Final Presentation

Subsea BOP Stack Shear/Seal Capability Modeling Tool
SwRI® Project No. 18.21614
BSEE Contract No. E15PC00006

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Agenda

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▪ Modeling Approach	9:30
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▪ Selection of Structural and Fluid Modeling Approach	
▪ Parametric Simulations	9:45
▪ Vendor Discussions and Validation Data	10:20
▪ Model Results Database	10:45
▪ Conclusions	11:30

Safety Moment

Be Aware of Your Surroundings

SwRI Introduction

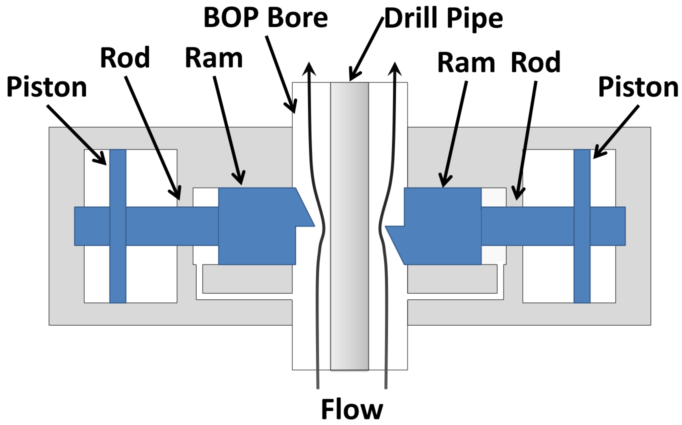
- SwRI is an independent, nonprofit applied R&D organization headquartered in San Antonio, TX
- Perform contract research for government and corporate clients
- SwRI is:
  - *Independent* – we do not compete with our clients
  - *Unbiased* – we do not have shareholders or stock
  - Perform work to maximize the benefit to the customer – novel intellectual property agreements
- SwRI facts:
  - Founded in 1947 by an oilfield business man, Tom Slick, Jr.
  - Nine technical operating divisions with a staff of approximately 2,700
  - $559 M revenue in FY2016
  - 41 R&D 100 awards

Operational Characteristics

- Applied RDT&E Services
- Revenue from Contracts
- Physical Sciences & Engineering
- Broad Technological Base
- Capital-Intensive Operation
- Internal Research Program

Project Overview - Objectives

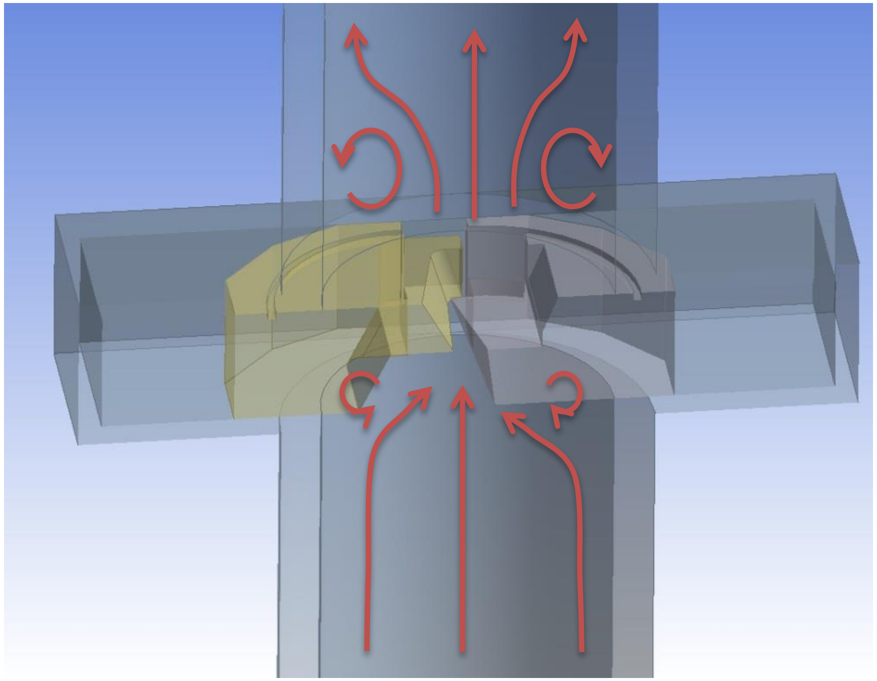
- Research simulation methods that combine mechanical (FEA) and fluids (CFD) analyses to better understand the effects of hydrodynamics on the BOP blind shear rams closing on flow
- Provide best practice guidance to BSEE on the simulation analysis approaches for future BOP analyses that incorporate the effects of closing on flow
- Perform a series of combined mechanical/fluid simulations that examine a range of different equipment and operating conditions
- Develop an extensible software tool that will allow BSEE to compare anticipated operating environments and conditions with a database of previous analysis results



This project focused on the operation of drill-pipe shear rams

Project Overview - Approach

- Research different methods that may be used to combine finite element analysis (FEA) and computational fluid dynamics (CFD) simulations to estimate the total shear ram force requirements under flowing conditions
- From the different methods evaluated, use the methodology that provides the most fidelity, subject to computational efficiency, in order to examine a range of different equipment and operating conditions
- Collect the simulation results into a database tool that allows the user to interpolate within the overall field of operating conditions



Incoming Turbulent Flow

Project Overview

- **What is the project trying to accomplish?**
  - In the absence of experimental results of shear ram performance under extreme pressures and flowing conditions, what is the optimal simulation methodology for accounting for hydrodynamic effects?
  - Are there significant parameters that affect the influence of hydrodynamic forces on shear rams?
  - Can a database of results be compiled to build a software tool that will allow BSEE to compare third-party evaluations of equipment and conditions to new permit applications?
- **What is it not trying to accomplish?**
  - This is not a manufacturer/equipment comparison study.
  - It is acknowledged that this is not a full-physics representation of the problem, but rather a study to provide an extra level of physical fidelity that incorporates hydrodynamic effects.
- **What physical effects are included or not included?**
  - Only single-phase flow of crude oil up the annulus is considered. Multiphase flow of crude or drilling mud is not being simulated. Flow within the drill pipe is not being considered.
  - Sand, debris, solid matter, and potential erosion effects are not within the scope of this work.
  - Evaluation of shear ram deformation or failure is not within the scope of this work.
  - Evaluation of the hydraulic systems or their designs that apply pressure to the shear rams is not within the scope of this work.
  - Only drill pipe is being considered within the simulations and auxiliary tubing/cables or drill-pipe connections are not included.
  - Off-center pipe and potential bowing/buckling/tension effects are not considered.
  - Potential operational characteristics, such as flow diversion away from the annulus, are not considered.

Project Tasks

- **Task 1: Define Baseline Condition and Parameter Variations**
- **Task 2: Baseline Studies and Modeling Approach Assessment**
- **Task 3: Parametric Simulations**
- **Task 4: Database Tool Development**

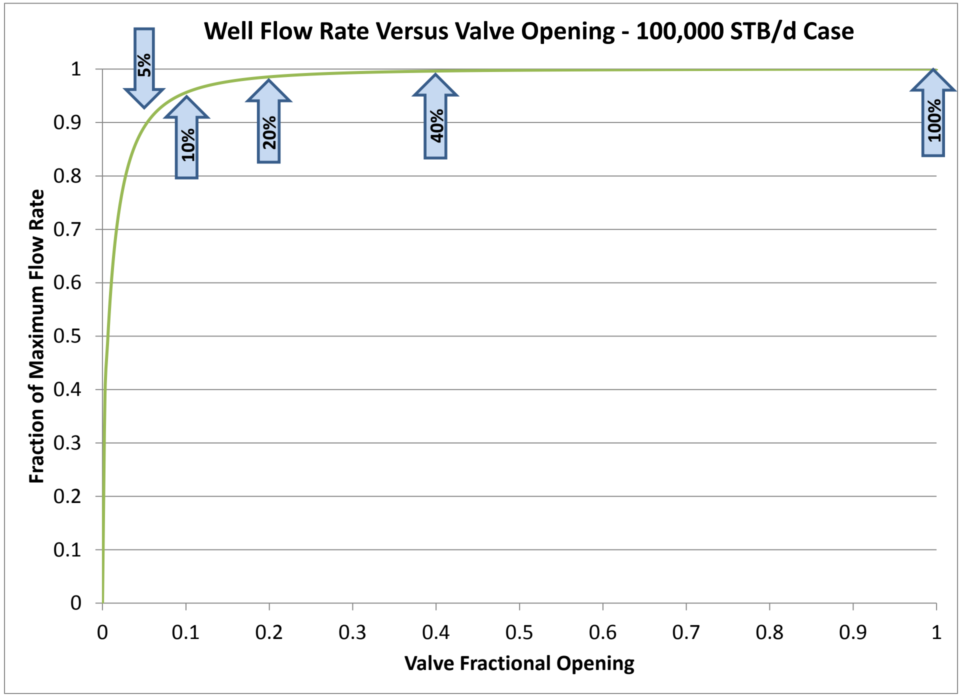
Baseline Case Definition

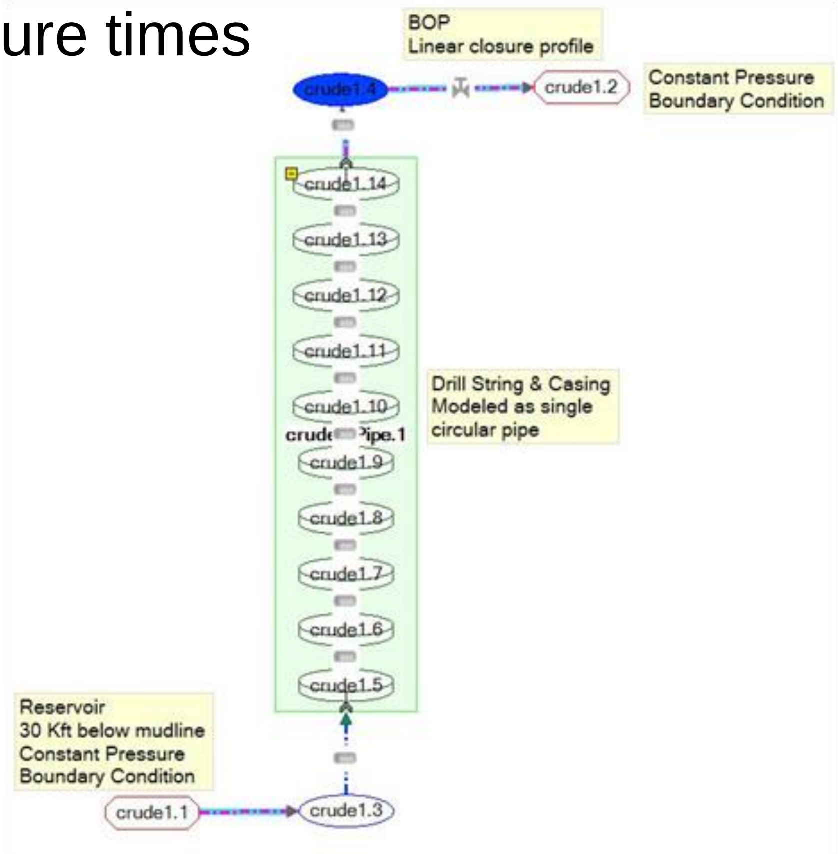
- A baseline set of conditions was selected to perform the initial analysis of different simulation approaches
- Accomplished mesh resolution study and CFD turbulence model selection

PARAMETER	VALUE	NOTES
Shear Ram Geometry	18.75-inch BOP with Baseline Ram Geometry	BSEE-specified, approximate geometry reproduced by SwRI
Shear Ram Closing Time	45 s	Specified by API Standard 53
Wellbore Dimensions	18.75 in	Representative Rig 49580
Well Depth	30,788 ft TVD 30,790 ft MD	BSEE-specified, representative Rig 49580
Maximum Anticipated Surface Pressure	14,177 psi	BSEE-specified, representative Rig 49580
Drill Pipe Dimensions	6.625-inch, 0.813-inch wall thickness , 50 lbs/ft	BSEE-specified, representative Rig 49580
Drill Pipe Material	S-135 Grade Drill Pipe	BSEE-specified, representative Rig 49580
Drill Pipe Axial Stress State	Neutral	Assumed conservative state
Produced Fluid Properties	API 35 GOR 1,397 scf/stb	Assumed representative GOM crude oil (Petrosky and Farshad 1993, 1995; BSEE 2016)
Annular Flow Rate	100,000 stb/d	BSEE-specified
Annular Flowing Pressure and Temperature at BOP Stack	11,000 psia 300°F	Calculated based upon representative reservoir conditions

Well Flow Rate and Flowing Conditions

- Five CFD simulations at 100%, 40%, 20%, 10%, 5%, and max shear of fractional area open to flow
- The hydrodynamic transients at the BOP location were computed for different BOP closure times



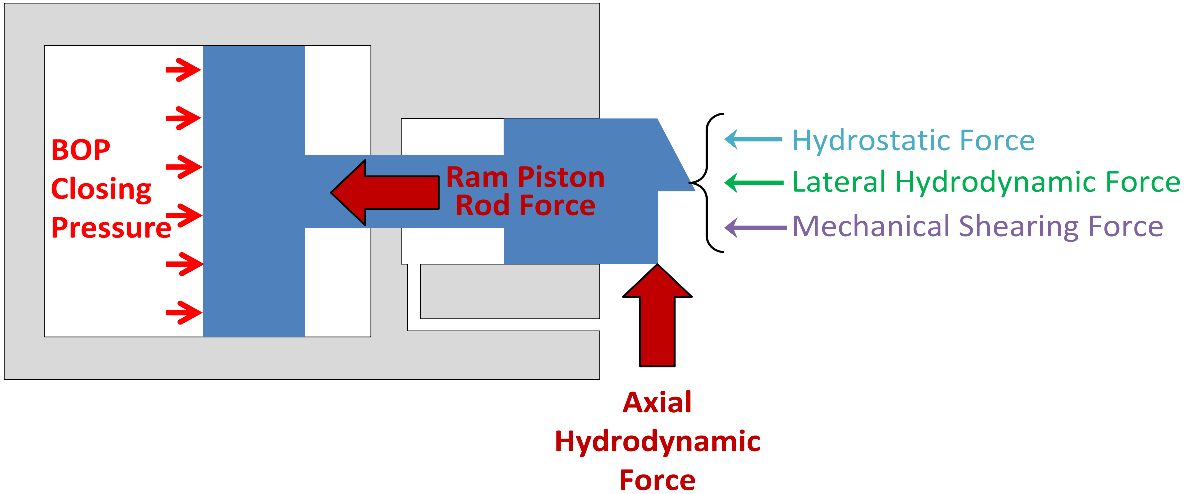


Modeling Approach

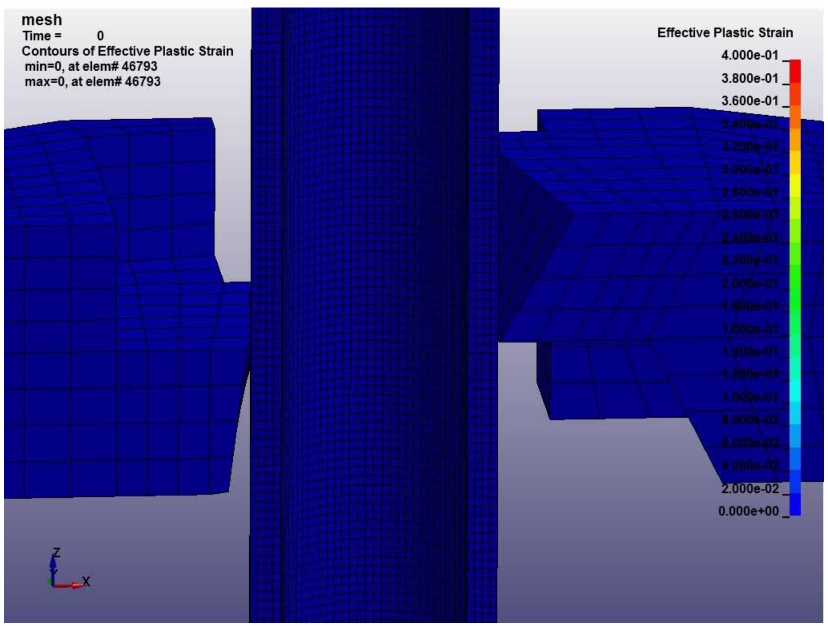
- Different methods for combining mechanical (FEA) and fluids (CFD) forces are investigated
- 1D well flow modeling was used to determine the conditions at the BOP stack and evaluate potential transient hydraulic pressure spikes
- A tiered approach to evaluating fluid-structure interaction (FSI) simulation methodologies was investigated:
  - Tier 1: FEA Only
  - Tier 2: CFD/FEA Linear Superposition
  - Tier 3: Lock-Step Coupled CFD/FEA
  - Tier 4: Dynamically Coupled CFD/FEA

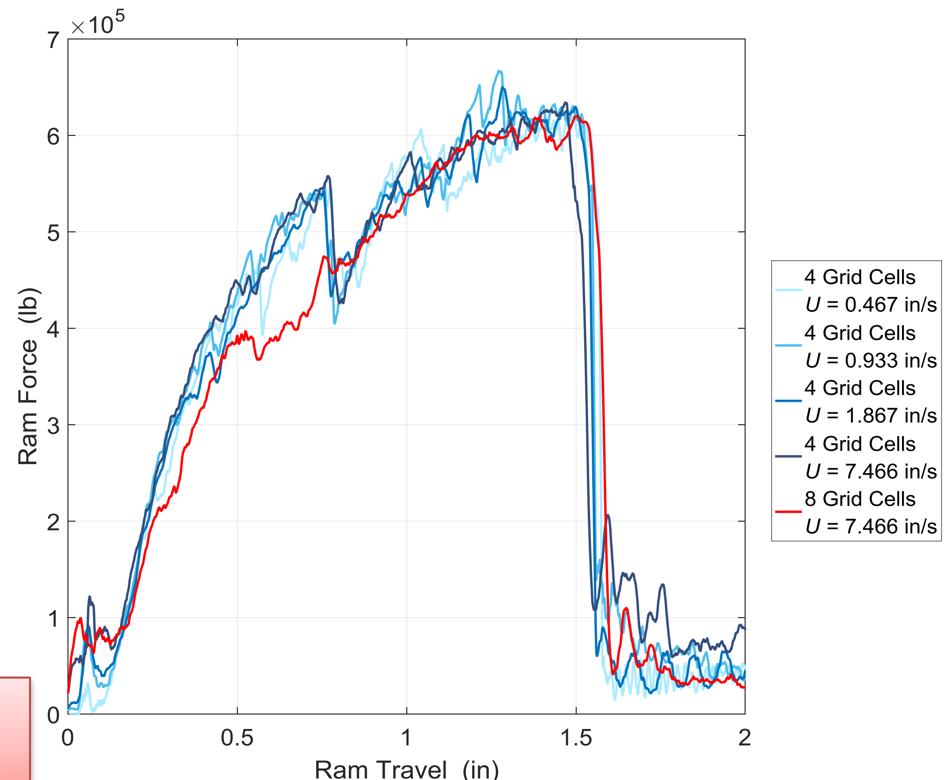
Tier 2 Simulation - Methodology

1. Used 1D flow model (OLGA®, SINDA/FLUINT) to compute the hydrostatic pressure, temperature, and fluid properties at the BOP. Also, the well modeling was used to assess the annular flow rate through the BOP as a function of area open to flow as the shear rams close.
2. FEA (LS-DYNA®) with a Johnson-Cook material model used to simulate the deformation and failure of the drill pipe as the rams are closed. Mechanical shearing forces were computed here.
3. Geometries from the FEA simulation were analyzed at discrete points in time (100%, 40%, 20%, 10%, and 5% of annulus flow area remaining).
4. CFD (ANSYS® Fluent®) used to compute the flow field around the ram and the hydrodynamic pressure on the ram faces and axial hydrodynamic force.



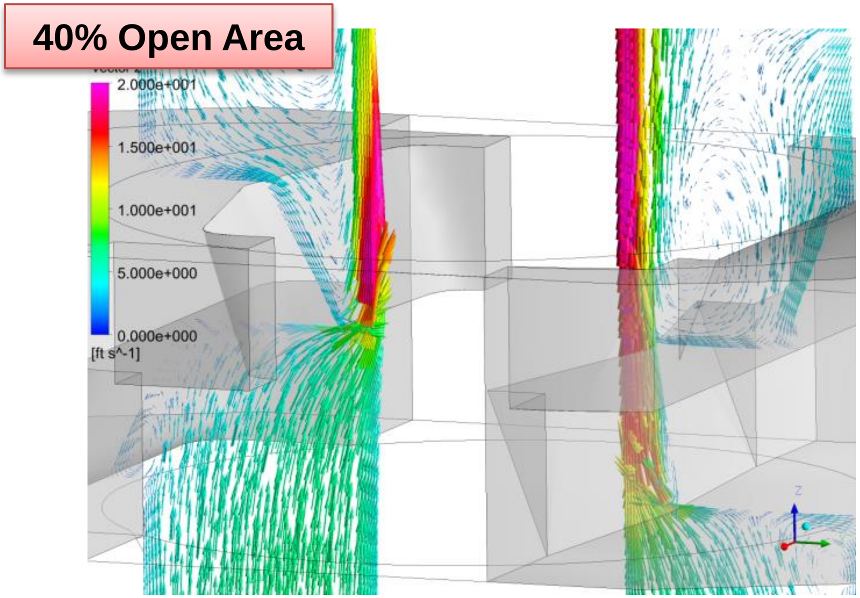
Baseline FEA Simulation

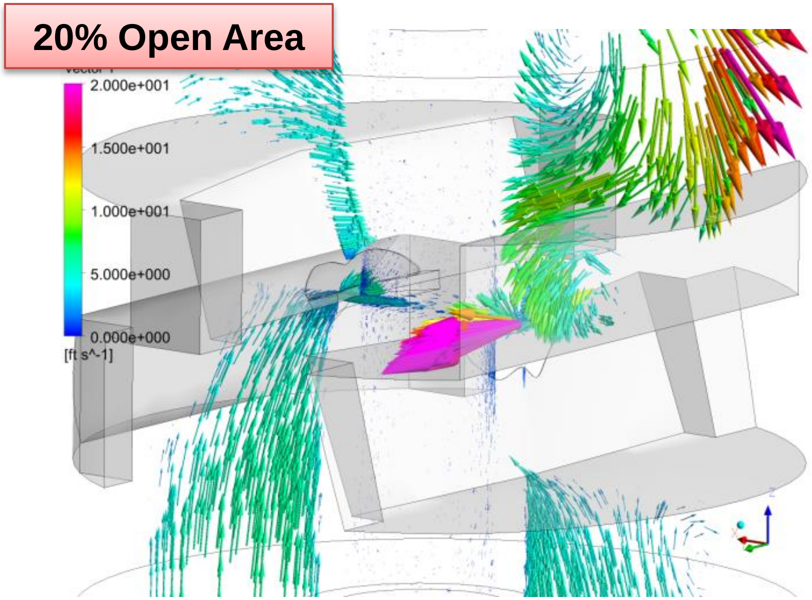


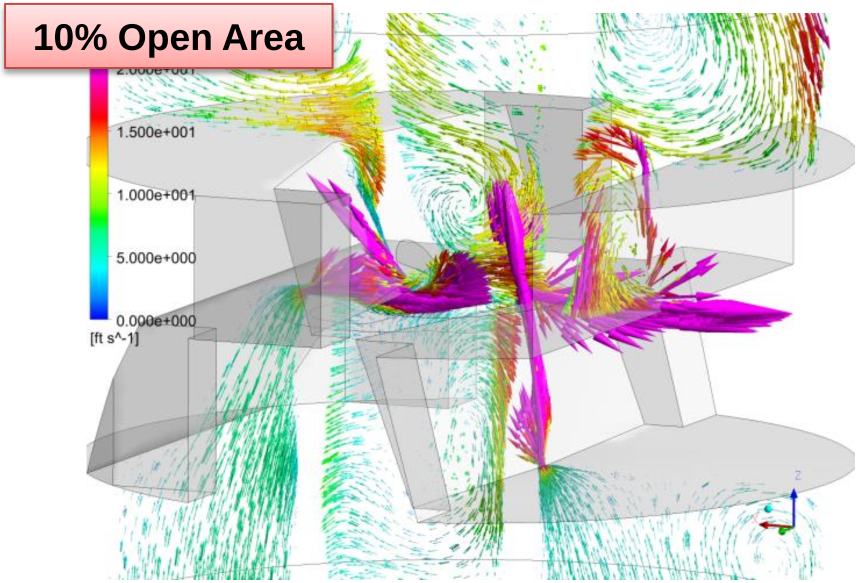


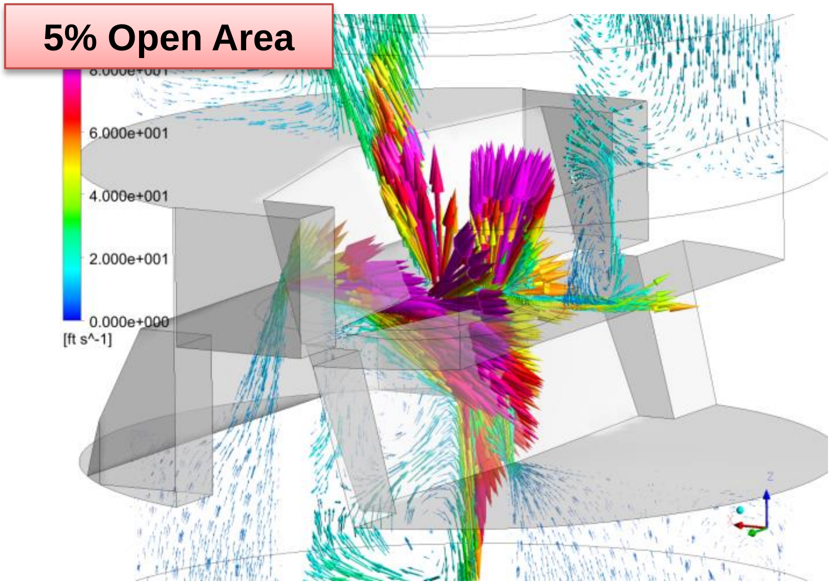
For the baseline case, the sharp edges of the blades results in a distinct "cutting" of the drill pipe.

Tier 2 CFD Simulations



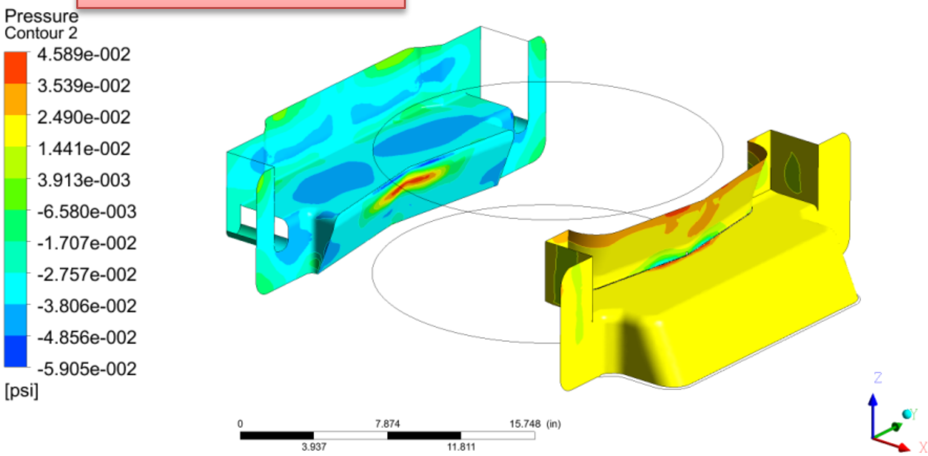




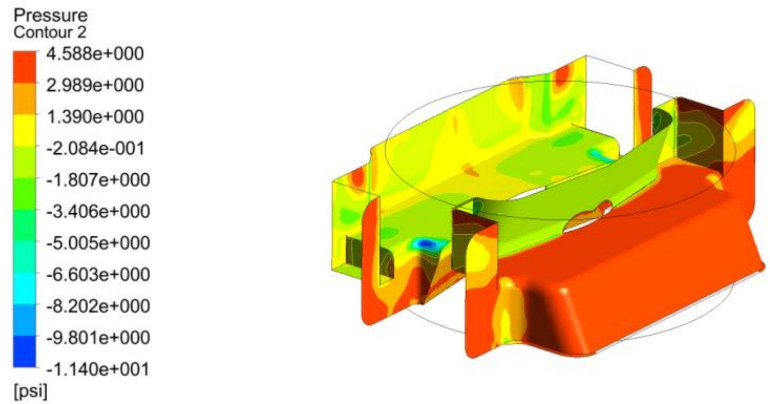


Tier 2 CFD Simulations

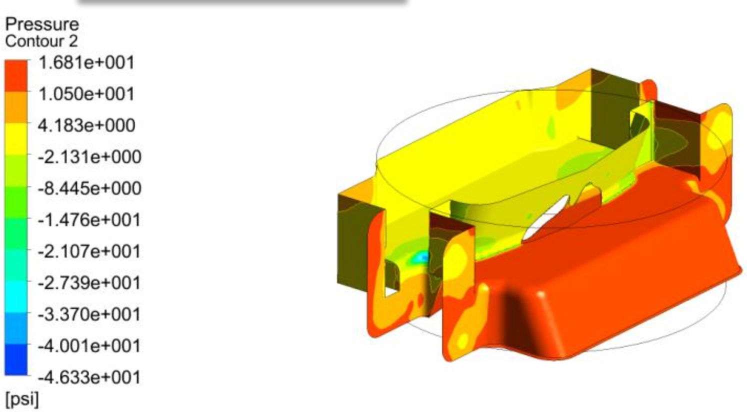
40% Open Area



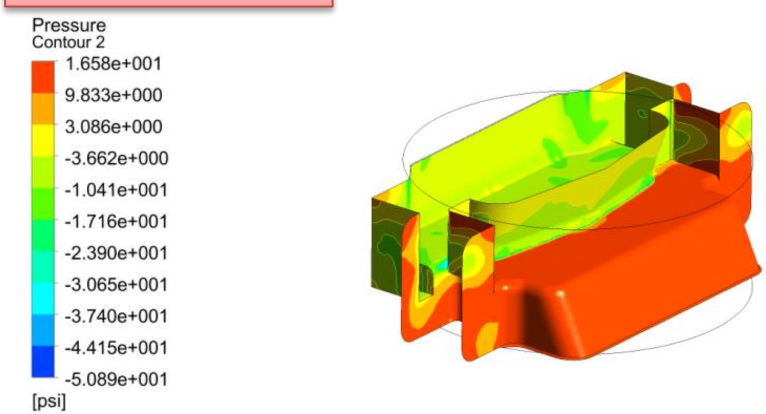
20% Open Area



10% Open Area



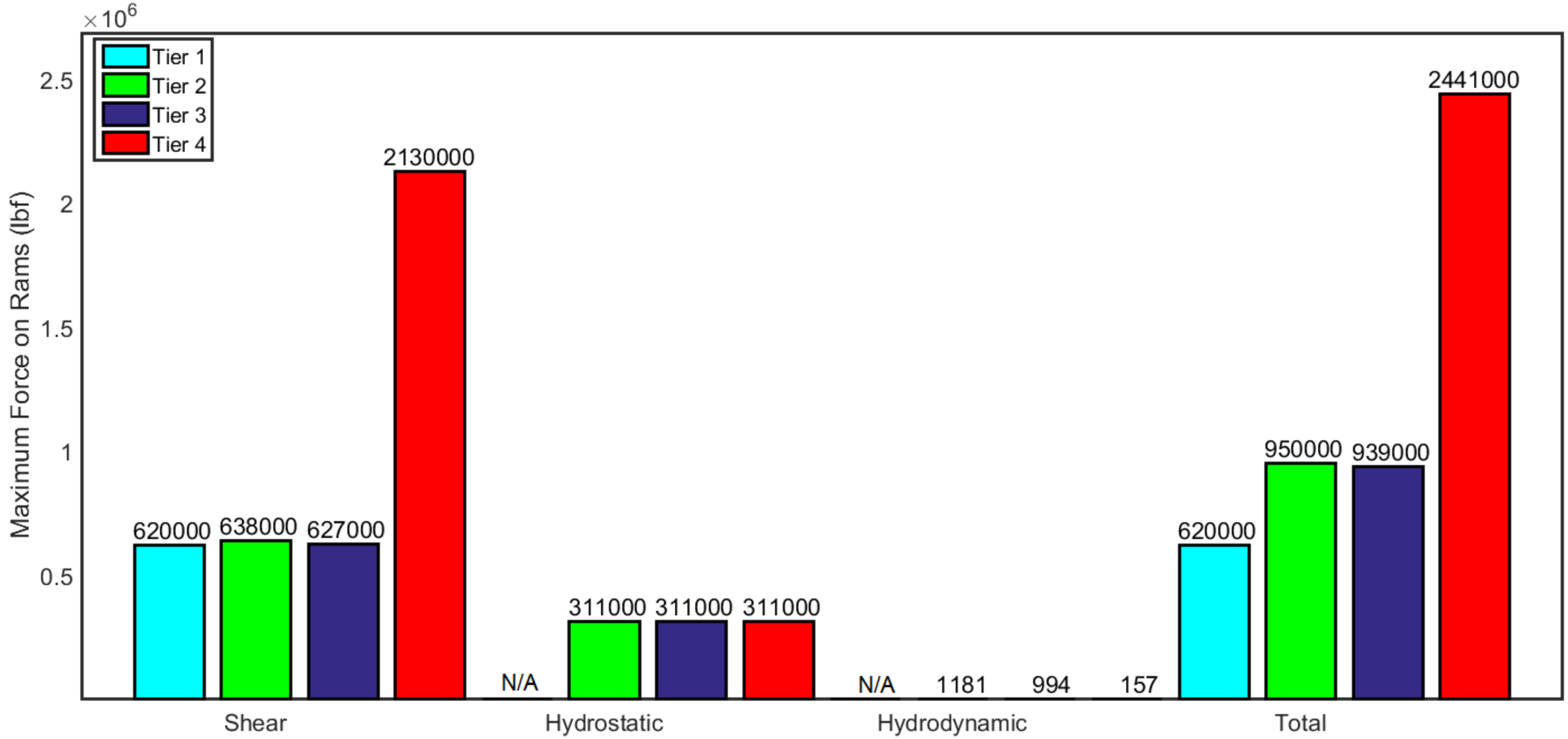
5% Open Area



Comparison of Simulation Tiers

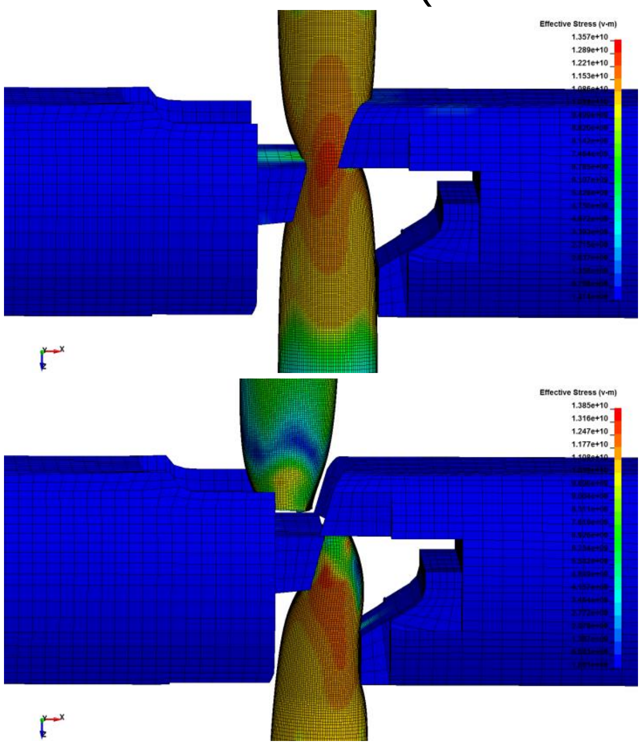
- Notes on Tier 1 and 4:
  - Tier 1 does not include hydrostatic or hydrodynamic forces
  - Tier 4 simulations are under-resolved and do not provide physically accurate results

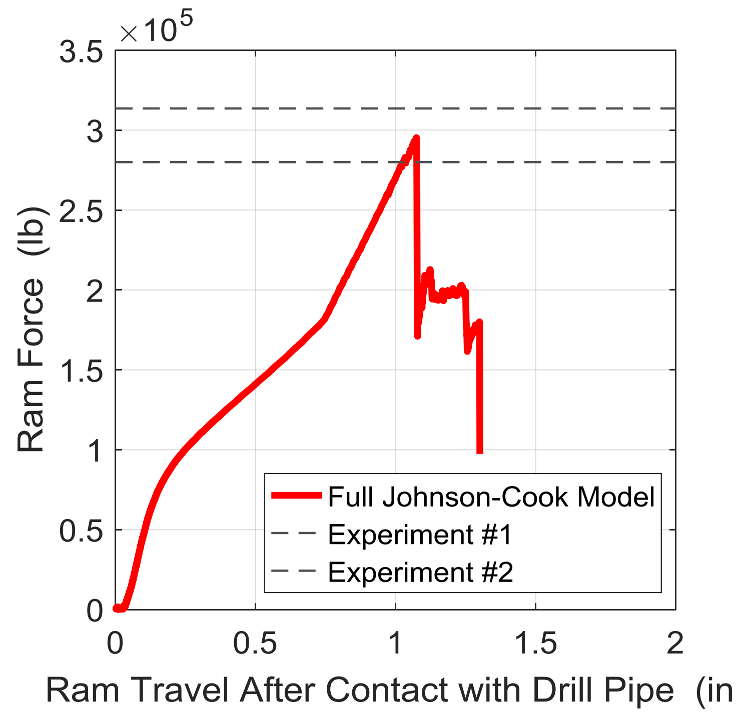
- ***Tier 2 simulations were selected for the parameter variation study in Task 3, because this method provides the same physical answer as Tier 3 at a fraction of the computational effort***



FEA Validation

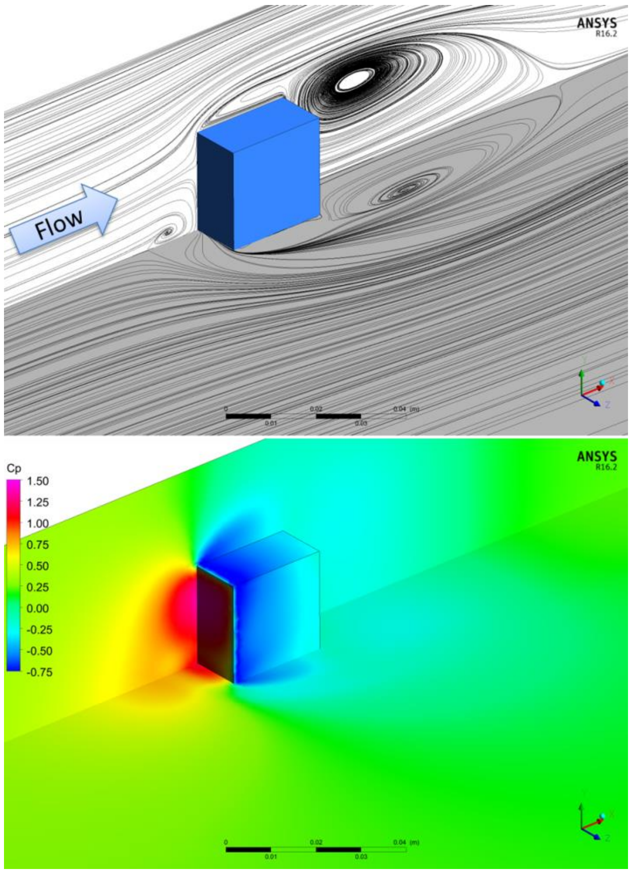
- Simulated experiments reported in “Final Report 01 – BOP Stack Sequencing and Shear Ram Design,” MCS Kenny, 2013
  - Good agreement with measured shear forces observed
  - Shearing of 3-1/2”, 13.3 lb/ft, S-135 drill pipe with 13 5/8” Cameron rams
  - Note that the simulation model and S-135 drill pipe material model were independently developed and not taken from the 2013 report
- Additional shearing simulations of 6 5/8”, 50 lb/ft, S-135 pipe have also been compared with OEM test data (not shown here)

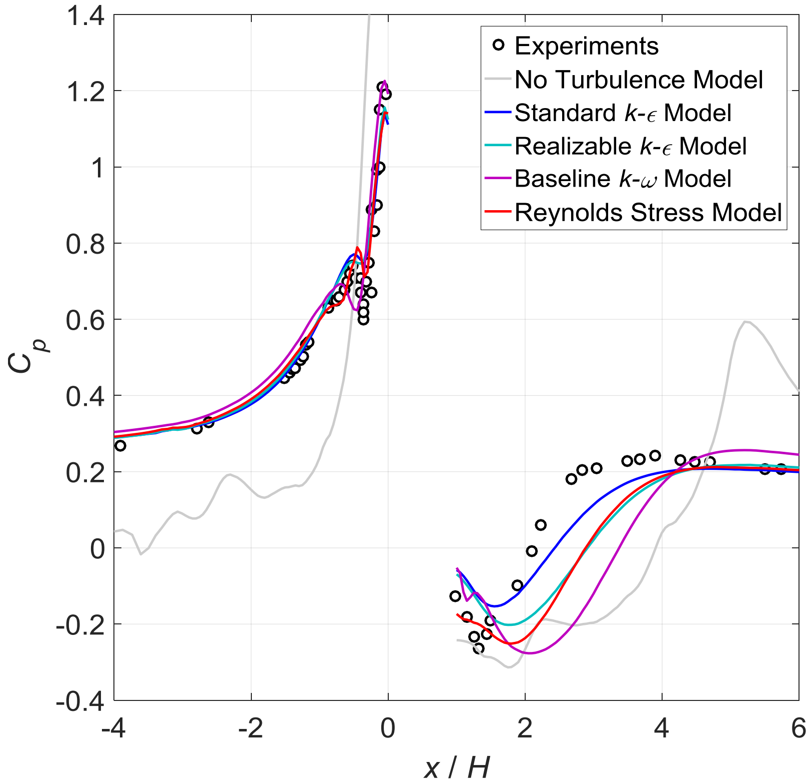




CFD Validation

- Overall, the hydrodynamic portion of the loads were determined to be small with respect to the mechanical and hydrostatic loads
- Validation CFD simulations of turbulent flow through and around a blockage shows that the CFD model implemented is capable of accurately determining the dynamic portion of the pressure load on the rams



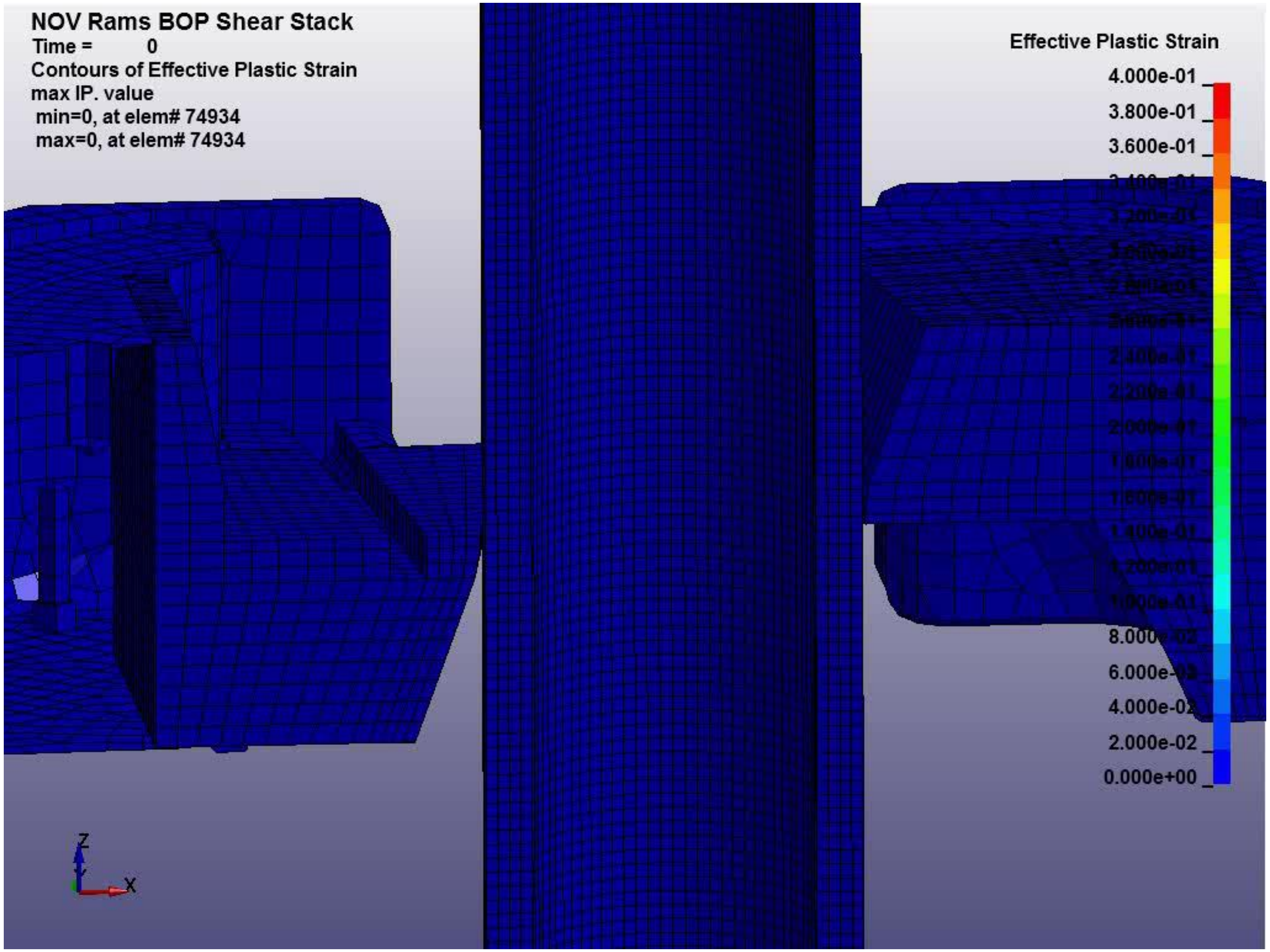


Martinuzzi, R., & Tropea, C. (1993, March). “The Flow around Surface-Mounted, Prismatic Obstacles Placed in a Fully Developed Channel Flow.” Transactions-American Society of Mechanical Engineers Journal of Fluids Engineering. Vol. 115. pp. 85–92.

Parameter Variation Study

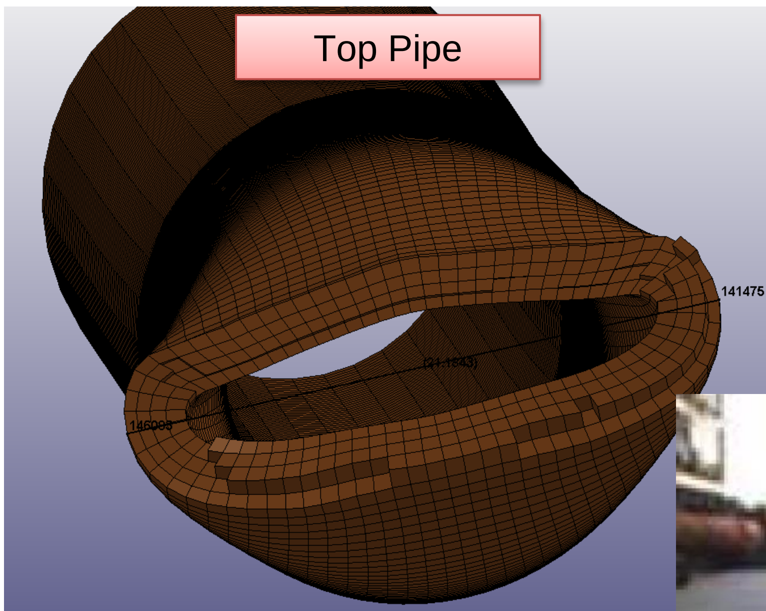
- Variations on the baseline case have been simulated to determine potential affects of hydrodynamic forces under different conditions
  - 3 different OEM ram geometries
  - 2 different ram closing speeds
  - 2 different annular flow rates
  - 3 different flowing pressures
  - 1 different fluid property
  - 2 different tubing geometries

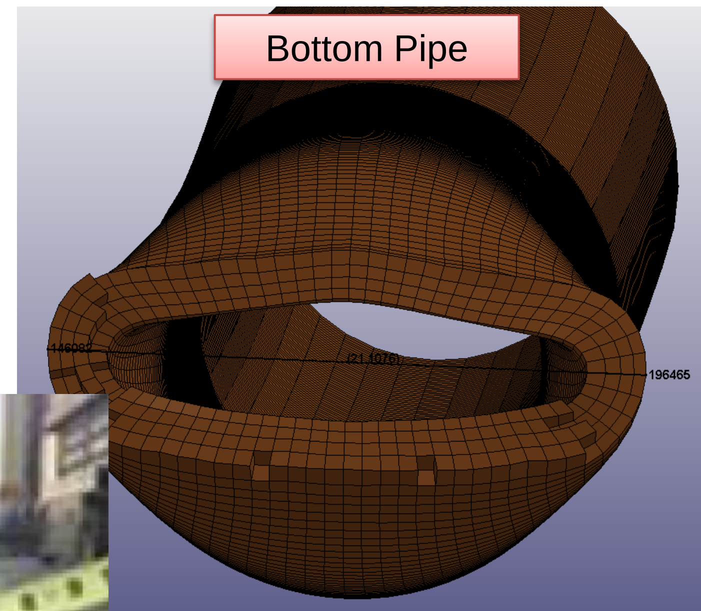
OEM #1

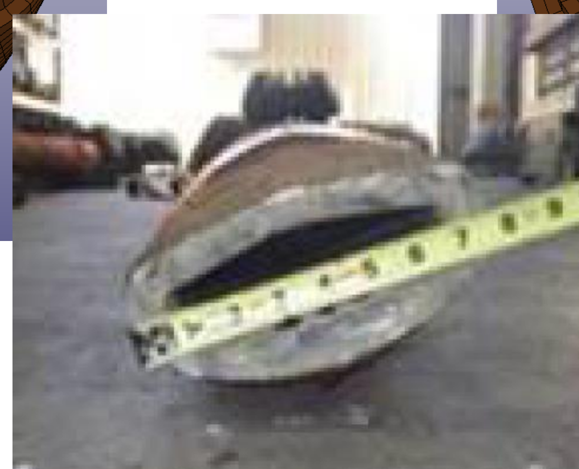

NOV Rams BOP Shear Stack
Time = 0
Contours of Effective Plastic Strain
max IP. value
min=0, at elem# 74934
max=0, at elem# 74934
Effective Plastic Strain
4.000e-01
3.800e-01
3.600e-01
2.000e-02
0.000e+00
Z
X

OEM #1 Comparison

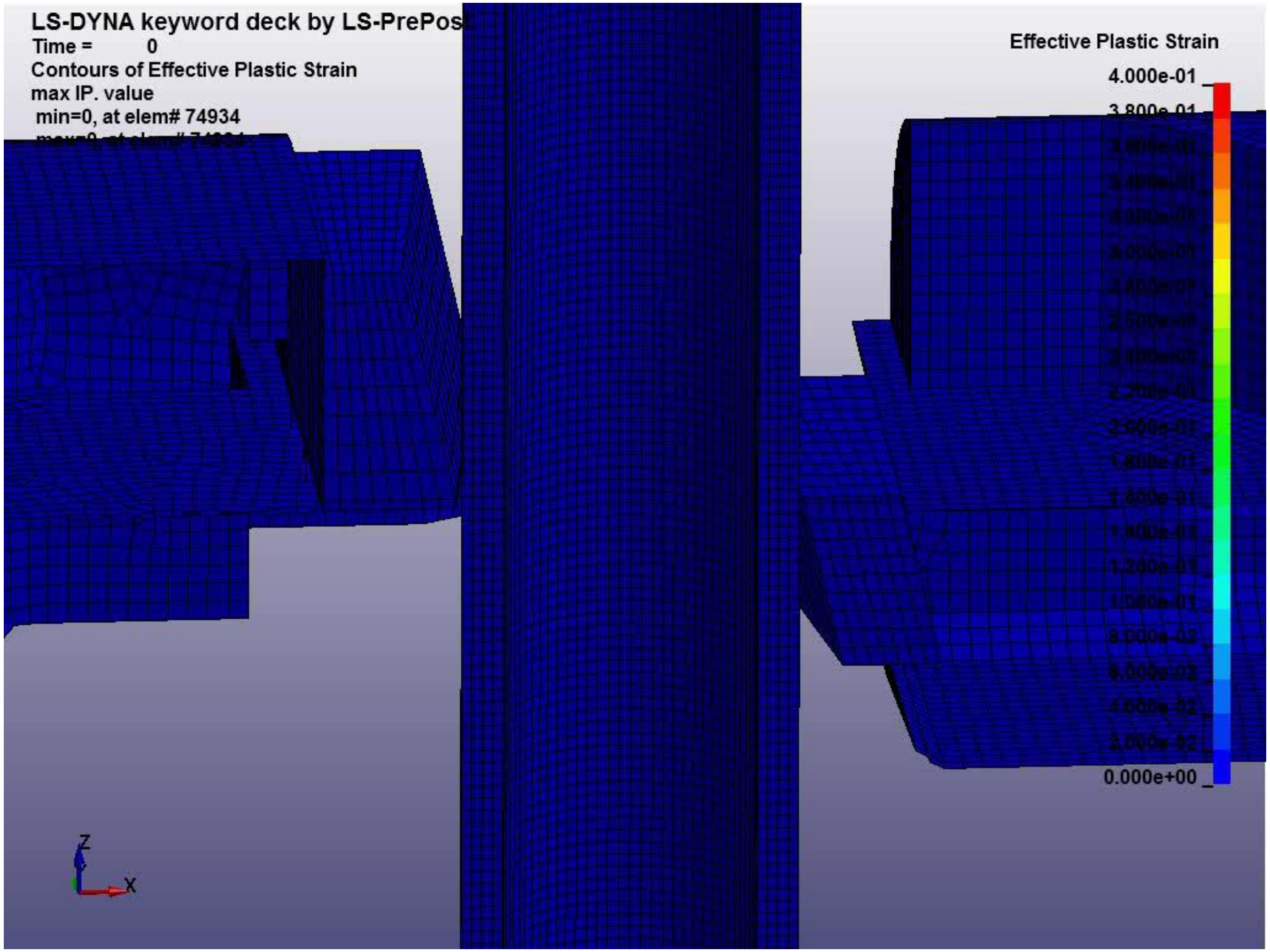
- Dimensions after pipe has failed:
  - Top pipe: 8.34” (wide) × 2.83” (narrow)
  - Bottom pipe: 8.31” (wide) × 2.85” (narrow)
- Overall shape and dimensions appears to agree with NOV test data
  - NOV test data appear to show ~ 8” dimension across (insufficient image resolution for more accurate measurement)







OEM #2



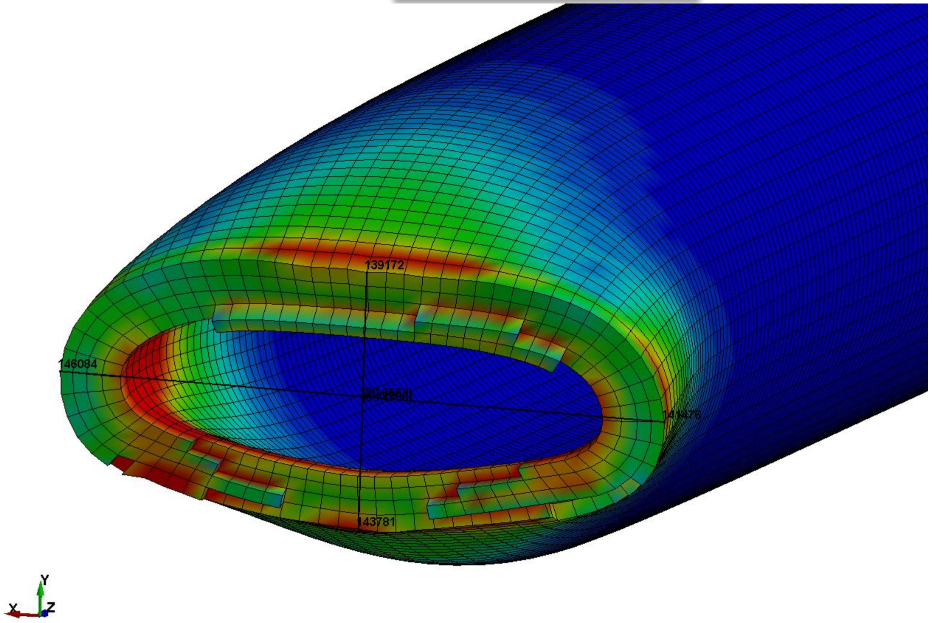
LS-DYNA keyword deck by LS-PrePos
Time = 0
Contours of Effective Plastic Strain
max IP. value
min=0, at elem# 74934
Effective Plastic Strain
4.000e-01
0.000e+00
Z
X

OEM #2 Comparison

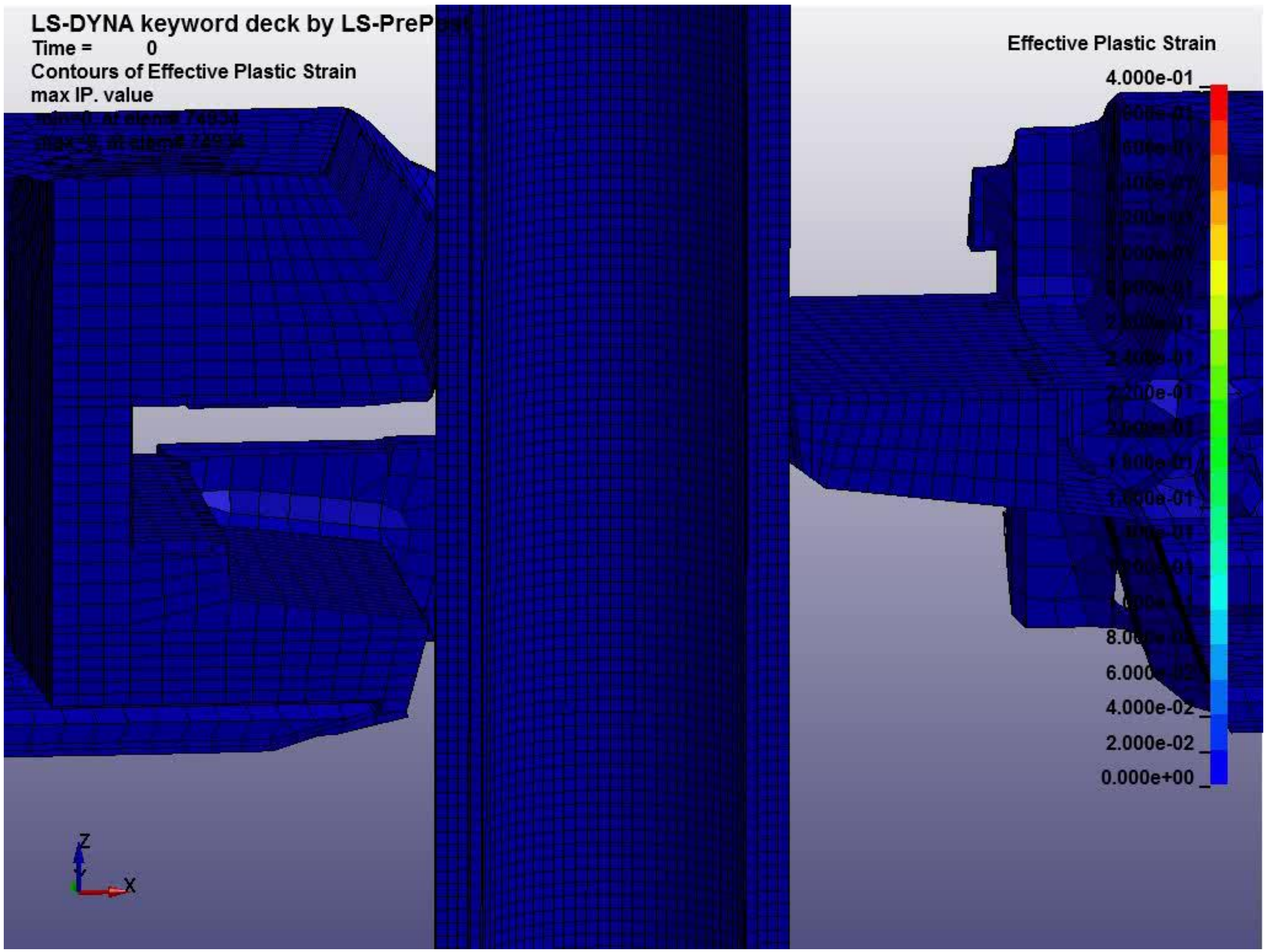
- Experimental results:
  - Top pipe width varies from ≈ 7.5”-8.0”
- Simulation results (immediately after pipe has failed):
  - Top pipe: 8.21” (wide) × 3.44” (narrow)
  - Bottom pipe: 8.34” (wide) × 3.17” (narrow)

Top Pipe

Top Pipe

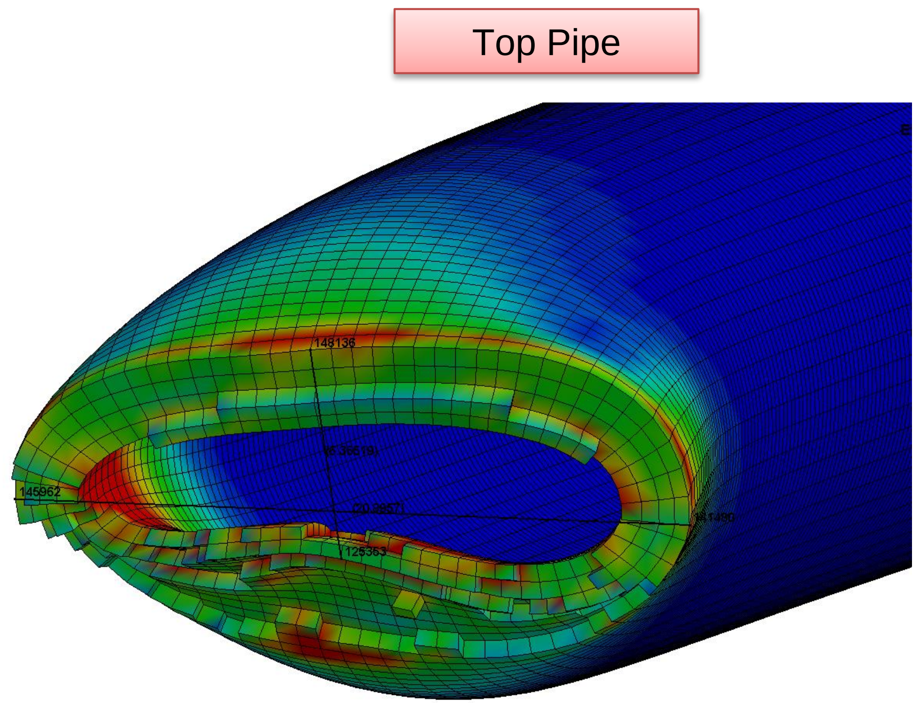


OEM #3

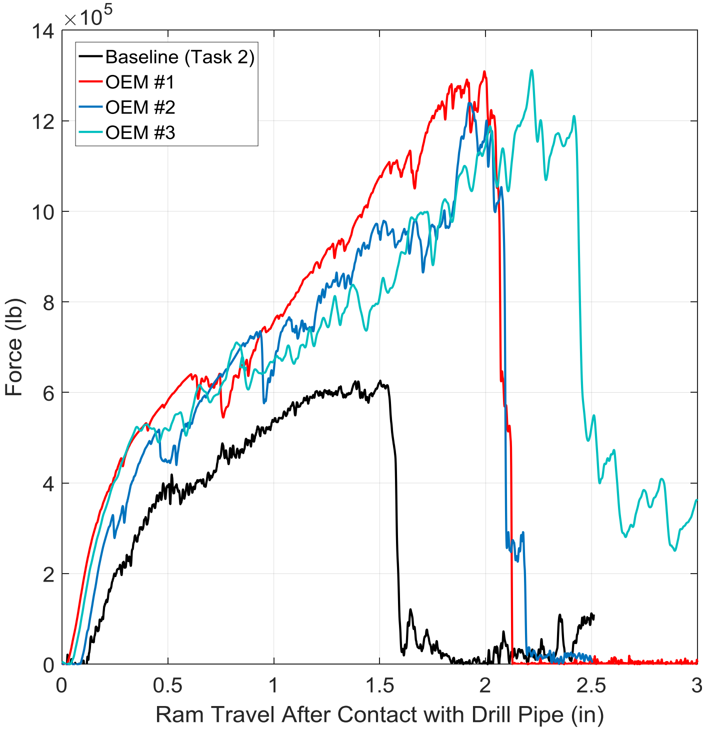

LS-DYNA keyword deck by LS-PreP
Time = 0
Contours of Effective Plastic Strain
max IP. value
Effective Plastic Strain
4.000e-01
4.000e-02
2.000e-02
0.000e+00
Z
X

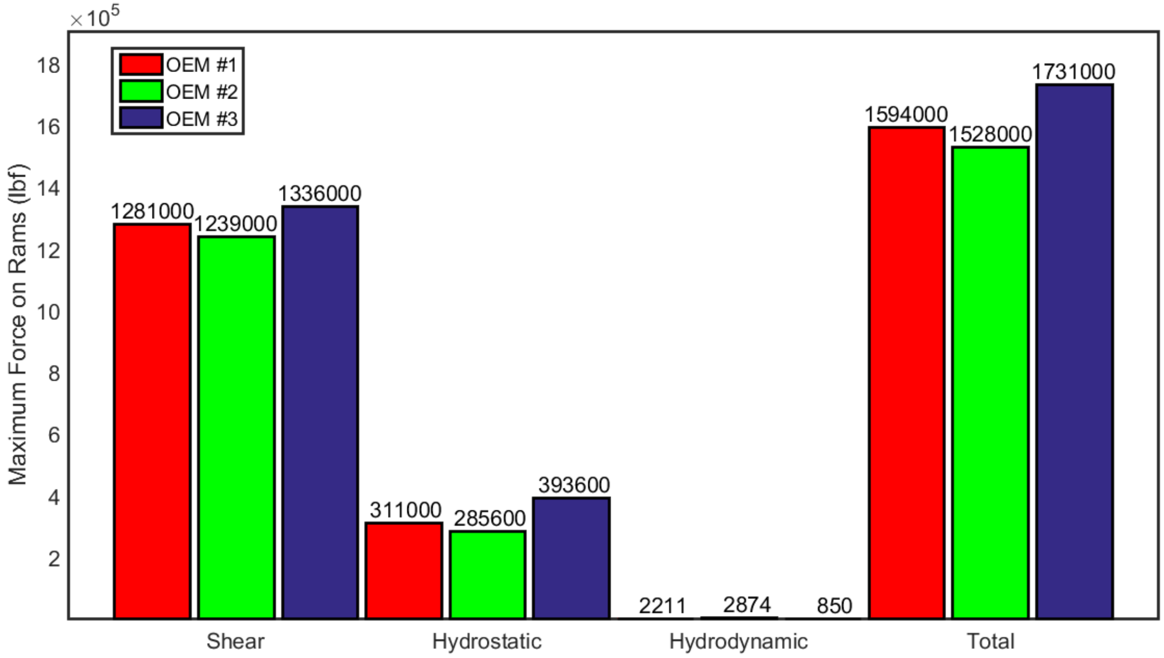
OEM #3 Comparison

- Experimental results:
  - Top pipe width varies from ≈ 8.75” × 3.75”
- Simulation results (immediately after pipe has failed):
  - Top pipe: 8.23” (wide) × 2.51” (narrow)
  - Bottom pipe: 8.15” (wide) × 2.70” (narrow)



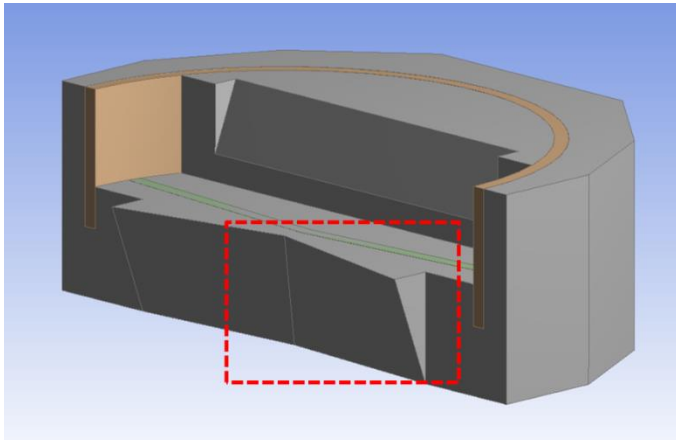
Variation in OEMs

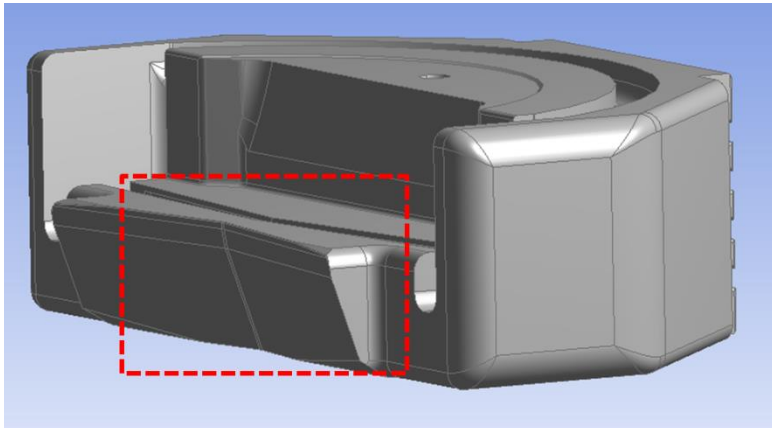


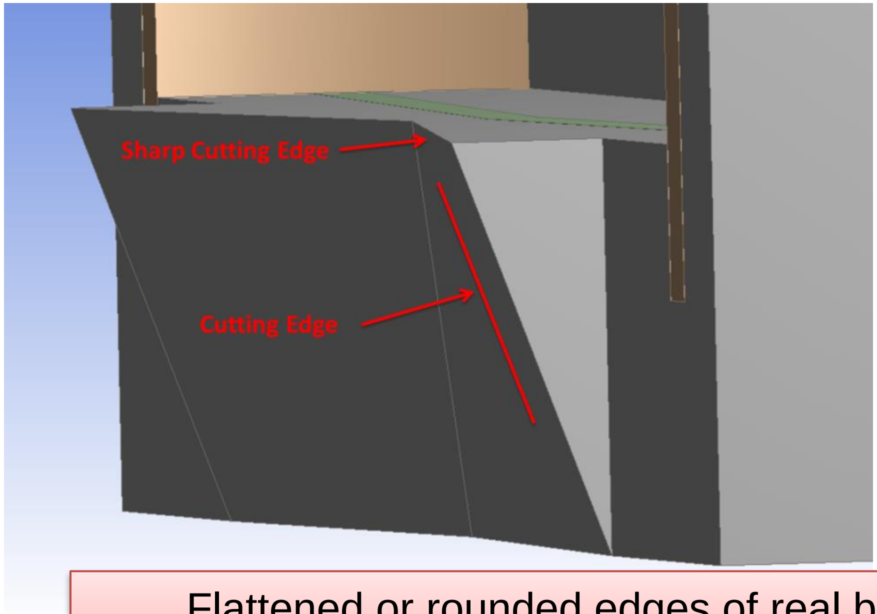


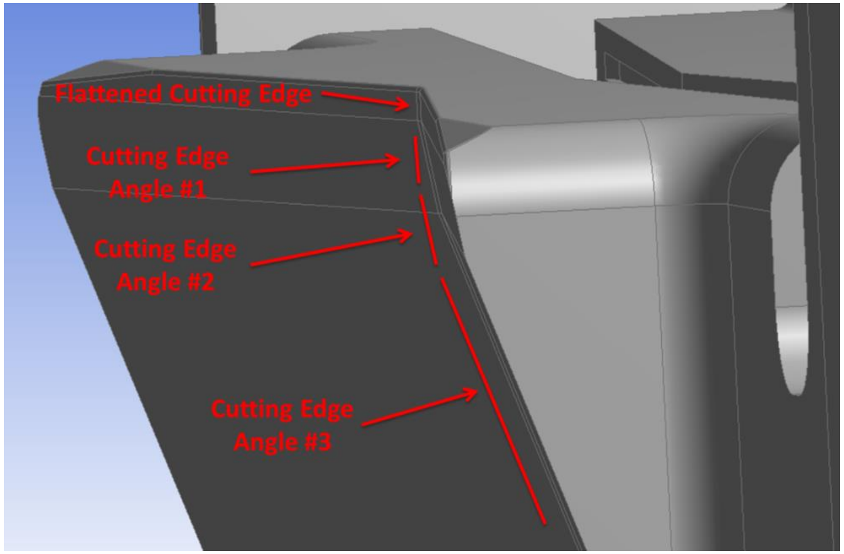
Simulation	Axial Hydrodynamic (lbf)
OEM #1	30,250
OEM #2	19,710
OEM #3	52,130

Baseline Geometry Comparison









Flattened or rounded edges of real blade geometries (exist in all OEM blade geometries) results in significant increase in mechanical shearing force requirements

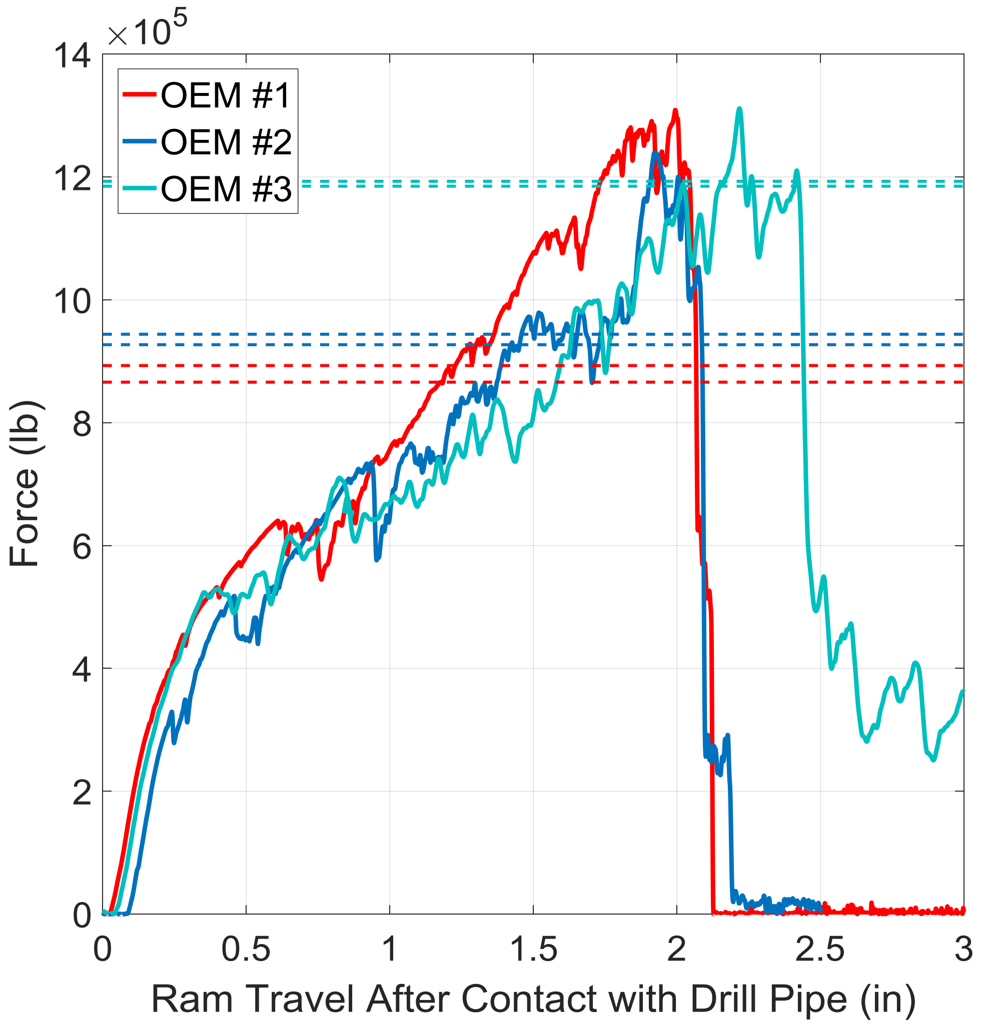
Additional FEA Validation – Mechanical Force

- Simulations agree reasonably well experimentally measured shear force values provided by the different OEMs

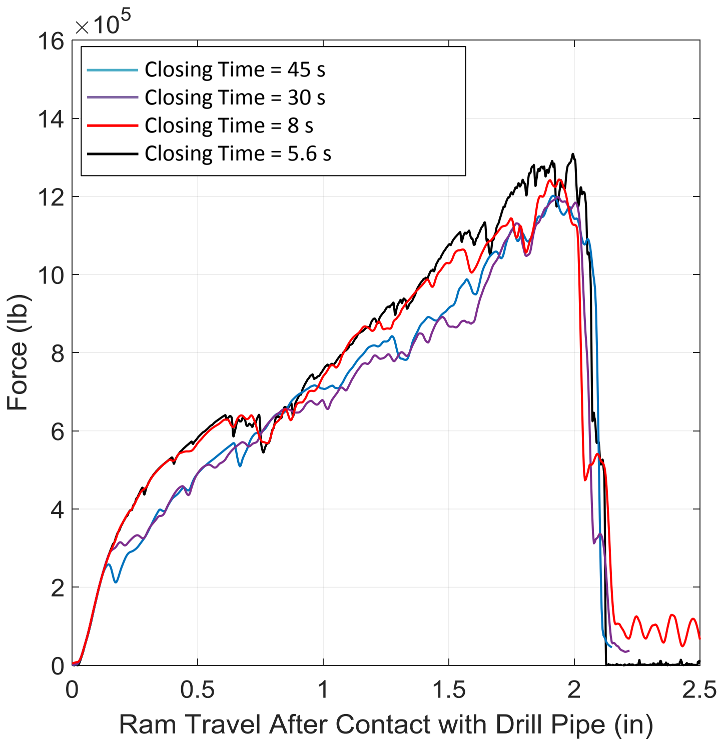
- The primary driver in the shear force uncertainty comes from the material properties of the pipe being sheared

- Simulation material properties
  - Yield Strength 149.4 ksi
  - Ultimate Strength 162.7 ksi
  - Elongation ≈ 13%

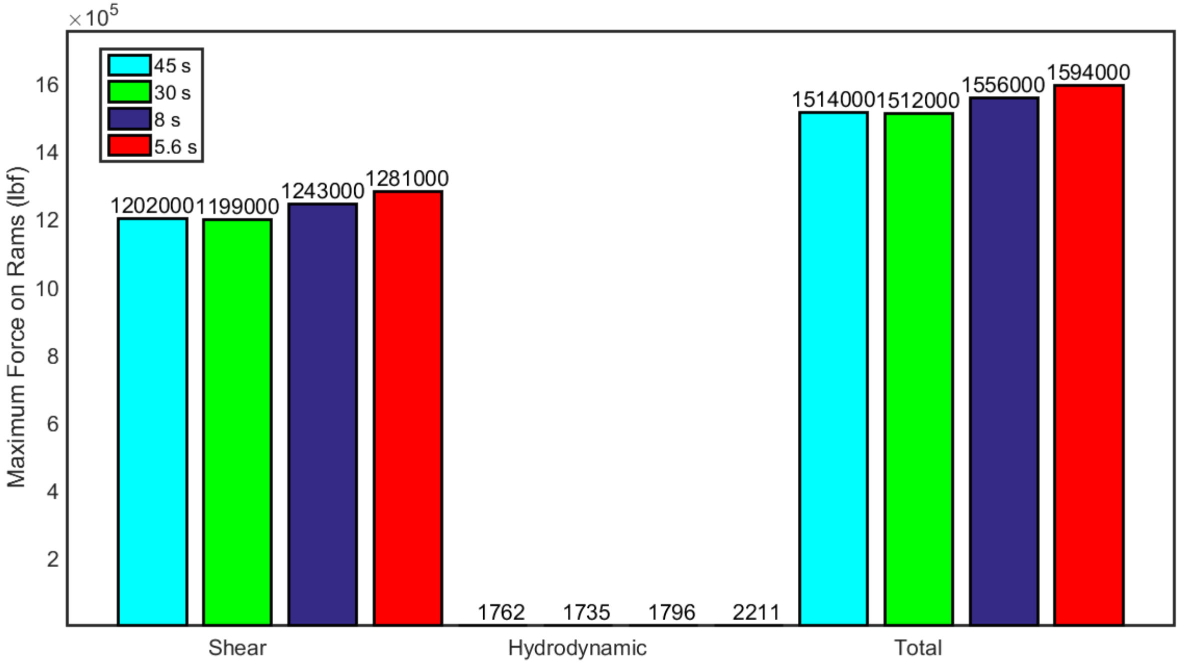
- Experiment results for pipes of various strengths:
  - Yield Strength 133 – 156 ksi
  - Ultimate Strength 148 – 169 ksi
  - Elongation ≈ 19 - 30%



Closing Speed Sensitivity



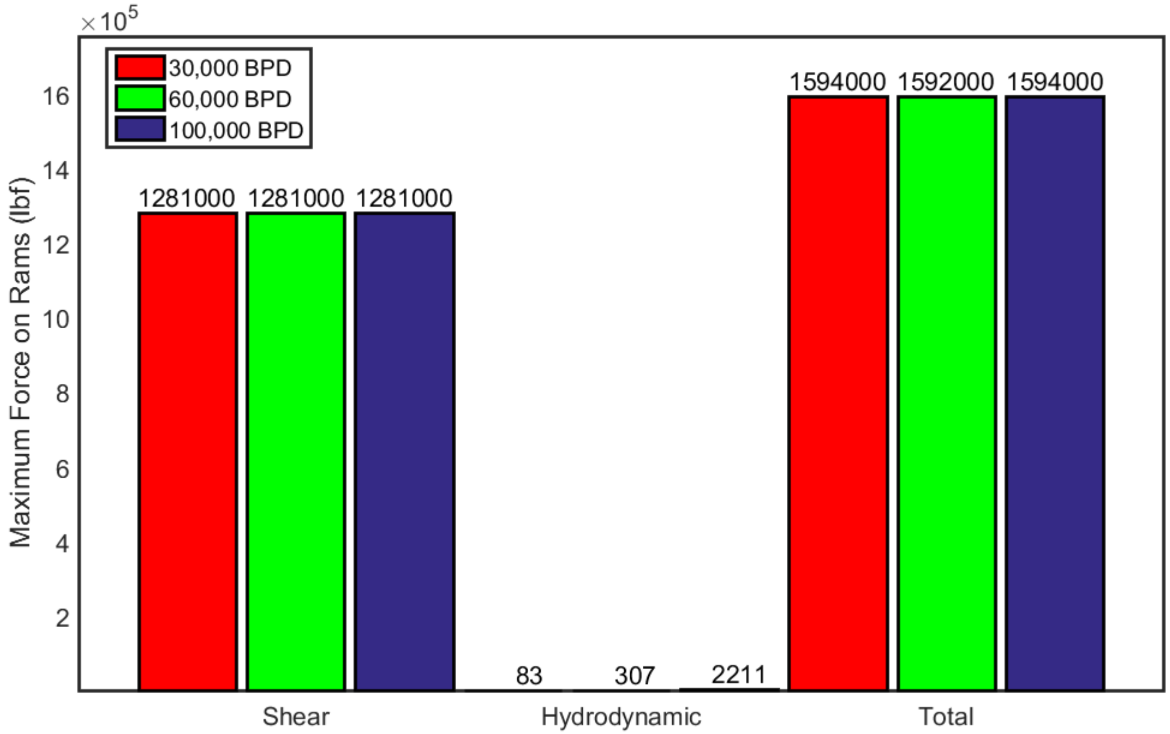
Hydrostatic Force= 311,000 lbf



Simulation	Axial Hydrodynamic (lbf)
45 sec	29,780
30 sec	29,645
8 sec	30,360
5.6 sec	30,290

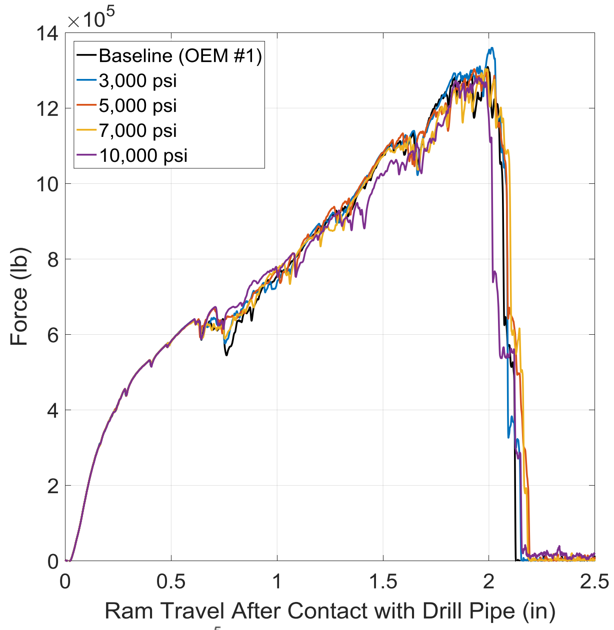
Flow Rate Sensitivity

Hydrostatic Force = 311,000 lbf

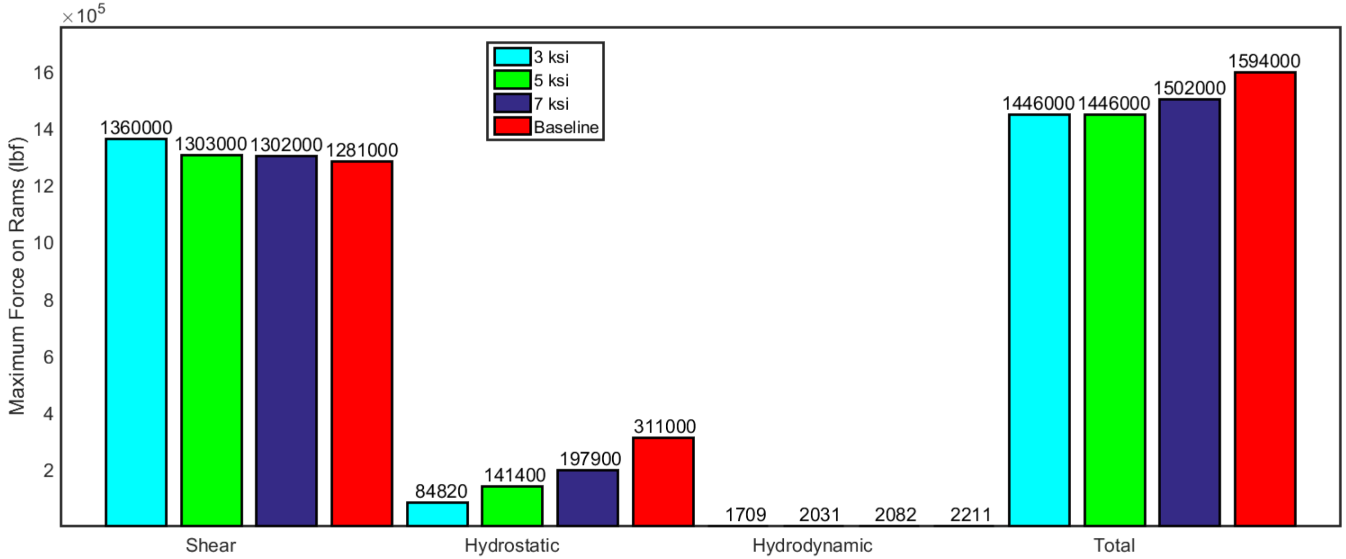


Simulation	Axial Hydrodynamic (lbf)
30,000 BPD	2,299
60,000 BPD	10,190
100,000 BPD	30,250

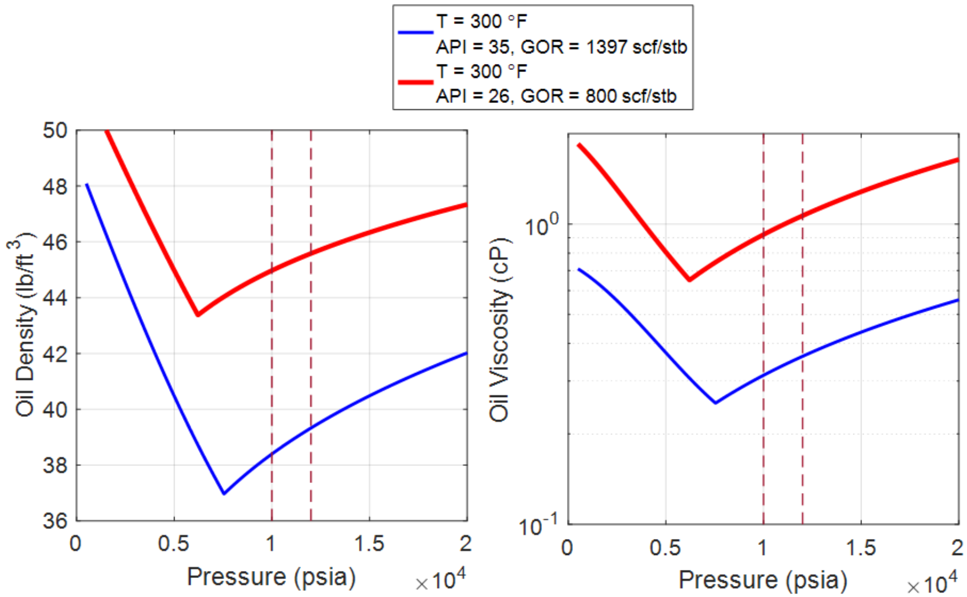
Pressure Sensitivity

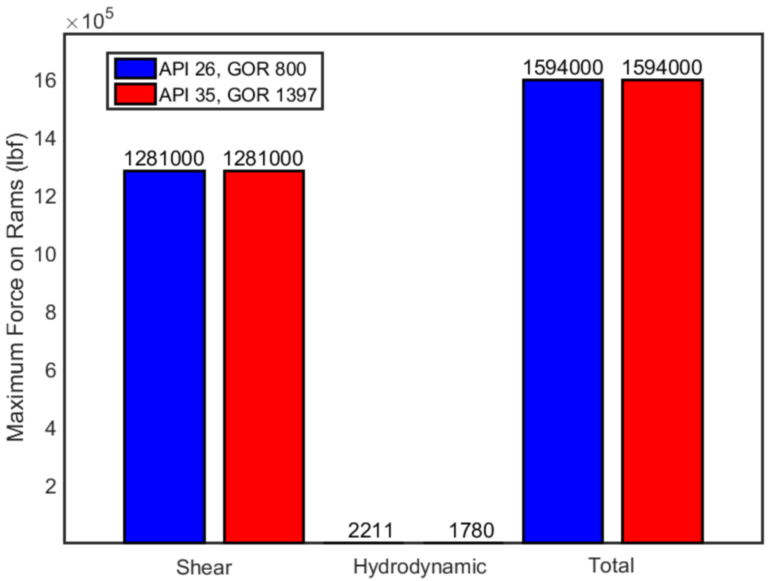


Flowing Pressure (ksi)	Density (in/ft³)	Viscosity (cP)	Axial Hydrodynamic (lbf)
3	43.68	0.516	29,000
5	40.47	0.373	29,650
7	37.66	0.273	31,470
11	38.88	0.344	30,250



Fluid Properties Sensitivity

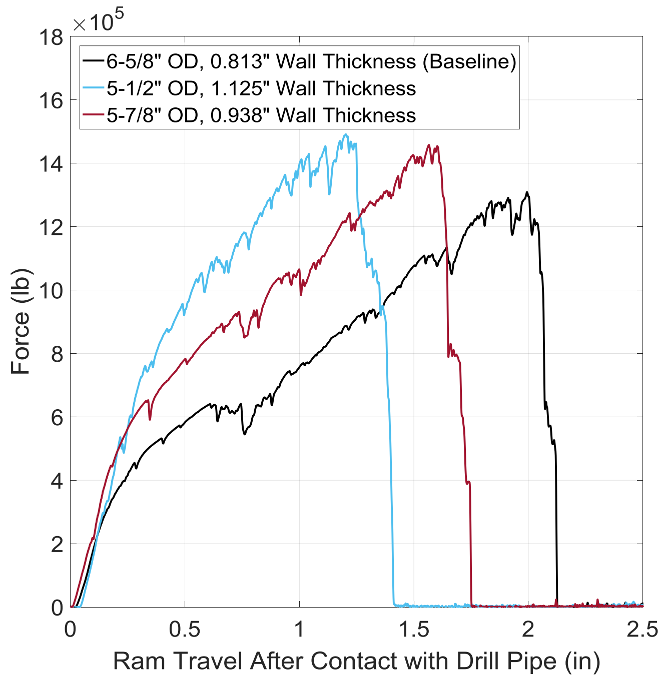




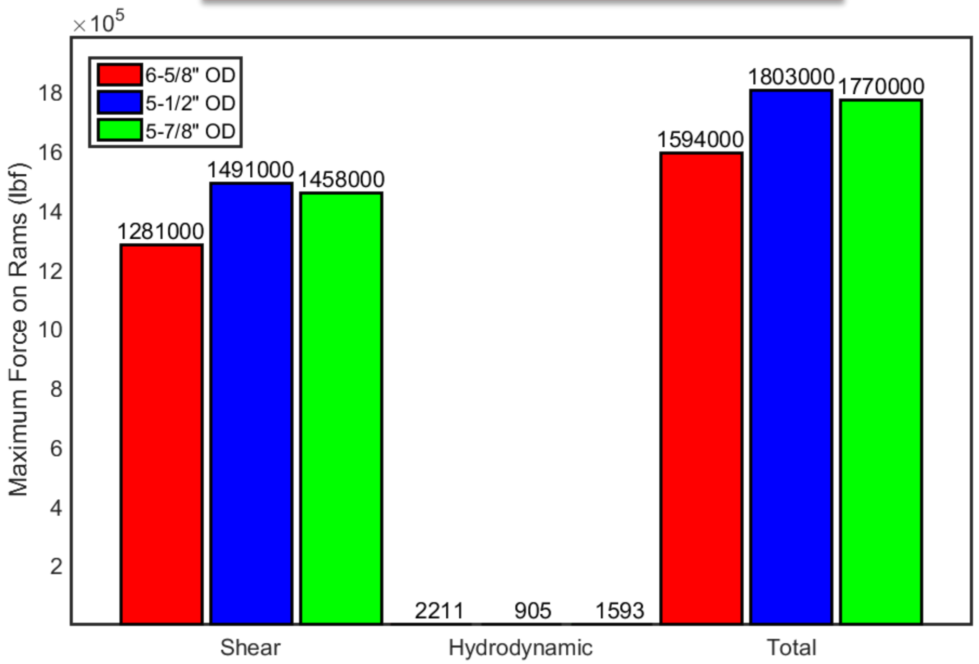
Hydrostatic Force = 311,000 lbf

Simulation	Axial Hydrodynamic (lbf)
API 26, GOR 800	25,290
API 35, GOR 1,397	30,250

Tube Geometry Sensitivity



Hydrostatic Force = 311,000 lbf



Simulation	Axial Hydrodynamic (lbf)
6 - 5/6” OD	30,250
5 - 1/2” OD	30,680
5 - 7/8” OD	37,800

Major Conclusions

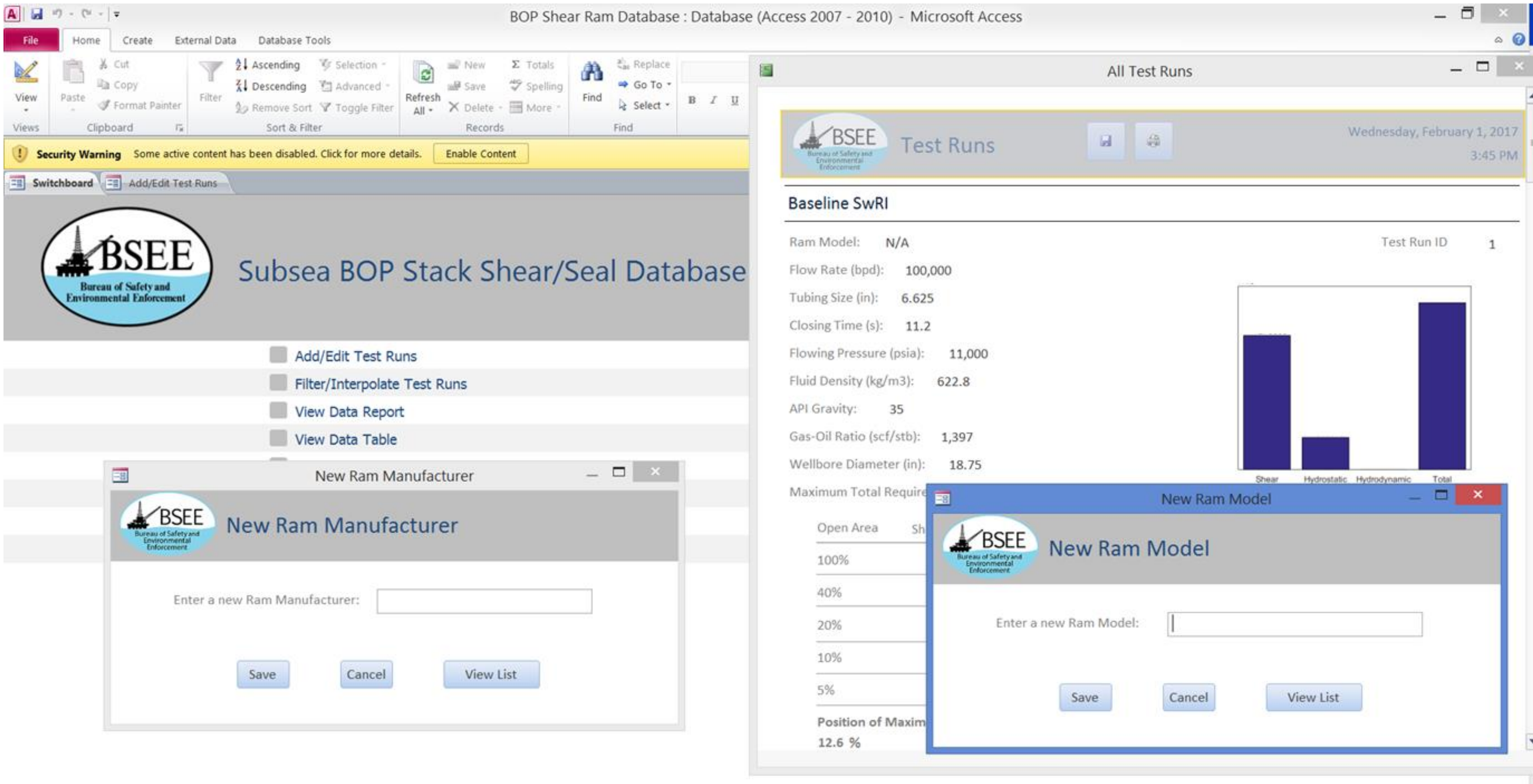
- Tier 2 Methodology (1-way FEA-CFD coupling) is appropriate for the combined structural and flow simulation of BOP shear ram closures.
- It is important to include realistic features of the ram parts that engage and shear the drill pipe.
- The mechanical force to shear the drill pipe is the dominant component of the forces acting on the rods.
- The hydrostatic and lateral hydrodynamic forces on the rod are small relative the drill pipe shear forces.
- The axial hydrodynamic forces are <5% of the total rod force, but the axial force impacts the seals and friction in the shear ram guides.

Caveat: The conclusions presented here are valid within the bounds of this study. Other flow scenarios (e.g., gas evolution) can lead to more severe fluid forces.

Parametric Study Conclusions

- OEM Geometry Sensitivity. There are differences in the details of the force profiles for the different OEM ram geometries. However, the computed maximum total rod forces for all three geometries are in close agreement.
- Simulated Closing Speed Sensitivity. A simulated closing speed that is faster than the actual speed reduces simulation turnaround time. There were small differences in the total rod forces for different speeds.
- Flow Rate Sensitivity. There was negligible effect of the flow rate on the total rod force for the flow range studied here. The axial force from the flow-wise pressure drop was significantly more sensitive to flow rate.
- Flowing Pressure Sensitivity. The flowing pressure directly affects the hydrostatic pressure. However, the hydrostatic pressure remains small (~6%-20%) compared to the mechanical shear force
- Fluid Sensitivity. This study considered only a single different type of oil than the baseline. The effects of this change were small. Other changes in fluids and flow regimes will likely be more dramatic; e.g., drilling mud with solids, slugging or churn flow resulting from gas evolution.
- Drill Pipe Sensitivity. This study considered two smaller sizes but thicker drill pipe compared to the baseline. The maximum total rod force increases with thickness, but more study is needed to make a broader conclusion.

Database Tool & Training



Live Demo/Training for Database Tool

Input & Feedback for BSEE Benefit

- Pipe material issues:
  - Material characterization of pipe
- Multiphase issues:
  - Erosion issues / solid particulates
  - Multiphase bubbly or slugging flows
- Pipe geometry issues:
  - Axial and radial stress states
  - Location of the pipe (e.g., non-centered)
  - Tool joints
- BOP Design issues:
  - Newer ram designs
- Potentially more realistic scenarios:
  - BOP sequencing, realistic closure scenario
  - Mud vs crude oil fluid properties
  - Vertical load force affecting closure
- Is a JIP appropriate for better leveraging research funds?

Immediate Phase 2 Potential

- Populate database with necessary values to provide BSRSD database with simulations necessary to allow for interpolation of most permit application requests
  - Additional pipes sizes, strengths
  - Addition BOP sizes
  - Pipe stress states
  - Pipe locations
  - Axial loads on BOP rams
  - Mud properties
- Fringe scenarios that have a significant effect on closing force requirements
  - Tool joints
- New technology
  - New ram designs
  - Realistic BOP sequencing
- Pipe material issues:
  - Material characterization of pipe
- Multiphase issues:
  - Erosion issues / solid particulates
  - Multiphase bubbly or slugging flows

Bigger Challenges

- Characterization of Drill Pipe Materials:
  - Newer proprietary pipe grades
  - Increased ductility
  - Variation in material properties
  - BOPs are having to address these challenges both in terms of new ram designs and new hydraulic systems
  - Yet, a complete understanding of the material failure process is not well documented
  - Better predictive characterization of the range of drill pipe materials (within S-135 and beyond) will provide the science required to fully understand what must be sheared, how it will fail, and how to define what requirements should be in place to ensure robust, reliable, optimized BOP performance

Bigger Challenges

- Multiphase issues (liquid/solid):
  - Shearing aspect: To what degree does drilling debris or produced fines affect the cutting edges of the rams?
  - Sealing aspect: Can metallic components or the elastomer seals be eroded to the point where the blind shear rams do not provide a seal?
  - How do flow rate, particle loading, erosive parameters, affect either of these critical shearing and sealing required functions?
  - Multiple OEMs have brought this issue up. JIP opportunity?
- Multiphase issues (liquid/gas):
  - Initial work has focused on single-phase crude oil effect
  - Depending on the depth of the well, fluid properties, and details of the kick event (i.e., under-balanced gas reservoir encountered), slugging may be an issue
  - If the gas-phase slug is passing through the BOP at the time of the closure, it may become sonically choked as the liquid train behind it pressurized the gas that is not flowing fast enough to escape
  - In this scenario, the effective net hydrostatic pressure on the rams could experiences a very significant increase
  - To what degree can different bubbly or slugging flows develop in a kick event and what is their affect on the closure force requirements of the BOP?