LOAD CAPACITY AND STIFFNESS CHARACTERISTICS OF SCREEN MATERIALS USED FOR SURFACE CONTROL IN UNDERGROUND COAL MINES

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ABSTRACT

Screen material in the form of welded wire mesh and geogrids are used in underground coal mines to prevent the fall of small pieces of rock from the roof between roof bolts. Further, if the screen is installed during the production cycle, roof fall injuries can be reduced significantly. Therefore, the National Institute for Occupational Safety and Health (NIOSH), because of the safety implications, conducted an evaluation of screen materials commonly used in U.S. coal mines to determine their support characteristics and identify the parameters that could affect their performance with respect to controlling the fall of rock from the roof surface.

To evaluate the load and stiffness characteristics of the screen, a test frame was designed and installed in the Mine Roof Simulator (MRS) at the NIOSH Pittsburgh Research Laboratory (PRL). With this test set up, the screen is bolted at four corners of the frame and a center load is applied. The test set up allows for up to 20 in of screen deflection while the load and screen defection are continuously recorded.

A series of tests were conducted to evaluate the effects of various parameters such as bolt tension, the type of load bearing surface and the size of bearing plates on welded screen performance. The most common screen material used in U. S. coal mines is an 8-gauge wire welded in a 4-by-4-in spacing or aperture. The peak screen load was normally limited by wire breakage. The conditions at the bearing plate influence the nature of the wire breakage. However, the screen stiffness was controlled by slippage at the bearing plates, and by weld and wire failure. The size of the bearing plate had a significant effect on the performance of the welded screen. Therefore, the design capacity of the 8-gauge screen is evaluated based on plate size. For a 6-by-6-in bearing plate the average peak load is 2,900 lb with a stiffness of 250 lb/in. For an 8-by-8-in bearing plate, the average peak load is 4,500 lb with a stiffness of 430 lb/in. These test results are based on a 4-by-4-ft bolt spacing. A geogrid mesh was also tested.

INTRODUCTION

Each year in underground U.S. coal mines, ground falls cause between 500 to 600 injuries and four to five fatalities. About 80 percent of the injuries and 10 to 15 percent of the fatalities are the result small rock pieces falling between roof bolts. When installed during the production cycle, the roof screen can significantly reduce these types of ground fall injuries (Robertson and Hinshaw 2001). As a result of the safety implications, the National Institute for Occupational Safety and Health (NIOSH) has an interest in promoting the use of roof screen to reduce the risk of ground fall accidents. Therefore, a testing program is being conducted at the Pittsburgh Research Laboratory (PRL) to evaluate the load performance characteristics of roof screen.

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-by-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 conclusions from the study were 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 this NIOSH study, the performance characteristics of an 8-gauge welded screen is evaluated using a laboratory test frame. The screen is tested in a configuration that simulates the installation in U.S. coal mines. The 8-gauge welded screen is the most commonly used mesh in the U.S. coal industry. However, none of the previous studies have tested this gauge of screen nor has screen manufactured in the U.S. been tested. To compliment the evaluation of the 8-gauge welded screen, a geogrid mesh was also tested.

EXPERIMENTAL SET UP AND TEST PROCEDURE

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 frame (figure 1). A one-foot-square load plate with rounded corners was used to apply the load to the center of the screen. With the MRS, the screen could be displaced up to 20 in. The tests were run in displacement control with a displacement rate of 2 in per min. A typical test would take approximately 10 min.

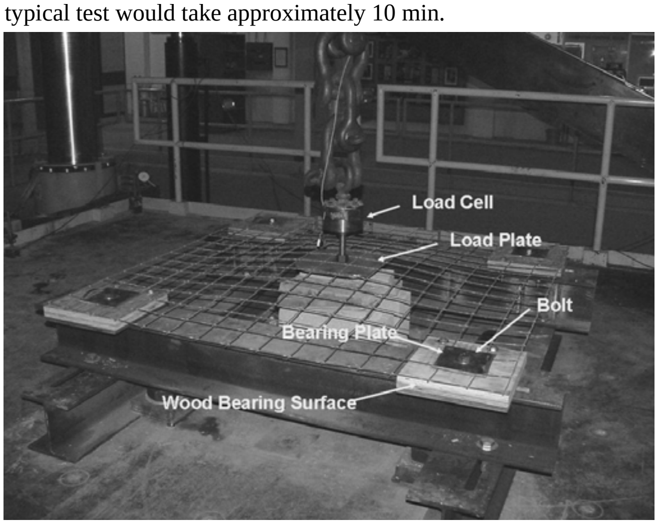

Figure 1. Test frame set up used to test the screen material. Bolt spacing is 4-by-4-ft.

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 transformer 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 and either 6-by-6-in or 8-by-8-in in size with a thickness of 3/8 in. A 1-½ in diameter washer was installed between the bearing plate and head of the bolt. Two types of load-bearing surfaces were used for the tests, either a steel or wood plate. These plates were one foot square and installed under the screen.

The screen was placed in a square configuration with respect to the test frame and bolts (figure 2). This is similar to the typical installation in an underground coal mine. With this arrangement, for the welded 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. The welded screen was sized to allow for a one-square (4 in) extension beyond the bolts on all sides. For the geogrid mesh, the overlap beyond the bolts was approximately 6 inches.

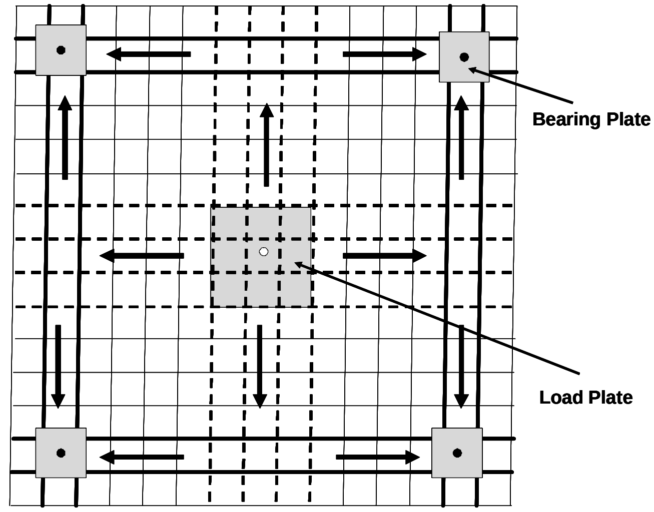

Figure 2. Schematic of screen test configuration with a square bolting pattern with respect to the screen. Heavy bold lines indicate the wires connecting the bolts and the dashed lines the wires crossing the load plate. The heavy arrows indicate the primary load transfer directions along the wires from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

ROOF SCREEN MATERIAL

An 8-gauge wire welded screen with a 4-by-4-in wire spacing was used for most of the tests. The screen wire has a nominal wire diameter of 0.162 in. For welded screen which is used to reinforcement 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 pounds-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). The area of the 8-gauge wire is 0.02 square inches, resulting in a minimum shear weld strength of 700 lb. The tensile strength of the wire must exceed 75,000 psi (ASTM A 83-97a, 2004). For the screens tested, the wire tensile strength based on the manufacturer's specifications was about 89,000 psi.

A geogrid mesh that was made from polypropylene was also tested. The aperture dimensions were 1-in in the machine direction (MD) and 1.2-in in the cross machine direction (XMD) (Tensar Earth Technologies 2005). The minimum rib thickness was 0.07 in. The ultimate tensile strength was 1,850 lb per one ft width (MD) and 2,050 lb per one ft width (XMD).

EXPERIMENTAL DESIGN

In this particular series of tests, a bolt spacing of 4-by-4-ft was maintained. All screens were displaced to 20 in. For the welded wire screen, the factors that were varied included the load surface of the test frame, the size of the bearing plate, and the tension applied to the bolt. The load surface was either wood or steel with either a 6-by-6-in or 8-by-8-in bearing plate. The amount of torque applied to the bolts was either 100, 150 or 200 ft-lb. From a torque-tension test on the bolts utilizing a load cell, a conversion factor of 57.5 lb/ft-lb was determined. This resulted in approximately 5,750, 8,625, or 11,500 lb of load being applied to the bolts and bearing plates from the torque. Because the bolts, nuts, washers and installation methods will be different in a mining situation than those used in this experiment, the torque-tension ratio will also be different. The combination of parameters used in the tests is shown below:

<u>8 gauge welded screen</u>

Series 1. 6-by-6-in bearing plates, steel surface, 5,750 lb of bolt tension,
Series 2. 6-by-6-in bearing plates, steel surface, 8,625 lb of bolt tension,
Series 3. 6-by-6-in bearing plates, wood surface, 5,750 lb of bolt tension
Series 4. 6-by-6-in bearing plates, wood surface, 8,625 lb of bolt tension,
Series 5. 6-by-6-in bearing plates, wood surface, 11,500 lb of bolt tension,
Series 6. 8-by-8-in bearing plates, wood surface, 5,750 lb of bolt tension,
Series 7. 8-by-8-in bearing plates, wood surface, 8,625 lb of bolt tension,
Series 8. 8-by-8-in bearing plates, wood surface, 11,500 lb of bolt tension.

<u>Geogrid Mesh</u>

Series 9. 6-by-6-in bearing plates, wood surface, 8,625 lb of bolt tension.

The number of screens tested for each series varied from 3 to 5.

TEST RESULTS

A load-displacement curve for one test is shown in figure 3. From such graphs several measurements are obtained relevant to the screen performance. The peak load is the maximum load just prior to a significant drop in load. In some cases, there may be a higher load that occurs after this point but beyond this initial peak load, the screen behavior is not consistent. The large drop in load indicates that the screen had some significant damage such as wire breakage. The yield load is identified as the point where there is a significant change in behavior from a general elastic screen response to inelastic behavior.

Screen stiffness is determined based on the slope of a line from the peak load to a point at 25 percent of peak load (figure 3). The screen stiffness is calculated from the following equation:

$$K_s = (L_p - L_{25})/(D_p - D_{25})$$

where
K_s = screen stiffness, lb/in,
L_p = peak load, lb,
L_{25} = load at 25 percent of peak load, lb,
D_p = displacement at peak load, in,
D_{25} = displacement at 25 percent of peak load, in.

A displacement offset (D_o) is determined 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 resist the load significantly.

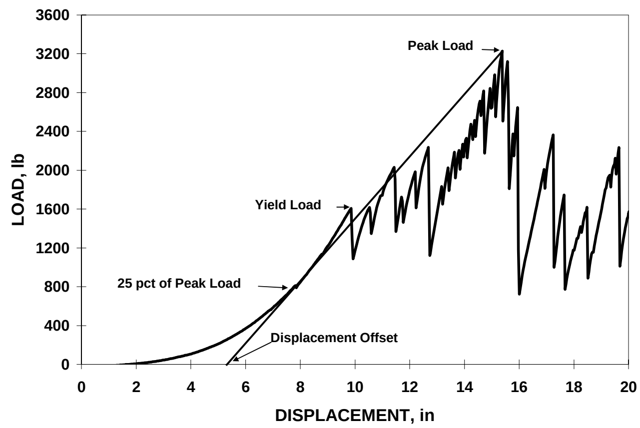

Figure 3. Load-displacement curve for a test on a welded screen showing key parameters used to evaluate the screen performance.

Table 1. Results of screen tests conducted in the MRS. Values are averages for each test series with the standard deviations given in parentheses.

Test	Torque (ft-lb)	Peak load (lb)	Peak displacement (in)	25 pct of peak Load (lb)	25 pct of peak Displacement (in)	Offset displacement (in)	Stiffness (lb/in)	Yield load (lb)	Yield displacement (in)
Welded Screen/6-by-6 Plate/Steel Load Surface									
Series 1	100	2780(467)	18.6	695	7.3	3.5(0.4)	186(36)	820(27)	7.7
Series 2	150	2890(416)	18.2	723	7.4	3.4(1.4)	202(37)	1460(277)	9.3
Welded Screen/6-by-6 Plate/Wood Load Surface									
Series 3	100	3283(782)	19.2	821	8.2	4.9(0.8)	230(75)	1033(153)	9
Series 4	150	3563(475)	16.7	884	8.1	5.4(0.2)	313(20)	1838(309)	10.5
Series 5	200	2100(265)	11.3	525	6.5	4.9(0.2)	325(30)	1800(300)	10.3
Welded Screen/8-by-8 Plate/Wood Bearing Surface									
Series 6	100	5533(350)	19.7	1383	10.8	7.7	452(36)	683(76)	7.3
Series 7	150	5467(115)	19	1333	9.5	6.6(0.2)	435(24)	1733(306)	10.4
Series 8	200	2450(10)	10.8	612	6.1	5.2(.06)	398(59)	2216(404)	10.3
Geogrid/6-by-6 Plate/Wood Load Surface									
Series 9	150	1308(298)	13.1	327	9.8	8.2 (0.9)	234(41)	1308(298)	13.1

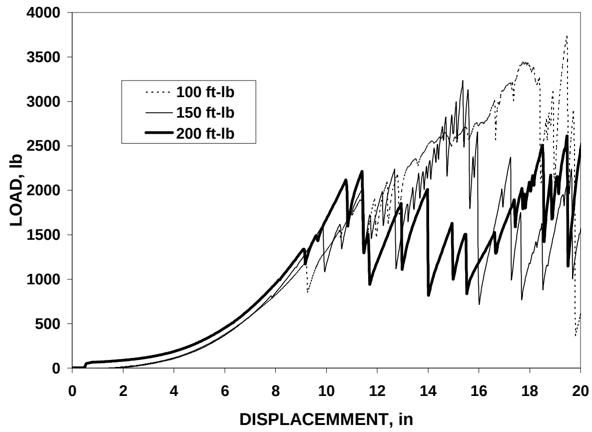

Figure 4. Load-displacement curves for screens tested with a 6-by-6-in bearing plate, wood load surface and bolts torques of 100, 150 and 200 ft-lb.

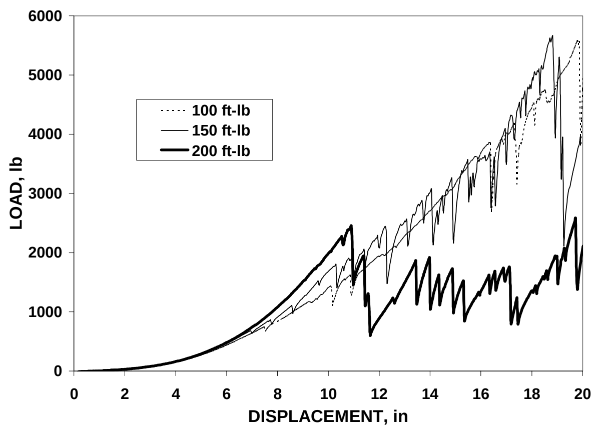

Figure 5. Load-displacement curves for screens tested with an 8-by-8-in bearing plate, wood load surface and bolt torques of 100, 150 or 200 ft-lb.

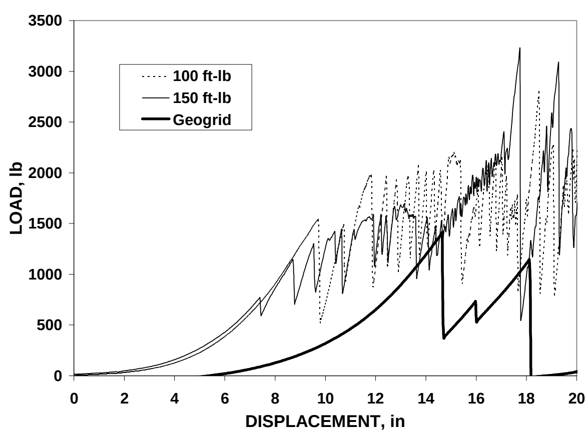

Figure 6. Load-displacement curves for screens tested with a steel load surface and bolt torques of either 100 or 150 ft-lb with a 6-by-6-in bearing plate. The load-displacement curve for a geogrid mesh with a 6-by-6-in bearing plate, a wood load surface and a bolt torque of 150 ft-lb is also shown.

Table 1 gives the average peak and yield loads and displacements along with the calculated stiffness and offset displacements for each series of tests. The standard deviations for specific parameters are given in parentheses. Load-displacement curves for specific tests are shown in figures 4 to 6.

The damage to each screen was also assessed by noting the number and location of the weld and wire failures. Figure 7 shows typical wire breakage to a screen. Figure 8 shows the average number of weld and wire failures per test for each test series. Of a total of 104 wire failures, 102 occurred along the eight wires directly connecting the bolts and bearing plates.

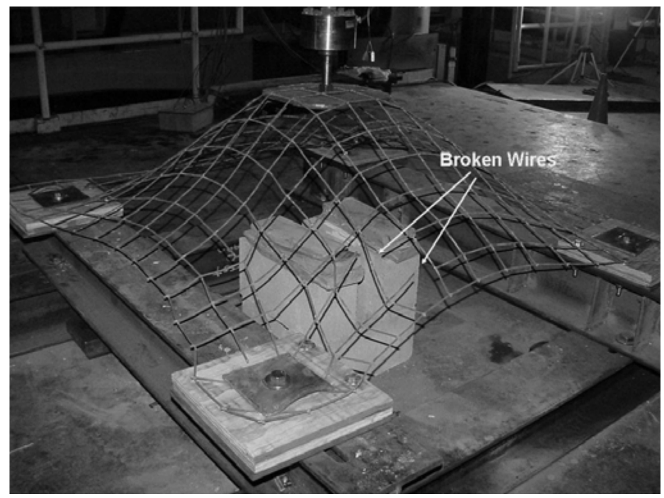

Figure 7. Damage to welded screen in the form of broken wires. The broken wires connect the bolts and bearing plates.

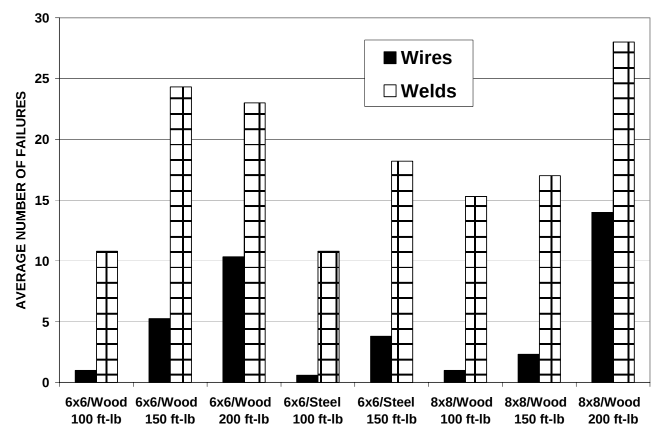

Figure 8. Amount and type of damage noted in each test series. The solid bars indicate the average number of broken wires and the hatched bars the average number of broken welds per test.

DISCUSSION OF RESULTS

The conditions at the bearing plates were varied for the welded wire test series. These conditions determine the yield load and the post-yield behavior as well as the peak load. The geogrid mesh was tested to provide a comparison to the 8-gauge welded screen.

Welded Wire Screen Behavior, Yield, and Failure Mechanisms

For the tests on the welded screen, because the load is applied to the center of the screen and the screen is square with the test frame and the bolt pattern, there are no wires connecting directly from the applied load to the bolts and bearing plates that hold the screen (figure 2). The load transfer occurs primarily from the wires that cross over the center load plate to the center portion of the eight wires that connect the bolts and bearing plates. These eight wires become critical to load transfer. As a result, distortion and shearing of the wire squares especially along the line from the bolts to the center load plate occurs (figure 9). The distortion can result in weld failure. If there are wires running directly from the applied load to the bolts and plates, such as when a diamond bolting pattern is used, the failure modes will be altered (Tannant 1995). Under such loading conditions wire breakage is the dominate failure mode.

Figure 9. Shear distortion of wire squares and slippage of wire from under the plates.

During the initial loading, the screen shows a soft load-displacement response because the wires lay horizontally with respect to the load direction and cannot resist the load. As the screen geometry changes during loading, the wires become more vertical and therefore can resist the load more effectively. This results in an increase in stiffness as more load is applied (figure 3). As the yield point is approached, the stiffness may remain the same or decrease slightly as a result of approaching failure. However, up until yield, the load-displacement curve is fairly smooth. At the yield point, a change in behavior occurs, caused by either slippage of the screen under the bearing plates or from the failure of one of the eight wires connecting the bolts that secure the screen to the test frame (figure 3). This failure or slippage will result in a sudden drop in load. However, welded screen, when wires break has the capability of transferring the load to other wires or when a sudden drop in load occurs from slippage the plate friction and load are sufficient again to allow for the load to build back up again. This periodic slippage or wire failure produces the saw toothed behavior that continues to the end of the test. Further, weld failure will occur during the post-yield phase that will also cause a sudden load drop. However, the larger drops are usually associated with wire breakage. It is the breakage of the wire that will generally limit the peak or maximum load that the screen develops. Slippage and weld breaks produce increased deflection or softening of the screen's load response.

Evaluation of Results

Factors that were varied in the tests included the bearing plate size, bolt torque, the load surface. The modification of the bearing plate conditions altered the screen performance by changing the yield point, post-failure behavior and ultimately the peak load and stiffness.

Changing the load surface and bolt torque, affected the degree of slippage. Slippage was the dominate form of post-yield displacement for the steel load surface and for a bolt torque of 100 ft-lb (figure 6). Increasing torque and changing to a wood load surface increased the yield loads (Table 1). The peak loads did appear to increase with the change in the load surface but only slightly with additional plate load. True peak loads for the steel load surface especially at a 100 ft-lb of bolt torque were not always achieved because of the 20 in displacement limit of the MRS. The reduced slippage and therefore displacement with the change to a wood load surface and increased bolt torque resulted in higher screen stiffness. Further, the degree of damage through 20 in of displacement is also significantly altered by the slippage at the plates. The least damaged screens were those with a torque of 100 ft-lb for either a steel or wood surface (figure 8). However some slippage still occurred at the highest torque level.

For test series 5 and 8 where the bolt torque was increased to 200 ft-lb with the wood surface, the wire squares directly under the bearing plates did not move with respect to the test frame and load surface and these squares were not distorted. Essentially, the screen was fixed under the plates. Slippage did occur to the wires leading from these fixed squares to the edge of the plate. As a result of the screen being fixed the peak load dropped significantly to an average of 2,275 lb while the average number of broken wires was at least double that of any other tests (figure 8.) Essentially, the yield load is controlled and yield behavior is dominated by wire breakage where the screen is fixed (figures 4 and 5). Without sufficient slippage at the plates, the system may be to stiff resulting in higher load concentrations in sections of the wires connecting the bolts thus causing early failure of these wires. Therefore, the failure of the wires will determine the yield and peak load and the post-yield behavior when the screen is fixed and there is little or no slippage to the wire squares directly under the bearing plates. The peak loads for all these tests are similar and may represent the lowest screen strength that could be expected.

At the two lower bolt torque levels where there was sufficient screen slippage at the bearing plates, the larger 8-by-8-in bearing plate significantly altered the screen performance over that of the smaller plates. For the larger plate, an average peak load of over 5,400 lb was achieved about 2,000 lb greater than the average peak loads for the 6-by-6-in plate with similar bolt torques. Further, the stiffness on average is increased by 40 to 95 percent depending on the torque. The larger plate provides better coverage across the wires and therefore the load is distributed more uniformly to more wires than the 6-by-6-in bearing plates while the wire lengths are shortened thus reducing the displacement. Also, the larger plates appear to be able to provide better control over the slippage.

The geogrid mesh tested has a lower peak load (1,308 lb) and stiffness (234 lb/in) than the 8-gauge welded wire screen tested under similar conditions (series 4). The peak load is at the yield load while there is no slippage at the plate. At yield the geogrid mesh fails in shear or by tearing along the edge of the plates resulting in a sudden drop in load (figure 10). The initial damage is sufficient to prevent any substantial increase in load above the yield load with further displacement. Further tests of other geogrid mesh are necessary to identify those that may have a similar capacity to the 8-gauge screen and to identify the factors that can affect geogrid mesh performance.

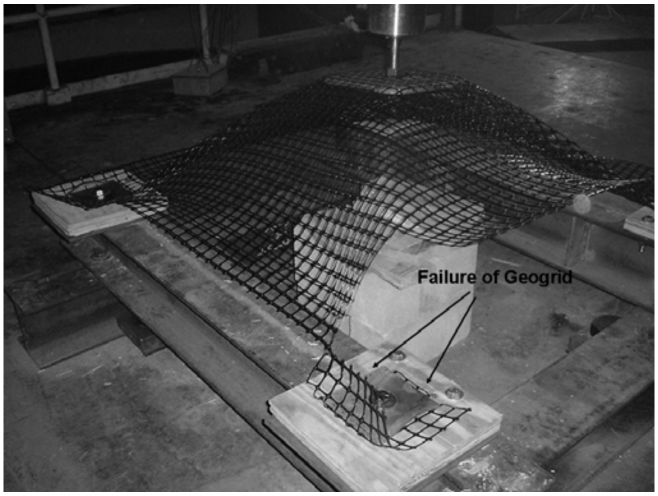

Figure 10. Geogrid mesh sheared along the bearing plate.

DESIGN CAPACITY OF 8-GAUGE WELDED SCREEN

To a large extent for the welded 8-gauge screen, the bearing plate conditions control the performance of the screen in terms of peak load and stiffness. Except for the change in plate size, such factors as the bolt torque level and load surface will probably not be able to be controlled sufficiently in a mine to allow for consistent results. Therefore, for general design purposes, the peak strength and stiffness should be based on an average of all the test results for the same plate size.

For an 8-gauge screen with a 6-by-6-in bearing plate for design purposes, based on twenty tests from series 1 to 5, the average peak load (L_p) is 2,900 lb, the average stiffness (K_s) is 250 lb/in and the offset displacement (D_o) is 4.4 inches. The standard deviation for the peak load is 660 lb, for the stiffness, 64 lb/in and for the offset displacement 0.09 in. The peak load is the design capacity of the 8-gauge screen for the 6-by-6-in bearing plate.

When an 8-by-8-in bearing plate is used the average peak load (L_p) is 4,500 lb, the average stiffness (K_s) is 430 lb/in and offset displacement (D_o) is 6.5 in. The standard deviation for the peak load is 1,540 lb, for the stiffness, 45 lb/in and for the offset displacement, 1.1 in. The average values for the 8-by-8-in bearing plates are based on nine tests.

The total displacement at any point up to the peak load can be approximated from the following equation:

$$D_t = D_o + L_s / K_s$$

where D_t = total screen displacement at given load, in,
D_o = displacement offset, in,
L_s = screen load, lb,
K_s = average stiffness, lb/in.

The total displacement of the screen can be used for design if this is the limiting factor rather than the peak load.

For the peak screen loads developed above, there is no safety factor. A margin of safety can be built into the design capacity by reducing the peak load by the standard deviation. Further, how the screen is installed with respect to the bolting pattern will affect the stiffness and displacement. With these tests, the screen was installed with a square bolting pattern. There are no wires connecting directly from the applied center load to the bolts (figure 2). If a diamond bolting pattern were used, there would be wires running directly from the center load to the bolts and plates. As a result, screen stiffness would be much higher with a diamond bolting pattern (Tannant 1995). However, the square bolting pattern with a center load represents a model for screen performance that should be applicable to U.S. coal mines. The stiffness and offsets are also based on a 4-by-4-ft bolting pattern. These parameters will change with a 5-by-5-ft pattern. Another limitation of these test results and design capacities for both plate sizes is that they are based on a center load and not a distributed load on the screen.

CONCLUSIONS

For this study, the test frame and set up were designed to evaluate screen performance with regard to how the screen is installed in U.S. coal mines. As a result, the screen was placed in a square configuration with respect to the test frame and bolt pattern. A center load was the applied to the screen with a one-foot-diameter plate. With this arrangement, no wires connected directly from the bolts to the center load plate.

For welded wire screen, plate conditions including the bolt torque, bearing plate size and load surface will affect the yield, peak load, and the stiffness. Slippage of the screen at the bearing plate, which is controlled by bearing plate conditions including bolt torque, will reduce the stiffness by allowing more displacement after yield. However, without slippage the peak load can be at or near the yield load because of wire breakage and the peak load will be less than if some slippage occurred. Fixing the screen under the bearing plates at the corners alters the screen behavior. Wire breakage also reduced the screen stiffness after yield. The most effective plate condition for enhancing screen performance was the use of a larger bearing plate. The larger bearing plate increased both the screen peak load and stiffness significantly.

The onset of yield is normally initiated by either slippage or wire breakage with wire failure usually limiting the peak load. Depending on the test, extensive weld failure occurred. These failures in general did not appear to initiate yield but reduced the screen stiffness by increasing the displacement after yield.

Except for the bearing plate size other plate conditions such as the bolt torque and load surface will be difficult to control in a mine. Therefore, the welded screen performance criteria were developed based on plate size only and a 4-by-4-ft bolting pattern. For the 8-gauge screen, with a 6-by-6-in bearing plate, the peak load is 2,900 lb with a stiffness of 250 lb/in. Using an 8-by-8-in bearing plate results in a the peak load of 4,500 lb with a stiffness of 430 lb/in.

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