NUMERICAL STUDY OF LIGNITE SAMPLES FRACTURE UNDER COMPLEX LOADING CONDITIONS

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Keywords: simulation, constrained boundary conditions, lignite fracture.

Abstract. Using the computer simulation the real loading conditions around the coal-bed deep under the surface was reproduced. The calculations were done on the basis of the method of Movable Cellular Automata (MCA). According to the results of simulations the mechanism of fracture of lignite lithotypes can changes from typically brittle to degradation-like or quasi-plastic depending on boundary conditions. Also the influence of loading conditions on fracture process was shown. Obtained results are in good agreement with experimental data. It shows that MCA method can be successfully applied for investigation of behavior and fracture of various heterogeneous media under standard test conditions as well as under very complex loading that is very difficult or impossible to reproduce using experimental procedures

Introduction

Lignite is known as a soft brown coal and is an intermediate stage between peat and coal. Lignite is highly heterogeneous [1 – 3]. It is impossible to study the mechanical behavior of lignite but rather its mechanical behavior in relation to a given structure. The heterogeneities and anisotropies of lithotypes strongly influence the mechanical and behavioral characteristics of lignite. This fact provokes a more or less large standard deviation with respect to the average value of the characteristics.

Usually the standard compression test procedure is used to analyze the mechanical properties of the lignite. This test includes loading with constant velocity and cyclic loading [4] and allows one to determinate strength, ultimate strain, elastic module and other physical and mechanical properties of the lignite. In addition, it is possible to study the fracturing character and fragmentation of lignite specimen after crushing. At the same time, lignite in real coal beds is under very complex loading [5]. For example at a depth of a coal-bed, each lignite volume is under conditions that are very close to comprehensive compression. Stress-strain state of lignite close to underground roadways is also very complex. Loading conditions include elements of compression, tension, bending, shearing, rupturing and other type of influence or combination of them. Obviously, it is difficult to reproduce such complex loading within the experimental conditions. Methods of computer simulations can be considered as a useful tool to analyze the influence of various loading on sample's mechanical properties and predict the direction of further investigations with the aim to find certain correlations.

In the paper we use the method of discrete approach named as a method of movable cellular automata (MCA). In the framework of the MCA method, we consider the simulated media as an ensemble of interacting finite size elements (automata) [6, 7]. The concept of the MCA method bases on the introduction of a new type of states, viz., the state of a pair of automata, in comparison to conventional cellular automata method. In the simplest case, there are two states of the pair:

linked and unlinked. The linked state is indicative for chemical bonds between elements and the unlinked state indicates that there is no chemical bond between automata (particles). Using various criteria for linked-unlinked switching, the direct simulation of such complicated processes as discontinuity formation, accumulation of damage, cracks generation and extension as well as processes connected with mass mixing is possible. Previously, the MCA method was successfully used for the investigation of features of deformation, damages accumulation and fracture of various heterogeneous materials like concrete [6], porous ceramics [8], composite materials [9], interface materials like geological media [10, 11] and other.
Therefore, the objective of this paper is to investigate the influence of constrained boundary conditions on response and fracture of brittle lignite specimens under uniaxial compression in the framework of numerical modeling.

Numerical model of constrained boundary conditions
The typical setup for carrying out the compression test with constrained boundary conditions is shown in the Fig.1. Uniaxial compression of the specimen was set by piston downward movement with constant velocity $V = 10$ m/s. From the bottom side, the specimen is fixed by unmovable supporting plate. The left and right unmovable walls impede the specimen widening during loading. Intermediate particles, that are located between external surfaces of the specimen and unmovable walls, imitate the real surroundings. According to the Fig1b, where linked pairs shown by lines between automata centers, the specimen was not linked to any surrounding particles of the setup. Parameters of response function in pair of interacting automata of the sample were fitted to the mechanical properties of lignite.

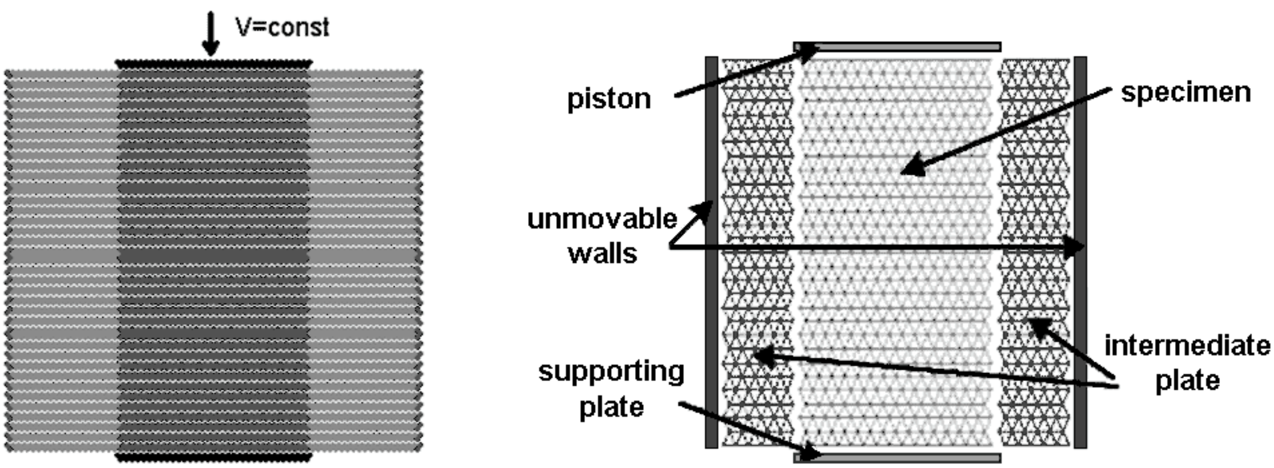
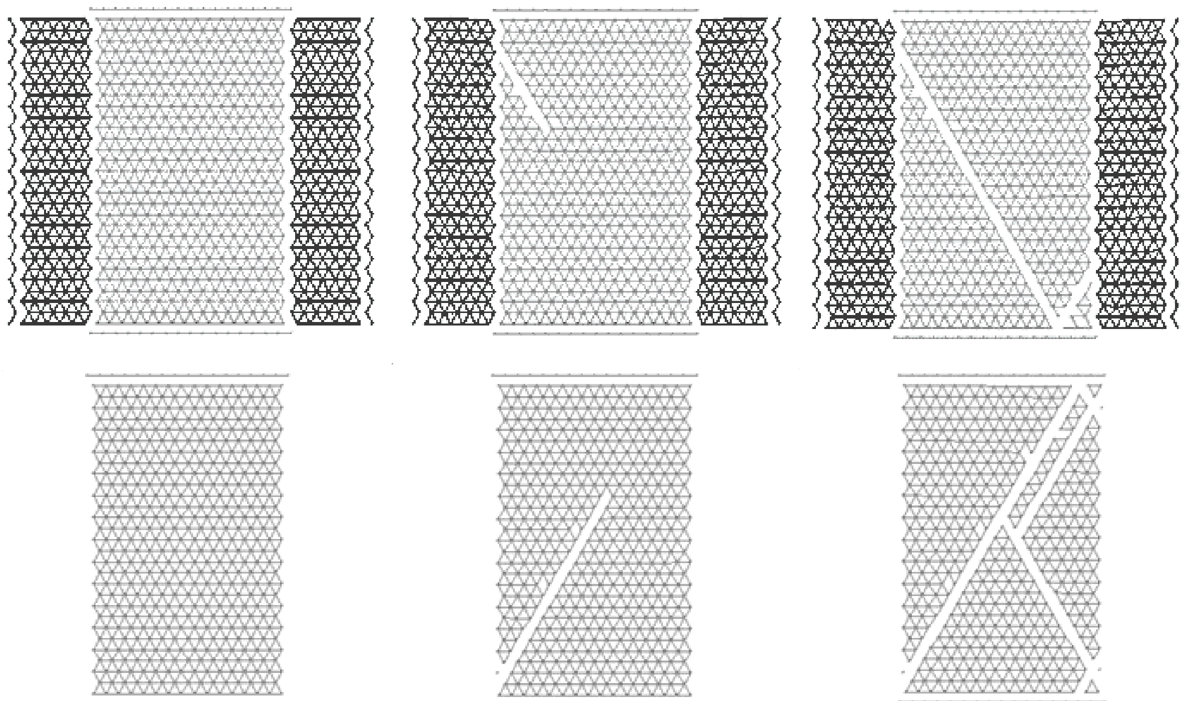


Fig. 1. Structure (a) and inter-automata bonds system (b) of the setup.

Results of simulations
Calculation results show that the response of a specimen under constrained conditions depends strongly on the state and properties of surroundings (intermediate particles). Below, the results of the test series with various values of the particles material elastic modulus E_p in the interval 50 MPa ÷ 900MPa are presented. Young modulus (E_{sp}) of the specimen material was equal to 200 MPa at all the tests. The regular compression test for the specimen with free external surfaces (in the absence of the particles and unmovable walls) was made also.
The following three types of tested specimen fracture were marked out.

Typically brittle fracture. Typically brittle fracture was observed for samples with material elastic modulus E_p between 0 and $0.4{*}E_{sp}$. It is characterized by macro-crack formation on one of the free external surfaces and its extension through the specimen with high velocity (up to one km/s). Fig.2a shows the evolution of the specimen with mechanically constrained external surfaces at E_p = 0.25*E_{sp}. It can be seen that macro-crack is initiated on of external surfaces of the specimen and extends through the material with high velocity (about one km/s). This macro-crack divides the specimen on couple of parts. Similar type of fracture is typical for all the specimens with mechanically constrained external surfaces at small values of elastic modulus of the particles (E_p < 0.4*E_{sp}).



a)

b)

Fig. 2. Structure evolution under uniaxial compression: a) E_p = 0.25*E_{sp}; b) free surfaces

Fig.2b shows the evolution of the specimen with free external surfaces. Comparison of the results presented in the Fig.2a and Fig.2b shows that fracture features of weakly constrained specimens and specimens with free external surfaces are very similar (typically brittle fracture).

Transition regime of the fracture. The fracture of setups with E_p belongs to the range between 0.4*E_{sp} and E_{sp} characterized by generation of numerous meso-cracks and single meso-damages before macro-crack initiates and extends. To illustrate this fact, Fig.3 shows the evolution of the specimen with mechanically constrained external surfaces at E_p = 0.4*E_{sp}. It can be seen that first, a numerous meso-cracks initiate at the external surfaces of the specimen. The meso-cracks mean the underdeveloped macro-cracks because each of them tends to become a diagonal macro-crack. However, due to mechanical constraint of external surfaces, these meso-cracks were stopped. At the same time, single meso-damages were initiated inside the specimen. Nevertheless, the stiffness of constraining parts is not high enough to prevent material from diagonal macro-crack development, which is initiated with loading increase and divides the specimen into two main fragments.
The following changes in specimen response take place with E_p increase:

a) macro-crack extension velocity considerably falls (up to 20 times);
b) number of meso-damages is increased before macro-crack initiation;
c) number and average length of meso-cracks decrease before macro-crack initiation.

Nevertheless, in this interval of E_p percentage of meso-damages is small (<15%), and fracture of specimens is typically brittle (Fig.3).

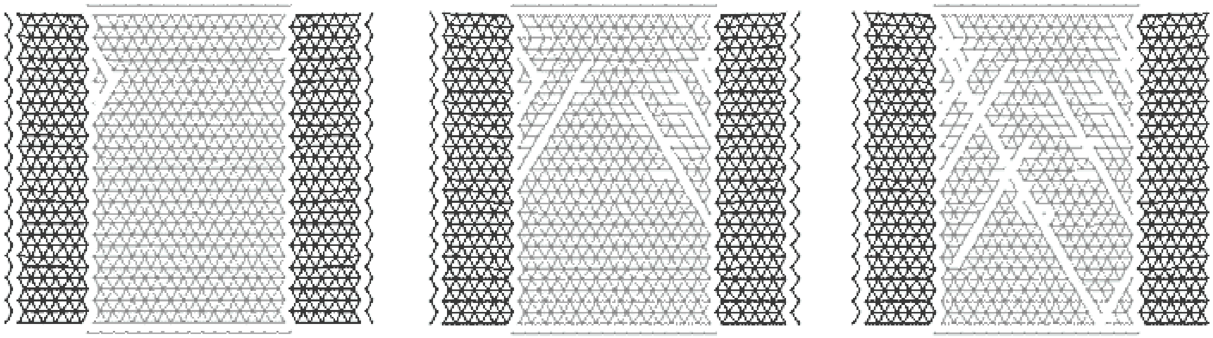
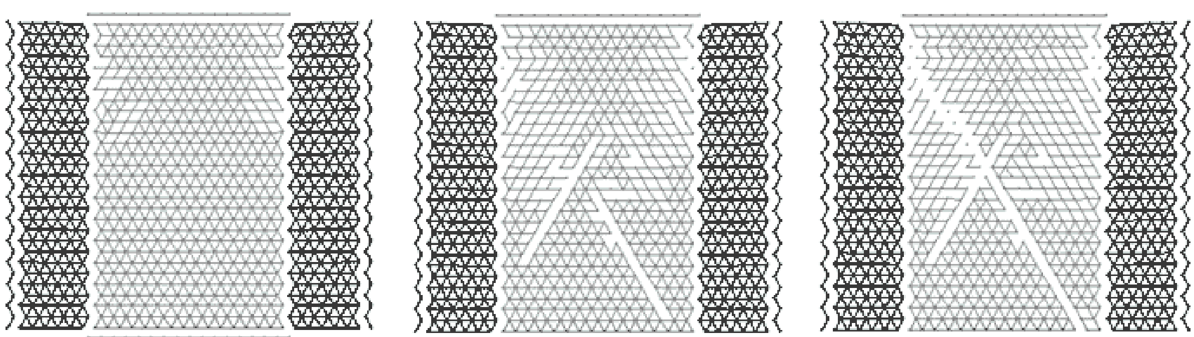


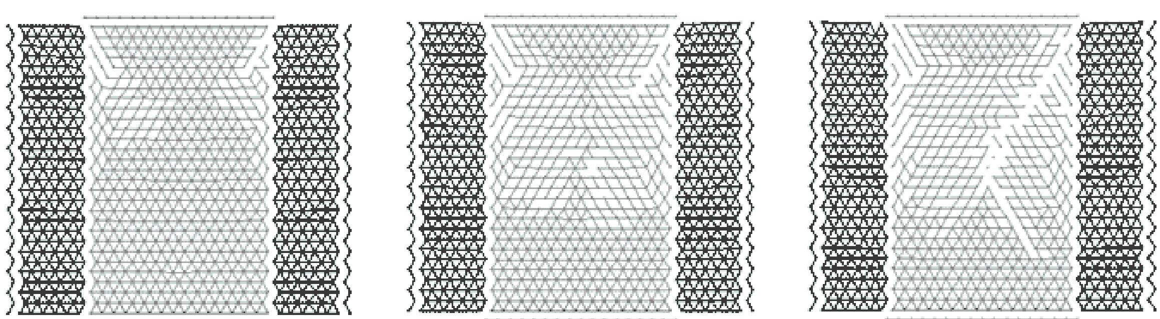
Fig. 3. Evolution of mechanically constrained brittle specimens ($E_p = 0.4*E_{sp}$).

"Degradation" type of the fracture ($E_p \geq E_{sp}$). The fracture of setups with elastic modulus E_p higher than E_{sp} can be named as "degradation". It is characterized by the presence of two strongly pronounced stages of fracture. Relaxation of local stresses in material on the first stage is realized by meso-damage areas formation and expansion. On the second stage, the macro-cracks gradually grow through the damage areas.

Fig.4a,b show the evolution of loaded specimens at $E_p = E_{sp}$ and $E_p = 4.5*E_{sp}$. It can be seen that extensive meso-damage areas are initiated near the external surfaces. During loading increase, these areas expand down and toward the interior of the specimen. Expansion velocity of damage areas depend on specimen deformation rate and in the first approximation this dependence can be considered as linear. On later stage of deformation, interior cracks are initiated in damage areas. These cracks can grow to the specimen surfaces and become macro-cracks.



a)



b)

Fig. 4. Evolution of mechanically constrained brittle specimens a) $E_p = E_{sp}$; b) $E_p = 4.5*E_{sp}$

It has to be noted that the velocity of macro-crack extension is $50 \div 100$ times lower than crack growth velocity during typically brittle fracture of specimens with free external surfaces. It is connected with the fact that under the degradation fracture regime the macro-cracks grow through the areas with large percentage of meso-damages, where local stresses are partially relaxed.

Compression test of lignite lithotypes

The next step of a numerical study was connected with investigation of different lignite samples behavior under loading conditions. The given automaton size with corresponding mechanical properties for each component was used. Lignite samples of two different categories (according to the classification adopted by the Velenje coal mine) were generated [3]. Fig. 5 shows the loading diagrams for samples of fine detritus and xylite.

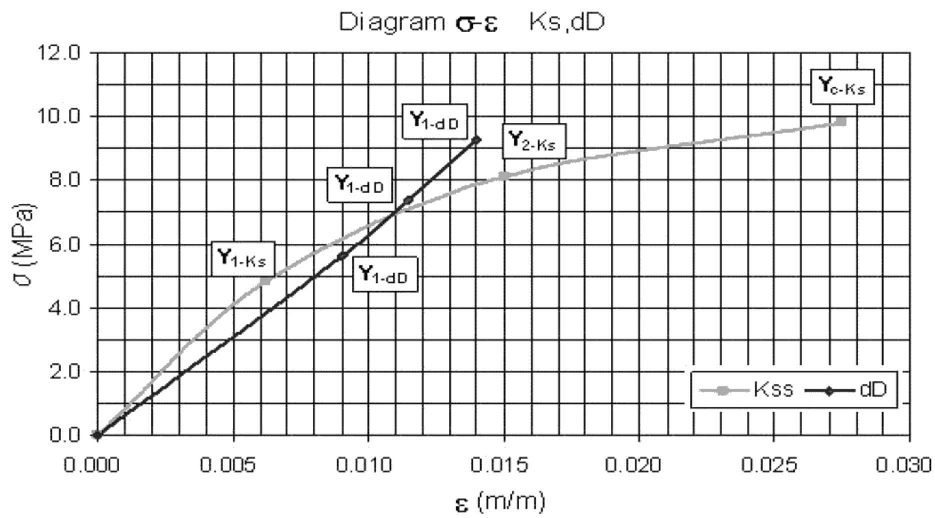


Fig. 5. Loading diagram for modeled materials with indication of characteristic points

Fine detritus (dD). Fine detritus consists of a very small plant fragments with sizes up to 1 cm. In terms of composition and structure dD is the most homogenous lignite component. It's characterized by strong fragmentation during fracture and destruction in air. Figure 6 shows the resulting structure of the fine detritus samples under uniaxial loading with use of constrained boundaries conditions. In tasks the value of modulus of elasticity of movable automata that define the boundary walls were varied. According to the results of modeling increasing of modulus of elasticity leads to multiple cracking of the sample of fine detritus in the area near the piston. Note that such behavior was also observed for the isotropic model coal sample which described above and shown in Figures 3 and 4. It is possible to see the changing the fracture pattern from typical brittle to quasi-plastic. This dependence also shows the resulting loading curves (Fig. 6).

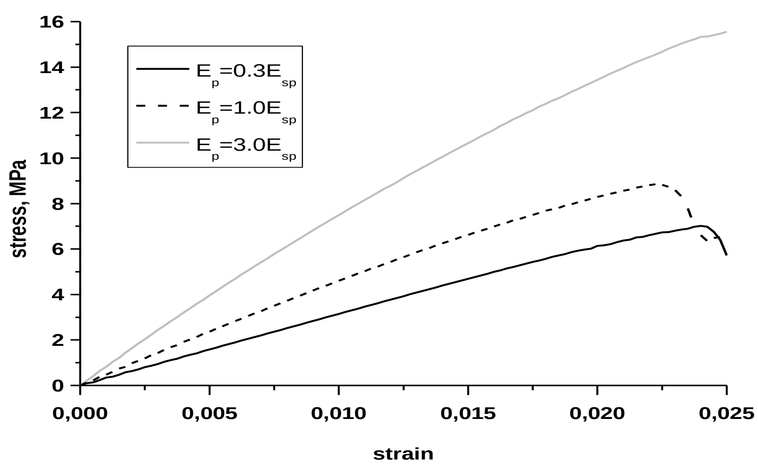
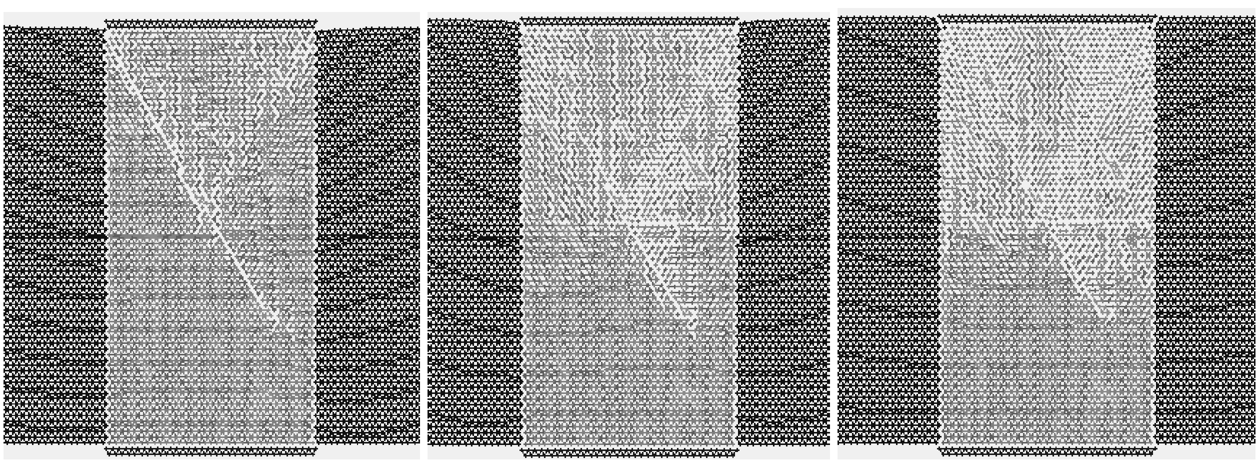


Fig. 5. Loading diagram for fine detritus samples with different degree of lateral constraint

Xylite (Kss). Xylite is the most anisotropic component of the lignite. Xylite samples usually contain various fragments of wood of different sizes, types and forms (trunk, branch, stumps). It is also important to take into account the orientation of the fibers with respect to the applied loading, since the response of the sample at this varies considerably. Xylite samples are characterized by the highest value of the strength of lignite components especially in case when the structure of the fibers coincides with the direction of loading. Fig. 7 demonstrates the influence of the value of modulus of elasticity of movable automata that define the boundary walls on the features of fracture of xylite samples. The orientation of the fibers was set at an angle of about 30 degrees to the direction of the external loading. It is possible to see that in contrast to the behavior of fine detritus sample increasing of modulus of elasticity of boundary automata does not lead to multiple fractures at the same deformation value. When the difference in values of elasticity modules is like $E_p = 3.0*E_{sp}$ the formation of a few single damages in the contact area of xylite sample with the piston is observed. According to the simulation the greatest number of damages is generated in case where the values of elasticity modules are similar ($E_p = 1.0*E_{sp}$). In this case, after a certain deformation of the sample, there is braking of interautomata links at the top of the sample, which is explained by a higher degree of lateral restraint compared with the case where $E_p = 0.3*E_{sp}$ (Fig. 7a). Nevertheless, the degree of lateral constraint of the sample is not enough for further resistance of xylite sample and the main crack is generated. The orientation of the main crack is coincides with the direction of the fiber structure.

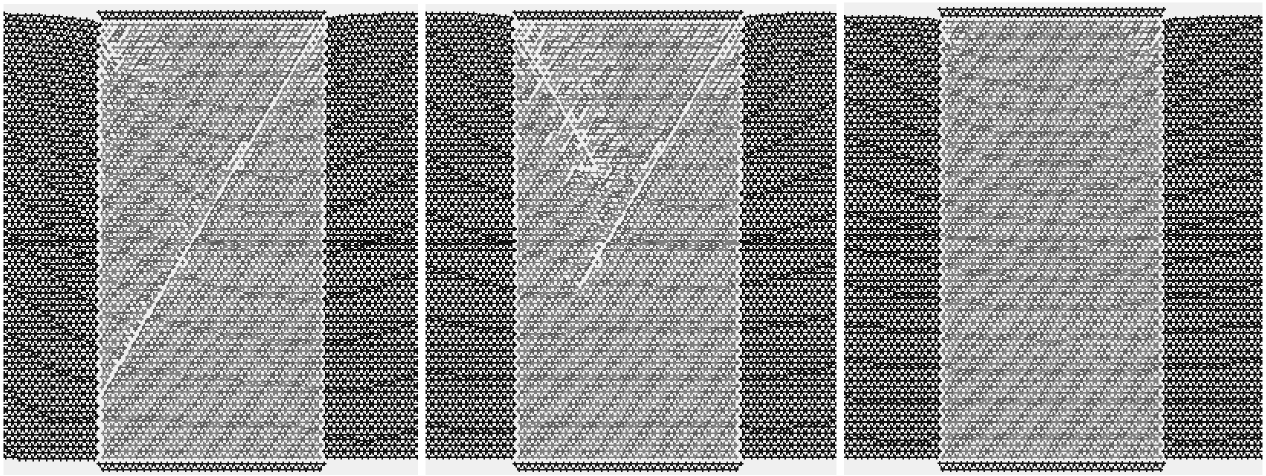


a) b) c)

Fig. 6. Resulting structure of fine detritus sample under uniaxial loading with use of constrained boundary elements of different hardness: a) $E_p = 0.3*E_{sp}$, a) $E_p = 1.0*E_{sp}$ and c) $E_p = 3.0*E_{sp}$.

The difference in the nature of the damages which were generated during loading stage is the cause of the peculiarities of behavior of the studied lithotypes in the simulation of various types of unloading. Since the destruction of the sample of fine detritus realized by the removal of one boundary wall while maintaining the vertical stress is accompanied by formation of a large number of small fragments. This type of behavior is the greatest danger in the development of coal-beds, as the multiple fragmentation of rock fracture is accompanied by a sudden outburst of different gases stored in gas-saturated rocks. In turn, the destruction of xylite sample is accompanied only by his cracking unit at sufficiently large fragments and does not pose a great danger of emission of gaseous mixtures, but only as a possible collapse of the walls of underground tunnels.

Based on the simulation results it is also possible to specify the conditions (the value of the stress, the depth, properties of the material environment) in which the destruction of this or any other component of lignite will represent the greatest danger.



a) b) c)

Fig. 7. Resulting structure of xylite sample under uniaxial loading with use of constrained boundary elements of different hardness: a) $E_p = 0.3*E_{sp}$, a) $E_p = 1.0*E_{sp}$ and c) $E_p = 3.0*E_{sp}$.

Summary

The results of modeling show that depending on components proportion the lignite demonstrates various types of behavior from brittle to quasi-plastic. These results are in good agreement with experimental data. It is necessary to note that several analogous computer-aided test series were made for specimens with various height-width ratios as well as various spatial distributions of mechanical properties in the material. In all the cases results of calculations show the change of fracture mechanism from typically brittle to degradation with E_p increase.

One of the main results is that the investigation of strength strain properties and features of lignite fracture based on standard procedures like compression or Brazilian test [12] is insufficient for understanding of lignite behavior in real bedding conditions. This fact means that conventional set of standard tests can be supplemented with other experiments that allow investigation of lignite response features at a depth of coal-bed as well as near the roadway roof and walls. As an example, the compression test for the cylinder, mechanically constrained by jacket with variable stiffness, can be proposed.

Comparing the results of modeling with experimental data [3] it is possible to say that the MCA method can be successfully applied for the investigation of lignite response and fracture under loading conditions of standard test as well as under very complex loading like in real coal-beds.

Acknowledgement

This work was partly supported by the integrated project No. 99 of SB RAS.

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