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XFEM-Based CZM for the Simulation of 3D Multiple-Stage Hydraulic Fracturing in Quasi-Brittle Shale Formations

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Abstract

The Cohesive Zone Model (CZM) engages the plastic zone and softening effects at the fracture tip in a quasi-brittle rock, e.g. shale, which concludes a more precise fracture geometry and pumping pressure compared to those from Linear Elastic Fracture Mechanics. Nevertheless, this model, namely planar CZM, assumes a predefined surface on which the fractures propagate and therefore, restricts the fracture propagation direction. Notably, this direction depends on the stress interactions between closely spaced fractures and can be acquired integrating CZM as the segmental contact interaction model with a fully coupled pore pressure-displacement, extended finite element model (XFEM). This later model simulates the fracture initiation and propagation along an arbitrary, solution-dependent path.

In this work, using XFEM-based CZM in Abaqus, we modeled four-stage 3D hydraulic fracturing in a triple-layer, quasi-brittle shale formation including slit flow and poro-elasticity for fracture and matrix spaces, respectively. We implemented a new method to connect our model to the infinite surrounding rock layers by replacing the horizontal stress boundary conditions with infinite elements around the solution domain of interest. Moreover, we characterized the cohesive segments by refining the stiffness, fracture initiation stress, and energy release rate using three geometric and accuracy criteria. Furthermore, we partitioned only the stimulation region into multiple XFEM enrichment zones to simulate multiple-stage fracture propagation, reduce computational expenses, and avoid unrealistic fracture growths around sharp edges.

We demonstrated the significance of operational parameters, rock mechanical properties, and loaded or fixed boundary conditions in fracture aperture and propagation direction in sequential and simultaneous four-stage fracturing cases. Also, having compared the multiple-stage fracturing results from planar CZM with those from XFEM-based CZM, we found that the stress shadowing effect of hydraulic fractures on each other can cause these fractures to rationally propagate out of plane. We investigated the effect of this arbitrary propagation direction on not only the fractures' height, length, aperture, and the required injection pressure, but also fractures' connection to the wellbore. This connection can be disrupted due to the near-wellbore fracture closure, which may embed proppant grains on the fracture wall, or screen out the fracture at early times.

Our results verified that the near-wellbore fracture closure strongly depends on three remarks: 1) the implemented model, planar or XFEM-based CZM; 2) the fracturing scenario, sequential or simultaneous; and 3) the fracture spacing. Ultimately, we proposed the best fracturing scenario and spacing to maintain the fractures connected to the wellbore for better proppant placement and subsequent production.