

# Experimental and Numerical Investigation of the Engineering Properties of a Utah Coal Considering the Effect of Anisotropy Due to Cleats

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This paper was prepared for presentation at the 52<sup>nd</sup> US Rock Mechanics / Geomechanics Symposium held in Seattle, Washington, USA, 17-20 June 2018. This paper was selected for presentation at the symposium by an ARMA Technical Program Committee based on a technical and critical review of the paper by a minimum of two technical reviewers. The material, as presented, does not necessarily reflect any position of ARMA, its officers, or members. Electronic reproduction, distribution, or storage of any part of this paper for commercial purposes without the written consent of ARMA is prohibited. Permission to reproduce in print is restricted to an abstract of not more than 200 words; illustrations may not be copied. The abstract must contain conspicuous acknowledgement of where and by whom the paper was presented.

**ABSTRACT:** The catastrophic failure in coal mines, known as bumps, is one of the most challenging engineering problems associated with coal mining in highly stressed conditions. In this study, coal samples obtained from a Utah coal mine are investigated by conducting laboratory tests. However, the results of the unconfined compressive test do not agree with the strength models of the classical strength formula because the strengths at certain orientations of cleats appear much higher than the estimation by the classical solution. The influence of non-persistent cleats on coal strength is, thus, also investigated using a numerical modeling approach. The 3DEC models are developed to randomly generate cleats with various lengths that follow a given degree of persistence in the numerical model. The 3DEC simulation results successfully replicate the results of the laboratory test for the coal strength with non-persistent cleats. It is concluded from the study that cleat persistence significantly affects the overall anisotropic strength of coal.

## 1. INTRODUCTION

Coal pillar bursts, or bumps, remain a most critical safety concern in underground coal mining, despite significant advancements in engineering controls. As shown in Fig. 1, between 1983 and 2014, there were nearly 400 cases of reportable dynamic failure accidents in coal and nonmetal mines, resulting in 20 fatalities, 155 lost-time accidents, and an estimated 48,000 lost man hours [1]. These events have been documented for well over 100 years within the American underground coal mining industry. Over this period of time, mining practices and support technologies have evolved considerably, resulting in an overall decrease in the rate of dynamic failure-related injuries and fatalities. 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 effort is 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

to prevent fatalities and accidents in highly stressed, bump-prone ground conditions.

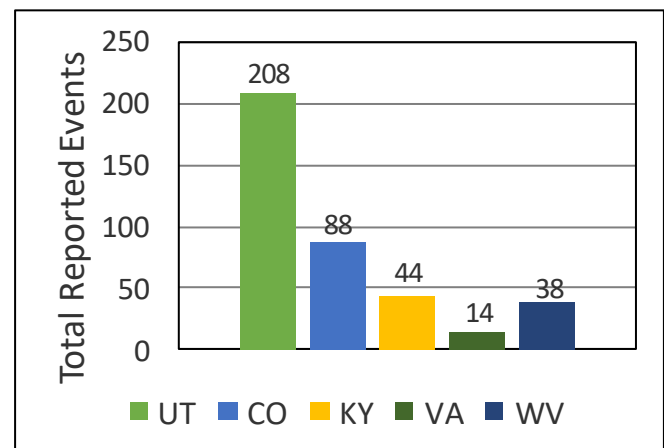


Fig. 1. Overall geographic breakdown of MSHA-reported dynamic failure events, 1983~2014.

In this study, an experimental investigation by laboratory testing is used to characterize the behavior and brittleness of a coal because the behavior of coal varies with respect to the angle between the geologic structure (such as cleat) and the loading direction (major principal stress). Also, in this study, the angle between the cleat and the loading direction is the included angle ( $\alpha$ ). Various values of the included angle are considered as a

testing condition and are used to determine the anisotropic strength.

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. 2, cleats are fractures that usually occur in two sets that are, in most instances, mutually perpendicular and also perpendicular to bedding [3].

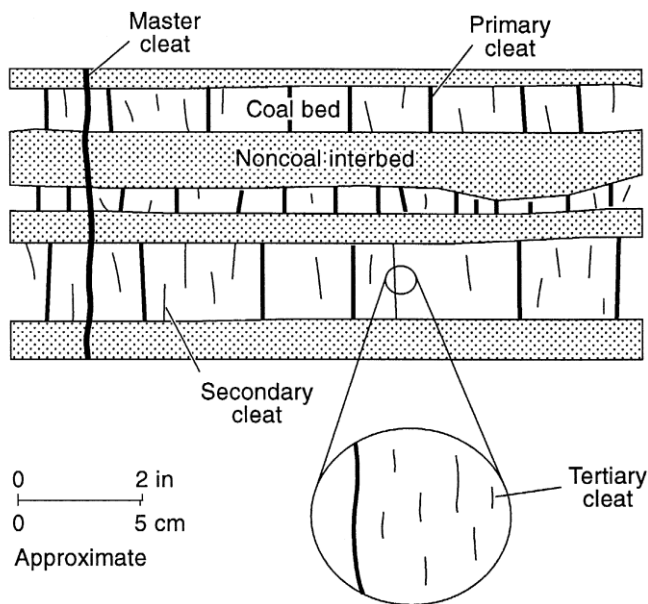


Fig. 2. Cleat hierarchies in cross-section view [3].

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 [4] 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 [5] 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 a significant role in determining anisotropy of strength and brittleness. The results also show that the numerical specimen exhibited one of the weakest strengths but the most brittle Hoek-Brown constants ( $m_i$ ) when the cleat is oriented at 30 degrees from the axial loading direction.

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

### 3.1. Sampling and testing method

For this study, cylindrical specimens were cored from several large Utah coal boulders. The direction of cleating was determined from each coal boulder so that specimens with cleating at  $0^\circ$ ,  $15^\circ$ ,  $30^\circ$ , and  $45^\circ$  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. 3. 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  $1 \times 10^{-6}/s$ .

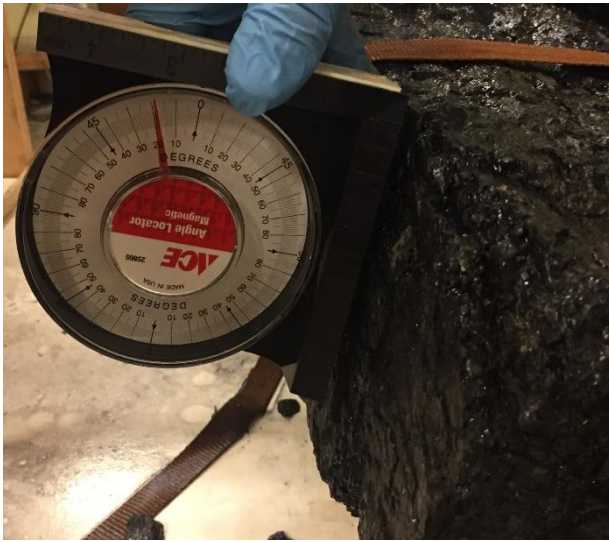


Fig. 3. Preparation of recovering a specimen considering the included angle of 15 degrees.

### 3.2. Comparison of the results to analytical and numerical solutions

After completion of the test, both the average and standard deviation of the testing result based on each of the three sample are plotted against the cleat orientation. Fig. 4 shows the result 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. This agrees well with the results of the recent research by Kim and Larson [2].

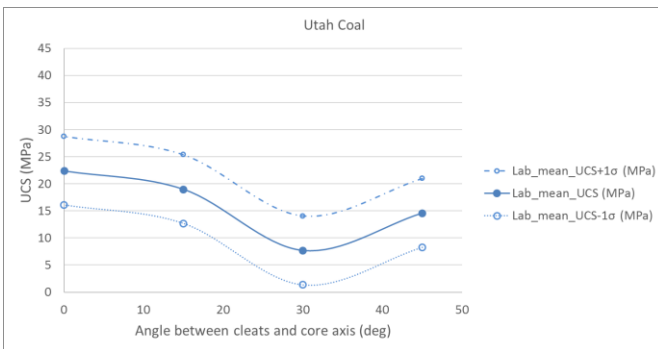


Fig. 4. The result of the unconfined compressive strength test, considering the angle of cleats.

In order to replicate this anisotropic behavior and calibrate with another model, e.g., an analytical or a numerical model, the analytical solution proposed by Jaeger and Cook [6] and numerical modeling using FLAC3D were considered. In the FLAC3D model, the ubiquitous joint model is chosen as the constitutive model to take into account the anisotropic behavior. Fig. 5 shows the results of the analytical and numerical analyses, superimposed as the average and standard deviation of the testing results. In general, the results of both the analytical and numerical approaches correspond to the testing results well, except when the cleat is inclined at 15 degrees to the loading direction. At the

angle at 15 degrees to the loading direction, the results of both the analytical and numerical analyses are located outside the variability of the lab testing.

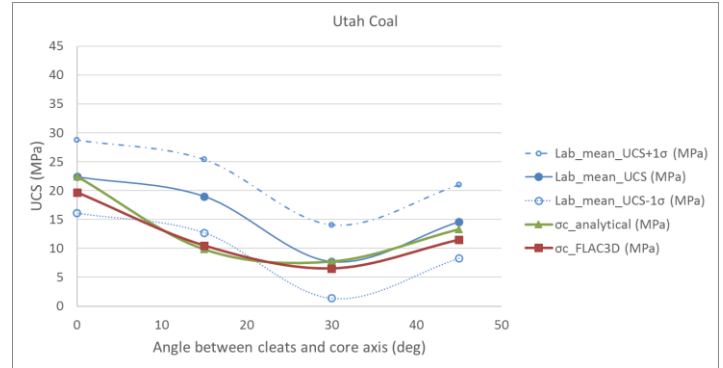
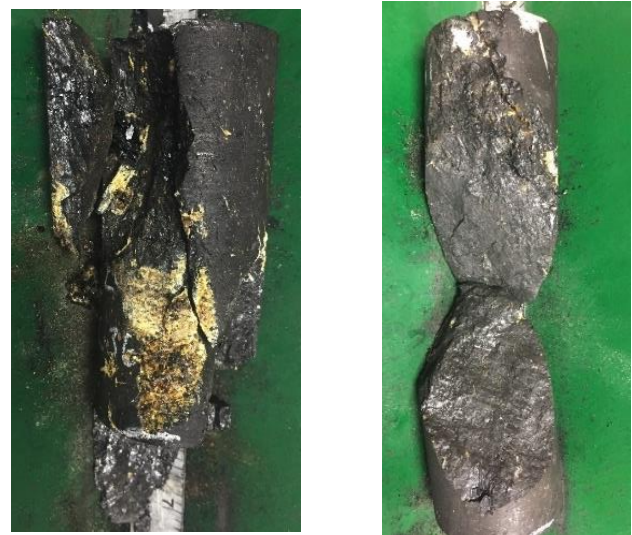


Fig. 5. Comparison of the UCS from the lab testing to the results of the analytical and numerical analyses.

We assume that this gap comes from lack of the consideration for persistence of the cleat since both the analytical and continuum (FLAC3D [7]) numerical analyses are not able to take persistence into account.

The distinct failure modes are observed after each of the tests, and the photographs are shown in Fig. 6. These figure show either splitting through the specimen or shearing along the structure in the sample. The sample with 15° of cleat shows that the matrix mainly breaks whereas the specimen with 30° of cleat shows the structure fails.



(a) 15°

(b) 30°

Fig. 6. Examples of the failed coal sample after the unconfined compressive strength: (a) shows the sample with 15° of cleat; (b) shows the sample with 30° of cleat.

## 4. 3DEC SIMULATION OF ROCK MASS STRENGTH AND ITS IMPLEMENTATION CONSIDERING NON-PERSISTENT JOINTS

### 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 [8]. 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 [9].

Kim et al. [10] 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 [11] 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.

For this study, we modified the approach proposed by Kim et al. [10] and Kim and Kaiser [11]. The aim of this investigation is to understand how joint persistence affects the overall rock mass strength. The 3DEC program [12] was chosen to model uniaxial compressive strength tests of fractured samples with different joint persistence. One has to be aware that there is no direct way to generate very short and isolated joints in 3DEC unless the joint is intersected by a fully persistent joint. However, the short joints can be generated as different material properties are assigned in the model. It is possible that short joints can be represented as a continuous discontinuity with only a specific section of the discontinuity allowed to slip. The ends of the discontinuity are prevented from slipping by setting the frictional resistance to a high value over these regions. This approach has already been verified using some simple examples [12].

#### 4.2. Rock mass strengths with different joint persistence

Material properties are assigned to individual segments of a joint element as illustrated in Fig. 7. For example, if a segment is a joint, then its tensile strength is assigned to zero. If a segment is rock, then the same material properties ( $c$  and  $\phi$ ) as intact rocks are assigned. In addition, both normal and shear joint stiffness for the rock segments are assigned very high values to glue the

joint together. Model calibration was conducted in order to verify this concept in which various persistence of joints are generated by assigning different material properties within a segment of the joint element instead of being generated using explicitly with a joint element in 3DEC.

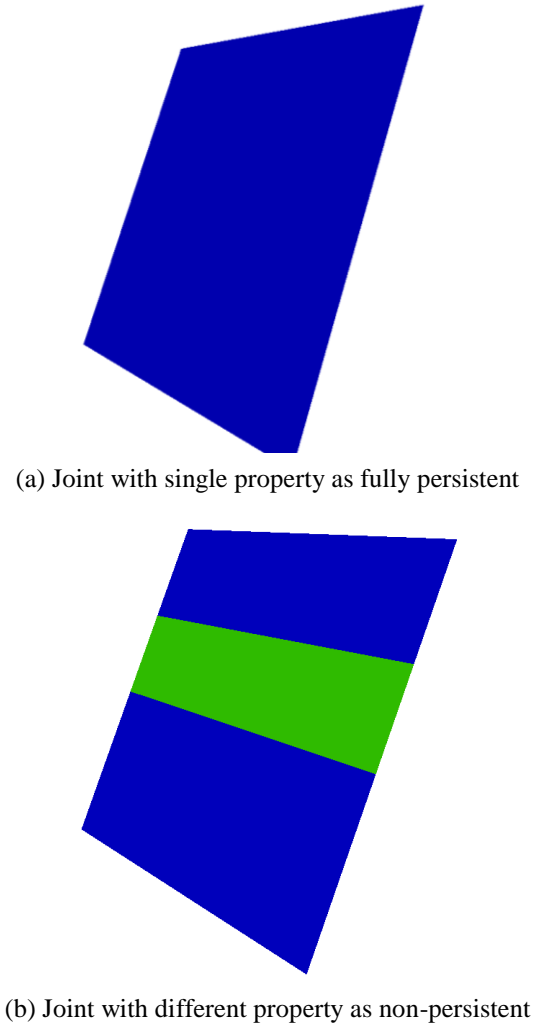


Fig. 7. The 3DEC joint elements considering joint persistence.

Simple models which contain joints with different joint persistences were run in order to investigate the influence of the joint persistence on the overall rock mass strength.

Fig. 8 shows both the stress-strain curves and the curve for 3DEC models embedding joints with different joint persistence by assigning the different material properties on the joint plane. A case with no joint is also simulated to examine an impact of the joint on the intact strength. The influence of the joint persistence on the global strength of the numerical specimens is very obvious. If the joint is not fully persistent, the global strength decreases up to approximately 60% of the intact strength. If the joint is fully persistent, the strength appears as approximately 35% of the intact strength in

this case. Therefore, the joint is possibly and logically able to control a global strength by means of handling the distribution of material properties on the joint plane.

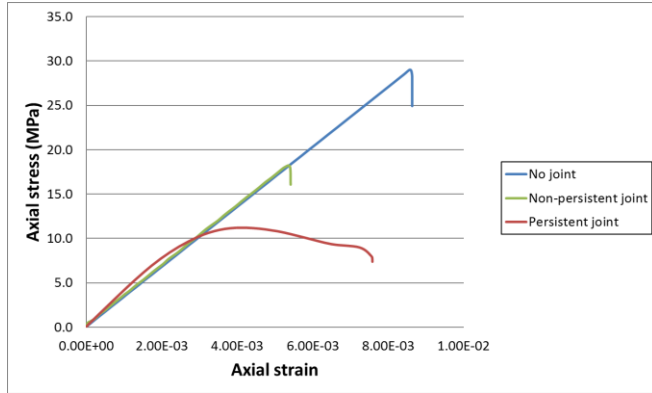
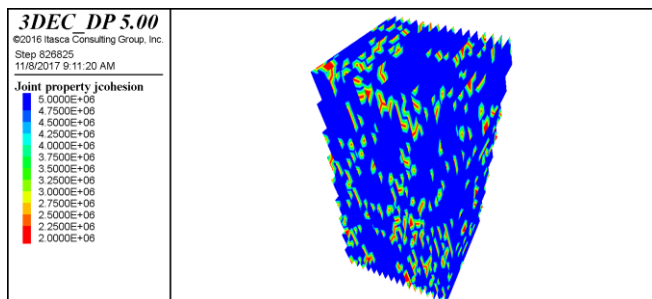


Fig. 8. An example of intact UCS versus UCS considering a joint persistence by means of assigning different material properties.

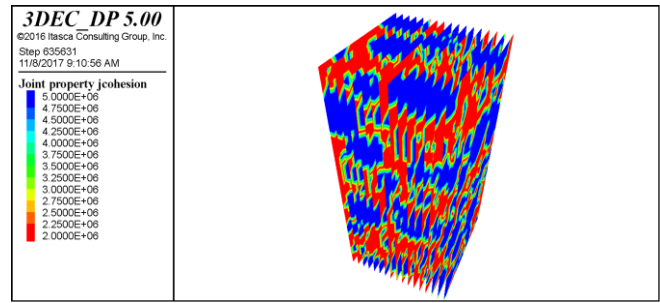
Based on this result, an in-house FISH function in 3DEC was developed to automatically and randomly assign a material property on the joint plane, using a probability function (e.g., normal, lognormal, or exponential distribution function). A series of 3DEC models with different joint persistences using this technique was prepared and simulated for the unconfined compressive strength test.

## 5. RESULTS AND DISCUSSION

A joint persistence ranging from 0.4 to 0.9 was considered in the 3DEC model. The material properties on the joint plane were statistically assigned using the FISH function. Fig. 9 shows the example of a 3DEC model with joint sets where (a) the persistence is equivalent to 0.4 and (b) the persistence is equivalent to 0.9.



(a)



(b)

Fig. 9. Examples of the joint sets showing the different joint persistence: (a)  $p = 0.4$  and (b)  $p = 0.9$ .

The result of the simulation of unconfined compressive strength test is shown in Fig. 10. 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 off-set at 15 degrees of the cleat orientation, all results from the 3DEC models are located within the variability of the lab testing results.

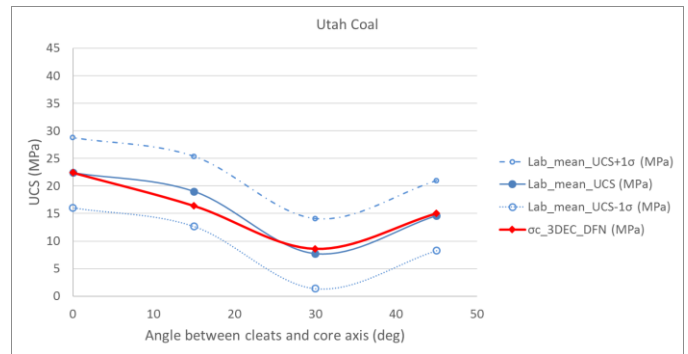


Fig. 10. Comparison of the UCS from the lab testing to the results of the 3DEC simulation.

## 6. CONCLUDING REMARKS

In this study, coal samples obtained from a Utah coal mine were investigated by conducting laboratory tests. The influence of non-persistent cleats on coal strength was, therefore, also investigated using a numerical modeling approach. The test results show that the mechanical characteristics appeared to be strongly anisotropic, which is associated with the orientation of cleats. However, the results of the unconfined compressive test do not agree with the strength models of classical strength formula because the strengths at certain orientations of cleats appear much higher than the estimation by the classical solution. If a joint is well developed in a rock mass, the non-persistent nature of joints significantly contributes to the enhancement of rock mass strength. A rock bridge that is defined as a small bridge of intact rock separating coplanar or non-coplanar discontinuities provides an effective cohesion to the joint and a rock block cannot fall or slide. The 3DEC models are developed to randomly generate cleats

with various lengths that follow a given degree of persistence in the numerical model. The 3DEC simulation results successfully replicate the results of the laboratory test for the coal strength with non-persistent cleats. It is concluded from the study that cleat persistence significantly affects the overall anisotropic strength of coal.

Since the coal shows that the mechanical characteristics are strongly anisotropic, a better characterization of coal for the design of excavations or pillars is an important step toward improving miner safety with respect to stability of underground workplaces and the prevention of fatalities. Using the proposed methodology beyond identifying rupture potential of coal by means of a rational characterization is a necessary step to accomplish the eventual elimination of coal pillar bursts or bumps related to worker injuries and fatalities. In the future, investigations should be conducted to help scientifically characterize and determine the rationale for the post-peak behavior of various coals as a function of anisotropic rock-mass conditions.

## ACKNOWLEDGEMENT

The authors are grateful to Dr. M. K. McCarter at the University of Utah for providing the Utah coal samples for this study.

## DISCLAIMER

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