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Strain Localization and Failure Evolution Analysis of Soft Rock-coal-soft Rock Combination Model

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Abstract: Roadways are often built in coal seam in mining area in view the weakly cemented soft rock strata in the western china. Stability of the coal roadway actually depends on the overall mechanical behavior of combined structure which is made up of roof, coal and floor. This study aimed to seek for the damage evolution law of three bodies model composed of soft rock and coal by numerical simulation in FLAC^{3D}. Different failure modes of the combined model were analyzed based on the linear elastic model, Mohr-Coulomb model and strain-softening model. The deformation rates and failure modes as well as the shear strain increments within the combined model were numerically modeled. Meanwhile, effects of thickness of coal seam on the mechanical behavior of the combined model were also analyzed. The results indicated that the thicker of coal seam lead to the steeper strain-softening branch of stress-strain curve, which caused the peak strength of the sample decreasing. With the increasing of confining pressures, deformation of the sample turned to the perfect plastic state and the shear bands decreased and became not evidence. The integral failure rate would be accelerated with the increasing of the thickness of coal seam. At the first decent stage of post-peak stress, strain localization of coal layer and soft rock near the interface can be seen as a precursor to the unstable failure of model. Formation and development of shear bands are mainly at the stress fluctuation stage of strain-softening branch.

Key words: Soft rock-coal-soft rock, strain softening, failure evolution, shear bands

INTRODUCTION

In China's western region of Xinjiang, Inner Mongolia, Ningxia, coal measures are mainly located in weakly consolidated soft strata composed of Cretaceous and Jurassic rocks with characteristics of low strength and easy to be weathered, which lead to poor construction and maintenance in rock roadway. Many mining disasters such as roof burst, coal bump and floor heaving which usually bring huge hidden trouble to the production of coal mine often appear after a coal roadway is excavated. Actually, the mining area is a compound structure composed of rock and coal and the geological dynamics hazards in mining are clearly dominated by the overall mechanical behavior of the whole model which is deeply related to the interaction between each unit. Therefore, it is very important to study the failure evolution of roof-coal-floor system for the prediction of mine disasters.

Up to now, behaviors of combined model composed of rock and coal were studied mainly by the uni-axial compression experiment (Li *et al*., 2005; He *et al*., 2010; Tien *et al*., 2006; Jaeger *et al*., 2007; Mogi, 2007; Petukhov and Linkov, 1979) and there are few reports on the research of failure evolution of composed coal-rock under tri-axial compression state. In recent years, some numerical simulation methods were adopted to analyze the deformation localization problems. Some local and foreign scholars (Wang, 2008; Zuo *et al*., 2011a; Liang *et al*., 2005; Zeng *et al*., 2006; Lade and Wang, 2001; Besuelle *et al*., 2000; Cao *et al*., 2012) studied the strain localization problems of single rock sample under uni-axial and tri-axial compression as well as the variation process of shear strain states. Zhou *et al*. (2009) analyzed the stress-deformation relationship and the variation by the tri-axial compression numerical test. Although many studies about the deformation and failure for two bodies model composed of rock and coal by numerical simulation have been achieved under assumption of coal failure, all these observations were just focused on the two bodies model of coal and rock while some test results have showed that the failure characteristics of three bodies model composed of rock and coal was entirely different (Li *et al*., 2011; Wang, 2006; Zuo *et al*., 2011b). Thus,

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these research results are not suitable for the combined model of soft rock-coal-soft rock which shows integral damage behavior.

In this article, damage evolution law of the three bodies model composed of soft rock and coal with different thickness of coal seam is studied by fast Lagrangian explicit finite difference code of continua for predicting the failure position and damage stage which provide references for the study of occurrence mechanism of rock burst.

CALCULATION MODEL OF COMPOSED COAL-ROCK SAMPLE

Geometry model: Figure 1 shows the geometric model and boundary conditions of combined sample based on standard specimen with a diameter of 50 mm and the ratio of height to diameter is 2. The model is divided into several hexahedron elements with equal size. Constant velocity $v = 2\times10^{-6}$/step is applied on the two terminal planes where only axial movement is allowed.

Numerical simulation is implemented in a setting that the two terminal soft rocks have identical height and the total height remain constant while thickness of coal seam can be changed. Physical parameters of model are tested under tri-axial compression test using specimens from Luxin coal mine as shown in Table 1.

Table 1: Mechanical parameters of the soft rock and coal in combined model

Sample	Elastic modulus E (Mpa)	Possio's ratio (μ)	Cohesion force C (Mpa)	Friction angle (ϕ/°)	Tensile strength σ_t (Mpa)
Mudstone	2100	0.252	3.5	44	1.110
Coal	710	0.272	1.5	40	0.146

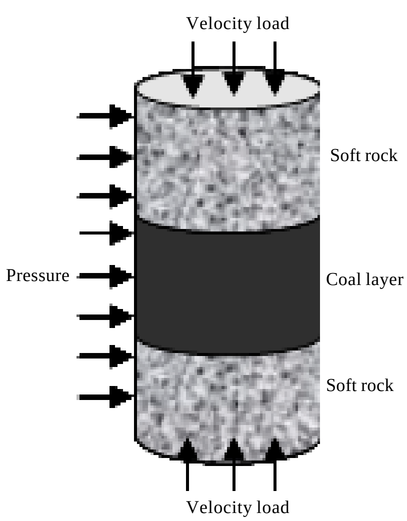

Fig. 1: Geometry and boundary conditions for model composed model of rock and coal

Constitutive model: Due to the obvious strain softening behavior of weakly consolidated soft rock under compression, a compound yield criterion composed of M-C yield criterion and tensile failure criterion is adopted for the numerical simulation. The yield function of M-C shear failure criterion can be written as:

$$F^s = \sigma_1 - \sigma_3\psi + 2c\sqrt{\psi} = 0 \tag{1}$$

where, $\psi = \tan^2(45°+\phi/2)$. c is the cohesion force and ϕ is the friction angel.

The yield function of tensile failure criterion is:

$$F^t = \sigma_3 - \sigma_t = 0 \tag{2}$$

where, σ_t is the uniaxial tensile strength of rock mass.

APPLICABILITY COMPARISON OF DIFFERENT CONSTITUTIVE MODELS FOR COMPOSED SAMPLE

Tunnel roof and floor are usually simplified as elastic springs in the present studies of rock burst in coal mine which is held that failure behavior of the coal tunnel only depend on the coal layer and rarely consider the integral failure of three bodies model composed of roof, coal and floor. However, roof shocking and floor heave frequently occur in the soft rock tunnel. Thus, different failure behaviors of the combined sample based on linear elastic model, Mohr-coulomb elastoplastic model as well as strain-softening model were discussed in order to select a proper model to accurately describe the mechanical behavior of soft rock. Attenuation of shear strength parameters of coal and soft rock with plastic strain are shown in Fig. 2a and b respectively when the strain-softening model is adopted. All the data are taken from the laboratory test and strength parameters show the laws of linear attenuation along with the plastic strain.

Figure 3a-c shows the shear strain bands and horizontal displacement distribution of combined sample on the basis of the three different constitutive models above when coal thickness is set as 30 mm and confining pressure is $\sigma_2 = \sigma_3 = 2$ Mpa. Obviously, the composed sample presents the same "X" type shear slip band under different models while significant differences show in shear zones. Shear bands of the linear elastic model as shown in Fig. 3a is inconsistent with the actual situation, because no damage occurs in soft rock. The initial failure results of M-C model as shown in Fig. 3b and strain-softening model shown in Fig. 3c are similar with each other while the two have an obvious difference in posterior failure stage. Stress will decreases with the

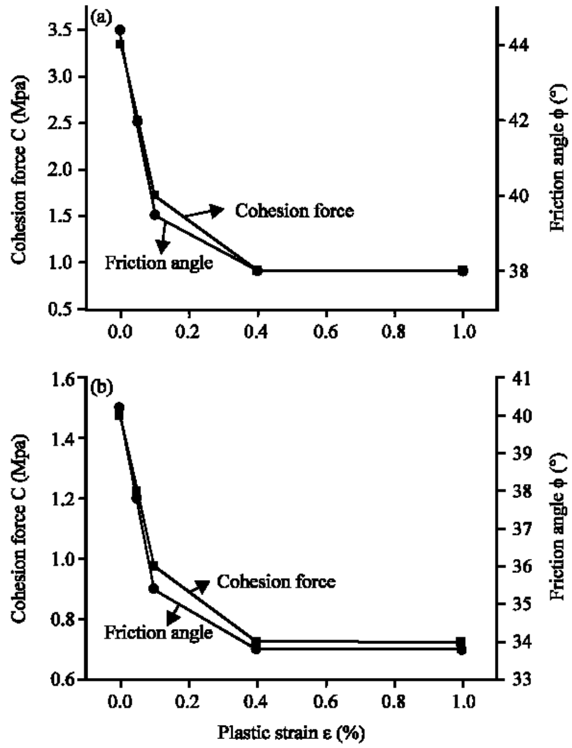

Fig. 2(a-b): Attenuation laws of friction angle and cohesion force with plastic strain, (a) Soft rock and (b) Coal

strain increasing in the post-peak stage of strain-softening model while stress remains nearly constant after peak intensity in M-C model. In view of the obvious softening behavior in soft rock, strain-softening constitutive model is adopted in the following analysis.

MECHANICAL BEHAVIOR OF COMPOSED SPECIMEN UNDER TRI-AXIAL COMPRESSION

Effect of coal seam thickness on the complete stress-strain curve: Figure 4a shows the effect of thickness of coal seam on the average compressive stress-strain curve (hereinafter using abbreviation stress-strain curve) at the top terminal plane when the confining pressure is set as $\sigma_2 = \sigma_3 = 2$ Mpa. No effect was found in linear stage, while rigidity of the model was reinforced after peaking point with the increasing of thickness of coal seam which resulted in brittle behavior. That is to say, strong interaction exists between soft rock and coal seam in strain-softening stage. The brittle behavior may lead to decrease of the energy absorption and consumption ability of coal seam and coal body burst easily occurs. In addition, the peak strength is weakened while coal seam becomes thickening.

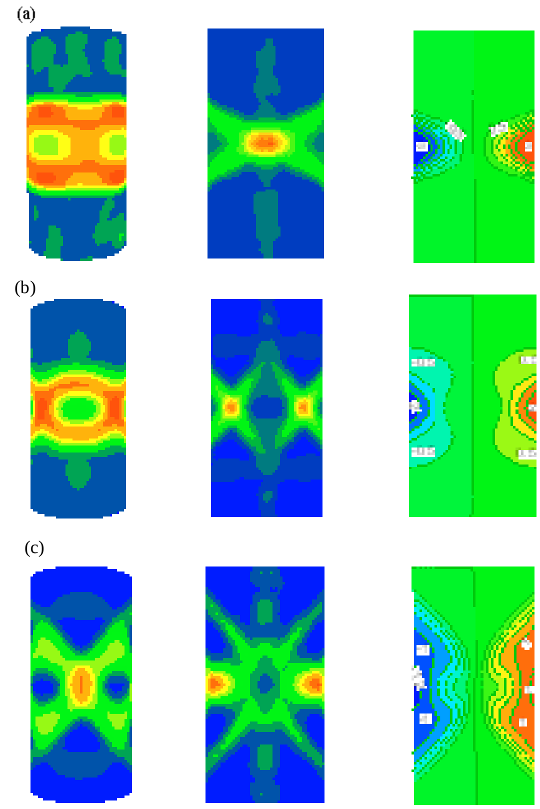

Fig. 3(a-c): Shear bands and horizontal displacement distributions of combined body under different models, (a) Linear elastic model, (b) Mohr-coulomb model and (c) Strain-softening model

Characteristics of the complete stress-strain curve under different confining pressures: Figure 4b illustrates different stress-stain curves under changing confining pressures when coal seam thickness is 30 mm. The peak strength increases with the increasing of confining pressures. When confining pressure increases to a certain degree, stress-strain curve will not enter into strain-softening stage but turn into ideal plastic step instead, such as the curve which shows full plastic deformation characteristic under high confining pressure $\sigma_2 = \sigma_3 = 13$ Mpa.

Effect of thickness of coal seam on damage rate of the composed sample: Changes of the deformation rate of shear band with the increasing of thickness of coal seam are shown in Fig. 4c. When the coal seam becomes thickening, developing rate of shear strain will increase which is especially obvious when the height ratio of coal and rock is greater than 3. Thus, Increasing of coal seam significantly weaken the integral strength of the composed coal rock.

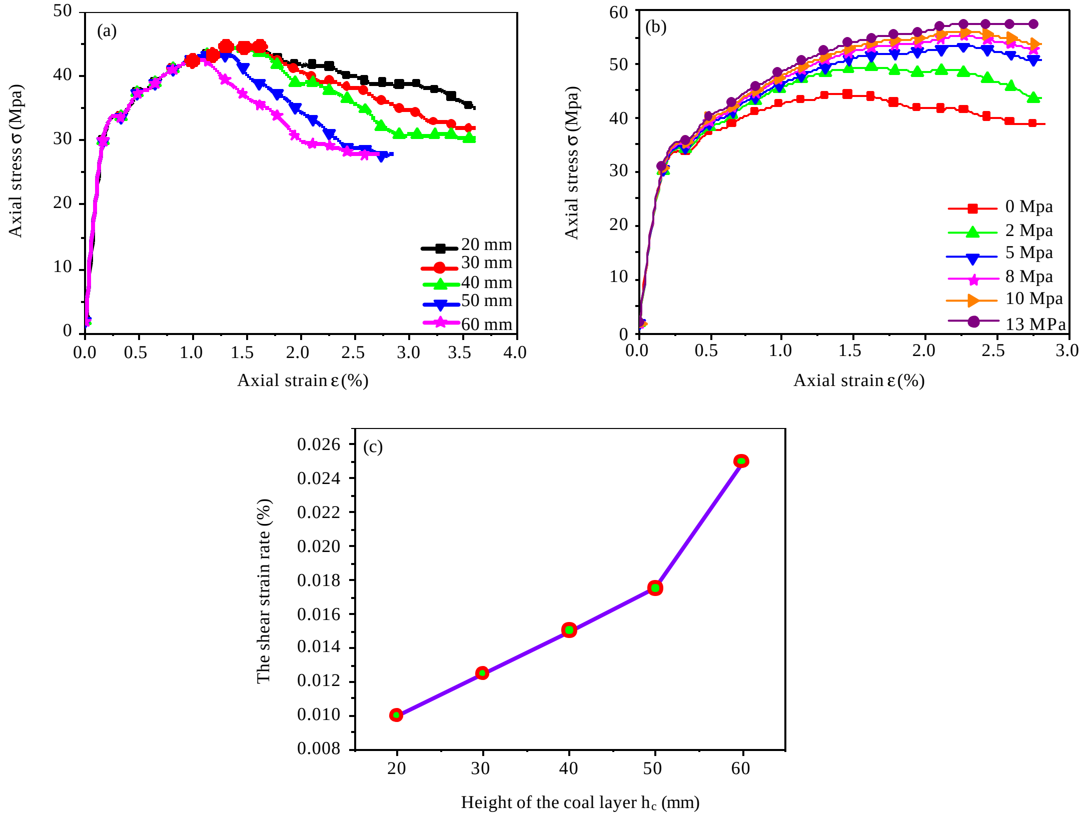

Fig. 4(a-c): (a) Effect of height of coal on complete stress-strain curve, (b) Effect of confining pressure on complete stress-strain curve and (c) Effect of height of coal on shear strain rate

Fracture evolution analysis of composed coal rock under tri-axial compression: Figure 5a shows the complete stress-strain curve of the model when thickness of coal seam is 30 mm and the confining pressure is s_2 = s_3 = 2 Mpa. In order to clearly analyze the failure process, the curve is divided into 5 stages and contour figures as shown in Fig. 5b (three-dimensional and surface slice figure) of shear strain rate are extracted from the corresponding load steps marked in the curve. The development of shear bands in combined model under different steps is analyzed as follows:

Step 1: Elastic stage OA(step 38): The shear strain rate field is uniform. As the model is still in elastic stage, no plastic deformation occurs

Step 2: Strain hardening stage AB(step 120): The shear strain rate in coal seam is increased, but the distribution is still uniform; Peak point B(step 207): The shear strain rate changes very little and shear zone is not found in the model

Step 3: Post-peak stage BC(step 280, step357): The model shows strain-softening behavior and the shear strain rate changes significantly which result in diminishing of elastic region. Regions of the coal seam and rock near the interface show strain localization although no obvious shear band appears

Step 4: Post-peak stage CD(step 500, step 765): The stress-strain curve is fluctuating and the shear strain rate on both sides of the contact surface has become very non-uniform. The length of shear zones increases gradually which extend to soft rock. X reticular form of shear bands is formed in step 765

Step 5: Post-peak stage DE(step 1000, step 1287): The shear bands are further developed in this stage and become relatively stable until step 1287 which has no changes with the increasing of strain. The composed coal rock is completely destroyed along the shear bands

Obviously, no apparent shear zone appears in the combined sample when the sample reaches to peak strength. At the first decent stage of post-peak curve, obvious strain localization of coal layer and soft rock near the interface appear and the shear strain rate increases

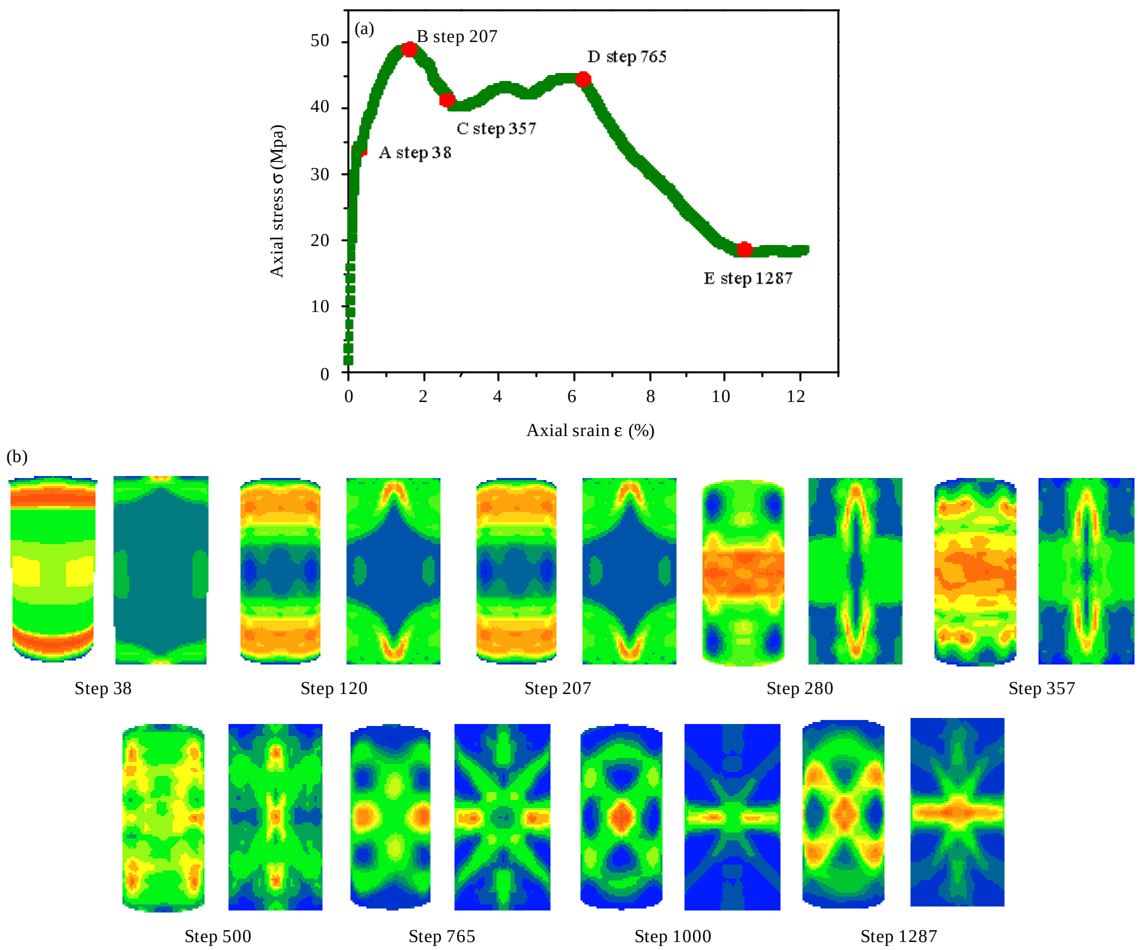

Fig. 5(a-b): Damage evolution process of the combined model, (a) Complete stress-strain curve of combined model and (b) Development of shear bands in combined model under different load steps according to (a)

significant which can be seen as a precursor to the unstable failure of model. The shear bands are mainly developed at fluctuation stage. When the stress decreases again, shear bands gradually become stable which will cause integral failure in the composed sample.

CONCLUSION

In order to predict the failure position and damage stages which provide references for the study of occurrence mechanism of rock burst, the damage evolution law of the three bodies model composed of soft rock and coal with different clamping coal thickness were established by fast Lagrangian explicit-finite-difference code of continua. Some conclusions are obtained from the simulation analysis as following:

- Three bodies model composed of soft rock, coal and soft rock shows obvious behavior of strain softening. Thus, the strain softening model is more suitable for its post-peak failure behavior compared with Mohr-coulomb model
- The thicker the thickness of coal seam, strain-softening branch of stress-strain curve of the model become more steep which will cause the peak strength of the combined sample decreasing and energy consumption capacity of coal seam diminishing and resulting in coal burst
- Deformation is developed towards the ideal elastoplastic state with the increasing of confining pressure. Shear bands are reduced and become uniform in plastic region. Thickening of coal seam will accelerate the integral damage failure

- At the first decent stage of post-peak curve, obvious strain localization of coal layer and soft rock near the interface appear which can be regarded as the starting stage of the integral failure. The shear bands are mainly developed at fluctuation stage

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