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Three-dimensional numerical modeling of effect of bedding layer on the tensile failure behavior in hollow disc models using Particle Flow Code (PFC3D)

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Abstract. This research presents the effect of anisotropy of the hollow disc mode under Brazilian test using PFC3D. The Brazilian tensile strength test was performed on the hollow disc specimens containing the bedding layers and then these specimens were numerically modeled by using the two dimensional discrete element code (PFC3D) to calibrate this computer code for the simulation of the cracks propagation and cracks coalescence in the anisotropic bedded rocks. The thickness of each layer within the specimens varied as 5 mm, 10 mm and 20 mm and the layers angles were changed as 0°, 25°, 50°, 75° and 90°. The diameter of internal hole was taken as 15 mm and the loading rate during the testing process kept as 0.016 mm/s. It has been shown that for layers angles below 25° the tensile cracks produce in between the layers and extend toward the model boundary till interact and break the specimen. The failure process of the specimen may enhance as the layer angle increases so that the Brazilian tensile strength reaches to its minimum value when the bedding layers is between 50° and 75° but its value reaches to maximum at a layer angle of 90°. The number of tensile cracks decreases as the layers thickness increases and with increasing the layers angle, less layer mobilize in the failure process.

Keywords: bedding layer; Brazilian test; anisotropy; crack; PFC3D

1. Introduction

The anisotropy of rocks is considered in most of mining, petroleum, civil and environmental engineering projects. The mechanical, thermal and hydraulic properties of many rock masses can be changed due to the loading directions and anisotropic characteristics of rocks. Therefore, in many engineering applications it is important to consider the anisotropic behavior of rocks in order to decrease the errors of different magnitudes depending on the degree of anisotropy (Amadei 1982, 1983, 1996, Barla 1974, Pinto 1966, 1970, 1979, Rodrigues 1966, Salamon 1968). The anisotropy in rocks is mostly due to the existence of layers, planes of weakness, cracks, bedding planes, schistosity, foliations, joints, fault and fault zone in the rock mass (Goodman 1993). The existence of a weak plane with in a rock sample may significantly affect the compressive and tensile strength of this anisotropic rock known as the transversely isotropic material (Chen 1998, Chou 2008, Exadaktylos 2001, Nasseri 1997, 2003, Ramamurthy 1993, Tien 2000). The failure modes of rock mass may also be different for various degrees of anisotropy due to weakness planes (Tien 2006, Tavallali 2010a, b).

Two different compressive failure modes may exist for the layered rocks i.e. the internal shear mode of failure and the sliding failure mode along the bedding planes but for the case of tensile failure there may exist three modes of failure including the pure tensile, pure shear or the mixed tensile and shear modes. However, the experimental studies performed on various rock types mainly the metamorphic and sedimentary rocks have shown that they have some 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). For example, sedimentary rocks can be considered as isotropic, transversely isotropic or anisotropic depending on the spacing and orientations of the bedding planes or lamination inherently exist due to their formation. On the other hand, the metamorphic rocks are anisotropic because they are structurally with schistosity and cleavage in nature (Singh *et al.* 1989, Ramamurthy 1993). Many researchers have been accomplished to study the cracks initiation, propagation and coalescence in the cracked specimens under different loading (Wu *et al.* 2010, Lancaster *et al.* 2013, Ramadoss 2013, Pan *et al.* 2014, Mobasher *et al.* 2014, Noel and Soudki, 2014, Haeri *et al.* 2014, Oliveira and Leonel, 2014, Kim and Taha, 2014, Tiang *et al.* 2015, Wan Ibrahim *et al.* 2015, Lee and Chang 2015, Kequan and Zhoudao 2015, Silva *et al.* 2015, Gerges *et al.* 2015, Liu *et al.* 2015, Haeri 2015a, b, c, Haeri *et al.* 2015a, b, c, Wasantha *et al.* 2015, Fan *et al.* 2016, Li *et al.* 2015, 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, Khodayar and Nejati 2018, Nazerigivi *et al.* 2018, Kim *et al.* 2018, Imani *et al*. 2017, Najigivi 2017). Tw identified in these research, wing crack and shear crack.

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The results show that the wing types of cracks have been cracks disappeared by increasing the confining pressure.

Several researchers studied the effects of scistisity on the indirect tensile strength of metamorphic rocks (Berenbaum and Brodie 1959, Hobbs 1963, Debecker and Vervoort 2009). They concluded that the Brazilian tensile strength (BTS) of different metamorphic rocks have been affected by the schistosity orientations. For the case of sedimentary rocks, the effect of layers orientation on the tensile strength of such rocks have been studied by performing the standard Brazilian tensile strength test on various rock samples. For example, Hobbs (1963) investigated the BTS of siltstone, McLamore and Gray (1967) of shale, Chen *et al.* (1998) as well as Tavallali and Vervoort (2010a, b) of sandstone. However, various modes of rocks failure have been studied and classified in the literature. Chen *et al.* (1998) studied the tensile failure of sandstone and proposed two modes of failure for this rock type i.e., the tensile splitting along the loaded diameter of sandstone disc samples and shear failure along the sandstone layers. On the other hand, Tavallali and Vervoort (2010b) also performed some Brazilian tensile tests on sandstone specimens and observed three types of failure in this rock type. They classified these failure modes as: (i) activation of rock layers (the fractures are formed and propagated parallel to the layers orientation), (ii) the central fractures produced at the central part of the specimen parallel to the loading direction, (iii) the fractures produced out of the center part of the specimen.

In this research, the indirect tensile tests on Brazilian disc specimens of layered rocks or laminated concretes are numerically modeled by a discrete element method (DEM) implemented in a two dimensional particle flow code (PFC3D) to study the effects of weak laminations on the failure strength and fracture patterns of concretes.

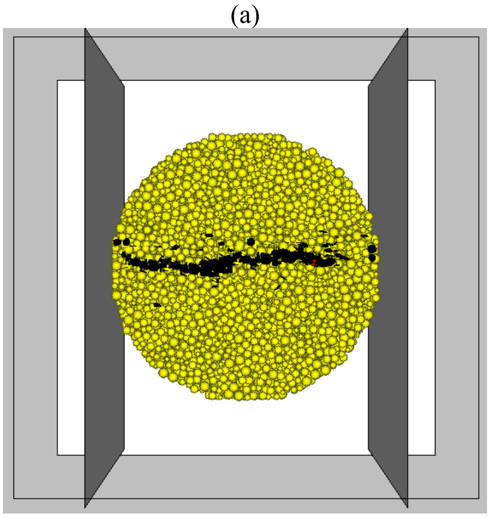
2. Numerical modeling with PFC3D

Particle flow code represents a rock mass as an assemblage of bonded rigid particles (Cundall 1971, Potyondy and Cundall 2004). In the two dimensional particle flow code (PFC3D), the cohesive and frictional bonds are considered to connect the circular discs which in turn are confined with planar walls to form a particle assembly. The particle contacts are simulated by the parallel bond model. The macro mechanical properties of the samples and the nature of the cracking and failure process during the loading can affect the bonding strengths of the particles with in the assembly. The particles friction can be adopted by specifying a suitable friction coefficient then the particles can be mobilized as long as they remain in contacts with one another in the particle assembly. As the applied normal stress exceeds that of the specified normal bond strength of the particles, the tensile cracks initiate with in the assembly. On the other hand, the shear cracks can be produced when the applied shear stress surplus that of the specified shear bond strength due to particle rotation or direct shearing of the particles. After the particle bonds break, the shear strength at the contact points immediately drops to zero while the bonding shear strength reduces to that of the residual frictional value (Itasca Consulting Group Inc. 2004, Cho *et al*. 2007, 2008, Potyondy and Cundall 2004, Sarfarazi 2014). All the micro mechanical properties of the particle assembly in PFC3D should be assigned at the first stage to describe the contact properties, contact friction, bond strength and bond stiffness. All these properties should satisfy the macro mechanical properties provided by considering the macro-behavior of real material samples in the laboratory tests. Therefore, PFC3D code uses a repeatable trial and error

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)	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)	70
Damping coefficient	0.7	Parallel bond normal strength, SD (MPa)	2
Contact young modulus (GPa)	40	Parallel bond shear strength, mean (MPa)	70
Stiffness ratio	1.7	Parallel bond shear strength, SD (MPa)	2

(a)



(b)

Fig. 1 Failure pattern in (a) physical sample, (b) PFC3D model

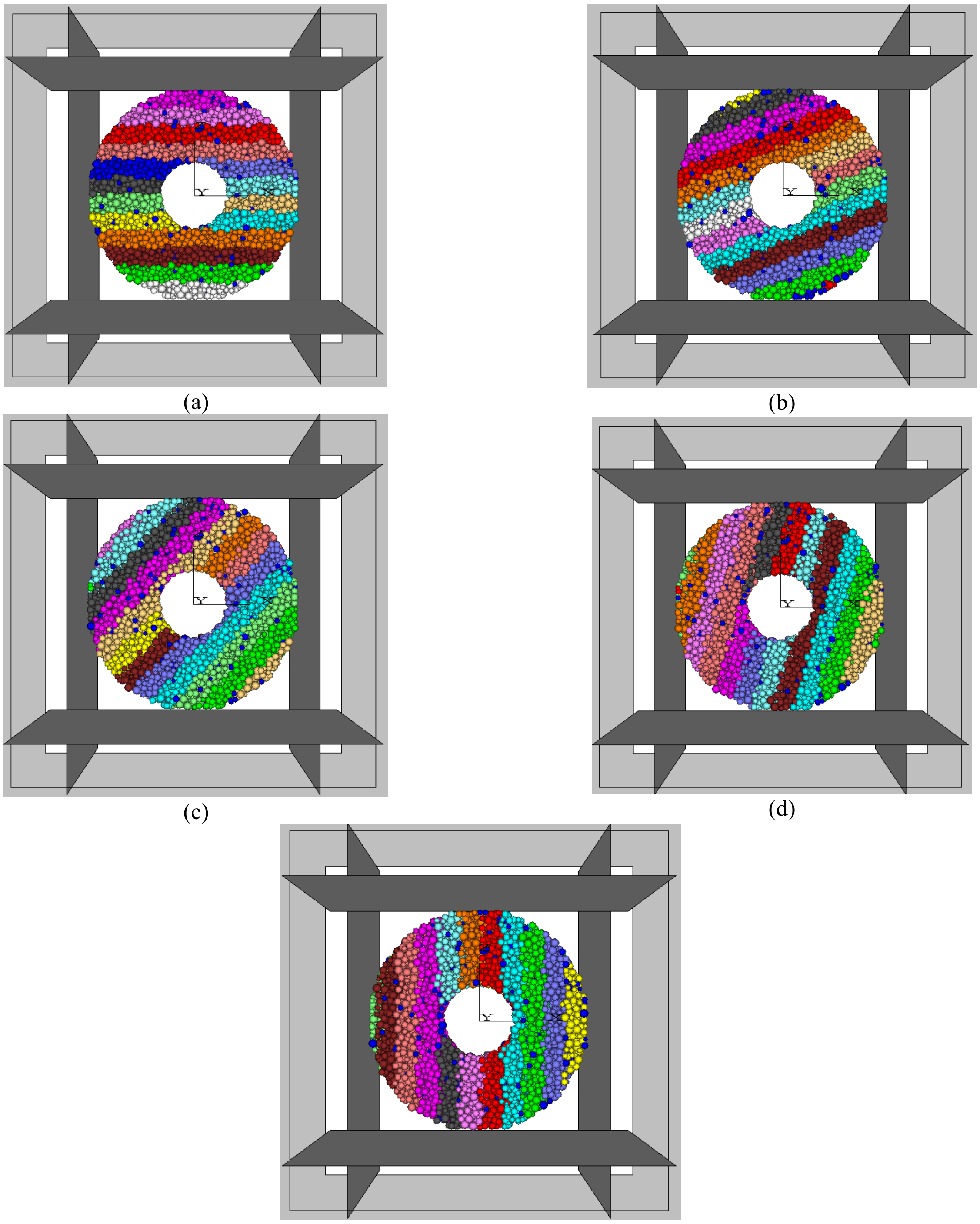


Fig. 2 Anisotropic concrete with layers thicknesses of 5 mm and layer angle of (a) 0°, (b) 25°, (c) 50°, (d) 75°, (e) 90°

Table 2 Brazilian tensile strength of physical and numerical samples

Physical tensile strength (MPa)	4.5 and 4.7
Numerical tensile strength (MPa)	4.5

algorithm to adjust these two micro and macro properties. This sophisticated computer code uses an explicit finite different algorithm for solving the equations of motions predicted by the Newton's second law. Therefore, this procedure can readily predict the initiation and propagation of cracks produced with in the assembly due to bond breakage and formation of fracture patterns during the failure process of the modeled sample (Potyondy and Cundall 2004).

Table 3 Micro properties used to represent the bedding interfaces

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

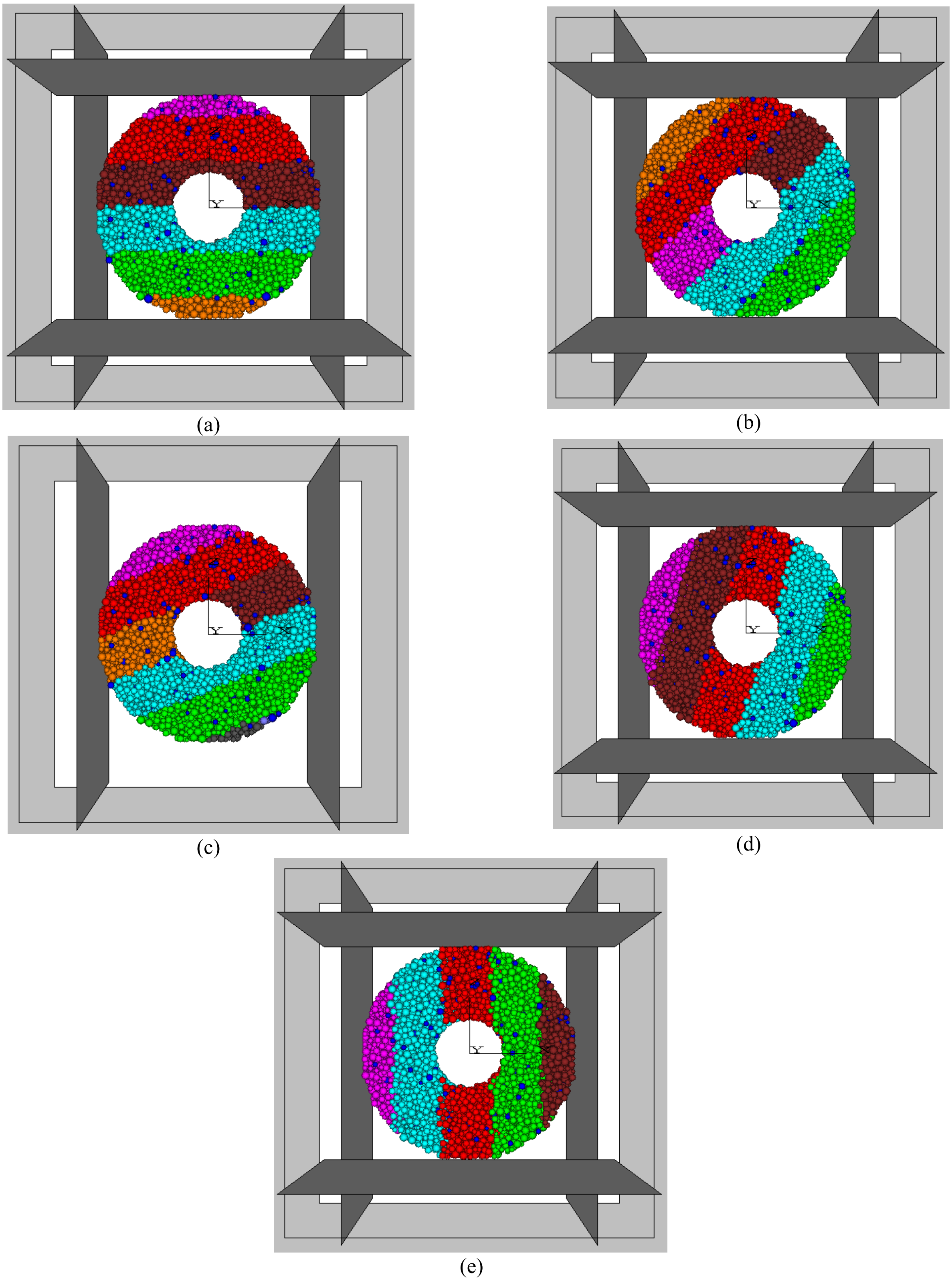
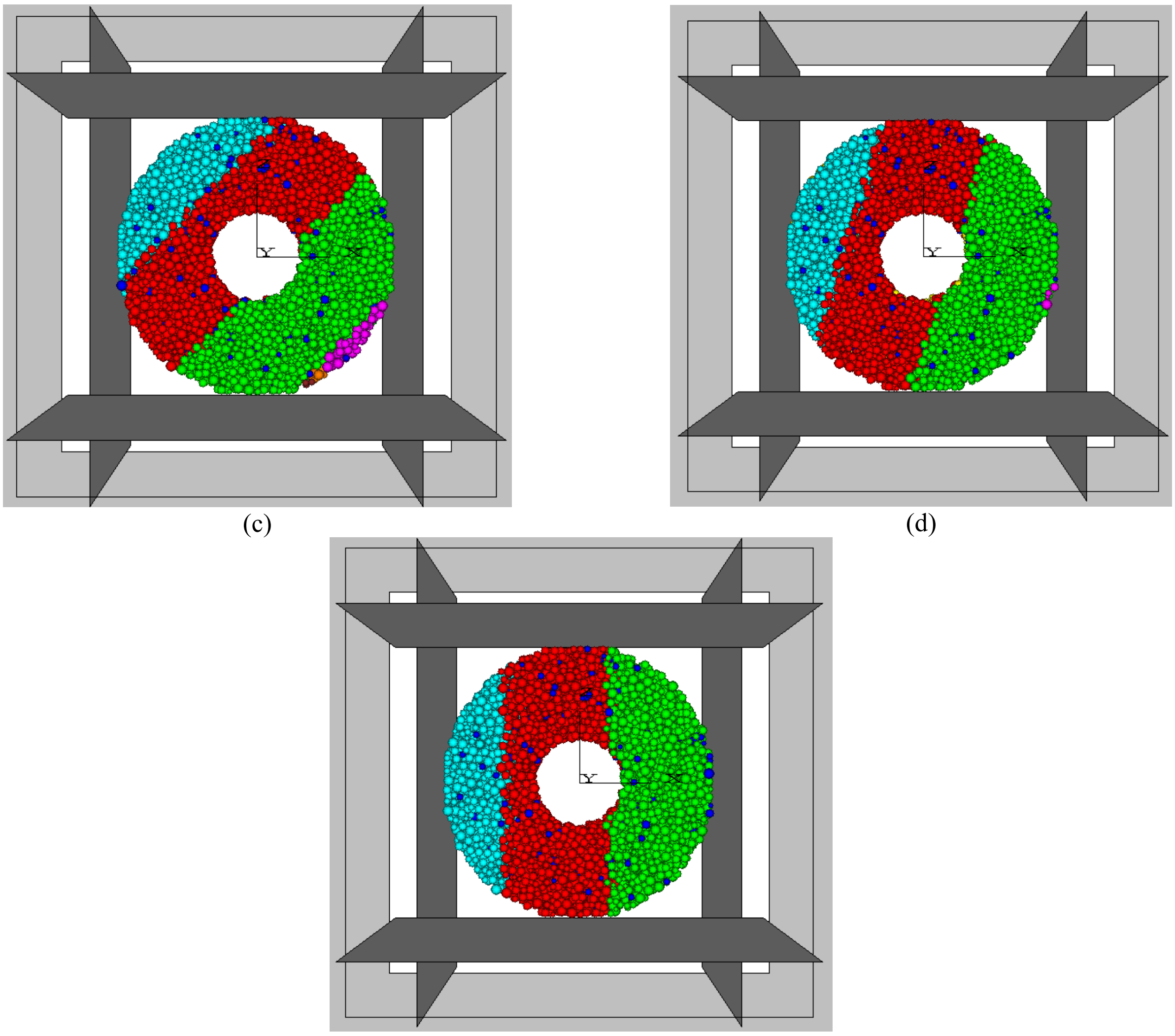


Fig. 3 Anisotropic concrete with layers thicknesses of 10 mm and layer angle of (a) 0°, (b) 25°, (c) 50°, (d) 75°, (e) 90°

2.1 Preparing and calibrating the numerical model

The Brazilian test was used to calibrate the tensile strength of specimen in PFC3D model. The standard process of generation of a PFC3D assembly to represent a test model involves four steps: (a) particle generation and packing the particles, (b) isotropic stress installation, (c) floating particle elimination, and (d) bond installation.

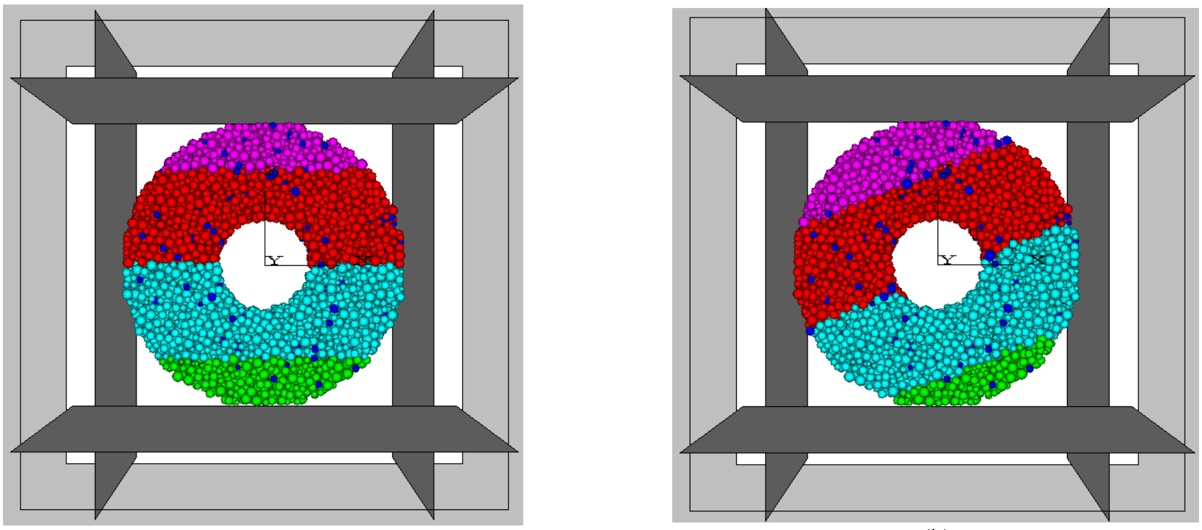
Adopting the micro-properties listed in Table 1 and the standard calibration procedures (Potyondy and Cundall 2003), a calibrated PFC particle assembly was created. The diameter of the Brazilian disk considered in the numerical



(c) (d)

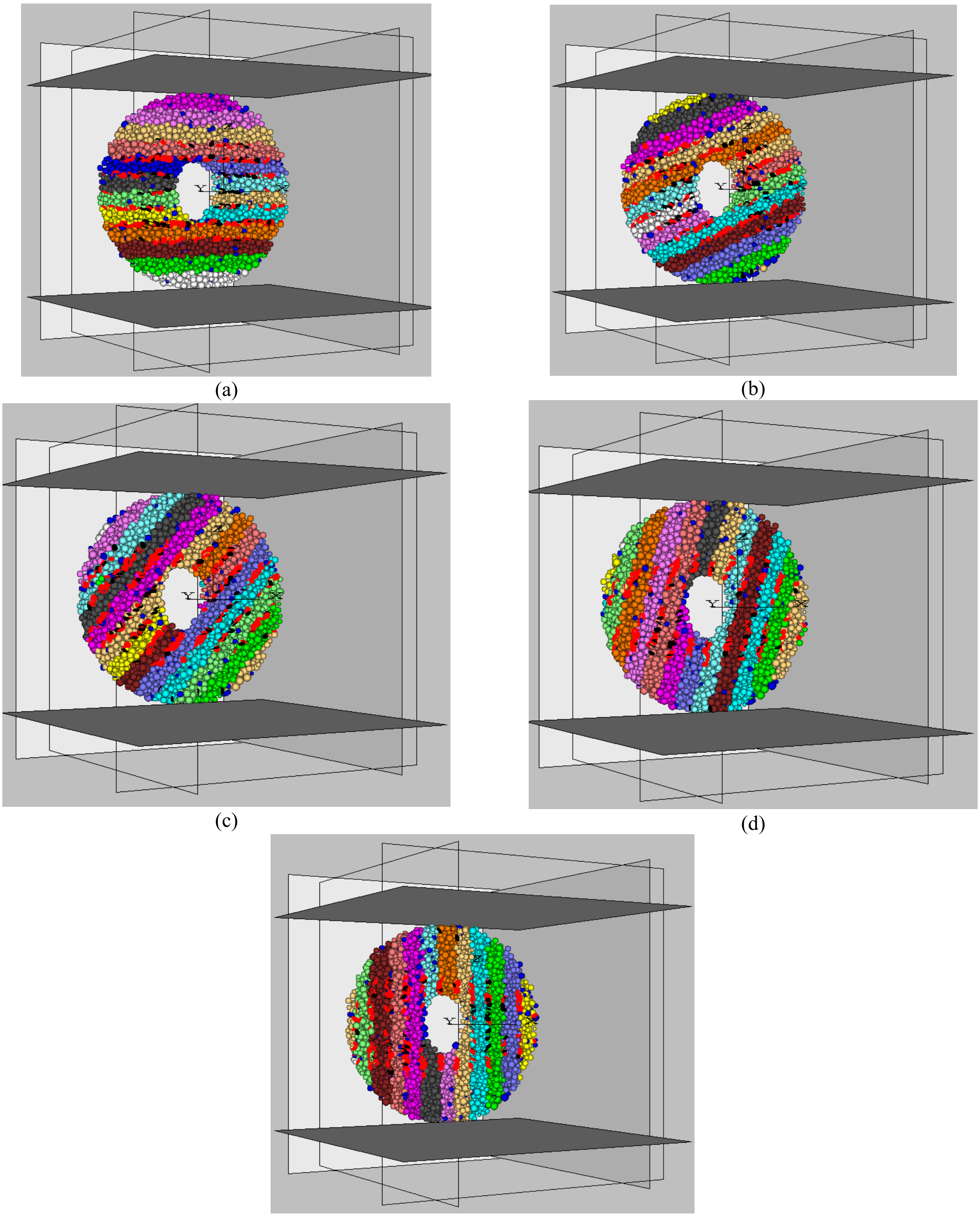
(e)

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



(a) (b)

tests was 54 mm and its thickness was 27 mm. The specimen was made of 11,615 particles. The disk was crushed by the lateral walls moved toward each other with a low speed of 0.016 m/s. Figures 1a, b illustrate the failure patterns of the numerical and experimental tested samples, respectively. The failure planes experienced in numerical



(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°

and laboratory tests are well matching. The numerical tensile strength and a comparison of its experimental measurements were presented in Table 2. This table shows a good accordance between numerical and experimental results.

2.2 Numerical Brazilian tests on bedding layers

2.2.1 Preparing the model

After calibrating PFC3D, Brazilian tests for anisotropic concrete were numerically simulated by creating a hollow

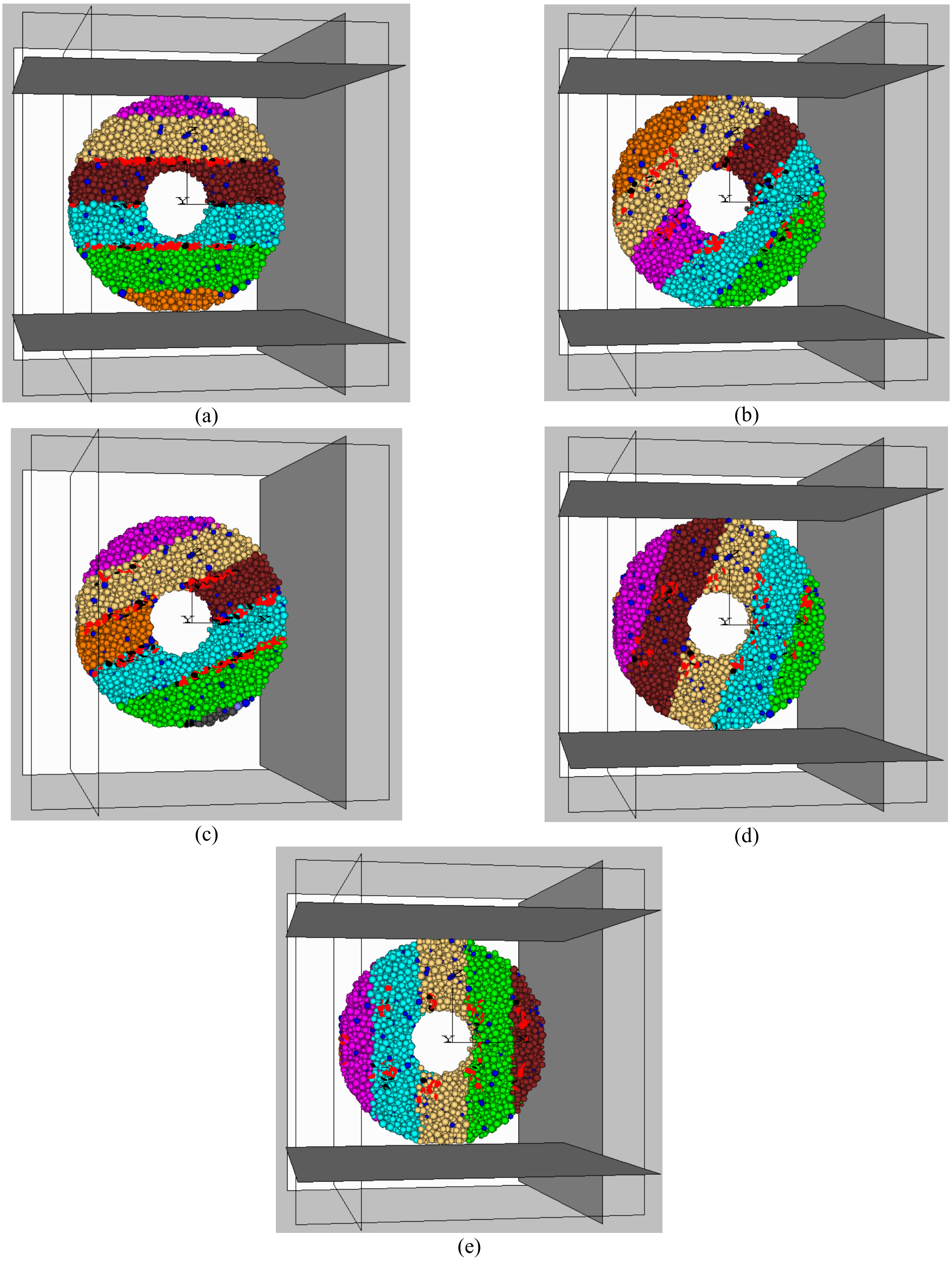


Fig. 6 Failure pattern in anisotropic concrete with layers thicknesses of 10 mm and layer angle of (a) 0°, (b) 25°, (c) 50°, (d) 75°, (e) 90°

circular model (Figs. 2, 3 and 4). PFC specimen diameter was 54 mm and its thickness was 27 mm. diameter of pore space was 15 mm. A total of 11,179 disks with a minimum radius of 0.27 mm were used to make up the hollow disc specimen. Particles were surrounded by four walls. Upper and lower walls was fixed and left and right wall move toward each other by rate of 0.016 mm/s. 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°.

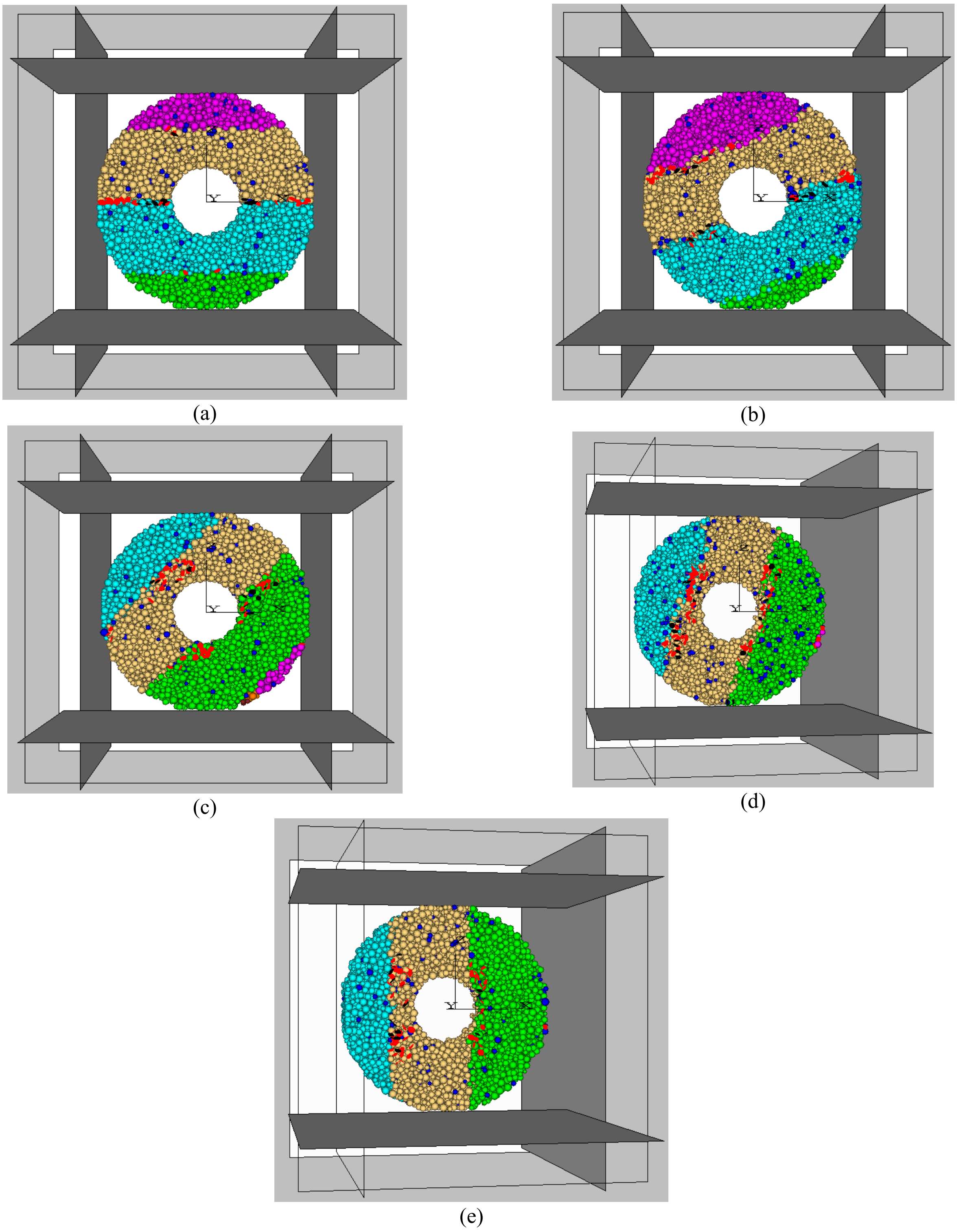


Fig. 7 Failure pattern in anisotropic concrete with layers thicknesses of 20 mm and layer angle of (a) 0°, (b) 25°, (c) 50°, (d) 75°, (e) 90°

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 3).

3. Results

3.1 The effect of layer angel 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 black line represent the tensile crack and shear crack, respectively.

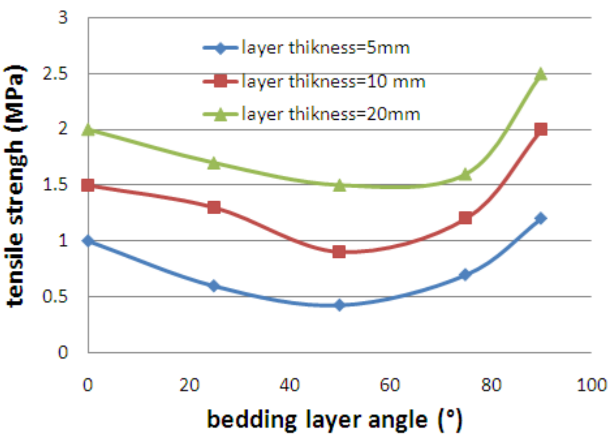


Fig. 8 The effect of bedding layer angle on the Brazilian tensile strength

As shown in Figs. 5(a), (b), Figs. 6(a), (b) and Figs. 7(a), (b), when the layers angle reduces below 25° the tensile cracks usually starts to initiate in between the layers. These cracks continue their propagation toward the model boundary. However, the crack tracing is too high. On the other hand, by increasing the layers angle the failure process is accompanied with less layer mobilization. Also, the failure trace is very short in this case. As far as the layers thickness is considered, the number of cracks decreases as the layers thickness increases (Figs. 5, 6, 7).

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

Fig. 8 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 25° and 75°. 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 hollow disc model has been investigated using PFC3D. firstly calibration of PFC3D was performed using laboratory 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 15 model were simulated and tested. The result shows that:

• When layer angle is less than 25°, tensile cracks initiates between the layers and propagate till coalesce with model boundary.

• When layer angle is less than 25°, the fracture 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.

• Brazilian tensile strength is minimum when bedding layer angle is between 25° and 75°. The maximum one is related to layer angle of 90°.

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