18th INTERNATIONAL CONFERENCE ON

GROUND CONTROL IN MINING

August 3 – 5, 1999

Sponsors

US National Institute for Occupational Safety and Health
US Mine Safety and Health Administration
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Modern Shield Technology: Better than Ever but Still Not Perfect

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ABSTRACT

A survey of the longwall industry was conducted to examine the performance of modern shield technology. The results of this survey indicate that state-of-the-art shields perform better and last longer than ever before, but premature failures do still occur. In addition, longwall operators are now using shields longer than ever before and a greater number of fatigue related failures on aging shields are now occurring. A generic assessment of these shield failures is provided, describing the nature of the failures and how widespread they are throughout the industry. An engineering assessment of shield design and factors that cause shield failures is made using both strength of materials and fracture mechanics principles. From this analysis, design practices to improve structural margins of safety and extend the life of the shield are proposed. The existence of unexpected shield failures indicate that current shield performance testing is at times inadequate. Recommendations are made relative to improved shield performance testing protocols including the benefits of testing in an active load frame such as the National Institute for Occupational Safety and Health's (NIOSH) Mine Roof Simulator. Even the most rigorous shield testing procedures, which strive to simulate in-service loading conditions, fail to consider key environmental issues, such as corrosion which is often the cause of structural fatigue failures in modern shields. The survey also indicated that hydraulic failures occur much sooner in the life cycle of a shield than structural failures, and although they can significantly degrade support capability, often go undetected for long periods of time. Methods to detect the hydraulic failures are also provided. The paper concludes with key points to maximizing shield design and life expectancy and ideas for future generation shield designs.

INTRODUCTION

The decline in the number of longwalls from a high of 118 in 1985 to 62 in 1999 has forced a reduction in the number of shield manufacturers from eight to two. The two major suppliers of shields to the US market are Joy and DBT America (formerly Mine Technik America or MTA). Their share of the market is split fairly evenly - Joy has 32 faces and DBT America has 30 faces (*1*). The author believes that the merger of the shield manufacturers has been beneficial to shield design in two ways. First, the merger has allowed the best of the British shield designs (Joy) and the best of the German designs (DBT America) to be brought forward. By combining the design strengths from each company, the result has been an improvement is both structural design as well as control system technology. Second, the fierce competition during the decade of the 1980's may have forced manufacturers to "cut corners" relative to design in order to compete for sales, resulting in deficiencies in design that led to premature structural failures and less than adequate control technology. Hence, while competition is generally healthy resulting in lower prices, there needed to be a better balance of quality and price than existed in the 1980's. The hard reality is that shield manufacturers have to make money in order to produce a quality product and to stand behind this product with warranties, and this capability was jeopardized in the past and has been improved with the recent mergers.

A survey of the longwall industry was conducted to evaluate problems with current shield technology and future needs. The survey indicates that shields are lasting longer than ever before, but that **premature failures still occasionally occur** and some mistakes from the past continue to be made in recent shield designs. No shield should fail prematurely these days due to poor design if sound performance testing is conducted. There is no substitute for performance testing, but it must be done properly, otherwise critical design deficiencies may not be discovered.

Due to the maturity of shield technology and the economic pressures of the mining industry, longwall operators are now keeping shields in service longer than ever before. In addition, due to the increases in longwall productivity, the number of operating cycles per year continues to increase. The result is that the operators are again pushing the envelope in terms of extending the life expectancy of the supports. **Today's shields are expected to last 60,000 - 70,000 cycles,** while ten years ago the life expectancy was around 35,000 cycles. Hence, while fatigue failures were not a design issue in the early generation of shield supports, they have become critical to the survival of most longwall operators in an ever increasingly competitive market. Much is being learned about the behavior of aging shields which are kept in service long enough to fail from fatigue as opposed to failure from poor design or replacement before the end of their useful life due to technological improvements.

Deciding when to retire an aging longwall face and the specifications for a new shield can be a critical decision for any longwall operator. Most mines do not have structural engineers that can actively participate in these decisions. This paper is written in part to provide mine operators with a better sense of design issues and engineering mechanics that are relevant to shield design. **The intent is not necessarily to have the operators learn enough to know all the answers, but to provide them with enough insight so they know what questions to ask** and what to look for relative to failures that may occur. These insights into shield design should also be beneficial to MSHA in evaluating the safety of longwall shields. The paper concludes with key points to maximizing shield design and life expectancy and ideas for future generation shield designs.

SURVEY OF SHIELD PERFORMANCE

Figure 1 illustrates the maximum capacity utilized throughout the history of the shield support. The "bigger-the-better" philosophy continues to prevail with state-of-the-art shields now providing 1,200 tons of support, nearly 4 times the capacity of the first shield support installed in the mid 1970's (*2*). The age distribution of the shields operating in 1999 is shown in figure 2. The range of operating life extends from 0 to 14 years of service. An average shield operates about 4,000 cycles per year, translating into a face production of approximately 2.5 million tons per year. Hence, an average 10-year-old shield would have 40,000 loading cycles. while a shield employed on a high production longwall (4 million tons per year) would have about 65,000 loading cycles. Approximately one third of the shields have been in operation from 4 to 6 years (16,000 - 24,000 cycles), and slightly more that than one-third (37%) have been operating for more than 6 years (24,000 loading cycles).

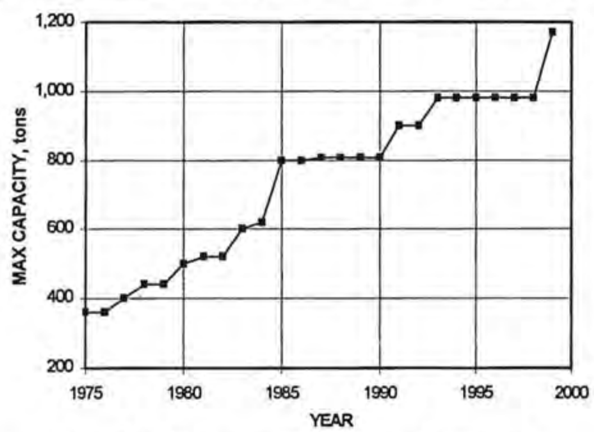

Figure 1. Maximum shield capacity utilization.

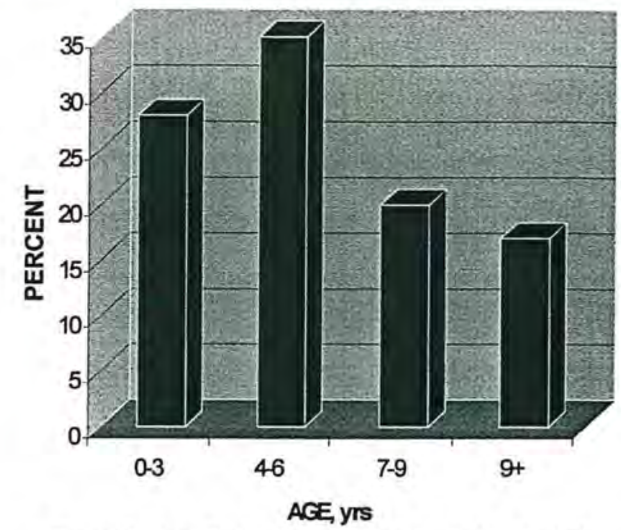

Figure 2. Age distribution of shields operating in 1999.

Figure 3 shows a near-linear relationship of structural failures with age. Failure is defined as structural damage to any support component. It does not necessarily mean catastrophic failure that renders the support inoperable. The linear relationship suggests that **there is more than just fatigue failures occurring,** since the frequency of fatigue failures should increase at a much greater rate as the shield ages. There were a wide range of structural failures reported. Most of the major failures involved either the leg sockets or pin joint problems (i.e., lemniscate link pins and clevises). These two failures are most likely to put a shield out of service and/or require structural modification to keep the support in service. Other structural failures occurred at areas of high stress concentration including the side shield on the canopy structure, the canopy capsule tilt cylinder bracket, the base bridge, the link cut out areas in the caving shield, various mounting brackets including the pilot-operated/yield valve manifold, and dishing of canopy skin covering plate. There were a few isolated cases of leg cylinder casing problems, but no catastrophic failures.

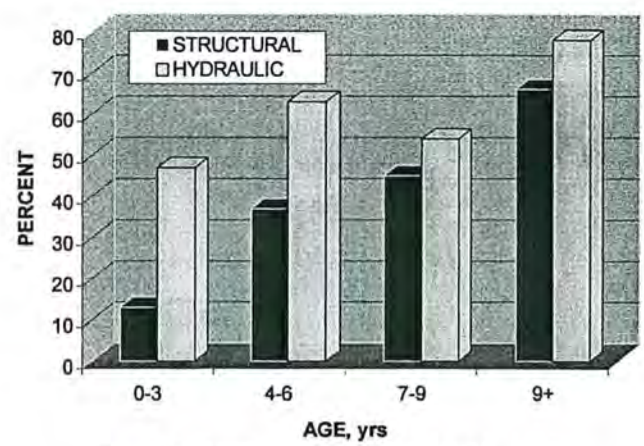

Figure 3. Distribution of structural and hydraulic failures on shields as a function of age.

There were **more hydraulic problems reported than structural problems** (figure 3), particularly in shields that have been in operation less than 6 years. There were nearly 4 times the number of hydraulic failures in shields operating 3 years or less and nearly twice as many for shields in the 4 - 6 year range than there were structural failures for the same age group. Obviously, the weak link in shield design is the hydraulic system. Numerous hydraulic failures or problems were reported. The high frequency of failures in the first 3 years of operation is distorted by failure of a component called a hydrafuse. The hydrafuse is a safety device incorporated by Joy as part of the leg cylinder design on their recent generation of shield supports in response to a fatality that occurred recently in Australia. An Australian mine worker was killed when the hydraulic fluid in the retract annulus of the leg cylinders was inadvertently pressurized while setting the support. Normally, the retract port is open through the return line back to the hydraulic reservoir whenever the leg cylinder is being pressurized. This is necessary since the pressure would be highly intensified (by a factor 30 or more) if the port was blocked, as in the case of the Australian fatality. The resulting pressure intensification caused the cylinder end cap to rupture, striking and causing a fatal injury to the mine worker.

The hydrafuse is incorporated into the retract circuit and acts as a yield valve to prevent the inadvertent build-up of pressure in the retract annulus of the leg cylinder. The design utilized by Joy features a brass clip that shears off at a predetermined load (hydraulic pressure). Once the clip is broken the "fuse" must be replaced. With a failure pressure of nearly twice the pump operating pressure, it was expected that the fuse would provide the desired safety on the rare occasions when there was abnormal pressure, and that replacement of the hydrafuse after the failure would not be much of an inconvenience. To the surprise of everyone, hydrafuse failures began occurring on several shields at several mines. The failures seemed to occur whenever the support had set idle for a period of time, and whenever the leg pressure was at or near yield pressure and almost always on the top stage retract circuit. A series of tests were conducted on a longwall shield under of variety of loading conditions at NIOSH in the Mine Roof Simulator in order to determine if unexpected pressures were occurring in the retract circuit. None were found. Similar measurements of retract pressure on active shields in underground mines that reported hydrafuse failures were taken by Joy, and again no abnormal pressure spikes were found. However, it is believed that a water-hammer effect is being created by the valve operation. Joy has since installed a restricter valve in the circuit to dampen out any potential pressure spike. Early indications from the field installations indicate that this may be working to prevent the undesirable failure of the hydrafuses. Unfortunately, the restricter also increases the time required to lower the top stage. Fortunately, in two-stage leg cylinder designs, the bottom stage is lowered first and lowering of the top stage is only required when the bottom stage is fully collapsed. Hence, the increased time to lower the top stage will not be a problem during most production mining.

Other cylinder problems caused pressure losses that limited support capacity. One example was due to poor fabrication where the internal bore of the top stage was off center resulting in a weakened casing that was unable to sustain the pressure intensification that occurred in the top stage. Other problems were reported with defective yield valves that would not reset resulting in the inability of the shield to adequately hold load after yielding. Similar problems were reported with the staging valve which also caused loss of pressure in the leg cylinders at a few mines. One mine reported clearance problems with the leg cylinder and the base rib plates where the cylinder leaned into the rib plates causing internal damage to the cylinder and seal leakage. Failures also occurred with the advance ram cylinders including failure of shuttle valve springs and structural failure of a hollow tube relay bar design.

Most hydraulic problems are related to internal leakage due to seal wear and/or corrosion of the cylinders. These problems typically begin when shields have been in service 4-6 yrs. As figure 3 shows, 60 pct of the shields had some sort of hydraulic problems during this time frame. Many problems go undetected for extended periods of time, resulting in degraded support capacity that can contribute to ground control problems in heavy loading conditions. Methods to detect the onset of internal hydraulic leakages are discussed later in the paper.

There is a trend towards the use of low treatment synthetic fluids in western mines. These "low treatment" systems utilize synthetic oils in concentrations of only 1 to 2 pct compared to the conventional 5 pct mineral oil/water emulsions. The major disadvantage of the synthetic "low treatment" system is that there is little room for error. A small drop in the oil concentration can lead to lubrication problems and accelerated corrosion of leg cylinder bores, pistons, and rods. Therefore, maintenance of the oil/emulsion is much more critical than in the "high treatment" systems, where the oil content can be reduced from 5 to 4 pct with little if any detrimental effects. Bacteria growth can also be accelerated in very low concentrations of oil emulsions, which can cause more severe corrosion problems than if there were no oil at all. One western mine reported severe leg cylinder corrosion due to problems with a low treatment synthetic emulsion on shields that have been in operation less than 3 years.

Problems with the electro-hydraulic control systems were also reported. These included sticking solenoid valves (problem with soaping in emulsion formulation) and chattering valves due to fluid dynamics at high flows. Most mines reported that there have been significant improvements made in the latest generation of electro-hydraulic controls. In particular, the DBT (MTA) PM-4 system seems to be a significant improvement over the previous generation PM-3 design.

ENGINEERING ASSESSMENT OF SHIELD DESIGN AND FACTORS THAT CAUSE FAILURES

Structural failure can be divided into the following four basic categories: (1) general yielding or excessive plastic deformation, (2) buckling or general instability, either elastic or plastic, (3) subcritical crack growth (fatigue, stress-corrosion, or corrosion fatigue) leading to weakening of the component or unstable crack growth, and (4) unstable crack extension, either ductile or brittle, leading to either partial or complete failure of a member. Structural shield failures are generally of types 1 and 3 and occasionally type 4. A better understanding of the cause of these failures can be obtained by reviewing the principles of engineering mechanics for structural design.

Classical structural engineering design is based primarily on a strength of materials approach. The goal of this approach is to define the load requirements for the structure, and then to proportion the sizes and shapes of the various components to prevent tension failure or to prohibit instabilities such as buckling in a compression failure. Failure is handled by employing safety factors to ensure that the allowable stress in components remain within the elastic range of the strength of the steel. These basic engineering principles are used in current shield design, except **much higher allowable stresses are permitted in shields** compared to the safety factors employed in the conventional design of structures such as buildings and bridges. Failures by general yielding, such as that shown in figure 4, are indications that shields have been designed without sufficient margins of safety to prevent yielding. This is in part due to the low life expectancy of early generation shield supports. As the demands for greater life expectancy grew, the manufacturers were forced to employ more conservative design approaches. However, even with state-of-the-art shields, it is safe to say that the margins of safety may still remain below that of conventional structural design where life expectancies are much longer and failure of any sort is unacceptable.

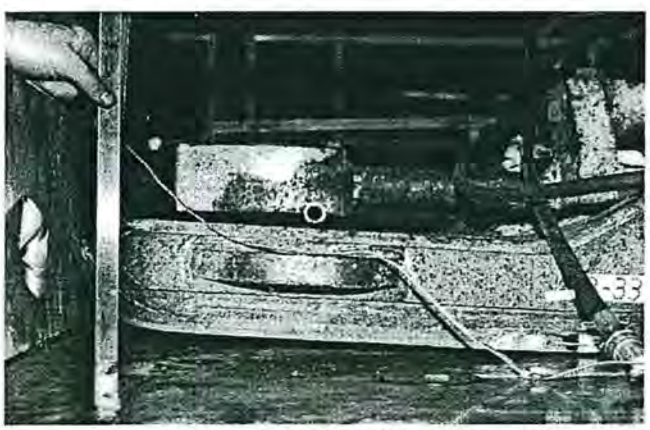

Figure 4. General yielding of toe of base unit in shield design from early 1980's.

Finite element modeling continues to grow in application as a powerful tool to optimize the design of complex structures. Recently, shield manufacturers have incorporated finite element modeling into their shield design practice. This practice has helped to improve the overall design of the current generation of high capacity longwall shields. An important criteria in the use of finite element modeling for shield design is to employ realistic boundary conditions. Unlike buildings in which the load applications are well defined and limited in scope, the various contact configurations of the shield canopy and base that are established by the mine roof and floor and strata caving mechanics, complicates the use of finite element modeling in shield design. Errors in the assumptions made in the boundary conditions, such as not properly constraining the model, can lead to poor shield design. Another very significant factor is to recognize the limitations of finite element modeling. A finite element model should be able to accurately define nominal stress developments in shield components, but may or may not (depending on the complexity of the model) accurately define areas of stress concentration which are critical to the long term structural integrity of the shield. The common practice is to model the shield as a homogenous structure. In reality, the weaknesses of a shield construction are often due to weldments where complex anisotropic properties occur that are not easily modeled. Without being able to accurately model these complexities, the best practice is to derate the model by incorporating factors of safety to account for these issues. However, this requires considerable experience by the modeler, which is best obtained through calibrations of models with empirical performance test data. Another limitation on the use of finite element modeling is the time required to construct and debug the model and to analyze various load conditions. An entire shield model may require as much as a full man-year of effort. The bottom line is that although progress has been made in applying this technology to improve shield design capabilities, **a shield should *not* be designed solely on the results of a numerical model.**

Since the longwall face and shield supports are advanced with each shearer cut, the shield is subjected to repetitive loading and the potential for fatigue related failures. Fatigue is the process of cumulative damage that is caused by repetitive fluctuating loads. Ductile as well as brittle materials are susceptible to fatigue failures. Since there is no large amount of plastic deformation prior to the fatigue failure even in ductile materials, **fatigue failures appear with little or no warning.** The failure mechanism is considered to be quite complex, but in general a fatigue crack is initiated at some microscopic or macroscopic stress riser. The crack itself then acts as a stress riser to promote localized yielding in the vicinity of the crack tip. In general, the more severe the stress concentration and the greater the load fluctuation, the shorter the time to initiate a fatigue crack. After a certain number of load fluctuations, the accumulated damage causes propagation of a crack or cracks leading to failure of the structure.

Conventional structural design for things such as machines and bridges employ relatively conservative design practices relative to fatigue loading to ensure the desired life and safety of the structures. The fatigue (endurance) limit of conventional steels typically is about 50 pct of the tensile (yield) strength. Generally speaking, this means that the nominal load (stress) developed in the shield components must be kept below 50 pct of the yield strength to prevent fatigue failures from occurring, thereby providing an indefinite life expectancy relative to fatigue failure. Such a design approach for shield supports would require much larger component sizes which would significantly increase the weight of the shield, and as such, are considered impractical for shield design. As the stress is increased beyond this endurance limit, the number of cycles to failure is reduced, starting at about 1 million load cycles. For a life expectancy of 100,000 cycles which is more representative for longwall shields, the allowable stress to prevent fatigue failure is much closer to the yield strength of the steel, suggesting that a factor of safety of 2 is not needed in shield design at least in relation to fatigue issues. Of course, these generalities are subject to the specific properties of the steel and the support construction. The allowable stress may be considerably less in some circumstances. For example, the allowable stress to prevent fatigue failure for a plate welded on the flange of an I-beam (similar to a plate welded on the bottom of the base pontoon) is only 15 ksi (*5*).

In addition to fatigue, stress corrosion causes failures to occur under ***statically*** applied loads with stress developments well below the yield strength of the material and independent of the number of load cycles. This can account for structural failures that occur at low production mines with aging shields where the number of cycles is low but the age is high. In other words, a shield doesn't necessarily have to have a lot of cycles to fail. The failure occurs due to crack initiation caused by the corrosion and subsequent propagation of this crack or material defects similar to that observed for fatigue loading. The author believes that **stress corrosion is a significant and mostly overlooked factor in current shield design**. The mine environment is often wet and acidic which accelerates corrosion of shield components as shown in figure 5. The base units in particular are subjected to extensive corrosion since the wet debris continually forms around and often covers much of the base structure. An area of particular concern is the leg socket which collects rock and coal debris throughout much of the shield's operating life. When combined with fatigue loading (corrosion-fatigue), stress corrosion causes a further reduction in the useful life of the longwall shield. Corrosion-fatigue damage occurs **more rapidly** than would be expected from the individual effects or from the algebraic sum of the individual effects of fatigue, corrosion, or stress-corrosion cracking.

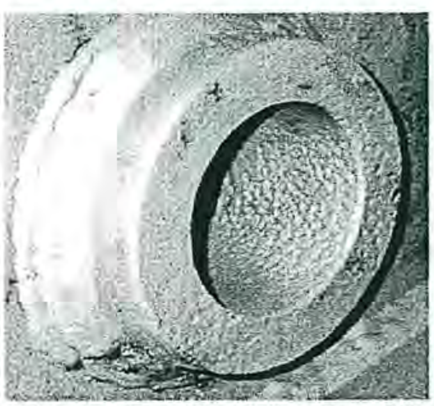

Figure 5. - Corrosion of a lemniscate link clevis.

The science of fracture mechanics was developed in the 1946 to 1966 period to analyze unexplained failures in several large scale complex structures where brittle fractures at stress levels no larger than were expected when the structure was designed were observed (*3*). However, it was not until the 1970's when fracture mechanics developed to the point where practical applications were considered and incorporated into the design of structures where brittle fracture and fatigue failure is of concern. The underlying premise in fracture mechanics is that real structures contain numerous discontinuities of some kind. These discontinuities can be flaws in weldments, poor fabrication practices where torch cutting leaves surface scars and abrasions, or cracks in base or weld materials due to things like corrosion. These discontinuities act as stress risers and unstable, rapid fracturing occurs when the stress intensity factor at the crack tip reaches a critical value. Such discontinuities certainly exist in longwall shields and are undoubtedly a **primary source of structural failures.**

The goal in fracture mechanics design is to keep the stress intensity level below the critical value that promotes crack propagation, much like the goal of strength of materials design is to keep the design stress within the material's elastic range. To ensure that a structure does not fail by fracture, the number of cycles to grow a small (often microscopic) crack to a critical crack length must be greater than the life of the structure. Hence, the key idea to consider in a fracture mechanics design is the ability of the steel to absorb strain energy. If the material has a high absorption capability, such as mild steel, crack growth will be limited to plastic flow of the material and general yielding will typically prevent brittle fractures from occurring. Conversely, the probability of fatigue related failures increases with low energy absorption materials. Unfortunately, from a fracture mechanics perspective, state-of-the-art shields are now constructed from high-strength steels (100,000 to 120,000 psi yield strength) which are much **more susceptible to brittle fracture** than the early generation of shield supports which were constructed from mild steel (35,000 to 45,000 psi yield strength). The motivation for the high strength steel of course is to minimize the size of the components and keep the weight of the shield down, which is an ever increasing challenge for the design engineers as the capacity of the shields continue to rise. In essence, the term high-strength steel is a misnomer for two reasons. First, the fracture toughness is reduced which means that the allowable stress, as a percent of the yield strength, must also be reduced to prevent fracture from occurring. In other words, the full advantage of increased strength of the steel may not be realized. Secondly, unlike lower strength steels where the weld material is of equivalent or higher strength of the base metal, it is not uncommon for weaker weld materials to be used in the high strength steel constructions.

There are three primary parameters that are important in fracture mechanics design: the material toughness (K_c), crack size (a), and the stress level (σ). Their relationship can be expressed mathematically by equation 1 and by examination of figure 6. To the right and above each curve is the region of failure, whereas below and to the left of each curve is a crack size at a specified stress level that will not cause failure. As seen in figure 6, a larger K_c (tougher steel) will shift the curve up and to right, indicating that for a given stress level (σ), a larger crack size (a) can be tolerated before global failure occurs. The general approach to shield design is then to formulate a fracture control plan by defining the largest crack size likely to be found in the structure and then estimating the stress intensity factor using equation 1. Once this is done, the allowable stress to prevent fracture for a specific steel can then be determined.

$$K_c = \sigma\sqrt{\pi a} \qquad (1)$$

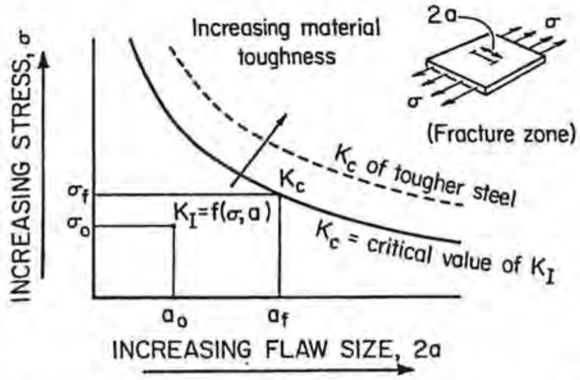

Figure 6. Fracture mechanics principles regarding material toughness, stress, and flaw size.

Some recommendations for fracture mechanics design that pertain to shield supports are summarized as follows:

1. For fatigue loading, the total life of a structure depends on the cycles required to initiate a crack and the cycles required to propagate the crack to a critical size that causes failure. Most of the life of a structure is spent in crack initiation. Therefore, any decrease in the initial flaw size has a very significant effect on the fatigue life of a structure. For example, doubling the initial crack size could reduce the life expectancy by a factor of 2 or more. This means that **weld quality** and fabrication practices or corrosion which creates a flaw in the material **can be very critical to the life expectancy of a shield.**

2. Fatigue is also significantly affected by the magnitude and stress reversal of the load fluctuation. Performance testing should ideally be conducted from no load to full yield pressure in the leg cylinders under various roof and floor contact configurations and displacement profiles that maximize the load fluctuation in each of the support components.

3. For welded constructions, the possibility of residual stresses exist. Depending on the toughness of the material, most cracks that initiate in the presence of residual stresses could arrest quickly as soon as the crack propagates out of the region of high residual stress, but the initial crack size for any subsequent crack growth will be fairly large and shorten the life expectancy of the structure. Hence, proper welding techniques to control residual stress developments can be critical to the life expectancy of the shield support.

DESIGN PRACTICES TO IMPROVE STRUCTURAL MARGINS OF SAFETY AND EXTEND SHIELD LIFE

Since most structural shield failures can be attributed to some form of fracture, the basic elements of fracture control can significantly improve shield life. These are: (1) use a lower design stress, (2) minimize stress concentrations, (3) reduce flaw size or control crack growth, (4) minimize corrosion, and (5) use materials of improved toughness. These factors are illustrated in figure 7.

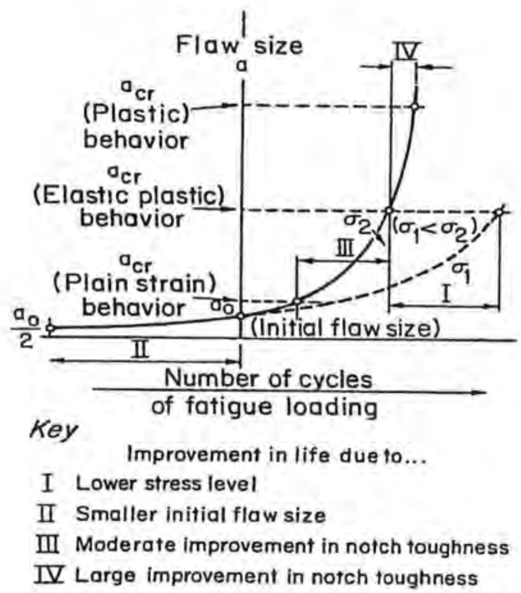

Figure 7. Impact of reducing flaw size or stress magnitude or increasing material toughness on extending life expectancy of a structure.

Lower Design Stress

Some margin of safety should be employed in the design stress relative to the yield strength of the steel. Civil engineers typically use a factor of 1.66, meaning that the allowable stress is about 60 pct of the yield stress for non-fatigue loading and further reduced by 50 pct or more when fatigue loading applies. While these levels of safety are not practical in shield design due primarily to cost and weight limitations, it is important to recognize that a small reduction in (tensile) stress developments will significantly reduce crack growth since the two are related by an exponential function. Past practices of designing to or near yield strength should be avoided in modern shield design where the life expectancy exceeds 50,000 loading cycles.

Link pins and clevises are a prime example of historically poor design practices in shield supports which continue even today. Deformation and/or excessive wear in the pin clevises is undoubtedly the primary cause of premature shield retirement and/or structural rebuild. There are clear indications that these areas are subjected to stress beyond the yield strength of the steel. This poor design is caused partly by manufacturers not giving sufficient credence to the load conditions which cause high loading in the caving shield - lemnsicate assembly, namely loss of frictional contact at the roof and floor interface and standing the support on the toe of the base. With the possible exception of shields designed for low seam heights, there is adequate space available to increase the bearing area of these clevises and pin diameters to reduce the stress and substantially improve the life expectancy of these components. The joint design problem also needs to recognize the importance of pin tolerance. First, the pin contacts only a portion of the clevis. Typically, arcs of 45 to 60 degrees are used in the design analysis. Obviously, the 45 degree arc assumption will lead to more conservative designs. Conservative assumptions should be made to allow for reduced areas as wear occurs (figure 8). Excessive pin tolerances can lead to point loading by allowing the pin to rack within the joint clevis as illustrated in figure 9. Corrosion effects are also often ignored or not sufficiently accounted for in the design of pins, despite the fact that corrosion is a leading cause of premature pin failures or abnormal wear. Corrosion causes pits to occur in both the pins and the clevises (figure 5) which can reduce the bearing area by 25 to 50 pct and cause a proportional increase in stress.

Figure 8. Reduction in lemniscate pin contact area for worn joint.

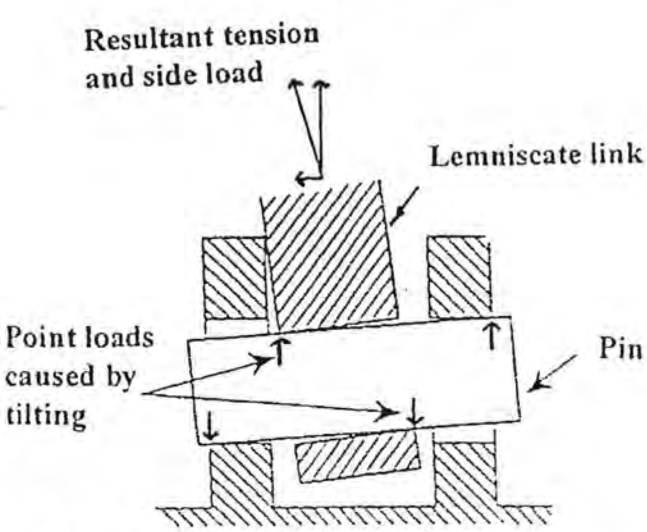

Figure 9. Ranking of lemniscate pin due to excessive pin wear or poor pin design tolerances that lead to stress concentrations and potential failures in the lemniscate joints.

Several failures have occurred where the leg socket casting weldments break due to fatigue or stress-corrosion, and thereby cause subsequent failure of the bottom base plate as the loading is transferred fully to the bottom plate instead of being distributed to the side rib plates. Most of the time the leg cylinder and casting punch through the bottom plate and into the mine floor rendering the support inoperable. A common modification to alleviate base leg socket failures of this nature is to add another plate to the under side of the base pontoon as shown in figure 10. Typically, this plate is about 1 inch thick and usually covers most of the length of the base pontoon. Reinforcement is also typically added to the top area of the side base plate. While this plate stiffens the side plate, its primary purpose is to restore the location of the centroidal axis, which was changed by the addition of the bottom plate, to its location in the original base design. Due to past failures of this nature support manufacturers are now beginning to incorporate a thicker bottom plate in the initial shield design.

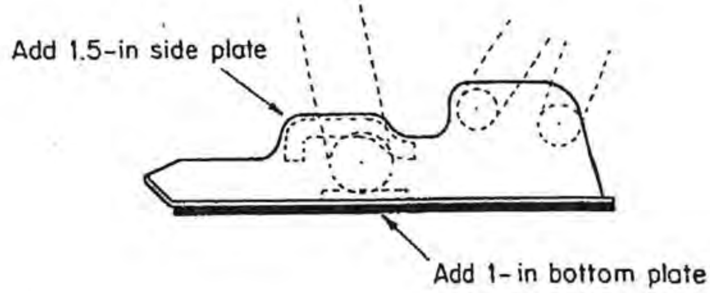

Figure 10. Modification made to strengthen base in order to prevent leg socket casting failures.

Some mines have successfully reduced operating stress levels by **derating the shield support** prior to underground installation. The derating is accomplished by simply installing yield valves with a lower operating pressure than specified in the design. Since the leg capacity controls the maximum load developments within the support, lower leg loads translates into reduced component loading. For example, if a 1,000 ton shield support is derated by 10 pct to a 900 ton capacity, the margin of safety relative to the tolerable crack size that will prevent fatigue fracture may increase by 20 to 30 pct.

If failures are observed underground, **procedures to reduce shield loading should be implemented.** A good practice to reduce face weighting is to maximize the rate of advance. Idle faces generally have a tendency to create higher shield loads. Also, setting forces should be optimized. Conventional wisdom has been to increase the set pressures or to ensure that full setting (pump) pressure is maintained. However, in displacement controlled loading where the load development is proportional to the shield stiffness and the support resistance is not controlling the ground movements, reducing the setting loads may also be an option to reduce the total loading on the support. Another possibility is to reduce the depth of the shearer cut. Much of the shield loading is generated from the shearer pass. A reduced cut may reduce shield loading, although there has not been any data collected to substantiate this hypothesis.

Another issue related to lowering the design stress is to ensure proper operation of the support once it is put into service in the mine. Stress developments are greatly enhanced whenever the support is stood on the toe of the base. When a shield is set with the canopy tip up, the leg forces will typically rotate the canopy into full roof contact and in the process lift the rear of the base off the ground. This base-on-toe configuration increases the magnitude of stress in the lemnsicate links by as much as 300 pct. Modern two-leg shields employ a control system for the canopy capsule cylinder which prevents setting the shield with the canopy tip up. Hence, if this system is deactivated by the mine personnel, the life expectancy of the pin joints and the entire shield can be significantly shortened.

Minimizing Stress Concentrations

There are numerous sources of stress concentrations in longwall shield supports. The most common is a change in geometry. These stress concentrations should be identified and their magnitudes quantified during the design and performance testing phase. One way to do this is to use photo-elastic plastics. The photo-elastic plastic can be applied to almost any area of the shield structure. Colored fringes will appear on the plastic when observed through a polarized lens that correlate to the stress profiles. **Stress intensity factors of 2-3 are not uncommon** for sharp changes in geometry such as holes or sharp bends in structural members.

One example of this is a lemnsicate link design with a bend in the link. The bent link is typically employed on a shield with a low profile designed to operate in low coal seams. The bend is necessary to provide clearance with the caving shield in the collapsed or low operating height. Lemnsicate links are primarily axially loaded members, but the "bent" geometry induces additional stresses due to bending, and thereby significantly reduces the margin of safety for this component. Figure 11 depicts failure of a bottom lemnsicate link on a 620-ton shield that occurred during performance testing at the NIOSH Safety Structures Testing Laboratory. Although the shield had 45,000 load cycles from underground service prior to the testing, a new link was installed on the shield that was performance tested in the laboratory. This was a new link design that was fabricated for the mine by an outside vendor (not the support manufacturer). Failure occurred after only 14,000 loading cycles. This failure illustrates two problems. First, the design (allowable stress) was too high. Test results revealed that the nominal stress in the link exceeded 90 pct of the material strength. In addition, it appeared that the link side plates had been torch cut, adding an additional stress riser to the already sharp change in geometry at the bend in the link in the area where the failure occurred. These two factors resulted in an unacceptable time to failure. Figure 12 illustrates another problem where the fabrication process left large flaws that led to premature fatigue failure of the base rib. This problem may have been alleviated if the surface was smoothed to remove most of the surface flaws.

Figure 11 - Failure of bottom lemniscate link.

Figure 12. Failure of base rib side plate where fabrication process left large flaws in surface structure.

Any hole in a structural plate is another area where stress is concentrated. The structural components of a longwall shield (canopy, caving shield, lemnsicate links, and base) are connected by a pin and clevis arrangement. These areas are also sources of stress concentration and fatigue failures on aging longwall shields (figure 13). Another example of a stress concentration caused by too sharp of a change in geometry is shown in figure 14. Holes are sometimes cut into the canopy or caving shield structure to accommodate the placement of hydraulic hoses. In the example shown in figure 14, failure occurred at the stress riser caused by the sharp corner in a cut-out on the caving shield made to accommodate hosing for the side shield. The best solution to this problem is to avoid the hole altogether and if the hole is necessary to make sure that the corner radius is as large as possible. Another example of failure due to stress risers created by sharp geometries is shown in figure 15, where a crack developed in the caving shield near the canopy hinge. A clean-out hole is often placed in the side of the base structure to facilitate removal of debris from the leg socket area. This too can be a source for concentration of stress. Since this is a critically loaded area of the base, care should be taken in the design to minimize the stress concentration by a incorporating a favorable geometry and orientation with respect to the stress field in this member.

Figure 13. Failure in base lemniscate link clevis.

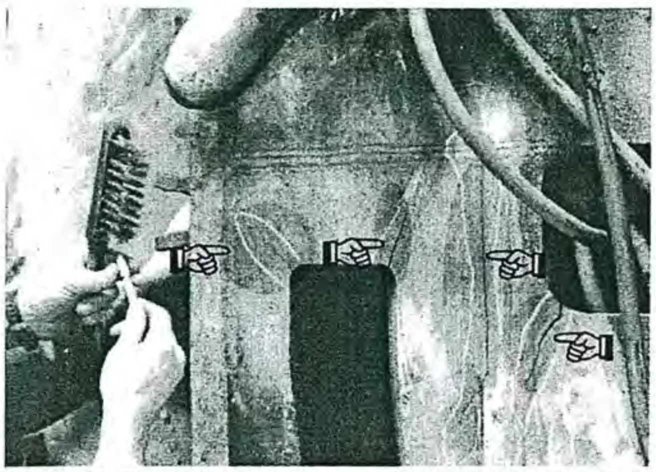

Figure 14. Failure due to stress concentrations in cut out sections of caving shield.

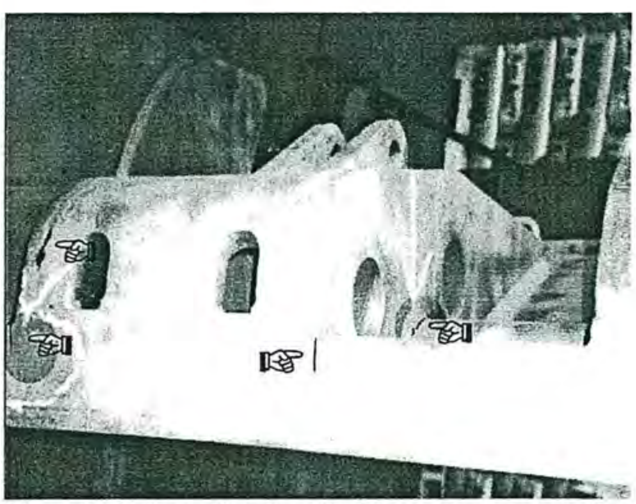

Figure 15. Failures of caving shield due to stress concentration in sharp corners where lemniscate links connect.

Figure 16 shows failure of a canopy leg socket casting due to a stress riser created by a sharp change in geometry. The failure in this case occurred in the casting itself. This failure occurred on several shield supports in the late 1980's, all of which utilized this same basic socket design. Again, this failure probably could have been prevented by a smoother geometry. Leg sockets are often a source of fatigue failures in aging longwall shields. The leg socket is a critical area since the full load developed within the hydraulic leg cylinder must be transferred into the canopy and base structures to be distributed to the mine roof and floor. An examination of the structural mechanics associated with these base socket failures has led to some other design changes that are intended to reduce the stress concentration in the leg socket casting/base structure connection. The rectangular geometry of the socket casting and its placement between the side rib plates of the base structure position it at right angles to the principal tensile stress caused by the bending of the base structure. This orientation creates a stress intensity factor which helps to promote fatigue-induced fracturing of the weldment. Some shields are now being designed with more of an elliptical or zipper shaped casting (figure 17) so that the front and/or rear edge is not perpendicular to the principal tensile stress, thereby resulting in a reduction of the stress intensity factor.

Figure 16. Failure due to stress riser created by sharp corner in canopy leg socket casting.

Figure 17. "Zipper-shaped" leg cylinder casting to avoid stress concentration caused by orientation of casting to principal stress field.

Reducing Flaw Size or Controlling Crack Growth

Weldments are an essential part of the shield fabrication process. However, since weldments are a primary source of structural flaws, the quality of the welds is critical. As the principles of fracture mechanics illustrate, the initial flaw size created by the welding process is critical to the crack propagation and the margin of safety achieved in this structure. Once a crack develops, it is desirable to keep the crack contained within the weld and not have it progress to the base material adjacent to the weld. This action may depend on the nature of the heat-affected zone in the immediate vicinity of the weld. In general, the heat affected zone results in anisotropic material properties and residual stresses that tend to reduce the toughness of the steel in this area and increase the likelihood of fracture into the base metal. For the high strengths steels used in modern shield supports, proper heating and cooling of the steel during the weldment process is crucial to preventing crack initiation and growth in the heat affected zone. This is why it is very difficult to conduct repairs to damaged shields underground, since it is virtually impossible to be able to preheat and properly cool the steel when welding at the longwall face. Another approach that can be used to keep crack growth contained to the weldments is to create breaks in the weldments. This practice is sometimes used in leg socket castings. The break in the weld at the corners of the casting acts like as a crack arrester to stop the growth of the crack. This same technique is used in the airplane industry by drilling holes in the metal at the end of an observed crack before it reaches a critical crack length.

Perhaps the best approach to avoid problems associated with weldments is to eliminate them when possible. A good example of this pertains to the leg socket design. A typical construction for the leg cylinder base socket is shown in figure 18. A casting 3-4 inches thick and 18-24 inches long with a spherical seat to accommodate the bottom of the hydraulic cylinder is placed on top of the bottom cover plate on the base pontoon, and is welded in place along the four sides of the top of the casting to the side rib plates and cross plates that connect the two side base plates together. This design is highly dependent on the welds to transfer load into the side rib plates and maintain the structural integrity of the socket connection. An alternative design that is now being employed in some canopy leg sockets to alleviate the weld fatigue problem is to cut rectangular holes into the side base rib plates and extend the width of the casting so that it bridges across the base but is supported by the side rib plates (figure 18). In this configuration, leg cylinder loading is transferred directly to the side rib plates of the base structure entirely through base metal contact, and is not dependent on the weldments to achieve this load transfer.

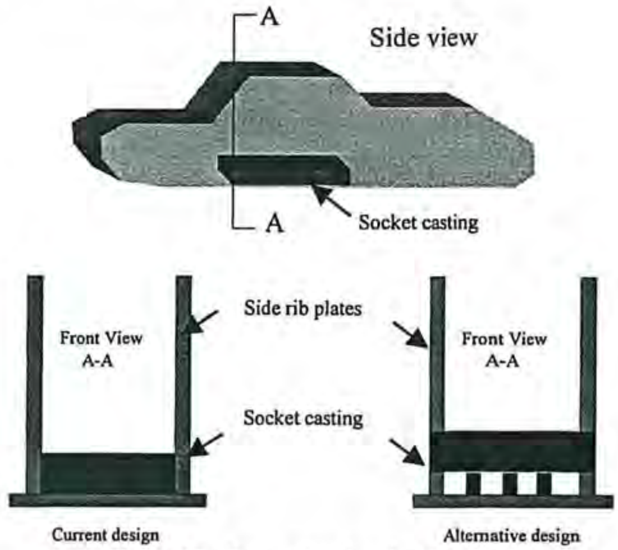

Figure 18. Conventional and alternative leg cylinder casting design.

Corrosion Control

Some steps can be taken to circumvent the problems caused by corrosion. The most convenient approach is to try to protect the shield from the environment. For shield supports, this mostly applies to painting with an industrial paint that is resistant to the wet mine environment. However, for some components such as the pins and clevises where there is considerable wear due to the kinematics of the shield during load application, painting or event plating with more resistant material is not an option. Impregnated pins with zinc phosphate through sheridizing has proven beneficial, but the effectiveness is limited due to the wear in the joint. Another option worth considering is some form of lubrication for these joints. A simple grease fitting would be an improvement, although somewhat impractical to maintain on an active longwall face. Hence, a sealed joint of some form would be preferable.

Tests have shown that compressive stresses on the surface of materials that are exposed to the environment will not necessarily minimize corrosion-fatigue crack initiation, but they can reduce the possibility of crack growth and thereby prevent failure from occurring. This could be done by induction hardening the joint pins. The concern with this approach would be that the induction hardening might make the pins more brittle.

Material Toughness

The strength of materials approach essentially ignores the toughness of the material, which as described is the most significant material property for fracture control. There is a tradeoff in the use of high strength steels if they provide superior strength but reduced toughness with greater chance for failure. Since the author is not familiar with the German and British steels used in the shield construction, no specific recommendations are made, but the issue should be investigated with the shield manufacturer when new shields are purchased.

ISSUES REGARDING PERFORMANCE TESTING

There is no substitute for performance testing to reveal design deficiencies. However, in order for performance testing to be effective, it must properly simulate the in-mine service conditions, and should always be conducted on a prototype shield *prior to* the start of production shield fabrication to ensure that any design deficiencies discovered in the performance testing can be properly corrected.

Simulation of the In-mine Service Conditions

There are two basic aspects to shield loading. The initial load condition is determined by actively setting the shield against the mine roof and floor. Subsequent loading is produced by the movement of the surrounding strata during the caving process and the associated internal forces developed within the support structure.

As the shield is set against the mine roof and floor, there is a tendency for the canopy to be displaced horizontally relative to the base. This is due to the resultant horizontal component of the leg forces, which causes either slippage of the canopy along the roof interface or displacement (compaction) of the fractured strata or debris immediately above or below the shield.

Once the shield is set against the mine roof and floor, load development within the shield is controlled by: (1) the contact configuration established with the mine roof and floor; (2) vertical displacement of the canopy relative to the base induced by deflection of the main roof beam and weight of fractured immediate roof strata being directly supported by the shield; (3) face-to-waste movement of the immediate roof as the strata breaks into disjointed blocks from the face abutment loading and loss of confinement; and (4) waste-to-face loading induced by gob material acting on the caving shield and/or the internal forces developed within the shield due to the leg forces and component reactions.

Performance Testing Load Frames

The first issue of significance in performance testing pertains to the capability of the load frame where the tests are conducted. There are three types of load frames available for full scale shield testing: (1) static load frame where shield loading is produced by pressurization of the leg cylinders by an external power supply, (2) active uniaxial load frames where the load frame can simulate roof-to-floor convergence, and (3) active biaxial load frames where both roof-to-floor convergence and controlled horizontal displacement of the canopy relative to the base can be provided.

Only a biaxial load frame, such as the unique Mine Roof Simulator at NIOSH's Pittsburgh Research Laboratory (figure 19) can truly simulate the ground movements associated with longwall mining. The limitation imposed by the static and active uniaxial load frame is the inability to simulate the forward translation of the canopy due to slippage on the mine roof and the face-to-waste racking of the shield. Table 1 depicts the significance of this behavior through measured strain responses in the lemnsicate links and base substructure during performance testing in the NIOSH Mine Roof Simulator load frame.

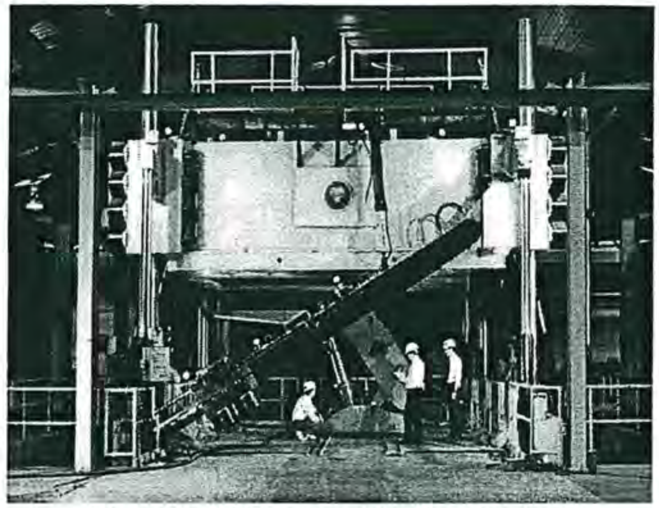

Figure 19. NIOSH unique Mine Roof Simulator.

Table 1. Significance of load condition (zero-friction test) on component stress development.

SHIELD COMPONENT	MINE A	MINE B	MINE C
TOP LINK	Measured strain, microstrain		
Restrained configuration	-1,608	-124	-338
Zero-friction configuration	-2141 (+33%)	-516 (+316%)	-1,033 (+205%)
BOTTOM LINK			
Restrained configuration	1,818	86	305
Zero-friction configuration	2,241 (+23%)	264 (+207%)	737 (+142%)
BASE			
Restrained configuration	-1,535	-1,060	-1,203
Zero-friction configuration	-1,745 (+14%)	-1,596 (+51%)	-3,676 (+206%)

Slippage of the canopy on the mine roof due to loss of frictional resistance at the roof interface can be simulated in static and uniaxial load frames by placing rollers on the canopy to create a "frictionless canopy test". Unfortunately, the zero-friction test with rollers on the canopy is not very practical for extensive cyclic loading since the rollers may require frequent adjustments due to frictional effects. Hence, this test is typically not included in the manufacturers performance testing protocol. If the frictionless canopy test cannot be conducted, then the support should be configured so that it is standing on its toe, which will require horizontal constraints at the toe of the base and rear of the canopy (at the caving shield connection). The horizontal force couple generated by this configuration allows load transfer to the caving shield - lemnsicate assembly, similar (although not as severe) to that obtained with the zero-friction test.

Likewise, face-to-waste racking of the shield cannot be directly simulated by a static or uniaxial load frame. The contact configuration which most closely duplicates the caving shield-lemnsicate assembly response for this condition in static or uniaxial load frames is to configure the support so that it is simply supported on the rear of the base. Face-to-waste racking of the shield canopy causes a reversal in the state of stress in the lemnsicate links from compression to tension. Since reversal of the loading accelerates fatigue failures, both the base-on-toe *and* the base-on-rear configuration should be incorporated into safety testing protocols conducted in static or uniaxial load frames.

State-of-the-Art Safety Performance Testing Protocols

Consolidation Coal Company has been instrumental in developing performance test standards for longwall shields. The "Consol test" consists of several combinations of canopy and base contact configurations which are categorized as follows: (1) offset yield loading, (2) base toe loading, (3) three-point canopy torsional loading, (4) two-point canopy torsional loading, (5) side shield loading and base torsional loading, (6) diagonal base contact, (7) three-point base contact torsional loading, (8) symmetric base edge loading, (9) asymmetric base edge loading, (10) leg socket loading, (11) canopy dishing. These tests are designed to be used in static or single axis loading frames.

NIOSH has also developed a protocol for safety performance testing that takes advantage of the biaxial loading capabilities of the unique Mine Roof Simulator load frame. The biaxial loading capabilities allow several test configurations to be incorporated into one loading cycle. There are three test series in the NIOSH protocol: (1) Test Series I -- Transfer of Horizontal Load To The Caving Shield-Lemnsicate Assembly (zero-friction test), (2) Test Series II -- Eccentric Twisting and Racking of the Canopy, and (3) Test Series III -- Leg Socket Shear Tests under Constrained Shield Conditions.

Further Enhancing Shield Safety Performance Testing

Proper simulation of the horizontal loading of longwall shields as described above will significantly improve shield safety performance testing. The one load condition which has not been given much consideration is lateral loading where the canopy is displaced laterally (sideways in a direction parallel to the coal face) relative to the base. This loading condition is most likely to occur for shields operating in high seam heights and in pitching seam operations. The sideways loading can also be caused by interaction among adjacent shields when setting, particularly when the side (caving) shield is protruding out too far. Some mines have eliminated side shields from their design for this reason. Lateral loading can easily be simulated in the NIOSH Mine Roof Simulator, however, there is no easy way to simulate this loading condition in static or uniaxial load frames. Canopy contact configurations that are designed to produce offset leg yielding (i.e load concentrated over one leg), three-point contacts designed to induce torsion, or base edge contact configurations that tilt the canopy and/or base produce some degree of lateral loading, but not nearly as much as when there is lateral displacement of the canopy relative to the base during the load application.

Even in the absence of high mining heights, some side loading can be developed by twisting of the canopy due to horizontal racking loads. The NIOSH Safety Performance Testing protocol addresses this issue by aligning the shield so that the direction of horizontal loading (applied displacement) follows a diagonal path from the left canopy tip to the right rear canopy corner as shown in figure 20. The diagonal path is reversed to the opposite corners to vary the direction of loading from left to right. The twisting action of the canopy creates point loading conditions in the shield joints as well as torsional loading of the caving shield - lemnsicate assembly. Since the joints do not have a degree of freedom in the lateral axis, this loading action causes accelerated deformation of the joint areas and premature failure of the connecting pins and clevises.

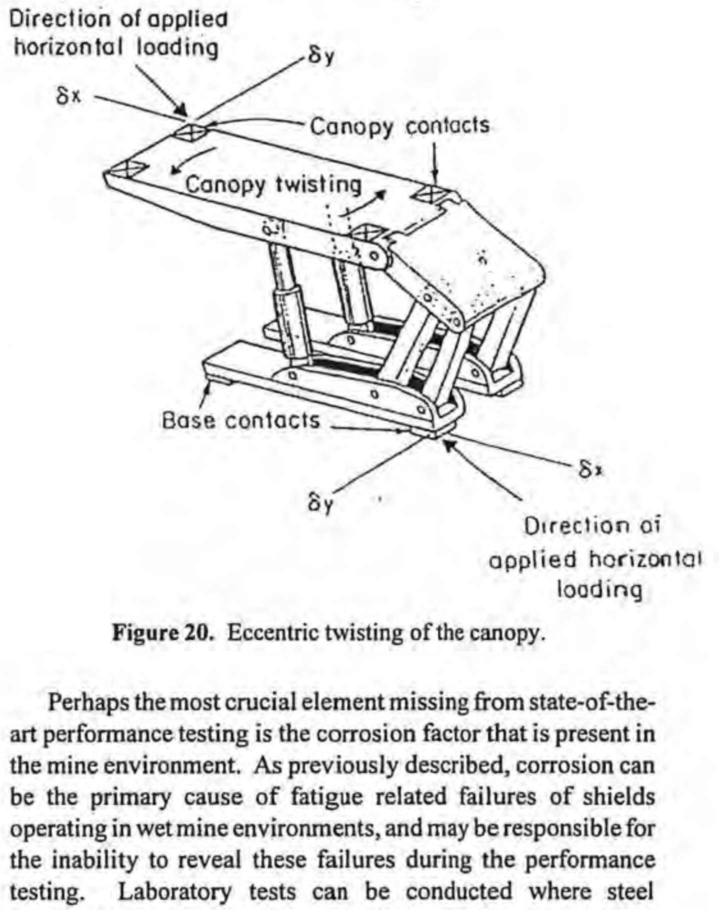

Figure 20. Eccentric twisting of the canopy.

Perhaps the most crucial element missing from state-of-the-art performance testing is the corrosion factor that is present in the mine environment. As previously described, corrosion can be the primary cause of fatigue related failures of shields operating in wet mine environments, and may be responsible for the inability to reveal these failures during the performance testing. Laboratory tests can be conducted where steel specimens are submerged in an environmental tank containing an acidic water similar to what is found in the mine. This would provide meaningful baseline data that may benefit future shield design. Unfortunately, such an approach is not practical

An impending problem with current plating technology is the environmental hazards associated with the plating process. Both chrome and bronze plating have environmental hazards associated with them that are likely to drive up the cost of these conventional plating methods in the near future. Since rebuilding of shield leg cylinders is a routine part of extended shield operation on every longwall, this can have a significant impact on the mining industry and new plating technologies need to be explored. Swanson Plating in Morgantown, West Virginia is now offering laser-controlled plating as an alternative. The laser technology in addition to being more environmentally friendly, reduces the heat affected zone by nearly two orders of magnitude and allows for much more controlled plating using materials that cannot be applied by conventional plating practices. More innovative solutions to consider would be the use of ceramic or composite materials that are much more corrosion resistant than the heavy metals currently used in cylinder construction.

CONCLUSIONS

The evolution of improved shield design continues with the current generation of shield supports. The previous generation of shield supports (1985-1995 era) experienced several serious structural failures. These included canopy sections falling off, bases cracking in half, leg sockets pushing though the base and canopy into the mine roof and floor, lemniscate links breaking, and pins bending and breaking. Generally, these problems have been addressed by the support manufacturers, but as the capacities continue to grow each new generation of shield supports must also go through the growing pains of finding design deficiencies. This is what is occurring now as isolated failures of modern shield design are again cropping up.

While proper shield design is not magic, there is an experience factor that cannot be overlooked. Unlike designing a building or a bridge where the load conditions are well known and fail-safe design philosophies can be readily employed, the mining environment is not well defined or easily understood. Mining engineers typically design to allow failure, while conventional structural engineers design to prevent failure. Furthermore, as the demand for extended shield life continues to grow, continued improvements in quality control and innovations in shield design must be developed if this requirement is to be realized.

While the design of longwall shields appears to be and is a complex issue, it would be beneficial to prospective shield buyers to learn the basic engineering principles associated with shield design issues as addressed in this paper. While it is not necessary to know all the answers, knowing what questions to ask is important. Hiring a structural engineering consultant is another option, but again be aware of the uniqueness of the mining environment and shield design issues.

There is no substitute for performance testing to ensure the integrity and safety of a new shield design. However, the performance testing must properly simulate the in mine loading conditions. The so called "Consol Test Program" has proven to be effective in eliminating shield deficiencies during prototype testing. Dynamic loading as provided by the NIOSH's unique Mine Roof Simulator load frame is the most accurate approach to simulating the in mine loading conditions. NIOSH has also developed a state-of-the-art safety performance testing protocol for shield supports that is now available to the longwall mining companies.

Corrosion is by far the most overlooked factor in both shield design and performance testing. Corrosion control practices are limited, but they need to be followed. Simple things such as using corrosion resistant paint and repainting of shields can be effective. Design changes need to be made to the pin joints and clevises which are subjected to high wear rates to avoid corrosion in these areas. Advanced plating technologies and more corrosive resistant materials need to be employed to improve hydraulic cylinder life, which is by far the weak link in a shield's life line.

If the trend of increasing the width of the shields is going to continue, design changes or the use of innovative materials such as composites, will be required in the near future. The weight of 2.0 meter wide shields is already a problem in high seam operations.

Finally, the following recommendations are made as key points on how to ensure your shield design meets your needs and how to maximize its life once it is put into service.

1. Identify you goals in buying a bigger shield. Are you looking for more support capacity to improve ground control or is your primary goal to extend the life of the shield. If your primary goal is to extend shield life and your previous support of lower capacity was providing adequate ground control, then consideration should be given to derating the shield. There is a clear correlation between increased loading and fatigue related failures. Derating a shield by reducing the operating yield pressure can provide an additional margin of safety and the extend the life of shields where high component stresses are observed. If you need the extra capacity for ground control *and* you want to improve the life expectancy, then be prepared to pay a premium for the shield and insist on a conservative design.

2. Make sure performance testing is completed before production shield fabrication begins. Allow enough time in the procurement cycle for performance testing of a prototype shield to be completed *before* fabrication of the production shields begins.

3. Make sure performance testing is properly done. Performance testing must properly simulate the in-service load conditions. Avoid test procedures which do not properly transfer load to the caving shield - lemniscate assembly.

4. Consider testing a shield to failure. This will tell you what failures to look for and give you insight as to when to look for them, and should be considered even if this means paying extra for the performance test.

5. Consider buying several extra shields. While this adds cost to the initial purchase, a good preventive maintenance program will pay big dividends in maximizing the life of a shield. For example, if 12 - 16 extra shields were purchased and recycled during each longwall move, problems such as leg cylinder rebuild and restoring pin tolerances to design specifications could be corrected as they arise, and preventive measures such as painting and crack inspection and repair could be done on a regular basis.

6. Avoid setting the shield with the canopy tip up. The worst case loading for longwall shields is to stand the support on the toe of the base. Most shields are equipped with a control system that controls the canopy capsule cylinder operation to allow the canopy to float as the support is being set to avoid setting the shield with the canopy tip up. *Do not deactivate* this system unless it is absolutely necessary.

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