SENSITIVITY OF GEOMECHANICAL VARIABLES THAT AFFECT THE HYDRAULIC FRACTURING USING FINITE ELEMENTS WITH EMBEDDED DISCONTINUITIES

Leidy Laura Alvarez Berrío

alvarezlaura08@gmail.com

Ph.D Student

Universidade Federal de Pernambuco, Recife, Brasil.

Igor Fernandes Gomes

gomes@ufpe.br

Proffesor

Universidade Federal de Pernambuco, Recife, Brasil.

Leonardo Jose Guimarães do Nascimento

leonardo@ufpe.br

Proffesor

Universidade Federal de Pernambuco, Recife, Brasil.

Aura Maria Zuleta Gomez

amzuletago@unal.edu.co

Master Degree Student.

Universidade Federal de Pernambuco, Recife, Brasil.

Licia Mouta

licia@ufpe.br

Proffesor

Universidade Federal de Pernambuco, Recife, Brasil.

Abstract. *Hydraulic Fracturing can be broadly defined as the process by which a fracture initiates and propagates due to hydraulic loading, like a pressure, applied by a fluid inside the fracture, this is a commonly used technique in petroleum engineering to enhance the well efficiency of reservoirs. Due to the importance of characterization of fracture and rock, a* *parametric sensitivity is developed in this work, for identifying the impact of elastic parameters, such as Young modulus, Poisson ratio, Biot coefficient and fluid properties, in the development of a fluid injection in a rock. The model was simulated in a numerical code that adopts a strong discontinuity approach to embedding discontinuities in a finite element mesh and provides a numerical fluid flow analysis in a deformable reservoir. The hydro-mechanical coupling has been determined by a law that relates the variation of permeability as a function of the displacement jump from the mechanical problem.*

Keywords: *Sensitivity, Geomechanics, Embedded Discontinuities.*

INTRODUCTION

Hydraulic fracturing is the process of pumping fluid into a wellbore at an injection rate that is too high for the formation to accept without breaking. During injection, the resistance to flow in the formation increases, the pressure in the wellbore increases to a value called the break-down pressure, that is the sum of the in-situ compressive stress and the strength of the formation.

Even in its most basic form, hydraulic fracturing is a complicated process to model, as it involves the coupling of at least three processes [1]:

1. the mechanical deformation induces by the fluid pressure on the fractures surfaces
2. the flow of fluid within the fractured
3. the fracture propagation.

The process of hydraulic fracturing of rock can be simulated through so many numerical approximations, that try to describe the formation and the propagation of discontinuities in continuous media [2]. The finite element method is an important tool in simulating this type of problem. Finite elements are probably the numerical method most used today for problems related to engineering, one of the reasons is the flexibility of working with heterogeneous and non-linear materials [2].

A technique of finite elements that allows to model the hydraulic fracturing in the porous medium is the continuous approximation of strong discontinuities. This technique describes the nonlinear behavior of the material in the discontinuous interface by a constitutive relation of continuous type, between stresses and strains.

For a good approximation of the problem is necessary consider the mechanism of propagation of the fracture and fluid flow inside the fracture is mutually related, this consists of a coupled hydro mechanical problem, which can be represented by a system of non-linear partial differential equations and solved by different levels of coupling [2].

To understand the importance of mechanical and flow coupling, in this work is developed a sensitivity analysis of mechanical and flow variables. This is to identify the difference and the impact of the change of these values on the response of a hypothetical hydraulic fracturing in a rock.

1 THEORICAL REMARKS

Usually the stress-strain response is modeled using theory of linear elasticity, which is represented by an integral equation that determines the non-local relationship between the fracture width and the fluid pressure. The fluid flow is represented by a non-linear partial differential equation that relates the fluid flow velocity, the fracture width and the gradient of pressure [1].

A typical hydraulic fracturing treatment starts with the creation of an initial path for the fracture. This is usually achieved by a technique called perforation in which specially designed shaped-charges are blasted on the wellbore walls with given orientations, perforating the casing and creating finger -like holes or weak points in the hydrocarbon – laden formation [1].

As previously mentioned, the finite element technique is a good numerical approximation for the analysis of hydraulic fracturing. This problem can be aborted using the mathematical development of the continuous approximation of strong discontinuities, which introduces the effect of a strain band within existing finite elements, has been accepted as an efficient technique for the simulation of fractures in quasi-fragile materials, such as concrete. It becomes unnecessary to use interface elements or mesh reconstruction over and over again, as discrete fracture methods require. The technique is consistent with the principles of continuum mechanics, in addition to reducing computational costs and simplifying the discretization of the fractured medium.

In order to represent the propagation of the discontinuity, instead of using adaptive mesh reconstruction techniques, this approach requires a construction scheme of the discontinuity trajectory.

This way of representing the fracture through narrow bands incorporated makes this technique suitable to be extended, with some simplicity, to represent hydro mechanical phenomena present in the process of hydraulic fracturing. This is due to the fact that the continuous approximation of strong discontinuities maintains the concepts of stress and strains, of continuum mechanics, also to represent discontinuous kinematic fields [2].

The formulation of finite elements with embedded discontinuities or also called strong discontinuities requires the proper consideration of aspects related to kinematic and static consistencies. The kinematic enrichment should reflect the position of the relative displacements (opening and sliding) of the interface. In addition, stress continuity must be correctly imposed to ensure the balance between the surface forces at the interface and the stress field at the surrounding continuous part.

The implementation of this technique in CODE_BRIGHT has been quite convenient and can be done in a non-intrusive way in the code. Since the jump in the field of displacements can be approximated as equivalent inelastic deformations, which can be calculated in the constitutive module of the program in finite elements, within the procedure of integration of stresses in the elements.

The standard MEF equations (without discontinuity) are used to represent the continuous part. The behavior of the discontinuity interface can be described by a constitutive equation that directly relates tensions and displacements (discrete model) or by a constitutive model of the continuous type, which relates tensions and deformations, according to the continuous approximation of strong discontinuities [3].

Figure 1 shows a triangular finite element of three nodes, domain Ωe, length le, with a strain localization band, Se, of width h, that divides the element into two parts, Ωe- and Ωe +, isolating node 1 Of nodes 2 and 3. For the sake of simplification, the formulation of built-in strong discontinuities will be presented below being limited to the study of the domain of this element [2].

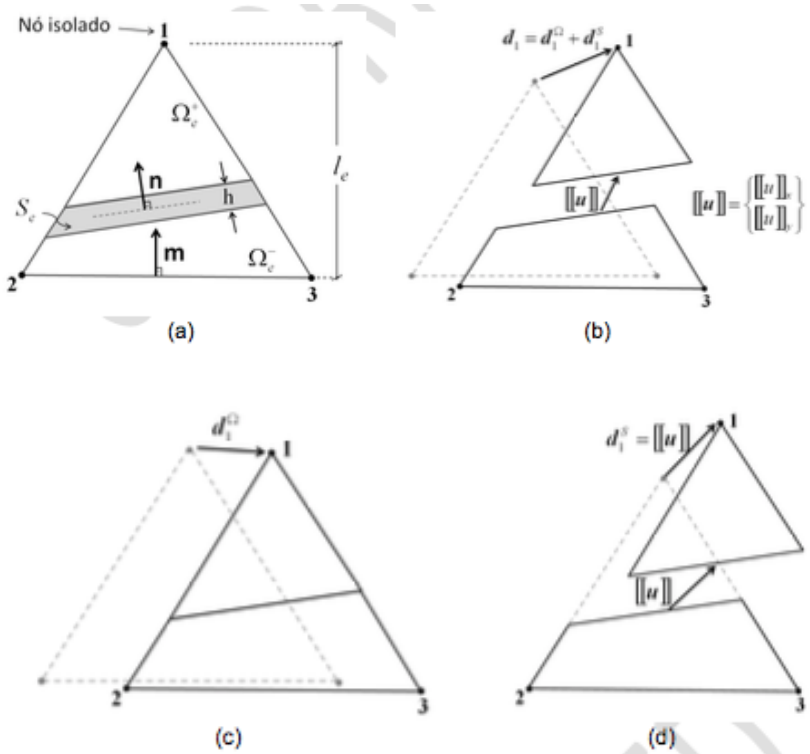

Figure 1 Decomposition of the displacement field: (a) undeformed element; (b) deformed member; (c) deformation of the continuous part; (d) relative movement due to discontinuity. *[2]*.

A fracture in a porous medium becomes a preferred path for the flow towards the discontinuity, which can be interpreted as an anisotropy induced, in the direction of the fracture, throughout the medium. Figure 2 shows the situation of the fractures incorporated in the finite elements, in this case, the permeability tensor of the element becomes anisotropic, with a higher permeability value in the fracture direction.

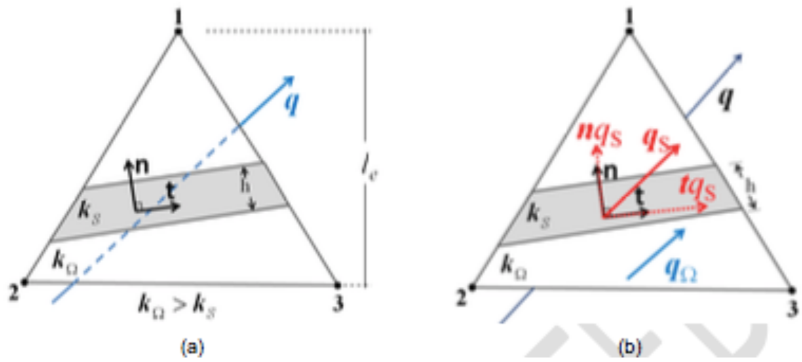

Figure 2 *(a) Element with embedeed fracture. (b) decomposition of the flow vector in the direction of discontinuity. [2].*

Considering the decomposition of the flux vector in the fracture in a normal and a tangential component, as shown in Figure 2 (b), it is assumed that there is no flow at the interface between the fracture and the continuous part of the element and all the flux at the fracture occurs in the direction of it.

It is important to highlight that the finite element program CODE_BRIGHT coupled the problem of fluid flow in oil reservoirs sensitive to the stress state. The equations of the flux problem are solved together with the equilibrium equation of the mechanical problem in a fully coupled scheme, where, for each Newton-Rapshon interaction, a single system of equations is solved for the entire mesh, where unknown are pressure (hydraulic problem) and displacement (mechanical problem) [2].

A fracture in a porous medium becomes a preferred path for the flow towards the discontinuity, which can be interpreted as an anisotropy induced, in the direction of the fracture, throughout the medium.

The mechanical behavior of the rock is represented by the damage model proposed in [2]. The mechanics of continuous damage are based on irreversible thermodynamic processes and were formulated to describe the mechanism prior to the formation of the macro fracture. The model assumes that the degradation of the material is a result of the growth and interconnection of the existing microcracks [4]. In this model, the concept of effective stress damage was introduced to describe the behavior of the damaged medium) [2].

In the fluid flow problem, the normal jump in the fracture, obtained in the mechanical problem, is used to update the element permeability using the cubic form to represent the fracture conductivity [2].

2 RESULTS

A finite element mesh is constructed in the GMSH program, with the measures of the model presented by Carrier in his work [6]. The mesh has 5021 elements, 2603 nodes and a height of the fracture of 0.15 m, half of the one presented by Carrier [6]. Figure 3 shows the mesh created and have a zoom where is disposed the material that contains the fracture.

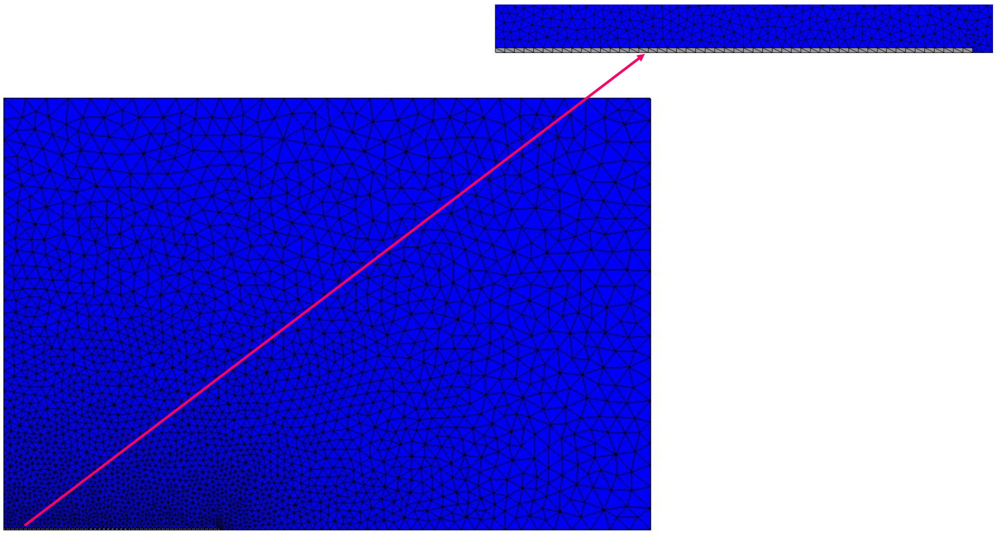

Figure 3 Mesh for Sensitivity Study.

Four elements are selected to perform the analysis of the behavior of the fracture and rock mechanical properties, two where the fracture is contained and two in the rock over the fracture as can see in the Figure 4. These points are chosen after having seen the results in the elements where the injection of the fracturing fluid is carried out directly, and are not representative results since a rapid and abrupt change of the properties is evidenced by being an area exposed directly to a change in stress due to new fluid in the fracture.

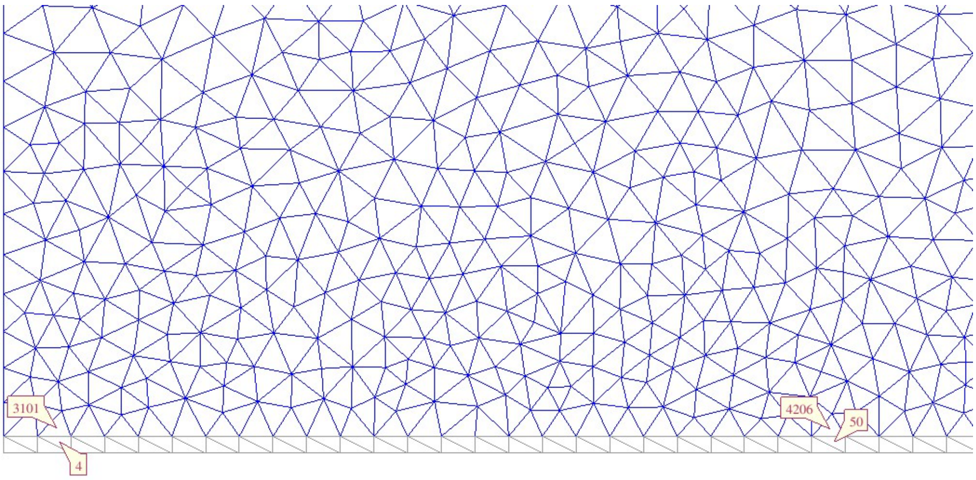

Figure 4 Elements for Study.

Table 2 shows the values used for the simulation of the base case, worked by Carrier [6]. It is also important to mention that the compressive force exerted on the sample is 3.7 MPa and the porosity of the medium is 20%.

The related values are characteristic of a competent rock with very low permeability.

Table 1 Values of Properties [6].

Fracture and Rock Properties			
E_young (MPa)	1.70E+04	**Fluid Properties**	
mu_poisson	2.00E-01	reference density (Kg/m3)	1000
sigm_y (MPa)	1.25E+00	compressibility	0.00001
alpha_biot	7.50E-01	reference pressure	0
thick_mech (m)	-1.00E-06	Q (Kg/s)	0.025
Intrinsic Permeab (m2)	1.00E-16		

Table 2 presents the values with which the sensitivity analysis is done to the mechanical properties, these values are chosen so that they are even characteristic of competent rocks decreasing or increasing in small orders their magnitude. A lower value is analyzed than the base case and another higher this in order to know what percentage of change has the fracture length and the response of the stresses and displacements of the rock and fracture analyzed.

Table 2 Values for the Sensitivity Study.

Properties	Value 1	Value 2
Young (MPa)	1.00E+03	2.50E+07
Poisson	0.35	0.15
Biot	0.5	0.85
Q (Kg/s)	0.05	0.0125

2.1 Base Case

The base case is run according to the data presented in

Table *1*, the results show an increase in the length of the fracture that goes from measuring 15 meters to 25.29 meters, an increase of 68.6% Figure 5.

The concentration of the displacements is in the area of the fracture where the fracturing fluid is injected, this causes the forces to be concentrated at this point as presented in Figure 6

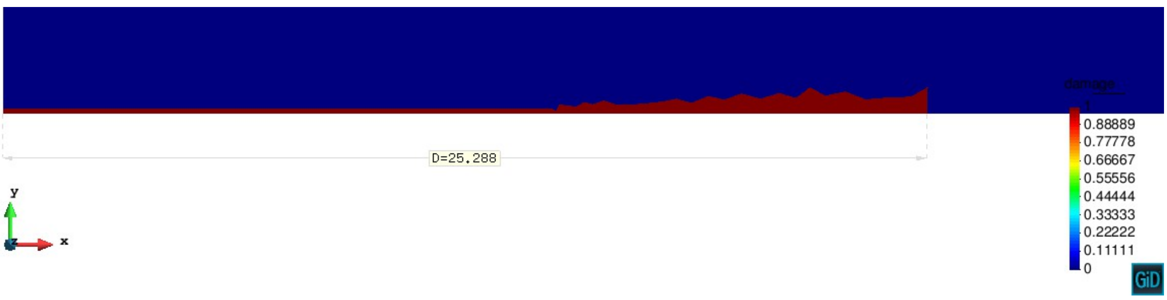

Figure 5 Damage and Length Results for Base Case.

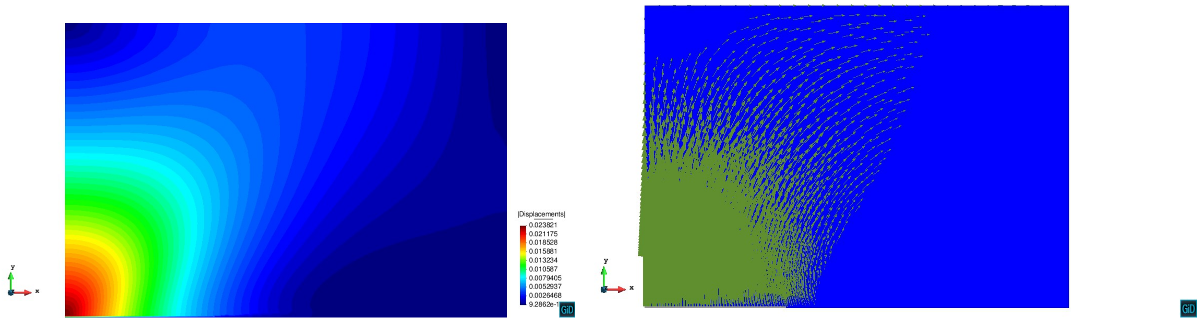

Figure 6 Displacements and Vectors Displacements for the Base Case.

Figure 7 shows the stress-displacement curve that allows to define the constitutive behavior of the material under study, it can be evoked that for the elements near the point of injection of the fracturing fluid there is a greater stress magnitude, therefore are reach higher values of displacement that are translated in appreciable deformations of the rock, on the other hand for the elements remote from the point of injection of the fluid, a stress relaxation is noticed until the disturbance of the fluid that influences in a mechanical reaction of the rock where begin to show displacement in the material.

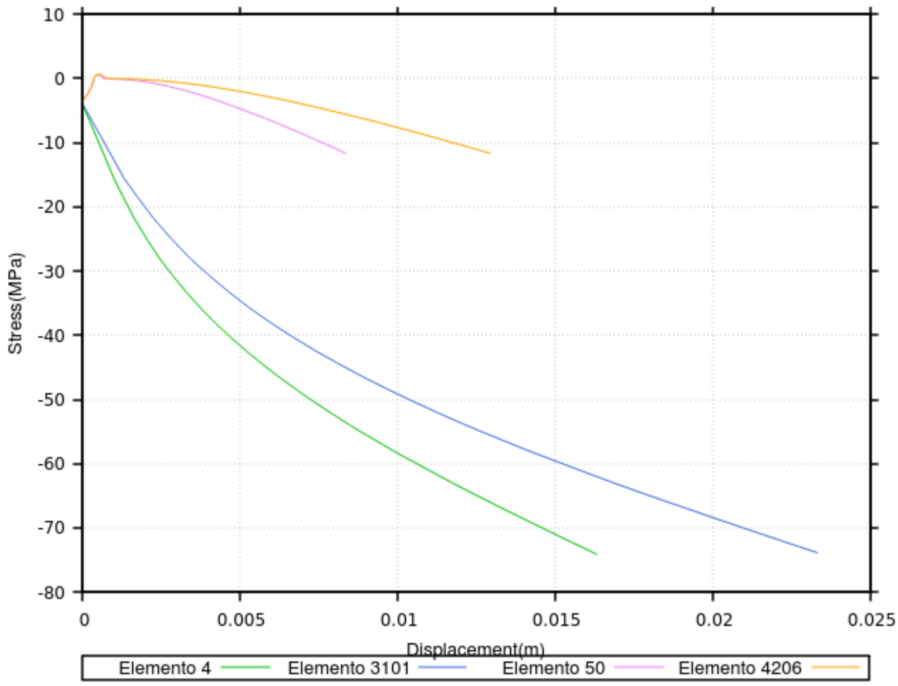

Figure 7 Stress-Displacement Curve Base case.

2.2 Sensitivity -Young Modulus

The young modulus, a constant that allows to measure the rigidity of a solid material [7], allows to know the impact of the injection of a fracturing fluid in a porous medium of low permeability. According to Figure 8, the above concept is evident, where it can be seen that for a lower stiffness value, $1x10^3$, a stress-displacement curve of greater magnitude is obtained, which reflects a greater deformation of the material.

It is possible to observe in the same way for the elements distant to the point of injection, an inflection in the stress - displacement curve, related to a relaxation of the material before the stress disturbance due to the pressure exerted by the fluid will reach these elements.

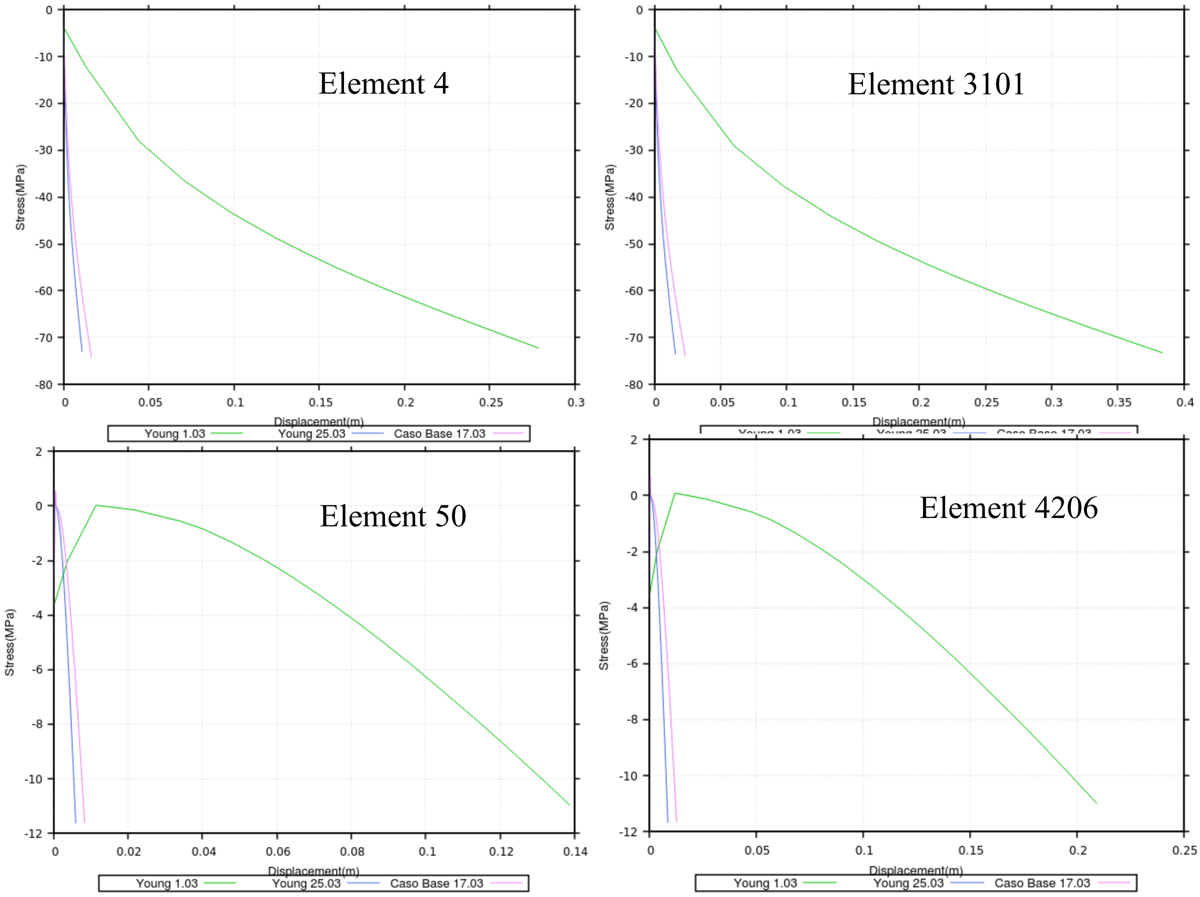

Figure 8 Stress-Displacement Curve Young Modulus.

Figure 9 shows the distance that reaches the fracture for the analyzed cases varying the young's modulus, when the material is more rigid with a value of 25, it is visible that it does not reach values of expansion within the rock as presented in the base case, this difference is 19%, with respect to the value of the base case and 35% with respect to the initial length of the fracture.

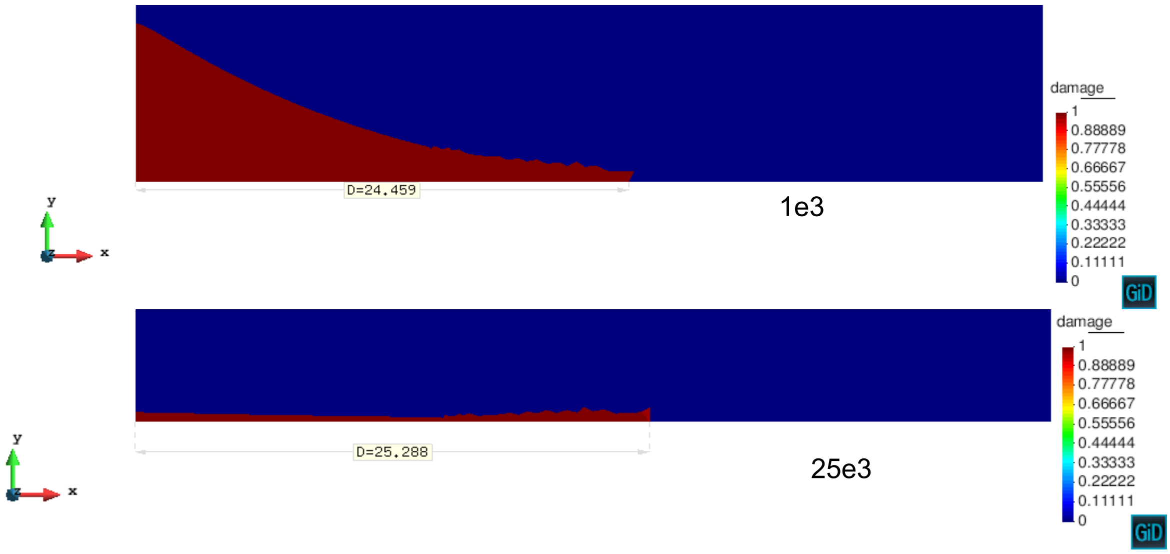

Figure 9 Damage and Length Results for Young Modulus.

2.3 Sensitivity –Biot Coefficient

The biot coefficient is the parameter that describes the relationship between the consistency of the multiporous rock and the consistency of the matrix. For practical purposes, generally it is considered equal to 1.0 being this representative value of a porous solid rock extremely plastic and with a maximum influence of pore pressure, on the other hand when considering a value of 0.0 is for a solid rock without pores and without influence of pore pressure [7].

The biot coefficient is generally obtained from the relation of the total module of the rock.

The biot coefficient values used for this sensitivity study represent an influence of the pore pressure on the rock, in Figure 10 we can see the stress - displacement behavior, where a slight difference in the displacement response is evident when this coefficient is varied, due to the influence that is allowed in the rock of the pressure of the fluid that is being injected to generate the hydraulic fracturing.

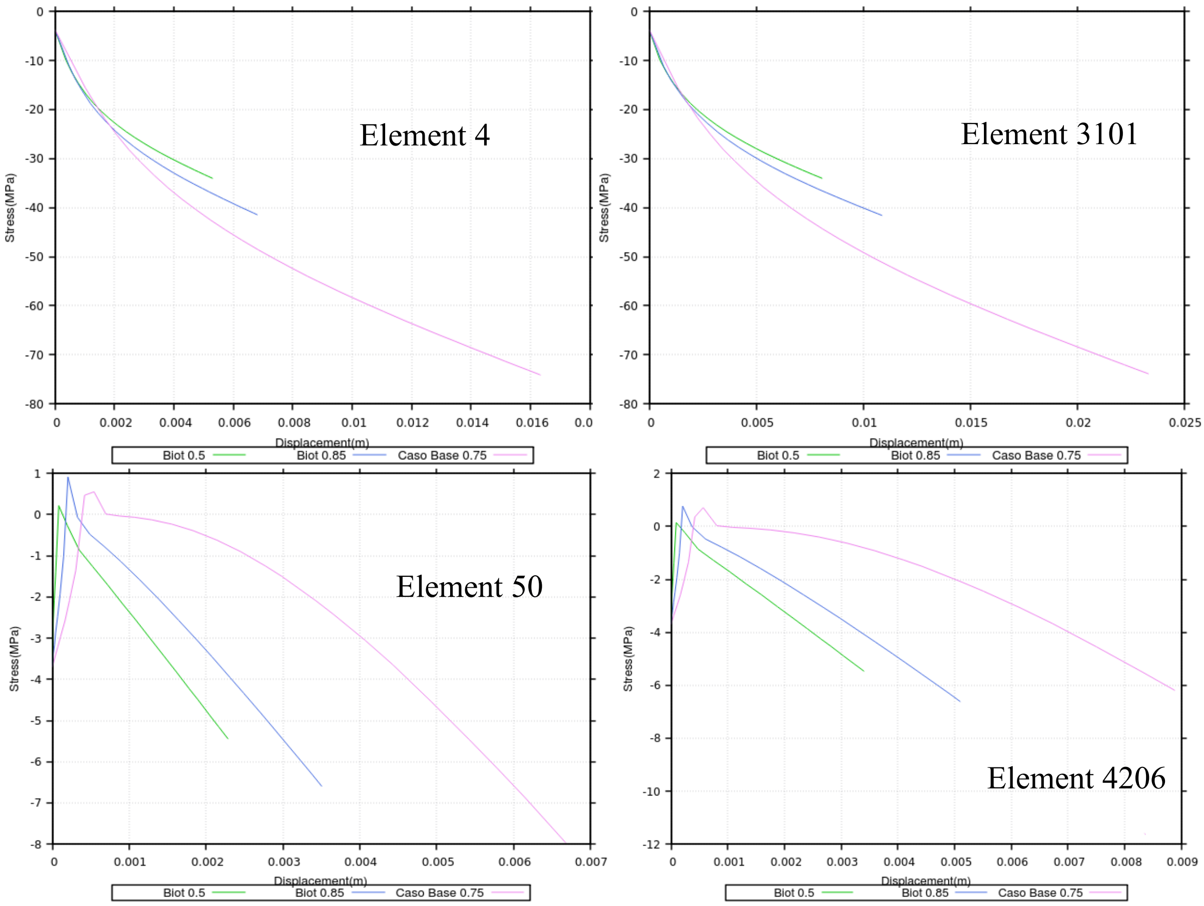

Figure 10 Stress-Displacement Curve Biot Coefficient.

Figure 11 presents the fracture reach length, it can be seen that for a biot coefficient of 0.5 a length of 16.3 meters is reached and for a coefficient of 0.85 a value of 18.6 meters is reached, which do not vary much from the initial value of the fracture, this allows to estimate a change in the response of the fracture behavior depending on the value of the biot coefficient.

Figure 11 Damage and Length Results for Biot Coefficient.

2.4 Sensitivity –Poisson Ratio

The poisson ratio that allows to obtain a response of the transverse deformation of a material [7], defines the behavior observed in Figure 12, where a slight difference in the stress-displacement response is shown when using different values of this aforementioned relation. An analysis of this response is due to the magnitude in the displacement of each curve, when doing simulation with a value of 0.35, greater displacement is achieved, which means that the rock is more deformable, contrary to a value of 0.15 where a rock more rigid that does not deform as much.

Another important result that can be observed in Figure 12 is the response obtained in elements 50 and 4206, farthest from the point of injection, where a change in the stress-displacement curve shift is evidenced, due to the relaxation of the stresses before the pressure disturbance reaches this point, it can also be observed that depending on the value of the poisson ratio of the fracture, this phenomenon will be evidenced at different time scales.

Figure 13 shows the fracture length attained for each of the sensitivity values used in the analysis, with a poisson ratio of 0.15, obtaining a length of 25,276 meters, a value close to that obtained in the base case, on the other side for the value of 0.35 gives a length of 22.7 meters, which corresponds to the higher rigidity of the material reflecting a higher poisson ratio.

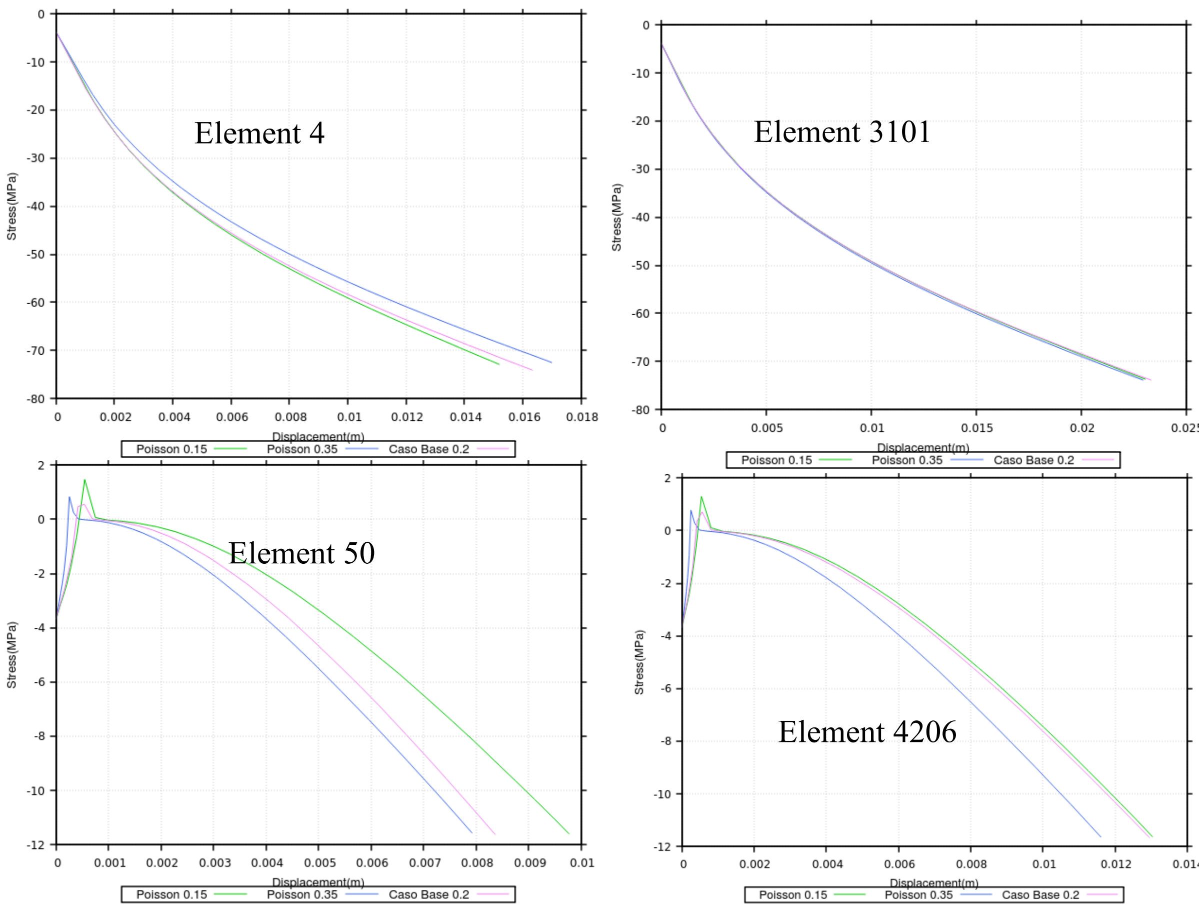

Figure 12 Stress-Displacement Curve Poisson Ratio.

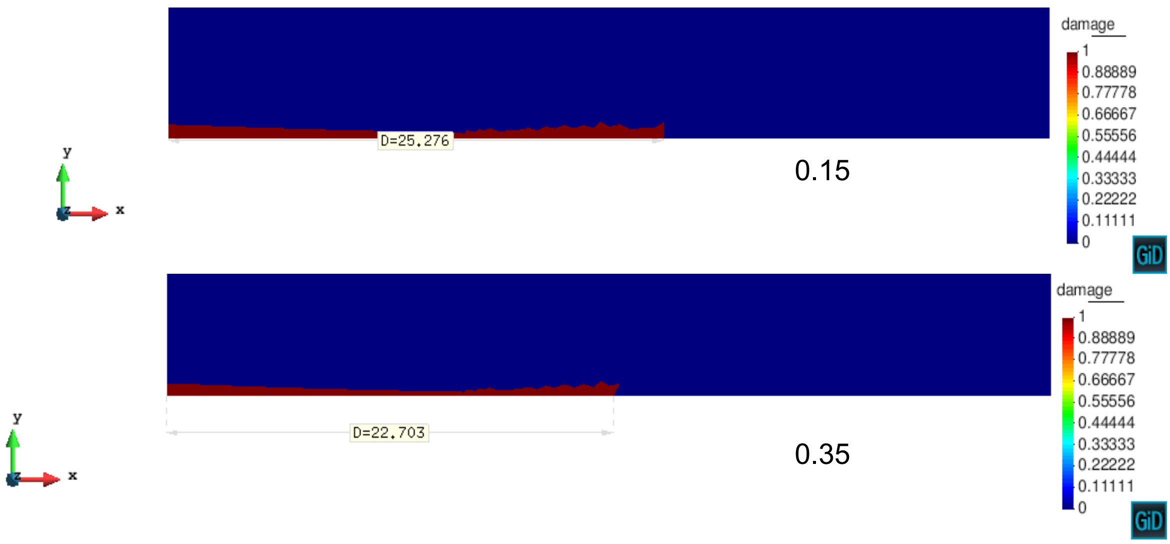

Figure 13 Damage and Length Results for Poisson Ratio.

2.5 Sensitivity – Flux

The impact of the injected flow rate on the fracture is evident depending on its magnitude, and as expected, when the injection rate is lower, the deformations in the rock will be smaller, this is important to take into account when performing a hydraulic fracturing, where the objective is to obtain a more permeable channel and that reaches the target zone, we also have to have considerations of stability of the channel and the formation around it.

The results of this analysis can be observed in the Figure 14.

Figure 15 shows the length that reaches the fracture, for an injection rate of 0.050 kg/s where a length of 30.9 meters is obtained, 22.4% difference of the length obtained in the base case and 106% of difference in length on the other hand, for an injection flow of 0.0125 kg/s a length of 17.4 meters is obtained, a value below the base case with a difference of 31% and two meters above the initial length of the fracture.

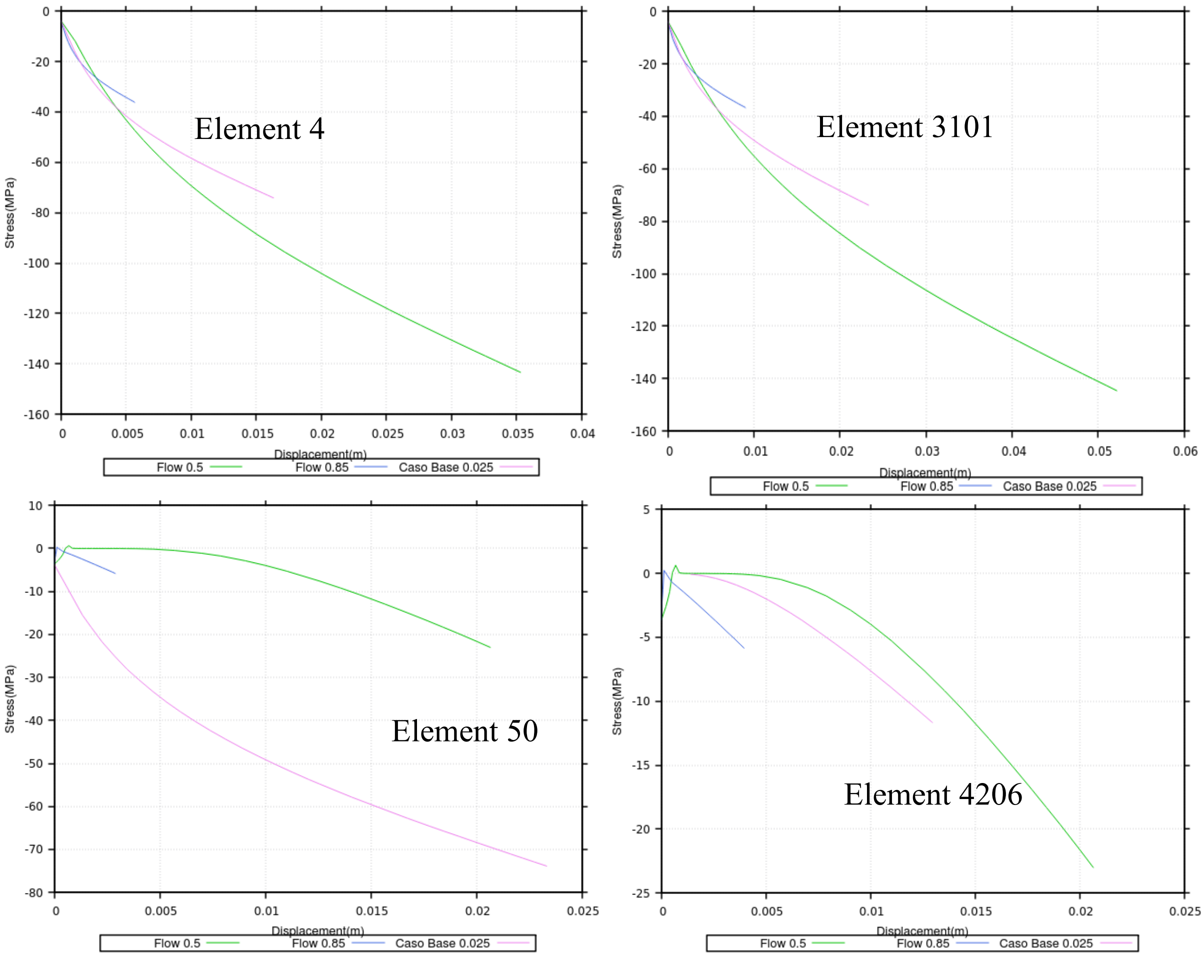

Figure 14 Stress-Displacement Curve Flux.

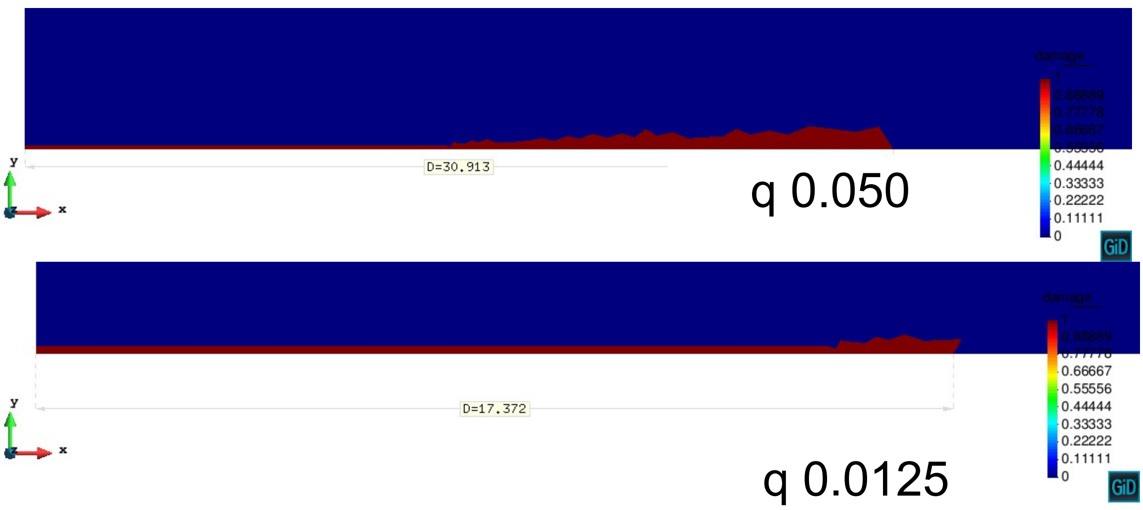

Figure 15 Damage and Length Results For Flux.

CONCLUSIONS

The technique of strong discontinuities allows a good approximation to simulate the hydraulic fracturing made in a competent rock of low permeability.

The sensitivity of properties related to the hydraulic fracturing simulation is important since it is a method of analysis of the impact of the variability on the magnitude of representative elastic constants of the rock.

The relaxation experienced by the rock before feeling the pressure disturbance, and the beginning that is perceived in this agreement to the magnitude of the property analyzed and to the time in which it occurs, is a very interesting result that allows to focus the analysis of the stress state at this point.

Biot coefficient, a fundamental constant in the simulation coupled of fluid flow with geomechanics, give very important results, since its change in magnitude allows an appreciable difference in the stress-displacement curve. This allows to emphasize the importance of knowing with certainty the representative value of this constant for a rock under study.

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