Comparison of viscoelastic/viscoplastic models for describing the creep and ratcheting behaviors of adhesives

Federal Aviation Administration

PI: Dr. Lloyd Smith

Postdoc: Dr. Yi Chen

Washington State University

JAMS

Joint Centers of Excellence for Advanced Materials

JAMS Technical Review

Apr. 20, 2023

A Center of Excellence AMTAS Advanced Materials in Transport Aircraft Structures

CECAM center of excellence for composites and advanced materials

Introduction

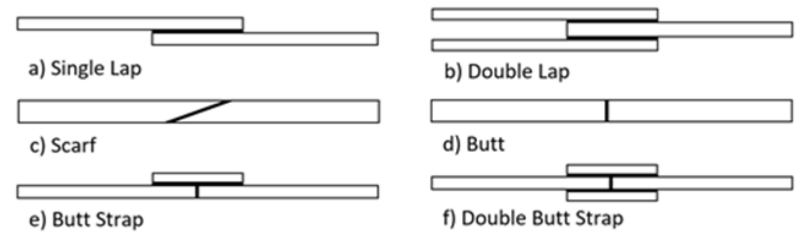
- **Project**
  - Durability of Bonded Aerospace Structures
- **Principal Investigators & Students**
  - Lloyd Smith
  - Yi Chen
- **FAA Technical Monitor**
  - Ahmet Oztekin
- **FAA Sponsors**
  - Larry Ilcewicz, Cindy Ashforth
- **Industry Partnerships/Other Collaborations**
  - Boeing, Will Grace,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

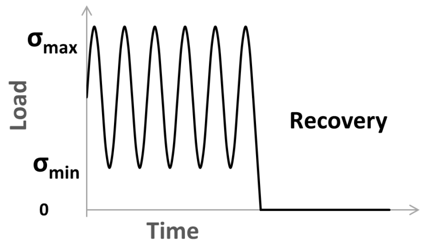
Outline

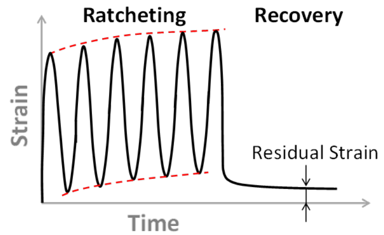
- Background
- Experiment Introduction
- Model Introduction
- Model Comparison
- Summary

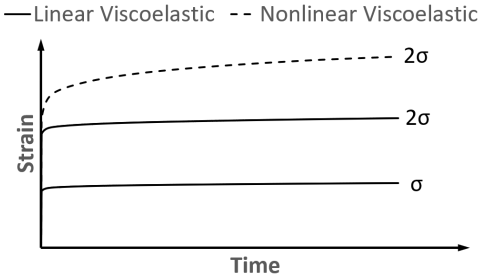
Background

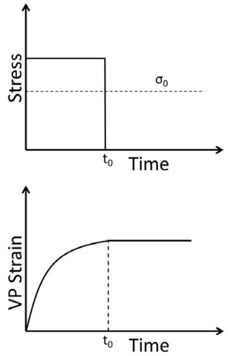
- **Adhesive films in bonded joints**
  - High shear load
  - Behave differently from adhesive bulks
  - Edge effect, higher shear near edge
  - Reliable strain measurement method
- **Strain response to cyclic loads**
  - Ratcheting
  - Time-dependent, Plastic
  - Material damage & fatigue life
- **Constitutive model**
  - Viscoelasticity, Viscoplasticity
  - Damage

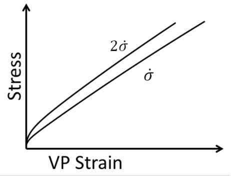












Aim

- **Finite Element Analysis**
  - Predictive capacity
  - Parameter calibration
  - Numerical implementation

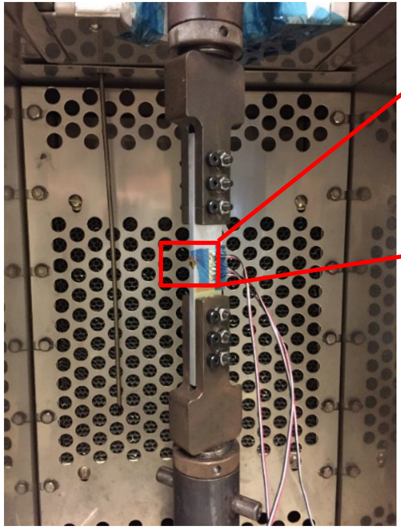
	ABAQUS	Proposed
Linear Viscoelastic	Time-Domain VE	
Viscoplastic	Power-Law Creep	
	Two-Layer VP	
Viscoelastic-Plastic	Parallel Rheological Framework	
Viscoelastic-Viscoplastic		Nonlinear VE-VP

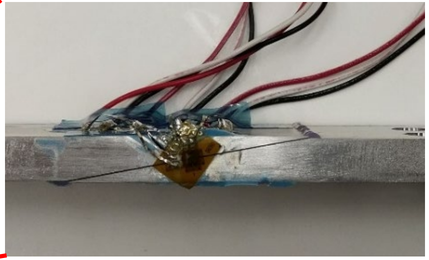
Outline

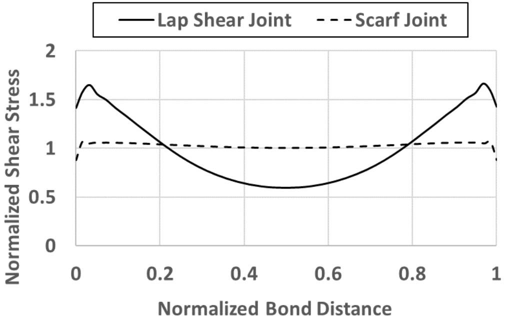
- Background
- Experiment Introduction
- Model Introduction
- Model Comparison
- Summary

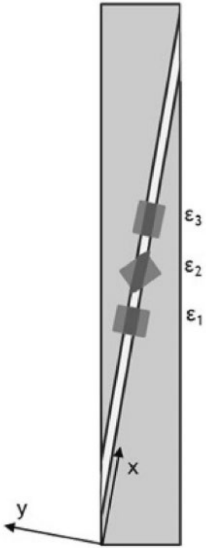
Experiment Setup

- Toughened adhesive: EA9696 (Henkel)
- 45-degree rectangular stacked rosette strain gage
- Scarf Joint: 10°

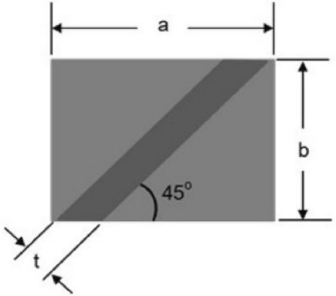








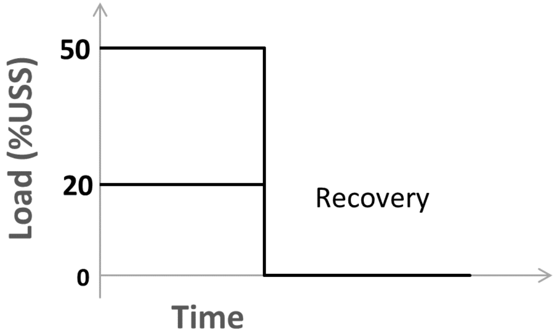
- $\varepsilon_1' = \varepsilon_1 a/t$
- $\varepsilon_2' = \varepsilon_2 a\cos(45°)/t$
- $\varepsilon_3' = \varepsilon_3 b/t$
- $\gamma_{xy} = 2\varepsilon_2' - \varepsilon_1' - \varepsilon_3'$

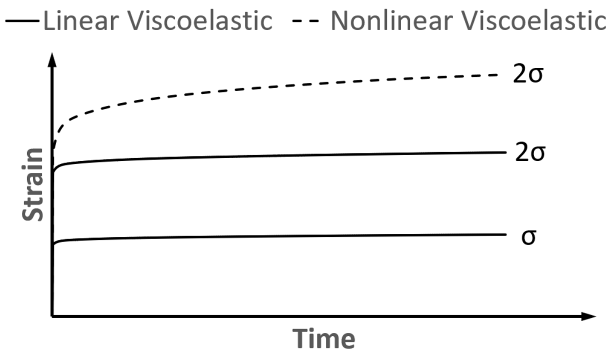


Krause, M., & Smith, L. (2021). Ratcheting in structural adhesives. *Polymer Testing*, *97*, 107154.

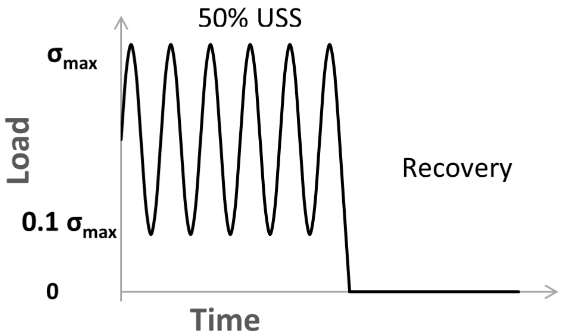
Creep & Ratcheting

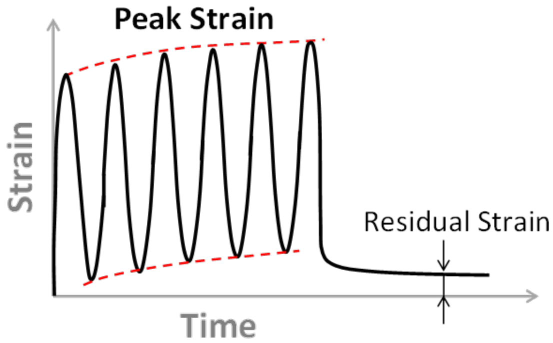
- Creep input



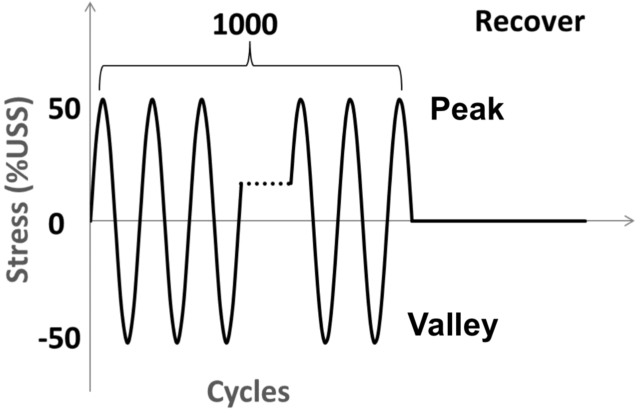


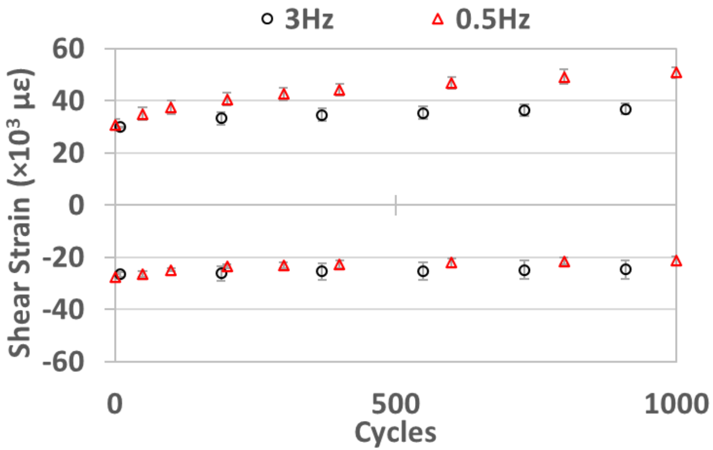
- Ratchet input, $R = \frac{\sigma_{min}}{\sigma_{max}} = 0.1$



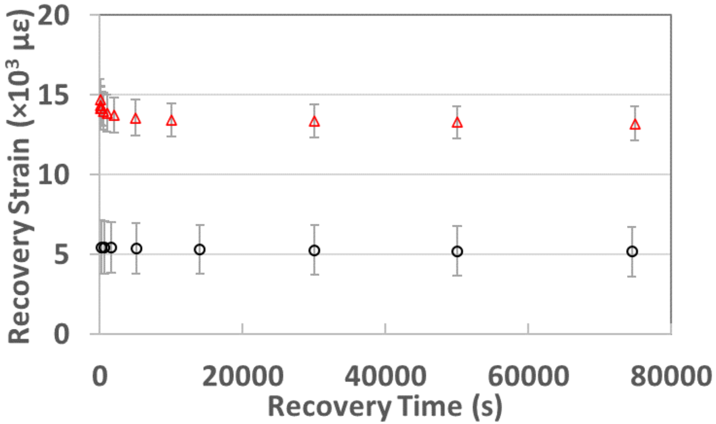


Fully Reversed Cyclic





- $R = \frac{\sigma_{min}}{\sigma_{max}} = -1$
- Ratcheting in tension was more significant than observed in compression
- More residual strain than observed during tensile cyclic tests
- Modulus degradation



Outline

- Background
- Experiment Introduction
- Model Introduction
- Model Comparison
- Summary

Model Introduction

	ABAQUS	Proposed
Linear Viscoelastic	Time-Domain VE	
Viscoplastic	Power-Law Creep	
	Two-Layer VP	
Viscoelastic-Plastic	Parallel Rheological Framework	
Viscoelastic-Viscoplastic		Nonlinear VE-VP

WASHINGTON STATE UNIVERSITY

Linear Viscoelastic

- **Time-Domain Viscoelasticity (L-VE)**

$$\tau(t) = G_0 \Upsilon(\mathrm{t}) + G_0 \int_0^t g_R(t-s)\dot{\gamma}(s)ds$$

$$g_R(t) = 1 - \sum_{i=1}^{N} \bar{g}_i \left(1 - \exp\left(\frac{-t}{\tau_i^G}\right)\right)$$

where $\gamma(\mathrm{t})$ & $\tau(\mathrm{t})$- time-varying shear strain & shear stress

G_0- instantaneous shear modulus

g_R- dimensionless shear modulus

N, τ_i^G, $\bar{g}_i$- material constants

Viscoplastic

- **Power-Law Creep (CRP)**

$$\dot{\varepsilon}_e^v = \{A\sigma_e^n[(m+1)\varepsilon_e^v]^m\}^{1/(m+1)}$$

where $\dot{\varepsilon}_e^v$ & ε_e^v - effective viscous strain & strain rate

σ_e- equivalent deviatoric stress

A, m, n- material constants. If m=0 & n=1, a linear dashpot

Viscoplastic

- **Two-Layer Viscoplastic (TL-VP)**

$$\varepsilon = \varepsilon^{ep} + \varepsilon^{ve} = \varepsilon^{e} + (1-R)\varepsilon^{p} + R\varepsilon^{v}$$

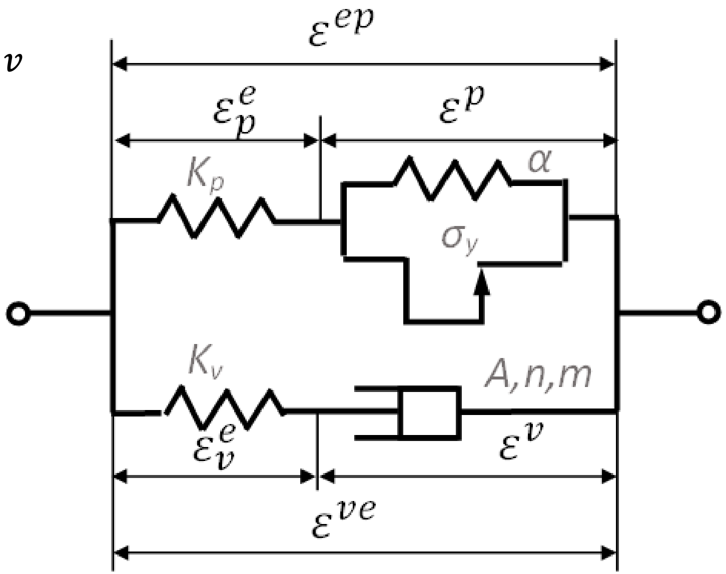
Elastic: $\varepsilon^{e} = R\varepsilon_{v}^{e} + (1-R)\varepsilon_{p}^{e}$

Plastic: $f = \sqrt{\frac{3}{2}(S_{ij}-\alpha_{ij})(S_{ij}-\alpha_{ij})} - \sigma_{y}$

$$\dot{\alpha}_{ij} = \frac{2}{3}C\dot{\varepsilon}_{ij}^{p} - \kappa\alpha_{ij}\dot{\varepsilon}_{e}^{p}$$

Viscous: $\dot{\varepsilon}_{e}^{v} = \{A\sigma_{e}^{n}[(m+1)\varepsilon_{e}^{v}]^{m}\}^{1/(m+1)}$

where $R = \frac{K_v}{K_v + K_p}$



Viscoelastic-Plastic

- **Parallel Rheological Framework (PRF)**

Elastic: $W_T = \sum_{i=0}^{N} s_i W(C_i^e)$

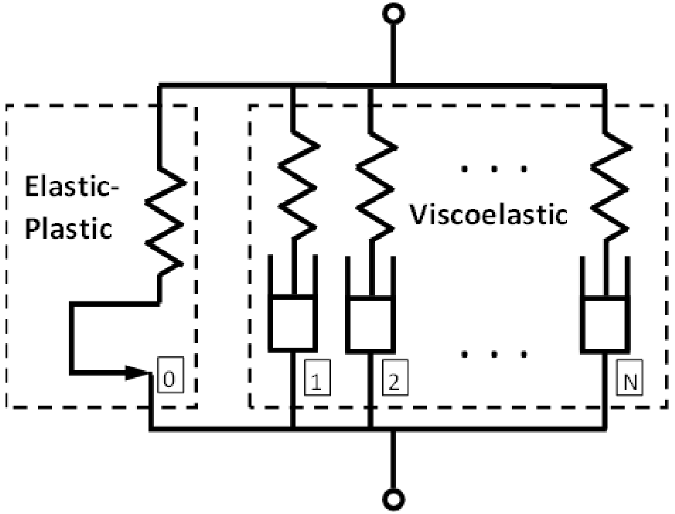
$\sum_{i=0}^{N} s_i = 1$

Plastic: $f = \sqrt{\frac{3}{2}(S_{ij} - \alpha_{ij})(S_{ij} - \alpha_{ij})} - \sigma_y$

$\dot{\alpha}_{ij} = \frac{2}{3} C \dot{\varepsilon}_{ij}^{p} - \kappa \alpha_{ij} \dot{\varepsilon}_e^{p}$

Viscous: $D^{cr} = \frac{3}{2q} \dot{\varepsilon}_e^{v} \bar{\tau}$

$\dot{\varepsilon}_e^{v} = \{A \sigma_e^n [(m+1)\varepsilon_e^v]^m\}^{1/(m+1)}$



Viscoelastic-Viscoplastic

- **Nonlinear Viscoelastic-Viscoplastic (VE-VP)**

- **Total Strain**

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

- **Viscoelastic Model (Schapery)**

$$\varepsilon^{ve}(t) = \frac{1}{1-D^{ve}} g_0 D_0 \sigma^t + g_1 \int_0^t \Delta D^{(\psi^t - \psi^\tau)} \frac{d(g_2 \sigma^\tau)}{d\tau} d\tau$$

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

Effect of hydrostatic stress

$$g_0 = \beta_1^j (\sigma_e)^{\beta_2^j} + \beta_3^j, \quad \text{j= +(tension) or – (compression)}$$

Reversed cyclic response

$$D^{ve} = \sum_{i=0}^{N} \zeta_i t^i$$

Viscoelastic-Viscoplastic

- **Nonlinear Viscoelastic-Viscoplastic (VE-VP)**

- **Viscoplastic Model (Perzyna)**

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

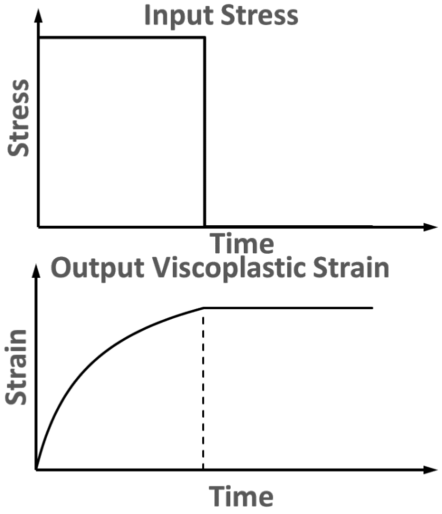
- **Yield function**

Drucker-Prager Yield+ Nonlinear Kinematic Hardening

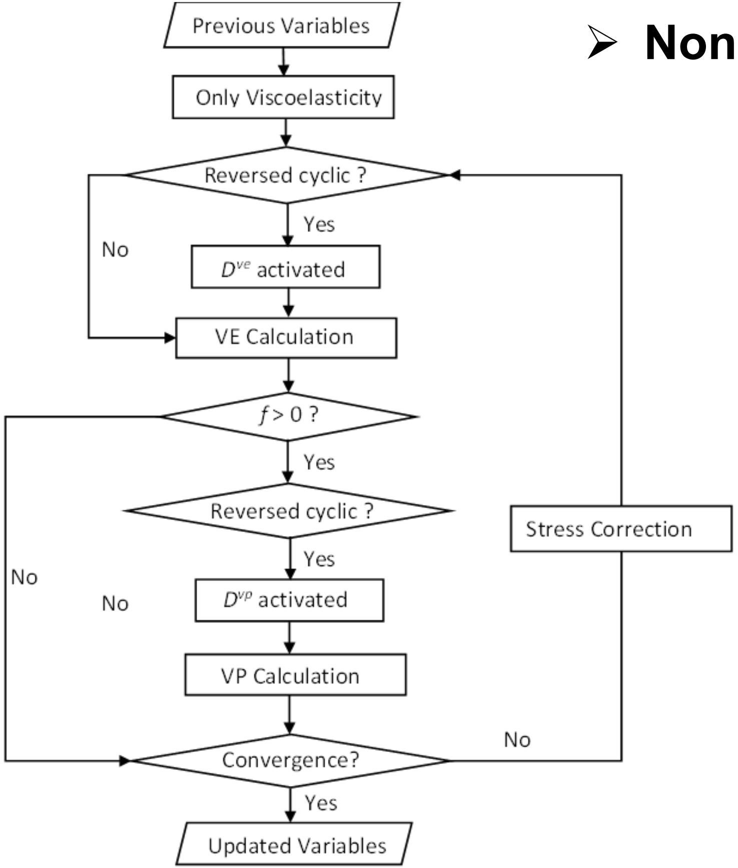
$$f = AI_1 + \sqrt{\frac{1}{2}(S_{ij} - \alpha_{ij})(S_{ij} - \alpha_{ij})} - (1 - D^{vp})B$$

Reversed cyclic response

$$D^{vp} = 1/t_D$$



Numerical Implementation

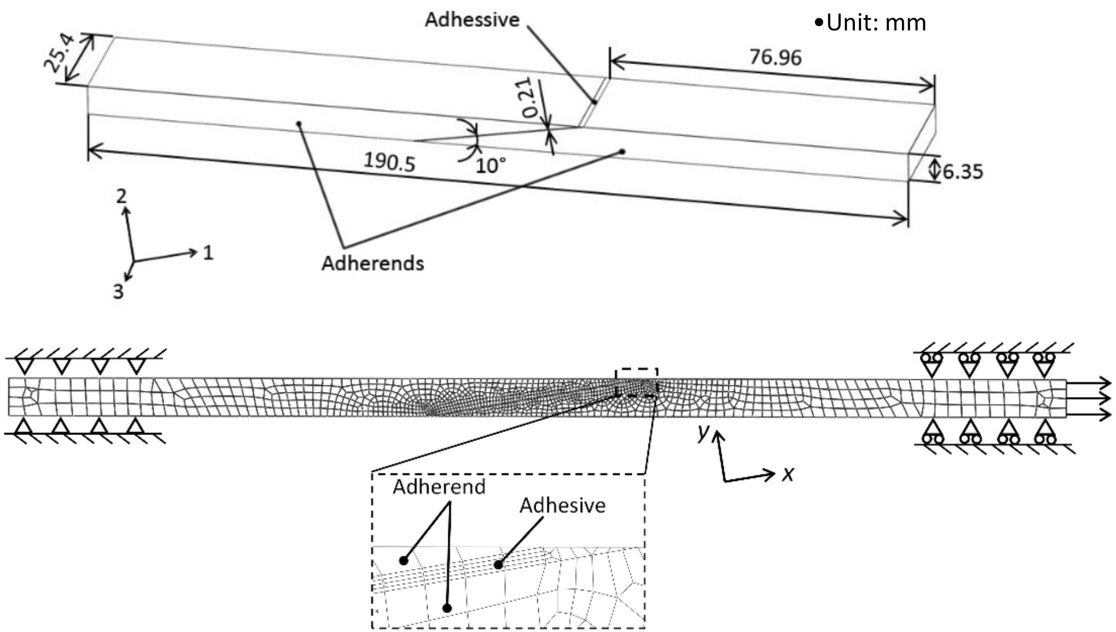


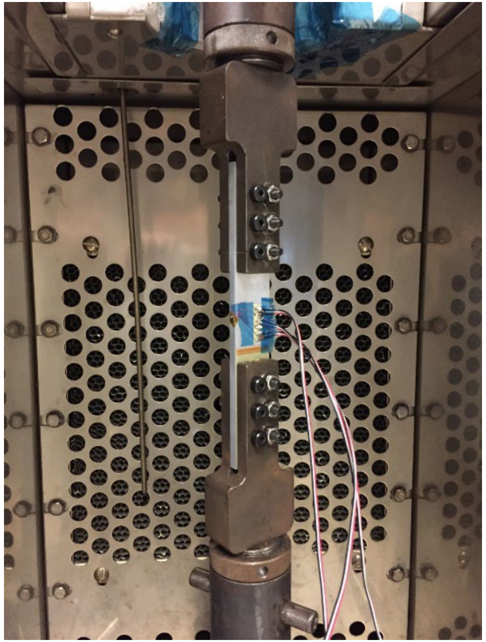
➢ Nonlinear Viscoelastic-Viscoplastic (VE-VP)

- First assume viscoelasticity only.
- Viscoplasticity is activated when load is beyond yield surface.
- Damage factors are activated under reversed cyclic loading.

Finite Element Model

- **Mesh & Boundary Conditions (Plane Strain)**





Model Calibration

Model	Component	Parameters	Test	Stress level	Loading/Recover time
L-VE	Prony Series	$\bar{g}_i$, τ_i^G	Creep	20% USS	10,000 s/ 80,000 s
CRP	Viscous	A, m, n	Creep	20% & 50% USS	10,000 s/80,000 s
TL-VP	Plastic	σ_y, C, κ	monotonic		
	Elastic & Viscous	R, A, m, n	Creep	20% & 50% USS	10,000 s/80,000 s
PRF	Hyperelastic	C_{10}, D_1	monotonic		
	Plastic	σ_y, C, κ	monotonic		
	Viscous	Y_k, A_k, m_k, n_k	Creep	20% & 50% USS	10,000 s/80,000 s
VE-VP	Prony series	D_i, λ_i, J_0, B_0	Creep	20% USS	10,000 s/80,000 s
	Nonlinear VE	g_1, g_2, a	Creep	50% USS	10,000 s/80,000 s
		g_0	monotonic		Varying rates
	Plastic	A, B, C, κ	monotonic	Tension & compression	Varying rates
	Viscoplastic	η, N	Creep	50% USS	
			Tensile cyclic	50% USS	Varying load durations
	Damage	D^{ve}, t_D	Reversed cyclic	50% USS	0.5 Hz

VE-VP Effect of Hydrostatic Stress

WASHINGTON STATE UNIVERSITY

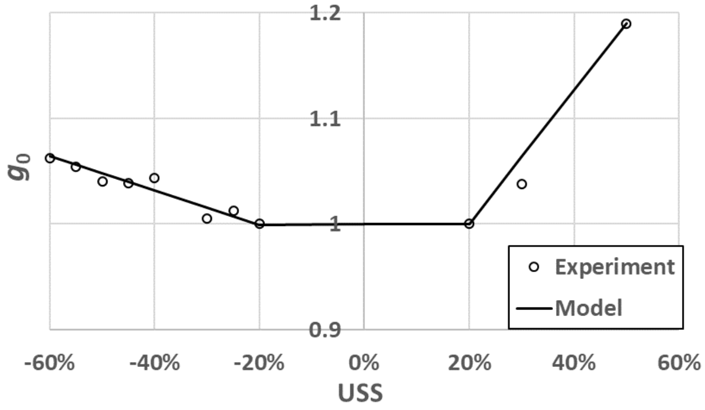
- **Nonlinear Viscoelastic-Viscoplastic (VE-VP)**

$$\varepsilon^{ve}(t) = \frac{1}{1 - D^{ve}} g_0 D_0 \sigma^t + g_1 \int_0^t \Delta D^{(\psi^t - \psi^\tau)} \frac{d(g_2 \sigma^\tau)}{d\tau} d\tau$$

- **Effect of hydrostatic stress**

$$g_0 = \beta_1^j (\sigma_e)^{\beta_2^j} + \beta_3^j$$

where j= +(tension) or – (compression)



- The effect of hydrostatic stress on VE response can be different int tension and compression.
- The effect can be reflected in the elastic response (g_0).

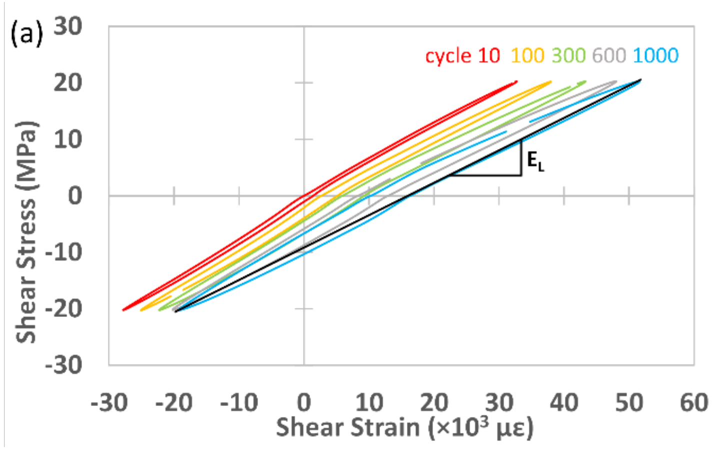
VE-VP Modulus Degradation

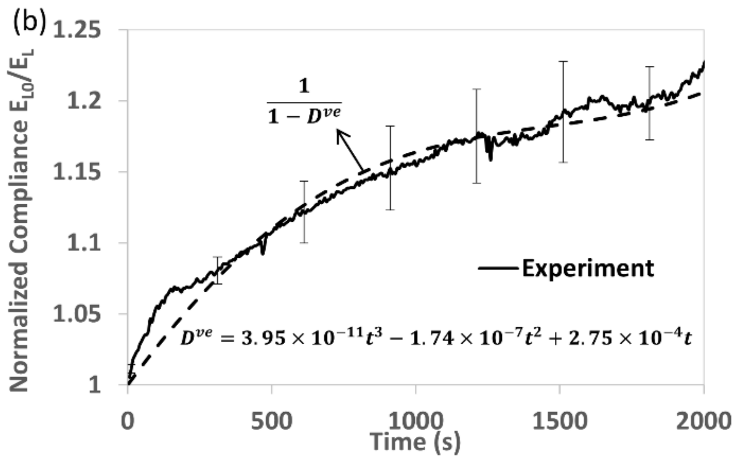
- **Nonlinear Viscoelastic-Viscoplastic (VE-VP)**

$$\varepsilon^{ve}(t) = \frac{1}{1 - D^{ve}} g_0 D_0 \sigma^t + g_1 \int_0^t \Delta D^{(\psi^t - \psi^\tau)} \frac{d(g_2 \sigma^\tau)}{d\tau} d\tau$$

- **Reversed cyclic response**

$$D^{ve} = \sum_{i=0}^{N} \zeta_i t^i$$

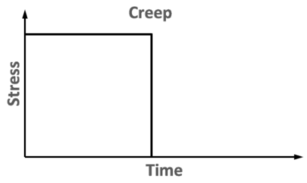




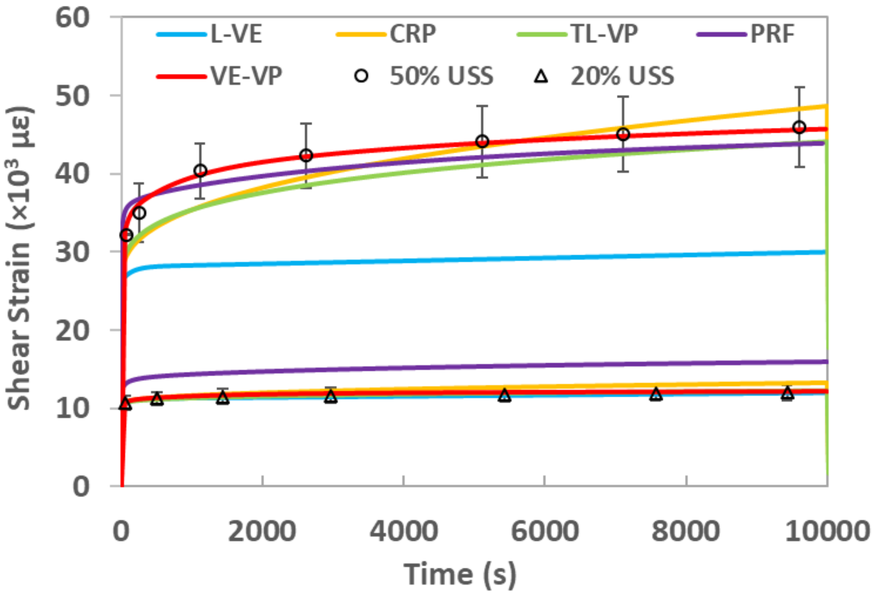
Outline

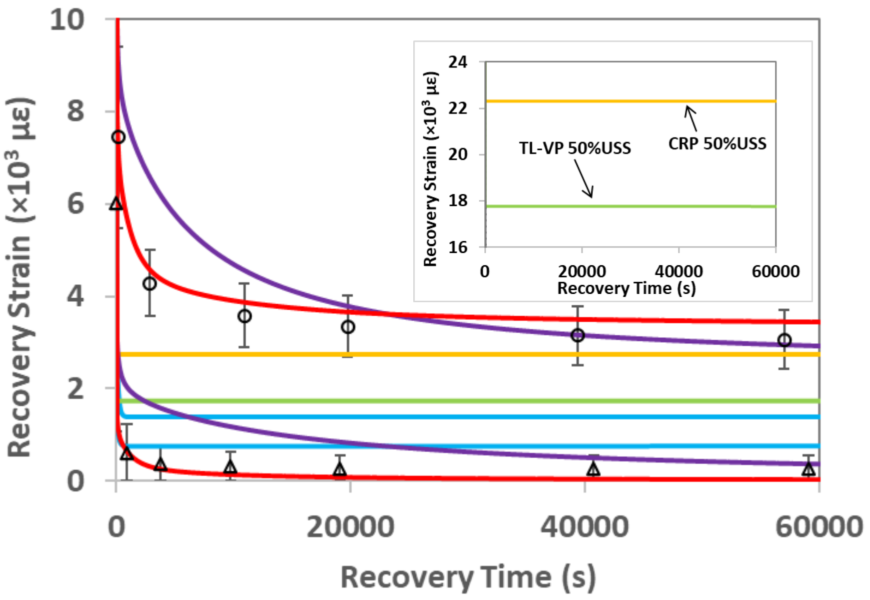
- Background
- Experiment Introduction
- Model Introduction
- Model Comparison
- Summary

Scarf Joint- Creep at 20% & 50% USS



WASHINGTON STATE UNIVERSITY

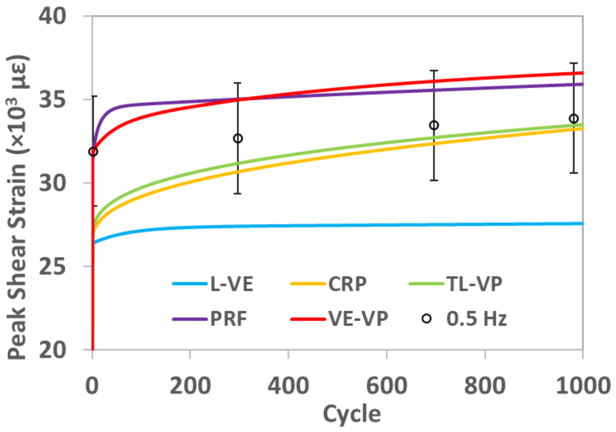


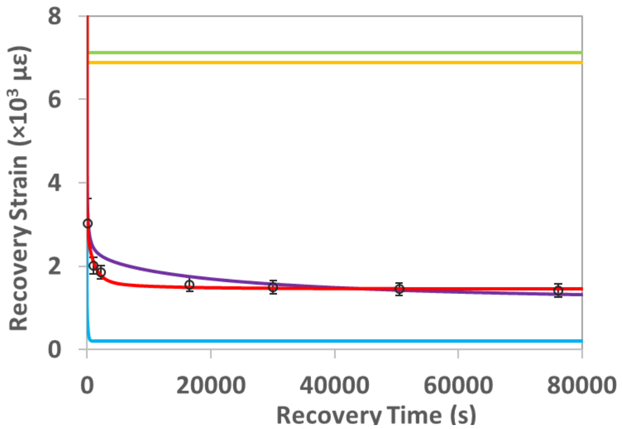


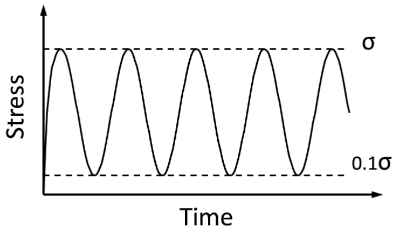
Scarf Joint- Ratcheting with R=0.1, 50% USS

WASHINGTON STATE UNIVERSITY

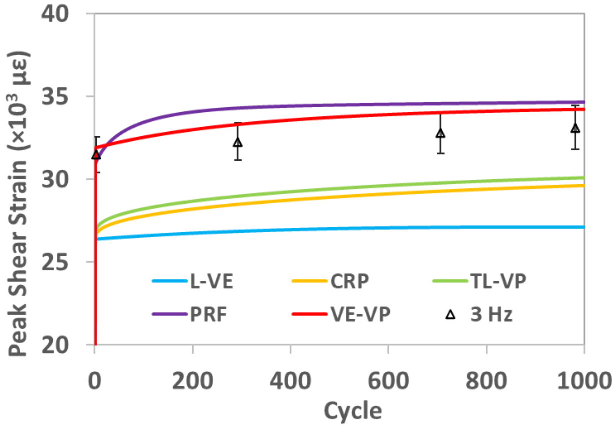
- 0.5 Hz

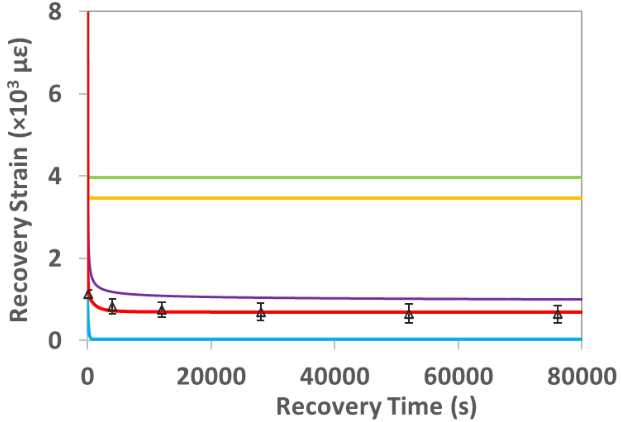




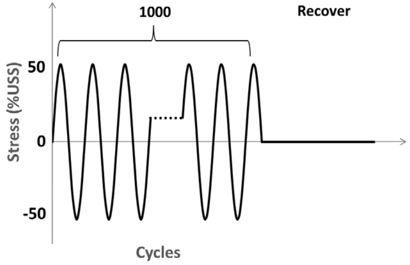


- 3 Hz

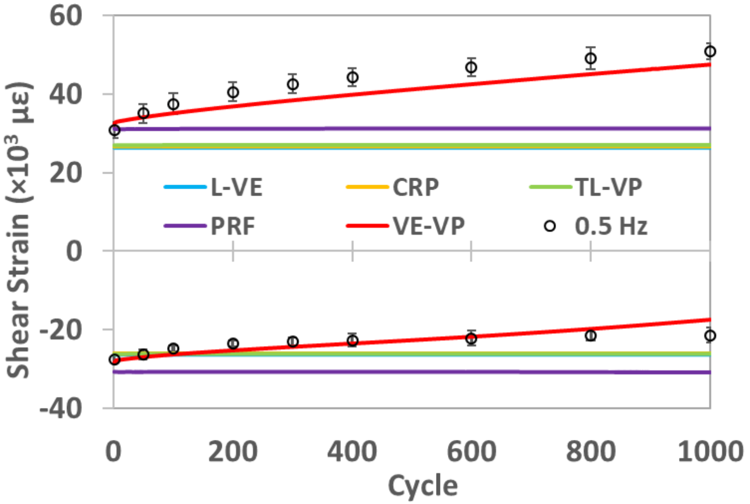


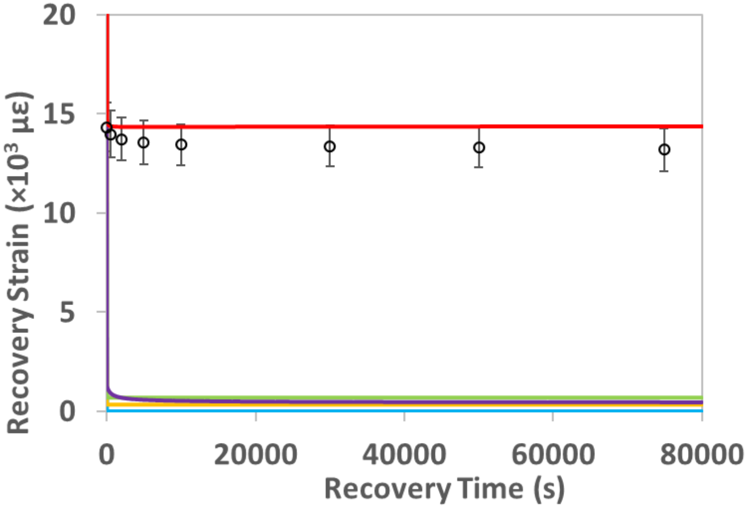


Scarf Joint- Ratcheting with R=-1, 50% USS



- 0.5 Hz

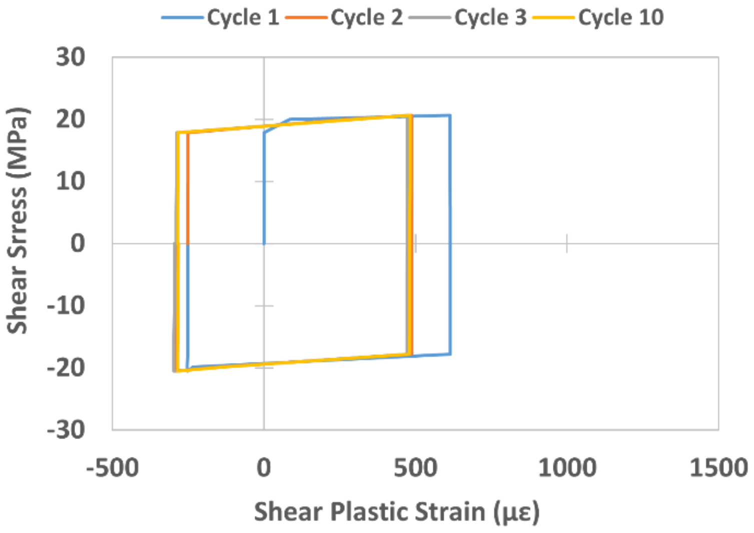




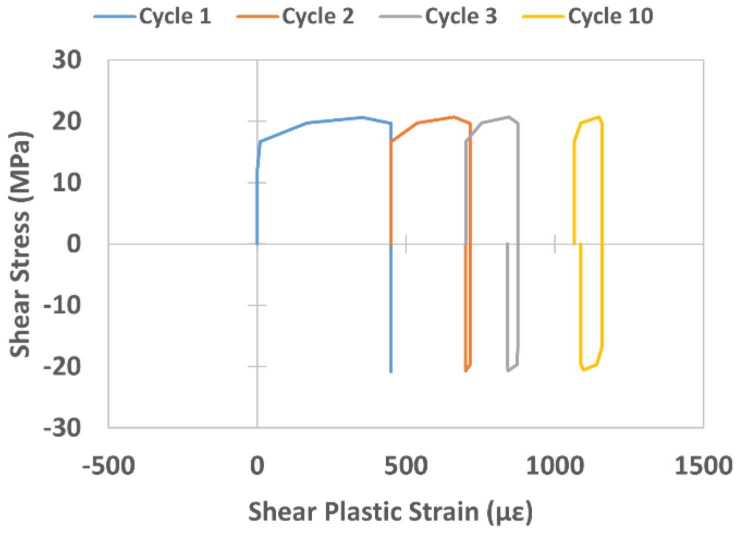
Scarf Joint- Ratcheting with R=-1, 50% USS

WASHINGTON STATE UNIVERSITY

- PRF Model

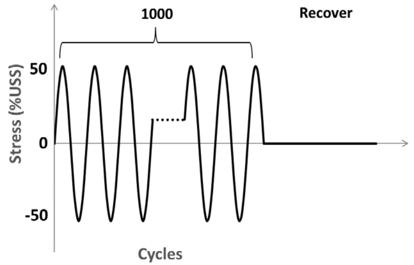


- VE-VP Model



Scarf Joint- Ratcheting with R=-1, 50% USS

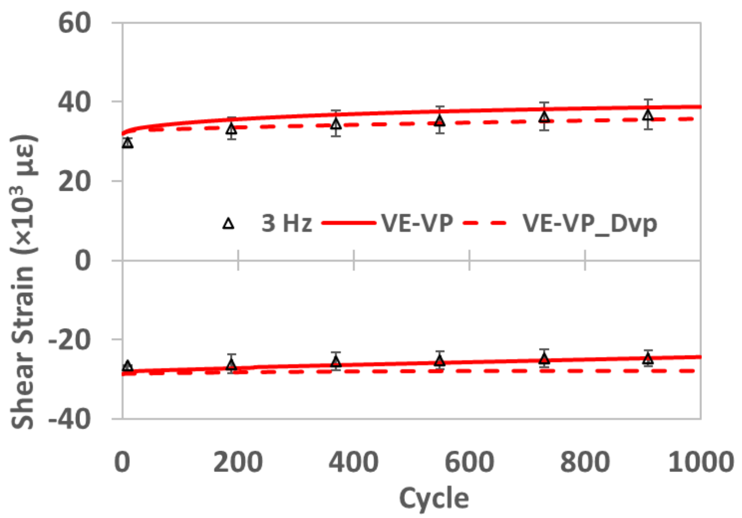
WASHINGTON STATE UNIVERSITY

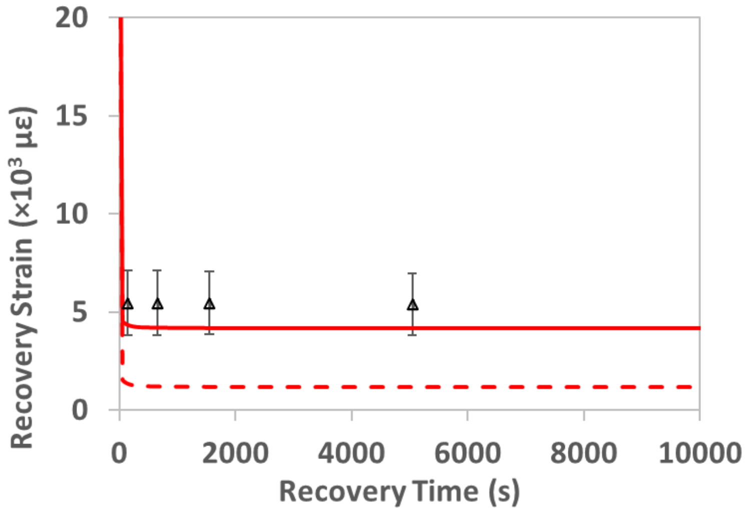


- 3 Hz

VE-VP_Dvp

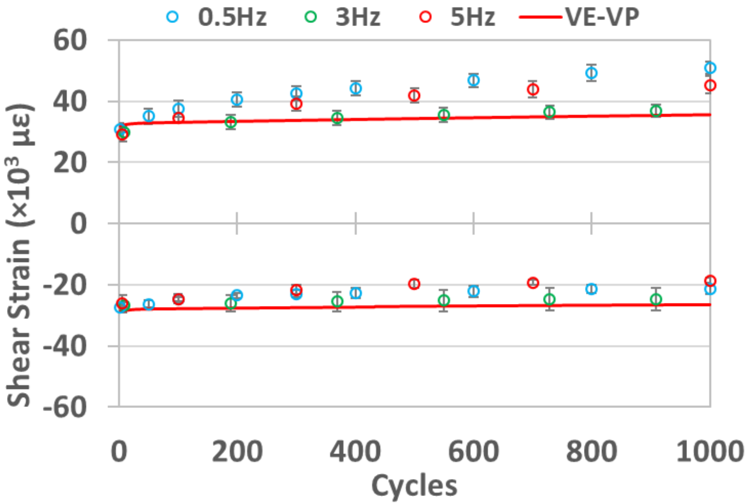
$$f = AI_1 + \sqrt{\frac{1}{2}(S_{ij} - \alpha_{ij})(S_{ij} - \alpha_{ij})} - (1 - D^{vp})B$$

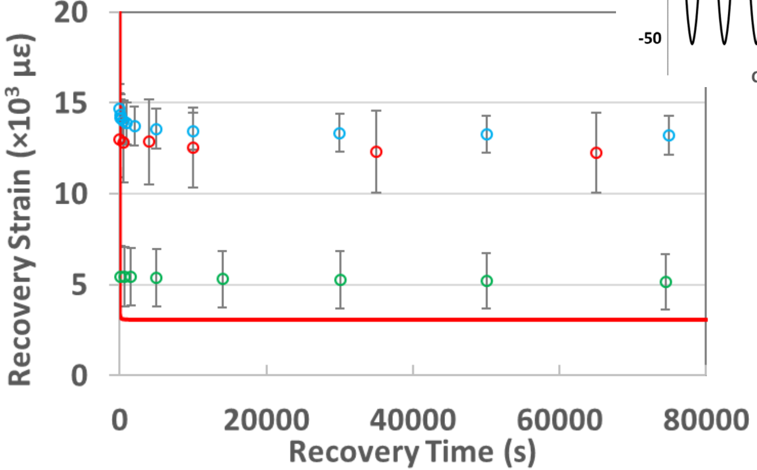


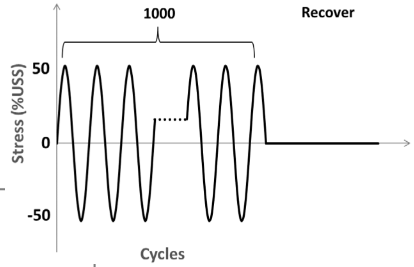


Scarf Joint- Ratcheting with R=-1, 50% USS

- 5 Hz







❖ Extensive permanent strain comparable to 0.5 Hz

❖ Temperature effect?

Outline

- Background
- Experiment Introduction
- Model Introduction
- Model Comparison
- Summary

Summary & Future Work

- **Parameter calibration is highly dependent on model complexity.**
- **Creep-recovery behavior is well described by the models involving both nonlinear viscoelasticity and plasticity/viscoplasticity.**
- **Nonlinear viscoelastic-plastic/viscoplastic models (PRF & VE-VP)could describe response to tensile cyclic load.**
  - Viscoplasticity is recommended for plastic prediction under varying frequencies and load durations.
- **VE-VP model showed good agreement with reversed cyclic test.**
  - Pressure-dependent yield criterion results in accumulative plastic deformation.
  - Hydrostatic stress affects viscoelastic response in tension and compression.
  - Damage factors are required for extensive permanent deformation.
- **Future Work**
  - Investigate reversed cyclic response at higher frequencies and longer load durations (ratcheting and permanent deformation).
  - Modify and validate constitutive model.

THANK YOU

Questions?

Contacts:

- Lloyd V. Smith (lvsmith@wsu.edu)
- Yi Chen (yi.chen6@wsu.edu)