Jet Propulsion Laboratory
California Institute of Technology

M2020 Percussion Drill

Validations and Predictions of Explicit Dynamics Simulations

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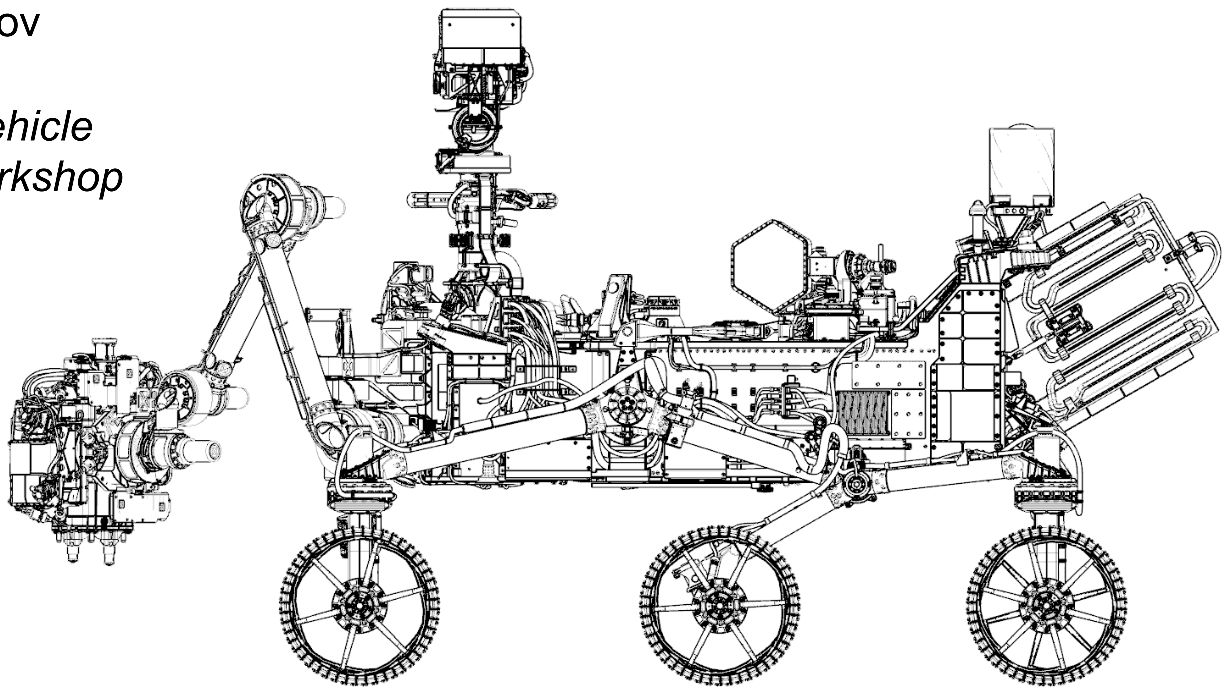
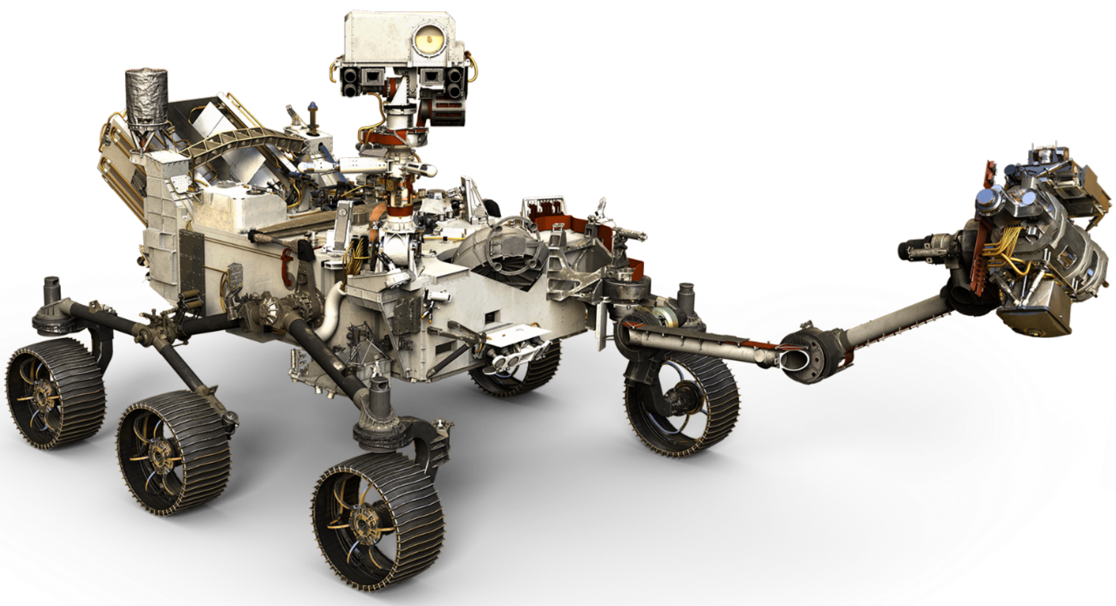
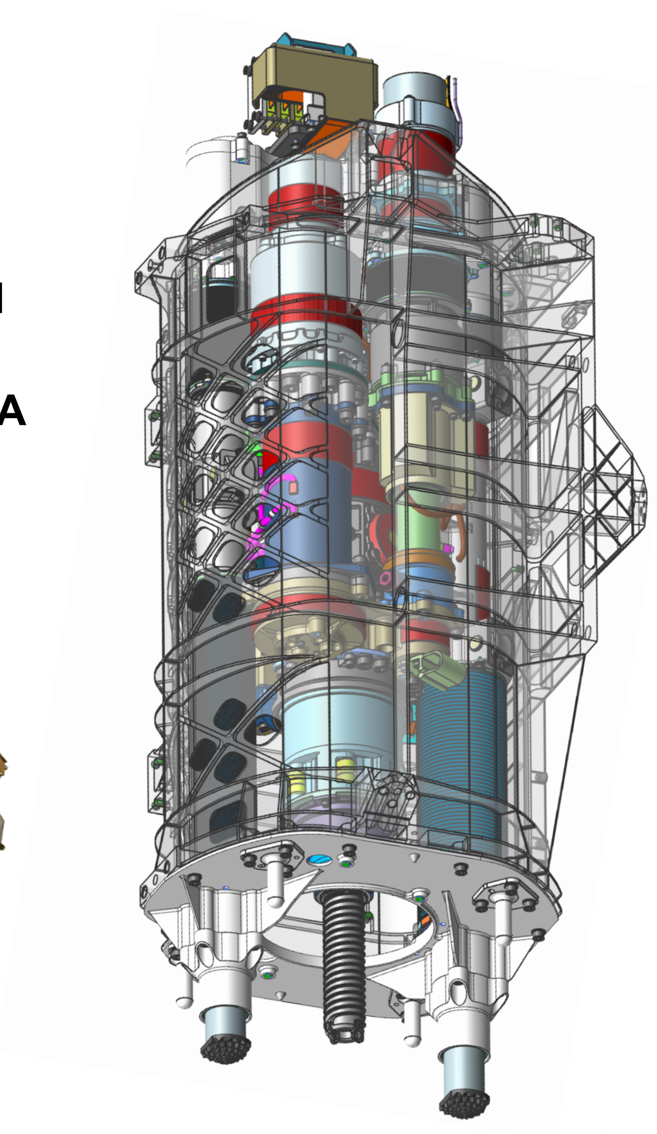


MARS 2020 PROJECT

M2020 Percussion Drill

- A key goal of the Mars 2020 mission is to collect rock and regolith samples from the Martian surface and store them in hermetically sealed sample tubes
- The percussion drill at the end of the rover arm is a critical subsystem of the Sample Caching System (SCS)
- Explicit Dynamics analysis using LS-DYNA has been used throughout the drill's design and certification
- **This presentation will give an overview of the LS-DYNA drill model validation process and highlight the predictive capabilities of the validated models**



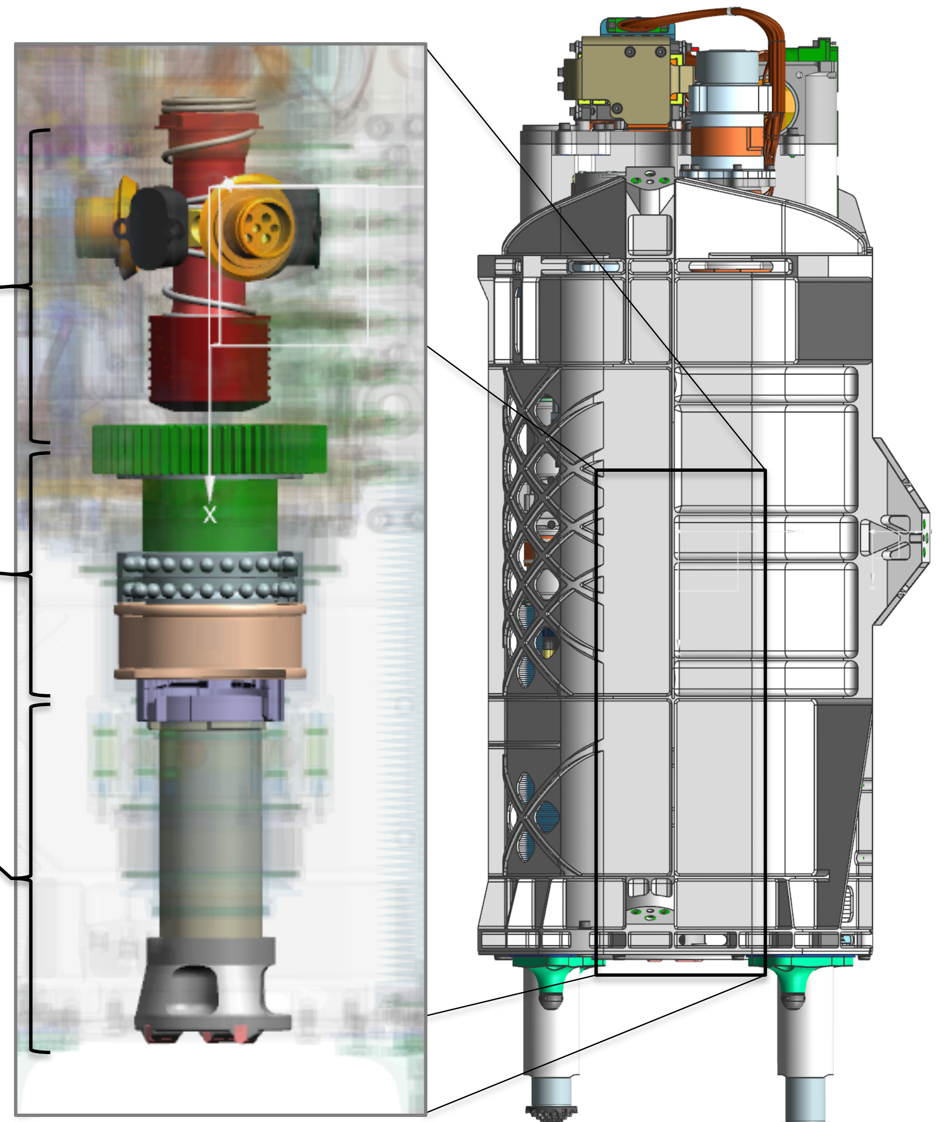


Drill Parts To Be Assessed

- Flight hardware closeout list

PART #	PART NAME
10465904-1	HAMMER
10465905-1	HAMMER SHAFT
10465907-1	NUT, HAMMER SHAFT BUSHING
10465908-1	SPRING, LOWER
10465909-1	SPRING, UPPER
10465912-1	DRIVER PLATE
10465914-1	BALL, DRIVER CRANK
?	DRIVER CRANK
10465754-1	ANVIL, CORER
10465755-1	HARDSTOP PLUNGER, ANVIL
10465511-1	CORING BIT
10465512-1	BIT EXCHANGE TANG
10465520-1_04	ANALYSIS: WELD JOINT
10465521-1	REGOLITH BIT
10465531-1	SHANK, ABRADING BIT
10465531-2	SHANK, ABRADING BIT, LAUNCH
10465532-1	HEAD, ABRADING BIT, LONG
10465532-2	HEAD, ABRADING BIT, SHORT

- Some adjacent hardware (spindle, bearings, etc.) also need input from impact analysis



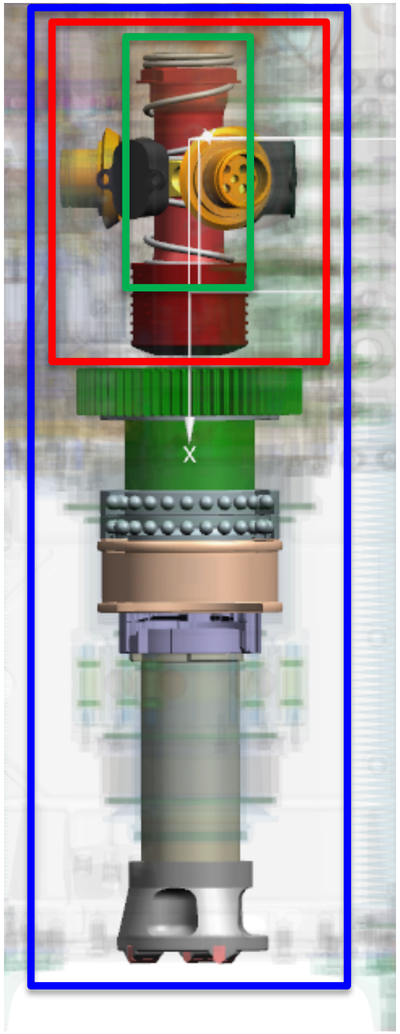
Flight drill CAD model in abrading bit config

Testing Needed for Drill Model Validation

- **Spring testing**
  - **Goal: Validate spring models against load/displacement test data**
  - If discrepancies found, adjust spring material modulus (within reason)
  - Model compression of each spring separately

- **Percussion unit testing**
  - **Goal: Validate percussion unit modeling against testbed data**
  - Load cell and hammer position test data used for model correlation
  - Aim to match mean value within 10%
  - Require drive plate, cranks, and bearings modeled in detail, plus 3D spring models
  - Different (simpler) boundary conditions than full drill model

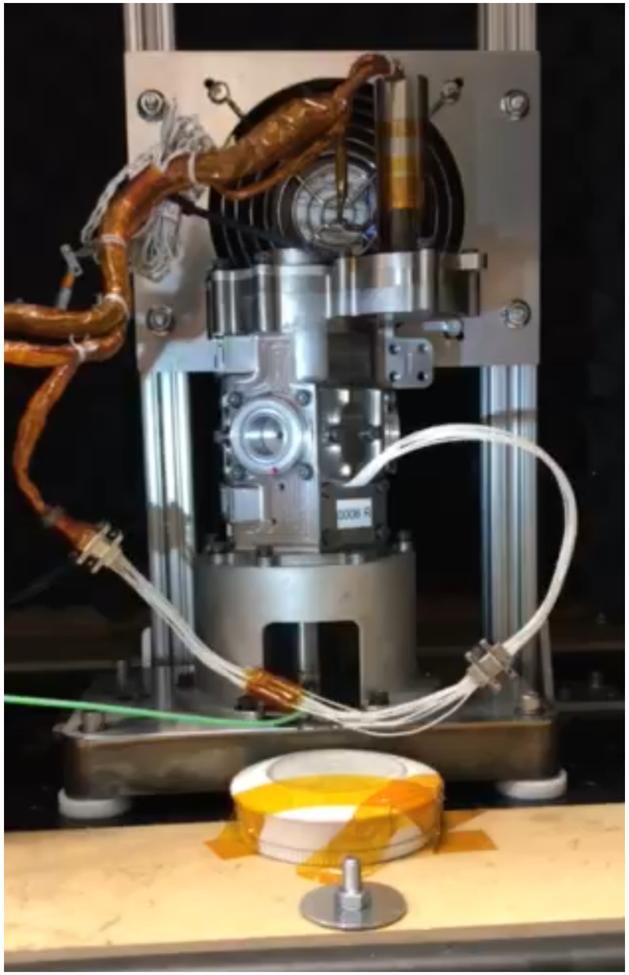
- **Drill modeling**
  - **Goal: Validate drill modeling approach using drill test data**
  - **Use a dummy bit instead of a real bit**
    - Simplified bit with better load cell interface; easier to model
    - Difficult to get good test data on load cell using real bits
  - Load cell and hammer position test data used for model correlation
  - Aim to match mean value within 10%
  - Key challenge: representative boundary conditions at interface to the rest of the drill



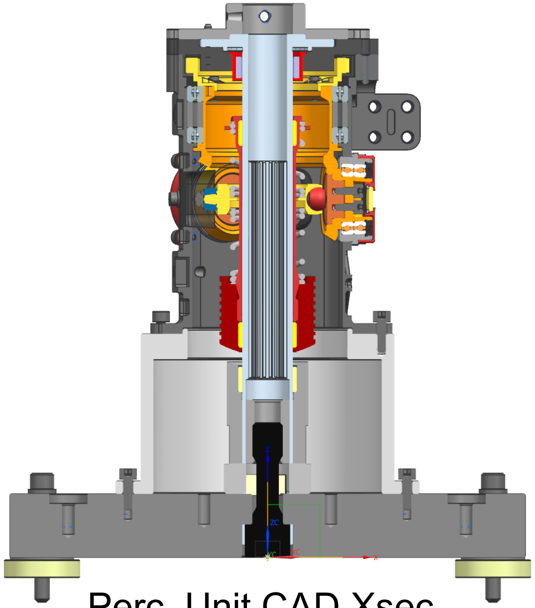
Spring and Percussion Unit Testing

Spring Stiffness Verification Testing

Percussion Unit Testbed



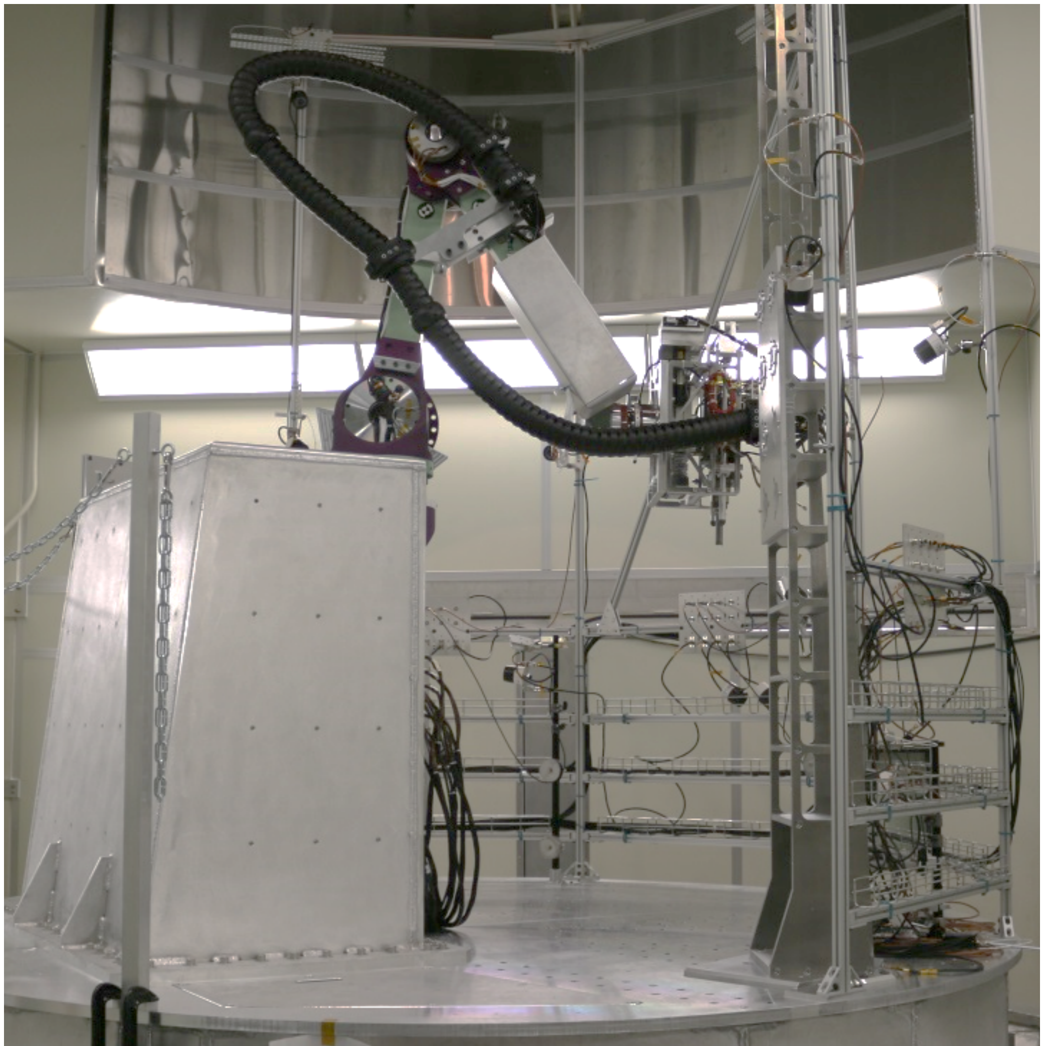
Hammer Assy



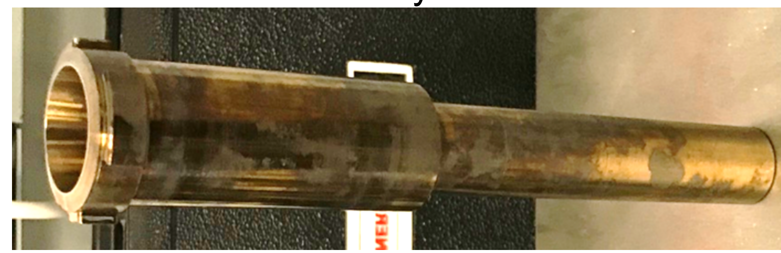
Perc. Unit CAD Xsec

EDU Drill Testing w/ Dummy Bit

Engineering Development Unit (EDU) Arm Testbed



Dummy Bit

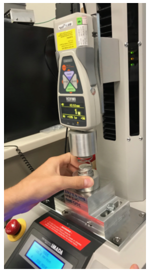


Dummy Bit Installed

Nominal Drill Modeling Approach Validation and Prediction Process Flow

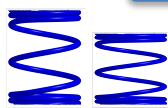
Legend
Physical testing
Analysis
Final results

Testing	***Model Validation***	***Prediction***



Spring testing

Load/disp data



Spring Models

Load/disp results

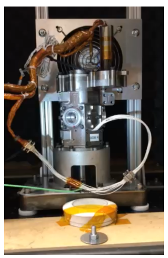
Do they match?

No

Adjust model

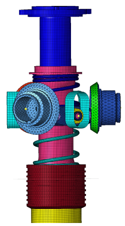
Yes

Model Validated



Perc. Unit
(a.k.a. EDU2)

Hammer pos data
Load cell data



Perc. Unit Model **Spring Models**

Hammer pos
Load cell results

Do they match within 10%?

No

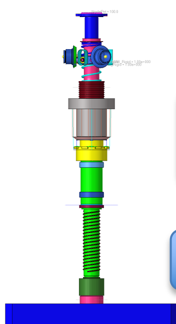
Adjust model

Yes

Model Validated

EDU drill
w/ dummy bit

Hammer pos data
Load cell data



Full Drill Model **Perc. Unit Model** **Spring Models**

Hammer pos
Load cell results

Do they match within 10%?

No

Adjust model

Yes

Model Validated

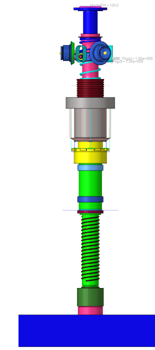
Flight Drill Loads Models

Ground percussion config.

Free percussion config.

Free Percussion Load Predictions

Ground Percussion Load Predictions



Mesh refinement / sub-modeling

Flight Drill Stress Models

Ground percussion config.

Free percussion config.

Free Percussion Stress Predictions

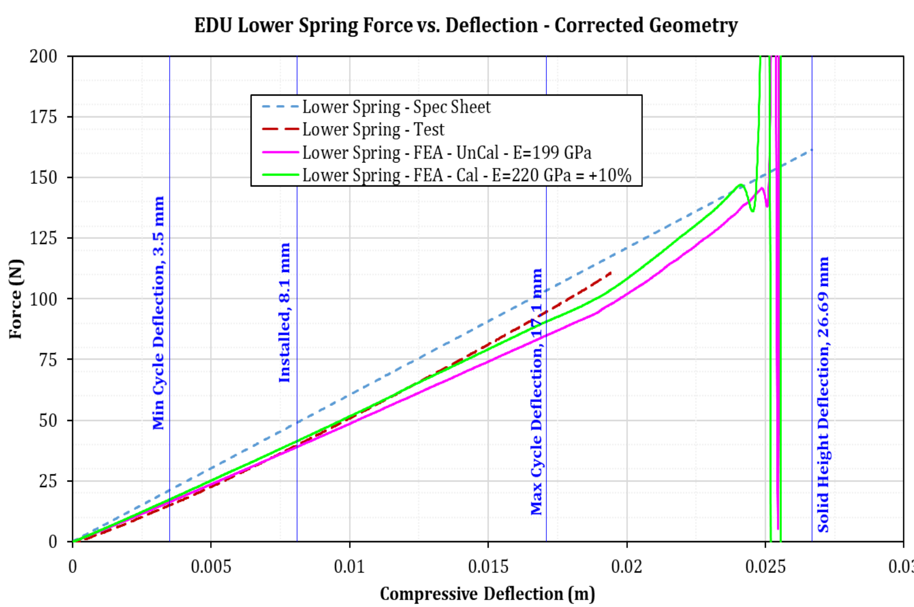
Ground Percussion Stress Predictions

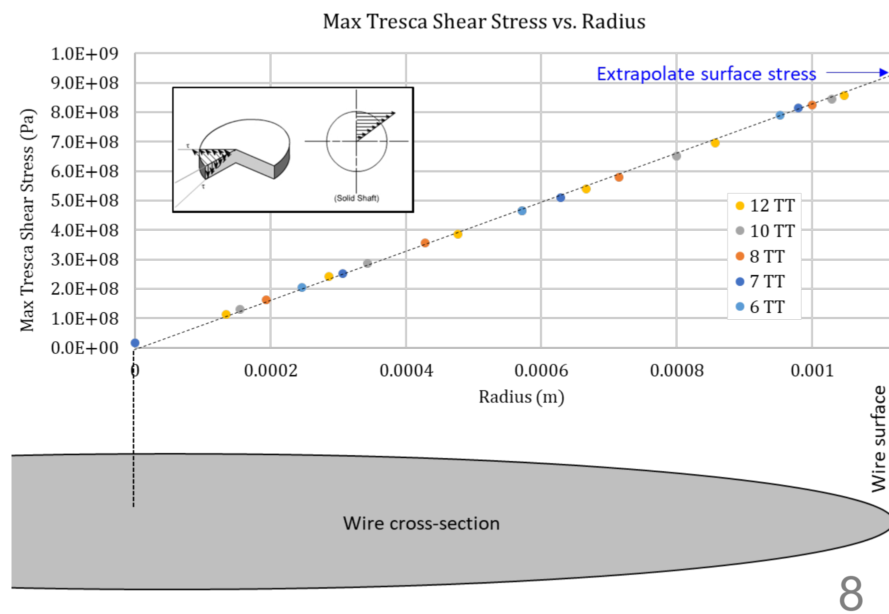
Spring Modeling

- Springs modeled with solid elements
- Moderate adjustment to spring elastic modulus to better match load/displacement test results
  - **Good test data correlation for both springs**
- Verified stress results with changing mesh fidelity
  - Expect linear shear stress through-radius
  - All model results laid along the same line
  - LS-DYNA only reports stresses at element centroids; causes apparent peak stress change
  - Can extrapolate to wire surface to determine peak spring stresses

6 TT

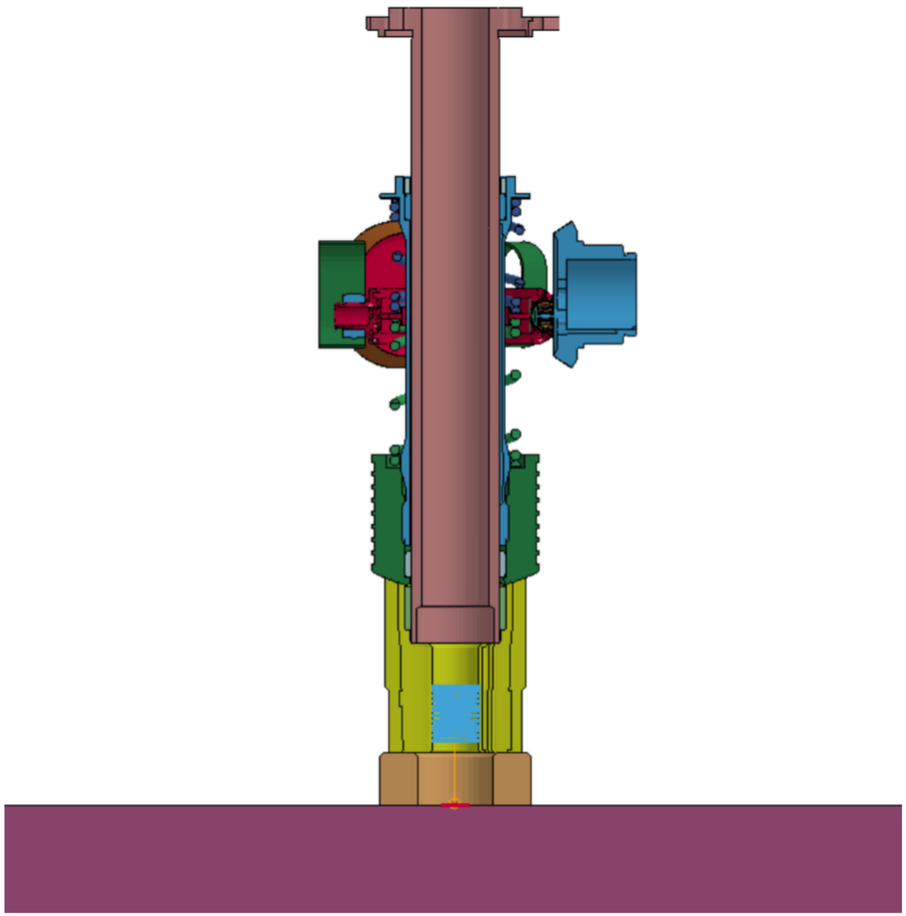
Peak stress: 790 MPa



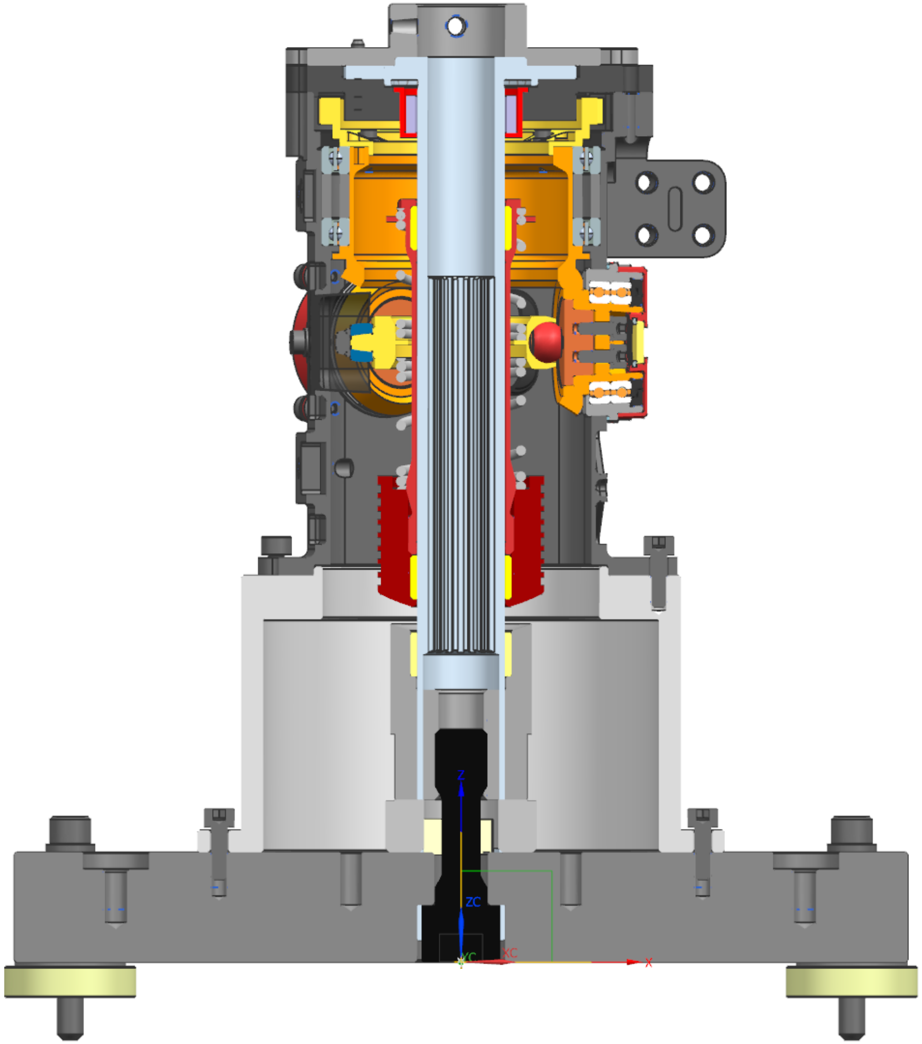


Percussion Unit Modeling

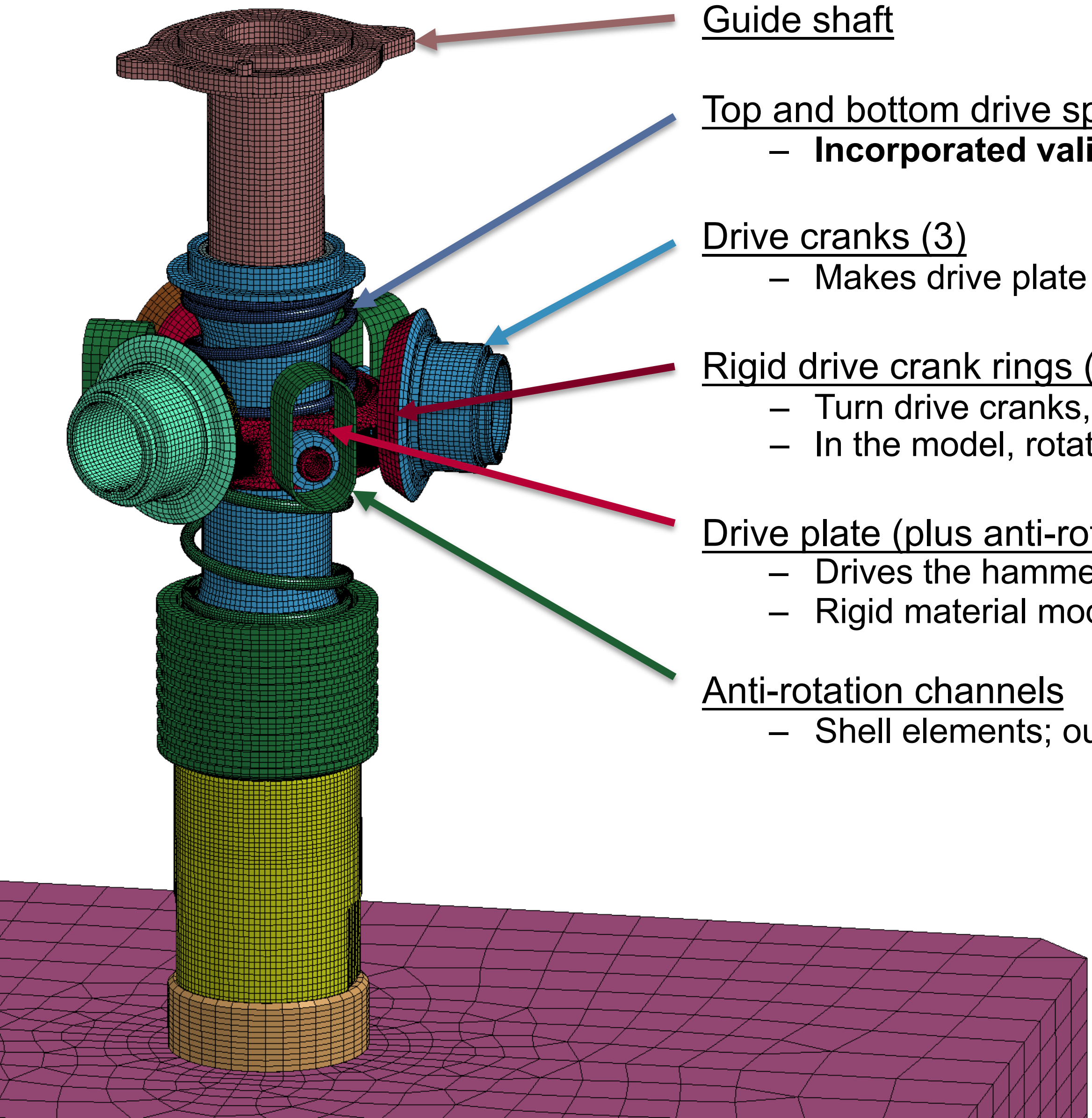
Percussion Unit LS-DYNA Model Xsec



Percussion Unit CAD Xsec



Percussion Unit Modeling



Guide shaft

Top and bottom drive springs
- **Incorporated validated spring models; preloaded**

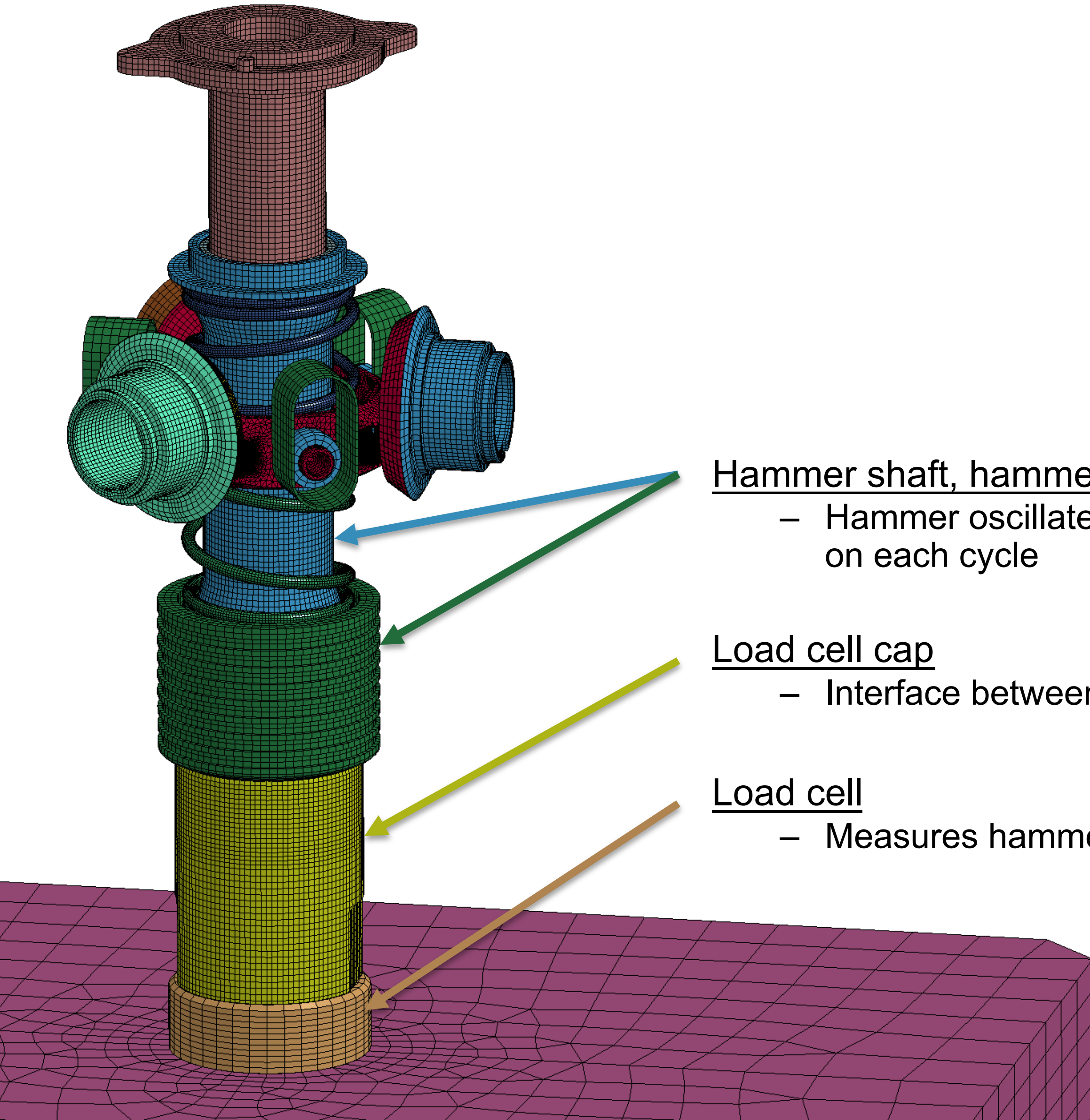
Drive cranks (3)
- Makes drive plate to oscillate up and down

Rigid drive crank rings (3)
- Turn drive cranks, replicating gear interaction
- In the model, rotate about vectors aiming radially outward

Drive plate (plus anti-rotation bearings)
- Drives the hammer assembly through the driver springs
- Rigid material model

Anti-rotation channels
- Shell elements; outer edge has a fixed BC

Percussion Unit Modeling



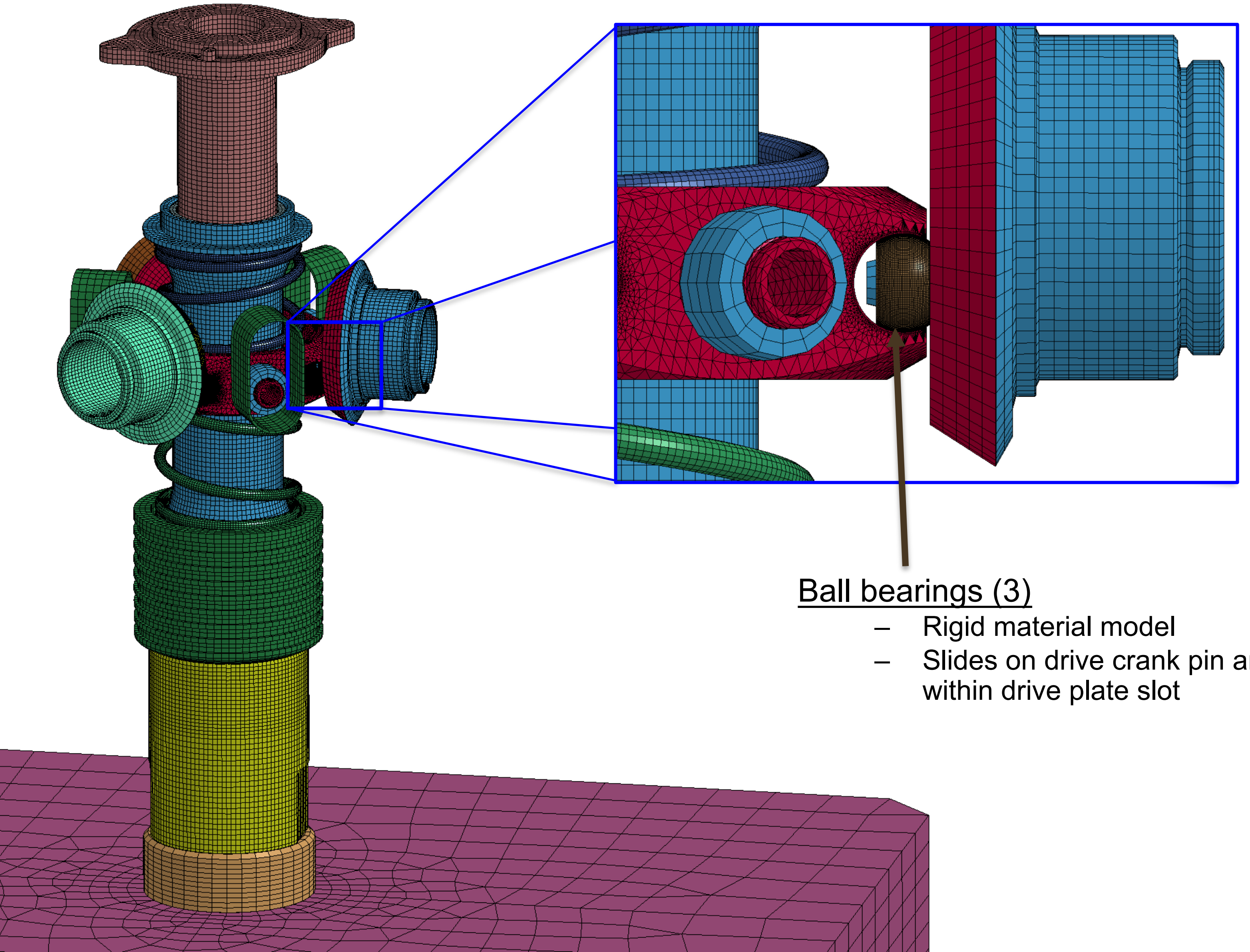
Hammer shaft, hammer, and bearings
- Hammer oscillates up and down, hitting load cell cap on each cycle

Load cell cap
- Interface between hammer and load cell

Load cell
- Measures hammer impact force

Baseplate
- Supports load cell
- Provides consistent boundary conditions for perc. unit testbed and EDU drill testbed

Percussion Unit Modeling

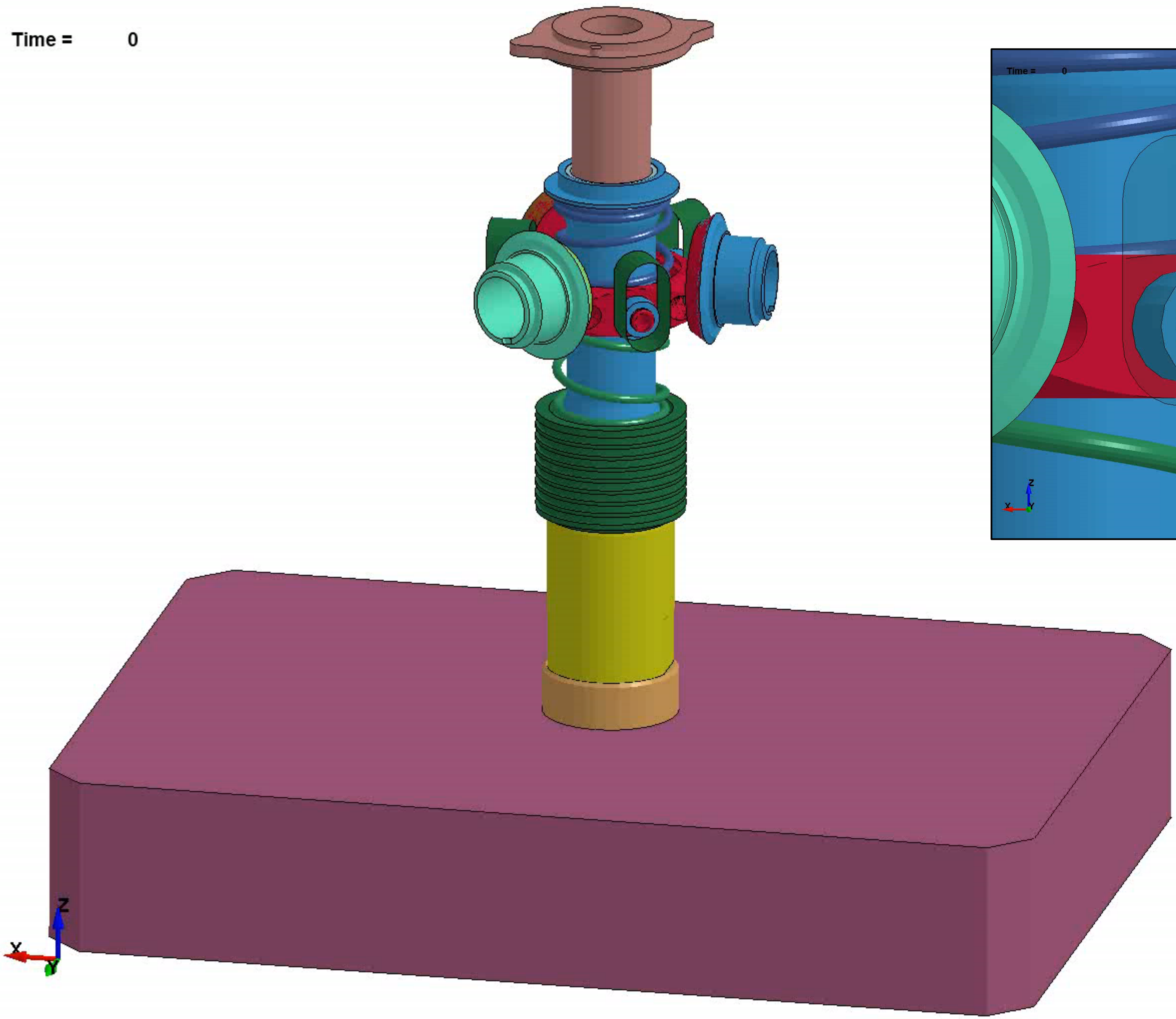


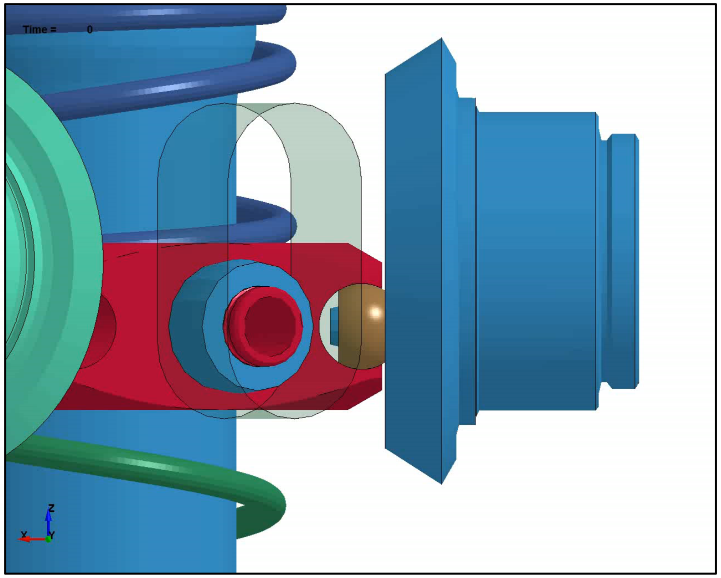
Ball bearings (3)

- Rigid material model
- Slides on drive crank pin and within drive plate slot

Percussion Unit Modeling

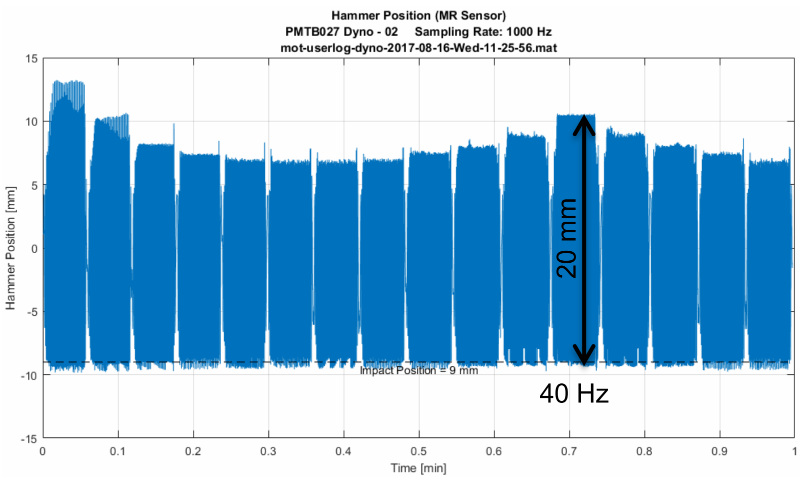
Time = 0



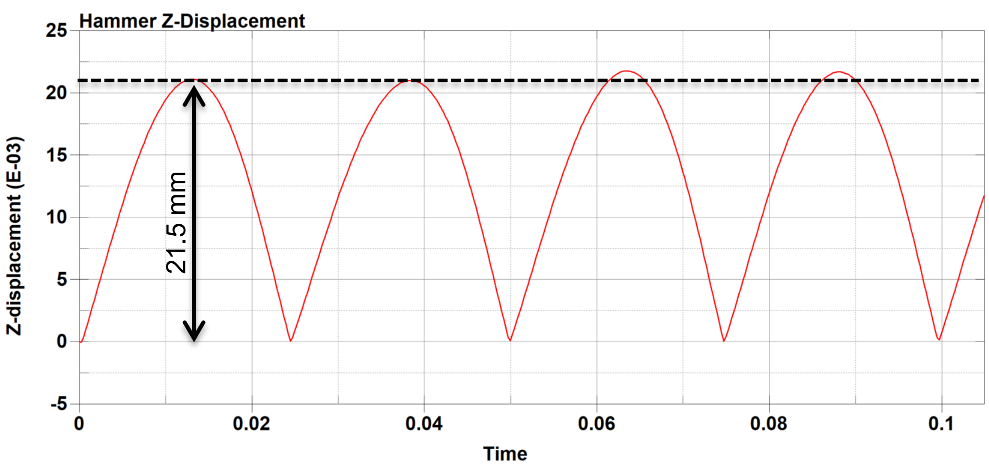


Perc. Unit Hammer Displacement – 40 Hz

Perc. Unit Dyno Test Results



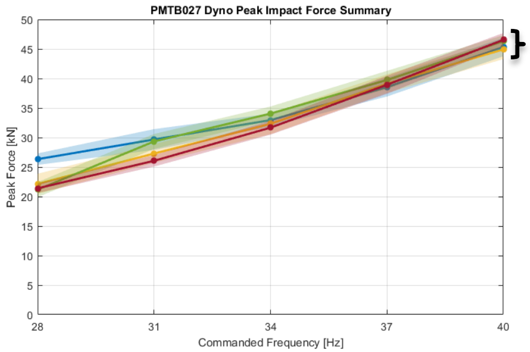
LS-DYNA Model Results

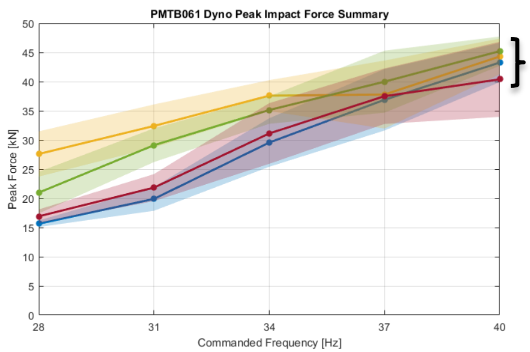


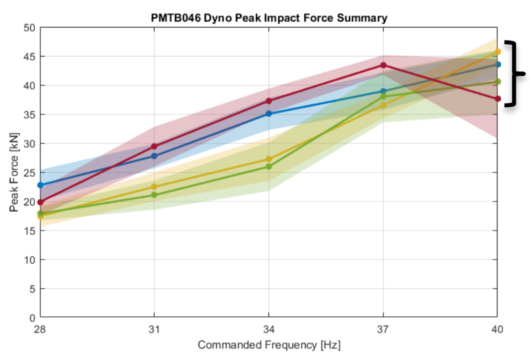
- Total hammer displacement from tests at 40 Hz percussion: 20 mm
- Total hammer displacement from latest model: ~21.5 mm, or +8% over-prediction
- **Matches hammer displacement within 10%**

Percussion Unit LC Loads – 40 Hz

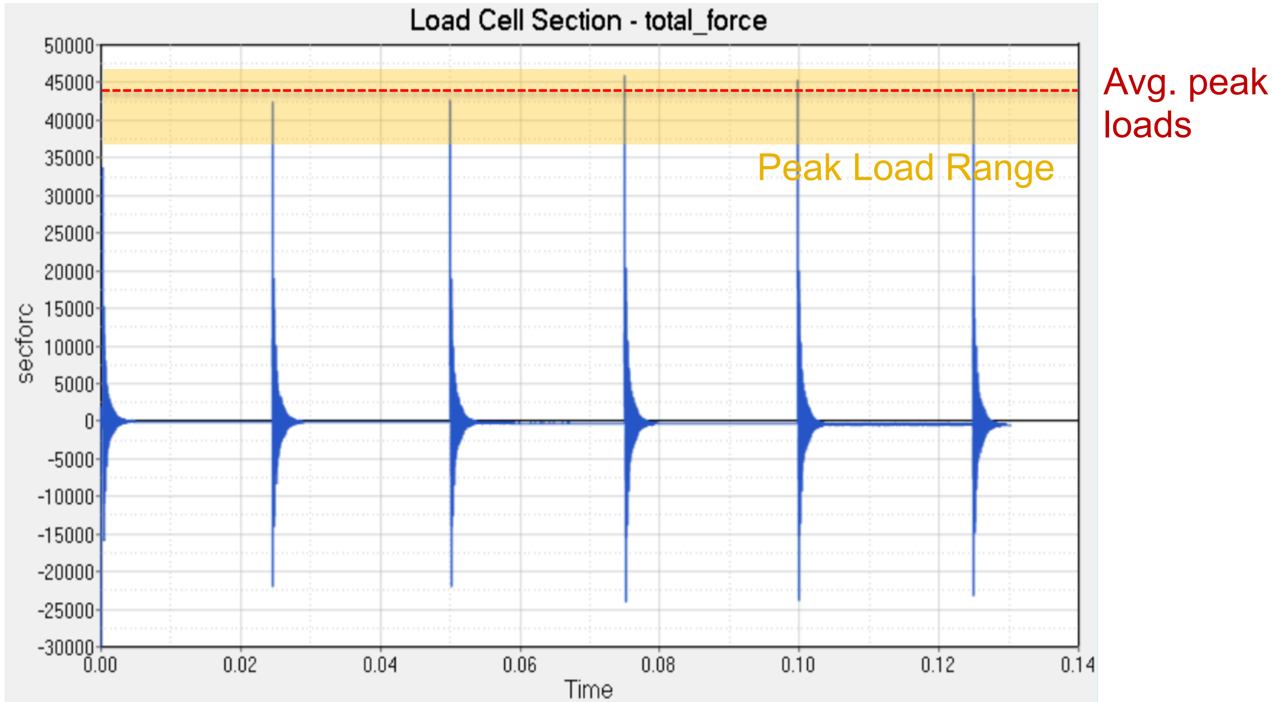
Perc. Unit Dyno Test Results







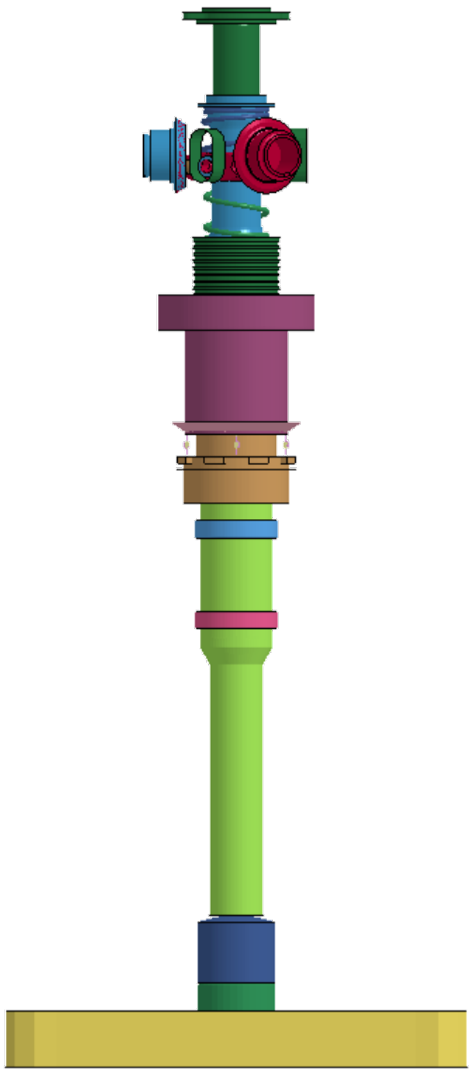
LS-DYNA Model Results



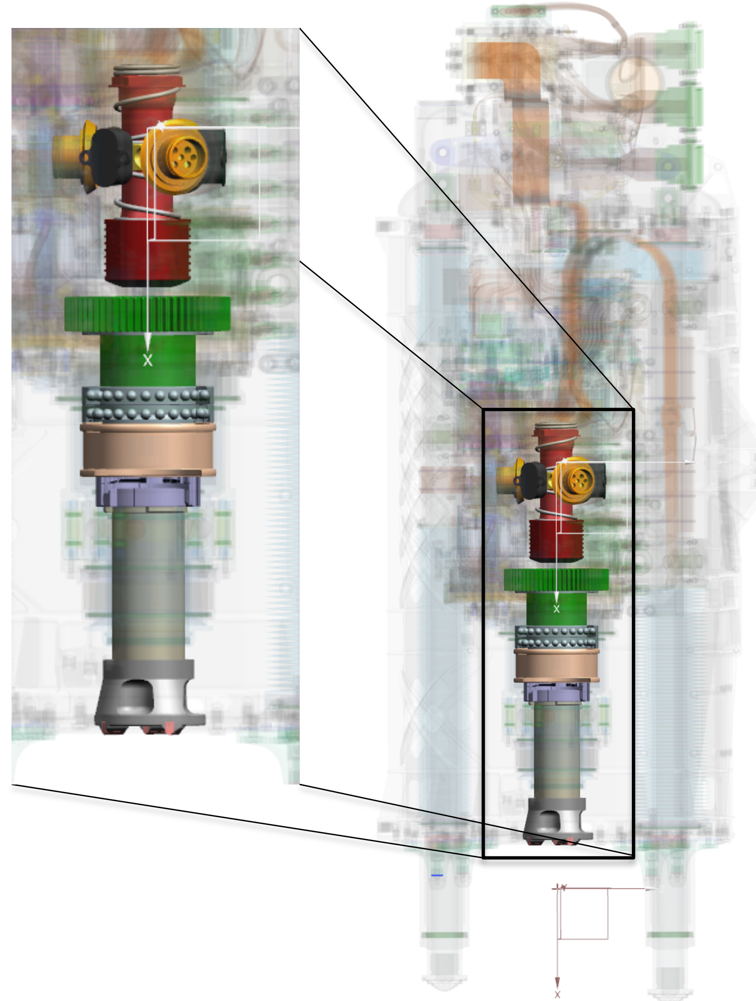
- Average peak loads from tests at 40 Hz percussion: 37-47 kN
- Average peak loads from latest model: ~44 kN
  - A little on the high end, but overall a good correlation!
  - **Matches load cell forces within 10%.**
  - Prefer to be on the higher end of loads, not lower, for conservatism
  - Model matches early test results (ex. PMTB027, top left graph) better than later testing; makes sense given that wear/run-in that occurs in real testing is not represented in models
  - <u>**Successful validation of percussion mechanism modeling**</u>

Drill Modeling

EDU Drill LS-DYNA Model

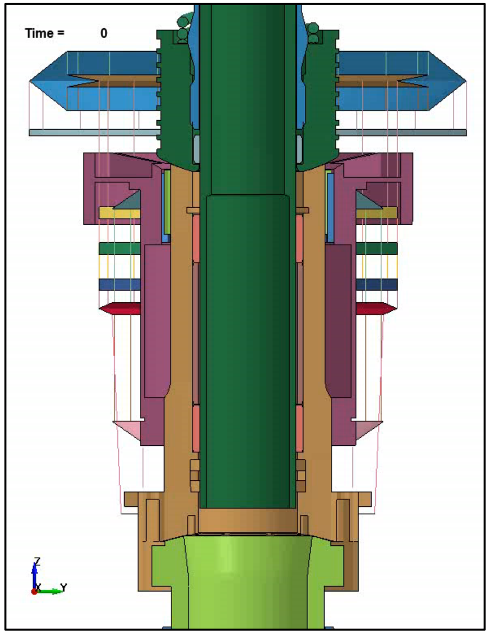


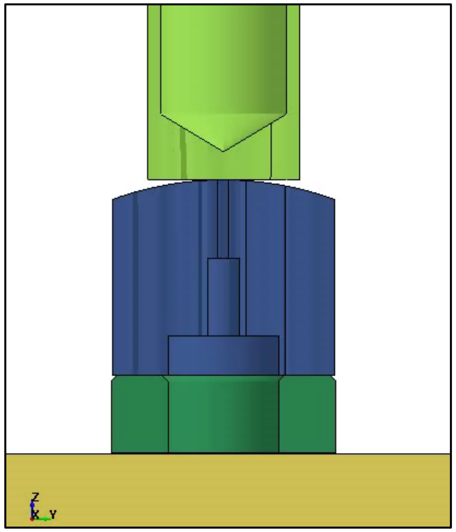
EDU Drill CAD



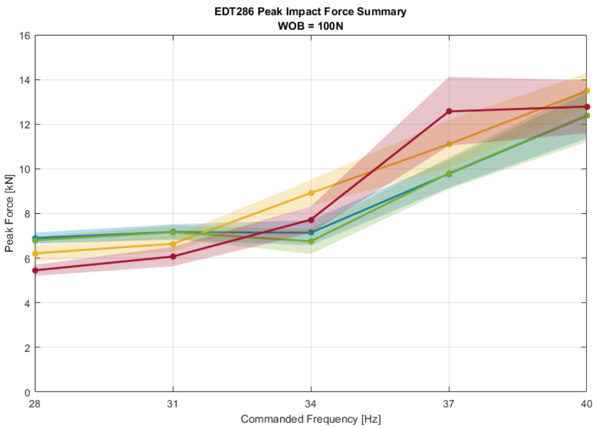
Flight drill CAD model in abrading bit config

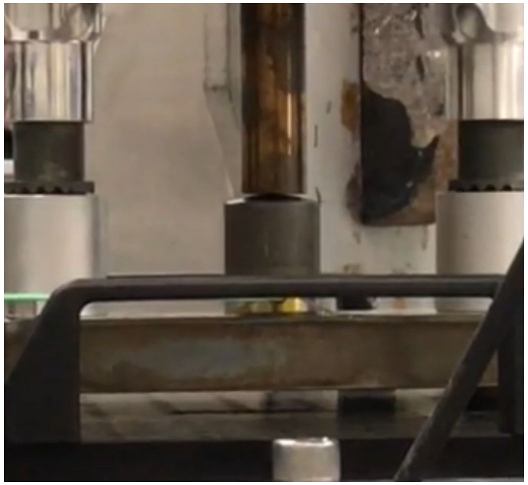
EDU Drill Model



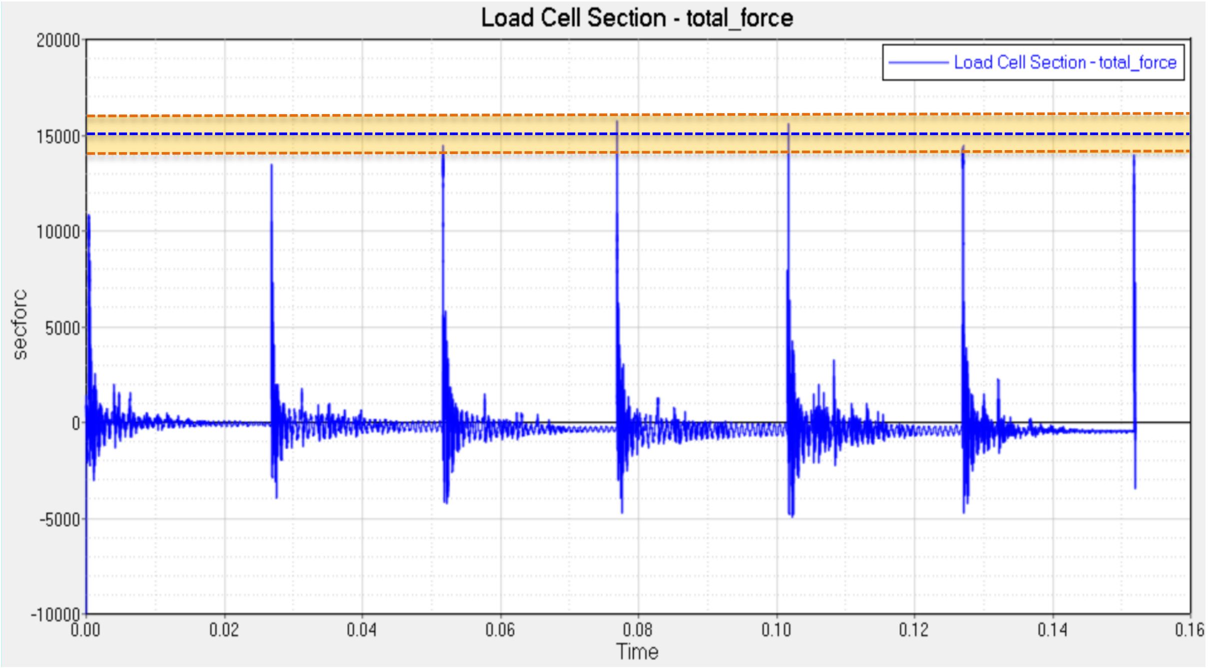


EDU Drill LC Loads – 40 Hz, WOB 100 N





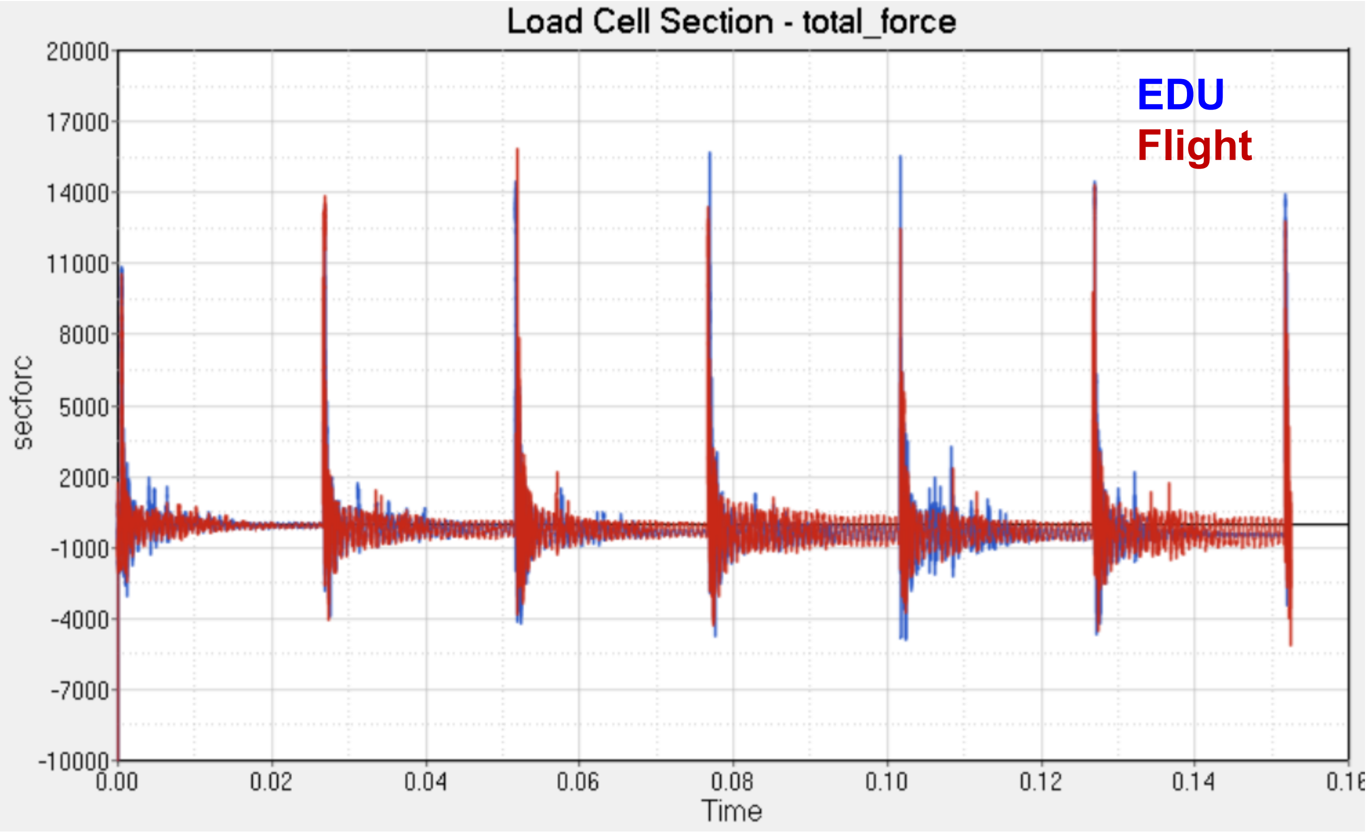
Dummy bit installed on EDU drill

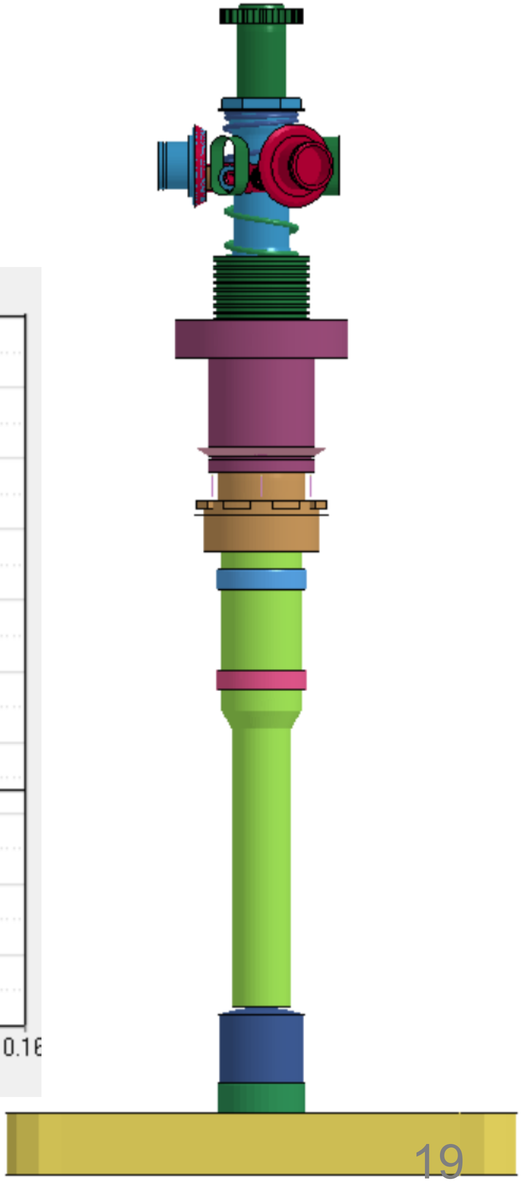


- Peak loads from test at 40 Hz, 100 N WOB: ~15 kN ± 1 kN
- Peak loads from latest model: ~15 kN
- **Successful validation of drill modeling approach**

Flight Drill Load & Stress Predictions

- Same validated drill modeling approach used to model Flight drill
- Both load and stress predictions possible
- In some regions, model too coarse for accurate stress predictions
- In these cases, can refine model locally or use sub-modeling



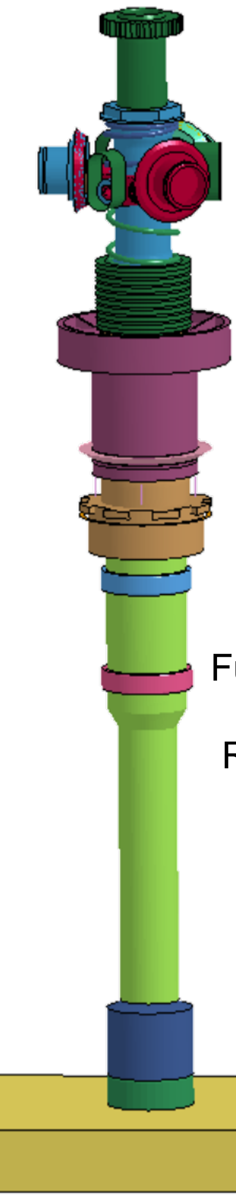


Bit Shaft Fillet Sub-Modeling

- Sub-model: Fine mesh of filleted area below bit tangs
  - Mesh aligns with element boundaries in full model so that displacements can be imposed
  - Small time step, but fewer elements, no contact, etc. → Short run time

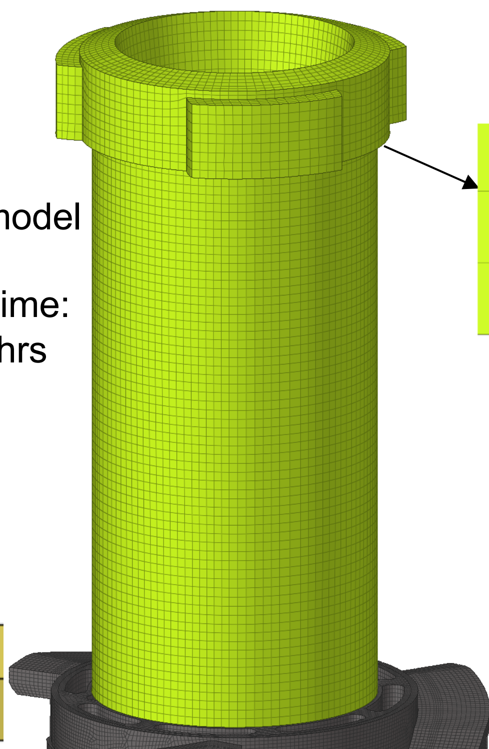
- Sub-model analysis procedure:

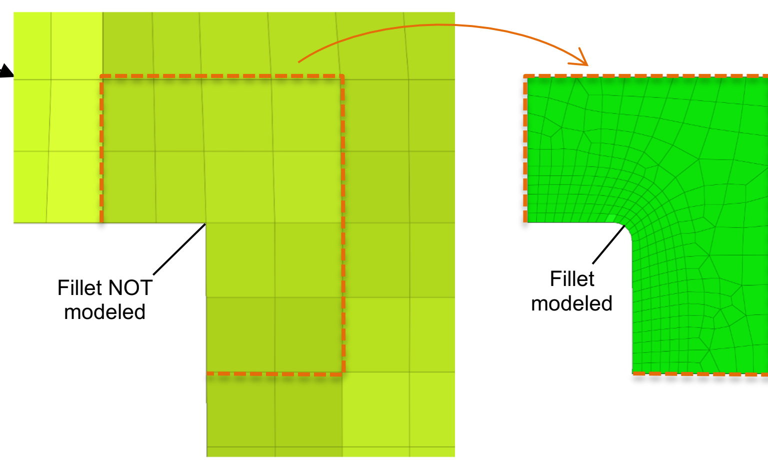
1. Run full model → 2. Extract displacements from element faces → 3. Impose displacements on sub-model boundaries



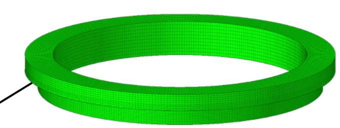
Full model

Runtime:
24 hrs





Cross-section views



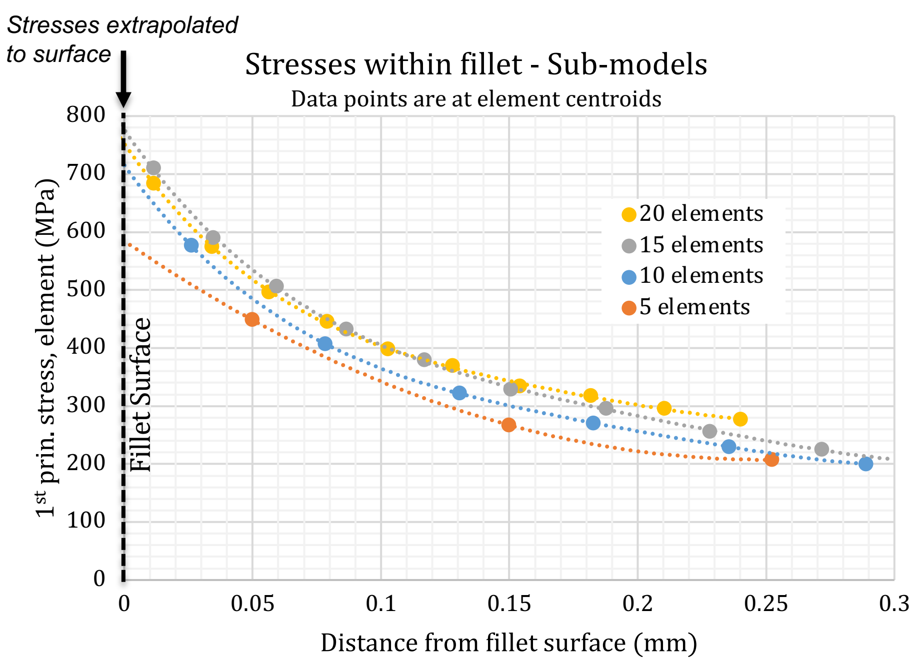
Sub-model

Runtime:
1 hr

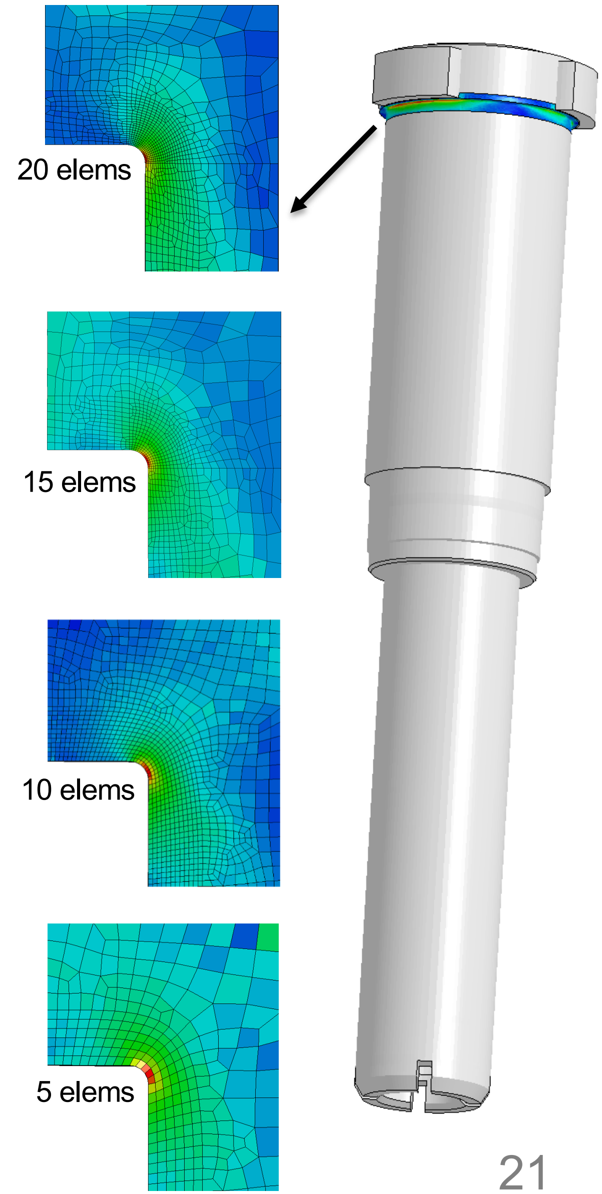
Bit Shaft Fillet Sub-Modeling Stress Convergence Results

Going Forward, Used 15 Elements Across Fillet Radius

- Varied elements over the fillet arc to assess stress convergence
- Results show stresses are converged by around 15-20 elements
  - Only 5% difference between 15 and 20 element peak stress
- Used 15 element model going forward
- Allows accurate fillet stress predictions with full transient response
  - Peak VM stress: 831 MPa   MSy (FSy=1.25) = +0.33
  - Peak S1 stress: 780 MPa   MSu (FSu=1.4) = +0.39

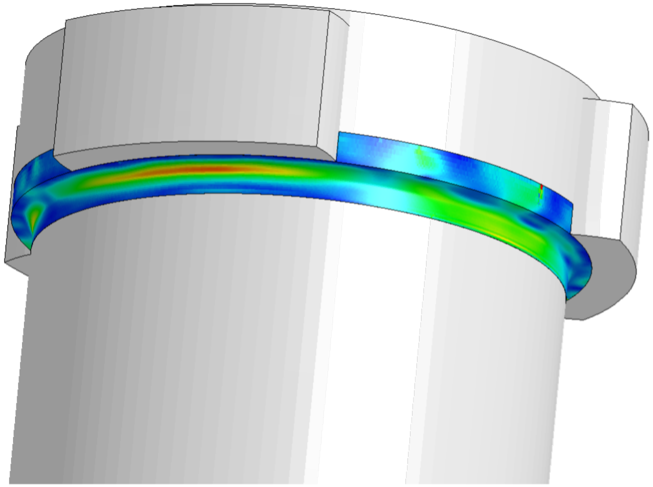


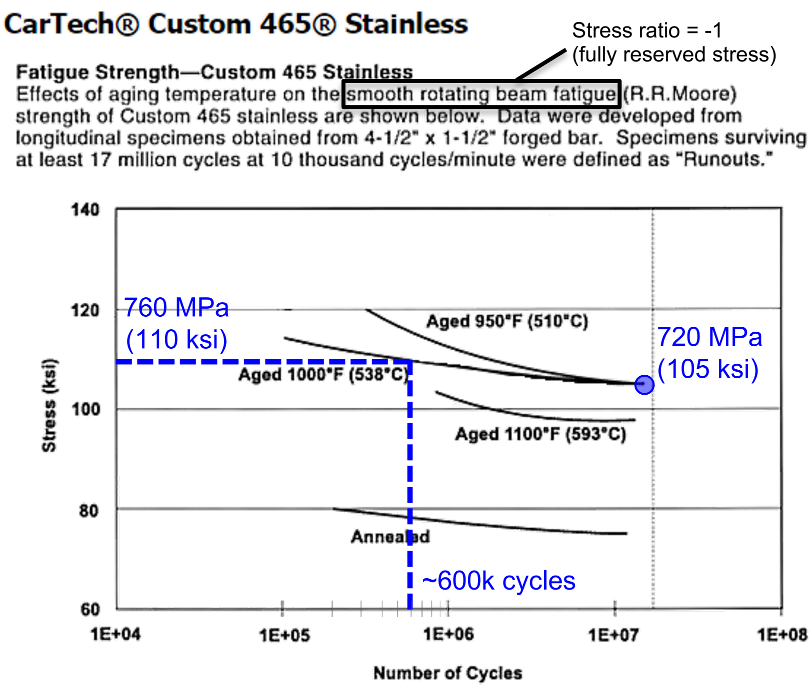
Elements	Peak stress (extrapolated)
20	760
15	780
10	720
5	580

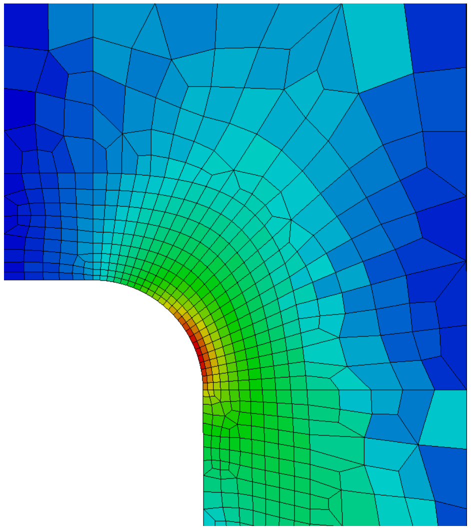


Fatigue Damage Predicted At 600k Cycles; For 4x Margin, Use Max Of 150k Cycles

- Believe Model 3 to be closest to reality while still conservative
  - Models 1 and 2 unrealistically stiff
  - Model 3 has chuck assembly compliance, but not drill body compliance, therefore still conservative
- Used Model 3 results to assess fatigue
  - Peak 1st prin. stress: 760 MPa (110 ksi)
  - Fatigue damage predicted at 600k cycles
  - **Require 4x margin on fatigue life; max of 150k cycles**







Conclusions

- A building block strategy was successfully adopted for developing a validated drill modeling approach
- Accurate predictions about the Flight drill loads and component stresses can be made using the modeling approach developed.
- Where additional model fidelity is needed, approaches such as sub-modeling have been successfully used to achieve stress-accurate models with reasonable runtimes and provide critical stress predictions
- LS-DYNA has been an invaluable tool throughout the drill's design