2016

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Publication Details

Faham Tahmasebinia, Ismet Canbulat, Chengguo Zhang, Serkan Saydam and Luming Shen, The Effect of Energy Transmission on Mine Coal Pillars, in Naj Aziz and Bob Kininmonth (eds.), Proceedings of the 16th Coal Operators' Conference, Mining Engineering, University of Wollongong, 10-12 February 2016, 108-115.

THE EFFECT OF ENERGY TRANSMISSION ON MINE COAL PILLARS

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ABSTRACT: Random kinetic energy induced from strain energy stored in mining structures can distribute the stresses in rock masses. This physical transformation from potential to kinetic energy can lead to a severe coal burst which can be highly damaging. An efficient tool that can evaluate this stress distribution can play an important role in the design and planning of coal pillars and mine layouts. This paper presents a novel three-dimensional finite element modelling methodology (3D FEM) that has been developed to determine the structural response of a pillar subjected to kinetic energy release. This methodology can be used to determine the areas where a pillar is susceptible to violent, uncontrolled failure as well as to study the structural responses of a coal pillar. As part of the study a parametric study of combination of softening parameters in both coal and coal/rock interface was conducted to determine critical regions in the pillars that may lead to a better design strategy in coal burst prone mines.

INTRODUCTION

Galvin (2015) stated that, the terms most commonly used to describe dynamic energy releases in underground coal mining are pressure (or coal) bumps and pressure (or coal) bursts. Both terms refer to dynamic energy events associated with stress levels in the rock mass (or coal). However, the commonly accepted difference between a pressure bump and a pressure burst relates to the magnitude and hence, the consequence. A pressure bump is a dynamic release of energy within the rock mass (or coal) in a coal mine, often due to intact rock failure or failure/displacement along a geological structure, that generates an audible signal, ground vibration, and potential for displacement of existing loose or fractured material into mine excavations. A pressure bump is also sometimes referred to as a bounce. A pressure burst is a pressure bump that actually causes consequent dynamic rock/coal failure in the vicinity of a mine opening, resulting in high velocity expulsion of this broken/failed material (or shakedown) into the mine excavation. The energy levels, and hence velocities involved can cause significant damage to, or destruction of conventional installed ground support elements such as bolts and mesh.

In metalliferous mining, a strain burst is usually referred to as a seismic event caused by a failure of a localised, relatively small volume of highly stressed rock in the immediate vicinity of an excavation. A rock burst, on the other hand, is a higher-energy event that can range up to magnitude 5 on the Richter scale. Most pressure bursts associated with coal mining would be classified as strain bursts in the hard rock mining sector (Galvin 2015). Coal burst has been recognised as one of the most catastrophic failures associated with coal mining, which can lead to injuries and fatalities of miners as well as significant production losses (Kusznir and Farmer 1983; Brauner 1994; Iannacchione and Zelanko 1995; Potvin 2009; Mark 2014 and Galvin 2015). Coal bursts are usually classified as a natural phenomenon directly attributable to the coal becoming over stressed. A number of techniques and methods have been developed in the past to attempt to determine the potential and critical zones for rock bursts in underground mines. Some of the techniques have been derived from the balance of energy around excavations, including a combination of strain energy, kinetic energy, and potential energy. Cook (1963) developed an Energy Release Rate (ERR) concept which has become one of the most popular techniques among the methods currently available (Cook 1976; Linkov 1994; Wang and Park 2001 and Wattimena *et al.,* 2012).

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MODELLING STRATEGY

As part of this study, a bord-and-pillar model to evaluate energy transmission in different strata layers due to different properties has been developed. A Mohr-Coulomb (MC) material that presents a constant strength after failure, and a Mohr-Coulomb strain-softening material (Wang and Park 2001; Islam *et al.,* 2009; Sirait *et al.,* 2013; Mortazavi and Alavi 2013; Nie *et al.,* 2014 and Poeck *et al.,* 2015) that can reach the peak strength and then decrease to a residual strength have been considered. It is suggested that the outcomes of the numerical modelling study together with the combination with other analytical techniques can be used to estimate both *in situ* stress as well as mining induced stress, where it may result in identifying the coal burst prone areas in a mine site. Another aspect of this study is that it takes into account the influence of the third dimension which can play a key role in interpretation of the result. Developing 3-dimensional Finite Element (FE) Models using dynamic solver (ABAQUS/Explicit), which is a convergence free solver, is one of the major advantages of the current simulations in comparison with the former simulations. Moreover, Poeck *et al.,* (2015) emphasised the advantages of the three dimensional FE modeling in comparison to 2-D models when considering the correlation of energy release values.

Table 1 lists the basic material properties used for overburden and coal material properties.

Table 1: Numerical modelling material properties

Material	Density (kg/m^{3})	Young's Modulus (Pa)	Poisson Ratio	Friction Angle (deg)	Cohesion (Pa)
Overburden	2350	23.4e9	0.26	------	-----
Coal	1313	3e9	0.2	23	1.69e6

Table 2 lists the changes in cohesion, friction and dilation angles applied to the strain-softening material with associated levels of strain (Poeck *et al.,* 2015). A bord-and-pillar panel layout in conjunction with different material properties, joint properties, and loading conditions were undertaken by Poeck *et al.,* (2015). In order to comprehensively extend the Poeck *et al.,*'s model (2015), a 3D pillar model that considers the different joint properties has been developed in this study (Figure 1). Consideration was also given to defining a joint interface between the coal and overburden rock.

Table 2: Softening parameters used in coal (after Poeck et al., 2015)

Strain	Cohesion (Pa)	Strain	Friction angle (deg)	Strain	Dilation angle (deg)
0.00000	1.69e6	0.00000	23	0.00000	2
0.00006	1.54e6	0.00007	27.5	0.00007	10
0.00008	1.47e6	0.00010	30	0.01360	10
0.03500	2e5	1.00000	30	0.01413	2
1.00000	2e5			1.00000	2

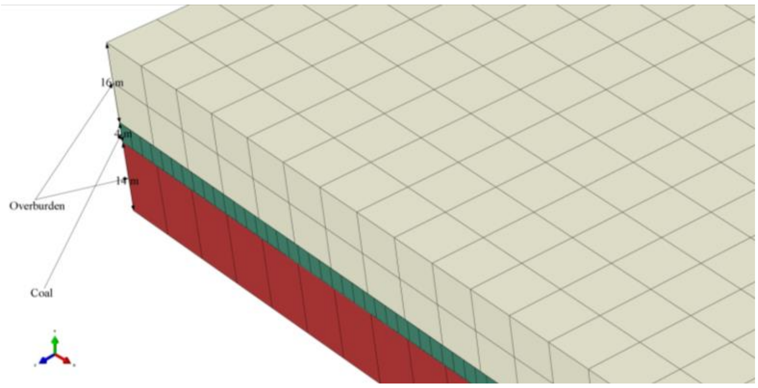


Figure 1: Illustration of a typical single pillar model

Based on the study by Poeck *et al.,* (2015), the three variations of joint properties included in the study were fixed (or tie condition) where there is no slip between the rock and coal interface. The Coal-rock interface Slip (CS) is presented by Coulomb-slip parameters, and Continuous Yielding (CY) is presented by displacement softening parameters. Table 3 lists the parameters applied to each of the constitutive joint models and Figure 2 shows the stress/strain behaviour of the MC and CY joints used in the coal/ rock interface.

Table 3: Joint properties used for the coal/rock interface (Poeck *et al.,* 2015)

	Coulomb Slip	Continuously Yielding
Shear Stiffness (Pa)	50.0e9	50.0e9
Normal Stiffness (Pa)	50.0e9	50.0e9
Initial Friction angle (deg)	20.0	40.0
Intrinsic Friction angle (deg)	----	15.0
Joint roughness (m)	-----	0.00015
Cohesion (Pa)	0.0	-----
Dilation angle (deg)	0.0	-----
Tensile Strength (Pa)	0.0	-----

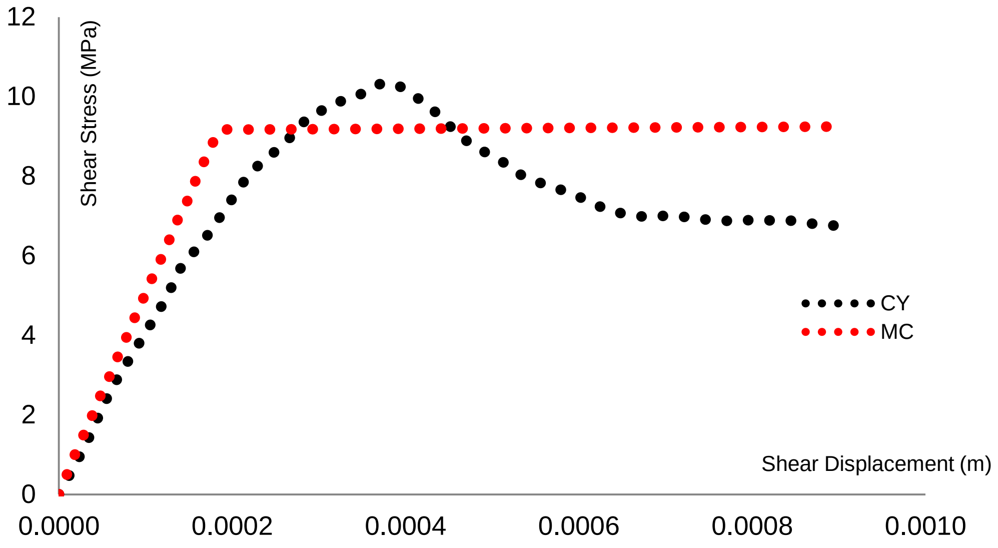


Figure 2: Stress/Strain behaviours used in coal/rock interface (after Poeck *et al.,* 2015)

NUMERICAL MODELLING SIMULATIONS

The numerical modelling layout presented in this paper was conducted using the commercial software package ABAQUS. All materials, including the rock and coal were modelled with the eight-node linear brick element (C3D8R) available in the ABAQUS library. Element C3D8R relies on reduced integration and hourglass control, and its meshing is carried out with the structured technique available in ABAQUS. The solution to the nonlinear problem was sought using the explicit dynamic analysis procedure available in ABAQUS (Tahmasebinia *et al.,* 2012). This approach is an improvement to an implicit formulation as it can handle the convergence problems encountered with nonlinear analyses of composite members efficiently when dealing with complex joint conditions.

In the previous studies, it was noted that ABAQUS/Standard could not ensure convergence of all simulations included in their realisations at high levels of deformation, despite the FE solution relied on the RIKS (which is a static solver) method based on an arc-length control procedure (Tahmasebinia *et al.,* 2013). The explicit dynamic analysis adopted in this study uses an explicit integration rule, where the equation of motion of the model is integrated in time using the explicit central-difference rule (ABAQUS User's Manual 2008). To perform quasi-static analyses with this approach, it is appropriate to artificially increase the mass of the model in order to keep its kinematic energy minor. This is achieved by using the FIXED MASS SCALING option available in ABAQUS, which requires utilisation of the minimum time increment used in the analysis based on which ABAQUS/Explicit determines the mass scaling factors adopted in the calculations.

DISCUSSION OF THE RESULTS

Different material properties and joint properties were simulated and tested. The results indicated that the softening behaviour in the Mohr–Coulomb has no significant influence on the absorption of strain energy. The major sources of the strain energy might be concerned with the rock or coal ejected when the coal burst takes place, and that kinetic energy of that material after the burst equals all of that strain energy minus the work that has to be done to create a crack (or series of cracks) to detach it from the surrounding rock or coal. However, when joint properties are considered, those that are continuously yielding would be presented best by CY and can play a key role on changing level of strain energy. With the tie condition (i.e., where there is no slip between the engaged surfaces), the energy released from the rock mass would be limited. This phenomenon indicates how ductility between the interfaces can change the failure mode as it can determine the levels of kinetic and strain energies. As an example, the Energy Release Rate (ERR) has been presented in different conditions as presented in Figure 3.

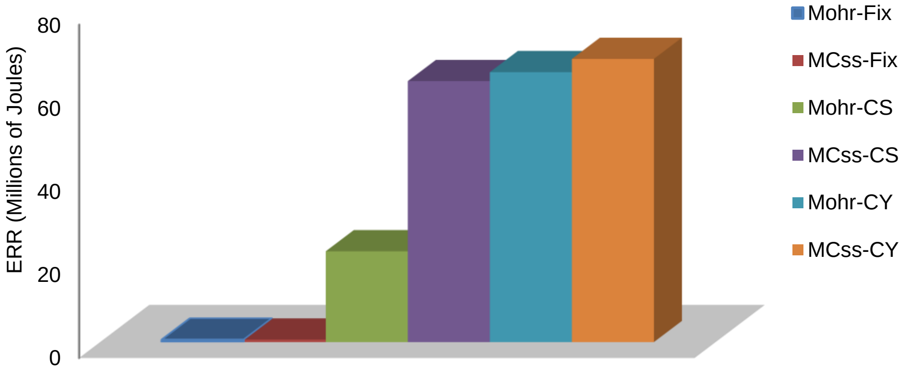
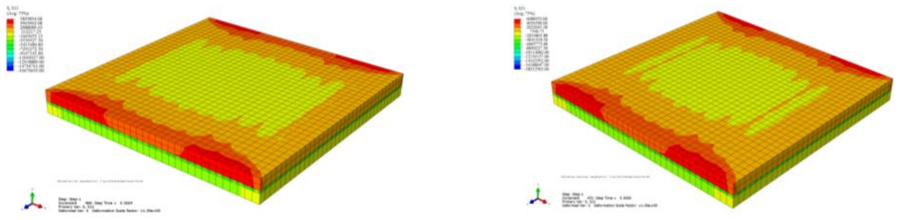


Figure 3: Energy Released Rate, Mohr = Mohr-Coulomb rock mass, CS: Coulomb slip interface, CY: Continuously Yielding interface)

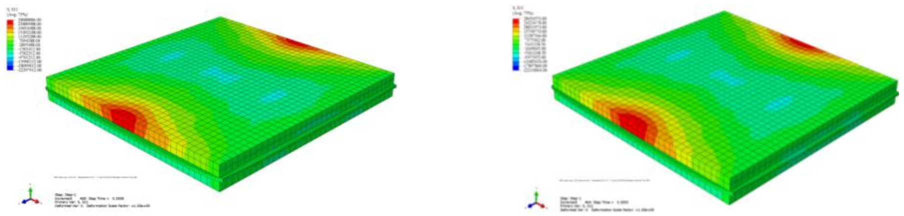
The same properties are used to compare in-plane horizontal stress distributions throughout the critical sections where it is situated near the edges in different material and joint properties (Figure 4). As is evident in Figure 4, the stress concentration would be over the entire model when there is a fixed interface as the allocated joint properties between the coal and overburden. This is because of the fact that there is no slip between the engaged surfaces. On the other hand, a local stress concentration was observed in both models where CS and CY joints were specified with slip joint properties between the major surfaces. Individually, the stress concentration is located at the edges of the model in which the slip direction was entirely restrained in that direction due to the possible particular geological structure of the mine.

A comparison between the strain energy as well as the kinetic energy due to the different joint properties (i.e., the fixed joint properties, the CS joint properties and the CY joint properties) is presented in Figures 5 to 7. Figure 5 presents the relationship between the kinetic and strain energy when there is a fixed condition between the coal and overburden layers. As expected, it is evident from this figure that the strain energy is higher than (almost 4.5 times) the kinetic energy due to the lack of movement between the simulated layers, which indicates that the strain energy can be notably stored inside the strata layers rather than releasing as a kinetic energy due to the lack of the slip between different layers.



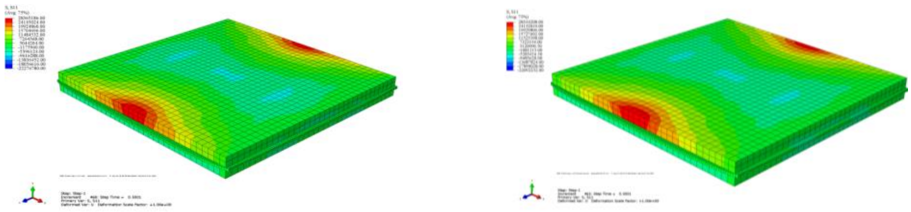
a) Mohr – Coulomb with the Fix interface

b) Mohr – Coulomb Hardening with the Fix interface



c) Mohr – Coulomb with the CS interface

d) Mohr – Coulomb Hardening with the CS interface



e) Mohr – Coulomb with the CY interface

f) Mohr – Coulomb Hardening with CY interface

Figure 4: Stress distributions due to the different material and joint properties

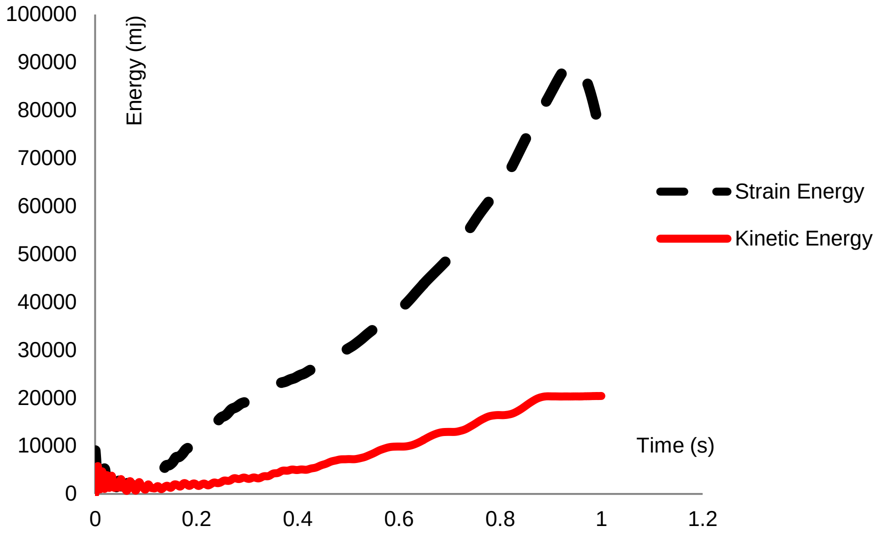


Figure 5: Strain and kinetic energies using fixed joint properties at different computing times

Both Figures 6 and 7, where the shear stresses between the joints are a function of slip between the layers, demonstrate that the kinetic energy is significantly higher (over 9.45 times) than the strain energy due to the movement between different layers. This finding is important as it is verifies the mechanism of how the stored energy can be released into the different parts of the rock/coal interface.

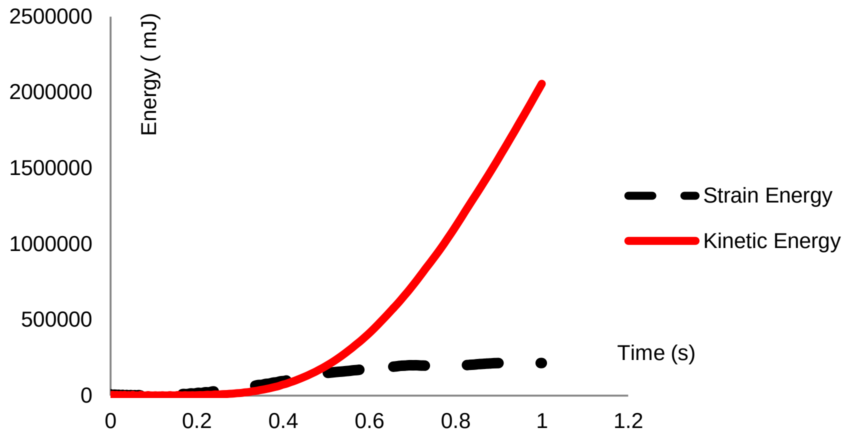


Figure 6: Strain and kinetic energies using CS joint properties at different computing times

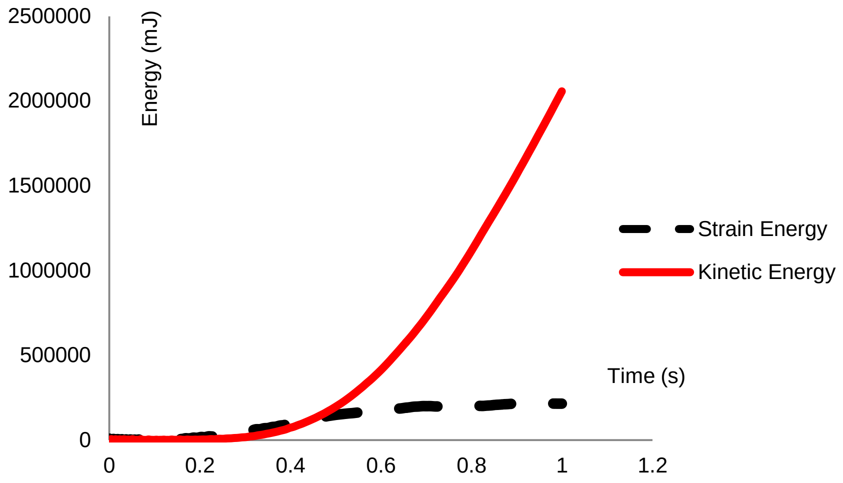


Figure 7: Strain and kinetic energies using CY joint properties at different computing times

From the above it is reasonable to conclude that in the burst-prone zones strata flexibility would be one of the critical considerations rather than only the strength and stiffness of the layers and joint properties. The kinetic energy, which can generally be transferred into the rock mass, can fully or partially be released from the strain energy which is stored in the rock mass. Thus, the source of the discussed strain energy may be significantly dependent on the geological structures (e.g. joint mechanical properties). Usually, the rock mass surrounding coal seams consists of considerable discrete layers. Therefore, it is possible that a significant amount of this strain energy can either be converted to active kinetic or passive thermal energy in different layers and it can lead to generating a large displacement as well as degradation of the rock mass which in turn might be highly distractive. Provided that $\left(\frac{E_{StrainEnergy}}{E_{KineticEnergy}}\right)=m$, therefore, *if* $m \geq 1$ then there is a tie or fixed joint between the layers. On the other hand, when $m \leq 1$ then there is a flexible joint between the simulated layers. This simple assessment can help determine rockburst-prone zones. This finding confirms that the numerical modelling as a robust tool can provide a reliable procedure to determine high-risk zones where a severe coal burst might occur. It is of note that the energy based design approach is a novel procedure when evaluating performance of mining structures. This approach can also be significantly extended by involving further key parameters such as energy dissipations due to the material damping between rock-mass layers as well as computing induced internal and external work as a results of relative movements between the layers. It is however appreciated that numerical modelling may not be the solution for every mine due to the complexity involved.

CONCLUSIONS

An assessment of strain energy and kinetic energy before and during excavation can help to assess the likelihood of a violent failure. In this paper, bord-and-pillar mining layouts were modelled based on the different joint properties. It was concluded that continuously yielding joint properties presented by CY result in more energy release and thus have a significant influence on the of failure mode. Therefore, the rock mass failure mode with different joint properties might be critically affected by the transmission of energy between the layers. Furthermore, full scale simulations are suggested to gain a better understanding of the interaction between the key elements that govern the failure mode, as well as the energy momentum that builds up between the major layers.

ACKNOWLEDGEMENT

This work was supported by an award under the Merit Allocation Scheme on the NCI National Facility at the ANU and part of the computational services used in this work were provided by Intersect Australia Ltd.

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