PERFORMANCE CHARACTERISTICS FOR WELDED WIRE SCREEN USED FOR SURFACE CONTROL IN UNDERGROUND COAL MINES

D. R. Dolinar, NIOSH, Pittsburgh, PA

ABSTRACT

The fall of small pieces of rock between roof bolts causes over 80 pct of the ground fall injuries in underground coal mines. Roof screen, if installed on the bolting cycle, can significantly reduce the number of these injuries. As the surface of the roof fails, the screen will have to retain the broken rock without failing or excessive deformation. Welded wire screen is the most common type of screen material used for roof surface control in underground coal mines.

The load-deformation characteristics and the load capacity of welded wire screen were evaluated in the laboratory in a specially built test frame. In the frame, the square screen sections were held in place by bolts and bearing plates at the four corners while a center load was applied to the screen.

The parameters evaluated included the wire gauge and configuration, the bearing plate loads and bolt spacing. The wire gauge of the tested screen was 4, 6, 8, 9 and 10. Maximum screen capacities for both load and displacement were developed for each of the wire gauge sizes along with the screen stiffness. This information can be used for screen selection and for the evaluation and determination of screen performance.

INTRODUCTION

Each year in underground coal mines there are between 400 to 500 injuries and 1 to 2 fatalities that are caused by the fall of relatively small pieces of rock between the roof supports. Essentially, the fall of these small pieces of rock cause over 80 pct of the ground fall injuries (Compton et al., 2007). In mines where welded wire screen is installed on cycle, the number of these types of injuries has been reduced significantly (Robertson and Hinshaw, 2001). Because of the potential for reducing ground fall injuries, the National Institute for Occupational Safety and Health (NIOSH) has an interest in increasing the use of welded wire screen. As part of this effort, NIOSH is evaluating the performance characteristics of welded wire screen as used in underground coal mines by conducting a laboratory testing program at the Pittsburgh Research Laboratory (PRL).

Tests to evaluate the performance characteristics of various types of screen or mesh have been conducted in both Canada and Australia. The earliest investigation of screen was done in Canada in the early 1980s (Pakalnis and Ames, 1983). In this study, various gauges of welded wire and chain link screen were tested by bolting the screens along a rib in an underground mine and conducting a pull test with a plate in the center of the screen. The welded screen had wire gauges of 4, 6, and 9 with 4 x 4-in wire spacing. The screen was installed and tested with the bolts in a diamond pattern with respect to the screen wire configuration. These tests established the general load-displacement behavior of the screen. Further, a relationship was also developed between the wire gauge or diameter and the screen load capacity.

Another later study, also conducted in Canada, evaluated welded screen performance on a laboratory test frame (Tannant, 1995). A center load was applied to the screen with the screen tested in both square and diamond configurations with respect to the bolts. The bolt load and bolt spacing were also varied in these tests. The welded screen gauges were 4, 6 and 9. While slippage of the screen at the plates was noted during these tests, it could be controlled by the bolt torque. Peak load capacities were determined for each gauge of wire with the load capacity increasing with wire diameter. Screen stiffness changed significantly with orientation of the wires with respect to the bolting pattern.

A test frame was also built in Australia to evaluate welded wire screen performance and the various parameters that could affect that performance (Thompson et al., 1999). Again, a center load was applied to the screen. The screen had a wire diameter of 0.22 in (4 gauge) and a wire spacing of 4 in. This is the most commonly used screen in the Australian mining industry. In these studies, various bolt spacings were used with the welded screen placed either in a square or diamond orientation with respect to the bolts. Bolt loads and bearing plate sizes were also varied. The primary conclusion from this study was that the stiffness is a function of the bolting pattern and screen configuration. Further, slippage of the screen at the bearing plates will affect the stiffness.

In a recent NIOSH study, the performance characteristics of an 8-gauge welded wire screen were evaluated using a laboratory test frame (Dolinar, 2006). The screen was tested in a configuration that simulates the installation in U.S. coal mines with the bolts placed in a square pattern with respect to the screen. The 8-gauge welded screen is the most commonly used screen in the U.S. coal industry. It was found in this study that the plate conditions including the bolt load, bearing plate size and load surface affect the yield and peak load and the stiffness of the welded wire screen. Further, screen performance was altered by whether the screen was fixed or was allowed to slip at the bearing plates.

Numerical modeling has also been used to evaluate screen performance (Murali et al., 2006). An advantage of the numerical modeling is that variables can be examined that are not easy to simulate in a laboratory test. In the modeling studies, the effects of variable screen sizes and wire gauges were examined. The modeling indicated that the displacements will be higher with the smaller screen sections that are generally used in the laboratory tests than for the full screens that are typically installed underground. Further, these models have also shown that most of the load is being carried by the wires that are directly under the bearing plates.

In this present NIOSH study, design parameters and capacities are developed based on laboratory tests to assist in the evaluation and selection of welded wire screen as used in U.S. coal mines. In this case, the effects of the wire gauge, bolt spacing and bearing plate loads on the screen capacity and displacement are evaluated. Further, the effects of alternative wire spacing configurations on screen performance are also examined. Numerical modeling of the welded wire screen is used to assist in the evaluation and interpretation of the results and in establishing some of the design parameters and capacities. Ultimately, the type of information obtained in this and similar studies will be used to develop design criteria to assist mine operates in the selection and use of roof screen in underground coal mines.

TEST FACILITIES AND PROCEDURES

A test frame was installed in the Mine Roof Simulator (MRS) that was designed with the capability of varying the bolt spacing from 4 to 5 ft with 4 bolts used to attach the screen to the test frame (figure 1). A one-foot square load plate with round corners was used to apply a center load to the screen. With the MRS, the screen could be displaced between 20 and 22 in. The tests were run in displacement control with a displacement rate of 2 in/min. This rate is sufficiently slow to assure that the screen is loaded statically and not dynamically. A typical test would take approximately 10 min.

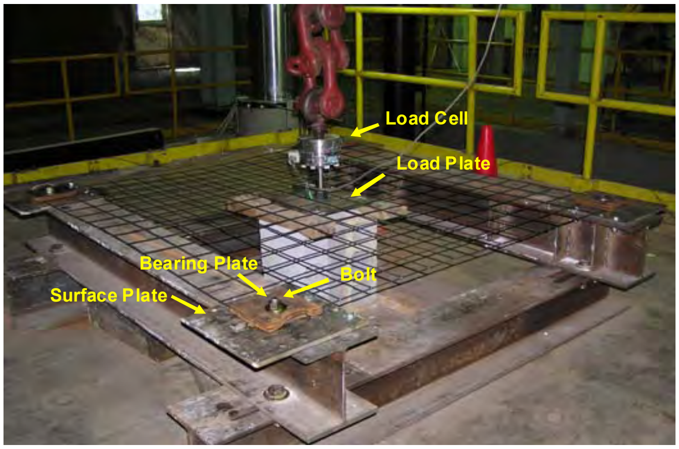

Figure 1. Test frame set up used to test the welded wire screen. Bolt spacing is 48 x 48-in.

The load was measured using a 20,000 lb external load cell with an accuracy of ± 20 lb. The screen displacement was monitored using the linear variable differential transducer for the MRS control system with an accuracy of ± 0.01 in. During the tests, a computer was used to record the load and displacement.

To hold the screen on the test frame, ¾-in diameter bolts were used with bearing plates. The bearing plates were flat, grade 4, 6 x 6-in sections with a thickness of ⅜ in. A 1-½-in diameter washer was installed between the bearing plate and head of the bolt. A steel load-bearing surface that consisted of one foot square plates attached to the frame was used under the screen.

The screen was placed in a square configuration with respect to the wire grid and the test frame and bearing plates that attach the screen to the test frame (figure 2). This is similar to the typical installation in an underground coal mine. With this arrangement, for the welded wire screen, load was transferred from the center load plate to the bolts through the center wires crossing the load plate then to the eight wires that directly connect the bolts and bearing plates.

WELDED WIRE SCREEN

Welded wire screen as manufactured consists of parallel series of high strength steel wires that are welded by machine into square or rectangular grids. In general, the important parameters for the welded screen are the cross-sectional area of the wires or gauge size and the wire spacing. The wire gauges used in this series of tests were 4, 6, 8, 9 and 10. Table 1 gives the wire diameter and cross-sectional area and the cross-sectional area per foot of screen for each gauge.

The wire spacing is designated by the longitudinal and transverse wire spacing. These terms are related to the manufacturing process and direction. For the longitudinal direction, the wire is continuously fed through the automatic welding machines from individual spools of wire. The transverse wires enter one at a time from the side of the machine and are individually welded to the longitudinal wires (Wire Reinforcement Institute, Inc., 2008). Because of the manufacturing process, it is much easier to alter wire spacing or add wires in the transverse direction than in the longitudinal direction. A 4 x 4-in wire spacing was tested for all 5 gauge sizes. For the 8-gauge screen, a 4 x 2-in pattern was also tested. In this case, the transverse wires were spaced at 2 in. Further, 8-gauge screens were tested with the 4 x 4-in spacing, but with two additional transverse wires near each end. This resulted in a 2-in wire spacing for a distance of 8 in from the two screen ends. The size of the welded screen tested was 60 x 60-in. A typical welded wire screen used underground will be 5 ft wide and 12 to 15 ft long. The weight of each type of screen is given in table 1.

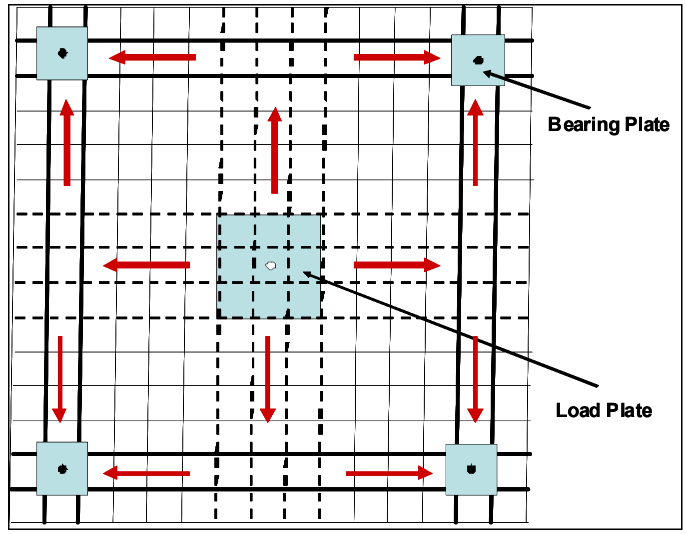

Figure 2. Schematic of screen test configuration with a square bolting pattern with respect to the screen. Heavy bold lines indicate the wires connecting the bolts and the dashed lines the wires crossing the load plate. The heavy arrows indicate the primary load transfer directions along the wires from the load plate to the bolts.

Table 1. Screen, wire, and weld specifications for welded wire screen. Unless noted, the values are for a wire spacing of 4 x 4-in.

Gauge	Diameter (in)	Area (in^2)	Area/ft (in^2)	Minimum weld strength, (lb)	Weight[1] (lb)
4	0.226	0.0403	0.1209	1,400	21.6
6	0.195	0.0299	0.0896	1,050	15.2
8	0.161	0.0201	0.0603	710	10.7
8T[2]	0.161	0.0201	0.0684	710	15.7
8R[3]	0.161	0.0201	0.0905	710	12
9	0.151	0.0177	0.0530	630	9.3
10	0.133	0.0138	0.0398	465	7.6

[1]This is the weight of a 60 x 60-in screen.
[2]The wire spacing is 4 x 2-in with a 2-in spacing for the transverse wires.
[3]The screen is reinforced with 2 extra wires in the transverse direction at each end of the screen.

For welded screen which is used primarily to reinforce concrete, there is no overall strength requirement. However, there are certain ASTM requirements regarding both the weld and wire strength. The weld capacity is based on the shear strength. The weld strength in lbs-force shall not be less than 35,000 multiplied by the nominal area of the wire in square inches when tested with the specified shear test (ASTM A-497-99, 2004). Table 1 gives the minimum weld strength for each wire gauge. The tensile strength of the wire must exceed 75,000 psi with a yield strength of 65,000 psi (ASTM A 83-97a, 2004).

EXPERIMENTAL DESIGN

In the tests, the parameters that were varied included the wire gauge and configuration, the bearing plate load and the bolt spacing. The wire gauge and configuration were given in the previous section. The bearing plate loads used were 4,500, 8,000, 15,000 and 25,000 lbs. The bolt spacing was either 48 x 48-in or 56 x 56-in. The bolt spacing was limited by the size of the screen that was used for the tests. Table 2 shows the test program that was conducted. For each series, 3 screens were tested.

Table 2. Experimental design used for testing and evaluation of the welded wire screen. Tests are designated by the x symbol.

Gauge	Plate Load,lb			
	4,500	8,000	15,000	25,000
Bolt Spacing 48 x 48 in				
4	x	x	x	x
6	x	x	x	x
8	x	x	x	x
9	x	x	x	x
10	x	x	x	x
8T[1]		x	x	x
8R[2]		x	x	x
Bolt Spacing 56 x 56 in				
8				x
9				x
10				x

[1]The wire spacing is 4 x 2-in with the 2-in spacing for the transverse wires.
[2]The screen is reinforced with 2 extra wires in the transverse direction at each end of the screen.

TEST RESULTS

A load-displacement curve for one of the tests is shown in figure 3. From such a graph, several parameters are obtained relevant to screen performance. The peak load is the maximum load just prior to a significant drop in load. The design load is the maximum load prior to any significant decrease in the stiffness of the screen. In some cases, there may even be a higher load than the peak that occurs, but beyond the design and peak loads the behavior is not consistent. The large drop in load is the result of significant screen slippage at the bearing plate or wire breakage. Screen stiffness is determined based on the slope of a line from the design load to a point at 20 percent of design load (figure 3). The screen stiffness is calculated from the following equation:

$$K_s = (L_d - L_{20})/(D_d - D_{20}) \quad (1)$$

where K_s = screen stiffness, lb/in,
L_d = design load, lb,
L_{20} = load at 20 percent of design load, lb,
D_d = displacement at design load, in, and
D_{20} = displacement at 20 percent of design load, in.

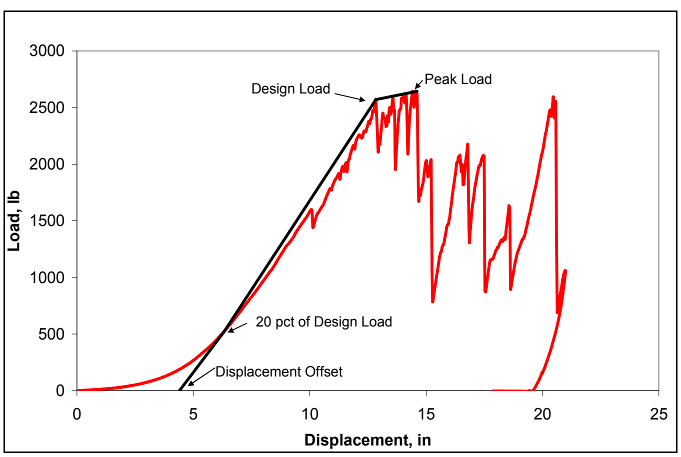

Figure 3. Load displacement curve for a test on a welded wire screen showing key parameters used to evaluate the screen performance.

A displacement offset (D_o) is defined as the intersection of the line used to calculate the stiffness and the x-axis (figure 3). The offset is the amount of deformation that will occur before the screen begins to significantly resist the load.

Table 3 (see Appendix) gives the average peak and design loads and the displacements along with the calculated stiffness and offset displacements for each series of tests. The standard deviations for specific parameters are given in parentheses.

EVALUATION OF TEST RESULTS

In evaluating the effects of the bearing plate load, wire gauge and configuration, and the bolt spacing, the design load is used and not the peak load. This is because there is a significant reduction in stiffness after the design load, indicating that the screen performance is being dominated by the slippage of the screen or the screen has been damaged sufficiently by wire breakage. Past the design load, the screen offers on average little resistance to further displacement. In several cases where the screen is tested under displacement control, there is a nearly zero or even negative screen stiffness beyond the design load. Under a dead weight rock load as would occur underground, the screen behavior should be plastic or nearly plastic after the design load. Once the rock load exceeds the design load, the screen could continue to deflect resulting in large displacements. Ultimately, the screen displacement would be stopped if a higher load, than the design load such as the peak or maximum load is approached because of the increase in stiffness or if the screen failed.

Bearing Plate Load

The behavior of the screen is in part controlled by whether the screen will slip or is fixed at the bearing plates (Dolinar, 2006). Bearing plate loads can control the degree the screen will slip or is fixed. Figure 4 shows the load-displacement curves for different bearing plate loads for the 8-gauge screen with a 4 x 4-in wire spacing and a 48 x 48-in bolt spacing. For the highest plate load, there is less displacement up to the design load and the sudden drops in load are due to wire breakage. Both conditions indicate that the screen is fixed at the bearing plate. For the fixed condition, wire breakage controls the design and peak load. For the lower plate loads, there is more displacement and the sudden drops in load are the result of the slippage of the screen at the bearing plates. The onset of noticeable slippage for the 4,500 lb plate load is about 600 lb and for the 8,000 lb plate load about 900 lb. Even before noticeable slippage, there is more displacement with the lower plate loads than for the fixed condition, indicating that there is displacement of the wire under the plates. There is, however, controlled slippage through the design load. After the design load, there is a much larger variability in the load. This significant change in behavior and the drop in screen stiffness is the result of a weld point or junction slipping out from under a bearing plate.

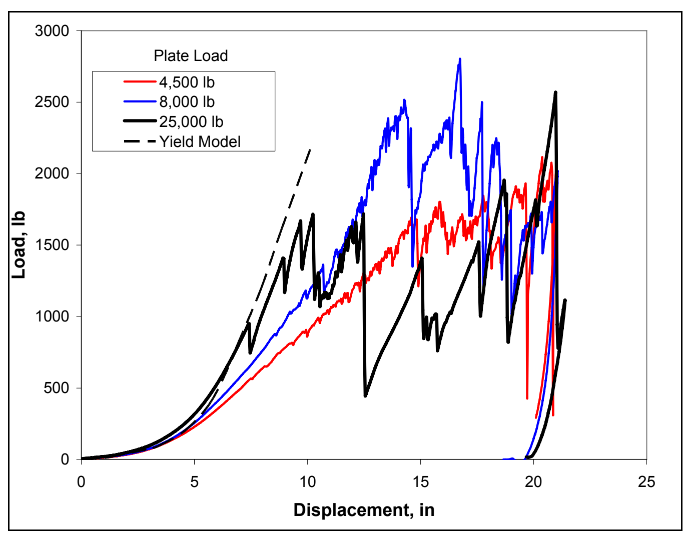

Figure 4. Load-displacement curves from selected tests on an 8-gauge wire screen at bearing plate loads of 4,500, 8,000 and 25,000 lb. The load-displacement curve from the numerical modeling of an 8-gauge wire screen that is fixed at the bearing plates is also shown. The yield model follows the 25,000 lb bearing plate test (fixed condition) fairly closely until the first wire breaks.

Numerical modeling can assist in evaluating the screen behavior (Murali et al., 2006). In this case, FLAC3D was used (Itasca, 2007). Pile and beam elements were used to simulate the mesh. The screen dimensions were 60 x 60-in with the screen fixed at the location of the bearing plates that simulate a 48-in bolt spacing. The steel wire properties were as follows: Young's modulus equal to 29 million psi, Poisson's ratio equal to 0.3, and yield strength equal to 65,000 psi. The wire cross-sectional area, the section modulus and the moment of inertia were calculated based on the wire gauge. The load-displacement curve with yield for a modeled 8-gauge screen is shown in figure 4. The yield model tracks the actual test results for the fixed condition (25,000 lb plate load) fairly closely until the first wire breaks. This again suggests the screen acts as being fixed at the bearing plates. Further, the modeled screen begins to yield at about 720 lb of load. This is well below the design load of 1,790 lb, though just below the load of about 900 lb when the first wire breaks.

From table 3, at the lower bearing plate loads of 4,500 and 8,000 lb, the design load increases with the higher plate load for all the wire gauges. Essentially, slippage of the screen at the bearing plates dominates the screen behavior and limits the design load. The increase in design load results from the additional frictional forces developed from the higher bearing plate loads. For the 8-, 9-, and 10-gauge screen, with the increase in plate load to 15,000 and 25,000 lb, the design load actually decreases. This is the result of sufficient plate load where the screen is either fixed or partially fixed at the bearing plate. In this case, the design load will be limited by wire breakage.

For the 4- and 6-gauge wires, the design load increases through 15,000 lb. Slippage that is affected by the bearing plate load still controls the screen performance. At a bearing plate load of 25,000 lb, the load-displacement curves indicate that some slippage is still occurring in the screen with these lower gauge wires (figure 5). The load-displacement curve from numerical modeling, using the yield criteria for a 6-gauge wire screen, is also shown on figure 5. Above about 1,200 lb of load there is more displacement from the tested screen than for the modeled screen. This again indicates that the screen is not completely fixed. However, it is sufficiently fixed that the larger load-drops at and after failure are the result of wire breakage and not slippage. It requires higher plate loads to fix the larger diameter wire screen at the bearing plates.

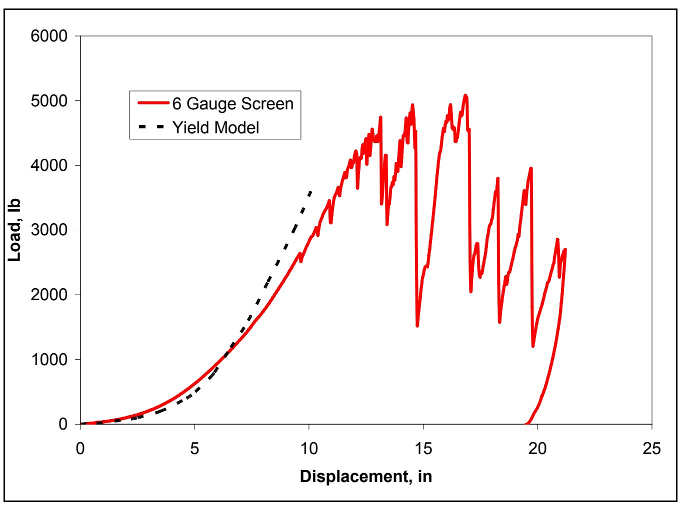

Figure 5. Load displacement curve for a welded wire screen with a 6-gauge wire and a bearing plate load of 25,000 lb. The load-displacement curve from the numerical modeling of a 6-gauge wire screen that is fixed at the bearing plates is also shown. Above a load of 1,200 lb, there is more displacement from the tested screen indicating that the screen is not completely fixed.

Wire Cross-Sectional Area

Figure 6 shows the design load versus the cross-sectional area of the wire per foot of screen for each wire gauge and for each bearing plate load for the 4 x 4-in wire spacing. Regression lines are shown for the 4,500-, 8,000-, and 25,000-lb bearing plate loads. At the lower bearing plate loads, the design load increases linearly and at the same rate with the cross-sectional area. The slope of the lines is just over 29,000 lb/in^2. At the two highest plate loads, the strength increases nearly linearly but at a rate of about 60,000 lb/in^2 and is comparable to that determined from a Canadian study of about 65,100 lb/in^2 (Pakalnis et al., 1983). At the two highest plate loads, the lighter gauge screens are fixed, and thus have a lower strength than the heavier gauge screens that are slipping. All the screens at the lower plate loads are slipping at the bearing plates. Therefore, the rate of strength increase with the cross-sectional area of the wire is dependent on the bearing plate conditions and whether the screen is fixed or slips.

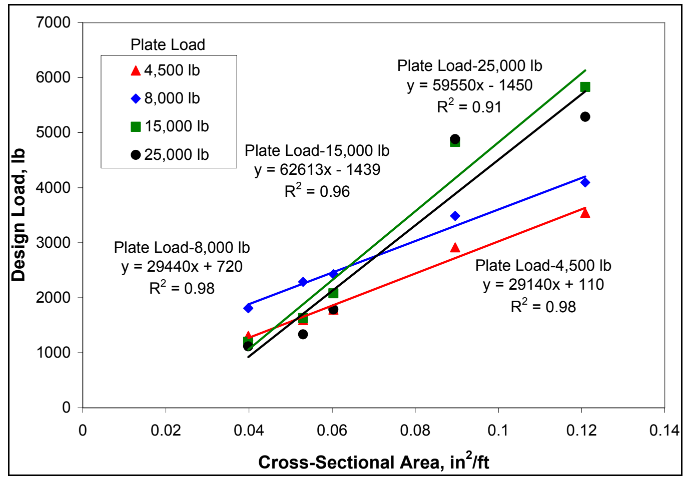

Figure 6. The effects of the cross-sectional area of the wire on the screen capacity using the design load.

Bolt Spacing

Two different bolt spacings were evaluated. However, the screen size limited the maximum bolt spacing that could be tested to 56 in. As a result, a bolt spacing of 60 in could not be evaluated. With an increase in bolt spacing to 56 in, the design loads are not significantly different from those with a bolt spacing of 48 in, when compared at the same bearing plate load of 25,000 lb where the screens are fixed at the bearing plates. However, the screen deflection has increased for the same screen load with the wider bolt spacing. Figure 7 shows the load-displacement curves for an 8-gauge screen for both the 48- and 56-in bolt spacing. Based on the tests for the load range from 200 lb to the design load, the average increase in displacement with the 8-in increase in bolt spacing is 1.21 times.

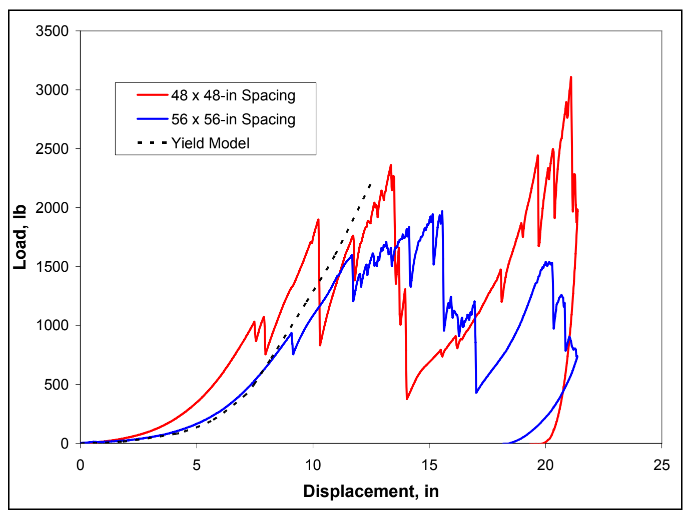

Figure 7. Load-displacement curves for an 8-gauge welded wire screen for both a 48 and 56 in bolt spacing for a bearing plate load of 25, 000 lbs (fixed). The load-displacement curve from the numerical modeling of an 8-gauge wire screen with a 56 in bolt spacing that is fixed at the bearing plates is also shown. The yield model follows the 25,000 lb bearing plate test (fixed condition) fairly closely until the first wire breaks.

The load-displacement curve from numerical modeling of the 56-in bolt spacing is also shown on figure 7. Except for the offset caused by a wire failure, the numerical model results closely follow the load-displacement curve for the wider bolt spacing. Based on numerical modeling, the average increase in displacement for the loads ranging from 200 lb to the design load is for the 8-gauge screen 1.22 times and for the 10-gauge screen 1.23 times. Again, the numerical model results are close to the test results. Therefore, the numerical models can be used to estimate the displacements resulting from the more standard bolt spacing of 60 x 60-in.

Because of geometric considerations, the set-up of the modeled screen a 60-in bolt spacing could not be developed that would be directly comparable to the results with a 48-in bolt spacing. However, a model with a 64-in bolt spacing was developed for an 8-gauge screen. The increase in displacement for this bolt spacing over the 48-in bolt spacing is 1.43 times. The amount of increase in displacement for a 60-in bolt spacing can then be determined by taking the average of the 56-in and 64-in model results. Based on the modeling, the amount of displacement with a 60-in bolt spacing should be 1.33 times higher than the 48-in bolt spacing.

Wire Configuration

Two wire configurations for the 8-gauge screen were tested that were different than the 4 x 4-in wire spacing. For both wire configurations, there are three transverse wires that cross under the bearing plate. This is in contrast to the two wires for the 4 x 4-in wire spacing. For the 8-gauge screen with a 4 x 2-in wire spacing with a plate load of 8,000 lb, the design load of 3,570 lb is comparable to that of the 6-gauge screen of 3,490 lb. Also, both screens have a similar stiffness and design load displacement. The weight of a 60 x 60-in sheet of the 4 x 2-in 8-gauge screen is 15.7 lb and the weight of the 6-gauge screen is 15.2 lb. Both screens are made from about the same amount of steel. However, at plate loads of 15,000 and 25,000 lb, the design load for the 4 x 2-in 8-gauge screen at 3,660 and 2,720 lb are much less than that for the 6-gauge screen of 4,830 and 4,880 lb. In this case, the 8-gauge screen is fixed at the bearing plates and the 6-gauge screen is either not fixed or only partially fixed. Because of the difference in performance at the higher plate loads, it would be better to use a 6-gauge screen with a 4 x 4-in wire spacing rather than an 8-gauge screen with a 4 x 2-in wire spacing. The only minor advantage of using the 4 x 2-in, 8-gauge screen is the retention of very small pieces of rock that might fall through the wider wire spacing.

Figure 8 shows a picture of the 8-gauge screen with the additional transverse reinforcement wires. There are two additional wires at each end of the screen resulting in a wire spacing of 2 in for a distance of 8 in. At the lower bearing plate load of 8,000 lb with the additional wires, the design load is 2,500 lb and the stiffness is 231 lb/in as compared to a design load of 2,430 lb and a stiffness of 258 lb/in with no extra wires. At a bearing plate load of 25,000 lb, with the added wires, the design load is 2,950 lb with a stiffness of 372 lbs/in as compared to a design load of 1,790 lbs with a stiffness of 295 lbs/in with no reinforcement.

At the lower bearing plate load, slippage controls the behavior and there is no benefit achieved with the additional wires. When the screen is fixed at the bearing plate, the added reinforcing wires increased the design load by 65 pct and the stiffness by 26 pct. The increase in strength and stiffness may be attributed to having three wires under the bearing plates in the transverse direction which provides an additional wire to transfer the load to the bearing plates and bolts. Because under the fixed condition wire failure controls the screen capacity, the strength increase is proportional to the number of wires under the bearing plate. Because there is only about 12 pct more material by weight and the reinforcing wires are transverse, there should be little increase in cost yet potentially significant gains in performance with the added wires. However as noted, the benefits are only seen when the screen is fixed.

DESIGN CAPACITIES OF WELDED WIRE SCREEN

The welded wire screen performance and capacity is dependent on the frictional conditions and the load at the bearing plates as well as any stress concentrations that may develop in any screen wires under the bearing plate. In an underground mining situation, these parameters will probably be highly variable and it will be assumed that there will be different degrees of slippage and fixity of the screen at the bearing plates. Therefore, to develop an estimate of in situ screen performance for design purposes based on the laboratory tests, the results from all the bearing plate load conditions will be averaged for a given wire gauge. The design loads will be used as the measure of the screen performance and capacity.

Figure 8. Wire configuration for 8-gauge screen with two additional reinforcing wires at each end of the screen. There are three transverse wires under the bearing plate.

Table 4 (see Appendix) gives the average design loads and displacements as well as the screen stiffness and displacement and load offsets for the different gauges of wire for a screen with a 4 x 4 in wire spacing. The displacements for the 60 x 60-in bolt spacing are 1.33 time that of the 48 x 48-in bolt spacing, the increase in displacement expected with the wider bolt spacing based on the numerical models with confirmation by the laboratory tests. Further, the results are based on using a 6 x 6-in bearing plate. Other studies have shown that a larger bearing plate can significantly increase the screen capacity (Dolinar, 2006).

The design loads and displacements are the suggested maximum values for the screen capacity as used underground and for screen selection. The design loads and displacements set practical limits for screen performance. Beyond the design loads, there is a significant change in behavior caused by wire breakage or slippage of the screen at the bearing plates. This results in excessive displacement of the screen. This does not mean that the welded wire screen cannot maintain higher loads than the design loads and still function in retaining material. The peak loads are on average about 10 pct higher than the design loads. Even higher screen loads were observed beyond the peak loads that are on average about 20 pct higher than the design loads. However, even though the screen may still function by retaining the rock material, there will be excessive displacement and screen damage at these higher loads. Ultimately, excessive screen displacement can become an operational issue. It should be noted that underground performance of the screen could be different than the laboratory test results.

The following equations can then be used to determine the average screen load or displacement from the values given in table 4. Based on the displacement, the screen load can be calculated from equation 2.

$$L_s = K_s \times D_s + L_o \qquad (2)$$

where L_s = screen load, lb,
D_s = screen displacement, in,
K_s = screen stiffness, lb/in, and
L_o = offset load, lb.

The load offset from table 4 is the intercept of the linear load-displacement curves with the load axis (figure 9). The offset load is negative. Based on the screen load, the displacement can be calculated from equation 3.

$$D_s = (L_s - L_o)/K_s. \quad (3)$$

With the offset load being negative the equations can only be used to calculate the screen loads and displacements beyond the offset displacement. In using the equations, it is assumed that it takes no load to reach the offset displacement.

Figure 9 shows the resulting linear load-displacement curves based on table 4 and the above equations for both bolt spacings. Essentially, these load-displacement curves and the values given in table 4 can be used to estimate the screen capacity and performance for the different gauge screen for both the 48 x 48-in and 60 x 60-in square bolt patterns. This information is for screen evaluation and selection as well as design requirements.

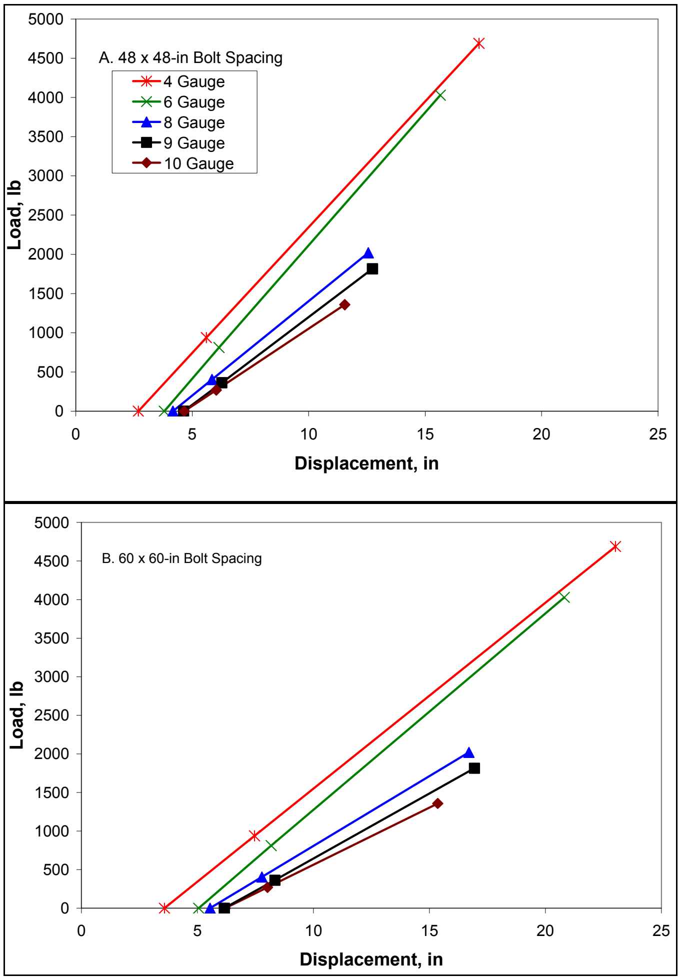

Figure 9. Linear load-displacement curves that can be used in the evaluation and selection of welded wire screen for a bolt spacing of A) 48 x 48-in and B) 60 x 60-in. These curves are based on the average design load and displacement.

With increasing wire diameter, the design load and in general the stiffness increase. For the most common screen used in U.S. coal mines, the 8-gauge wire screen with a 4 x 4-in wire spacing, the design load is just over 2,000 lb at a displacement of 12.6 in for the 48-in bolt spacing. In general, the 8- and 9-gauge screens are fairly close in performance characteristics with the thinner wire screen obviously having less strength and stiffness. The large difference in strength and stiffness occurs between screens with 6- and 8-gauge wires, where the capacity of the 6-gauge screen is approximately twice that of the lighter 8-gauge screen.

CONCLUSIONS

Laboratory tests were conducted to develop load-displacement characteristics that could be used in the evaluation of the performance of welded wire screen. In these tests, the wire size and configuration, bearing plate loads and bolt spacing was varied. Screen capacities are based on the design load and displacement. The design load and displacement is the point on the load-displacement curve where there is a significant reduction in screen stiffness.

Bearing plate loads determined whether the screen slipped or was fixed. In general, a fixed screen will have a lower design load and displacement. When a screen is fixed, the capacity will be limited by wire breakage, and if allowed to slip, the capacity will be controlled by friction and the bearing plate load. Therefore, the bearing plate loads affect the screen capacity and performance.

Bolt spacing primarily affects the amount of screen displacement that occurs. Changing the bolt spacing from 48 to 60-in increased the screen displacement by 33 pct. Essentially, the wider bolt spacing reduced the screen stiffness thus resulting in more displacement for the same load. The wider bolt spacing does not appear to alter the screen load capacity.

For the different wire gauges, there is a linear relationship between wire cross-sectional area per foot and the screen load capacity. However, the rate of increase will vary depending on whether the screens are fixed or slip at the bearing plates. When the screens slip, the load capacity increases at a rate of about 29,000 lb/in^2. At the highest bearing plate loads where the lighter gauge screens are fixed and the heavier gauge screens slip, the rate of increase is nearly 60,000 lb/in^2.

An 8-gauge welded wire screen with a 4 x 2-in wire spacing weighs slightly more than a 6-gauge screen with a 4 x 4-in wire spacing. However, depending on the bearing plate load, the 8-gauge screen will either have an equal or lower load capacity than the 6-gauge screen. Therefore in most situations, the 6-gauge screen should be used rather than the 8-gauge screen with a 4 x 2-in wire spacing.

With the addition of reinforcing wires at each end of a welded screen, improved performance only occurred when the screen was fixed. In this case, the design load and stiffness were significantly increased. This was the result of a third wire under the bearing plate. No increase in the load capacity occurred when the screen was allowed to slip. However, if some additional support may be required, consideration should be given to adding the reinforcing wire, because there is potential for significant improvement in screen performance with only a minimal increase in cost.

Design loads and displacements were established for the welded wire screen for each wire gauge and for two bolt spacings. The design loads and displacements are the suggested maximum values for screen capacity. The screen stiffness and offset displacement were also developed for each wire gauge. This information can be used for screen selection and in the evaluation of the underground screen performance.

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APPENDIX

Table 3. Results of the tests conducted on the welded wire screen. Values are averages for each test series with standard deviations given in parentheses.

Wire gauge	Plate load (10^3 lb)	Design		20 pct of design load		Displacement offset (in)	Stiffness (lb/in)	Peak	
		Load (lb)	Displacement (in)	Load (lb)	Displacement (in)			Load (lb)	Displacement (in)
Bolt Spacing 48 x 48 in									
4	4.5	3,540 (290)	20.1 (1.0)	710	5.3	1.6 (0.3)	192 (13)	3,610	20.7
4	8.0	4,090 (150)	17.0 (1.0)	820	5.4	2.6 (0.2)	291 (20)	4,846	18.6
4	15.0	5,830 (160)	17.2 (0.1)	1,170	6.2	3.4 (0.2)	419 (23)	6,590	19.3
4	25.0	5,290 (320)	15.0 (0.7)	1,060	5.6	3.2 (0.3)	448 (43)	5,290	15
6	4.5	2,920 (470)	17.3 (1.7)	580	5.9	3.0 (0.2)	202 (13)	3,140	19.5
6	8.0	3,490 (390)	16.0 (0.7)	700	6.0	3.6 (0.3)	284 (22)	4,320	19.0
6	15.0	4,830 (390)	15.6 (0.4)	990	6.7	4.4 (0.2)	432 (32)	4,990	16.1
6	25.0	4,880 (950)	13.7 (1.6)	980	6.1	4.2 (0.3)	514(39)	4,950	14.1
8	4.5	1,780 (280)	15.0 (1.6)	360	6.1	3.8 (0.1)	158 (4)	2,100	19.4
8	8.0	2,430 (250)	14.0 (0.6)	490	6.4	4.5 (0.3)	258 (22)	2,640	14.6
8	15.0	2,080 (420)	11.3 (1.4)	420	5.8	4.4 (0.2)	314 (11)	2,380	13.6
8	25.0	1,790 (120)	10.0 (0.1)	360	5.1	3.9 (0.1)	295 (5)	2,020	11.2
8R[1]	8.0	2,500 (160)	14.8 (0.6)	500	6.1	4.0 (0.1)	231 (7)	2,500	14.8
8R[1]	15.0	2,560 (210)	13.2 (1.2)	510	6.0	4.2 (0.1)	284 (18)	2,630	13.6
8R[1]	25.0	2,950 (470)	12.3 (1.4)	590	6.0	4.4 (0.1)	372 (16)	3,120	13.1
8T[2]	8.0	3,570 (470)	16.0 (2.1)	710	6.3	3.9 (0.1)	296 (12)	4,820	20.7
8T[2]	15.0	3,660 (20)	13.4 (0.2)	730	6.0	4.2 (0.1)	397 (15)	4,240	17.8
8T[2]	25.0	2,720 (170)	10.4 (0.1)	540	5.0	3.6 (0.1)	405 (25)	2,720	10.4
9	4.5	1,590 (260)	15.0 (0.9)	320	6.8	4.8 (0.8)	154 (20)	2,040	19.1
9	8.0	2,290 (250)	14.0 (1.3)	460	6.8	5.0 (0.3)	252 (14)	2,450	14.9
9	15.0	1,630 (130)	10.6 (0.4)	330	5.8	4.6 (0.2)	271 (27)	2,130	14.0
9	25.0	1,750 (280)	11.4 (1.1)	350	5.6	4.1 (0.1)	241 (9)	1,890	13.3
10	4.5	1,310 (200)	13.5 (1.1)	260	6.3	4.5 (0.1)	145 (15)	1,760	17.6
10	8.0	1,810 (330)	12.0 (1.0)	360	6.7	5.4 (0.3)	275 (28)	2,020	13.4
10	15.0	1,200 (320)	10.7 (1.4)	240	5.8	4.5 (0.3)	187 (23)	1,300	11.6
10	25.0	1,120 (70)	10.1 (1.2)	220	5.3	4.2 (0.2)	201 (29)	1,170	11.0
Bolt Spacing 56 x 56 in									
8	25.0	1,620 (30)	11.6 (0.4)	330	6.3	5.1 (0.1)	252 (18)	1,740	12.9
9	25.0	1,710 (280)	12.8 (0.7)	380	7.1	5.4 (0.2)	232 (21)	1,970	14.3
10	25.0	1,210 (100)	11.1 (0.5)	240	6.6	5.7 (0.1)	224 (14)	1,210	11.1

[1]The screen is reinforced with 2 extra wires in the transverse direction at each end of the screen.
[2]The wire spacing is 4 x 2-in with the 2-in spacing for the transverse wires.

Table 4. Design loads, displacements and performance characteristics for various wire gauges used for the evaluation and selection of welded wire screen.

Wire gauge	Design		Stiffness (lb/in)	Offset Load (lb)	Offset Displacement (in)	20 pct of Design Load	
	Load (lb)	Displacement (in)				Load (lb)	Displacement (in)
48 x 48-in Bolt Spacing							
4	4,690	17.3	320	-860	2.7	940	5.6
6	4,030	15.7	340	-1,270	3.8	810	6.2
8	2,020	12.6	240	-1,000	4.0	400	5.9
9	1,820	12.7	220	-1,040	4.7	360	6.3
10	1,360	11.6	200	-920	4.7	270	6.0
60 x 60-in Bolt Spacing							
4	4,690	23.0	240	-860	3.6	940	7.5
6	4,030	20.9	260	-1,270	5.0	810	8.4
8	2,020	16.8	180	-1,000	5.3	400	7.8
9	1,820	16.9	170	-1,040	6.2	360	8.4
10	1,360	15.4	150	-920	6.2	270	8.0