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Numerical simulating research on orifice pre-splitting blasting in coal seam

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Abstract

Aiming at the actual problems such as bad effect of gas drainage, slow mining speed, high cost and so forth of drilling along layers in mining face of coal seam of low air-permeability but high gas-content, effect of orifice pre-splitting blasting on crack extending in coal seam was studied through adopting ANSYS/LS-DYNA software. Different diameters and depths of holes were set in the simulation, and groups were divided through using method of controlling variable volume. Results show that when depth of hole is fixed, with diameter of hole increasing, time for elements at the same location to receive stress shortens gradually, and when diameter of hole is fixed, with depth of hole increasing, time for elements at the same location to receive stress prolongs gradually, that is, the bigger the diameter of hole is, the more easily cracks extend in coal seam, and the deeper the hole is, the more adversely cracks extend in coal seam . This conclusion can provide theoretical basis for researching the gas drainage effect of actually applying orifice pre-splitting blasting.

Keywords: forming cracks through pre-splitting blasting; LS-DYNA; numerical simulation; orifice dynamite

1. Introduction

In China, 95% of coal production is underground mining. With the increase of mining depth, mining mechanization and gas emission in coal seam, gas explosion and coal and gas outburst have been the major contradiction for accidents of coal mine keeping high level in China. So the key to solve safety problems of coal mine is controlling gas effectively [1]. Extracting gas in coal seam, strata and goaf with special equipments and facilities is an important measure for reducing gas emission in coal mine tunnel, decreasing concentration of gas in mining face and also preventing gas explosion and coal and gas outburst.

During the process of mining face promoting, stress-distribution of coal body of forward working face must be changed, pressure relieving zone must be kept long enough and air-permeability of coal body must be increased at the same time so as to achieve full pre-emission of gas in coal seam and prevent coal and gas outburst happening. Theoretical analysis and field test show that the risk of outburst of coal seam can be reduced and eliminated efficiently by adopting deep-hole pre-splitting method to control loose blasting. But carrying out deep-hole pre-splitting blasting in coal body has some shortcomings as follows [2–4]: first of all, if dynamites cannot react completely in blasting process, mining work would be more dangerous. Secondly, compared with orifice pre-splitting blasting, preparing work of deep-hole pre-splitting blasting is more complex. Orifice pre-splitting blasting in gas containing coal body has enough different characteristics to make itself distinguished from common pre-splitting blasting and loose blasting, preparation and installation of blasting equipments of it are also special because parameters of gas-pressure are needed to be considered in situation of coal and gas

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co-existing, at the same time, blasting operating regulation must be strictly observed to ensure safety as gas is flammable and explosive. So, it has great researching value to apply technology of orifice pre-splitting blasting in the field of gas drainage.

Therefore, numerical simulation of deep-hole pre-splitting blasting in coal body was carried out through adopting ANSYS/LS-DYNA. The objective of simulation was exploring the influence of depth and diameter of blasting hole on pre-splitting result so as to provide theoretical basis for determining depth and diameter of blasting hole in actual blasting.

2. Basic principle of forming cracks through coal seam pre-splitting blasting

The technology of pre-splitting blasting has been widely applied in blasting and excavation of rock foundation, slope, underground chamber and so on. It plays the role of protecting remaining rock and peripheral environment, such as resisting crack and relieving concussion, which fully shows its good technical and economic benefits to engineering construction [5].

Coal seam pre-splitting blasting makes use of stress wave generated by dynamites, gas produced by explosion and pressure of gas in coal seam to exert influence on coal body, at the same time produces non-healing cracks in coal body with help of controlling hole of free surface so as to increase rate of gas drainage and shorten time of gas drainage. Its essence is changing physical properties of coal body and flowing characteristics of gas in affected zones through making use of the crack-network formed in the blasting process, so as to achieve the goals of reducing ground stress and increasing permeability of coal seam. Predecessors have made many research on mechanism of forming cracks through pre-splitting blasting and put forward related conditions of nucleus forming, splitting starting, crack extending, splitting stopping and so forth of blasting crack, and also made many valuable conclusions [6]. But existing blasting theories mostly take rock medium as researching object [7], having not made systematic research on law of blasting crack forming and developing in gas containing coal body.

Essence of coal seam pre-splitting blasting is changing physical properties of coal body and flowing characteristics of gas in affected zones through making use of the crack-network formed in the blasting process, so as to achieve the goals of reducing ground stress and increasing permeability of coal seam. The formation of cracks in process of pre-splitting blasting is the result of interaction of three factors [8] which are compressed stress wave generated by explosion, high-pressure gas and pressure of gas. Cracks take blasting hole as starting point, firstly run through coal seam in horizontal direction to become splits, then extend toward each direction to produce larger cracks, making scope of cracks in coal seam expand to become crack-network, subsequently reducing resistance of gas drainage and increasing air-permeability and amount of gas drainage, so the overall efficiency of gas drainage is greatly improved.

3. Numerical simulation and analysis of orifice pre-splitting blasting

In recent years, rapid developing of computer provides important means for thorough research of blasting theory. The numerical simulation of blasting process takes different numerical computing methods as means to obtain solution of model of blasting process. It has important significance for thoroughly understanding phenomenon and mechanism of blasting of rock.

With developing of blasting technology, simulating blasting with computer, which is a kind of new technology and method in blasting field, has been paid more and more attention. In recent years, research on simulating blasting with computer has made great achievements, and some fruitful blasting models have been established and played important role in engineering. Although numerical simulation has great progress, numerical simulation of blasting is difficult and corresponding program is complicated due to complexity of blasting. Among the numerous programs produced, there isn't one program being recognized as perfect until now, as they are constantly improved and developed. In China, the blasting software which has greatest influence is LS-DYNA program series. Through adopting function of material model being self-defined by user of LS-DYNA program, the goal of simulating pre-splitting blasting numerically can be achieved so as to thoroughly analyze mechanism of coal seam pre-splitting blasting and provide reference for optimizing blasting parameters.

The results of coal seam pre-splitting blasting is producing compressed crushed circle which is cylindrical and blasting crack-surface which ran through controlling hole in coal body, with purpose of increasing the scope of crushing and fissuring areas, and reducing ground stress and pressure of gas as much as possible so as to increase air-permeability and gas drainage rate of coal seam. The numerous cracks in coal body produced by pre-splitting blasting are directly related to air-permeability of coal seam, as their distributing density, length and angle are all difficult to be measured directly, and their specific parameters at different zones cannot be expressed with determined mathematic formula, only can be described indirectly through change of parameters of coal body such as stress, strain, displacement and so forth, which can be achieved through numerical simulation of coal seam pre-splitting blasting.

3.1. Building model

3.1.1. Basic hypothesis

Blasting in solid medium dielectric is a super dynamic process, but the mechanism of coal seam pre-splitting blasting is the co-affecting result of explosive blast, gas produced by explosion and pressure of gas, as it is different from general blasting, therefore assumptions were made as followings:

(1) Explosive blast produced by pre-splitting blasting firstly exerts influence on wall of blasting hole and produces compressed crushed circle and initial radial cracks, then gas generated by blasting and pressure of gas exert influence on crack-surface in form of quasi-static, driving cracks to extend. So compressed crushed circle and crack-surface were seen as free surfaces, and other coal bodies and rock bodies were seen as isotropic self elastic-plastic bodies.

(2) Because length of blasting hole is much larger than its diameter, so blasting process was analyzed as problem of plane strain.

(3) The expansion of blasting generating gas was an adiabatic process.

(4) Influence of aqueous phase in coal seam was ignored, and only the fluid-solid interacting relationship between gas and coal body was considered.

3.1.2. Mechanical model

As shown in Fig.1, special coal body was selected as object of which working face extended inward 30 m and radius was 20 m (what is shown in Fig.1 is a quarter of model of object which can be complemented completely through using symmetrical operation while simulating), and a hole was bored at center of mining face, as depth and radius of it followed simulating conditions. Dynamites were placed near orifice of mining face in style of uncoupling. As shown in Fig.2, V4, V6, V8 are the parts of dynamites, V2, V5, V7 and V9 are air, and V1 is stemming, and they are all contained in steel pipe marked by blue. The effect of stemming is to prevent dynamites from releasing energy outward as much as possible. For this purpose, external part of the steel pipe was blocked with flange, and external part of mining face was further supported with hydraulic support.

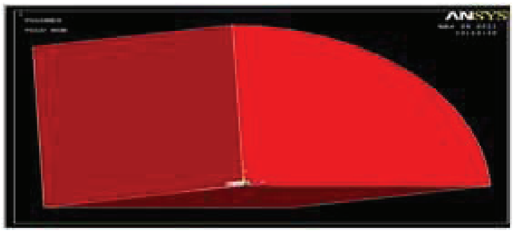

Fig. 1. Model of orifice pre-splitting blasting.

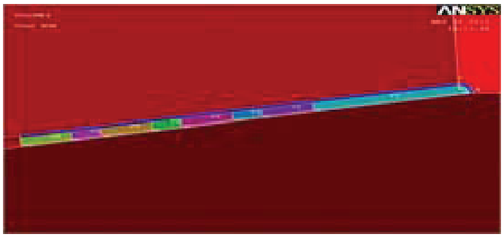

Fig. 2. Dynamite placing diagram.

This model basically meets all requirements of actual blasting and clearly shows the basic situation of blasting of orifice dynamite. But this model is hard to be solved: first of all, due to large difference of size of coal body, dynamite and blasting hole, resulting in quantity levels of mesh size being hard to reach agreement while dividing mesh, great burden would be caused to computer and simulation could not carry on if mesh is tried to divide unanimously, in addition, due to many entities existing in model and their contact varying from time to time, procedure of defining their contacts can be too cumbersome.

So above model was simplified as follows:

Special coal body was selected as object of which work face extended inward 30m and radius was 20 m (what is shown in Fig.1 is a quarter of model of object which can be complemented completely through using symmetrical operation while simulating), and a hole was bored at center of mining face, as depth and radius of it followed simulating conditions., which is shown in Fig.3.

Dynamite was placed at orifice, as its length and diameter were respectively 0.5 m and 75 mm. Parts of coal body were not set entity except part of dynamite. Specific information is shown in Fig.4, the red part in the figure is coal body, and the part marked by V1 is dynamite.

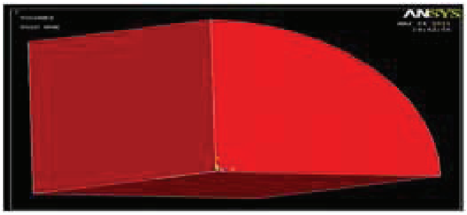

Fig. 3. Simplified orifice blasting model.

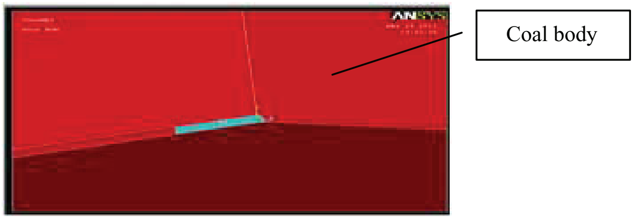

Fig. 4. Simplified dynamite placing diagram.

3.1.3. Conditions of boundary

(1) Due to a quarter of model being adopted in process of building model, so symmetric set should be carried out. The two surfaces A12, A13 shown in Fig.5 were set as symmetrical surfaces, respectively appeared symmetry with flat *YZ* and flat *XZ*.

Fig. 5. Schematic diagram of surfaces of model.

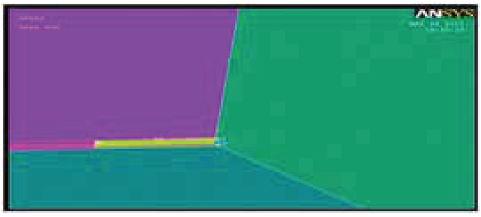

Fig. 6. Schematic diagram of surfaces of dynamite.

(2)In order to prevent mining face from being destroyed in process of blasting, displacements of surface A11 shown in Fig 5 and surface A4 shown in Fig.6 in *Z* direction were all set as zero in simulation.

(3) Because ability of computer is limited, numerical model of limited volume must be adopted to take the place of infinite actual coal seam when numerical simulation carried on, and in order to prevent boundary effect of stress wave in surrounding border, two surfaces contacting with coal body in model were set as non-reflecting boundaries.

3.1.4. Parameters of model

(1) Unit of substance.

Dynamite and coal body are the two substances in the model, all adopting SOLID164 entity unit which is explicit structural and used for 3-D, being consist of eight nodes and only used for dynamic explicit analysis, and also supporting all approved non-linear characteristics.

(2) Material model and related parameters.

Material model of coal body adopted follow-up plastic (relating to strain rate) material model, as this kind of model has isotropic property, servo hardening property or mixed property, relating to strain rate and tolerating failure. The parameters needed to be brought in while defining model include: modulus of elasticity (EX), density (DENS), Poisson's ratio (NUXY), yielding strength and shearing modulus. The characteristics of stress-strain can only be determined under one condition of temperature. Specific parameters are shown in Table 1.

Table 1. Physical mechanic parameters of coal seam

Density/($kg \cdot m^{-3}$)	Modulus of elasticity/MPa	Poisson's ratio	Yielding strength/MPa	Shearing modulus/MPa
1.2×10^3	622	0.25	4.57	0.4

LS-DYNA has special material model of dynamite, so only corresponding values are needed to be set. Specific parameters are shown in Table 2.

Table 2. Parameters of dynamite

Density/(kg·m^{-3})	Exploding speed/m/s	C-J pressure/GPa	Parameters of equation of JWL condition					
			A/GPa	B/GPa	ω	R_1	R_2	E_0/(J·m^{-3})
1.05×10^{3}	3 200	6.1	741	13	0.35	5.2	1.3	3.2×109

In order to research the influence of depth and diameter of hole on blasting effect, five groups of juxtaposed models with different depths and diameters of hole were set up. Specific information is shown in Table 3.

Table 3. Parameters of juxtaposed model

Group number	1	2	3	4	5
Depth of hole/m	10	15	15	15	20
Diameter of hole/mm	90	80	90	100	90

(3) Dividing mesh.

Mesh of body was divided in simulation. Due to large difference of size of coal body and dynamite, and limitation of hardware of computer, mesh of body could only be divided sparsely, so formation of crack could not be seen from the result, and blasting effect could only be recognized through distribution of stress.

In simulation, line section of coal body was divided by 50 cm, radial line and deep directional line of dynamite section were respectively divided into two parts and four parts. In order to divide mesh easily, section of coal body was cut up. Specific method is shown in Fig.7.

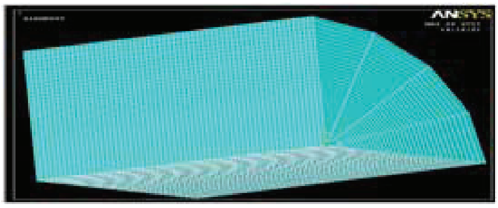

Fig. 7. Dividing reseau of model.

(4) Setting time.

According to difference of groups, the running time of simulation was set as 0.000 8 s and 0.008 s.

(5) Setting contact.

The contact between dynamite and coal body which are the two substances in model was defined as STS common contact.

(6) Setting output of file.

Format of output of file was defined as d3plot so that LS-DYNA could post-process LS-Prepost. Number of steps needed to export file was set as 1 000.

3.2. Solution of model

3.2.1. Explanation of simulating process

(1) Model building process was finished in preprocessing machine of ANSYS. Sweeping style of dividing mesh was adopted in model. Keyword file (K file) could be exported after setting each parameter respectively.

(2) Because preprocessing machine of ANSYS didn't support material model of dynamite, specific parameters had not been brought in while defining properties of material and modification was carried out until K file forming. Material model of dynamite was defined through adopting following keywords:*MAT_HIGH_EXPLOSIVE_BURN. Pressure per unit of explosive products of dynamite adopted equation of JWL condition, that is:

$$P = A\left(1 - \frac{\omega}{R_1 V}\right) e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right) e^{-R_2 V} + \frac{\omega E_0}{V} \quad (1)$$

In this formula, A, B, R_1, R_2 and ω are all parameters of material, V is relative volume, and E_0 is initial internal energy.

3.2.2. Simulating results

What are shown in Fig.8 are screenshots of different time during process of simulating explosion. Two representing elements in model were selected to reveal results. The location of these two elements are shown in Fig.9 (in this figure a model of which depth and diameter of hole are respectively 15 m and 90 mm is revealed), as one is 11 m away from explosive point radially, the other one is 25 m away from explosive point axially.

(1) A group of contrastive results of models of which depths of holes are all 15 m but diameters of holes are different are as follows, as selected element is 11 m away from explosive point radially, like element H4231 in Fig.9.

(2) A group of contrastive results of models of which diameters of holes are all 90mm but depths of hole are different are as follows, as selected element is 25 m away from explosive point axially, like element H20 in Fig.9.

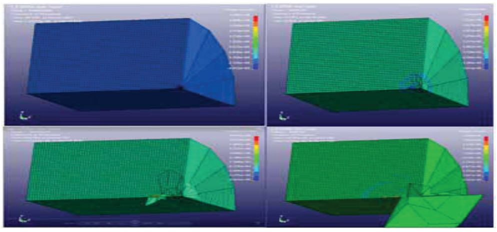

Fig. 8. Screenshots of blasting process.

Fig. 9. Selecting elements of model.

3.2.3. Analysis of simulating results

(1) As shown in Fig.10, Fig.11 and Fig.12, when depth of hole was fixed, with diameter of hole increasing, time for elements at the same location to receive stress shortened gradually. When diameter of hole was respectively 80mm, 90mm and 100 mm, time for element A4231 to receive stress was respectively 0.8ms, 0.68 ms and 0.66 ms.

Thus what can be known is that the bigger diameter of hole is, the shorter time for coal body to receive explosive stress is, and the more opportunely stress spreads in coal body. So from the side of explosive stress wave exerting influence on cracks in coal body, the bigger diameter of hole is, the more opportunely cracks extend.

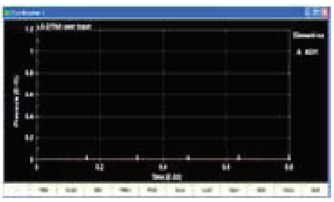

Fig. 10. Hole's diameter is 80 mm.

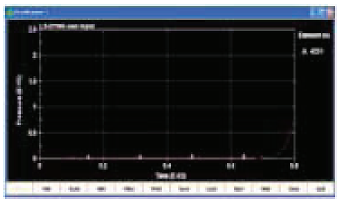

Fig. 11. Hole's diameter is 90 mm.

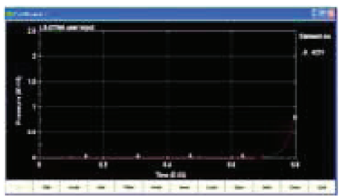

Fig. 12. Hole's diameter is 100 mm.

(2) As shown in Fig.13, Fig.14 and Fig.15, when diameter of hole was fixed, with depth of hole increasing, time for elements at the same location to receive stress prolonged gradually. When depth of hole was respectively 10 m, 15 m and 20 m, time for element A30, A20 and A10 to receive stress was respectively 3.1 ms, 3.4 ms and 4.1 ms.

Thus what can be known is that the deeper the hole is, the longer time for coal body to receive explosive stress is, and the more adversely stress spreads in coal body. So from the side of explosive stress wave exerting influence on cracks in coal body, the deeper the hole is, the more adversely cracks extend.

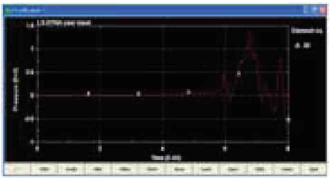

Fig. 13. Depth of hole is10 m

Fig. 14 Depth of hole is 15 m.

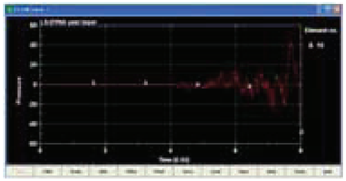

Fig.15. Depth of hole is 20 m.

4. Conclusions

From the side of stress wave exerting influence on coal body, stress-time curves of representing elements were analyzed and following conclusions are finally made:

(1) When depth of hole is fixed and diameters of holes are respectively 80 mm, 90 mm and 100 mm, time for element A4231 to receive stress is respectively 0.8 ms, 0.68 ms and 0.66 ms, which means that the bigger the diameter is, the faster stress wave spreads radially, namely the bigger the diameter is, the farther stress wave spreads radially in fixed range of time.

(2) When diameter of hole is fixed and depths of holes are respectively 10m, 15 m and 20 m, time for element A10 to receive stress is respectively 3.1 ms, 3.4 ms and 4.1 ms, which means that the deeper the hole is, the slower stress wave spreads axially, namely the deeper the hole is, the nearer stress wave spreads axially in fixed range of time.

(3) From the side of stress wave exerting influence on cracks, the larger the scope of influence of stress wave is, the more opportunely cracks emerge. On this basis, this simulation gets the following results: in range of data set, the bigger diameter of hole is, the more easily crack extends in coal body, and the deeper the hole is, the more adversely cracks extend in coal seam.

But result is often not decided by only single factor. The formation of cracks in coal body has something to do with gas produced in blasting. In actual blasting, dynamites inevitably crush near coal body more or less which lead to loss of energy and affect crack making effect of stress wave in coal body, and exerting effect outward to mining face by dynamites can also result in loss of energy. Above situations are all idealized or simplified in this simulation, and only the factor of stress wave is considered. Synthesized effect on cracks extending in coal body of all kinds of factors and distribution of contribution of them are all needed to be further researched.

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