NUMERICAL SIMULATION OF HYDRAULIC AND NATURAL FRACTURE INTERACTION AND PROPAGATION

Julio Alberto Rueda Cordero

julio.rueda@aluno.puc-rio.br

Graduate Program in Civil Engineering - Pontifical Catholic University of Rio de Janeiro.

R. Marquês de São Vicente, 225 - Gávea, Rio de Janeiro - RJ, 22430-060

Cristian Mejia Sanchez.

crisms@tecgraf.puc-rio.br

Tecgraf Institute /Puc-Rio

R. Marquês de São Vicente, 225 - Gávea, Rio de Janeiro - RJ, 22430-060

Deane Roehl

droehl@puc-rio.br

Pontifical Catholic University of Rio de Janeiro.

R. Marquês de São Vicente, 225 - Gávea, Rio de Janeiro - RJ, 22430-060

Abstract. *Production of unconventional reservoirs has revolutionized strongly the oil and gas industry through the development of innovative applications such as horizontal drilling, microseismic monitoring and shale stimulation by hydraulic fracturing. However, pre-existing fractures in hydrocarbon reservoirs complicate hydraulic fracture propagation and microseismic interpretation of the stimulation effectiveness. In addition, the interaction of hydraulic fractures and natural fractures may lead to complex networks of fractures, which can connect with shallower aquifers or geological faults increasing the risk of fault activation. This work presents a numerical technique using the finite element method to study the interaction between hydraulic fractures and natural fractures in order to predict the direction of fracture propagation. Fractures were simulated using a coupled hydro-mechanical interface finite element with damage and Mohr-Coulomb constitutive models to represent the hydraulic and natural fracture behaviors, respectively. Several scenarios were simulated for hydraulic fracture regarding the intersection with natural fracture. The comparison between the numerical results and the published experimental results by Blanton (1982) show good agreement. The three main possibilities of interaction events, opening, crossing and arrest, are predicted. Finally, the results show the influence of the in-situ stresses on the interaction between natural and hydraulic fracture.*

Keywords: *hydraulic fracturing, propagation, Interaction hydraulic and natural fracture.*

INTRODUCTION

The production of unconventional reservoirs has revolutionized the oil and gas industry strongly through the development and innovative applications, such as horizontal drilling, shale stimulation by hydraulic fracturing and microseismic monitoring of the stimulation. However, the production of unconventional oil fields can generate environmental damages due to fractures propagation, which can connect them to shallower aquifer layers or geological faults with a potential risk of reactivation (Rutqvist et, al. 2013; Shen et al. 2014). Therefore, it is necessary to perform different types of studies and analysis to predict the behavior of hydraulic fracture and its interaction with natural fractures in order to reduce the associated risks and increase the oil recovery in a safe and responsible way. On the other hand, if the direction of fracture propagation is known, hydraulic fracturing design can be optimized in order to stimulate a greater amount of natural fractures in a controlled way increasing the recovery of unconventional deposits.

Several analytical and numerical models have been developed to simulate and understand the hydraulic fracture performance. The analytical models predict the geometry of the hydraulic fractures and most of them are based on the solution of simple geometries, such as the PKN and the KGD model (Geertsma and de Klerk 1969; Khristianovic and Zheltov 1955; Nordgren 1972; Perkins and Kern 1961; Sneddon 1946). These techniques do not require a detailed description of rock properties and their approximations contain simplifications in relation to the aperture and the crack pressure field.

Recent research has focused directly on the development of numerical algorithms for the modeling of hydraulic fracture propagation in layered formations, which is characterized by their different mechanical properties, in-situ stresses and natural discontinuities. Hydraulic fracturing is a complex process and its numerical modeling represents a great challenge. The difficulty arises mainly from the non-linear coupling process, which involves at least the interaction of three different phenomena (Weng, 2010): induced rock deformation by the fluid pressure on the fracture surface, fluid flow inside the fracture and fracture propagation into rock formation.

The Finite Element Method, one of the most widely used methods for the study of continuous media problems, is also widely applied in the modeling of natural discontinuities and hydraulic fracturing. When the hydraulic fracture propagates in a flat form perpendicular to the minimum horizontal stress, a good choice for its modeling is using interface finite elements with the constitutive behavoir governed by a damage model, so-called “cohesive interface element” (Bendezu et al.,2013; Zielonka et al. 2014).

This work presents a numerical technique using the Finite Element Method to study the interaction between hydraulic fractures and natural fractures with the objective of predicting the direction of fracture propagation. The fractures are simulated in a fully coupled analysis using the hydromechanical interface element with damage constitutive model and Mohr-Coulomb constitutive model to represent the behavior of the hydraulic fractures and the natural fractures, respectively.

1 INTERACTION BETWEEN HYDRAULIC FRACTURES AND NATURAL FRACTURES

Fracture interaction is one of the most important factors that must be taken into account to model the hydraulic fracture propagation in naturally fractured reservoirs. This includes the interaction between hydraulic fractures and natural fractures as well as the interaction between themselves. This problem has been the subject of several approaches: analytical models (Potluri et al. 2005), numerical studies (Gonzales, et al. 2015) and experiments (Blanton, 1982; Gu, et a l. 2011). Based on the literature review, the interaction between hydraulic fractures and natural fractures is mainly influenced by the rock properties (tensile strength, toughness, permeability, porosity), the in-situ stresses, the fluid properties (pressure, viscosity) and the natural fracture properties (geometry, orientation, cohesion, friction angle, initial aperture, permeability).

The behavior of a hydraulic fracture when it intercepts a natural fracture is one of the main causes for the creation of complex fractures networks. Several events may occur during the hydraulic fracture propagation towards the natural fracture and subsequent to this, see Figure 1. In order to understand and model the mechanisms that govern these events Gu et al. (2011) divided the process in different scenarios, as shown in Fig. 1.

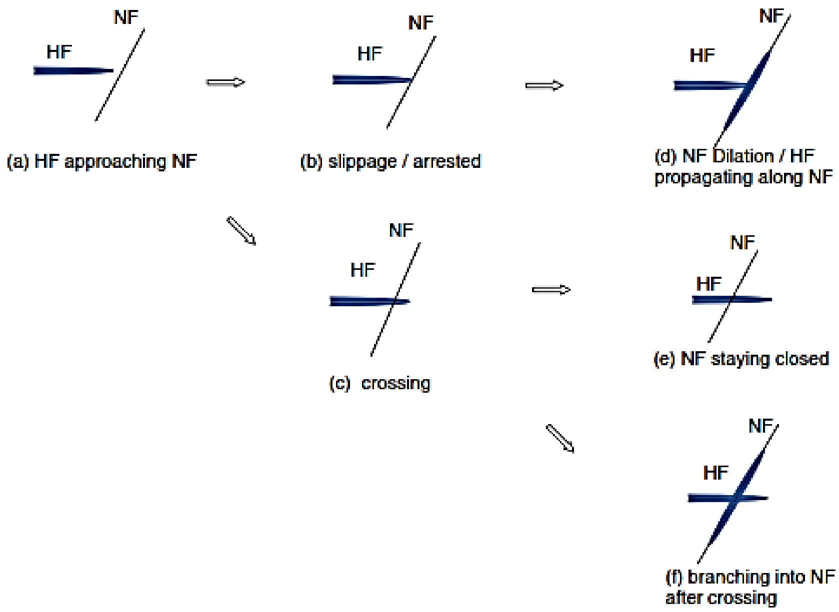

Figure 1. Schematic representation of possible interactions between hydraulic fracture and natural fracture.

2 FRACTURE CONSTITUTIVE MODELS

The constitutive models associated to the hydraulic fracture and natural fracture are summarized below:

Proceedings of the XXXVIII Iberian Latin-American Congress on Computational Methods in Engineering
P.O. Faria, R.H. Lopez, L.F.F. Miguel, W.J.S. Gomes, M. Noronha (Editores), ABMEC, Florianópolis, SC, Brazil, November 5-8, 2017.

2.1 Damage constitutive model

The hydraulic fracture propagates perpendicular to the minimum in-situ stress and its propagation can be modeled using cohesive interface elements. In this case, the cohesive response is usually specified directly in terms of the traction t on the crack surface and the displacement jump δ across the crack surface.

The cohesive zone model assumes initially linear elastic behavior followed by the initiation and evolution of the degradation process, which precedes interface failure. The element degradation begins when the traction or separation reaches a specific value that satisfies a certain criterion of damage initiation, as shown in Fig. 2.

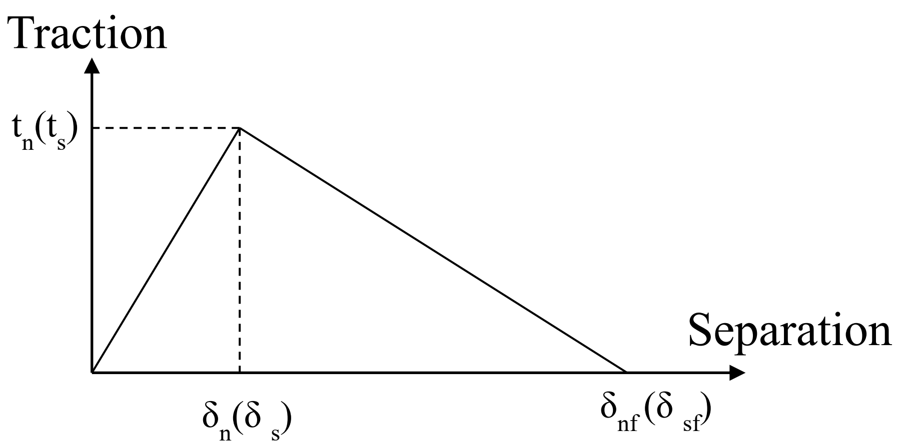

Figure 2. traction-separation response

The damage evolution describes the degradation process once the initiation criterion is satisfied. This degradation process is therefore given by:

$$t_n = \begin{cases} (1-D)\bar{t}_n, \quad \bar{t}_n \geq 0 \\ \bar{t}_n \quad \text{compression stress without damage} \end{cases} \tag{1}$$

$$t_s = (1-D)\bar{t}_s \tag{2}$$

where $\bar{t}_n$ and $\bar{t}_s$ are the effective normal stress and the effective shear stress, respectively. The scalar variable D takes the value zero at the point of damage initiation and 1 when the element is totally degraded.

In this work, a quadratic nominal stress and linear softening are adopted as a damage-initiation criterion and damage evolution law, respectively.

2.2 Mohr-Coulomb constitutive model

Initially, the behavior of the natural fractures follows the linear elastic model where the stress and strain increments are evaluated through a symmetric elastic constitutive matrix, which can be represented as:

$$D_e = \begin{bmatrix} k_s & 0 \\ 0 & k_n \end{bmatrix} \quad (3)$$

where k_n and k_s are the normal and the shear stiffness, respectively.

The Mohr Coulomb criterion with zero cutoff was adopted to model the natural fracture behavior. The Mohr-Coulomb failure criterion assumes that the effective shear stress τ reaches the limit value expressed in terms of the effective normal stress σ'_n (negative compression), as follows:

$$\tau = c - \sigma'_n \tan\phi \quad (4)$$

where c is the material cohesion; ϕ is the friction angle. This constitutive model was implemented as a user material subroutine UMAT, more details about the implementation can be found in Rueda (2013).

2.3 Cubic law for fluid flow

Fluid flow inside the fracture may occur in the longitudinal and normal directions as shown in Fig. 3.

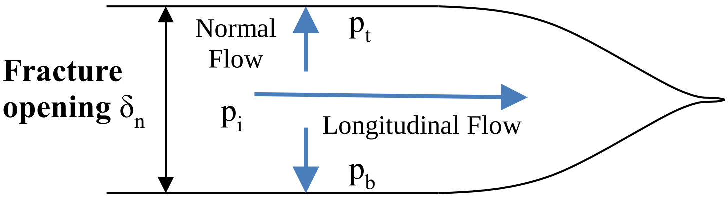

Figure 3. The fracturing fluid flow pattern within the cohesive element

The longitudinal flow within the fracture is considered incompressible and Newtonian, and its hydraulic conductivity k_l can be defined according to the cubic law as:

$$k_l = \frac{\Delta_n^3}{12\mu} \quad (5)$$

where μ is the dynamic viscosity and δ_n is the displacement jump normal to the crack surface.

The normal flow may represent the infiltration of fluid into the formation and it can be modeled defining leakoff coefficients according to:

$$\begin{aligned} q_t &= c_t(p_i - p_t) \\ q_b &= c_b(p_i - p_b) \end{aligned} \quad (6)$$

where, q_t and q_b are the normal fracturing fluid flow through the top and bottom surface, c_t and c_b are the leakoff coefficient at the top and bottom, p_i is the pore fluid pressure inside the fracture; and p_t and p_b are the pore fluid pressure at the top and bottom surface.

3 MODEL IMPLEMENTATION

The intersection between the hydraulic fracture and natural fracture requires a special treatment in order to ensure the continuity of the fluid field. The hydraulic fracture and natural fracture are modeled using a triple-noded coupled interface element, which shares a common node at the intersection. This method has a great advantage for the crossing of multiple fractures using interface elements.

The initial stresses are calculated using the SIGINI user subroutine, which takes into account the orientation of the interface element to compute its shear and normal stress. The rock formation is modeled as an impermeable medium with linear elastic behavior and discretized using quadrilateral elements CPE4 (4-node bilinear with displacement degree of freedom) under plane strain condition.

4 VALIDATION AGAINST EXPERIMENTAL DATA

The experimental results presented by Blanton (1982) allow the validation of the numerical method. Shale blocks of 30 cm x 30 cm have been prepared with a pre-existing fracture oriented at different angles (30 °, 45 °, 60 °, 90°) and subject to different compressive stresses. Afterwards, the fluid is injected to propagate the hydraulic fracture. The numerical simulation was carried out for a shale block with a pre-existing fracture oriented at 60° (experimental test # 4, 8 and 21), as shown in Fig. 5. These experimental tests were chosen to validate the numerical method because they reported the three scenarios of interaction obtained experimentally: crossing, arrest and dilation.

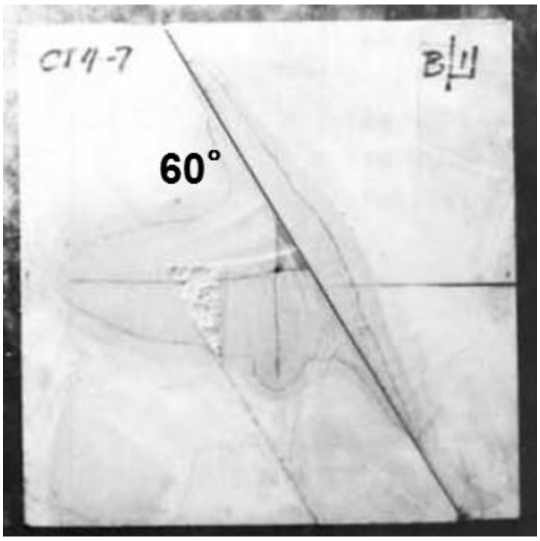

Figure 4. Geometrical model selected for numerical simulation

The vertical and horizontal stresses for each test are detailed in the following table:

Table 1 – Selected tests for validation (Blanton, 1982)

Experimental condition for test in Devonian Shale			
Test #	NF orientation	Horizontal stresses (MPa)	
		σ_{max}	σ_{min}
CT- 8	60 °	20	5
CT- 21	60 °	14	5
CT- 4	60 °	12	10

The properties of the rock, the natural fracture, the hydraulic fracture and the fracturing fluid used in the numerical model are summarized in the following table:

Table 2. Hydraulic and mechanical properties for the numerical tests

Categories	Variables	Values
Rock Properties	Young's Modulus, E(GPa)	1.00E+06
	Poisson's ratio, υ	0.22
Hydraulic fracture Properties	Normal nominal stress, t_n (kPa)	3100
	Shear nominal stress, t_s (kPa)	3100
Natural fracture Properties	Friction Angle, φ(°)	37
	cutoff	0
	Cohesion, c	0
Pumping parameters	Fluid viscosity, μ(centipoise)	1
	Injection rate , q(m3/s)	8.20E-08

4.1 Numerical results and analysis

The influence of the in-situ stresses on the intersection between hydraulic fracture and natural fracture during injection process is analyzed in this section.

For the CT-8 test, the differential stress is 15 MPa, the hydraulic fracture crosses the natural fracture because the dilatation of the natural fracture is restricted by the maximal horizontal stress, as shown in Figure 5.

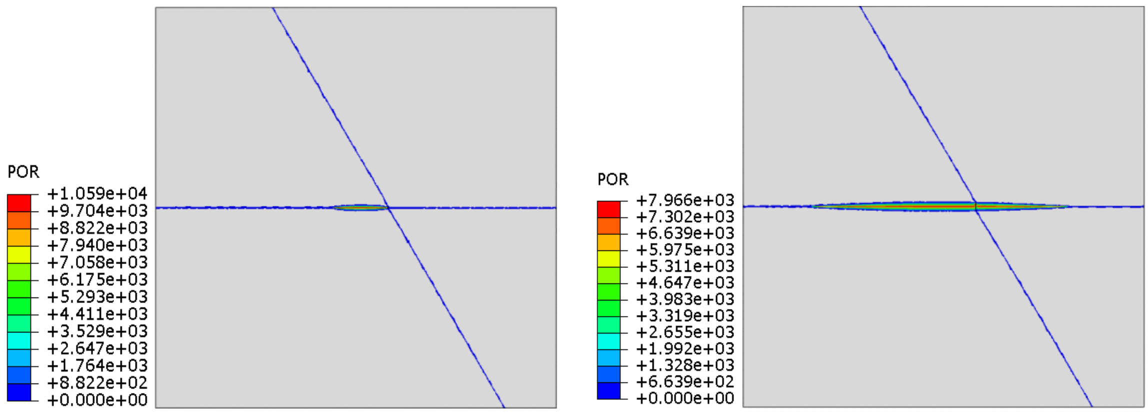

Figure 5. The fracture propagation processes for CT- 8 test.

For the CT-21 test, the differential stress is 11 MPa. In this case some fluid escape into the natural fracture due to slippage; subsequently the hydraulic fracture is arrested as shown in Figure 6.

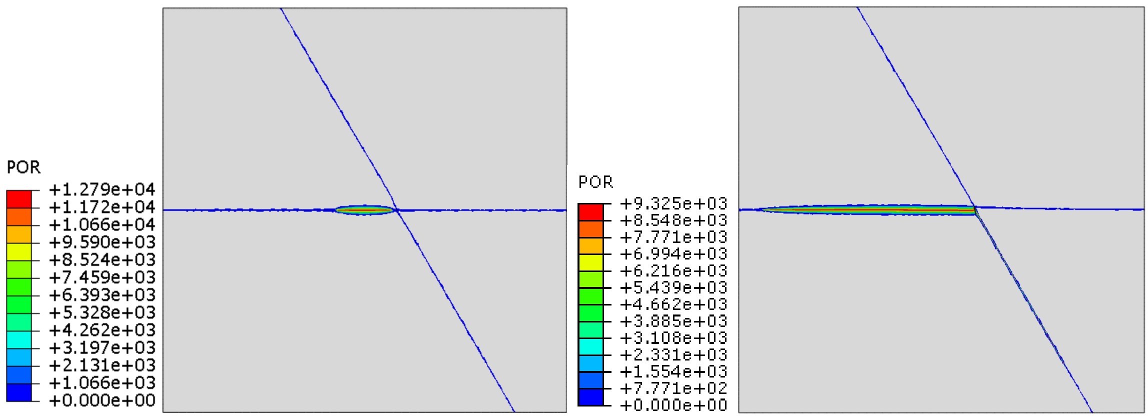

Figure 6. The fracture propagation processes for CT- 21 test.

For the CT-4 test, the differential stress is 2 MPa. The natural fracture is dilated because the fluid pressure is larger than the normal compressive stress on the natural fracture.

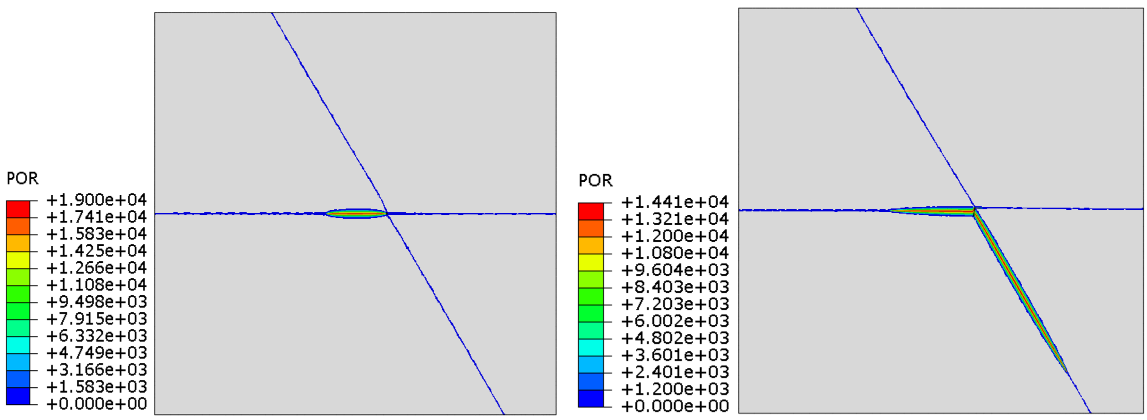

Figure 7. The fracture propagation processes for CT- 4 test.

The wellbore pressure on the CT-8, CT-21 and CT-4 for fracture propagation is 8 MPa, 9.5 MPa and 14.5 MPa, respectively. The comparison of the experimental results with the numerical results is shown in table 3. The developed methodology predicts the interaction features according to the experimental tests.

Table 2. Comparison between numerical method and experimental test results

Experimental condition for test in Devonian Shale					
Test #	NF orientation	Horizontal stresses (MPa)		Experimental interaction type	Numerical interaction type
		σ_{max}	σ_{min}		
CT- 8	60 °	20	5	**Crossing**	**Crossing**
CT- 21	60 °	14	5	**Arrest**	**Arrest**
CT- 4	60 °	12	10	**Opening**	**Opening**

CONCLUSIONS

The numerical simulation of the interaction between the hydraulic fracture and the natural fracture considering the proposed treatment at the intersection of interface elements was successful. Different possibilities of HF/NF interaction such as crossing, arrest and opening were predicted correctly, in comparison to the experimental results given by Blanton (1982). The modes of intersection, arresting, crossing and opening were influenced mainly by the difference between the horizontal stresses.

This methodology will be applied in futures works for more complex analysis such as hydraulic fracturing into multilayered rock formation containing natural fractures with different orientations. In addition, it can be extended to 3D simulations.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Shell Brazil and CAPES for the financial support.

REFERENCES

Bendezu, Marko A. L., Carvalho, Eulher C., Roehl, Deane., Romanel, Celso., 2013. Finite element modeling of the hydraulic fracture problem in impermeable media using a cohesive zone model. Cilamce.

Blanton, T.L., 1982. An Experimental Study of Interaction Between Hydraulically Induced and Pre-Existing Fractures. SPE Unconventional Gas Recovery Symposium, Pittsburgh, Pennsylvania, SPE of AIME.

Davies, R. J., et al., 2014. Oil and Gas wells and their integrity: Implications for shale and unconventional resourse exploitation. Marine and petroleum geology. Pages 239-254.

GEERTSMA, J., 1966. Problems of rock mechanics in petroleum production engineering. In: First Congress of the International Society of Rock Mechanics. 585–594.

Gonzales. M., Dahi. A. T., 2015. A cohesive model for modeling hydraulic fractures in naturally fractured formations. Society of petroleum engineers. SPE.

Goossens, M., Mittelbach, F., & Samarin, A., 1994. *The LaTeX Companion*. Addison-Wesley.

Khristianovic, S., Zheltov, Y., 1955. Formation of vertical fractures by means of highly viscous fluids. In: Proceedings of the 4th World Petroleum Congress, Rome, vol. II, pp. 579 586.

Nordgren. R. P., 1976. Propagation of a Vertical Hydraulic Fracture. SPE 3009.

Perkins, T. K., and Kern, L. R. 1961. Widths of hydraulic fractures. J. Pet. Tech. 13:937–949. Prats, M. 1961. Effect of vertical fractures on reservoir behavior—Incompressible fluid case. Soc. Pet. Engrs. J. 1:105–108.

Potluri, N.K., Zhu, D., 2005. The Effect of Natural Fractures on Hydraulic Fracture Propagation. SPE European Formation Damage Conference, Sheveningen, The Netherlands, SPE.

Rueda, J., 2013. Reativação de falhas geológicas com modelo numérico discreto e distribuído. Dissertação de Mestrado. Puc Rio.

Rutqvist, J.; Rinaldi, A. P.; Cappa, C. F. et al., 2013. Modeling of fault reactivation and induced seismicity during hydraulic fracturing of shale-gas reservoirs. Journal of Petroleum Science and Engineering.

Shen. G., Shen. X., Wang. S., 2014. Numerical and Experimental Studies on Fracture Propagation at a Bi-material Interface and Its Application to Hydraulic Fracturing. ARMA.

Sneddon. IN., 1946. The distribution of stress in the neighbourhood of a crack in an elastic solid. Proceedings of the Royal Society of London, pp. 229-260.

Weng. X., 2010. Numerical investigation of interaction between Hydraulic fractures and natural fractures. Texas A&M University. Thesis of master of science.

Gu H, Weng X., 2011. Hydraulic fracture crossing natural fracture at nonorthogonal angles: a criterion and its validation. SPE. Schlumberger.

Zielonka MG, Searles KH, Ning J, Buechler SR., 2014. Development and Validation of Fully-Coupled Hydraulic Fracturing Simulation Capabilities. SIMULIA Community Conf SCC2014, pp. 1–31.