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HIGH-FIDELITY PHYSICS-BASED MODELLING OF EXPLOSION SEALS FOR COAL MINES

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ABSTRACT

This paper presents a new approach to analytical design of coal mine seals to safely resist explosions during their intended life. Under the current Australian regulations, ventilation control devices (VCD) such as seals and stoppings are required to be tested to achieve pressure ratings of 14, 35, 70, 140 or 345 kPa. Since full-scale testing of seals under various loading regimes is economically prohibitive, a new trend is emerging where high-fidelity physics-based models calibrated using only one full-scale test are employed to predict ultimate strength of seals. In this paper, the explicit dynamics non-linear finite element code LS-DYNA is used to develop high-fidelity physics-based (HFPB) computer simulations to predict the results from physical testing of coal mine seals. Test data from live gas/coal dust deflagration explosions at Lake Lynn, PA, USDA are used to simulate a realistic loading environment caused by 140 kPa (20-psi) explosions. The benefits of the new approach are also outlined.

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). 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 and also lack of ability to effectively measure and define 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 what influenced the performance of ventilation seals when subjected to an explosion overpressure.

The 1994 explosion at Moura No. 2 Mine renewed the focus on VCDs within Australian coal mines with closer examination of the design and construction of seals. This resulted in new legislation in Queensland that gave 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 research undertaken at this time after the recommendations of Task Group 5, Tecrete Industries introduced an explosion rated shotcrete based Meshblock seal with an overpressure capacity of 140 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 (1997) requires a seal to "withstand a static horizontal overpressure of 20 pounds per square inch (140 kPa). Previous research by the former U.S Bureau of Mines (Weiss et al, 1999) indicated that it would be unlikely for overpressures exceeding 140 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.

In this paper, the explicit dynamics non-linear finite element code LS-DYNA is used to develop a HFPB computer model for a 300 mm thickness Meshblock seal. Test data from live gas/coal dust deflagration explosions at Lake Lynn, PA, USDA are used to simulate a realistic loading environment caused by 140 kPa (20-psi) explosions. It is demonstrated that coal mine seal design based on HFPB modelling can provide the most accurate prediction of the complex underground coal mine environment.

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 1 presents an example of a 140 kPa (20-psi) experimental pressure-time curve that can be used for dynamic analysis of seals.

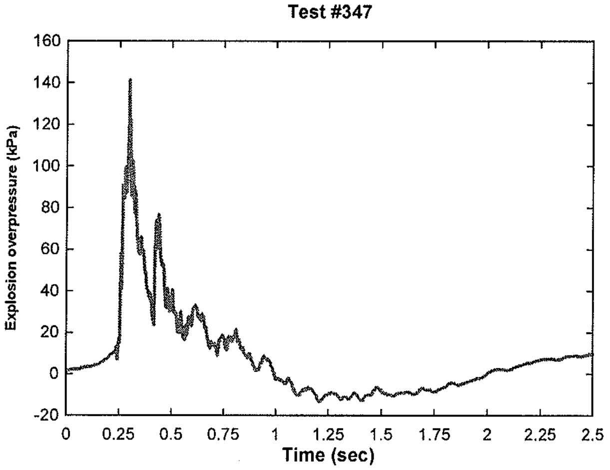

Fig. 1: 140 kPa (20-psi) explosion pressure-time curve for dynamic analysis of seal

Finite element modelling

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 modeled for 300-mm thick seals. The rib keys are modeled 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 2(a) shows the components of the seal model used in this study.

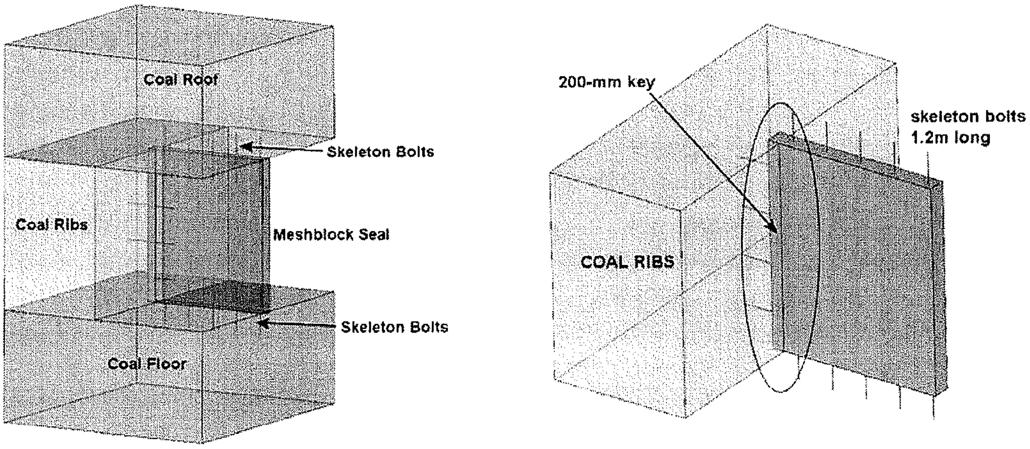

Fig. 2: Modelling of (a) roadway and strata enclosing seal; (b) keys for ribs and bolts

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 2(b) 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.

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 & 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.

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

Tab. 1: Material properties for models of roof, floor and ribs

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.

Structural response of 300-mm seal to 140 kPa explosion load

Predicted crack patterns in the 300-mm Meshblock™ seal at about 1.0 sec after the explosion are shown in Figure 3(a). The seal displaces laterally about 6 mm at the mid point of the wall and reaches residual permanent deformation of about 2 mm at 1.0 sec as shown in Figure 3(b). 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 140 kPa (20-psi) explosion loading. Crack pattern shown in Figure 3(a) 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. Figure 4 shows principal compressive stress and maximum shear stress distributions in the coal ribs, floor and roof. 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. The maximum shear stresses reach about 1.0 MPa in the roof and floor within an area of about 150 mm wide on both sides of the seal and about 120 mm deep.

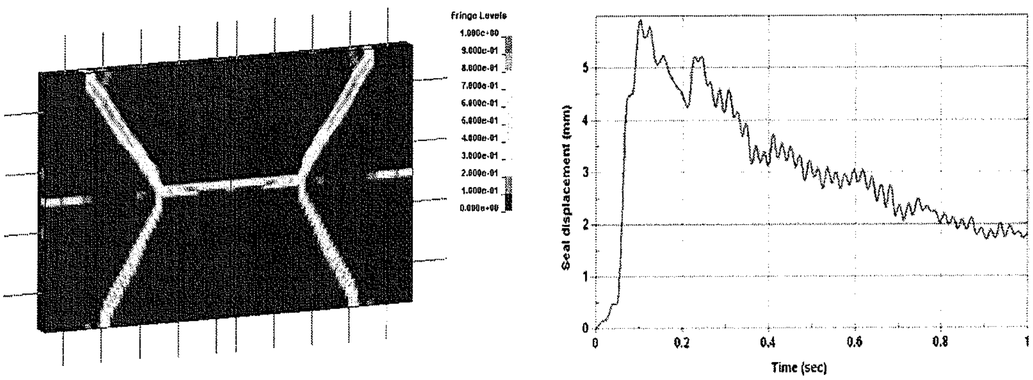

Fig. 3: (a) Concrete damage contours on the outbye side of 300-mm seal; (b) Time history of displacements at mid-point of seal

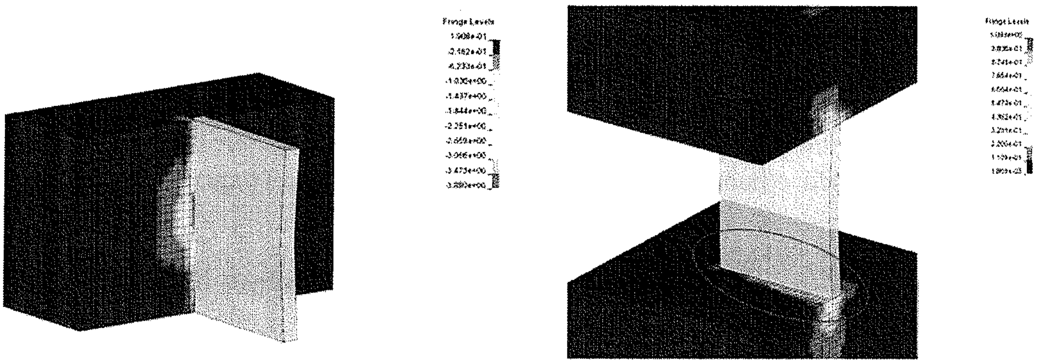

Fig. 4: (a) Principal compressive stress distribution in coal ribs; (b) shear stress distribution in floor and roof

CONCLUSIONS

In this paper, a high-fidelity physics based finite element model for explosion rated Meshblock ventilation seals was developed. This model is suitable for computing dynamic responses of coal mine ventilation seals 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 to enable the design of a grouting program as part of seal construction.

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BRIEF BIOGRAPHY OF PRESENTER

Alex Remennikov is an Associate Professor at the University of Wollongong. His research areas include analysis and design of steel and concrete structures subjected to abnormal loads such as blast and impact.