surprising since overlaps are always present in situ. The test program achieved 3 successful overlap tests (Figures 5 and 6) with these results compared to respective baselines:

- weldmesh: peak load 9% less, displacement 38% less, energy dissipation 32% less
- chainlink mesh: peak load 62% more, displacement 10% less, energy dissipation 9% less.

The bolted overlap was pinned against opening by the testing configuration and was not typical of field conditions. At overlaps the proximity to bolts caused the mesh to strain more per unit displacement, and also to tighten asymmetrically, resulting in increasing misalignment of the pulling plate as the tests proceeded. The stretch of chainlink mesh was sufficient to survive this problem, however both weldmesh tests resulted in rupture of wires when strain capacity was exhausted.

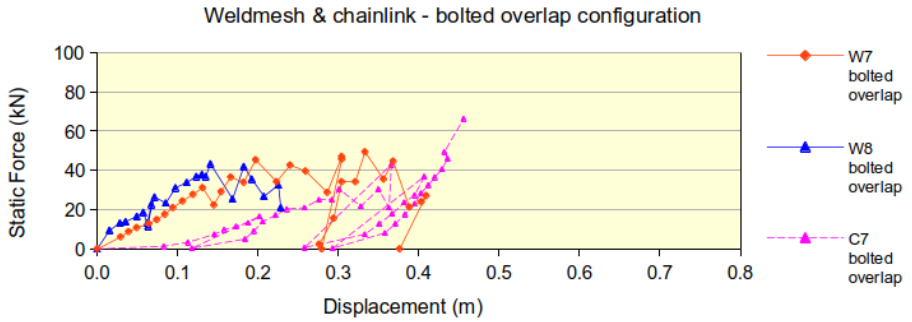


Figure 5 Bolted overlap configuration test results. Force versus displacement for tests as indicated

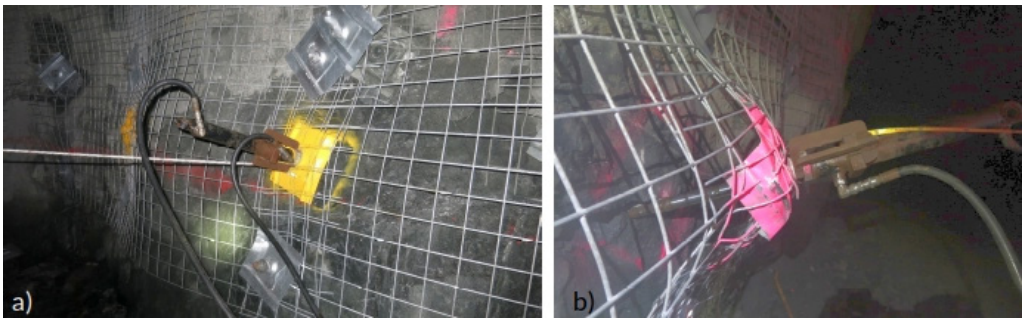


Figure 6 Bolted overlap configuration. (a) W7 (setup test start); (b) W8 (snapped wires test end)

5.3 Cut wire performance

Mesh results for cut wire performance are shown in Figure 7. In the relevant tests, one wire adjacent to the puller plate was cut before the test (Figure 8), with these results compared to respective baselines:

- weldmesh: peak load 28% more, displacement 9% more, energy dissipation 13% more
- chainlink mesh: peak load 17% less, displacement 3% less, energy dissipation 37% less.

For weldmesh, the cut wire did not reduce peak load. In fact, the W9 test achieved 67 kN, the highest of any weldmesh test. The stiff welded construction meant that cut wire load was efficiently transferred to adjacent wires. By contrast, for chainlink mesh, the C8 cut wire unravelled under increasing strain and significantly compromised performance, with peak load 33 kN.

It was noted that for chainlink mesh, high strain in the plane of the mesh caused loaded wires to elastically distort and straighten out in the principal load direction. Wires adjacent to the cut wire underwent this distortion in preference to accepting load. The broken wire, being unstrained, was seen to gradually twist and unwind node by node while strain in adjacent wires increased. The low-stiffness mesh distorts much more than weldmesh, which facilitates the cut wire to unravel. This shows that the mesh design primarily governs the load transfer performance, while the strand or weld strength governs the point of rupture. This result differs from that reported in the WASM locked boundary tests, where it appears that the cut wire load redistributes to directly adjacent wires which, being locked at their ends, take up the additional load without significant additional distortion, so the cut wire does not unravel.

It is acknowledged that many industry professionals may be surprised by the observations of unravelling chainlink mesh wires in the in situ tests, especially since in the laboratory tests with locked boundaries, such

unravelling does not occur. However, the laboratory outcome does not reflect the in situ result for chainlink mesh in the tested configurations, and observations in the mine also sometimes include the unravelling of chainlink mesh strands.

In underground operations, cut wires often occur through drilling, fly rock, and impact from mining equipment. Equipment-damaged mesh is usually not under high tension, so cut wires can be accommodated. However, if a seismic disturbance imposes high strain, the operational damage can be a liability for cut wires in both types of mesh – weldmesh tears and chainlink mesh unravels.

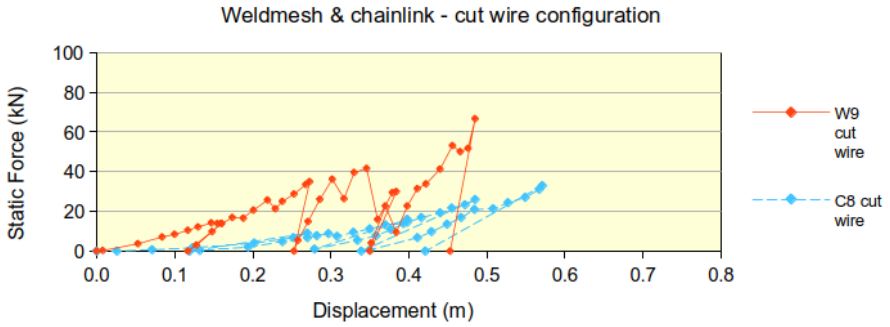


Figure 7 Cut wire configuration test results. Force versus displacement for one test of each mesh type



Figure 8 Centre configuration with cut wires. (a) W9 initial cut; (b) W9 end of test; (c) C8 initial cut; (d) C8 substantial wire unravelling at end of test. There were other cases of chainlink mesh wires snapping during testing: (e) C12 wire ruptured near the end of the test; and (f) C5 (fibrecrete one-edge) mesh wires snapped and tore apart near puller plate. Weldmesh wires in many tests ruptured at welds (not shown here) and at the puller plate (e.g. Figure 4, Figure 6)

5.4 Centre configuration performance with fibrecrete edges

Results for these configurations are shown in Figures 9 and 10. One weldmesh test was achieved for all 4 perimeters fibrecrete, with 5.4 kJ at 0.17 m displacement at which point 3 wires snapped and the test was terminated. The fibrecrete-locked-perimeter substantially downgraded this mesh performance: energy dissipation was 55% of baseline, and displacement at failure 31% of baseline.

Three chainlink mesh tests with one fibrecrete edge were conducted. Wires snapped and tore apart at the pulling plate in one test, while 2 tests continued to maximum ram displacement capacity. Results were like or exceeding average baseline chainlink mesh configuration.

Two chainlink mesh tests were conducted with fibrecrete proximity on all 4 perimeter edges. Results were:

- 2.7 kJ at 0.32 m displacement (wires snapped at the pulling plate)
- 7.2 kJ at 0.26 m displacement (reached maximum ram load capacity).

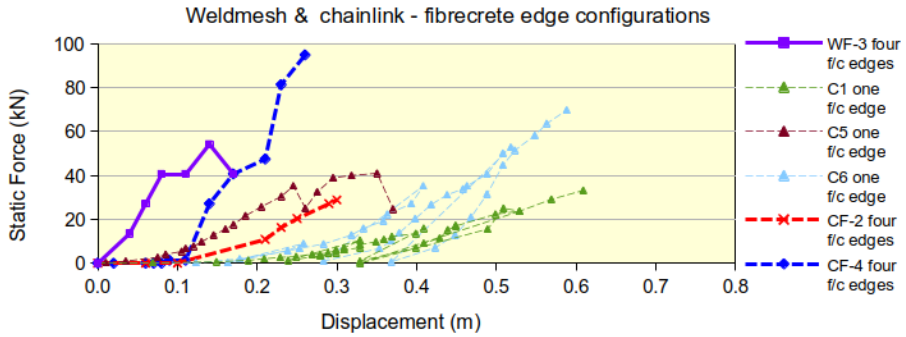


Figure 9 Centre configuration with fibrecrete edges: test results for one-edge or 4-edge configurations. Force versus displacement for one weldmesh and 5 chainlink mesh tests



Figure 10 Fibrecrete edge configurations. (a) C1 end of test with single fibrecrete edge at top of view; (b) WF-3 (all edges fibrecrete) showing wires ruptured at puller plate, not at welds; (c) CF-4 setup at start of test; (d) CF-4 at end of test

6 Comparison with published data

Figure 11 presents a comparison with published in situ data for the same or similar meshes. Data sources for the comparison were:

- Independence long nickel mine in situ static tests (Whiting 2017, Tables 1 and 2, same weldmesh).
- NIOSH static laboratory tests (Benton et al. 2022, Table 1: for 6-gauge [4.12 mm] weldmesh; 9-gauge [3.76 mm] 5 cm aperture fencing chainlink mesh, i.e. not high tensile; 1.8 x 1.8 m panels bolted at corners).
- WASM static laboratory tests (Villaescusa et al. 2023, Figure 9.26, same meshes).

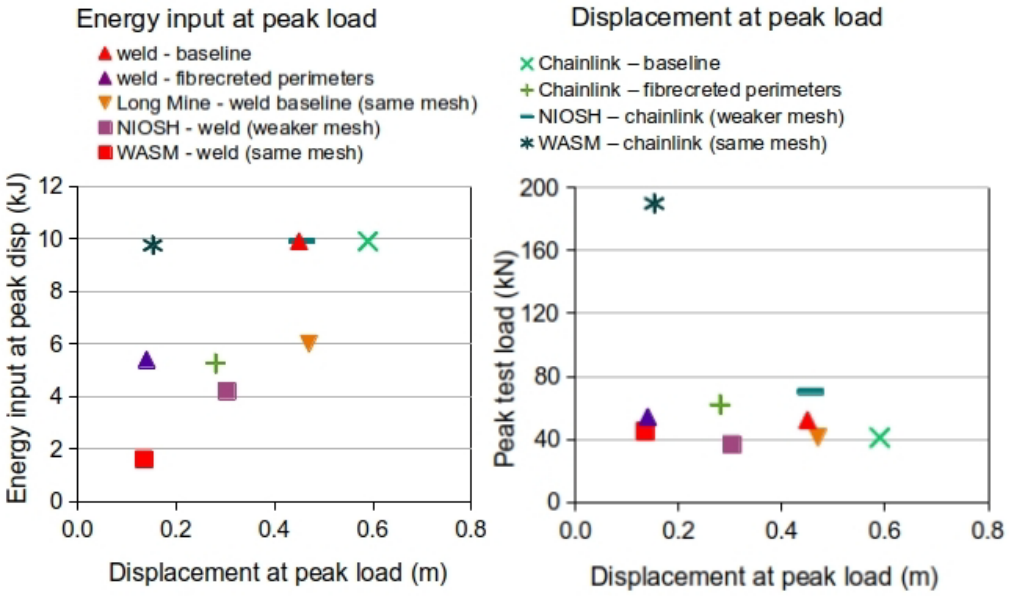


Figure 11 Comparison of average in situ data versus other published data

From Figure 11 it is seen that:

- The Long Nickel Mine in situ baseline tests overlapped those in this paper: similar loads, similar displacement at peak load, but lower energy.
- The NIOSH results comparatively underperform, as expected considering the mesh types were weaker (the NIOSH test configuration was between that of WASM and this mine, and the results came out in between also).
- The WASM weldmesh data overlapped the in situ weldmesh with fibrecrete perimeters for load and displacement, but returned less energy dissipated.
- The WASM chainlink mesh data was quite different to the other chainlink mesh tests, returning much higher load at much lower displacements.

Further comparison with WASM results is shown in Figures 12 and 13. All the in situ baseline tests experienced much larger displacements than WASM results for the same loads. This outcome was expected, and in agreement with Villaescusa et al. (2023, Section 11.4.4) in discussing test results for combined schemes (bolts and mesh) who observed that

> *"the damage to the mesh has been clearly affected by the boundary conditions, which include very tight mesh installation and very small loading areas. However, it is expected that a much larger displacement would be experienced by in situ ground support schemes."*

The single in situ weldmesh test (WF-3) with fibrecrete-locked perimeters performed like the configurations in WASM laboratory static mesh tests. The 2 in situ locked-perimeter chainlink mesh tests (CF-2, CF-4) had somewhat lesser displacement, positioning them a little closer to the WASM results for similar mesh. Unfortunately, the 'patch panel' limited dimensions permitted only 0.3 m wide fibrecrete perimeters, which in hindsight was unable to provide the full desired fixity.

The data shows that the less stiff the boundary condition, the more the displacement that occurs as the mesh responds to the load. Performance of mesh bolted at corners must differ from the WASM performance. It could be supposed that weldmesh, being stiff, would not be distorted much differently for all edges locked versus 4 corners pinned by bolts, but the test observations show that is not true. For chainlink mesh, the distortion is greater than for weldmesh. Edge locking results in quite different performance.

It is considered that the very tight mesh installation in WASM laboratory testing has led to their different mesh energy capacities, as well as mesh failures occurring at much smaller displacements compared to typical in situ installations. For weldmesh, since displacement and load are both low, the energy capacity in laboratory tests will also be low and not representative of in situ conditions.

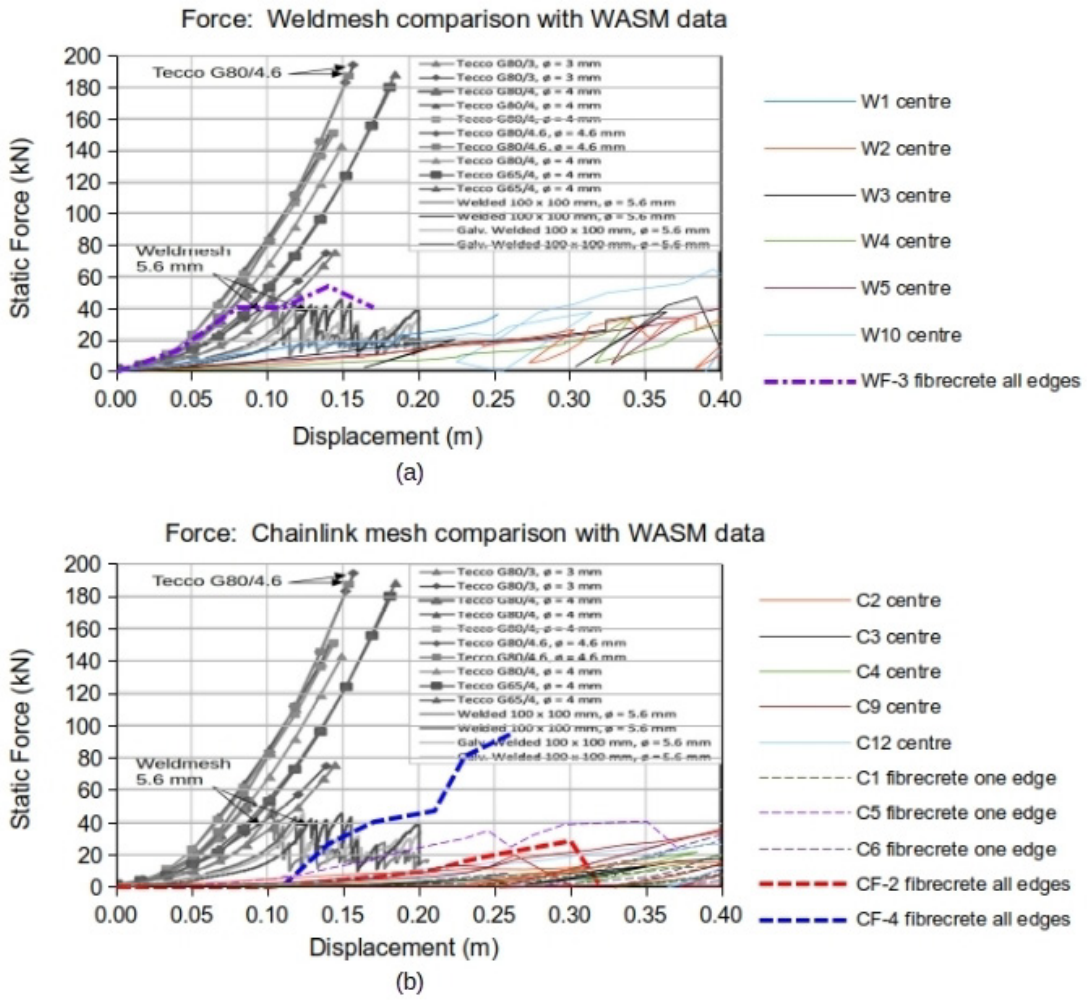


Figure 12 Force versus displacement comparison of in situ data with WASM static laboratory test data. In situ data is shown in colour for several weldmesh and chainlink mesh test configurations. The grey background is copied from Villaescusa et al. (2023, Figure 9.26), with the tests of the same mesh types arrowed and indicated. (a) WF-3 with fibrecrete all edges equalled the best of the WASM weldmesh locked-perimeter tests; (b) CF-4 with fibrecrete all edges moved part way towards the WASM dataset

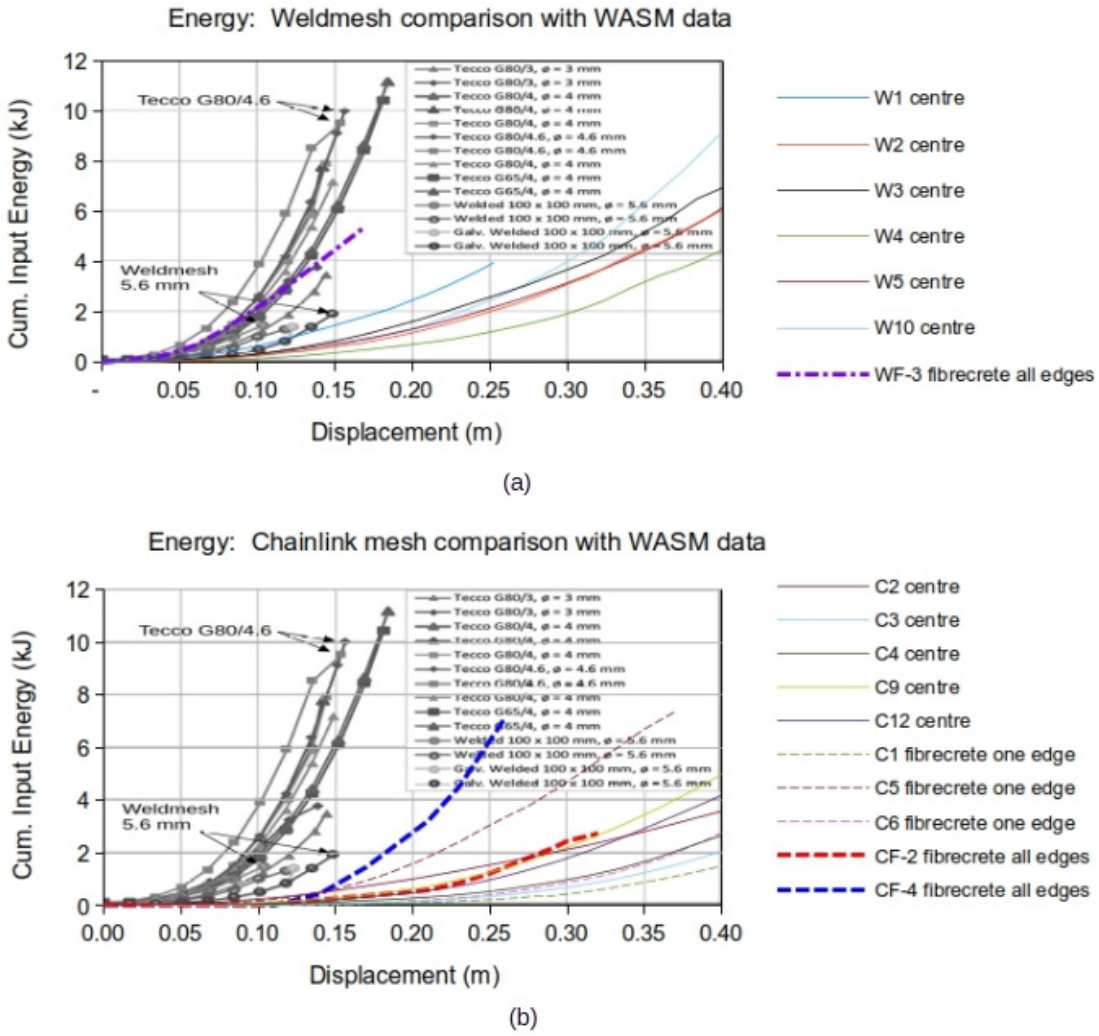


Figure 13 Energy versus displacement comparison of in situ data with WASM static laboratory test data. In situ data is shown in colour for several weldmesh and chainlink mesh test configurations. The grey background is copied from Villaescusa et al. (2023, Figure 9.26), with the tests of the same mesh types arrowed and indicated. (a) WF-3 with fibrecrete all edges equalled the best of the WASM weldmesh locked-perimeter tests; (b) CF-4 with fibrecrete all edges moved part way towards the WASM dataset

7 Mesh stiffness analysis

7.1 Mesh stiffness findings

Mesh deflection secant stiffness data is included in Tables 2 and 3. For the baseline configuration, weldmesh is 1.3 to 3.4 times stiffer than chainlink mesh, but the difference lessens for other configurations stiffened by means of bolted overlaps or by fibrecrete for locked perimeters. The few locked-perimeter cases show preferential load benefit to the less-stiff mesh due to the locked configuration, i.e. the chainlink mesh locked performance load improves relatively more than that of the locked weldmesh. The one-edge fibrecrete-locked configuration is considered representative of some in situ conditions; however, the 4-edge fibrecrete-locked configuration was devised to emulate WASM laboratory tests and is not normally used in situ.

Figure 14 examines the important relationship between mesh stiffness and energy input or dissipation. The higher the mesh stiffness, the higher the energy dissipation required to cause 0.4 m mesh displacement. The 0.4 m displacement point was selected since beyond that amount, rock mass damage is excessive and it is preferable to dissipate as much energy as achievable before the displacement reaches 0.4 m.

High mesh stiffness is clearly beneficial, and stiffness can be increased by means such as fibrecrete spraying to slightly embed the mesh into the fibrecrete. This technique is recommended to improve chainlink mesh performance.

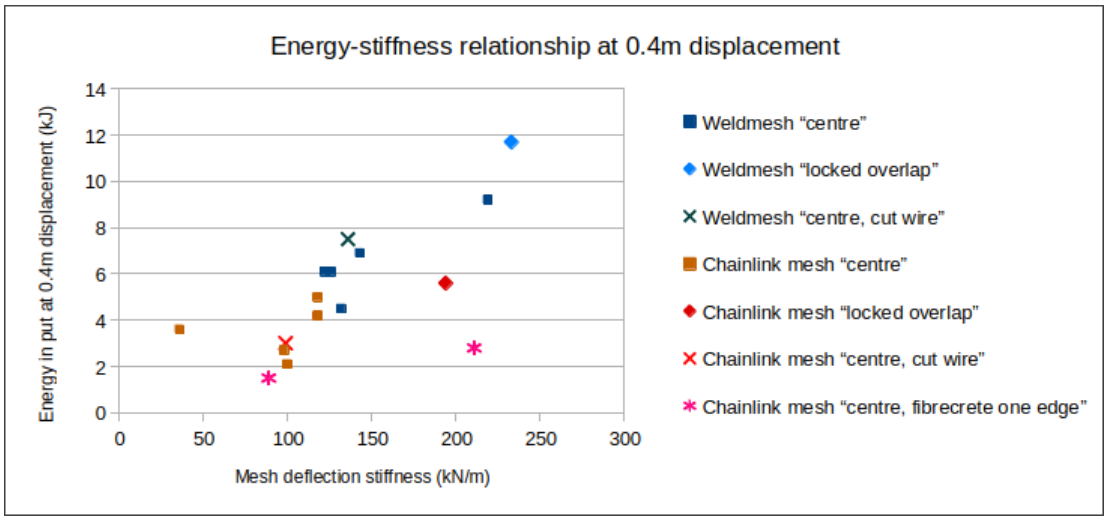


Figure 14 Energy-stiffness relationship for tested meshes. Only the subset of tests that reached 0.4 m displacement are shown. For this displacement, the weldmesh was generally superior. The upper-performing chainlink meshes were like the lower-performing welded meshes

7.2 Optimum mesh stiffness and displacement control

It is considered that if an optimum mesh stiffness exists for a situation, it would be the stiffest mesh that contains the fracturing or ejecting rock mass without any ground support components rupturing.

Fibrecrete, cable bolts, or closer spacing of rockbolts may be used to increase stiffness of the mesh, particularly for chainlink mesh. Closer bolt spacing allows for shorter bending moments, improving the mesh performance. For bolts a target displacement limit of 0.3 m or 0.4 m is adopted by many practitioners. For mesh the target displacement limit should be small, and probably like that adopted for bolts.

Deformation or bulking control of strainburst seismic damage is vital, alongside support pressure control. To the extent that deformation grows, a large volume of rock mass has bulked and depth of failure probably has increased. Several authors discuss this aspect:

> *"It is the local deformation or strain control by the steel mesh rather than the imposed confining pressure that reduces the bulking." (Kaiser 2016 discussing the gabion support concept)*
>
> *"The objective of design is to select a combined scheme that is capable of greater energy dissipation at less displacement compared with the rock mass demand." (Villaescusa et al. 2016, in reference to selecting ground support schemes)*
>
> *"In highly stressed ground, rock mass bulking cannot be prevented but can be controlled or at least partially suppressed by effective support measures." (Cai & Kaiser 2018, Section 2.4.2)*
>
> *'The installed rock support components must therefore be able to reinforce the rock so as to minimise rock mass bulking." (Cai & Kaiser 2018, Section 3.3.2)*

During a seismic strainburst or crush disturbance, the rock mass fails under compressive strain tangential to the free surface (i.e. as distinct from ejection by incoming energy pulse directed essentially radially towards the free surface). Rock becomes fractured and broken and equilibrium is lost, but if adequately contained, the fractured rock mass behaves as an energy sink, dissipating energy via loading and fracturing interactions of the fragments against each other. Firmly contained broken rock is an energy sink that is not usually appreciated, but it is central to the gabion support concept in Cai & Kaiser (2018). Bolts and surface support

must be stiff enough to provide this containment in synergy, opposing the bulking of the zone of fractured rock, and limiting both bolt deformation and surface support displacement.

8 Conclusions

The test program highlighted that mesh capacity and failure behaviour are sensitive to the installed configuration boundary conditions. Baseline centre configuration (i.e. 4 corners pinned by bolts) average working capacities were (where '+' means data includes truncated peaks; true peaks would be higher):

- weldmesh (6 tests): load 52+ kN, displacement 0.45+ m, energy dissipation 9.9+ kJ
- chainlink mesh (5 tests): load 41+ kN, displacement 0.59+ m, energy dissipation 9.5+ kJ.

Chainlink mesh needed much more displacement than weldmesh to achieve its load and energy capacity. If displacement was limited to about 0.6 m weldmesh was superior, but it has the critical flaw that it fails when displacement becomes excessive. Beyond about 0.6 m chainlink mesh energy capacity approximately equalled that of weldmesh, and with increasing displacement it likely would be superior to weldmesh, but that was not able to be assessed in these tests.

A target displacement limit of 0.4 m may be adopted beyond which rock mass damage is excessive. Baseline centre configuration capacities at 0.4 m displacement were:

- weldmesh: load 45 kN, energy dissipation 6.6 kJ
- chainlink mesh: load 23 kN, energy dissipation 3.5 kJ.

Results for bolted overlap configuration tests compared to respective 100% baselines were:

- weldmesh (2 tests): load 89%, displacement 62%, energy dissipation 78%
- chainlink mesh (1 test): load 162%, displacement 78%, energy dissipation 85%.

The bolted overlap was pinned against opening by the testing configuration and was not typical of field conditions. The proximity to bolts caused the mesh to strain more per unit displacement, and while the stretch of chainlink mesh was sufficient to survive this problem, both weldmesh tests resulted in rupture of wires when strain capacity was exhausted.

Results for cut wire performance compared to respective 100% baselines were:

- weldmesh (1 test): load 128%, displacement 109%, energy dissipation 113%
- chainlink mesh (1 test): load 81%, displacement 97%, energy dissipation 63%.

Cut or ruptured strands in chainlink mesh were seen to unravel in several tests. It was noted that for chainlink mesh, high strain in the plane of the mesh caused loaded wires to elastically distort and straighten out in the principal load direction, in preference to accepting load. Many industry professionals may be surprised by the observations of unravelling chainlink mesh wires in the in situ tests, especially since in the laboratory tests with locked boundaries, such unravelling does not occur. However, the laboratory outcome does not reflect the in situ result for chainlink mesh in the tested configurations, and observations in the mine also sometimes include unravelling of chainlink mesh strands.

Results for configurations with all edges fibrecrete-locked compared to respective 100% baselines were:

- Weldmesh (1 test): load 104%, displacement 31%, energy dissipation 55%. The fibrecrete-locked-perimeter substantially downgraded this mesh performance, with results similar to the low energy capacity and low displacement of the WASM locked-perimeter tests.
- Chainlink mesh (2 tests): load 154%, displacement 47%, energy dissipation 56%. These chainlink mesh tests came part way towards the WASM locked-perimeter configuration results.

Edge locking resulted in quite different performance compared to baseline, more like the WASM locked-perimeter laboratory results. The few locked-perimeter cases show preferential load benefit to the less-stiff mesh due to the locked configuration, i.e. the chainlink mesh locked performance load improves relatively more than that of the locked weldmesh. The results for these configurations increase confidence in the validity of the other outcomes without locked perimeters.

Comparisons with 3 test catalogues reported in the literature were illuminating:

- The Long Nickel Mine in situ baseline tests overlapped those in this paper, as expected for the same test equipment and similar configurations.
- The NIOSH results comparatively underperformed, as expected considering the mesh types were weaker and configurations not the same.
- The WASM weldmesh data overlapped the in situ weldmesh with fibrecreted perimeters for load and displacement, but returned less energy dissipated, while the WASM chainlink mesh data was quite different to the other chainlink mesh tests, returning much higher load at much lower displacements. It appears that the WASM mesh energy capacities are sensitive to the very tight mesh boundary conditions used, resulting in mesh failures occurring at much smaller displacements compared to typical in situ installations.

Mesh stiffness data revealed an important relationship between mesh stiffness and energy dissipation. The higher the mesh stiffness, the higher the energy dissipation required to cause 0.4 m mesh displacement. It is considered that if an optimum mesh stiffness exists for a situation, it would be the stiffest mesh that contains the fracturing or ejecting rock mass without any ground support components rupturing. A stiffer mesh should more firmly contain the rock mass during the failure process, which provides an energy sink that is not usually appreciated. In practice the stiffness of chainlink mesh can be increased by means such as fibrecrete spraying to slightly embed the mesh into the fibrecrete.

Finally, it was apparent that it is the mesh design that primarily governs the load transfer performance, while the strand or weld strength governs the point of rupture. In these tests, the key weldmesh superior aspect identified was higher stiffness that generates higher support pressure per increment of displacement, so it does not rely on large displacements to reach a high energy capacity. However, it is vulnerable to weld rupture. The biggest advantage of chainlink mesh was the larger displacements it can accommodate without rupture.

The quasi-static findings are considered to be slightly conservative compared to dynamic conditions, and also conservative since some data relates to truncated peaks. The test catalogue was small and results quite variable, so data is not considered to be statistically representative. Overall this test program has provided guidance for engineers in selecting mesh capacity that is appropriate for the particular installation boundary conditions in their mines.

Acknowledgement

Appreciation goes to the mine staff and operators who facilitated this major testing program taking nearly 2 years to complete. Thanks to Matty from Rocktech who stored the Meshmaster 1000 rig under his desk for many years and assisted with its refurbishment for this program.

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