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Efficient Multi-Linear Elastic-Plastic Model Calibration for Accurate Reduced-Order Fastener Models

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Minisymposium #203: Data-driven Modeling Using Uncertainty Quantification, Machine Learning and Optimization

PRESENTED BY

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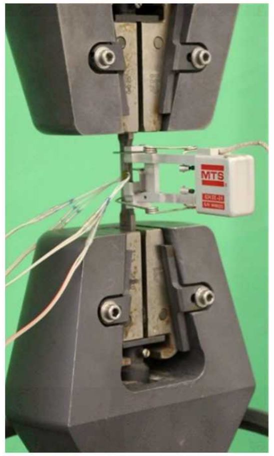
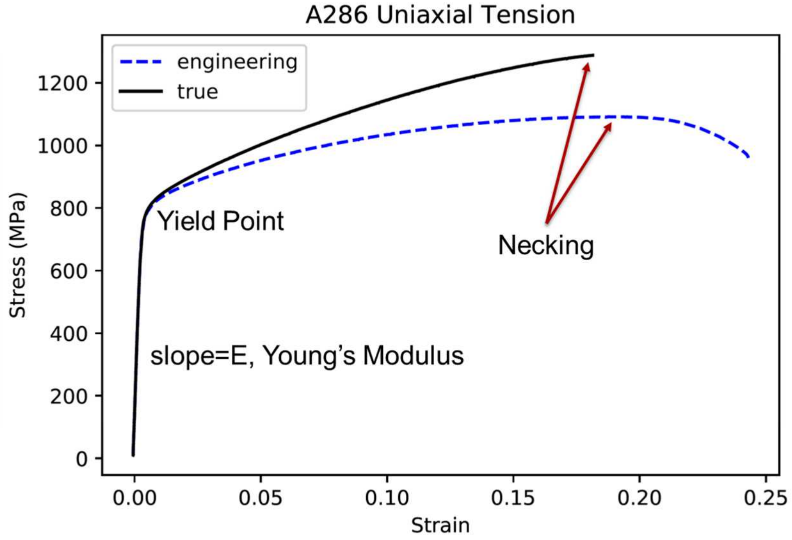
Motivation

Material Calibration

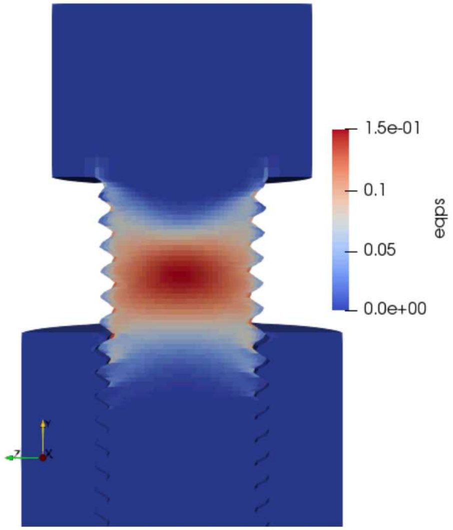




Complex components and structures cannot always be calibrated at at the material level.

- Material isn't homogenous in structure
- Complex mechanics not captured

Structural Calibration



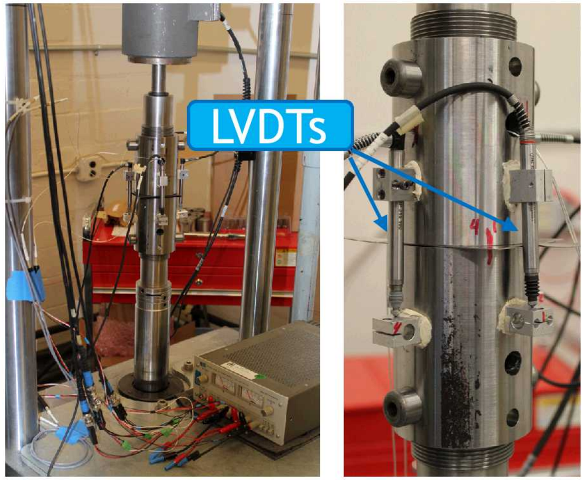


Image: [1]

Sometimes, calibration at the structural level is necessary to obtain best performance for components.

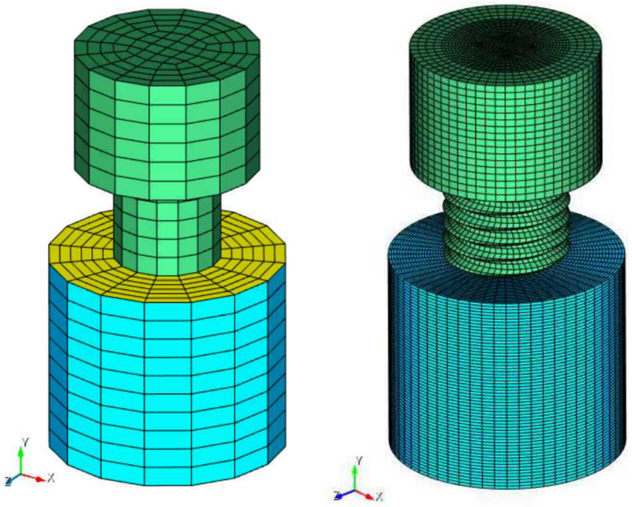
- Cannot directly obtain true stress-strain behavior
- Measurements are non-local so more complex models are necessary to calibrate effectively

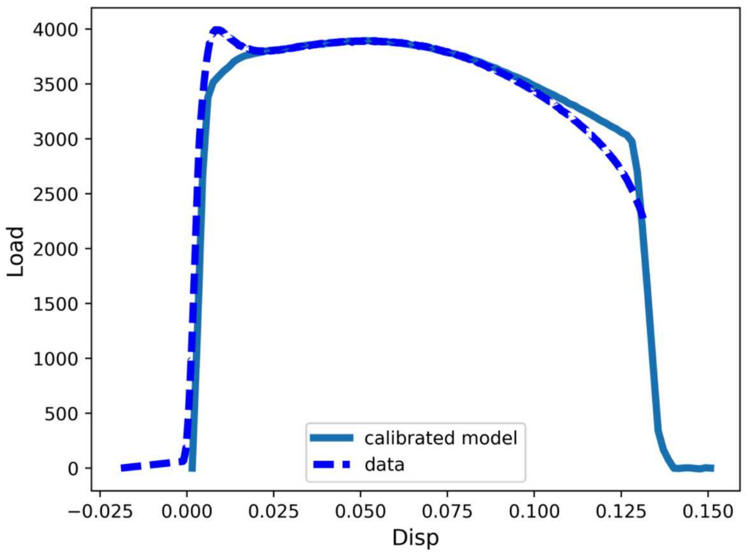
Need a tool that can perform structural calibrations

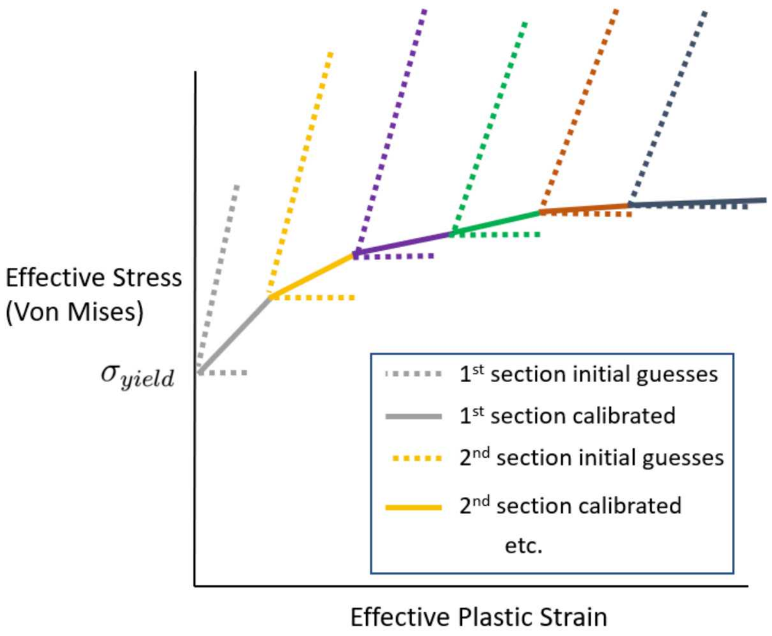
[1] Grimmer, P.W., Mersch, J. P., Smith, J. A., Veytskin, Y.B., Susan, D.F., "Modeling Empirical Size Relationships on Load-Displacement Behavior and Failure in Threaded Fasteners" *2019 AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, AIAA SciTech Forum, AIAA2019-2268, San Diego, CA, 2019.

Outline

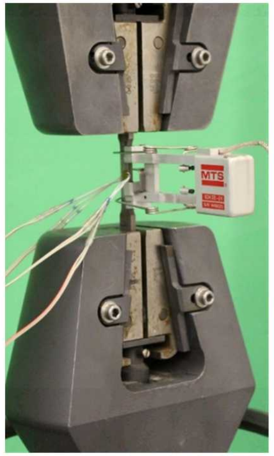
- Conventional Hardening Curve Calibration Methods
- Incremental Calibration Method
- Considerations for Structural Calibration
- Examples

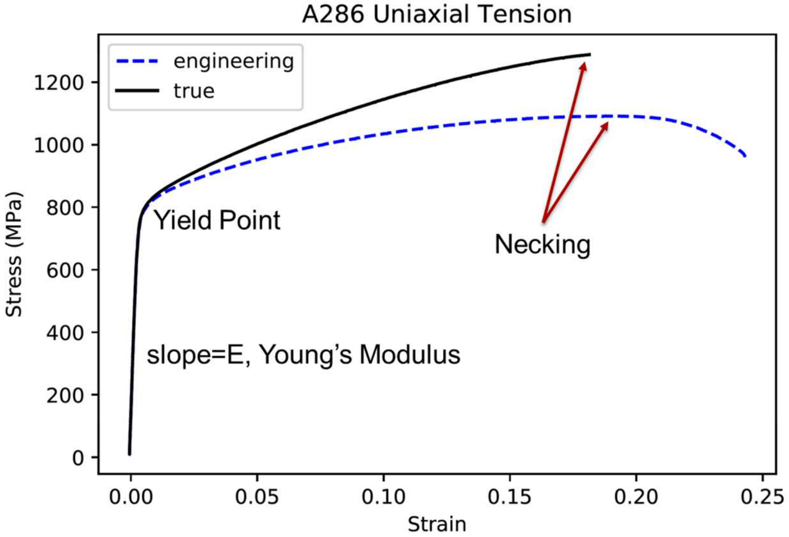


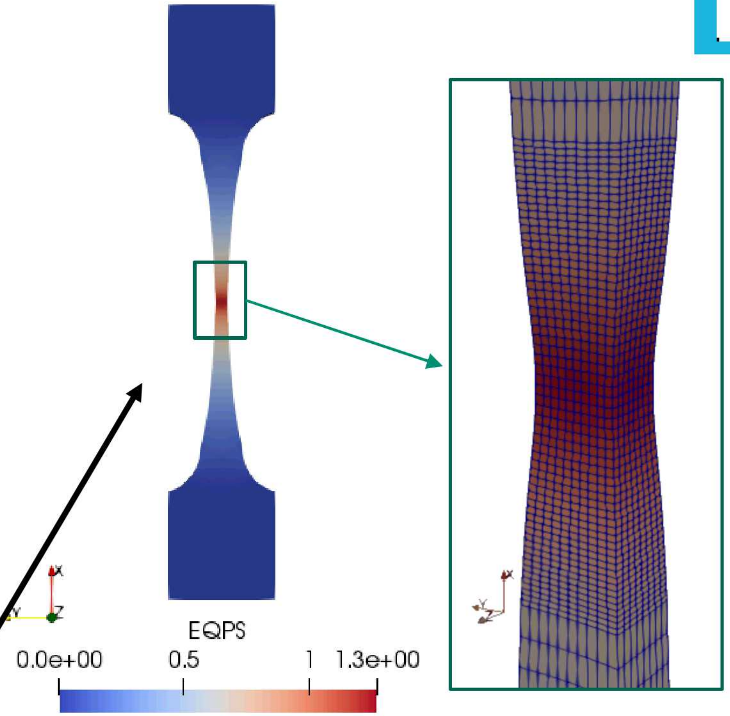




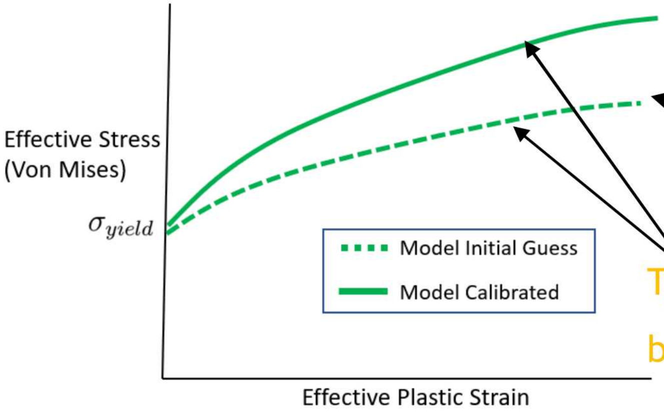
Hardening Curve Calibration: Conventional Methods



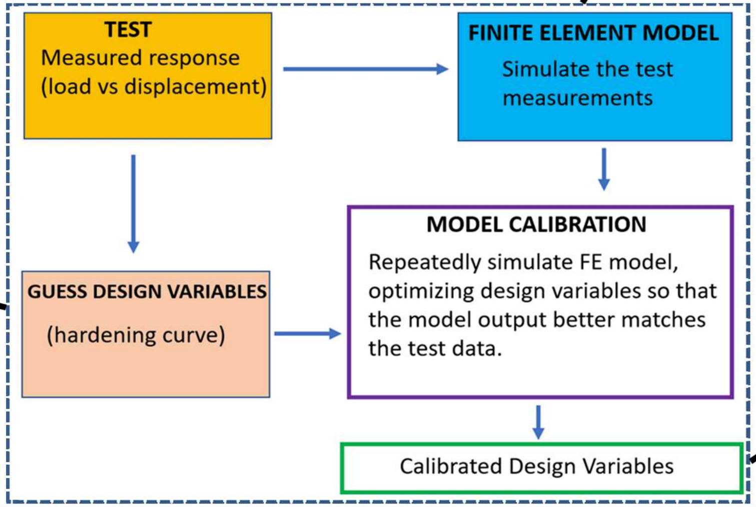


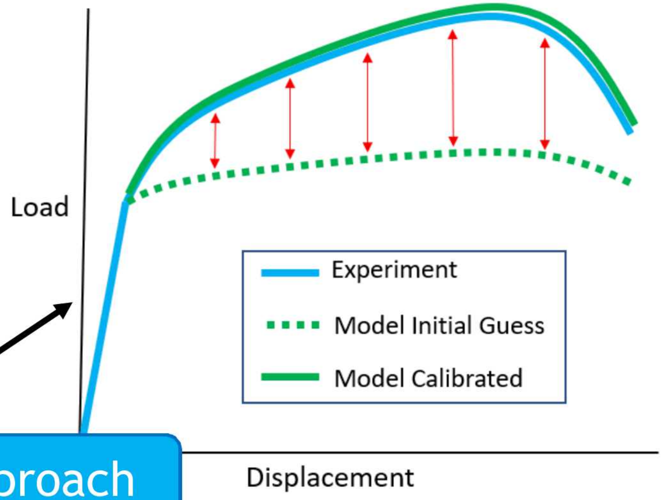


Method #1: Construct equivalent stress-strain curve by hand up to necking



Typically described by analytical function





Method #2: General Inverse FEA Optimization Approach

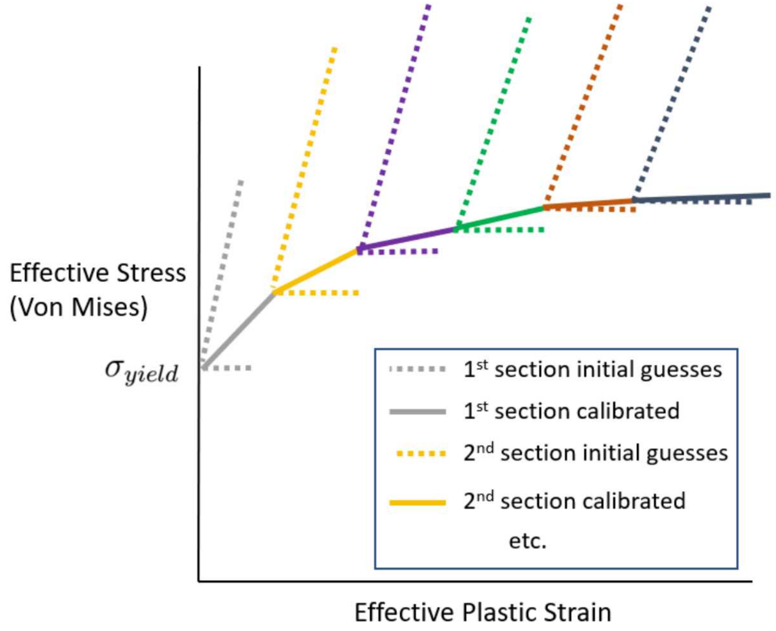
Hardening Curve Calibration: Incremental Method

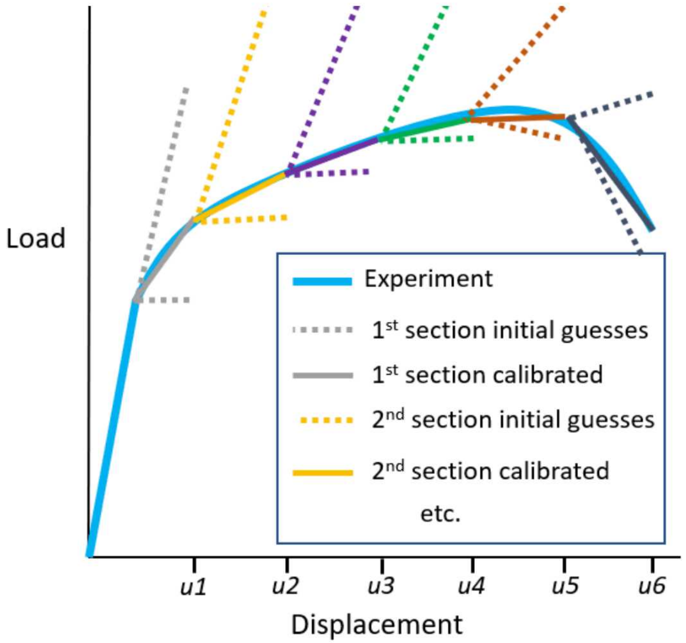
Alternative approach is to use an incremental solution strategy, calibrating each individual segment of the piecewise linear hardening curve

- Increased flexibility – not as limited by model form
- Now can use a root finding algorithm rather than cost function minimization

Still performing an inverse problem, so post-peak stress behavior can be calibrated.

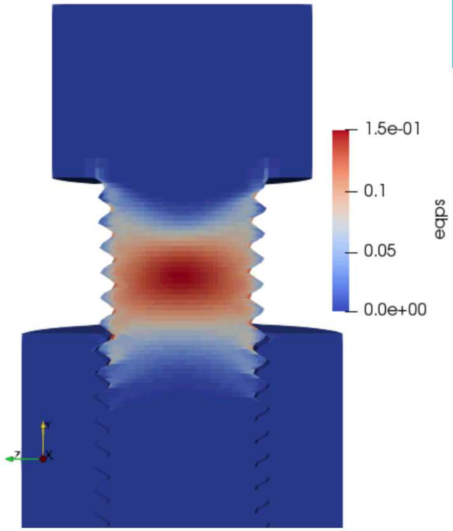
- Calculating equivalent stress-strain from a uniaxial tension test only valid to ultimate load
- Incremental method is faster – not running full simulation each time.





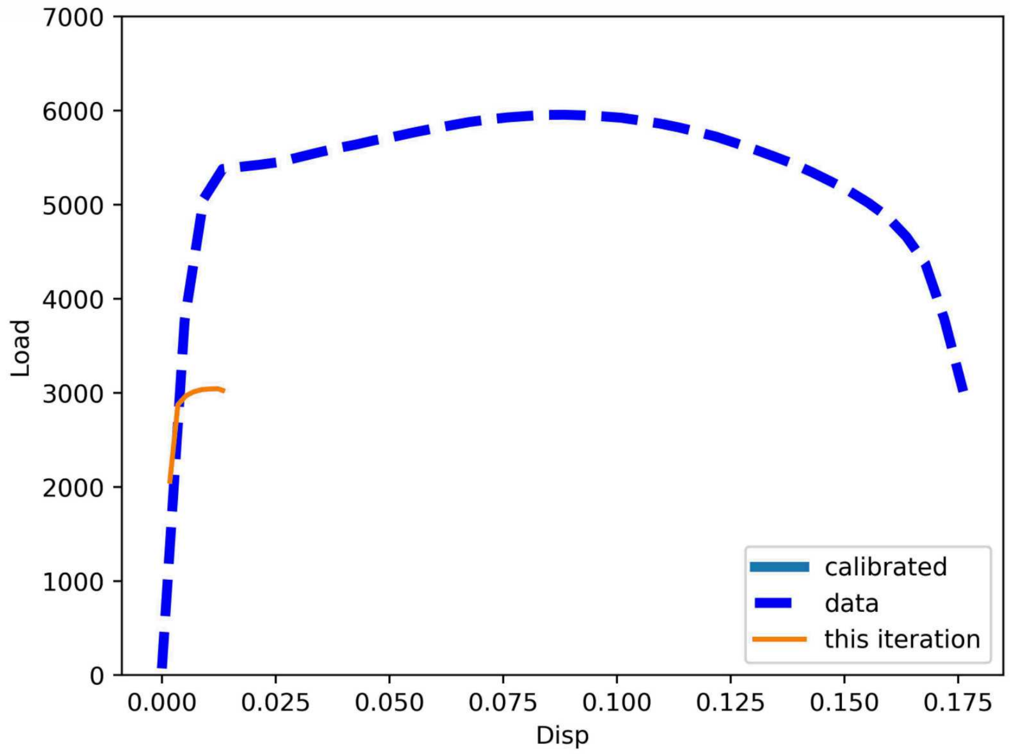
The incremental method provides an efficient approach for material parameter calibration

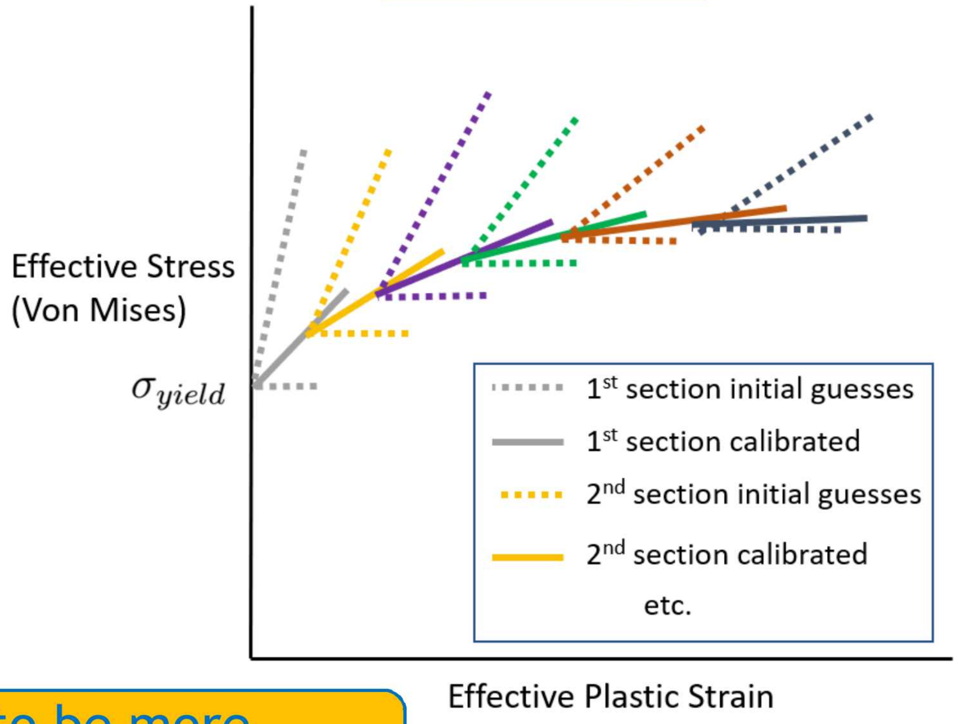
Considerations for Calibrating Structural Models



Complex strain gradients complicate material calibration, especially incremental approaches

- Load values are sensitive to multiple points on the hardening curve
- Don't want to calibrate all the way out to the maximum plastic strain seen in the model
- **Solution: cut back the applied displacement for the next iteration, and cutback the point on the hardening curve you calibrate to accordingly.**





This method facilitates structural models to be more effectively calibrated to arbitrary load-displacement responses

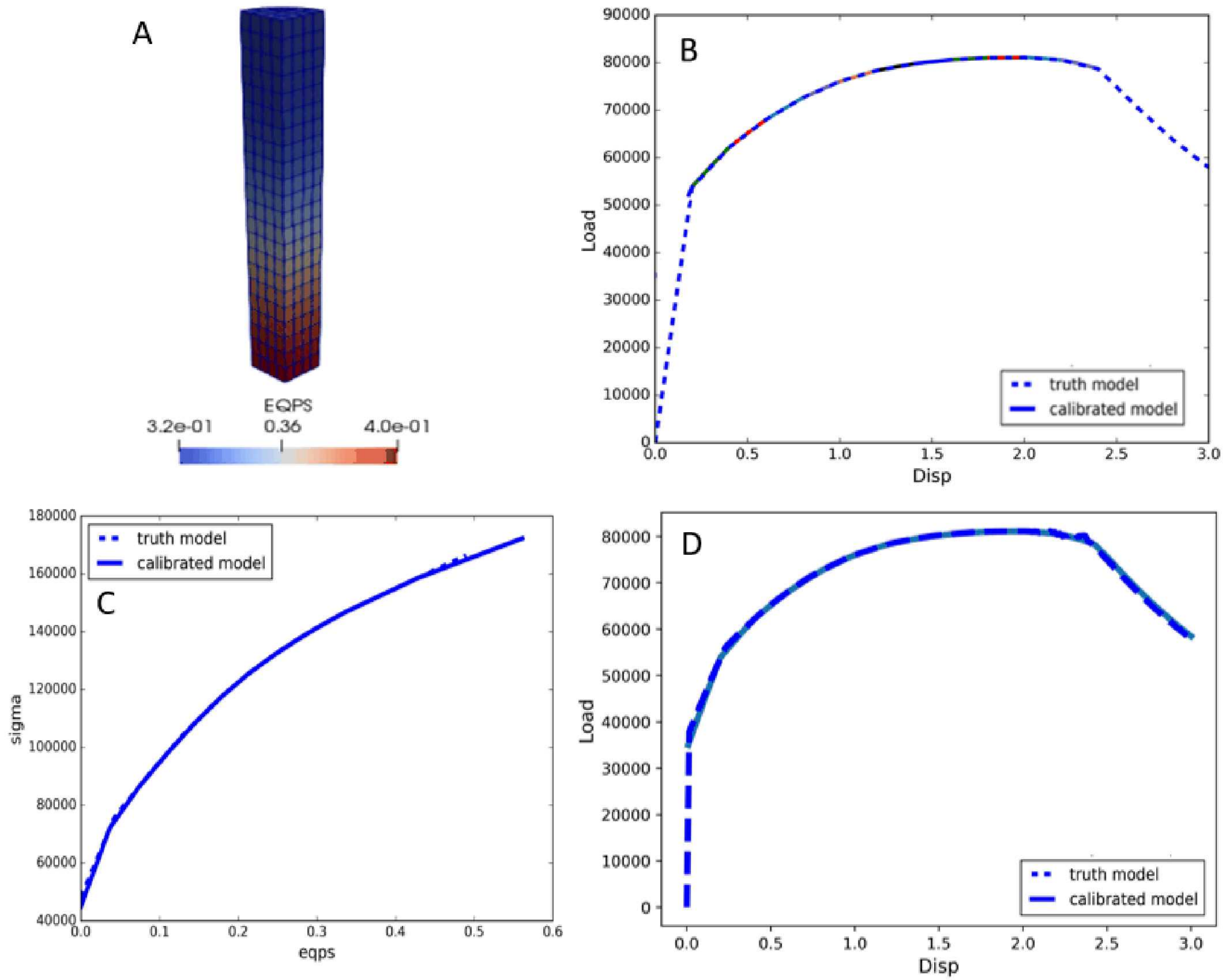
Example: Uniaxial Tension – Capturing Post-Peak Behavior

A.) FE model--symmetry BC's used to represent full cylinder.

B.) Load vs Displacement Incremental Calibration Results

C.) "Truth" hardening curve compared to the calibrated hardening curve

D.) Model re-ran once with calibrated hardening curve to verify the incremental approach matches the final model

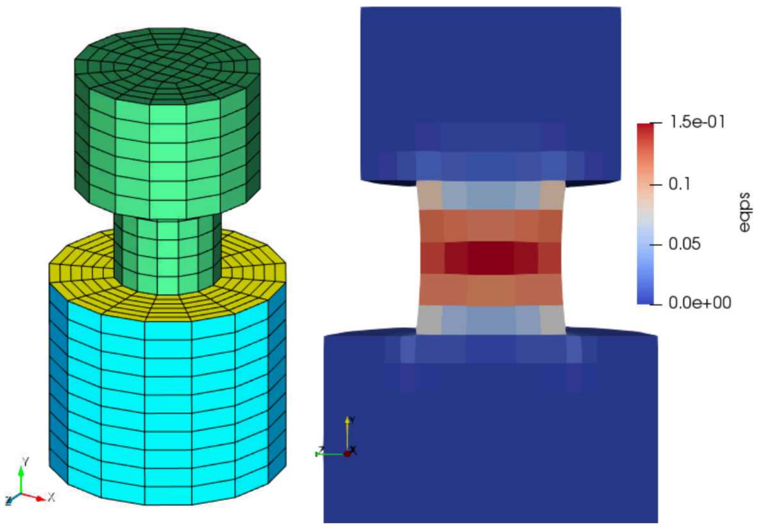


Example: Fastener Models – Calibrating Structural Response

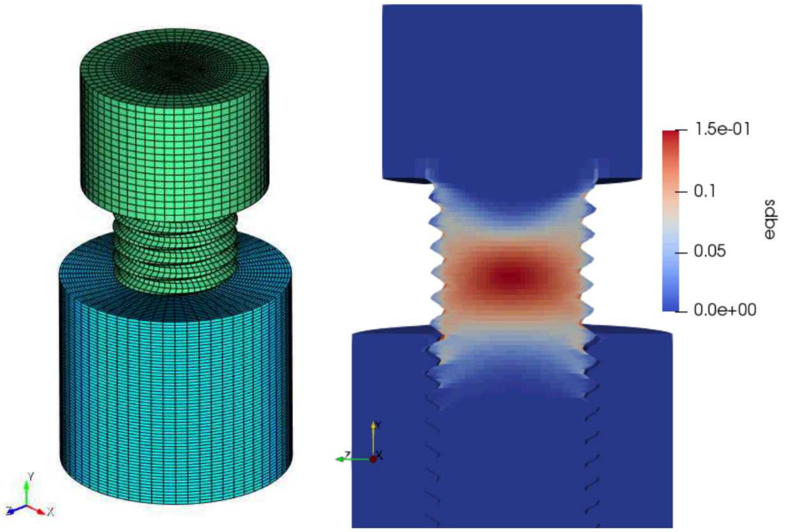
Calibrating two different fastener models to tension load-displacement test data

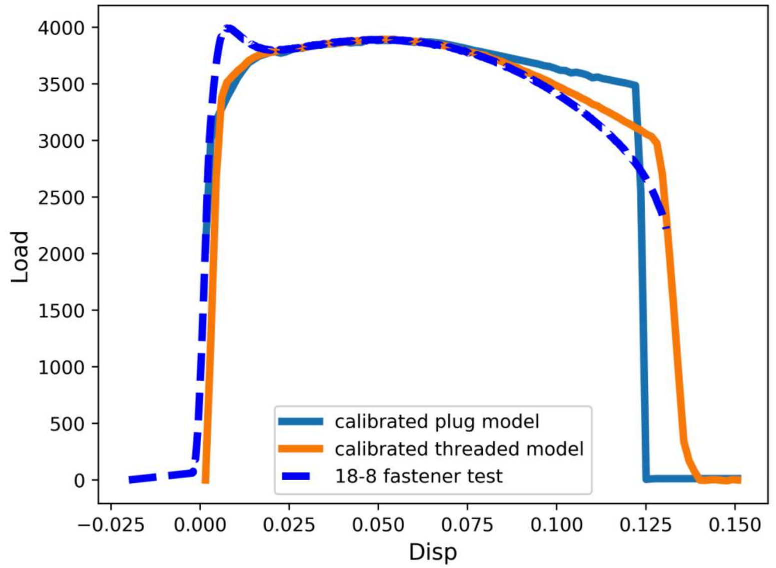
Hardening curves not the same – different mechanics are captured in the model and the structures material properties must change accordingly.

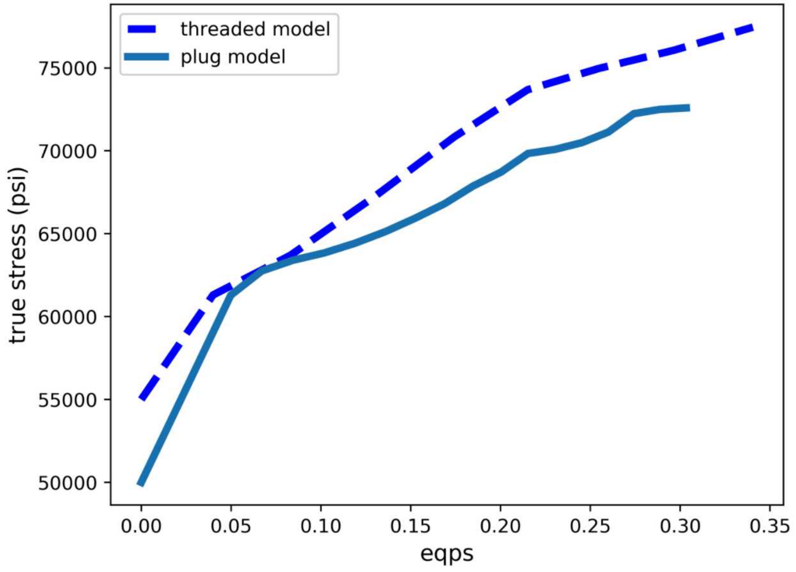
Plug model



Threaded model







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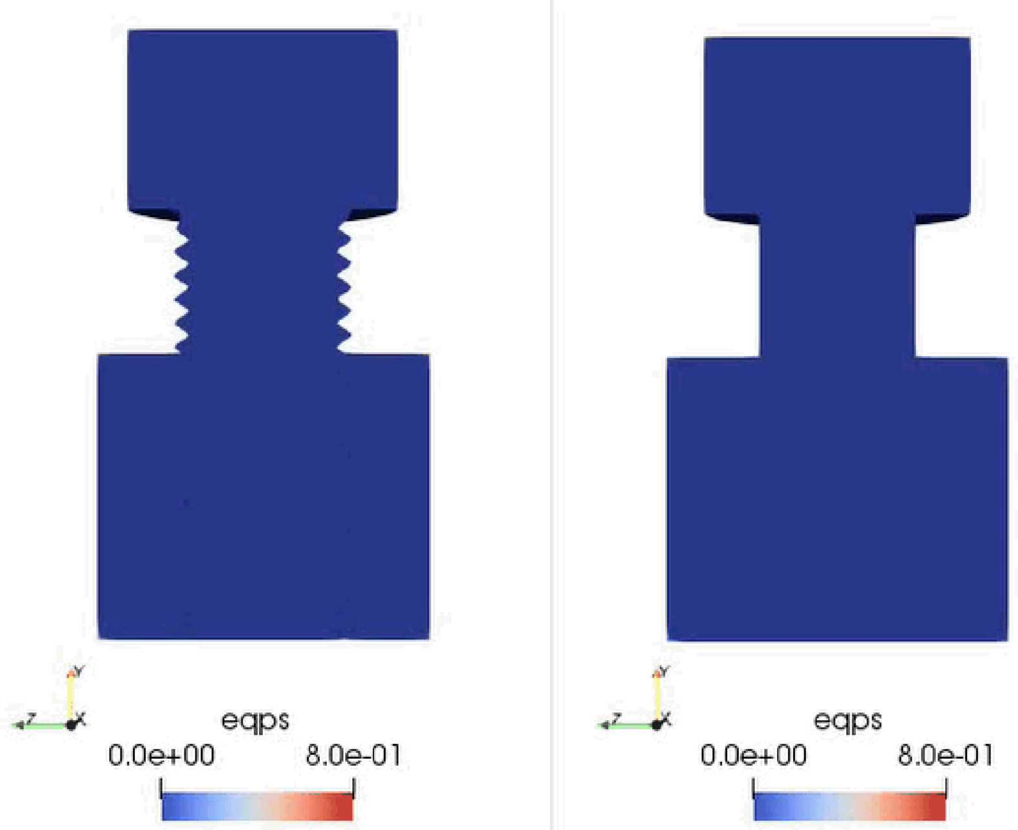
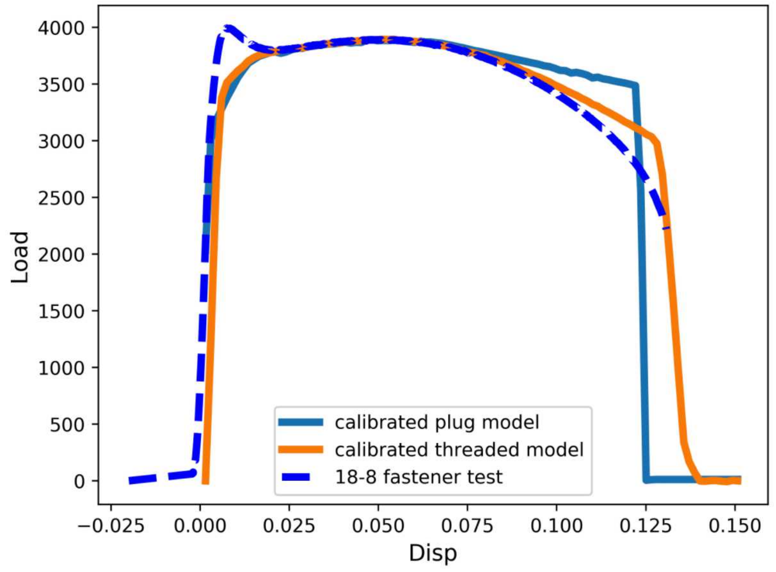
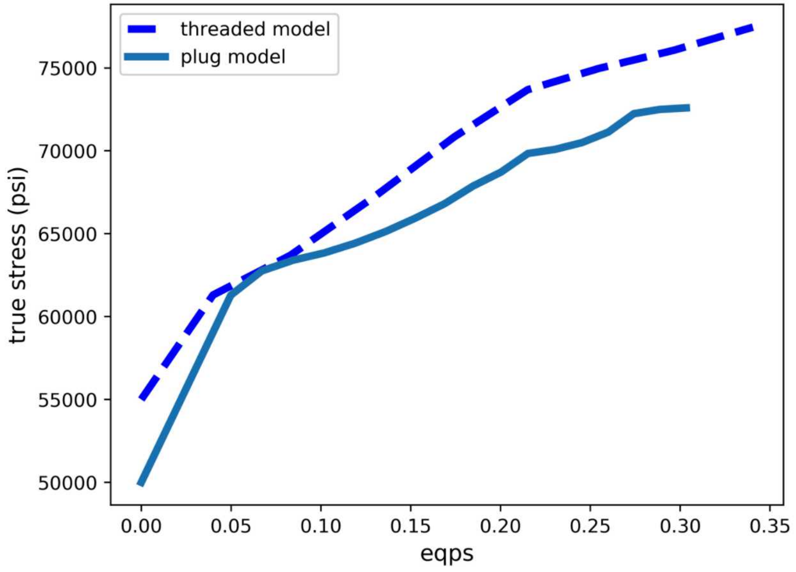


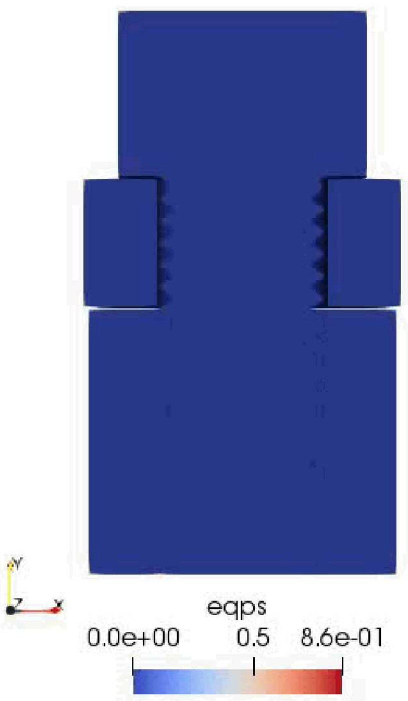




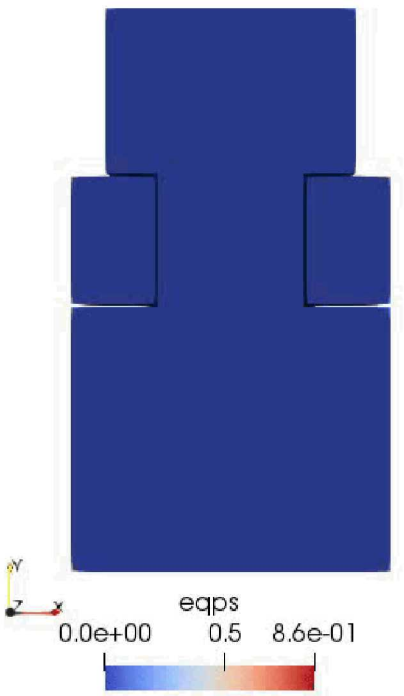
Example: Fastener Models

- Why calibrate multiple levels of fidelity?
  - While they give the same response in tension, the higher fidelity threaded model gives more reasonable results in shear
  - More geometric and mesh fidelity allows for more generally accurate model

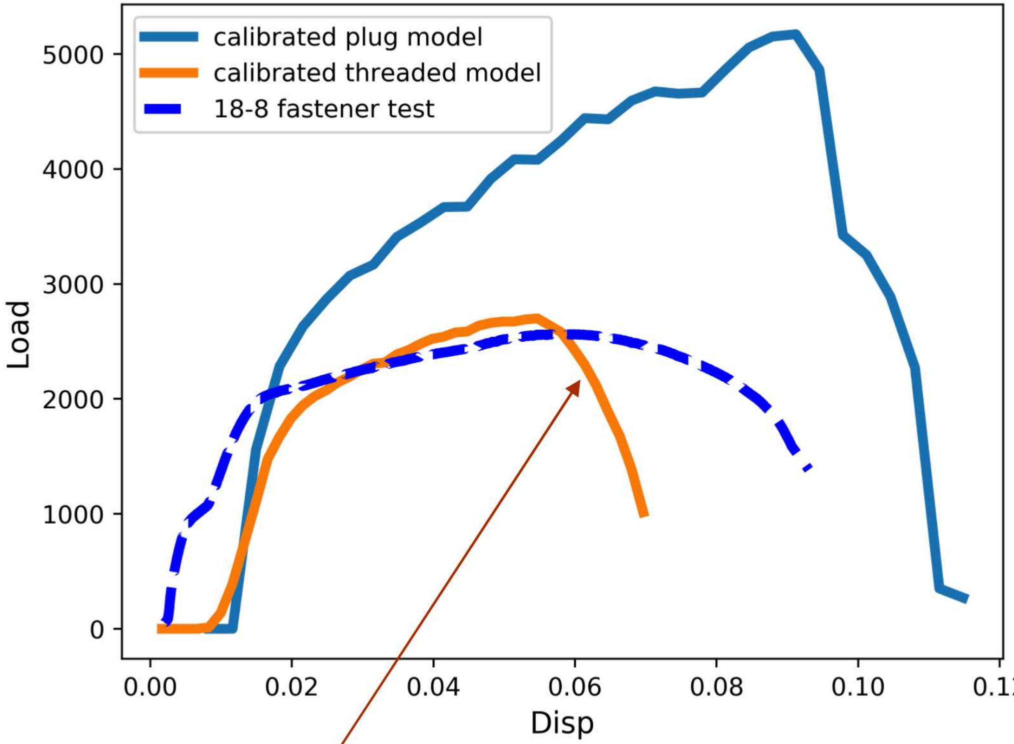
Threaded model



Plug model



Shear Results



Improving the ultimate failure prediction would be possible with a better material failure model

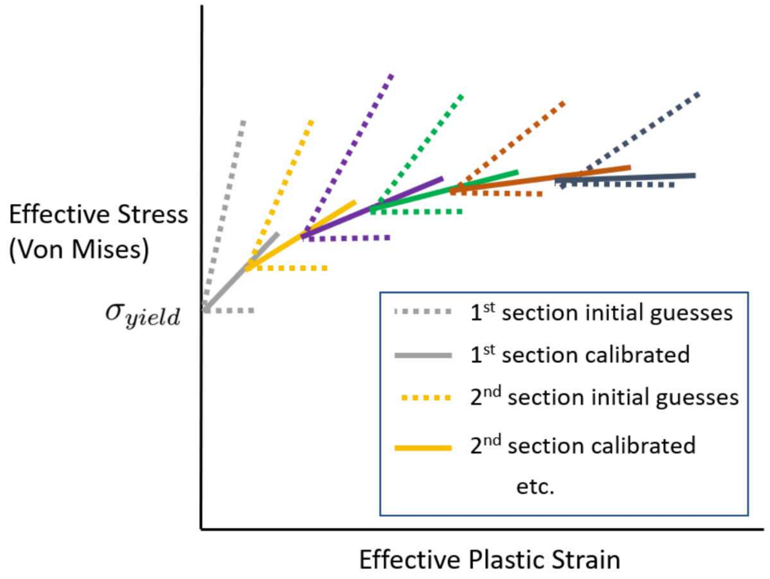
Conclusions

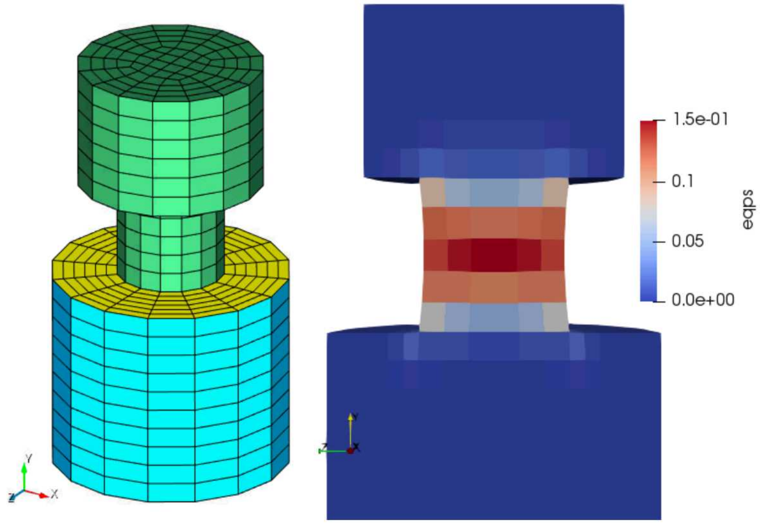
Developed tool that can efficiently calibrate models at a structural level.

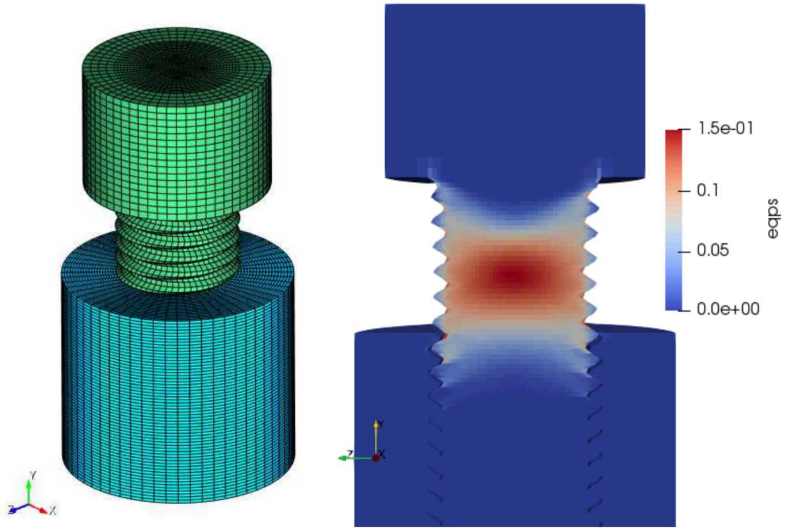
- Enables the calibration of complex components such as fasteners
- Can perform calibrations for unique loadings and loading conditions

Still utilizing an incremental approach

- Not running full simulation – time saved in calibration
- Maintaining model flexibility – not limited by model form







Thank you!

Questions?

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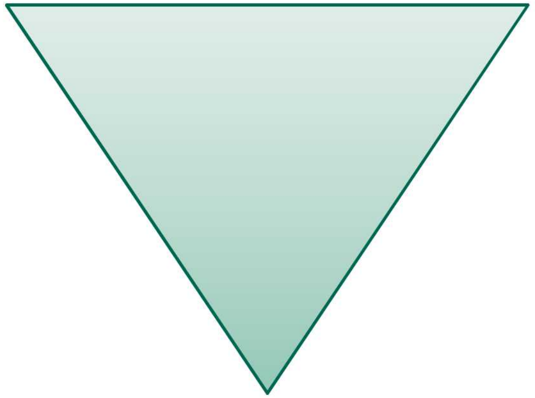
Nonlinear Material Model Calibration

Background: what is being calibrated?

Broad



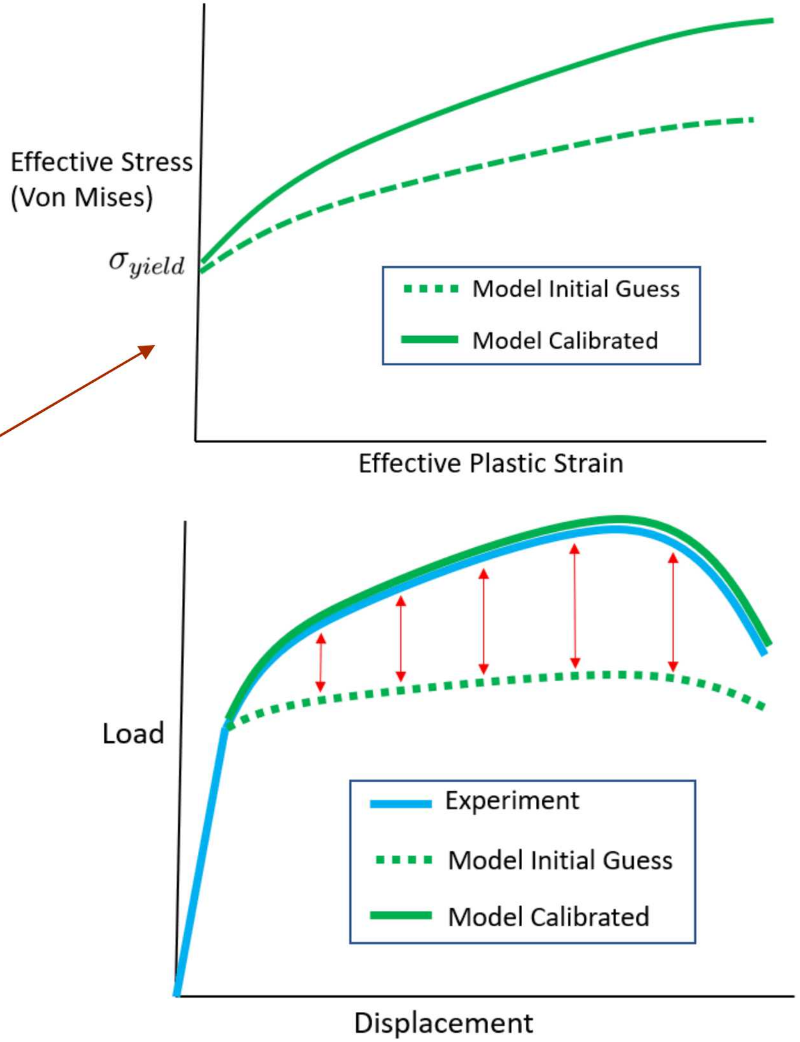
Specific to this talk

Nonlinear solid mechanics

Material modeling

J2 Metal Plasticity

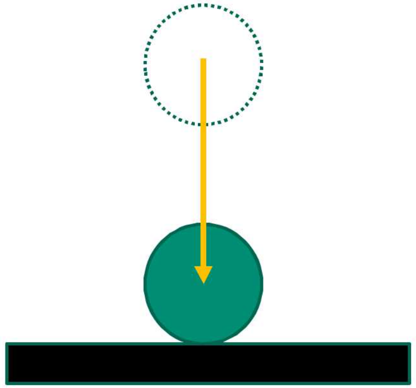
Strain Hardening



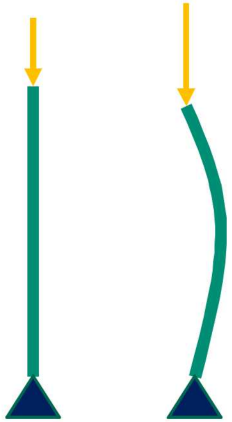
Nonlinear Solid Mechanics

- At Sandia we perform nonlinear solid mechanics simulations of various systems
- *Nonlinear* : the solution doesn't scale proportionally to the applied loading
  - In general the solution must be solved incrementally
  - Types of nonlinearity in solid mechanics simulations
    - Contact
    - Geometric (large deformations)
    - **Material**
      - This is the aspect that usually needs to be calibrated

Contact: initially, the two bodies do note exert force on each other, but after some displacement they abruptly do



Geometric: the initially straight beam buckles after some loading, leading to a reduction in load carrying capacity

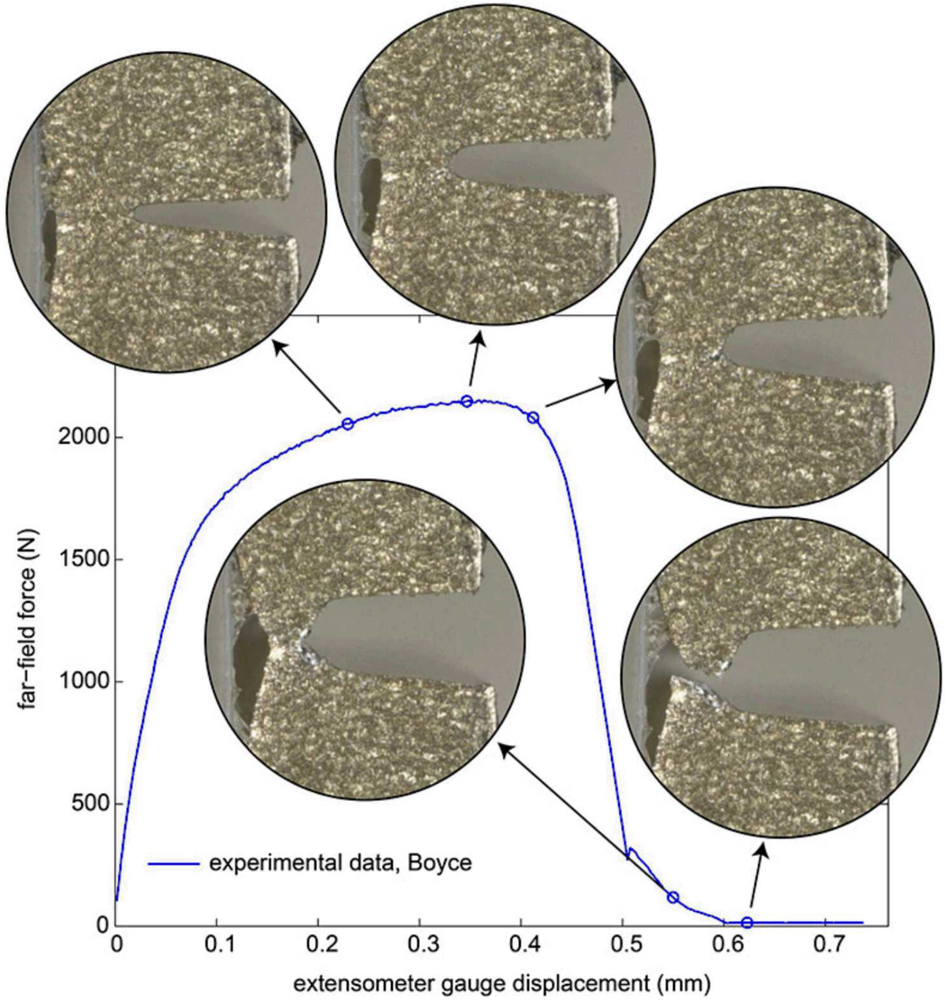


While we rely on our FEA codes to accurately simulate contact and geometric nonlinearities, material nonlinearity is largely modeled phenomenologically, dictated by user-defined parameters

Material Modeling

- For solid mechanics, materials are often classified according to their:
  - Homogeneity: spatial variation
  - Anisotropy: directional dependence
  - Nonlinearity: how does stiffness change with strain?
  - Inelasticity: if unloaded, does material return to original state?
- Whether a material can be considered homogeneous or isotropic depends on the length-scales of interest.
  - For most practical engineering calculations for metal structures, we assume isotropic and homogeneous materials.
- Beyond very small strains, metals yield and have **inelastic, nonlinear** deformations (plasticity).
  - FEA of components for design evaluation can assume linear elasticity and still be extremely valuable
  - However, if you want to accurately simulate the response of metal components under large deformations, must account for their plasticity
    - If extreme loading is involved, material failure may also need to be modeled

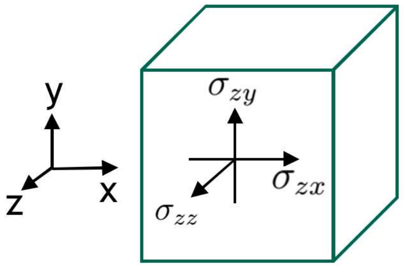
Tension test of a notched stainless steel 304L specimen [1]



[1] Emery et. al., 2015 (https://doi.org/10.1002/nme.4935)

J2 Metal Plasticity

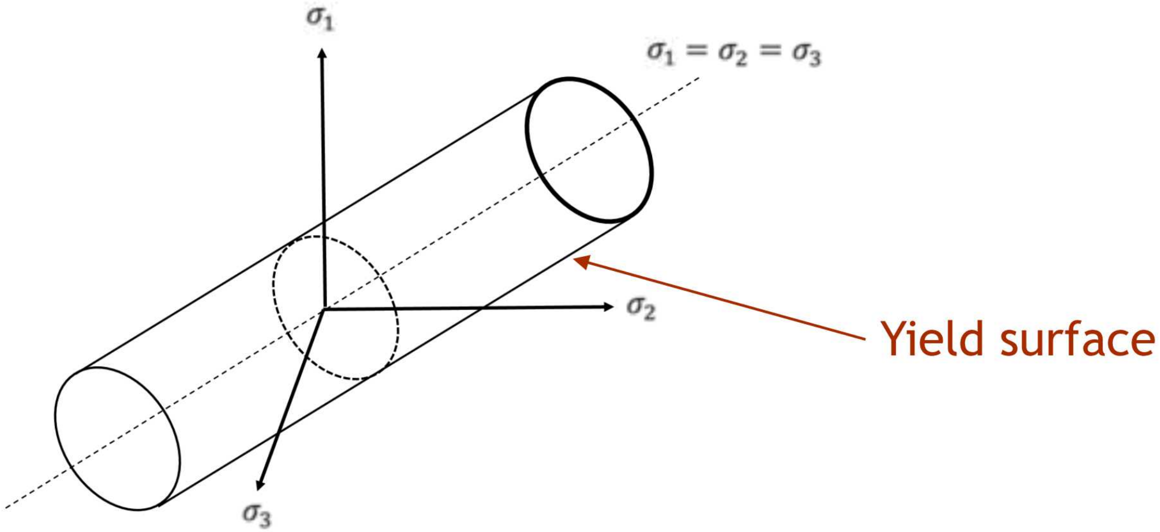
- Stress tensor can be decomposed into:
  - Volume changing (volumetric) deformation
    - Related to normal stresses
  - Shape changing (deviatoric) portion
    - Related to shear stresses
- Metals generally plastically deform due to deviatoric stresses **S**
  - The "second invariant" of the deviatoric stress tensor is called J2.
  - Von Mises stress comes from J2
    - Conveniently, Von Mises stress is equal to applied stress in uniaxial tension
  - Von Mises is a common "yield criterion" for metals
    - Von Mises stress defines a cylindrical 3D **yield surface** in "principal stress space", with its axis along hydrostatic stress states
    - If a given material element's principal stresses give a Von Mises stress that is higher than the yield stress, the element will deform plastically



$$\begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix} = \sigma_{ij}$$

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

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

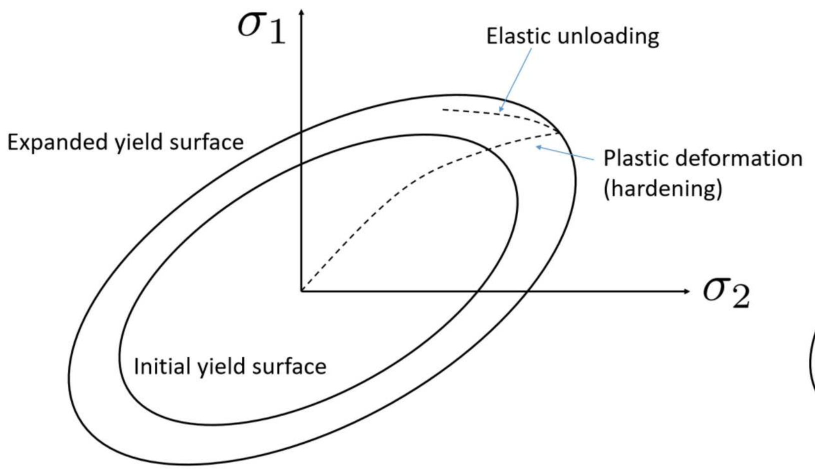


Strain Hardening

- If a metal continues to be loaded past yield, it begins "hardening"
  - Complicated microstructural causes that can't be practically modeled, so phenomenological models are used
- This can be understood as the yield surface expanding (isotropic hardening) or translating (kinematic hardening) to accommodate the increasing Von Mises stress
- Very ductile alloys (e.g. 304L stainless steel) can accommodate a lot of plastic strain/hardening before fracture
- For J2 plasticity, the hardening behavior can be described with a "hardening curve"
  - This can be obtained from a uniaxial tension test, up until necking
- In general, a hardening curve can only be directly obtained from a test if the test has a uniform state of strain (or if one can reasonably be assumed)
  - If not, an inverse calibration procedure must be used

We often need to calibrate the hardening curve for a given material model so that it gives the correct response in a system model

Isotropic Hardening



Kinematic Hardening