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Numerical simulations of fracture shear test in anisotropy rocks with bedding layers

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Abstract. In this paper the effect of bedding layer on the failure mechanism of rock in direct shear test has been investigated using particle flow code, PFC. For this purpose, firstly calibration of pfc2d was performed using Brazilian tensile strength. Secondly direct shear test consisting bedding layer was simulated numerically. Thickness of layers was 10 mm and rock bridge length was 10 mm, 40 mm and 60 mm. In each rock bridge length, bedding layer angles changes from 0° to 90° with increment of 15°. Totally 21 models were simulated and tested. The results show that two types of cracks develop within the model. Shear cracks and tensile cracks. Also failure pattern is affected by bridge length while shear strength is controlled by failure pattern. It's to be noted that bedding layer has not any effect on the failure pattern because the layer interface strength is too high.

Keywords: direct shear test; anisotropy; bedding layer; tensile crack; PFC2D

1. Introduction

The design and numerical modelling of rock structures may require the knowledge of anisotropic properties as input during the structural failure analyses under various loading conditions. Some investigators such as Liu *et al*. (2012) concluded that the tensile strength of the rock structure may gradually decrease as the bedding angle changes from 0° to 90°. They also reported that (based on Brazilian splitting tests) three kinds of failure modes may occur for the anisotropic slate specimens. These failure modes are stated as: the pure tensile failure, the pure shear failure and the mixed tensile and shear failure. In another work, Liu *et al*. (2013) derived a useful formula for the bedded rock which relates the tensile strength of the specimen to the bedding angle. This relation reveals the tensile strength anisotropy of the Brazilian slate discs based on Hoek-Brown criterion and the analytical solution of the elastostatic problem assuming plane stress condition. Then, they established another equation to obtain the tensile strength of a bedded rock using the single weak plane theory.

On the other hand, Cai and Kaiser (2004) considered the isotropic and anisotropic properties of the simulated Brazilian discs of rock specimens by an FEM/DEM coupled approach named ELFEN. They also studied the effect of pre-existing fissures on the strength of these numerically simulated rock specimens. Based on their research, they concluded that both rock anisotropy and pre-existing fissures have considerable influence on the tensile strength and crack initiation and propagation modes of these rock specimens. In a recent research, Tavallali and Vervoort (2010) proposed a reasonable relationship between the failure strength and the layer orientation by accomplishing some Brazilian splitting tests on the specimens of a layered rock are all related to the inclination angle of the layers (rock anisotropy). In another research, Tavallali and Vervoort (2013) performed some experiments on the samples of layered sandstone, to explore the effect of layer orientation and shape on the failure pattern of these rocks. Based on their experimental results they concluded that the fracture pattern in layered sandstones usually are in form of a combination of tensile and/or shear fractures. In these cases, the thickness of the layer is more important than the number of layer boundaries per specimen. Some Brazilian discs specimens from different rock types (sandstone, gneiss and slate) were tested by Dan *et al*. (2013). These splitting tests carried out to consider the effect of anisotropy on the strengths of these rocks. They showed that the rock tensile strength is mainly affected by the degree of anisotropy because the more anisotropic gneiss and slate rocks revealed the stronger dependence of tensile strength due to the specimens orientation related to the applied loading direction in the laboratory testing machine. A series of Brazilian disc tests were carried out by Khanlari *et al*. (2014) on three types of sandstones with different average number of lamination boundaries per centimetre. They observed two major modes of failure in the laminated sandstone specimens. Recently, many numerical and experimental studies were devoted to this important engineering context (Wu *et al*. 2010, Lancaster *et al*. 2013,

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Mobasher *et al*. 2014, Noel and Soudki 2014, Oliveira and Leonel 2014, Kim and Taha 2014, Tiang *et al*. 2015, Wan Ibrahim *et al*. 2015, Silva *et al*. 2015, Gerges *et al*. 2015, Liu *et al*. 2015, Haeri *et al*. 2015a, b, Wasantha *et al*. 2015, Fan *et al*. 2016, Li *et al*. 2016, Sardemir 2016, Sarfarazi *et al*. 2016, Shuraim 2016, Wang *et al*. 2016, Haeri *et al*. 2016a, b, Haeri and Sarfarazi 2016, Haeri and Marji 2016, Sarfarazi and Haeri 2016).

Several numerical modelling researches have also been carried out using the sophisticated finite difference codes specially prepared for discontinuous media. Among these codes, the Particle flow code (PFC) which is actually discrete element based commercial software has been widely used for the mechanical analyses of discontinues. This computer code first introduced in the field of rock mechanics which can be effectively used for analysing the microscopic mechanism of all kinds of rock materials (Cundall and Strack 1979). Since its evolution, PFC has been widely used to model many rock mechanics problems at different engineering scales, for example, two dimensional particle flow code (PFC2D) has been used by Zhang and Wong (2012, 2013). They carried out the numerical simulation of the fracturing mechanism and crack analyses in rock-like material containing a single and/or two fissures under uniaxial compression. They mainly studied the stress and displacement distributions associated with the crack coalescence process in rock like materials. The shear behaviour of rock like materials have also been studied using PFC2D by Ghazvinian *et al*. (2012, 2013). They simulated the shear behaviour of rock-like materials by modelling the specimens containing two edge planar and non-coplanar non-persistent joints under direct shear test. The macro-mechanical properties and meso-mechanism strengths of rock materials under direct shear were studied (using PFC2D simulation software) by Bewick *et al*. (2013, 2013). The main objective of the present research work is to evaluate the effect of bedding layers angle and rock bridge lengths on the strength and shearing failure behaviour in isotropic rock specimens during direct shear tests in the laboratory. This study is performed by using a two dimensional particle flow code (PFC2D) for simulating the Brazilian discs of rock-like materials. The shortcomings of PFC method are when the ratio of uniaxial strength to tensile strength is too high. In this condition the calibration process lead to failure.

2. Numerical simulation

The rock anisotropy due to bedding planes are the most versatile features of many rock types which considerably affect the strength and fracturing mechanism of these materials under different loading conditions. In the present work, the PFC2D is used to simulate the rock anisotropy due to bedding planes and the rock bridge lengths during the direct shear testing of bedded rocks.

2.1 Bonded particle model and Particle Flow Code 2D (PFC2D)

The discrete element method (DEM) in form of a two dimensional particle flow code (PFC2D) is used to model the bedded rock types. This code considers the modelling material as an assembly of rigid particles that can move independently and may interact at contact points (Itasca 1999 version 3.1; Potyondy and Cundall 2004). Then, the Lagrangian explicit finite difference method is adopted to calculate the movements and interaction forces of particles with in the assembly. The two linear and non-linear contact models considering the frictional sliding at the contact points can be used. In this study, the linear contact model provides an elastic relation in between the relative displacements and contact forces at the particles interfaces. A parallel bonding model can be generated in PFC2D by sing the required subroutines provided in Itasca 1999; version 3.1. The appropriate micro properties can be established for a typical particle assembly by conducting a useful calibration procedure because the contact properties and bonding characteristics of the particles cannot be determined directly from tests performed on laboratory model samples. However, the experimental laboratory tests provide the macro-mechanical parameters of the materials reflecting the continuum behaviour. In the present study, an inverse modelling procedure based on the trial and error approach was used to determine the appropriate micro-mechanical properties of the numerical models from the macro-mechanical properties determined in the laboratory tests. The trial and error approach relate the two sets of material properties (Itasca 1999) and involve the assumption of micro-mechanical properties at the first stage and then compare the strength and deformation characteristics of the numerical models with those of the laboratory samples. Finally, the micro-mechanical properties that give a simulated macroscopic response close to those of the laboratory tests results are then adopted for the numerical simulation of the discontinuous jointed blocks.

2.2 Preparing and calibrating the numerical model

In the present work, the Brazilian tensile strength test is used to calibrate the tensile strength of the modelled specimen in PFC2D. The PFC2D is used to generate the particle assembly representing the test model considering the following four steps: (i) particle generation and packing,

Table 1 Micro properties used to represent the intact rock

Parameter	Value	Parameter	Value
Type of particle	disc	Parallel bond radius multiplier	1
Density (kg/cm^3)	3000	Young modulus of parallel bond (GPa)	40
Minimum radius (mm)	0.27	Parallel bond stiffness ratio	1.7
Size ratio	1.56	Particle friction coefficient	0.4
Porosity ratio	0.08	Parallel bond normal strength, mean (MPa)	40
Damping coefficient	0.7	Parallel bond normal strength, SD (MPa)	2
Contact young modulus (GPa)	40	Parallel bond shear strength, mean (MPa)	40
Stiffness ratio	1.7	Parallel bond shear strength, SD (MPa)	2

Fig. 1 Failure pattern in physical sample

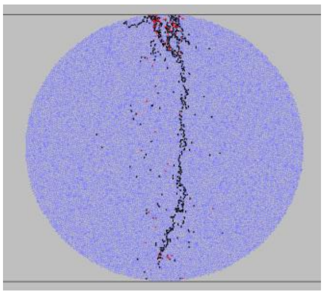


Fig. 2 Failure pattern in PFC2D model

(ii) installing the isotropic stress condition, (iii) eliminating the floating particles, and, (iv) installing the particle assembly bonds (Potyondy and Cundall 2003).

In this way the calibrated PFC particle assembly modelling was established by taking the diameter of the Brazilian disc as 54 mm. A total number of 5,615 particles were used and the modelled disc was then crushed by letting the lateral walls to move toward each other with a low speed of 0.016 m/s. Table 1 shows the micro properties used to represent the intact rock. The required micro properties that should be defined for the solution of a typical geomechanically problem include: the modulus of ball-to-ball contacts, the stiffness ratio (i.e., kn over ks), the ball's coefficient of friction, the normal and shear strengths of the parallel bond, the standard deviation ratio of the mean of both normal and shear strengths of the bond, the minimum ball radius, the parallel-bond radius multiplier, the parallel-bond modulus, and the parallel-bond stiffness ratio. The resulting failure pattern obtained by both experimental and numerical modelling of the Brazilian disc samples are presented in Figs. 1 and 2, respectively. These results show that the failure planes experienced in numerical and laboratory tests are well matching. The numerical tensile strength of the Brazilian discs are compared with the results obtained by the experimental laboratory measurements and presented in Table 2. The results shown in this table demonstrate that there is a good accordance in between the numerical and experimental tensile strength results.

2.3 Direct shear test model preparation using Particle Flow Code

The direct shear test modelling of the rock like materials was performed after calibrating PFC2D. The anisotropic rock samples used for the direct shear tests were numerically simulated by creating the rectangular models (Figs. 3-5). The PFC specimen dimension was 100 mm×100 mm. To make this PFC specimen, a total number of 11,179 discs with a minimum radius of 0.37 mm were used. These models were formed containing the bedding layers with thicknesses of 10 mm, 40 mm and 60 mm at a constant bridge length of 10 mm. The layer's angularity changes from 0° to 90° with the increment of 15°. As a whole, 21 specimens containing different bedding layer were prepared to investigate the

Table 2 Brazilian tensile strength of physical and numerical samples

Physical tensile strength (MPa)	2.5 and 2.7
Numerical tensile strength (MPa)	2.5

Table 3 Micro properties used to represent the bedding interfaces

Parameter	Value	Parameter	Value
n_bond	1e3	s_bond	1e3
fric	0.25		

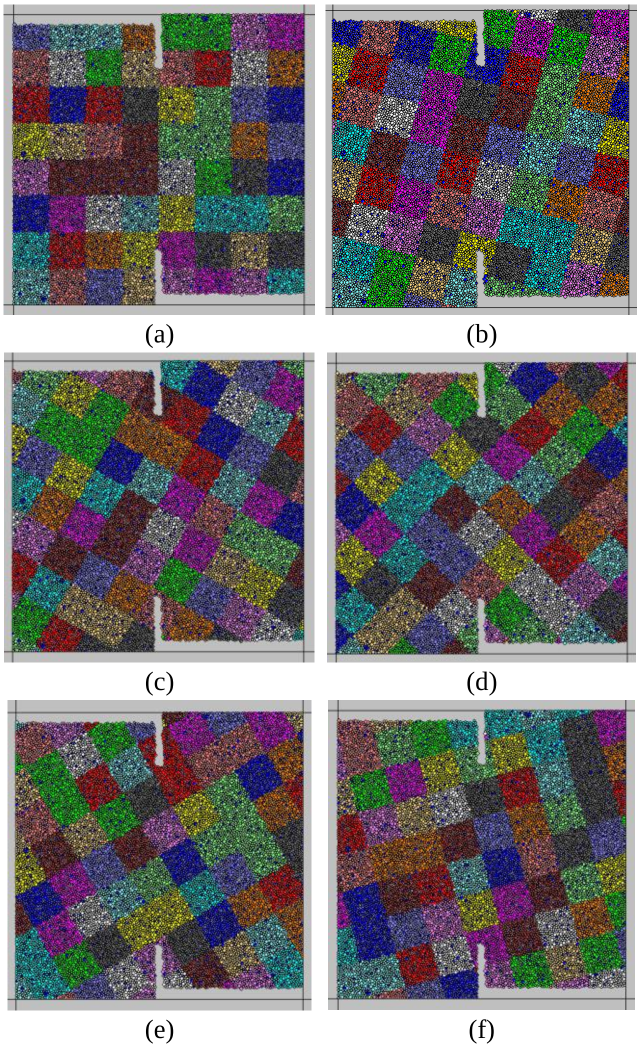
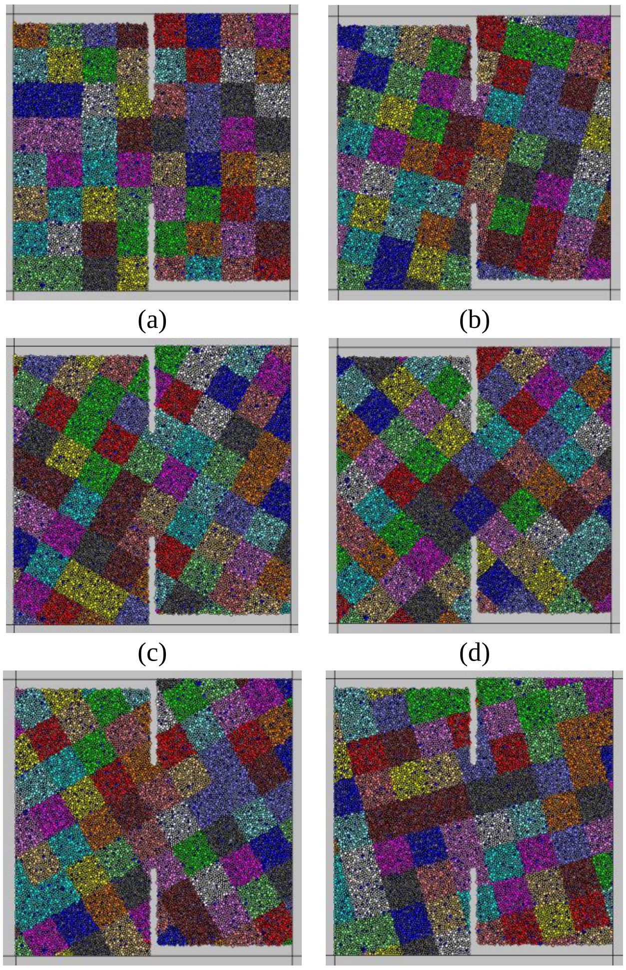
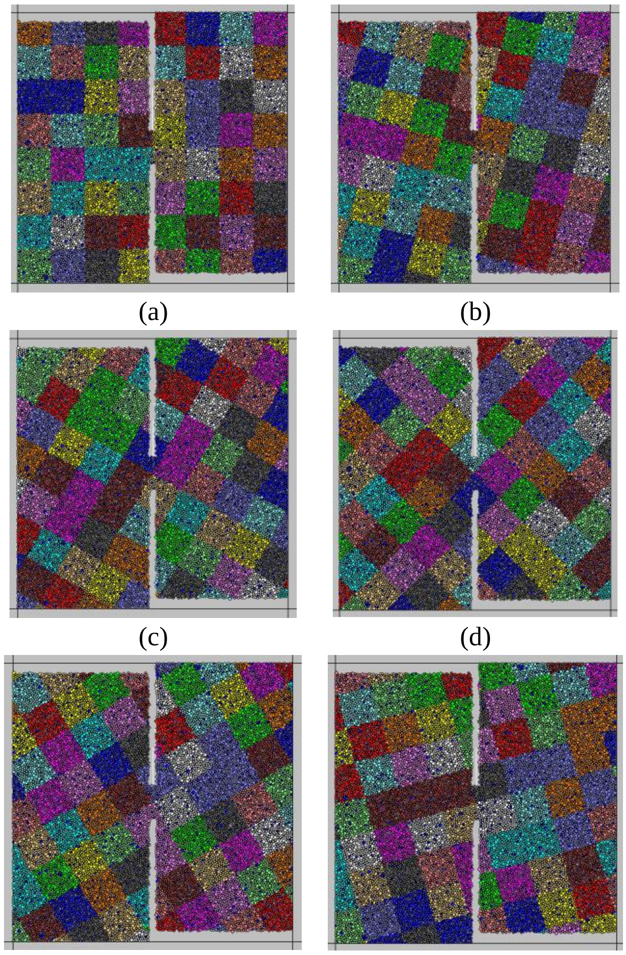


Fig. 3 Direct shear test with bedding layer angle of (a) 0°, (b) 15°, (c) 30°, (d) 45°, (e) 60°, (f) 75°, (g) 90°; rock bridge length is 60 mm



(a) (b) (c) (d) (e) (f)

Fig. 4 Direct shear test with bedding layer angle of (a) 0°, (b) 15°, (c) 30°, (d) 45°, (e) 60°, (f) 75°, (g) 90°; rock bridge length is 40 mm



(a) (b) (c) (d) (e) (f)

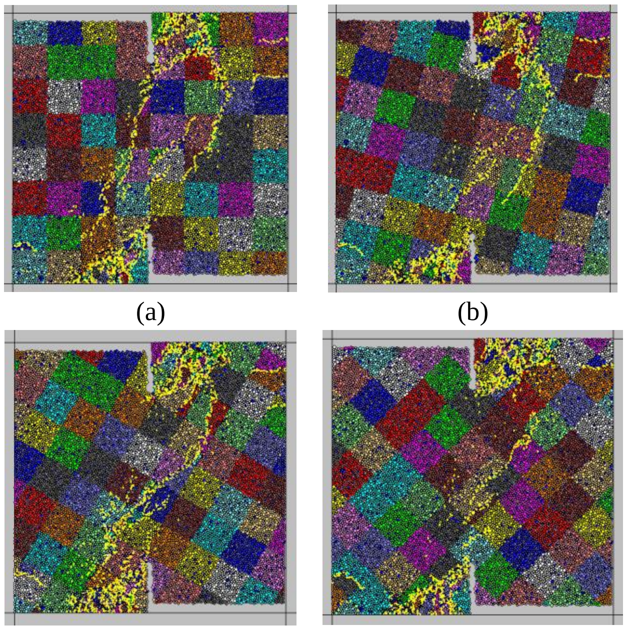
Fig. 5 Direct shear test with bedding layer angle of (a) 0°, (b) 15°, (c) 30°, (d) 45°, (e) 60°, (f) 75°, (g) 90°; rock bridge length is 10 mm

influence of Layers thickness and layer angularity (the material anisotropy) on the failure behaviour of these models. To apply the shear loading to the modelled samples, two narrow band of particles were removed from the upper and lower of each testing model (Fig. 3). These direct shear testing were performed under a constant normal loading of 1 MPa. The Micro-properties of the bedding layer interfaces were chosen as given in Table 3.

3. Result and discussion

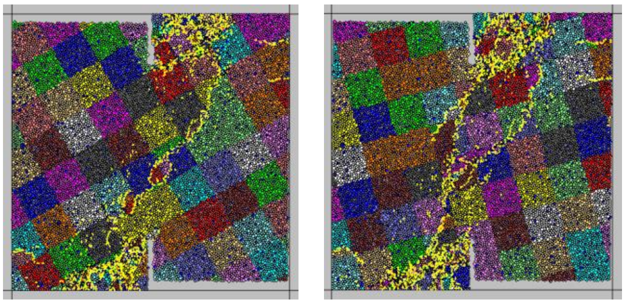
3.1 The effect of bedding layers angle on the failure mechanism of models:

Figs 6-8 show failure pattern in the model with bridge length of 10mm, 40 mm and 60 mm, respectively. Yellow line and black line represent tensile crack and shear crack, respectively. When bridge length is 60 mm (Fig. 6), tensile cracks initiate from two places i.e., at tip of the notches and in the model edge. In this condition several shear band propagates through the model and lead to model failure. It is to be noted that bedding layer has not any effect on the



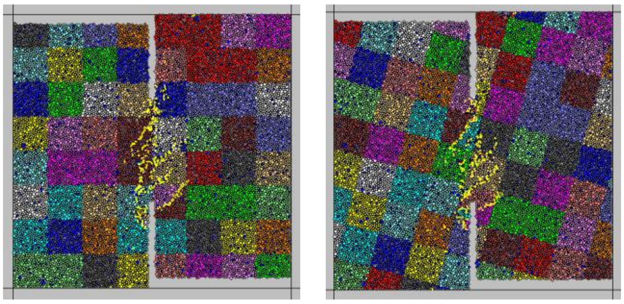
(a) (b) (c) (d)

Fig. 6 Shear failure patterns of model with bedding layer angle of (a) 0°, (b) 15°, (c) 30°, (d) 45°, (e) 60°, (f) 75°, (g) 90°; rock bridge length is 60 mm

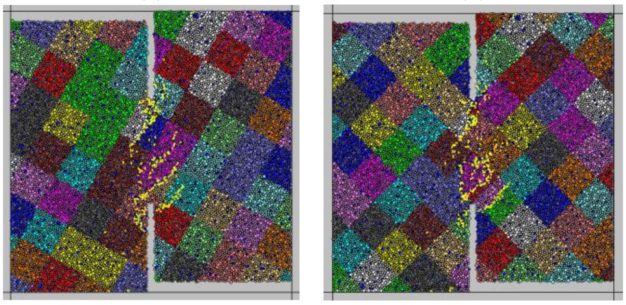


(e) (f)

Fig. 6 Continued



(a) (b)



(c) (d)

(e) (f)

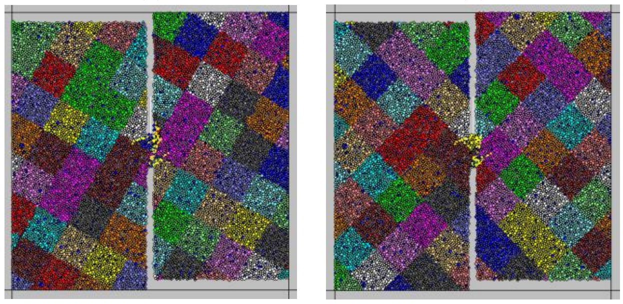
Fig. 7 Shear failure patterns of model with bedding layer angle of (a) 0°, (b) 15°, (c) 30°, (d) 45°, (e) 60°, (f) 75°, (g) 90°; rock bridge length is 40 mm

failure pattern because tensile strength of bedding interface is too high.

When bridge length is 40 mm (Fig. 7), tensile cracks initiate at tip of the notches. In this condition, only bridge failure with several shear bands. It's to be noted that bedding layer has not any effect on the failure pattern because tensile strength of bedding interface is too high.

When bridge length is 10 mm (Fig. 8), two wing cracks initiate at tips of the notches. In this condition, bridge failure with one tensile crack. It's to be noted that bedding

(a) (b)



(c) (d)

(e) (f)

Fig. 8 Shear failure patterns of model with bedding layer angle of (a) 0°, (b) 15°, (c) 30°, (d) 45°, (e) 60°, (f) 75°, (g) 90°; rock bridge length is 10 mm

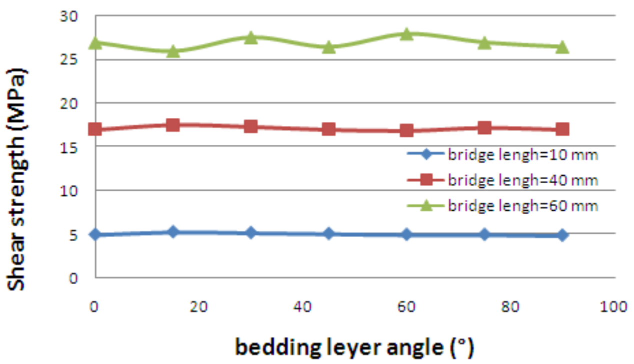


Fig. 9 The effect of bedding layer on the punch shear test strength

layer has not any effect on the failure pattern because tensile strength of bedding interface is too high.

3.2 The effect of bedding layer on the biaxial compressive strength:

Fig. 9 shows the effect of bedding layer on the shear strength. As can be seen, shear strength is constant by increasing the bedding layer angle. Also shear strength is decreased by decreasing the bridge length.

4. Conclusions

The effect of bedding layer on the shear failure mechanism of rock has been investigated in direct shear test using particle flow code. For this purpose, firstly calibration of pfc2d was performed using Brazilian tensile strength. Secondly direct shear test consisting bedding layer was simulated numerically. Thickness of layers were 10mm and bridge lengths were 60mm, 40 mm and 10 mm. In each bridge length, bedding layer angles changes from 0° to 90° with increment of 15°. Totally 21 models were simulated. The results show that:

• When bridge length is 60 mm, tensile cracks initiate from two places i.e., at tip of the notches and in the model edge. In this condition several shear band propagates through the model and lead to model failure. It is to be noted that bedding layer has not any effect on the failure pattern because tensile strength of bedding interface is too high.

• When bridge length is 40 mm, tensile cracks initiate at tip of the notches. In this condition, only bridge failure with several shear bands. It is to be noted that bedding layer has not any effect on the failure pattern because tensile strength of bedding interface is too high.

• When bridge length is 10 mm, two wing cracks initiate at tips of the notches. In this condition, bridge failure with one tensile crack. It is to be noted that bedding layer has not any effect on the failure pattern because tensile strength of bedding interface is too high.

• Shear strength is constant by increasing the bedding layer angle. Also shear strength is decreased by decreasing the bridge length.

References

Bewick, R.P., Kaiser, P.K. and Bawden, W.F. (2013), "DEM simulation of direct shear: 2. Grain boundary and mineral grain strength component influence on shear rupture", *Rock Mech. Rock Eng*., **47**(5), 1673-1692. https://doi.org/10.1007/s00603-013-0494-4.

Bewick, R.P., Kaiser, P.K., Bawden, W.F. and Bahrani, N. (2013), "DEM simulation of direct shear: 1. Rupture under constant normal stress boundary conditions", *Rock Mech. Rock Eng*., **47**(5), 1647-1671. https://doi.org/10.1007/s00603-013-0490-8.

Cai, M. and Kaiser, P.K. (2004), "Numerical simulation of the Brazilian test and the tensile strength of anisotropic rocks and rocks with pre-existing cracks", *Int. J. Rock Mech. Min. Sci.*, **41**, 478-483.

Cundall, P.A. and Strack, O.D.L. (1979), "A discrete numerical model for granular assemblies", *Geotechnique*, **29**, 47-65.

Dan, D.Q., Konietzky, H. and Herbst, M. (2013), "Brazilian tensile strength tests on some anisotropic rocks", *Int. J. Rock Mech. Min. Sci.*, **58**, 1-7. https://doi.org/10.1016/j.ijrmms.2012.08.010.

Fan, Y., Zhu, Z., Kang, J. and Fu, Y. (2016), "The mutual effects between two unequal collinear cracks under compression", *Math. Mech. Solid*., **22**, 1205-1218. https://doi.org/10.1177/1081286515625436.

Gerges, N., Issa, C. and Fawaz, S. (2015), "Effect of construction joints on the splitting tensile strength of concrete", *Case Stud. Constr. Mater.*, **3**, 83-91. https://doi.org/10.1016/j.cscm.2015.07.001.

Ghazvinian, A., Sarfarazi, V., Schubert, W. and Blumel, M. (2012), "A study of the failure mechanism of planar non-persistent open joints using PFC2D", *Rock Mech. Rock Eng.*, **45**, 677- 693. https://doi.org/10.1007/s00603-012-0233-2.

Haeri, H. and Marji, M.F. (2016), "Simulating the crack propagation and cracks coalescence underneath TBM disc cutters", *Arab. J. Geosci*., **9**(2), 124. https://doi.org/10.1007/s12517-015-2137-4.

Haeri, H. and Sarfarazi, V. (2016), "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., Khaloo, A. and Marji, M.F. (2015a), "Experimental and numerical simulation of the microcrack coalescence mechanism in rock-like materials", *Strength Mater*., **47**(5), 740-754. https://doi.org/10.1007/s11223-015-9711-6.

Haeri, H., Khaloo, A. and Marji, M.F. (2015b), "Fracture analyses of different pre-holed concrete specimens under compression", *Acta Mech. Sinica*., **31**(6), 855-870. https://doi.org/10.1007/s10409-015-0436-3.

Haeri, H., Sarfarazi, V. and Hedayat, A. (2016a), "Suggesting a new testing device for determination of tensile strength of concrete", *Struct. Eng. Mech*., **60**(6), 939-952. https://doi.org/10.12989/sem.2016.60.6.939.

Haeri, H., Sarfarazi, V., Fatehi, M., Hedayat, A. and Zhu, Z. (2016b), "Experimental and numerical study of shear fracture in brittle materials with interference of initial double", *Acta Mech. Soil. Sinica*., **5**, 555-566. https://doi.org/10.1016/S0894-9166(16)30273-7.

Itasca Consulting Group Inc. (2004), Particle Flow Code in 2-Dimensions, Problem Solving with PFC2D, Version 3.1, Itasca Consulting Group Inc., Minneapolis.

Khanlari, G., Rafiei, B. and Abdilor, Y. (2014), "An experimental investigation of the Brazilian tensile strength and failure patterns of laminated sandstones", *Rock Mech. Rock Eng*., **48**(2), 843-852. https://doi.org/10.1007/s00603-014-0576-y.

Kim, J. and Taha, M.R. (2014), "Experimental and numerical evaluation of direct tension test for cylindrical concrete specimens", *Adv. Civil Eng.*, **2014**, Article ID 156926, 8. http://dx.doi.org/10.1155/2014/156926.

Lancaster, I.M., Khalid, H.A. and Kougioumtzoglou, I.A. (2013), "Extended FEM modelling of crack propagation using the semi-circular bending test", *Constr. Build. Mater.*, **48**, 270-277. https://doi.org/10.1016/j.conbuildmat.2013.06.046.

Li, S., Wang, H., Li, Y., Li, Q., Zhang, B. and Zhu, H. (2016), "A new mini-grating absolute displacement measuring system for static and dynamic geomechanical model tests", *Measur.*, **82**, 421-431. https://doi.org/10.1016/j.measurement.2017.04.002.

Liu, X., Nie, Z., Wu, S. and Wang, C. (2015), "Self-monitoring application of conductive asphalt concrete under indirect tensile deformation", *Case Stud. Constr. Mater.*, **3**, 70-77. https://doi.org/10.1016/j.cscm.2015.07.002.

Liu, Y.S., Fu, H.L., Rao, J.Y., Dong, H. and Cao, Q. (2012), "Research on Brazilian discsplittingtestsfor anisotropyof slateunder influenceofdifferent bedding orientation", *Chin. J. Rock Mech. Eng.*, **31**, 785-791. (in Chinese)

Liu, Y.S., Fu, H.L., Rao, J.Y., Dong, H. and Zhang, H.M. (2013), "Tensile strength of slate based on Hoek-Brown criterion", *Chin. J. Rock Mech. Eng.*, **35**, 1172-1177. (in Chinese)

Liu, Y.S., Fu, H.L., Wu, Y.M., He, Y.W. and Dong, H. (2013), "Study on Brazilian splitting test for slate based on single weak plane theory", *J. China Coal Soc.*, **38**, 1775-1780. (in Chinese)

Mobasher, B., Bakhshi, M. and Barsby, C. (2014), "Backcalculation of residual tensile strength of regular and high performance fibre reinforced concrete from flexural tests", *Constr. Build. Mater.*, **70**, 243-253. https://doi.org/10.1016/j.conbuildmat.2014.07.037.

Noel, M. and Soudki, K. (2014), "Estimation of the crack width and deformation of FRP-reinforced concrete flexural members with and without transverse shear reinforcement", *Eng. Struct.*, **59**, 393-398. https://doi.org/10.1016/j.engstruct.2013.11.005

Oliveira, H.L. and Leonel, E.D. (2014), "An alternative BEM formulation, based on dipoles of stresses and tangent operator technique, applied to cohesive crack growth modeling", *Eng. Anal. Bound. Elem.*, **41**, 74-82. https://doi.org/10.1016/j.enganabound.2014.01.002.

Potyondy, D.O. (2015), "The bonded-particle model as a tool for rock mechanics research and application: current trends and future directions", *Geosystem. Eng.*, **18**, 1-28. https://doi.org/10.1080/12269328.2014.998346.

Sardemir, M. (2016), "Empirical modeling of flexural and splitting tensile strengths of concrete containing fly ash by GEP", *Comput. Concrete*, **17**(4), 489-498. https://doi.org/10.12989/cac.2016.17.4.489.

Sarfarazi, V. and Haeri, H. (2016), "A review of experimental and numerical investigations about crack propagation", *Comput. Concrete*, **18**(2), 235-266. http://dx.doi.org/10.12989/cac.2016.18.2.235.

Sarfarazi, V., Faridi, H.R., Haeri, H. and Schubert, W. (2016c), "A new approach for measurement of anisotropic tensile strength of concrete", *Adv. Concrete Constr.*, **3**(4), 269-284. http://dx.doi.org/10.12989/acc.2015.3.4.269

Sarfarazi, V., Ghazvinian, A., Schubert, W., Blumel, M. and Nejati, H.R. (2013), "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.

Shuraim, A.B., Aslam, F., Hussain, R. and Alhozaimy, A. (2016), "Analysis of punching shear in high strength RC panels-experiments, comparison with codes and FEM results", *Comput. Concrete*, **17**(6), 739-760. https://doi.org/10.12989/cac.2016.17.6.739.

Silva, R.V., Brito, J. and Dhir, R.K. (2015), "Tensil strength behaviour of recycled aggregate concrete", *Constr. Build. Mater.*, **83**, 108-118. https://doi.org/10.1016/j.conbuildmat.2015.03.034.

Tavallali, A. and Vervoort, A. (2010), "Effect of layer orientation on the failureof layered sandstone under Braziliantest conditions", *Int. J. Rock Mech. Min. Sci.*, **47**, 313-322. https://doi.org/10.1016/j.ijrmms.2010.01.001.

Tavallali, A. and Vervoort, A. (2013), "Behaviour of layered sandstone under Brazilian test conditions: Layer orientation and shape effects", *J. Rock Mech. Geotech. Eng.*, **5**, 366-377. https://doi.org/10.1016/j.jrmge.2013.01.004.

Tiang, Y., Shi, S., Jia, K. and Hu, S. (2015), "Mechanical and dynamic properties of high strength concrete modified with lightweight aggregates presaturated polymer emulsion", *Constr. Build. Mater.*, **93**, 1151-1156. https://doi.org/10.1016/j.conbuildmat.2015.05.015.

Wan Ibrahim, M.H., Hamzah, A.F., Jamaluddin, N., Ramadhansyah, P.J. and Fadzil, A.M. (2015), "Split tensile strength on self-compacting concrete containing coal bottom ash", *Procedia-Soc. Behav. Sci.*, **198**, 2280-2289. https://doi.org/10.1016/j.sbspro.2015.06.317.

Wang, T., Xu, D., Elsworth, D. and Zhou, W. (2016c), "Distinct element modeling of strength variation in jointed rock masses under uniaxial compression", *Geomech. Geophys. Geo-Energy Geo-Resour.*, **2**, 11-24. https://doi.org/10.1007/s40948-015-0018-7.

Wasantha, P., Ranjith, P., Zhang, Q. and Xu, T. (2015), "Do joint geometrical properties influence the fracturing behaviour of jointed rock? An investigation through joint orientation", *Geomech. Geophys. Geo-Energy Geo-Resour.*, **1**, 3-14. http://dx.doi.org/ 10.1007/s40948-015-0001-3.

Wu, W., Wang, G.B. and Mao, H.J. (2010), "Investigation of porosity effect on mechanical strength characteristics of dolostone", *Rock Soil Mech.*, **31**, 3709-3714.

Zhang, X.P. and Wong, L.N.Y. (2012), "Cracking processes in rock-like material containing a single flaw under uniaxial compression: A numerical study based on parallel bonded-particle model approach", *Rock Mech. Rock Eng.*, **45**, 711-737. https://doi.org/10.1007/s00603-011-0176-z.

Zhang, X.P. and Wong, L.N.Y. (2013), "Crack initiation, propagation and coalescence in rock-like material containing two flaws: A numerical study based on bonded-particle model approach", *Rock Mech. Rock Eng.*, **46**, 1001-1021. https://doi.org/10.1007/s00603-012-0323-1.

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