DESIGNING EXPLOSION RATED VENTILATION SEALS FOR COAL MINES USING HIGH-FIDELITY PHYSICS-BASED COMPUTER MODELLING

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ABSTRACT: Questions have been raised about the effectiveness of ventilation control devices (VCDs) to safely resist explosions during their intended life. This functionality depends on the ability of the VCDs and in particular seals to withstand changes in the behaviour of the strata, particularly where longwall abutments influence the stress regime in and around the chain pillars. As a consequence of an explosion impact on a seal, the surrounding strata could experience increased loads possibly resulting in permanent deformation and requiring grout consolidation. These aspects of seal design have been investigated using advanced numerical analysis.

Globally since the early 20th century, to protect underground personnel, ventilation seal designs have been required to be tested at an internationally recognized explosion test gallery to achieve pressure ratings required by legislation. The last two decades has seen advances in materials technology and engineering of structures. It has become accepted practice to use numerical methods to provide engineering ratings for mine seals in line with other industries where the elimination of prototype testing provides more rapid product introduction to the market. Before presenting the results of numerical analysis, structural aspects of seal design are simply explained including arching behaviour and the contribution of dynamic magnification due to impact loads.

High-fidelity physics-based computer simulations using software LS-DYNA were able to predict the results from physical testing of mine based seals in a most realistic way. Test data from live gas/coal dust deflagration explosions at Lake Lynn, PA, USDA along with pressure-time curves recently developed by the National Institute of Occupational Safety and Health as a result of the study of explosive atmospheres, were used to simulate a realistic loading environment caused by 138 kPa (20-psi) and 345 kPa (50-psi) explosions in physics-based models of seals.

INTRODUCTION

Explosions of gases and of coal dust have always been a basic hazard in coal mines and to this day continue to be the cause of disasters in coal mines. The advancement of knowledge in seal design and construction has tended to be driven by these disasters. In response to the alarming number of fatal explosions and fires in U.S underground coal mines the Bureau of Mines was set up on July 1st, 1910 (Tuchman and Brinkley, 1990) and likewise in Poland, Experimental Mine Barbara conducted live tests on mine seal designs typically constructed in coal mines since 1925. Various experimental mine facilities around the world conducted live explosion tests in the absence of mathematical models that could adequately describe seal response to such explosions. There was also no means to physically measure and define seal response to real time explosion impulses. It was in 1930 that experimental work involving measurement of seal response to explosions by the U.S Bureau of Mines started an understanding structurally of what influenced the performance of ventilation seals when subjected to an explosion overpressure.

It is important to define what attributes a seal requires before discussing the finer details of structural design and load bearing capacity. During the normal course of underground coal mining, it sometimes becomes necessary to install permanent seals to isolate abandoned or worked out areas of the mine. This practice eliminates the need to ventilate those areas. Seals may also be used to isolate fire zones or areas susceptible to spontaneous combustion. To effectively isolate areas within a mine, a seal should

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control the gas air exchanges between the sealed and open areas to prevent toxic and / or flammable gases from entering active workings and oxygen from entering the sealed areas.

be capable of preventing an explosion initiated on one side from propagating to the other side, and

continue its intended function when subjected to a fire test incorporating a specific (AS 1530.4 - 1990) time-temperature heat input (Tuchman and Brinkley, 1990).

The 1994 explosion at Moura No. 2 Mine renewed the focus on Ventilation Control Devices (VCD) within Australian coal mines with closer examination of the design and construction of seals. Prior to the enactment of new regulations on 16 March, 2001 in Queensland, introduction of the Queensland Mines Department Approved Standard for Ventilation Control Devices provided prescriptive ratings for seals and stoppings and required live testing of seals and stoppings in an "internationally recognized mine testing explosion gallery". As part of the enormous amount of research undertaken at this time after the recommendations of Task Group 5 (Oberholzer and Lyne, 2002) in establishing practical design criteria to assist mining engineers to minimize the risks of seal failure, Tecrete Industries introduced explosion rated shotcrete based Meshblock seals with an overpressure capacity of 138 kPa (20 psi) and 345 kPa (50 psi). Gateroad seal design more or less conformed to seal ratings used in the United States since 1971 where it was stated in 39 CFR 75.335 (Mine Safety and Health Administration – Title 30 Code of Federal Regulations, 1997) requires a seal to "withstand a static horizontal overpressure of 138 kPa (20 psi). Previous research by the former U.S Bureau of Mines (Weiss *et al*, 1999) indicated that it would be unlikely for overpressures exceeding 138 kPa to occur very far from the explosion origin provided that the area on either side of the seal contained sufficient incombustible and minimal coal dust accumulations.

Recent tragic accidents at Sago, WV and Darby, KY Mines in 2006 caused by methane explosions behind sealed off areas brought the issue of safety of mine seals to the attention of regulatory authorities. Following the enactment of the 2006 Miner Act and MSHA's issuance of the emergency temporary standard (ETS) more stringent performance standards have been adopted for mine ventilation seals. There is a minimum standard of 345 kPa (50 psi) (designed, constructed and maintained) for a specific pressure-time curve, when the atmosphere inside the sealed volume is monitored and maintained inert. In the United States more commonly pressure rated seals have a capacity for 827 kPa (120 psi) in line with the findings of the NIOSH study entitled, "Explosion Pressure Design Criteria for New Seals in U.S Coal Mines" (Zipf, Sapco and Brune, 2007). The findings of this report have challenged globally established beliefs in seal design and explosion propagation.

It is in the light of these stringent new standards and questions asked by mine operators in Australia, that the design of Minova's Meshblock 138 kPa (20 psi) and 345 kPa (50 psi) overpressure rated shotcrete seals were investigated early in 2009 using computer based numerical simulations to investigate such complex phenomena as behaviour of seals under explosion loads and the effect of strata convergence on explosion rating. Engineer designed steel access hatches are used for degassing purposes in some Australian mines and the effect of these hatches on seal integrity is also investigated. It is now normal practice in most industries to use numerical methods for the design of critical structures although the integration of software in the design process has a long way to go. A recent example is the Boeing 777 which was digitally designed using 3D solid modelling technology that included integrating spatially three million parts with CAD software and finite element modelling of components.

STRUCTURAL DESIGN CONSIDERATIONS FOR VENTILATION SEALS

There are several existing simplified methods that can be used to provide ventilation seal design. However only high-fidelity physics-based computer simulations are able to predict the results from physical testing of mine based seals in a most realistic way. Explosion testing is still extensively used to test existing designs and NIOSH's relatively new hydraulic test facility provides a cost effective method to develop stress-strain response data using a water load as an alternative to full-scale (Sapco, Harteis and Weiss, 2008) explosion testing. In order to provide a "fit for purpose" seal design the conditions that the seal will be subject to for its intended life must be defined.

IMPOSED STRESS CHANGES ON VENTILATION SEALS

Imposed stress changes that may affect the structural integrity of the seal (and surrounding strata) and hence its ability to safely resist an explosion load are as follows:

Gate road seals are subject to changing longwall abutment loads during coal extraction as the face moves past the seal located in the chain pillar cut-through. The roadway periphery and hence the seal is subject to convergence conditions and increased vertical loads due to dilation of coal mine strata.

Chains pillars experience increased vertical load and lower stiffness coal plies can be crushed within the chain pillar increasing stresses within the seal material.

Aquifers that are breached by caving during extraction and water from the longwall equipment can flood the seal. Water will leak through the path of least resistance. This water could pass across the boundary between the seal and the enclosing strata, through a porous seal or through the surrounding coal mine strata along cleats, joints and bed separation. At certain pressures it is possible that surrounding plies could be hydraulically separated providing a leakage path.

The existing primary and secondary support affects the load that the seal experiences due to convergence.

Mobilization of joint sets and fault planes due to mining induced stress changes.

Considerations of structural behavior

The U.S. Bureau of Mines (Rice, Greenwald and Howarth, 1930) conducted a series of explosion tests and found that restraining the edges of a seal caused a dramatic increase in seal strength to a level much higher than that predicted by plate theory. As the seal experiences an explosion load, it bends and pushes outwards on the surrounding strata. The development of this strength-enhancing mechanism will depend on a number of parameters including the stiffness and strength of shotcrete material and mine strata, seal thickness, and the height of crosscuts.

Basically there are two structural engineering approaches to designing seals to resist explosions, two – way arches [described in this paper] and plug-type failure, with both possible failure modes dependant on the structural reaction of the surrounding strata. The arching mechanism for wall behaviour is most applicable when the wall thickness to wall height ratio [T:H] ranges from 1/15 to ¼ (Zipf, Sapco and Brune, July 2007) and fits in with Meshblock seal thicknesses that ranges from 200-600 mm. For lower T: H ratios a flexural failure mode applies and for higher ratios (found in plug-type seals) a shear failure mechanism along the roadway contact is more applicable.

Arching behaviour in shotcrete seals

The arching mechanism (Refer to figure 2) is thoroughly described in study undertaken in an ACARP (Pearson *et al*, 2000) report which described the structural response of explosions on 325 mm thickness Meshblock seals. As the seal is subject to increasing horizontal loads a compression arch forms within the thickness of the seal. A compressive stress is imposed on the surrounding strata. The strength of the seal is limited by the crushing strength of the shotcrete and the response is essentially independent of the steel reinforcement. As the seal is increasingly loaded, tensile cracks form along yield lines (see Figure 3) to essentially form plastic hinges. The intact shotcrete is initially in the form of a shallow arch. As the load increased the cracks deepen increasing the depth of the arch and essentially increasing the compressive forces on the intact shotcrete until compression failure occurs.

The arching mechanism will not develop if the roof and floor rocks have very low stiffness and strength and lower strength bending will predominate. The formation of plastic hinges is shown from test work at NIOSH's Lake Lynn laboratory in 1997 where crack propagation lines are shown after a seal has experienced an explosion. Crack propagation commences at the seal centre and migrates outwards in a horizontal line and up into the corners in the pattern shown.

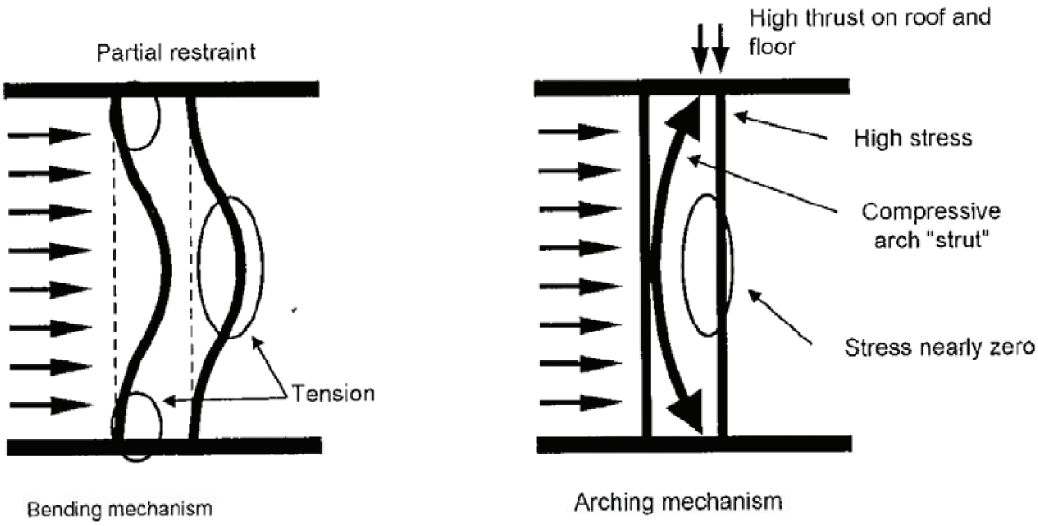


Figure 2 - Structural mechanisms for horizontal seal loads

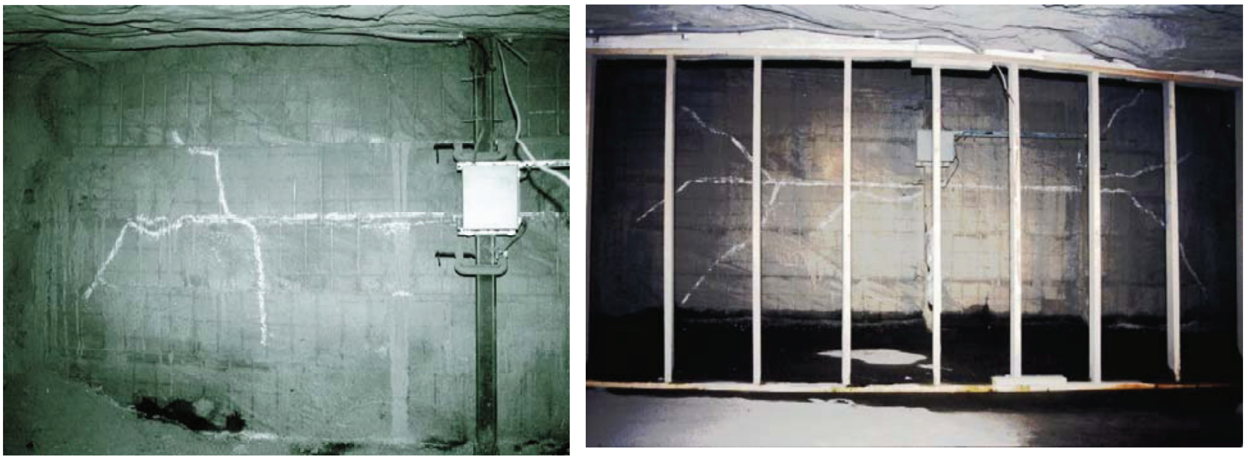


Figure 3 - Formation of yield lines in Meshblock™ seals

Meshblock seals are practically unreinforced when compared to, for example, concrete slabs which normally require a mesh of reinforcement on the tension side. The vertical and horizontal bolts were installed at mid-section of each seal, hence not contributing to its flexural strength significantly. In spite of such arrangements, the obtained capacities are many times larger than those obtainable in reinforced concrete slabs designed in accordance with modern codes of practice (e.g. AS3600-2009). For such (and larger) seal height: seal width ratios it is conservative to assume that the applied pressure is carried entirely by strips spanning in the vertical direction The attainment of large ultimate capacities for such strips can be attributed to development of significant lateral restraints H (see Figure 4(a)) exerted by the mine strata. Figure 4(b) shows that the lateral compressive force H on the cross-section at mid-span significantly reduces the tensile stresses caused by bending, hence delaying the initiation of cracking.

The static strength of 325 mm Meshblock seals was determined by ACARP study (Pearson *et al*, 2000) using numerical modelling and compared with data from the Lake Lynn Experimental Mine (LLEM) explosion tests undertaken by Tecrete Industries in conjunction with BHP Coal in 1997. Figure 5 shows the ultimate capacity of the 2.74-m high seals from calculations and shows good agreement with the LLEM test results. In the example considered by Pearson *et al* (2000), the seal deflection of 6 mm at the mid-point translated to only 1.3 mm between roof and floor at the arch supports. These results will be later verified with recent 138 kPa (20 psi) and 345 kPa (50 psi) Meshblock seal design using LS-DYNA software.

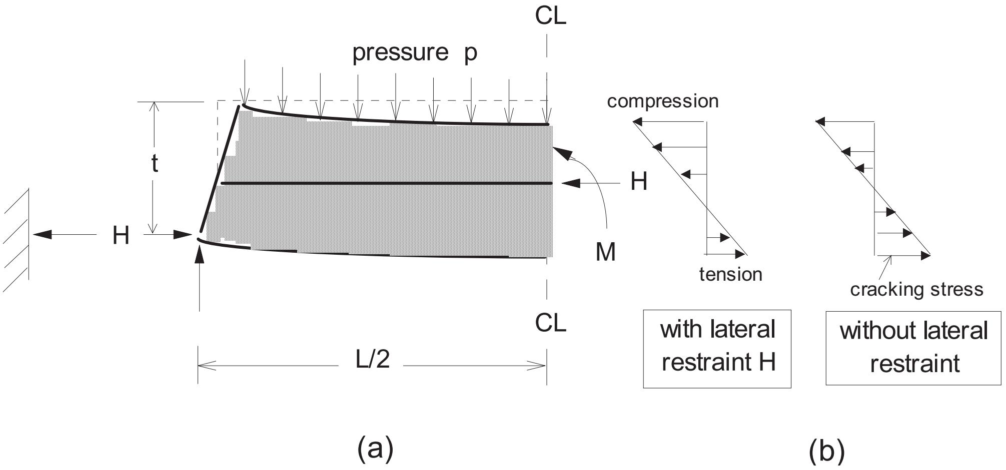


Figure 4 - Effect of lateral restraint H on delaying of crack initiation

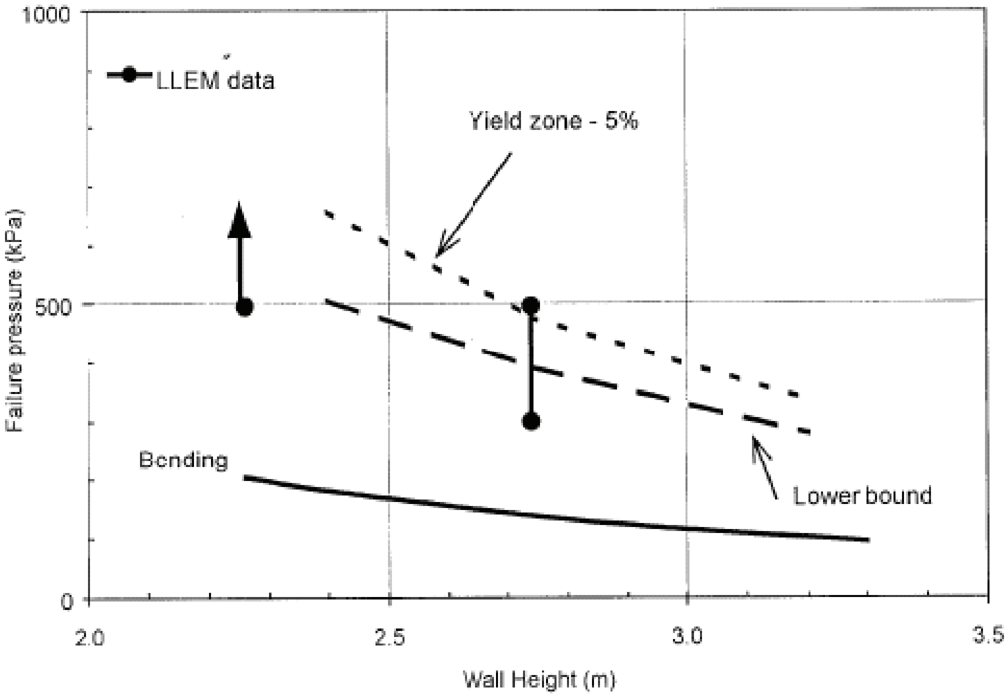


Figure 5 - Capacity of 325 mm seal (50 MPa concrete) showing computed and LLEM results

Dynamic magnification effects of explosions on seals

One of the approaches to predicting response of mine seals to explosion loads is based on an equivalent dynamic modelling technique. Equivalent dynamic modelling is based on the fundamental premise that the structural response obtained by conducting a pure static analysis, with applied load increased from the original level by a certain factor, will be identical to a full dynamic analysis of the same structure conducted with the actual load. The magnification factor used for such analysis is called the Dynamic Load Factor (DLF).

Currently, the DLFs used in coal mine seal designs are derived from Single-Degree-of-Freedom (SDoF) models assuming elastic behaviour. When structural response is assumed to be elastic, then the theoretical maximum DLF is 2.0 (for triangular load pulse with zero rise time). Therefore, most of the "equivalent" dynamic models use a factor of 2 to increase the peak dynamic load before conducting static analysis on a mine seal. Because multiple modes of structural response could contribute to the response of seals, the DLFs estimated from SDoF models may not be applicable for coal mine seals. Furthermore, the worst-case DLF = 2 corresponds to elastic behaviour of the seal. When a portion of the seal gets damaged and becomes plastic or softens due to concrete failure, the elastic DLFs may not be conservative for predicting the response of seals.

Figure 6 resents a maximum response of an elastic SDoF system for a triangular explosion pulse with finite rising time. This shows the range of dynamic magnification responses that explosion test pressure-time (P-T) curves at LLEM could produce. T is the rise time of the explosion and Tn is the natural period of the seal and it is seen that when the ratio is close to 1 the maximum impact and acceleration of the seal occurs.

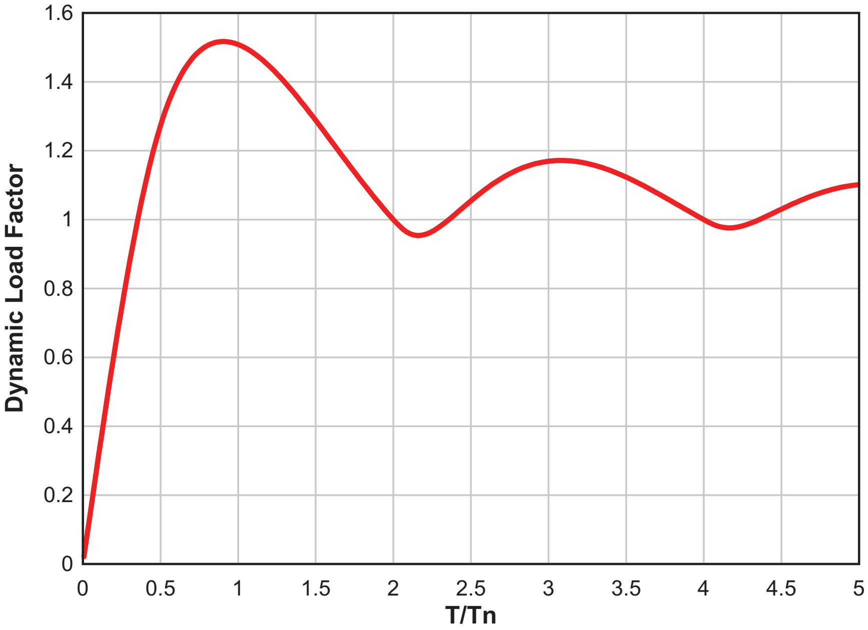


Figure 6 - Maximum response of elastic SDoF system for triangular load pulse with finite rising time

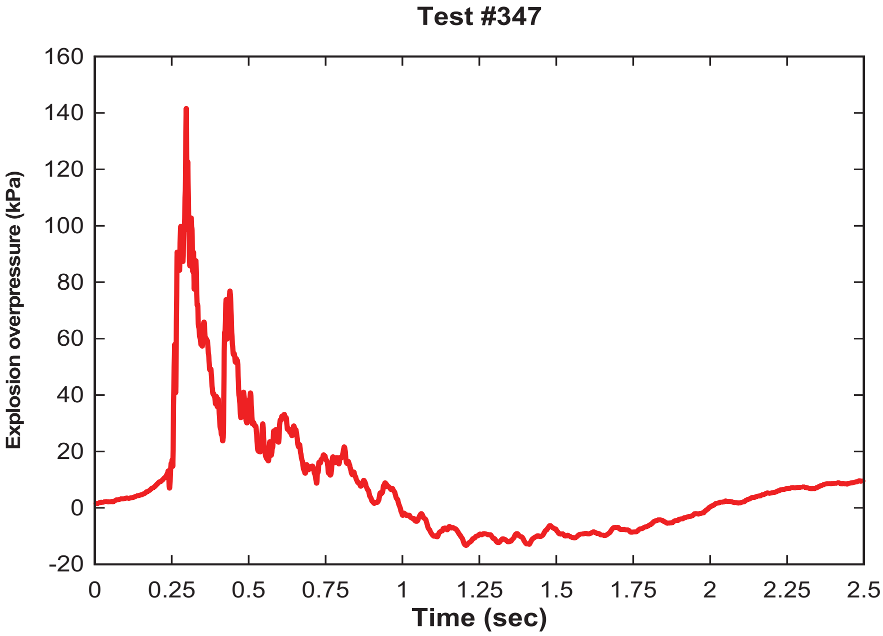
The data from explosion testing of Meshblock seals (Weiss et al, 1999) also indicated that in some cases the recorded times at peak pressures did not match the times of seal failure. This signifies the need for time-history dynamic analysis, an important aspect of this study. Further examination of the pressure time histories reveals an impact-type input of energy to some seals when comparing their natural periods in bending response (computed in the pre-test round of analyses) with the duration of pressure pulses. In such cases the dynamic response amplification (e.g. maximum seal displacements) will depend on the ascending and descending portion of the pressure-time diagram.

HIGH-FIDELITY PHYSICS-BASED MODELLING OF SEALS

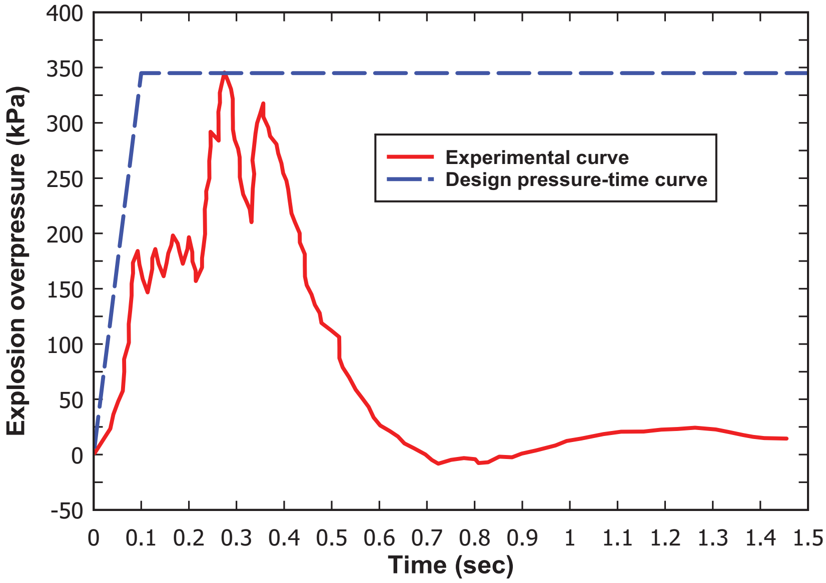
Explosion pressure-time curves for seal analysis

The test data from live gas/coal dust deflagration explosions at Lake Lynn, PA, USDA can be used to simulate a realistic loading environment caused by 138 kPa (20 psi) and 345 kPa (50 psi) explosions in physics-based models of seals. Figure 7 presents examples of 134 kPa (20 psi) and (50 psi) 345 kPa experimental pressure-time curves that can be used for dynamic analyses of seals.

Figure 7(b) also includes the 345 kPa (50-psi) design pressure-time curve, recommended by NIOSH (Zipf *et al*, 2007) with the rise time (time to reach peak pressure) of 0.1 sec. From the comparison with the experimentally derived curve (Lake Lynn Experimental Mine) in Figure 7(b), one can observe that the design curve is characterised by the pressure rise rate that is more conservative than indicated by experimental gas explosions. In this paper only the 20 psi experimental curve is used to analyse the example 300-mm thick Meshblock seals.



(a)



(b)

Figure 7 - (a) 138 kPa (20-psi) curve; (b) 345 kPa (50-psi) explosion pressure-time curves for dynamic analysis of seal

Structural analysis using 3-D finite element models

Finite element analysis software

LS-DYNA, a general purpose transient dynamic finite element program (LS-DYNA, 2008) was used to develop the finite element models in this study. LS-DYNA is used to solve multi-physics problems including solid mechanics, heat transfer, and fluid dynamics either as separate phenomena or as coupled physics, e.g., thermal stress or fluid structure interaction. LS-DYNA is an industry accepted dynamic first-principle based code for analysis of structures under extreme loads generated by blast and impact events with the ability to compute large deformations due to flexure, shear, and material failure.

Model description

As an example, the shotcrete seal which is 3.4 m high and 300 mm thick is analysed in this paper. Due to the symmetry of the seal, the boundary conditions, and the loading about the central vertical plane, the model includes only one half of the seal allowing for a model width of 2.7 m. The model includes roof and floor skeleton bolts (650 MPa steel) of 21.7 mm diameter that are placed at 600 mm centres around the periphery. The 200-mm deep rib keys are modelled for 300-mm thick seals. The rib keys are modelled with a single row of 1200 mm long bolts with 600 mm tails protruding and 600 mm full encapsulation.

To simulate the seal-rock interfaces, floor, ribs and roof are explicitly modelled as large solid bodies surrounding the seal. The overall thickness of the floor and the roof in the model is 2.5 m. The Meshblock seals have 1.8 metres of coal in the roof and 0.6 metres of coal in the floor. The remaining depth is filled with the rock materials. Figure 8 shows the components of the seal model used in this study.

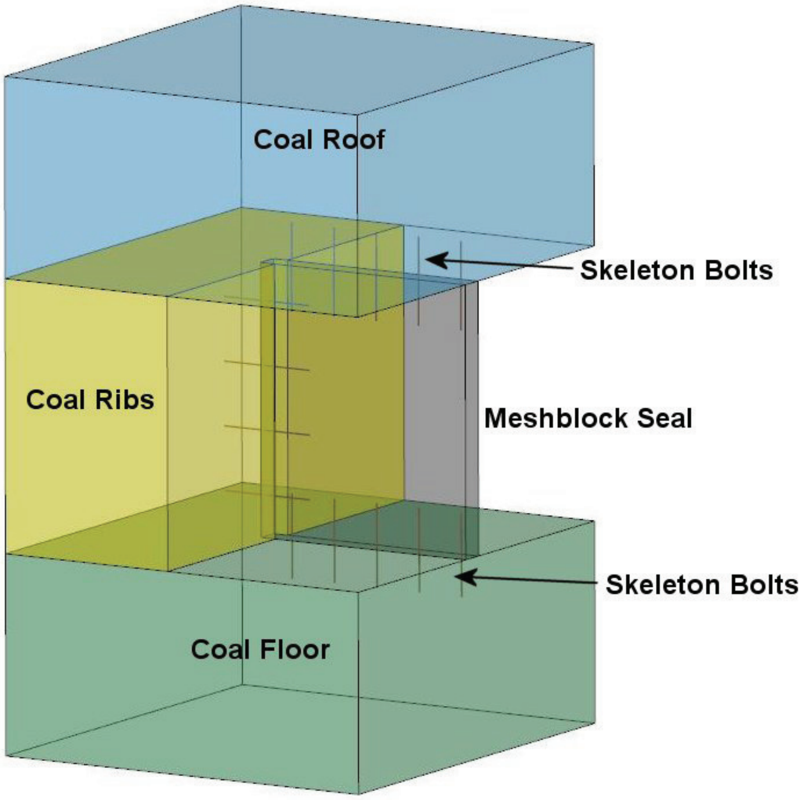


Figure 8 - Model of roadway and strata enclosing seal

In the finite element model, solid elements with a single integration point were used to model the shotcrete seal and the surrounding coal and rock materials. Overall model dimensions and the sizes of finite elements were determined from a mesh convergence study. The mesh convergence study included a number of runs of the model with variable model dimensions and increasing levels of mesh refinement. In the final model, the concrete seal was modelled with 50-mm cube solid elements, and the surrounding rock was modelled with 250-mm cube solid elements.

Beam elements were used for the skeleton bolts in the ribs, roof and floor. Each beam element shared two of the solid element nodes to model the strain compatibility between the steel and the concrete. As a result, slip between the steel reinforcement and the concrete was included explicitly in the model. Slip occurs as a function of the failure of the concrete attached to the reinforcing bars. Reinforcing bars were extended 600 mm into the ribs, roof and floor to provide sufficient anchorage length. The bond between the steel bars and the rock was modelled using constrained conditions provided by LS-DYNA for connecting meshes of dissimilar densities.

Figure 9 shows the finite element model of the rib keys. The rib key is modelled by extending the concrete seal model into the body of the coal ribs. Interaction between the key and ribs is simulated using surface to surface contact surfaces. The full model of the seal consists of 127 050 nodes, 336 beams, and 114 000 solid elements.

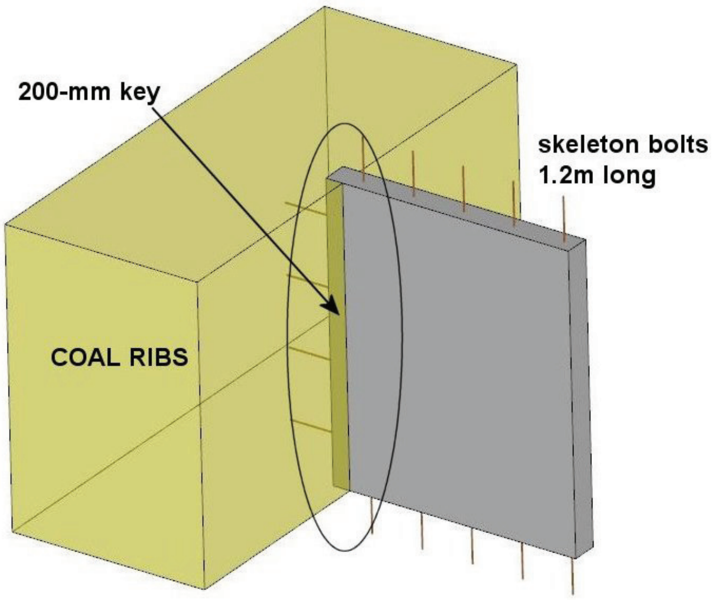


Figure 9 - Modeling the keys for the ribs and the skeleton bolts

Material Models

The concrete model employed for modelling the shotcrete seal was model 159 in LS-DYNA implemented in keyword format as MAT_CSCM_CONCRETE for Continuous Surface Cap Model. The model formulation includes a smooth and continuous intersection between the failure surface and hardening cap. The model includes isotropic constitutive equations, yield and hardening surfaces and damage formulations to simulate softening and stiffness reduction. A rate effects formulation increases strength with strain rate. The model has been thoroughly tested by several US Governmental agencies (Murray and Lewis, 1995; Murray, 2007) for predicting damage in concrete under severe impact and blast loads, which has demonstrated its reliability and accuracy. Default input values for model parameters were used in this study. Default material parameters are generated by the model based on the specification of the unconfined compression strength. In this study, the unconfined compression strength of 50 MPa was used based on the test data from testing of Hanson shotcrete in Queensland.

Roof, floor and ribs were modelled using Material Type 173 based on Mohr-Coulomb criterion in LS-DYNA. The material has a Mohr Coulomb yield surface, given by τmax = C + σn tan(phi), where τmax = maximum shear stress on any plane, σn = normal stress on that plane, C = cohesion, phi = friction angle. The tensile strength is given by σmax = C / tan(phi). After the material reaches its tensile strength, further tensile straining leads to volumetric voiding. Material 173 is intended to represent soils, rock and other granular materials.

The appropriate material modelling parameters for roof, floor and ribs are summarised in Table 1 for the boundary roadway conditions investigated in this study. It should be noted that coal mine strata are variable in geomechanical properties with adjustments required when considering bulk properties as compared to laboratory test results of intact cored specimens. Coal shows (directional) compressive strength variations due to variable cleat, moisture and gas content changes, stone partings, varying macerals shown in laminae found in a vertical seam section and changing ash content. Table 1 material properties represent values that have been used when modelling mine strata for ground support and chain pillar design.

Table 1 - Material properties for models of roof, floor and ribs

Boundary Roadway Condition	Material	Young's Modulus (MPa)	Poisson's Ratio	Friction Angle (deg)	Cohesion (MPa)
Roof	Coal	3,000	0.4	30	1.0
	Stone	5,000	0.2	35	5.0
Floor	Coal	3,000	0.4	30	1.0
	Stone	5,000	0.2	35	5.0
Ribs	Coal	3,000	0.4	30	1.0

Predictions of response of the 300-mm Meshblock seal to 20-psi explosion loading

Based on the finite element model shown in Figures 8 and 9, and the loading and material properties described above in this section, non-linear transient dynamic analyses were carried out for the example Meshblock seal design. Crack patterns for the seal are visualised using the contours plots representing damage levels from zero to one calculated by the concrete model. A contour value of zero indicates no damage, so concrete strength and stiffness are those originally specified as input values. A contour value of one indicates maximum damage and severe cracking, in which the concrete strength and stiffness are reduced to zero.

Predicted crack patterns in the 300-mm Meshblock™ seal at about 1.0 sec after the explosion are shown in Figures 10 and 11. The seal displaces laterally about 6 mm at about 0.1 sec explosion duration and reaches residual permanent deformation of about 2 mm at about 1.0 sec, as shown in Figure 12. It can be noted that the concrete damage is mainly located on the outbye side of the seal (non-impact side) and is characterised by tensile cracks forming a typical yield line pattern characteristic of the rectangular panels with all four edges simply supported. This result confirms that the seal responds as a two-way slab where the keys, the bolts and the interface friction provide effective supporting boundary conditions to the seal. Damage contour values between 0.5 and 0.8 indicate that the concrete strength and stiffness along the damage regions have significantly reduced but the level of damage is not severe. Moreover, no elements have eroded in the calculations. This indicates that the overall integrity of the seal was maintained after being exposed to the 20-psi explosion loading. Crack pattern shown in Figure 3 for the similar Meshblock seal design explosively tested in the Lake Lynn Experimental Mine in 1997 provides experimental validation of the numerically simulated results for the 300-mm seal example.

Closer examination of the computed results indicates that the rib keys play a significant role in the response of the seal to blast loads. Figures 13 and 14 show principal compressive stress and maximum shear stress distributions in the coal ribs near the keys. It can be noted that the ribs experience large bearing stresses with the maximum value of about 3.9 MPa at the mid-height level of the seal. From Figure 14, the maximum shear stress in the ribs near the keys is about 1.4 MPa which exceeds the shear strength of coal of 1.0 MPa. Large shear stresses extend up to 120 mm into the rib.

Figure 15 shows the contours of maximum shear stresses in the roof and floor strata. The maximum shear stresses reach about 1.0 MPa in the roof and floor within the area of about 150 mm wide on both sides of the seal and about 120 mm deep. The results of high-fidelity physics-based analyses can be used to support the grouting program for seal construction if required. They can provide a justification for Polyurethane or cement grouting of the potential yield zones in order to increase compressive, tensile and shear strength of the rib, floor and roof materials in the immediate strata.

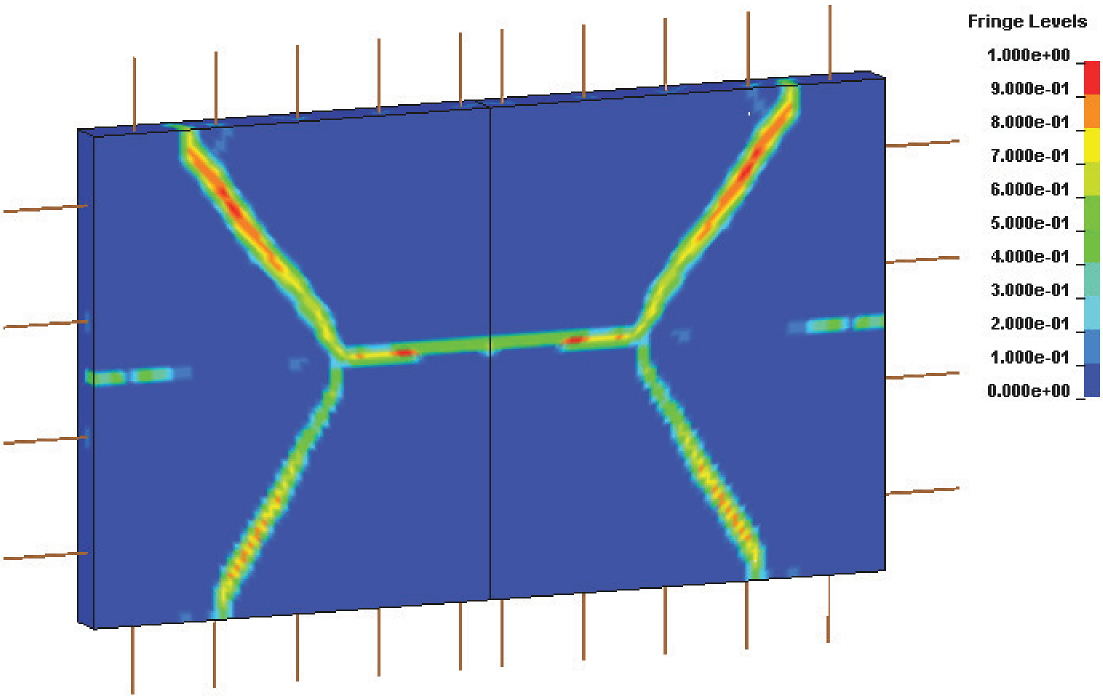


Figure 10 - Concrete damage contours on the outbye side of 300-mm Meshblock seal (load was applied to the inbye surface)

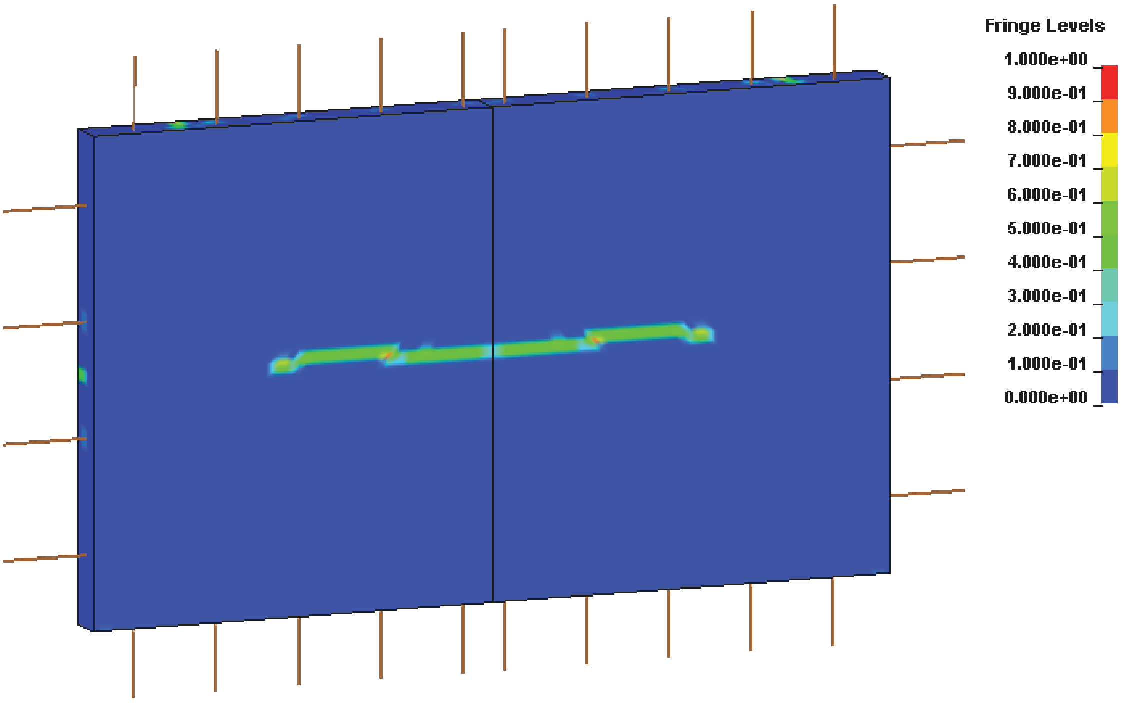


Figure 11 - Concrete damage contours on the inbye surface of a 300-mm Meshblock™ seal

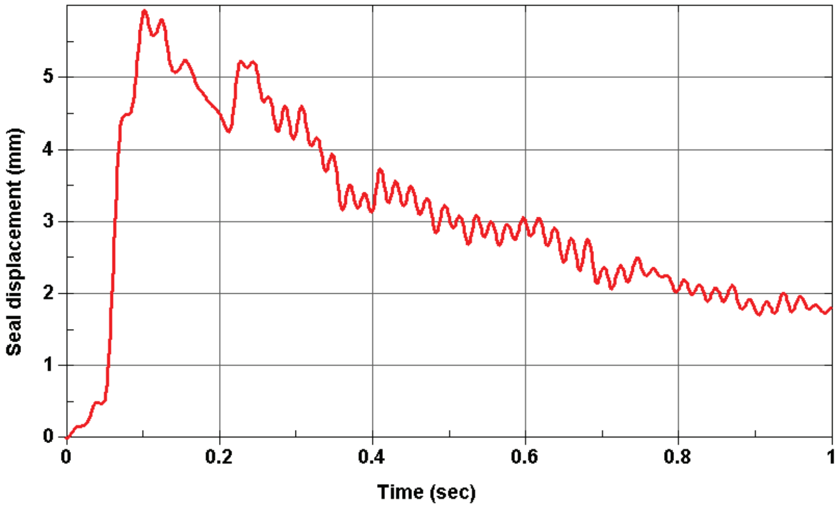


Figure 12 - Time-history of peak deformations of a 300-mm Meshblock™ seal

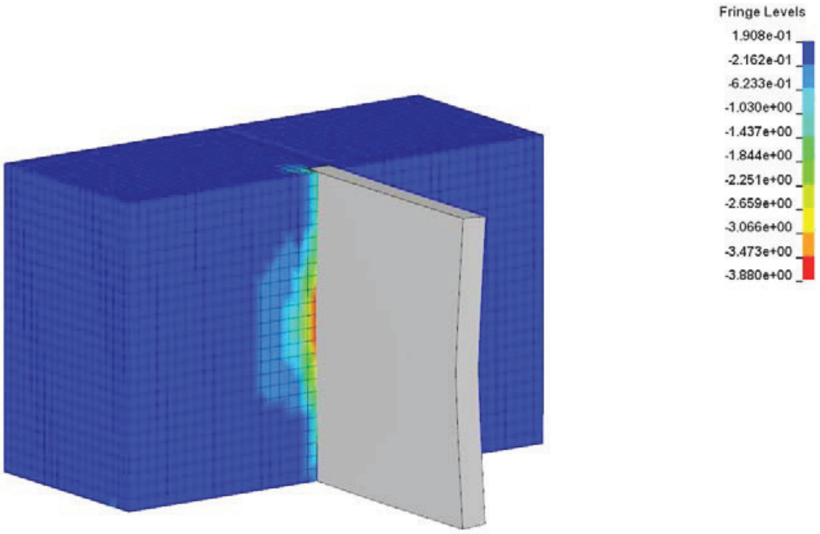


Figure 13 - Principal compressive stress distribution in coal rib

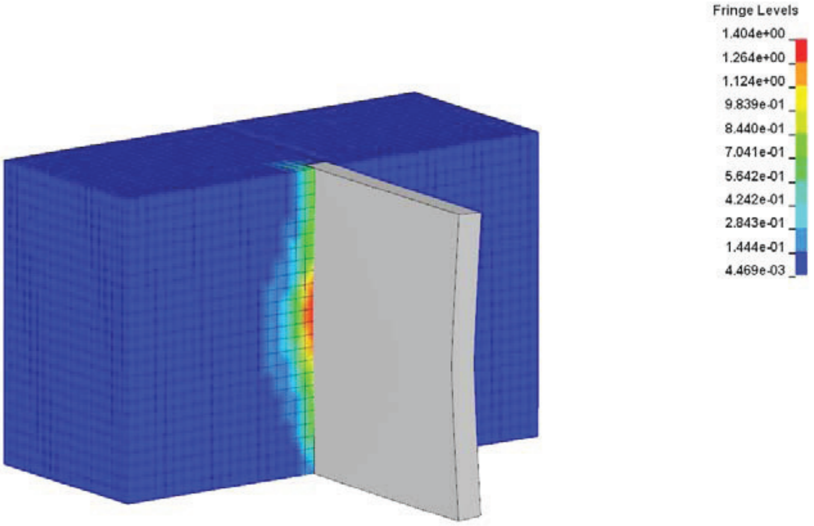


Figure 14 - Maximum shear stress distribution in coal rib

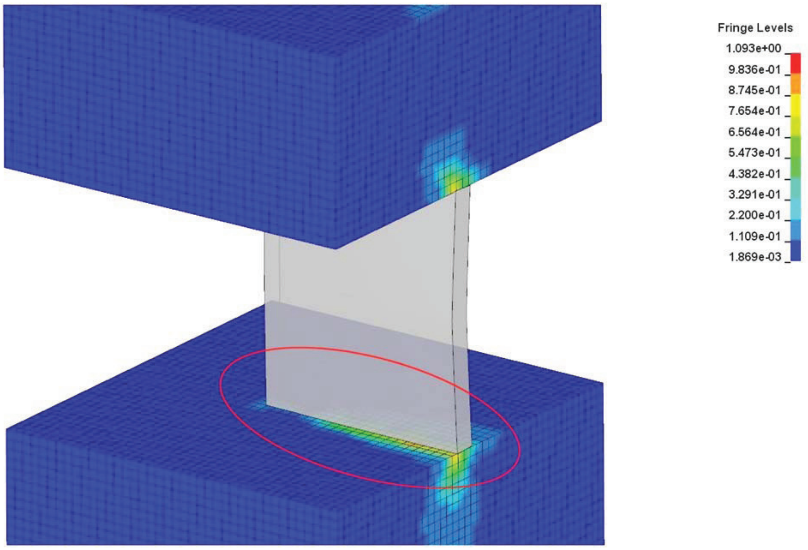


Figure 15 - Maximum shear stress distribution in floor and roof

CONCLUSIONS

A history of coal mine disasters at the beginning of the 20th century which saw increasing production rates and mechanisation, led to an increased research effort into the protection of underground miners from the explosive potential of coal dust (stone dust applications coal dust control)and gas concentrations. In the absence of advanced structural engineering techniques and materials science knowledge many researchers around the globe concentrated on live testing of VCDs using controlled explosions. Despite advances in understanding structural engineering aspects of seal design (Rice, Greenwald and Howarth, 1930), it is only in the last two decades that attempts have been made to physically measure seal response to explosions and to simulate seal behaviour with advanced structural techniques. Explosion testing still seen as an important safeguard for proving seal ratings is now used in conjunction with numerical methods using computer based tools that have been developed for other industries using well understood construction materials. Queensland Mines Department Approved Standard for Ventilation Control Devices was introduced in 1996, and during this period several generic ventilation seal systems were being introduced into coal mines, some being unique to Australia.

One such seal, Meshblock, introduced into Australian mines in 1994 is constructed of cement based shotcretes. Meshblock has been subjected to explosion test programs with outcomes previously summarised in an engineering model, however new questions such as the effect of strata convergence on explosion rating need to be answered.

In this paper, a high-fidelity physics based finite element model for the explosion rated Meshblock ventilation seals was developed. The model is suitable for computing dynamic responses of ventilation seals in coal mines subject to explosion loading. The seal model includes the concrete material model that incorporates many important features of concrete behaviour, such as tensile fracture energy, shear dilation, effects of confinement, and invariant failure surfaces. Damage metric is used to gauge the evolution of the concrete's behaviour from elastic to elasto-plastic, and to softening or fracture.

Numerical modelling and simulation of the explosion rated ventilation seals can be undertaken in stages to determine their resistance to explosion loads, the combined effects of explosion loads and roof to floor convergence and finally to establish the ultimate capacity of ventilation seals and their overall response. Detailed investigation of the interface stresses between the seal and the surrounding strata can provide important information for the grouting program for seal construction.

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