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Numerical simulation of the effect of bedding layer geometrical properties on the punch shear test using PFC3D

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Abstract. In this research the effect of bedding layer angle and bedding layer thickness on the shear failure mechanism of concrete has been investigated using PFC3D. For this purpose, firstly calibration of PFC3d was performed using Brazilian tensile strength. Secondly punch shear 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 25°. Totally 15 model were simulated and tested by loading rate of 0.016 mm/s. The results show that when layer angle is less than 50°, 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 note that number of cracks decrease with increasing the layer thickness. The minimum shear punch test strength was occurred when layer angle is more than 50°. The maximum value occurred in 0°. Also, the shear punch test tensile strength was increased by increasing the layer thickness.

Keywords: bedding layer; shear punch test; anisotropy; tensile crack; PFC3D

1. Introduction

The anisotropy behavior of concrete is of importance in many civil and concrete engineering applications and has been thoroughly demonstrated by many researchers. Concretes have some apparent anisotropic characteristics because their mechanical, hydraulic, thermal and seismic properties may vary with the direction of loading. Most of the engineering applications of concrete do not consider its anisotropic properties which may cause errors of different magnitudes depending on the degrees of rock anisotropy (Amadei 1982, 1983, 1996, Barla 1974, Pinto 1966, 1970, 1979, Rodrigues 1966, Salamon 1968). The anisotropy in concretes is usually in form of layers which are the planes of weaknesses such as schistosity, beddings, fault zones, joints and cracks (Goodman 1993). The compressive and tensile strengths of rocks are mainly affected by the weakness planes and their orientation with respect to the loading directions. These rocks are often called transversely isotropic rocks and have been treated in the literature by many researchers (Chen 1998, Chou 2008, Exadaktylos 2001, Nasseri 1997, 2003, Ramamurthy 1993, Tien 2000). The rock failure modes are manly affected by the variation of the bedding (layers) directions (Tien 2006, Tavallali 2010a, b).

It has been shown that the bedded concrete may have two kinds of compressive failure modes: the internal compression shear failure mode and the bedding plane sliding failure mode. On the other hand, they may exhibit three kinds of tensile failure modes as: the pure tensile failure, the shearing failure and the combined tensile and shearing failure modes. However, many experimental and numerical works have been carried out to study the cracks initiations and cracks propagations in many brittle materials under different loading conditions: (Silling 2000, Zhou 2004, Zhou *et al.* 2004, Zhou *et al.* 2007, Zhou *et al.* 2008, Wu *et al.* 2010, Zhou *et al.* 2012, Zhou *et al.* 2012, Lancaster *et al.* 2013, Ramadoss 2013, Pan *et al.* 2014, Zhou *et al.* 2014, Mobasher *et al.* 2014, Noel and Soudki 2014, Oliveira and Leonel 2014, Haeri *et al.* 2014, Kim and Taha 2014, Tiang *et al.* 2015, Wan Ibrahim *et al.* 2015, Silva *et al.* 2015, Gerges *et al.* 2015, Lee and Chang 2015, Kequan and Zhoudao 2015, Zhou *et al.* 2015, Liu *et al.* 2015, Zhou *et al.* 2015, Wasantha *et al.* 2015, Li *et al.* 2015, 2016, Haeri 2015a, b, c, Haeri *et al.* 2015a, b, c, Fan *et al.* 2016, Sardemir 2016, Sarfarazi *et al.* 2016, Shuraim 2016, Yaylac 2016, Haeri *et al.* 2016a, b, c, Haeri and Sarfarazi 2016, Wang *et al.* 2016, 2017, Akbas 2016, Rajabi 2016, Mohammad 2016, Bi *et al.* 2016, 2017, Wang 2018).

It has been experimentally shown by many investigators that several rock types specially those of metamorphic and sedimentary types, may inherently have 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). The sedimentary rocks can be treated as isotropic or transversely isotropic depending on the spacing of their beddings or laminations developed during their formation while, the metamorphic rocks are treated as anisotropic due to the effects of both schistosities and cleavages in their intrinsic textures (Singh *et al.* 1989, Ramamurthy 1993). The Brazilian tensile

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strength (BTS) of different metamorphic rocks considering the effects of the schistisity orientations have been studied in various researches works (Berenbaum and Brodie 1959, Hobbs 1963 and Debecker and Vervoort 2009). The double punch test was used by Hobbs (1963) on siltstone and by McLamore and Gray (1963) on shale. They both considered the effect of layers direction on the indirect tensile strength of sedimentary rocks. Chen *et al*. (1998) as well as Tavallali and Vervoort (2010a, b) repeated these works on sandstone samples. Chen *et al*. (1998) studied the failure behavior of sand stone and proposed two major modes of failures i.e., the tensile splitting along the loaded diameter of sandstone samples and the shear failure along the sandstone layers. On the other hand, Tavallali and Vervoort (2010b) tested the Brazilian disc type specimens of sand stones and identified three types of rocks failure modes for these anisotropic rocks i.e., (i) the fracture produced due to activating the layers (the fractures are produced and propagated roughly parallel to the layers direction), (ii) the central cracks (these fractures are developed roughly parallel to the loading direction but in the central part of the specimen (they usually situated on both sides of the specimens central line in between the two loading lines), and (iii) the non-central cracks (the fractures produced outside the central part of the specimen).

However, various modes of tensile failures of concretes samples have been observed and classified to simulate the anisotropic behaviors of rocks and rock-like materials. Therefore, this study numerically simulates the results of shear punch tests on modeled laminated concrete samples to determine the effect of weakness planes (laminations) on the failure strength and fracture patterns of these rock-like materials.

The shear punch test proposed by Backers (2002), is method for determination of shear strength of concrete (Fig. 1).

In this test, a concrete cylinder is placed vertically between the loading platens of the machine and is compressed by two steel punches placed on the top and bottom surfaces of the cylinder. The specimen splits across many vertical diametric planes similar to the split-cylinder test, but the testing arrangement for the new test may be reduced. The relation is proposed by Backers (2002)

$$\sigma = \frac{F}{A} \tag{1}$$

Where, σ is shear strength, F is failure load, A is area of bridge section.

2. Numerical modeling with PFC2D

Particle flow code represents a rock mass as an assemblage of bonded rigid particles (Cundall 1971, Potyondy and Cundall 2004). In its two dimensional version (PFC2D), circular disks are connected with cohesive and frictional bonds and confined with planar walls. Parallel bond model was adopted for this study to simulate the contacts between particles. Values assigned to the strength bonds influence the macro strength of sample and the nature of cracking and the failure occurs during the loading. Friction is activated by specifying coefficient of friction and is mobilized as long as the particles stay in contact. Tensile cracks occur when applied normal stress exceeds specified normal bond strength. Shear cracks are generated as applied shear stress surplus the specified shear bond strength either by rotation or by shearing of particles. Tensile strength at the contact immediately drops to zero after the bond breaks, while shear strength decreases to the residual friction value (Itasca Consulting Group Inc. 2004, Cho *et al.* 2007, 2008, Potyondy and Cundall 2004, Sarfarazi 2014). For all these microscopic behaviors, PFC requires only a selection of basic micro-parameters to describe contact, bond stiffness, bond strength and contact friction. But, these micro-parameters should provide a macro-scale behavior for the material being modeled. An inverse modeling technique based on the trial and error approach is adopted in PFC3D (Itasca

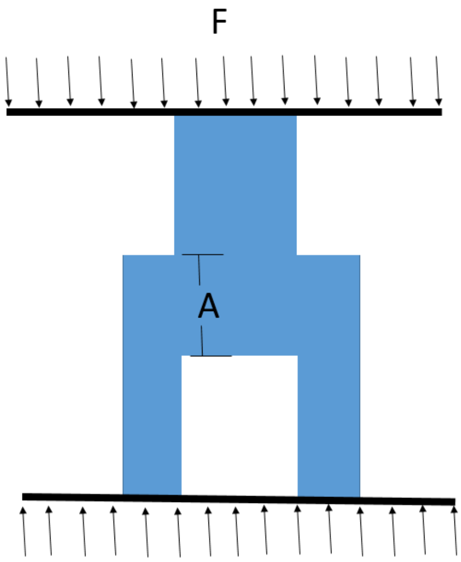


Fig. 1 Shear punch test, Backers (2002)

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/m^3)	3500	Young modulus of parallel bond (GPa)	32
Minimum radius (mm)	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		

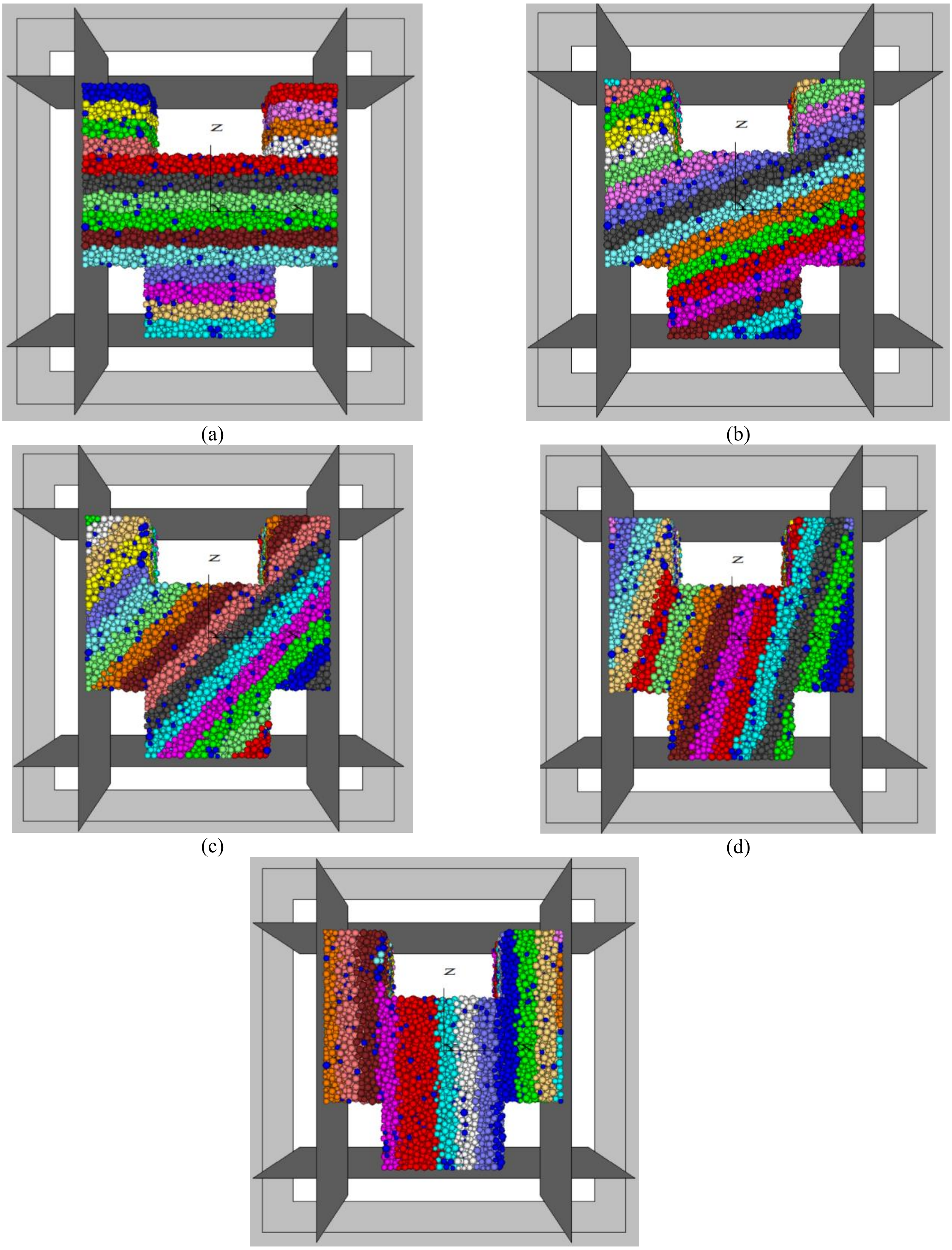


Fig. 2 anisotropic concrete with layers thicknesses of 5 mm and layer angle of (a) 0°, (b) 25°, (c) 50°, (d) 75°, (e) 90°

1999) to determine the appropriate micro mechanical properties of the particle assembly from the macro mechanical properties given by the experimental tests for the numerical simulation of any geo-mechanical problem. The code uses an explicit finite difference scheme to solve the equation of force and motion, and hence one can readily track the initiation and the propagation of bond breakage (fracture formation) through system (Potyondy and Cundall

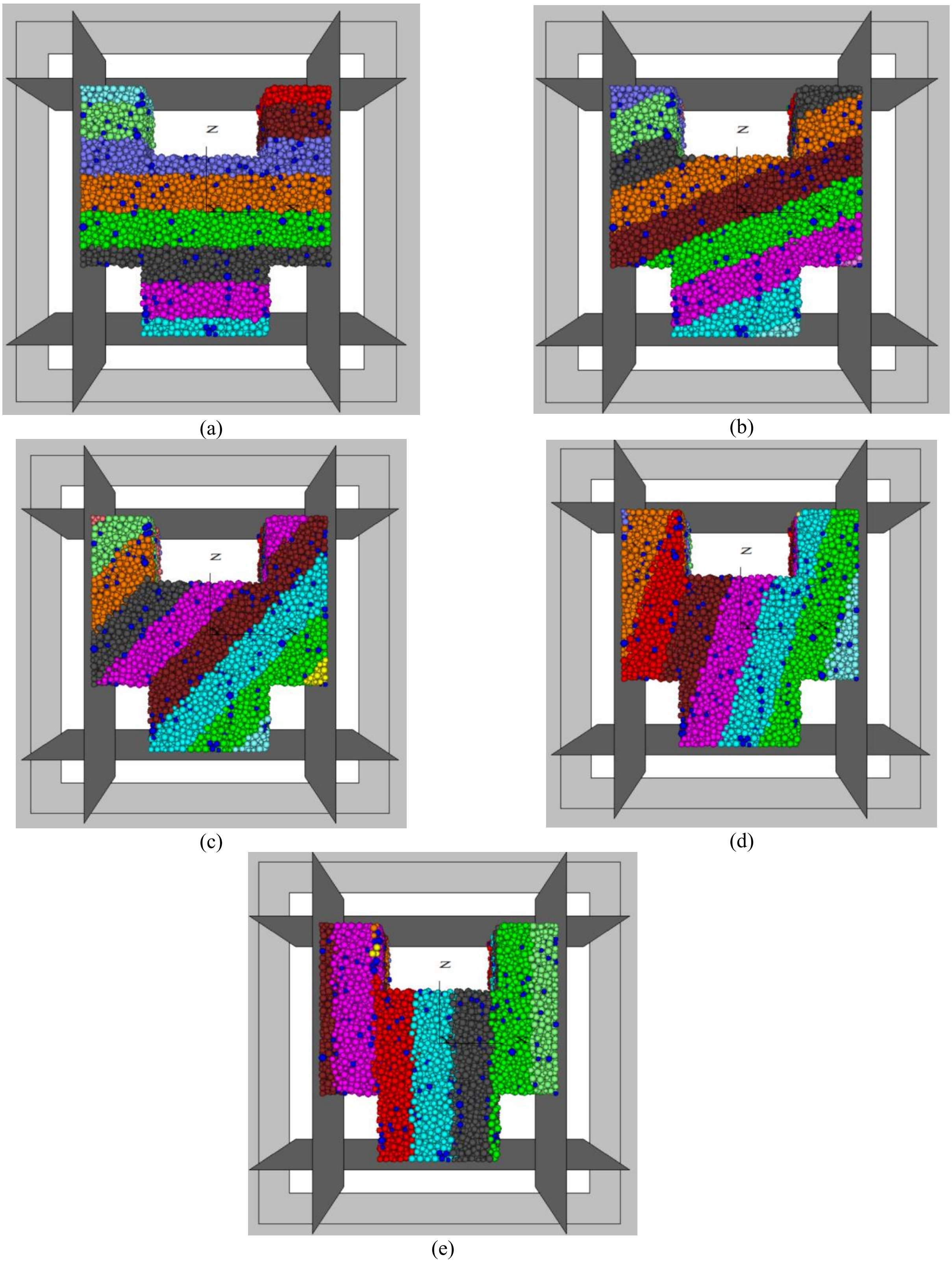


Fig. 3 Anisotropic concrete with layers thicknesses of 10 mm and layer angle of (a) 0°, (b) 25°, (c) 50°, (d) 75°, (e) 90°

2004). The limitations of DEM are: (a) Fracture is closely related to the size of elements, and that is so called size effect. (b) Cross effect exists because of the difference between the size and shape of elements with real grains. (c) In order to establish the relationship between the local and macroscopic constitutive laws, data obtained from classical geomechanical tests which may be impractical are used (Donze *et al*. 2009).

The advantages of PFC2D/3D compare to other numerical simulation are:

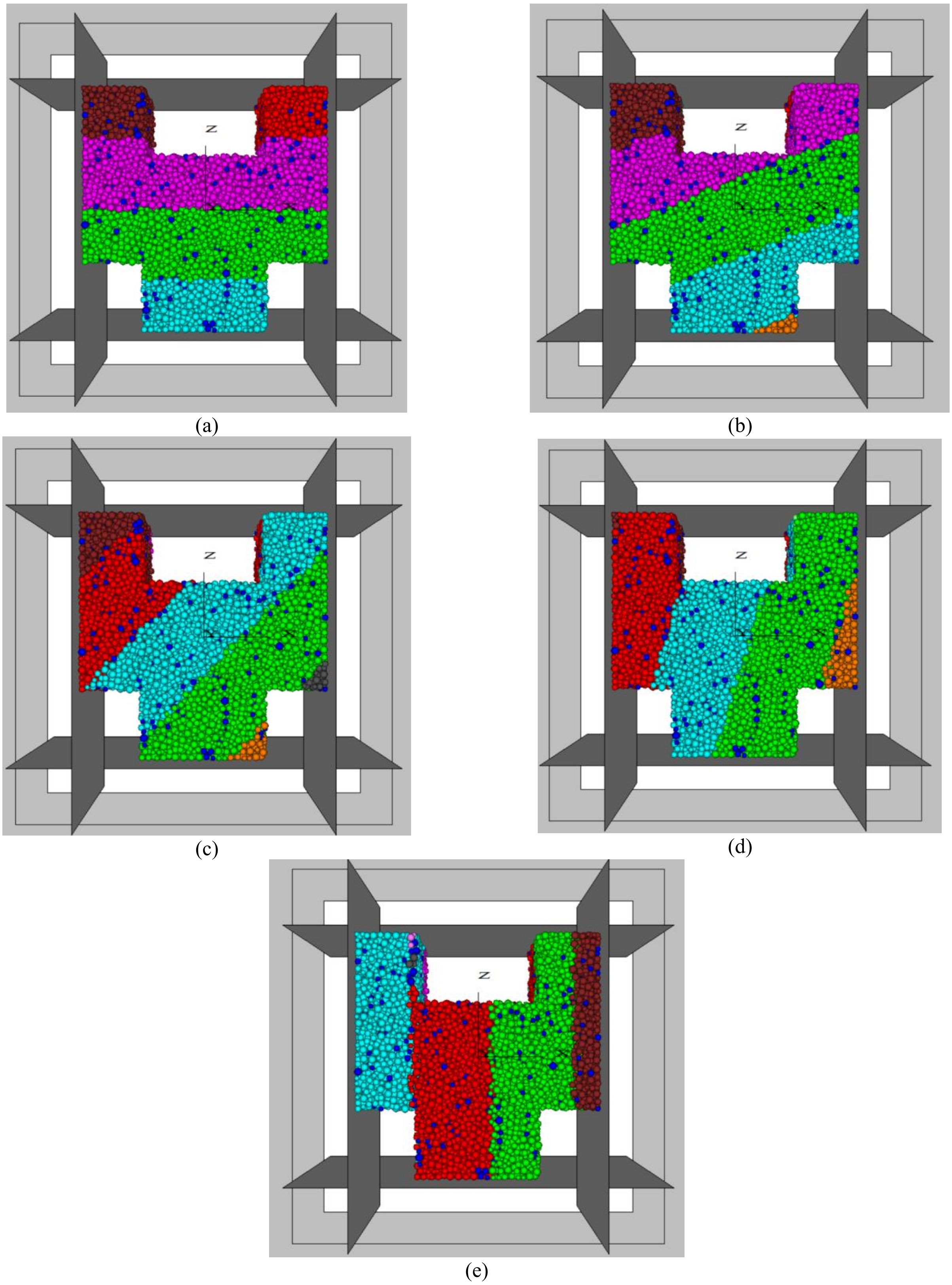


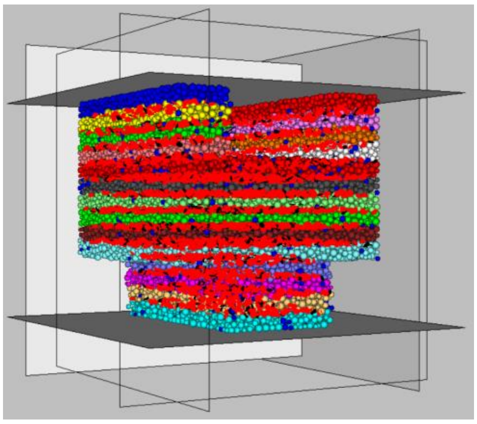
Fig. 4 Anisotropic concrete with layers thicknesses of 20 mm and layer angle of (a) 0°, (b) 25°, (c) 50°, (d) 75°, (e) 90°

1. They could predict crack initiation, propagation and coalescence in model by simple programing.

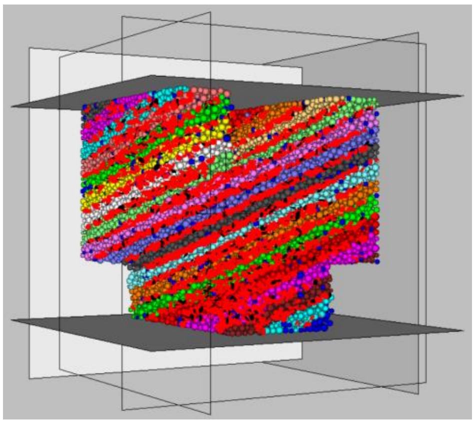
2. The run time is too short.

A calibrated PFC particle assembly was created by adopting the micro-properties listed in Table 1 and the standard calibration procedures (Potyondy and Cundall 2004).

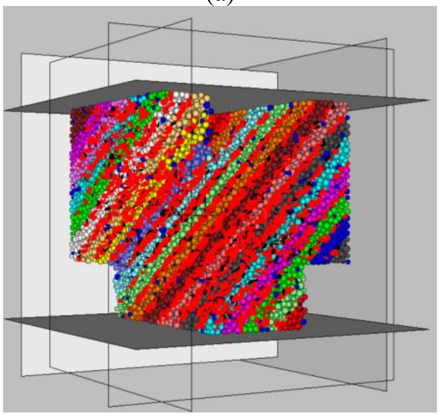
2.1 Numerical tests



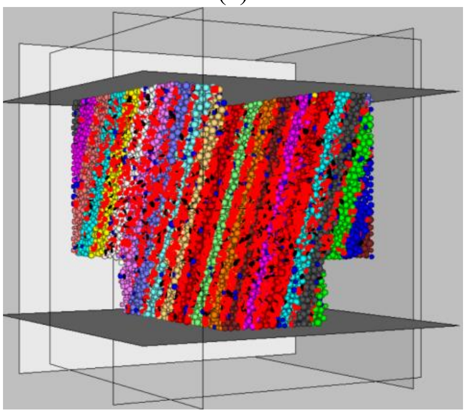
(a)



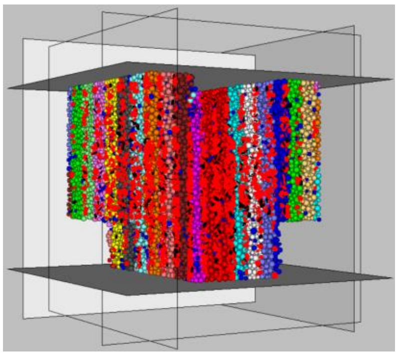
(b)



(c)



(d)



(e)

Fig. 5 Failure pattern in anisotropic concrete with layers thicknesses of 5 mm and layer angle of (a) 0°, (b) 25°, (c) 50°, (d) 75°, (e) 90°

2.1.1 Preparing the model

After calibrating PFC2D, shear punch tests in anisotropic concrete were numerically simulated by creating a rectangle model (Figs. 2, 3 and 4). PFC specimen dimension were 100 mm×100 mm. two rectangular band was removed from right and left of the model also one rectangular band was deleted from middle of the model (Figs. 2, 3 and 4). A total of 18,189 disks with a minimum radius of 0.27 mm were used to make up the specified specimen. Particles were surrounded by six walls. 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 25°.

In total, 15 specimens containing different bedding layer were set up to investigate the influence of Layers thickness and layer angularity on failure behavior of models. Micro-properties for bedding layer interfaces was chosen too low (Table 2). Two upper and lower loading walls move toward each other by rate of 0.016 mm/s.

3. Results

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

Figs. 5, 6 and 7 shows the effect of layer thickness and layer angels on the failure pattern of models. Red line and yellow line represent the tensile crack and shear crack, respectively.

When layer angle is less than 50° (Fig. 5(a), (b) and (c), Fig. 6(a), (b) and (c), Fig. 7(a), (b) and (c), tensile cracks

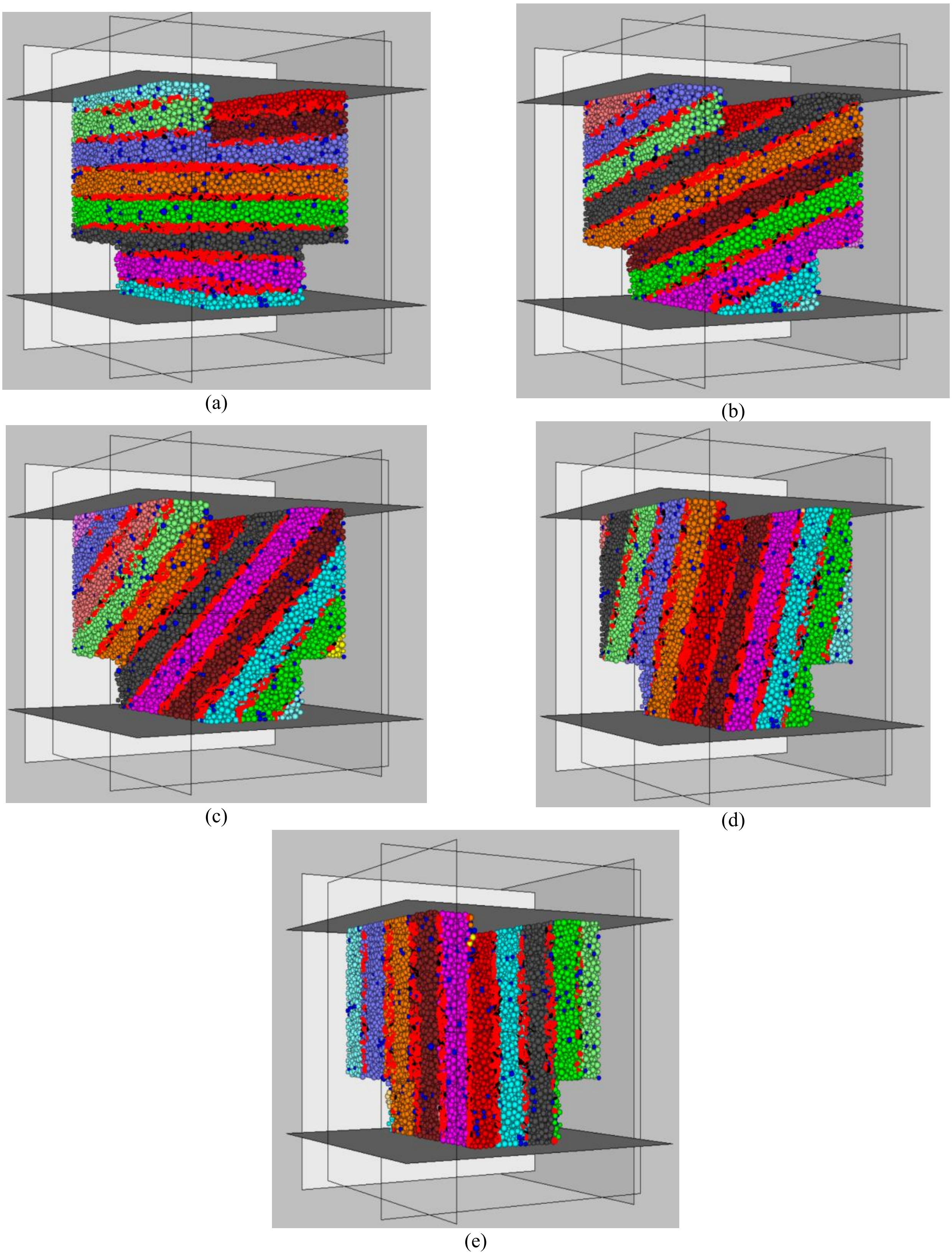
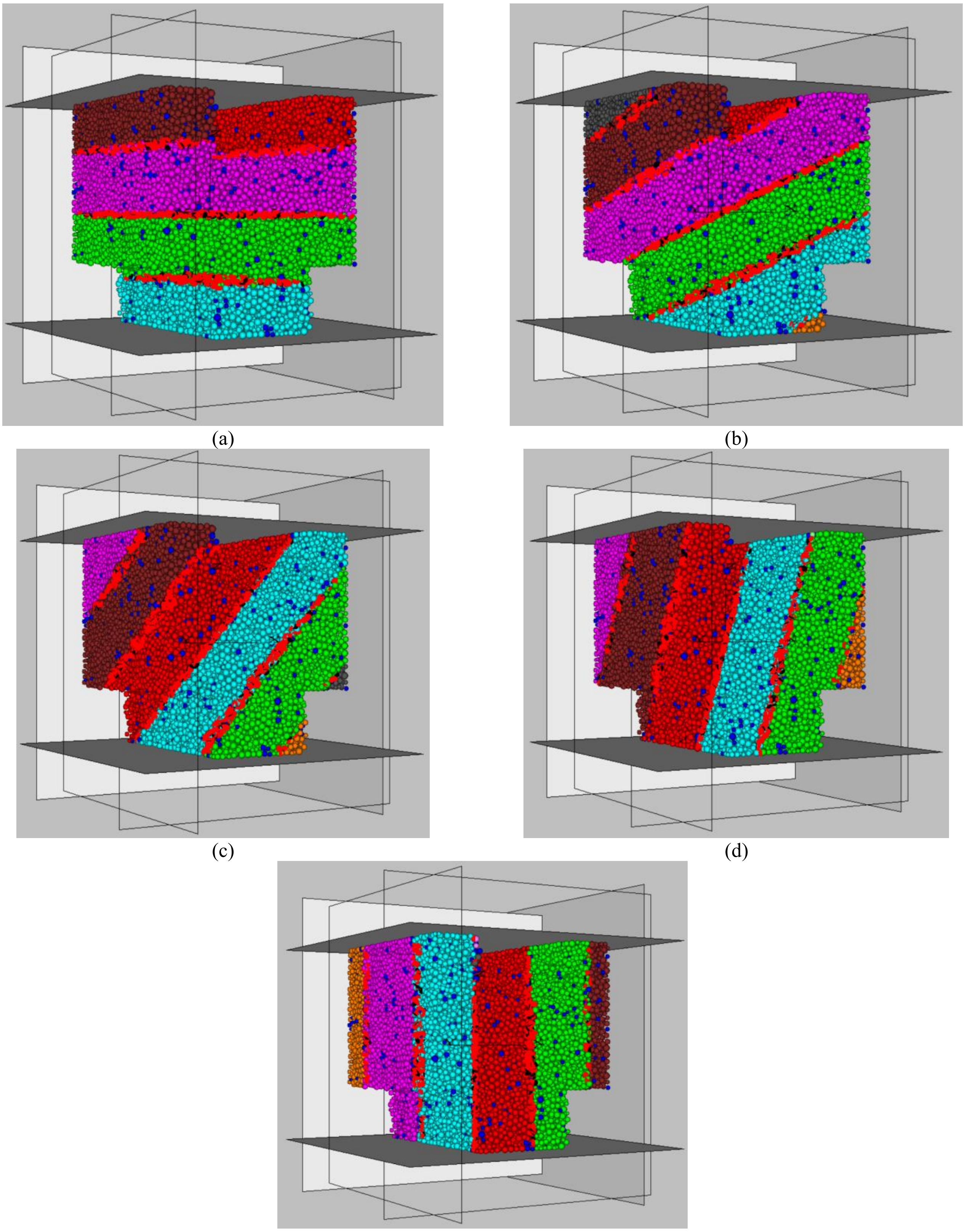


Fig. 6 Failure pattern in anisotropic concrete with layers thicknesses of 10 mm and layer angle of (a) 0°, (b) 25°, (c) 50°, (d) 75°, (e) 90°

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 note that number of cracks decrease with increasing the layer thickness (Figs. 5, 6, 7).



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

Fig. 7 Failure pattern in anisotropic concrete with layers thicknesses of 20 mm and layer angle of (a) 0°, (b) 25°, (c) 50°, (d) 75°, (e) 90°

3.2 The effect of bedding layer specification on the double punch test tensile strength

Fig. 8 shows the effect of bedding layer angle on the punch shear strength. Also, the results of bedding layer thickness have been shown in this figure. The minimum

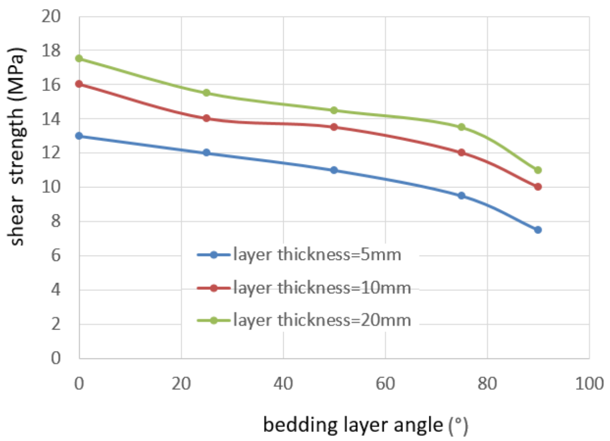


Fig. 8 The effect of bedding layer angle on the shear strength

Double punch test strength was occurred when layer angle is more than 60°. The maximum value occurred in 0°. Also, the punch shear strength was increased by increasing the layer thickness.

4. Conclusions

In this work the effect of bedding layers angle and layers thickness on the shear punch test failure mechanism of concrete has been investigated using PFC3D. Firstly calibration of PFC3d was performed using laboratory Brazilian tensile strength. Secondly punch 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 25°. Totally 15 model were simulated and tested. The results show that when layer angle is more than 60°, shear cracks initiates between the layers and propagate till coalesce with model boundary. The results show that when layer angle is less than 50°, 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 note that number of cracks decrease with increasing the layer thickness. The minimum shear punch test strength was occurred when layer angle is more than 50°. The maximum value occurred in 0°. Also, the shear punch test tensile strength was increased by increasing the layer thickness.

References

Akbas, S. (2016), "Analytical solutions for static bending of edge cracked micro beams", *Struct. Eng. Mech.*, **59**(3), 66-78.

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

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

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.

Backers, T., Stephansson, O. and Rybacki, E. (2002), "Rock fracture toughness testing in mode ii punch-through shear test", *Int. J. Rock Mech. Min. Sci.*, **39**, 755-769.

Barla, G. (1974), "Rock anisotropy: Theory and laboratory testing", *Rock Mech.*, 131-16.

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

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.

Bi, J., Zhou, X.P. and Xu, X. (2017), "Numerical simulation of failure process of rock-like materials subjected to impact loads", *Int. J. Geomech.*, **17**(3), 16-28.

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**, 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**, 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. Analy. Meth. Geomech.*, **32**(3), 219-234.

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

Donze, F.V., Richefeu, V. and Magnier, S.A. (2009), "Advances in discrete element method applied to soil rock and concrete mechanics", *Electr. J. Geol. Eng.*, **8**, 1-44.

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**, 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. (2015b), "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.*, **5**, 555-566.

Haeri, H. (2015a), "Influence of the inclined edge notches on the shear-fracture behavior in edge-notched beam specimens", *Comput. Concrete*, **16**(4), 605-623.

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. (2015c), "Influence of the inclined edge notches on the shear-fracture behavior in edge-notched beam specimens", *Comput. Concrete*, **16**, 605-623,

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**, 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.

Kequan, Y.U. and Zhoudao, L.U. (2015), "Influence of softening curves on the residual fracture toughness of post-fire normal-strength mortar", *Comput. Mortar*, **15**(2), 102-111.

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.

Lee, S. and Chang, Y. (2015), "Evaluation of RPV according to alternative fracture toughness requirements", *Struct. Eng. Mech.*, **53**(6), 55-67.

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.

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.

Li, Y., Zhou, H., Zhu, W., Li, S. and Liu, J. (2015), "Numerical study on crack propagation in brittle jointed rock mass influenced by fracture water pressure", *Mater.*, **8**(6), 3364-3376.

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.

Lu, F.Y., Lin, Y.L., Wang, X.Y., Lu, L. and Chen, R. (2015), "A theoretical analysis about the influence of interfacial friction in SHPB tests", *Int. J. Imp. Eng.*, **79**, 95-101.

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.

Mohammad, A. (2016), "Statistical flexural toughness modeling of ultra-high performance mortar using response surface method", *Comput. Mortar*, **17**(4), 33-39.

Nasseri, M.H. Rao, K.S. and Ramamurthy, T. (1997) "Failure mechanism in schistose rocks", *Int. J. Rock Mech. Min. Sci.*, **34**(3-4), 21-39.

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.

Pan, B., Gao, Y. and Zhong, Y. (2014), "Theoretical analysis of overlay resisting crack propagation in old cement mortar pavement", *Struct. Eng. Mech.*, **52**(4), 167-181.

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

Pinto, J.L. (1970), "Deformability of schistous rocks", *Proceedings of the 2nd International Congress of Rock Mechanics*, 2-30.

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*, 359-363.

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

Rajabi, M., Soltani, N. and Eshraghi, I. (2016), "Effects of temperature dependent material properties on mixed mode crack tip parameters of functionally graded materials", *Struct. Eng. Mech.*, **58**(2), 144-156.

Ramadoss, P. and Nagamani, K. (2013), "Stress-strain behavior and toughness of high-performance steel fiber reinforced mortar in compression", *Comput. Mortar*, **11**(2), 55-65.

Ramamurthy, T. (1993), *Strength, Modulus Responses of Anisotropic Rocks, In: Hudson, J.A., Editor Comprehensive Rock Engineering*, Oxford, Pergamon Press, **1**, 313-329.

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

Saeidi, O., Rasouli, V., Geranmayeh Vaneghi, 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.

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), 23-35.

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

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

Mater., **83**, 108-118.
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**, 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**, 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**, 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.
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. Soc. Behav. Sci*., **198**, 2280-2289.
Wang, Q.Z., Feng, F., Ni, M. and Gou, X.P. (2011), "Measurement of mode I and mode II rock dynamic fracture toughness with cracked straight through flattened Brazilian disc impacted by split Hopkinson pressure bar", *Eng. Fract. Mech*., **78**(12), 2455-2469.
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.
Wang, X., Zhu, Z., Wang, M., Ying, P., Zhou, L. and Dong, Y. (2017), "Study of rock dynamic fracture toughness by using VB-SCSC specimens under medium-low speed impacts", *Eng. Fract. Mech*., **181**, 52-64.
Wu Z.J., Ngai L. and Wong, Y. (2014), "Investigating the effects of micro-defects on the dynamic properties of rock using numerical Manifold method", *Constr. Build. Mater*., **72**, 72-82.
Yaylac, M. (2016), "The investigation crack problem through numerical analysis", *Struct. Eng. Mech*., **57**(6).
Zhang, Q.B. and Zhao, J. (2014), "Quasi-static and dynamic fracture behaviour of rock materials: Phenomena and mechanisms", *Int. J. Fract*., **189**, 1-32.
Zhao, Y., Zhao, G.F. and Jiang, Y. (2013), "Experimental and numerical modelling investigation on fracturing in coal under impact loads", *Int. J. Fract*., **183**(1), 63-80.
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. and Qian, Q.H. (2015), "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., Zhang, Y.X. and Ha, Q.L. (2008), "Real-time computerized tomography (CT) experiments on limestone damage evolution during unloading", *Theoret. Appl. Fract. Mech*., **50**(1), 49-56.
Zhou, X.P. (2004), "Analysis of the localization of deformation and the complete stress-strain relation for mesoscopic heterogeneous brittle rock under dynamic uniaxial tensile loading, International journal of solids and structures", **41**(5/6), 1725-1738.
Zhou, X.P., Gu, X.B. and Wang, Y.T. (2015), "Numerical simulations of propagation, bifurcation and coalescence of cracks in rocks", International journal of rock mechanics and mining science, **80**, 241-254.
Zhou, X.P., Ha, Q., Zhang, Y. and Zhu, K. (2004), "Analysis of deformation localization and the complete stress-strain relation for brittle rock subjected to dynamic compressive loads", *Int. J. Rock Mech. Min. Sci*., **41**(2), 311-319.
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. and Yang, H.Q. (2007), "Micromechanical modeling of dynamic compressive responses of mesoscopic heterogenous brittle rock", *Theoret. Appl. Fract. Mech*., **48**(1), 1-20.
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.

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