Performance of full scale welded steel mesh for surface control in underground coal mines

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Welded steel mesh has been widely utilised in underground coal mines for surface control for a long time. Previous studies on its behaviour were mainly conducted on relatively small sections of mesh in the laboratory. In this paper full scale pull tests on two types of welded steel mesh were performed in the laboratory, with the load-displacement response recorded. In addition to the laboratory tests numerical modelling was also completed. Weld shear tests together with tensile and bend tests on steel wires were also undertaken to provide the input parameters and other relevant information for the numerical models. It was found that the load-displacement curves generated by the physical tests and numerical models matched well. The platen used to pull the mesh was a dome like seat rather than the commonly used flat plate. The influence of the two types of platen on mesh behaviour was investigated numerically, the results showed that the flat plate yielded greater load at first wire failure but for all practical purpose a similar load-displacement curve.

Introduction
Welded steel mesh, being a traditional surface support component, has been used successfully in underground coal mines to help control the roof and rib for many years (Nemcik et al. 2009). It normally consists of longitudinal wires with transverse wires welded to them, it is usually applied in underground mines together with rock bolts or cable bolts. It is common knowledge that it is not practical to stop mining induced fractures from forming but it is possible to enhance the excavation surface condition by applying a support system at an early stage. The objective of rock support in this case is to preserve the rock’s self-supporting ability by limiting the movement of key blocks rather than attempting to hold the dead weight of the loosened rock. Although mesh is a passive support material, it is able to prevent broken rock from falling down and provide confinement to the unstable rock mass. In order to determine the performance capabilities of mesh for underground surface support, an extensive testing program has been completed. This testing program has been complemented by numerical modelling and the results compared.

Tannant (2001) compared the load capacity and stiffness of welded wire, chain link and expanded metal mesh by pulling a 0.3 m by 0.3 m square steel plate through a 1.2 m by 1.2 m section of mesh. It was found that welded wire mesh had the stiffest initial load-displacement response which indicated that welded wire mesh should have better support performance than the other two meshes as it can inhibit rock loosening more effectively. Chain link and expanded metal mesh were reported to have greater displacement at peak load than welded wire mesh. The influence of wire gauge on the load bearing capacity of welded wire mesh was also investigated and the result showed that the peak load increased as the wire diameter went up.

The effect of the size of the area of mesh loading and bolt spacing on the load-displacement behaviour of welded wire mesh was investigated by Thompson (2001). In these tests, rock loading was simulated by pulling a loading frame upwards through a section of steel mesh bolted to a concrete slab floor. It was found that the stiffness of the mesh increased as the bolt spacing decreased. The size of the mesh loading area did not have much influence on the peak load of the mesh but significantly affected the displacement at peak load, specifically a smaller loading area resulted in greater displacement at peak load.

A series of laboratory tests were conducted by Dolinar (2006) to evaluate the influence of bolt tension, the
type of load bearing surface and the size of bearing plate on welded steel mesh performance. In this study, a 0.3 m by 0.3 m square plate with rounded corners was employed to apply the load to the centre of 8-gauge (4.1 mm) welded mesh, which is the most commonly used mesh in U.S. coal mines. The mesh size was 1.5 m by 1.5 m and the bolt spacing was 1.2 m by 1.2 m. The mesh stiffness was calculated from the equation: 
\[ K_s = (L_p - L_{25})/(D_p - D_{25}) \]
where \( K_s \) is the screen stiffness, \( L_p \) is the peak load, \( L_{25} \) is the load at 25% of the peak load, \( D_p \) is the displacement at peak load and \( D_{25} \) is the displacement at 25% of the peak load. This equation was different from that employed in the study of Tannant (2001) in which 
\[ K_s = (L_p - L_{50})/(D_p - D_{50}) \]. The primary conclusions drawn from the study were that bolt tension, bearing plate size and load bearing surface influenced the yield, peak load and the stiffness of the mesh. Increasing the bearing plate size significantly increased the mesh peak load and stiffness as a larger plate enabled the load to be distributed to more wires.

Another study of Dolinar (2009) investigated the effect of wire gauge and configuration, the bearing plate load and bolt spacing on the behaviour of welded steel mesh. A new equation 
\[ K_s = (L_p - L_{20})/(D_p - D_{20}) \]
was used to calculate the mesh stiffness in this study. Also reported was whether mesh slip was a function of bearing plate load. While changing bolt spacing did not alter the load capacity of the mesh, it affected the apparent stiffness of the mesh with wider bolt spacing having lower stiffness. The test results confirmed Tannant’s (2001) statement that increasing the wire diameter can enhance the load capacity of the mesh. It was also found that the addition of reinforcing wires at each end of the welded mesh can contribute to a significant improvement in mesh load capacity and stiffness, but only when the mesh was fixed and no slippage occurred.

Gadde, Rusnak and Honse (2006) applied numerical modelling to study the behaviour of welded wire mesh as it can overcome the practical constraints in the laboratory and it is not as expensive. The accuracy of the numerical modelling was firstly verified by comparing the results from the modelling with those from laboratory tests conducted by other researchers. It is important to note that the modelling in this study was only conducted up to the point where there was a monotonic increase in the load versus displacement curve, i.e. the first peak. The modelling showed that most of the load was carried by the wires lying under the bearing plates, and the small mesh size usually tested in the laboratory produced a higher maximum displacement than that gained in the full size mesh test as there was more restraint in the latter scenario. A recent study (Shan et al., 2014) compared the behaviour of steel mesh and a thin spray-on liner (TSL) in reinforcing strata with weak bedding planes and strata prone to guttering. It was shown that a TSL had better performance over steel mesh in restricting the softening of fractured strata.

Although there are many papers on determining the characteristics of welded mesh sheets, data on the mechanical properties of the steel wire utilised when fabricating the mesh used in underground coal mines is limited. For this reason, tensile and bend tests on the steel wire and shear tests on the welds were conducted in this study to provide input parameters for the numerical modelling. All tests were done in accordance with the corresponding Australian Standards.

As pointed out above (Gadde, Rusnak & Honse 2006), the behaviour of full size mesh in a pull test is different to that of the often used small sections of mesh, and the data on full scale mesh tests are scanty. In this study the performance of full scale mesh in a pull test was investigated. In order to more closely resemble the loading regime in underground coal mines, loading is simulated by pulling a spherical seat instead of the usually used square plate. Two types of mesh (roof and rib mesh) were tested in this study, and the mesh sizes were 1.35 m by 3.6 m and 1.5 m by 4 m respectively.

**Tensile tests on individual wires**

Previous studies (Villaescusa 2004) found that welded mesh has three failure modes; tensile failure of the wire, shear failure at the weld points and failure on the Heat Affected Zone (HAZ). In this study, the tensile
characteristics of 5 mm and 7 mm were investigated. The tensile test was conducted according to Australian Standard AS 1391-2007: Metallic materials - Tensile testing at ambient temperature. The test set up is shown in Figure 1. As shown in the figure, an extensometer was attached to the sample during the test so that the strain could be accurately recorded. The load was applied under displacement control and the loading rate was 2 mm/min up to yield and then rose to 3 mm/min to failure. Five samples for each wire diameter were tested, and it was found that the tensile strength of the 5 mm diameter steel wire was 460MPa and the 7 mm diameter wire was 560MPa. As expected the Young’s Moduli of the wires were both around 200GPa.

![Figure 1 Tensile test set up](image1)

![Figure 2 Bend test set up](image2)

**Bend test on individual wires**

In these tests 5 mm and 7 mm wires were subjected to a three point bend test. The bend tests were done in accordance with Australian Standard AS 2505.2-2004: Metallic materials - Method 2 - Bars, rods and solid shapes - Bend tests. The test set up is illustrated in Figure 2. In these tests, the steel wire was supported by two rollers with a span of 130 mm, and the load was applied to the wire by pushing another roller downward at a loading rate of 10 mm/min, the test terminated at 50 mm displacement. The load versus displacement curves are shown in Figure 3.

It is apparent from the figure that the 7 mm diameter wire is stronger than the 5 mm diameter strand. While the displacements at yield for the two types of steel wire were similar, being around 2.70 mm, a significant difference in yield load existed, approximately 0.41kN for the thinner steel strands and 1.25kN for the thicker. It is also evident that the thicker steel wire is stiffer than the thinner one. From beam theory the deflection at yield, \( y \), can be calculated using the following equation (1)

\[
y = - \frac{PL^3}{48EI}
\]  

(1)

Where P is the load, L is the support span, E is the young’s modulus and I is the second moment of area. Substituting the corresponding values into the Equation (note: the diameter for the thinner steel wire was taken as 5.3 mm, the measured value) the displacements at yield for the two wires are 2.40 mm and 2.43 mm respectively, which are very close to the laboratory results.
The performance of the two diameters of wire in the bend test was also investigated by numerical modelling using Fast Lagrangian Analysis of Continua in 3 Dimensions (FLAC\textsuperscript{3D}), which is an explicit finite difference program. The single steel wire was simulated by the beam structural element in FLAC\textsuperscript{3D}. Boundary conditions corresponding to the physical test were imposed on the nodes of the beam structural elements, namely, no translation in the y-direction and no rotation about the x- and z-axes. The input parameters for the steel strands are listed in Table 1. Figure 4 illustrates the laboratory test results and numerical modelling results, it can be seen that the two results matched well.

**Table 1** Input parameters

<table>
<thead>
<tr>
<th>Steel Strand Diameter (mm)</th>
<th>Young’s Modulus (GPa)</th>
<th>Poisson’s ratio</th>
<th>Plastic moment (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>200</td>
<td>0.3</td>
<td>14</td>
</tr>
<tr>
<td>7</td>
<td>200</td>
<td>0.3</td>
<td>45.5</td>
</tr>
</tbody>
</table>

(Shear testing of welds)

As mentioned above, weld shear is one of the three failure modes of weld mesh. The weld shear strength also plays an important role in rock support as it affects the load transfer mechanism during the loading process. Tests to determine the weld shear strength of steel mesh were based on Australian Standard AS 1304-1991 which stipulates that ‘the minimum breaking load in newtons (N) shall not be less than 250 multiplied by the
nominal area of the longitudinal wire in square millimetres. The test apparatus used in this study was a version of that suggested in the Standard, and is shown in Figure 5. Figure 6 illustrates the test setup and the test results are described in Table 2.

All together 8 samples were tested with 7 samples undergoing failure at the heat affected zone (HAZ failure) and the other one breaking because of tensile failure of the wire. None of the samples experienced weld shear failure, this indicated that the weld shear strength is significantly greater than the failure load stipulated in the standards.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Failure mode</th>
<th>Failure load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HAZ</td>
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</tr>
<tr>
<td></td>
<td>HAZ</td>
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<tr>
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<td></td>
<td>wire</td>
<td>10.2</td>
</tr>
<tr>
<td></td>
<td>HAZ</td>
<td>10.2</td>
</tr>
</tbody>
</table>

**Full scale pull tests on welded steel mesh**

It is common knowledge that the best way to study mesh behaviour is to conduct full scale tests on it. As pointed out above many researchers have performed tests on welded wire mesh in the laboratory, but almost all the mesh sections tested were within a size range up to 1.5 m by 1.5 m. Testing on smaller sections of the mesh was shown to produce different deformation characteristics when compared with larger mesh sections in the laboratory (Tannant 2001) and from numerical modelling (Gadde, Rusnak & Honse 2006). In order to accurately evaluate mesh performance, the sizes of the mesh sections tested in this study were 1.35 m by 3.6 m and 1.5 m by 4 m, which are essentially full size sections as applied to the roof and ribs of coal mines. The load was applied to the mesh by pulling a dome platen upward through the mesh (Figure 7) rather than the usually used flat plate. It was hypothesised that the dome would load the mesh in a manner similar to a failing roof in coal measures rocks.

Figure 7 shows the test setup. The mesh was bolted to a ‘Strong Floor’ with a bolt spacing of 1 m by 1 m. In order to limit slippage of the mesh, a torque wrench was used to apply 240 Nm of torque to the bolts to provide a consistent pre-tension force, timbers were also placed between the bolts to stop them sliding along the holding rails. The dome was used to apply a centre load to the mesh. The tests were run in displacement control mode with a loading rate of 24 mm/min, which is slow enough to simulate static loading while allowing
the test to be conducted in a reasonable timeframe. Load was measured by a 100kN load cell with an accuracy of ±0.2kN and displacement was monitored by a linear variable differential transducer (LVDT) with an accuracy of ±0.6 mm.

Two types of mesh were tested. Mesh type A (roof mesh) consisted of 5 mm diameter longitudinal and transverse steel wires with 7 mm diameter longitudinal reinforcing wires passing below the load bearing plate, and mesh type B (rib mesh) consisted of 4 mm diameter steel wires without reinforcing steel wires. The mesh A section was 1.35 m by 3.6 m and mesh B was 1.5 m by 4 m, in both case bolts were placed at 1.0 metre centres.

All together 5 welded mesh sections were subjected to the pull test, with 4 of them being mesh type A and the other one being mesh type B. The load versus displacement curves are shown in Figure 8. The ‘saw tooth’ in the curves is caused by slippage of the mesh underneath the rock bolt plates and the big drops in load are due to wire failure or mesh slippage. It is obvious from the graph that the roof mesh with larger wire diameter displays greater peak load capacities compared with the thinner rib mesh. In fact, the peak load of mesh A is around 48kN, while the peak load of mesh B is only 21kN, less than half that of mesh A. It is interesting to note that while the difference in peak load for the two mesh types is significant the difference in displacement at peak load is not so remarkable. It is also worthwhile to notice that the two different meshes did not show much difference in stiffness before they experienced displacement of approximately 310 mm, after which mesh B experienced wire failure while mesh A can still accept an increasing load. Another important phenomenon observed during the tests is that almost all of the wire failure of mesh A occurred near the loading dome, however, all the wire failure for mesh B occurred near the load bearing plates. This shows the effect of the 7 mm reinforcing wires in the roof mesh.
The behaviour of mesh A was also studied by numerical modelling using FLAC3D. As the single steel wire subject to bending was successfully simulated with the beam structural element in FLAC3D, the welded steel mesh was modelled as a collection of beam structural elements with links corresponding to the weld points in the mesh. Slippage was not considered in the modelling as it is near impossible to obtain the relevant input parameters. Domed platen loading was simulated by increasing the number of loading nodes as displacement increases. The material properties used in the model were the same as those employed in the modelling of the steel wire bend test. The simulation was only conducted to the point at which the first wire breaks. Figure 9 shows the displacement of the mesh when the first wire broke. The load-displacement curve derived from the numerical modelling was compared with that from one of the laboratory tests. It is evident from Figure 10 that the two curves match well. Specifically, the load at first wire failure is 41.2kN and the corresponding displacement is 460 mm for the model, while the two corresponding values in the laboratory test were 42kN and 456 mm. The stiffness of the curve from the numerical modelling is greater than that of laboratory test, which is due to the fact that while there is no slippage in the model, slippage did happen in the physical test even though significant torque was applied to the bolt to try to prevent the mesh from slipping.
In order to study the influence of the loading plate shape on the behaviour of welded mesh, another model was developed to evaluate the behaviour of the mesh when loaded using a flat plate. The load-displacement curves of the two models are illustrated in Figure 11, it can be seen that they are similar, with only a slight difference in the initial stage caused by the method of simulating the gradual increase of the loading area when using the domed platen.

![Figure 10](image1.png)  
**Figure 10** Comparison of the load versus displacement curves between laboratory test and numerical modelling

![Figure 11](image2.png)  
**Figure 11** Comparison of the load versus displacement curves between dome loading and flat plate loading

**Conclusion**

Welded steel mesh is commonly used for surface support in underground coal mines around the world. Due to its widespread use, scholars have done much work to study the performance of mesh in the laboratory, however, almost all the laboratory tests conducted were not on full scale mesh sheets. It has already been shown that sheet size affects the behaviour of welded mesh in pull tests, so for this reason, this study aimed to investigate the characteristics of full scale welded steel mesh during pull tests in the laboratory and compare the results of the lab tests with those obtained from numerical modelling.

Tensile and bend tests on the steel wires used to fabricate the mesh and weld shear tests were conducted to provide the numerical models with appropriate input parameters. Two grades of mesh sheets were tested in the study, one fabricated using 5mm diameter steel wire with 7 mm reinforcing wires, the other utilising 4 mm diameter steel wire. As expected, the steel wire with the greater diameter accepted a greater load before failure, which ultimately would impact on the load bearing characteristics of the fabricated sheet. With respect to the bend test, the 7 mm diameter reinforcing wire produced a higher yield load compared with the 5 mm diameter wire, and its load-displacement response in the ‘initial-to-yield’ section was also stiffer than the other one. Using the data from the tests, numerical modelling was conducted to simulate the bend test using the beam structural element of FLAC®3D, the load-displacement curves from numerical modelling matched well with those derived from the laboratory test, which indicated that the beam element is able to accurately simulate the steel wire. Welded steel mesh is usually used together with rock bolts in underground coal mines. During the loading process, the load applied to the mesh is gradually transferred to the region near the loading area and eventually to the rock bolt. The load transfer mechanism is closely related to the weld strength between individual wires, thus, investigation of the weld shear strength of the mesh is of significant importance. Of eight weld shear tests conducted in this study none of them failed due to weld failure, demonstrating that the weld of the mesh was of good quality and more than met the test standard. This is confirmed by the fact that there was no weld failure in the pull tests on full scale welded steel mesh. For this reason, weld failure was not considered in the numerical model.

The load-displacement response of two different types of mesh (mesh A and mesh B) was measured by conducting full scale pull tests in the laboratory. In order to simulate the mesh loading conditions of coal
measures rocks, the load was applied by pulling a domed platen through the mesh rather than the usual flat platen. Mesh A, a roof mesh which was fabricated from 5 mm wires, had a much greater peak load, much larger load at first wire failure and slightly stiffer initial load-displacement response than mesh B, a rib mesh fabricated from 4 mm wires. The deformation characteristics of the two meshes were similar, with a displacement at peak load of around 500 mm. The in situ support capacity of the mesh is mainly dependent on the rocks self-support ability and the strength of the mesh wires. Mesh A is better than mesh B for rock support as it had a stiffer initial load-displacement response, which means it can prevent rock unravelling at lesser displacements and help to maintain the self-support ability of the rock mass, the individual wires of mesh A could also accept a higher load before failure.

Numerical modelling was also conducted to obtain the load-displacement behaviour of mesh A. Testing was simulated up to the first wire failure and the curve of the simulation was in good agreement with that of the laboratory tests except that the former appears to be slightly stiffer than the latter, probably because slippage of the mesh was ignored in the model. The difference between dome loading and flat plate loading was also studied numerically. Flat plate loading produced a slightly higher load at first wire failure and stiffer initial load-displacement behaviour. This was a result of the method of simulating the increasing surface area of the dome that came into contact with the mesh as deflection increased. For all practical purposes the difference can be ignored.

References


