Hydraulic Fracturing Simulation for Fracture Networks

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Abstract*: The term 'Unconventional Reservoirs' is used in the oil and gas industry for hydrocarbon reservoirs that have very low permeability in the magnitude of microdarcy (µd) and therefore rely on artificially introducing pathways for fluids and gases, commonly by using hydraulic fracturing techniques, to enable economic production. This approach of using fracturing stimulation campaigns is also increasingly used to improve production in mature oil and gas fields. Industry estimates for North America indicate that more than half of all stimulation treatments have no impact on production, despite this technique having been in use in numerous onshore wells for more than a decade. Creating fractures connecting the source rocks to the well whilst allowing fluids to flow, either with new hydraulic fractures and/or activating existing natural fracture sets can have a large impact on production. Optimising the current approach based on determining its many parameters and adapting experience based knowledge to other regions in the world poses a complex challenge with the goal to understand and predict the effectiveness of the stimulation campaigns. Significant progress in the simulation of fluid driven crack propagation for a single fracture occurred with recent updates of Abaqus capabilities including coupled fracture and pore fluid flows with porous medium deformation. This paper looks at the challenges using different modelling approaches using Abaqus such as Cohesive Elements (COH), Extended Finite Element Method (XFEM), Smooth Particle Hydrodynamics (SPH) and coupled Eulerian Lagrangian methods (CEL) with the goal to extend applications to more complex geometries with interaction of multiple fractures and stress shadowing effects.*

Keywords*: Cohesive Elements, Coupled Analysis, Coupled Lagrange Euler (CEL), Crack Propagation, Damage, DFN, Drilling, Fracture Initiation, Fracture Propagation, Geomechanics, Horizontal Wells, Pore Pressure, Poro-Elasticity, Reservoir, Smooth Particle Hydrodynamics (SPH), Wellbore, XFEM.*

1. Introduction

A large number of publications on the topic of 'Unconventional Reservoirs' are available and only a few key points are summarized here with the focus on Hydraulic Fracturing Simulation using Abaqus' coupled pressure-deformation capabilities, including cohesive elements, extended finite element method and other techniques.

For production from unconventional reservoirs, it is important to overcome the limitations in flow rates caused by the low permeability. One aspect is increasing the reservoir contact, i.e. the length of the wellbore positioned inside the reservoir. Given the restricted vertical height typically available compared to the large horizontal distances, directional drilling has become a key technology as horizontal wells can significantly increase the length of the wellbore in contact with the reservoir. The second key technology is increasing the flow into the well using pathways created by hydraulic fracturing. Injection fluids are pumped into the well to open fractures at specific points, then particles, called proppant, are added to keep the fractures open. Proppant selection (one example is fine-grained sand) includes a choice of particle sizes to fit into the fractures and volume and stiffness will influence the extent to which the fractures remain open and permeable.

This leads to three major challenges:

1. Lateral placement of the wells
2. Placing of fracturing stimulation stages along the well
3. Fracture design and operational parameters

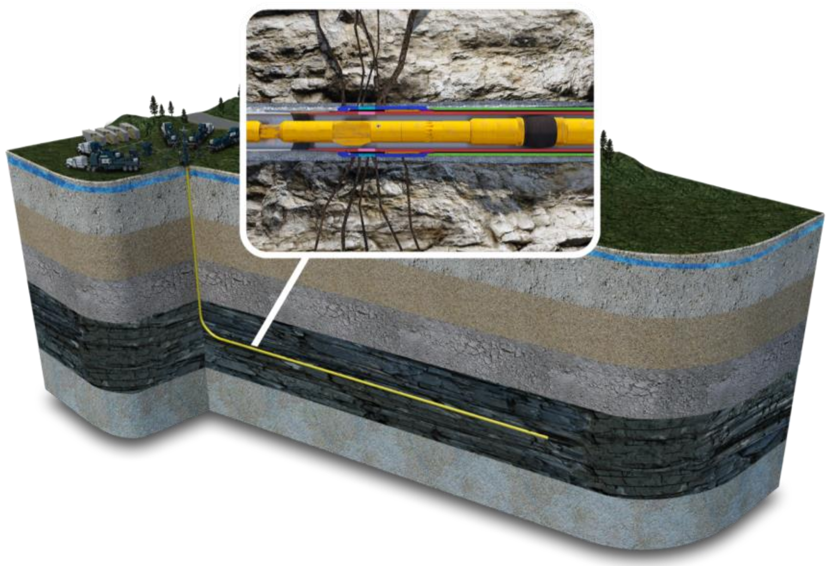


Figure 1. Schematic of a horizontal well and hydraulic fracturing stage.

Knowledge of the in-situ stress is required in the design process. With the assumption that the major principal stresses in the earth's crust are usually well aligned with the vertical and horizontal directions (note these are always compressive unlike in engineering applications), one can divide the possible stress states into:

- *Normal Faulting* – the vertical stress is the major principal stress, $S_v > S_{Hmax} > S_{hmin}$
- *Strike-Slip* – the vertical stress is the intermediate principal stress, $S_{Hmax} > S_v > S_{hmin}$
- *Reverse Faulting* – the vertical stress is the minor principal stress, $S_{Hmax} > S_{hmin} > S_v$

Geomechanical modelling allows us to further constrain major and minor principal stress, using information such as borehole breakouts in image or caliper data, tensile fractures, leak-off tests, etc. For a complete textbook on these topics, the authors refer to (Zoback, 2008). In complex environments, i.e. in the presence of viscous materials such as salt (Van der Zee, 2011) or thermal stress due to injection (Holland, 2015), a 4D Geomechanics approach using the Finite Element Method is required to determine the stress state.

The importance of the stress state becomes apparent with the knowledge that hydraulic fractures propagate normal to the smallest principal stress. Therefore, in a reverse faulting environment, a fracture would be in a horizontal plane and a horizontal well cannot achieve multiple independent fractures, whereas in normal faulting and strike-slip environments the horizontal well can be aligned with the least principal stress and multiple hydraulic fractures can be staged. The stress anisotropy, the difference between major and minor principal stress, can also have a major impact on hydraulic fracturing, as low stress anisotropy can lead to complex fracture networks due to interaction and stress shadowing effects.

A number of additional aspects are important:

- Reservoir and rock mass properties are heterogeneous. This aspect requires a 3D volume modelling approach and statistical methods for representation in the simulations.
- Operational considerations, including the pressure pumping equipment selection, fluid/proppant properties and energy requirements will determine the allowable ranges for select simulation parameters.
- Fracture initiation in strong formations can introduce a shift in the importance of parameters from those known and designed, such as fluid and proppant properties, to those unknown or having high uncertainty, such as stress and fracture toughness of rock.

Finally, it should be noted that an important application area is found in geothermal energy. The same processes described above are involved, but additional complexity arises from the fluid and rock temperatures having a significant influence on the scenario.

Industry benefits of a full 3D hydraulic fracturing simulation capability are found in:

- Optimizing the use of hydraulic fracturing technology, including rig and drilling time, fluid and proppant quantities, energy requirements and other cost factors.
- Reducing the number of fracturing campaigns that do not add to production. Currently, many designs rely on experience and an expensive trial-and-error approach.

2. Hydraulic fracturing overview

Many practical approaches are used in the industry to create calibrated models, typically using a number of assumptions to reduce problem complexity to the level where analytical solutions are available or fast numerical methods can capture certain aspects of the problem. Common model categories for the different software solutions include:

1. Single planar fracture
2. Discrete Fracture Networks
3. Complex fractures

As the vocabulary used around the general topic of hydraulic fracturing simulations can be ambiguous, examples for each category are shown below. The aim of this paper is to contribute to the understanding and development of simulation capabilities for complex fractures.

2.1 Single planar fracture

One of the advantages of fast analysis of a single fracture using numerical methods is to provide real-time advice on operational parameters and react to changes in observed versus predicted behavior. Fractures performed inside the reservoir, bounded by cap rock and basement, can comprise hundreds of meters of length. This type of analysis, including the use of log data from the well, can be used to adjust fluid volumes, pressures, proppant concentration, etc., and has been used in the industry for decades. The inclusion of proppant transport allows predictions of fracture conductivity (Figure 2), one of the direct measures of the success of the treatment.

Assumptions regarding fracture geometry and analytical forms with a list of references are summarized in Economides (2013).

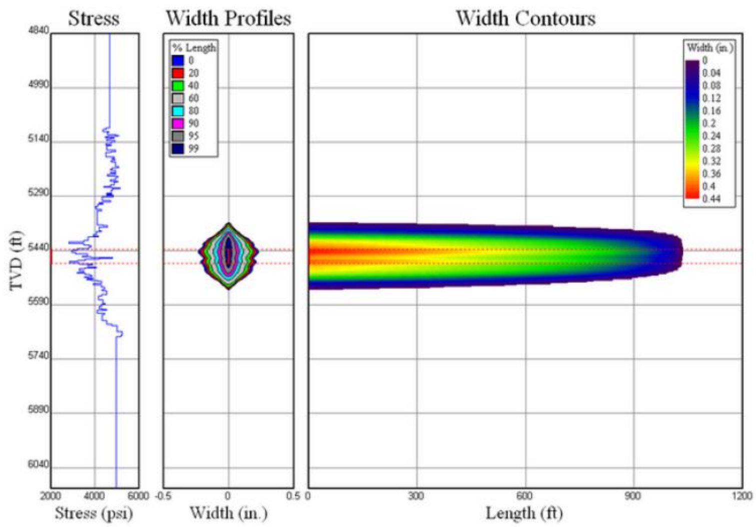


Figure 2. Example composite plot of fracture width contours (Meyer, 2014)

2.2 Discrete Fracture Networks

For fractured reservoirs, the connectivity of conductive fractures is important for well trajectory planning. Assuming critically stressed fractures (ratio of shear and normal stress exceeding the friction coefficient) are conductive, mapping current and future stress states, following depletion or injection, onto the fracture planes, a network of connected fractures can be used to assess production scenarios. This is done by creating representative planar features where the distributions for spacing and orientation can come from wellbore image analysis or seismic attributes, referred to as Discrete Fracture Networks (DFN), and resolving the geometric intersections. Introducing new fractures is typically not part of the workflow in this category. An example for a DFN analysis of reservoir fractures connected to a wellbore performed using JewelSuite™ is shown in Figure 3.

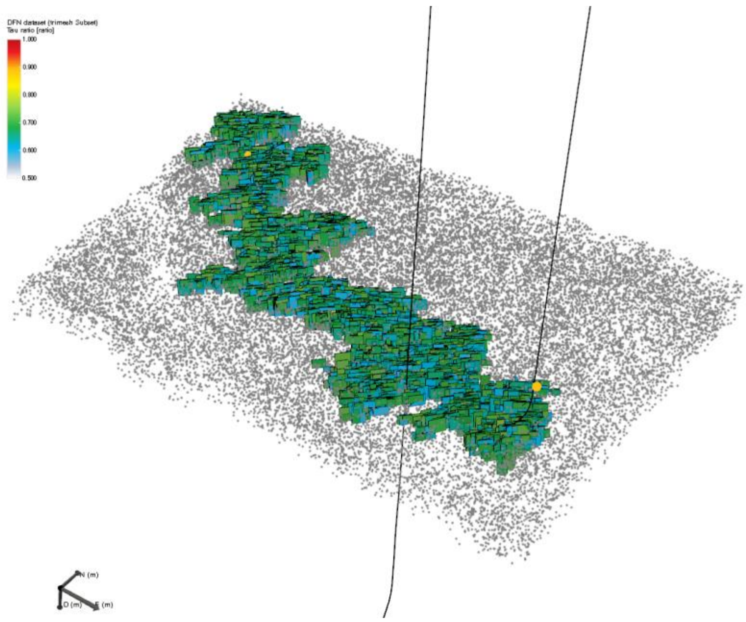


Figure 3. DFN connectivity analysis with JewelSuite™ (Holland, 2014).

2.3 Complex Fractures

The assumption of a single planar fracture extending from the wellbore (simple fracture) is often not justified and more complex fractures can evolve. In cases of low-stress anisotropy, reservoir depletion can lead to a change in the stress regime and new fractures in a hydraulic fracturing stimulation campaign at a later stage can open perpendicular to the initial set of fractures. This can create a complex fracture network, allowing a much larger total fracture volume as shown in the schematic in Figure 4, after (Fisher, 2004) and (Warpinski, 2008). Additionally, three-dimensional effects can occur on a small scale in the near wellbore volume, as the stress concentration and flux around the well can distort the fracture geometry and reorientation can occur. These effects influence fracture aperture and can become problematic for fluid transport of the proppant around the curvature of the fracture.

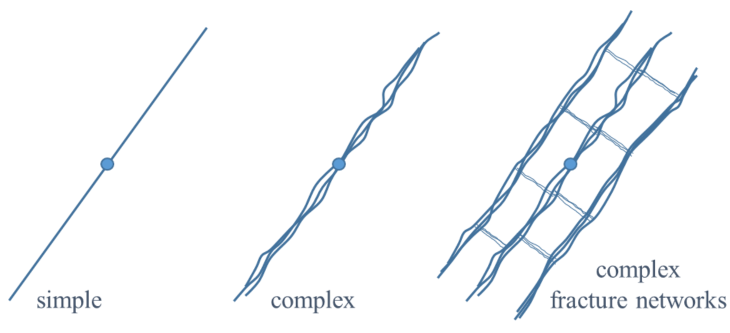


Figure 4. Complex Fracture Network (Fisher, 2004; Warpinski, 2008).

3. Fluid-driven fracture propagation

Independent of the question of whether fractures are pre-existing features of the rock mass or introduced by fluid-driven fracture propagation, any simulation of rock mass behavior under deformation quickly converges on the difficulty of introducing discontinuities into the modeling approach.

3.1 Discontinuous modelling of rock

This is at first a geometric challenge, which for finite element analysis translates into a meshing challenge, as both the lateral dimension (thickness) of the fracture in the surrounding rock mass is very small compared to both the typical joint spacing and the required discretization along the fracture path. This impacts computation of the stress intensity factor and the crack tip opening deformation for realistic fracture propagation simulation. The ratio becomes extremely unfavorable when considering reservoir dimensions (reservoir thickness in tens of meters, fracture length hundreds of meters in some cases) compared to fracture openings in the range of millimeters or below.

In the last ten years, significant progress has been made in modeling the mechanical behavior of jointed rock, with the three-dimensional volumes in the simulation often referred to as Synthetic Rock Mass (SRM). Those simulations performed with Abaqus/Standard and Abaqus/Explicit, both under static (including explicit quasi-static simulation) and dynamic loading (rock bursts, blasting and seismicity) significantly improved with the introduction of cohesive elements in Abaqus version 6.5-1. Examples of geomechanical modeling of faults in Abaqus are shown in (Arndt, 2007a) using a continuum approach with fine mesh discretization and an implementation showing discontinuous behavior for frictional fault sliding using the general contact capabilities in Abaqus/Explicit (Arndt, 2007b) for problems where the high confinement stress justifies the lack of cohesion for this modeling approach. The use of the explicit solver allowed efficient use of the parallel solver on a cluster of 32 CPUs, addressing the model size requirements in excess of 10 million degrees of freedom. The first application of Abaqus for SRM samples using cohesive elements and a Discrete Fracture Network (DFN) approach is shown in (Arndt, 2009). Here, the discontinuous nature of rock mass is represented with samples containing representative joint spacing and orientation using both the cohesive element approach, but underlying contact allows complete separation at the joints on mobility of the newly formed particles. The question of scalability of rock strength parameters is investigated and applied to problems of fragmentation in mass mining methods. This leads to further developments for a fully coupled pore-pressure deformation examples introducing flow in conductive faults in (Beck, 2010), with the limitation that no change in permeability or any fracture opening and propagation was considered. An approach to calibrate the strength of joints is shown in (Arndt 2013), where the different behaviors observed on different length scales are used to derive properties for rock mass consisting of parallel bedding planes explicitly contained in very detailed models. A detailed review of numerical methods used in rock mechanics and rock engineering including modelling of fracture processes and of fluid flow and heat transfer in rock masses can be found in (Brown, 2012).

Crack opening and coupled pressure deformation both for cohesive elements and XFEM were introduced in Abaqus version 6.14-1. A detailed overview of both methods together with validation using analytically solvable cases is provided by (Zielonka, 2014). It is shown that for all regimes, mapped by first fluid storage dominated by either crack opening or leakage and second by energy dissipation by either fluid viscosity or fracture toughness, Abaqus shows good agreement with analytical solutions and convergence of results quality for mesh refinement.

3.2 Choice of modeling approach

For the purpose of discussing advantages and limitations of the various modeling approaches possible for fluid-filled fractures using Abaqus, it seems worthwhile, in the author's opinion, to differentiate those methods that integrate the multi-physics challenge into a single analysis technique (or element formulation approach) and methods that require defining an interface between two very different simulation methods (i.e. a region where results quantities such as pressure or deformation are exchanged).

The latter category is independent of the question of having an internal coupling interface defined in Abaqus or requiring external coupling with an independent simulation code (co-simulation). Theoretically, a coupled multi-physics approach defining an interface could take advantage of the different domains (a coupled pore-pressure deformation continuum/discontinuum domain combined with a purely fluid filled domain) using different discretization. Whilst most of the examples mentioned in the above discussion regarding the modeling of faults and SRM use explicit time integration (Abaqus/Explicit), therefore providing the advantage of overcoming the numerical instabilities that are commonly introduced by strain-softening materials, no pore-pressure coupled modeling capabilities are currently available in Abaqus/Explicit. Still, multi-physics simulations using Abaqus/Explicit might be of interest for approximating fluid fracture propagation in low-permeability cases. Therefore, using this differentiation of methods in this second category only co-simulation could be considered capable of fully coupled simulation.

The explicit method solver solution time, scales approximately linearly with element number, if all other aspects including element size (determining stable time increment) remain similar. This allows very large models to be analyzed, in particular in combination with the explicit parallel solver, allowing efficient scalability for several hundred CPUs. Information on the scalability of the implicit solver for this problem type was not available to the authors.

The main options for hydraulic fracturing simulation using Abaqus/Standard are:

- Cohesive Elements
- eXtended Finite Element Method (XFEM)

Additional options include using Abaqus/Explicit (currently limited to fluid fracture propagation without coupled pore pressure) or third-party software:

- Coupled Lagrange Euler (CEL)
- Smooth Particle Hydrodynamics (SPH)
- Co-simulation

As this work focuses on the analysis capabilities provided by the suite of Abaqus software products, the very general case of co-simulation with other analysis products has not been investigated. Emphasis should be given to the fact that from the entries in the list above, only XFEM allows a simulation without the requirement to introduce a possible fluid fracture path predefined in the model. Fracture surfaces cannot intersect because each element can only contain a single enhancement. For all analysis cases, a pre-existing or initial fracture has to be introduced.

A coupled CEL-continuum approach has been briefly investigated and shown to open closed fractures with a fine discretization of the fluid domain, but insufficient progress diverted the work to the other methods.

Many of these modeling approaches require further development effort to increase coverage of the physical effects the simulation aims to replicate, but as complexity increases, the validation of simulation results becomes a challenge. Analytical solutions are not available to capture the full range of desired effects and validation would either require a meaningful laboratory test setup or a full field data approach. The latter case is desirable, but quantities that can be measured in-situ are limited and costs can be prohibitive. Alternatively, simulation results from other codes can be used and the work presented in this paper is also used to validate simulation results performed with the GEOS framework at the Lawrence Livermore National Laboratory (Settgast, 2014).

3.3 Coupled pressure-deformation cohesive elements

Abaqus/Standard provides cohesive elements with constitutive behaviours for:

- Coupled pressure-deformation (Poroelasticity)
- Normal and tangential pore fluid flow
- Element degradation and crack opening
- Crack fluid flow (Poiseuille flow)

An example problem in (Abaqus, 2014a), "10.1.5 Hydraulically induced fracture in a wellbore" demonstrates the application of coupled pressure-deformation cohesive elements to this type of problem. A pumping stage propagates a fracture, the high pressure fracturing fluids then bleed-off into the reservoir, boundary conditions substitute the effect of proppant to preserve the fracture width and subsequent reservoir drawdown occurs.

This method faces the limitation that the crack path must be defined in advance in the mesh.

3.4 XFEM

With the validation results from (Zielonka, 2014) it is shown that XFEM can used as an alternative solution to the cohesive approach above. (Abaqus, 2014b), "1.19.5 Propagation of hydraulically driven fracture using XFEM" also demonstrates good agreement between both methods. The question of how XFEM fractures behave in complex stress fields seems to remain open, as rotation of the principal stresses in the above example does not generate a curved fracture.

3.5 SPH

To investigate the ability to model fluid flow inside the fracture using Abaqus with a view on further applications to rough fracture surfaces and proppant transport, the Smooth Particle Hydrodynamics (SPH) capability in Abaqus/Explicit has been used in a common benchmark problem: the Poiseuille flow between stationary parallel plates with parameters listed in Table 1. This simulation shows very good agreement with the analytical solution as shown in Figure 5 and Figure 6.

Table 1. Parameters for plane Poiseuille flow (Morris, 1997; Holmes, 2011)

	Variable	Value
Width	*L*	0.001 m
Viscosity	*μ*	0.001 Pa s
Density	*ρ*	1000 kg/m^3
Pressure Gradient	F	0.0001 m/s^2

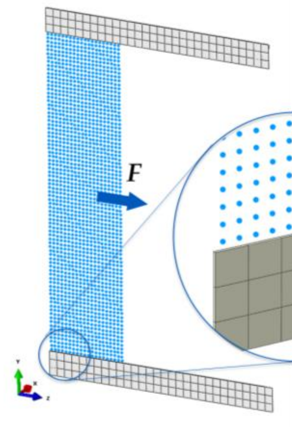


Figure 5. Abaqus model with solid element mesh parallel plates and SPH particles seeded in the fluid domain.

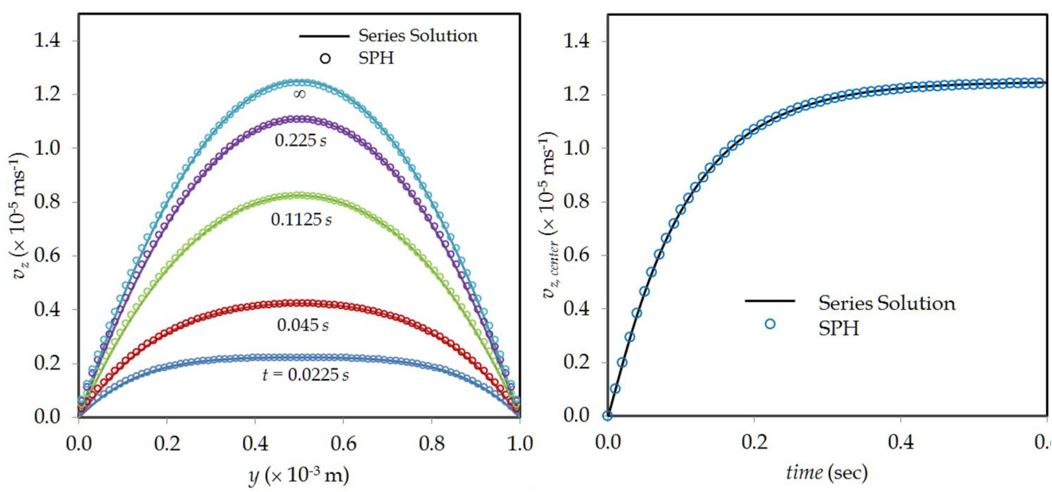


Figure 6. Comparison of the predicted SPH flow velocity with analytical solution (height profile evolution over time, left, center velocity, right).

Investigations confirming mesh refinement (or particle density) convergence of this method and on the influence of artificial viscosity to control stable time increment size on shear viscosity were performed as well. These findings and continuation questions are outside the scope of this paper and will be published separately in the future.

4. Application of cohesive element hydraulic fracture simulation

Three examples were investigated that used the cohesive element approach, based on the validation for both cohesive elements and XFEM to correctly describe fluid-filled fracture propagation and success in modelling intersecting fractures.

4.1 2D Simulation with intersecting fractures

To test the simulation capabilities for intersecting fractures, a quasi 2D-model with square geometry is constructed in CAE. Abaqus/CAE 6.14-1 does not support the 12-node displacement and pore pressure three-dimensional cohesive element in the "Mesh" module. Meshing can be performed by using the 8-node, three-dimensional cohesive element and subsequently editing the element type. The optional offset parameter allows the automatic generation of the mid-surface nodes (nodes 9-12) that contain only pore pressure degrees of freedom. This can be performed in Abaqus/CAE via Model, Edit Keywords or separately editing the input file to modify the entry for the element definition for type COH3D8 by changing the element type and specifying an offset value:

ELEMENT, TYPE=COH3D8P, OFFSET=offset*

The mesh stack orientation should be defined in the "Mesh" module to ensure the cohesive elements are inserted correctly.

This approach does not allow generating intersecting fractures. In this case, all connected elements need to have common pore pressure nodes, which is not compatible with the underlying geometry and requires either further editing or mesh generation via scripting. The independent constitutive and geometric thicknesses of the elements would allow inserting zero thickness cohesive elements at all element boundaries without distortion of the mesh.

For this example, a model is created by defining a single layer of C3D8P elements (regular mesh, 100m x 100m, 1m size) intersected by a narrow geometry domain of 0.01m to contain the cohesive elements (COH3D8P) in the mid-planes. The center piece solid element is deleted and one node for each side of the layer is created in the center to be used as common pore pressure nodes on the four attached cohesive elements.

The parameters from validation cases in (Zielonka, 2014) are used in the simulations (Young's modulus E = 17 GPa, Poisson Ratio ν = 0.2, Fluid viscosity μ = 1 cPoise). An initial open fracture is defined on the left side, with the initial length chosen as 25% of the model dimensions, using the keyword:

***INITIAL CONDITIONS, TYPE=INITIAL GAP**
ElementSet

Both pressure and inflow volume-controlled boundary conditions yield the same results, either using:

```
*BOUNDARY
NodeSet, 8, 8, InjectionPressure
```

or

```
*CFLOW, AMPLITUDE=RampUp
NodeSet, , InjectionVolumeRate
```

Following an initial ***GEOSTATIC** step to ensure equilibrium of the initial conditions for stress and pore pressure, a ***SOILS, CONSOLIDATION** analysis step is performed using the unsymmetric matrix solver as required for this problem type. Changes in pore pressure can be large, so an adequate choice of the convergence tolerances for pore pressure, defined using the UTOL parameter, is necessary. The initial in plane stress is set to S_{11} = 15MPa, S_{11} = 10MPa and S_{33} = 10MPa. For the second model, S_{11} and S_{33} are swapped, rotating the stress 90 degrees.

The fracture propagation for the two models is shown in the time sequence in Figure 7 using the fracture aperture variable (PFOPEN) and a 500x displacement magnification.

The simulation demonstrates the expected behavior. Initial tests were performed with the injection in the center and initial gaps defined for all four cohesive elements connected to the central pore pressure nodes to confirm fracture propagation occurs only in the plane normal to the least principal stress. In this example the possible fracture paths are limited to the cohesive element regions, so in the scenario where the least principal stress is horizontal, a redirection of the fracture propagation direction can only occur at the center of the model. At this stage the fracture does not propagate further laterally.

An important observation in the sequence of pictures is the reduction of aperture of the horizontal fracture as the fluid escapes into the vertical fracture and stress shadowing occurs. This very realistic behavior has significant implications for real-life stimulation treatments, as proppant transport inside the fluid is affected in rather complex ways and the proppant might choke the fracture tip.

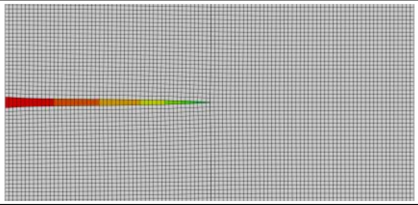
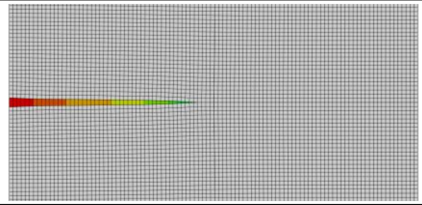
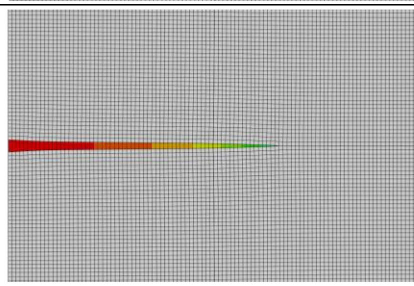
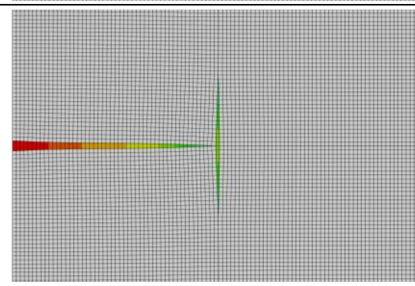
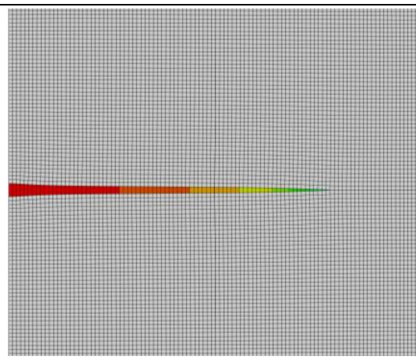
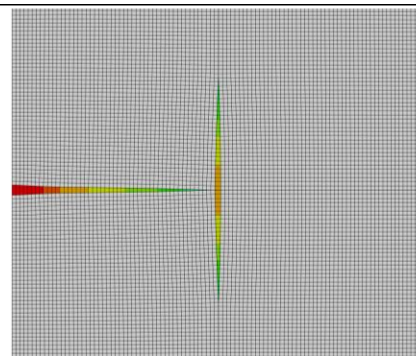
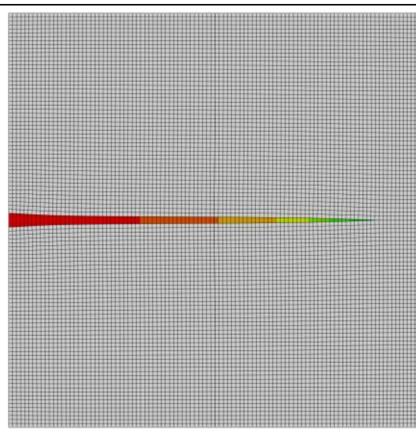
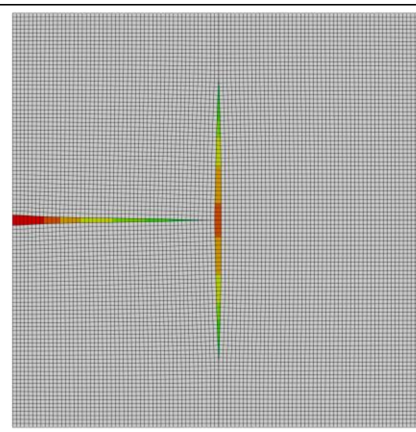
Time	S_H = 15.0 MPa / S_V = 10.0 MPa	S_H = 10.0 MPa / S_V = 15.0 MPa
300 s		
600 s		
900 s		
1200 s		

Figure 7. Evolution of fluid injection showing fracture aperture (PFOPEN) for cohesive elements with displacement magnification of 500x.

4.2 Validation against experimental data

Results in (Blanton, 1982) allow the validation against experimental data. Here, samples of dimensions 30cm x 30cm have been fabricated using synthetic rock blocks (“hydrostone”) with existing fractures embedded at different angles (90°, 45°,60°) and subjected to different tri-axial compressive stress states before fluid injection propagates a hydraulic fracture. Three of these experiments, showing all three different observed interaction modes in the same model geometry, were chosen for validation (Table 2).

Table 2. Validation experiments chosen from (Blanton, 1982)

Test	Fracture Angle θ	S_{XX}	S_{ZZ}	Interaction Mode
CT-4	60°	12.0 MPa	10.0 MPa	Opening
CT-8	60°	20.0 MPa	5.0 MPa	Crossing
CT-21	60°	14.0 MPa	5.0 MPa	Arrest

As several parameters from the experiments, such as injection fluid pressure and hydrostone strength (fracture toughness), are not provided in the paper because we follow the argumentation in (Fu, 2012) to narrow the possible range according to observations from the tests. This also allows for comparison with these and other numerical simulations using the same reference. Contrary to the approach in (Fu, 2012), where crack propagation crossing the natural fracture is not allowed and the stress intensity factor K_I is evaluated instead, the Abaqus simulation allows crossing through the natural fracture by extending the cohesive elements to the specimen boundary.

An initial gap opening has to be specified in the model for the cohesive elements at which fluid injection occurs as in the previous example. It would seem obvious to use the same approach to create the natural fracture, but the element degradation of the shear stiffness changes the stress equilibrium in the geostatic step significantly, especially in the case of high differential stress (CT-8). The fracture toughness has no major influence on the fracture propagation; therefore, it is sufficient to have the natural fracture closed both in the initial conditions and in equilibrium by choosing a shear strength larger than the shear stress on the inclined plane. The presence of cohesive elements subsequently allows the fracture to open.

A coarser regular mesh and a finer advancing front mesh with ~4000 and ~20,000 elements, respectively, have been tested with similar results. A time sequence of the three cases is shown in Figure 8, where the fine mesh is suppressed for better clarity. Displacements are magnified 100x.

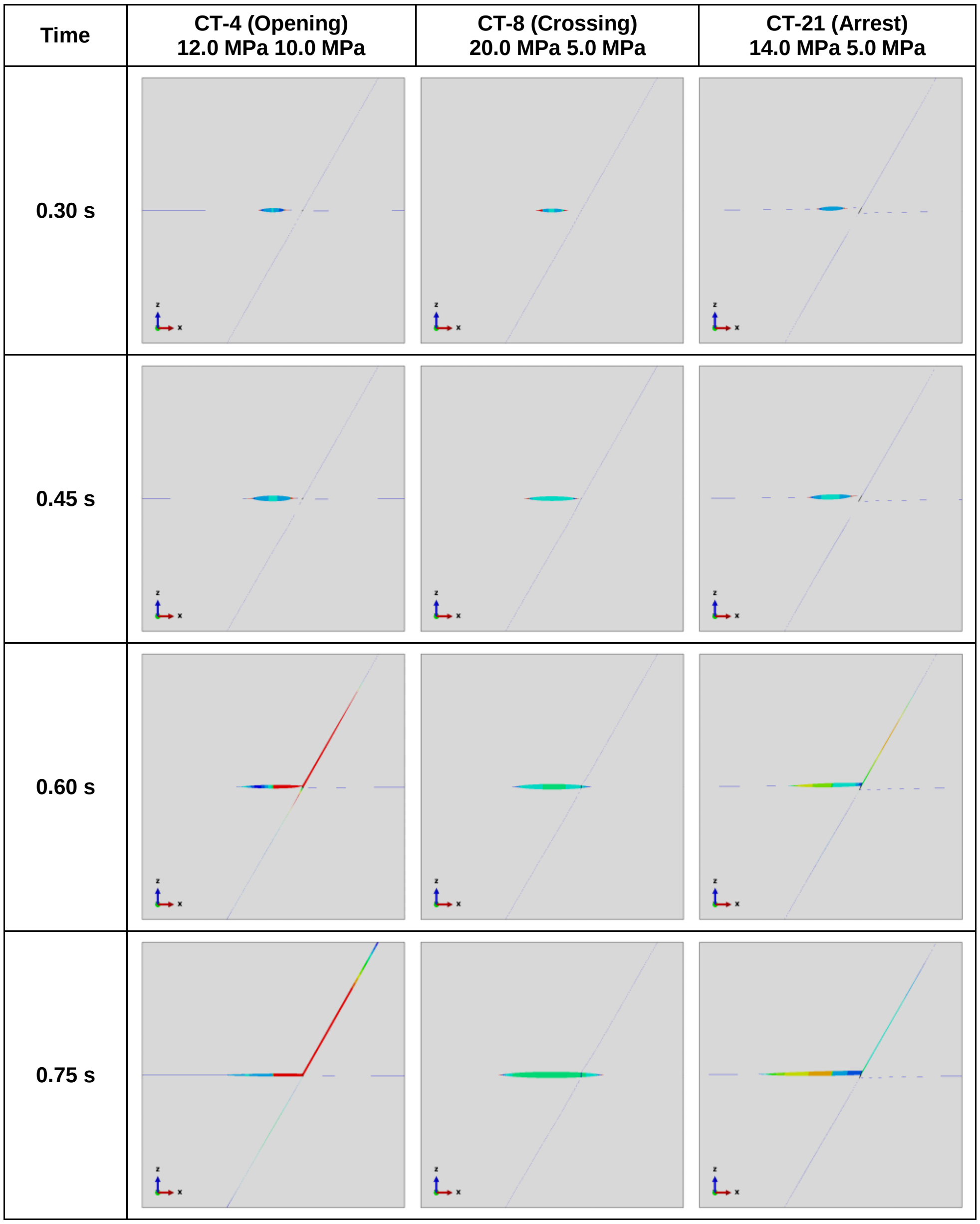


Figure 8. Evolution of fluid injection showing gap flow volume rate (GFVR).

As shown in the evolution of fracture gap flow volume rate, all three tests show the correct fracture interaction mode. CT-21 does show minor fluid propagation along the natural fracture, but this is small compared to the fluid volume and fracture opening on the other side of the injection point. Again, higher confining stress shows a smaller crack opening in CT-4 as in the previous example.

4.3 3D Simulation with parallel fractures

Current research into the interaction of different fracture stages, stress shadowing between parallel fractures and alternative sequencing between adjacent parallel wells ('Zipper Frac') demonstrates the significance of 3D simulation capabilities. (Bunger, 2014) and (Izadi, 2015) provide analyses of the parameters for closely spaced fractures and a detailed analysis of the zipper frac concept using a continuum damage approach with Abaqus is presented in (Shen, 2014).

The chosen test case for 3D simulation of parallel fractures with cohesive elements is the simultaneous propagation of equally spaced fractures under the assumption of equal injection pressure, neglecting wellbore hydraulics and perforation friction effects. A 3D model was built using Abaqus/CAE, including the wellbore geometry ($7^5/_8$ in diameter), a reservoir volume of 40m vertical extent with cap rock above and basement below for a total height of 60m, five parallel planes meshed with cohesive elements with 5m separation, and partitioning to allow for mesh transition from the well. Lateral symmetry is used to reduce element numbers. No vertical symmetry was used while building this model to allow for gravity and stress gradient effects (although the case presented here does not include these effects). The model geometry and mesh with ~100,000 elements are shown in Figure 9.

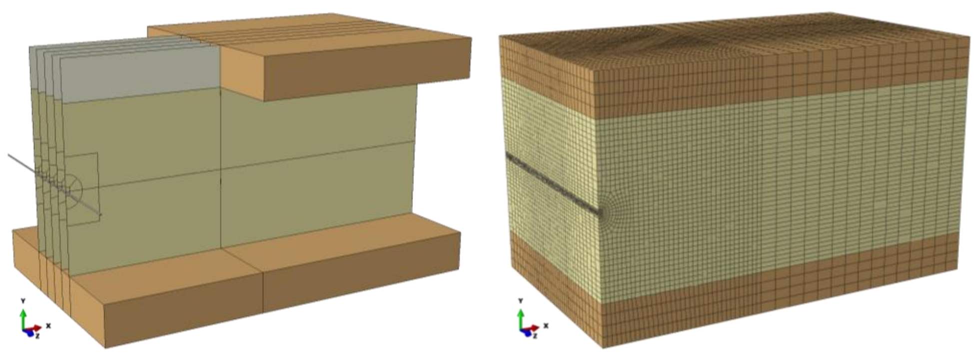


Figure 9. 3D model with horizontal well, reservoir volume, five planes containing cohesive elements for hydraulic fractures (left) and mesh discretization (right).

Using pressure boundary conditions as in the previous examples, volume flow and fracture propagation occurs. Higher lateral stress and rock stiffness in the cap rock and basement provide fracture containment inside the reservoir.

Unlike a simulation with a constant volume flow rate for each fracture, the constant pressure generates flow rates affected by the stress changes. The inner fractures become restricted by the presence of neighbors on both sides and fracture aperture and total volume are reduced significantly as seen in Figure 10. This quantitative simulation experiment is consistent with published simulation results. Further work is required to quantify the effects above and validate results against other available sources.

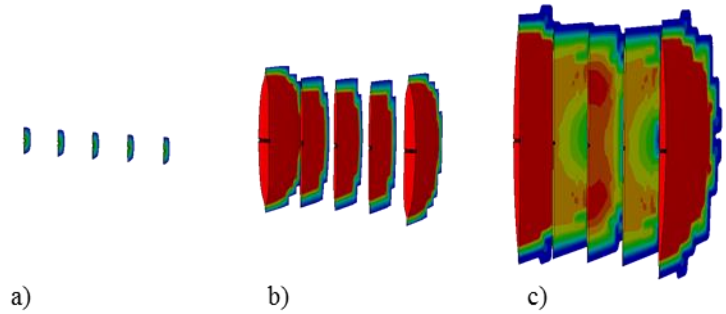


Figure 10. Evolution of fracture aperture in simultaneous parallel fractures.

Analysis times for this 3D problem are in the range of several hours using a single computer with 16 CPU cores, indicating that there is no immediate practical limitation for this simulation approach.

5. Conclusions

The stated challenge for this paper is to extend applications to more complex geometries with interaction of multiple fractures and stress shadowing effects. By choosing the cohesive element approach in Abaqus/Standard it becomes possible to perform 3D hydraulic fracturing simulations that satisfy the following criteria:

- The analysis capability includes essential physical behaviors such as coupled pressure-deformation (Poroelasticity), fracture propagation and fracture fluid flow with leak-off.
- Validation of propagation of a single fluid-filled fracture against analytical solutions, such as KGD geometry and Penny-shaped cracks, and mesh convergence have been shown (Zielonka, 2014).
- Successful validation of 2D fracture interaction observed in experiments. Different interactions modes such as fracture diversion (or opening), crossing a natural fracture, and arrest are predicted correctly.
- The implementation of intersecting cohesive elements used in the 2D examples can be extended to include all element boundaries in the model in 3D, providing a general 3D simulation capability.
- Interaction of parallel fractures in 3D simulations and qualitatively correct behaviors as stress-shadowing-limiting fracture apertures, as shown in simulations using other codes, is observed.
- Acceptable performance and time incrementation for large 3D problems is demonstrated, combined with scalability using the parallel solver.

A major limitation lies in the necessary choice of either using cohesive elements or XFEM. Cohesive elements placed at solid element boundaries limit the possible fracture path to element boundaries and XFEM does not support intersecting fractures or nucleating new fractures.

These are common challenges in the focus on coupled 3D hydraulic fracturing simulation capabilities for the oil and gas industry in recent years and the desire to include more effects will drive further developments. With the approach shown in this paper Abaqus in its current release can be used to increase understanding of interaction of fractures in stimulation campaigns and to help reduce expensive trial-and-error approaches.

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