Design and testing of high capacity surface support

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Abstract

Steel wire weld mesh is a common industry standard surface support used in underground mining, traditionally installed with mining drills during the bolting cycle. As underground mining depth and stress increase, mining methods and their sequences at these depths place challenges on conventional surface support options. These challenges have provided a need for high capacity surface support options that improve development efficiency, reduce the need for secondary ground support installation and is easily installed with current mining equipment. A 5m² mesh testing machine was built, suspending a 9500kg concrete slab, designed with multiple hold down points to test varying bolting patterns. Mesh load and displacement is accurately measured using a data acquisition system which pushes against the restrained mesh module with an available 200kN load and 1200mm displacement capacity. A testing program comparing conventional surface support, straps and combinations of both were tested for baseline results. New module designs incorporating existing mesh types and new design concepts were manufactured to allow for single pass installation during a bolting cycle. Nine mesh types, mesh/strap combinations and new mesh module designs were compared using the same test method. Based on these results, two high capacity mesh module types are produced. This paper will detail the test program, load and displacement results and underground mesh module performance, describing the two high capacity mesh modules function within the development cycle and manual handling.

Keywords: *surface support, high capacity, development efficiency, mesh module, ground support*

1 Introduction

Various mesh testing methods and facilities are available to complete static testing of steel mesh types, although limitations in testing capacity, varying combinations of mesh types and module size can limit planned project scope. Further consideration was given to long term availability of facilities which allow experimentation and product development. Due to these limitations, a decision to build a static test facility was necessary.

A program was prepared to test and compare various mesh types currently used in the underground hard rock mining industry and develop product types that meet the following criteria:

- Achieve 200kN and limit displacement to 400mm.
- Can be easily manufactured with minimal capital required to development manufacturing equipment.
- Are easy to install using current installation methods.
  - Twin boom Jumbo drill method using a bolt and drill steel to install mesh.
  - Bolting drill with dedicated mesh handling boom.
- Design mesh sheets that remove secondary process required to install straps to increase surface support capacity.
- Economical to manufacture.

The testing program required designing and building a static mesh testing machine necessary to develop mesh modules which meet the criteria described. The testing facilities function is to support product development, provide an understanding of varying mesh type performance when tested within fixed loading and boundary constraints and provide ongoing testing process for quality control.

2 Static Test Facility

The function of properly installed mesh underground is to control fall of ground caused by the inward movement of rock between installed ground support elements in an excavated tunnel. In geotechnical domains where there is poor rockmass or soft rock, the ground can squeeze between the installed supporting elements and tendons, which push the rockmass and surface support into the excavated drive as seen in Figure 1.

Figure 1 Example of rock and fibrecrete pushing inward against the weld mesh into the excavated drive

The development of the test facility considered five main functions in its design as follows:

1. Design a facility that pushes the mesh module, similar to the inward movement caused from loading of surface support.

2. Has an external boundary size to test large mesh sheets, or multiple mesh modules to evaluate loading on mesh overlap.
3. Mesh modules restrained by rock bolts and plates utilizing bolting patterns where the mesh modules are to be used.
4. Has the required load and displacement capacity to test the mesh modules.
5. System utilises a calibrated load cell and string potentiometer to measure load and displacement.

2.1 Static Test Facility Design

A 5m² mesh testing machine was built, suspending a 9500kg concrete slab, suspended and bolted to a steel frame 1400mm above the ground. The concrete slab has multiple hold down point through holes drilled to test varying bolting patterns. Bolts and plates which are supplied to the mining operation are used to anchor the mesh modules onto the concrete slab, which corresponds to the bolting pattern utilized in the mine design. The mesh testing facility has a 200kN hydraulic cylinder which pushes through a 500mm² hole in the centre of the concrete slab and a 450mm spherical plate, loads against the restrained mesh module bolted onto the concrete slab. Load and displacement is accurately measured using a calibrated data acquisition system, with a system capacity of 200kN load and 1200mm displacement capacity.

Figure 2 Static Mesh Testing Facility with testing process in progress

Although below 1.8 metres in height, guarding was erected around the perimeter of the frame to provide operator safety. Two large staircases at one end of the test facility provide safe entry and exit points when handing full size mesh modules.

2.2 Static Mesh Testing Method

The method of testing the mesh modules in this paper, is to secure the mesh samples with J-Tech Bolts and 150mm x 150mm x 8mm thick volcano plates. The J-Tech Bolt, widely used in the Australian mining market was used in the mesh testing process as it is supplied to the mining operation the testing program was develop for. The J-Tech bolt has been subjected to a thorough program to test, gather data and validate the bolt performance in varying geotechnical domains. The bolt development included:

- Finite element (FE) modeling, the simulation reviews the J-Tech bolt design evaluating the effects of threadbar geometric variation and threadbar and nut engagement results under high stress.
- Coating friction response and the effects of thread tolerance extremes on the bolt failure mode.
- In-situ system testing, laboratory and underground short encapsulation testing.
- Resin mixing testing and validation of varying mixing devices.
- Double shear testing.
- Successful dynamic testing at varying velocity and mass to understand the systems potential capacity and effectiveness in dynamic mining environments.

The J-Tech Bolt specifications are detailed in Table 1.

Table 1 J-Tech Bolt Technical Specifications

Description	25mm Bar Properties Minimum		25mm Bar Properties Typical		General Data
	MPa	kN	MPa	kN	
Yield Strength Steel	500	215	565	245	-
Tensile Strength of Steel	600	260	685	294	-
Standard Elongation	Min	15%	Typ	20%	-
Shear Strength Tested	-	-	-	221	-
Bar Diameter (mm)	Core	23	Major	25	-
Cross Sectional Area (mm^2)	-	-	-	-	433
Mass per Metre (kg/m)	-	-	-	-	4.3
Recommended Drill Hole Size	-	-	-	-	35-38
150^2 x 8mm Volcano Plate Min Collapse Load			-	-	>294kN

The volcano plate used is the largest plate that can fit onto the bolting carousel used to install the J-Tech bolts. The plate size provides a small loading area, therefore maximising the surface support capacity supports load distribution when installed.

Throughout all testing completed, the mesh sheet size was $2.2m^2$. All bolt holes were set at one metre spacing around the perimeter of each mesh module. Due to the location of the hydraulic cylinder loading plate being in the centre of each mesh sheet, this prevented a bolt being in the centre of the mesh module.

The J-Tech hold down bolt location provided a baseline for all mesh samples in the testing program. It must be noted that no centre bolt is utilized due to the location of the hydraulic cylinder. Having an extra bolt restrain the mesh centre, would increase mesh testing load and reduce displacement. Due to the varying mesh sheets, the standardized mesh testing process to bolt the boundary of the mesh sheet was chosen. An example of the mesh testing bolt pattern is seen in Figure 3.

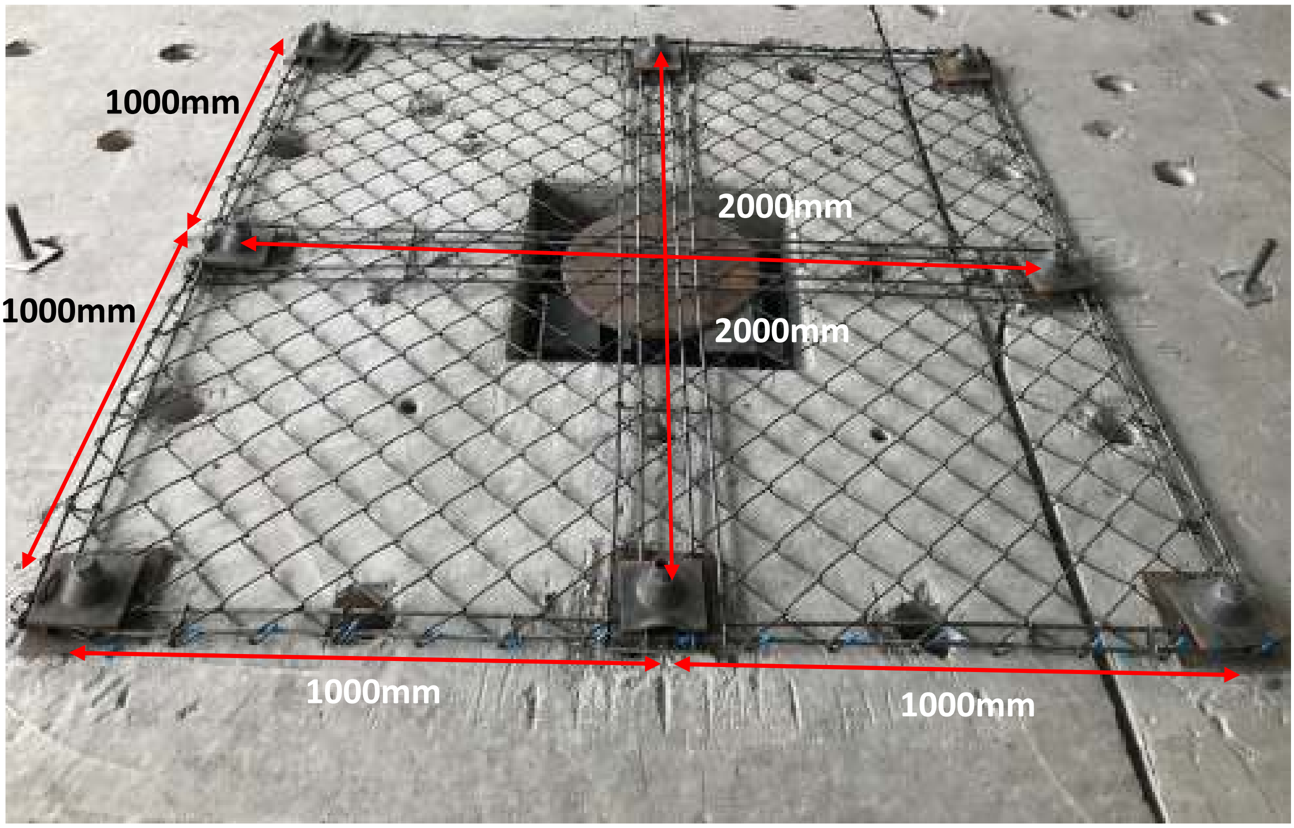


Figure 3 Mesh testing distance between J-Tech hold down bolts

3 Mesh Testing Program Results

Mesh testing was carried out on nine different mesh combinations as seen in Figure 4. Three tests were completed on all mesh combinations, except the Cable Strap and Woven Mesh, where only one test was completed, due this particular combination exceeding the test facilities capacity. The nine mesh testing combinations are described below:

1. 5.6mm weld mesh; 100 x 100mm aperture; 500 MPa wire; Hot Dip Galvanized.
2. 5.6mm weld mesh; 100 x 100mm aperture; 500 MPa wire; Hot Dip Galvanized with Osro Strap.
3. 8.0mm weld mesh; 100 x 100mm aperture; 500 MPa wire; Hot Dip Galvanized.
4. 10mm Woven Mesh; 100 x 100mm aperture; High Tensile wire; Hot Dip Galvanized.
5. 10mm Woven Mesh; 100 x 100mm aperture; High Tensile Wire; Hot Dip Galvanized with Cable strap.
6. 5mm Chain link mesh; 100mm aperture; Low Carbon wire.
7. 5mm Chain link mesh and Longitudinal High Tensile 10mm wire module.
8. 5mm Chain link mesh and Longitudinal/Vertical High Tensile 10mm wire module.
9. 5mm Chain link mesh and Diagonal High Tensile 10mm wire module.

Results from the testing provided confirmed where the majority of time would be invested in developing a higher capacity mesh module. The results of the testing are detailed in Table 1.

Images from testing various combinations are seen in Figure 5. Figure 6 shows testing of 5.6mm hot dipped galvanized weld mesh, an industry standard surface support tested thoroughly at various testing facilities.

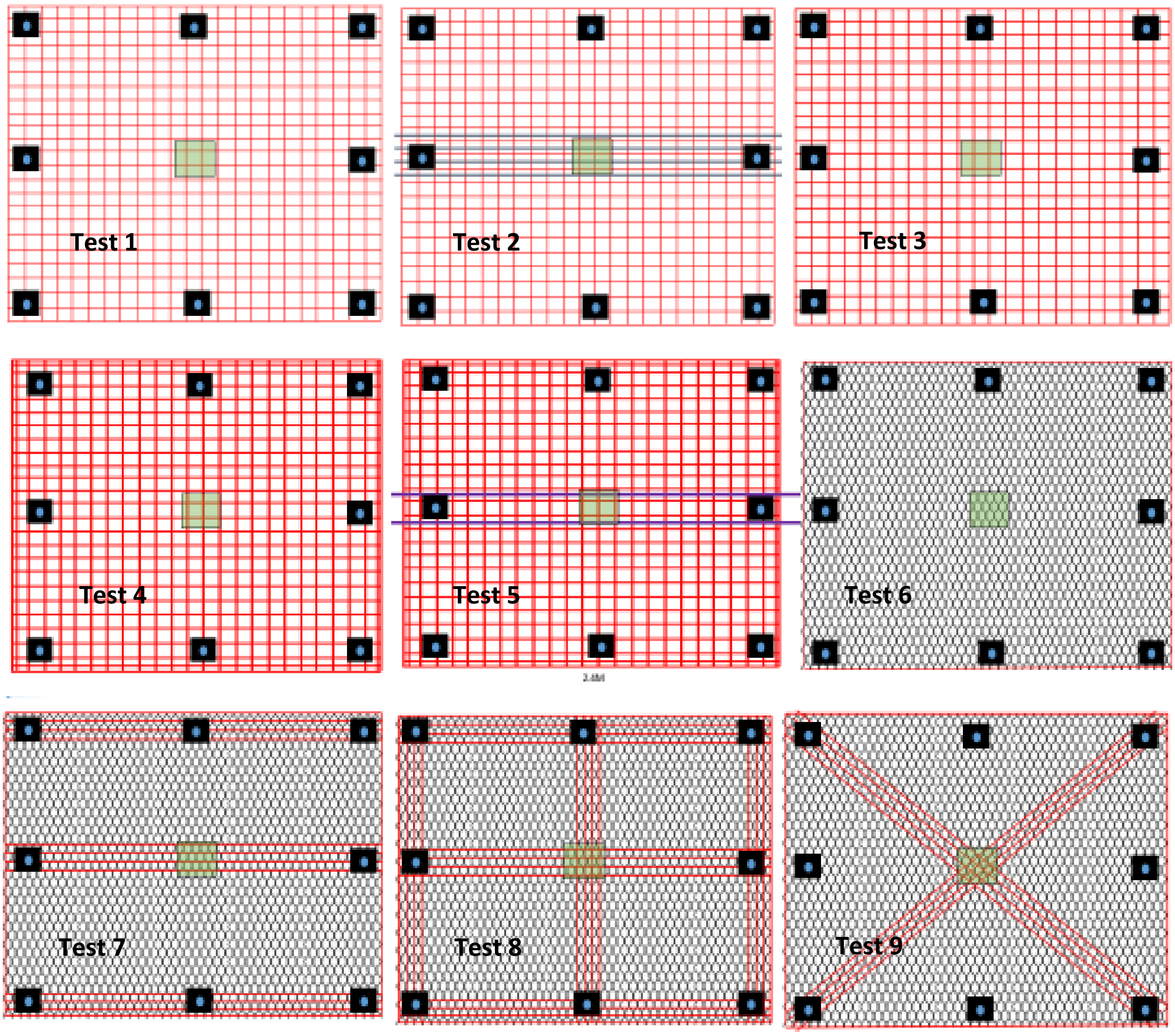


Figure 4 Mesh testing program showing 2.2m x 2.2m module and hold down bolt locations at 1.0m x 1.0m spacing

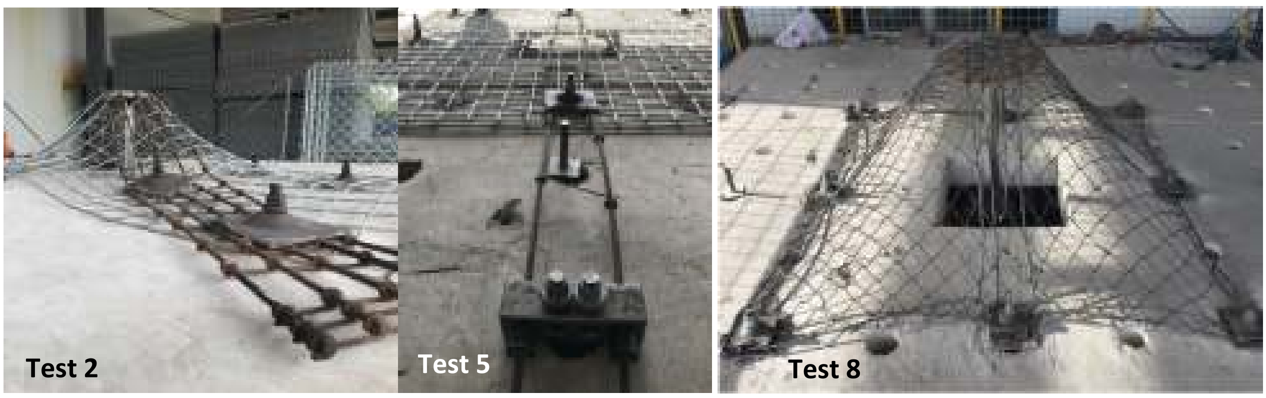
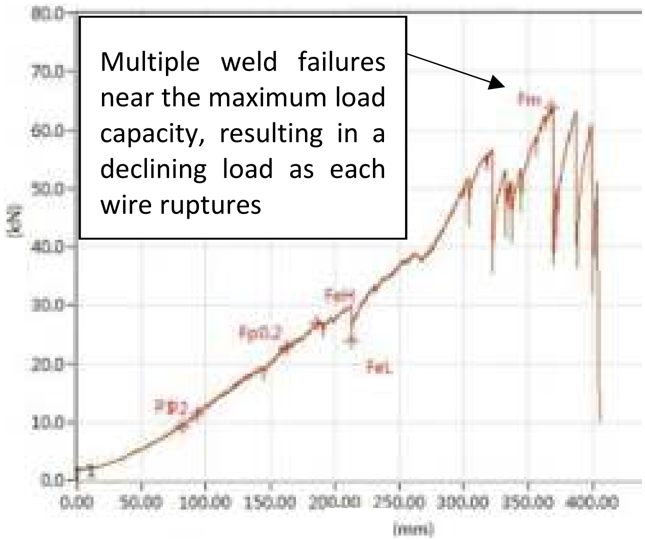


Figure 5 Mesh module testing in progress showing Test 2, Test 5 and Test 8.



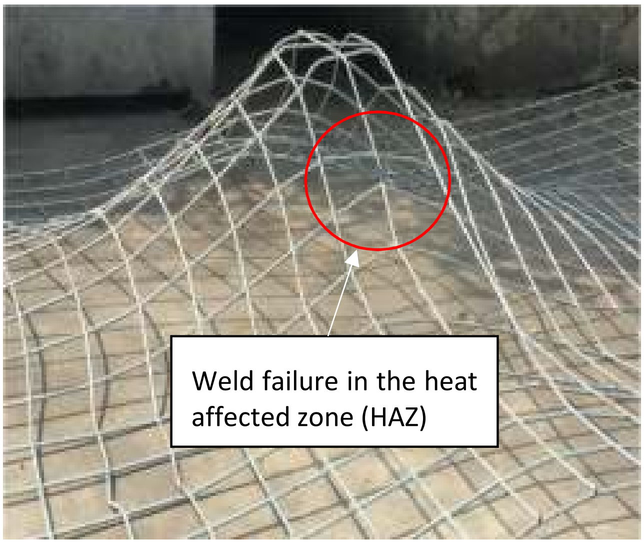


Figure 6 **Sample 3 of Test 1. 5.6mm Galvanized weld mesh achieving a load of 64kN and displacement of 360mm at maximum load capacity. The failure mode of each test are weld failures in the heat affected zone (HAZ)**

All mesh modules were welded together and premature mesh failures were a result of weld and wire breaking within the HAZ. Various weld and wire failures are seen in Figure 7.

Figure 7 **Weld and wire failure mode, breaking the wire in the HAZ**

The failures mode from welded wire caused significant variability in results as seen in Table 1, which were prevalent in the higher tensile 10mm wires. Consistency of test results when evaluating the performance of the 5.6mm and 8mm diameter wires were noticeable. Although the failure mode in the HAZ was similar, results were consistent, most likely due to the automated resistance welding process used in manufacturing the weld mesh sheets. This process provides significant benefits when quality control processes are adhered to, giving the mesh sheet improved load capacity and greater control in test results.

Table 1: Mesh Testing results of the nine mesh variations

Test #	Mesh Description	Load (kN)			Displacement at Max Capacity (mm)		
		Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
1	5.6mm weld mesh; 100 x 100mm aperture; 500 MPa wire; HDG	73	64	64	330	310	360
2	5.6mm weld mesh; 100 x 100mm aperture; 500 MPa wire; HDG with Osro Strap	71	88	78	660	540	380
3	8.0mm weld mesh; 100 x 100mm aperture; 500 MPa wire; HDG	95	88	94	405	400	400
4	10mm Woven Mesh; 100 x 100mm aperture; High Tensile wire; HDG	140	138	137	550	480	583
5	10mm Woven Mesh; 100 x 100mm aperture; High Tensile Wire; Hot Dip Galvanized with Cable strap	200	-	-	300	-	-
6	5mm Chain link mesh; 100mm aperture; Low Carbon wire	37	50	43	580	650	788
7	5mm Chain link mesh and Longitudinal High Tensile 10mm wire module	99	98	156	800	510	860
8	5mm Chain link mesh and Longitudinal/Vertical High Tensile 10mm wire module	150	172	190	550	830	680
9	5mm Chain link mesh and Diagonal High Tensile 10mm wire module	66	92	92	800	840	781

4 Mesh Module Development

Two mesh modules showed promising test results. Test 4, 10mm Woven Mesh; 100 x 100mm aperture; High Tensile Wire; Hot Dip Galvanized and Test 8, 5mm Chain link mesh and Longitudinal/Vertical High Tensile 10mm wire module. Focus in developing these two mesh modules was undertaken.

Due the failure modes when testing, various wire strengths and steel grades were evaluated to increase the load and provide greater consistency in results. This resulted in selecting a steel which provided improved temperature resistance and higher ductility. Although loads increased and consistency of results improved, wire failure modes remained within the HAZ. To further improve consistency of results, a change in the manufacturing process of the mesh modules was reviewed.

The change involved introducing pre-bent looped wires into the manufacturing process. This significantly reduced failures of wire within the HAZ, increased achieved loads and provided more consistency of results and sheet displacement. The two sheets are named as follows:

1. WM Module – 10mm Woven Mesh; 100 x 100mm aperture; double welded wires; restraining loops at hold down points.
2. ST Mesh Module – 5mm chain link mesh; 10mm wire loops laced vertically and horizontally through the chain link mesh; spiral twists pressed around the locking/opposing wire.

The ST mesh seen in Figures 8 show the wire loops, restraining parallel wires and joining of wires at junctions through looped ends. These ends are pressed together to close up wire loops, which provides stiffer loading results as seen in Figure 9.

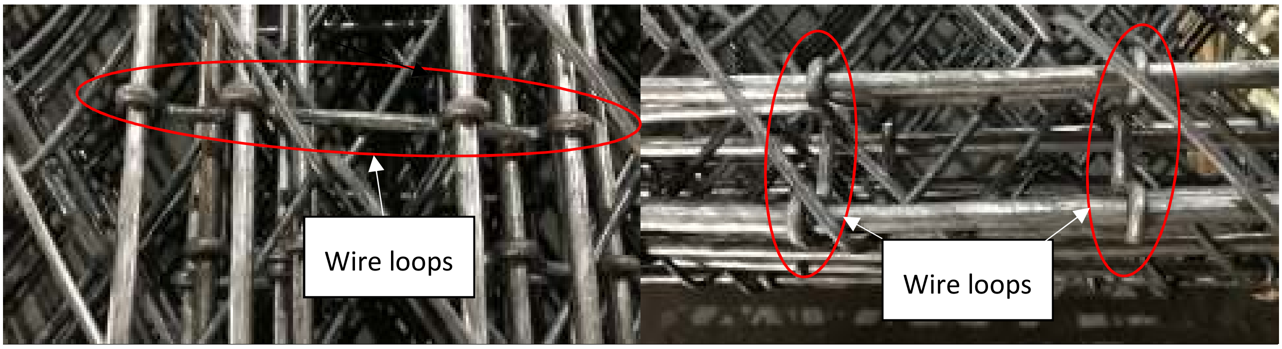


Figure 8 ST Mesh spiral twists in 10mm wire shown interlocked with parallel wires and pressed together

Figure 9 ST Mesh spiral twists in 10mm wire shown interlocked and pressed together

The Woven Mesh module still retains the welded wire perimeter. The Woven Mesh is a very stiff sheet that allows for easy installation underground. To improve loading at bolting locations, wire loops were introduced into the design to reduce point loading around the bolt and plate and transferring the load back in front of the plate to unwelded wires. Figure 10 shows wire loops after being loaded to 200kN and transferring of load in front of the plate and rock bolts pinning the mesh.

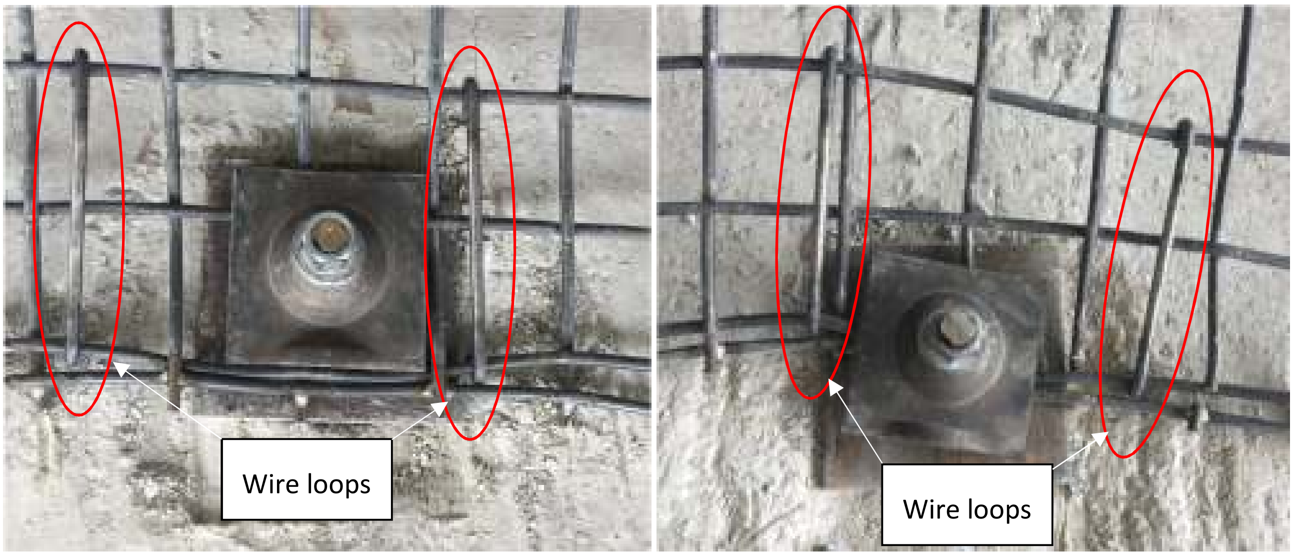


Figure 10 Woven Mesh shown with wire loops transferring load from perimeter wires, to wires in front of the plate to reduce point loading of wires behind the J-Tech bolt

5 Woven Mesh and ST Mesh Static Test Results

The Woven Mesh and ST Mesh modules underwent thorough testing to improve the design and confirm the manufacturing process. Without the Static Mesh Testing Facility, development, validation and ongoing quality control of the mesh modules would not be possible.

The results of ST Mesh testing are shown in Table 2 and corresponding load/displacement graphs are shown in Figure 11. Images of the ST Mesh testing process before and after displacement are seen in Figure 12.

Table 2: ST Mesh testing results from five samples

Test #	Mesh Description	Load Achieved (kN)	Displacement at Maximum Load (mm)	Displacement Total Tested (mm)
1	ST Mesh Module; 2200mm x 2200mm	178.84	450	700
2	ST Mesh Module; 2200mm x 2200mm	175.41	690	699
3	ST Mesh Module; 2200mm x 2200mm	200.70	457	457
4	ST Mesh Module; 2200mm x 2200mm	186.03	435	521
5	ST Mesh Module; 2200mm x 2200mm	171.29	438	536

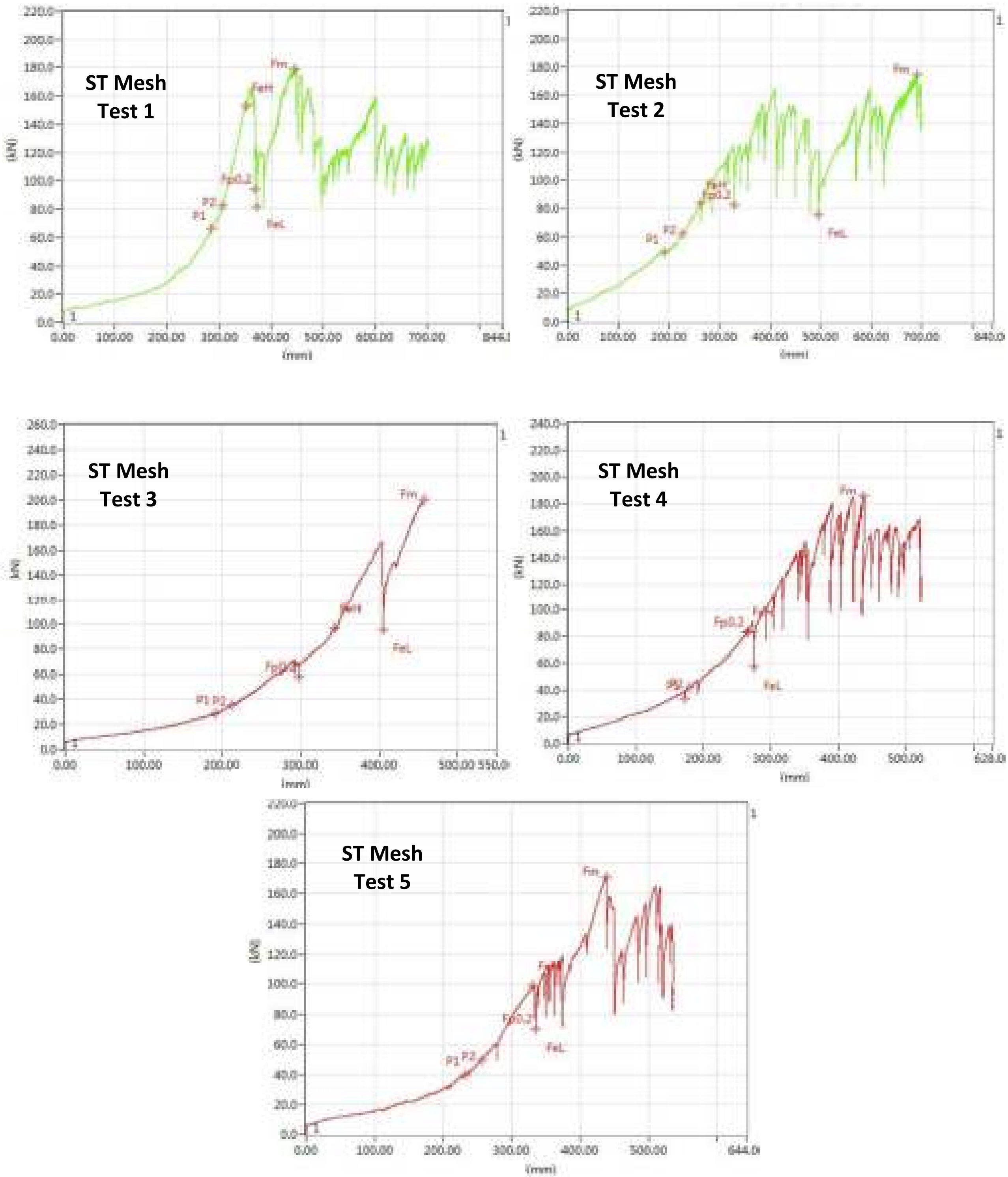


Figure 11 ST Mesh Testing load/displacement graphs corresponding with test results in Table 2

Figure 12 ST Mesh preparation and testing process. Test # 1 shown

Table 3: Woven Mesh testing results from eight samples

Test #	Mesh Description	Load Achieved (kN)	Displacement at Maximum Load (mm)	Displacement Total Tested (mm)
1	Woven Mesh Module; 2200mm x 2200mm	194.29	445	475
2	Woven Mesh Module; 2200mm x 2200mm	204.73	369	369
3	Woven Mesh Module; 2200mm x 2200mm	199.25	492	560
4	Woven Mesh Module; 2200mm x 2200mm	188.26	441	576
5	Woven Mesh Module; 2200mm x 2200mm	192.75	643	682
6	Woven Mesh Module; 2200mm x 2200mm	190.25	462	608
7	Woven Mesh Module; 2200mm x 2200mm	205.92	465	465
8	Woven Mesh Module; 2200mm x 2200mm	198.95	530	582

The results of Woven Mesh testing are shown in Table 3 and corresponding load/displacement graphs are shown in Figure 13. Images from the Woven Mesh testing before and after displacement are seen in Figure 14.

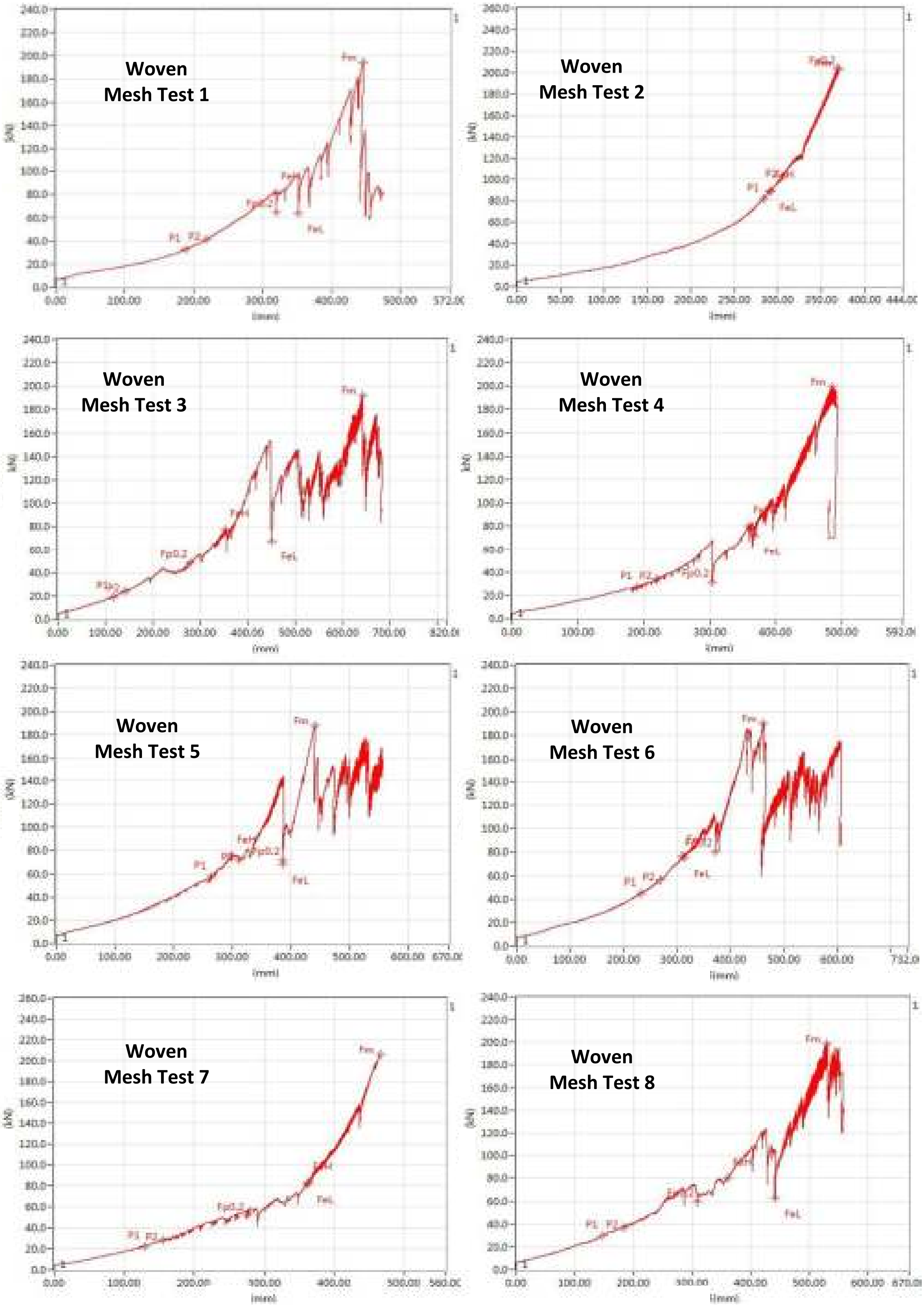


Figure 13 Woven Mesh testing load/displacement graphs corresponding with test results in Table 3

Figure 14 Woven Mesh preparation and testing process. Test # 1 shown

6 Mesh Handling and Installation

The ST and Woven Mesh modules have been designed to allow for easy installation using standard bolting and jumbo machines. There is no requirement to change current installation practices, nor is there a requirement to fit additional aids, structures or equipment to install the mesh.

The mesh module size and weight allow two operators to carry the sheets to the face. The mesh module weight is as follows:

- ST Mesh module 2200mm x 2200mm = 40kg each
- Woven Mesh 2200mm x 2200mm = 65.1kg each

The sheet design allows the mesh to conform to rock face during bolting and pushing against the mesh sheets with the boom after installation.

Chain link mesh is commonly used in mining operations susceptible to dynamic and quazi-static geotechnical domains. Chain link mesh rolls have been successfully installed using an automated roll mesh handling system (Coates et al., 2009), or by manual secondary process methods, but these application requires introducing new systems and equipment to mining operations. The ST Mesh allows the introduction of a chain link mesh using traditional installation practice as seen in Figure 15.

Figure 15 Installation of Woven Mesh and ST Mesh modules

To further ensure operator safety, the Woven Mesh is flush cut, similarly to weld mesh supplied from quality manufacturers. The ST Mesh is supplied with plastic caps on exposed wires on two sides of the sheets, preventing operators from potential puncture wounds or cuts from cut wires, as seen in Figure 16.

Figure 16 Plastic caps inserted over each individual wire for operator safety and frames for underground transport

7 Improvement and continued development

Throughout the facility development and testing process, improvements were required to test mesh modules which started exceeding 200kN. A decision to build an improved facility to accurately test and understand mesh capacity at higher loading was undertaken. The new and improved mesh testing facility as shown in Figures 17, show the following improvements:

- Increase load capacity to 1000kN.
- Increase stroke capacity to 1200mm.
- Increase test bed size and mass to 14000kg.
- Replace mesh protective mesh screen with Perspex to improve test viewing and eliminate small pieces of steel from potentially passing through the mesh panels when mesh testing.
- Place curtains around the perimeter of the test facility to improve viewing and images.
- Cover concrete test bed with a steel plate to prevent damage to the concrete from regular testing.

Figure 17 Improved mesh testing facility with 1000kN hydraulic cylinder, larger test bed with steel plate cover, viewing platform and Perspex protective screening around the perimeter

To improve production initiatives and installation stiffness, a second detailed review of welding of mesh panels was completed. Standard wire grades used for traditional 5.6mm weld mesh, fail prematurely with the larger wire diameters. Further research and testing of additional specialty steel grades and welding wire was conducted, until a suitable steel grade and chemistry was suitable for the application. Utilising a welding process increases the mesh stiffness, reducing the mesh displacement which is in-line with the displacement capacity of selected dynamic support elements. Testing of both Woven Mesh and ST Mesh shown in Figure 18 and 20, include changes in steel wire selection and welding processes to increase mesh capacity, reduce displacement and improve installation performance by providing increased mesh sheet rigidity.

Figure 18 Improved Woven Mesh preparation and testing utilizing the improved test facility

The larger rod size of the cylinder and fixing ensure minimal horizontal movement when testing, this will improve system longevity and results by operating in the lower ranges of the cylinder capacity. Load/displacement graphs utilizing the new test facility are shown in Figure 19 and 21.

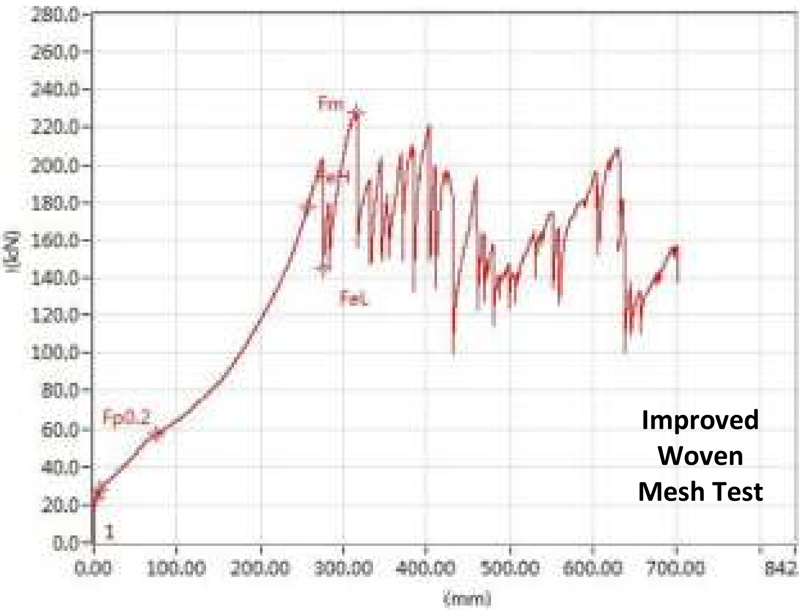


Figure 19 Improved Woven Mesh test result achieving 227kN. The displacement at maximum load is reducing to 320mm, whilst maintaining residual high loading capacity throughout the 700mm test range

Figure 20 Improved ST Mesh preparation and testing utilizing the improved test facility

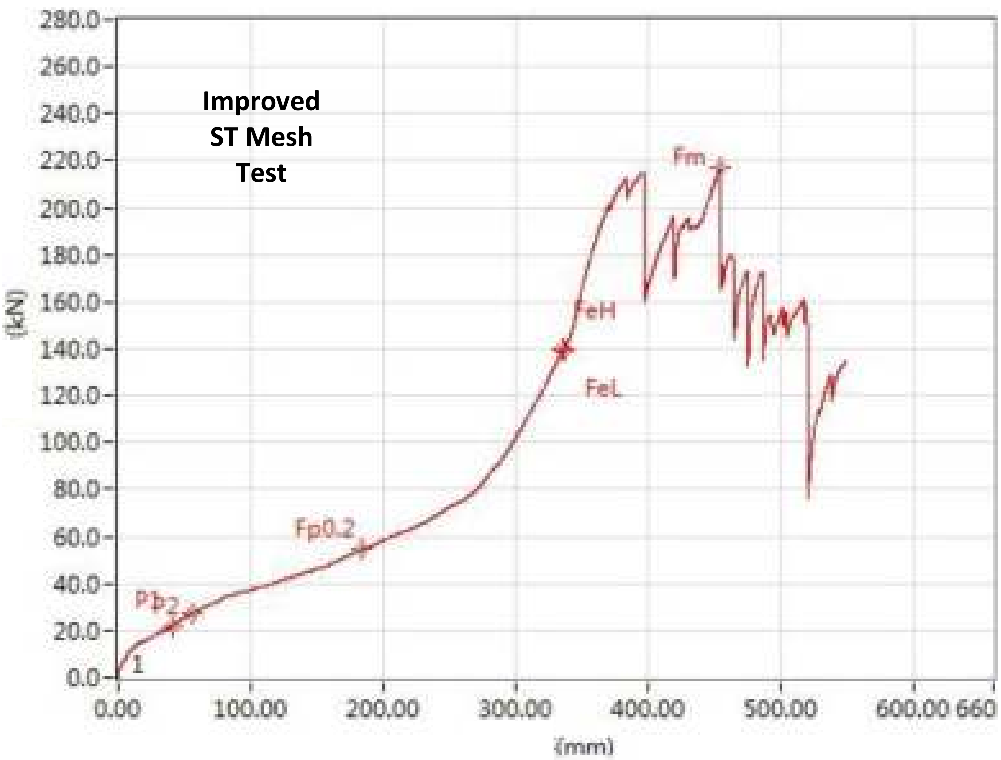


Figure 21 Improved ST Mesh test result achieving 217kN. The displacement at maximum load is 455mm, although loads at 380mm are near to the maximum load capacity

Test five detailed in Section 3 of this paper was completed a second time, now that the mesh test facility could accommodate the higher loading required. The high load capacity allowed the system to be tested to destruction, as shown in Figure 22. The test result of 355kN achieved was slightly above the cable typical breaking load of 330kN. During testing, one strand of the cable failed, triggering all remaining strands over the next 100mm of displacement to fail in tensile loading as seen in Figure 23.

Figure 22 Woven Mesh and 17.8mm cable strap testing utilizing the improved test facility

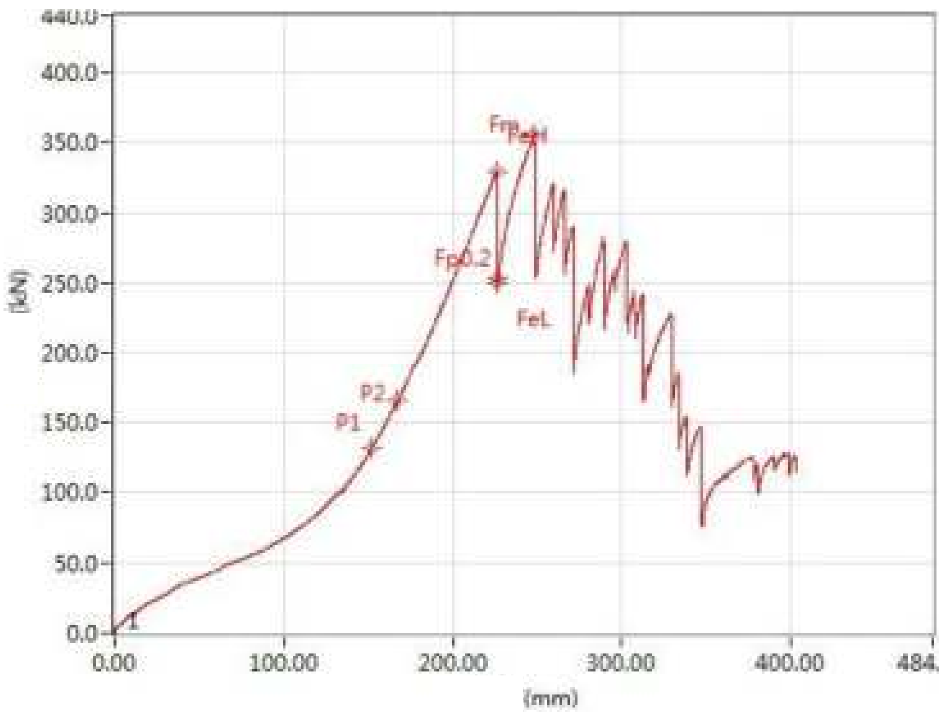


Figure 23 Woven Mesh and 17.8mm cable strap test result achieving 355kN. The displacement at maximum load is 255mm

9 Quality control

Testing of traditional type weld mesh using torque appears to be an industry standard, provided by specifications published by Onesteel/Smorgon Steel. From research conducted, most mesh manufacturers use this method of mesh testing to determine online, post-production and pre-shipment results as indications of weld strength. This is however never used in isolation, with the more scientific test method of weld direct shear testing as prescribed in AS/NZS 4671:2001.

Both testing methods employ different loading directions on the weld when tested as shown in Figure 24.

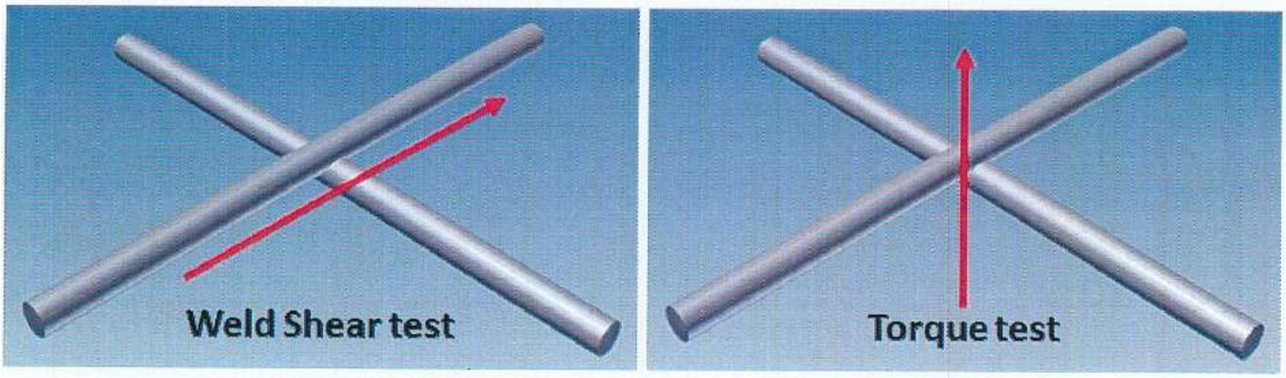


Figure 24 Loading direction on welded when employing different test processes

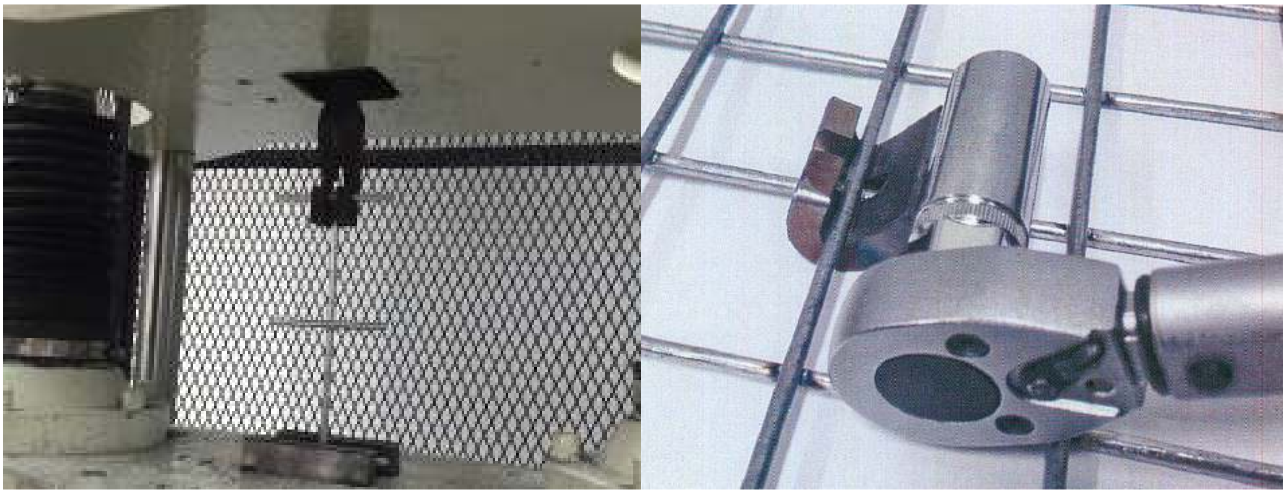


Figure 25 Weld shear and torque test methods employed

Although these test methods support controlling traditional mesh manufacturing quality control, they do not test the full mesh module.

The purpose of designing and manufacturing the mesh testing facility, was not only to support mesh module design, but to provide ongoing testing for quality control purposes. This provides confidence that the product delivered to a mining operation will achieve set specifications.

A flow chart detailing the manufacturing and testing process is shown in Figure 26.

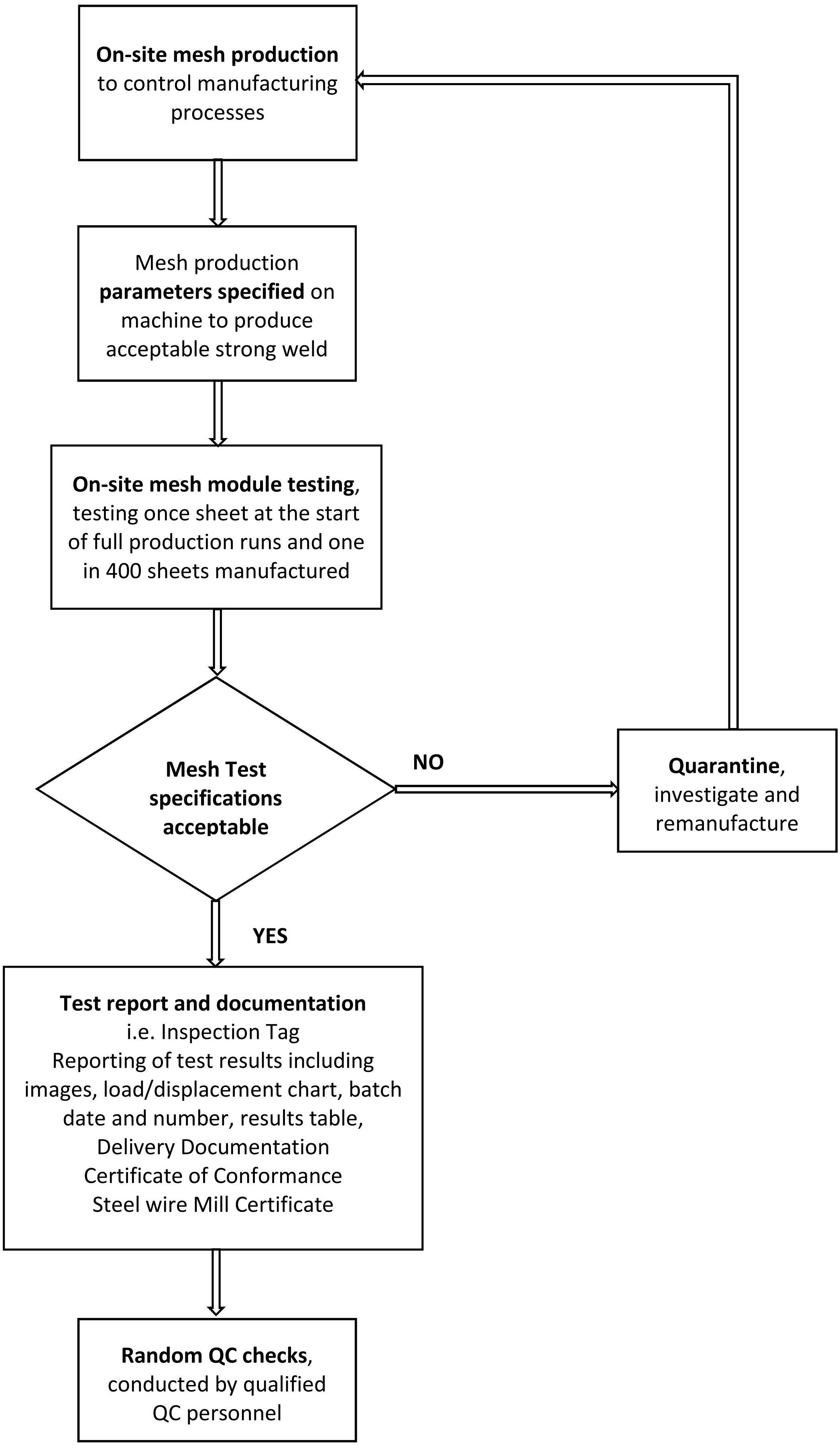


Figure 26 ST and Woven Mesh manufacturing flow chart

10 Conclusion

The static mesh testing facility has allowed safe development of high capacity mesh modules. Mesh modules are now exceeding 200kN and the higher 1000kN test facility was manufactured to compensate for higher test loads being achieved. Further development and validation of higher capacity surface support systems using a bolt to restrain the centre of the sheet, mounted to the platen is to be completed. The improvement by increasing cylinder capacity will support continuation of testing, further improving products and understand static failure modes of surface support systems at higher loads.

The use of the ST and Woven Mesh modules has allowed operations to move away from secondary installation process. Secondary process is frustrating to operators and removes machines away from planned development process, normally required to complete installations of straps or cables to increase the surface support capacity. Eliminating secondary process provides significant operational improvement and cost savings. As many of the secondary tasks have significant manual process, removing the tasks reduces operational hazards and exposure to varying risks.

Having access to test equipment is critical for product development and quality control. Utilising the facility for ongoing quality control provides confidence in both manufacturing process, end products being supplied to mining operations and engineers using the products in their ground support designs.

Acknowledgement

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