Structural Engineering and Mechanics, *Vol. 69, No. 1 (2019) 43-50*
DOI: https://doi.org/10.12989/sem.2019.69.1.043

Numerical simulation of the effect of bedding layer on the tensile failure mechanism of rock using PFC2D

Vahab Sarfarazi[1a], Hadi Haeri[*2] and Mohammad Fatehi Marji[3b]

[1]*Department of Mining Engineering, Hamedan University of Technology, Hamedan, Iran*
[2]*Young Researchers and Elite Club, Bafgh Branch, Islamic Azad University, Bafgh, Iran*
[3]*Department of Mining Engineering, Yazd University, Yazd, Iran*

(Received April 7, 2018, Revised October 24, 2018, Accepted November 13, 2018)

Abstract. In this research, the effect of bedding layer on the tensile failure mechanism of rocks has been investigated using PFC2D. For this purpose, firstly calibration of PFC2d was performed using Brazilian tensile strength. Secondly Brazilian test was performed on the bedding layer. Thickness of layers were 5 mm, 10 mm and 20 mm. in each thickness layer, layer angles changes from 0° to 90° with increment of 15°. Totally, 21 model were simulated and tested by loading rate of 0.016 mm/s. The results show that when layer angle is less than 15, tensile cracks initiates between the layers and propagate till coalesce with model boundary. Its trace is too high. With increasing the layer angle, less layer mobilizes in failure process. Also, the failure trace is very short. It's to be noted that number of cracks decrease with increasing the layer thickness. Also, Brazilian tensile strength is minimum when bedding layer angle is between 45° and 75°. The maximum one is related to layer angle of 90°.

Keywords: bedding layer; Brazilian test; anisotropy; crack; PFC2D

1. Introduction

The anisotropy of rocks is an important property which should be considered in many engineering applications such as mining, tunneling and civil where the surface and underground rock excavations and structures are to be designed in different types of rock masses.

Many rock masses exhibit some apparent anisotropic characteristics so that most of their mechanical, thermal, seismic, and hydraulic properties may vary with direction of applied loading. It means that no consideration of the anisotropy may produce considerable errors in the engineering application of rock masses in different rock structures (Amadei 1982, 1983, 1996, Barla 1974, Pinto 1966, 1970, 1979, Rodrigues 1966, Salamon 1968). Among these the layered rocks impose anisotropy because they usually contain many planes of weaknesses in form of random cracks, schistosity, joints, beddings, faults and fault zones As an example, the anisotropy may has profound effects on the compressive and tensile strengths of rock masses because these rocks contain the weak planes called the transversely isotropic planes (Chen 1998, Chou 2008, Exadaktylos 2001, Nasseri 1997, 2003, Ramamurthy 1993, Tien 2000. As the direction of the bedding (weak) planes changes the failure process of a bedded rock mass also changes (Tien 2006, Tavallali 2010a, b). Two kinds of failure process may occur in a bedded rock formation: i) the compressive failure process which includes the internal compression shear failure usually occurs along the bedding planes in form of sliding failure, and ii) three forms of tensile failure process may occur in forms of pure tensile failure or shearing failure or both tensile and shearing failures. The experimental results obtained from the laboratory tests conducted on many rock samples of different rock types have shown that in several types of rocks (especially those of metamorphic and sedimentary types) there are some kind of inherent or structural anisotropy (Saeidi *et al.* 2013, Hoek 1964, McLamore and Gray 1967, Horino and Ellickson 1970, Kwasniewski 1993, Nasseri *et al.* 2003, Al-Harthi 1998).

Most of the sedimentary rocks may be considered as isotropic or anisotropic rocks depending on the spacing in between the bedding planes or lamination of the rock structure during their formations. In most cases, the metamorphic rocks can be considered as anisotropic due to their inherent structures in form of schistosity and cleavage (Singh *et al.* 1989, Ramamurthy 1993). The effects of schistosity orientation on the Brazilian tensile strength (BTS) of many metamorphic rocks have been studied by several researchers such as Berenbaum and Brodie (1959), Hobbs (1963) and Debecker and Vervoort (2009). The indirect tensile strength of most sedimentary rocks is also affected by the layer orientations and has been investigated based on the Brazilian tensile tests in many rock mechanics laboratories (Hobbs 1963, McLamore and Gray 1967, Tavallali and Vervoort 2010a, b, Chen *et al.* 1998). Various modes of rock failures have been reported in the rock mechanics literature. These rock failure tests have been conducted on several anisotropic rock samples. Chen *et al.* (1998) conducted some experimental works and suggested two major modes of tensile splitting of the sandstone

*Corresponding author, Assistant Professor
E-mail: h.haeri@bafgh-iau.ac.ir or haerihadi@gmail.com
[a]Assistant Professor
[b]Associate Professor

http://www.techno-press.com/journals/sem&subpage=7 ISSN: 1225-4568 (Print), 1598-6217 (Online)

samples along the loaded diameter of the specimens and one shear modes of failure along the sandstone layers. In another experimental investigation, Tavallali and Vervoort (2010b) identified three types of failure modes in the Brazilian disc-shaped specimens of anisotropic rocks under indirect tensile conditions i.e., i) activation of layers (fractures are formed roughly parallel to the layers direction), ii) formation of central fractures [these fractures are induced roughly parallel to the loading direction at the central part of the specimen, and iii) development of non-central fractures. A few experiments and simulations have been reported for the breakage analysis of rock-type and concrete specimens under different loading (Zhou *et al.* 2014, Haeri *et al.* 2014, Zhou *et al.* 2012, Lancaster *et al.* 2013, Mobasher *et al.* 2014, Noel and Soudki 2014, Oliveira and Leonel, 2014, Kim and Taha 2014, Tiang *et al.* 2015, Haeri 2015, Haeri *et al.* 2015a, b, c, Wan Ibrahim *et al.* 2015, Silva *et al.* 2015, Gerges *et al.* 2015, Liu *et al.* 2015, Fan *et al.* 2016, Li *et al.* 2016, Sardemir 2016, Shuraim 2016, Sarfarazi *et al.* 2016, Haeri *et al.* 2016a, b, c, Haeri and Sarfarazi 2016). Many numerical methods can be applied to investigate the effect of bedding Layer geometrical properties on the punch shear test, such as General Particle Dynamics (GPD) (Bi *et al.* 2017, Zhou *et al.* 2016, Bi *et al.* 2015). Peridynamics(PD) (Silling 2000, Zhou 2015, Yunteng 2017, Wang 2018), The Extended Finite Element Method (Zhou 2015a, b).

In this study, the Brazilian discs of laminated rocks are numerically simulated to approximately determine the effects of weak (laminar) planes on the failure strengths and fracture patterns of the bedded rocks.

2. Numerical modeling with PFC2D

A particular rock mass can be considered as an assemblage of rigid particles bonded to each other at a specified number of contact points (Cundall 1971, Potyondy and Cundall 2004). In a two dimensional particle flow code (PFC2D), the circular discs are modelled in such a way that they are connected to each other at the specified contact points considering the cohesive and frictional bonds and then confined with planar walls. In this study, the parallel bond modelling approach is adopted to numerically simulate the contacts points in between the bonded particles. However, the assigned values for the bonding strengths influence the macro strength of the simulated samples, the nature of cracking and the failure process occurs during the loading. As far as the particles stay in contact, the specified coefficient of friction is mobilized. When the applied normal stress exceeds that of the specified normal bonding strength, the tensile cracks are occurred within the sample. On the other hand, the shear cracks are generated when the induced shear stress surplus those of the specified shear strengths of the bonding due to rotation or in-plane shearing of particles. After the bond breaks, the tensile strength at the contact immediately drops to zero while the shear strength of the bond decreases to that of the residual friction value (Itasca Consulting Group Inc. 2004, Cho *et al.* 2007, 2008, Potyondy and Cundall 2004, Sarfarazi *et al.* 2014). In PFC2D, it is only necessary to select the basic micro-parameters to describe the contact bond stiffness, the bond strength and the coefficient of contact friction for all these microscopic behaviors. It is of particular importance that these micro-parameters should provide a macro-scale behavior for the material being modeled.

Table 1 micro properties used to represent the intact rock

Parameter	Value	Parameter	Value
Type of particle	disc	Parallel bond radius multiplier	1
density	3500	Young modulus of parallel bond (GPa)	32
Minimum radius	0.27	Parallel bond stiffness ratio	2
Size ratio	1.56	Particle friction coefficient	0.5
Porosity ratio	0.08	Parallel bond normal strength, mean (MPa)	20
Damping coefficient	0.7	Parallel bond normal strength, SD (MPa)	2
Contact young modulus (GPa)	32	Parallel bond shear strength, mean (MPa)	20
Stiffness ratio	2	Parallel bond shear strength, SD (MPa)	2

Table 2 micro properties used to represent the bedding interfaces

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

For the solution of each particular problem, this discrete element code uses an explicit finite difference scheme to solve the equation of force and motion. Therefore, one may easily track the initiation and propagation of bonding fractures through the particles system (Potyondy and Cundall 2004). However, a calibrated PFC2D modelling an assembly of particles can be created by adopting the micro-properties listed in Table 1 and by using the standard calibration procedures (Potyondy and Cundall 2004).

2.1 Numerical biaxial tests on non-persistent open joint

2.1.1 Preparing the model

After calibrating PFC2D, some typical Brazilian tests were numerically simulated for modelling the anisotropic rock samples by creating a circular modelling scheme as shown in Figs. 1, 2 and 3, respectively. The diameter of each modelled specimen was selected as 54 mm and a total number of 8,179 discs each having a minimum radius of 0.27 mm were used to complete the numerical modelling of the specimen. All particles in the assembly were surrounded by two walls of the specimen. Bedding layers were formed in the model. Layers thicknesses were 5 mm, 10 mm and 20 mm. in constant layer thickness, the layer angularity changes from 0° to 90° with increment of 15°.

In total, 21 specimens containing different bedding layer were set up to investigate the influence of Layers thickness and layer angularity on failure behavior of models. Micro-

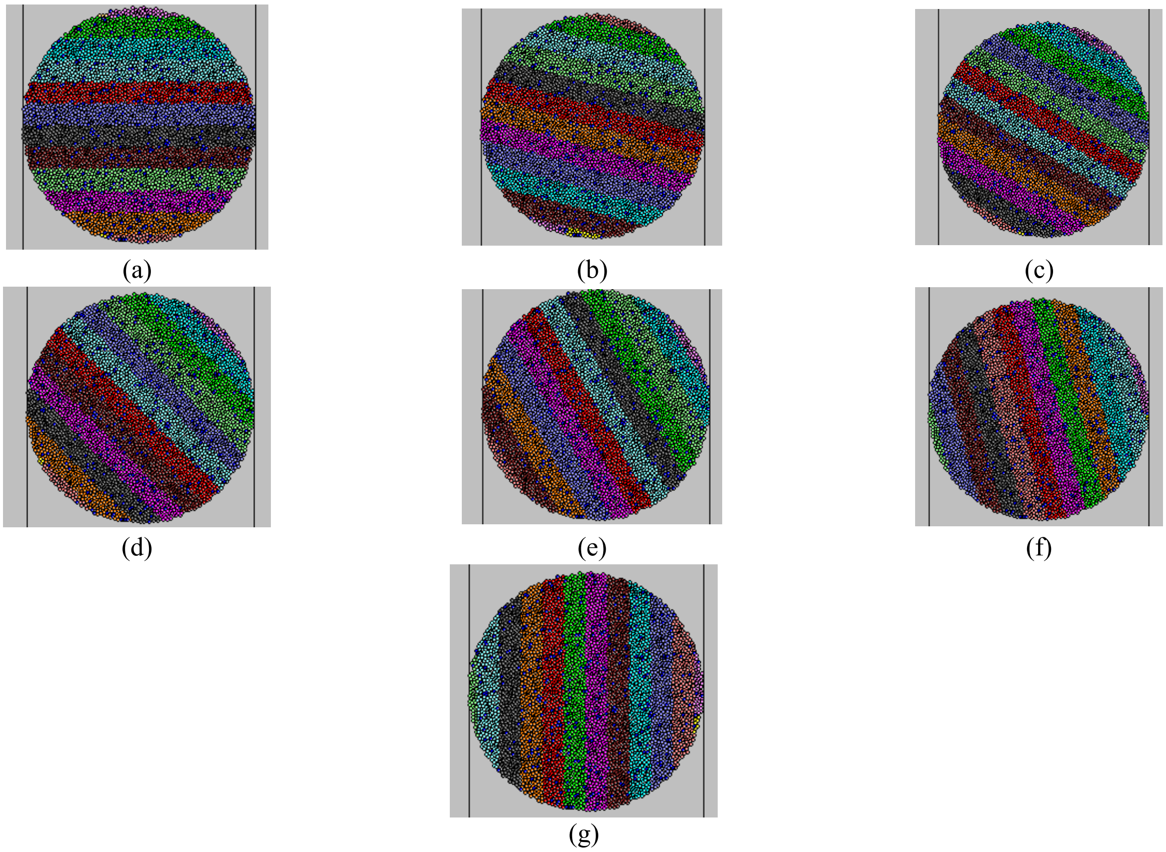


Fig. 1 Anisotropic rock with Layers thicknesses of 5 mm and layer angle of (a) 0°, (b) 15°, (c) 30°, (d) 45°, (e) 60°, (f) 75° and (g) 90°

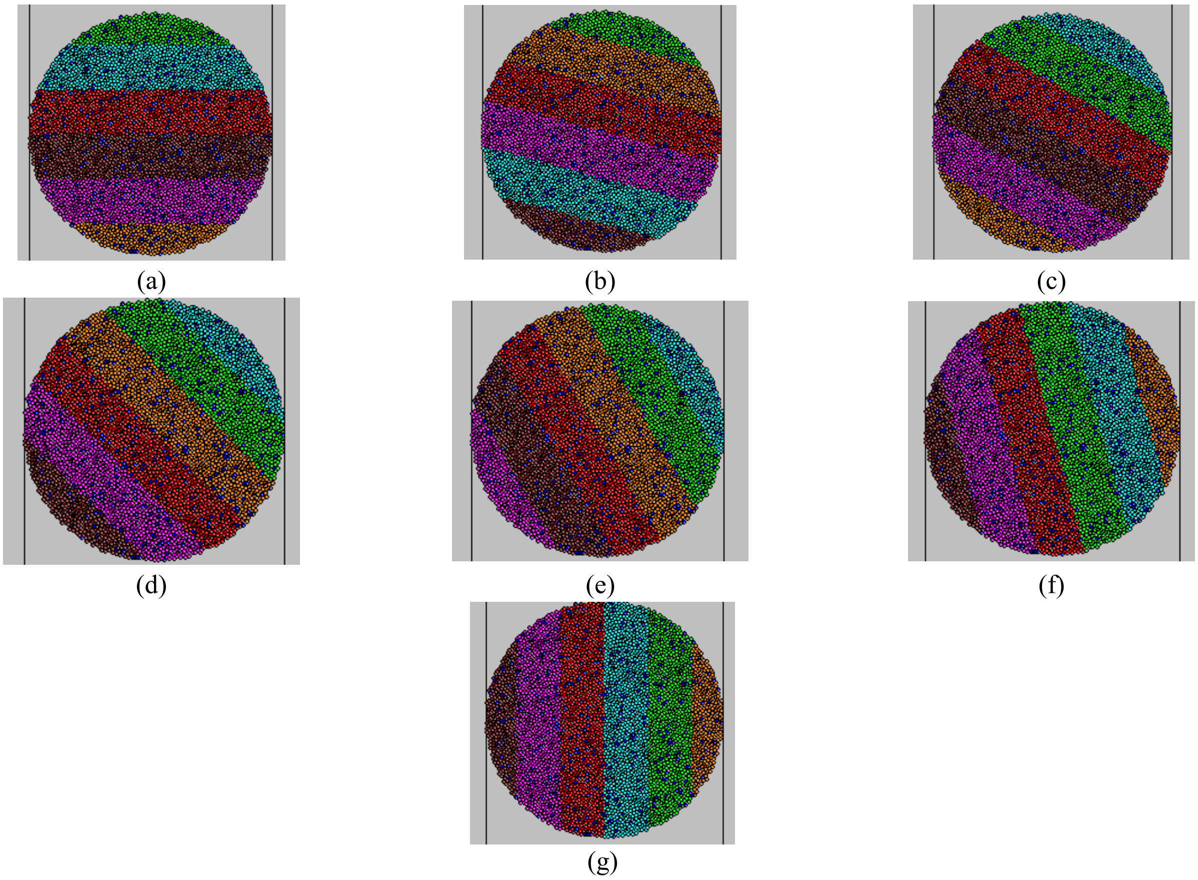
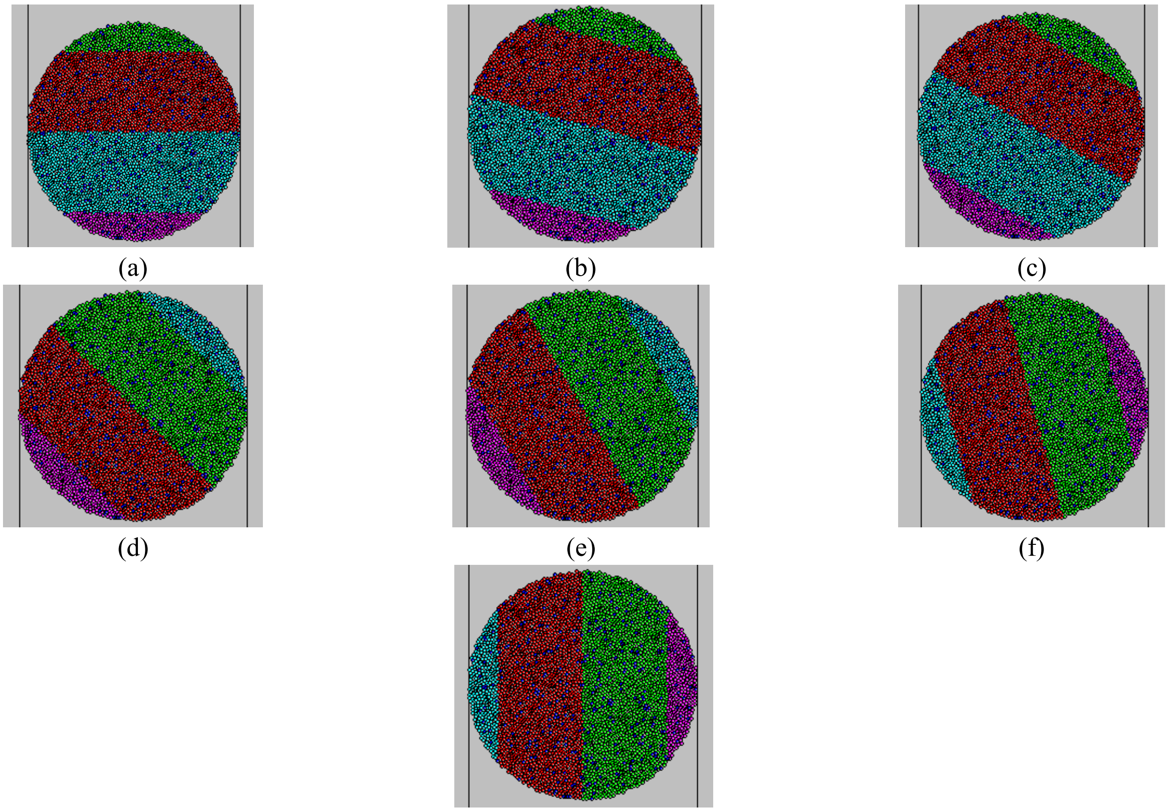
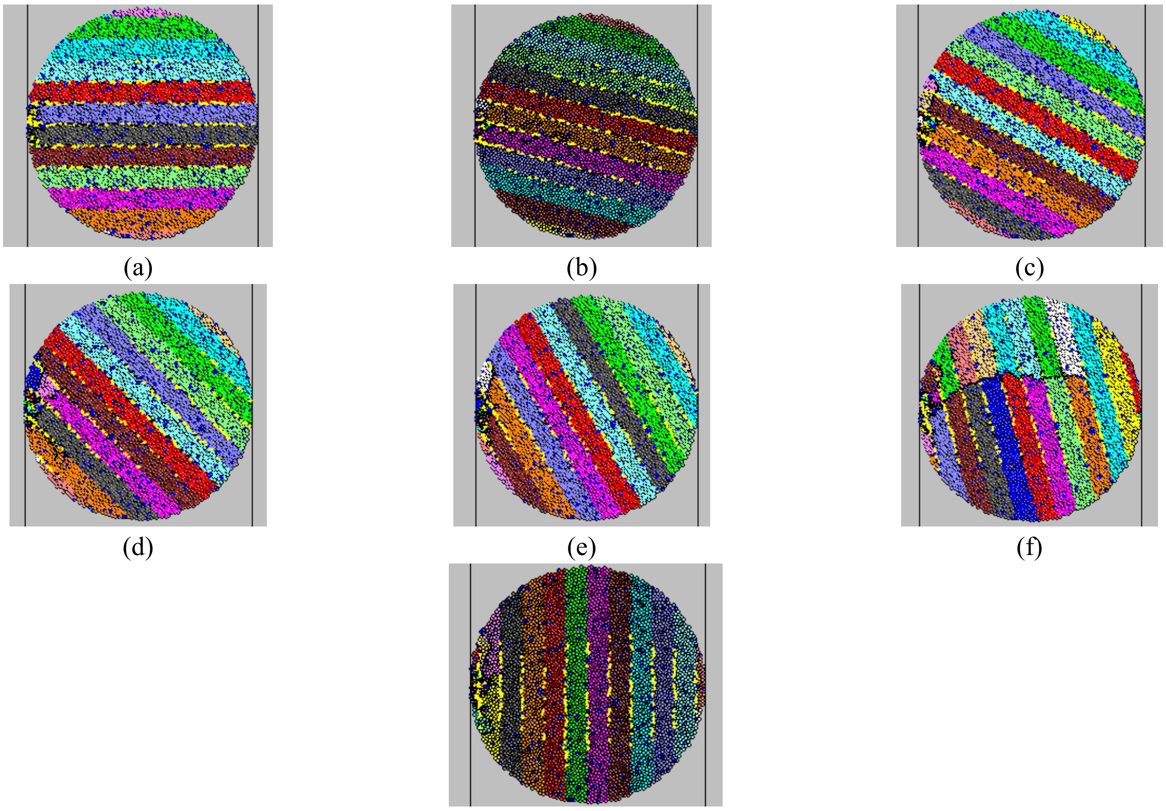


Fig. 2 Anisotropic rock with Layers thicknesses of 10 mm and layer angle of (a) 0°, (b) 15°, (c) 30°, (d) 45°, (e) 60°, (f) 75° and (g) 90°



(g)

Fig. 3 Anisotropic rock with Layers thicknesses of 20 mm and layer angle of (a) 0°, (b) 15°, (c) 30°, (d) 45°, (e) 60°, (f) 75° and (g) 90°



(g)

Fig. 4 Failure pattern in anisotropic rock with layers thicknesses of 5 mm and layer angle of (a) 0°, (b) 15°, (c) 30°, (d) 45°, (e) 60°, (f) 75° and (g) 90°

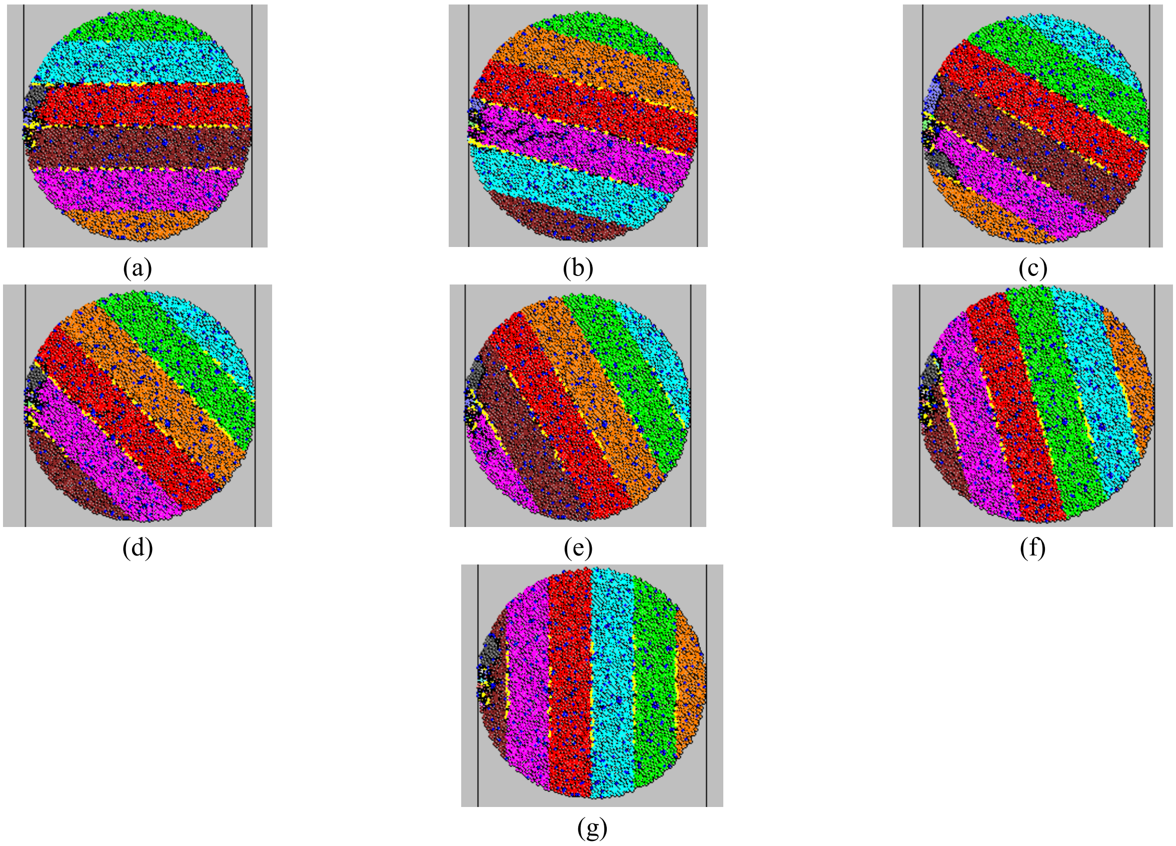


Fig. 5 Failure pattern in anisotropic rock with layers thicknesses of 10 mm and layer angle of (a) 0°, (b) 15°, (c) 30°, (d) 45°, (e) 60°, (f) 75° and (g) 90°

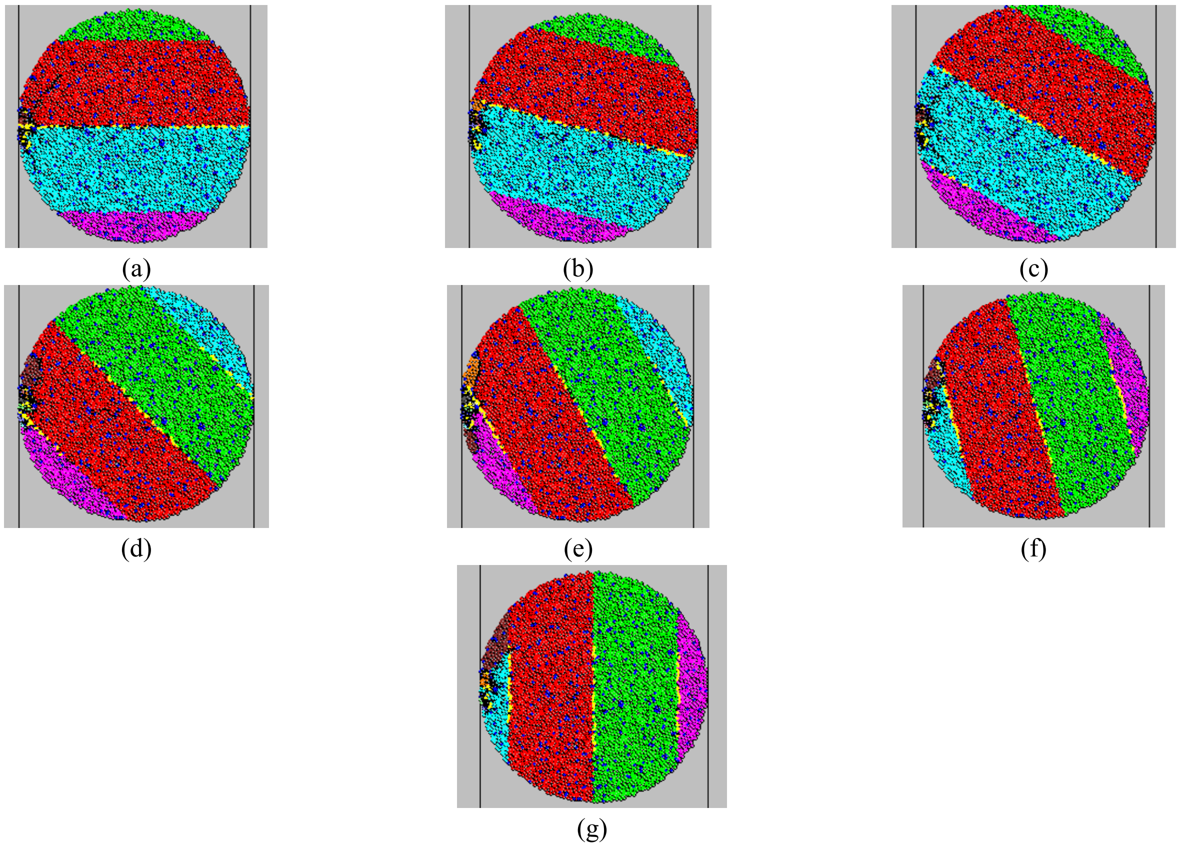


Fig. 6 Failure pattern in anisotropic rock with layers thicknesses of 20 mm and layer angle of (a) 0°, (b) 15°, (c) 30°, (d) 45°, (e) 60°, (f) 75° and (g) 90°

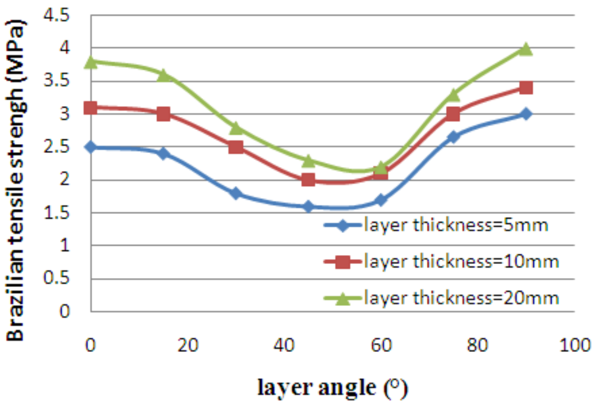


Fig. 7 the effect of bedding layer angle on the Brazilian tensile strength

properties for bedding layer interfaces was chosen too low (Table 2).

3. Results

3.1 The effect of layer angel on the failure pattern of models

Figs. 4, 5 and 6 shows the effect of layer thickness and layer angels on the failure pattern of models. Red line and black line represent the tensile crack and shear crack, respectively.

When layer angle is less than 15 (Fig. 4(a), (b), Fig. 5(a), (b), Fig. 6(a), (b)), tensile cracks initiates between the layers and propagate till coalesce with model boundary. Its trace is too high. With increasing the layer angle, less layer mobilizes in failure process. Also, the failure trace is very short. It's to be noted that number of cracks decrease with increasing the layer thickness (Figs. 4, 5, 6). It's to be notes that in Fig. 4(f), one shear crack goes through the model because the loading step has maximum value in this figure.

3.2 The effect of bedding layer specification on the Brazilian tensile strength

Fig. 7 shows the effect of bedding layer angle on the Brazilian tensile strength. Also, the results of bedding layer thickness have been shown in this figure. The minimum Brazilian strength was occurred when layer angle is between the 30° and 60°. The maximum value occurred in 90°. Also, the Brazilian tensile strength was increased by increasing the layer thickness.

4. Conclusions

In this work the effect of bedding layers angle and layers thickness on the Brazilian failure mechanism of rock has been investigated using PFC2D. Firstly calibration of PFC2d was performed using laboratory Brazilian tensile strength. Secondly Brazilian test was performed on the bedding layer. Thickness of layers were 5mm, 10mm and 20mm. in each thickness layer, layer angles changes from 0° to 90° with increment of 15°. Totally 21 model were simulated and tested. The results show that:

- When layer angle is less than 15°, tensile cracks initiates between the layers and propagate till coalesce with model boundary. Its trace is too high.
- With increasing the layer angle, less layer mobilizes in failure process. Also, the failure trace is very short.
- It's to be noted that number of cracks decrease with increasing the layer thickness.
- Also, Brazilian tensile strength has minimum value when bedding layer angle is between 45° and 75°. The maximum one is related to layer angle of 90°.

References

Al-Harthi, A.A. (1998), "Effect of planar structures on the anisotropy of ranyah sandstone Saudi Arabia", *Eng. Geol.*, **50**(1-2), 49-57.

Amadei B, Rogers, J.D. and Goodman, R.E. (1983), "Elastic constants and tensile strength of anisotropic rocks", *Proceedings of the 5th International Congress of Rock Mechanics*, A189-196.

Amadei B. (1996), "Importance of anisotropy when estimating and measuring in situ stresses in rock", *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.*, **33**(3), 293-325.

Amadei, B. (1982), "The influence of rock anisotropy on measurement of stresses in-situ", Ph.D. Dissertation, University of California, Berkeley, U.S.A.

Barla, G. (1974), "Rock anisotropy: Theory and laboratory testing", *Rock Mech.*, 131-169.

Bi, J., Zhou, X.P. and Xu, X.M. (2017), "Numerical simulation of failure process of rock-like materials subjected to impact loads", *Int. J. Geomech.*, **17**(3), 04016073.

Bi, J., Zhou, X.P. and Qian, Q.H. (2016), "The 3D numerical simulation for the propagation process of multiple pre-existing flaws in rock-like materials subjected to biaxial compressive loads", *Rock Mech. Rock Eng.*, **49**(5), 1611-1627.

Berenbaum, R. and Brodie, I. (1959), "The tensile strength of coal", *J. Inst. Fuel*, **32**(222), 320-326.

Chen, C.S., Pan, E. and Amadei, B. (1998), "Determination strength of anisotropic Brazilian tests of deformability and tensile rock using", *Int. J. Rock Mech. Min. Sci.*, **35**(1), 43-61.

Cho, N., Martin, C.D. and Sego, D.C. (2007), "A clumped particle model for rock", *Int. J. Rock Mech. Min. Sci.*, **44**(7), 997-1010.

Cho, N., Martin, C.D. and Sego, D.C. (2008), "Development of a shear zone in brittle rock subjected to direct shear", *Int. J. Rock Mech. Min. Sci.*, **45**(8), 1335-1346.

Chou, Y.C. and Chen, C.S. (2008), "Determining elastic constants of transversely isotropic rocks using Brazilian test and iterative procedure", *Int. J. Numer. Anal. Meth. Geomech.*, **32**(3), 219-234.

Debecker, B. and Vervoort, A. (2009), "Experimental observation of fracture patterns in layered slate", *Int. J. Fract.*, **159**(1), 51-62.

Exadaktylos, G.E. and Kaklis, K.N. (2001), "Applications of an explicit solution for the transversely isotropic circular disc compressed diametrically", *Int. J. Rock Mech. Min. Sci.*, **38**(2), 227-243.

Fan, Y., Zhu, Z., Kang, J. and Fu, Y. (2016), "The mutual effects between two unequal collinear cracks under compression", *Math Mech. Sol.*, **22**(5), 1205-1218.

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.

Goodman, R.E. (1993), *Engineering Geology-Rock in Engineering Construction*, John Wiley and Sons, Inc., New York, U.S.A.

Haeri, H. (2015), "Propagation mechanism of neighboring cracks in rock-like cylindrical specimens under uniaxial compression", *J. Min. Sci.*, **51**(3), 487-496.

Haeri, H., Sarfarazi, V., Fatehi, M., Hedayat, A. and Zhu, Z. (2016c), "Experimental and numerical study of shear fracture in brittle materials with interference of initial double", *Acta Mech. Soil. Sinic.*, **29**(5), 555-566.

Haeri, H. (2016), "Propagation mechanism of neighboring cracks in rock-like cylindrical specimens under uniaxial compression", *J. Min. Sci.*, **51**(5), 1062-1106.

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.

Haeri, H., Khaloo, A. and Marji, M.F. (2015b), "Fracture analyses of different pre-holed concrete specimens under compression", *Acta Mech. Sinic.*, **31**(6), 855-870.

Haeri, H., Khaloo, A. and Marji, M.F. (2015c), "A coupled experimental and numerical simulation of rock slope joints behavior", *Arab. J. Geosci.*, **8**(9), 7297-7308.

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.

Haeri, H., Sarfarazi, V. and Lazemi, H. (2016b), "Experimental study of shear behavior of planar non-persistent joint", *Comput. Concrete*, **17**(5), 639-653.

Haeri, H. and Sarfarazi, V. (2016), "The effect of non-persistent joints on sliding direction of rock slopes", *Comput. Concrete*, **17**(6), 723-737.

Haeri, H., Shahriar, K. and Marji, M.F. (2013), "Modeling the propagation mechanism of two random micro cracks in rock samples under uniform tensile loading", *Proceedings of the ICF13*.

Haeri, H., Shahriar, K., Fatehi Marji, M. and Moarefvand, P. (2014), "On the crack propagation analysis of rock like Brazilian disc specimens containing cracks under compressive line loading", *Lat. Am. J. Sol. Struct.*, **11**(8), 1400-1416.

Hobbs, D.W. (1963), "The strength and stress-strain characteristics of coal in triaxial compression", *J. Geol.*, **72**(2), 214-223.

Hoek, E. (1964) "Fracture of transversely isotropic rock", *J. S. Afr. Inst. Min. Met.*, **64**, 501-518.

Horino, F.G. and Ellickson, M.L. (1970), *A Method of Estimating Strength of Rock Containing Planes of Weakness*, Report of Investigation 744, US Bureau of Mines.

Itasca Consulting Group Inc. (2004) *Particle Flow Code in 2-Dimensions (PFC2D)*, Version 3.10, Minneapolis, U.S.A.

Kim, J. and Taha, M.R. (2014), "Experimental and numerical evaluation of direct tension test for cylindrical concrete specimens", *Adv. Civil Eng.*, 1-8.

Kwasniewski, M. (1993), *Mechanical Behavior of Transversely Isotropic Rocks*, In: Hudson, J.A. (ed), *Comprehensive Rock Engineering*, Pergamon, Oxford, **1**, 285-312.

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.

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", *Measure.*, **82**, 421-431.

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.

McLamore, R. and Gray, K.E. (1967), "The mechanical behavior of transversely isotropic sedimentary rocks", *Trans. Am. Soc. Mech. Eng. Ser. B*, 62-76.

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.

Nasseri, M.H., Rao, K.S. and Ramamurthy, T. (1997), "Failure mechanism in schistose rocks", *Int. J. Rock Mech. Min. Sci.*, **34**(3-4), 219.

Nasseri, M.H.B., Rao, K.S. and Ramamurthy, T. (2003), "Anisotropic strength and deformational behavior of Himalayan schists", *Int. J. Rock Mech. Min. Sci.*, **40**(1), 3-23.

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.

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. Analy. Bound. Elem.*, **41**, 74-82.

Pinto, J.L. (1970), "Deformability of schistous rocks", *Proceedings of the 2nd International Congress of Rock Mechanics*.

Pinto, J.L. (1979), "Determination of the elastic constants of anisotropic bodies by diametral compression tests", *Proceedings of the 4th International Congress of rock Mechanics.*

Pinto, J.L. (1966), "Stresses and strains in anisotropic orthotropic body", *Proceedings of the 1st International Congress of Rock Mechanics*, Lisbon, Portugal.

Potyondy, D.O. and Cundall, P.A. (2004), "A bonded-particle model for rock", *Int. J. Rock Mech. Min. Sci.*, **41**(8), 1329-1364.

Ramamurthy T. (1933), *Strength, Modulus Responses of Anisotropic Rocks*, In: Hudson, J.A., Editor, *Comprehensive Rock Engineering*, Pergamon Press, Oxford, **1**, 313-329.

Rodrigues (1966), "Anisotropy of granites: Modulus of elasticity and ultimate strength ellipsoids ,joint systems, slope attitudes, and the correlations", *Proceedings of the 1st International Congress of Rock Mechanics*, Lisbon, Portugal.

Saeidi, O., Rasouli, V., GeranmayehVaneghi, R., Gholami, R. and Torabi, R. (2013), "A modified failure criterion for transversely isotropic rocks", *Geosci. Front.*

Salamon, M.D.G. (1968), "Elastic moduli of a stratified rock mass", *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.*, **5**(6), 519-512.

Sardemir, M. (2016), "Empirical modeling of flexural and splitting tensile strengths of concrete containing fly ash by GEP", *Comput. Concrete*, **17**(4), 489-498.

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.

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.

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.

Silva, R.V., Brito, J. and Dhir, R.K. (2015), "Tensile strength behaviour of recycled aggregate concrete", *Constr. Build. Mater.*, **83**, 108-118.

Silling, S.A. (2000), "Reformulation of elasticity theory for discontinuities and long-range forces", *J. Mech. Phys. Sol.*, **48**(1), 175-209.

Singh, J., Ramamurth, T. and Venkatappa, R.G. (1989), "Strength anisotropies in rocks", *Ind. Geotech. J.*, **19**(2), 147-166.

Tavallali, A. and Vervoort, A. (2010), "Effect of layer orientation on the failure of layered sand stone under Brazilian test conditions", *Int. J. Rock Mech. Min. Sci.*, **47**(2), 313-322.

Tavallali, A. and Vervoort, A. (2010), "Failure of layered sandstone under Brazilian test conditions: Effect of micro-Scale parameters on macro-scale behaviour", *Rock Mech. Rock Eng.*, **43**(5), 641-645.

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.

Tien, Y.M. and Kuo, M.C. (2006), "An experimental investigation of the failure mechanism of simulated transversely isotropic rocks", *Int. J. Rock Mech. Min. Sci.*, **43**(8), 1163-1181.

Tien, Y.M. and Tsao, P.F. (2000), "Preparation and mechanical properties of artificial transversely isotropic rock", *Int. J. Rock Mech. Min. Sci.*, **37**(6), 1001-1012 .

Wang, Y., Zhou, X.P. and Kou, M. (2018), "Peridynamic investigation on thermal fracturing behavior of ceramic nuclear fuel pellets under power cycles", *Ceram. Int.*, **44**(10), 11512-11542.

Yunteng, W., Zhou, X.P. and Shou, Y. (2017), "The modeling of crack propagation and coalescence in rocks under uniaxial compression using the novel conjugated bond-based peridynamics", *Int. J. Mech. Sci.*, **128**, 614-643.

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", *Proc.*-Social *Behav. Sci.*, **198**, 2280-2289.

Zhou, X.P., Shou, Y.D., Qian, Q.H. and Yu, M.H. (2014), "Three-dimensional nonlinear strength criterion for rock-like materials based on the micromechanical method", *Int. J. Rock Mech. Min. Sci.*, **72**, 54-60.

Zhou, X.P., Xia, E.M., Yang, H.Q. and Qian, Q.H. (2012), "Different crack sizes analyzed for surrounding rock mass around underground caverns in Jinping I hydropower station", *Theoret. Appl. Fract. Mech.*, **57**(1), 19-30.

Zhou, X.P., Bi, J., Qian, Q.H. (2015a), "Numerical simulation of crack growth and coalescence in rock-like materials containing multiple pre-existing flaws", *Rock Mech. Rock Eng.*, **48**(3), 1097-1114.

Zhou, X.P., Gu, X.B. and Wang, Y.T. (2015b), "Numerical simulations of propagation, bifurcation and coalescence of cracks in rocks", *Int. J. Rock Mech. Min. Sci.*, **80**, 241-254.

Zhou, X.P. and Yang, H.Q. (2012), "Multiscale numerical modeling of propagation and coalescence of multiple cracks in rock masses", *Int. J. Rock Mech. Min. Sci.*, **55**, 15-27.

CC