The Effect of Joint Number and Joint Angle on The Failure Mechanism of Mine Pillar

vahab sarfarazi (✉ vahab.sarfarazi@gmail.com)

Hamedan University of Technology

hossein karimi javid

Hamedan University of Technology

kaveh asgari

Shahid Bahonar University of Kerman

Research

Keywords: PFC2D, Physical test, rock pillar, joint

Posted Date: May 5th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-480234/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

Experimental and discrete element methods were used to investigate the effects of joints number and joint angle on the failure behaviour of rock pillars under uniaxial compressive test. Gypsum samples with dimension of 200 mm×200 mm×50 mm were prepared. The compressive strength of model material was Within the specimen, imbeded joint were provided. The joint lengthn was 6 cm. in constant joint length, the number of joints were one, two and three. In experimental test, the angle of diagonal plane related to horizontal axis were 0, 30, 60 and 90 degree. In numerical test, the angle of diagonal plane related to horizontal axis were 0, 15, 30, 45, 60, 75 and 90 degree. The axial load rate on the model was 0.05 mm/min. the results showed that the failure process was mostly governed by both of the non-persistent joint angle and joint nubmer. The compressive strengths of the specimens were related to the fracture pattern and failure mechanism of the discontinuities. Furthermore it was shown that the shear behaviour of discontinuities is related to the number of the induced tensile cracks which are increased by increasing the joint angle. The strength of samples increases by increasing both of the joint angle and joint number. Finally, the failure pattern and failure strength are similar in both methods i.e. the experimental testing and the numerical simulation methods.

Introduction

Due to this fact that rock mass is a geological structure that is characterized by a set of blocks of varies (one or more) types of rock mass and is separated by cracks of different nature, the characteristic of pillars in broken rock mass is their complex mechanical behavior (Ranjith 2004). Uniaxial compression loading method in a stiff testing machine is common method for the investigation of the pillar-failure mechanism in experimental tests (Gill et al. 1993; sarfarazi 2014, 2016 (a)-(b), 2017; haeri 2016a-d). In fact, servo-controlled testing machines are a precious tool for starting the failure of rock samples at the prescribed deformation rate. However, stiffness ratio of the rock to the machine is a critical factor and it can lead to instability (Hudson et al. 1972), and consequently the complexity of interpreting the results. Generally, when a high-strength pillar penetrates into a failed material like soft and weak rocks in the roof or bottom of a mine, it leads to quick releasing of stored energy in the pillar system and usually it accelerates the failure progress (Tang et al. 1997a; Tang 2000). Under real and field circumstances when the applied stress exceeds peak of its uniaxial compressive strength the pillar load capacity decrease to a residual value and failure occurs. Recognizing the pillar-failure mechanism is vital in design studies. Evaluation of The pillar strength can be done in three ways: empirical, statistical or analytical methods (Sheorey 1993).

In general, researchers have used different evaluation approaches, For instance, some researchers have used empirical and semi-statistical methods for calculations of the uniaxial compressive strength of pillar (Tang et al. 1997b). However, this method also has disadvantages, for example in deep mines where there is a high level of stress behavior of rock pillars is nonlinear, this method isn't explicit. In

addition, Kaiser (1950) indicated that the stress-induced damage in a rock pillar is irreversible. Another issue is related to the parallel pillars, these kind of pillars can be fall at different times and it leads to probable interaction effects between adjacent damaged pillars. Furthermore due to the heterogeneous character of the rock mass the failure mechanisms of each pillar can also be different. As a result, it is difficult to predict the final uniaxial compressive strength of the pillars. Numerical methods in comparison to simplified laboratory tests and analytical methods have the advantage of being able to model complex boundary circumstances and material characteristics, also this approach can model the mechanisms involved in rock pillar failure (Mortazavi et al. 2009). Murali Mohan et al. (2001) in Indian coal mines using FLAC3D simulated failed and stable pillars. Chen et al. (2009) in a tunnel excavation process used numerical method to investigate the effects of rock pillar width on the stability behavior of three and four parallel tunnels. Results of numerical method indicated that the interaction effects were dependent not only on the geological conditions and tunnel cross section, but also on the widths of rock pillar. Kaiser and Tang (1998) studied the pillar rock burst mechanism with a double-rock sample model and simulated the progressive failure process in a pillar. Due to the advancement of computer science and the high computing power of computers, most researchers in recent decades have become interested in the numerical methods of determining mechanical parameters of the fractured mass (Yang 2015, Min 2003, Esmaili 2010, Ivars 2011, Martina 2000; Coli 2011; Khani 2013a; Khani 2013b; Ozkan Erdem 2015; Gao 2018; Qiu 2019; Sarfarazi 2021; Wang 2016; Zou 2016). In this study, uniaxial tests for rock pillar containing non-persistent joints are carried out using experimental test and numerical simulations. Two parameters were changed i.e. Joint angle and joint number. The evolutions of the failure pattern and uniaxial compressive stresses with different joint dip angles and joint numbers have been estimated.

Uniaxial Compression Test For Rock-like Specimens With Echelon Joint

In these experiments Rock-like materials were used for simulating fractured rock masses. The materials were mixed well and a weight ratio of 2 to 1 gypsum to water was prepared. The sample size (length * width * height) was 20 cm * 20 cm * 10 cm. To create open cracks, a thin metal plate is pre-inserting into the material and removing it after initial hardening of specimen (Fig. 1). To eliminate accidental error and increase the scientificity of the experiment, three identical prefabricated crack test blocks were prepared for each group.

Linear non-persistent cracks were formed in the model. The length of joint was 6 cm and for a constant joint length, the number of joints were one (Fig. 2), two (Fig. 3). and three (Fig. 4). the angle of diagonal plane related to horizontal axis were 0 (Fig. 2a, 3a and 4a), 30 (Fig. 2b, 3b and 4b), 60 (Fig. 2c, 3c and 4c) and 90 (Fig. 2d, 3d and 4d) degree.

The specimens were placed in a cool and ventilated condition for 28 days (Figs 5-7).

the electrohydraulic universal testing machine was used to performing the uniaxial compression test for the non-persistent joints.

The experimental system includes the test bed, loading control system and data acquisition system. The specimen was placed in the center of the base and maintained the horizontal contact with the base. During the experiment, the displacement loading rate was controlled to 0.05 mm/min (Fig 8).

Experimentally Observed Failure Patterns

3.1. Failure pattern of experimental specimens

a) Number of imbedded joint was 1

Fig. 9 shows the failure pattern of specimens with oriented plane angle of 0, 30, 60 and 90. When joint angle was 0 (Fig. 9a), two tensile wing cracks initiated from joint walls and distributed parallel to loading axis till integrated with boundaries of sample. Also, two secondary cracks initiated from joint tips and propagates parallel to loading axis till integrated with the sample walls. When joint angle was 30 (Fig. 9b), two tensile wing cracks initiated from joint tips and distributed parallel to loading axis till integrated with boundaries of sample. When joint angle was 60 (Fig. 9c), two tensile wing cracks initiated from joint tips and distributed parallel to loading axis till integrated with boundaries of sample. Also, two secondary cracks initiated from joint tips and propagates parallel to loading axis till integrated with the sample walls. When joint angle was 90 (Fig. 9d), splitting failure was occurred in sample. The joint has not any effect in failure process. In all samples, the Failure surface was smooth without pulverized material. This is representative of tensile crack.

b) Number of imbedded joints was 2

Fig. 10 shows the failure pattern of specimens with oriented plane angle of 0, 30, 60 and 90. When joint angle was 0 (Fig. 10a), four tensile wing cracks initiated from joint walls and distributed parallel to loading axis till integrated with boundaries of sample. two other secondary cracks initiated from outer joint tips and propagates parallel to loading axis till integrated with the sample walls. Also, two secondary cracks initiated from inner joint tips and led to rock bridge failure. When joint angle was 30 and 60 (Fig. 10b and c), four tensile wing cracks initiated from outer joint tips and distributed parallel to loading axis till integrated with boundaries of sample. Also, two secondary cracks initiated from inner joint tips and led to rock bridge failure. In these configurations the columns of gypsum were separated from sample walls. When joint angle was 90 (Fig. 10d), splitting failure was occurred in sample. The joint has not any effect in failure process. In all samples, the Failure surface was smooth without pulverized material. This is representative of tensile crack.

c) Number of imbedded joints was 3

Fig. 9 shows the failure pattern of specimens with oriented plane angle of 0, 30, 60 and 90. When joint angle was 0 (Fig. 11a), four tensile wing cracks initiated from joint walls and distributed parallel to loading axis till integrated with boundaries of sample. two other secondary cracks initiated from outer joint tips and propagates parallel to loading axis till integrated with the sample walls. Also, four

secondary cracks initiated from inner joint tips and led to rock bridges failure. When joint angle was 30 and 60 (Fig. 11b and c), four tensile wing cracks initiated from outer joint tips and distributed parallel to loading axis till integrated with boundaries of sample. Also, four secondary cracks initiated from inner joint tips and led to rock bridges failure. In these configurations the columns of gypsum were separated from sample walls. When joint angle was 90 (Fig. 11d), splitting failure was occurred in sample. The joint has not any effect in failure process. In all samples, the Failure surface was smooth without pulverized material. This is representative of tensile crack.

3.2. The effect of joint number and joint angle on the strength of samples

Fig 12 shows the effect of joint angle on the strength of models. This figure was presented for three joint number. The strength of samples was increased by increasing the joint angle. The minimum of compressive strength occurs when joint angle was 30. The strength of sample was increased by increasing the joint number.

Numerical Model

4.1 Particle Flow Code

One of the models used to evaluate the model particles cyclically is the PFC2D model, this model is a set of discrete circular particles and uses the explicit time-step circulation rule (Potyondy and Cundall 2004). The contact force between particles is based on the law of force-displacement and the particles motion are according to the Newton's second law

As a discrete element model (DEM), “contact bond model” and “parallel bond model” are two main types of the bond particle model. In the contact bond model, particles are held together a point of glue and contacts cannot transfer torque. While in the parallel bond model particles are joined by surface layer of glue and contacts can tolerate torque that induced by particles rotation. Thus, the parallel bond model can represent a cement-like substance (Fig. 13), such as rock (Potyondy and Cundall 2004). The force between particles is reflected through the contact force chain and a bond breakage will occur then, when the local stresses exceed the parallel bond strength micro cracks are formed.

4.2 PFC2D Model Preparation and Calibration the for Rock-Like Material

In this paper for preparation a test model the standard process of generating a PFC2D assembly were used, this process entirely is described by Potyondy and Cundall 2004. The process consists of particle generation, packing the particles, isotropic stress installation (stress initialization), floating particle (floater), elimination and bond installation. Since the specimens were small gravity effect and the gravity-induced stress gradient effect on the macroscopic behavior is neglectable. Calibration of particles properties and parallel bonds in bonded particle model were carried out using Uniaxial compressive strength and Brazilian test (Ghazvinian et al. 2012). Adopting the micro-properties are listed in Table 1 and the standard calibration procedures (Potyondy and Cundall 2004), a calibrated PFC particle assembly was created. Fig 14 a and b shows the experimental uniaxial compression test and numerical simulation, respectively. Fig 14 c and d shows experimental Brazilian test and numerical simulation, respectively. The results show good correlation between experimental test and numerical simulation. Also, as indicated in Table 2 the obtained specimen properties from the numerical models such as elastic modulus, Poisson's ratio, UCS values are nearly similar to the experimental values.

Table 1. Micro properties used to represent the intact rock.

Model height (mm)	108	Porosity	0.08
Model width (mm)	54	Elastic modulus	170
Expansion coefficient	1.2	friction coefficient	0.5
density	2200	Tensile strength	0.1
Minimum particle diameter	0.6	Tensile strength standard deviation	0.01
	1.2	Compressive strength	0.5
Maximum particle diameter			
Material pressure	0.1	compressive strength standard deviation	0.05

Table 2. Comparison of macro-mechanical properties between experiments and model

Mechanical properties	Experimental results	PFC2D Model results
Elastic modulus, (GPa)	5	5
Poisson's ratio	0.18	0.19
UCS, (MPa)	7.4	7.4
Brazilian tensile strength (MPa)	1	1.05

4.3. Numerical compressive Tests on the Non-Persistent Open Joint

After calibration of PFC2D, uniaxial tests for jointed rock were numerically simulated by creating a box model in the PFC2D (by using the calibrated micro-parameters) (Figs. 15-17). The PFC specimen had the dimensions of 100 mm × 100 mm. A total of 13438 disks with a minimum radius of 0.27 mm were used to make the box specimen. Two walls exist at the upper and lower of the model. The non-persistent joints were formed by deletion of bands of particles from the model (Figs. 15-17). In general, the models containing two and three non - persistent joints were constructed. The small prefabricated crack in this experiment was 1 mm wide and 20 mm long. The large prefabricated crack was 1 mm wide and 40 mm long. The angle of joint with larger length related to horizontal axis was 0, 30, 60, 90, 120 and 150. Twelve types of Y shape non-persistent joints were used in this numerical simulation. The crack arrangement and specimen number of each specimen were depicted in Figs. 15-17. It should be noticed that this joint configuration is similar to experimental one. Upper and lower walls applied uniaxial force on the model. The compression force was registered by taking the reaction forces on the upper wall.

4.4. Failure mechanism of numerical model

a) Number of imbedded joints was 1

Fig. 18 shows the failure pattern of specimens consisting one joint with angle of 0, 15, 30, 45, 60, 75 and 90 for both of the crack initiation stage and final stage. The green line and red line are representative of tensile crack and shear crack, respectively. Fig 19 shows stress versus strain curve for these configurations. When joint angle was 0, In crack initiation stage (Fig 18a), four tensile cracks initiated from joint wall and propagate parallel to loading axis. Also, both of the shear and tensile cracks initiated from joint tips. The crack initiation stress was equal to 2.5 MPa (Fig 19a). In the final stage (Fig 18b), four tensile and shear cracks initiated from joint tips and distributed diagonally related to loading axis till integrated with sample boundary. In this configuration, the "v" shape columns of rock were separated from the model. The final stress was equal to 2.85 MPa (Fig 19a).

When joint angle was 15, In crack initiation stage (Fig 18b), two tensile cracks initiated from joint wall and propagate parallel to loading axis. The crack initiation stress was equal to 2 MPa (Fig 19b). In the final stage (Fig 18c), four tensile and shear cracks initiated from joint tips and distributed diagonally related to loading axis till integrated with sample boundary. In this configuration, the "v" shape columns of rock were separated from the model. The final stress was equal to 2.65 MPa (Fig 19b).

When joint angle was 30, In crack initiation stage (Fig 18e), two tensile cracks initiated from joint wall and propagate parallel to loading axis. The crack initiation stress was equal to 2.5 MPa (Fig 19c). In the final stage (Fig 18f), four tensile and shear cracks initiated from joint tips and distributed diagonally related to loading axis

till integrated with sample boundary. In this configuration, the “v” shape columns of rock were separated from the model. The final stress was equal to 3.15 MPa (Fig 19c).

When joint angle was 45, In crack initiation stage (Fig 18g), two tensile cracks initiated from joint tip and propagate parallel to loading axis. The crack initiation stress was equal to 2.8 MPa (Fig 19d). In the final stage (Fig 18h), four tensile and shear cracks initiated from joint tips and distributed diagonally related to loading axis till integrated with sample boundary. In this configuration, the “v” shape columns of rock were separated from the model. The final stress was equal to 3.5 MPa (Fig 19d).

When joint angle was 60, In crack initiation stage (Fig 18i), two tensile cracks initiated from joint wall and propagate parallel to loading axis. The crack initiation stress was equal to 3MPa (Fig 19e). In the final stage (Fig 18j), four tensile and shear cracks initiated from joint tips and distributed diagonally related to loading axis till integrated with sample boundary. In this configuration, the “v” shape columns of rock were separated from the model. The final stress was equal to 3.5 MPa (Fig 19e).

It's to be note that, the area of “v” shape column was increased by increasing the joint angle from 0 to 60. When joint angle was 75, In crack initiation stage (Fig 18k), two tensile cracks initiated from joint tip and propagate parallel to loading axis. The crack initiation stress was equal to 4 MPa (Fig 19f). In the final stage (Fig 18l) several shear bands developed in model and lead to failure of the model. In this condition presence of joint has not any effect on the fracture propagation. The final stress was equal to 4.65 MPa (Fig 19f).

When joint angle was 5, In crack initiation stage (Fig 9m), two tensile cracks initiated from joint tip and propagate parallel to loading axis. The crack initiation stress was equal to 4.2 MPa (Fig 19g). In the final stage (Fig 9n) several shear bands developed in model and lead to failure of the model. In this condition presence of joint has not any effect on the fracture propagation. The final stress was equal to 5.1 MPa (Fig 19g).

In all models, the strain value in maximum stress stage was 3.5×10^{-4} .

b) Number of imbedded joints was 2

Fig. 20 shows the failure pattern of specimens consisting two joints with angle of 0, 15, 30, 45, 60, 75 and 90 for both of the crack initiation stage and final stage. The green line and red line are representative of tensile crack and shear crack, respectively. Fig 21 shows stress versus strain curve for these configurations. When joint angle was 0, In crack initiation stage (Fig 20a), four tensile cracks initiated from joint wall and propagate parallel to loading axis. Also, both of the shear and tensile cracks initiated from joint tips. The crack initiation stress was equal to 2.7 MPa (Fig 21a). In the final stage (Fig 20b), four tensile and shear cracks initiated from outer joint tips and distributed diagonally related to loading axis till integrated with sample boundary. In this configuration, the “v” shape columns of rock were separated from the model. It's to note that both of the tensile cracks and shear cracks lead to rock bridge failure. The fish eye mode failure occurs in rock bridge. The final stress was equal to 3.5 MPa (Fig 21a).

When joint angle was 15, In crack initiation stage (Fig 20c), four tensile cracks initiated from joint tips and propagate parallel to loading axis. The crack initiation stress was equal to 2.5 MPa (Fig 21b). In the final stage (Fig 20d), four tensile and shear cracks initiated from outer joint tips and distributed diagonally related to loading axis till integrated with sample boundary. In this configuration, the “v” shape columns of rock were separated from the model. It's to note that both of the tensile cracks and shear cracks lead to rock bridge failure. The fish eye mode failure occurs in rock bridge. The final stress was equal to 3.25 MPa (Fig 21b).

When joint angle was 30, In crack initiation stage (Fig 20e), four tensile cracks initiated from joint tips and propagate parallel to loading axis. The crack initiation stress was equal to 3 MPa (Fig 21c). In the final stage (Fig 20f), four tensile and shear cracks initiated from outer joint tips and distributed diagonally related to loading axis till integrated with sample boundary. In this configuration, the “v” shape columns of rock were separated from the model. It's to note that both of the tensile cracks and shear cracks lead to rock bridge failure. The fish eye mode failure occurs in rock bridge. The final stress was equal to 3.75 MPa (Fig 21c).

When joint angle was 45, In crack initiation stage (Fig 20g), four tensile cracks initiated from joint tips and propagate parallel to loading axis. The crack initiation stress was equal to 3.8 MPa (Fig 21d). In the final stage (Fig 20h), four tensile and shear cracks initiated from outer joint tips and distributed diagonally related to loading axis till integrated with sample boundary. In this configuration, the “v” shape columns of rock were separated from the model. It's to note that both of the tensile cracks and shear cracks lead to rock bridge failure. The fish eye mode failure occurs in rock bridge. The final stress was equal to 4.2 MPa (Fig 21d).

When joint angle was 60, In crack initiation stage (Fig 20i), four tensile cracks initiated from joint tips and propagate parallel to loading axis. The crack initiation stress was equal to 4 MPa (Fig 21e). In the final stage

(Fig 20j), four tensile and shear cracks initiated from outer joint tips and distributed diagonally related to loading axis till integrated with sample boundary. In this configuration, the “v” shape columns of rock were separated from the model. It's to note that both of the tensile cracks and shear cracks lead to rock bridge failure. The fish eye mode failure occurs in rock bridge. The final stress was equal to 4.5 MPa (Fig 21e).

It's to be note that, the area of “v” shape column was increased by increasing the joint angle from 0 to 60.

Also, the area of failure surface of rock bridge decreased by increasing the joint angle.

When joint angle was 75, In crack initiation stage (Fig 20k), two tensile cracks initiated from joint tip and propagate parallel to loading axis. The crack initiation stress was equal to 4.5 MPa (Fig 21f). In the final stage (Fig 20l) several shear bands developed in model and lead to failure of the model. In this condition presence of joint has not any effect on the fracture propagation. The final stress was equal to 5 MPa (Fig 21f).

When joint angle was 90, In crack initiation stage (Fig 20m), two tensile cracks initiated from joint tip and propagate parallel to loading axis. The crack initiation stress was equal to 4.7 MPa (Fig 21g). In the final stage (Fig 20n) several shear bands developed in model and lead to failure of the model. In this condition presence of joint has not any effect on the fracture propagation. The final stress was equal to 5.1 MPa (Fig 21g). In all models, the strain value in maximum stress stage was 4.2×10^{-4} .

c) Number of imbedded joint was 3

Fig. 22 shows the failure pattern of specimens consisting three joint with angle of 0, 15, 30, 45, 60, 75 and 90 for both of the crack initiation stage and final stage. The green line and red line are representative of tensile crack and shear crack, respectively. Fig 23 shows stress versus strain curve for these configuration. When joint angle was 0, In crack initiation stage (Fig 22a), six tensile cracks initiated from joint wall and propagate parallel to loading axis. Also, both of the shear and tensile cracks initiated from joint tips. The crack initiation stress was equal to 3 MPa (Fig 23a). In the final stage (Fig 22b), four tensile and shear cracks initiated from outer joint tips and distributed diagonally related to loading axis till integrated with sample boundary. In this configuration, the “v” shape columns of rock were separated from the model. It's to note that both of the tensile cracks and shear cracks lead to rock bridges failure. The fish eye mode failure occur in rock bridges. The final stress was equal to 3.6 MPa (Fig 23a).

When joint angle was 15, In crack initiation stage (Fig 22c), six tensile cracks initiated from joint wall and propagate parallel to loading axis. Also, both of the shear and tensile cracks initiated from joint tips. The crack initiation stress was equal to 3 MPa (Fig 23b). In the final stage (Fig 22d), four tensile and shear cracks initiated from outer joint tips and distributed diagonally related to loading axis till integrated with sample boundary. In this configuration, the “v” shape columns of rock were separated from the model. It's to note that both of the tensile cracks and shear cracks lead to rock bridges failure. The fish eye mode failure occur in rock bridges. The final stress was equal to 3.65 MPa (Fig 23b).

When joint angle was 30, In crack initiation stage (Fig 22e), six tensile cracks initiated from joint wall and propagate parallel to loading axis. Also, both of the shear and tensile cracks initiated from joint tips. The crack initiation stress was equal to 3.2 MPa (Fig 23c). In the final stage (Fig 22f), four tensile and shear cracks initiated from outer joint tips and distributed diagonally related to loading axis till integrated with sample boundary. In this configuration, the “v” shape columns of rock were separated from the model. It's to note that both of the tensile cracks and shear cracks lead to rock bridges failure. The fish eye mode failure occur in rock bridges. The final stress was equal to 3.75 MPa (Fig 23c).

When joint angle was 45, In crack initiation stage (Fig 22g), six tensile cracks initiated from joint wall and propagate parallel to loading axis. Also, both of the shear and tensile cracks initiated from joint tips. The crack initiation stress was equal to 3.8 MPa (Fig 23d). In the final stage (Fig 22h), four tensile and shear cracks initiated from outer joint tips and distributed diagonally related to loading axis till integrated with sample boundary. In this configuration, the “v” shape columns of rock were separated from the model. It's to note that both of the tensile cracks and shear cracks lead to rock bridges failure. The fish eye mode failure occur in rock bridges. The final stress was equal to 4.25 MPa (Fig 23d).

When joint angle was 60, In crack initiation stage (Fig 22i), six tensile cracks initiated from joint wall and propagate parallel to loading axis. Also, both of the shear and tensile cracks initiated from joint tips. The crack initiation stress was equal to 4 MPa (Fig 23e). In the final stage (Fig 22j), four tensile and shear cracks initiated from outer joint tips and distributed diagonally related to loading axis till integrated with sample boundary. In this configuration, the “v” shape columns of rock were separated from the model. It's to note that both of the

tensile cracks and shear cracks lead to rock bridges failure. The fish eye mode failure occur in rock bridges. The final stress was equal to 4.5 MPa (Fig 23e).

It's to be note that, the area of "v" shape column was increased by increasing the joint angle from 0 to 60.

Also, the area of failure surface of rock bridge decreased by increasing the joint angle.

When joint angle was 75, In crack initiation stage (Fig 22k), two tensile cracks initiated from joint tip and propagate parallel to loading axis. The crack initiation stress was equal to 4.5 MPa (Fig 23f). In the final stage (Fig 22l) several shear bands developed in model and lead to failure of the model. In this condition presence of joint has not any effect on the fracture propagation. The final stress was equal to 4.9 MPa (Fig 23f).

When joint angle was 90, In crack initiation stage (Fig 22m), two tensile cracks initiated from joint tip and propagate parallel to loading axis. The crack initiation stress was equal to 4.5 MPa (Fig 23g). In the final stage (Fig 22n) several shear bands developed in model and lead to failure of the model. In this condition presence of joint has not any effect on the fracture propagation. The final stress was equal to 5 MPa (Fig 23g).

In all models, the strain value in maximum stress stage was 4.8×10^{-4} . It can be concluded that the strain value in maximum stress stage increased by increasing the joint number.

By comparison between Figs 9-11 and Figs 18, 20 and 22, It can be concluded that failure pattern is similar in both of the experimental test and numerical simulation.

4.5 The effect of oriented plane angle and joint angle on the strength of samples

Fig 24 shows the effect of joint angle on the strength of models. This figure was presented for three joint number. The strength of samples was increased by increasing the joint angle. The minimum of compressive strength occurs when joint angle was 30. The strength of sample was increased by increasing the joint number.

By comparison between Fig 12 and Fig 24 It can be concluded that failure strength is nearly similar in both of the experimental test and numerical simulation.

Conclusion

Experimental and discrete element methods were used to investigate the effects of joints number and joint angle on the failure behaviour of rock pillars under uniaxial compressive test. Gypsum samples with dimension of 200 mm×200 mm×50 mm were prepared. The compressive strength of model material was Within the specimen, imbeded joint were provided. The joint lengthn was 6 cm. in constant joint length, the number of joints were one, two an three. In experimental test, the angle of diagonal plane related to horizontal axis were 0, 30, 60 and 90 degree. In numerical test, the angle of diagonal plane related to horizontal axis were 0, 15, 30, 45, 60, 75 and 90 degree. The axial load was applied to the model by rate of 0.05 mm/min. the results show that:

- When joint angle was less than 75

When joint angle was 15, two tensile wing cracks initiated from outer joint tips and distributed diagonally related to loading axis till integrated with boundaries of sample. Also, two wing cracks initiated from inner joint tips and propagates diagonally till integrated with the hole wall. Two vertical tensile cracks initiated from the joint walls and propagate parallel to loading axis till integrated with sample boundary. When joint angle was 30, one tensile wing cracks initiated from outer tip of left joint and distributed diagonally related to loading axis till integrated with boundaries of sample. Also, two vertical tensile cracks initiated from the joint walls and propagate parallel to loading axis till integrated with sample boundary. When joint angle was 45, one tensile wing cracks initiated from outer tip of right joint and distributed diagonally related to loading axis till integrated with boundaries of sample. Also, two vertical tensile cracks initiated from the joint walls and propagate parallel to loading axis till integrated with sample boundary. In this

conditions, the rock bridges were broken during the test. Failure surface was smooth without pulverized material. This is representative of tensile crack.

- When joint angle was more than 75

In crack initiation stage, two tensile cracks initiated from joint tip and propagate parallel to loading axis. In the final stage, several shear bands developed in model and lead to failure of the model. In this condition presence of joint has not any effect on the fracture propagation.

- The area of “v” shape column was increased by increasing the joint angle from 0 to 60.
- The area of failure surface of rock bridge decreased by increasing the joint angle.
- The strain value in maximum stress stage increased by increasing the joint number.
- The wing crack angle related to joint plane decrease by increasing the joint angle.
- The strength of samples was increased by increasing the joint angle.
- The minimum of compressive strength occurs when joint angle was 30.
- The strength of sample was increased by increasing the joint number.
- The failure pattern is similar in both of the experimental test and numerical simulation.
- Failure strength is similar in both of the experimental test and numerical simulation.

References

Coli N, Berry P. and Boldini D. 2011. In situ nonconventional shear tests for the mechanical characterization of a bimrock. *Int. J Rock Mech. Min Sci.* **48**: 95-102.

<https://doi.org/10.1016/j.ijrmms.2010.09.012>

Chen SL, Lee SC, Gui MW (2009) Effects of rock pillar width on the excavation behavior of parallel tunnels. *Tunn Undergr Space Technol* **24**:148–154

Esmaili K., Hadjigeorgiou J. and Grenon M. 2010. Estimating geometrical and mechanical REV based on synthetic rock mass models at Brunswick Mine. *Int. J Rock Mech. Min Sci.* **47**(6): 915-926.

<https://doi.org/10.1016/j.ijrmms.2010.05.010>

Gao W., (2018) [Influence of interaction between coal and rock on the stability of strip coal pillar.](#) *Geomechanics and Engineering, An Int'l Journal* , **16**(2):23-41.

Gill DE, Aubertin M, Simon R (1993) A practical engineering approach to the evaluation of rockburst potential. In: Young RP (ed) Rockbursts and seismicity in mines, pp 63–68

Haeri, H. and Sarfarazi, V. (2016a), “The effect of micro pore on the characteristics of crack tip plastic zone in concrete”, *Comput. Concrete*, **17**(1), 107-12. DOI: <https://doi.org/10.12989/cac.2016.17.1.107>

- Haeri, H. and Sarfarazi, V. (2016b), "The effect of non-persistent joints on sliding direction of rock slopes", *Comput. Concrete*, **17**(6), 723-737. <https://doi.org/10.12989/cac.2016.17.6.723>
- Haeri, H. and Sarfarazi, V. (2016c), "The deformable multilaminate for predicting the elasto-plastic behavior of rocks", *Comput. Concrete*, **18**, 201-214. DOI: <https://doi.org/10.12989/cac.2016.18.2.201>
- Hudson JA, Crouch SL, Fairhurst C (1972) Soft, stiff and servocontrolled testing machines: a review with references to rock failure. *Engng Geol* **6**:155–189
- Haeri, H., Sarfarazi, V. and Lazemi, H.A. (2016d), "Experimental study of shear behavior of planar non-persistent joint", *Comput. Concrete*, **17**(5), 639-653. DOI: <https://doi.org/10.12989/cac.2016.17.5.649>
- Ivars D.M., Pierce M.E. and Darcel C., et al. 2011. The synthetic rock mass approach for jointed rock mass modelling. *Int. J Rock Mech Min Sci.* **48**(2): 219-44. <https://doi.org/10.1016/j.ijrmms.2010.11.014>
- Khani A. 2013. Numerical investigation of the effect of fracture intensity on deformability and REV of fractured rock masses. *International Journal of Rock Mechanics and Mining Sciences.* **63**, 104-112. <https://doi.org/10.1016/j.ijrmms.2013.08.006>
- Khani A., Baghbanan A., Norouzi S. and Hashemolhosseini H. 2013. Effects of fracture geometry and stress on the strength of a fractured rock mass. *International Journal of Rock Mechanics & Mining Sciences.* **60**, 345-352. <https://doi.org/10.1016/j.ijrmms.2013.01.011>
- Kaiser J (1950) An investigation into the occurrence of noises in tensile tests or a study of acoustic phenomena in tensile tests. Ph.D thesis, Tech. Hosch. Munchen, Munich, Germany
- Kaiser PK, Tang CA (1998) Numerical simulation of damage accumulation and seismic energy release during brittle rock failure. Part II: Rib pillar collapse. *Int J Rock Mech Min Sci* **35**(2):123–134
- Mortazavi A, Hassani FP, Shabani M (2009) A numerical investigation of rock pillar failure mechanism in underground openings. *Comput Geotech* **35**:691–697
- Murali Mohan G, Sheorey PR, Kushwaha A (2001) Numerical estimation of pillar strength in coal mines. *Int J Rock Mech Min Sci* **38**:1185–1192
- Salamon M (1970) Stability instability and design of coal pillar workings. *Int J Rock Mech Min Sci* **7**:613–631
- Martina C.D. and Maybee W.G. 2000. The strength of hard-rock pillars. *International Journal of Rock Mechanics & Mining Sciences.* **37**, 1239-1246. [https://doi.org/10.1016/S1365-1609\(00\)00032-0](https://doi.org/10.1016/S1365-1609(00)00032-0)
- Min K.B. and Jing L. 2003. Numerical determination of the equivalent elastic compliance tensor for fractured rock masses using the distinct element method. *Int. J Rock Mech. Min Sci.* **40**(6): 795-816. [https://doi.org/10.1016/S1365-1609\(03\)00038-8](https://doi.org/10.1016/S1365-1609(03)00038-8)

- Ozkan Erdem B. and Ceylanoğlu A. 2015. Characterization of jointed rock masses for geotechnical classifications utilized in mine shaft stability analyses. *International Journal of Rock Mechanics and Mining Sciences*. **73**, 28-41.
<https://doi.org/10.1016/j.ijrmms.2014.10.001><https://doi.org/10.1016/j.ijrmms.2014.10.001>
- Potyondy, D.O. & Cundall, P.A., (2004). A bonded-particle model for rock, *International Journal of Rock Mechanics and Mining Sciences*, **41**, 1329–1364. <https://doi.org/10.1016/j.ijrmms.2004.09.011>
- Protosenya A. and Verbilo P. 2016. Forecast Jointed Rock Mass Compressive Strength Using a Numerical Model. MATEC Web Conf., 73: Article number 04006.
- Qiu P., Wang j., (2019) rock burst criteria of deep residual coal pillars in an underground coal mine: a case study . *Geomechanics and Engineering, An Int'l Journal* , **19**(6):121-134.
- Ranjith P.G., Fourar M., Pong S.F., Chian W. and Haque A. 2004. Characterization of fractured rocks under uniaxial loading states. *International Journal of Rock Mechanics and Mining Sciences*. **41**: 43-8.
<https://doi.org/10.1016/j.ijrmms.2004.03.017>
- Sheorey PR (1993) Design of coal pillar arrays and chain pillars. *Comprehensive rock engineering*, vol 2. Pergamon, Oxford, pp 631–670
- Sarfarazi, V.; Haeri, H.; Shemirani, A.; Zhu, Z. (2017) “Shear Behavior of Non-Persistent Joint under High Normal Load”. *Strength Mater.* **49**, 320–334. <https://doi.org/10.1007/s11223-017-9872-6>
- Sarfarazi, V. and Haeri, H., (2016a), “Effect of number and configuration of bridges on shear properties of sliding surface”, *J. Min. Sci.*, **52**(2), 245-257. <https://doi.org/10.1134/S1062739116020370>
- Sarfarazi, V., Faridi, H.R., Haeri, H. and Schubert, W. (2016b), “A new approach for measurement of anisotropic tensile strength of concrete”, *Adv. Concrete Constr.*, **3**(4), 269-284. DOI: <https://doi.org/10.12989/acc.2015.3.4.269>
- Sarfarazi, V., Ghazvinian, A., Schubert, W., Blumel, M. and Nejati, H.R. (2014), “Numerical simulation of the process of fracture of Echelon rock joints”, *Rock Mech. Rock Eng.*, **47**(4), 1355-1371.
<https://doi.org/10.1007/s00603-013-0450-3>
- Sarfarazi V., Abharian S., (2021) Physical test and PFC modelling of rock pillar failure containing two neighboring joints and one hole . *Smart Structures and Systems, An Int'l Journal* . **27**(1):67-78.
- Tang CA (1997a) Numerical simulation of progressive rock failure and associated seismicity. *Int J Rock Mech Min Sci* **34**:249–262
- Tang CA, Chen ZH, Xu XH, Li C (1997b) A theoretical model of the Kaiser effect in rock. *Pure Appl Geophys* **150**:203–215

Tang CA, Tham LG, Lee PKK, Tsui Y, Liu H (2000) Numerical tests on micro–macro relationship of rock failure under uniaxial compression, Part II: constraint, slenderness and size effects. *Int J Rock Mech Min Sci* **37**(4):570–577

Wang P. 2016. Numerical analysis on scale effect of elasticity, strength and failure patterns of jointed rock masses. *Geosciences Journal*. 20(4): 539-549. <https://doi.org/10.1007/s12303-015-0070-x>

Yang J. P., Chen W. Z., Yang D. S. and Yuan J. Q. 2015. Numerical determination of strength and deformability of fractured rock mass by FEM modeling. *Computers and Geotechnics*. **64**, 20-31. <https://doi.org/10.1016/j.compgeo.2014.10.011>

Zou J., Xia Zh., (2016), Theoretical solutions for displacement and stress of a circular opening reinforced by grouted rock bolt . *Geomechanics and Engineering, An Int'l Journal*, **11**(3):78-91.

Figures

Figure 1

a) the frame with dimension of 200mm× 200mm × 100mm, a special plastic fiber with dimension of 200mm × 200 mm × 100 mm was put into the frame, the shim inside the plastic fiber, b) adjustment the

wooden box inside the frame, c) adjustment the shim inside the frame, d) slurry inside the box, e) the aluminum sheet is removed from the mold.

Figure 2

Three echelon joints with angle of; a) 15, b) 30, c) 45; oriented plane angle was equal to 30.

Figure 3

Three echelon joints with angle of; a) 15, b) 30, c) 45; oriented plane angle was equal to 45.

Figure 4

three echelon joints with angle of; a) 15, b) 30, c) 45; oriented plane angle was equal to 60.

Figure 5

Three echelon joints with angle of; a) 15, b) 30, c) 45; oriented plane angle was equal to 30.

Figure 6

Three echelon joints with angle of; a) 15, b) 30, c) 45; oriented plane angle was equal to 45.

Figure 7

Three echelon joints with angle of; a) 15, b) 30, c) 45; oriented plane angle was equal to 60.

Figure 8

Specimen are placed between the plates of the loading machine.

Figure 9

Failure pattern in specimens containing one joint with angle of; a) 0, b) 30, c) 60, d) 90.

Figure 10

Failure pattern in specimens containing two joints with angle of; a) 0, b) 30, c) 60, d) 90.

Figure 11

Failure pattern in specimens containing three echelon joints with angle of; a) 15, b) 30, c) 45; oriented plane angle was equal to 60.

Figure 12

the effect of joint angle on the strength of models.

Figure 13

behavior of the grain-bonding system, Potyondy and Cundall 2004.

Figure 14

a) Experimental compression test, b) numerical compression test, c) experimental Brazilian test and d) numerical Brazilian test, e) axial force versus axial strain for numerical uniaxial compressive test, f) axial force versus axial strain for numerical Brazilian test.

Figure 15

Three echelon joints with angle of; a) 15, b) 30, c) 45; oriented plane angle was equal to 30.

Figure 16

Three echelon joints with angle of; a) 15, b) 30, c) 45; oriented plane angle was equal to 30.

Figure 17

Three echelon joints with angle of; a) 15, b) 30, c) 45; oriented plane angle was equal to 30.

Figure 18

Crack evolution in specimen containing one joint during the two stages of the loading; a) crack initiation stress for joint angle of 0, b) peak stress for joint angle of 0, c) crack initiation stress for joint angle of 15, d) peak stress for joint angle of 15, e) crack initiation stress for joint angle of 30, f) peak stress for joint angle of 30, g) crack initiation stress for joint angle of 45, h) peak stress for joint angle of 45, i) crack initiation stress for joint angle of 60, j) peak stress for joint angle of 60, k) crack initiation stress for joint

angle of 75, l) peak stress for joint angle of 75, m) crack initiation stress for joint angle of 90, n) peak stress for joint angle of 90,

Figure 19

Variation of axial stress versus strain in specimen containing one joint with angle of; a) 0, b) 15, c) 30, d) 45, e) 60, f) 75, g) 90,

Figure 20

Crack evolution in specimen containing two joint during the two stages of the loading; a) crack initiation stress for joint angle of 0, b) peak stress for joint angle of 0, c) crack initiation stress for joint angle of 15, d) peak stress for joint angle of 15, e) crack initiation stress for joint angle of 30, f) peak stress for joint angle of 30, g) crack initiation stress for joint angle of 45, h) peak stress for joint angle of 45, i) crack initiation stress for joint angle of 60, j) peak stress for joint angle of 60, k) crack initiation stress for joint

angle of 75, l) peak stress for joint angle of 75, m) crack initiation stress for joint angle of 90, n) peak stress for joint angle of 90,

Figure 21

Variation of axial stress versus strain in specimen containing one joint with angle of; a) 0, b) 15, c) 30, d) 45, e) 60, f) 75, g) 90,

Figure 22

Crack evolution in specimen containing two joint during the two stages of the loading; a) crack initiation stress for joint angle of 0, b) peak stress for joint angle of 0, c) crack initiation stress for joint angle of 15, d) peak stress for joint angle of 15, e) crack initiation stress for joint angle of 30, f) peak stress for joint angle of 30, g) crack initiation stress for joint angle of 45, h) peak stress for joint angle of 45, i) crack initiation stress for joint angle of 60, j) peak stress for joint angle of 60, k) crack initiation stress for joint

angle of 75, l) peak stress for joint angle of 75, m) crack initiation stress for joint angle of 90, n) peak stress for joint angle of 90,

Figure 23

Variation of axial stress versus strain in specimen containing one joint with angle of; a) 0, b) 15, c) 30, d) 45, e) 60, f) 75, ; g) 90,

Figure 24

the effect of joint angle on the strength of models.