ENHANCED SURFACE CONTROL FOR ROOF AND RIB SUPPORT

Stephen C. Tadolini, *Vice President*
Excel Mining Systems, Inc.
Cadiz, Ohio USA

Dennis R. Dolinar, *Mining Engineer*
National Institute for Occupational Safety and Health
Pittsburgh Research Laboratory
Pittsburgh, Pennsylvania USA

ABSTRACT

The risk of injury caused by minor roof falls continues to increase in underground mining. Most ground control injuries result from small rock falls that occur in a supported area, but do not involve the failure of the support system. In the roof, these are the "skin failures" that occur between previously installed primary or secondary bolting systems. To minimize skin failures and the associated accidents, several devices were designed and tested in the laboratory to maximize stiffness, minimize material thickness and weight, and ease material storage and handling on roof bolting machines. The goal of this project was to design and evaluate devices that can be installed with traditional primary or secondary roof supports, and that are easy to handle/install under temporary or previously supported roof.

BACKGROUND

Surface control can be a critical component of effective roof and rib support systems. Proper surface control devices, with adequate stiffness characteristics, can help minimize or even eliminate progressive roof and rib failures. While there is no universal method that can be applied for roof and rib stabilization, combinations of bolts, mesh (steel and nylon grid) straps and plates vary depending on the type of fracture patterns/cleating and the immediate roof characteristics. Full "liner" supports, arguably the most effective, can be time consuming, cumbersome, and expensive. While these disadvantages can be partially offset with reductions in personal injuries or fewer production delays, they are seldom implemented.

To help illustrate the scope of the problem, injuries from the Mine Safety and Health Administration (MSHA) data base were examined from 1995 to 1999. Every year MSHA compiles the reportable injuries and accidents with information defined and required by the Code of Federal Regulations, title 30, part 50. During this 5-year period there were 4,100 reported injuries resulting from roof falls, bumps, rib falls, and roof skin failures (figure 1). Roof skin failures are defined as rock falls from the surface of the roof to a depth of 2 ft but not limited in the other dimensions. A roof fall encompasses a thickness greater than 2 ft. In each of the five years there were about 800 reported injuries and 10 to 15 fatalities from ground falls in underground coal mines. However, 98% of these injuries, usually including 3 to 4 fatalities, resulted from relatively minor falls of rock from the roof and ribs in coal mines. In 1997, a typical year, 671 injuries (82% of the total) were from these small roof falls, while 128 injuries (16%) were from rib falls. Only 13 of the injuries in 1997 resulted from large roof falls that involved the failure of the primary support system. The other 799 injuries occurred in areas where the roof had been supported and therefore should have been safe.

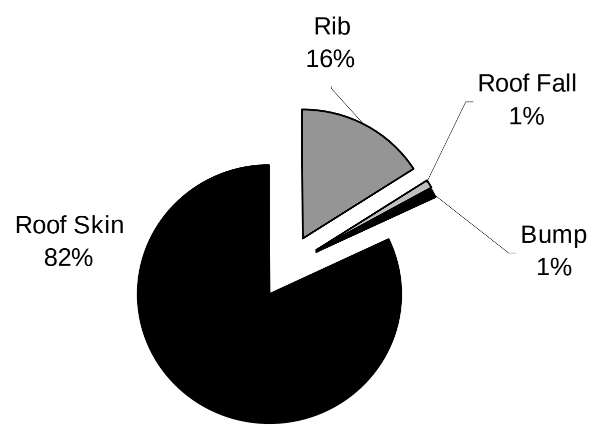

Figure 1. Percent of injuries by ground fall type in underground coal mines

The activity that is most at risk from these minor falls is roof bolting. In 1997, 44% of roof skin injuries occurred during the roof bolting cycle. Rib falls are more widely distributed, with 19% occurring during roof bolting and 17% during continuous miner operation. More importantly, over 75% of both the reported rib and roof fall accidents occurred at or near the working faces (inby feeder breakers). Much of the previous ground control research has concentrated on massive roof falls, and not on the small pieces of rock between supports. Injuries from large roof falls typically account for less than 15 injuries per year, while the injuries from small rock falls have numbered around 800 per year. The mining machine industry has reacted to the problem of small rock falls by developing canopies and shields to protect roof bolters and miner operators. Current surface control systems placed on equipment, principally roof bolt machines, to protect workers have been credited for reducing the number and intensity of accidents (1-2). Rib bolting and other support measures have been successful where properly applied. Often, however, the hazards from skin failure go unrecognized, so no support is applied, or when applied the support is ineffective.

Another area of concern is the remote control operation of a continuous mining machine since the operator is standing beside the machine under supported roof but not under a canopy. The operator is continuously walking or moving near the rib and under freshly cut but supported roof. Material can fall between the typical roof bolt bearing plates and thin roof mats, and strike the operator. Injuries to miner operators caused by small rock falls in such situations, represent 9% of all ground fall injuries.

This investigation examines systems that can be placed between the bearing plate and the mine roof to increase and maintain adequate surface control. The designed systems will enhance surface control by covering as large an area as possible without sacrificing performance or stability. The system must be stiff enough to resist downward motion and subsequent collapse if larger amounts of material separate and fall, must be easy to install, and cost effective. Ideally, the same systems should be applicable to support rib areas at critical horizons and locations to minimize slumping for failing ribs. Dual-use systems minimize material handling and reduce the costs associated with storage and handling.

FUNCTION, DESIGN AND PHYSICAL DIMENSIONS OF TESTED PLATES

Function

The main function of the large surface plates is to maintain and control the surface or skin area around the roof bolt. Essentially, the plate is designed to maintain a much larger area around the bolt than the bearing plate. The surface plates are used in conjunction with the standard bearing plates. This function is achieved by the stiffness (resistance to movement) and by the large area covered by the surface plate.

A normal bearing plate must be designed to form a bearing surface for the roof bolt, control the rock on the surface in the immediate vicinity of the roof bolt, allow the bolt to retain tension and allow the bolt to resist rock movement (3, 4). Essentially, the bearing plate is an important element in maintaining the function of the roof bolt.

Design

The tested plates were fabricated from 18 to 20 gauge (0.055 to 0.036-in thick) non-graded steel. Four types of plates were tested that include a traditional W-Strap, a 19-in diameter circular plate, and a 17-in square plate with two rib-designs. Figure 2 shows the traditional W-Strap fabricated from 0.055 in thick material with final dimensions of 18-in long and 12-in wide with a 1-in diameter hole punched in the center.

A circular plate, shown in figure 3, has a 19-in diameter and 0.036-in thickness. A hole is punched in the center to accommodate bolt insertion.

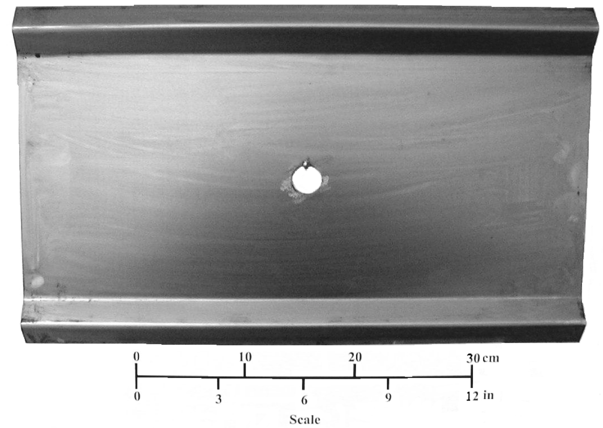

Figure 2. A traditional W-strap with a 1-in hole in the center

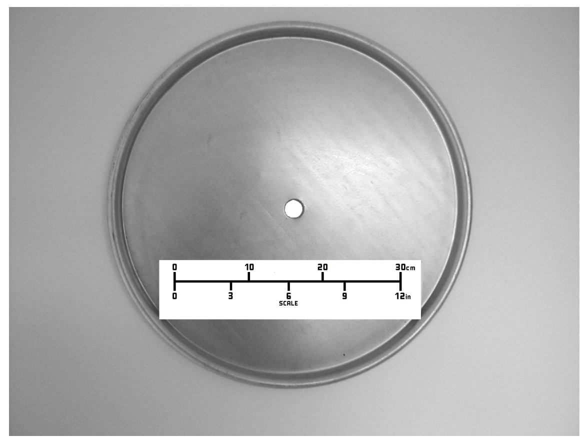

Figure 3. The 19-in circular plate

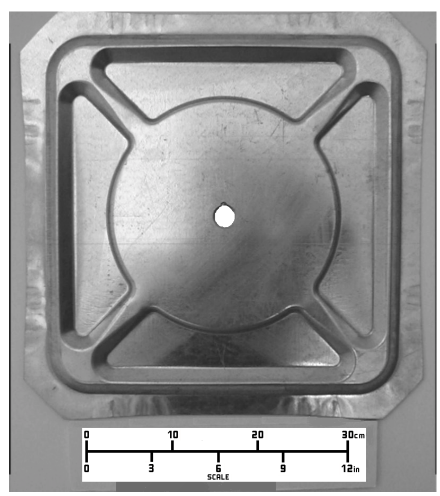

Figure 4. The 17-in square plate with 4 internal spokes

Two different internal structural designs were evaluated for the 17-in square plates, one with 8 internal spokes and one with 4 internal spokes (figures 4 and 5). Both types of plates were made from 0.048-in thick steel material.

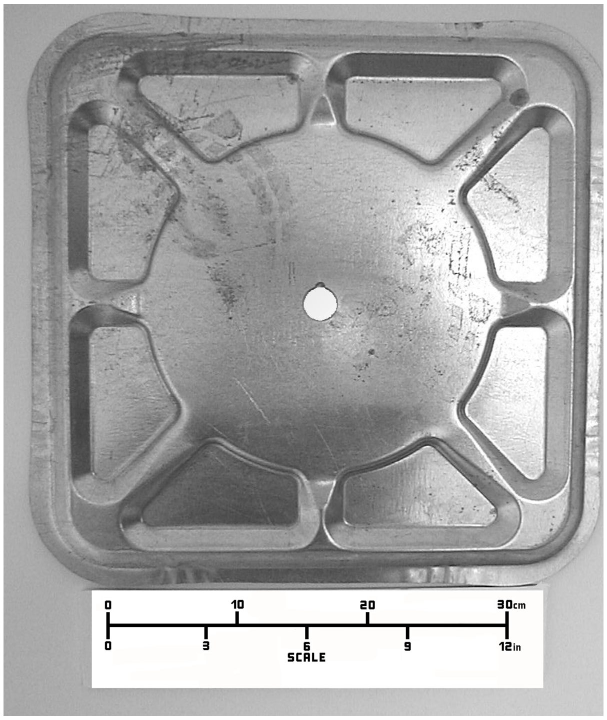

Figure 5. The 17-in square plate with 8 internal spokes

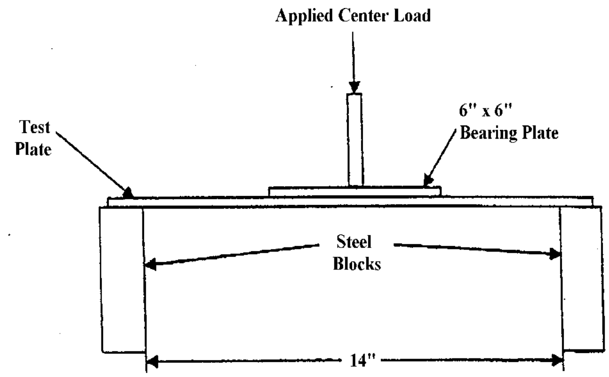

Figure 6. Test apparatus placed in Tinus Olsen machine

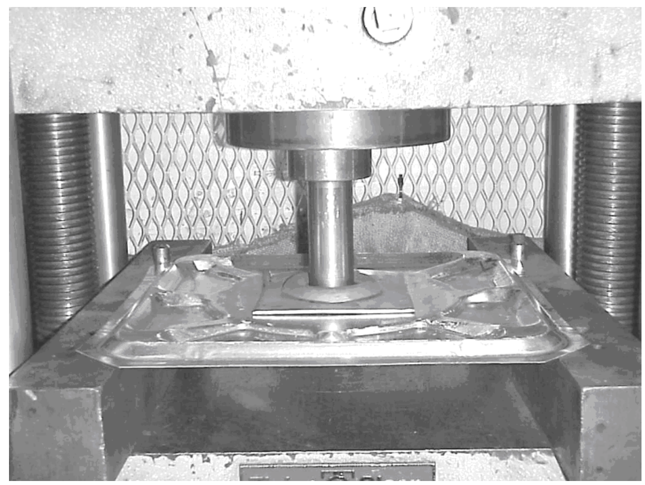

Figure 7. The test machine and loading apparatus design. All plates were tested with the same configuration.

Testing of Large Surface Plates

A laboratory test was used to evaluate performance of the large surface plates. Figure 6 shows the test frame set up. The test consisted of setting the plates on two supports, 14 in apart then applying load to the center of the plate. American Society of Testing Materials (ASTM) tested and approved bearing plates are required on all of the systems to comply with CFR Regulations. To simulate this required condition, the center load was applied through a 6-in by 6-in bearing plate as shown in figure 7. Both load and deformation were measured and recorded during these tests. The square plates were tested with the supports parallel to the edges as well as at a 45° angle to evaluate the diagonal plate properties of the 17-in square plates.

The load-deformation graphs for each tested plate are shown in figure 8 through 11 and summarized in Table 1. The peak and yield strengths are given in terms of the load with the yield strength determined where the load-deformation curve begins to flatten or deviates noticeable from a straight line. The stiffness was calculated as the secant line from no load to the yield strength and is the load required to produce a given deformation. The stiffness is a measure of the ability of the support to resist rock movement. The energy is the area under the load deformation curve up to yield and is a measure of the support toughness.

Table 1. Results of center point tests conducted on large surface plates.

Plate Type	Strength, lbs		Deformation yield, in	Stiffness, yield, lbs/in	Energy, yield, in-lbs	Area, in^2
	Peak	Yield				
Square (17 in) 4-spoke, parallel	886	800	0.60	1,400	220	289
Square (17 in) 4-spoke, diagonal	1,375	1,290	1.70	760	1,100	289
Square (17 in) 8-spoke, parallel	550	450	0.40	1,133	94	289
Square (17 in) 8-spoke, diagonal	825	725	1.40	520	500	289
Circular (19 in)	520	400	0.20	1,531	80	284
W-Strap	633	633	0.29	2,180	92	216

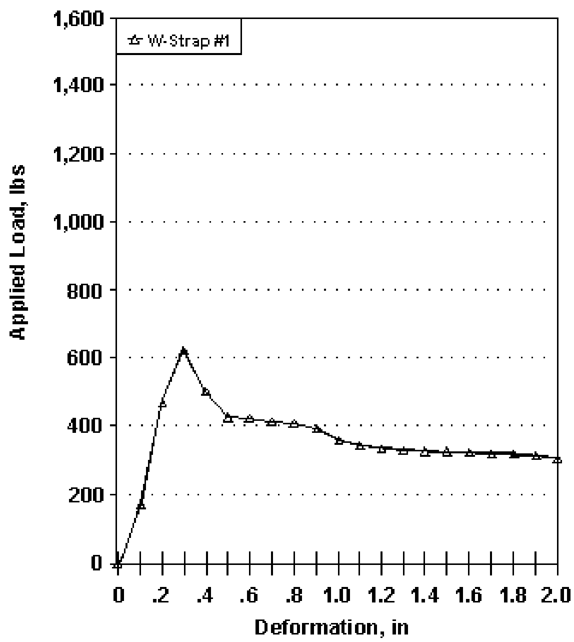

Figure 8. Results of load tests performed on W-strap

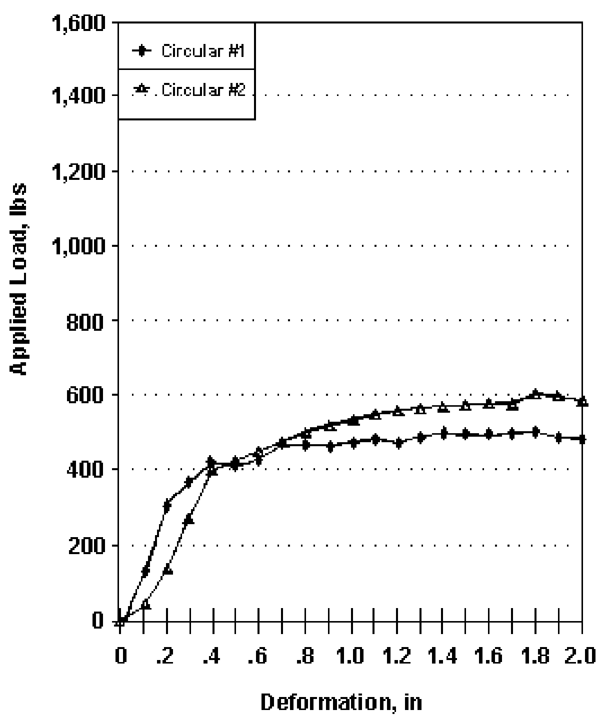

Figure 9. Results of load tests performed on 19-in diameter circular plates

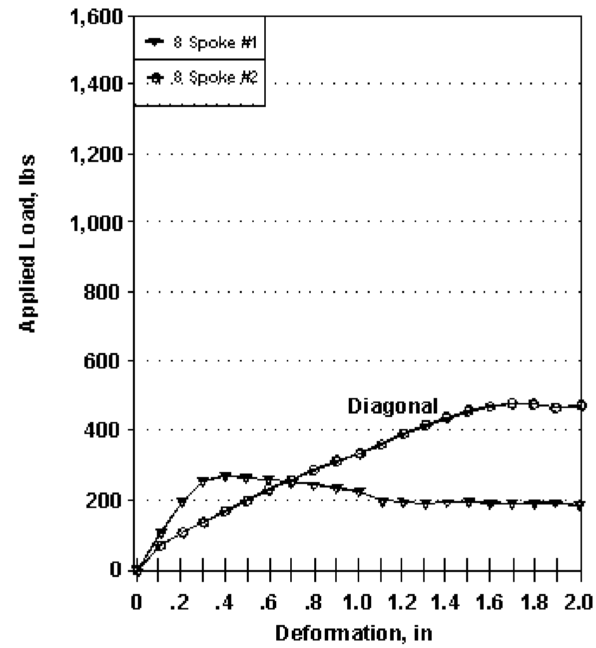

Figure 10. Results of load tests performed on 17-in square plates with 8 spokes (parallel and diagonal)

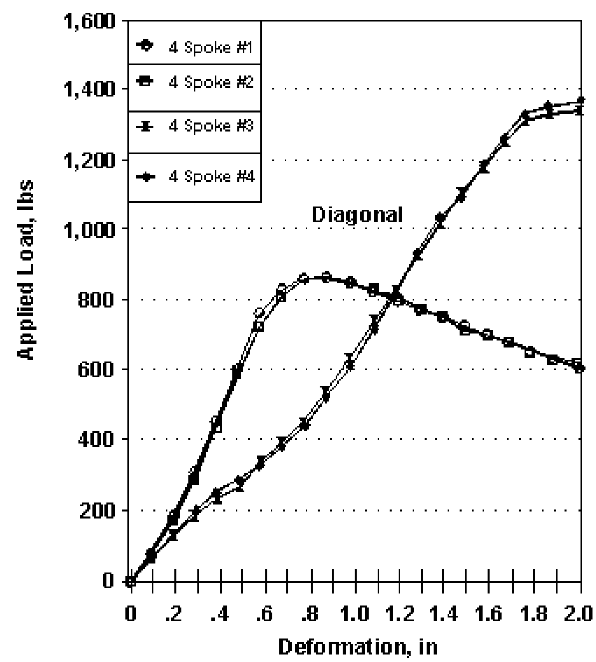

Figure 11. Results of load tests performed on 17-in square plates with 4 spokes (parallel and diagonal)

Analysis of Laboratory Tests

From the tests curves, it appears the deformation, plate yield and ultimate failures result from bending the plates. Some deformation may have been the result of punching of the bearing plate into the center of the larger plates.

Results

The test results indicate that the 4-spoke square plate has the highest yield and peak load while the circular plate has the lowest strength. The square plate design appears to be fundamentally stronger than the circular plate; especially the 4-spoke plate, though both plates have nearly the same surface area. The area of the circular plate is 283 in^2 and the square plates are 289 in^2. The W-strap has an intermediate strength between the circular and square plates even though the plate is thicker than the other plates. When comparing the square plates, the 4-spoke plate is significantly stronger than the 8-spoke plate. The four extra spokes parallel to the plate edges act to weaken the plate essentially by providing a weak point (crease) where the plate bends. This proves that careful attention must be given to the internal structural design of the plates. The square plates are much stronger when tested across the diagonals. This is the result of more material and structure in the plate corners, adding strength to the plate across that direction of bending.

The yield strength should be used and not the peak strength for design and evaluation of the large plates. Once the roof surface begins to fail and the plate goes into yield, because the rock will act as a dead weight load on the plate, the plate will continue to deform with little or no increase in the load. The rock load will be transferred from the plate only when the rock falls from the roof caused by excessive deformation of the plate. When this happens, the support has failed and its only function is to retain loose material. Therefore, the plate performance beyond yield is not considered important.

When considering the stiffness of the plates, the circular plate is 1,000 lbs/in and the 17-in square, 4-spoke plate is 1,400 lbs/in. Much of this stiffness appears to come from the external or edge structure of the plates. The stiffness of a square flat plate without any structure is only 75 lbs/in (calculated). For the 8-spoke square plate the added spokes reduce the stiffness to less than that of the 4-spoke plate. The four spokes connecting the raised circular section surrounding the plate center with the center edge of the plate added no stiffness to the structure, because they did not extend across the entire plate width as do the edge deformations and, therefore, they do not increase resistance to bending. Further, these four added spokes altered the edge structure at the critical point of the center edge of the plate where the largest bending moment occurs and thus reduced the stiffness. The W-strap has a higher stiffness, than either the circular or square plates but only in one direction because of their design. This increased stiffness may result from a smaller width of flat steel plate between the edge ridges than the other two plates. Some of the plate displacement results from the deformation of this flat section of the plate. The greater the distance between the edge ridges, the less rigid the flat section of the plate becomes.

EFFECTS OF PLATE SIZE ON PERFORMANCE

From the laboratory test set up, the strength and stiffness of the plates are determined across a standard length of 14 in. However, it is the full plate dimensions that will determine the actual stiffness and strength and govern how the plates will perform in situ. With plate dimensions larger than 14 in, the bending moment generated from the load will increase. Further, the expected rock load will also increase with the plate dimensions. With the larger bending moment, the plate deflection will increase while the plate stiffness will decrease unless compensated by the plate structure through the moment of inertia. Essentially, the larger the plate, the greater the bending moment developed by the rock load which will result in a reduction in plate strength and stiffness.

The plate strength will be determined from the stresses that develop in the plate from the bending moments. The following equation can be used to determine the maximum bending moment generated during the laboratory test (5):

$$S_{max} = \frac{F_T L_T Z}{4 I_y}$$

where: S_{max} = Maximum outer fiber stress, psi
Z = distance from neutral axis, in
F_T = maximum plate load (yield), lbs
L_T = length between supports, in
I_y = moment of inertia of the plate, in^4.

This equation provides an approximation of the stresses developed in the plate because this equation assumes a line load across the surface plate. Also, for the complex structure of the plates, it is difficult to calculate both the moment of inertia and the distance of the maximum stress from the neutral axis.

However for the same shape plate, the maximum load for a plate with a larger dimension between supports can be determined by equating the maximum stress based on the standard laboratory test and that expected for the larger dimension. The relationship is:

$$F_A = \frac{F_T L_T}{L_A}$$

where: F_A = maximum load (yield) for actual plate dimensions, lbs
F_T = maximum plate load (yield), lbs
L_A = plate width, in.
L_T = length between supports, in

Essentially the strength of the plate is determined by using the laboratory strength, the ratio of the laboratory test span (14 in), and the actual plate dimension. For the 17-in four spoke plate the yield load from the test was 800 lbs where the calculated yield strength for the full plate width is 660 lbs. For the circular plate, with a tested yield strength of 400 lbs, the yield strength across the full width would be 295 lbs. For the W plate, with a tested yield strength of 633 lbs, the yield across the full length is 490 lbs.

The increased plate dimensions will also affect the plate stiffness. The change in stiffness can be calculated using the plate load and deformation at yield. The following equation can be used to approximate the plate deflection based on a two-point test with a concentrated line load across the plate:

$$D = \frac{FL^3}{48EI_y}$$

where: D = plate deflection, in
F = yield load of plate, lbs
L = width of plate, in
E = elastic modulus of the steel, psi
I_y = moment of inertia of the plate, in^4.

This load-deformation equation can be used to estimate the moment of inertia from the laboratory test results for the different plates. Using the load and deformation at yield, the moment of inertia for the 17-in four spoke plate is 2.7×10^{-3} in^4, the Circular plate is 2.0×10^{-3} in^4, and the W-Strap is 4.4×10^{-3} in^4.

The calculated deflection at yield for a full width of the 17-in square plate is 0.9 in. Based on the calculated yield load of 660 lbs, the plate stiffness is 740 lbs/in as compared to the tested plate stiffness of 1,400 lbs/in. For the Circular plate, the calculated deformation is 0.7 in at the yield load of 295 lbs with a resulting stiffness of 400 lbs/in. This compares to the tested stiffness of 1,000 lbs/in. For the W-strap, the calculated deformation is 0.6 in at a yield load of 490 lbs resulting in a stiffness of 785 lbs/in where the measured stiffness was 2,130 lbs/in. The increased dimensions significantly decrease the surface plate stiffness.

The stiffness and strength of larger plates of similar structure to those tested should have significantly lower strengths and stiffness. For a twenty-four in square four spoke plate the estimated strength is 470 lbs and a stiffness of 260 lbs/in. For a twenty-four in diameter Circular plate, the estimated strength is 235 lbs and a stiffness of 200 lbs/in. The assumption made for these calculations is that the distance to the neutral axis is the same as the tested plates and the moment of inertia of the plates is the same. The first assumption is correct only if the lateral plate dimensions are altered. The second assumption is correct if only increasing the lateral dimensions of the plate increases the moment of inertia. However, the flat portion of the plates adds little to the moment of inertia. The moment of inertia for a 0.48 in thick plate, with a 24 in width is 2×10^{-4} in^4 and with a 17 in width, is 1.5×10^{-4} in^4. The difference in the moment of inertia resulting from the increased width is about two orders of magnitude less than the moments of inertia of the plates. Therefore, simply increasing the lateral dimensions only have a minimal affect on the moments of inertia.

Using the standard tests, both the strength and stiffness of the plates can be determined across a standard dimension. Comparisons can be made between plates to determine what might be a more effective design. However, the size of the plates must be considered in determining how the plates may perform in situ. Increasing the plate dimensions can significantly decrease both the strength and the stiffness. The above analysis was developed as an example to illustrate how the plate dimensions will affect the plate performance. These examples are somewhat over simplified as to how the plates may actually perform in situ. The in situ performance will not only be affected by the plate size but the manner in which the plate is loaded.

CONCLUSIONS

The fall of the small rocks or skin material accounts for about 82% of the average 800 reported accidents from ground falls. The activities of roof bolting and operating the miner have been identified as the jobs with the most exposure to these accidents. This investigation examined the systems that can be placed between a bearing plate and the mine roof to minimize these small failures and help maintain adequate surface control.

The test results indicate the 4-spoke, 17-in square plate achieved the highest yield and peak load while the circular plate had the lowest strength. The square plate design appears to be fundamentally stronger than the circular plate; especially the 4-spoke plate, even though both plates have nearly the same surface area. The area of the circular plate is 283 in^2 and of the square plates 289 in^2. The tests on the two types of square plates revealed the 4-spoke plate is significantly stronger than the 8-spoke plate. The four extra spokes parallel to the plate edges act to weaken the plate, essentially by providing a weak point (crease) where the plate can bend, illustrating that careful attention must be given to the internal structural design of the plates. The yield strength should be used and not the peak strength for design and evaluation of the large plates. This is because the skin or surface of the rock is a soft system. Once the load comes on the plate there may be little load transfer as the system goes into yield except when the surface rock falls. When this occurs the support has failed its only function to retain material.

Even with the same stiffness as the circular plate, the 4-spoke plate has a much higher energy or toughness at yield . Essentially, the 4-spoke plate can absorb substantial more load and deformation than the circular plate and still function while providing the same resistance to rock movement. Because of the higher toughness but with the same stiffness, the 4-spoke has to be considered superior.

The W-strap has a higher stiffness than both the 4-spoke spider and circular plates. However, the energy at yield is less than half that for the 4-spoke plate but almost three times the energy of the circular plate. The W-strap is certainly a better support than the circular plate up to yield. At lower loads, the W-strap will resist rock movement better than the 4-spoke plate. However, the superior toughness of the 4-spoke means that this plate will continue to function well after the W-strap has failed. In this case the increased stiffness is a trade-off with the superior toughness. It is important to remember that the W-strap provides substantially less surface coverage and is more of a one-dimensional support than either the 4-spoke or circular plates.

By using the same amount of material and thickness, an engineered design of a plate can be significantly improved. The next phase of this investigation will access the field performance of the 4-spoke plates under actual mining conditions and loading histories. The ultimate goal remains to provide improved surface control and protection for the personnel working in mines with spalling roof and rib conditions.

REFERENCES

1. Bauer E.R., Pappas, D.M., Dolinar D.R., McCall F.E. and Babich, D.R. Skin Failure of the Roof and Rib in Underground Coal Mines. In: Peng S. S. and Mark C., eds. Proceedings of

the 18th International Conference on Ground Control in Mining. Morgantown, WV, West Virginia University, 1999, pp108-115.

2. Bauer E.R. and Dolinar D.R. Skin Failure and Rib Support Techniques in Underground Coal Mines. Proceedings: New Technology for Coal Mine Roof Support. Pittsburgh, PA, National Institute for Occupational Safety and Health IC 9453, 2000, pp 99-109.

3. Stillborg, B. Professional Users Handbook For Rock Bolting. Series on Rock and Soil Mechanics V 15, Trans Tech Publications, 1986, 145 pp.

4. Franklin, J. and Dusseault, M. Rock Engineering. McGraw-Hill, 1989, 600 pp.

5. Roark, R. Formulas for Stress and Strain. McGraw-Hill, 1965, 432 pp.