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The effect of varying testing configurations on the performance of welded mesh

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Abstract

Mine mesh is a surface support element commonly used in underground mining and plays a critical role in controlling loose material, retaining fractured rock, limiting progressive unravelling around excavations, and maintaining the inherent support capacity of the rock mass. Published test results and product specifications are typically derived from laboratory scale testing used to simulate in situ conditions. This laboratory testing is conducted with varying fixing conditions, loading configurations and sheet sizing.

This paper presents the test results from research which revisits the effect of commonly used laboratory testing configurations on measured mesh performance and compares these results to quasi-static testing on full-size mesh sheets fixed in a typical underground bolting configuration.

The results from this research form the basis of a recommended testing configuration and process for future product development and testing.

Keywords: *surface support, mesh, fixing conditions, full-scale testing, support capacity, testing configuration*

1 Introduction

Maintaining safe and stable excavations is critical in underground mining. Any loss of stability carries significant operational costs and, most importantly, creates direct safety risks for personnel working underground. An effective ground support system is central to geotechnical risk management requiring an understanding of the performance and capacity of individual support elements and their interaction within a system, for example between reinforcement and surface support. Steel mesh is a commonly utilised surface support often playing a critical role in controlling loose materials, retaining fractured rock, limiting progressive unravelling around excavations, and maintaining the inherent integrity of the rock mass (Potvin & Hadjigeorgiou 2008; Potvin & Hadjigeorgiou 2020; Morkel et al. 2023; Schunnesson et al. 2019).

Although rockbolts and cable bolts provide confinement and anchorage in the rock mass (Potvin & Hadjigeorgiou 2020), the performance of the support system depends heavily on the surface support to maintain integrity at the excavation boundary. If the mesh fails prematurely, smaller rock fragments are released, load transfer to reinforcement elements is disrupted, and the excavation rapidly deteriorates. The importance of surface support within a ground support system has made the study of mesh behaviour increasingly important. Laboratory and field-testing programs have therefore become indispensable tools for quantifying mesh capacity, deformation characteristics, and overall contribution to the system performance.

Despite many established testing approaches, there remains a gap in how closely conventional test methods reproduce in situ conditions. Previous research suggests that laboratory test results do not replicate the complex in situ loading mechanisms of underground application (Hadjigeorgiou & Stacey 2018). Complicating this further is the many possible variables that can influence a laboratory test result, these factors include

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the size of test rig frame; the degree to which bolts are tensioned; fixing conditions; and the size, shape and orientation of the loading plate. These factors are not standardised across research programs and testing facilities (Hadjigeorgiou & Stacey 2018; Karampinos & Hadjigeorgiou 2021; Morkel et al. 2023; Villaescusa et al. 2023, 2013). An example of this inconsistency is the practise of fixing the test sheets in a test rig by shackling each aperture around the mesh perimeter to the test rig (Morton 2009), or by bolting the mesh sheet to the test rig in various configurations (Roberts et al 2018; Benton et al 2022).

The absence of a standardised testing methodology for welded mesh results in published performance data that is not comparable for results generated by different testing facilities. Additionally, it is not clear which of these methodologies correlate to the in situ performance of the installed mesh in an underground environment. The purpose of this research was to quantify the impact of varying laboratory testing configurations, namely the fixing conditions, on the recorded load and deformation capacity of welded mesh under quasi-static loading conditions. The results from this testing program were also compared to the results of underground testing to identify which laboratory configurations best correlate to mesh performance as installed underground.

2 Experimental methodology

2.1 Testing equipment

Testing was conducted using 2 test facilities, a small-scale test facility capable of testing mesh sheets up to 1.5 × 1.5 m large; and a full-scale facility capable of testing mesh sheets up to 4.5 × 2.4 m in size. Both facilities are located at the Jennmar mesh factory in Perth, Western Australia.

The small-scale test rig shown in Figure 1 comprises an adjustable frame into which test sheets are positioned, and an overhead mounted load screw which is driven by an electric motor to apply load onto the centre of a test sample. Load is applied to the test sample using a square steel plate 250 × 250 mm in dimension. The 10 mm thick plate is reinforced around it's perimeter to prevent any flexure of the plate during loading. Test sheets can be fixed into the frame by either shackling the perimeter of the sheet to the frame, or by bolting through the mesh apertures at determined locations – typically in the corners of the mesh. The mesh test rig has a load capacity of 10 tonne.

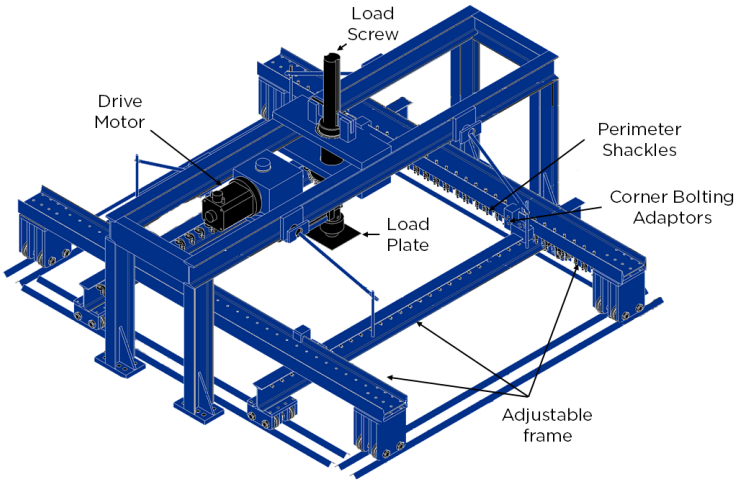


Figure 1 Laboratory test rig for small-scale mesh testing

The test rig is controlled via a proprietary custom computer program with sensors recording applied load and displacement of the load plate fixed to the bottom of the load screw. The recorded data is presented in real-time as a load-deformation plot, Figure 2, and is stored to an electronic database upon conclusion of each test.

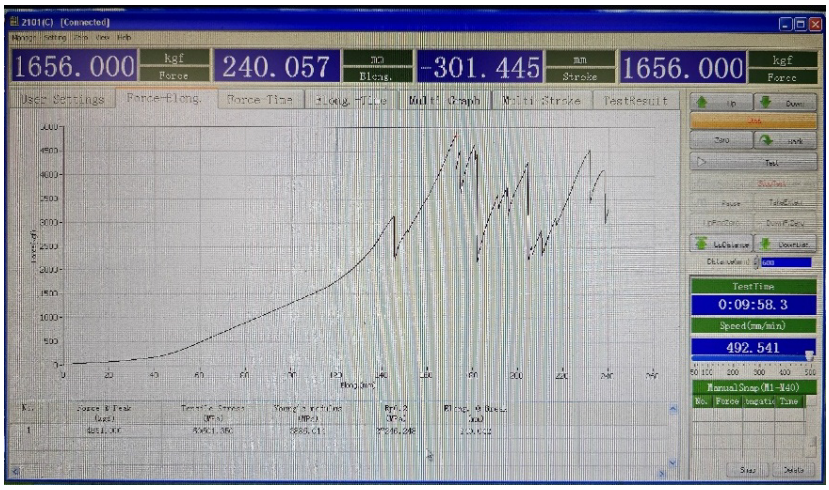


Figure 2 Control and data recording program for small-scale Laboratory test rig for small-scale mesh testing

The full-scale testing was conducted by fixing 4.5 × 2.4 m sheets of mesh into position using a 1.4 × 1.05 m bolting pattern, Figure 3. To achieve this threaded steel sockets were fixed into the laboratory floor and M24 high tensile bolts were threaded into these sockets together with a combi plates to bolt each test sample into place. Load was applied to the test samples using a loading plate lifted by a 5 tonne overhead crane.

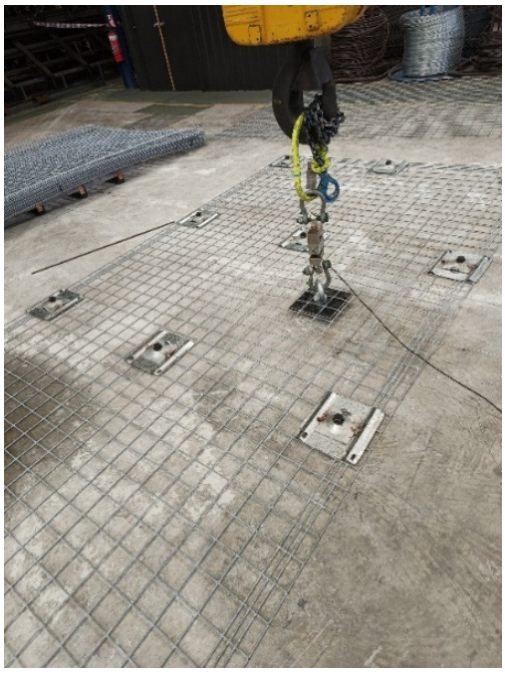


Figure 3 Laboratory test setup for full-scale mesh testing

The instrumentation used to capture applied load and displacement of the loading plate are shown below. Figure 4 shows the data acquisition device, load cell, linear transducer attached to the bottom of the loading plate, and signal amplifier utilised to record and process input data.

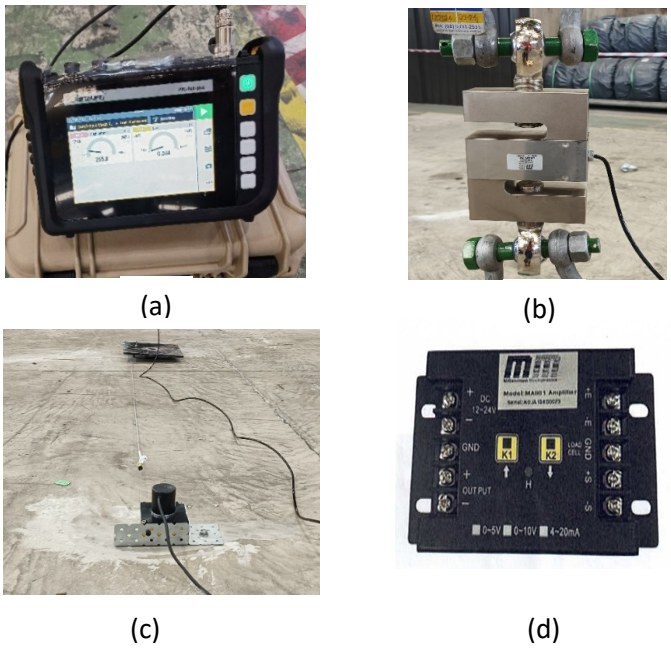


Figure 4 Instrumentation for full-scale testing. (a) Data acquisition device; (b) Load cell; (c) Linear transducer; (d) Signal amplifier

2.2 Fixing condition and loading configurations

Small-scale laboratory testing was conducted on 1.2 × 1.2 m weld mesh sheets either shackled to the test rig at each aperture around their perimeter, as shown in Figure 5a, or bolted to the test rig in each corner of the test sheet (Figure 5b). The shackles used for fixing boundary edges were 13 mm 2 tonne D-shackles, the corner bolted samples were fixed in place using high tensile M24 bolts and standard 300 × 280 mm combi plates. Load was applied to the test samples at a rate of 50 mm/min using a 250 × 250 mm square plate until either failure of the mesh or the displacement limit of the load screw was reached.

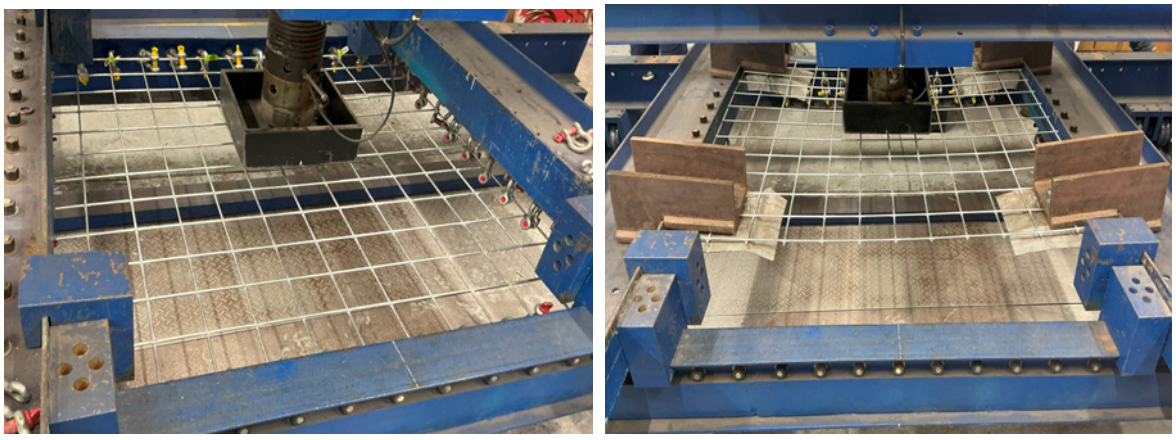
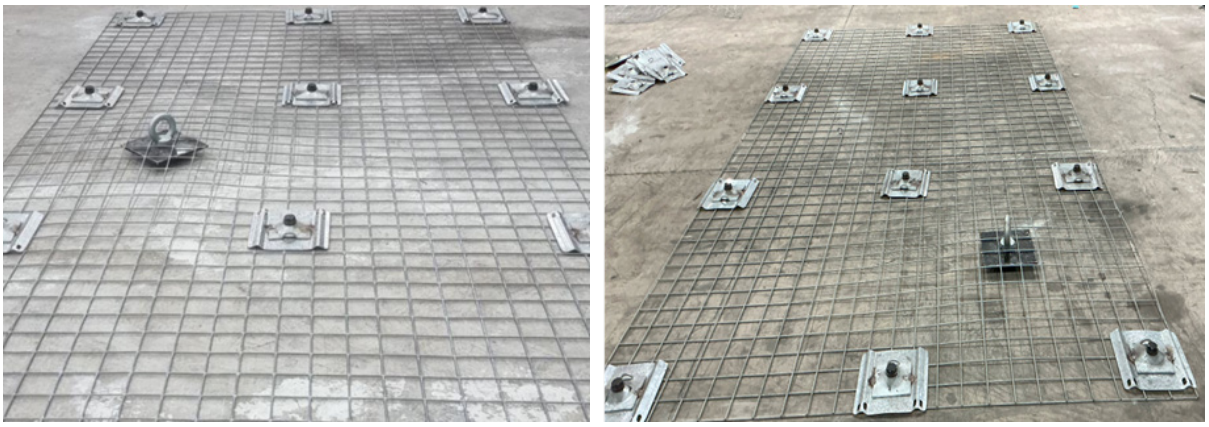


Figure 5 Small-scale test configuration for samples. (a) Shackled around perimeter; (b) Bolted in corners

Large-scale laboratory testing was conducted on 4.5 × 2.4 m sheets of weld mesh bolted in place with a bolt spacing of 1.4 × 1.05 m. Load was applied at 2 different locations in the sheets: at the mid-length of the sheet length between 4 central bolts as shown in Figure 6a, and in one corner of the sample, as shown in Figure 6b. Load was applied to the mesh using a 250 × 250 mm steel plate, lifted by the overhead crane. The crane utilised for these tests is limited to a working load of 5 tonne and testing was halted at this load and not at ultimate failure of the mesh samples.



(a) (b)

Figure 6 Full-scale test configuration for samples. (a) Loaded in centre; (b) Corner of sheets

A summary of the fixing condition, loading position and testing limitation for each test configuration is provided in Table 1.

Table 1 Test configurations and load limitations

Sample size	Fixing condition	Fixing pattern	Loading position	Limitation	Comment
Small-scale	Shackled	0.1 m	Centre	Mesh	Boundary wire failure
Small-scale	Corner bolted	1.0 m	Centre	Stroke	Loading cylinder stroke (450 mm)
Full sheet	Bolting pattern	1.4 × 1.05 m	Middle length	Load	Crane load limit (5 tf)
Full Sheet	Bolting pattern	1.4 × 1.05 m	Corner	Load	Crane load limit (5 tf)

3 Results

Table 2 provides a summary of the four different configurations tested and the number of samples tested for each. The table also includes a key to the data labelling for each dataset, for example, small-scale shackled sample 1 is denoted as ‘S1’.

Table 2 Test configurations and load limitations

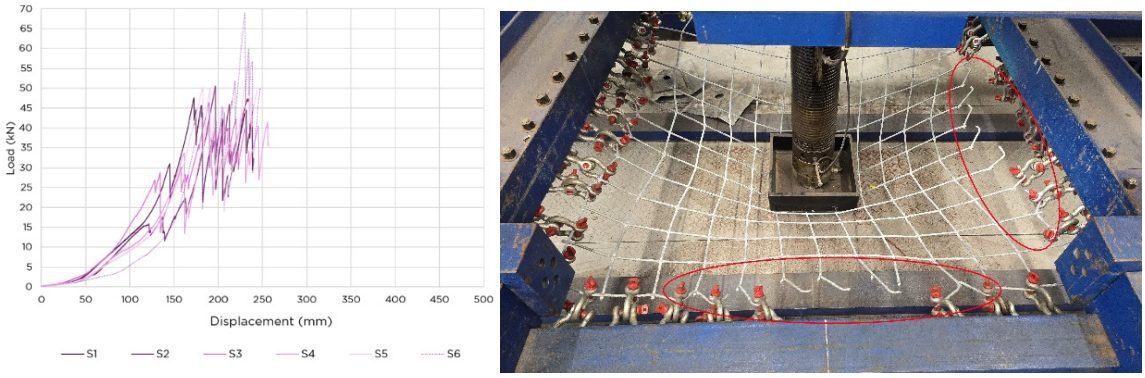
Sample size	Fixing condition	Loading position	Number of samples	Series label
Small-scale	Shackled	Centre	6	S(#)
Small-scale	Corner bolted	Centre	6	B(#)
Full sheet	Typical bolting pattern	Mid-length	6	FS-M(#)
Full Sheet	Typical bolting pattern	Corner	3	FS-C(#)

3.1 Small-scale tests

The first series of tests conducted was on six 1.2 × 1.2 m sheets of Ø5.6 × 100 mm aperture welded mesh, fixed to the test frame via shackles in each aperture around the perimeter of the test sheet. The results for this testing configuration are plotted in Figure 7a and show a consistent response until failure of a first strand

occurs at approximately 160–200 mm of deformation. Note that any earlier dips in the load deformation curves were due to movement and bedding down of the shackles as they took up load.

It was noted that fixing the sheet boundary in the horizontal and vertical axis does not allow for representative deformation of the mesh perimeter. This in turn resulted in strain within the mesh strands being transferred directly along the central wires in the sheet to the mid-length of each perimeter, with first mesh strand failure beginning at in the mid-point of the sheet perimeters as shown in Figure 7b.



(a) (b)

Figure 7 (a) Load–deformation results; (b) Failure points for small-scale shackled samples

The same failure mode was documented by Morton (2009) and hence a comparison of these results to the previously published data was conducted. In Figure 8 the current test results are identified as S1–S6 and a sample of results digitised as per Morton (2009) are identified as MT017–MT076. Despite slight differences inherent in each test facility, and a 100 mm difference in the sample sizes, the results from both test programs are similar to approximately 200 mm where strand failures occur indicating this is consistent when test sheets are fixed around the perimeter.

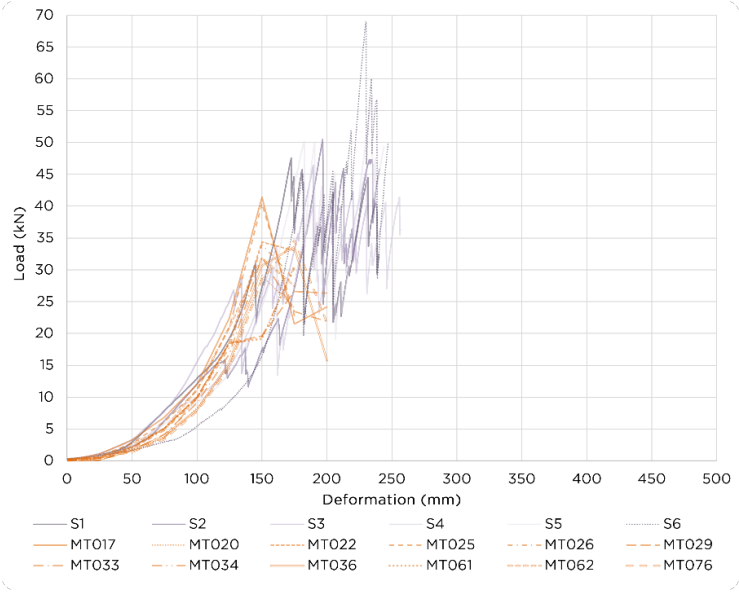
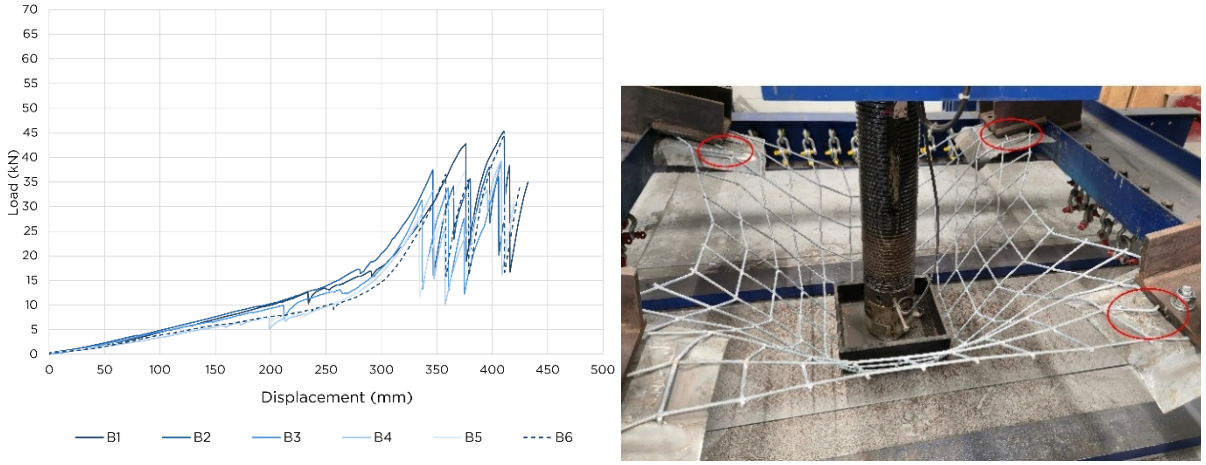


Figure 8 Comparison between results for shackled perimeters (after Morton 2009)

The second series of testing was conducted on six 1.2 × 1.2 m sheets of Ø5.6 × 100 mm aperture welded mesh, fixed to the test rig by a bolt and combi plate in each corner of the test sheet. The results for these tests are plotted in Figure 9a and again show consistent performance for the test configuration up to first strand failure. This testing configuration yielded noticeably higher degrees of deformation before failure than the shackled perimeter tests, with lower ultimate load capacity. Observation of the sheets during testing

indicates that boundaries of the test sheets were able to perform in X, Y and Z directions, resulting in load being transferred diagonally across the mesh sheets from the central loading plate to each bolted corner. The failure points for mesh loaded in this manner is in the corner strands at the bolting location, Figure 9b. Similar behaviour was also documented in Morton (2009).



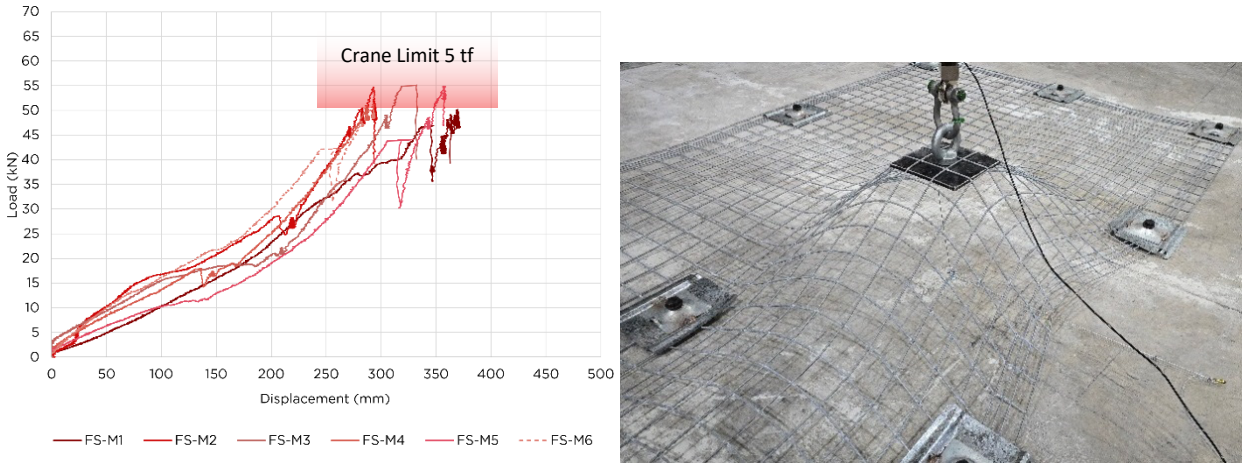
(a) (b)

Figure 9 (a) Load–deformation results; (b) Failure locations for small-scale bolted samples

3.2 Full-scale tests

The first series of full-scale testing was conducted on six 4.5 × 2.4 m sheets of Ø5.6 × 100 mm aperture welded mesh, bolted down in a set bolting pattern, load was applied to the mid-line of the sheet. The results for this testing configuration are plotted in Figure 10a, showing a consistent response until tests were halted between 280 and 350 mm.

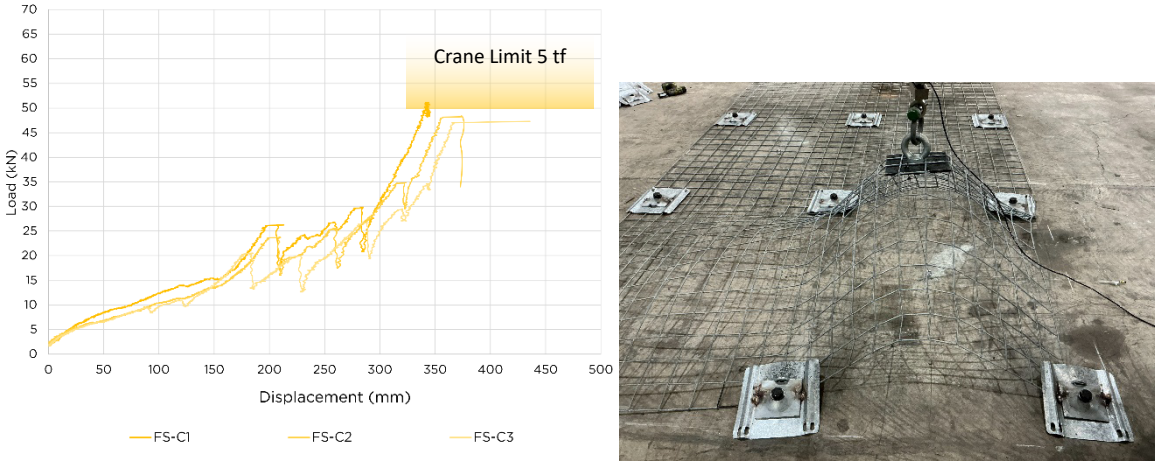
Note that testing was halted at approximately 50 kN due to the loading limit of the overhead crane utilised to lift the loading plate, and based on the initial laboratory results it was anticipated that 50 kN would be sufficient to induce failure of the mesh strands. Analysis of the mesh as it deformed under the applied load showed that the applied force is distributed across the mesh sheet similarly to the small-scale bolted test samples. However, the ability of the mesh to deform at the 1.2 × 1.2 m induced boundary of the small-scale testing, and the ability to mobilise wires beyond the 1.2 × 1.2 m footprint provides additional support capacity to the mesh resulting in higher load capacity than documented in small-scale lab testing. Hence, the full-size mesh samples could not be tested to destruction.



(a) (b)

Figure 10 (a) Load–deformation results; (b) Deformed shape for full-scale bolted samples loaded at mid-length

A second series of full-scale testing was then conducted on three 4.5 × 2.4 m sheets of Ø5.6 × 100 mm aperture welded mesh bolted down in the same pattern, but with load applied to a corner of the sheet. The results for this testing configuration are plotted in Figure 11a, showing a consistent response until tests were halted at the crane's load limit.



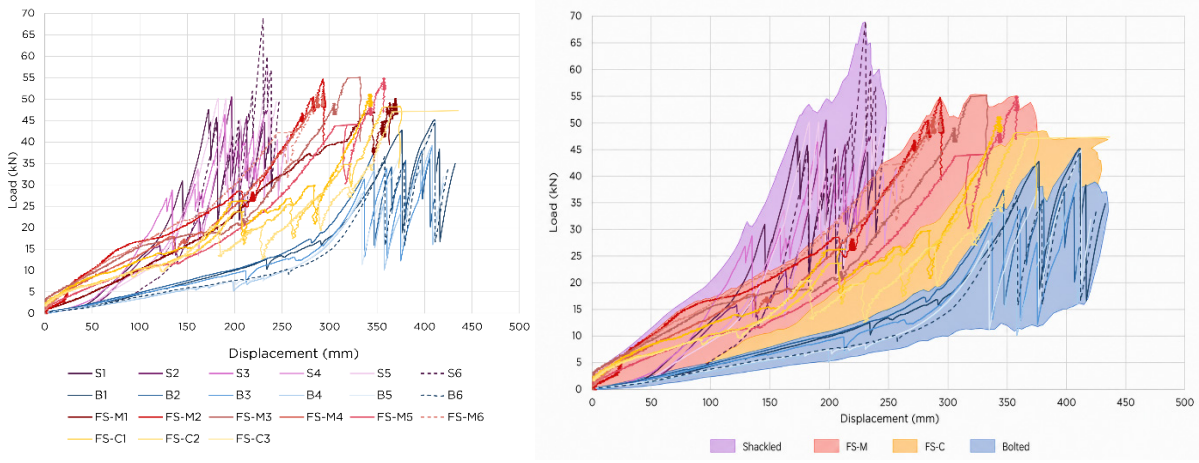
(a) (b)

Figure 11 (a) Load–deformation results; (b) Deformed shape for full-scale bolted samples loaded in corner

The deformation of the mesh under this loading condition was higher than when loaded at the mid-length of the sheet. Observation of the mesh deformation under load showed that the 2 free edges of the corner act much like the small-scale, corner bolted samples with the mesh edge deforming and being unable to transfer load to additional wires in those directions. Resulting in more deformation of the sheet for similar applied load.

4 Discussion

Review of the results from the 4 test configurations confirms that the sample size and testing configuration have a significant effect on the resultant product performance, as evidenced in Figure 12a comparing all laboratory test results on a single plot. For ease of reference going forwards, the test results are plotted as estimated performance envelopes for each test configuration shown in Figure 12b.



(a) **(b)**

Figure 12 (a) Load–deformation plots for all laboratory tests; (b) Performance envelopes

4.1 The influence free edges on deformation capacity

It is evident that the number of free edges on a test sample, relative to the loading position, has as significant impact on the resultant deformation measured. As the number of free edges in a sheet is increased, the deformation of the sheet increases. This is evidenced in Figure 12 where the deformation increases in the following order:

- shackled samples (no free edges) have the least deformation
- the FS-M samples (1 free edge) have increased deformation
- the FS-C samples (2 free edges) further increased deformation
- the Bolted samples (4 free edges) have the greatest deformation.

4.2 The influence free edges on load capacity

It is evident that the number of free edges on a test sample, relative to the loading position, has as an impact on the resultant load capacity of the mesh. Figure 12 shows that a sheet with 4 free edges (Bolted) had the lowest load to failure, and that full-size sheets with 2 (FS-C) and then one free (FS-M) edge sustained higher loading, noting that the full-sized sheets could not be loaded to maximum load capacity due to the load limitation of the crane.

It was observable during testing that where the mesh sheet extended past the quadrant wherein load was applied, that mesh strands outside of this quadrant were activated and sustained load, see Figure 10b and Figure 11b. The higher loads observed in shackled test samples are due to the load being distributed to a number of shackles along each perimeter, whereas bolted test samples concentrate the loading on either one or 2 wires at each bolting location.

4.3 Failure location

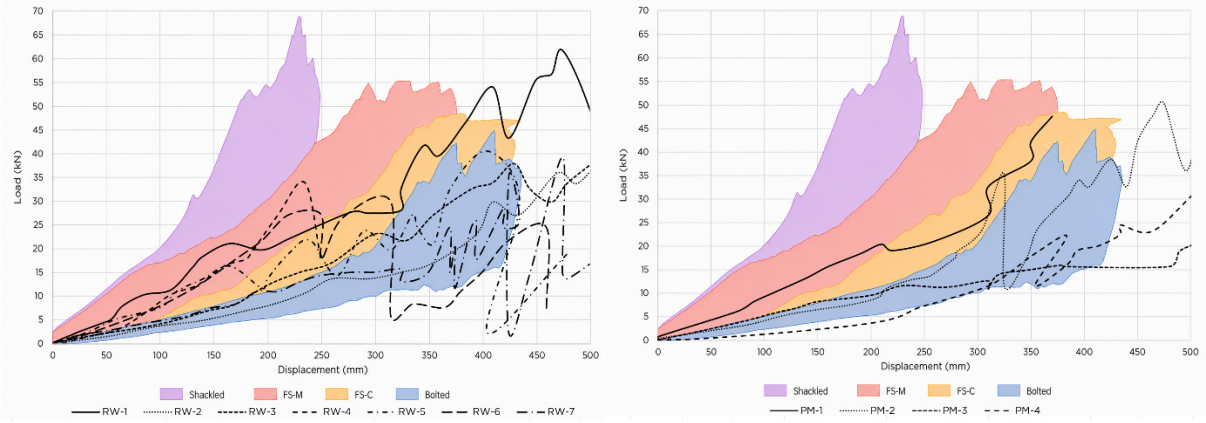
It was observed that fixing all perimeters of mesh samples (shackled configuration) results in ultimate wire failure along one or more perimeter wires, Figure 7b. When mesh is fixed with either a 4-corner or full-scale bolting patterns, the failure location was in all instances adjacent to bolting positions; see Figures 9b, 10b and 11b. This correlates to the same failure mechanisms previously documented in the research by Morton (2009).

4.4 Bolting pattern

From this testing program the effect of the bolting pattern on mesh deformation or load capacity could not be quantified, given the greater impact of the changes in mesh boundary conditions. Future testing of variable bolting spacings whilst keeping all other parameters constant would be suggested to determine this.

4.5 Comparison to underground testing

A further analysis of these results was conducted by comparing the laboratory testing to results from underground testing on welded mesh by Whiting (2017) and Mikula et al. (Mikula, pers. comm., 31 May 2026). The laboratory testing envelopes are overlaid with the test results recorded underground by Whiting in Figure 13a and Mikula et al. in Figure 13b. The test results from Whiting (2017) include testing of mesh in both corner positions and at the overlap of mesh sheets, with the overlap tests recording stiffer load responses. The results from Mikula (pers. comm., 31 May 2026) do not include any testing at the mesh overlap and hence the lower indicated performance envelope.



(a) (b)

Figure 13 Comparison of laboratory testing to underground test data from (a) Whiting (2017) and (b) Mikula (2026)

The comparison of the laboratory results to the underground testing suggests that laboratory testing of full-size mesh sheets, bolted with a typical pattern and loaded in a corner segment of the mesh, most accurately correlates to measured underground performance during initial deformation to approximately 300 mm. Once deformation begins to exceed 300 mm, a test sheet bolted in 4 corners more accurately correlates to underground. This is summarised in Table 3 which compares each of the different laboratory test configurations to the results from underground testing.

Table 3 Comparison of laboratory testing to underground testing

Sheet size	Fixing condition	Loading position	Stiffness	Ultimate load capacity
Small-scale	Shackled	Centre	Over-stated	Over-stated
Small-scale	Corner bolted	Centre	Similar	Under-stated
Full sheet	Typical bolting pattern	Mid-length	Slightly higher	Similar
Full Sheet	Typical bolting pattern	Corner	Similar	Similar

5 Conclusion

Laboratory testing was conducted on conventional welded mesh manufactured from Ø5.6 mm wires with an aperture spacing of 100 mm. The testing confirmed that the sample size and testing configuration significantly affects the recorded performance of the welded mesh.

Whilst it is acknowledged that the inherently variable nature of the installation of ground support in application makes the quantification of performance in the underground environment difficult, comparison of the results from this research to underground testing, suggests that the testing of full-sized mesh sheets loaded in a corner segment, or small-sheets bolted in the corners, provides a close correlation to actual underground performance.

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