PROJECT 2: EVALUATION OF THE NONLINEAR MECHANICAL RESPONSE IN THREADED FASTENERS

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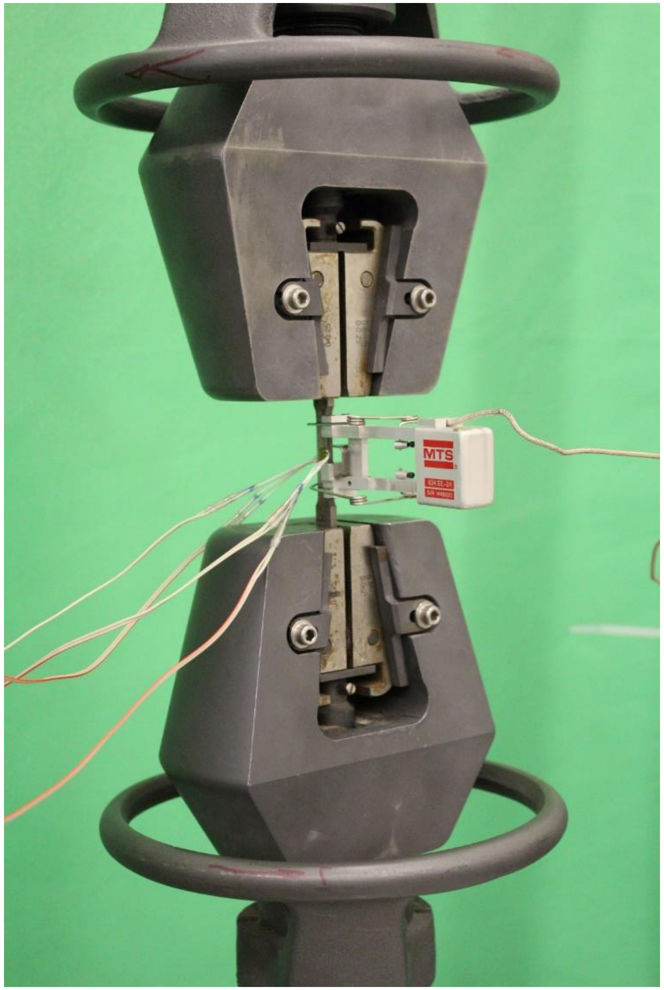
From Macroscopic Tensile Tests to Microscopic Mechanical Response of Components



OBJECTIVES

- Calibrate constitutive models to uniaxial tension test data provided by SNL for Steel A286.
- Attempt to reproduce test results for A286 fastener tension data with FEMs of test.
- Evaluate reduced order fastener modelling approaches.
- Investigate more complicated load cases that expose differences in the constitutive models.

Background: Modeling Fasteners

- In analysis of complex assemblies, fastened joints between components should be engineered.
- There might be many fasteners, and modeling them all in detail is not feasible.
- Reduced order fastener models must be used.
- In transient analyses involving extreme loading conditions, significant plastic strain can occur in the fasteners. This requires fastener models that still accurately capture the post-yield behavior of the actual fasteners.

With only a limited amount of tension testing data, how accurately can we produce simplified models for various fasteners without having test data on each one?

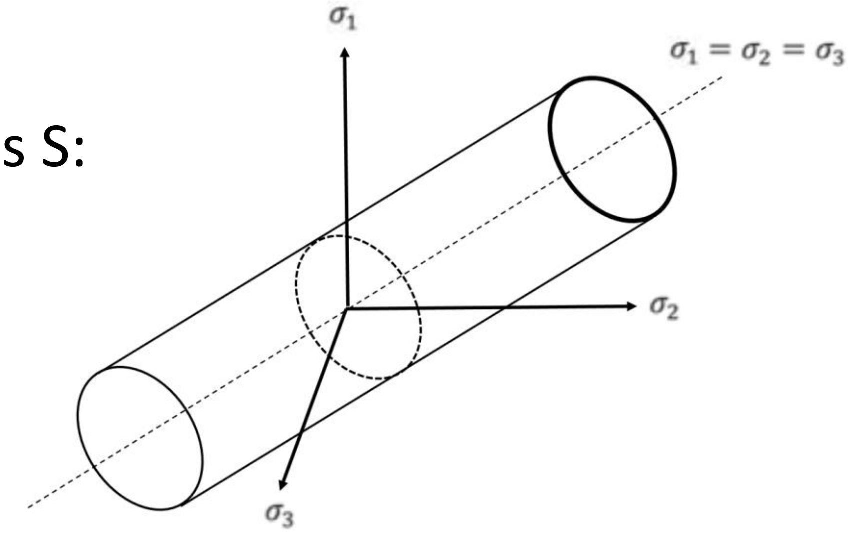
Background: Yield Surface

- Von Mises Yield Criterion:

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

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

  - This defines a cylindrical 3D yield surface in principal stress space.
    - Axis is along hydrostatic stress states

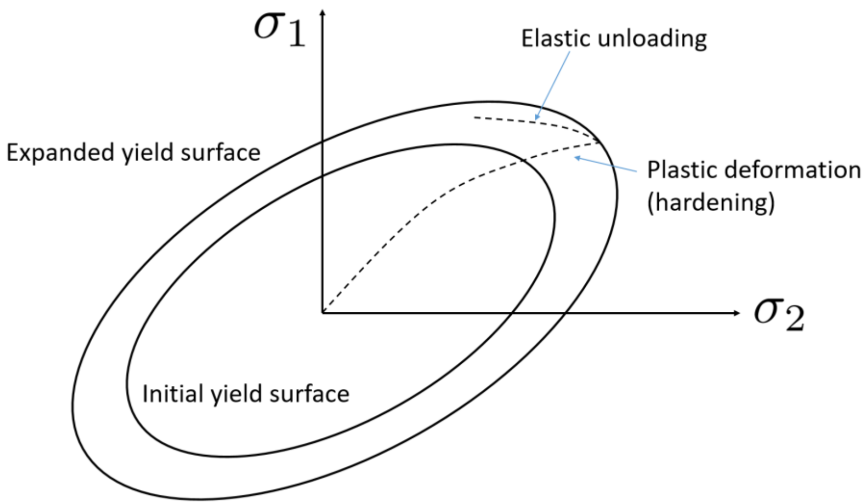


- σ_{vm} comes from deviatoric stress S:

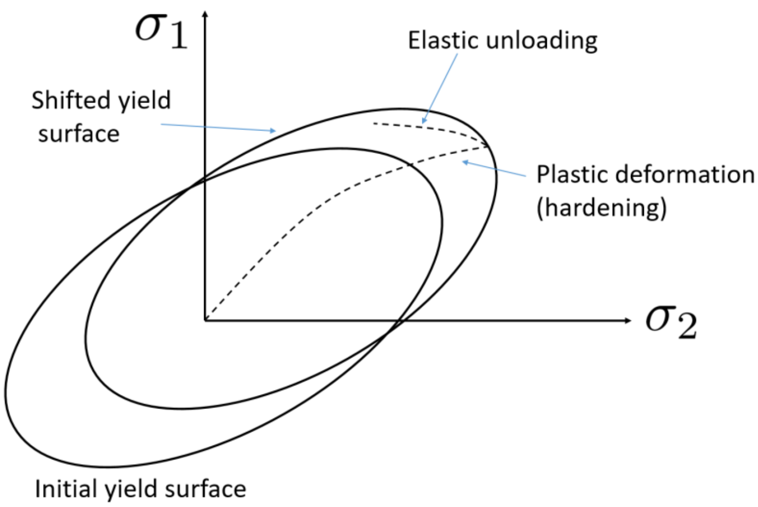
$$\sigma_{ij} = S_{ij} + \tfrac{1}{3}\sigma_{kk}\delta_{ij}$$
$$J_2 = \tfrac{1}{2}S_{ij}S_{ij}$$
$$\sigma_{vm} = \sqrt{3J_2}$$

Background: Constitutive Models

- Isotropic Hardening
  - Yield Surface retains its shape and is symmetric about the origin
  - Increases uniformly as the material deforms plastically



- Kinematic Hardening
  - Yield Surface retains its shape and size
  - Shifts as the material deforms plastically



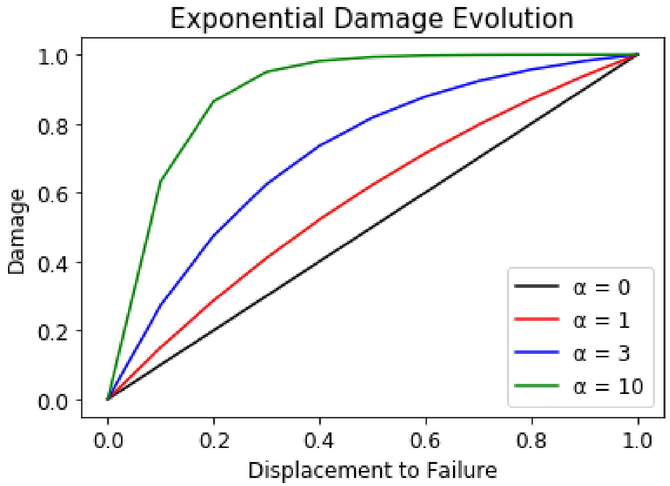
Constitutive Models Background

- Hardening Curve Definition
  - Multi Linear Elastic-Plastic
    - Linear piecewise hardening curve defined with discrete pairs of equivalent plastic strain and yield stress
  - Johnson-Cook
    - Yield stress follows an analytical function of the equivalent plastic strain
    - Can take into account strain rate dependence and temperature effects
    - Ideal for high strain rate deformations

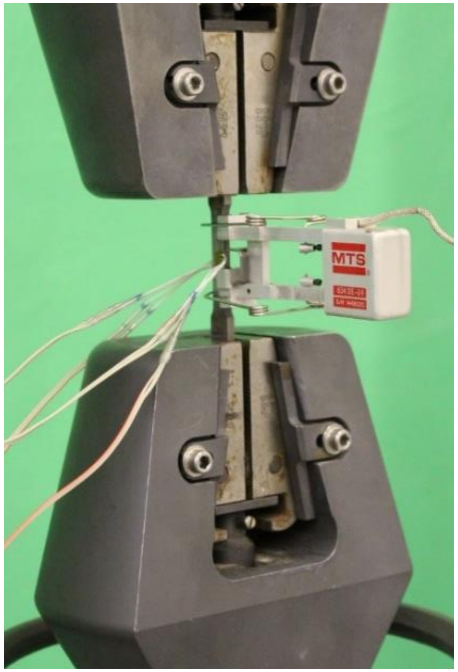
$$\sigma_e = [A + B(\epsilon_e^p)^n][1 + Cln(\frac{\dot{\epsilon}_e^p}{\dot{\epsilon}_{eo}^p})][1 - \hat{T}^m]$$

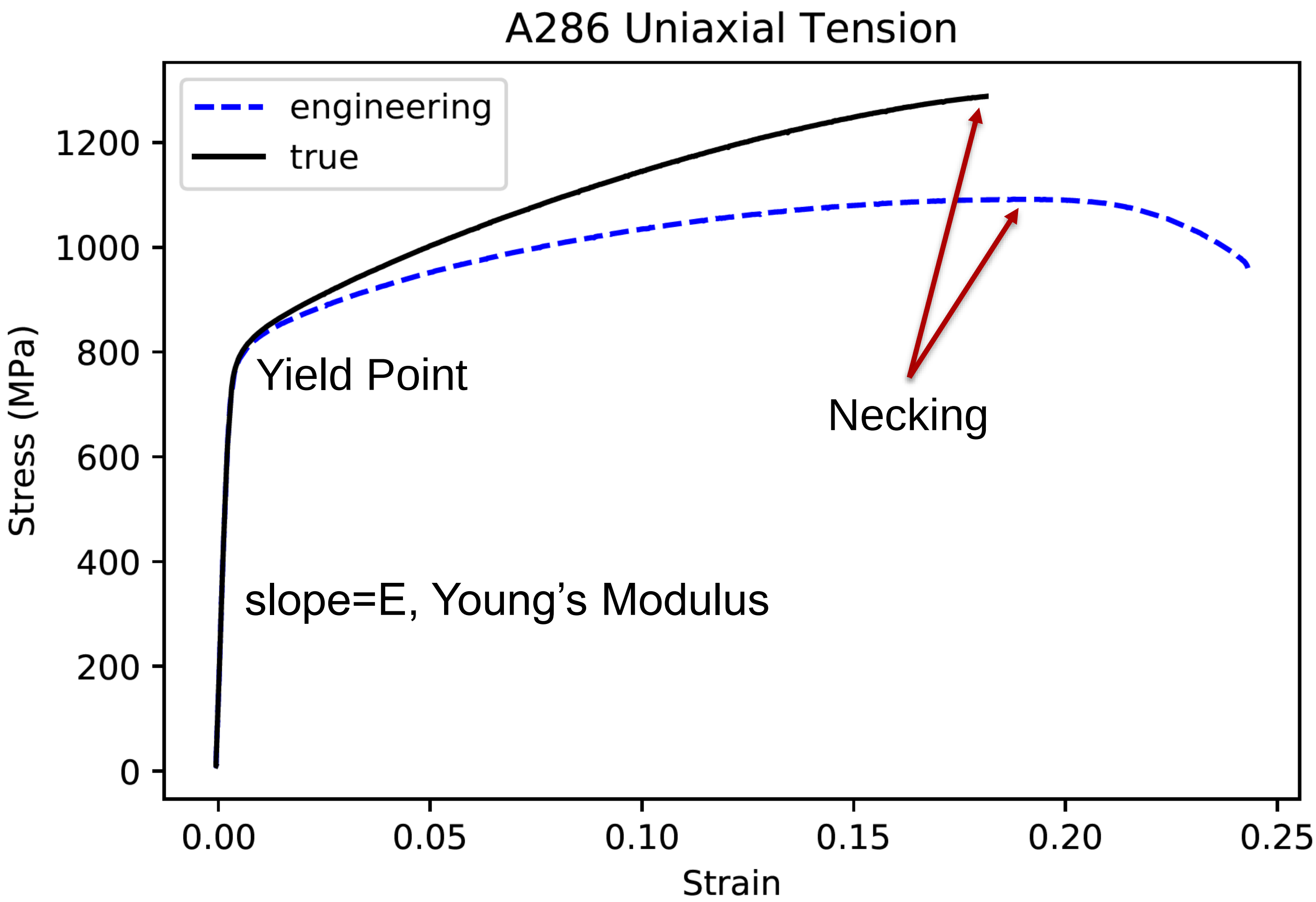
Damage Criterion

- Initiation: Ductile damage
  - Phenomenologically predicts the onset of damage due to void nucleation, growth, and coalescence
  - At a local equivalent plastic strain (fracture strain) damage “initiates”
- Evolution: Independent of damage initiation model
  - Progressive degradation of material stiffness, leading to material failure
  - Can be described exponentially

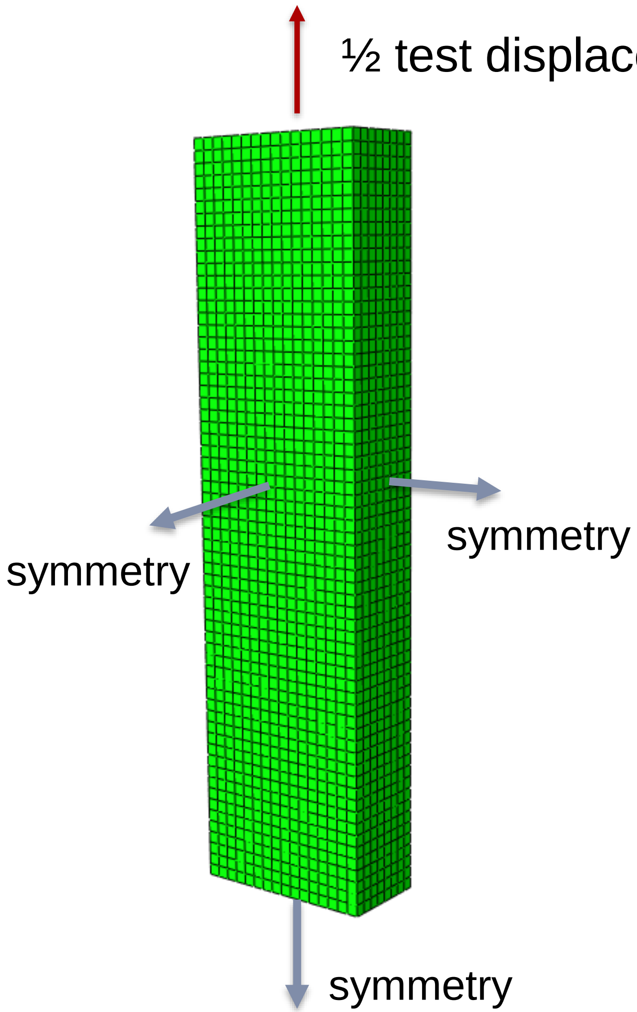


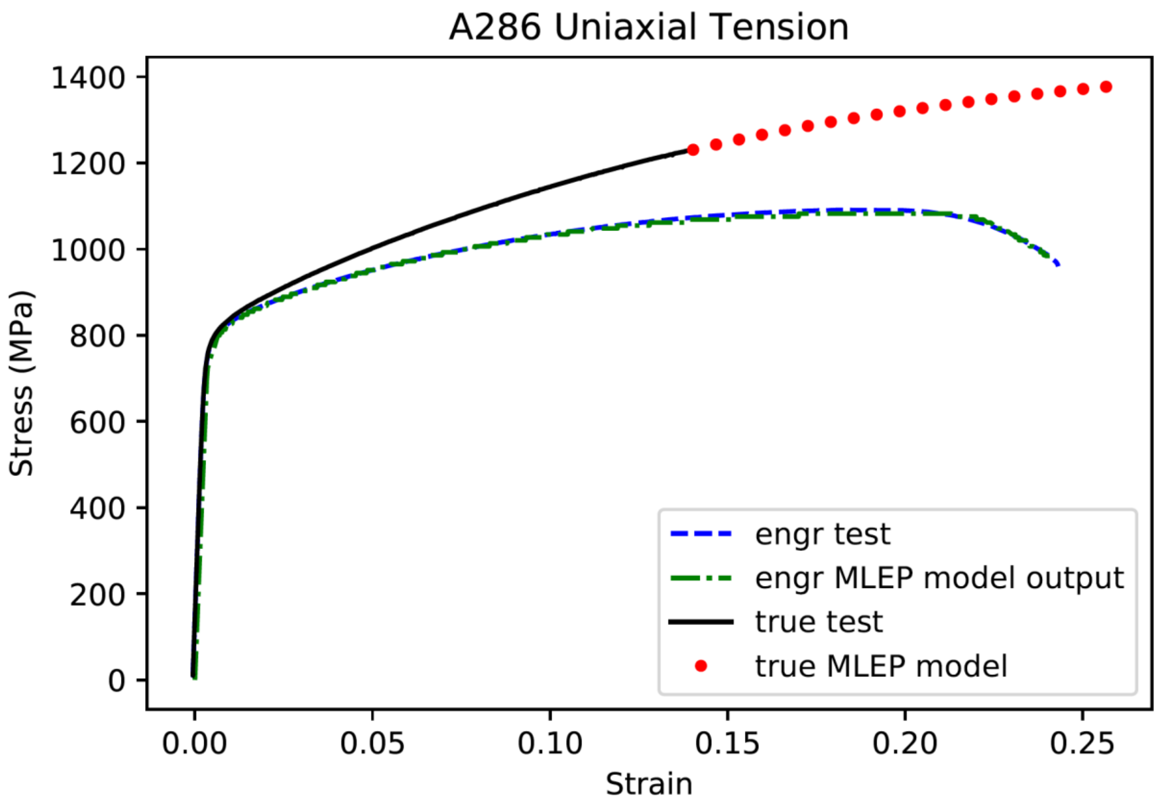
A286 Tension Test (SNL)





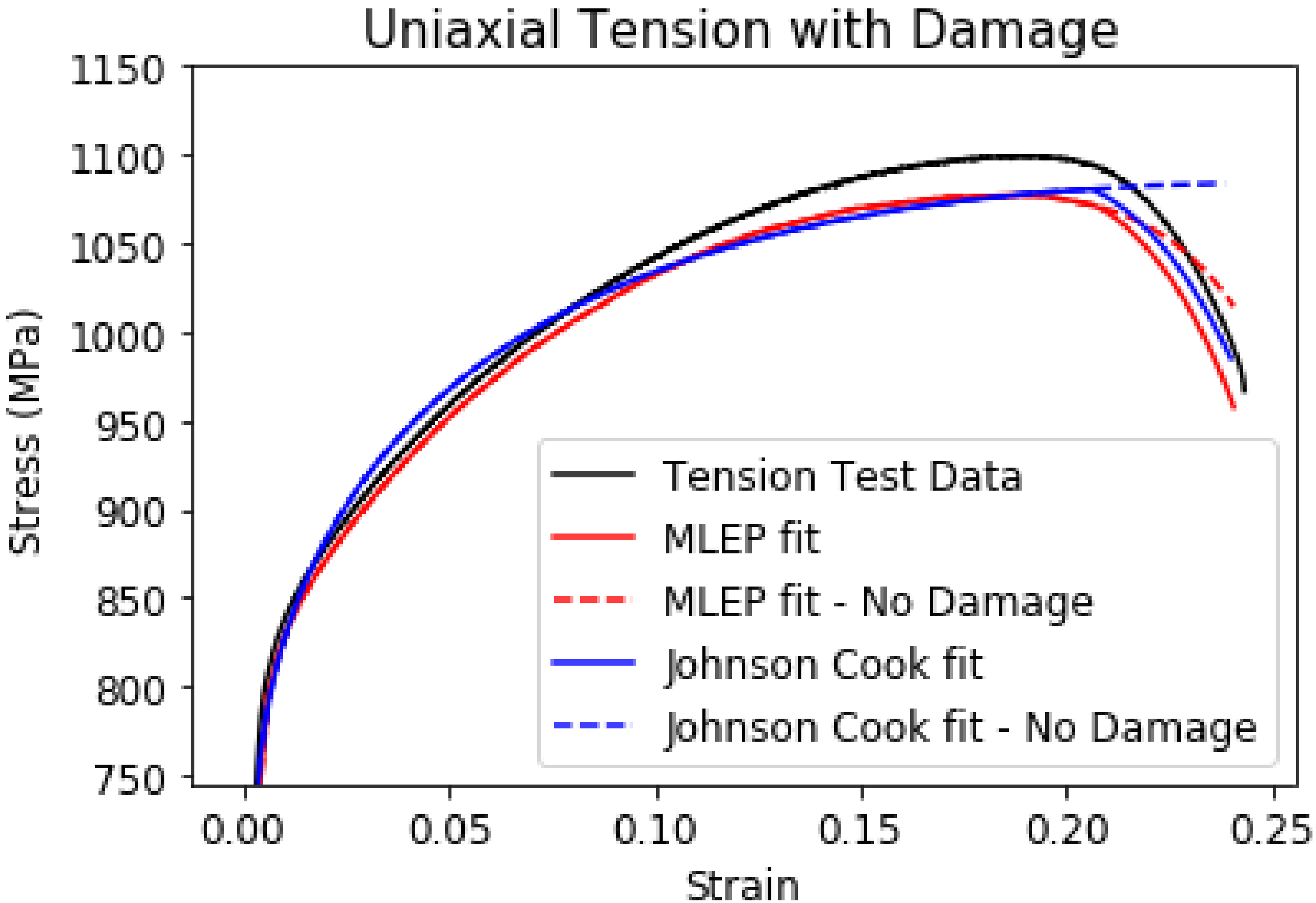
Uniaxial Tension Calibration



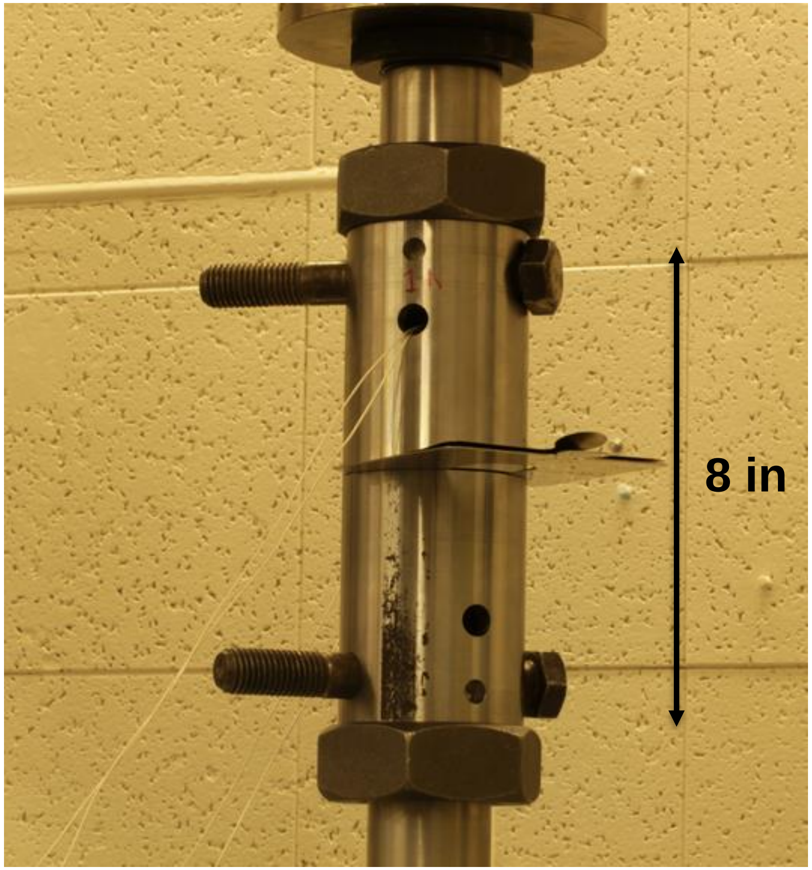


Uniaxial Tension FEM used for calibration

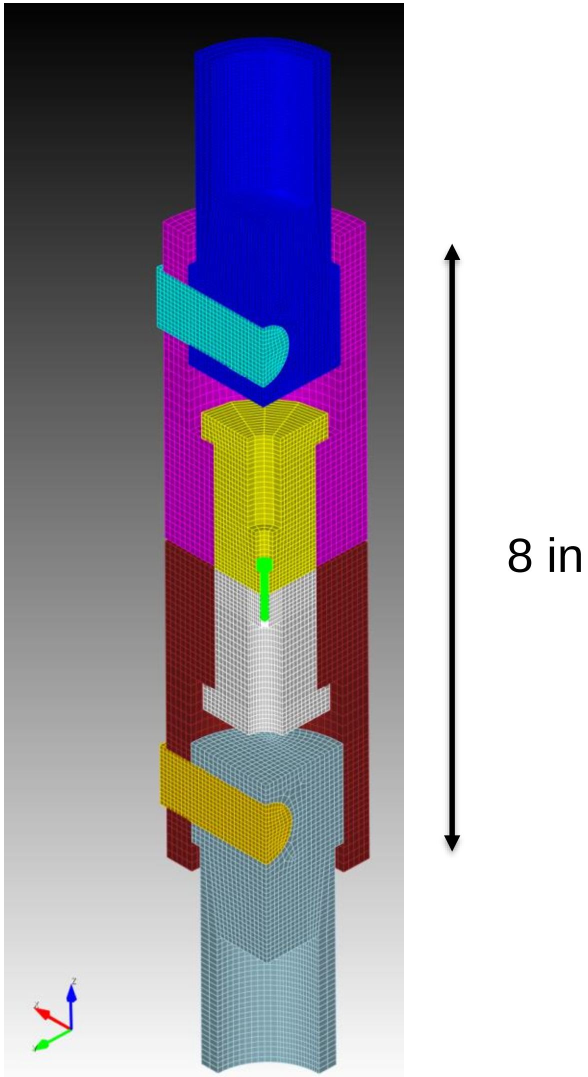
Uniaxial Tension Calibration



Fastener Test Setup



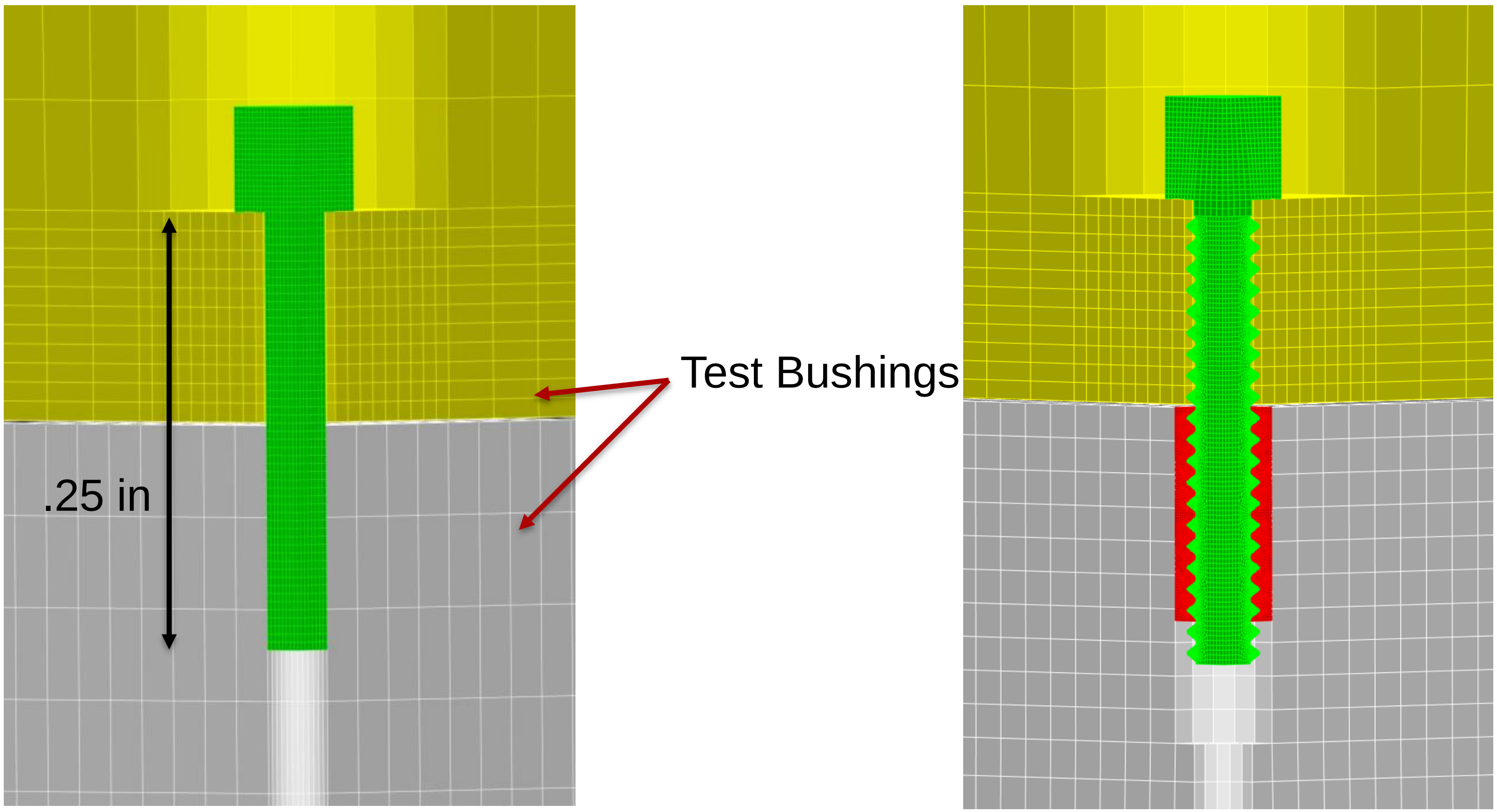
Real Test



FEM of test (quarter symmetry)

Reduced Order Fastener Models

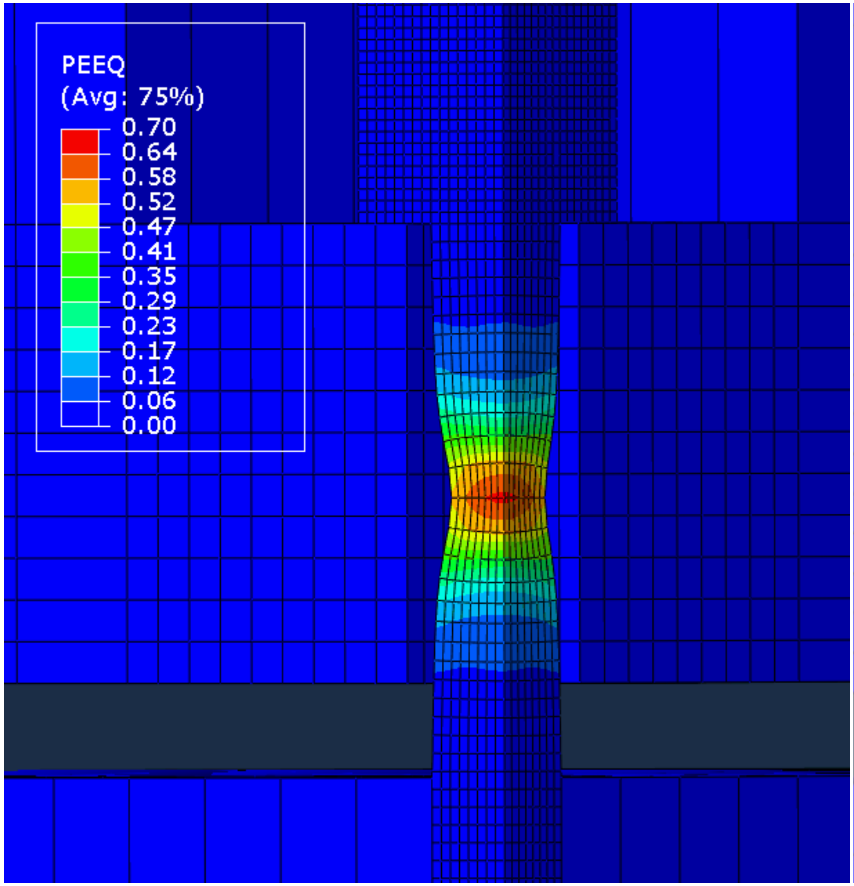
- Two types of simplified fastener models (#0-80 pictured)

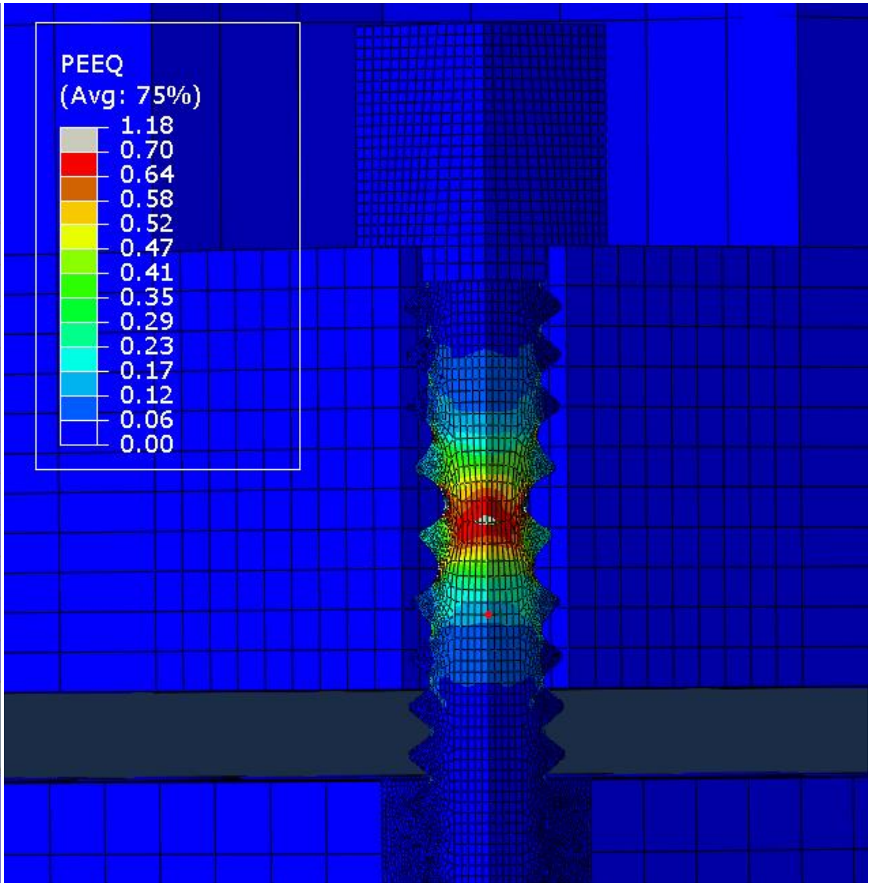


Plug model

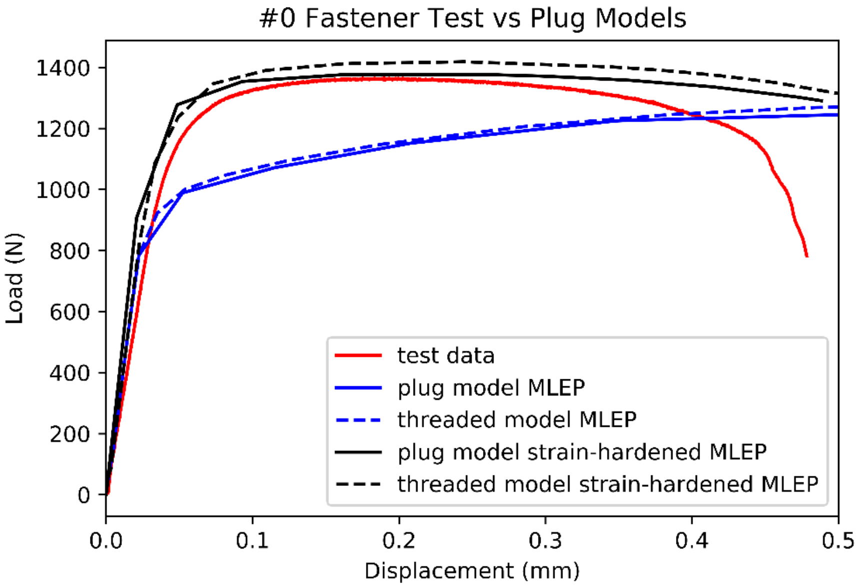
Threaded model

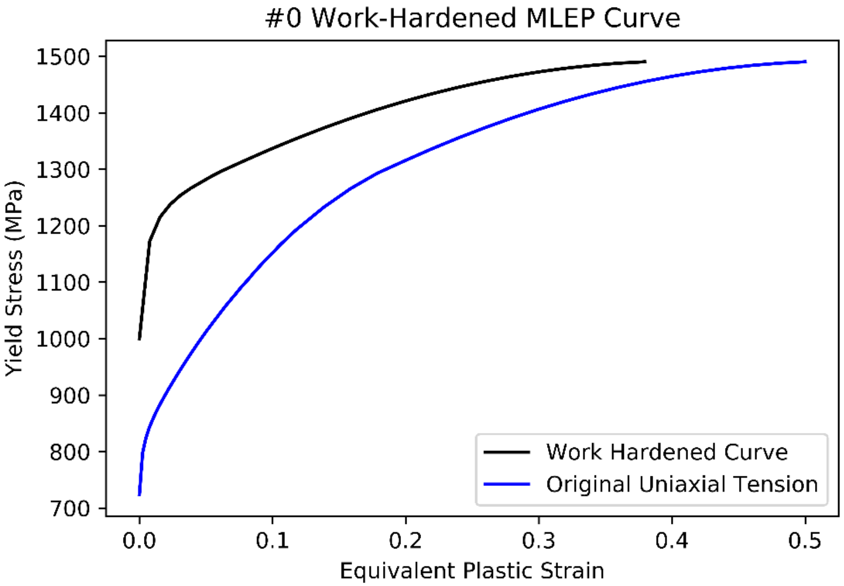
Equivalent Plastic Strain in Models





Blind Predictions of Fastener Test Data





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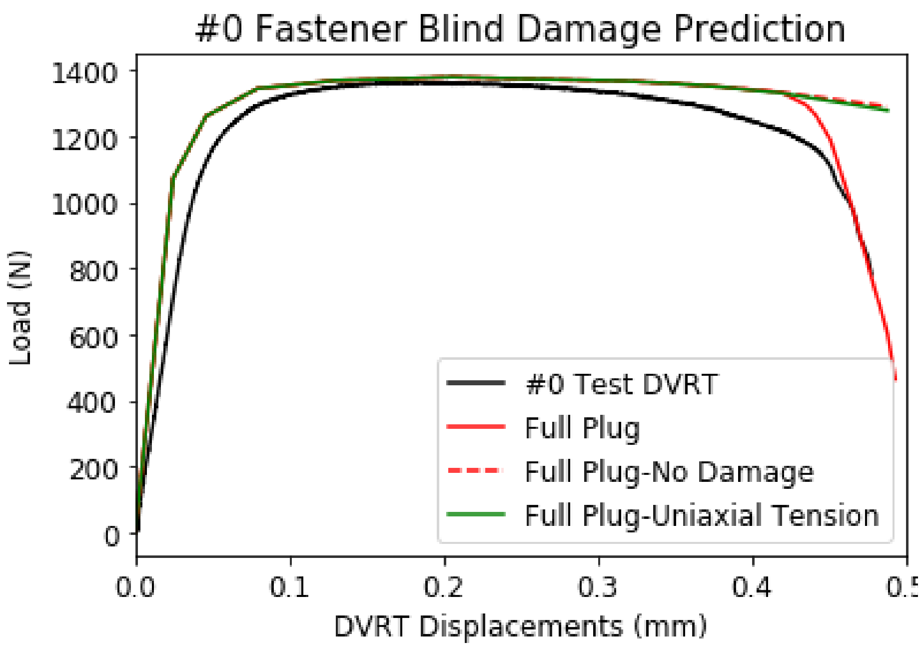
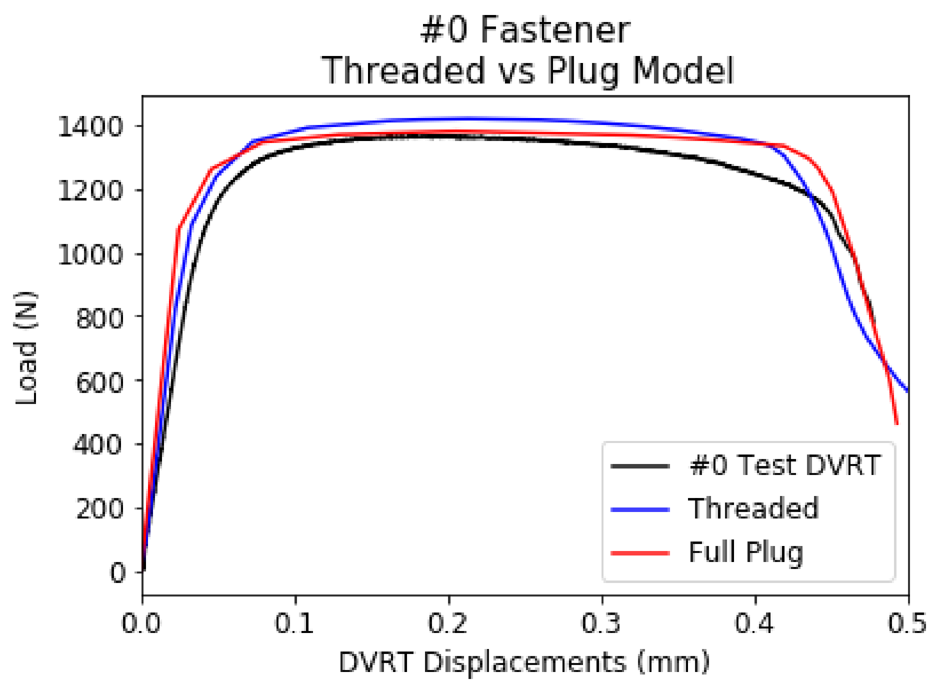
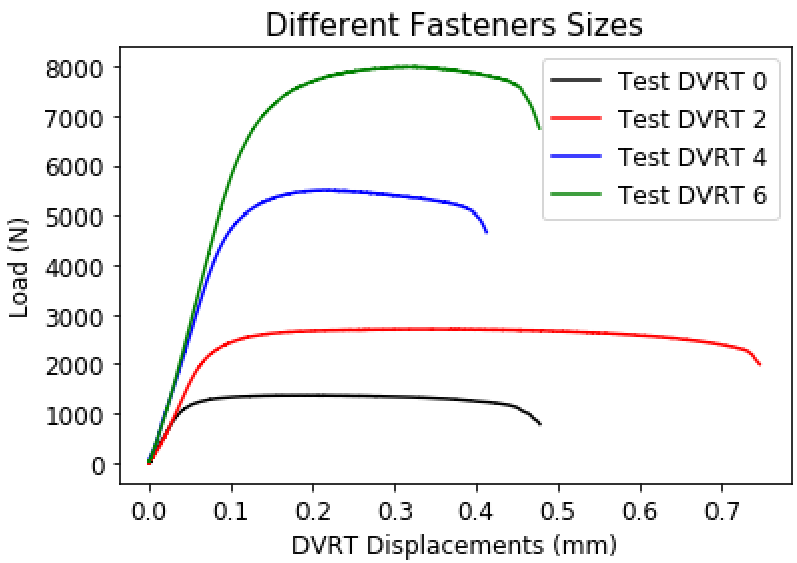
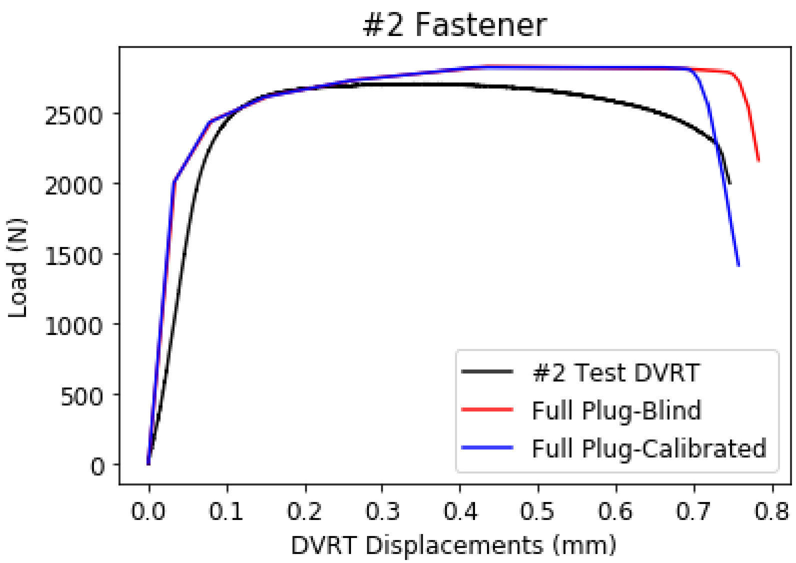
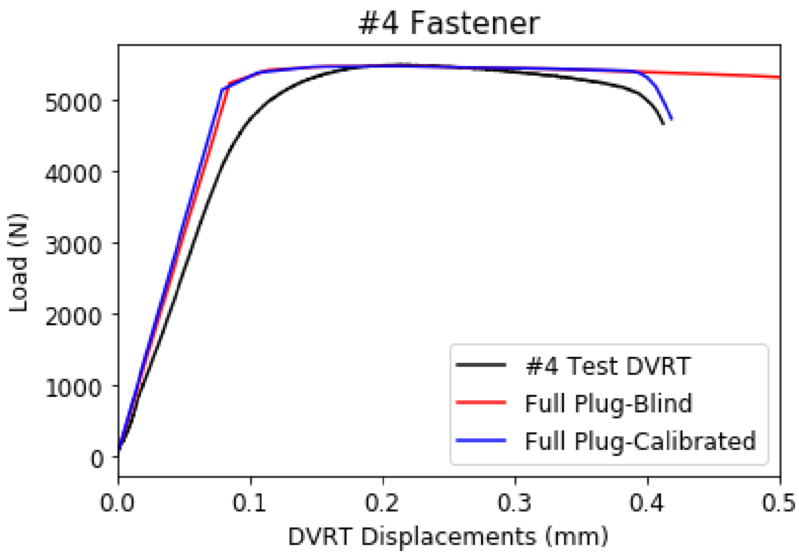


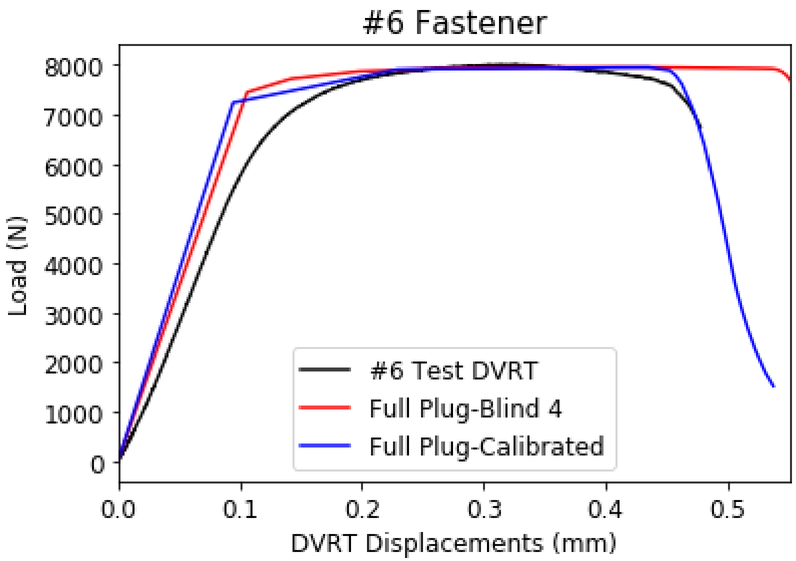


Extrapolating MLEP to Other Sizes

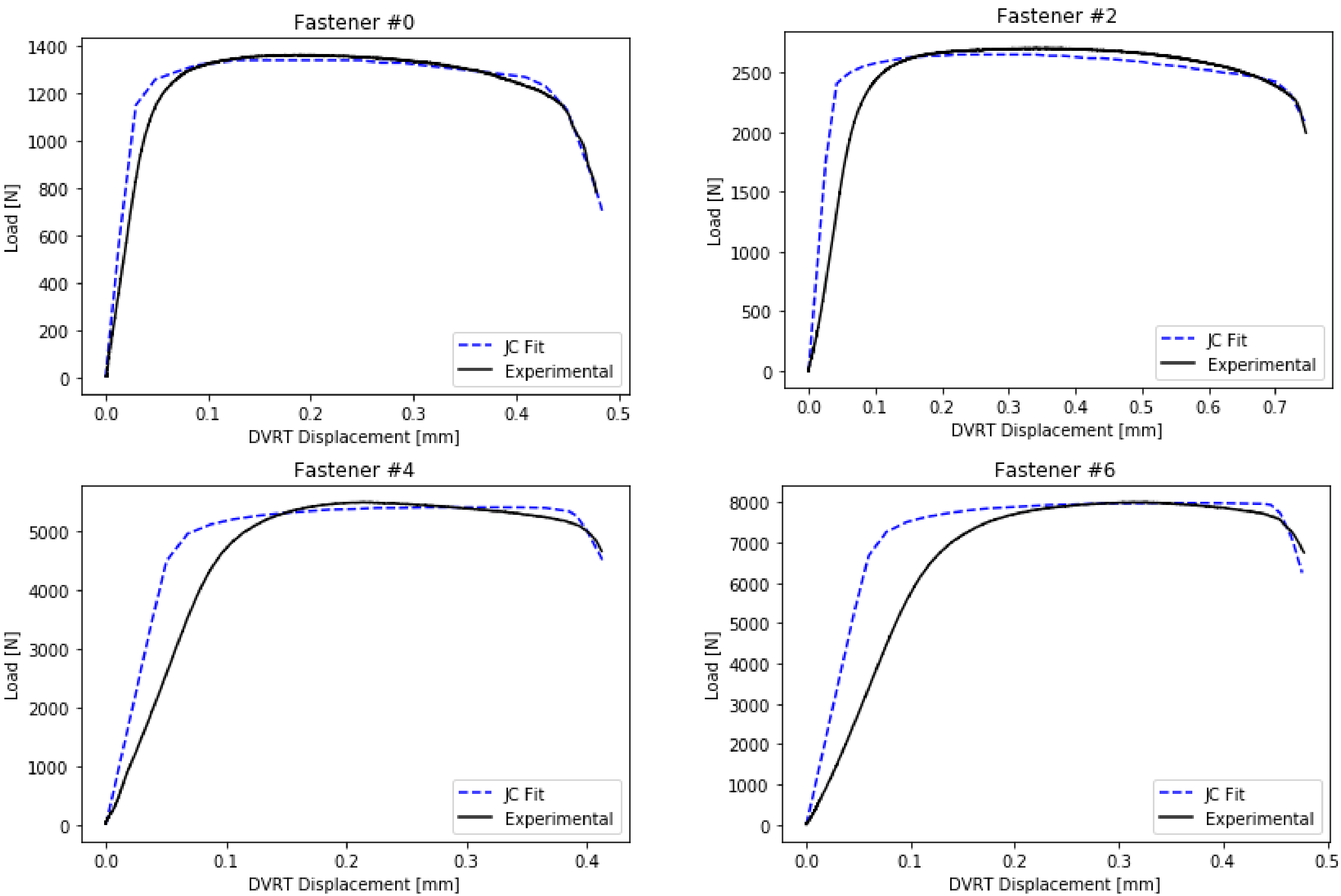








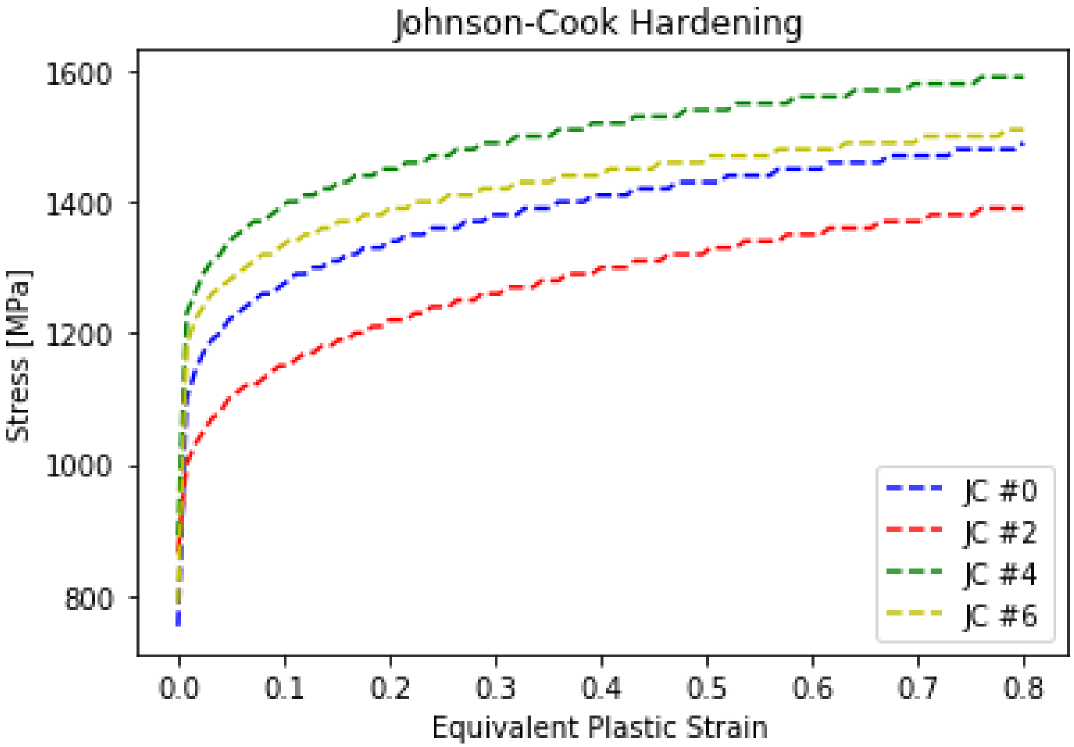
Johnson-Cook Fastener Calibrations



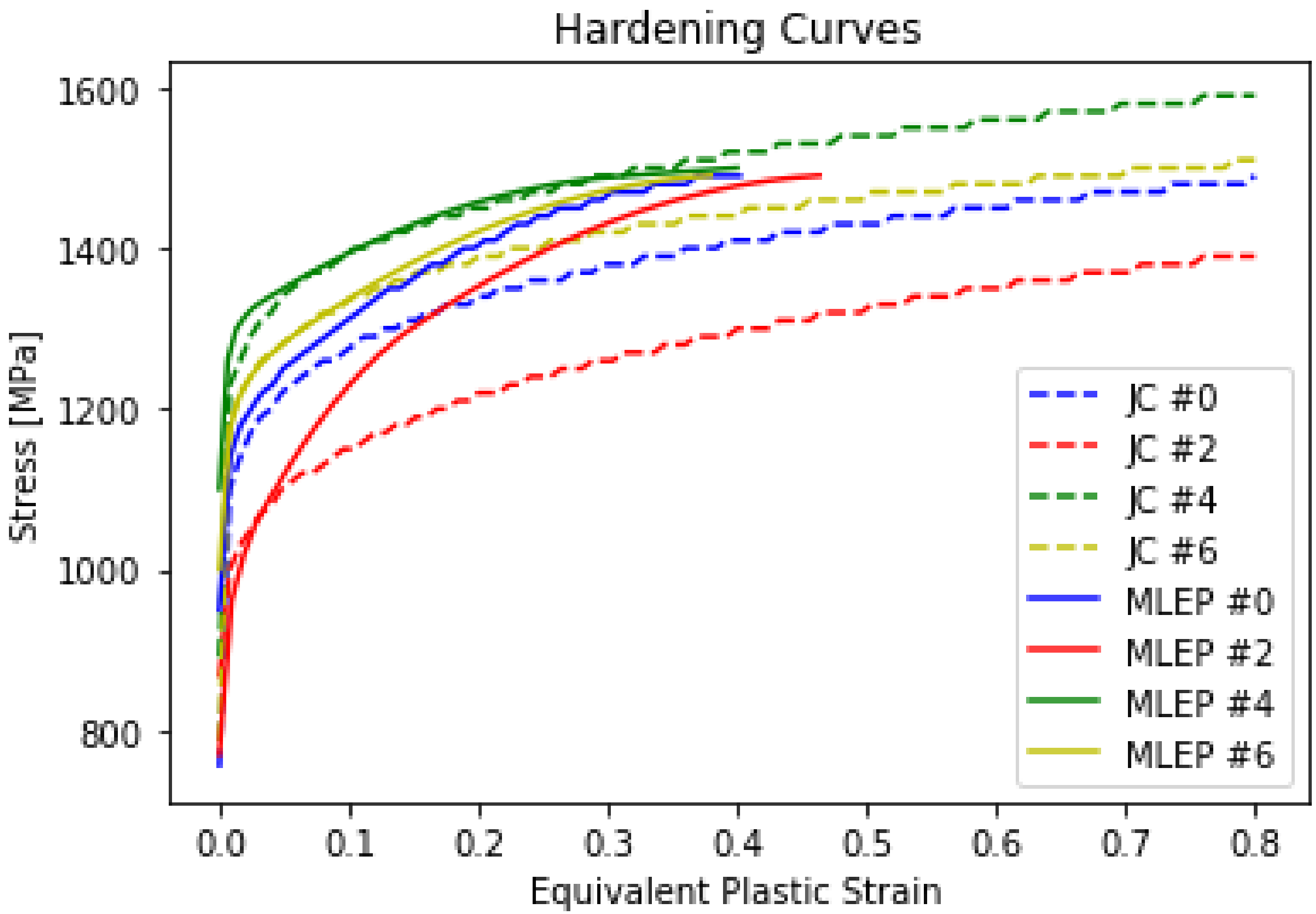
Johnson-Cook Hardening Curves

Parameters	#0	#2	#4	#6
A	752.74	865.05	890.87	786.50
B	760.02	565.59	725.53	743.02
n	0.1627	0.2963	0.1603	0.1325

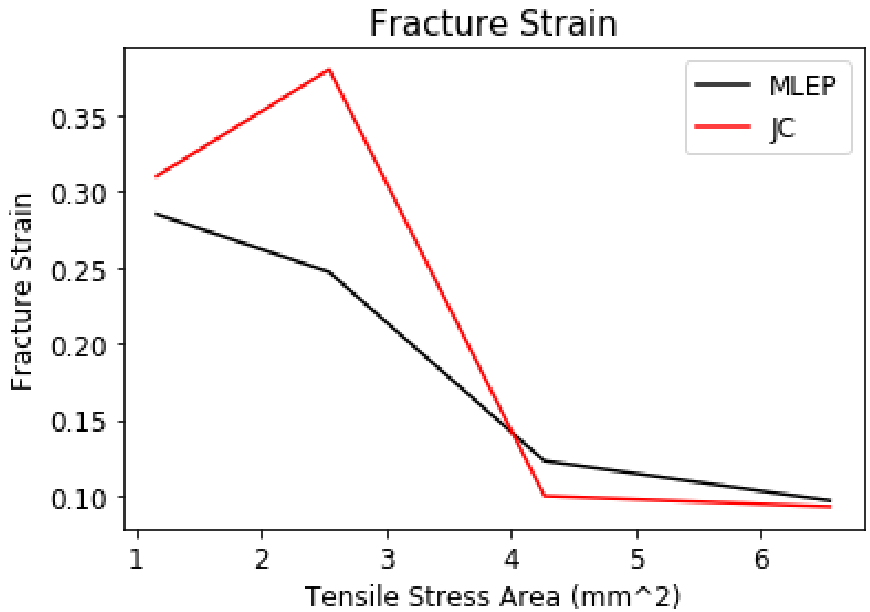
$$\sigma = \mathrm{A} + \mathrm{B}(\varepsilon_P)^n$$



Hardening Curves



Trend of Damage Parameters

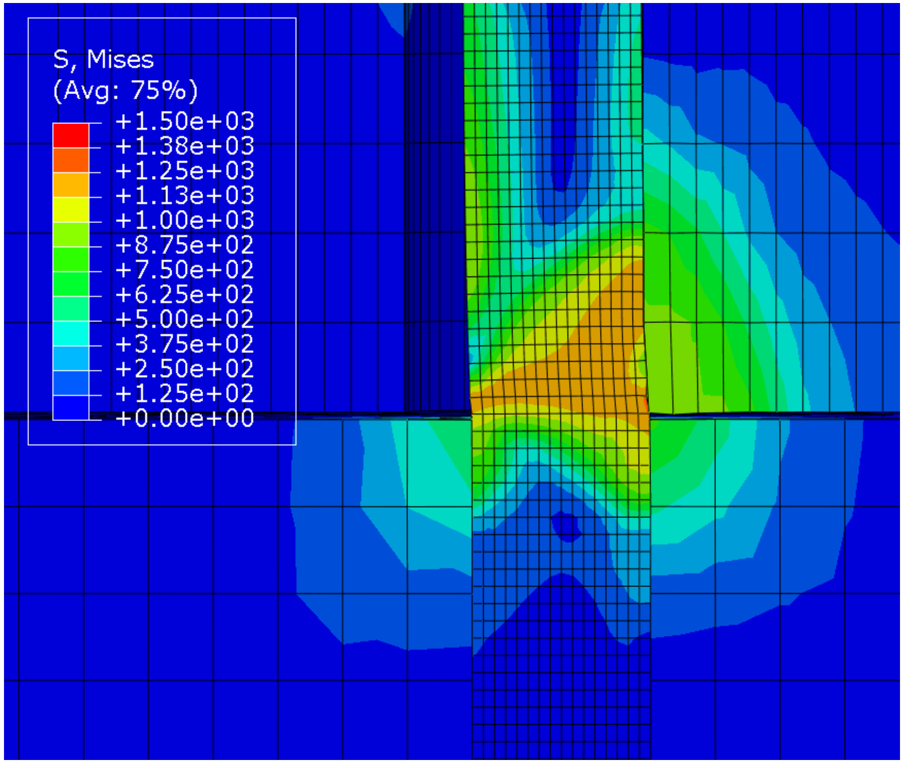


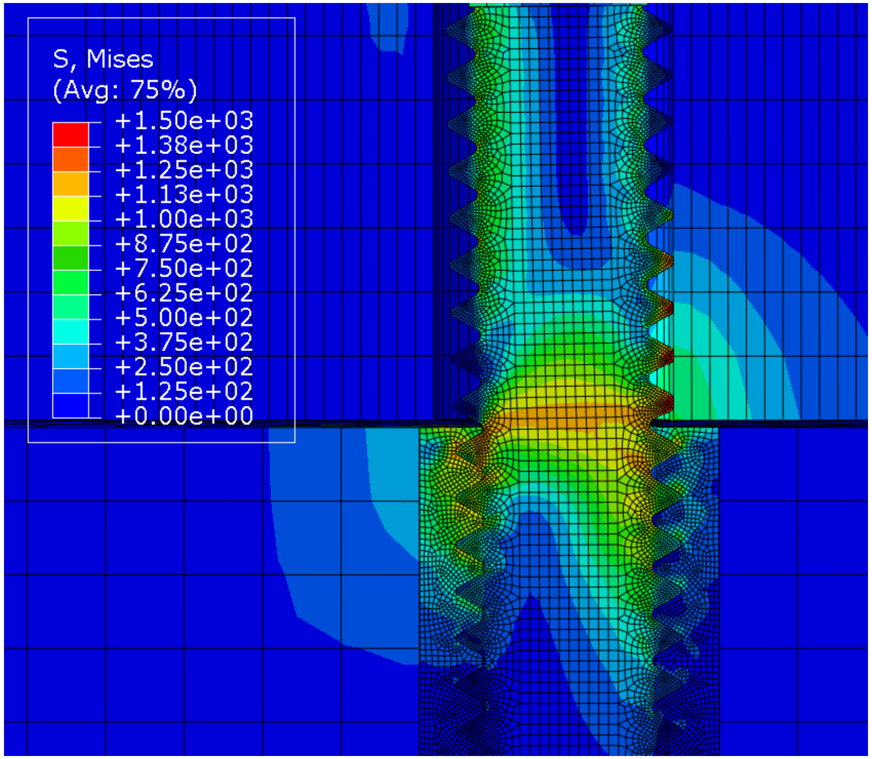
Model	Fracture Strain		Displacement at Failure (mm)		Alpha	
Smooth Specimen	**0.23**	0.19	**1.27**	0.508	**1**	1
#0 Plug	**0.285**	0.31	**0.1**	0.1	**8**	7
#2 Plug	**0.247**	0.38	**0.1**	0.1	**8**	7
#4 Plug	**0.123**	0.1	**0.1**	0.1	**7**	6
#6 Plug	**0.097**	0.093	**0.1**	0.1	**7**	7
	Bold: MLEP		Regular: Johnson Cook			

Combined Loading

Shear

- Shearing deformations applied with BC's similar to SNL tests.





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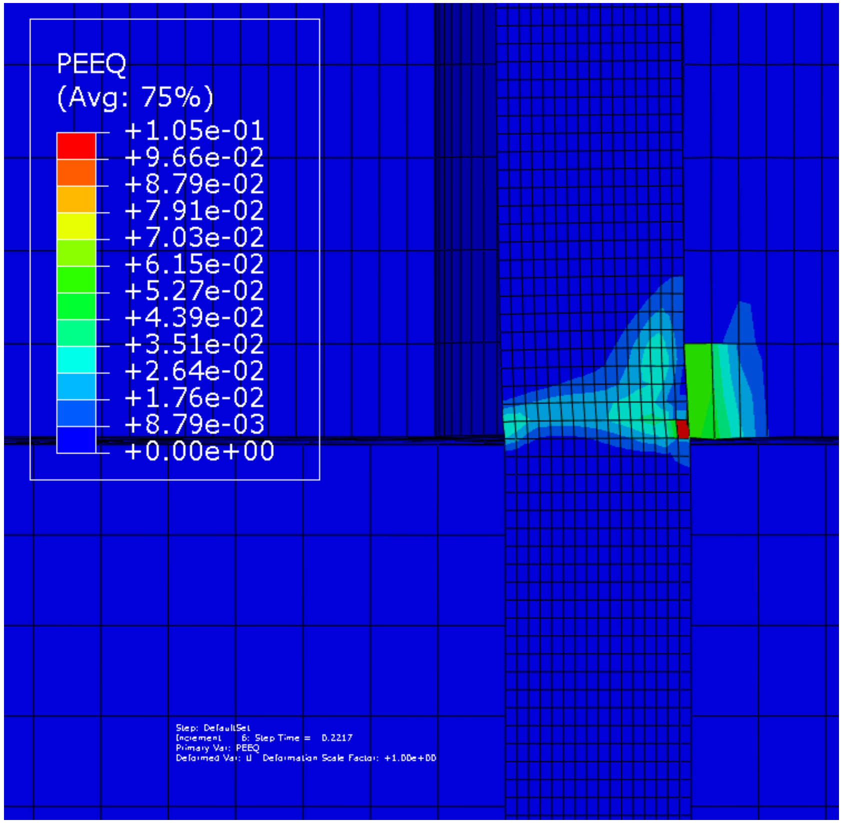
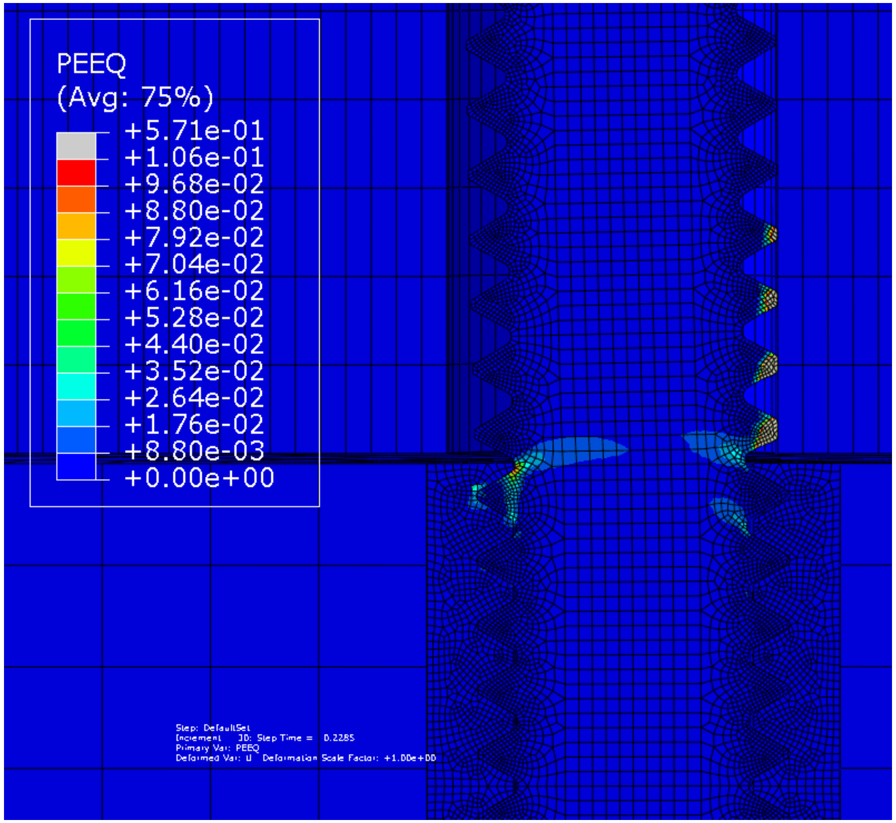
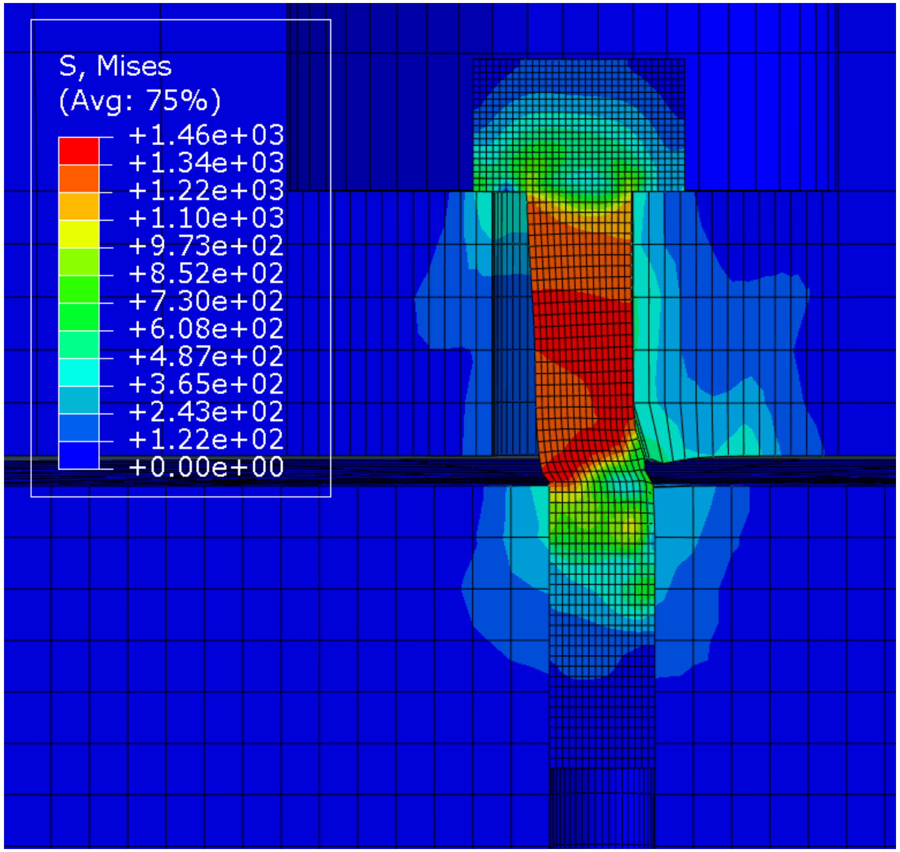




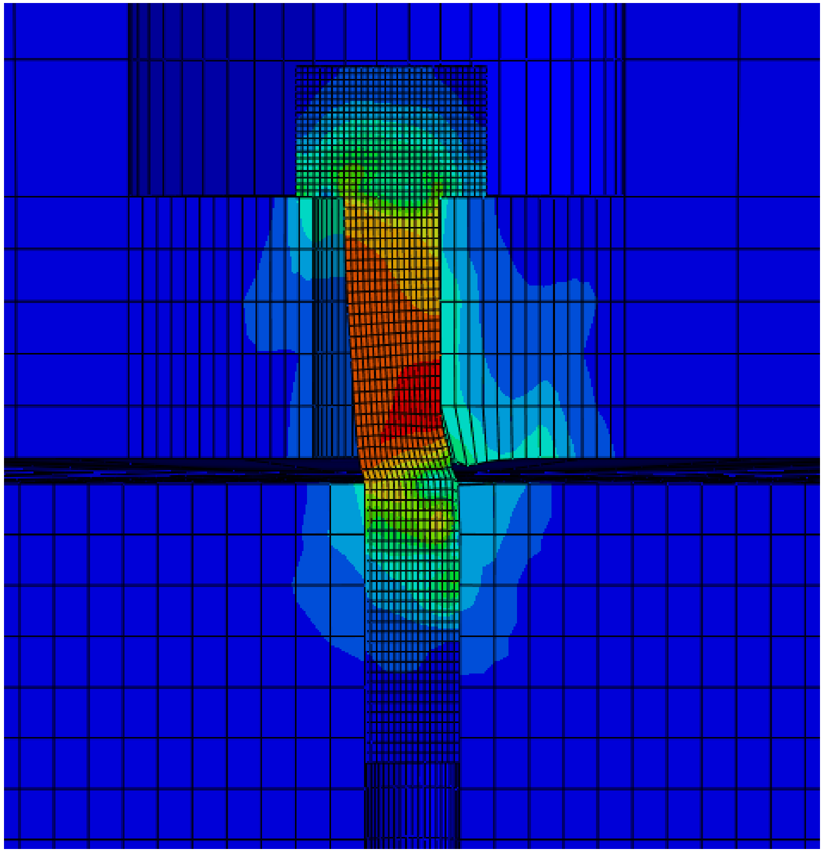
Shear then Tension

- Non-proportional loading exposes differences between isotropic and kinematic hardening

Isotropic



Kinematic



Shear then Tension

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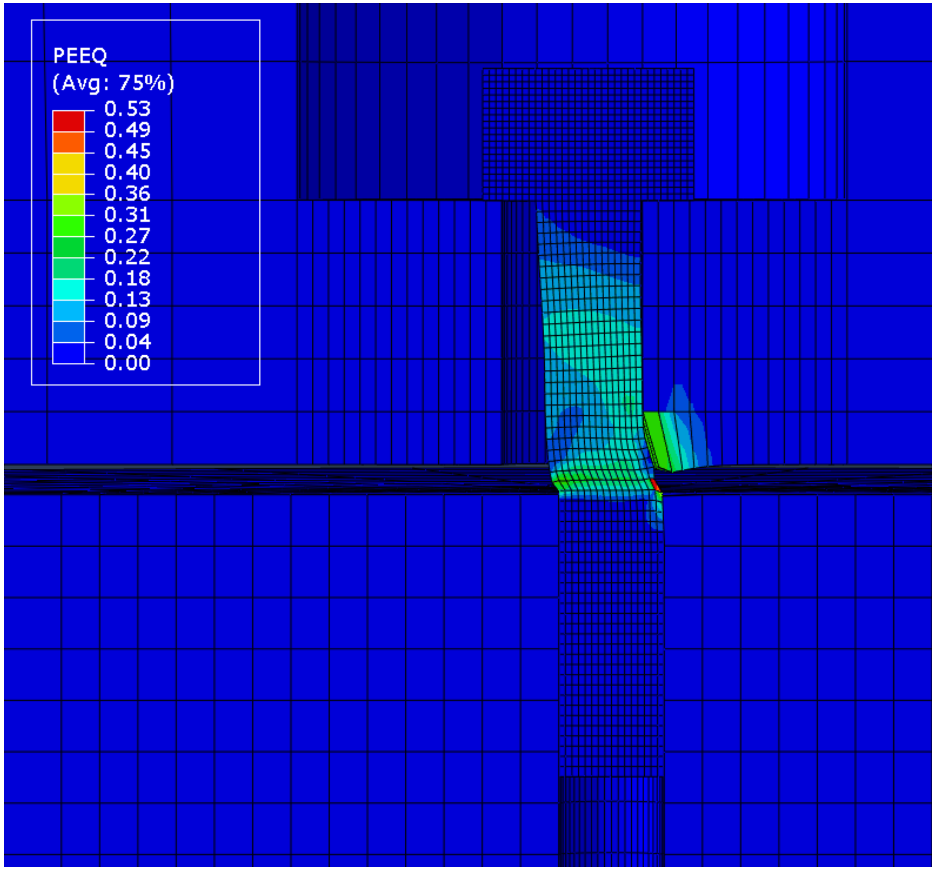
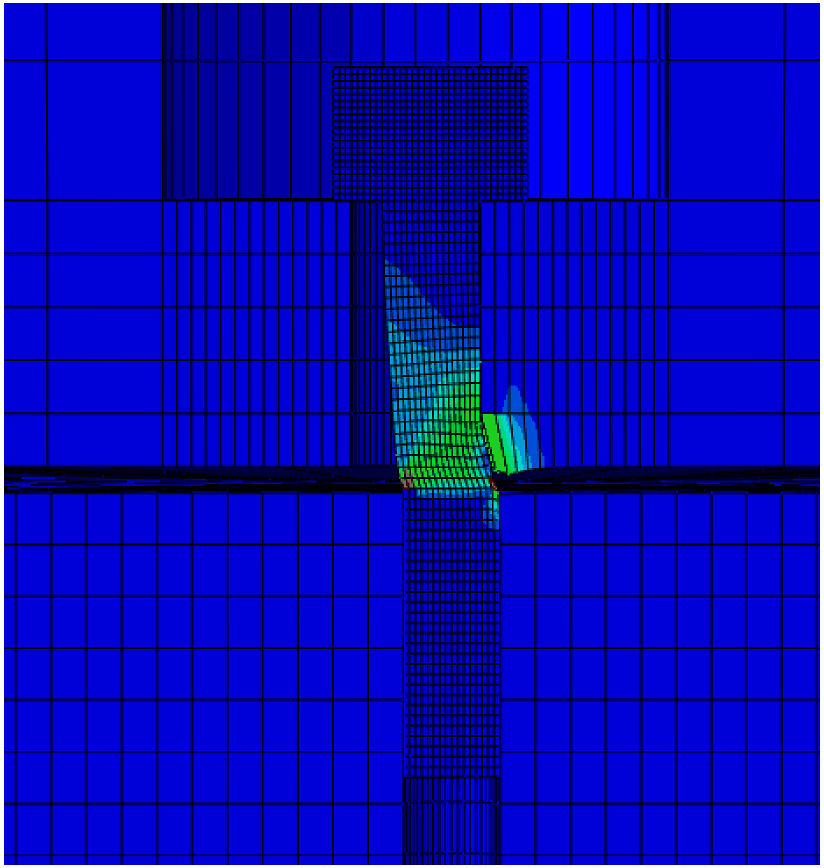
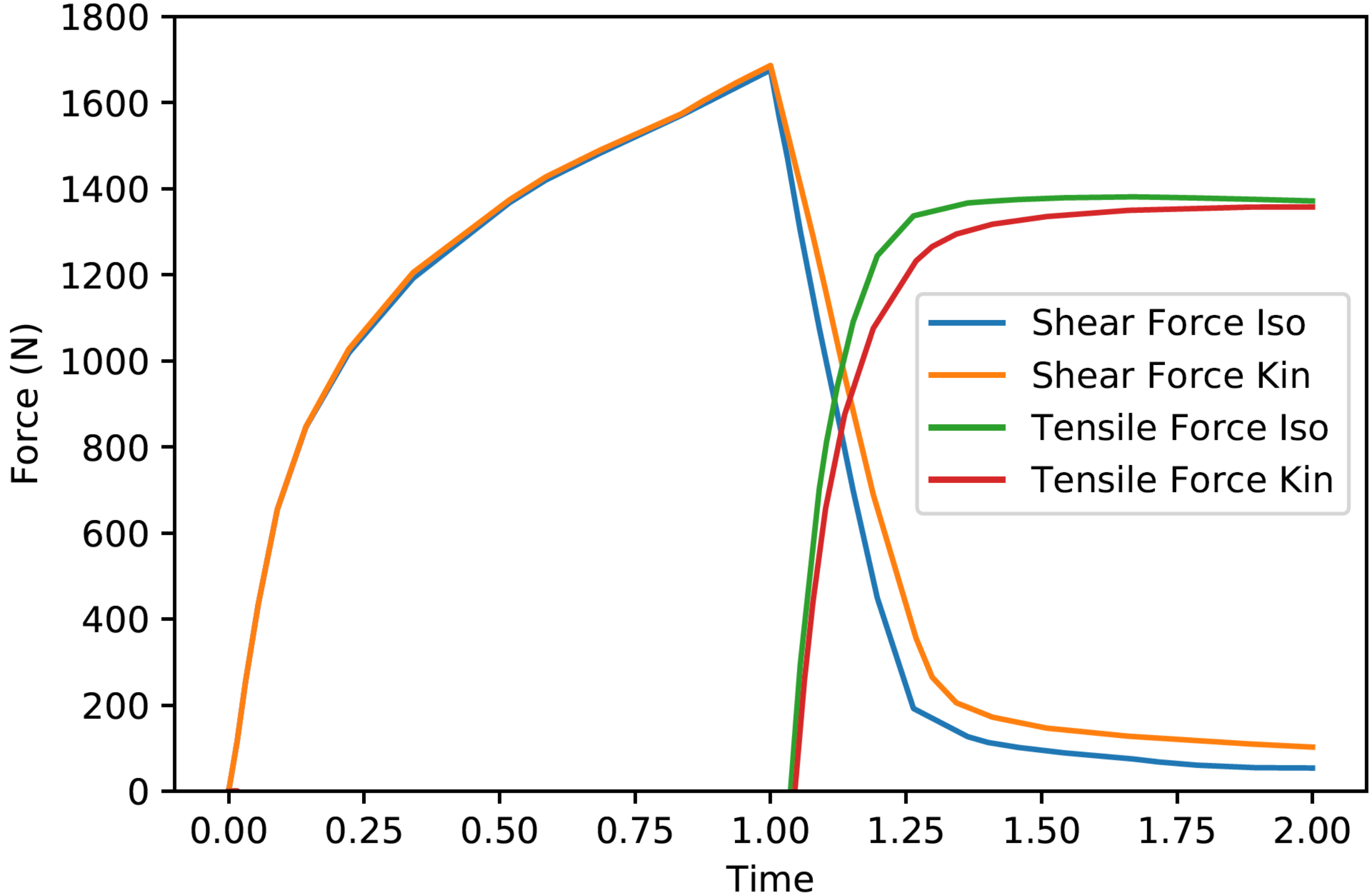
Isotropic



Kinematic



Shear then Tension



Conclusions

- The hardening curve of the original material can be shifted to approximate the hardening curve of a fastener.
  - Different fasteners have different yield stresses, but the Johnson-Cook hardening curves all have the same shape.
  - All the fasteners have yield stresses between 1000 and 1300 MPa.
- In uniaxial tension the material nonlinearities dominate, so the plug model can sufficiently describe the fastener.
- One set of damage criterion values cannot be universally applied for a given material. Generally, the fracture strain varies for different specimen sizes.
- There are small differences in stress and plastic strain fields between isotropic and kinematic hardening when plug models undergo non-proportional loading.

Future Work

- Explore strain rate dependencies using Johnson-Cook calibrations to dynamic data.
- Quantify the error in the damage calibrations for different specimens of the same material.
- Investigate the influence of the angle at which shear loadings are applied.
- Explore the application of non-proportional loadings (e.g. torsion-tension) and their influences in each of the constitutive models used.

Acknowledgments

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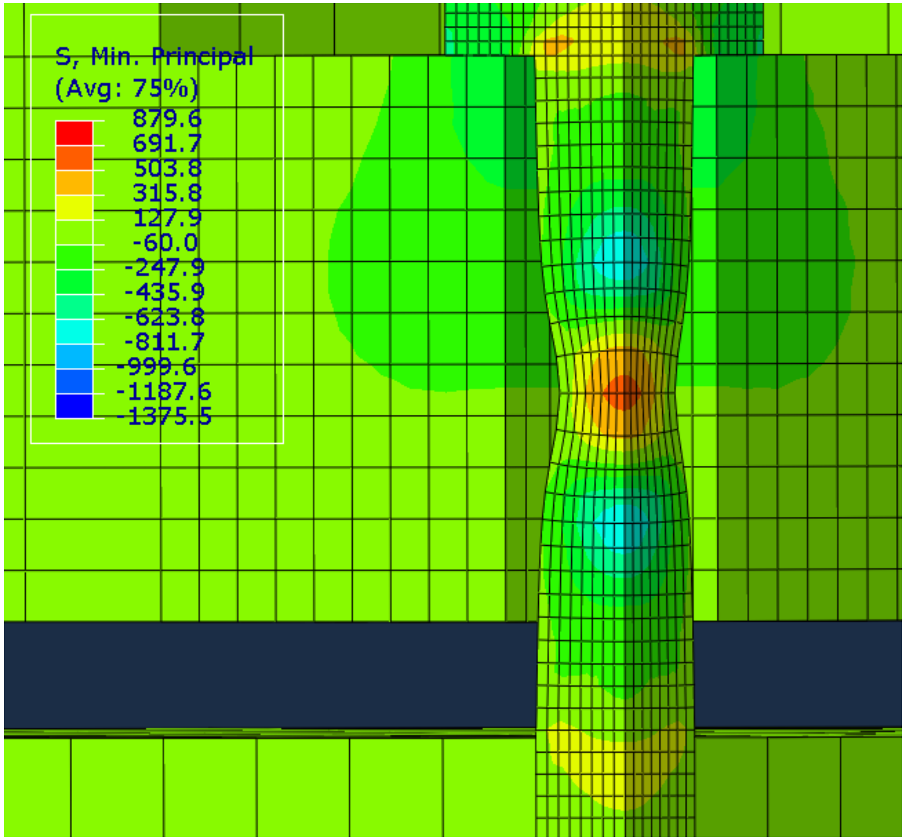
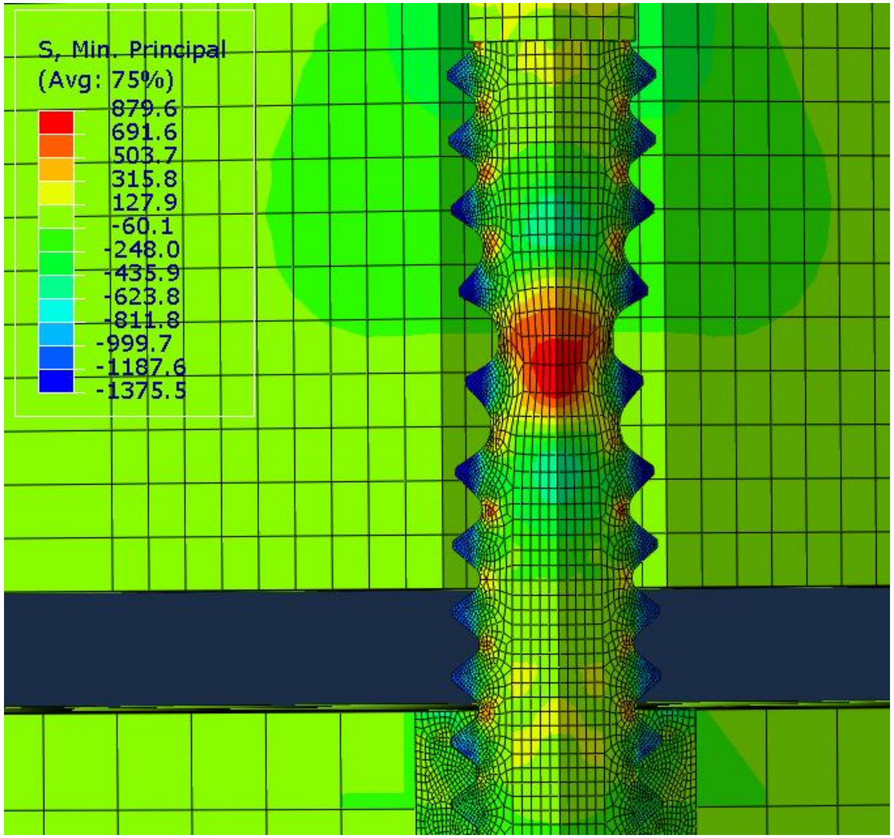
Minimum Principal Stress in Models





Background: Stainless Steel A286

- Stainless steel alloy, commonly used in high performance, high temperature applications.
- Several key advantages:
  - Retains strength and corrosion resistance at high temperatures
  - Can be precipitation hardened
  - Heat treatable
- SNL has provided tension test data for smooth specimens, and tension and shear test data for various sized threaded fasteners of A286 for our study.