Comparison of methods: dynamic versus hydrostatic testing of mine ventilation seals

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Introduction

Tragic mining disasters in West Virginia (Sago Mine) and Kentucky (Darby Mine) in 2006 greatly heightened interest in the development of quality seals to protect miners from blast effects and toxic gases produced by uncontained gob explosions. Following the enactment of the 2006 Miner Act and the U.S. Mine Safety and Health Administration (MSHA) issuance of the Emergency Temporary Standard (ETS) on the Sealing of Abandoned Areas in 2007, MSHA is conducting detailed technical evaluations of all proposed seal designs for each underground sealing location. These technical evaluations are based on sound structural engineering design approaches followed by certification of as-built construction. MSHA will also accept the results from full-scale testing of mine seals. If full-scale performance testing is required to develop seal stress-strain response data, the authors propose a hydrostatic test method as an alternative to full-scale explosion testing. This method uses water to load the seal to pressures at least twice the expected dynamic design load to determine stress-strain data. This article contrasts the full-scale explosion and hydrostatic testing of mine seals using a simple dynamic system model and principles.

There are many three-dimensional, finite-element codes for designing various load-bearing structures that can simulate not only the seal itself, but also the interaction of the seal with the surrounding support strata. However, when studying a single mode of seal response, the basic analytical model used in most blast-design applications is the single-degree-of-freedom (SDOF) system. In the current study, the U.S. Army's Wall Analysis Code (WAC) (Slawson, 1995) was used to identify test conditions where hydrostatic pressure loading can serve as an alternative yet equivalent test method to full-scale methane-air explosions for evaluating the strength performance of mine ventilation seals. Such hydrostatic tests would build confidence in design methodology through comparisons between pretest predictions and actual measurements, as well as provide a timely, cost-effective means of seal testing.

Abstract

From 2001 to 2007, the Pittsburgh Research Laboratory (PRL) of the National Institute for Occupational Safety and Health (NIOSH) conducted studies to develop alternative methodologies to full-scale explosion testing for determining the ultimate strength of mine seals. As a result, the PRL developed and proposes an alternative seal-strength evaluation method based on a hydrostatic pressure-loading concept. The researchers suggest pressure loading a seal using water to twice the expected dynamic design load. The hydrostatic chamber test offers a means of validating seal designs, establishing appropriate resistance functions and determining the ultimate strength of seals through testing to failure. This article contrasts the full-scale explosion and hydrostatic testing of mine seals using a simple dynamic system model and principles.

Single-degree-of-freedom system (SDOF)

All structures possess more than one degree of freedom regardless of how simple their construction. However, many structures can be adequately represented as a SDOF system for purposes of analysis. The accuracy of an SDOF approximation depends on how well the deformed shape of the structure and its resistance can be represented with respect to time. The procedure for obtaining the equivalent SDOF approximation for a structural component is based on its deformed shape under the applied loading and the strain energy equivalence between the actual structure and the SDOF approximation.

Equivalent mass, stiffness and loading are obtained through the use of transformation factors. Chapter 3 of the U.S. Department of Army, the Navy and the Air Force design manual TM 5-1300 (1990) contains tabulated transformation factors for typical structural elements, including slabs. The derivations of the equations for the transformation factors are also given in this reference and used in the WAC.

The WAC is an SDOF model developed for the U.S. Army Engineer Waterways Experiment Station (WES), Structures Laboratory (Slawson, 1995). WAC was developed to provide a tool for the easy calculation of the response of typical walls subjected to blast loads. The WAC can calculate the resistance function ($R(y)$, pressure-deflection) of a wall given its construction details, including dimensions, material properties and support conditions or accepts user defined resistance functions based on experimental data. The WAC transforms the wall model to an equivalent SDOF model, calculates the actual and SDOF equivalent loads and solves the equation of motion to determine the response time history of a central point on the wall.

The equation of motion for an SDOF system is

$$M\cdot y''(t) + C_d\cdot y'(t) + R(y(t)) = F(t) \qquad (1)$$

where

M is the equivalent or "lumped" mass of the system;

C_d is the damping coefficient taken as 5 percent of the critical value, i.e. very lightly damped;
$y(t)$ is the placement of the mass as a function of time t;
$y'(t)$ is the velocity of the mass or first derivative displacement;
$y''(t)$ is the velocity of the mass or second derivative displacement;
R is the structural resistance as a function of displacement y; and
$F(t)$ is the structural load as a function of time, i.e. expected blast pressure history.

Mine seals and one-way arching failure

The U.S. Bureau of Mines (Rice et al., 1930) conducted a series of tests and found that restraining the edges of a seal caused a dramatic increase in the seal strength to a level much higher than predicted by plate theory. Full-scale explosion experiments also showed concrete walls that were recessed into the roof, ribs and floor and had a thickness to width ratio of at least 0.1 resisted much higher pressures than the theoretical design pressure. These results showed that recessing the ends of the concrete wall into the surrounding strata allows the wall to act as a "flat arch." This arching behavior transmits a lateral thrust to the strata, which then act as a buttress to prevent seal movement. According to Anderson (1984), seal failure data from tests conducted in the NIOSH chambers correlated well with the following simplified formula for one-way-arching action in transverse laterally loaded masonry wall panels

$$Pmax = Fc*(T/H)^2 \qquad (2)$$

where
$Pmax$ is the predicted ultimate failure pressure;
Fc is the effective compressive strength of the block and mortar; and
T and H are the thickness and height of the seal, respectively.

In the current study, the SDOF model WAC was used to contrast the differences in seal deflection as a function of seal loading rate. The analysis option chosen in the WAC was an "unreinforced wall with one-way arching." In this option, the supports are rigid at the roof and floor, while the sides of the walls are unrestrained. This arching model for wall behavior applies best when the wall height to wall thickness ratio is greater than 4 and less than 15. Note that in the actual mine environment, this mode of failure would require stiff abutments at roof and floor to mobilize the arching effect. Otherwise, the resistance of the seal to the blast would be reduced significantly.

In the arching failure mechanism, the wall is assumed to crack horizontally at mid-height and at the roof and floor upon application of the blast load. As shown in Fig. 1, the two wall segments remain rigid, rotate through an angle θ and develop arching forces to resist the blast loading. The wall will begin to crush at the points indicated by the vertical solid arrows in Fig. 1, and the magnitude of the resisting forces will depend on the compressive strength of the wall material and the contact area at the crush points.

Figure 2 shows the WAC-calculated resistance function ($R(y)$) for a 1.8-m- (6-ft-) high, 6.1-m-(20-ft-) wide, 406-mm- (16-in.-) thick unreinforced masonry solid block wall (herein referred to as the "example seal"). This example seal was used for comparing the dynamic and static responses calculated with the WAC for assumed and actual experimental mine pressure histories. As shown in Fig. 2, the displacement is linear to about 4.3 mm (0.17 in.), ~1.48 MPa (~214 psig), i.e., in the elastic range. In the elastic range, the deflection of the seal will return to its starting deflection (zero) when the pressure is removed. Above 4.3 mm (0.17 in.), the response of the seal enters the elastic-plastic range, and above approximately 8.6 mm (0.34 in.), 1.63 MPa (237 psig), the seal response is in the fully plastic range, where the seal will either suffer

FIGURE 1

One-way arching failure mechanism in WAC.

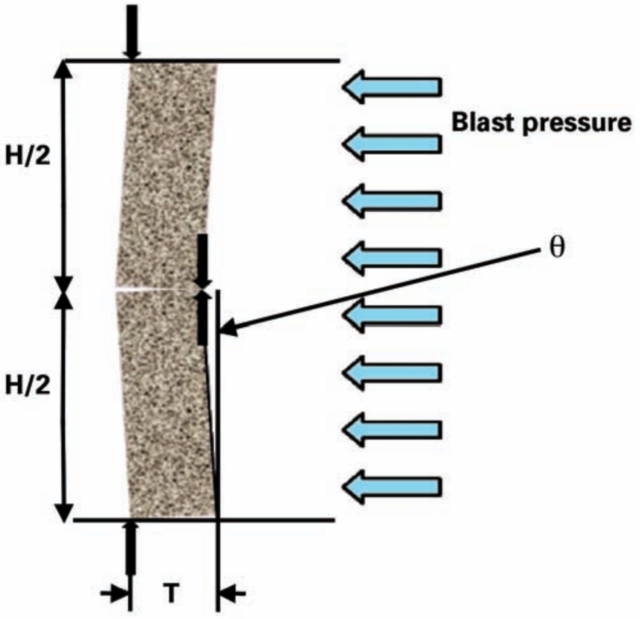
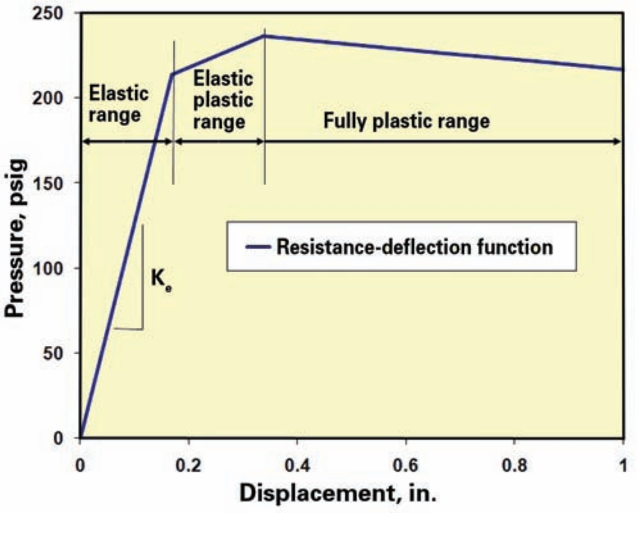


FIGURE 2

WAC-calculated resistance function for the example seal assuming one-way roof-to-floor arching.



permanent displacement and/or failure. All calculated dynamic responses were in the elastic or slightly elastic-plastic range implying that the example seal sustained little or no permanent damage.

Response of the example seal using simulated pressure histories

The WAC is used in the following analysis of the example seal to illustrate the ranges for dynamic and static responses. The seal loading $F(t)$ is assumed in this case to be a uniform pressure history. Shown in Fig. 3 are five simulated pressure histories used in the analyses. Each pressure history peaks at 830 kPa (120 psig) with corresponding rise times of 0, 2, 4, 8 and 16 ms.

WAC calculates the undamped natural period of the wall (example seal) by using the stiffness K_e and mass M as shown in

$$T_n = 2\pi\,(M/K_e g)^{1/2} \qquad (3)$$

where

M is the equivalent or "lumped" mass of the system (lb),

K_e is the elastic stiffness for slabs (psi/in.) and

g is the acceleration of gravity (in./sec^2).

The WAC-calculated natural period is 8 ms for the example seal (solid-concrete-block with a compressive strength of 17.2 MPa (2,500 psi) and a density of 2,080 kg/m^3 (130 pcf)). The WAC-calculated, one-way arch natural periods for a 6.1-m- (20-ft-) wide, 406-mm- (16-in.-) thick example seal as a function of height and compressive strength, [10.3 to 17.2 MPa (1,500 to 2,500 psi)] varied from 6 to 36 ms for seal heights ranging from 1.5 to 3.7 m (5 to 12 ft).

Figure 4 shows the WAC-calculated centerline displacement for the example seal when subjected to the five pressure loading histories shown in Fig. 3. The largest dynamic deflection of 4.8 mm (0.19 in.) occurred when the example seal was instantaneously (0 ms rise time) loaded to 830 kPa (120 psig). At rise times of 2 and 4 ms, the peak displacement of the example seal decreased as the pressure rise times increased. When the pressure rise time from a dynamic load was greater than or equal to the natural period of the seal (8 ms for the example seal), a maximum deflection of 2.4 mm (0.095 in.) occurred. This is the same deflection that would be obtained from a 830-kPa (120-psig) static load applied slowly. When a seal sustains a blast, i.e., a rapidly applied load, the protection that the seal can provide is based on its dynamic resistance. The applied dynamic load for a particular situation can be regarded as having some equivalent static load. An equivalent static load is defined as a load that is distributed in the same manner as the dynamic load and produces the same shear and bending moment at any given cross-section of the seal as the dynamic load.

FIGURE 4

WAC-calculated centerline deflection for the example seal as a function of the simulated pressure loadings shown in Fig. 3. NP is the natural period of the example seal (8 ms).

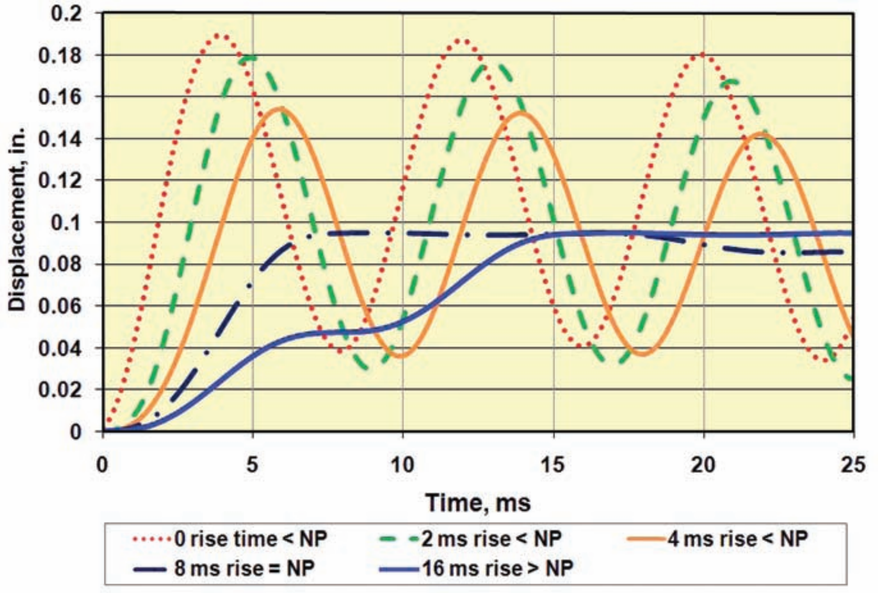
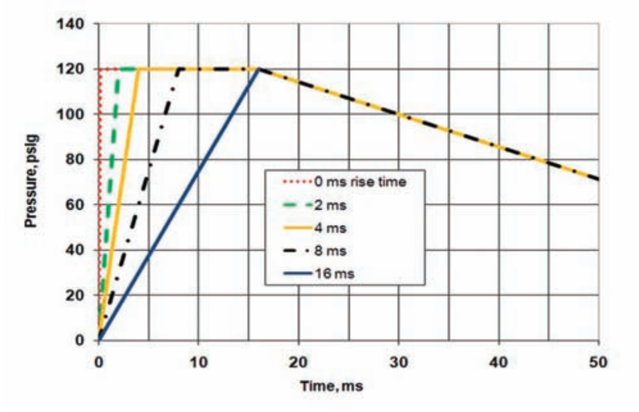


FIGURE 3

Simulated pressure loading histories *F*(*t*).



To best compare the dynamic and static response of an elastic system, the Department of Army, the Navy and the Air Force (1990) Design Manual TM5-1300 refers to the concept of dynamic load factor (DLF) sometimes referred to as the Dynamic Magnification Factor (DMF). DLF used here is defined as the ratio of the maximum dynamic deflection produced by rapid loading of pressure P to the deflection that would have resulted from the static or slow application of pressure P.

$$DLF = X_m/X_s \qquad (4)$$

where

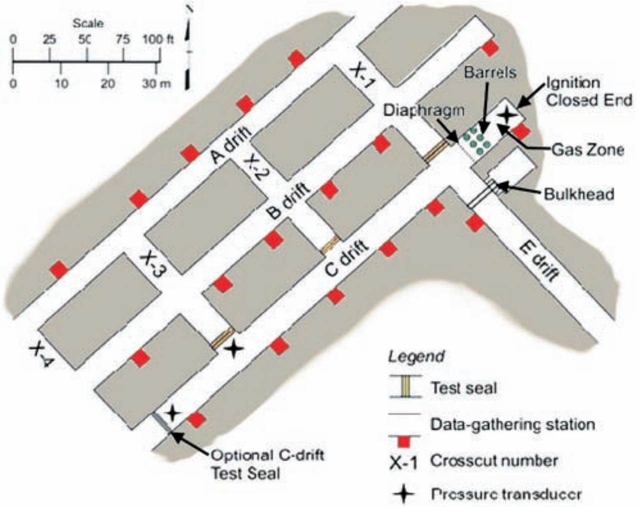
X_m is the maximum dynamic deflection produced when the peak pressure is applied rapidly and

X_s is the static deflection or the displacement produced in the system when the peak pressure is applied slowly.

Because deflections, spring forces and stresses in an elastic system are all proportional, the DLF may be ap-

FIGURE 5

Seal test area in the LLEM.



plied to any of these to determine the ratio of dynamic to static effects.

In many structural problems, only the maximum value of the DLF is of interest. For the most prevalent load case, namely, the rectangular and step load with instantaneous or 0 ms pressure rise time, the maximum value of the DLF is 2. This indicates that all maximum displacements, forces and stresses due to the dynamic load are twice the value that would be obtained from static analysis for the same maximum pressure. It should be noted that under particular circumstances, the DLF could exceed 2, for example, if the seal is subjected to numerous shocks at or very near the natural period of the seal. The WAC calculations help demonstrate that the response of any given candidate seal design for explosion isolation is dependent on the peak explosion pressure exerted on the seal and, equally important, the rise time to peak pressure relative to the natural period of that seal.

Response of example seal using actual LLEM pressure histories

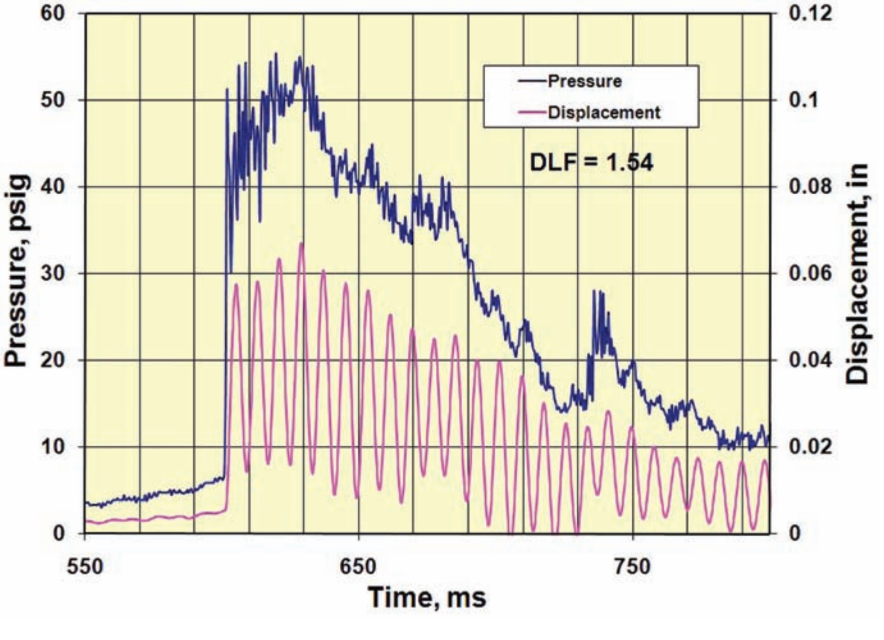
LLEM drift explosions. Recently, NIOSH conducted larger-scale experiments within the LLEM to simulate, in part, the dynamic response of seals relevant to the direction of blast loading and the influence of reflected waves on seal response. The measured pressure histories from these experiments were used in the WAC to calculate the dynamic displacement of the example seal.

Figure 5 is a close-up plan view of the seal test area in the multiple-entry area of the LLEM (Weiss et al., 2002, 2008). Methane-air explosions were conducted in C-drift, which was blocked with a test seal constructed perpendicular to the axis at ~98 m (~320 ft) from the closed end ignition zone, as shown in Fig. 5. The gas-ignition zone was confined by a plastic diaphragm across C drift, 14 m (47 ft) from the face. About 18.7 m^3 (661 cu ft) of natural gas was injected into the ignition zone to produce a mixture of ~10 percent CH_4 in air. The 187 m^3 (6,610 cu ft) flammable methane-air mixture filled only ~15 percent of the total sealed volume. The flammable gas was ignited at the face, and the pressure pulse propagated out C-drift past the seals in cross-cuts X-1, X-2 and X-3, as shown in Fig. 5. In this system, a reflected pressure wave results when the head-on pressure wave impacts the seal across C-drift. This reflected pressure wave then propagates back toward the ignition source, impacts the closed end, reflects and propagates back outby. Pressure histories from an LLEM explosion test sampled at 5,000 Hz and recorded at pressure transducers indicated by "✦" in Fig. 5 were then used in WAC to calculate the dynamic displacement of the example seal had that seal been constructed in those locations.

Shown in Fig. 6 is the explosion history recorded in front of an actual test seal constructed across C-drift 98 m (320 ft) from the closed end. This history shows the pressure of the reflected wave to be approximately 360 kPa (52 psig), followed by several oscillations with a peak pressure of about 390 kPa (57 psig). Also shown in Fig. 6 is the WAC-calculated dynamic displacement of the example seal if subjected to this same pressure loading. The WAC-calculated DLF for the example seal was ~1.54 times the expected static deflection of the 390 kPa (57 psig) load. Therefore, a static test of about 610 kPa (88 psig) (~1.54 x 57 psig) is needed to produce the same response as the explosion test of 390 kPa (57 psig).

FIGURE 6

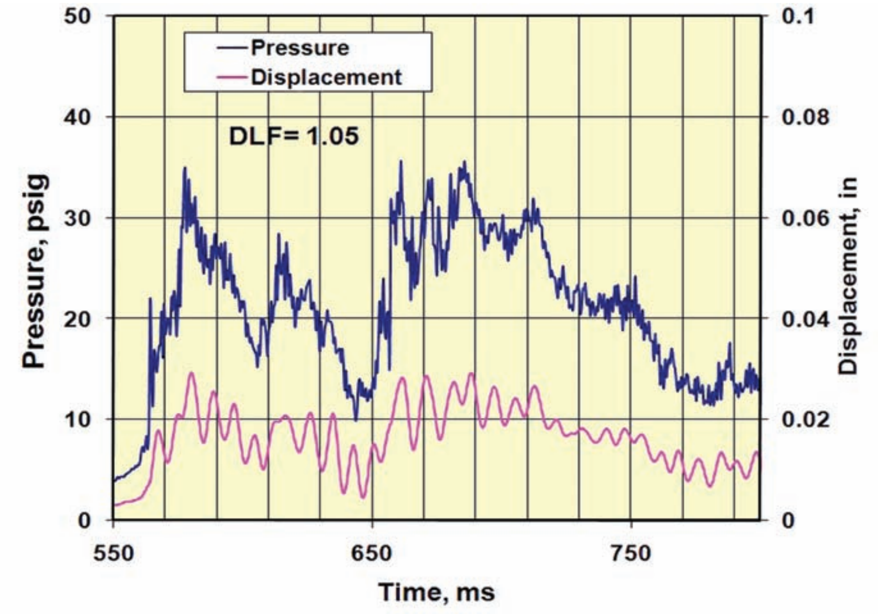
Pressure history from the confined LLEM test and WAC-calculated center displacement from the example seal had it been located 98 m (320 ft) from the face of C-drift (see Fig. 5).



Using the pressure history of the LLEM test recorded at a test seal in Crosscut 3, the WAC-calculated dynamic displacements for the example seal are shown in Fig. 7. The initial outgoing peak pressure wave impacting the Crosscut 3 test seal was approximately 240 kPa (35 psig), while the reflected pressure wave returning from the C-drift seal produced a second peak of approximately 250 kPa (36 psig). The calculated DLF for the example seal for this same pressure loading was 1.05. This DLF would suggest that a static test of only ~260 kPa (~38 psig) (~1.05 x ~36 psig) is needed to produce the same response as the 250 kPa (36 psig) dynamic test.

FIGURE 7

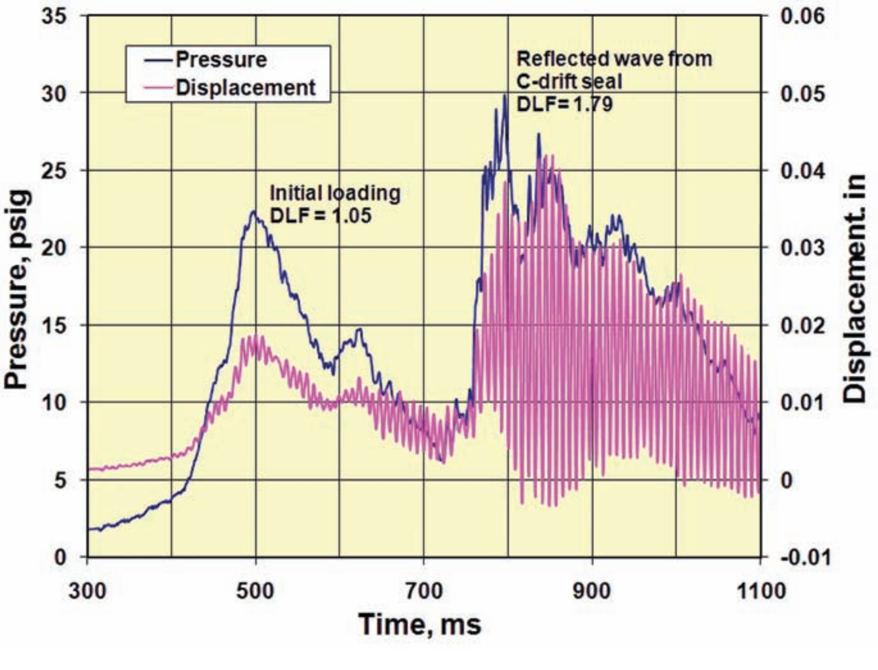
Pressure history from the confined LLEM test and the WAC-calculated center displacement for the example seal had it been located in Crosscut 3.



Shown in Fig. 8 is the actual recorded pressure history from a sensor located near the closed end ignition zone during the confined LLEM test, as well as the WAC-calculated response of the example seal had it been placed across the closed end of C-drift during this test. The initial pressure built slowly as the fireball expanded and the flame and pressure propagated away from the ignition. The calculated DLF for this first peak pressure loading of 150 kPa (22 psig) was approximately 1.05. When the reflected wave returned from the test seal located across C-drift 98 m (320 ft) away and impacted the simulated example seal located at the face, WAC calculated a much higher DLF of 1.79. Although the calculated displacement frequency before and after the pressure wave reflection is the same, the amplitude increases significantly. This increase in amplitude is due in large part to the more rapid rate of loading produced by the reflected wave, similar to the seal response shown in Fig. 4.

FIGURE 8

Pressure history from the confined LLEM test and the WAC-calculated displacement of the example seal had it been located at the closed end ignition zone of C-drift.

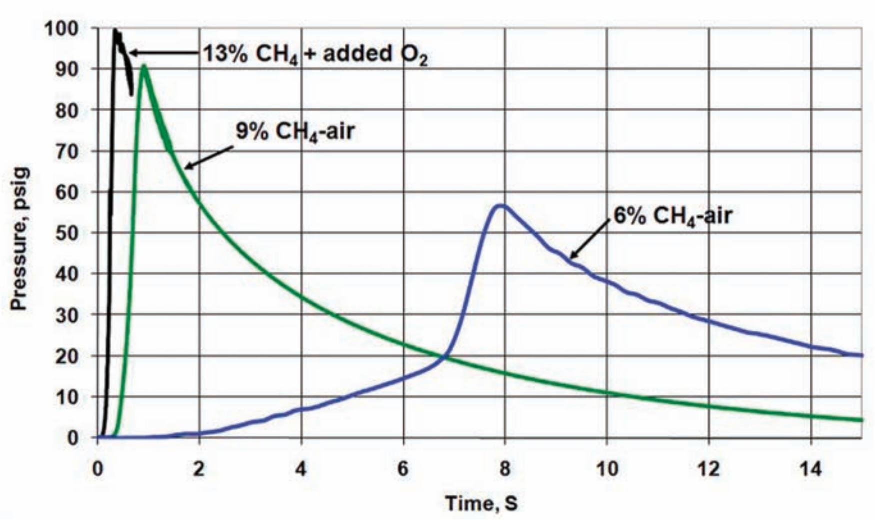


As these studies indicate, several factors influence the dynamic load and, subsequently, the DLF. These factors include the location of the seal in the entry and the occurrence of multiple reflecting waves. In the current studies, these factors produced DLFs that ranged from 1.05 to 1.79, with peak pressure loadings ranging from 150 to 390 kPa (22 to 57 psig). Because there are many unknown factors that may occur in an actual underground coal mine explosion, it would be prudent to design the seal based on a static load of twice the dynamic performance pressure (DLF of 2), which is appropriate for most designs responding within the elastic range. If design engineers know of specific circumstances in which pressure loading might match the natural period of the seal, then a higher DLF may be required for design and testing. When designing a seal using a dynamic loading model, such as WAC or three-dimensional dynamic numerical model, then one should use a pressure loading history with an instantaneous pressure rise to the peak design pressure lasting for ≥2 times the natural period of the seal. For new seal designs, MSHA (2007) uses an instantaneous pressure rise lasting for 1.5 seconds.

Chamber tests using methane explosions. A large-scale underground chamber was constructed within LLEM to conduct hydrostatic and confined explosion pressure-loading evaluations of seals (Sapko et al., 2005).

FIGURE 9

Chamber explosions pressure histories recorded during testing of an actual standard-type, 2.6-m- (8.6-ft-) high, 5.5-m- (18-ft-) wide, 406-mm- (16-in.-) thick solid concrete block seal.



The 6.1-m- (20-ft-) wide, 2.7-m- (9-ft-) high, 3.0-m- (10-ft-) deep chamber can accommodate a seal design with a cross-sectional area up to 16.7 m^2 (180 sq ft).

To determine the response and ultimate failure pressure of various seal designs, methane was injected into the ~42.5 m^3 (~1,500 cu ft) closed volume behind the seal, mixed and then ignited in the geometric center. Figure 9 shows three of these explosion pressure-loading histories. The combustion of 6 percent methane-air mixture, the slowest burning rate tested, peaked at about 8,000 ms at 390 kPa (56.5 psig), while the most rapid burning rate, 13 percent methane with added oxygen, peaked at 340 ms at 690 kPa (100 psig). Note the maximum theoretical pressure from the constant volume (no leakage or heat loss) of 9 percent methane-air in a sealed chamber would be about 770 kPa (112 psig). However, due to gas leakages through and around the perimeter of the seal and heat loss, the empirical peak pressure was about 630 kPa (91 psig) for the 9 percent mixture. As the combustion rate increased for the oxygen enriched mixture, there was less time for significant pressure loss due to gas leakage from the chamber.

When the actual pressure history from the most rapid burning rate test was used to then calculate the deflection response of the example seal, the time to peak pressure of 690 kPa (100 psig) was 340 ms. This 340 ms rise time is very slow compared to the 8 ms natural period of the example seal and therefore is essentially equivalent to a static load despite being an explosion test. The calculated dynamic deflection of 2 mm (0.078 in.) is the same deflection one would obtain with an equivalent static load of 690 kPa (100 psig) (DLF = 1).

Chamber tests using water. After conducting the chamber tests using methane explosions, new seals were constructed and water pressure was then used to hydrostatically load seals of the same design. To achieve this hydrostatic loading, the chamber was filled with water while air was displaced through a top vent pipe. When water was observed venting through the pipe, the air vent valve was closed, allowing the water pressure behind the seal to increase. The water pressure history, as recorded from a transducer located on the test seal at 1.5 m (5 ft) above the floor peaks at 220 kPa (32 psig) in 68 min.

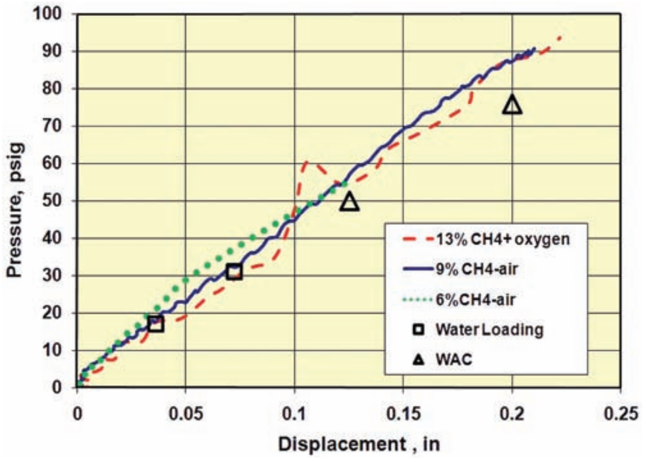
Figure 10 shows the corresponding centerline deflection for three confined explosions tests for a 2.5-m- (8.3-ft-) high, 406-mm- (16-in.-) thick solid concrete-block test seal. The deflections increased linearly with increasing pressure at a nearly constant rate for all three explosions. Also shown is the response of another seal of the same design subjected to water loading. The centerline response of the seal was nearly the same as the explosion tests despite different rates of pressure loadings. All rates of loading generated from explosion and water loading tests conducted in the chamber were much longer than the natural period of the seal, and their responses were consistent with a static load (DLF of 1). Figure 10 also shows the WAC calculated resistance-displacements for the test seal when subjected to the pressure history obtained from the 13 percent methane-air plus added oxygen. The WAC calculated resistance-displacements are in reasonable agreement with water and explosion loading experiments indicating that one way roof-to-floor arching is an appropriate mode of resistance for these tests. Taken together, these results indicate that the hydrostatic approach coupled with an SDOF model shows promise as a tool for mine seal design and testing. Studies are underway to further refine and quantify the response of various seal designs under different loading conditions.

Summary

These studies demonstrate that hydrostatic testing of mine seals is a reasonable alternative or adjunct to

FIGURE 10

Comparison of experimental deflection responses of an actual solid-concrete-block seal design in the chamber exposed to three methane air explosions and water loading test.



full-scale explosion testing. Hydrostatic chamber testing allows for multiple water loadings for stress-strain measurements and for determining the ultimate strength of the seal through testing to failure. Furthermore, empirical resistance data derived from the hydrostatic testing of seals can then be used to improve or validate the WAC and other design codes. Because it is not possible a priori to predict the dynamic load at each seal location surrounding a coal mine gob, the authors suggest statically designing or testing seals to at least twice the expected dynamic performance pressure, i.e., a DLF of 2.

The current studies show reasonable agreement in seal performance between explosion and hydrostatic tests and the WAC. The arching mechanism of resistance described in this report requires the seal to have stiff abutments at roof and floor to mobilize the arching effect. The study details results obtained with limestone strata that provided near ideal rigid supports. Structural engineering designs specifying mine strata interface and supports must be addressed to ensure the in situ performance of the seal design.

Sound structural engineering design followed by certification of as-built seal construction, coupled with hydrostatic performance testing as needed, will help facilitate the development of reliable seals and enhance the level of protection for underground personnel.

Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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