Experimental Validation of Simulation Capabilities for Hydraulic Fractures Propagating in a Porous Medium

Jing Ning, Gilbert Kao, Nikolay M. Kostov, Kevin H. Searles, Scott R. Buechler and Pablo F. Sanz

ExxonMobil Upstream Research Company

22777 Springwoods Village Parkway, Houston, TX 77389

Abstract: *The problem of a fluid-driven (hydraulic) fracture propagating in a porous medium is studied using recently co-developed capabilities in SIMULIA® Abaqus Standard ("Abaqus") for fully-coupled simulation of hydraulic fracturing. The hydraulic fracturing simulation capabilities are validated against lab-scale experimental results. A Polyaxial Test Cell (PTC) is set up for controlled hydraulic fracturing in fabricated rock samples allowing different testing conditions of confining stress, injection rate, and rock and fluid properties. Two representative regimes of fracture propagation (toughness/storage and viscosity/leak-off) are selected to compare against numerical simulations carried out in Abaqus. Fracture propagation and fracturing fluid flow are modeled using coupled pressure/deformation cohesive elements, while the porous medium deformation and pore-fluid flow in the rock are modeled with coupled "pore-pressure/deformation" continuum finite elements. Injection pressure response and fracture and leak-off geometries agree well with corresponding experimental results. The experimental validation of the newly co-developed hydraulic fracturing simulation capabilities within Abaqus provides confidence for accurately modeling field-scale, fluid-driven fracturing applications including drill cuttings and water injection, stimulation of unconventional reservoirs, lost returns and other drilling operations.*

Keywords: *Geomechanics, fluid-driven fracturing, pore pressure, leak-off, cohesive elements*

1. Introduction

Hydraulic fracturing has significant application for the oil and gas industry and has been a very active research area over the past several decades. From a simulation viewpoint, there are substantial technical challenges in coupling the physics of fluid flow, poromechanics, and fracture mechanics. Solving hydraulic fracturing problems not only requires a deep fundamental understanding of the physical mechanisms, but also the ability to study these problems at field-representative time and length scales. Many attempts have been made to address the problem using different numerical approaches (Ortiz and Pandolfi, 1999; Detournay et al., 2006; Garagash 2006). However, most are based on research codes that are impractical for representing actual reservoir conditions and often lack the computational capabilities (e.g., cluster parallel computing) required to solve field-scale problems (Dahi-Taleghani and Olson 2011, Abbas et. al 2014). Traditional industry tools routinely make assumptions and simplify the physics in order to model the problem at applicable scales, often providing unrealistic predictions and non-physical behavior (Clearly 1980; Meyer 1989; Warpinski et al., 1994). To address this challenge, fully-coupled hydraulic fracture simulation capabilities were co-developed between ExxonMobil Upstream Research Company and Dassault Systems Simulia Corporation. These capabilities leverage the existing Abaqus non-linear soils consolidation analysis procedure, and incorporate two formulations for fracture modeling, *i.e.*, cohesive elements (CZM) and the extended finite element method (XFEM).

Zielonka et al. (2014) described the aforementioned formulations in great detail and provided validation against approximate analytical solutions defining a parametric space of four limiting propagation regimes for hydraulically driven fractures (Figure 1). These semi-analytical solutions exist in the form of regular asymptotic expansions (Bunger et al., 2005; Detournay et al., 2006; Garagash, 2006; Hu and Garagash, 2010; Garagash et al., 2011; Peirce and Detournay, 2008; Savitski and Detournay, 2002) and result from assuming: (i) an infinite domain, (ii) material fully impermeable, (iii), material linear elastic, (iv) linear-elastic fracture mechanics, and (v) Carter's leakoff model (Howard et al., 1957; Charlez 1997). Good agreement between the Abaqus and asymptotic analytical solutions served as a first pass of validation for successful development of fully coupled simulation capabilities (example shown in Figure 2).

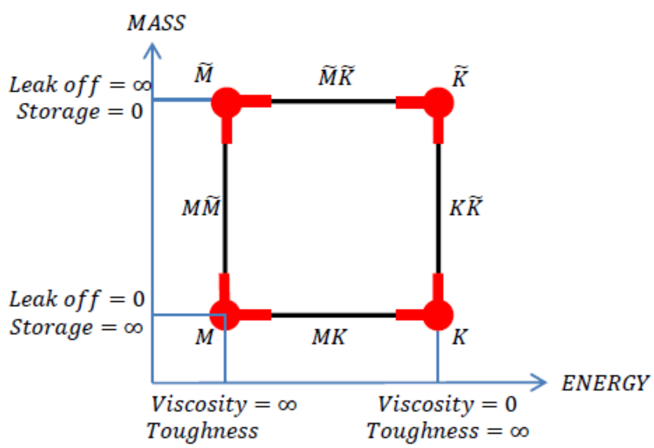
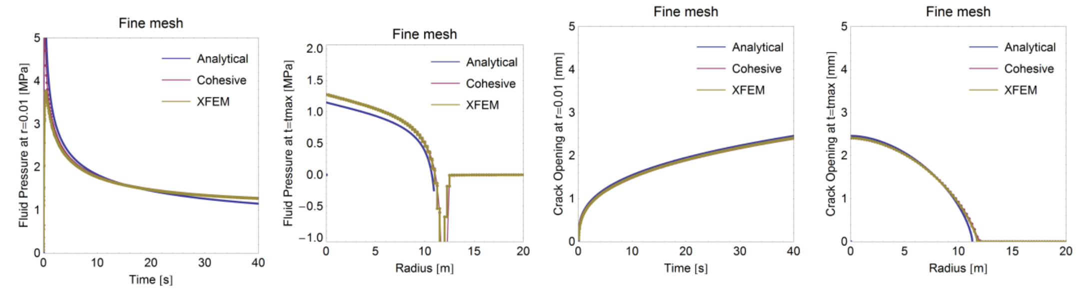


Figure 1. The parametric space representing the four limiting propagation regimes of hydraulically driven fractures (Garagash et al., 2011; Zielonka et al., 2014).



2a. $p(r = 0.01, t)$ 2b. $p(r, t = t_{max})$ 2c. $p(r = 0.01, t)$ 2d. $w(r, t_{max})$

Figure 2. Validation examples for the M-vertex propagation regime (after Zielonka et al., 2014).

In the present work, we extend validation of the co-developed simulation capabilities to the laboratory scale. Results from an in-depth experimental program are presented to demonstrate good test repeatability and provide insight across a broad range of rock and fluid properties, and in-situ stress conditions. The high quality of test results provide a suite of benchmark experimental tests for model validation. The modeling approach using Abaqus is presented along with a comparison between the numerical simulations and physical experiments for two representative propagation regimes.

2. Experiments

Unique experimental capabilities have been developed in-house based on a Polyaxial Test Cell (PTC) apparatus for controlled hydraulic fracturing in rocks. The experimental test data helps to better understand and characterize the fundamental physical mechanisms of hydraulic fracture initiation and propagation. Three-dimensional loads can be applied to represent the in-situ stress conditions that reservoir rocks may experience. The computer controlled hydraulic system can apply up to 1 million lbs of force and 20,000 psi of injection pressure. The testing workflow begins with internally standardized procedures for fabricating large-scale hydrostone samples having dimensions of 12 in. x 12 in. x 18 in. (see Figure 3a). A through-drilled or cast-in-place borehole is then created in the hydrostone with a 2 in. section in the center representing an "open-hole completion" (Figure 3b). Dry samples are loaded into the polyaxial load platens and viscous fluid with colored dye is then injected into the hydrostone through the wellbore in a controlled manner. Pressure responses and acoustic emissions are collected in real-time for data analysis purposes. The post-test analysis (Figure 3d) enables the ability to compare numerical results (pressure response and fracture/leak-off geometry) to experimental data by reconstructing the 3-D fracture geometry from thinly sliced hydrostone sections.

A suite of parametric experimental studies covering a wide range of rock and fluid properties, as well as in-situ stresses, was carried out as a benchmark. These test results demonstrate good repeatability and provide insight into field-scale applications where wellhead pressure is often the only measured data available. Two test cases representing fracturing in tight rock (referred to here as the "no leak-off" case) and permeable reservoir rock (referred to here as the "leak-off" case) are chosen for experimental validation of the Abaqus simulation capabilities.

Figure 3a. Rock Fabrication.

Figure 3b. Borehole Creation.

Figure 3c. Sample Loading and Fracturing.

Figure 3d. Post-test Analysis.

3. Model

The representative model used for simulating the PTC experiments is shown in Figure 4a. A 3-D model is used for simulating the “no leak-off” case while a 2-D model is used for simulating the “leak-off” case. This is due to the increased computational cost associated with the added complexity of capillary pressure modeling described in greater detail below. A half-symmetry assumption is used for the finite element models, and in-situ stresses of 1000 psi, 500 psi, and 1000 psi are applied to the surfaces (in x, y, z, orientation). The 3-D fracture is expected to propagate in the X-Z plane with the fracture opening against the minimum stress direction (SY, Figure 4a). The 2-D fracture model is based on a plane strain assumption by modeling only a small section in the Z direction (highlighted by the dashed blue line in Figure 4a). Fluid is injected into the borehole and hydrostone through pipe elements in both the 2-D and 3-D models.

Fracture propagation and fracturing fluid flow are modeled using coupled pressure/deformation cohesive elements in Abaqus, while the porous medium deformation and pore-fluid flow in the surrounding formation are modeled with coupled “pore-pressure/deformation” continuum finite elements (Abaqus User’s Manual Version 6.14). Pipe elements are used to connect the fluid flow from the injection inlet to the hydrostone. The overall number of elements is 12,349 and 275,544 for the 2-D and 3-D models, respectively (see Figure 4b).

The input parameters for the fluid and hydrostone properties, including Young's modulus and fracture toughness, are derived from measurements made directly on hydrostone core plugs taken from the larger test samples during the fabrication process. The intent of this modeling approach is to validate the newly co-developed numerical capabilities in Abaqus by incorporating physically measured input parameters and representing the full physics, and not simply "tuning" the models to achieve desired results.

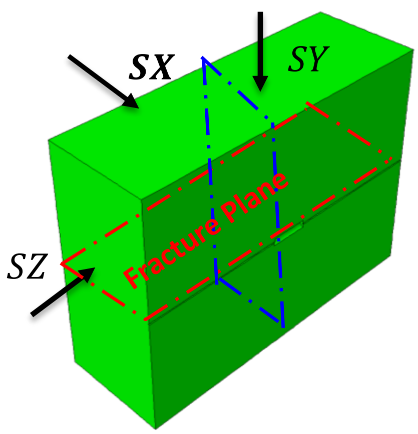


Figure 4a. 3-D Model Schematic.

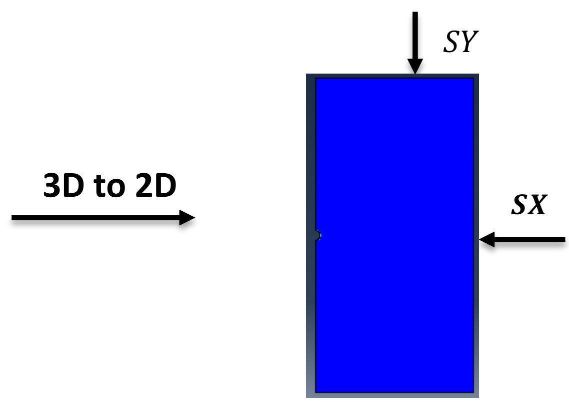


Figure 4b. 2-D Model Schematic.

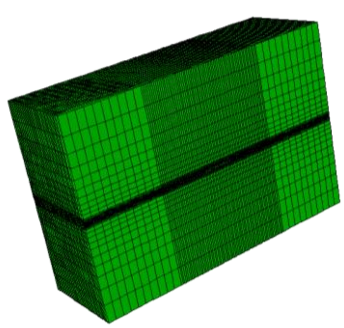


Figure 4c. 3-D Mesh.

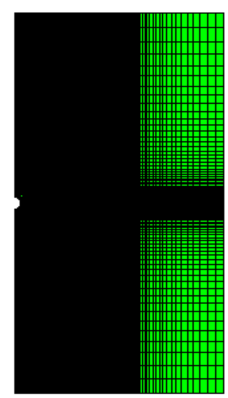
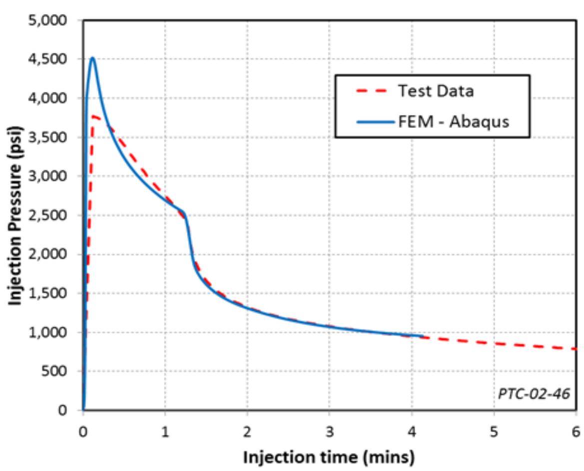


Figure 4d. 2-D Mesh.

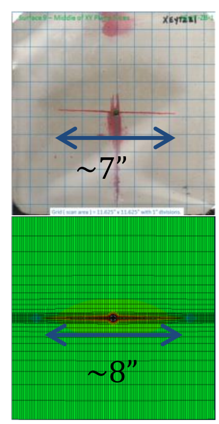
4. Results

The PTC results for the fracture geometry and fluid leak-off profile in the hydrostone vary depending on the specific testing conditions (e.g., fracturing fluid viscosity and formation permeability). The first validation, completed on a Super-X hydrostone sample (permeability of ~0.28 mD), fractured with 13 mL of dyed, high viscosity fluid (35,000 cSt) at an injection rate of 2.5 ml/min. The resulting fracture profile is considered the "low leak-off" case in which most of the injected fluid drives fracture propagation instead of leaking off into the surrounding formation through the fracture surface area (see details in Figure 5). Due to the low leak-off behavior in this test, the hydrostone is modeled in Abaqus without any poro-mechanics and capillary effects (imbibition and drainage behavior) being modeled in the surrounding formation.

The matched results for the pressure response and fracture (leak-off) geometry between Abaqus and the PTC test are presented in Figure 5. The differences in the breakdown pressure may potentially be due to system compressibility (not accounted for in the Abaqus modeling), rock heterogeneities, and mesh sensitivity. The Abaqus simulated injection pressure during fracture propagation and fracture closure (shut-in) agrees very well with experimental results. Comparisons of fracture extent associated with the pressure response can be seen in Figure 5b. The top figure is the experimental leak-off profile within a thin section representing the X-Y plane. The thin red line goes through the 3/8" wellbore and shows a 7 in. bi-wing fracture with a very limited leak-off profile, as can be seen by the red dye. The bottom figure presents the 3-D finite element modeling results demonstrating a similar final fracture length (~8 in. versus ~7 in.) and leak-off profile.



5a. Pressure response: Test data vs Abaqus model results.



5b. Fracture geometry.

Figure 5. Fracture results comparison for no leak-off case.

The second validation case is for "high leak-off" category in which an significant amount of leak-off occurs during the experimental test. The selected test is carried out on a hydrostone sample (permeability of ~15 mD) fractured with 200 ml of red-dyed fluid having a lower viscosity (1332 cSt) at an injection rate of 5 ml/min. The main difference in the results of the "no leak-off" and "high leak-off" cases is the presence of capillary pressure effect.

Unlike typical saturated reservoir conditions, the PTC experimental tests are carried out on dry hydrostone. In the "no leak-off" case, this would not require capturing the capillary effects as no significant injected fluid is being imbibed into the formation due to capillary pressure. However, for the second validation case, this can be found to be a significant factor in the observed fracture propagation and pressure response, and needs to be accounted for in the model. As a result, a 2-D model with more mesh refinement is adopted for accurately resolving the saturation front within the model.

To further illustrate the impact of capillary effects, two modeling results are presented in Figures 6a and 6b for comparison. Figure 6a shows the fracture propagation in a fully saturated formation without capillary pressure effects while Figure 6b shows the fracture propagation in a formation with partial saturation. Notice that the fracture propagates at a much slower speed within a partially saturated formation because a greater fraction of the injected fluid is used to fill remaining pore space in the formation. This results in a reduced volume of injected fluid to drive the fracture forward.

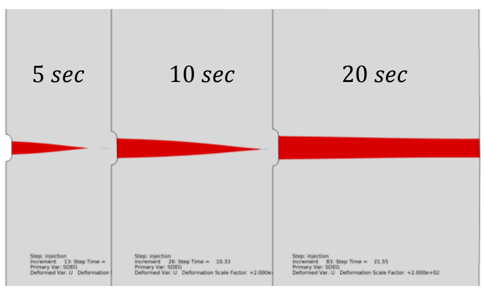


Figure 6a. Fracture propagation in fully saturated formation.

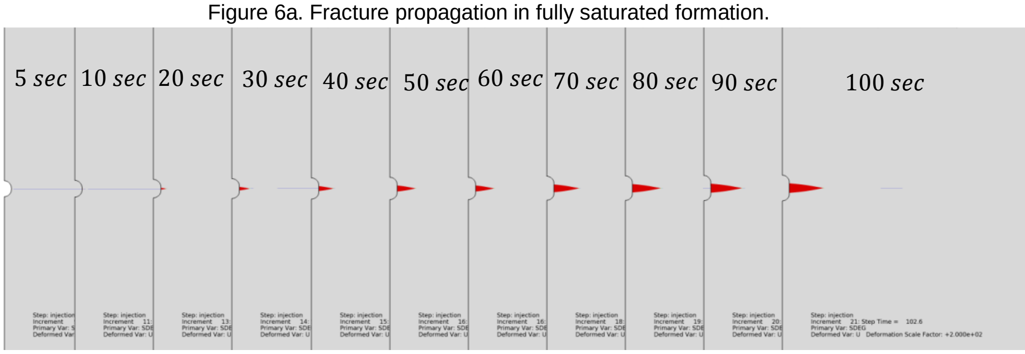
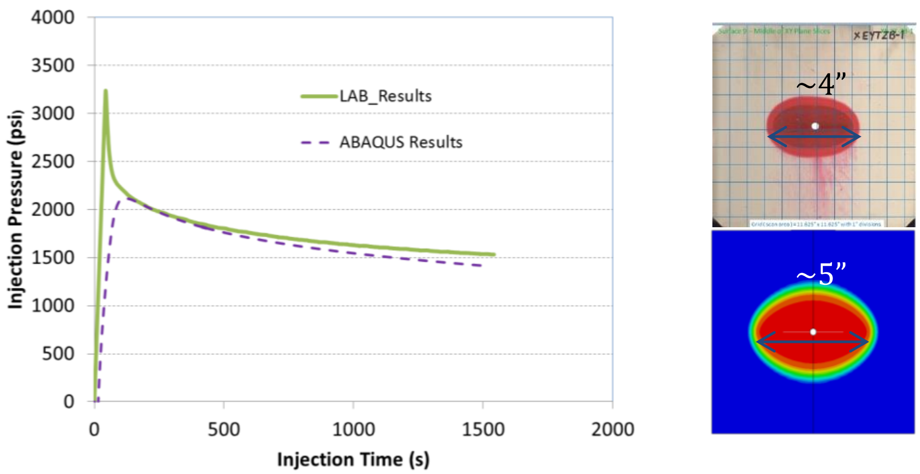


Figure 6b. Fracture propagation in a formation with partial saturation.

The matched results between lab-scale experiments and numerical modeling for the “high leak-off” case are shown in Figure 7. Similar to the “no leak-off” case, the propagation pressure prediction agrees well with the test result for the majority of the 20 minutes of injection. The final fracture length and leak-off profile are shown in Figure 7b; as expected, significant leak-off occurs resulting in a smaller fracture length compared to the “no leak-off” case (for reference 200 ml was injected in the “high leak-off” case compared to 13 ml in the “no leak-off” case). The agreement of leak-off profile for both the Abaqus simulation and experimental results further validates the co-developed capabilities for solving more complex, fully coupled problems involving hydraulically-driven fracturing.



7a. Pressure response. 7b. Fracture geometry.

Figure 7. Fracture results comparison for leak-off case.

The agreement between models and physical experiments validates the implementation of numerical capabilities for solving the fully coupled hydraulic fracturing problem and establishes confidence in ability to model physical behavior over a wide spectrum of conditions. It fills the gap between analytical problems having known solutions and complex, large-scale applications where pressure response is the only available downhole indicator. Fracture modeling using the advanced capabilities currently available in Abaqus helps to identify and develop solutions to address certain subsurface challenges such as fracturing in tight rocks and fracture behavior for lost returns during drilling operations.

5. Conclusions

This work is intended to further validate the Abaqus hydraulic fracturing capabilities co-developed between ExxonMobil Upstream Research Company and Dassault Systemes Simulia Corporation using two representative categories of lab-scale experiments. Good agreement between the Abaqus and experiment results for two benchmark problems establishes a foundation for these new technologies to support oil and gas problems involving fluid-driven fractures such as cuttings disposal, wellbore integrity and lost returns, water injection, and unconventional stimulation. For these problems, traditional fracture modeling tools currently struggle to model the key physical mechanisms at field scales.

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