Describing the Viscoplastic Response of Aerospace Adhesives

Federal Aviation Administration

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Student: Yi Chen

Washington State University

Joint Centers of Excellence for Advanced Materials

JAMS Technical Review

Sept. 9, 2021

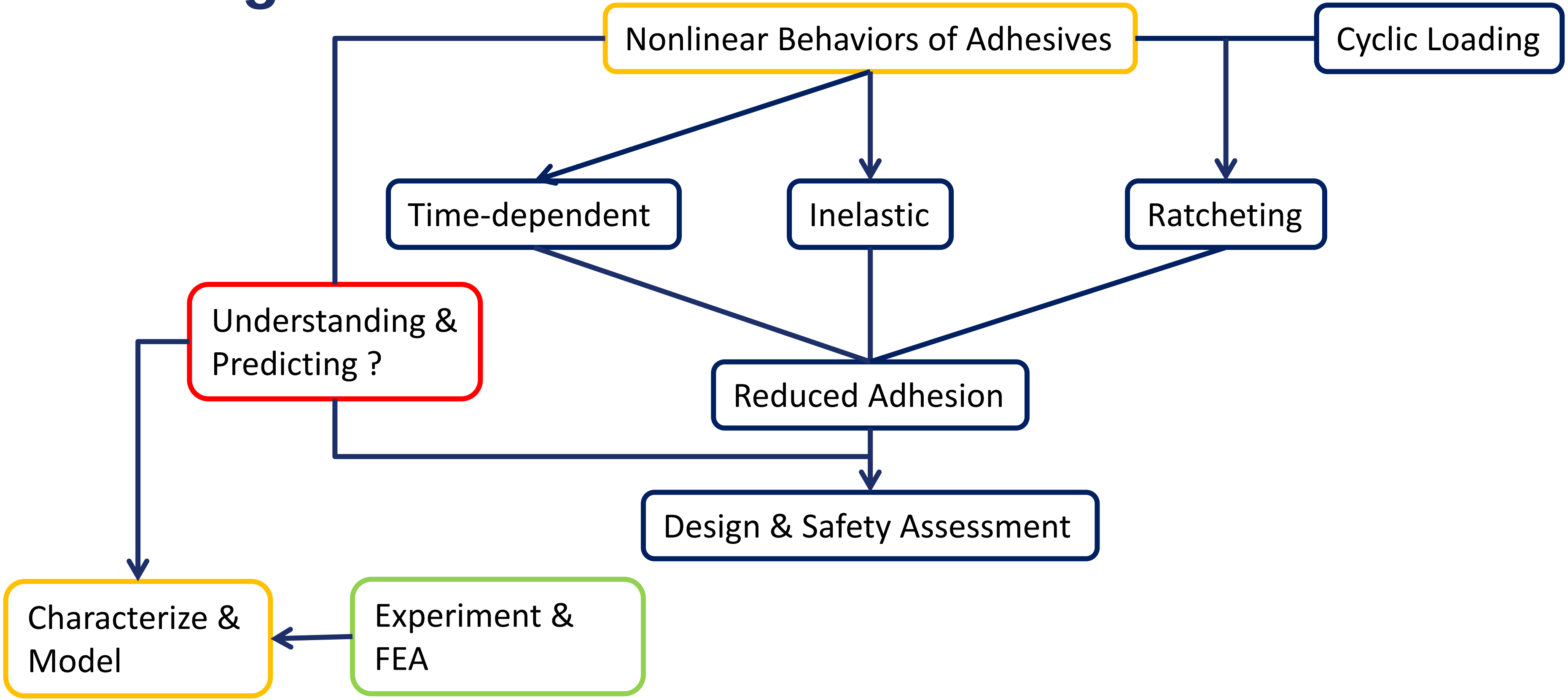
A Center of Excellence AMTAS Advanced Materials in Transport Aircraft Structures

CECAM center of excellence for composites and advanced materials

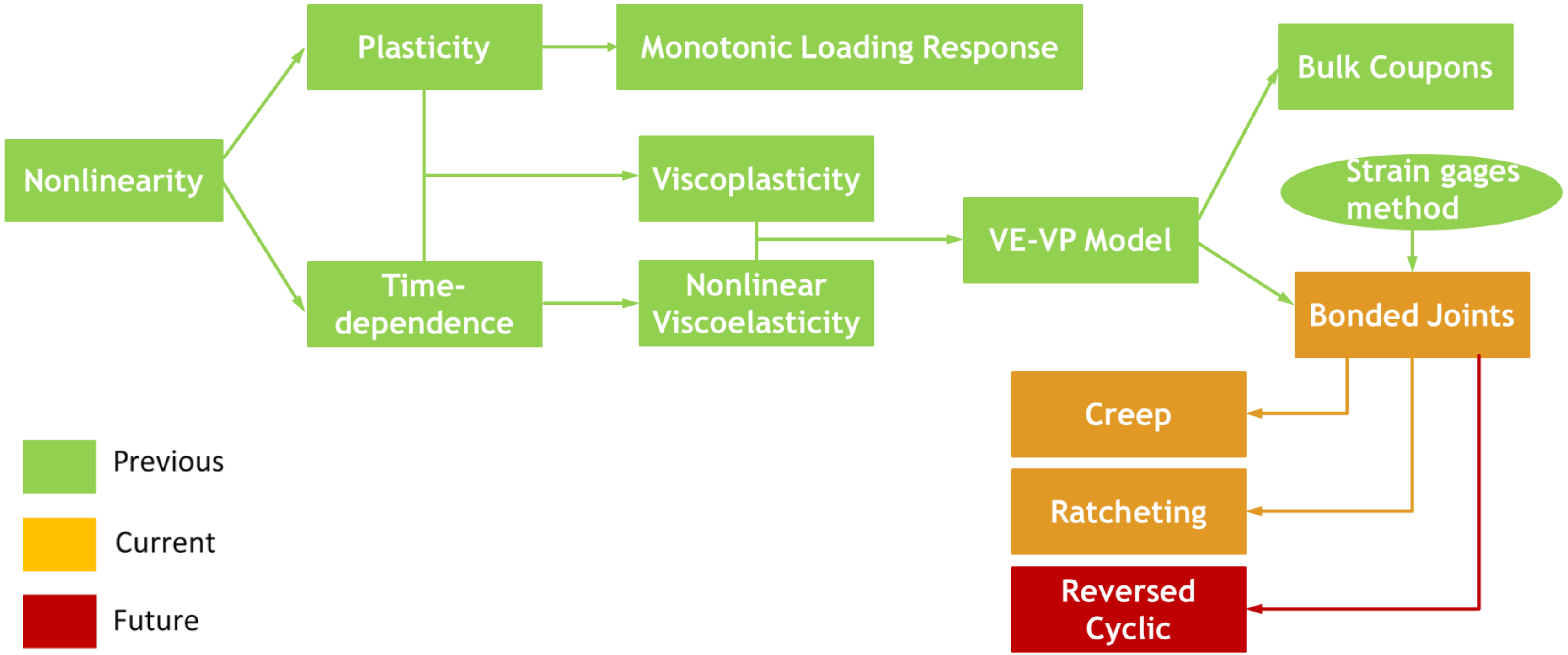
Introduction

- **Project**
  - Durability of Bonded Aerospace Structures
- **Principal Investigators & Students**
  - Lloyd Smith
  - Yi Chen
- **FAA Technical Monitor**
  - Ahmet Oztekin
- **Other FAA Personnel**
  - Larry Ilcewicz
- **Industry Partnerships/Other Collaborations**
  - Boeing, Will Grace, Kay Blohowiak, Ashley Tracey
- **Source of matching contribution for the current award**
  - WSU and Boeing

Background


Nonlinear Behaviors of Adhesives
Cyclic Loading
Time-dependent
Inelastic
Ratcheting
Understanding & Predicting ?
Reduced Adhesion
Design & Safety Assessment
Characterize & Model
Experiment & FEA

Work Introduction



Current Work

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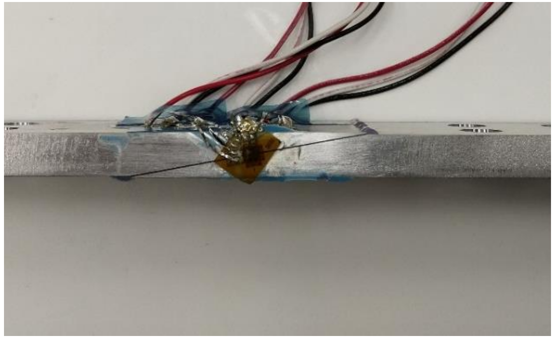
    - Ratcheting-Recovery of Scarf & Lap Shear Joints
    - Comparison between VE-VP & VE-P

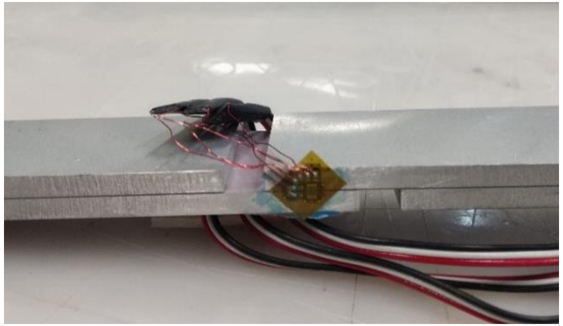
Test Coupons

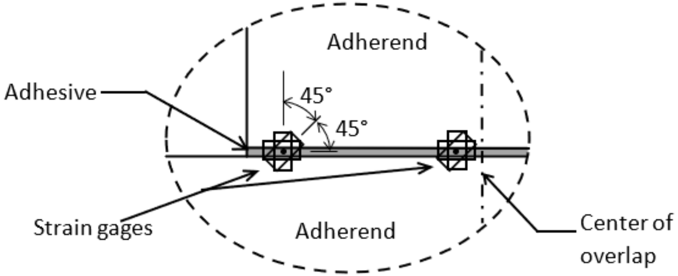
- **Toughened: EA9696; Standard: FM300-2**
- **45-degree rectangular stacked rosette strain gage**

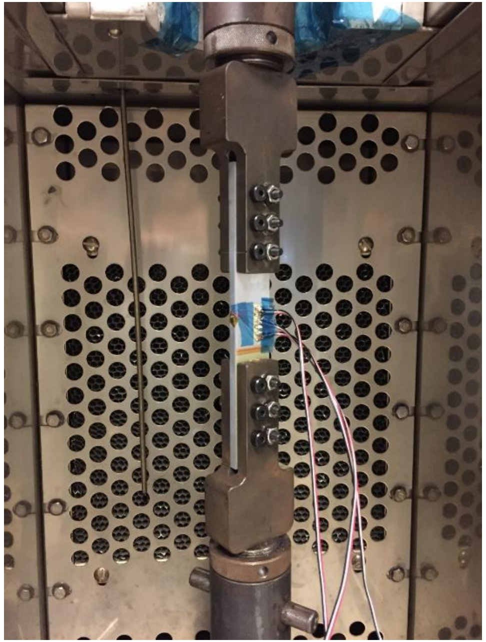
- **Scarf Joint: 10°**



- **Lap Shear Joint**

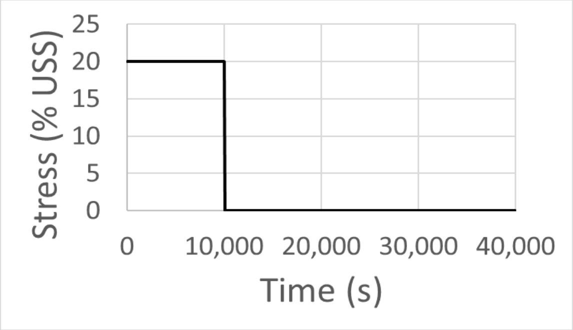


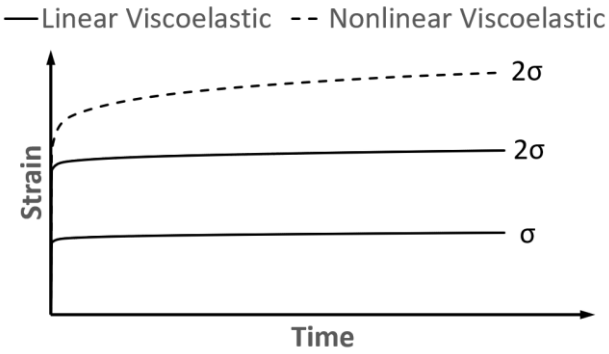




Creep & Ratcheting

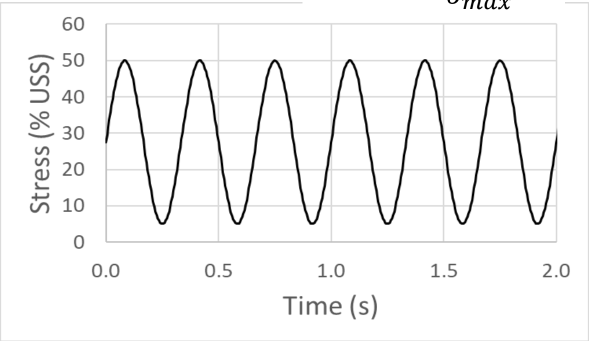
Creep input

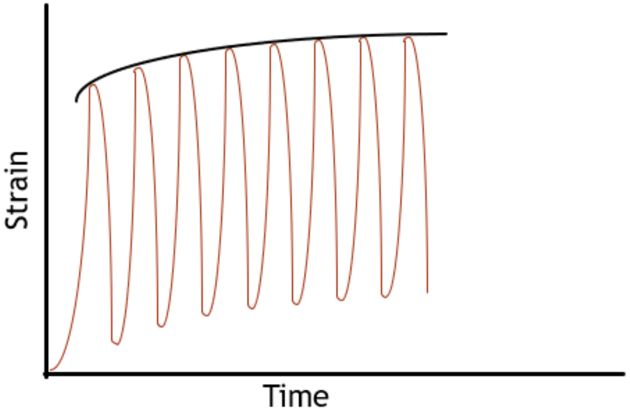




Ratchet input

- $R = \frac{\sigma_{min}}{\sigma_{max}}$





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Nonlinear Viscoelastic-Viscoplastic Model

- **Total Strain:**

$$\varepsilon_{ij}^{tot} = \varepsilon_{ij}^{ve} + \varepsilon_{ij}^{vp}$$

- **Viscoelastic Model (Schapery)**

$$\varepsilon^{ve}(t) = g_0 D_0 \sigma^t + g_1 \int_0^t \Delta D^{(\psi^t - \psi^\tau)} \frac{d(g_2 \sigma^\tau)}{d\tau} d\tau$$

$$\psi^t = \frac{t}{a}$$

$$\Delta D^{\psi^t} = \sum_{n=1}^{5} D_n \left(1 - \exp(-\lambda_n \psi^t)\right)$$

g_0, g_1, g_2, a - nonlinear parameters dependent on stress at current time t, σ^t
D_0, D_n, λ_n – parameters in Prony series

Nonlinear Viscoelastic-Viscoplastic Model

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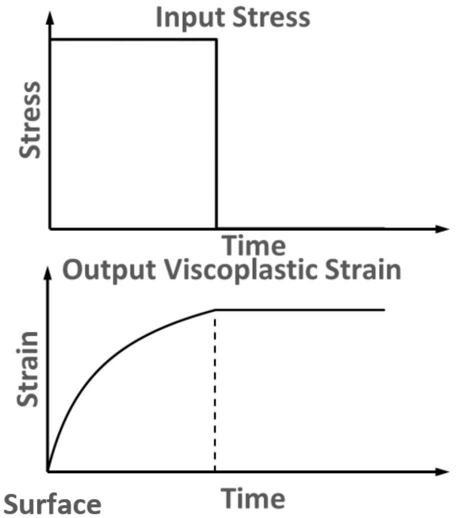
- **Viscoplastic Model (Perzyna)**

$$\dot{\varepsilon}^{vp} = \dot{\lambda} m = \eta\langle\phi(f)\rangle \frac{\partial f}{\partial \sigma_{ij}} = \eta \left\langle \left(\frac{f}{\sigma_y^0}\right)^N \right\rangle \frac{\partial f}{\partial \sigma_{ij}}$$

η – viscosity parameter

N - constant



- **f Yield Function**

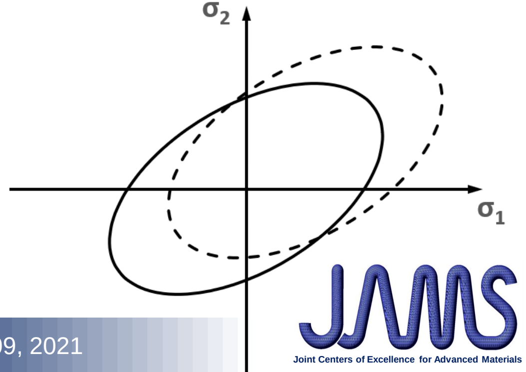
Von Mises Yield criterion + Nonlinear Kinematic Hardening

$$f = \sigma_e - \sigma_y^0 = \sqrt{\frac{3}{2}(S_{ij} - \alpha_{ij})(S_{ij} - \alpha_{ij})} - \sigma_y^0$$

$$\dot{\alpha}_{ij} = \frac{c}{\sigma_y^0}(\sigma_{ij} - \alpha_{ij})\dot{\varepsilon}_e^{vp} - \kappa \alpha_{ij} \dot{\varepsilon}_e^{vp}$$

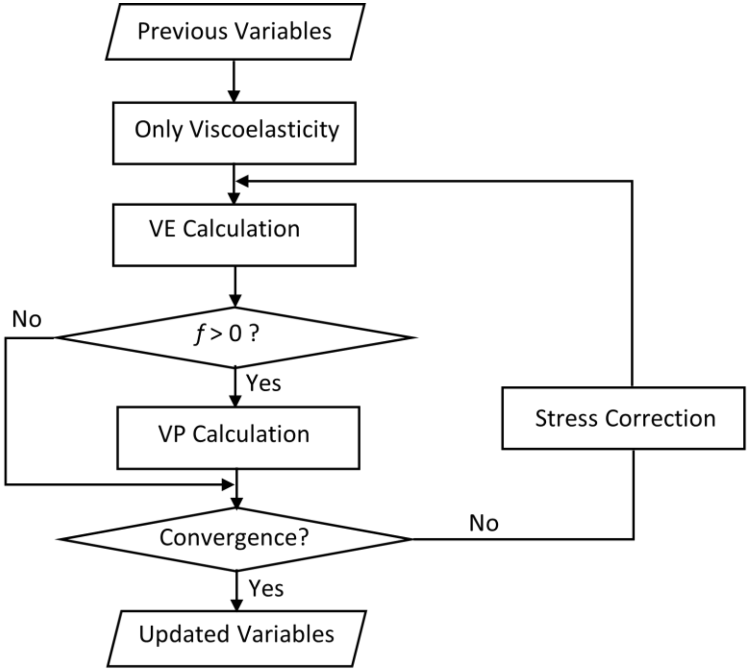
α_{ij} - back stress

ε_e^{vp} - effective viscoplastic strain



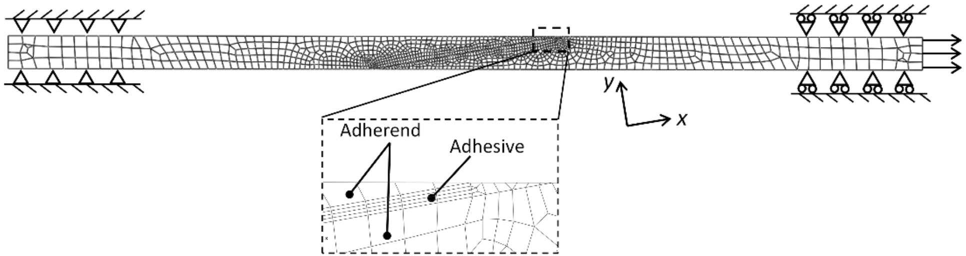
FE Model

- **Flow Chart**

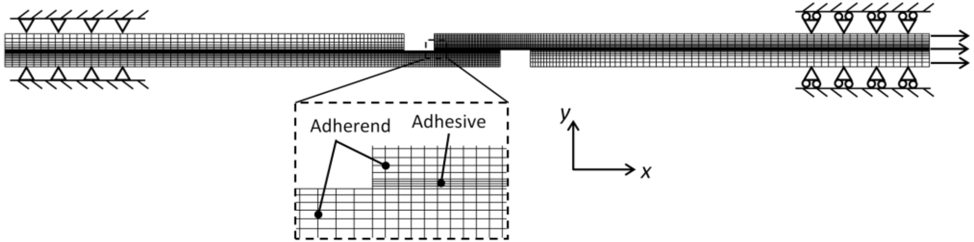


- **Mesh & Boundary Conditions**

Scarf Joint



Lap Shear Joint



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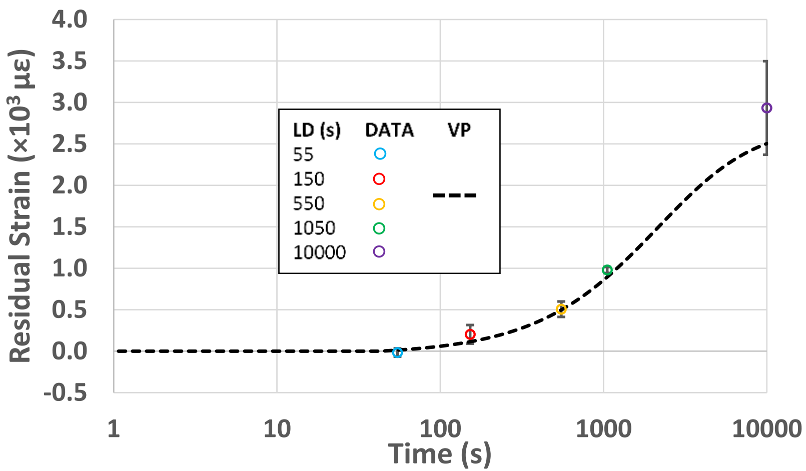
Parameters Calibration

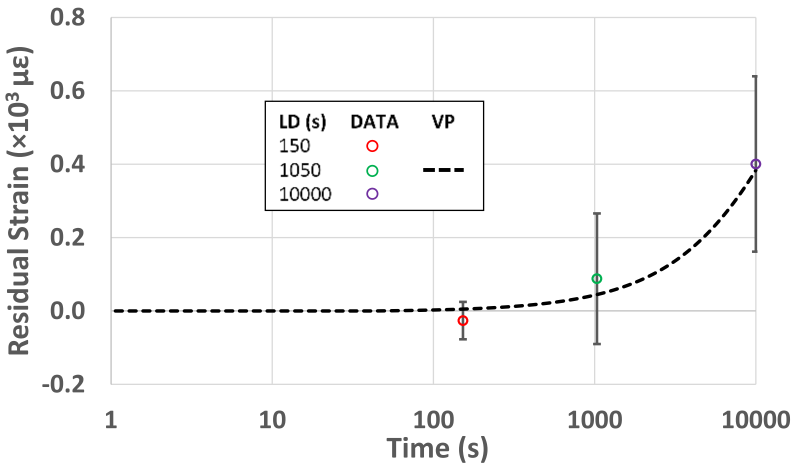
- Creep Data without Permanent Strain → Viscoelasticity
- Uniaxial Tension Test → Yield Criterion and Hardening Rule
- Residual Strain of Creep Experiments with Varying Load Durations → Viscosity Parameters

Fitting of Viscoplastic Components

•EA9696



•FM300-2



Scarf Joint- Creep at 50% USS

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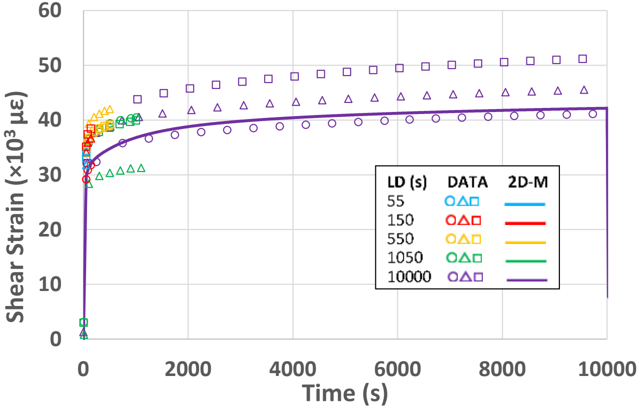
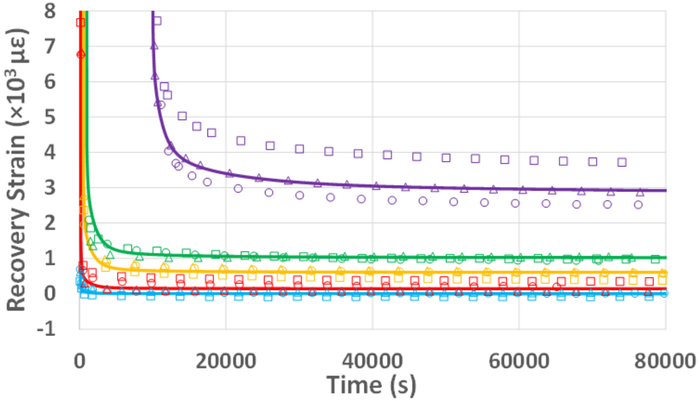
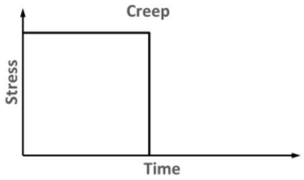
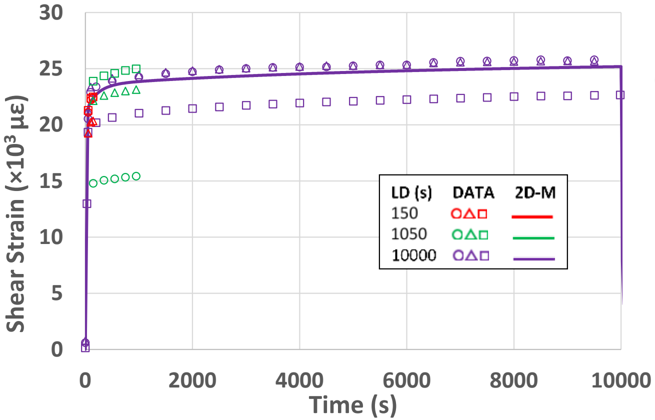
- EA9696

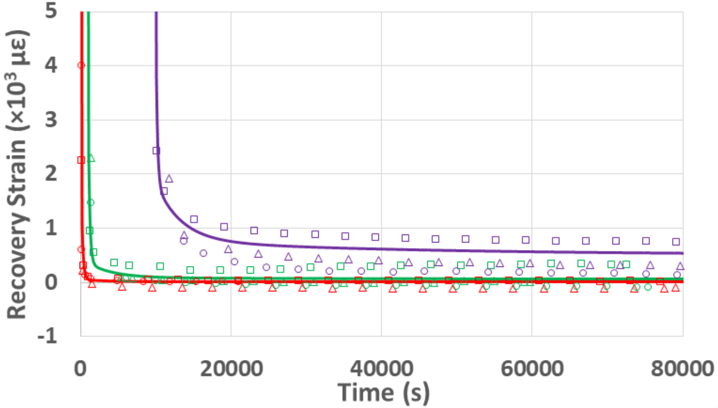






- FM300-2





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Scarf Joint- Ratcheting with R=0.1, 50% USS

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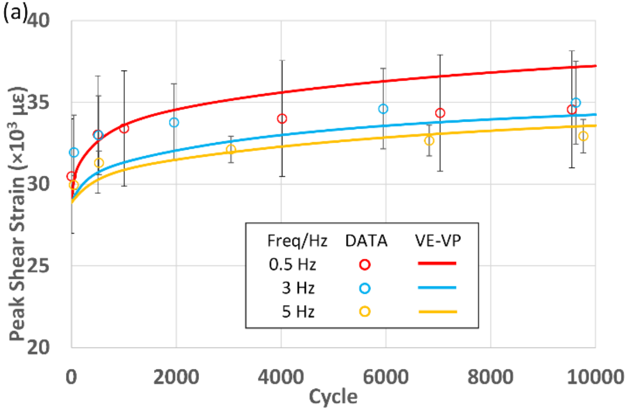
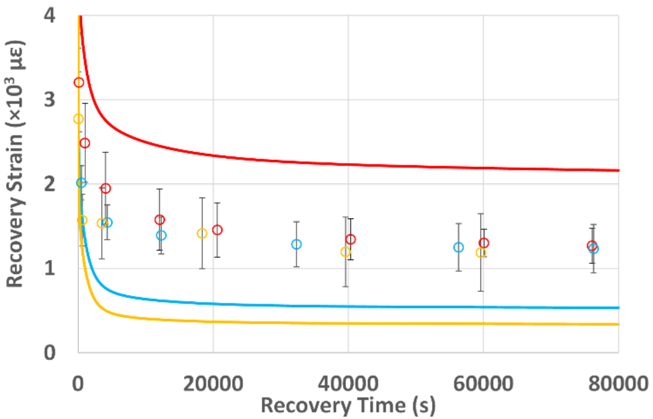
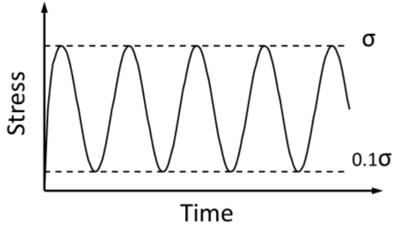
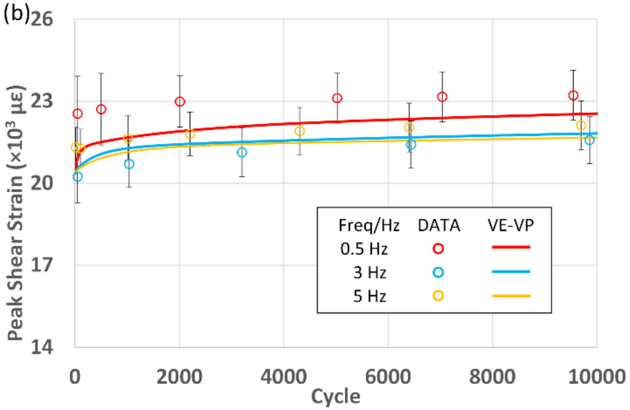
- EA9696

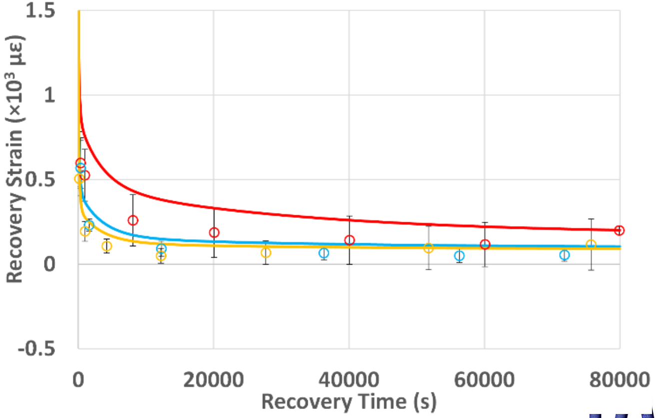






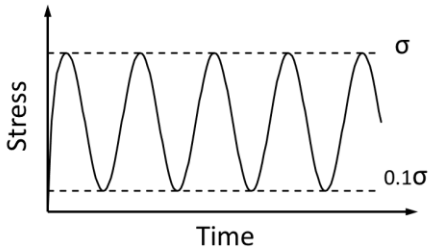
- FM300-2

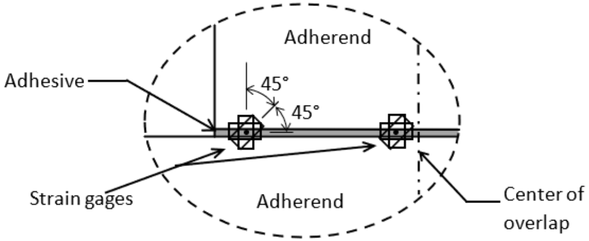


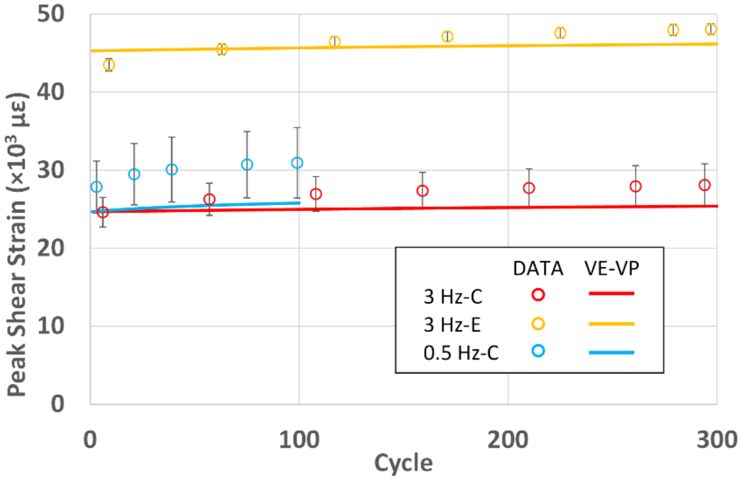


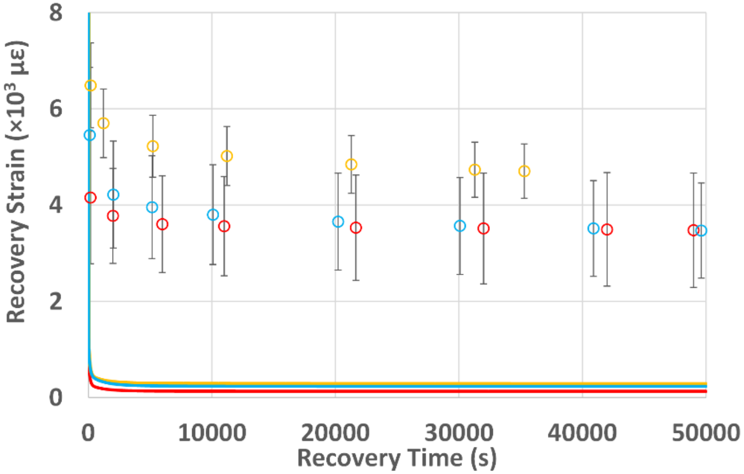
Lap Shear Joint- Ratcheting with R=0.1, 50% USS

- EA9696



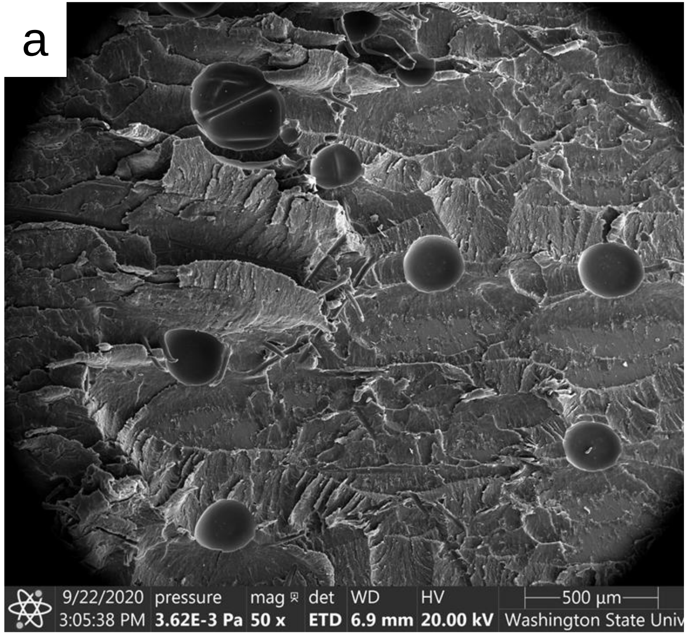


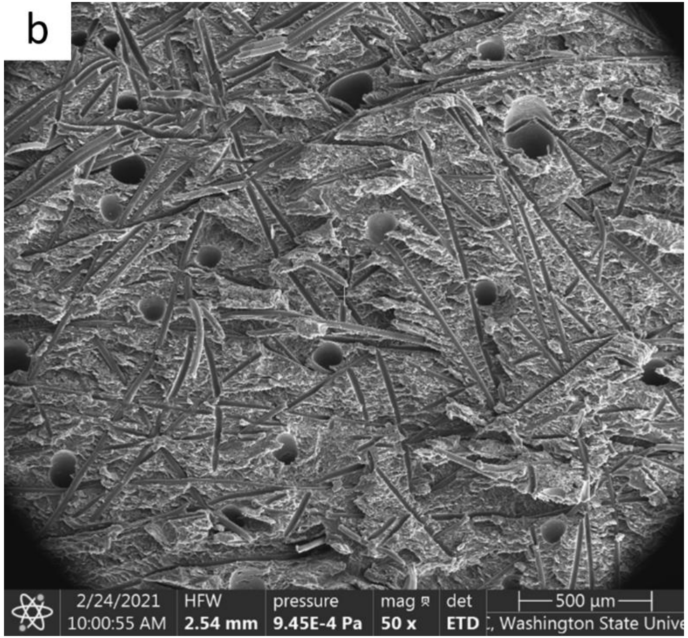




Failure Modes

- Different failure mechanisms.
  - EA9696

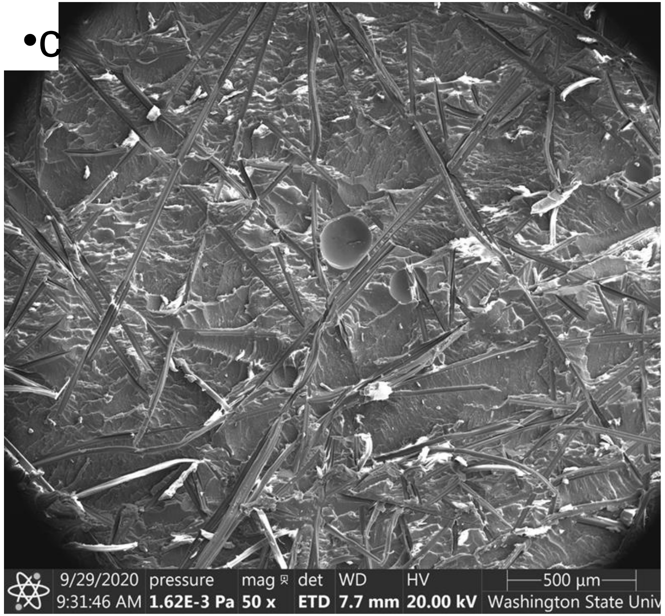


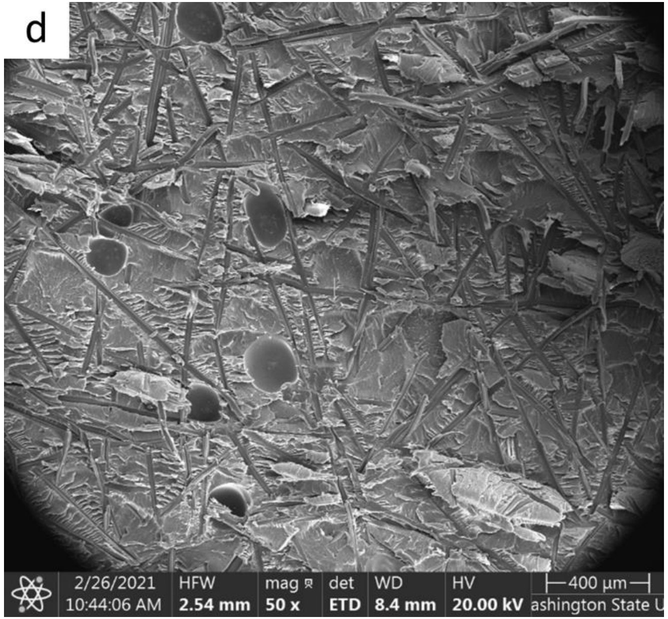


- SEM images of fracture surface from (a) ratcheting and (b) creep experiments.

Failure Modes

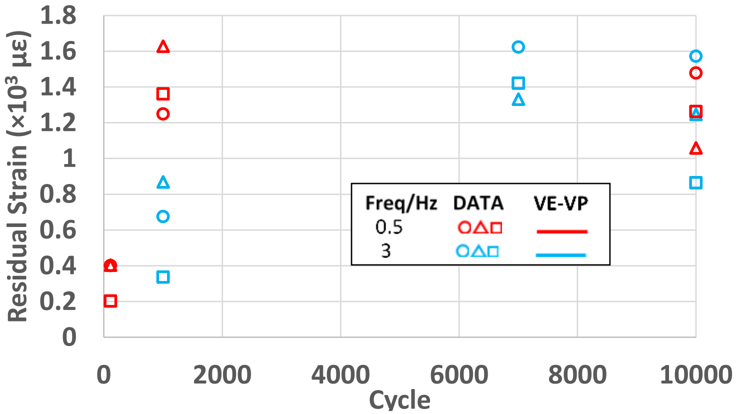
- Similar failure mechanisms.
  - FM300-2
  - c

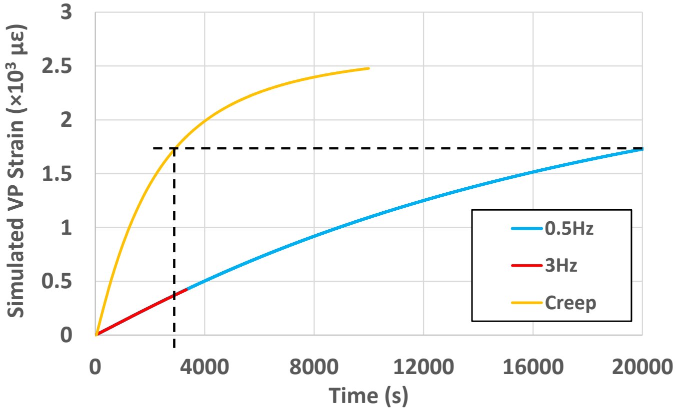


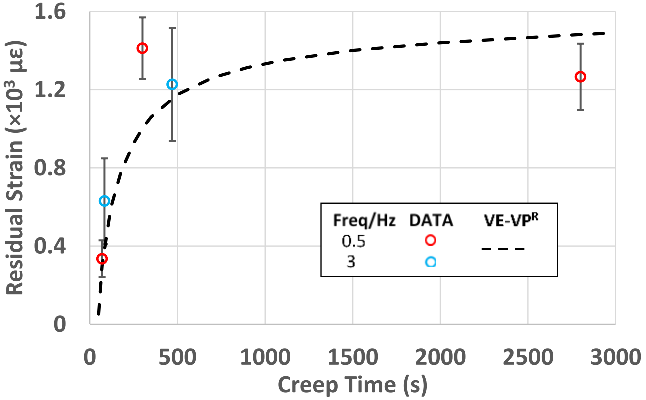


- SEM images of fracture surface from (c) ratcheting and (d) creep experiments.

Re-calibration for Viscoplasticity- EA9696







Viscoelastic-plastic Model

Total Strain:

$$\varepsilon_{ij}^{tot} = \varepsilon_{ij}^{ve} + \varepsilon_{ij}^{p}$$

VE: Schapery's model

P: Von Mises + Nonlinear Kinematic Hardening

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Scarf Joint- Ratcheting with R=0.1, 50% USS

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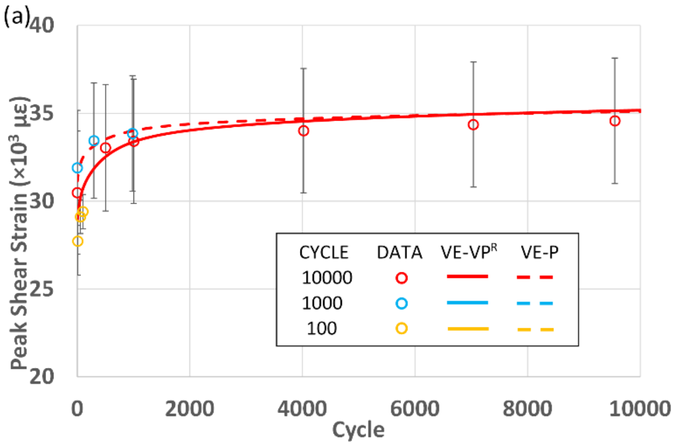
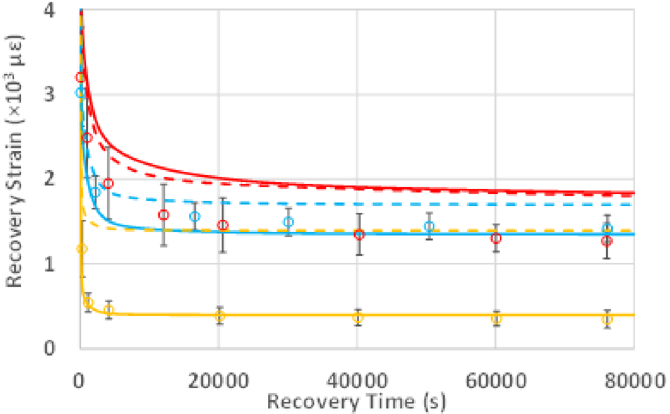
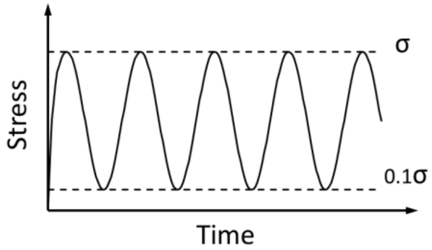
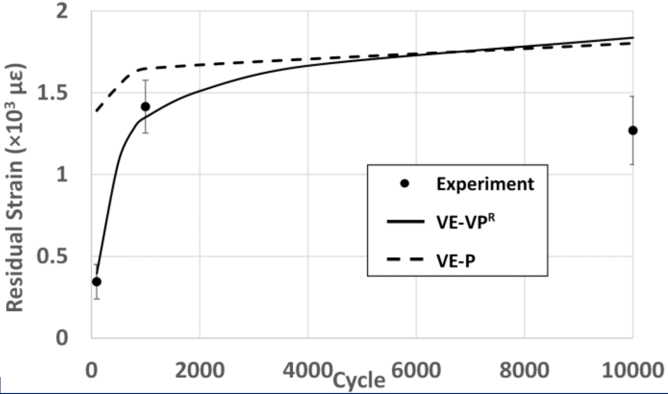
- EA9696- 0.5 Hz



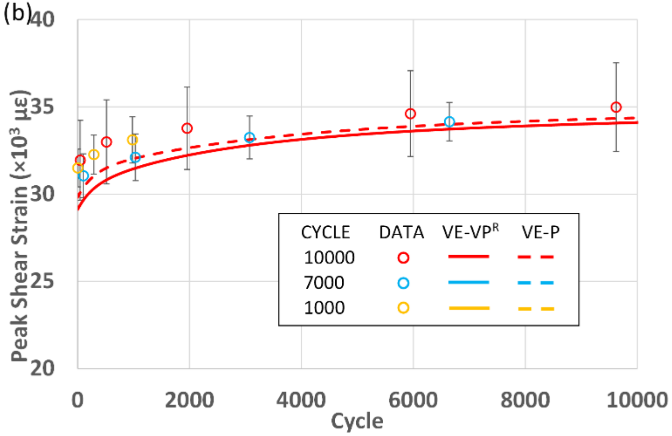


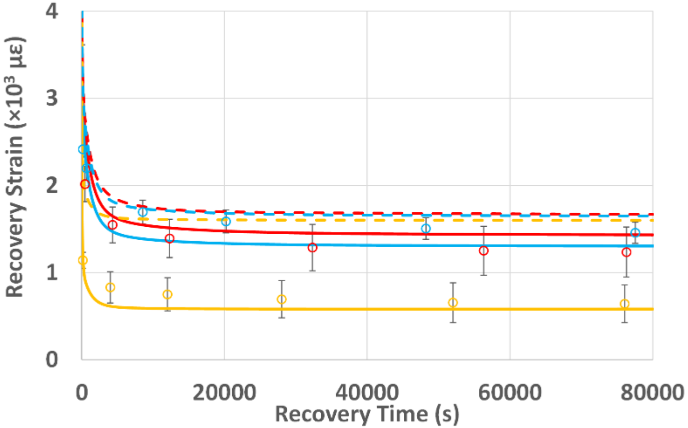


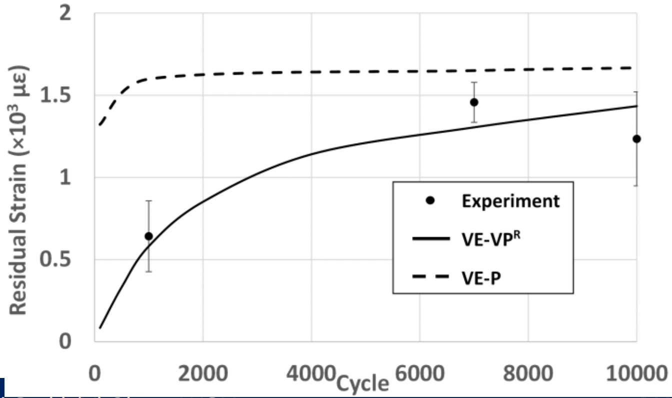


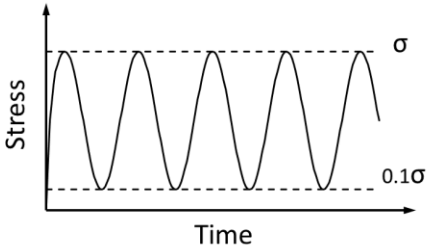
Scarf Joint- Ratcheting with R=0.1, 50% USS

- EA9696- 3 Hz



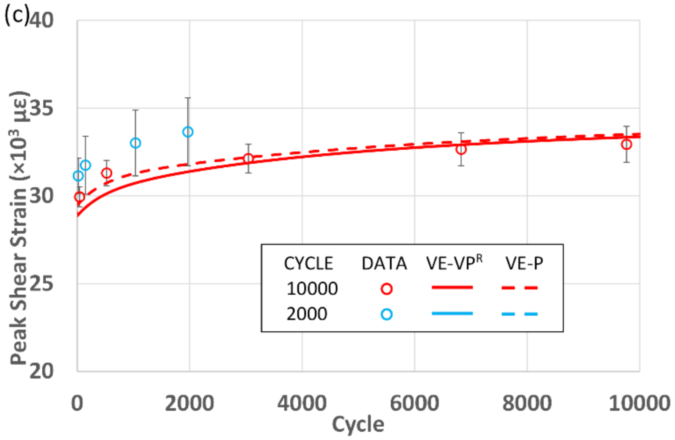


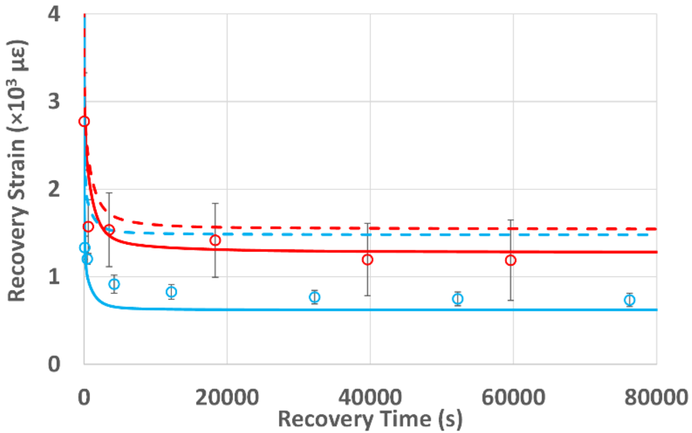


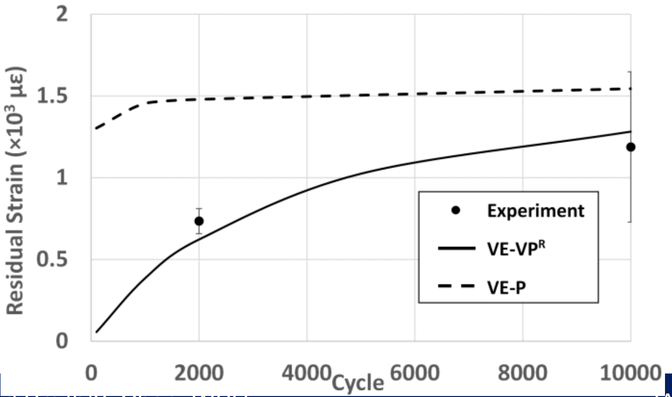


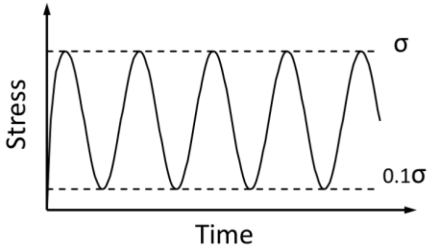
Scarf Joint- Ratcheting with R=0.1, 50% USS

- EA9696- 5 Hz



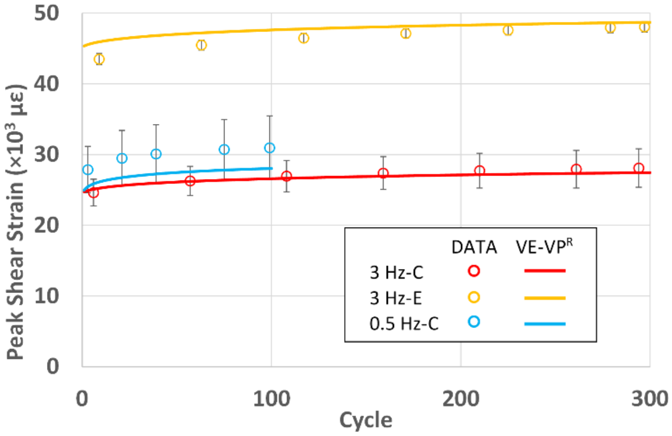


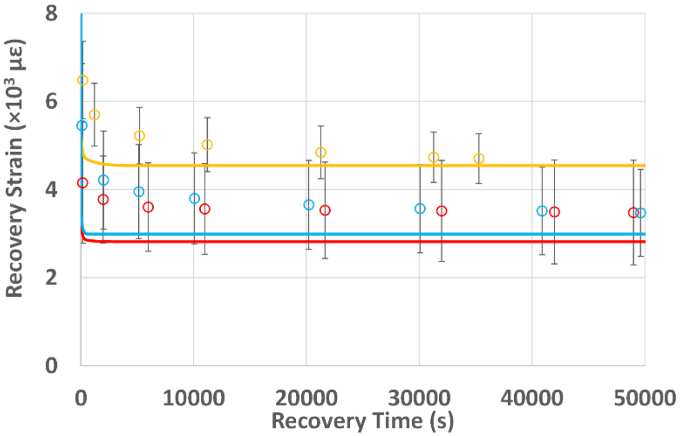


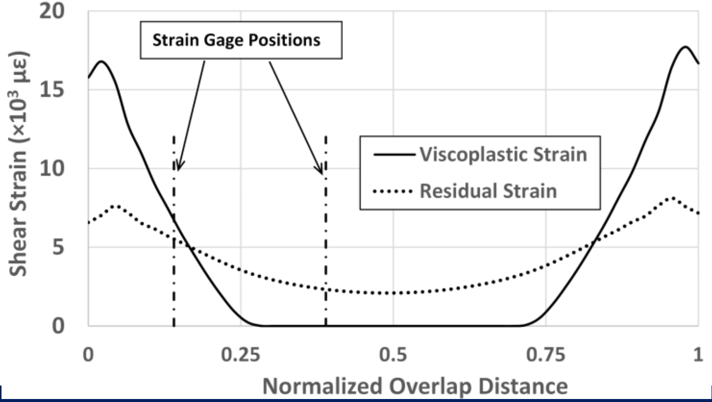


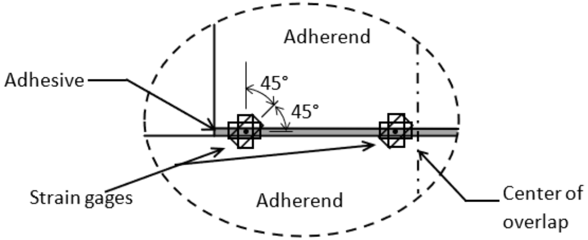
Lap Shear Joint- Ratcheting with R=0.1, 50% USS

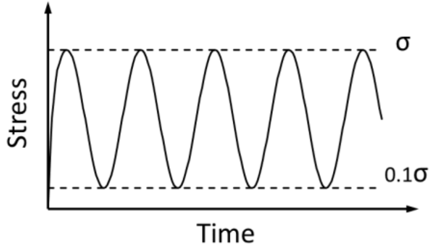
- EA9696











Conclusion

- VE-VP model can describe the creep behavior of scarf joints.
- Ratcheting Behavior of EA9696
  - Exhibit significant viscoplasticity, rather than plasticity.
  - Failure modes that dependent on loading history suggest a cause for the change in temporal response.
  - VE-VP model can predict the ratcheting behavior (0.1R) of scarf and lap shear joints with the recalibrated parameters.
  - VE-P model only agreed well for long time scales.

Future Work

- Modify VE-VP model to simulate the ratcheting behavior under reversed loadings.

Technical Publications

- Chen, Yi, and Lloyd V. Smith. "A nonlinear viscoelastic–viscoplastic model for adhesives." Mechanics of Time-dependent Materials (2020): 1-15.
- Mohapatra, Preetam C., and Lloyd V. Smith. "Adhesive hardening and plasticity in bonded joints." International Journal of Adhesion and Adhesives 106 (2021): 102821.
- Krause, Michael, and Lloyd Smith. "Ratcheting in structural adhesives." Polymer Testing 97 (2021): 107154.
- Chen, Yi, and Lloyd V. Smith. "A Nonlinear Viscoelastic-Viscoplastic Constitutive Model for Adhesives Under Creep." Mechanics of Time-dependent Materials (2021). (*Accepted*)
- Chen, Yi, and Lloyd V. Smith. "Ratcheting and recovery of adhesively bonded joints under tensile cyclic loading." Mechanics of Time-dependent Materials (2021). (*Submitted*)
- Chen, Yi, and Lloyd V. Smith. "Ratcheting and recovery of adhesives under tensile cyclic loading." SAMPE Europe Conferences, 2021. (*Submitted*)
- Chen, Yi, and Lloyd V. Smith. "Inelastic Response of Structural Aerospace Adhesives." Structural Adhesives:Properties, Characterization and Applications. Scrivener Publishing, 2021. (*Planned*)

THANK YOU