Numerical simulations and experimental test in the development of hydraulic fracturing processes

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Abstract. The economic feasibility of the exploitation of unconventional oil and gas resources is enhanced when it is possible to analyze a priori, with a reasonable accuracy, the effects of different hydraulic fracturing schemes (different fracturing fluids, different proppant concentrations, etc.) and compare them with the results in terms of the predicted production, enabling therefore the selection of the optimal alternative. Two basic ingredients for these analyses are a reliable numerical technique and an adequate geomechanical characterization of the reservoir.

The use of the Discontinuous Galerkin Method (DGM) to simulate fracture processes is discussed, with the perspective of implementing this technique to simulate the hydraulic fracturing of shale formations. It is important to remark that resulting models capture the proper fracture mechanical physics required to model nucleation and propagation of fractures.

Two examples are discussed. First, the well-known Brazilian Test is modelled; in this case the dominant phenomenon is fracture nucleation. Second, a Brazilian Test including a slot is modelled, this is a typical fracture mechanics test used for studying fracture propagation in rocks.

Keywords. Fracture mechanics, Hydraulic Fracturing, Numerical Simulations, Brazilian Test

1. Introduction

The strong momentum that hydraulic fracturing processes [1] are attaining nowadays in the oil industry, for the exploitation of unconventional gas and oil reservoirs, encourages operating companies, oil service companies, software development companies and academic institutions to invest increasing resources in the research and development of hydraulic fracturing computational simulators.

There are many numerical methodologies for modeling fracture processes, each of them with their own advantages and limitations. For example, in the method of diffuse

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fracture, the structural impact of the crack is simulated using an "equivalent" elasto-plastic material model and therefore propagation is not described in details [2][3][4]. On the other hand, the XFEM methodologies allow correctly modeling the fracture spread from the point of view of fracture mechanics, but these methods present a low efficiency for parallel processing implementation; however, an efficient parallel implementation is a strong requirement for being able to model large 3D domains [5][6][7][8].

The use of finite elements with continuous displacement interpolations is quite complex for multi-cracking parallel implementations due to the need of a step-by-step remeshing to follow the cracks growth [9]. The first techniques that incorporated discontinuous interpolations were not directed towards parallel implementations either [10].

The adopted simulation technique based on the Discontinuous Galerkin Method (DGM) as developed in Refs. [11][12][13][14], is discussed in this paper.

As a first step to validate the adopted modeling technique the well-known Brazilian Test is analyzed, a case in which the dominant phenomenon is fracture nucleation and therefore a test not adequate for analyzing the capability of the numerical technique to simulate fracture propagation.

As a second step a test in which fracture propagation is the dominant phenomenon is analyzed: the Brazilian Test with a slot [15][16], and the numerical and experimental results are compared.

The simulation results are very encouraging and the available capability for simulating the hydraulic fracturing process is presently being extended by coupling to the mechanical problem the fluid circulation problem.

2. Fracture modelling

In Figure 1(a) it is shown a schematic representation of a fracture propagation process at the continuum level.

Rock fractures resulting from hydraulic fracturing processes are discrete, i.e. the fractures are discontinuity surfaces within the material. To model the discontinuous nature of the problem in question, the DGM technique was adopted. DGM is a generalization of the solid mechanics problem weak formulation which incorporates, from the beginning, the presence of discontinuities in the solution, as in fracture processes.

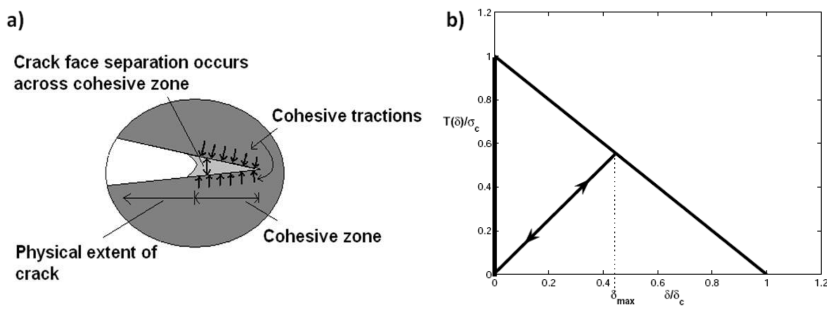

Figure 1. **a)** Fracture propagation. **b)** Cohesive law

In the finite element model the fracturing is localized at the inter-element surfaces: before the employed fracture mechanic criterion indicates fracture initiation, the cohesive tractions (*T*) impose the displacements continuity through those surfaces; afterwards those tractions are a function of the crack opening displacement (δ) as shown in Figure 1(b) for a mode I fracture; in this figure σ_c is the fracture strength of the rock material and δ_c is the maximum fracture opening before all the cohesion is lost. In the same figure it is shown the model implemented for an unloading / reloading process. The area between the axes and the $T(\delta)$ curve is the material fracture energy per unit volume which is a material property [17].

For a mixed mode fracture:

$$\mathbf{T} = \frac{T}{\delta}(\beta^2 \Delta_t + \Delta_n \vec{n}) \quad (1)$$

Where the crack opening displacement (δ) is:

$$\delta = \sqrt{\beta^2 \Delta_t^2 + \Delta_n^2} \quad (2)$$

In the above equations Δ_n is the transversal opening and Δ_t is the tangential displacement of the opening fracture. $\vec{n}$ is the normal axis to the fracture surface and $\beta = {}^{K_{IIc}}/_{K_{Ic}}$ is a material property defined in [17]. Where K_{Ic} and K_{IIc} are the material toughness for mode I and mode II fracture respectively [17].

When implementing the DGM, the material inside the elements is modeled using standard phenomenological material models: elasticity, elasto-plasticity, visco-elasticity, visco-plasticity, etc., while in the inter-element surfaces "interface elements" are used, with two distinct ingredients:

- A phenomenological fracture indicator that triggers the incorporation into the model of the fracture process. It is essential to establish that the correct characterization of the fracture initiation depends on the success of the simulations.
- A fracture energy release law as the one depicted in Figure 1(b).

Besides the ability to describe the discrete nature of the fracture, the proposed method has the distinct advantage of avoiding the need for topological changes in the mesh as a crack propagates, allowing the propagation of cracks through processor edges and presenting scalability in parallel calculations. Another significant advantage of the method is that it preserves the consistency and stability in non-fractured areas of the mesh [14].

3. The Brazilian test model

The Brazilian test is the standard industrial test used to determine, by means of the lateral compression of a cylindrical sample, the strength of a cohesive material (e.g. rock, concrete, etc.).

The theoretical bases for the Brazilian test are the analytical solutions that have been obtained by many researches for isotropic or transverse isotropic materials under loads that are distributed over a small arc of the disc's perimeter [20]. The ultimate theoretical load for this test is:

$$P_{ult} = \frac{\sigma_c \pi D t}{2} \quad (3)$$

where D is the cylindrical sample diameter and t is its length.

Two numerical analyses were performed using two different 3D meshes. The finer mesh has 4038 elements and the coarse mesh has 666 elements.

In both cases, Hertz type contact boundary conditions were implemented for the loads application.

The model numerical results are indicated in Table 1:

Table 1. Brazilian Test – Numerical results

Mesh type	$\boldsymbol{P_{ult}^{num} / P_{ult}^{analit}}$
Coarse Mesh	1.04
Fine Mesh	0.98

From the obtained numerical results the following observations can be made:

- For the Brazilian Test case the numerical results are almost independent of the mesh density.
- The test was simulated using different compression rates and the results are quite independent of the loading velocity.

It should be noticed that in the Brazilian Test the transversal stresses, the ones that produce the sample rupture, are very homogeneous across the loading diameter; hence, almost all the points along the vertical diameter break at the same time: it is a fracture initiation test rather than a fracture propagation test.

4. The Brazilian Test with a slot

The difference with the test discussed in the previous section is that now the cylindrical sample has a through slot, as shown in Figure 2(a). The notched Brazilian disc method is widely used in characterizing rock fracture toughness. Using this specimen, a large number of fracture tests have been carried out on different rock materials under mixed modes I–II loading [21].

As it is shown in Figure 2(a), changing the slot orientation (α-angle) with respect to the compression direction (vertical) different combinations of mode I and mode II can be tested [15][16]. For the mode I test $\alpha = 0°$ and for the mode II test $\alpha = 28°$ was used.

The sample will break under load with fractures propagating from the slot corners; therefore, it is a very valuable fracture propagation test [15][16].

The 3D meshes used to analyze the problem are shown in Figure 2(b). To assess on the mesh quality, a quality factor was defined as the ratio of the elements characteristic length with respect to the material cohesive length [17] [18] [19]:

$$l_c = \frac{\pi E\ G_c}{8(\sigma_{fr})^2} \quad (4)$$

As it can be seen in Figure 2(b), in the coarse mesh the cohesive zone length is smaller than the characteristic length of the elements, but in the fine mesh the cohesive length is larger than the characteristic length of the elements being this an important condition to simulate fracture [19].

In order to evaluate the loading velocity effect and taking into account that the real loading velocity ($\sim 0.1\ mm/min$) cannot be used in the numerical simulations (excessive processing time), two compression velocities were considered in the models: $100\ \mathrm{mm/min}$ and $1{,}000\ \mathrm{mm/min}$.

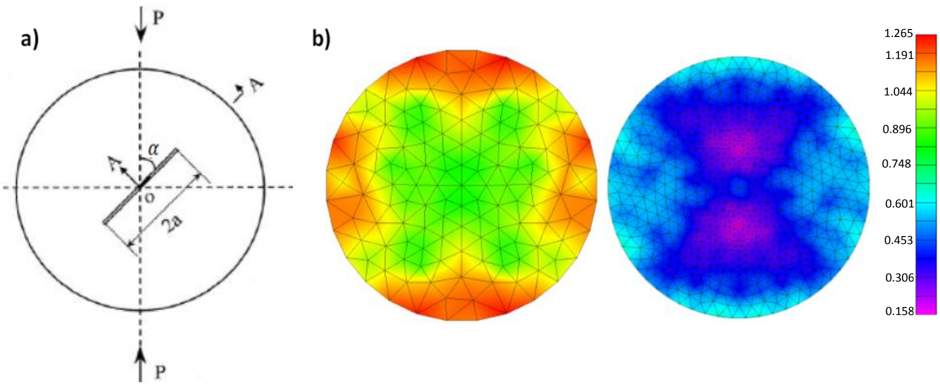

Figure 2. a) Cylindrical sample with a through slot [15]. **b)** Meshes used to model the notch Brazilian Test. The contour map indicates the mesh quality factor l/l_c (see Eq. (4) for more details).

The results for the coarse mesh are shown in Figure 3(a); it is evident that this mesh does not incorporate any strain rate effect. In a like manner, the results for the finer mesh are shown in Figure 3(b); in this case, the results are able to pick-up the typical strain rate effect of fracture processes [18].

In order to validate the simulations results, several experiments were performed. Synthetic materials were used to mimic the rock's composition of the Vaca Muerta formation in Neuquina basin. This rock type was selected due to its importance in unconventional oil and gas reservoirs. The decision on the use of synthetic material was taken due to the difficulty in obtaining consolidated rock samples from outcrops. The use of synthetic samples for comparison of results was considered sufficiently valid.

Table 2. Mechanical properties of synthetic sample

Property	Value
Young Modulus	21.5 GPa
Maximum Stress	43.7 MPa
Poisson Ratio	0.19
Density	2405 Kg/m^3

The mechanical properties of the samples are listed in Table 2. The tests were performed by changing the angle of the central notch to promote the fracture propagation in mode I and II.

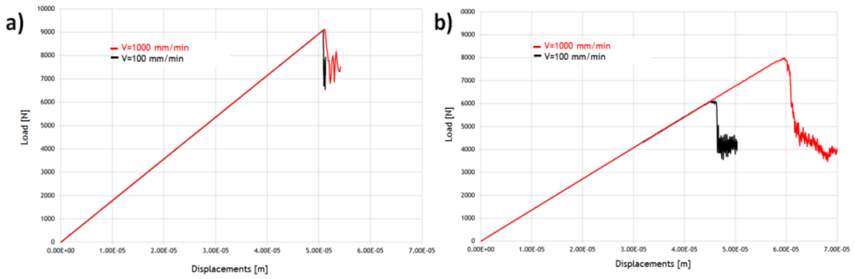

Figure 3. Results for the Brazilian test with a slot. **a)** Coarse mesh results. The black line represents the response of the specimen with a load velocity 100 mm/s. The red line represents the response of the specimen with a load velocity 1000 mm/s. **b)** Finer mesh results for 100 mm/s (red) and for 1000 mm/s (black).

Figure 4 shows the fracture toughness obtained from the experimental test in mode I propagation. The following expression, given by [15], was used for the calculation of K_{IC}:

$$K_{IC} = \frac{P\sqrt{a}N}{\sqrt{\pi}RB} \qquad (5)$$

where R is the radius of the Brazilian disk (0.05 m); B is the thickness of the disk (0.025 m); P is the compressive load at failure; a is the half crack length (0.015 m) and N is a non-dimensional coefficient which depend on $a/_R$ and the orientation angle α of the notch with the direction of loading. For the test in mode I, $N = 1$.

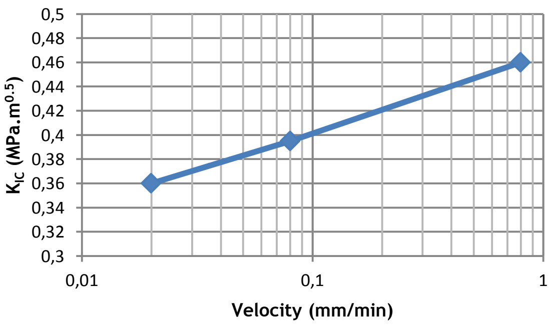

Figure 4. Variation of the fracture toughness for the synthetic samples as function of the loading velocity.

Taking into account the minimum velocity of load used in the simulations (see Figure 3 as reference), the compressive load at failure is 9087.83 N. Under these conditions, the stress intensity factor K_{IC} (Eq. (5)) predicted with the numerical simulations is $0.502 \text{ MPam}^{0.5}$, varying in only a 6% from the value obtained in the experiments, a very acceptable value considering that the simulations loading velocity is much higher than the experimental loading velocity.

Finally, in figure 5, several pictures of the experimental results are shown for the mode I propagation case and for the mode II case.

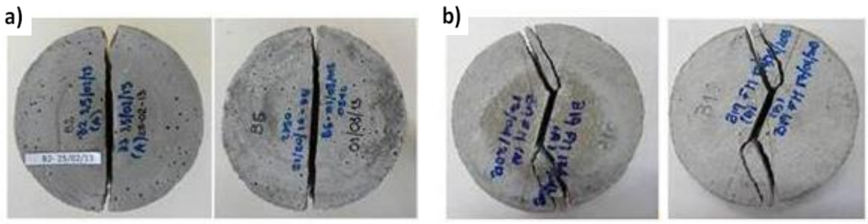

Figure 5. Experimental results for the Brazilian test with a slot for mode I. **a)** $\alpha = 0°$. **b)** $\alpha = 28°$.

In Figure 6, a comparison between the experimental and numerical results explores the effect of using different failure criteria to predict the fracture occurrence.

From the analysis of the fractures patterns, the maximum normal stress criterion seems to be the one that best fits the experimental result in mode II propagation.

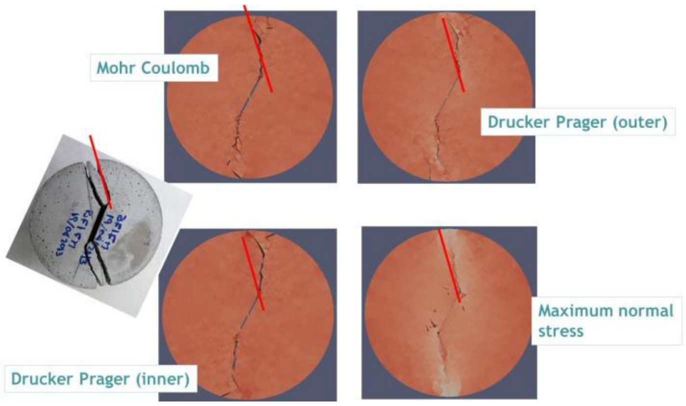

Figure 6. Brazilian Test with a slot: experimental vs. numerical results

5. Conclusions

A finite element simulator based on the Discontinuous Galerkin Method is being implemented for the simulation of hydraulic fracturing processes in shale reservoirs.

In this paper the first numerical experiments are presented showing that the computational simulator under development can accurately model fracture initiation and fracture propagation.

Several numerical simulations of the Brazilian test with and without slot have been developed. The compressive load at failure and the fracture toughness were compared with experimental results from synthetic samples (mimicking the rock's composition of the Vaca Muerta formation in Neuquina basin) achieving in all cases technologically acceptable approximations.

Although the fracture simulator allows the use of different fracture criterions, in the performed simulations, the maximum normal stress criterion seems to be the best option to approximate the experimental fracture pattern.

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