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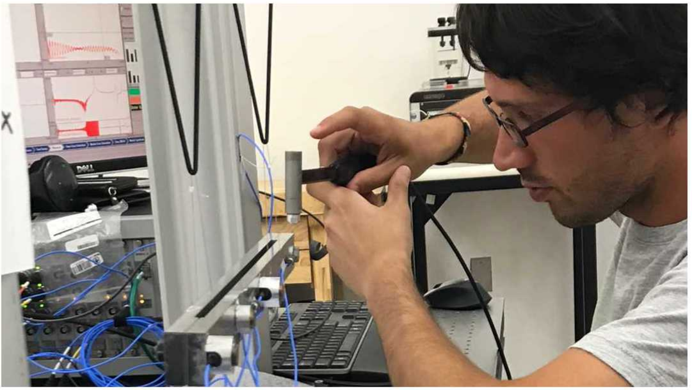

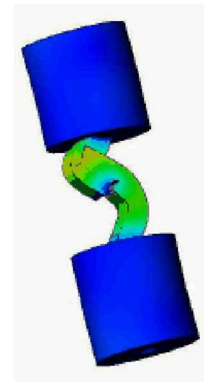

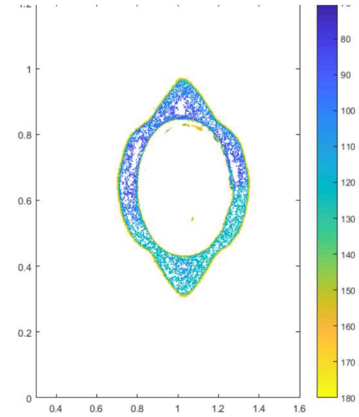

Constructing Optimal Surrogate Models for Bolted Fasteners in Multiaxial Loading

Ernesto Camarena, Anthony Quintana, Victoria Yim

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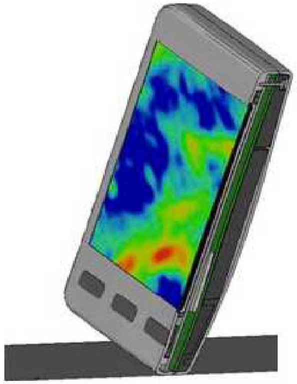
Introduction

- Simulations of structural systems in adverse environments
- Prohibitive computational burden of hundreds of fasteners
- Enormous length scale differences
  - System size, O(1e3 mm)
  - Bolt size, O(100 mm)
  - Thread size , O(1 mm)
- Common fastener modeling
  - So-called "Plug"
  - Analysts rely on pure tension data: no other load angles



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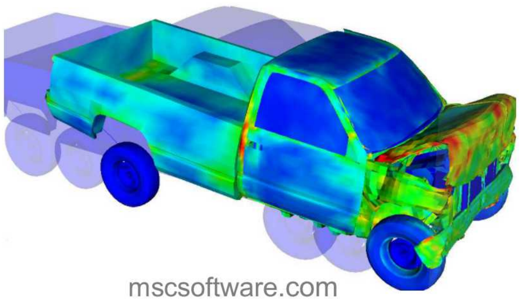

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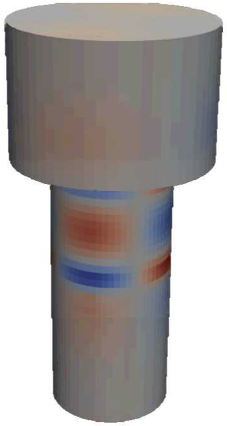


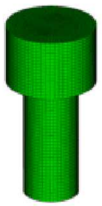
"Plug"

Motivation

- Research questions:
  - How well do plug models work for an arbitrary loading pull direction?
  - How can plug modeling be modified to improve predictive behavior?
- Solution--Compare plug model to:
  - Experiment data at various load pulls
  - A fully threaded FE model

Methodology: Overview

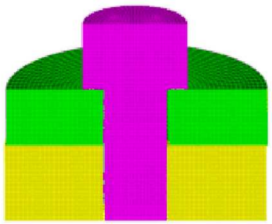
Calibrate Numerical Hardening Curve to Experiments



- Implicit solve, no contact
- 0° load angle (tension only)

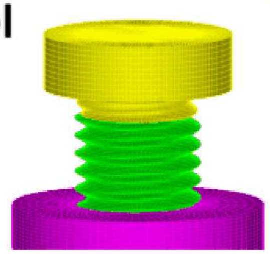
Numerical Plug Model

- Explicit w/ contact
- 0°, 30°, 60°, 90° cases
- Compare w/ experiments @ SNL



Numerical Threaded Model

- Explicit w/ contact
- 0°, 30°, 60°, 90° cases
- Compare w/ experiments @ SNL

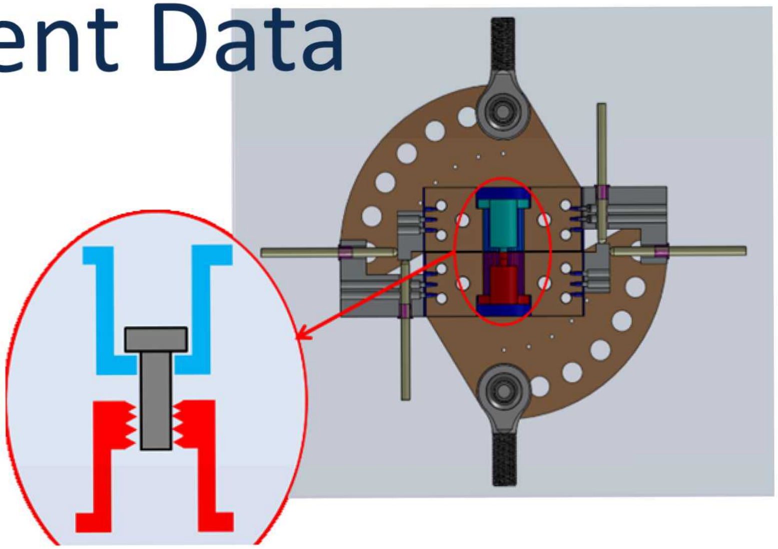


Compare Plug vs. Threaded Model

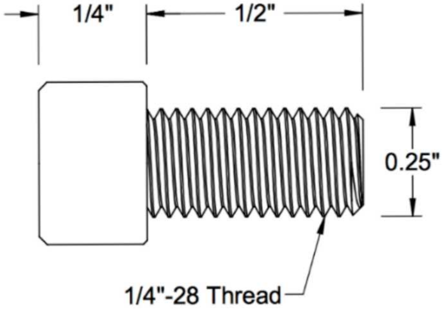
- 0°, 30°, 60°, 90° cases

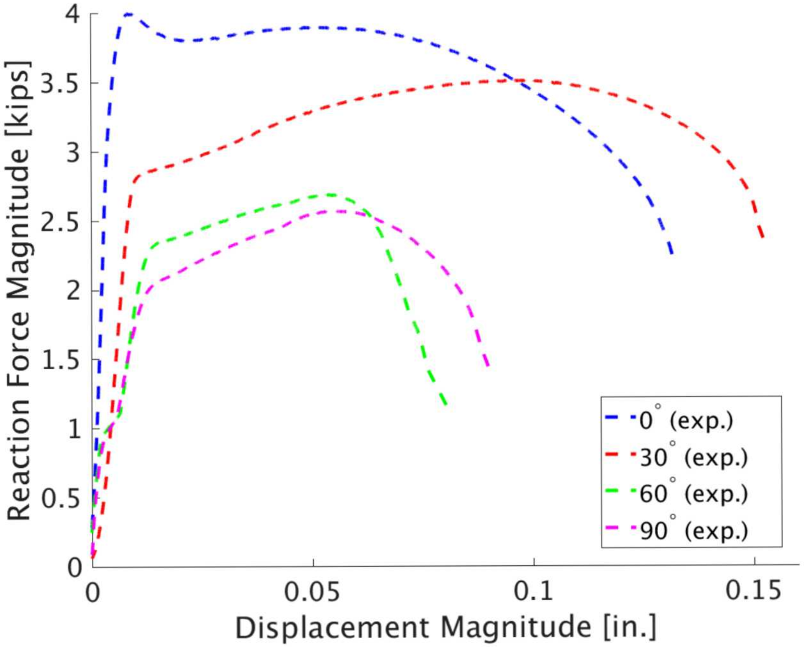
Methodology: Experiment Data

- Multiaxial fastener test setup
  - Setup allows for displacing at various angles



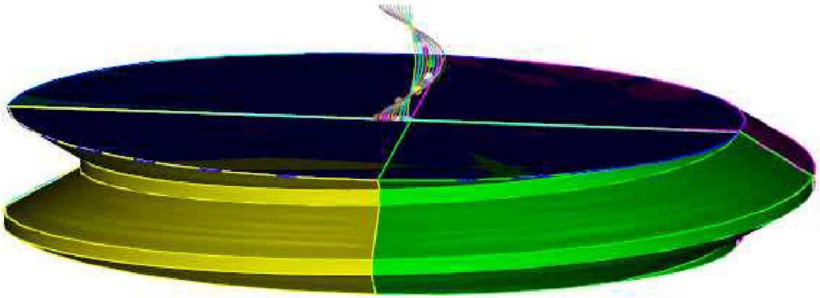
- Fastener details:
  - 18-8 Stainless steel
  - UNF thread type

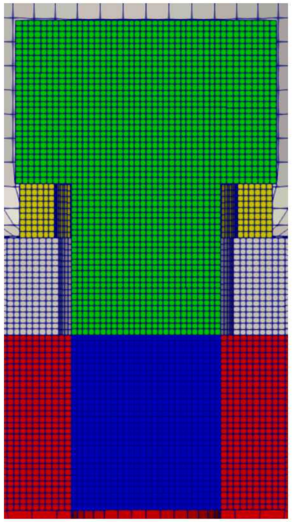


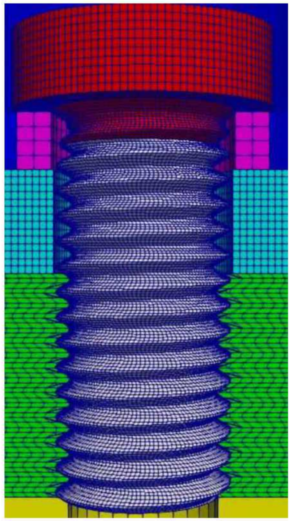


Methodology: Geometry and Mesh

- Geometry
  - Plug uses relatively simple geometry
    - Tensile stress radius
  - Threaded model created in slices along helix
    - Fully 3D model
- Mesh
  - Refined regions near fastener
  - Coarse mesh for upper and bottom bushing

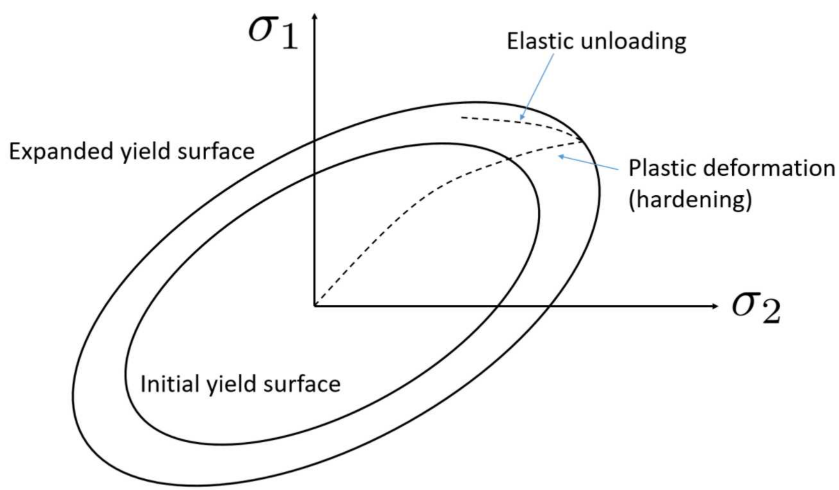






Methodology: Constitutive Model

- **Elasticity:** Young's Modulus = 30e6 psi, Poisson's Ratio= 0.3
- Plasticity
  - Isotropic Hardening
    - Multi-linear elastic-plastic hardening curve
      - Yield stress = 93e3 psi
    - Yield Surface retains its shape and is symmetric about the origin
    - Increases uniformly as the material deforms plastically
  - Rate independent



Methodology: Failure Criteria

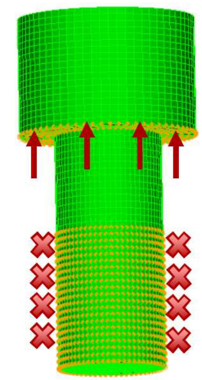
- Hardening Curve Definition: Multi Linear Elastic-Plastic (MLEP)
  - Linear piecewise hardening curve defined with discrete pairs of equivalent plastic strain (EQPS) and yield stress.

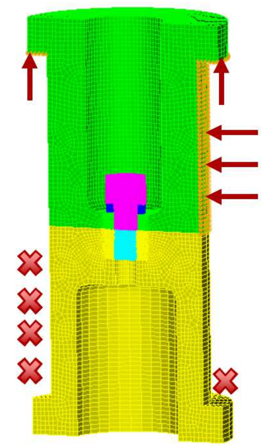
$$D_{ij} = {D_{ij}}^{e} + {D_{ij}}^{P}$$

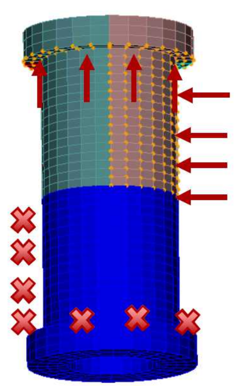
- Failure Models
  - Element death based on EQPS limit.
  - Ductile Failure Model (ml_ep_fail)
    - Failure in a given element initiates when its tearing parameter (t_p) reaches a critical value. The element stiffness then decreases with increasing crack opening strain (strain in the direction of the max principal stress).

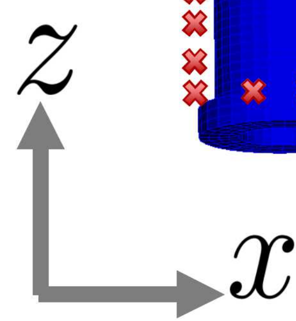
Methodology: Boundary Conditions

- Basic Plug
  - 0° case: only +z displacement
- Plug with Bushings & Threaded Model
  - 0° case:
    - Displace +z face of upper bushing
    - Fixed lower z face of bottom bushing
  - 30°, 60°, and 90° case:
    - Displace +x face of upper bushing
    - Displace +z face of upper bushing
    - Fixed lower –x face of bottom bushing
    - Fixed lower z face of bottom bushing

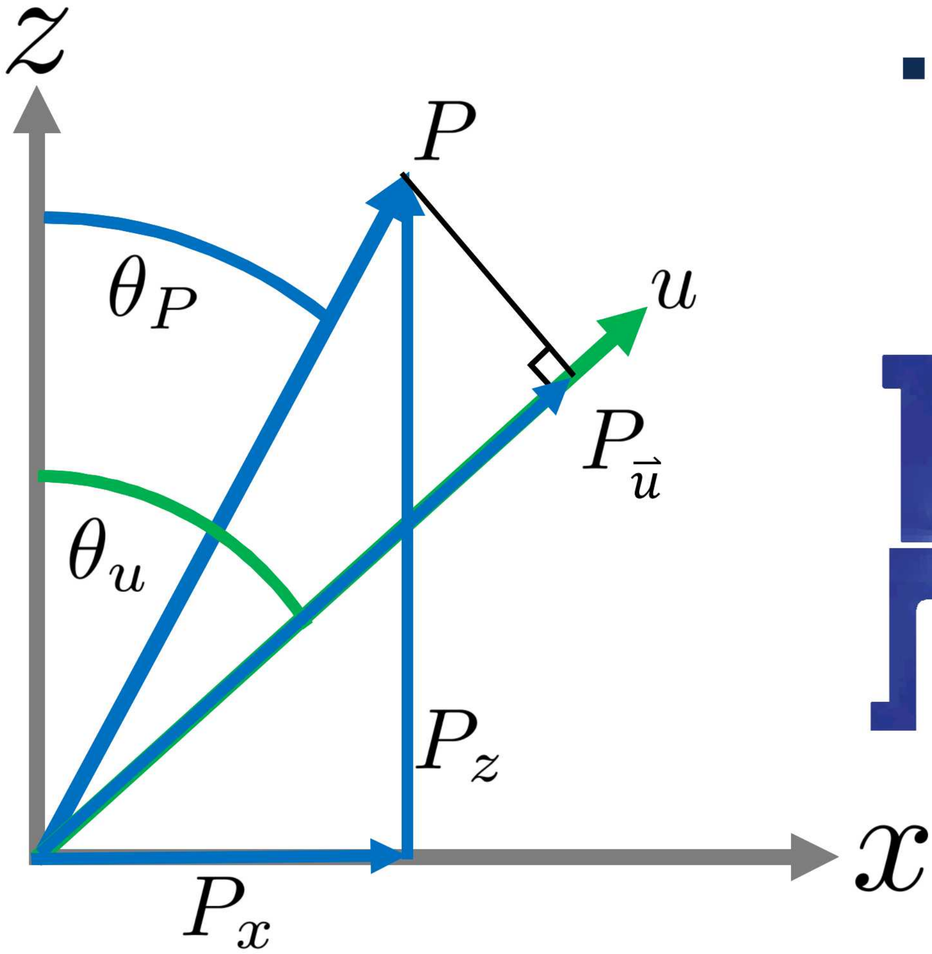




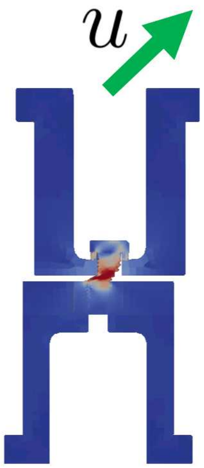




Methodology: Post-Processing



- Load projection
  - 30° & 60°

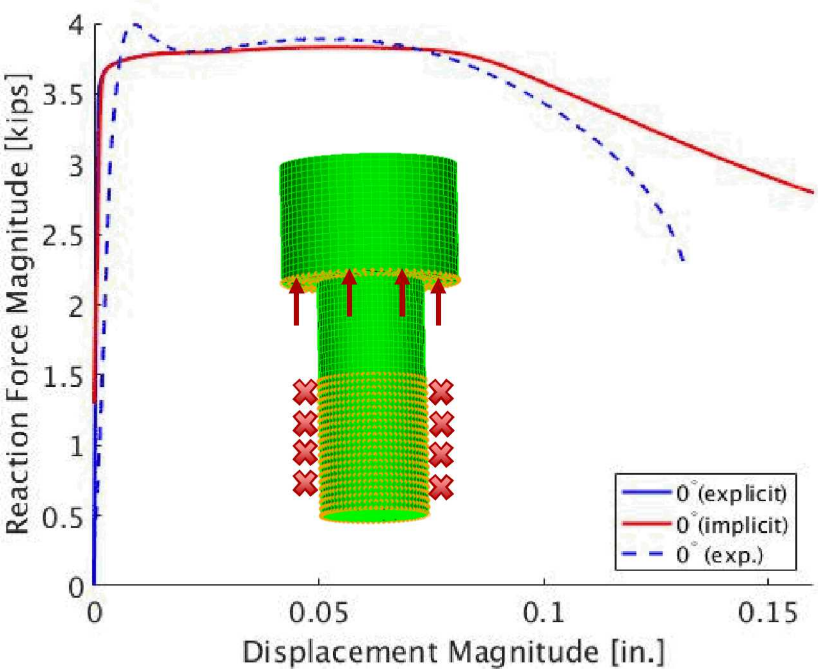


$$\theta_P = \arctan\left(\frac{P_x}{P_z}\right)$$
$$P_{\vec{u}} = P\cos\left(\theta_u - \theta_P\right)$$

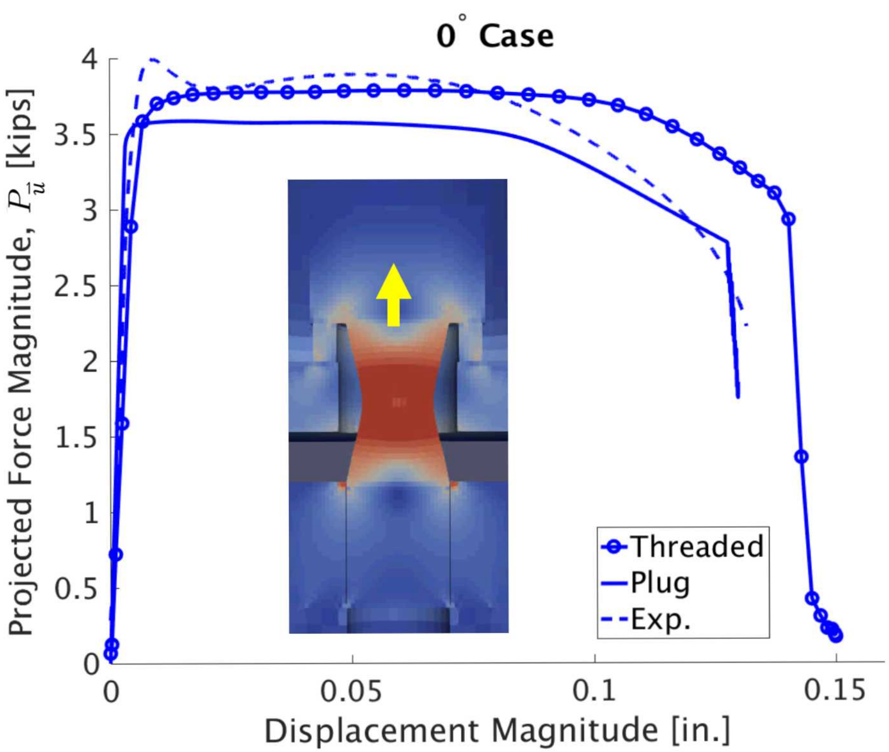
- Smoothing: moving average

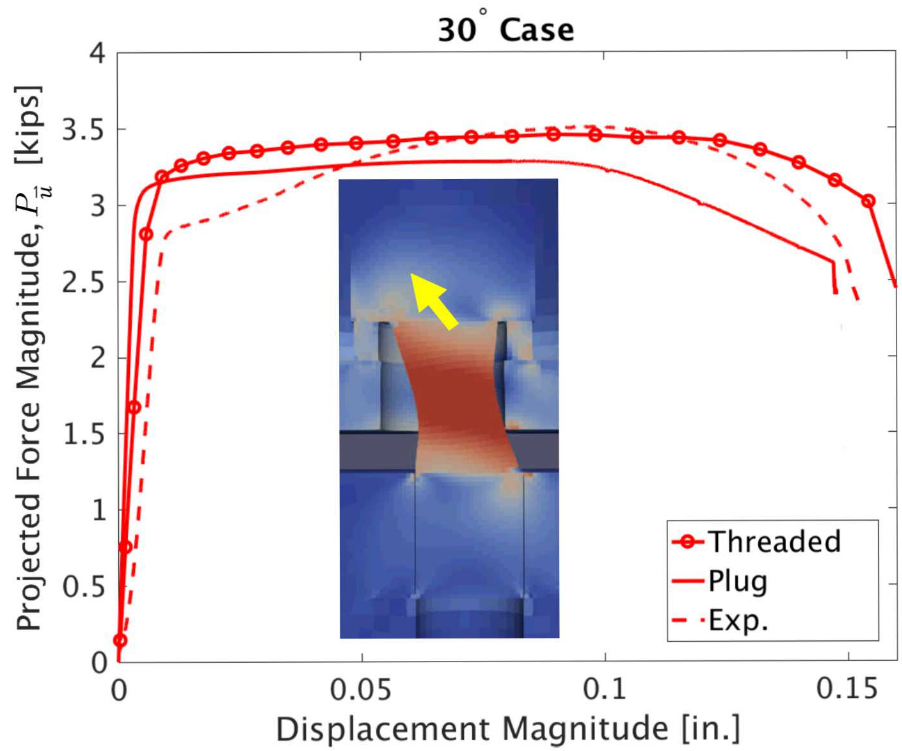
Methodology: Numerical Procedures

- Implicit vs. Explicit
  - In order to account for the frictional contact between the plug and bushing an explicit model is required
  - For calibration purposes, the basic plug is analyzed using both implicit and explicit models
  - The hardening curve developed for the plug with bushing and threaded model are based on the this basic plug



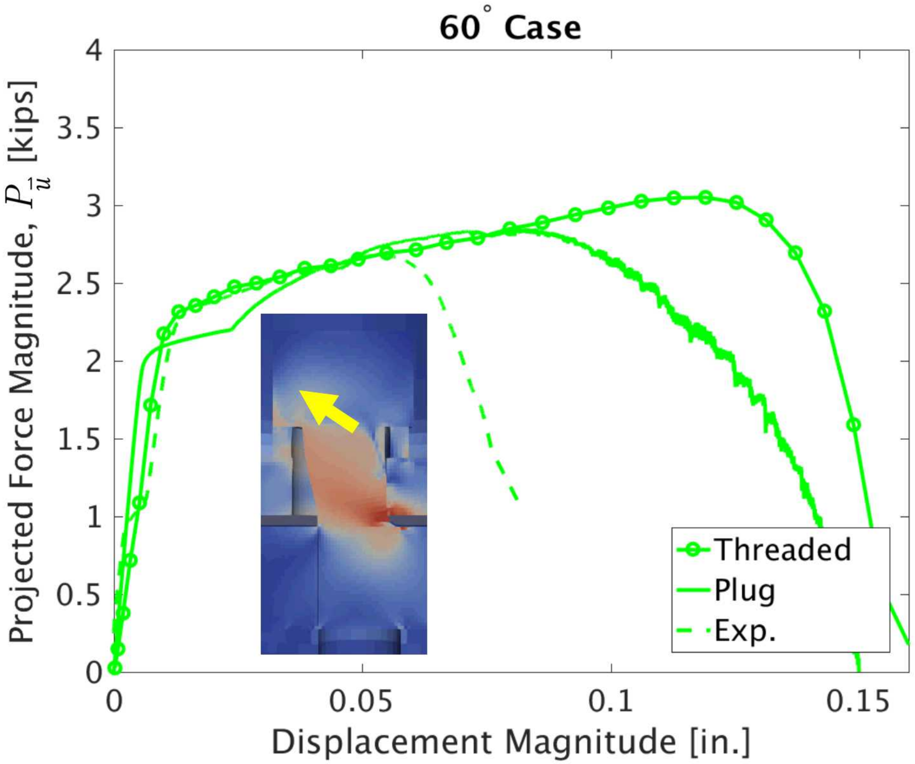
Results: FE vs. Experiments

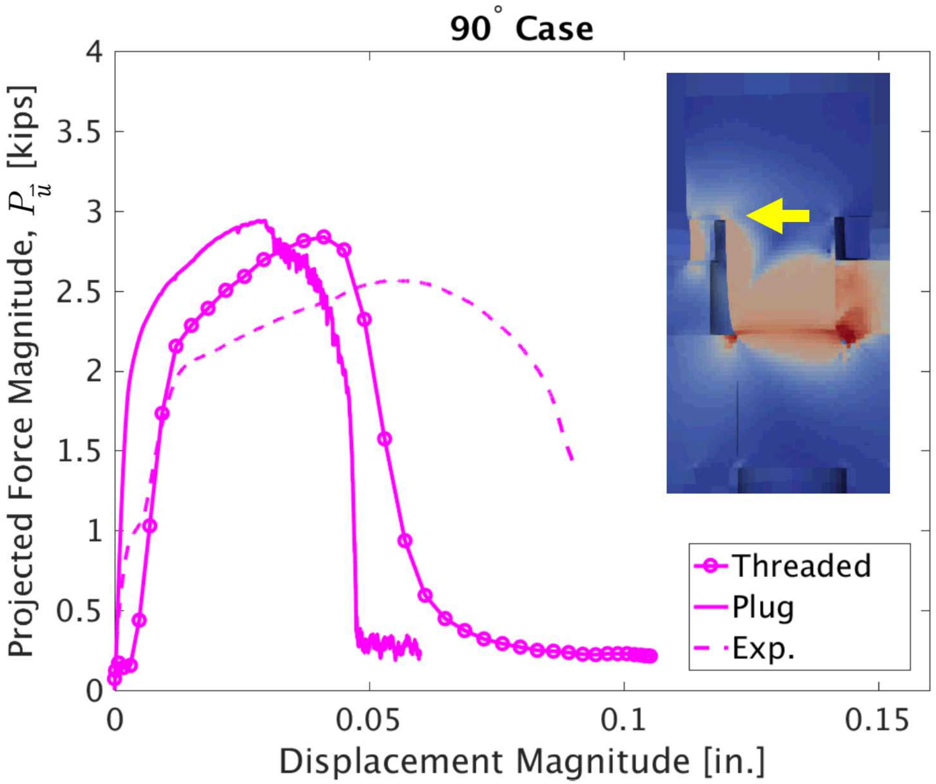




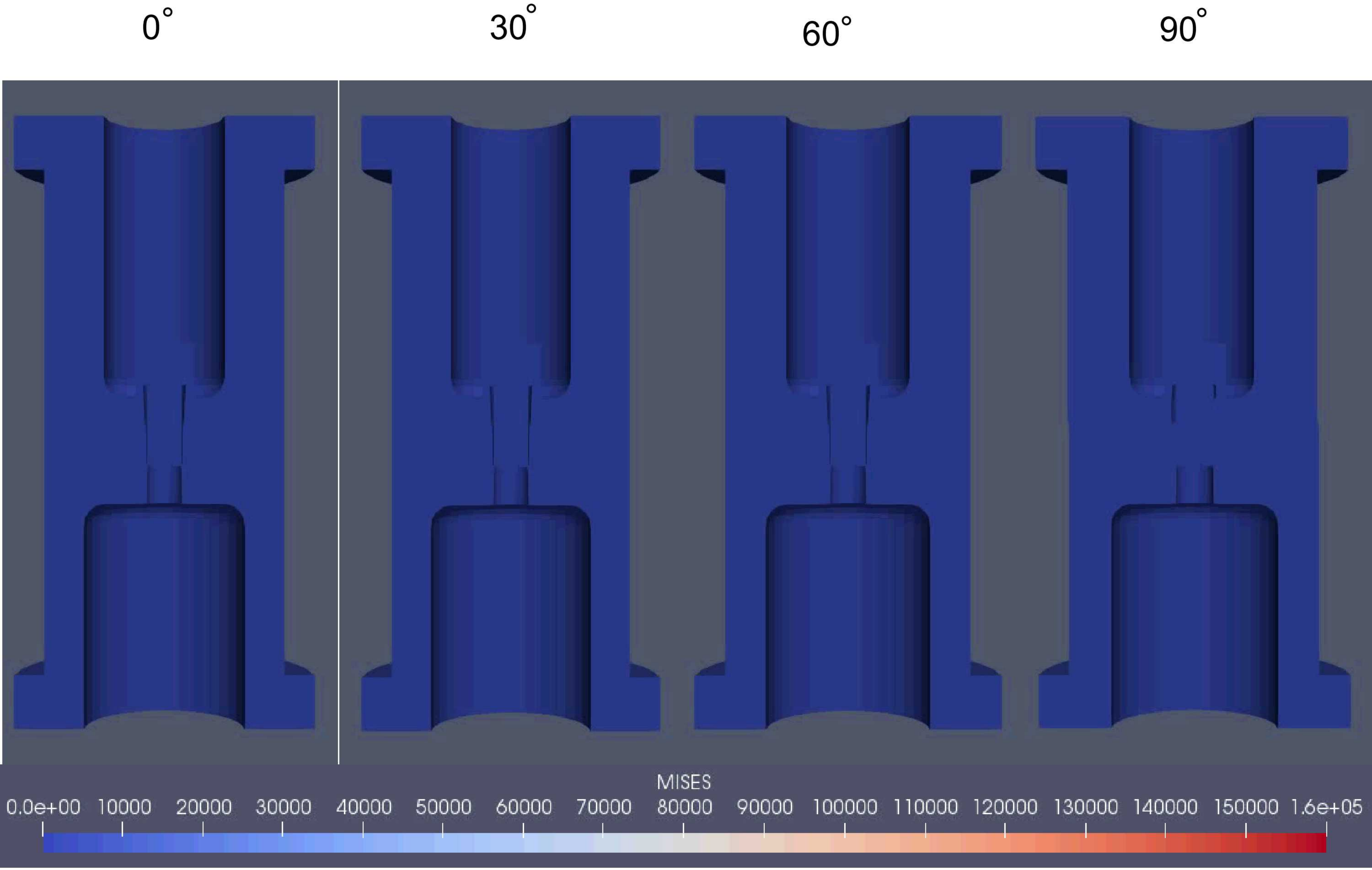
- Element death on EQPS
- Plug model radius: tensile stress area

Results: FE vs. Experiments



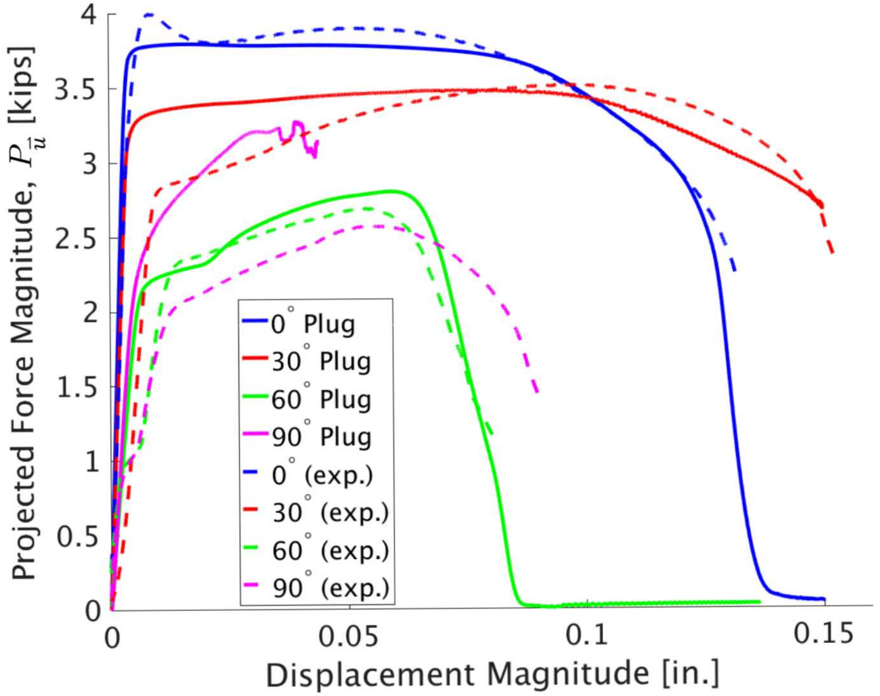


- Element death on EQPS
- Plug model radius: tensile stress area

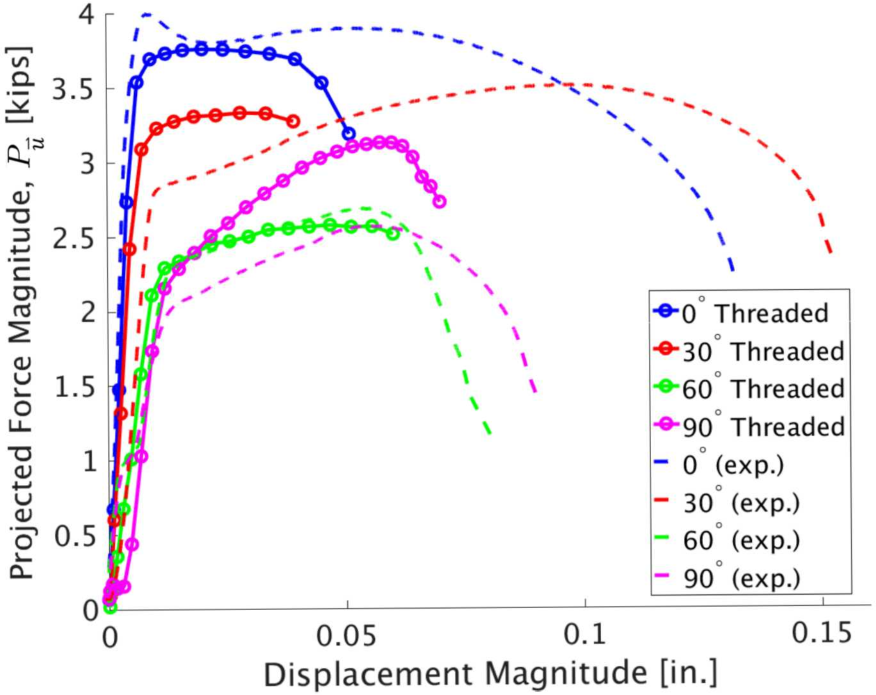


0°
30°
60°
90°
MISES
0.0e+00
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
110000
120000
130000
140000
150000
1.6e+05

Results: Ductile Damage Failure Model



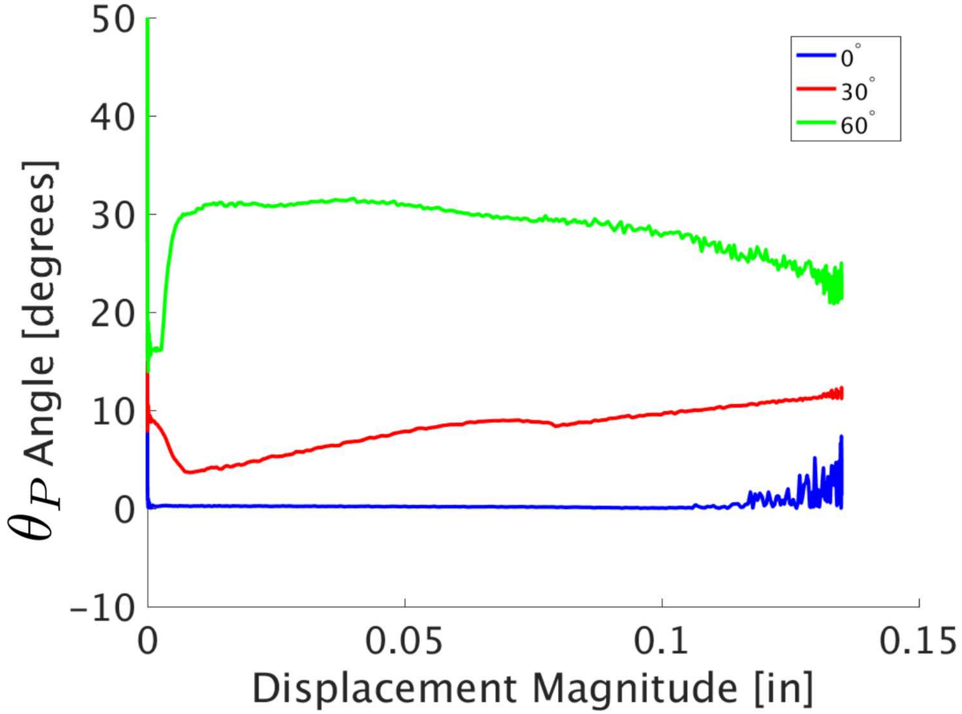
a) Plug Model

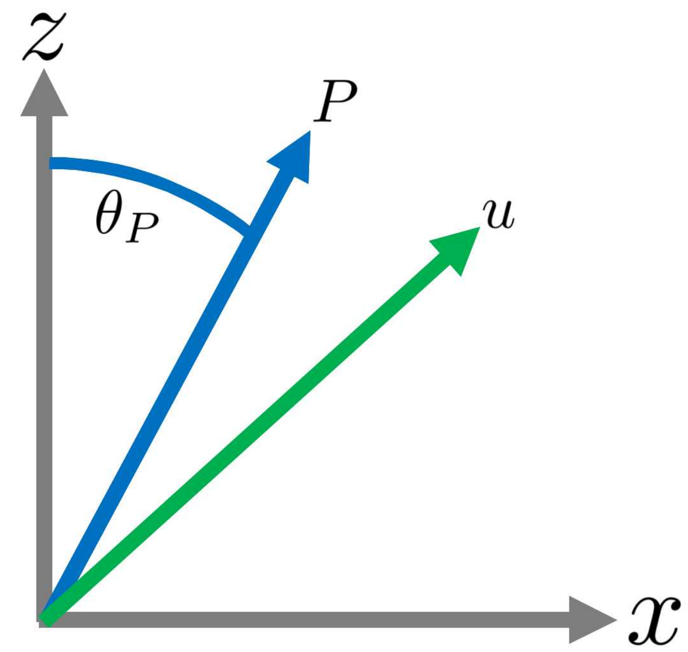


b) Threaded Model

- ml_ep failure shown

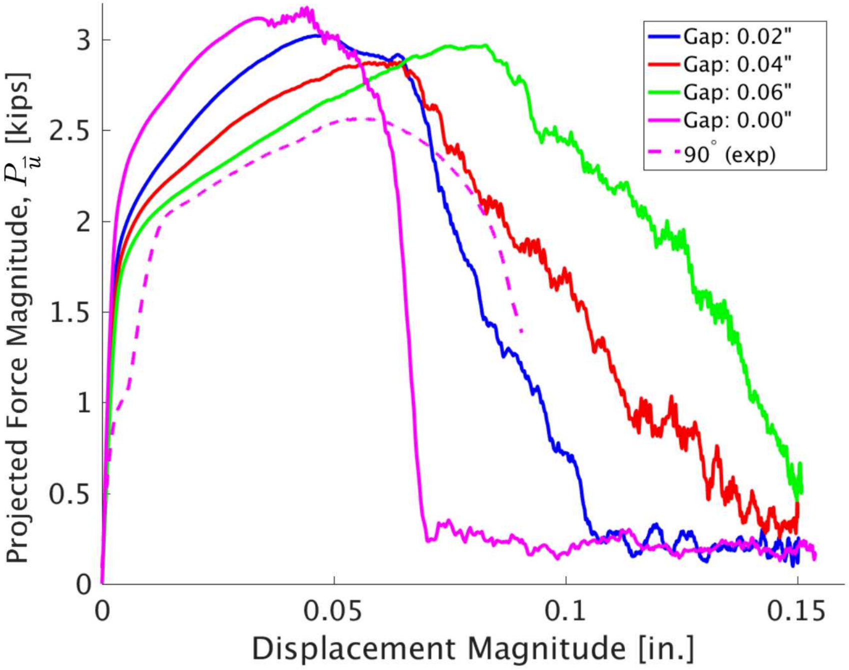
Results: Load Angle vs. Displacement



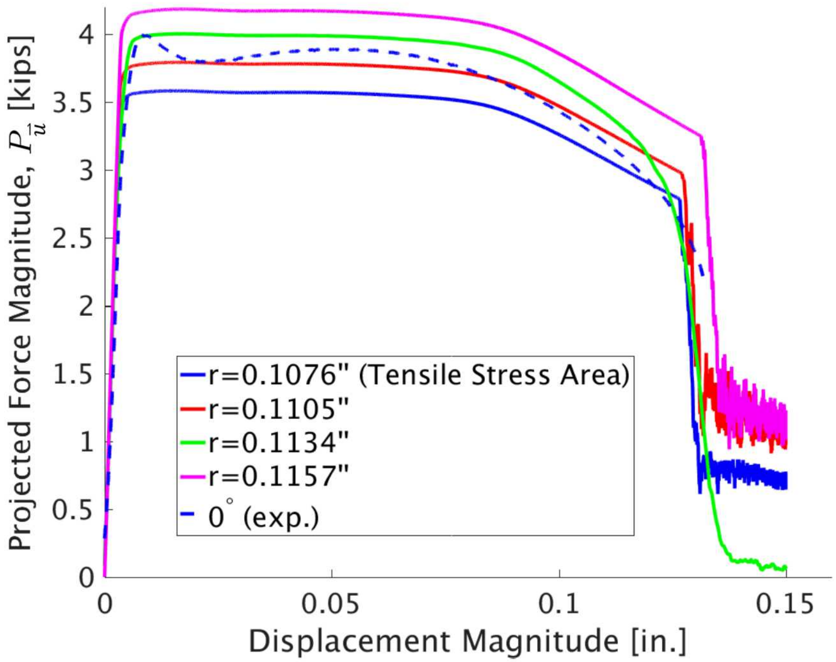


Results: Parameter Studies

- Various studies including: Effect of preload, friction, and yield stress



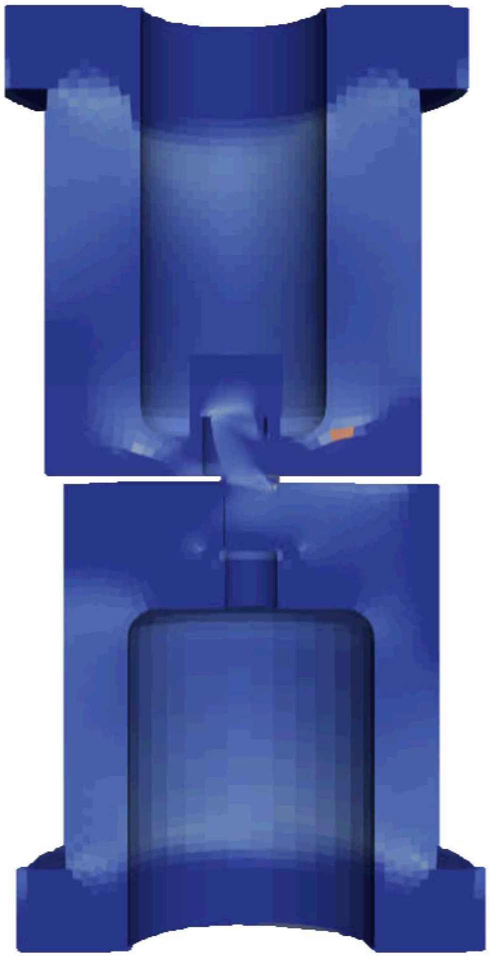
a) Initial bushing gap



b) Plug radius, r

Conclusion

- Plug model comparisons to:
  - Experiment data
  - A fully threaded FE model
- Research answers:
  - Plug models compare favorably for overall load-displacement behavior
  - Agreements to experiments were possible when load projection was considered
  - The failure models considered do not fully capture trends presented in experimental data



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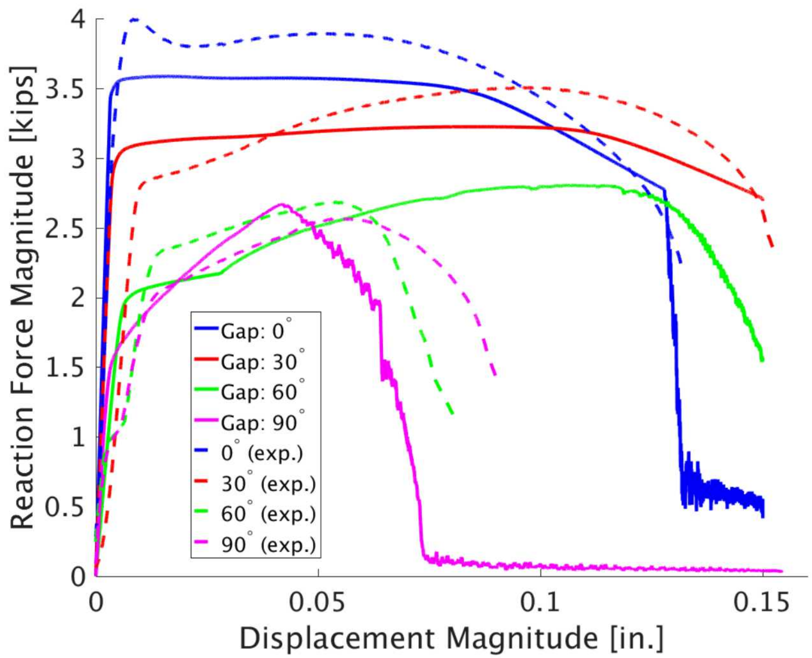
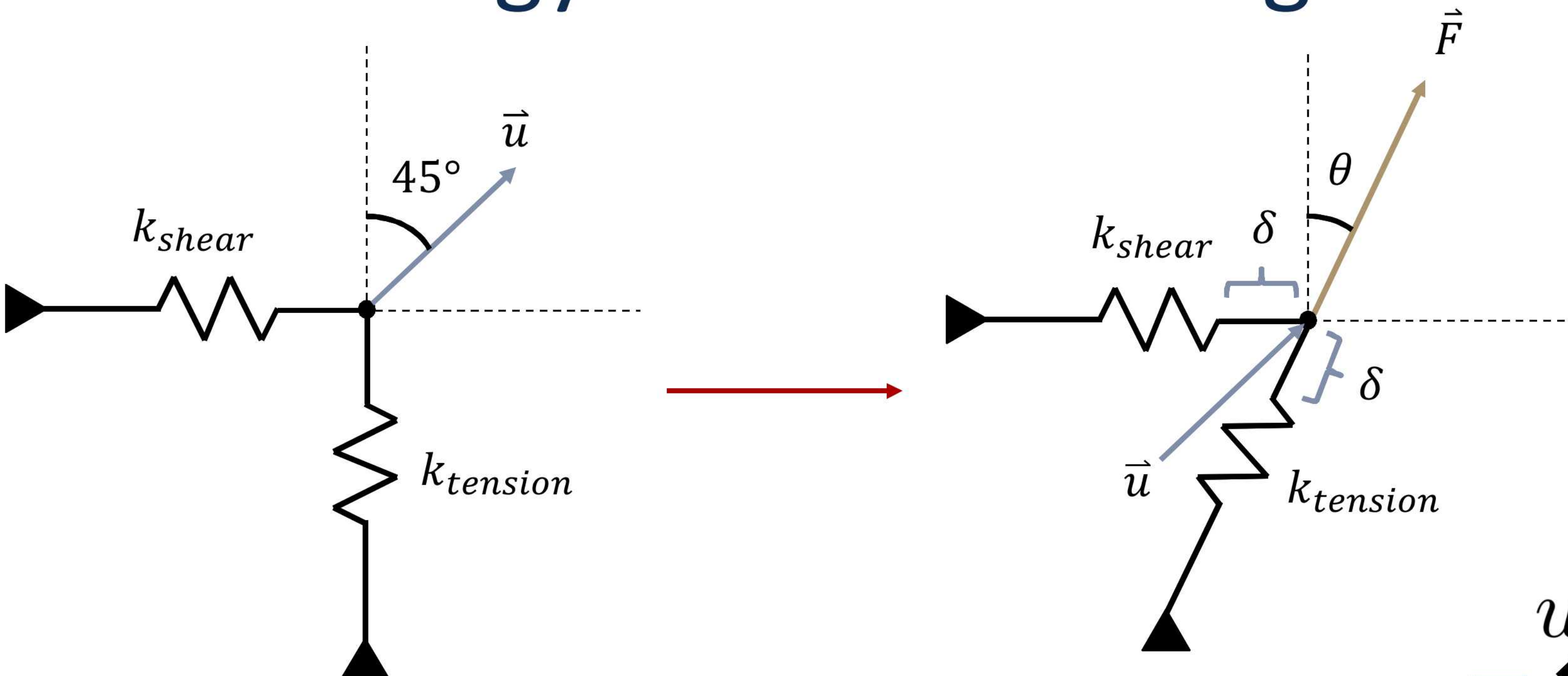
Backup Slides



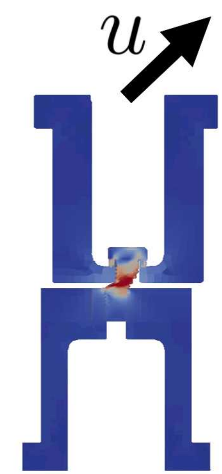
a) Plug model with initial gap of 0.04”

Methodology: Post-Processing



$$k_{tension} > k_{shear}$$
$$\theta < 45°$$

$$F_{tension} = k_{tension} * \delta$$
$$F_{shear} = k_{shear} * \delta$$
$$F_{tension} > F_{shear}$$



Backup Slides

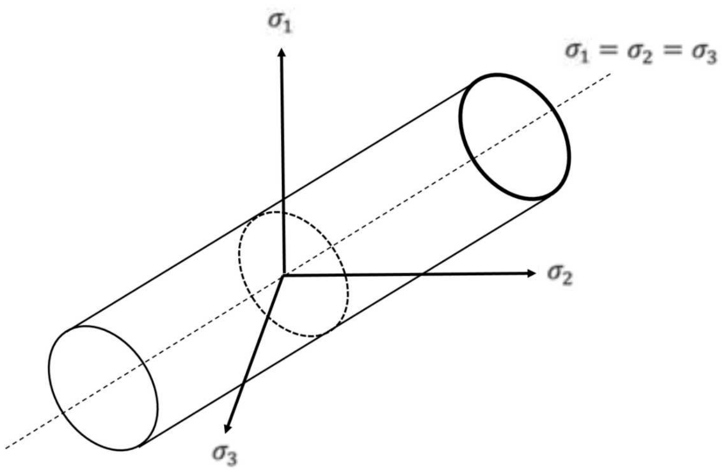
- Von Mises Yield Criterion:

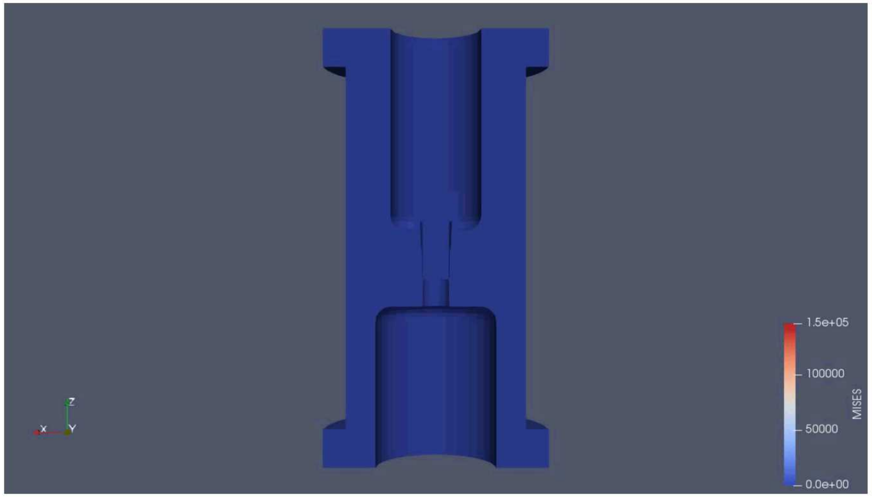
$$\sigma_{vm} = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]}$$

(Where $\sigma_{1,2,3}$ are the principal stresses, respectively)

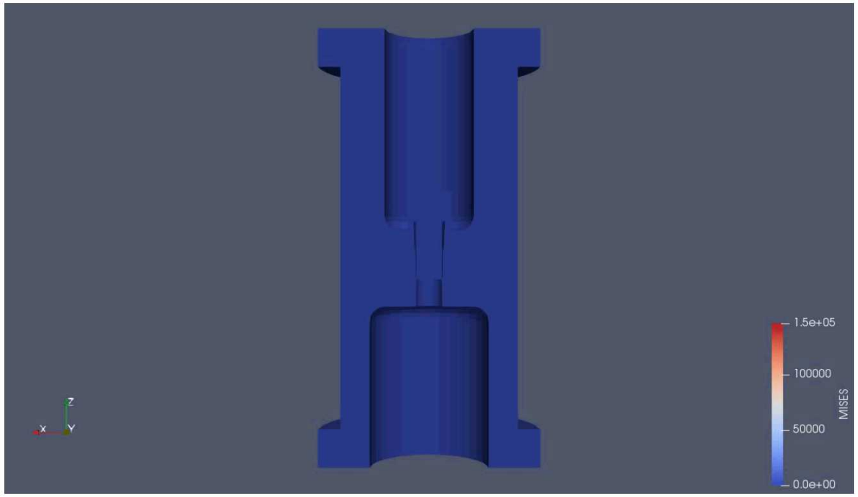
  - This defines a cylindrical 3D yield surface in principal stress space.
    - Axis is along hydrostatic stress states
  - σ_{vm} comes from deviatoric stress S:

$$\sigma_{ij} = S_{ij} + \frac{1}{3}\sigma_{kk}\delta_{ij}$$
$$J_2 = \frac{1}{2}S_{ij}S_{ij}$$
$$\sigma_{vm} = \sqrt{3J_2}$$

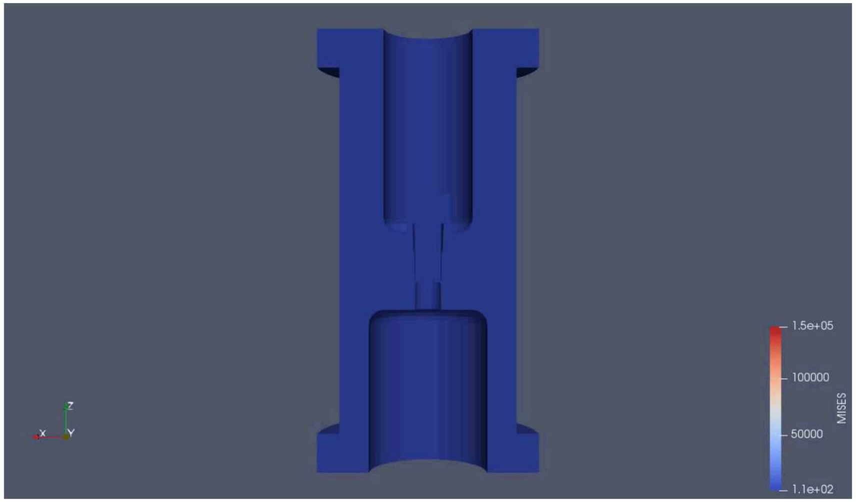




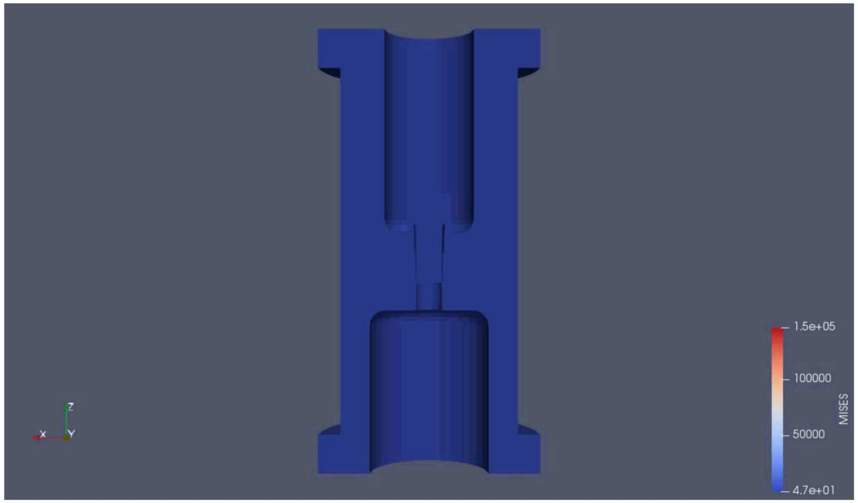
0-deg



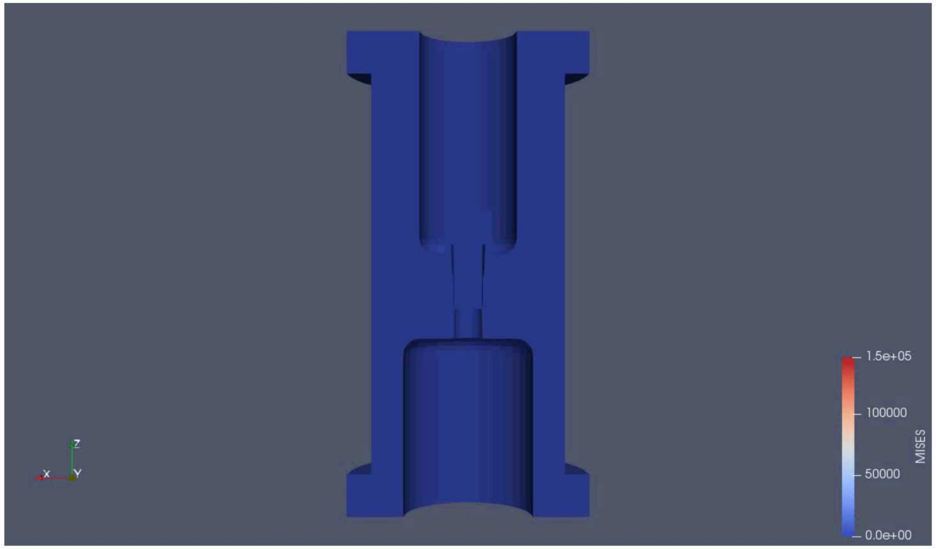
0-deg with tear



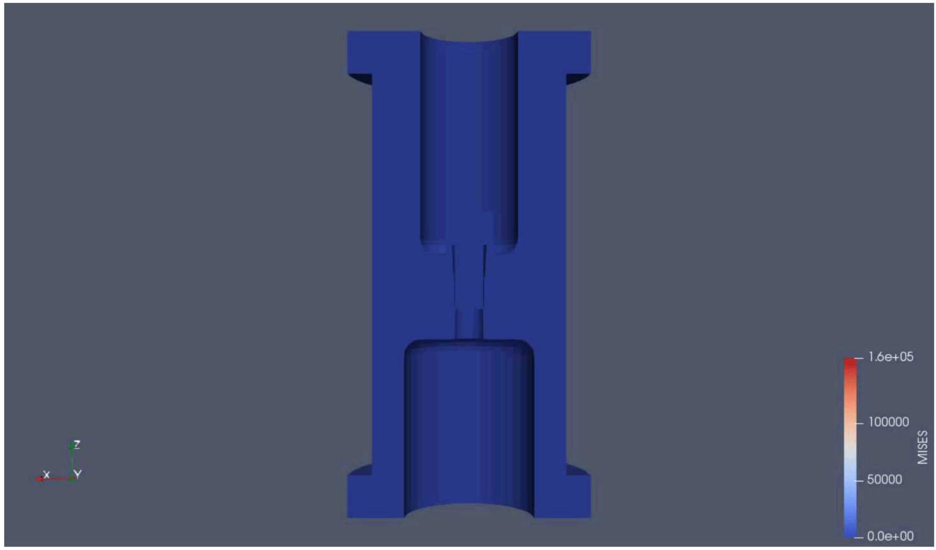
30-deg



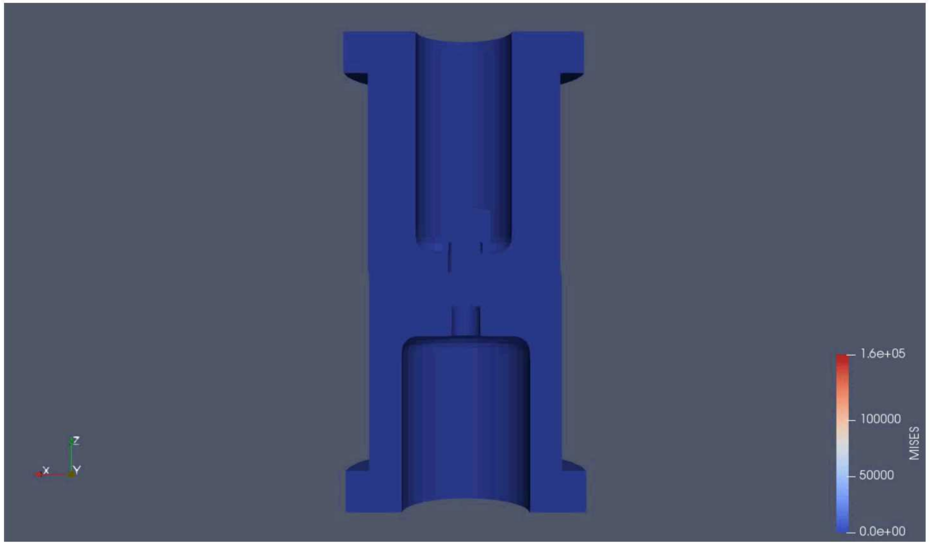
30-deg with tear



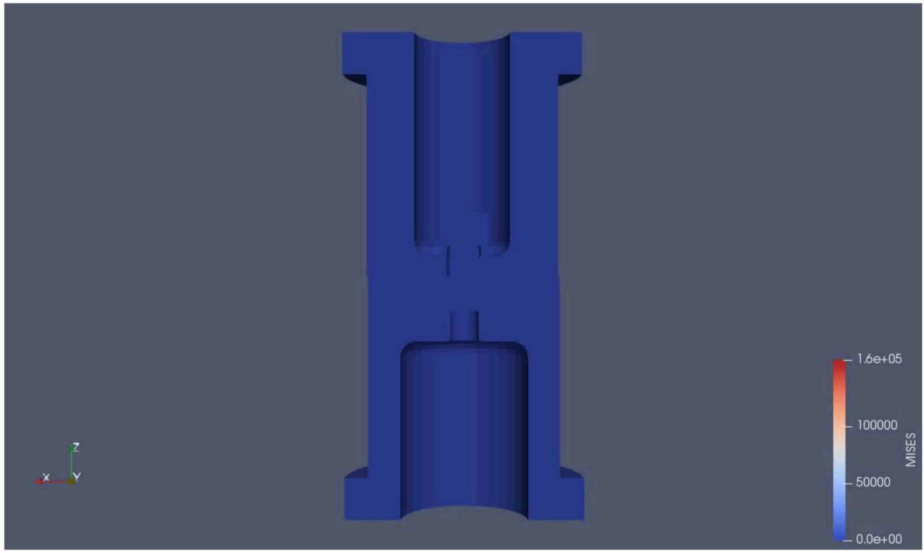
60-deg



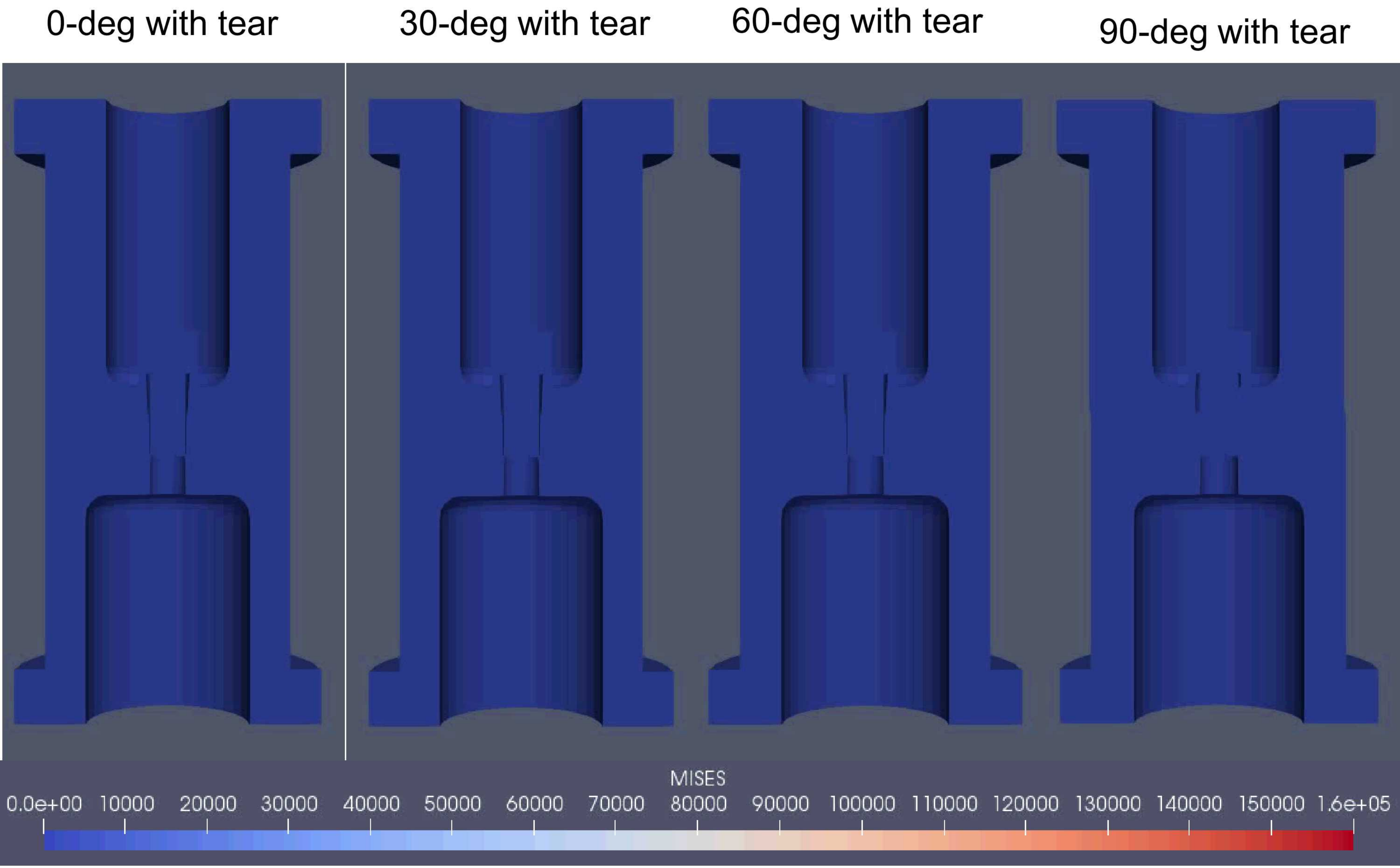
60-deg with tear



90-deg



90-deg with tear


0-deg with tear
30-deg with tear
60-deg with tear
90-deg with tear
MISES
0.0e+00 10000 20000 30000 40000 50000 60000 70000 80000 90000 100000 110000 120000 130000 140000 150000 1.6e+05