

## BEHAVIOR OF FULL-SCALE WELDED-WIRE SCREEN FOR LARGE MINE ROOF SKIN FALLS

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### ABSTRACT

From 2013–2017, there were over 1,120 documented injuries, including fourteen fatalities, from ground falls in underground mines in the United States (MSHA 2017). The majority of these ground-fall injuries were not caused by a major roof collapse, but from falls of smaller rocks from the immediate roof. Roof screen can significantly reduce the number of these injuries and has been widely used in underground coal mines for surface control. Because of the potential of reducing ground-fall injuries, the National Institute for Occupational Safety and Health (NIOSH) is further evaluating the performance characteristics of welded-wire screen as used in underground coal mines by conducting a laboratory testing program using the Mine Roof Simulator (MRS) in NIOSH's Bruceton Research Center Laboratory in Pittsburgh, PA.

The load-displacement characteristics of an 8-ft x 12-ft area of 8-gauge welded-wire screen were evaluated using a test frame designed for testing multiple load-pull locations. In previous tests, load-pull contact was always in the center of the bolted screen section. In this study, larger pull contact areas are used to simulate roof falls. The information obtained in this and similar studies can be used to better understand the loading behavior and surface control capability of roof screen in underground mines.

### INTRODUCTION AND BACKGROUND

The large majority of ground-fall injuries are caused by falls of smaller rocks from the immediate roof. Various controls are currently being used in mines to control this surface rock, including the use of wire roof screen. In mines where wire roof screen has been installed, injuries from rock falls have been reduced dramatically (Robertson and Hinshaw, 2001). Roof screen has the potential to prevent hundreds of injuries caused by the fall of small rocks between permanent roof supports (Compton et al., 2007). Because of this potential for reducing ground-fall injuries, the National Institute for Occupational Safety and Health (NIOSH) is evaluating the performance characteristics of welded-wire screen as used in underground coal mines by conducting a laboratory testing program in the Mine Roof Simulator (MRS) in NIOSH's Bruceton Research Center Laboratory in Pittsburgh, PA.

Previous tests to evaluate the performance characteristics of various types of screen have been conducted by the University of Alberta (Tannant, 2001). In this study, the load-displacement properties of welded-wire, chain-link, and expanded-metal mesh were measured by performing full-scale pull tests. A flat steel plate was pulled through a screen test sample that was bolted to a special test frame while the pulling force and mesh displacement were measured. These tests established the general load-displacement behavior of the screen. Peak load capacities and stiffness were determined for each screen type, showing how welded-wire mesh has a much stiffer initial loading response, whereas chain-link and expanded-metal mesh have large displacement capabilities and exhibit significant post-peak ductility.

Three-dimensional (3D) numerical modeling has also been used to evaluate the performance characteristics of roof screen (Murari, Rusnak, and Honse, 2006). Numerical modeling provides an alternative approach in deriving the load-displacement characteristics

of roof screen with reasonable accuracy prior to the initial yield load point. After the yield point, the complexity of the failure mechanism is problematic to model due to the difficulty in determining if the load shed events are caused by wire slippage or the failure of the weld, wire, or any combination of these factors. Based on a 3D numerical model parametric study, load-displacement responses were evaluated by nonlinear numerical models, which showed the importance of boundary conditions at the bearing plates. With most of the load capacity being carried by the wires that are directly under the bearing plates, screen stiffness and yield load capacity could be obtained by ensuring that the maximum possible number of wires are securely held by the bearing plates.

In previous NIOSH studies, laboratory tests were conducted to develop performance characteristics that could be used in the evaluation of welded-wire screen (Dolinar, 2006; 2009). The wire size and configuration, bearing plate loads, and bolt spacing were varied, using a laboratory test frame capable of varying bolt spacing from 4 to 5 feet with four bolts used to attach the screen to the frame. In these studies, the screen capacities were altered by the bearing plate size and load contact type. Also, the screen performance was affected by slippage at the bearing plates.

NIOSH also previously studied the performance characteristics of an 8-ft x 12-ft panel consisting of two sections of 8-gauge welded-wire screen, using a large laboratory test frame with multiple load-pull locations (Batchler, 2018). In these tests, the effects of the displacement loading rate, load-pull contact geometry, and roof channel on the screen load-displacement characteristics were evaluated.

An Australian study measured the load-displacement response of two different wire screen designs from large-scale pull tests (Shan, et al., 2014) and compared them to numerical modeling. Large-scale pull tests were performed on welded-wire screen sections measuring 4.25-ft x 12-ft and 5-ft x 13-ft, using a single dome plate instead of the usual flat steel plate. The load-displacement curves derived from the numerical modeling were similar to the full-scale laboratory tests, with only slight differences resulting from the model not being able to replicate the slippage of the screen under the bearing plates.

In the current NIOSH study, laboratory tests were conducted on isolated sections of screen using various sized pull point contact areas to simulate the effects of larger roof falls. The information obtained in this and similar studies can be used to better understand the loading behavior and surface control capability of roof screen in underground mines.

### TEST FACILITY AND PROCEDURES

A test frame (Figure 1) was installed in the Mine Roof Simulator (MRS) that was designed to accommodate testing an 8-ft x 12-ft welded-wire roof screen panel. A 4-ft bolt spacing was used to secure the screens to the frame. Load was applied to isolated sections of the screened area, using various sized load-pull geometries. With the MRS capabilities, the screen could be displaced up to 20 in. The pull tests were conducted in displacement control with a displacement rate of 2 in/min.

## WELDED-WIRE ROOF SCREEN

One of the most common roof screen designs used in U.S. coal mines is an 8-gauge wire welded into a 4-in x 4-in spacing or aperture with a nominal wire diameter of 0.161 in. There are currently no standards for the properties of welded-wire screen used in mines. The requirements for the strengths of the wire and weld are those developed for concrete reinforcement and are associated with ASTM specifications related to that application. According to these ASTM requirements, the weld strength in pounds-force should not be less than 35,000 multiplied by the nominal area of the wire in square inches when tested in accordance with the designated ASTM tests (ASTM A-497-99, 2004). The area of the 8-gauge wire is 0.0201 in<sup>2</sup>, resulting in a minimum weld strength of 710 lb with a calculated shear stress strength of 528 lb. The tensile stress of the wire must exceed 75,000 psi (ASTM A-823-97A, 2004; Dolinar, 2006).

## EXPERIMENTAL DESIGN

In this series of tests, research was conducted to study the effects of varying the load contact area and position of the load-pull location to simulate a large roof fall. A schematic of the screen test configurations with the bearing plate bolting pattern and an example of the pull contact area is shown in Figure 2. This bolt pattern is consistent with the typical installation currently used in underground coal mines. With this test configuration, the screen loading is transferred from the load area through the corresponding screen wires crossing the loading contact area, then typically to the perpendicular wires that directly connect to the bearing plates (Dolinar, 2006). Figure 3 shows the various configurations of the test layouts and pull locations for this series of tests. The loading is measured with a load cell(s) at each of the pull locations.

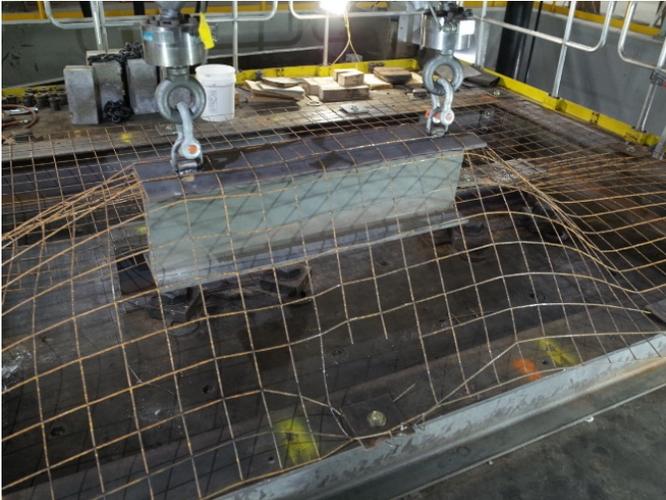
## TEST RESULTS

Ten different test configurations were evaluated during this study as shown in Figure 3. A representative load-displacement response for one of the tests is shown in Figure 4. The test data was analyzed to determine the peak load, stiffness at peak load, yield load, and stiffness at yield load (Table 4). 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 during the initial screen loading. Generally, the yield load is determined by the first major load shed event. Calculated screen stiffness related to the yield load was determined based on the slope of the line from the yield load to a 20% offset displacement (see Figure 4). After the yield load point is reached, there is often a loss of load caused by some form of significant screen damage. Slippage at the bolted interface produces a jagged load response, whereas permanent damage from either wire or weld breakage is seen as a large, sharp load drop. This screen slippage or damage is categorized as a load shed event. The peak load is the maximum load capacity of the screen. It is generally preceded and followed by a load shed event, indicating that some form of failure has occurred. Similarly, the peak load stiffness is calculated from the load reduction due to a major load shedding event prior to the restoration of load leading to the peak load.

Load shed events are then sorted into one of three categories based on the magnitude of the load shed: (1) wire slip event, 15–528 lb, (2) weld break event, 528–1,130 lb, or (3) wire-break event above 1,130 lbs.

## EVALUATION OF TEST RESULTS

Four different parameters were evaluated in the full-scale laboratory test: (1) Effect of the pull contact location related to the bearing plate bolting pattern, (2) Effect of the size of pull contact geometry when centered within the bearing plate bolting pattern, (3) Effect of a single large area contact pull compared to multiple small load contact pull locations, and 4) Effect of a single contact compared to two separate load contacts across overlapped screen sections.

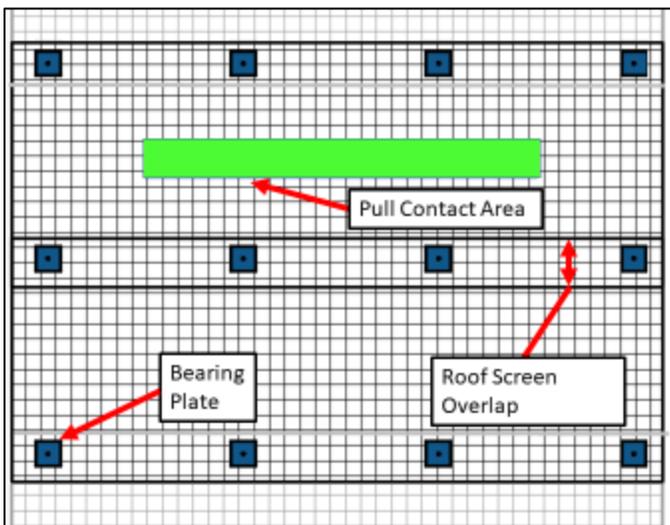


**Figure 1.** Test frame setup used to test the welded-wire screen with large pull contact areas. Bolt spacing was 4 ft x 4 ft.

The screen loading was measured using 20,000-lb load cells with an accuracy of  $\pm 20$  lb, respectively, on each pull chain attached to the loading pull contact area. The screen displacement was monitored using a Temposonics magnetostrictive linear position sensor with a  $\pm 0.01$ -in accuracy. This test data was recorded at a sampling rate of 5 Hz.

The bolts securing the bearing plates and the wire mesh to the frame had a 0.75-in diameter and were placed on a 4-ft x 4-ft pattern. The bearing plates were 6-in x 6-in, grade 4 with a 0.3-in thickness. The load reaction frame was constructed from W12x50 steel beams. In order to limit slippage of the screen, the nuts on the bolts were torqued to 150 lb-ft to generate approximately 15,000 lb of force on each bearing plate.

Two screen sections were placed in a rectangular configuration with respect to the test frame and bolts (Figure 2). With this arrangement, load was transferred from the pull contact areas through the screen, to the bolts and bearing plates. The 8-ft x 12-ft screen panel consisted of two 5-ft x 15-ft screen sections bolted to the test frame. Twelve inches of each screen section overlapped in the middle of the test frame while the 3-ft extra length simply overhung on the test frame. The welded-wire screen positioned on the reaction frame was sized to include a one-mesh square (4-in) extension beyond the bolts on all sides.



**Figure 2.** Schematic of screen test configuration with square bolting pattern with respect to the screen.

screen increased by 22%. However, beyond the yield load, the impact performance of the tests was less consistent. This increased variability occurs as a result of additional wire slippage and damage to the screen wire distortion and shearing of the screen wires.

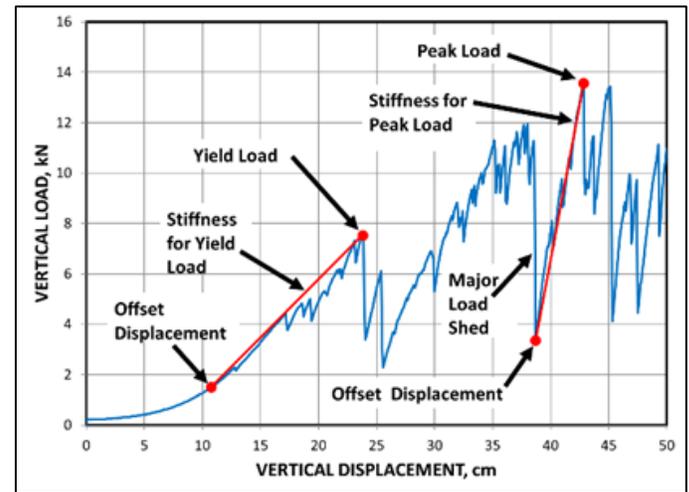


Figure 4. Load-displacement response for a test on a welded-wire screen, showing key parameters used to evaluate the screen performance.

Table 1. Results of the welded-wire screen tests conducted in the Mine Roof Simulator (MRS). Values are averages for each test series.

Test Configuration	Pull Contact Size	Pull Contact Dimensions	Yield Load Capacity	Stiffness at Yield Load	Peak Load Capacity	Stiffness at Peak Load
		inches	kip	kip/in	kip	kip/in
1	Medium	43 x 8	1.31	0.57	5.26	2.99
2	Medium	43 x 8	0.99	0.42	4.32	1.67
3	Small	28 x 8	2.90	0.53	5.89	3.39
4	Small	28 x 8	0.87	0.36	4.04	2.79
5	Large	96 x 8	2.47	0.95	5.19	3.43
6	Medium	43 x 8	4.54	1.56	8.74	6.06
7	Small	28 x 8	3.15	0.76	6.99	4.03
8	Small - Square	12 x 12	2.36	0.40	4.96	1.37
9	Small - Square	12 x 12	3.67	0.85	7.35	4.77
10	Small - Square	12 x 12	2.57	0.61	8.48	3.07

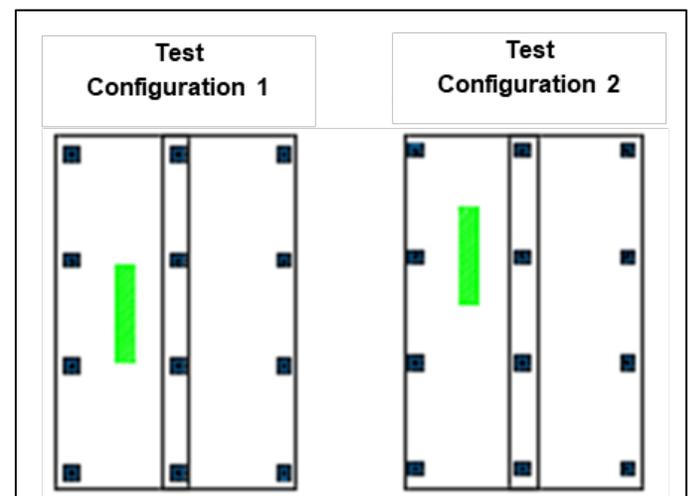


Figure 5. Test configurations to determine the effect of mid-sized pull contact location relative to the bearing plate bolting pattern. (Pull locations shown in green; bolt contact plates shown in blue).

The screen performance behavior for this test parameter was also assessed by evaluating the number of load shed events that occurred from either a wire slip, weld break, or wire break. A load shed event is

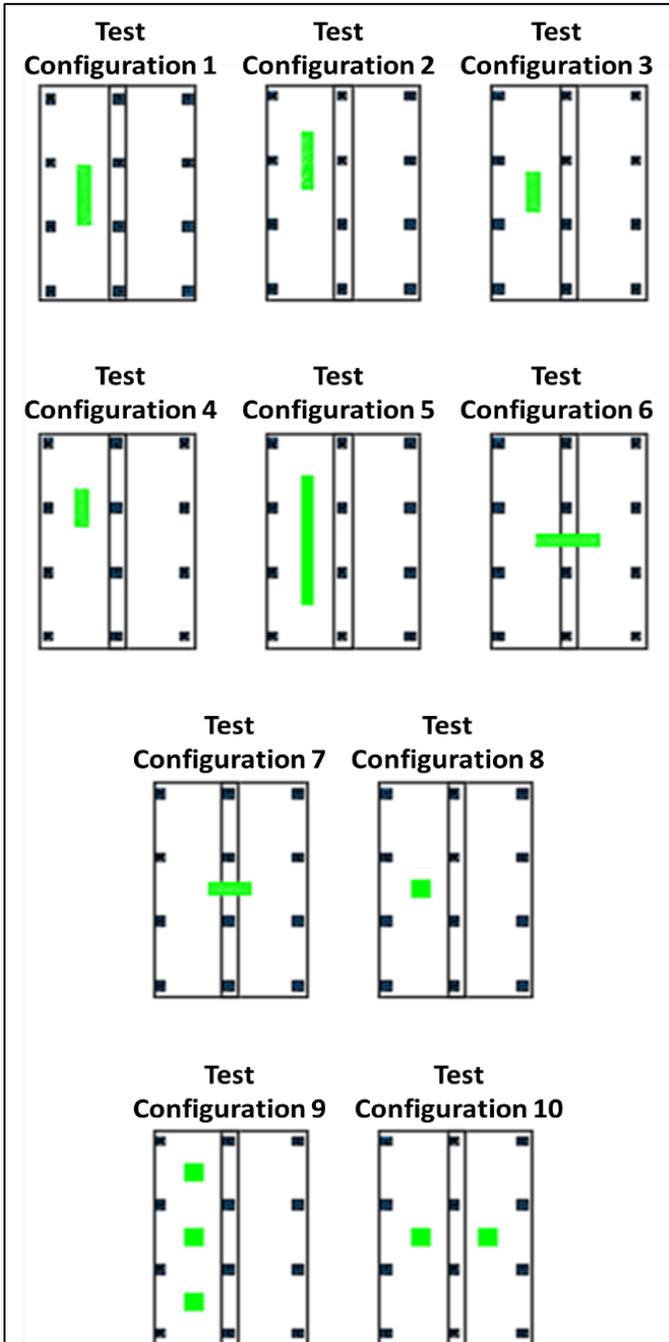


Figure 3. The various tests configurations conducted in this study (pull locations shown in green).

### Effect of Pull Contact Location Relative to the Bearing Plate Bolting Pattern

The performance characteristics for test configuration 1 and 2 (Figure 5) were evaluated to determine the effect of the medium pull contact area relative to the bearing plate bolting pattern. The experimental data indicates that the location of the pull point contact area (43 in x 8 in), relative to the bearing plate bolting pattern, can affect the behavior of the screen. Figure 6 compares the yield and peak load capacity of the two test configurations. Applied load for test configuration 1 (centered load) exhibited a yield load capacity increase of 33% compared to test configuration 2 (loading between bolts) while also increasing the yielding stiffness by 37%. This is conceivably due to the majority of the applied load being distributed between the four bearing plates for test configuration 1 and only two bearing plates for test configuration 2. Also, the observed peak load capacity of the

defined as a sudden drop of load capacity greater than 15 lbf. Figure 7 shows the number of wire slips, weld breaks, and wire breaks per test for both of the test configurations. The location of the pull point contact area relative to the bearing plate bolts did affect the amount of wire break load shed events. From the results shown in Figure 7, there was a 64% increase in wire-break load shed events when the location of the pull point contact is in the center of the bolt bearing plate pattern. For test configurations 1 and 2, the wire-break load sheds occurred within the same displacement range (7.2–19.75 inches), but for test configuration 1 the amount load shed events was more densely populated. However, the number of wire-slip and weld-break events were similar.

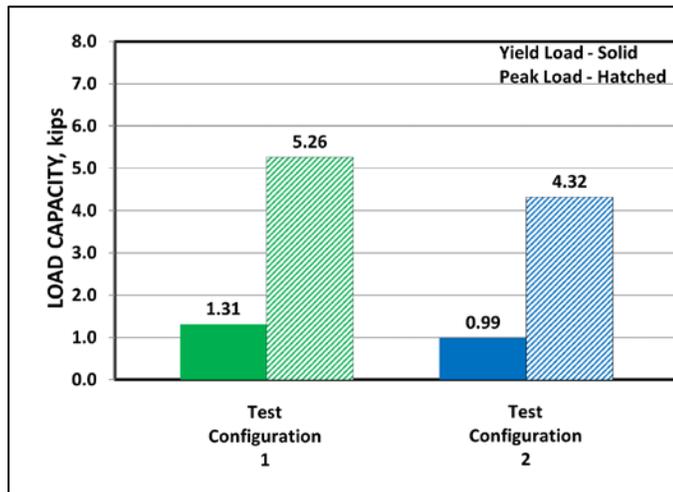


Figure 6. The effect of a mid-sized load contact area relative to the bolt bearing plates.

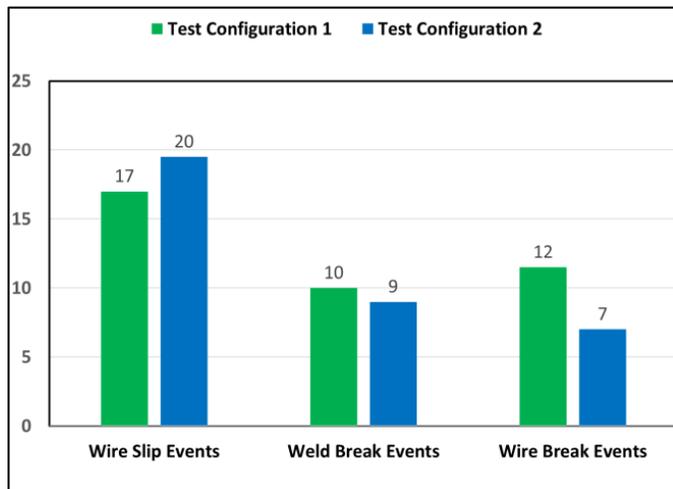


Figure 7. Number and type of load shed events for mid-sized load contact area relative to the bolt bearing plate position.

This test parameter was then examined using a smaller (28-in x 8-in) load contact area to determine if the results would be repeated for a smaller load contact area. Test configurations 3 and 4 (Figure 8) used the 28-in x 8-in load contact area to evaluate the effect of the pull point contact area relative to the bearing plate bolting pattern. Similar to the previous results, these test results reinforce that the location of the load contact area will affect the performance characteristics of the welded-wire screen (see Figure 9). Test configuration 3 exhibited an increase of 235% yield load capacity compared to test configuration 4, while also providing a 47% increase in the yield stiffness. Similarly, the observed peak load capacity of the screen increased by 130%.

However, the resulting screen damage for the smaller area contact (28-in x 8-in) varied somewhat from the previous tests. There

was a 35% decrease in wire slips for test configuration 4 (see Figure 10). However, the number of wire breaks and weld breaks were similar for this test series.

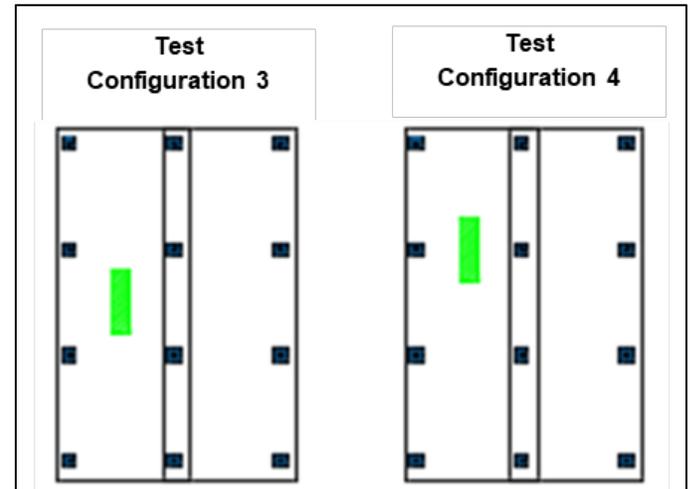


Figure 8. Test configurations to determine the effect of small-sized pull contact location relative to the bolt bearing position. (Pull locations shown in green, bolt contact plates shown in blue).

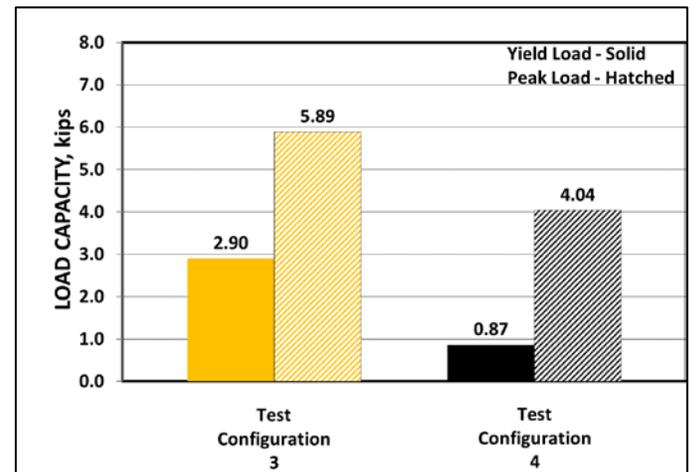


Figure 9. The effect of a small-sized load contact area relative to the bolt bearing plate position.

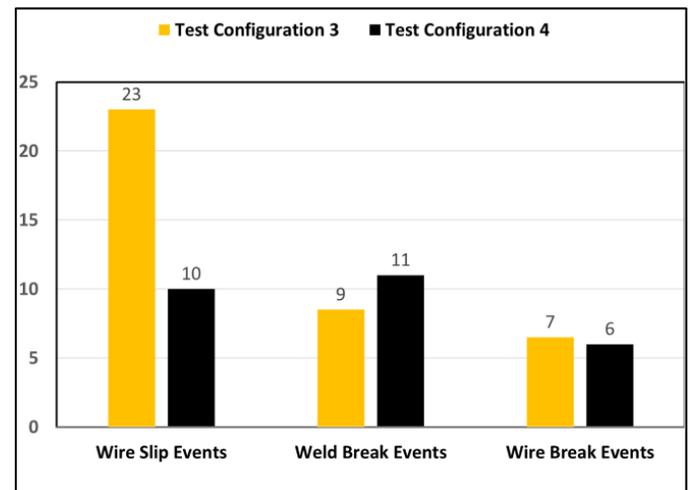
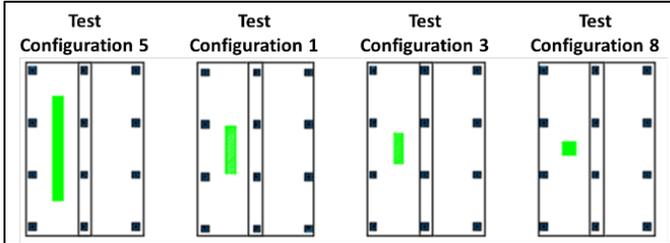


Figure 10. Number and type of load shed events for small-sized load contact relative to the bolt bearing plate position.

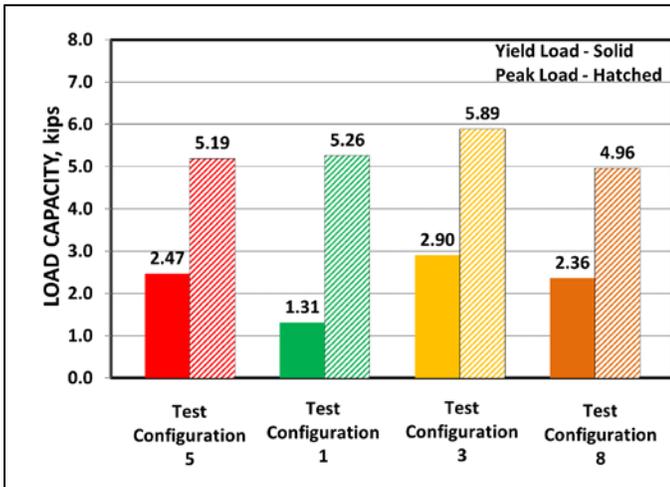
**Effect of the size of pull contact geometry when centered within the bearing plate bolting pattern**

Four different test configurations were evaluated to determine the effect of size of the pull contact geometry when centered in the bearing plate bolting pattern. Test configuration 5 (96-in x 8-in), test configuration 1 (43-in x 8-in), test configuration 3 (28-in x 8-in), and test configuration 8 (12-in x 12-in) were evaluated (see Figure 11).



**Figure 11.** Test configurations layouts to determine the effect of the size of pull contact geometry when centered within the bolt bearing plate bolting pattern. (Pull locations shown in green; bolt contact plates shown in blue.)

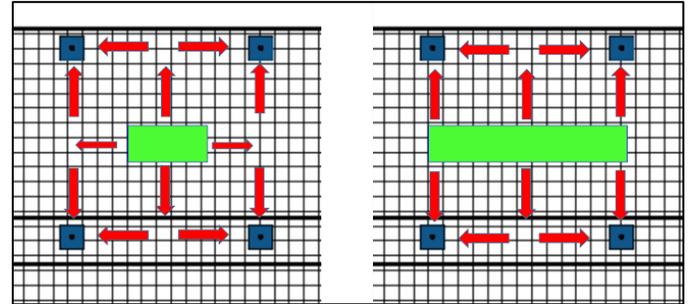
Screen stiffness is a measure of how quickly the screen system develops its load carry capacity in relation to the displacement caused from roof skin failure. The stiffness for each of the four test configurations were evaluated and the results are shown in Table 1. The stiffness of the screen increased as the size of the contact area increased. For example, the stiffness at the yield load capacity of the 12-in x 12-in contact area (test configuration 8) was 0.40 kips/in. The yield load stiffness increased by 138% to 0.95 kips/in for the 96-in x 8-in contact area (test configuration 5).



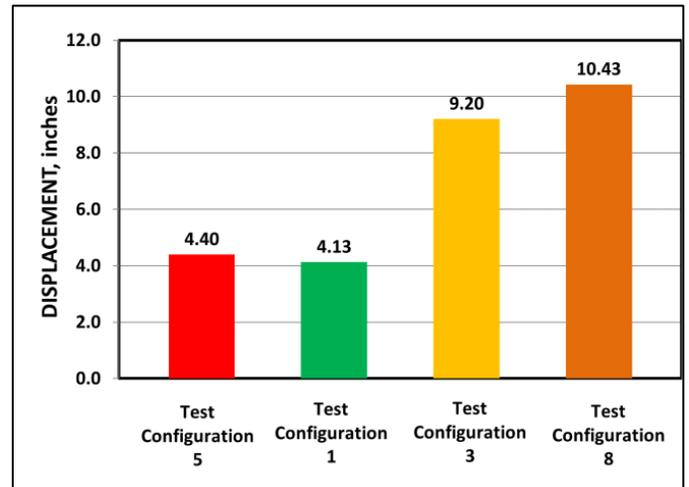
**Figure 12.** The effects of the load contact geometry on the screen yield and peak load capacity (test parameter 2).

Figure 12 compares the yield and peak load capacity for the four test configurations. The yield load capacity ranged from 2.36–2.90 kips for test configurations 3, 5, and 8. However, when compared to test configuration 1, there was a lower observed yield load capacity of 1.31 kips. This is due to the primary load transfer directions along the wires from the load contact area to the bearing plates. For test configurations 3, 5, and 8, the applied load was transferred in two directions to wires leading to the bolt contacts (see Figure 13). For test configuration 1, part of the load was transferred in a single direction directly to the bolt contacts.

Although the stiffness is higher for test configuration 1 compared to test configurations 3 and 8, the yield load is lower since the yield load occurred at significantly less displacement (see Figure 14). Generally the yield load capacity is higher when the screen yields at a higher displacement despite its lower stiffness. Test configuration 5 did not follow this trend because the load transfer from the larger pull load area affects more bolts and bearing plate locations.

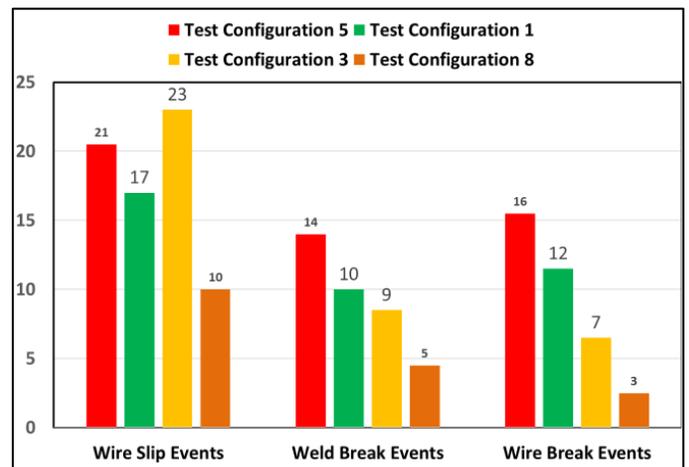


**Figure 13.** The arrows indicate the load transfer paths from the pull contact area to the bearing plates. The schematic shows two load transfer paths: a partial direct path (right side) and a full indirect path (left side).



**Figure 14.** The effects of load-pull geometric size on the displacement at the yield load capacity arranged in order of largest to smallest pull contact size.

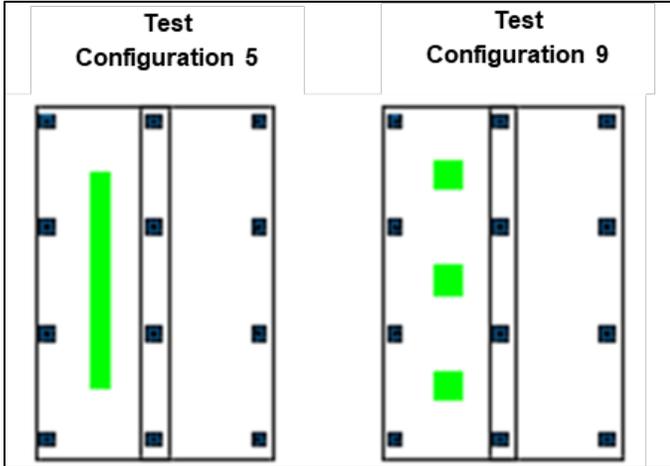
Changing the size of the load-pull geometry also affected the amount of load shed events. As shown in Figure 15, the smallest load contact area (test configuration 8) resulted in 11 fewer weld breaks and 13 fewer wire breaks compared to the largest load contact area (test configuration 5). These test results suggest that screen performance behavior and load shed events are affected by the size of the load-pull contact area.



**Figure 15.** Number and type of load shed events for each test configuration related to the size of the pull contact.

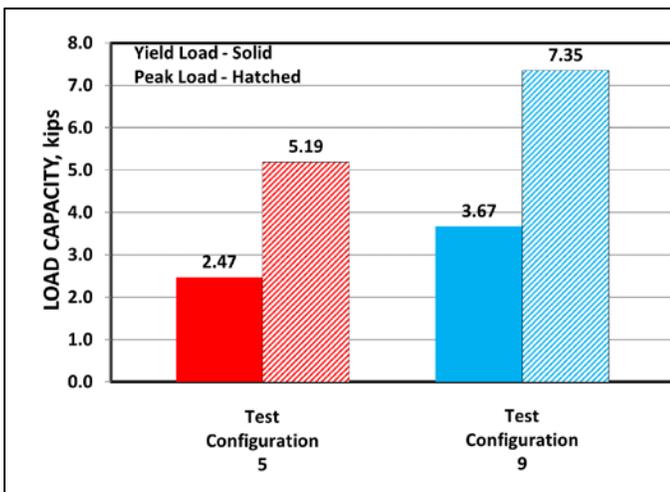
**Effect of a single large load contact compared to multiple small load contacts and pull locations**

For this test parameter, isolated sections of screen were loaded using multiple smaller-sized load contacts (12-in x 12-in) and compared to a single large load contact (96-in x 8-in) acting as the same screen section (see Figure 16). The goal of this test series is to simulate larger roof falls.



**Figure 16.** Test configurations to determine the effect of a single large load contact compared to multiple small load contacts and pull locations. (Pull locations shown in green; bolt contact plates shown in blue).

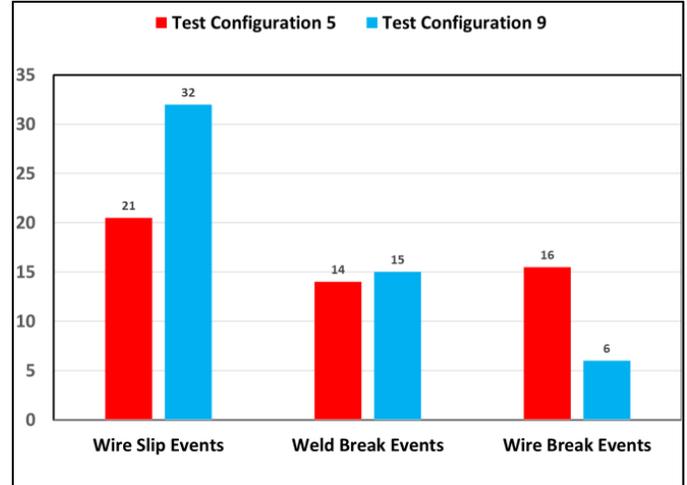
Figure 17 displays the yield and peak load capacity for test configurations 5 and 9. For test configuration 9, the total load was equal to the sum of the individual load measurements at the three contact areas. The yield and peak load capacity was increased by 37% and 27%, respectively, for the configuration with 3 load-pull contacts. The lower load capacity for the larger contact area configuration is likely caused by the loading being applied beyond more than one 4x4-ft section in the bolting pattern. This effect reinforces the results seen in the previous section where the load capacity is lower when the pull contact area passes across the width of the bolted areas instead of only in the center of the bolted pattern. There was no significant difference in yield load stiffness and only a 22% increase in the peak load stiffness between these two test configurations (see Table 1).



**Figure 17.** The effects of a single large load contact geometry (test configuration 5) versus multiple small load contact geometries (test configuration 9) on the screen yield and peak load capacity.

The observed screen damage for the individual load contacts (test configuration 9) differed from that of the single contact load (test configuration 5). There was an increase of 11 wire slips for the single

large load contact (see Figure 18), while the number of wire breaks decreased by 10. This is probably caused by part of the larger contact load being transferred directly to the wires leading to the bolt contacts. This resulted in a higher stiffness but less displacement, causing more of the screen wires to break. The failure of the wires then determines the post-yield behavior of the screen.



**Figure 18.** Number and type of load shed events for single versus multiple load contacts.

**Effect of a single contact compared to two separate load contacts across overlapped screen sections**

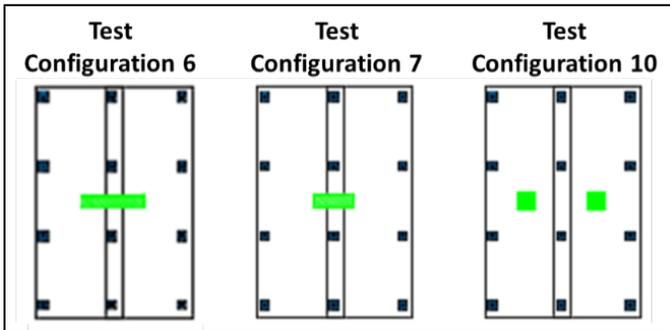
When installing roof screen, end sections of the screen are overlapped to ensure continuous coverage of the mine roof (see Figure 19). The performance characteristics for test configurations 6, 7, and 10 (see Figure 20) were evaluated to determine the effect of the pull contact area relative to the overlapped section of the screen. The experimental data (see Figure 21) indicated that the single load contact (test configurations 6 and 7) had a higher yield load capacity than the multiple load contacts (test configuration 10). The single load contact (configurations 6 and 7) exhibited a yield load capacity increase of 44% and 22%, respectively, compared to multiple load contacts (configuration 10). There was less of a difference in the peak load capacity.



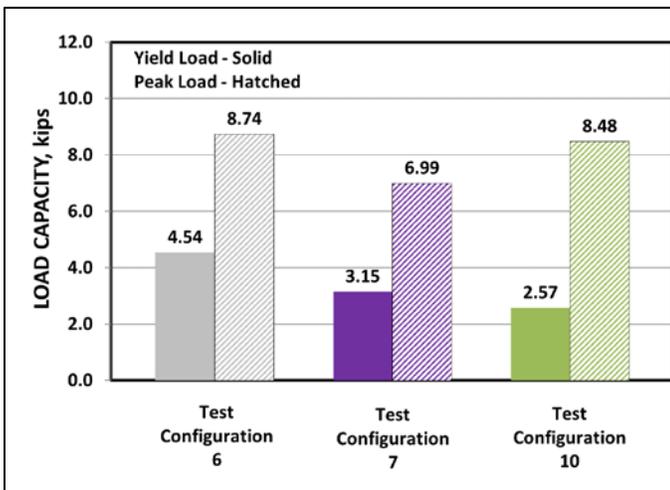
**Figure 19.** Overlapping screen installed in a coal mine.

The screen performance for this test series was also assessed by evaluating the number of load shed events that occurred from either a wire slip, weld break, or wire break. From the results shown in Figure 22, there were significantly fewer weld breaks for the single contact compared to the multiple contact configuration. Conversely, there was significantly more wire breaks for the single contact versus the multiple contact test. These results reinforce the hypothesis that

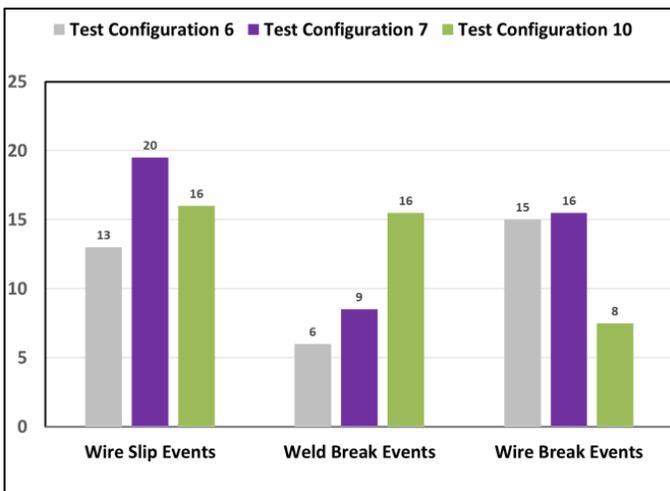
there is an increase in load shed events when the contact load capacity is transferred directly from the load contact to the wires leading to the bolt contacts.



**Figure 20.** Test configurations used to determine the effect of a single contact compared to two separate load contacts across overlapped screen sections. (Pull locations shown in green; bolt contact plates shown in blue).



**Figure 21.** The effects of a single large load contact versus multiple small load contacts on overlapping sections of screen.



**Figure 22.** Comparing the amount and type of load shed events for a single large load contact versus multiple small load contacts on overlapping sections of screen.

### CONCLUSIONS

Laboratory tests were performed by NIOSH researchers to evaluate the load-displacement characteristics of an 8-ft x 12-ft panel

of 8-gauge welded-wire roof screen. In this study, laboratory tests were conducted on isolated sections of screen using various sized pull point contact areas to simulate the effects of various sized roof failures. The screen capacities were measured with respect to yield and peak load and the associated stiffness. The screen damage and impact on performance was analyzed with regard to wire slips, weld breaks, and wire breaks.

This study showed that the location of the load with respect to the bearing plate bolt pattern can influence the screen response and performance. When the applied load is directed between the bolted pattern, the load capacity and stiffness of screen is decreased. There is also an increase in the number of wire breaks associated with the change location of the load with respect to the bolt bearing plates. A larger contact also increased the screen load capacity when the applied load is contained within the center of the bearing plate bolting pattern. However, if the load contact geometry extends beyond the bolting pattern, the load capacity can be decreased.

This study also analyzed the effect of a single large contact versus multiple smaller contacts. It was observed that the multiple smaller contacts resulted in a larger yield and peak load capacity. This is probably caused by the large load contact area applying load between the bolting pattern and decreasing the load capacity of the screen. The exception for this behavior is when the applied load is across overlapped sections of screen. When this occurs, the load capacity of the screen is larger with the single large contact than the multiple smaller contacts.

Ultimately, the information obtained in this and similar studies can be used to better understand the loading behavior and surface control capability of roof screen in underground mines.

### DISCLAIMER

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH). Mention of any company or product does not constitute endorsement by NIOSH.

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