

Numerical Assessment of the Anisotropic Strengths of a Utah Coal considering the Spatial Characteristics of Discontinuities using Discrete Fracture Networks

Kim, B. H.

Mine Safety Branch, SMRD, NIOSH, CDC, 315 E Montgomery Avenue, Spokane WA 99207 USA

Larson, M. K.

Mine Safety Branch, SMRD, NIOSH, CDC, 315 E Montgomery Avenue, Spokane WA 99207 USA

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ABSTRACT: In this study, 3DEC modeling in conjunction with the Discrete Fracture Networks (DFNs) technique was performed to better understand the true anisotropic behavior of the specimens acquired from a bump-prone underground coal mine. The spatial characteristics of the discontinuities (i.e., cleats and bedding planes) as input data for the 3DEC model are estimated based on the results of the laboratory tests and field observations. The DFNs explicitly generated the coal seam that was poorly or well cleated, indicating the different spacing between cleat apertures using the probability distribution functions on fracture density (or frequency) and size. The heterogeneity of the engineering properties (i.e., cohesion and tensile strength) are also considered by Monte Carlo simulations. As a result, the 3DEC model and DFNs technique demonstrated that the results of the simulations agreed well with the results of the laboratory test. These calibrated results can be used as we seek to evaluate bump risk by modeling at field scale.

1. INTRODUCTION

U.S. underground coal mines reported 25,171 accidents related to ground control between 2000 and 2019. Of these accidents, 158 involved fatalities or resulted in permanent or total disability [1]. Although techniques and practices of mining are highly advanced, coal pillar bursts or bumps continue to occur. Many uncertainties remain because of the highly anisotropic characteristics of coal seams that are associated with geologic structure and the mining-induced spatial redistribution of stress in coal pillars [2]. Thus, to prevent fatalities in underground coal mining, continuous efforts are required to better understand the catastrophic failure mechanisms in coal mines.

This paper is developed as part of an effort by the National Institute for Occupational Safety and Health (NIOSH) to identify risk factors associated with bumps in the prevention of fatalities and accidents in highly stressed, bump-prone ground conditions. Kim et al. [3] and Kim et al. [4] characterized the behavior and brittleness of a coal based on the laboratory testing results. They presented that the behavior of coal varied with respect to the angle between the geologic structure (such as cleats) and the loading direction (major principal stress). Kim et al. [4] modified the approach proposed by Kim et al. [5] and Kim and Kaiser [6] to understand how joint persistence affects the overall rock mass strength. They developed a 3DEC

model that randomly generates cleats in the coal seam with various lengths that follow a given degree of persistence. Although the results of the modeling agreed with the observations of the laboratory test, the bedding planes in the coal seam were ignored but were implicitly considered by assigning the equivalent material properties for the bedding planes in the model.

In this study, 3DEC modeling [7] in conjunction with the built-in DFNs technique is performed to better understand the true anisotropic behavior of the specimens acquired from a bump-prone underground coal mine. The spatial characteristics of the discontinuities (i.e., cleats and bedding planes) as input data for the 3DEC model are estimated based on the results of the laboratory tests and field observations. The heterogeneity of the engineering properties (i.e., cohesion and tensile strength) are also considered by Monte Carlo simulations. As a result, the 3DEC model and DFNs technique demonstrated that the results of the simulations agree well with the results of the laboratory test. These calibrated results can be used as we seek to evaluate bump risk by modeling at field scale.

The next section discusses the cleat in coal seams and its impact on the mechanical behavior of coal. Then, Section 3 describes the approach used for the laboratory testing methods, including sample preparation and conditions. Following this description, Section 4 explains the approaches that are appropriate for examining the

strength as a function of orientation between cleat and loading direction and compares these approaches to the analytical and numerical analysis.

2. BACKGROUND AND METHODS – SPATIAL CHARACTERISTICS OF COAL CLEATS

Fractures occur in nearly all coal beds and can exert fundamental control on coal stability, minability, and fluid flow. As illustrated in Fig. 1, cleats are fractures that usually occur in two sets that are, in most instances, mutually perpendicular and also perpendicular to bedding [8].

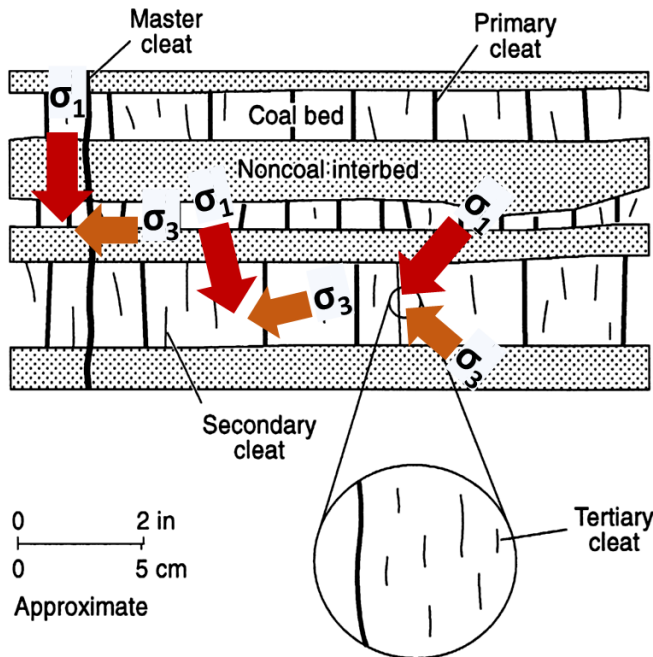


Fig. 1. Cleat hierarchies in cross-section view (after [8]).

Generally, cleat occurs with spacing on a scale of only 1–6 cm. Many researchers have found and reported that the spatial characteristics of cleat in terms of its angle to the principal stress would control not only global strength, but also impact the relative brittleness of the coal. Agapito and Goodrich [9] reported that Western U.S. dynamic failure events are associated with coals that are poorly cleated, indicating wider-than-usual spacing between cleat apertures. Hebblewhite and Galvin [10] noted localized variability in cleat distribution in conjunction with the location of the double fatality coal burst at the Austar mine in Australia in 2014. In addition, the resultant anisotropy would be influenced by the geometric relationship between the direction of mine development and the orientation of in-situ stress. More recently, Kim and Larson [2] found that the cleats play a significant role in determining the anisotropy of strength and brittleness. The results also showed that the numerical specimen exhibited one of the weakest strengths but the most brittle Hoek-Brown constants (m_i) when the cleat was oriented at 30 degrees from the axial loading direction. The arrows

in Fig. 1 indicate that the principal stresses do not always act perpendicular to the cleats plane. Therefore, the included angle between the principal stresses as illustrated by the arrows in Fig. 1 and cleats orientation governs the anisotropic strength and behavior of a coal.

3. UNCONFINED COMPRESSIVE STRENGTH TEST IN THE LABORATORY AND ITS COMPARISON TO BOTH ANALYTICAL AND NUMERICAL ANALYSES

3.1. Sampling and testing method

Kim et al. [4] investigated the anisotropic strength of the Utah coal in the laboratory. The direction of cleating was determined from each coal boulder so that specimens with cleating at 0° , 15° , 30° , and 45° relative to the sample long axis could be obtained. A core drill was mounted on a hand-constructed frame that could support the large coal samples. A large mounting jig was constructed to hold the coal samples in the specific orientations relative to the drilling angle, as shown in Fig. 2. Then, a water-cooled diamond bit was used to core three specimens from each of the four orientations. All samples in this study were cored to an approximate diameter of 44 mm and cut to be within the ASTM (D 4543-08) recommended 2.0 to 2.5 length-to-diameter ratio. The ends of the specimen were ground on a surface grinder to be within the ASTM (D 4543-08) flatness tolerance of 0.025 mm. Specimen end flatness and perpendicularity tolerances were verified using a flatness testing gauge. During the study, 12 unconfined compressive strength (UCS) tests were performed at Montana Tech of the University of Montana. The tests were performed on a TerraTek Model FX-S-33090 closed-loop, digital, servo-controlled load frame. The testing stack consisted of a TerraTek 250-kip load cell to measure force, two impervious end caps, two Schaevitz MHR 500 LVDTs to measure axial displacement, a TerraTek radial cantilever transducer to measure lateral strain, and spherical seats to ensure uniform loading of the specimen. The UCS tests were done in accordance with ASTM (D7012). The UCS test procedures were run under strain rate control with specimens axially loaded at a strain rate of $1 \times 10^{-6}/s$.

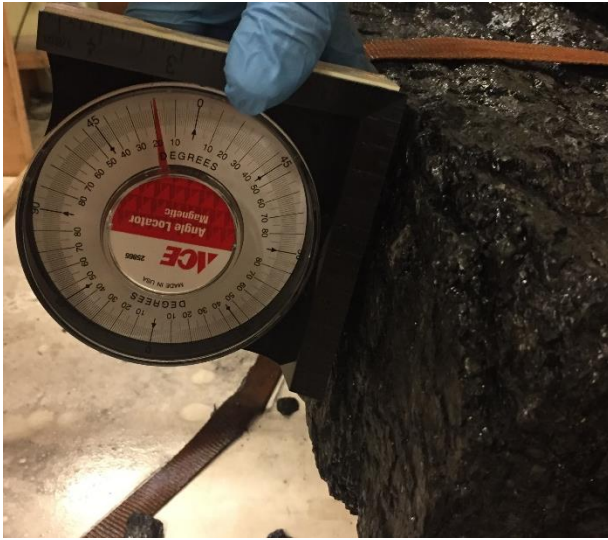


Fig. 2. Preparation of recovering a specimen considering the included angle of 15 degrees.

3.2. Comparison of the results to analytical and numerical solutions

After completion of the UCS test, both the average and standard deviation of the testing results based on each of the three samples are plotted against the cleat orientation. Fig. 3 shows the results of the unconfined compressive strength test where the specimen exhibited one of the weakest strengths when the cleat is oblique at 30 degrees to the loading direction.

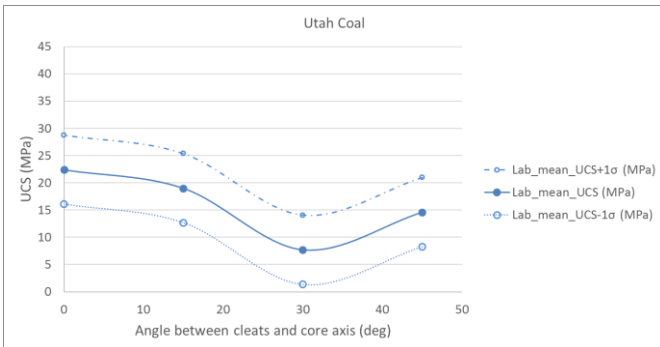


Fig. 3. The results of the unconfined compressive strength test, considering the angle of cleats.

Kim and Larson [11] conducted the FLAC3D modeling to replicate the anisotropic behavior and calibrate with the analytical solution proposed by Jaeger and Cook [12]. Fig. 4 shows the results of the analytical and numerical analyses, superimposed as the average and standard deviation of the testing results. Although the results of both the analytical and numerical approaches corresponded to the testing results well, Kim and Larson found that the results of both the analytical and numerical analyses are located outside the variability of the lab testing at the angle at 15 degrees to the loading direction,.

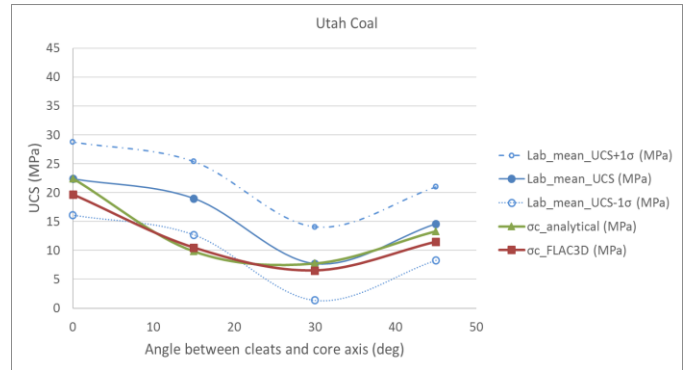
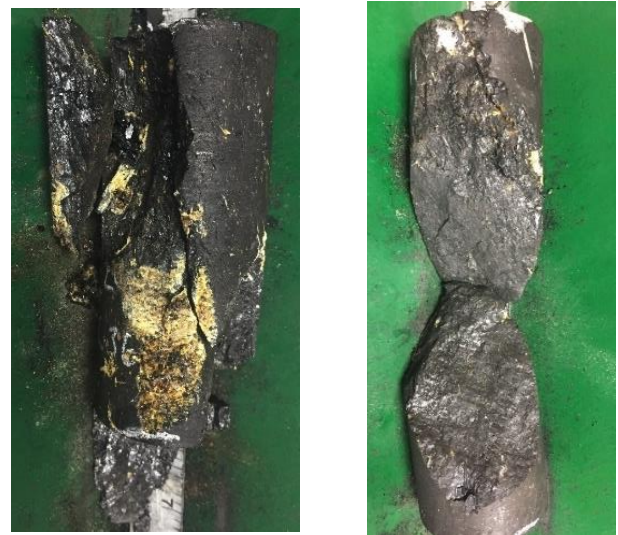


Fig. 4. Comparison of the UCS from the lab testing to the results of the analytical and numerical analyses.

Kim and Larson concluded that this gap comes from not considering the spatial characteristics of the cleats, i.e., persistence of the cleat, since both the analytical and continuum numerical analyses are not able to take persistence into account.

Distinct failure modes are observed after each of the tests, and the photographs are shown in Fig. 5. This figure shows either splitting through the specimen or shearing along the structure in the sample. The sample with 15° of cleat shows fracturing mainly through the matrix, whereas the specimen with 30° of cleat shows failure along the structure.



(a) 15°

(b) 30°

Fig. 5. Examples of the failed coal sample after the unconfined compressive strength: (a) shows the sample with the cleats at 15° to the loading direction; (b) shows the sample with the cleats at 30° to the loading direction.

4. 3DEC SIMULATION OF ROCK MASS STRENGTH AND ITS IMPLEMENTATION CONSIDERING THE ANISOTROPIC COAL STRENGTH

4.1. Background

Fractures usually occupy only a part of the surface extended by the joint plane to a given rock volume. Persistence is the term used to describe the area of extent

or size of a discontinuity within a plane [13]. A rock bridge is defined as a small bridge of intact rock separating coplanar or non-coplanar discontinuities. Persistence estimation can be done by comparing either the sum of the trace length relative to a characteristic length of a collinear scan line or the sum of individual joint surface areas to the surface of a coplanar reference area [14]. Kim et al. [15] investigated the influence of rock bridges on rock mass strength using both statistical analysis and numerical modeling approaches. They developed a user-defined function in UDEC to randomly generate joints with various lengths that follow given joint persistence in the numerical model. Mechanical property degradation of the intact rocks was also considered in the model. Kim and Kaiser [6] conducted a 3DEC modeling experiment that contained joints with different joint persistence. These models were run in order to investigate the influence of the joint persistence on the overall rock mass strength. The results of two models with joint persistence (p) factors of 0.9 (close to 1 means a fully persistent joint, but intact) and 0.1 (close to 0 means no joint) were compared. They found that the behavior of the sample with $p = 0.1$ was very close to 60% of intact rocks. Kim and Larson [11] modified the approach proposed by Kim, et al. [15] and Kim and Kaiser [6]. They replicated the results of the laboratory test for the coal strength with nonpersistent cleats. It was concluded from the study that cleat persistence significantly affected the overall anisotropic strength of coal.

In this study, 3DEC modeling in conjunction with the built-in DFNs technique is performed to better understand the true anisotropic behavior of the specimens acquired from a bump-prone underground coal mine. The spatial characteristics of the discontinuities (i.e., cleats and bedding planes) as input data for the 3DEC model are estimated based on the results of the laboratory tests and field observations.

The different dip angles of the bedding planes are considered to generate the DFNs for the anisotropic coal in a 5-cm \times 5-cm \times 10-cm numerical specimen.

Two sets of models of test samples are presented in this section so that the angles of the mean bedding planes are horizontal and 30° from horizontal—where horizontal is the plane that is perpendicular to the length of the simulated specimen.

The orientations of the cleats and bedding planes are plotted in a stereographic projection as shown in Fig. 6.

The Fisher distribution based on these orientations is taken to generate the DFNs. In order to replicate the cleats and bedding planes that are observed and measured on the coal specimens at laboratory, the Power-law distribution is chosen to determine the sizes of the cleats (0.1 cm \sim 1.0 cm) and the bedding planes (1.0 cm \sim 10.0 cm), respectively.

The generated DFNs are illustrated in Fig. 7. Fig. 7(a) presents the case with an included angle of 0° and Fig. 7(b) shows the case with the included angle of 30°, respectively.

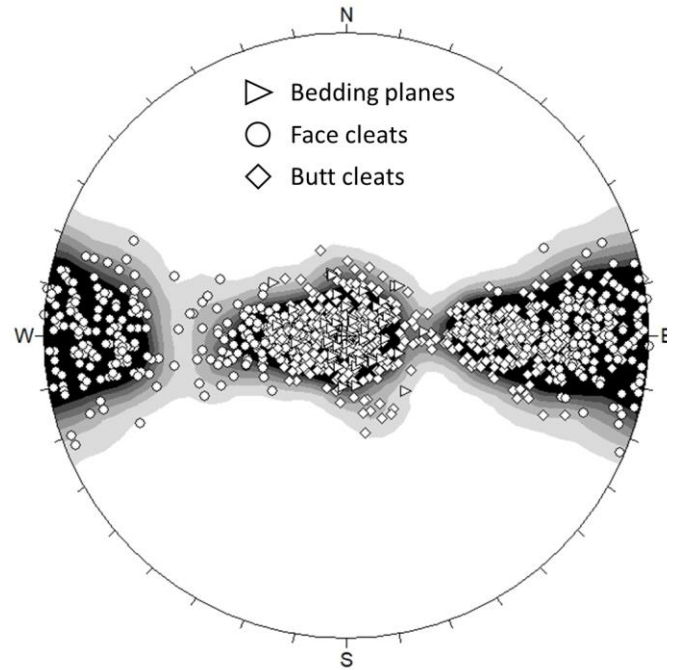


Fig. 6. The orientations of the cleats and bedding planes are plotted in a stereographic projection.

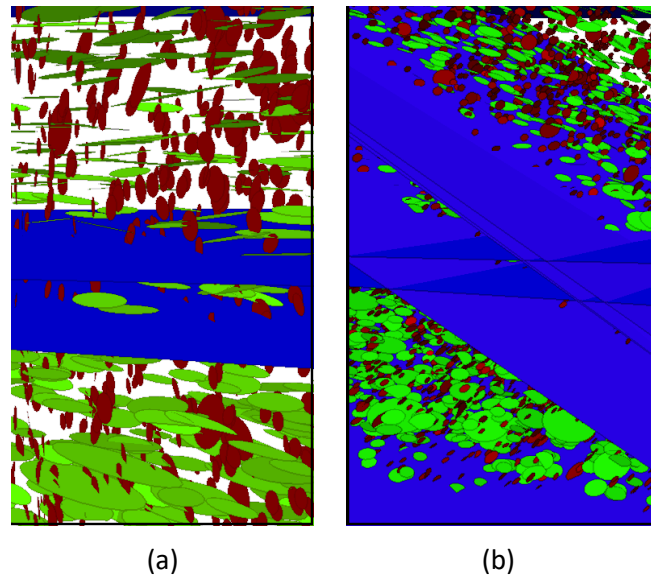


Fig. 7. Face and butt cleats (red and green disks) perpendicular to bedding planes (blue plane) created by the DFNs: (a) horizontal bedding planes and (b) oblique bedding planes.

The heterogeneity of the engineering properties (i.e., cohesion and tensile strength) in the 3DEC models is also considered by Monte Carlo simulations. The heterogeneous strengths can be modeled by populating

the blocks and block contacts of the model with probability distributions. In the 3DEC models, the blocks are defined as elastic and zoned with an approximate edge length of 0.1 m. The built-in Mohr C++ plug-in is used in the models. In order to create the numerical specimens, each block contact is assigned a cohesion and a tensile strength value randomly selected from the probability distributions generated by the Monte Carlo simulation as shown in Fig. 8. The range of the cohesion and the tensile strength is 2.7 ± 1.8 MPa and 0.28 ± 0.19 MPa, respectively. All sub-contacts forming each contact are assigned the same tensile strength and cohesion.

Fig. 9 shows the final outputs after the DFNs and Monte Carlo simulations that are the numerical specimens for an unconfined compression testing in 3DEC to characterize the anisotropic coal strength.

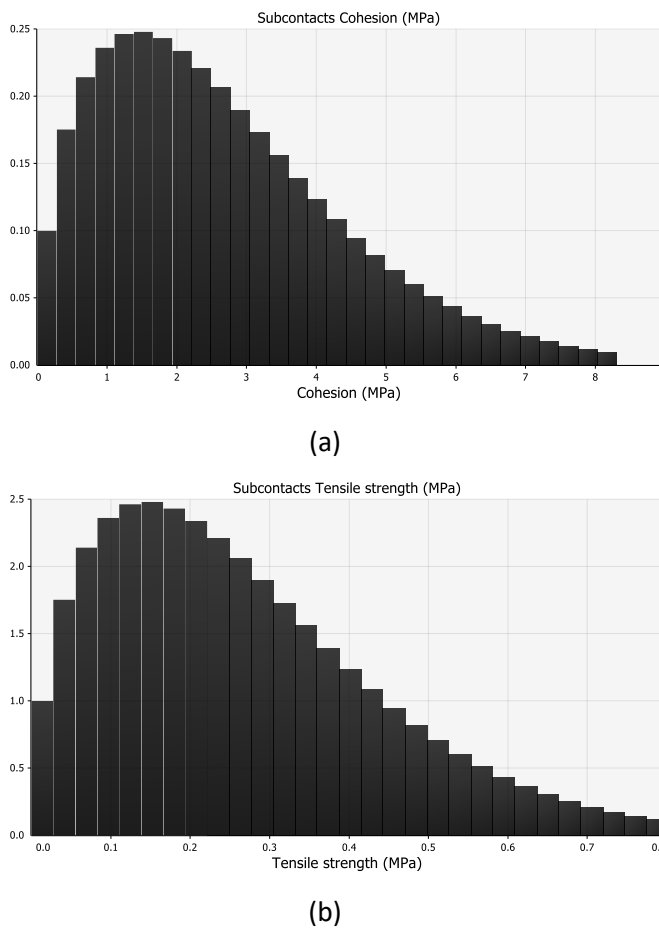


Fig. 8. The probability distributions generated by the Monte Carlo simulation for (a) cohesion and (b) tensile strength.

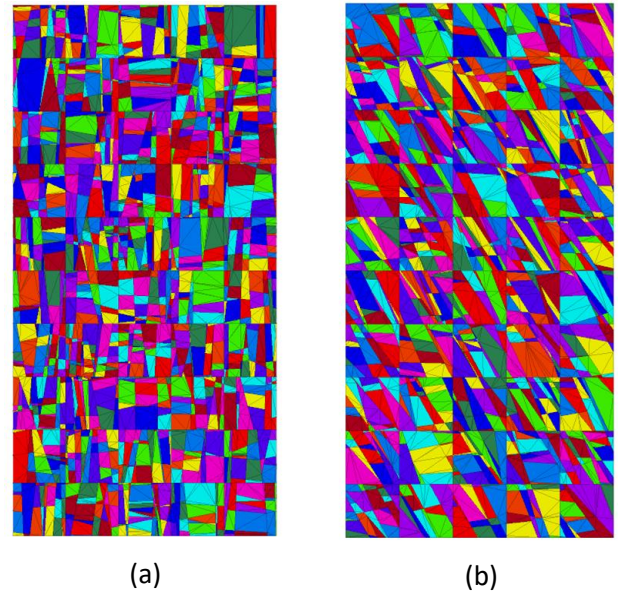


Fig. 9. Prepared numerical specimens in 3DEC using DFNs and Monte Carlo simulations: (a) included angle = 0° and (b) included angle = 30° .

5. RESULTS AND DISCUSSION

The 0° and 30° of the included angles in terms of the geometry of the cleats and bedding planes are considered in the 3DEC model. The material properties on the contacts of the blocks in the 3DEC model are statistically assigned using the FISH function.

The results of the simulation of unconfined compressive strength test are shown in Fig. 11. The change of the strength estimated by the 3DEC model agrees well with the result of the laboratory test. Although it can be found that there is an offset at 15° of the cleat orientation, all results from the 3DEC models are located within the variability of the lab testing results.

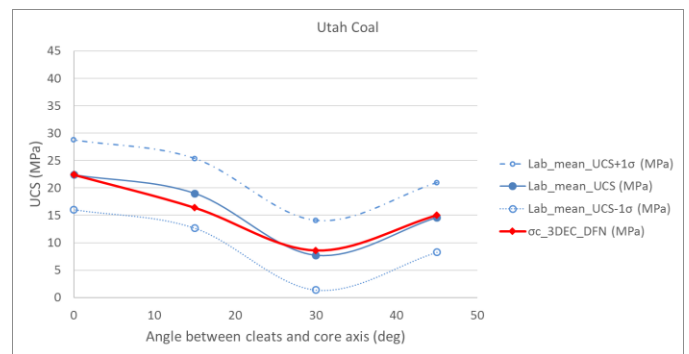


Fig. 10. Comparison of the UCS from the lab testing to the results of the 3DEC simulation.

The comparison of the failure modes in the physical and numerical specimens are shown in Fig. 11. Fig. 11(a) shows the failure in the specimens with the included angle of 0° . The specimens mostly failed by breaking through the matrix of the specimens both in the physical and numerical specimens. Fig. 11(b) presents the failure in the

specimens with the included angle of 30° . The specimens mostly failed by shearing along the plane parallel to the primary cleats and bedding plane both in the physical and numerical specimens.

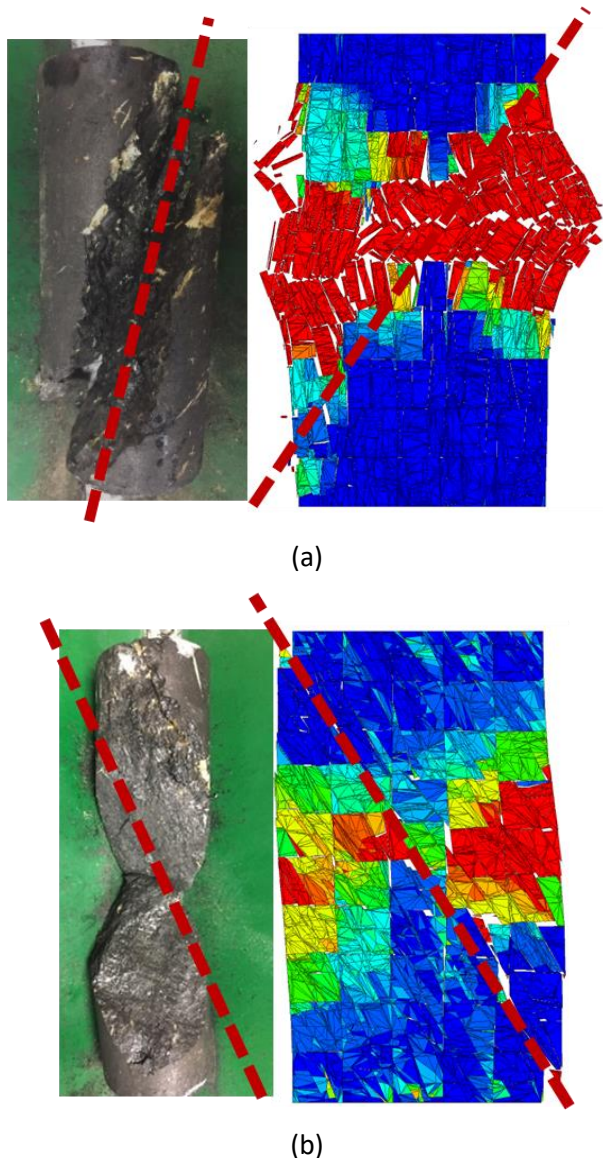


Fig. 11. Comparison of the failure modes in the physical and numerical specimens: (a) included angle = 0° and (b) included angle = 30° .

6. CONCLUDING REMARKS

In this study, coal samples obtained from a Utah coal mine are characterized by conducting 3DEC modeling in conjunction with DFNs simulation. The aim of the analysis is to create an explicit numerical specimen for investigating the influence of cleats and bedding planes on anisotropic coal strength. The spatial characteristics of the discontinuities (i.e., cleats and bedding planes) as input data for the 3DEC model are estimated based on the results of the laboratory tests and field observations. The heterogeneity of the engineering properties (i.e., cohesion

and tensile strength) are also considered by Monte Carlo simulations. The results show that the mechanical characteristics appeared to be highly anisotropic, which is associated with the orientation of cleats and bedding planes. The 3DEC model and DFNs technique demonstrated that the results of the simulations agree well with the results of the laboratory test. These calibrated results can be used as we seek to evaluate bump risk by modeling at field scale for the future research.

Since the coal shows that the mechanical characteristics are highly anisotropic depending on cleats and bedding planes, a better characterization of coal for the design of openings or pillars is a critical step toward improving miner safety with respect to stability of workplaces in underground mines and the prevention of fatalities. Using the proposed methodology beyond identifying rupture potential of coal by means of a rational characterization is an important step to accomplish the eventual elimination of coal pillar bursts or bumps related to worker injuries and fatalities.

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DISCLAIMER

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health. Mention of any company or product does not constitute endorsement by NIOSH.

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