Durability of adhesive bonded joints in aerospace structures

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Durability of adhesive bonded joints in aerospace structures

- Principal Investigators & Researchers
  - Lloyd Smith
  - Preetam Mohapatra, Yi Chen, Michael Krause
- FAA Technical Monitor
  - Ahmet Oztekin
- Other FAA Personnel Involved
  - Larry Ilcewicz
- Industry Participation
  - The Boeing Company: Will Grace, Peter VanVoast, Kay Blohowiak

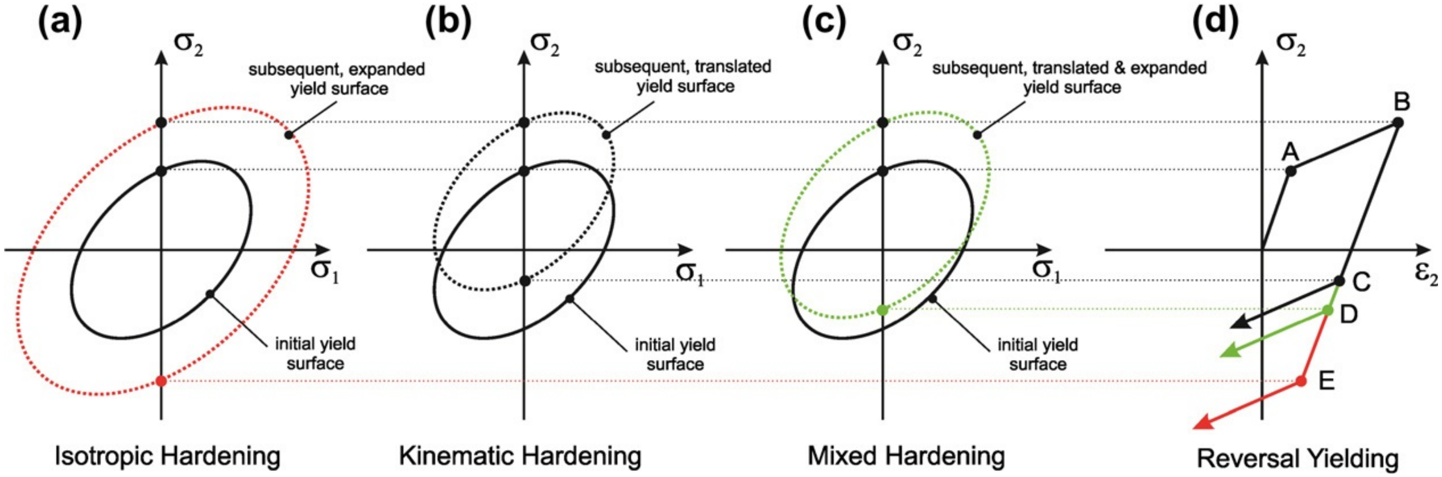
Durability of bonded aircraft structure

- Motivation and Key Issues
  - Adhesive bonding is a key path towards reduced weight in aerospace structures.
  - Certification requirements for bonded structures are not well defined.
- Objective
  - Describe plastic adhesive response.
  - Develop time-dependent adhesive models.
- Approach
  - Experiments designed to clarify constitutive relations.
  - Develop FEA Models of adhesive bonds.
  - Compare models with experiments that are unlike constitutive tests.

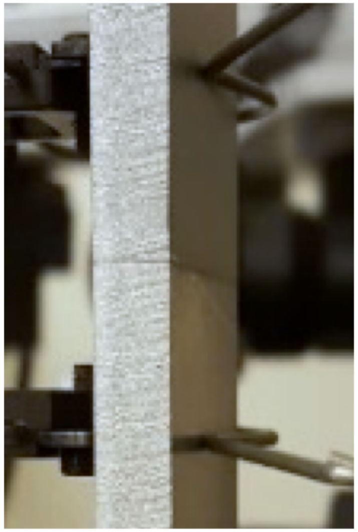
Durability of adhesive bonded joints in aerospace structures

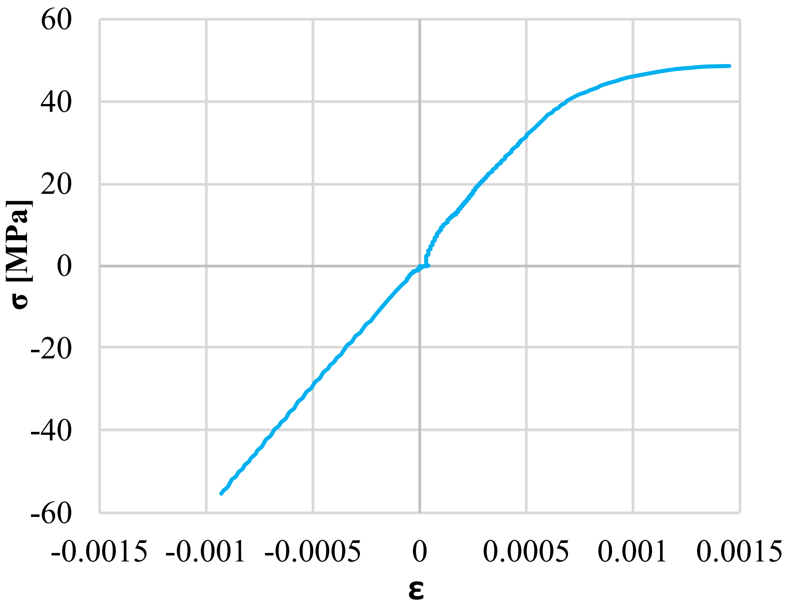
- **Nonlinearity in Bonded Joints**
  - **Plasticity**
    - Yield criterion
      - 1. Influence of yield criteria
      - 2. Biaxial tests (Arcan)
    - Hardening rule
      - 3. Cyclic tests
      - 4. FEA model
  - **Time Dependence**
    - Tension (closed form)
      - 1. Creep, non-linear response
      - 2. Ratcheting, experiment
    - Shear (FEA)
      - 3. Creep, model development
      - 4. Ratcheting, model application

Plasticity : Hardening Rule: Challenges



Ref: Muransky O. et al [Metal Plasticity]

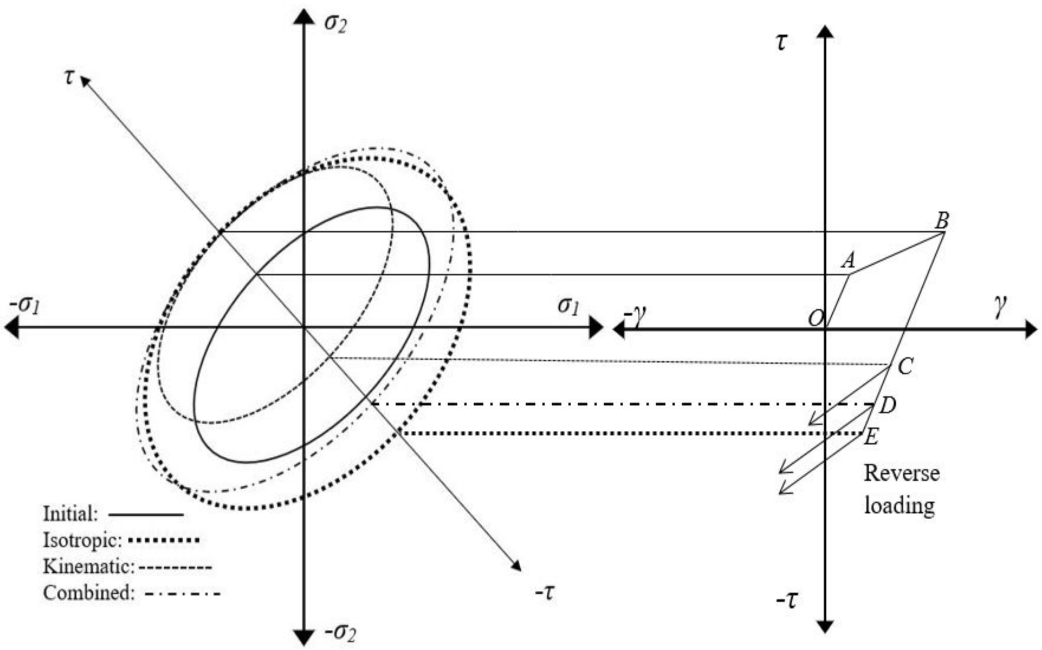


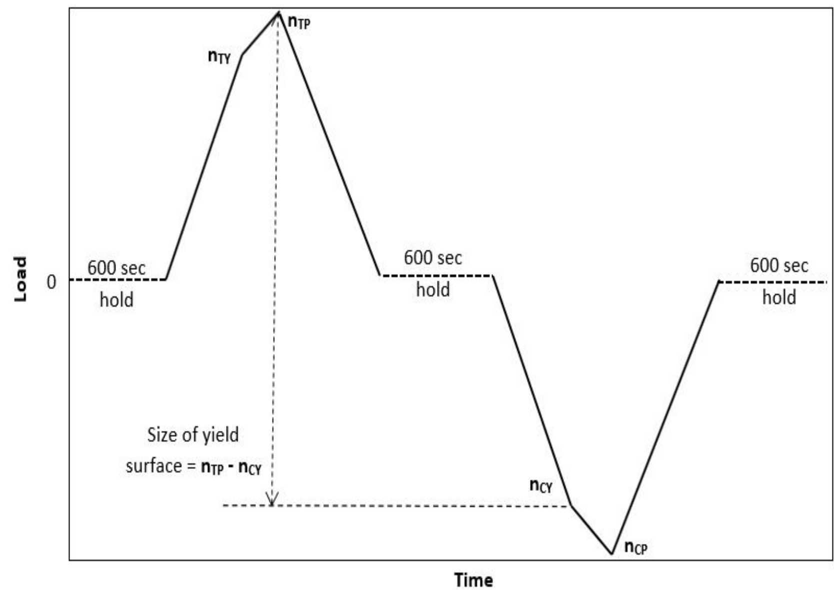


What we found:

To quantify hardening in thin film adhesives we need to load and unload in a shear stress state

Plasticity : Hardening Rule: in Shear





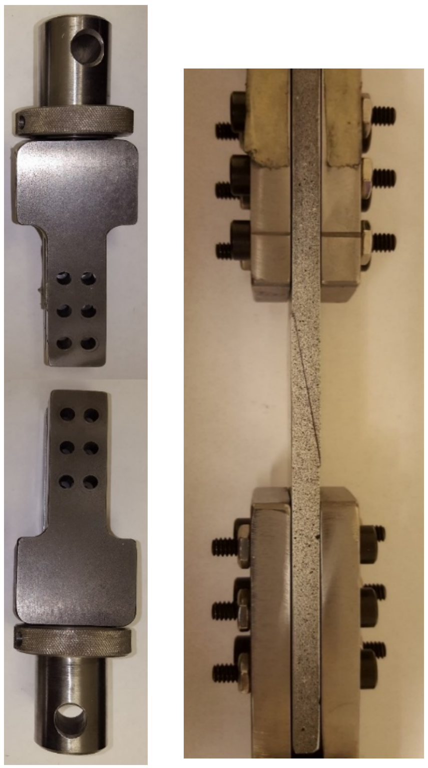
- Initial size : $Y_o = 2\tau_A$
- Kinematic: $Y_k = \tau_B - \tau_C = 2\tau_A$
- Isotropic: $Y_i = \tau_B - \tau_E = 2\tau_B$
- Combined: $2\tau_A < Y_c = (\tau_B - \tau_D) < 2\tau_B$
- $k = \frac{\tau_B + \tau_D}{2(\tau_B - \tau_A)}$

Schematic presentation of cyclic shear loading

- tensile yield (n_{TY})
- tensile peak (n_{TP})
- compressive yield (n_{CY})
- compressive peak (n_{CP})

Size of yield surface at Nth cycle: $n_{TP} - n_{CY}$

Plasticity : Hardening Rule: Testing



Scarf fixture for tension-compression testing and assembly

Cyclic testing of scarf joint on an Instron to quantify adhesive hardening

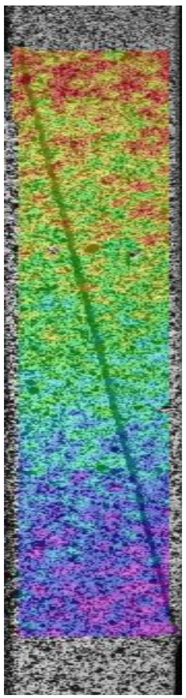
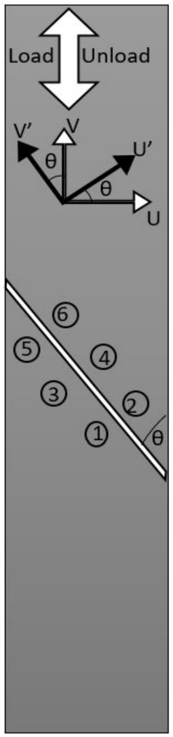


Image analysis software (Vic 3D) used to analyze speckle images for strain calculation

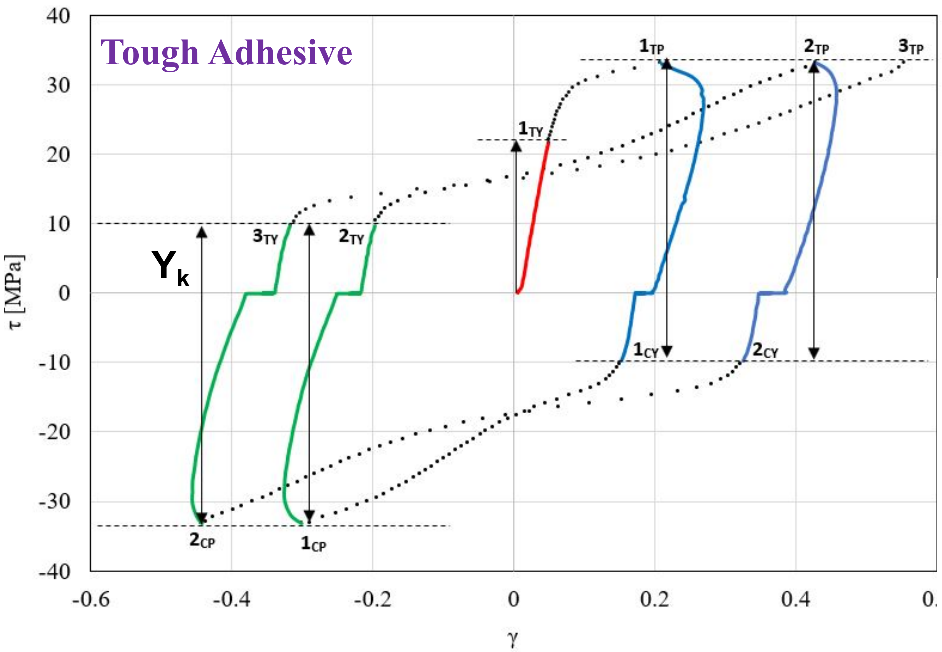


Schematic locations of points tracked to calculate strain

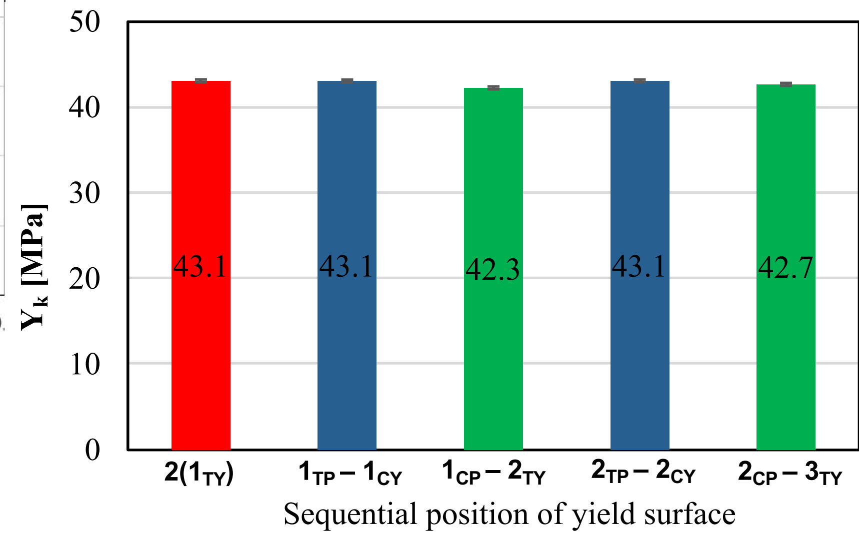
$$\tau_{avg} = \frac{F\cos\theta}{A}$$

$$\gamma_{12} = \frac{dV'_{1-2} - \left(\frac{\tau_{avg}(D-t)}{G}\right)}{t}$$

Plasticity : Hardening Rule: Quantification



- 0.2% offset criterion used to determine yield point
- Y_k ~ 43.1 MPa

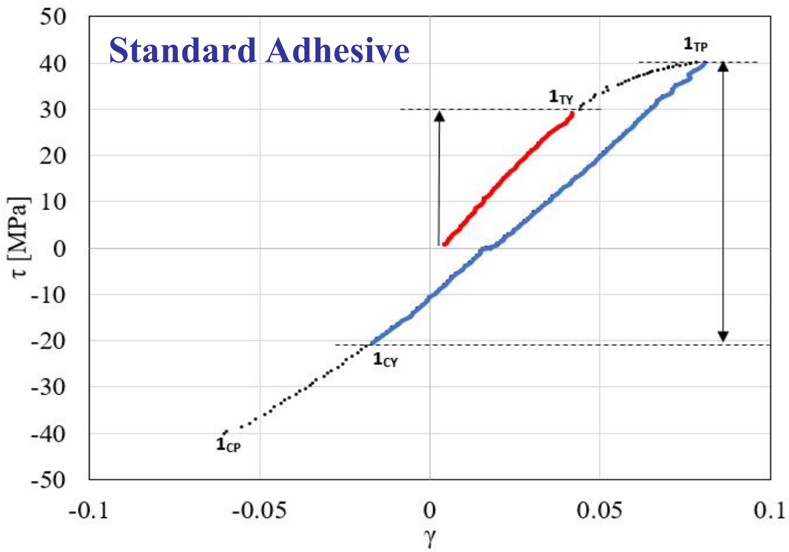


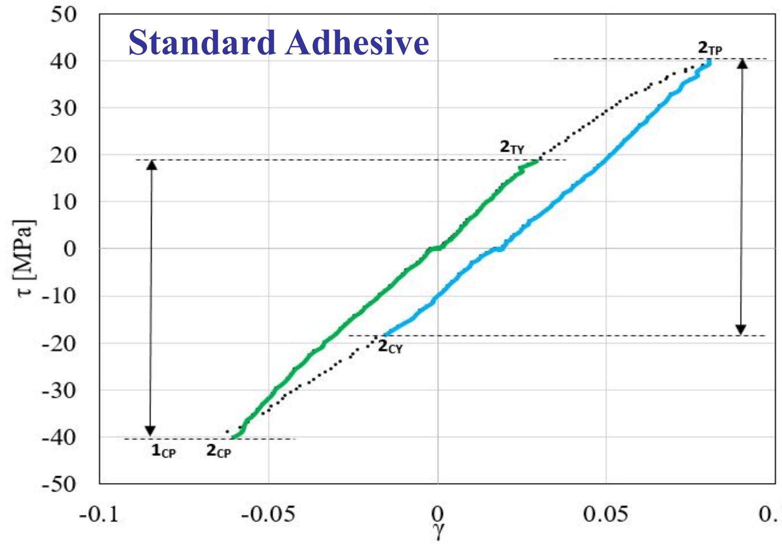
Initial size : $Y_o = 2\tau_A = 43.1$

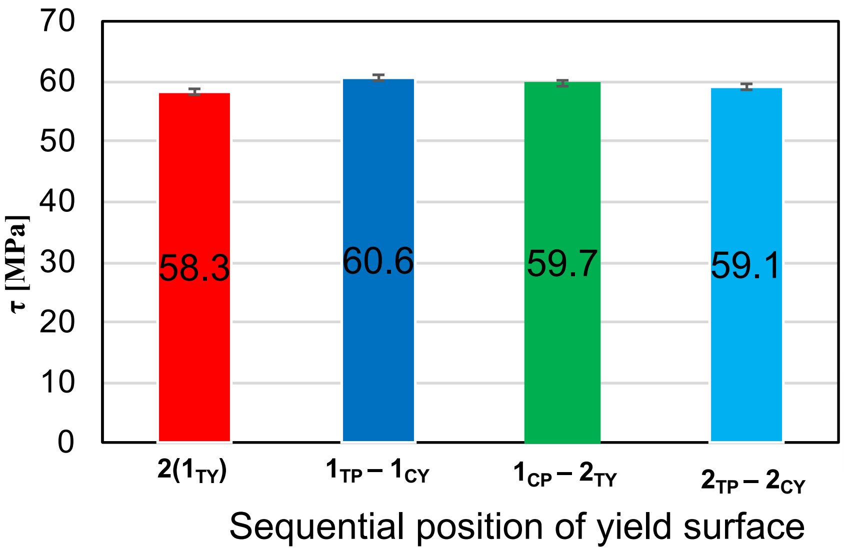
$$Y_k = \tau_B - \tau_C = 43.1$$

What we found: kinematic behavior dominated hardening mechanism of tough adhesive.

Plasticity : Hardening Rule: Quantification







- 0.2% offset criterion used to determine yield point
- 80 ksi (isotropic) > 60 ksi (actual size) > 58 ksi (kinematic)

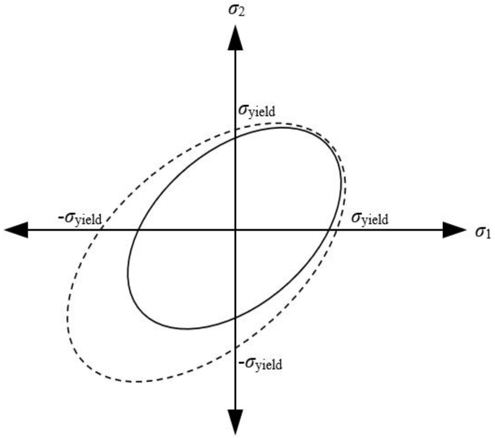
$$k = 91\%$$

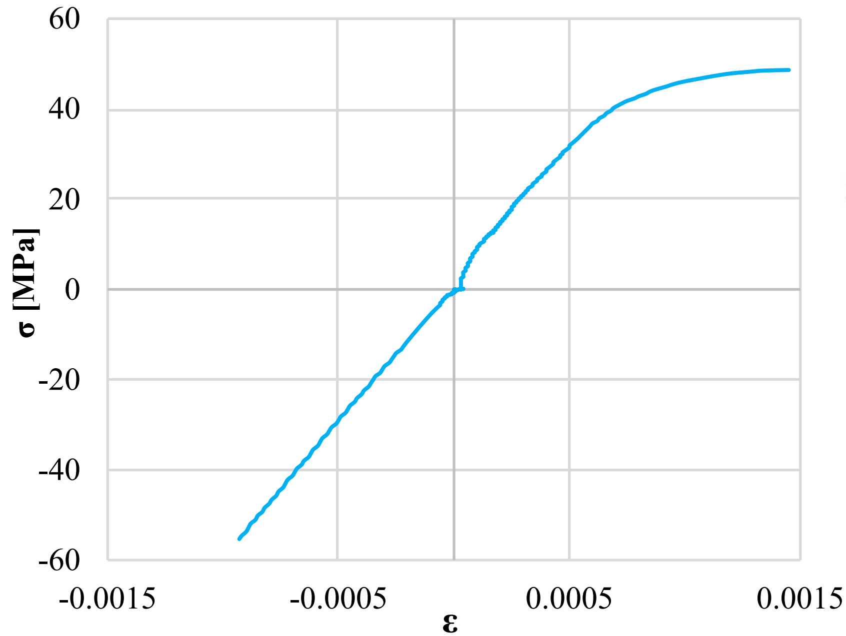
(91% kinematic & 9% isotropic)

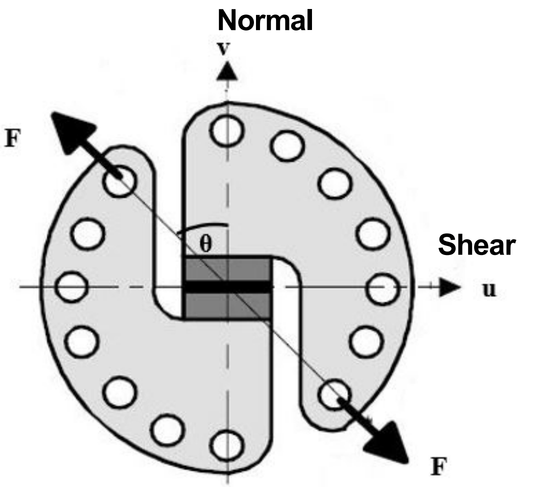
What we found:

Standard adhesive demonstrated combined hardening

Plasticity: Yield Criterion: Challenges







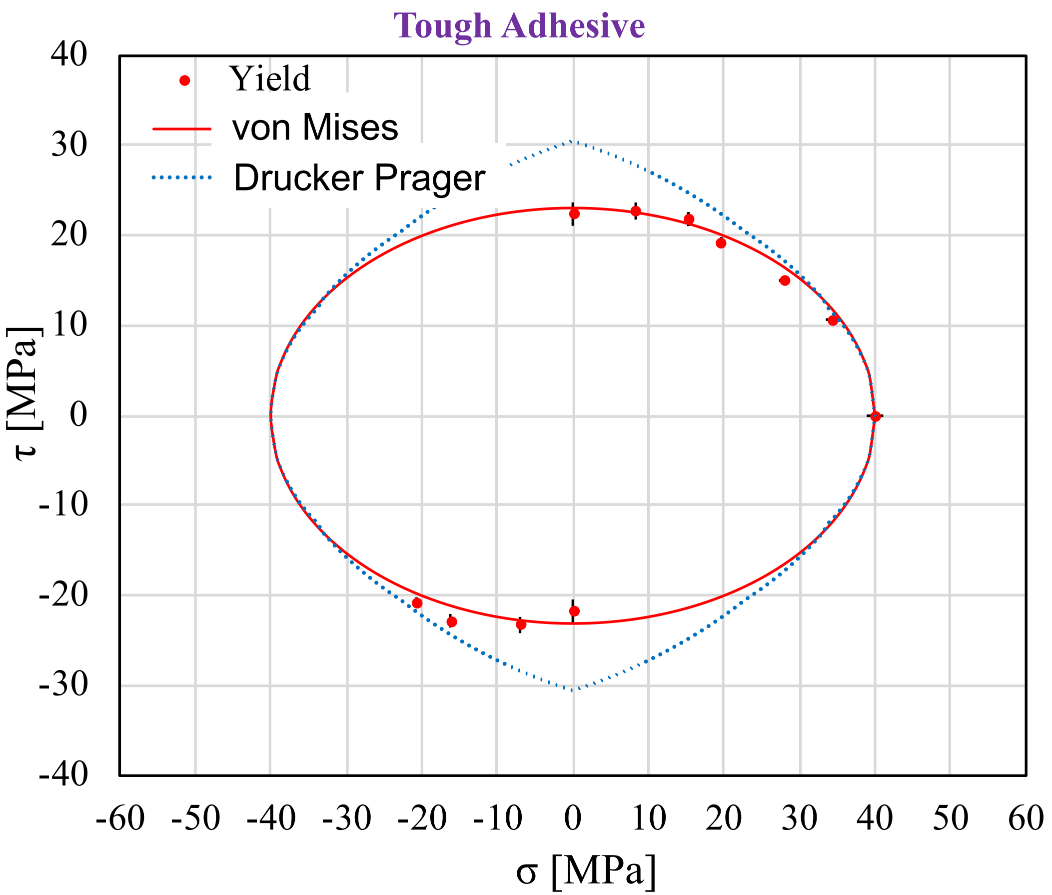
Schematic yield surface in normal-normal stress state:

Solid line = von Mises (typically used for metals)

Dotted line = Drucker-Prager (typically used for rocks, concrete, soil)

- Adhesive joints don't soften at yield in compression.
- Consider normal-shear

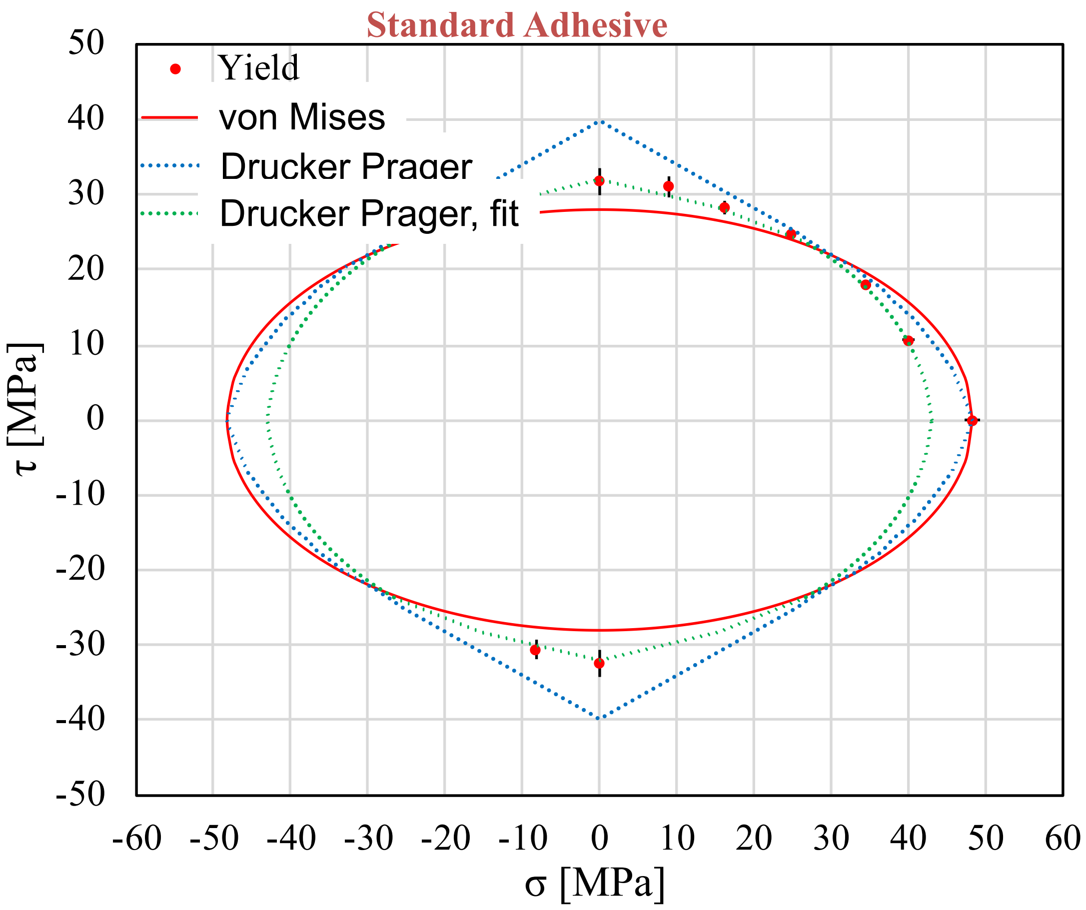
Plasticity: Yield Criterion: Test Results



What we found:

von Mises: best fit

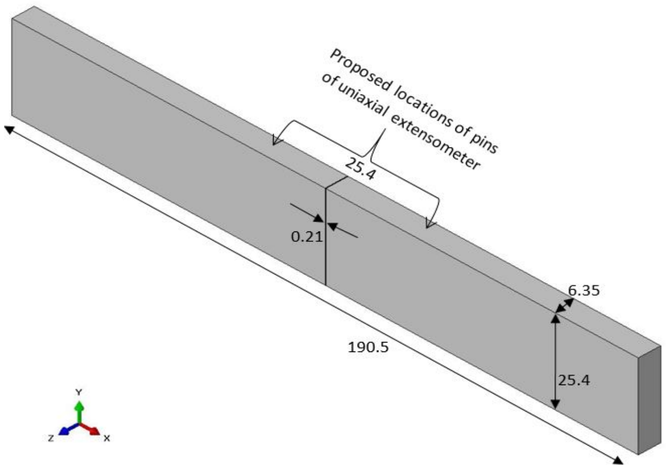
Plasticity: Yield Criterion: Test Results



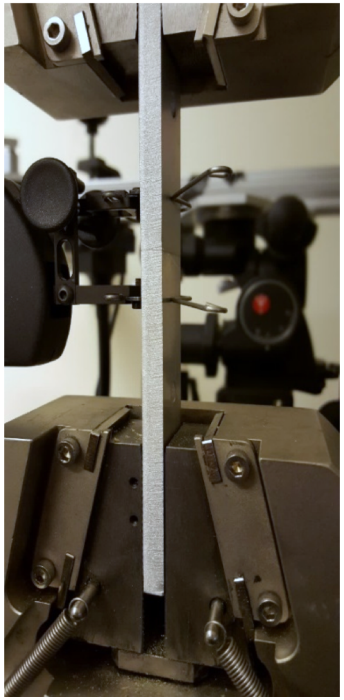
What we found:

von Mises: generally best fit

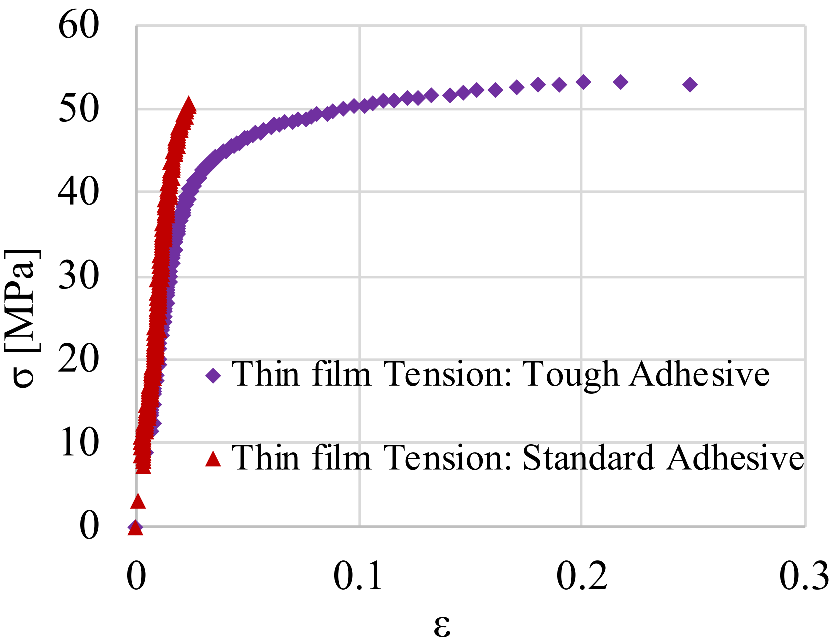
Plasticity: Numerical Modeling: Tensile Input Properties



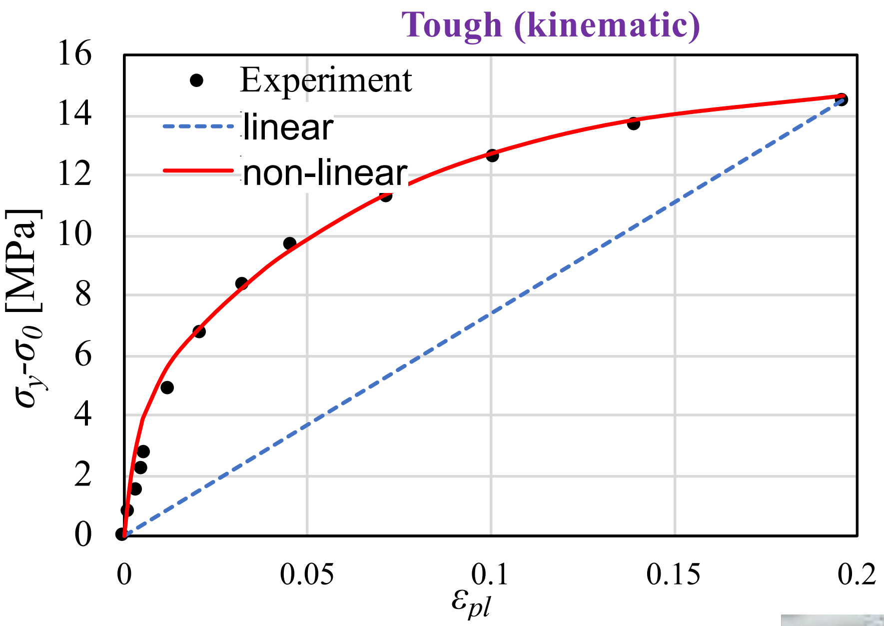
Schematic butt joint with dimensions, load applied in the X direction

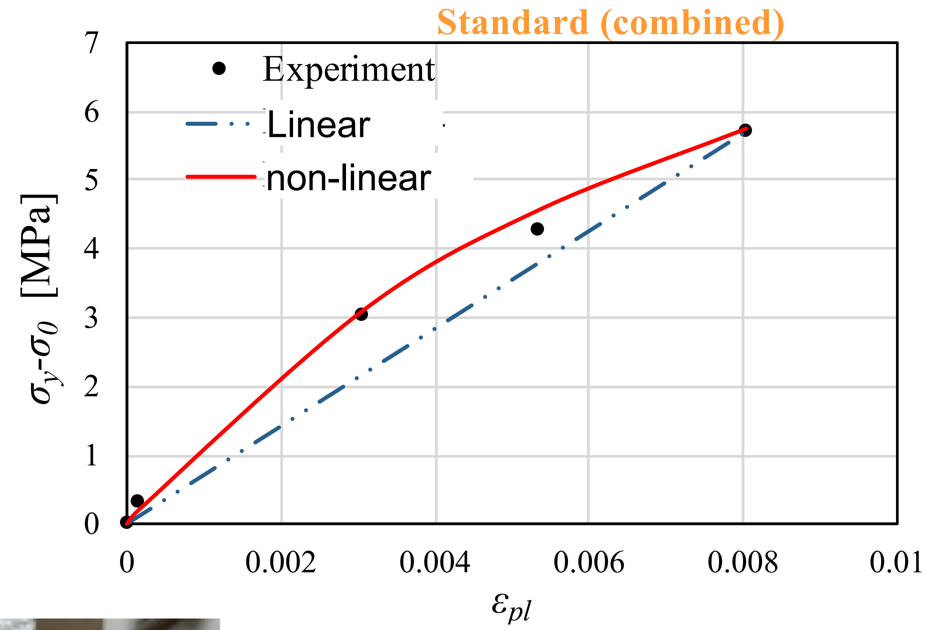


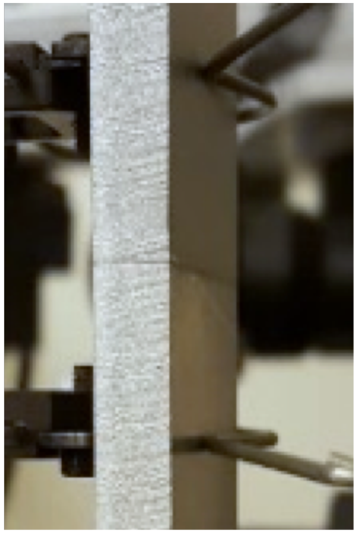
Butt joint being tested on an Instron load frame



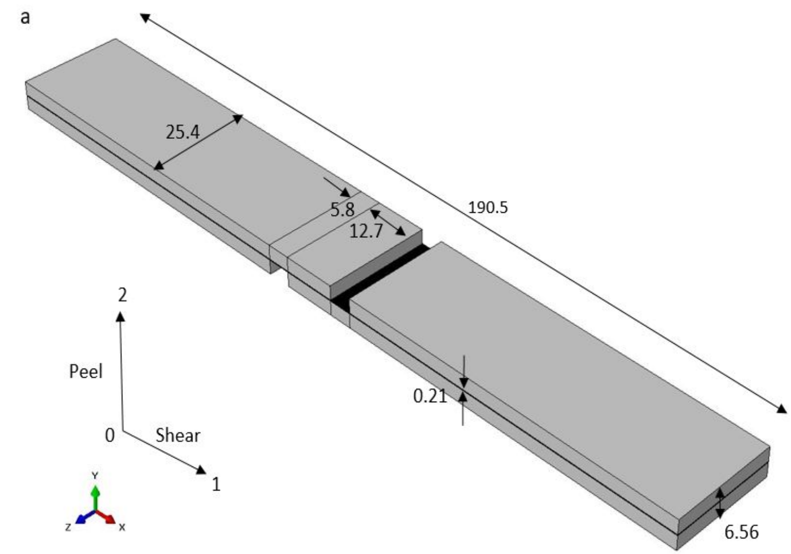
Plasticity: Numerical Modeling: Tensile Input Properties

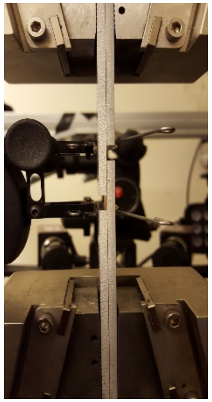




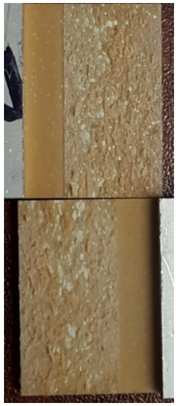


Plasticity: Numerical Modeling: Shear Joints

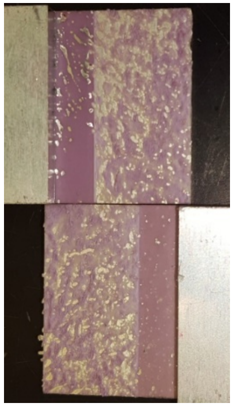




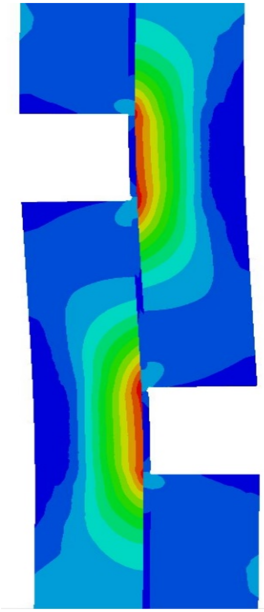
Testing on Instron



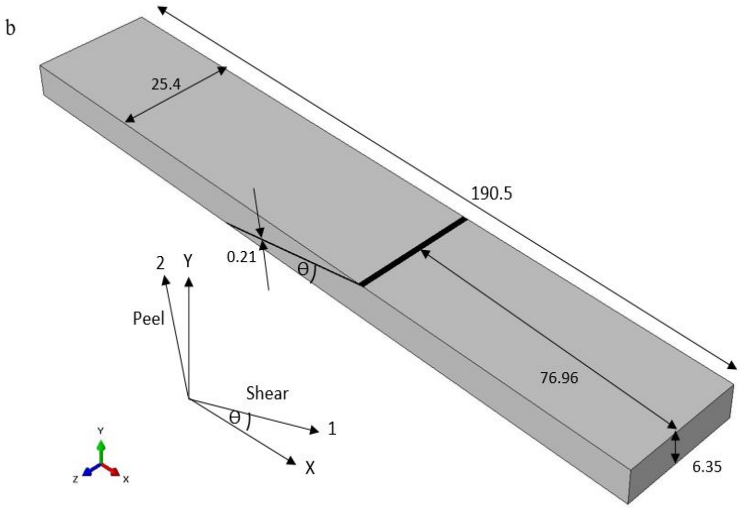
Standard adhesive

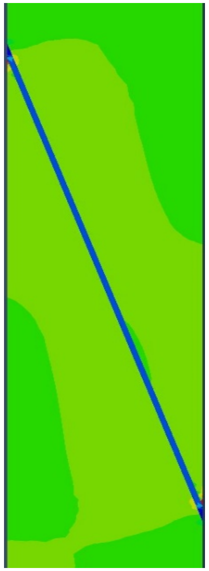


Tough adhesive



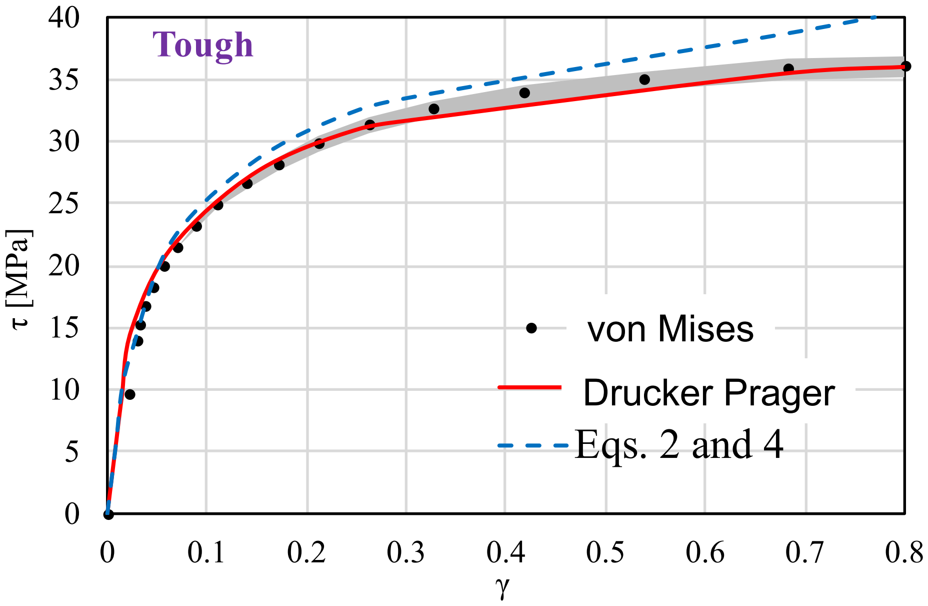
FEA

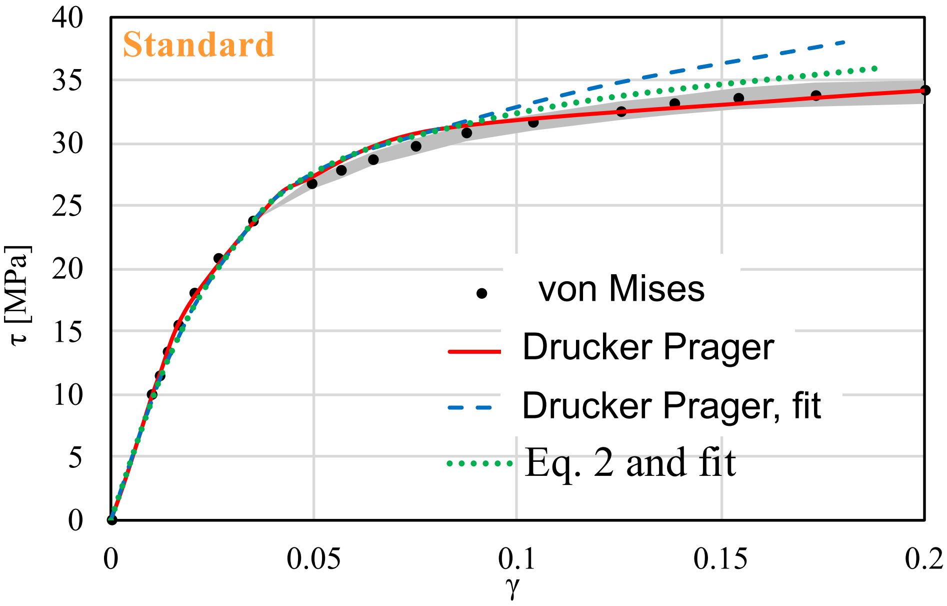




FEA

Plasticity: Validation of Yield Criterion (lap shear coupon)

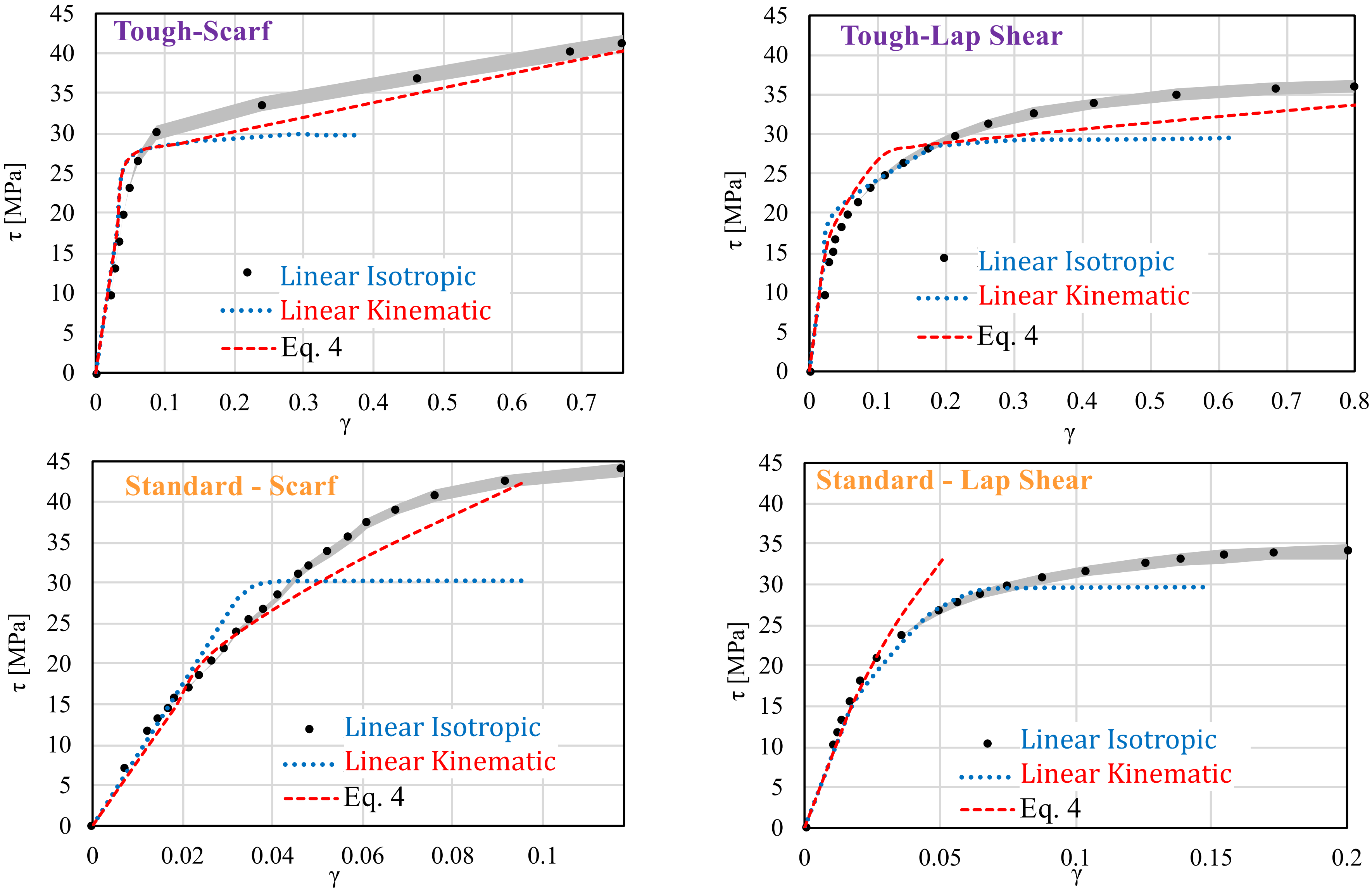




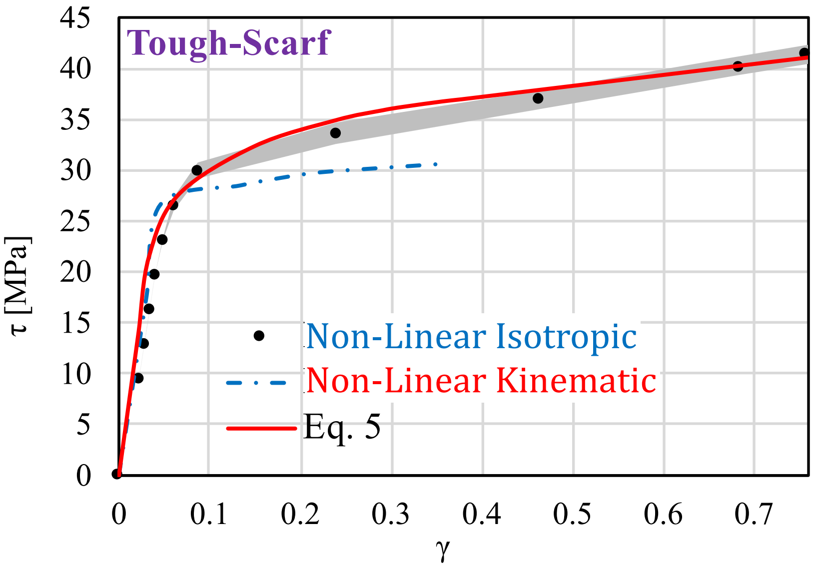
What we found: use of mixed mode lap-shear joint

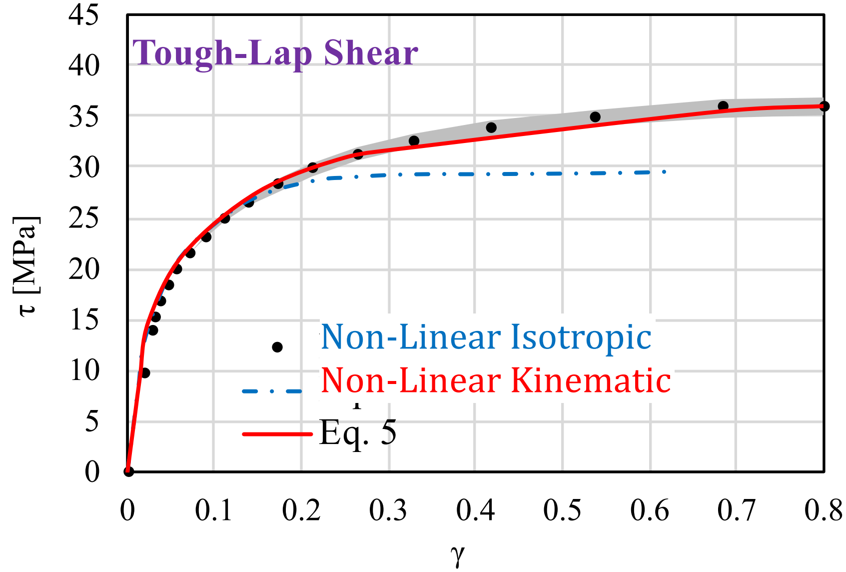
- von Mises criterion better explains adhesive yielding
- Adhesive yielding is not sensitive to hydrostatic pressure.

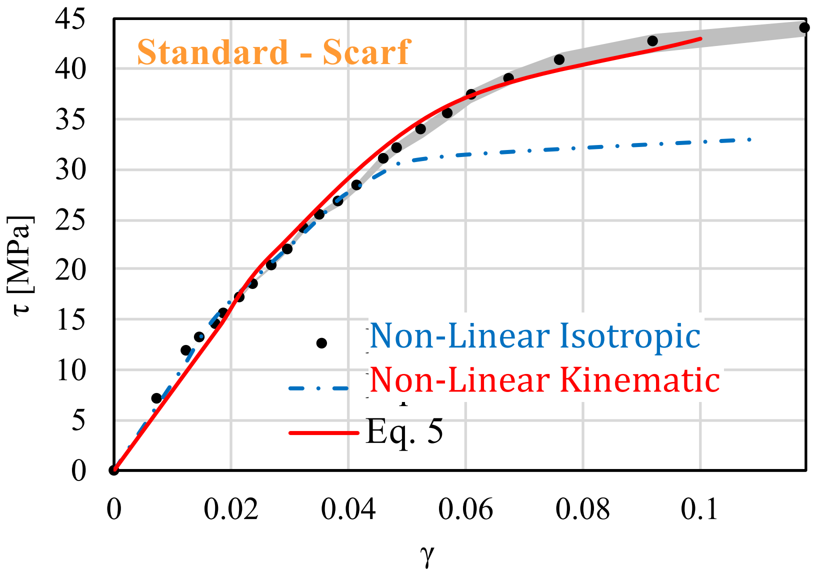
Plasticity: Numerical Modeling: Validation of Hardening Rule

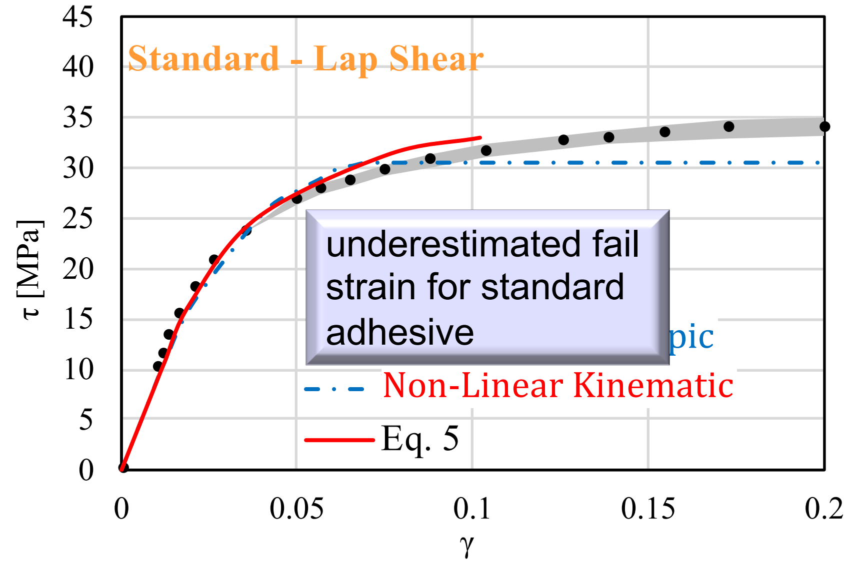


Plasticity: Numerical Modeling: Validation of Hardening Rule

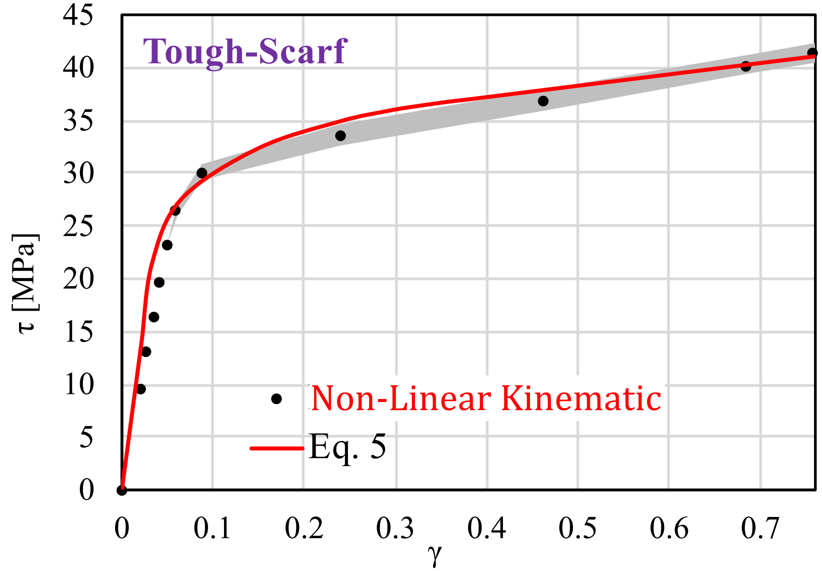


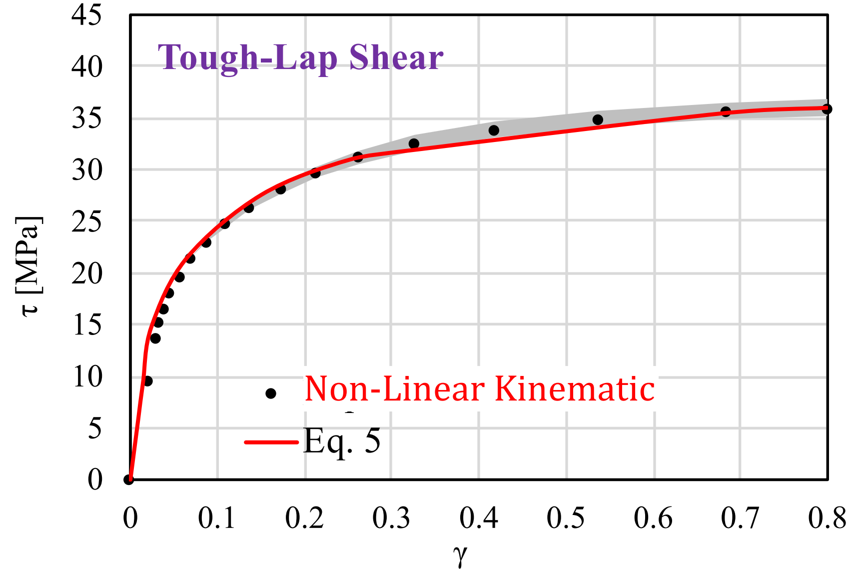


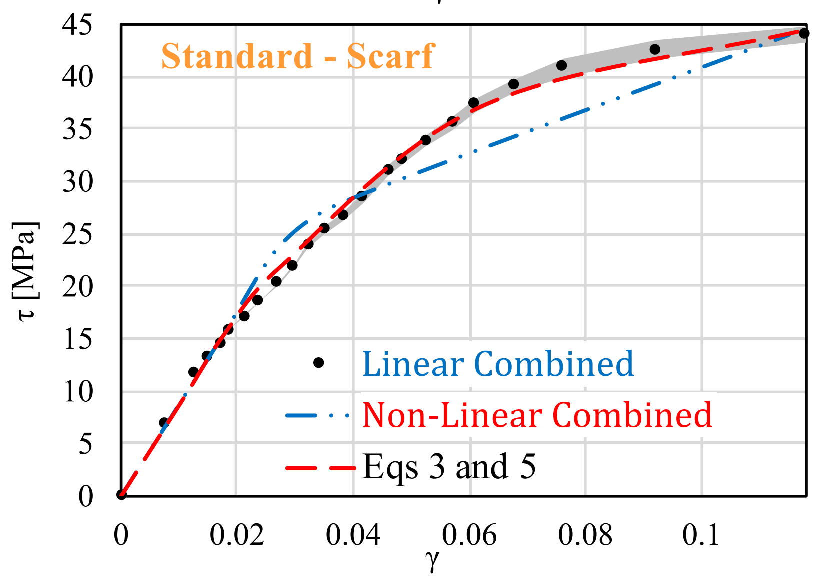


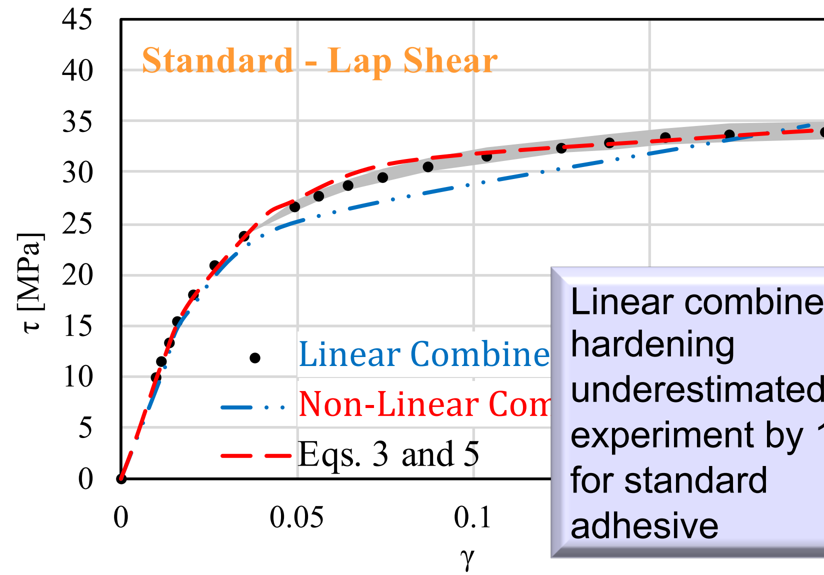


Plasticity: Numerical Modeling: Validation of Hardening Rule









Linear combined hardening underestimated experiment by 13% for standard adhesive

Plasticity : Summary

- Assuming plastic properties can lead to error in numerical modeling.
  - Little has been done to characterize adhesive plastic response
- Arcan fixture was effecting in creating uniform shear with minimal peel stress.
- Adhesives considered here followed von Mises yielding
  - not influenced by hydrostatic pressure.
- Adhesives in this work tended to follow kinematic hardening
  - Isotropic hardening is commonly assumed
  - Nonlinear kinematic hardening governed the tough adhesive behavior.
  - Nonlinear combined hardening (90% kinematic) described standard adhesive.

Time dependence (viscoelasticity/viscoplasticity)

Background

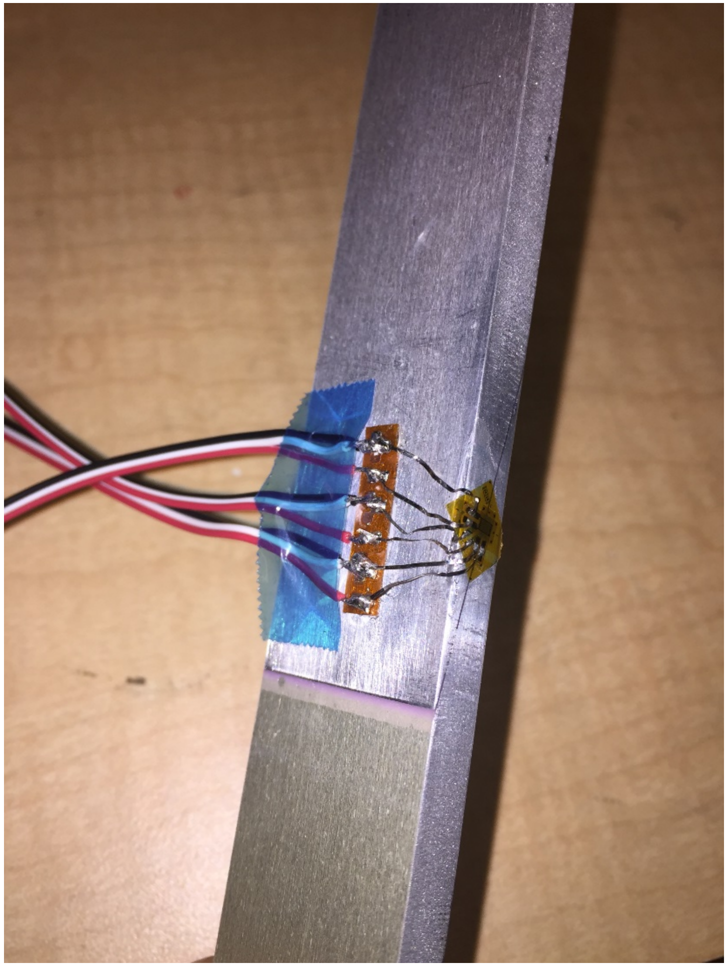
- The time-dependent behavior of adhesives is important for durability
- Little work has been done on adhesive ratcheting effects
- Shear response tends to be more important than normal stress

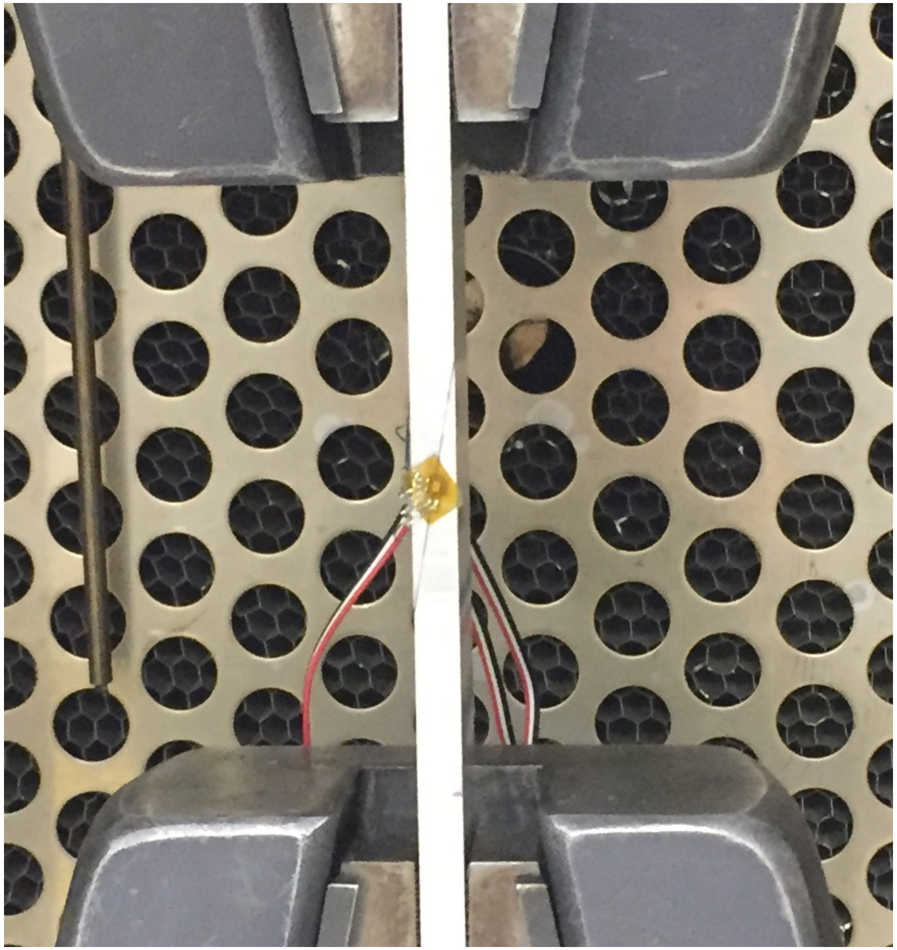
Objectives

The final objective is to build a shear viscoelastic modeling on bonded joints for ratcheting

- FEA viscoelastic model of bulk adhesives under cyclic normal stress (07/31/2019)
- FEA viscoelastic model of bonded joints under shear (12/31/2020)

Measuring Adhesive Strain in Bonded Joints





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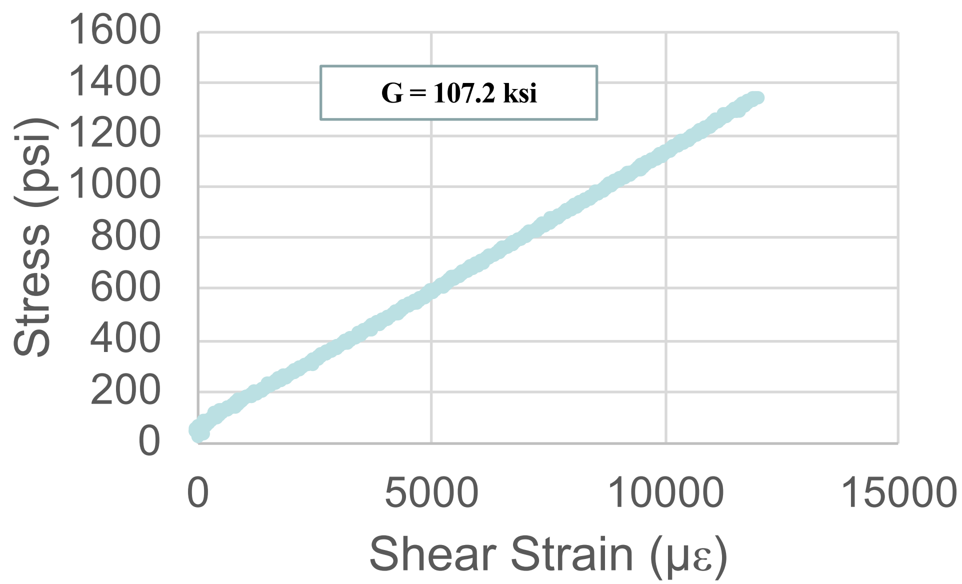
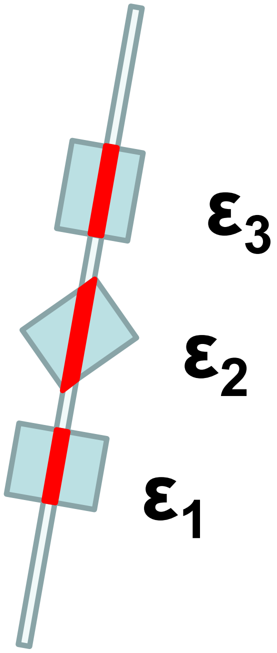
Rosette Strain Gages

- **Divide each strain component by 0.13**
  - **Fraction of the gage covering the adhesive**
  - **Strain in adherend was 2% of the adhesive and neglected**
- $\gamma = 2\varepsilon_2 - \varepsilon_1 - \varepsilon_3$

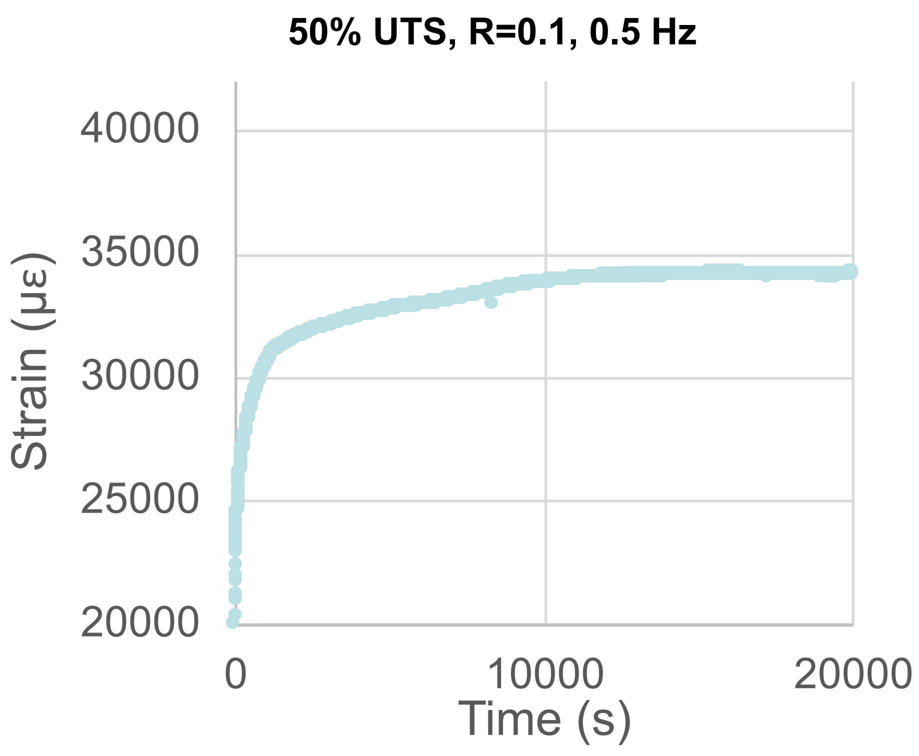


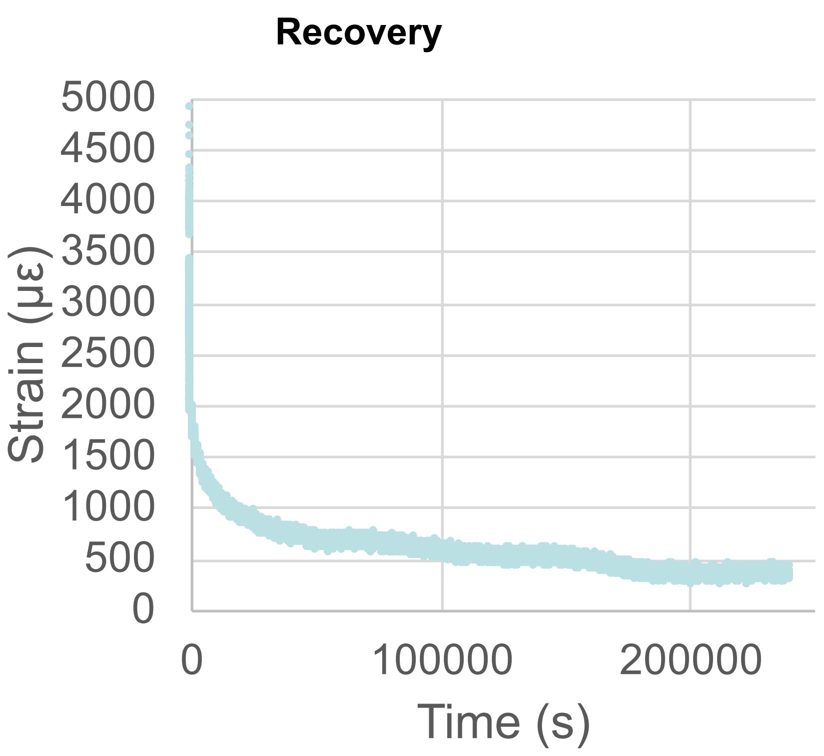


Strain Gages Covering Adhesive

10000 Cycle Ratchet Test

- **EA9696 Scarf Joint**





Approach: Time dependence (viscoelasticity/viscoplasticity)

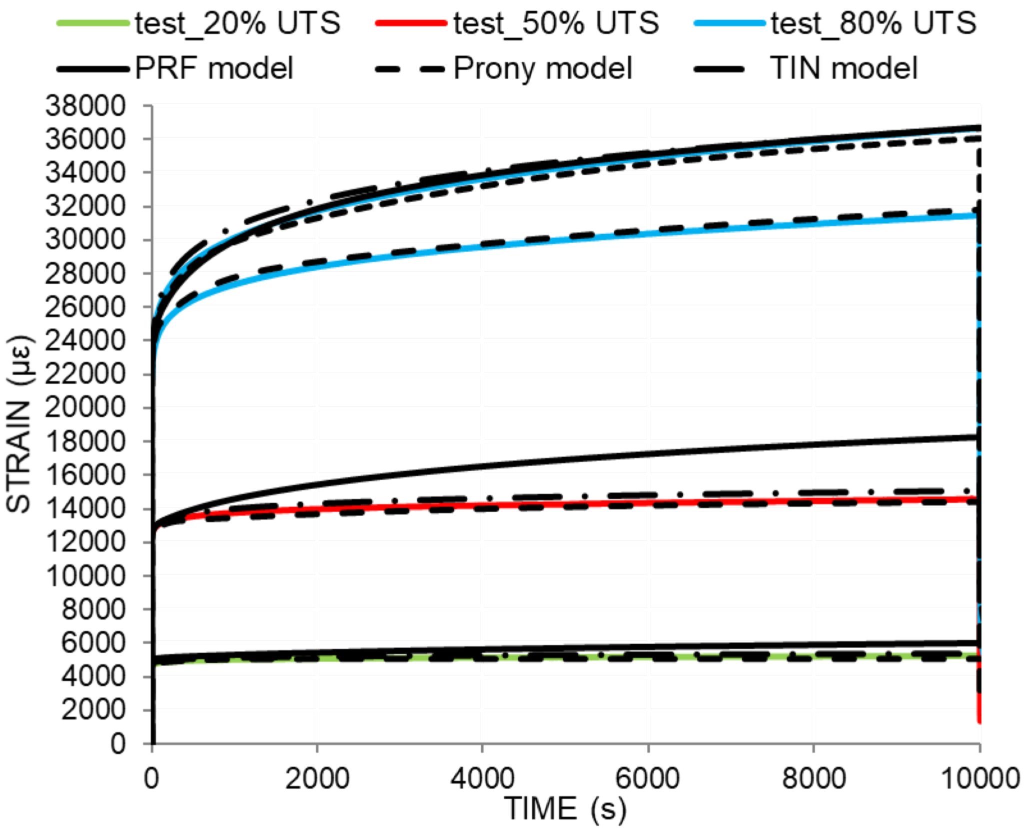
- Comparisons of viscoelastic analytical/ numerical models

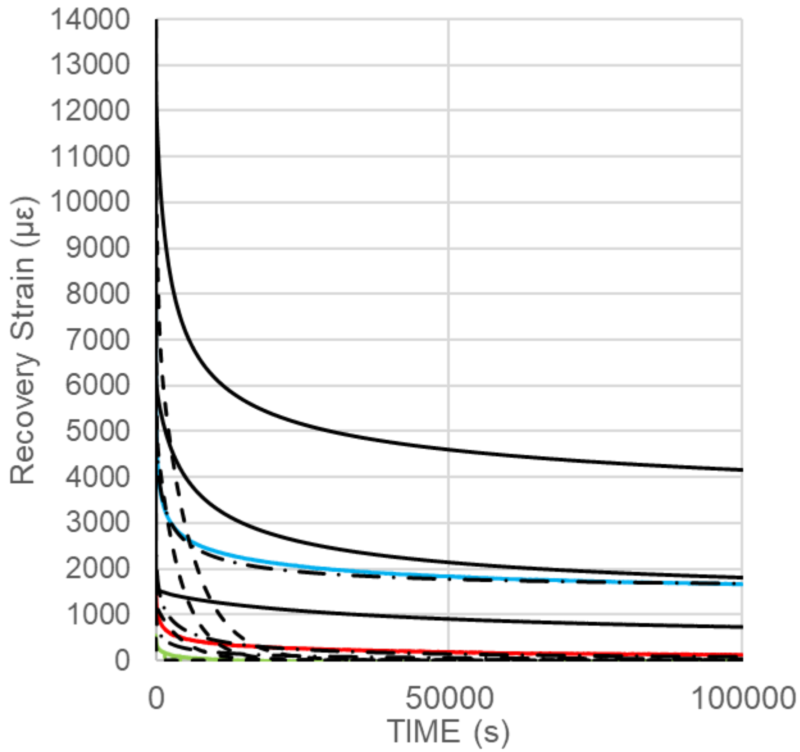
	Model	Calibration	Disadvantages
Triple Integral Nonlinear (TIN)	Extended Boltzmann superposition integral, nonlinear	From creep tests under load of 20%, 50% and 80% UTS, general	Numerically unstable; Significant time cost.
Specific Linear Model (SLM)	Boltzmann Superposition integral, single term	From creep tests under load of 20%, 50% and 80% UTS, tailored	Linear.
Prony	Linear viscoelastic model in ABAQUS, summation	From creep tests under load of 20%, 50% and 80% UTS, tailored	Linear; No permanent strain for recovery stage.
Parallel Rheological Framework (PRF)	Nonlinear viscoelastic model in ABAQUS	From long term creep test data under load of 50% and 80% UTS, general	Cannot describe the response to different percent UTS simultaneously.

Approach: Time dependence (viscoelasticity/viscoplasticity)

Modeling on Bulk resin

- **EA9696 Creep**



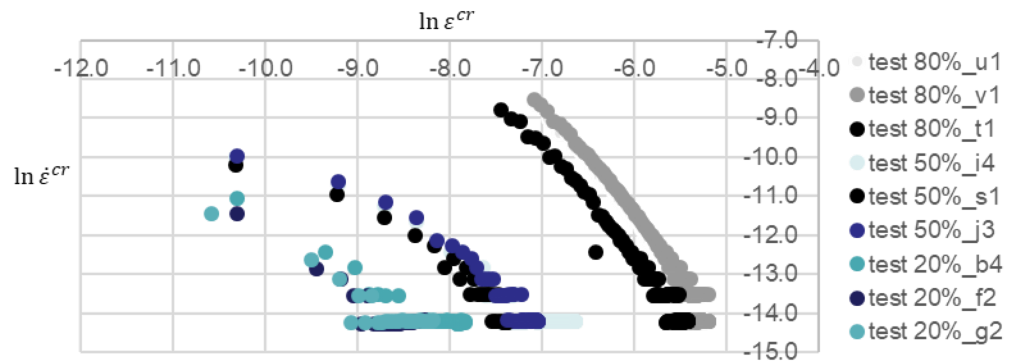


PRF

– The <u>viscous</u> part in PRF model: $\dot{\varepsilon}^{cr} = \{A\tilde{q}^n[(m+1)\varepsilon^{cr}]^m\}^{\frac{1}{m+1}}$

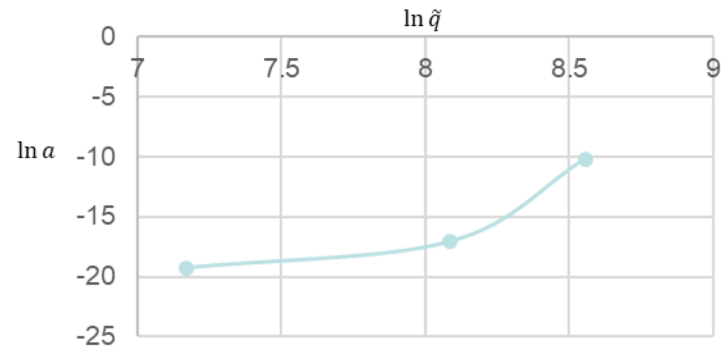
– Taking the log of both sides we have: $\ln \dot{\varepsilon}^{cr} = \ln a + \frac{m}{m+1} \ln \varepsilon^{cr}$, where $a = A^{\frac{1}{m+1}} \tilde{q}^{\frac{n}{m+1}} (m+1)^{\frac{m}{m+1}}$

– But, experiment is only linear at 80% UTS



– Log of *a* and $\tilde{q}$ should also be linear

- But they are not experimental

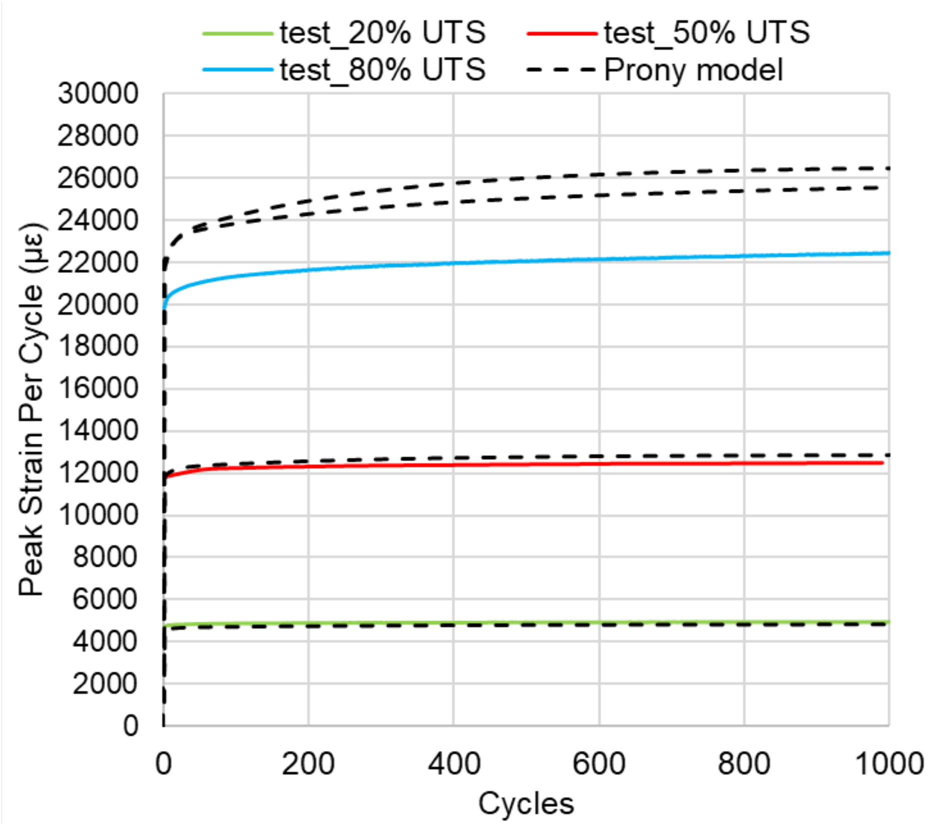


– Therefore, PRF is not well suited for EA9696

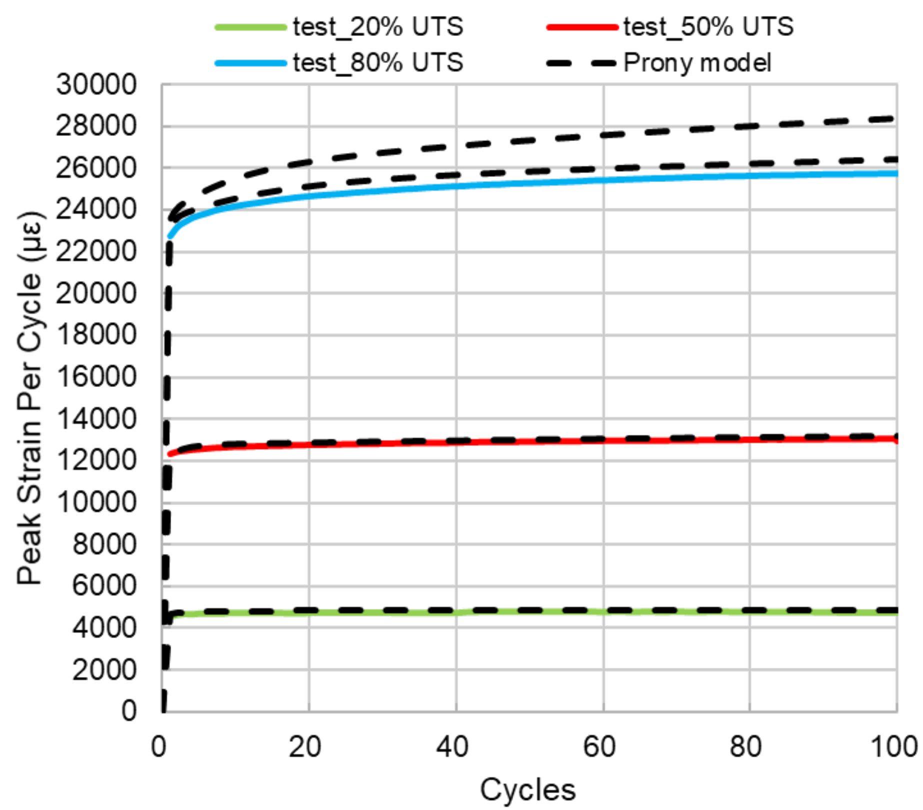
Approach: Time dependence (viscoelasticity/viscoplasticity)

Modeling on Bulk resin

- EA9696, 0. 5Hz, R=0.1



- EA9696, 0.025Hz, R=0.1



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Summary & Future Work

- 80% UTS has large experimental variation in creep and cyclic stress
- PRF FEA model cannot describe strain response from applied creep and cyclic stress
- Damage from cyclic stress appears to depend on both stress magnitude and rate, but could be due to batch differences

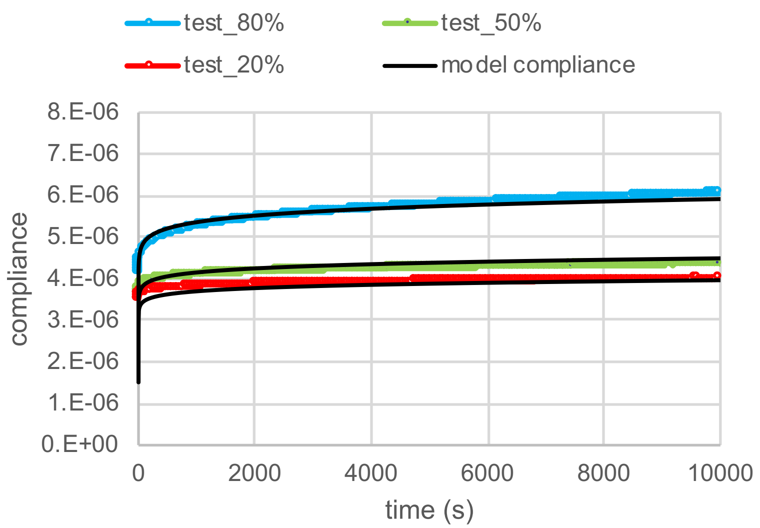
- Perform additional tests at 80% UTS
  - Creep, 1 ks and 10 ks
  - Cyclic tests, R=0.1, 0.025 – 5 Hz.

Summary & Future Work

- Another non linear model (NPL)

$$D(t) = D_0 e^{\left(\frac{t}{t_0}\right)^m}, \qquad \text{where } t_0 = Ae^{-\alpha\sigma^2}$$

Next step is to input it as a User Subroutine into ABAQUS PRF model.



- Enable plasticity in PRF model