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Experimental Evaluation and Discrete Element Modeling of Shale Delamination Mechanism

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Abstract

In this research work, X-ray diffraction (XRD) tests and petrographic studies are performed to analyze the mineral composition and lamination in the shale rock specimens. Afterward, point load (PL) and uniaxial compressive strength (UCS) tests are carried out on the anisotropic laminated shale rock. Based on the macro-mechanical properties of these tests, the discrete element method implemented in a two-dimensional particle flow code (PFC2D) is adjusted to numerically simulate the shale rock specimens. The aim of this work is to validate the numerical models by failure process, stress-strain curves, and peak failure strengths of the shale samples. Therefore, point load test is used for assessing the pattern failure mechanism, and uniaxial compressive strength test is performed for obtaining the stress-strain curves and peak strength failure points in the laboratory shale rock samples. Validation of peak strengths criteria provides the best results; the determination coefficient values for lab and numerical modeling with (R^2 = 0.99). Several numerical models are prepared for estimating the mechanical behavior of shale rocks in PFC2D. The smooth joint model (SJM) is used for preparing the consistent and appropriate constitutive models for simulating the mechanical behavior of laminated shale. It is concluded that SJM provides more reasonable results for laminated shale rock that can be used for several petroleum engineering projects, especially in the central geological zone of Iran.

1. Introduction

Rock discontinuities can be classified into two types, inherent discontinuities, e.g. lamination and bedding planes, and structural discontinuities such as joints and fractures. Inherent discontinuities lead to anisotropic mechanical behaviors of rocks. Inherent discontinuities caused by depositional changes and characterized by regularly aligned weak planes due to the laminated texture of the shale rocks. The thin layers (lamina) sometimes may break away under various loading environments into parallel layers less than one centimeter in thickness. Shale is one of the most widely occurrence rock and constitute about 55% of all sedimentary rocks found both at earth surface and deep underground [1]. Shale is a fine-grained, brittle, soft, and easily eroded clastic sedimentary rock mainly composed of silt-size and clay-size particles [2]. Sedimentary rocks are characterized by the size, shape, and arrangement of their grains known as texture [3]. Texture is the primary property, and has a significant role in influencing all types of behaviors in a rock specimen [4]. Shale is characterized by laminated texture in which thin lamina breaking with an irregular curving fracture surface, which is parallel to the bedding plane [5]. Succession of lamination arises due to fluctuations in the depositional environment that direct to dissimilarities in grain size, clay ratio, organic material range, and microfossil content [6]. Additionally, the failure of laminated rock is known as delamination, which occurs under particular stress conditions at ordinary circumstances [7]. Through its complicated behavior, shale rock gained much more attention in

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various fields of engineering such as petroleum engineering, rock mechanics, civil engineering, mining, and tunneling engineering [8]. Shale rock causes perilous problems in various engineering projects which may cost up-to billions of dollars per year. Laminated rock is considered as a transversely isotropic material with different deformation properties at different lamination directions [9]. Lamination is an inherent discontinuity and significantly effects on the growth of failure [10]. The appearance of the laminar planes (weak plane between lamina) has a significant effect on the mechanical behavior and strength of shale rock [11]. It is noticed that mechanical properties of laminated shale rock create instability problems in rock slopes, borehole walls, and underground spaces [12]. The researchers have studied to understand the transversely anisotropic behavior of shale. Furthermore, shale rock composed primarily of clay, organics, and brittle minerals such as quartz, feldspar, and pyrite. The petrographic aspects of shale may govern the mechanical behavior of rock specimen [13]. Mineral composition of a shale sample is very easy to obtain and can be determined precisely by conducting laboratory analysis such as X-ray diffraction (XRD) testing [14]. The XRD results correlate well with rock mechanics tests such as uniaxial compressive strength and point load test, to assess the mechanical behavior at certain levels. In the recent development, the numerical simulation approaches have arisen as a promising means in various scientific and engineering domains including petroleum, mining, and civil engineering. However, the standard rock mechanics tests including uniaxial compressive strength (UCS), point loads (PL), and direct shear (DS) tests provided the sound bases for numerical modeling technics used in geo-mechanics applications. Several researchers have studied the mechanical behavior of rock and obtained reasonable results from the comparison between numerical modeling and the result of laboratory tests. The digital image correlation techniques has applied for the linear and non-linear fracture parameter analysis in the quaternary binder concretes [15, 16]. The objective of this study is to construct a numerical model for the delamination of shale rock by using the distinct element method DEM in Particle Flow Code (PFC2D). The uniaxial compressive strength test and point load tests were carried out on laminated shale rock samples, and then calibrated the laboratory test (macro-mechanical properties) and numerical modeling (micro-mechanical properties) carried out by pattern failure mechanism, stress-strain curves, and peak stress failure. In this research work, a smooth joint contact model is applied for the simulation of delamination in shale rock. Shale is the most commonly occurred sedimentary rock in the central geological zone of Iran. This study will be helpful in understanding the behavior of shale rock in the stability of open pit mines and underground mines, and the construction of roads, dams, and tunnels in the central geological zone of Iran.

2. Data Collection

2.1. Preparation of shale specimen

Shale rock specimens are used for laboratory tests taken from the outcrops of the Taft formation, which are from the Cretaceous geological age. Taft formation is located in the Fahraj district. Faraj is a village in Fahraj rural district, which is located 30 km southeast of the central district of Yazd county (Figure 1). These shale specimens are typically laminated; therefore, fresh and representative rock samples are collected to ensure the integrity and uniformity of the shale specimens for use in laboratory tests. Laminated shale specimen was established according to the standard of the International Society for Rock Mechanics (ISRM) and the American Society for Testing and Materials (ASTM). An outcrop specimen with dimensions of sample 120 cm × 60 cm × 60 cm was used for laboratory testing, as shown in Figure 1. The tests were performed with a high rate of accuracy in the well-developed engineering geology laboratory of the Yazd University. Point load test and uniaxial compressive strength test were carried out to determine the effect of lamination on the anisotropic behavior of laminated shale to the different laminated directions under the influence of loading (Figure 2).

A sampling of shale rock is a serious issue due to its transversely anisotropic characteristics. Therefore, point load test is one of the best and alternative methods for determining the mechanical characteristics of laminated shale rock samples. Ten irregularly shaped shale rocks specimens were subjected to point loading according to the standard of the International Society of Rock Mechanics (ISRM); the results are summarized in Table 1. During the point load tests, shale samples were subjected to two types of directions, one type of lamination was parallel to loading, and the other type of lamination was perpendicular to the loading. Seven uniaxial compressive strengths were performed on the laminated shale rock specimens; the results are summarized in Table 2. During the UCS tests, a load was applied both parallel and perpendicular with respect to the direction of lamination (Figures3 and 4).

Figure 1. Sampling site of shale rock and outcrops samples.

Table 1. Point load test data for laminated shale rock samples.

Sample ID	Dimensions of samples Length (mm)	Width (mm)	Force (KN)	Compressive strength (MPa)	Tensile strength (MPa)	Effective point load index Is_{50}
			Loading parallel to lamination			
SH-1	34	40	0.40	1.08	0.0092	0.045
SH-2	58	49	0.35	0.96	0.076	0.040
SH-3	76	64	0.30	0.82	0.0041	0.034
SH-4	43	57	0.45	0.12	0.086	0.050
SH-5	69	55.5	0.30	0.85	0.071	0.035
			Loading perpendicular to lamination			
SH-6	40	44	0.80	2.16	0.0184	0.090
SH-7	45	53	0.75	2.05	0.0102	0.085
SH-8	61	55	0.875	2.25	0.190	0.10
SH-9	78	58	1	2.72	0.018	0.11
SH-10	82	51	0.60	1.47	0.0096	0.061

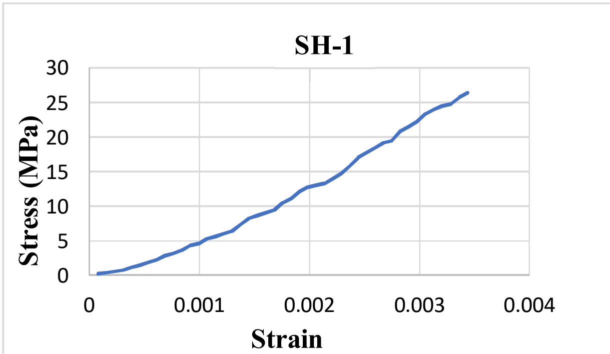
Figure 2. Prepared shale specimens for point load test and uniaxial compressive strength test.

2.2. Minerals composition and lamination analysis

The minerals in laminated shale contain mainly quartz, illite, calcite, Muscovite, and clinocholre. In general, the mineral composition of shale varies with the depths and locations, which can lead to different properties. The XRD analysis was conducted with the XPERT PRO model. The result obtained in the form of diffractogram of sample with relevant intensity and 2 theta position of each peak of the diffractogram is shown in Figure 5. In order to identify these peaks, current d-spacing is compared with the standard list of d-spacing given by joint committee on powder diffraction standard (JCPDS, 1974) [17]. Figure 6 shows the XRD test result of laminated shale specimens, indicating the mineral composition and proportion of shale specimens. From Figure 6, it can be noticed that this shale specimen contains mainly quartz, calcite, and clay group minerals including illite, Muscovite, and clinocholre. The proportion of quartz mineral is somehow more than the clay minerals. On the other hand, quartz has a significant impact on the degree of brittleness of shale, which is a key factor impacting the mechanical behavior of shale. In this work, the mineral composition analysis support laminated shale specimen to proceed for further rock mechanical tests. Because of the presences of appropriate content of brittle minerals (quartz), otherwise, it is very tough to perform the rock mechanical tests when the brittle minerals are less than clay group minerals.

Table 2. Uniaxial compressive strength test data for laminated shale rock samples.

Sample ID	Uniaxial compressive strength (MPa)	Modulus of elasticity (MPa)
Loading perpendicular to lamination		
SH-1	26.30	6541
SH-2	22.83	6064
SH-3	18.57	8776
Loading parallel to lamination		
SH-4	15.41	4250
SH-5	13.15	7276
SH-6	10.84	3540



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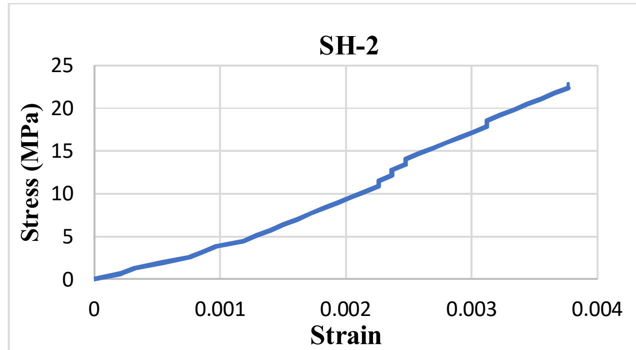

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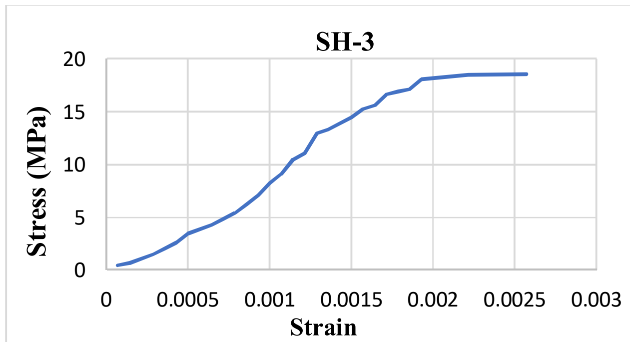

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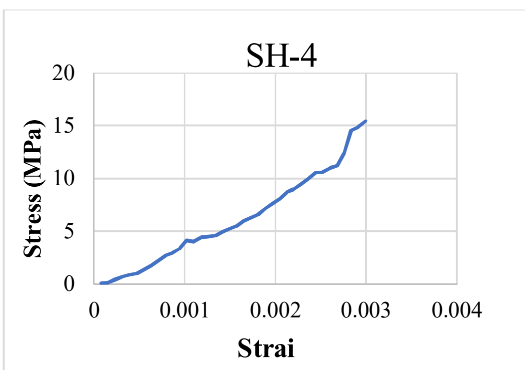
Figure 3. UCS test loading perpendicular to lamination.



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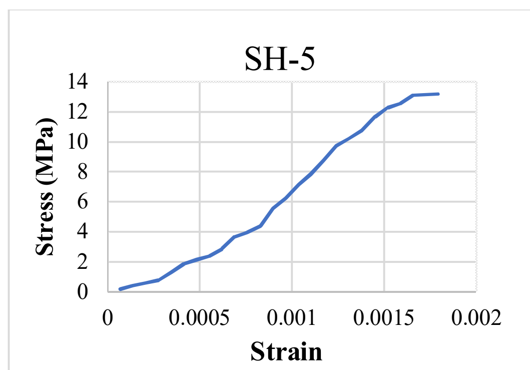

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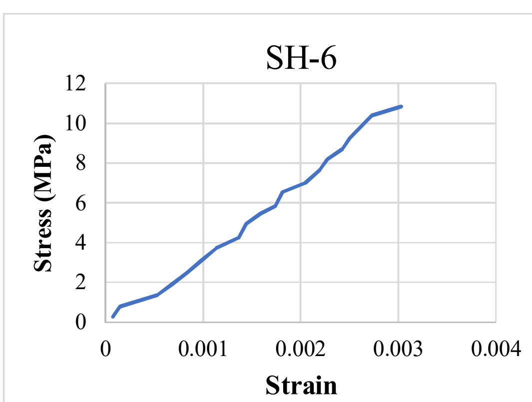

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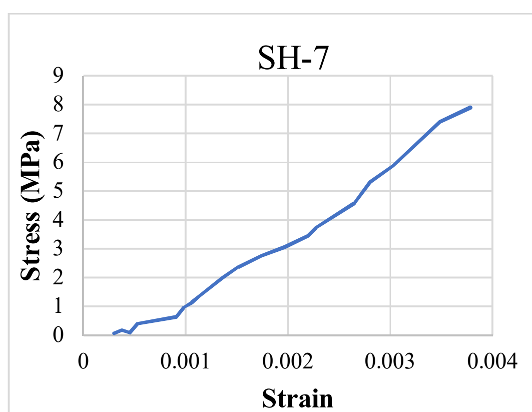


(d)

Figure 4. UCS tests loading parallel to lamination.

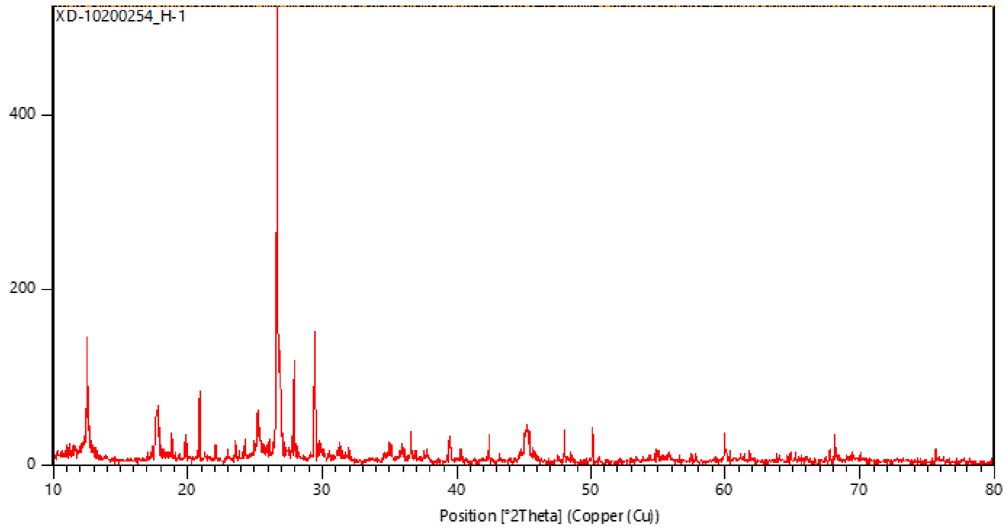


Figure 5. X-ray diffractogram of laminated shale sample.

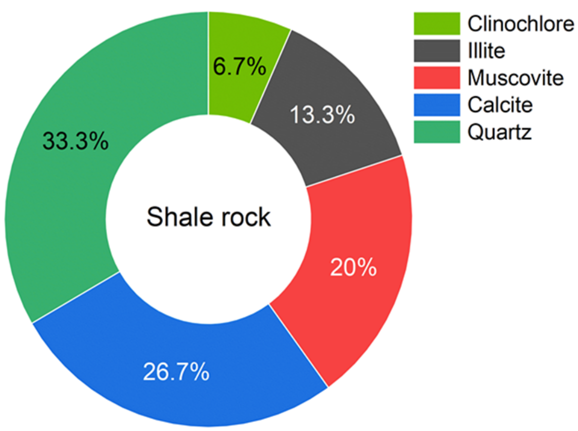


Figure 6. Mineral composition and proportion.

Furthermore, as we know, shale is one of the most complicated and sensitive rock types. Therefore, it is essential to analyze the specimen under a microscope to confirm and check for lamination. For this purpose, petrographic analysis was performed on the laminated shale rock samples. Thin-section slides were prepared in the laboratory, and examined under a high-resolution microscope. Thin section studies show that the shale rock samples contain an interval of mudstone and siltstone laminae (Figure 7) Mudstone laminae contain mica sheets, and the results show that the presence of mud stone laminae most likely leads to a ductile behavior of the rock (due to the presence of mica sheets and clay minerals). At the same time, silty laminae will be more brittle. On the other hand, veins and fractures filled by silica (quartz) and calcite can have a brittle behavior. The thickness of the laminates varies from 2 to 3 mm. Dissolution porosity in calcite veins laterally, the thickness of mud stone laminae is almost constant but the thickness of silty laminae is slightly variable.

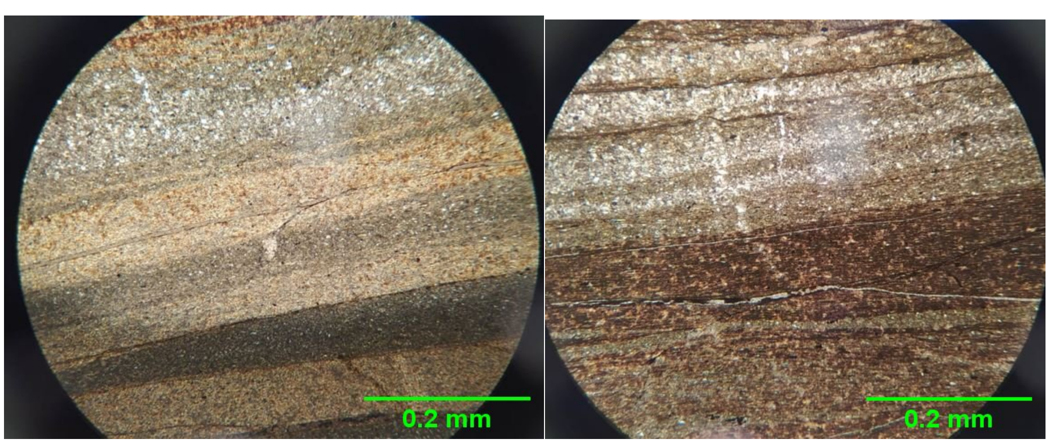


Figure 7. Photomicrograph of laminated shale rock samples.

3. Numerical modeling for Delamination of Shale Rock

The mechanical behavior of laminated shale rock is strongly dependant on the mechanical and geometric properties of lamination. Several empirical and analytical methods have been proposed in the last few decades to estimate the effect of lamination on the mechanical behavior of shale. However, a robust method that can consider the effect of inherent discontinuity (lamination) on the mechanical behavior of shale rock is not still available. The expeditious advancement of computer technology has provided the opportunity to numerically simulate the mechanical behavior of laminated rock. Particle flow code (PFC) is a promising numerical approach to study the mechanical behavior of structural and inherent discontinuities (Table 3).

Table 3. Previous studies of numerical modeling in PFC for rock discontinuity.

Researcher	Description	Method
Wanne and Young [18]	Numerical studies were carried out on thermally-induced fracturing around openings in granite.	PFC2^D
Lee and Jeon [19]	Studied the fracture behavior of granite and obtained a reasonable comparison between the PFC2D modeling and the result of laboratory tests.	PFC2^D
Zhao [20]	Studied the mechanism of the failure process in rocks such as the initiation and propagation of cracks from pre-existing flaws, has been analyzed using BPM.	PFC2^D
Khazaei, et al. [21]	Analyzed the fracturing process in the intact rock through the acoustic emission energies using numerical model simulation with PFC3D.	PFC3^D
Bahaaddini, et al. [22]	Experimental and numerical study of asperity degradation in the direct shear test	PFC2^D
Ozturk and Altinpinar [23]	Uniaxial compressive strength tests and point load tests were performed on trona and interbed of volcano-sedimentary rock, and a numerical model developed using the distinct element method (DEM) in the particle flow code (PFC) software	PFC2^D
He and Afolagboye [24]	Constructed a numerical model using the distinct element method (DEM) in particle flow code to understand the effect of lamination on the anisotropic behavior of shale.	PFC2^D
Yin and Yang [25]	Simulating the mechanical behavior of artificial transversely isotropic rock under uniaxial compression.	PFC2^D
Zhou, et al. [26]	The flat-joint model (FJM) and the smooth-joint model (SJM) were used to simulate shale matrix and layer planes.	PFC2^D
He, et al. [27]	The PFC2D-based model was used to estimate the indirect tensile mechanical behavior of shale rock	PFC2^D

PFC is a distinct element method (DEM) framework software in which the intact material is represented by a composite of spherical (in 3D) or circular (in 2D) particles bonded together, called bonded particle model (BPM). The discrete element method (DEM) has become a powerful planform for a variety of numerical modelling applications in soil mechanics, fluid mechanics, and rock mechanics. The distinct element method was first developed to study the impact of microscale properties on the macro-scale response of rock material. DEM has been widely used to study the effect of grain interlocking on the strength of a rock, the role of porosity on the deformability of rock, particle size distribution, the influence of fluid viscosity, and the fracturing process of shale rock [28].

Numerical modeling has been utilized for the influence of delamination on the mechanical behavior of transversely anisotropic laminated shale at a laboratory scale. In this work, the numerical model is based on the distinct element method (DEM). The DEM with particle flow code (PFC) is a more practical and robust method for modeling fracture initiation and propagation under complicated stress conditions. In the distinct element method, the groups of rigid particles or deformable blocks are in contact and connected by a bond to define a continuum. Furthermore, the bond is re-contacted if the particle or block can break after reaching its strength. Particle Flow Code (PFC) has been used to analyze the effect of delamination of shale rock. Although the experimental methods distinctly indicate the anisotropic behavior of laminated shale rock samples, it is tough to reveal the mechanical behavior of shale by laboratory tests. Hence, the numerical models in particle flow code (PFC) show the micro-level failure mechanism of the laminated shale samples.

3.1. Smooth joint contact modeling for lamination of shale

The smooth joint model is the best contact model to simulate planar interface behavior with dilation. Furthermore, the smooth joint has the ability to model all the contact between particles that lie on the opposite sides of the joint. A smooth joint model is a good tool for analyzing the macroscopic behavior of a linear elastic and frictional interface with dilation. The behavior of the bonded interface is linear elastic up to the strength limits are overreached, which makes the interface unbounded. This unbounded interface is linearly elastic and frictional with dilation, with slip adjusted by assessing coulomb limits on the shear force. The interface does not resist relative rotation. A force is updated in the force-displacement law (Figure 8). Parallel bonds and contact bonds are commonly used in PFC (Figure 9). In the parallel bond model, the moments generated with particle rotation are opposed by a set of elastic springs uniformly spread over a finite-sized section lying on the contact plane and centered at the contact point. In the contact bond model, an elastic spring with constant shear and normal stiffnesses act at the constant points between particles, allowing only forces to be transferred.

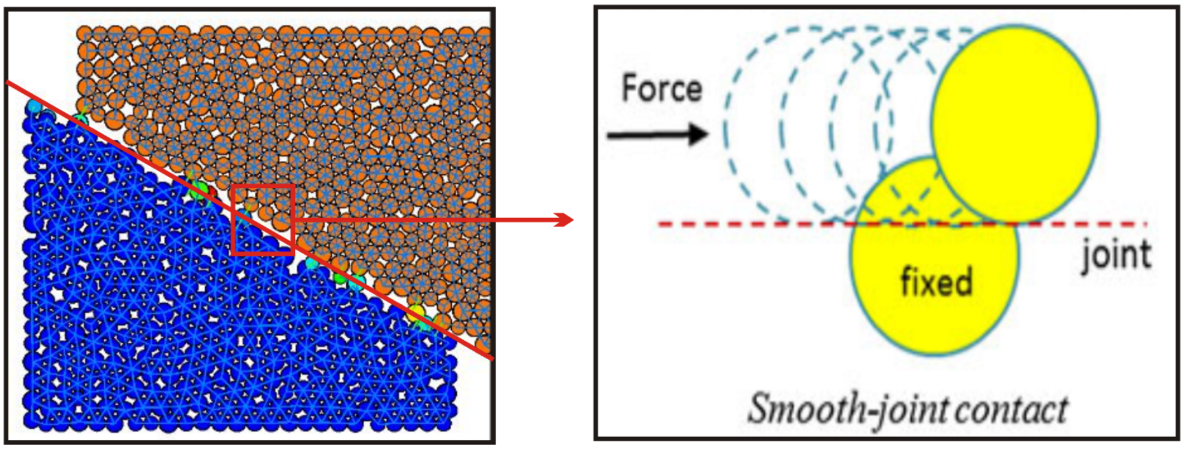


Figure 8. Detailed behavior of smooth joint model [29].

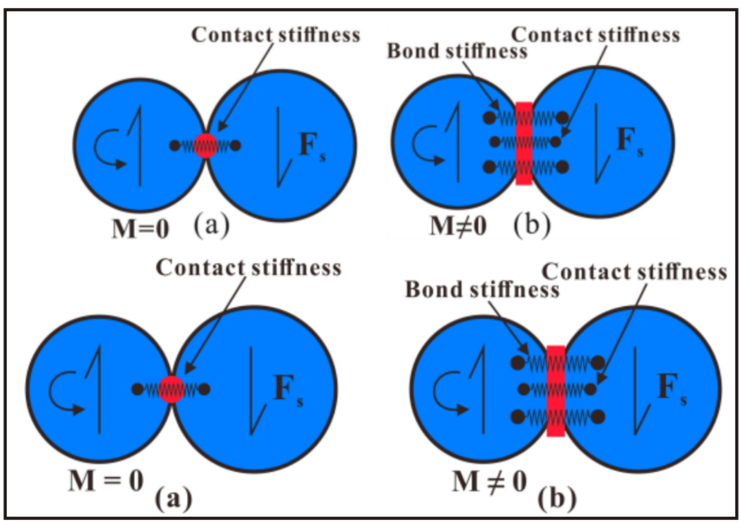


Figure 9. a). Contact bond model b). Parallel bond model [30].

In the past two decades, the parallel bond model has been widely used in the fragmentation and fracturing process in rock. However, the parallel bond model for synthetic rock mass revealed unrealistically low ratios of the simulated unconfined compressive strength to the indirect tensile strength. The second drawback is that a direct adoption of circular particles cannot fully capture the behavior of complex shaped and highly interlocked grain structures. Another problem in the particle flow code for the particle-based material is the inherent roughness of interface surfaces representing rock discontinuities, which is artificially added strength with bonded or frictional rock joints. Several enhancements have been proposed in the PFC to address these issues.

Ivars, et al. [31] have combined BPM with SJM for a collaborative network, leading to the development of the so-called synthetic rock mass, which aims to numerical estimate the anisotropy of rock mass, which cannot be obtained with empirical methods. Previous studies of the Smooth joint model for rock joints are given in Table 4. SJM would play a significant role in predicting the numerical properties of anisotropic laminated shale rock.

Table 4. Previous studies by SJM to characterize the behavior of anisotropic rocks.

Researcher	Description	Model
Chiu, et al. [32]	Modelling a joint with different roughness	SJM
Hu, et al. [33]	Parametric studies of SJM on mechanical properties of jointed rock masses	SJM
Chong, et al. [34]	Numerical Investigation of bedding plane parameters of transversely isotropic shale	SJM
Aziznejad, et al. [35]	Static and dynamic responses of the anisotropic rock foundation	SJM
Shang, et al. [36]	Modelling direct tensile behavior of anisotropic rocks	SJM
Park, et al. [37]	Modelling anisotropic uniaxial compressive and tensile strength	SJM
Chong, et al. [38]	Study of effects of layer orientation on the mechanical behavior of shale	SJM
Huan, et al. [39]	SJM-based model used for the mechanical properties of transversely isotropic rock mass	SJM
Lei, et al. [40]	Experimental and numerical investigations carried out on the meso-fracture mechanism of Longmaxi shale with different crack-depth ratios	SJM
Lei, et al. [41]	Study of the shale fracture behavior with different bedding properties	SJM

3.2. Calibration of micro-parameters

Calibration of parameters is an essential part of numerical modeling. Nevertheless, in PFC2D, it is hard to obtain the micro-parameters experimentally. The calibration of micro-parameters of particles is carried out based on the macro-mechanical properties of the specimen. The PFC model has been used to the correlation between the microscopic and macroscopic properties of rocks. However, the highly non-linear behavior of particle interaction may result in non-optimal microscopic parameters. Trial error is the best method to obtain more appropriate and reasonable micro-parameters by fitting the macro-mechanical properties. Several researchers have used the trial error method for the calibration of macro-mechanical parameters with micro-mechanical parameters [42-45]. The trial-error method is a continuous process until the correlation between numerical and experimental results reaches a reasonable range. In this section pattern failure mechanism, stress-strain curves, and peak strength failure criteria have been used for the calibration of micro-parameters with macro-parameters of laminated shale rock based on the trail-error method.

To calibrate the macro-mechanical properties (point load test) with micro-mechanical properties, for this purpose, developed a point load model consisting of smooth joint fracture as a fractional lamination plane in PFC2D. A geometric model with dimensions of sample 50 mm × 50 mm × 20 mm is presented in (Figure 10). Furthermore, the laminated plane subjected parallel and perpendicular with respect to loading in PFC2D is shown in Figure 11. The micro-parameters for the laminated plane used in the smooth joint contact model are presented in Table 5.

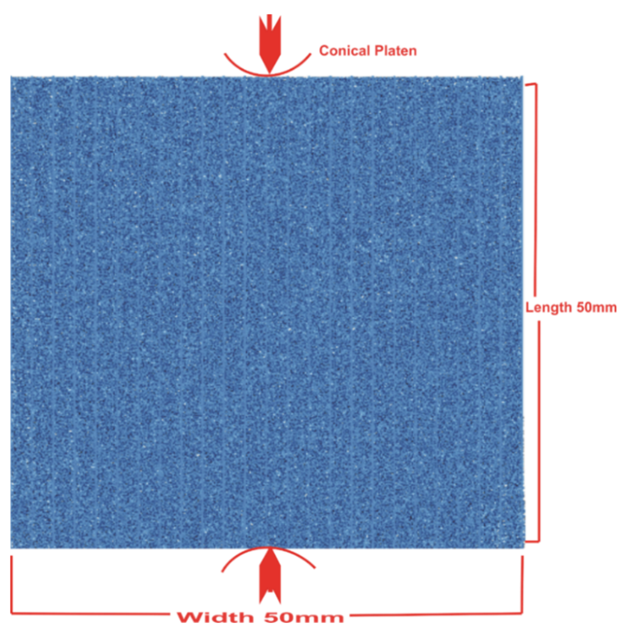


Figure 10. Model geometry of point load test in PFC.

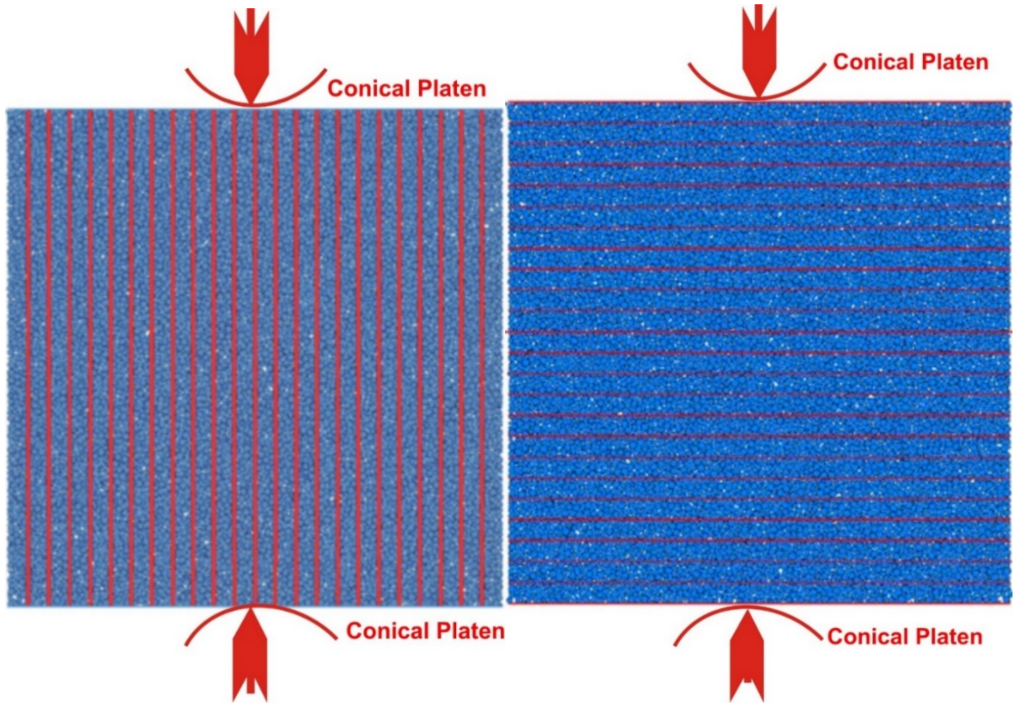


Figure 11. Orientation of lamination parallel and perpendicular to loading rate in PFC.

Table 5. Micro-parameters of lamination used in smooth joint contact model.

Micro-parameters	Values
Normal stiffness of the smooth joint (GPa/m)	20
Shear stiffness of the smooth joint (GPa/m)	6.86
Tensile strength of the smooth joint (MPa)	0.018
Shear strength of the smooth joint (MPa)	0.10
Friction coefficient	3.5
Smooth joint-large	1

In order to acquire further more reasonable results for the mechanical behavior of laminated shale rock specimen, developed a flat joint model in PFC2D to calibrate the macro-mechanical properties (uniaxial compressive strength test) with micro-mechanical properties. The flat joint contact model can allow the user to accurately match both the compressive strength and direct tensile strength of hard rock. A geometric model for the UCS test in numerical modeling with dimensions of sample 54 mm × 125 mm × 20 mm is presented in (Figure 12). Furthermore, the laminated plane subjected parallel and perpendicular with respect to loading in PFC2D is shown in (Figure 13). The calibration method has been performed for the lamination perpendicular and parallel to loading, and their results are presented in Figure 14. The properties of micro-parameters used in the flat joint model are presented in Table 6.

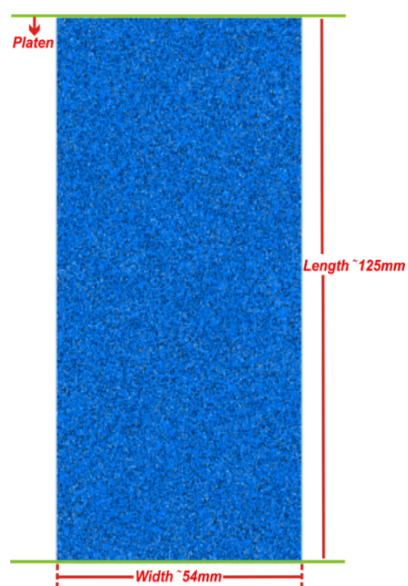


Figure 12. Model geometry of uniaxial compressive strength test in PFC.

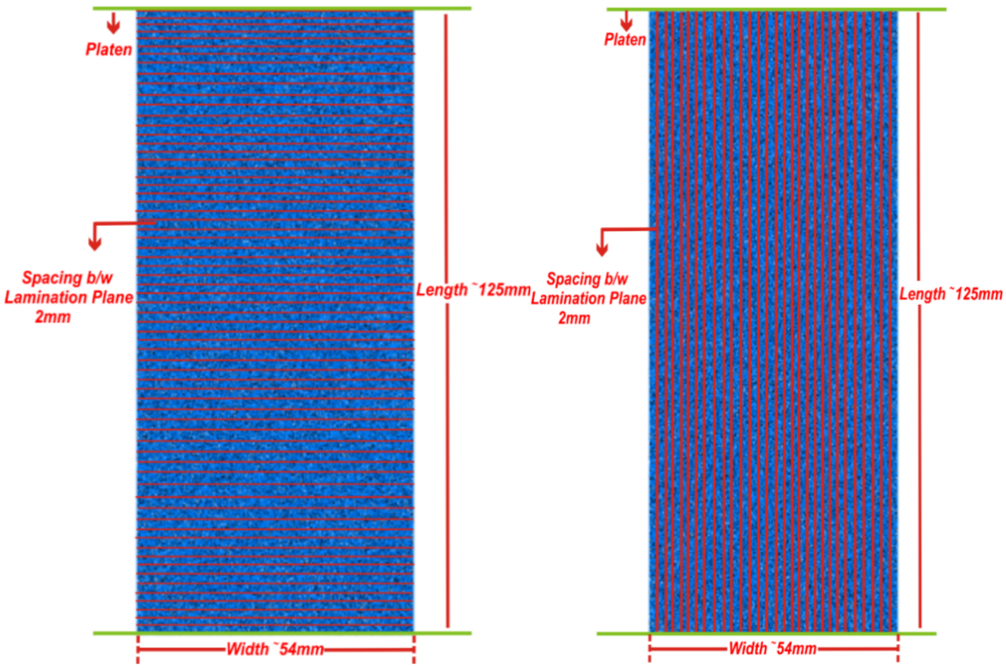
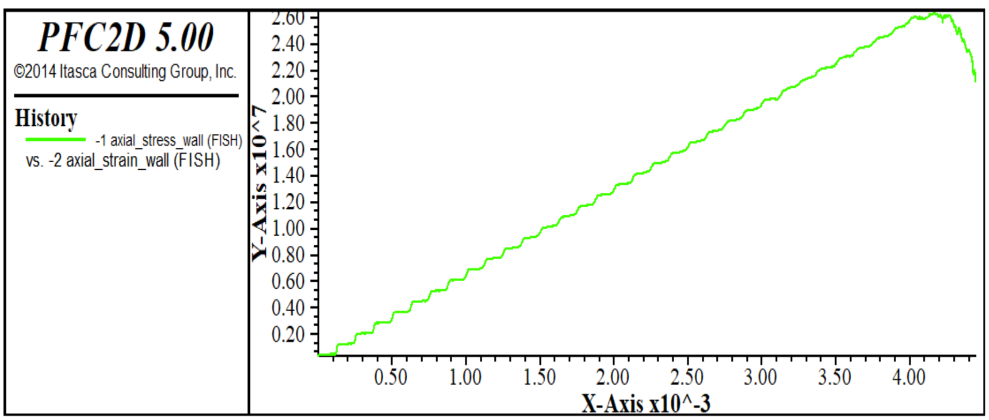


Figure 13. Orientations of lamination perpendicular and parallel to loading in PFC.



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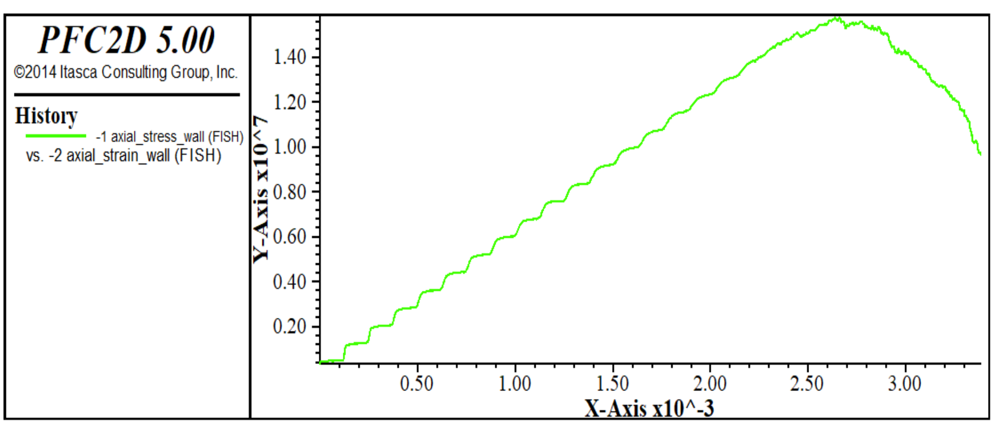

(b)

Figure 14. Output of calibration method for the lamination a) Perpendicular, b) Parallel to loading.

Table 6. Micro-parameters used in flat joint contact model.

Micro-parameters	Value
Particle density (kg/m^3)	2330
Young's modulus of the flat joint bond (GPa)	0.6
Ratio of normal to shear stiffness of the flat joint bond	0.1
Particle friction coefficient	0.7
Flat joint bond tensile strength (MPa)	0.36
Flat joint bond cohesion (MPa)	0.4
Friction angle (degree)	25

4. Validation of Numerical Model

In this section, numerical model validation was performed by pattern failure mechanism, stress-strain curve, and peak strength criteria. Furthermore, the point test load was used for the pattern failure mechanism criteria. The smooth joint model was applied in the point load test for the lamination of shale in both directions, parallel and perpendicular to loading. Furthermore, obtained a reasonable agreement between the smooth joint modeling in PFC2D and the pattern of failure mechanism in the point load test is shown in (Figures 15 and 16). During the point load tests, when the orientation of lamination is parallel to loading shows that splitting starts from inside of lamination planes and continues in the direction of the lamination. When loading perpendicular to the lamination plane, the crack propagation will be affected by the lamination, and in this case, the SJM model will be able to model these conditions well. The uniaxial compressive strength test was used for stress-strain curve criteria. The flat joint model was applied in the uniaxial compressive strength test for the lamination of shale in both directions, parallel and perpendicular to loading. Statistical analysis was performed to validate the uniaxial compressive strength test. Moreover, the statistical analysis provided the best results, which are presented in Figure 17 and Table 7. They validated compression between the flat joint modeling in PFC2D and the stress-strain curve of the laboratory UCS tests (Figure 18 and Table 8).

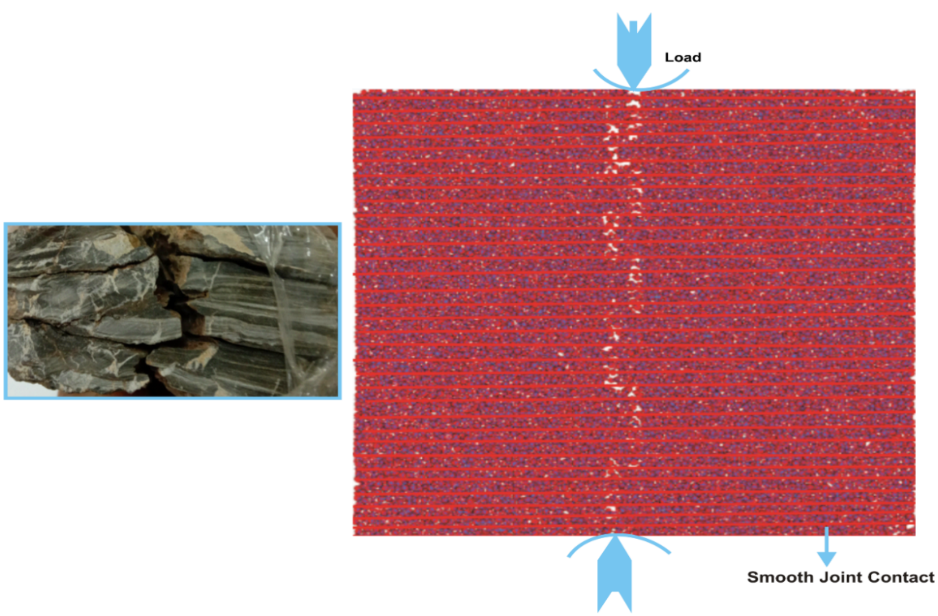

Figure 15. SJM in point load test with the lamination direction perpendicular to loading.

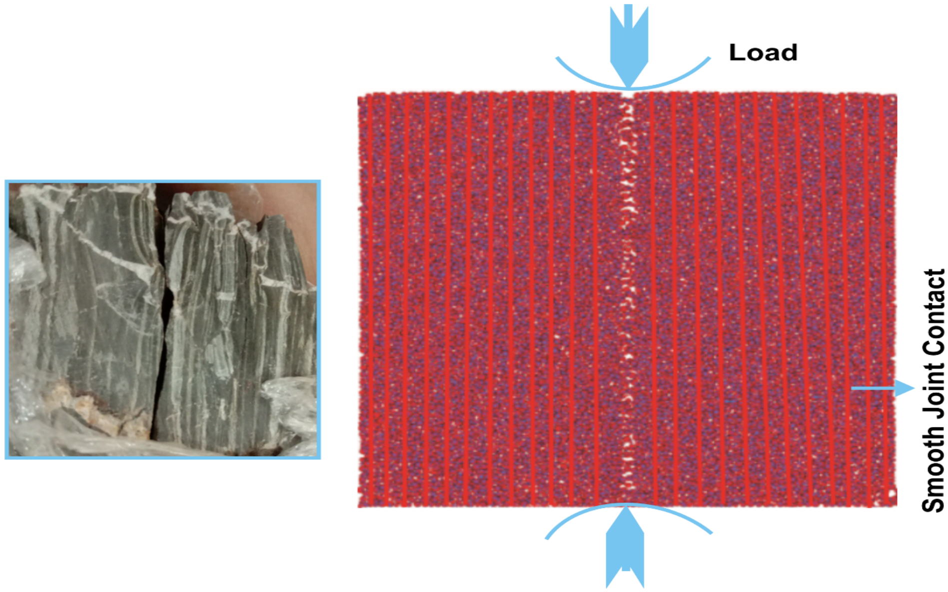

Figure 16. SJM in point load test with the lamination direction parallel to loading.

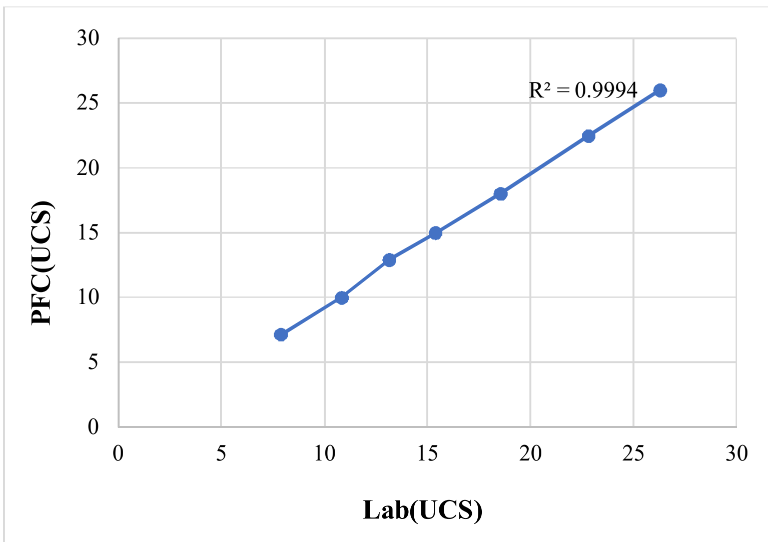

Figure 17. Scatter plot predicated for lab (UCS) and PFC (UCS).

Table 7. Statistical parameters for validation of UCS.

	Lab (UCS)		PFC (UCS)	
Distribution function	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**
Normal	16.420	6.56	14.267	5.53

Table 8. Validation of compressive strength in (PFC) and laboratory UCS tests.

	UCS (MPa)	
Sample ID	**Lab**	**PFC**
SH-1	26.30	26.01
SH-2	22.83	22.50
SH-3	18.57	18.05
SH-4	15.41	15.00
SH-5	13.15	12.90
SH-6	10.84	10.00
SH-6	7.90	7.15

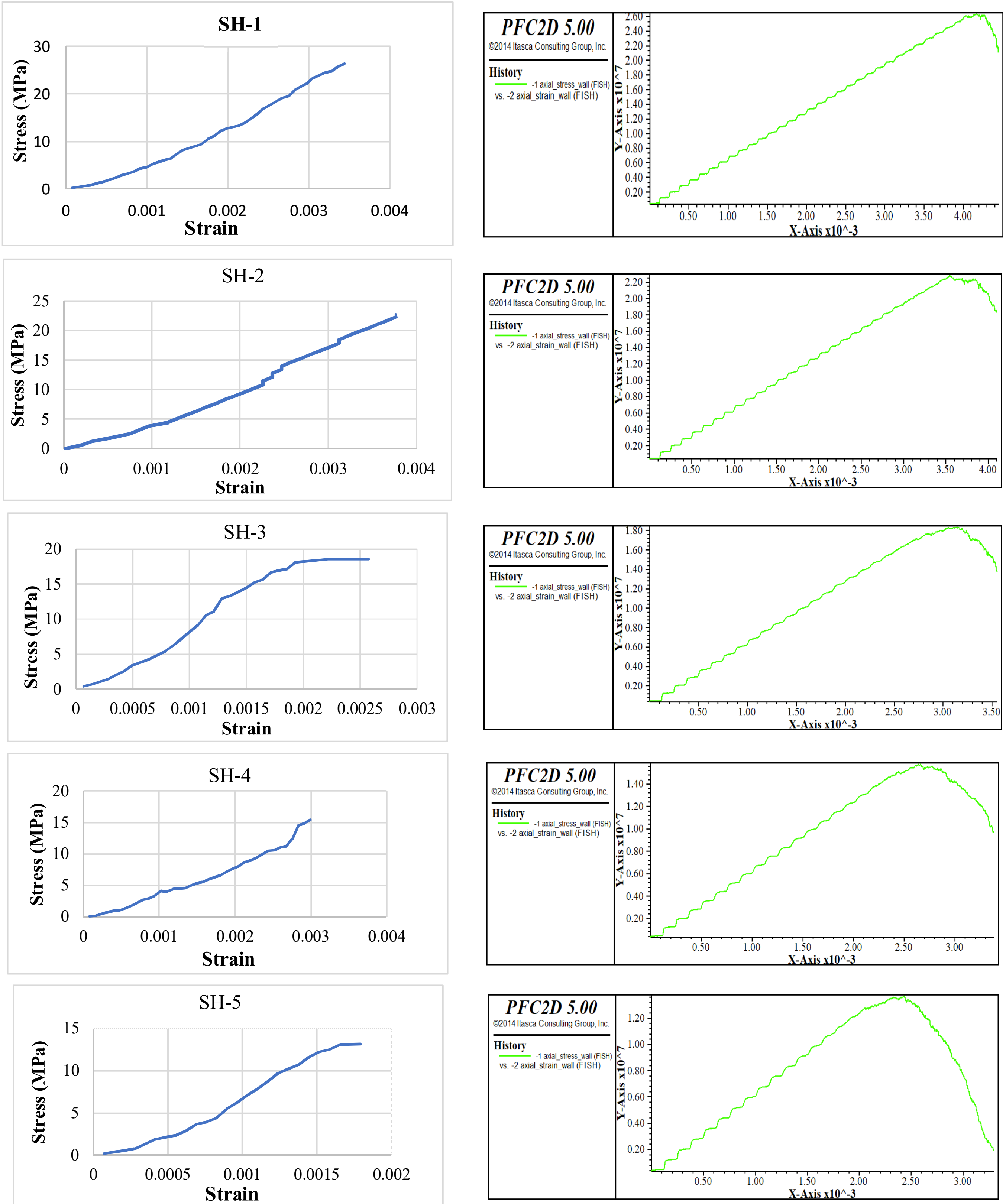

Figure 18. Validation of macro-parameters (UCS tests) with micro-parameters (PFC).

5. Conclusions

In this research work, the petrographic studies and the XRD tests were used to analyze the mineral composition and lamination properties of shale rock samples. The uniaxial compression and point load tests were accomplished to obtain the macroscopic mechanical characteristics of the anisotropic laminated shale rock in the laboratory. The PFC2D models were prepared, and the microscopic mechanical characteristics of the shale sample models were validated with the laboratory testing results by failure process, stress-strain curves, and peak failure strengths of the real shale samples. The mechanical behavior of the laminated shale models was predicted using the smooth joint model (SJM) adopted in PFC2D. The following main conclusions were gained through these analyses:

- During the point load tests, when the orientation of lamination was parallel to loading shows that splitting starts from inside of lamination planes and continues in the direction of the lamination.
- The uniaxial compression tests were carried out on the shale rock samples, and the real stress strain curves were obtained in laboratory.
- The micro-parameters used for PFC2D models were calibrated with the point load, and uniaxial compressive tests were performed on the shale specimen.
- Several numerical models were developed for simulating thee lamination of shale rock samples using PFC2D, and then the most accurate and validated SJM was implemented in the numerical model for the delamination analysis. Validation of peak strengths criteria provide best results; the determination coefficient values for lab and numerical modeling with (R^2 = 0.99).
- 2D-DEM with particle flow code (PFC) is a more practical and robust method for modeling fracture initiation and propagation under complicated stress conditions. Combining the smooth joint model (SJM) and flat joint model (FJM) provided the best result for the anisotropic behavior of laminated shale in PFC2D.
- When loading perpendicular to the lamination plane, the crack propagation will be affected by the lamination, and in this case, the SJM model will be able to model these conditions well.
- The combination of experimental and numerical methods shows that inherent discontinuity (lamination) has a strong influence on crack initiation and propagation in shale rock.

Shale is a more demandable rock in the field of unconventional reservoir systems, and billions of dollars are invested in the extraction of oil and gas from shale rock. Hydraulic fracturing in shale is very difficult and sensitive. The mechanical behavior of laminated shale rock requires to study the effect of in-situ stresses, fluid mechanics modeling, and calibrating by modern computing methods such machine learning method.

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ارزیابی آزمایشگاهی و مدل‌سازی المان گسسته برای بررسی مکانیزم شکست سطوح لایه بندی در سنگ شیل

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چکیده:

در این کار تحقیقاتی، آزمایش‌های پراش پرتو ایکس (XRD) و مطالعات پتروگرافی برای تجزیه و تحلیل ترکیب کانی شناسی و لامینا سیون در نمونه‌های سنگ شیل انجام گردید. سپس از آزمایش‌های بارنقطه‌ای و مقاومت فشاری تک محوری برای تعیین مقاومت و ناهمسانگردی نمونه‌های شیل استفاده شد. برمبنای خواص مکانیکی بدست آمده از این آزمایش‌ها، مدل‌سازی عددی به روش المان گسسته با استفاده از کد جریان ذرات دوبعدی (PFC2D) برای شبیه‌سازی فرآیند شکست نمونه‌های شیل صورت گرفت. هدف از این کار اعتبار سنجی مدل‌های عددی برمبنای نحوه‌ی شکست، منحنی‌های تنش ـــ کرنش و مقاومت حداکثر نمونه‌های شیل بود. از آزمایش بارنقطه‌ای برای تعیین نحوه‌ی الگوی شکست در نمونه‌ها برای دو حالت بارگزاری موازی با سطوح لامیناسیون و عمود بر این سطوح استفاده شد و همچنین، آزمایش مقاومت فشاری تک محوری برای بدست آوردن شکل منحنی تنش ـــ کرنش و تعیین نقطه‌ی حداکثر مقاومت فشاری نمونه‌ها بکار گرفته شد. پس از انجام مدل‌سازی و کالیبره کردن خواص میکرو مکانیکی بین دانه‌ای و سطوح لامیناسیون تعریف شده در مدل‌سازی براساس نتایج آزمایش‌های مقاومت فشاری تک محوری و بارنقطه‌ای، اعتبارسنجی گردید که برمبنای حداکثر مقاومت بیشترین همبستگی را با داده‌های واقعی نشان داد (R^2=0.99). مدل‌های رفتاری مختلفی برای تخمین رفتار مکانیکی سنگ شیل در نرم افزار PFC2D انتخاب گردید که مدل رفتاری درزه‌ی صاف (SJM) مدلی سازگار و مناسب برای شبیه‌سازی رفتار لامیناسیون در شیل تشخیص داده شد. ابن پژوهش نشان داد که مدل رفتاری SJM نتایج قابل قبول و نزدیکتر به واقعیت را برای رفتار سنگ‌های شیل دارای لامیناسیون نشان می‌دهد که می‌توان از آن برای مدل‌سازی رفتار سنگ‌های شیل دارای لامیناسیون در پروژه‌های مهندسی نفت بخصوص در مناطق ناحیه‌ی زمین‌شناسی مرکزی ایران استفاده کرد.

کلمات کلیدی: سنگ شیل، PFC2D، شکست سطوح لامیناسیون، مدل درزه صاف، روش اجزای گسسته.