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# DEM modeling of high strain rate well bore fracturing via high pressure pulsed gas combustion

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## 1 INTRODUCTION

Itasca's *PFC2D* and *PFC3D* (Itasca 2018) DEM-based fracture modeling codes were utilized to model the high strain rate single pulse fracturing of laboratory-scale confined open and cased bore synthetic rock samples via a rapid, tunable, high pressure gas combustion process. The 2D and 3D *PFC* models were developed to both give guidance to the experiment design as well as validate the modeling approach and details of the material properties model. The effects of applied strain rate (pressurization rate) and peak strain (peak pressure) on the initial fracture characteristics relative to general high strain rate pressure loading theory (Cuderman 1981, Schatz et al. 1987) are demonstrated. In addition, full diameter cased and perforated non-directional and directional fracturing were both numerically and experimentally demonstrated using a pre-perforated casing.

NaturaFrac, Inc. is developing a pulsed gas combustion based well bore fracturing technology whereby a high pressure, combustible gaseous mixture is rapidly combusted to produce repetitive, high level, controllable well bore strain rates to induce complex fractures in the near- and far-bore formation. Since this technology utilizes an easily replenishable gaseous propellant mixture, the section of well bore under operation can be subjected to multiple, tailored applications of pressure and gas flow pulses. The strain rate and peak strain of the initial and subsequent gas pulse operations is fully adjustable and is capable of producing a complex fracture network in the formation at near bore and extended distances. The strain rate and peak strain levels can be dynamically adjusted/optimized to produce a complex fracture network relative to hydraulic fracturing methods without overly damaging the near bore formation as is common with solid explosives/propellant-based fracturing technologies.

Laboratory-scale (~24" diameter × ~24" length), confined cylindrical samples of synthetic rock (Hydrostone Super-X denoted as HS-X hereafter) were manufactured and tested with both sub-scale and full-scale bore diameters. *PFC2D* models using HS-X material properties (based on both published literature (e.g. Bahorich 2012) and low strain rate tensile and compressive strength characterization of the HS-X cored material from the actual fracturing samples) in a sub-scale (3.65" ID) bore were subjected to various dynamic pressure loadings. The applied pressure loadings (rate and peak amplitude) were guided by theoretical calculations and confirmed with experimental results. The importance of strain-rate dependent properties was realized and *PFC2D* and *PFC3D* were modified to take this into account at a very coarse level.

The same experimental technique was then modified to apply similar strain rate levels in a cased (perforated) configuration at the intended full well bore diameter (7-5/8" OD/6-1/2" ID P-110 casing) also using HS-X as the synthetic material. A corresponding *PFC3D* model of the perforated casing and confined sample was developed. 360deg. and ~180deg. directional complex fracturing was both numerically predicted and experimentally demonstrated.

## 2 DESIGN AND ANALYSIS

*PFC2D* models were developed to simulate the dynamic fracture propagation in a sub-scale bore, laboratory scale axisymmetric confined HS-X sample. The laboratory sample consisted of a 24-3/8" OD, 1" thick wall ASTM A36 steel shell, 1" thick Butyl rubber liner, and molded/poured HS-X synthetic rock which had a 3.65" nominal bore cored out from each end. Material properties (BTS, UCS, density, Vp, etc.) were characterized from multiple test samples extracted from the resulting cores. Three-dimension perforated case fracturing was modeled with *PFC3D* (with significant assistance from Itasca) in the same laboratory scale sample shell and 1" rubber liner, but with a pre-perforated casing molded into the sample during the HS-X pouring. Due to model size and run-time constraints only a "thin slice" 3D model was developed incorporating at least one full row of perforations in the axial direction to mitigate end face boundary condition effects.  Similarly, a "directional" *PFC3D* model was also generated and contained casing perforations only 180 deg. of the molded-in casing circumference as was intended to demonstrate direction fracturing capabilities. These three separate *PFC* models and laboratory samples are shown in Figure 1. Time-accurate fracture propagation simulations were performed with both 2D and 3D models utilizing representations of the measured and/or computational fluid dynamics (CFD) calculated bore pressure history and compared with the experimental results.

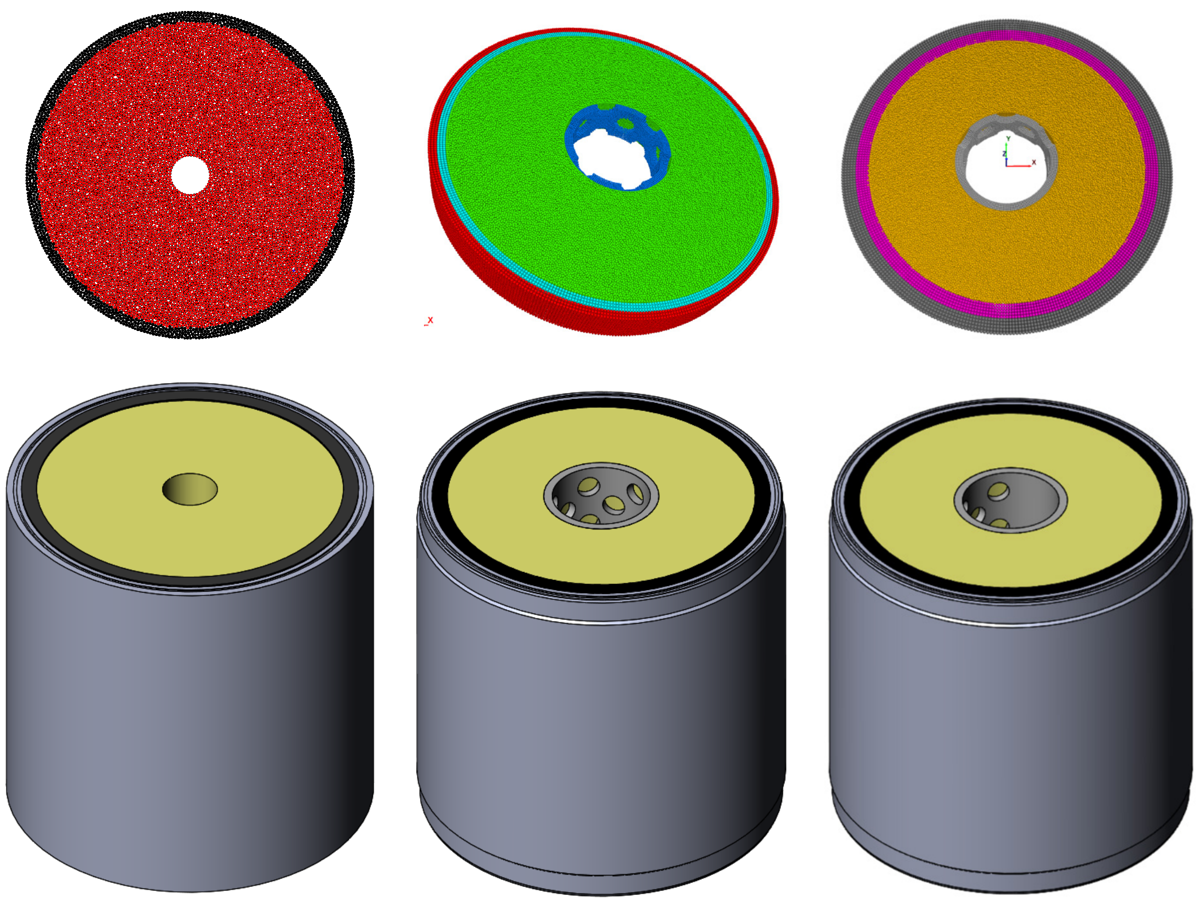

Figure 1. CAD representations of 24" OD × 24" length laboratory scale HS-X fracturing samples in rubber lined steel shell and images of their corresponding *PFC2D* and *PFC3D* DEM models: (Left) 3.65" ID cored open bore *PFC2D* model and fracturing sample and (Middle/Right) molded-in 6-1/2" ID pre-perforated cased bore *PFC3D* models and fracturing samples.

## 3 RESULTS AND DISCUSSION

*PFC2D* and *PFC3D* time-accurate simulations were performed utilizing representations of the internal pressure profiles generated during the experiments. Baseline HS-X material properties were estimated from open literature and cored material BTS, UCS, density test results along with wave speed measurements. Simulations were run with element sizes and time steps shown to produce fracture pattern results independent of the element size and time step.

It was found that strain rate effects could not be adequately represented by a constant material property model across all element. Essentially the HS-X material fractured too easily near the bore compared to that observed in multiple experiments and hence material micro-properties were made to be either functions of radial distance from the bore hole or cylindrical layers of decreasing tensile strength were incorporated into the model based on the numerically measured strain rates derived from simulations which utilized constant micro-properties. Micro-property scaling factors, based on data from effective strength measurements taken across the strain rates of interest (see Zhang 2016), were utilized to adjust the micro-properties relative to their base values depending on the strain rates experienced. Once adjusted to account for strain rate effects the fracture patterns seen in the 3.65" diameter open bore simulations closely matched those observed in the experiments in both the high and low strain rate regions of the samples. These micro-property adjustments were then used in the *PFC3D* simulations with very good success.

High level comparison between the 2D open bore and 3D cased bore (360 deg. and directional) simulations and the corresponding experiments are shown in Figure 2. These comparisons indicate that the *PFC2D* and *PFC3D* simulations were able to capture the approximate number of major fracture as well as the fracture complexity produced in the laboratory samples. Additionally, the directional fracture simulation and experiment results also show very good qualitative agreement, thus demonstrating the concept of directional initial well bore fracturing and the ability of *PFC3D* to capture the directionality of the fracture pattern.

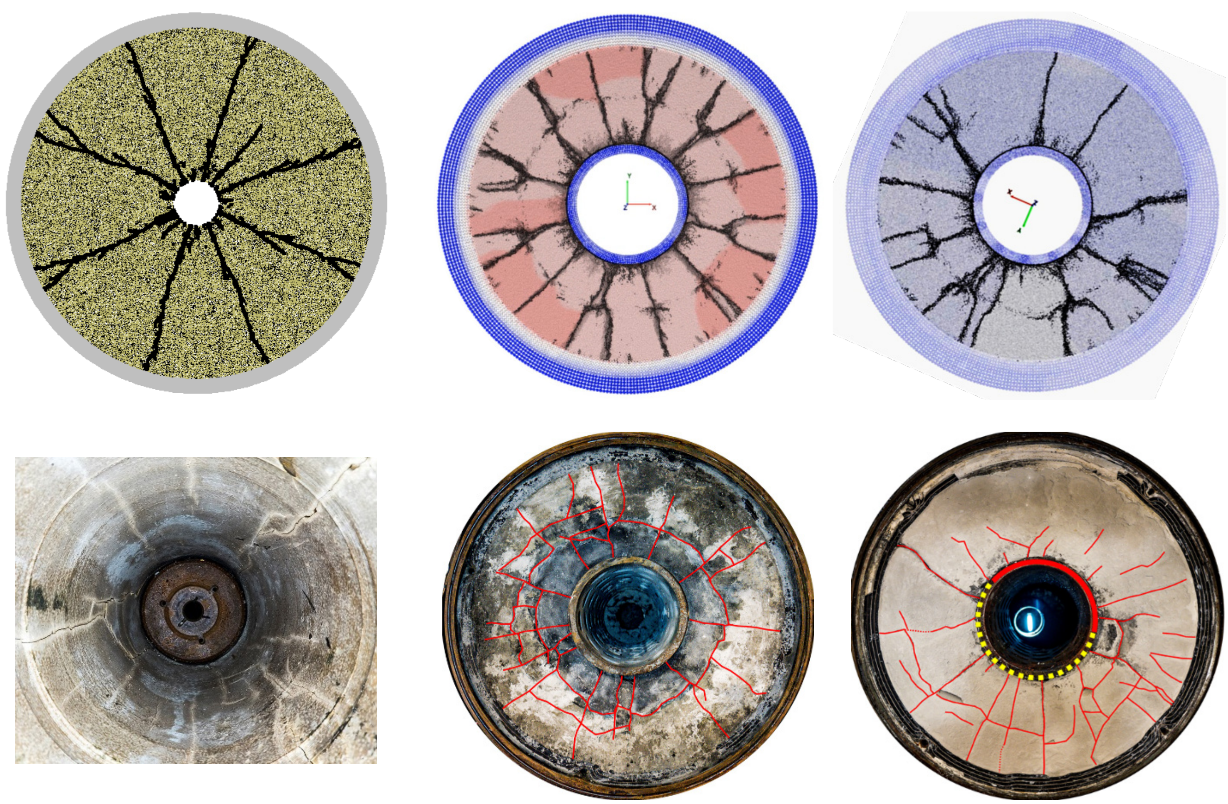

Figure 2. High level comparison between experimental results and numerical simulations of the resulting fracture patterns produced in HSX material from high pressure combustion loading of the 3.65" ID bore (left) and cased (pre-perforated) 6-1/2" ID bore (middle and right). Location of the perforated sector of the casing is highlighted as a dashed yellow line on the bottom right.

## 4 CONCLUSIONS

*PFC2D* and *PFC3D* models of dynamic fracture propagation in a synthetic rock (Hydrostone Super-X) using pressure profiles equivalent to those produced in laboratory scale experiments qualitatively matched well against the experimentally observed fracture patterns. Of particular interest is the demonstration both numerically and experimentally of the ability to produce a directional fracture pattern in the near bore environment.

These initial *PFC2D* and *PFC3D* model development efforts and validation against experimental results show great promise to be used as engineering development tools for predicting the necessary pressure pulse profiles (pressure rise rate and peak) in real formations (elevated rock strength, anisotropic properties, inhomogeneous materials, etc.) under field conditions (3D stress fields, faults, etc.). Further *PFC* development efforts will be challenged with simulating larger models (3D) with realistic rock/formation properties as well as gas-in-fracture effects, especially during multiple pulse loading scenarios.

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