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Montney Shale Geomechanical Challenges: 2D and 3D FEM/DEM Numerical Simulations of a Layered Material Fracturing in Compression

Keneti, S. A. R.

EBA, A Tetra Tech Company, Oceanic Plaza, 9th Floor, 1066 West Hastings Street, Vancouver, V6E 3X2, British Columbia, Canada

Pak, R. A.

Golder Associates Ltd., 500 - 4260 Still Creek Drive, V5C 6C6, Burnaby, British Columbia, Canada

Wong, R. C. K.

Department of Civil Engineering, Schulich School of Engineering, University of Calgary, T2N1N4, Calgary, Alberta, Canada

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ABSTRACT: In this study a series of numerical analysis have been carried out to assess the suitability of the FEM/DEM technique to simulate UCS test of a horizontally layered material, the Montney shale. The strength parameter of the Montney samples reported by Keneti and Wong (2011) were used as the input data to 2D and 3D models in the ELFEN program. When the failure criterion within the intact material was met in the model, a new crack was generated which could be visualized by re-meshing the updated geometry with the pre-existing foliations and the new cracks. The results were analyzed in terms of the "global mechanical response" obtained by assessing if the fracturing response is comparable to the recorded behavior in the UCS test of the Montney shale. The entire fracturing process was shown to be simulated well by ELFEN during fractures initiation and propagation processes.

1. INTRODUCTION

The large volume and long-term potential, attractive gas prices and exceptional interest in world markets, bring the unconventional gas into the front of our energy future. Shale gas is one of a number of "unconventional" sources of natural gas, including coalbed methane tight sandstones, and methane hydrates [1]. In North America, there are several shale gas opportunities, shown in Fig. 1. Located in a large area spanning the British Columbia and Alberta border, the Montney Formation is one of the largest economically feasible resource plays in North America (Fig. 1). The Montney is a primary hydrocarbon target with an estimated undiscovered 15 oil pools (22 to 54 × 106 m^3) and 427 gas pools (23,258 × l06 m^3) in its three major play areas: Sub-crop South-Fir, Distal Shelf-Glacier, and Sub-crop North-Ring. The estimated volumes for the Montney are approximately 50% of the estimated undiscovered oil and gas in the Western Canada Sedimentary Basin for the Triassic ([2] and [3]). The Montney resource covers a considerable area, more than 90,650 km^2, with varying geological and reservoir properties from the east to the west (Fig. 2). The Mid to Lower Triassic-age deposit contains sandstones on the shallower (900 m) eastern boundary of the play, grading to siltstone and shale in the deeper (2,450 m) western boundary of the play. In the western portion, near Dawson Creek, the gas shale is thick, thermally mature with high organic content, whereas in the northern section, north of Fort St. John, the Montney shale has higher clay content and decreased silica, reducing the brittleness of the formation and its favorability for creating reservoir permeability and flow capacity with hydraulic stimulation [4].

As new exploratory drilling continues to reveal the broad range of facies in the Montney, it adds to both the complexity and potential of this relatively distinctive formation in western Canada [5]. Sedimentary rocks like shale commonly show inherent anisotropy (directional variation in material properties) because of the influence of depositional geological processes on constitutive behaviour. Anisotropy is considered as a key factor during investigation and analysis of deviated boreholes, borehole stability, stress-strain behaviour, initiation and propagation of fracture and fluid flow [6]. Predicting the geomechanical response of the shale material during hydraulic fracturing operation in the field needs better understanding of their geomechanical behaviour under laboratory testing as well as throughout simulation by numerical approaches.

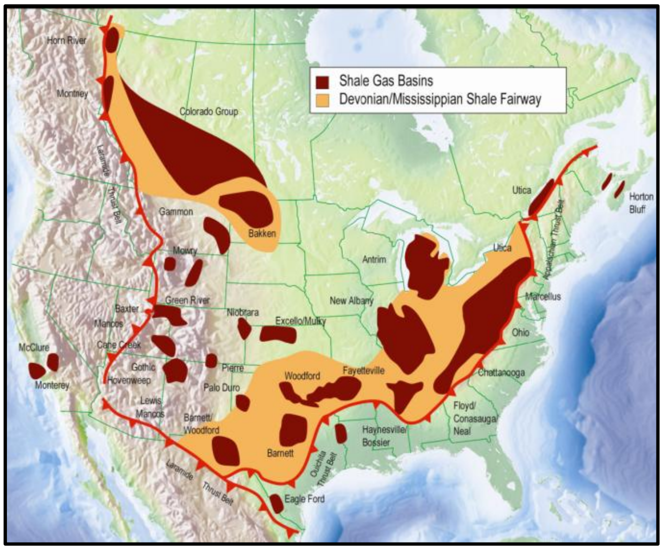


Fig. 1. Shale gas plays of North America [1].

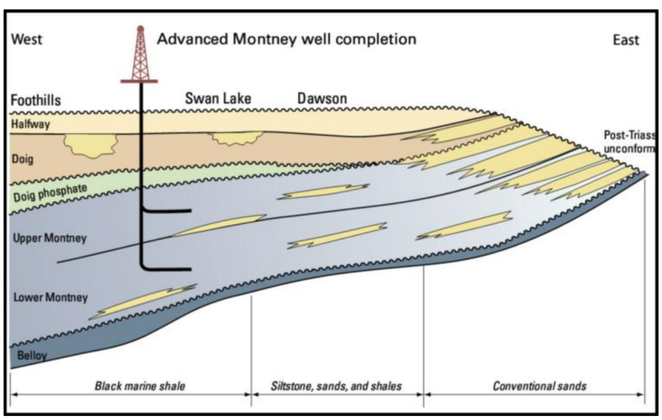


Fig. 2. Montney-Doig resource plays [4].

There are many practical problems in jointed media where discontinuities are dominant in the analysis. The conventional numerical methods such as Finite Element Method (FEM), which are mostly continuity based, are clearly not suitable for using in such situations [7]. Thus, the methods such as discrete elements methods (DEM), Discontinuous Deformation Analysis (DDA) and combined Finite-Discrete Element Method (FEM/DEM) have been developed in the past to model a discontinuous media. In FEM/DEM, continuum behaviour is modeled through finite elements while discontinuous behaviour is analyzed by discrete elements [8]. The effect of layering and the direction of loading on the samples behaviour were studied by Mahabadi et al. [8] by employing a modified FEM/DEM research code presented in [9] by Munjiza. The applicability of the combined finite-discrete element method to model laboratory scale experiments was shown through their simulations of Brazilian disc tests for both a homogeneous rock and a layered rock. The results suggested that the presence of layers and direction of loading with respect to them plays a major role in mechanical behaviour of the models.

Stefanizzi et al. [10] simulated a series of numerical analyses using the finite/discrete element code ELFEN and showed the suitability of this approach to simulate standard rock mechanics tests. ELFEN provides a unique ability to model fracture initiation and propagation, as it simulates the transition from continuum to discontinuum [10].

In this study, the uniaxial compression test conducted by Keneti and Wong [11-13] on Montney shale sample has been simulated by ELFEN (Rockfield Software, 2010). The results have been analyzed in terms of the "global mechanical response" obtained by evaluating if the fracturing response is realistically represented.

2. EXPERIMENTAL WORKS ON THE MONTNEY SHALE

Keneti and Wong [11-14], investigated some geomechanical properties of the Montney shale throughout laboratory investigations. From their study, it was found that the pre-existing planes of weakness play a major role in failure and anisotropic behavior of the Montney shale. From the Brazilian and point load strength tests, the tensile strength in the horizontal direction was dominated by the bond strength of the intact structure (6-15.3 MPa), whereas that in the vertical direction was controlled by the existing natural beddings (0.7-2.8 MPa) [11 and 12].

Compressive strength, compressive elastic modulus in the vertical direction and Poisson's ratio were measured from the unconfined compressive strength test as 99 MPa, 25 GPa, and 0.1, respectively. The final mode of fracture was mainly shearing at top and bottom of the sample, rather than the common vertical splitting around the core center [13]. Tensile and compressive elastic moduli in the horizontal direction were also measured from Brazilian test as 31 GPa and 40 GPa, respectively [12]. From the direct shear tests using double shear boxes, the Montney samples sheared through the foliation planes as well as through the rock material which resulted in higher shear strength parameters compared to the reported values for shale. From the results, the cohesion was found as 20 MPa and the peak friction angle was about 40^{o} [14].

3. FEM/DEM MODELS FOR COMPRESSIVE LOADING OF THE MONTNEY SHALE

The unconfined compression of cylindrical rock samples is widely performed in rock engineering projects in order to determine the uniaxial compressive strength, σ_c, and the elastic constants Young's modulus, E_c, and Poisson's ratio, ϑ, of the rock material. Although it seems to be a straightforward technique, great attention must be paid in interpreting results obtained in a uniaxial compressive test. Its results are affected by the rock composition, loading condition and the condition of the test samples. Even for rock having the same geological name, the test results will vary with the grain size, porosity, the nature and extent of cementing between the grains, degree of weathering and micro-fissuring, and the levels of pressure and temperature that the rock has been subjected to throughout its history [15].

The main feature of the test preparations should be to subject the testing sample to uniform boundary conditions with a uniform uniaxial stress. Consequently, a uniform displacement field would be generated all over the sample. However, the sample might be prevented from deforming uniformly due to "end effects". The sample would be restrained near its ends due to friction between its ends and the loading platens and differences between the elastic properties of rock and steel. The result of such restraint is that shear stresses are developed at the contact area of the sample and the loading platen. This means that the axial stress is not always a principal stress and therefore, stresses within the sample are not uniaxial.

As a consequence of the end effects, the stress distribution varies throughout the testing sample in a uniaxial compressive strength test as a function of the geometry of the sample. As the height to diameter (H/D) ratio increases, a greater proportion of the sample volume is subjected to an approximately uniform state of uniaxial stress. Therefore, it has been suggested that a H/D ratio of at least 2 should be used in uniaxial compression [15].

In the ELFEN model of the UCS test simulation, the geometry of the specimen was set same as the sample tested in the laboratory and its properties were also assigned the same as the obtained experimental results. The modeled specimen had a diameter of 76 mm and a height of 160 mm (i.e. the H/D ratio is 2.1). Location of each pre-existing fracture was found by Computer Tomography (CT) technique and presented in the model (Fig. 3). A homogeneous isotropic sample was also modeled for studying the failure process of the Montney in absence of the pre-existing weak planes.

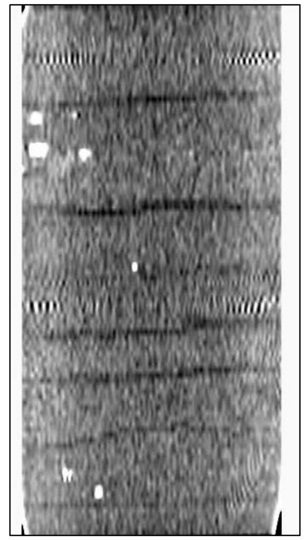


Fig. 3 Foliations in Montney cores observed in computer tomography analysis.

The constant vertical velocities of 0.5 mm/s and 2 mm/s were applied to the 2D and 3D models, respectively, to simulate the compressive loading. These displacement rates were chosen only for the calculation time efficiency purpose in the numerical simulation. However, it is not representative of the real loading condition as the loading rate is normally much slower during the experiment. A mesh size of 10% of the unit length was assumed for the platens and the sample in 2D and 3D models. The platens outer boundaries were set free to move in the loading direction (vertical) and were fixed in the horizontal direction in 2D and 3D models. Therefore, the specimen could freely expand in a minimal end effect condition.

The FEM/DEM code ELFEN only considers Mode I (tensile) fracture initiation and propagation. Therefore, only fractures created by exceeding the tensile strength of the material can be visualized. The Rankine Rotating crack model coupled with a Mohr-Coulomb failure criterion was assigned to simulate the material behavior in 2D and 3D models.

Although it is practical in ELFEN code, the effects of heterogeneity was not considered in the current study as the objective of this study was investigation of the influence of the pre-existing cracks on failure of material in UCS test. Hence, the matrix was considered as homogenous and the discontinuity parameters K_n, K_t and μ_f were assigned to simulate the pre-existing weak planes in the 2D model. For the 3D model, weaker material properties were assigned to the pre-existing cracks of 1mm thickness. The assumed fracture energy parameter was based on the author's experience and the available literature. However, no sensitivity analysis was done on this critical parameter in current study. Table 1 summarizes the material properties used for the UCS test numerical simulation.

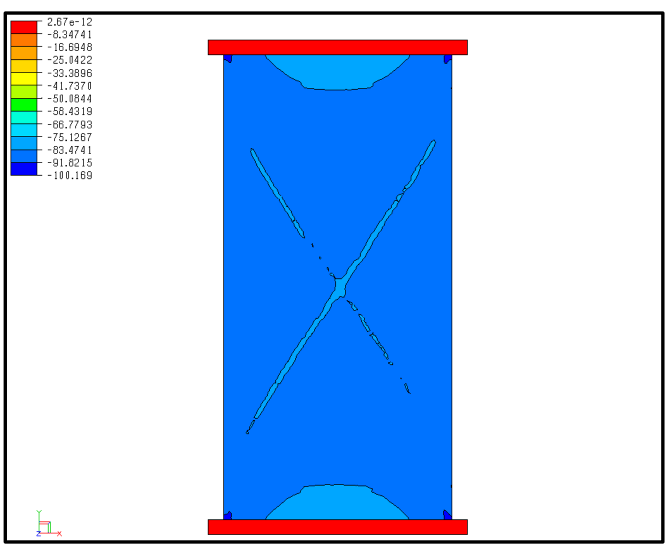
Table 1. Properties of the matrix and pre-existing fractures in 2D and 3D numerical simulation of the UCS test

Compressive Elastic Modulus (E_c), GPa	25
Poisson's Ratio (ϑ)	0.1
Friction Angle (φ)	31
Cohesion (C), MPa	20
Tensile Strength (σ_t), MPa	10
Fracture Energy (G_f), N/mm	0.003
Pre-existing Fractures Parameters in 2D Model: K_n , N/mm^3 K_t , N/mm^3 μ_f	 2.5×10^4 2.5×10^3 0.65
Pre-existing Fractures Parameters in 3D Model: Cohesion (C), MPa * Other parameters (E_c, ϑ, and φ) were assigned to be the same as the matrix material properties.	 10

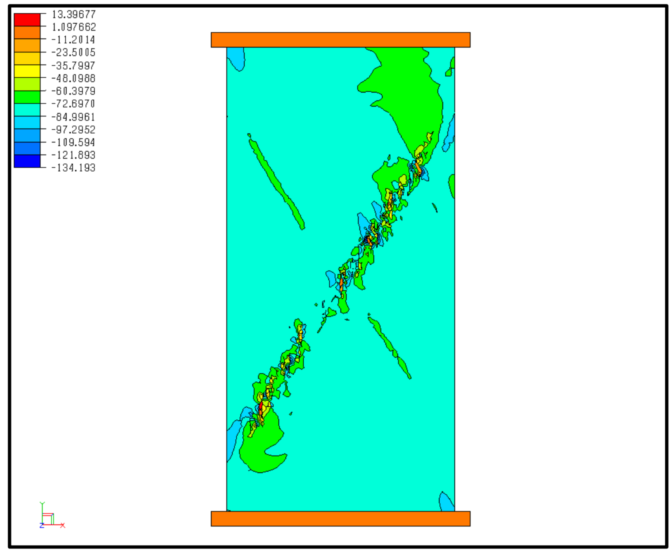
4. RESULTS AND DISCUSSIONS

The results obtained in terms of fracture pattern at different time-steps as well as the vertical stress distribution before and at the peak stress level are presented for the 2D and 3D homogenous and layered models throughout figures 4 to 7.

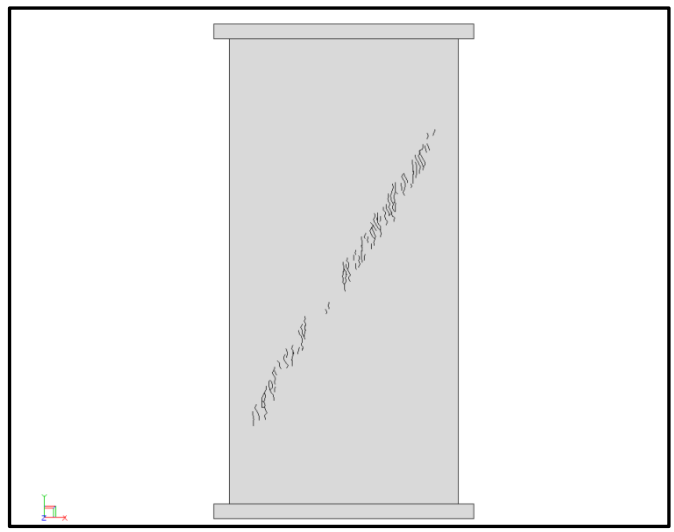
From Fig.4, one can see that in case of the homogenous model FEM/DEM approach predicted the commonly observed failure pattern in the UCS experiments: creation of fracture in a single plane of 45 + φ/2 at the cylinder's central part then propagation of the splitting cracks towards its corners.



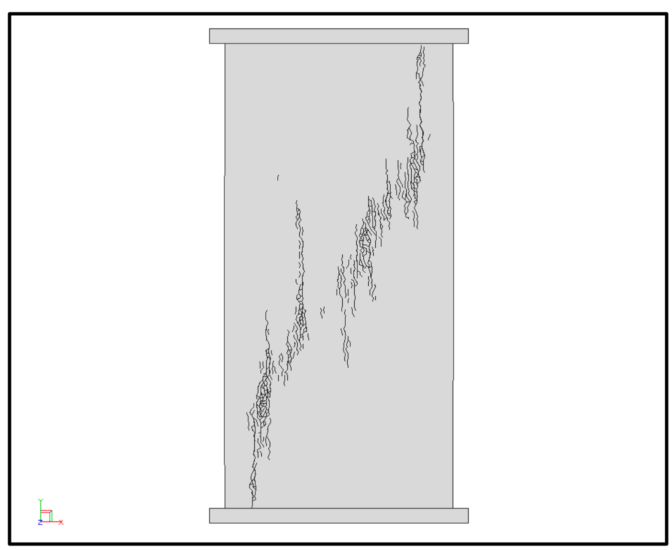
a- S_{YY} before the peak stress level.



b- S_{YY} at the peak stress level.



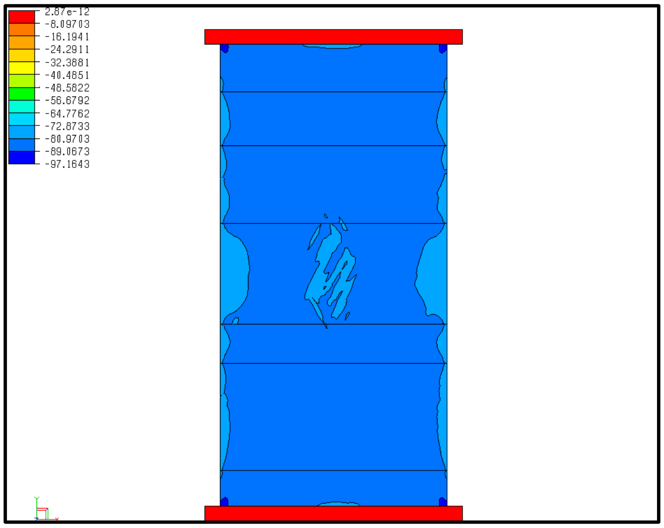
c- Fracture pattern at its initial stages.



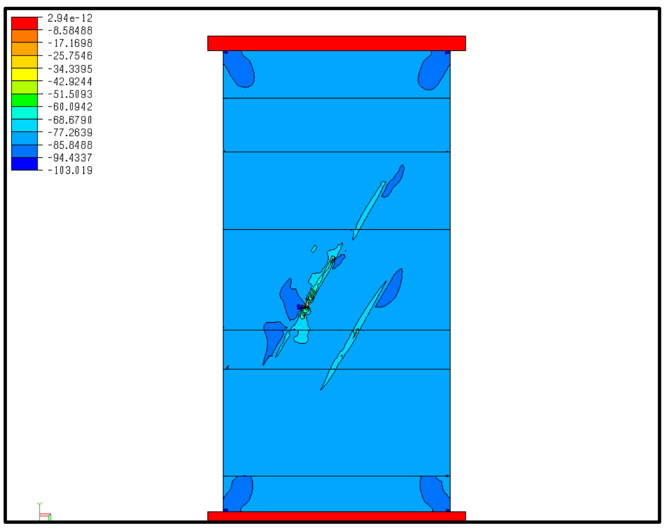
d- Fracture pattern at its final stages.

Fig. 4. Fracture pattern and stress distribution for the homogenous model in 2D.

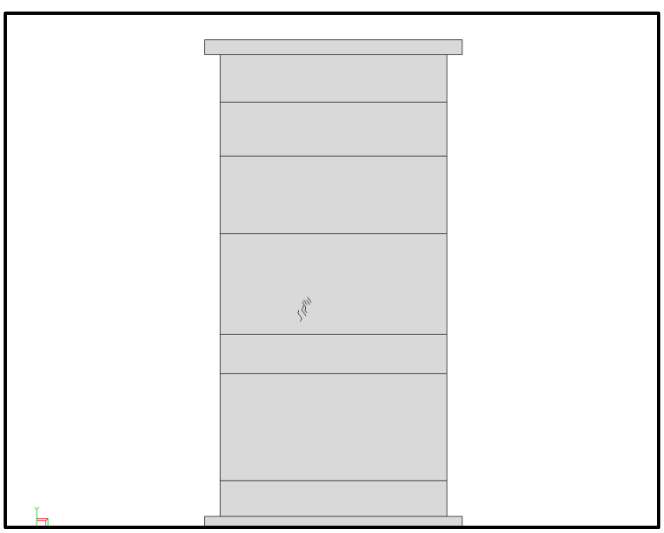
Fig. 5 shows that introducing the pre-existing cracks into the 2D model resulted in a pattern of multi-fracture planes, possibly due to stress re-distribution and concentration around the existing cracks.



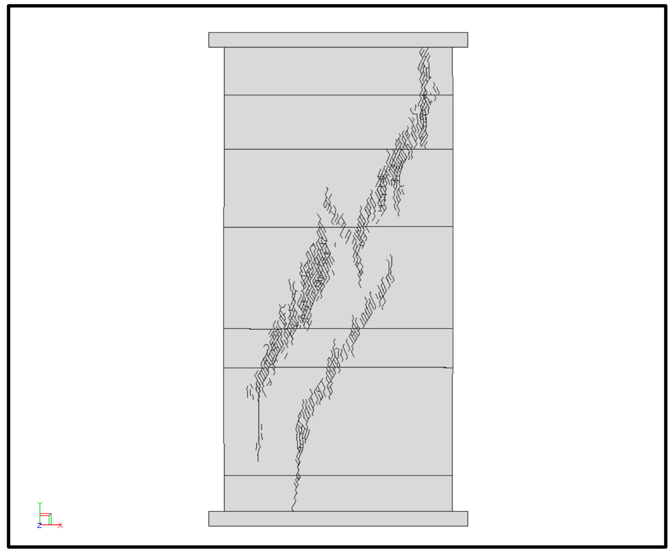
a- S_{YY} before the peak stress level.



b- S_{YY} at the peak stress level.



c- Fracture Pattern at its initial stages.

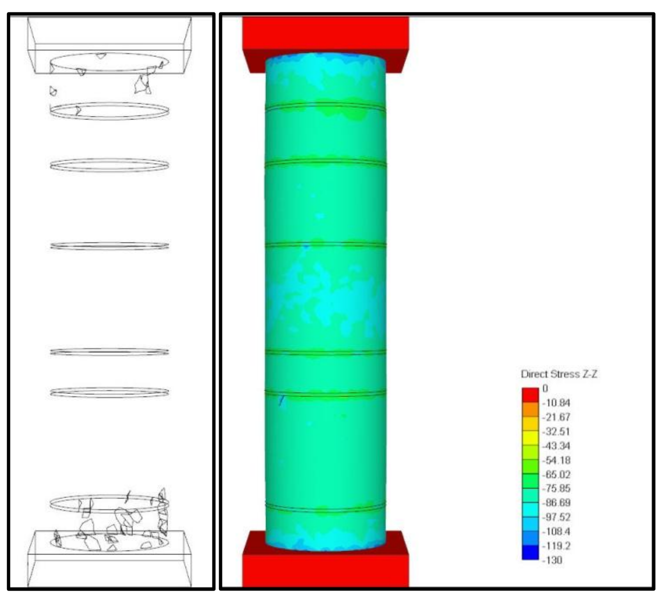


d- Fracture pattern at its final stages.

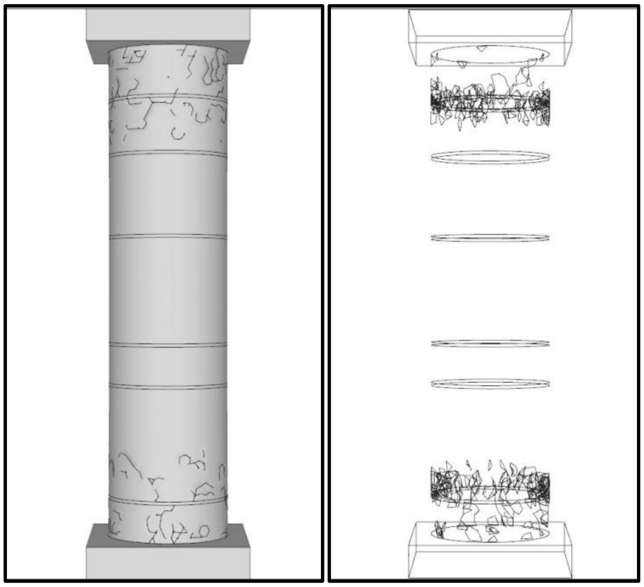
Fig. 5. Fracture pattern and stress distribution for the layered model in 2D.

It should be noted that although fracture patterns are different in a homogenous and a horizontally layered models, the strength of the specimens are quite the same (about 85 MPa). This is in agreement with the theoretical works by Jaeger (1960) that the strength and failure surface in compressive loading is not affected by the horizontal or vertical sets of discontinuities [15]. In these cases, sample would behave like an intact material in which many factors such as stress conditions, discontinuity surface conditions (infilling, asperities, etc.), joints spacing, as well as the rock material by itself would play important roles in the strength and final failure mode of the specimen [14].

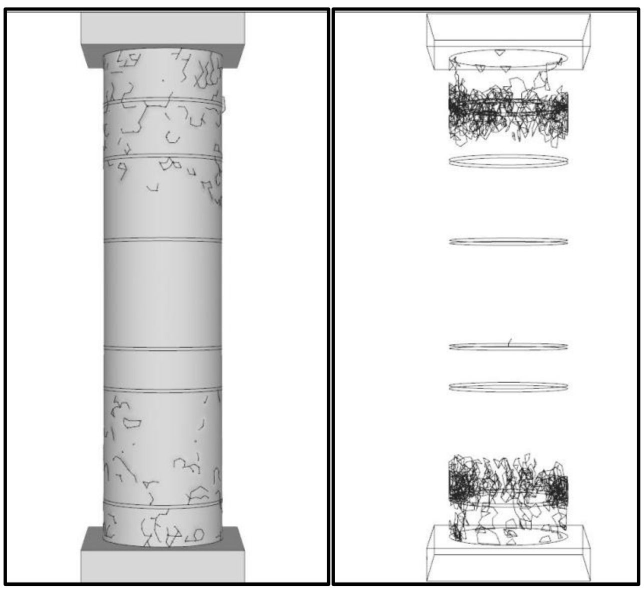
Results of the 3D model are shown in Fig. 6 for the horizontally layered specimen.



a- S_{ZZ} and initiated fractures at the peak stress.



b- Fracture propagation at its initial stages.



c- Fracture propagation at its final stages.

Fig. 6. Fracture pattern and stress distribution for the layered model in 3D.

As can be seen, fractures started from both ends of the specimen and extended to the central part of the 3D model. This contradicts with the 2D model's result in which failure started at about the mid-height of the specimen. In addition, the peak strength in 3D model is about 100 MPa (i.e. the measured strength in the experiment) which is higher than that obtained from the 2D model.

Fig. 7 shows the failure progress in the Montney shale under UCS test recorded by high-speed camera and Fig. 8 shows the failed sample [13]. As can be seen from these figures, the 3D FEM/DEM model has achieved a good correspondence with the experimental observations in which Montney sample failed at both ends rather than the typical results observed in UCS test of homogenous materials.

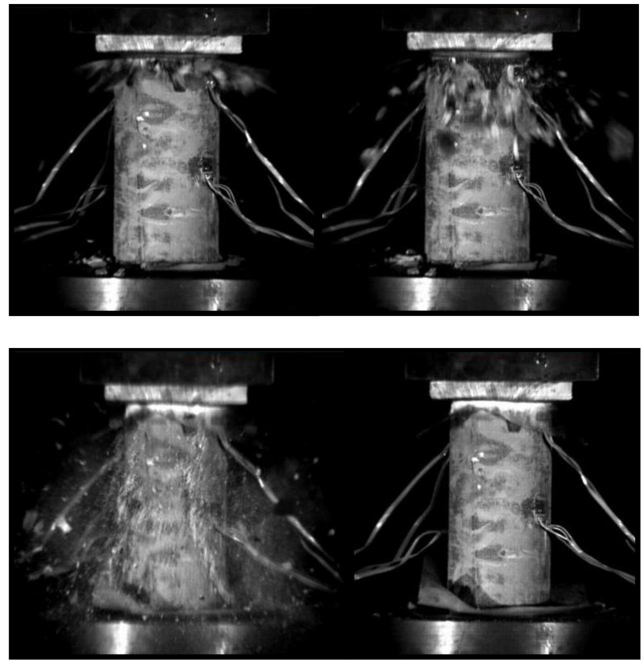


Fig. 7. Failure progress in Montney shale under UCS test [13].

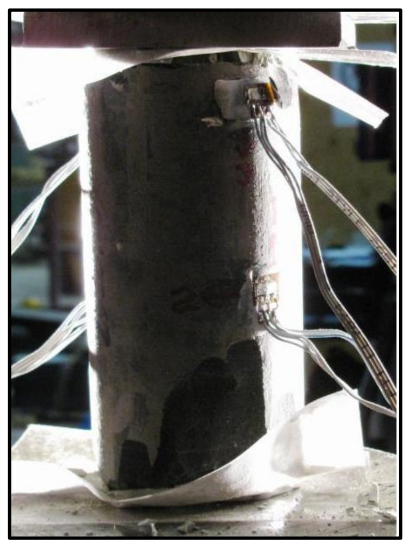


Fig. 8. Montney sample failed throughout the UCS test.

5. CONCLUSIONS

In this study a series of numerical analysis were carried out to assess the suitability of the FEM/DEM technique to simulate UCS test of a horizontally layered material, the Montney shale. Experimentally obtained input parameters were used as input to assist ELFEN in a successful simulation of UCS test in 2D and 3D. The results were analyzed in terms of the "global mechanical response" obtained by assessing if the fracturing response is rationally represented. The fracturing process was shown to be simulated well during fractures initiation and propagation processes. It was found that a 3D model matches better than a 2D model to the experimental results obtained for the Montney shale in terms of fracturing pattern and the material strength. However, the location of the fractures initiation and final state of the failed sample do not need to be assumed in the ELFEN simulation. Fracturing can occur suddenly and show a variety of mechanisms when certain local stress conditions are satisfied in the model.

The applicability of the ELFEN to simulate laboratory scale experiments was proven during the course of this study. It should be noted that the assumed fracture energy parameter was based on the author's experience and the available literature. It is therefore recommended to experimentally investigate this parameter and do sensitivity analysis on the selected value on the simulation results.

Future works can examine its suitability for simulation of larger scale problems. As an example of its application for simulation of field scale problems could be borehole stability analysis in anisotropic media and numerical simulation of hydraulic fracturing conducted in layered reservoirs such as the Montney shale.

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