WASHINGTON STATE UNIVERSITY

Durability of Bonded Aircraft Structure

AMTAS 2019

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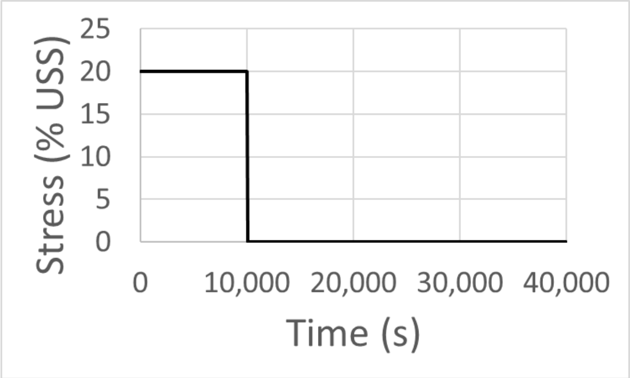
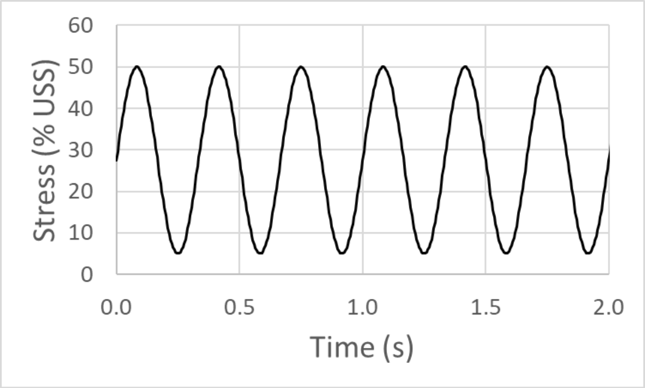
Outline

- Characterizing adhesives
  - Experimental data
    - Shear strain in a scarf joint
    - Cyclic Loading
      - Varying frequency
      - Varying R ratio
  - Viscoelastic-Viscoplastic Model
    - Model introduction
    - 1D model for bulks
    - 3D model for scarf joints

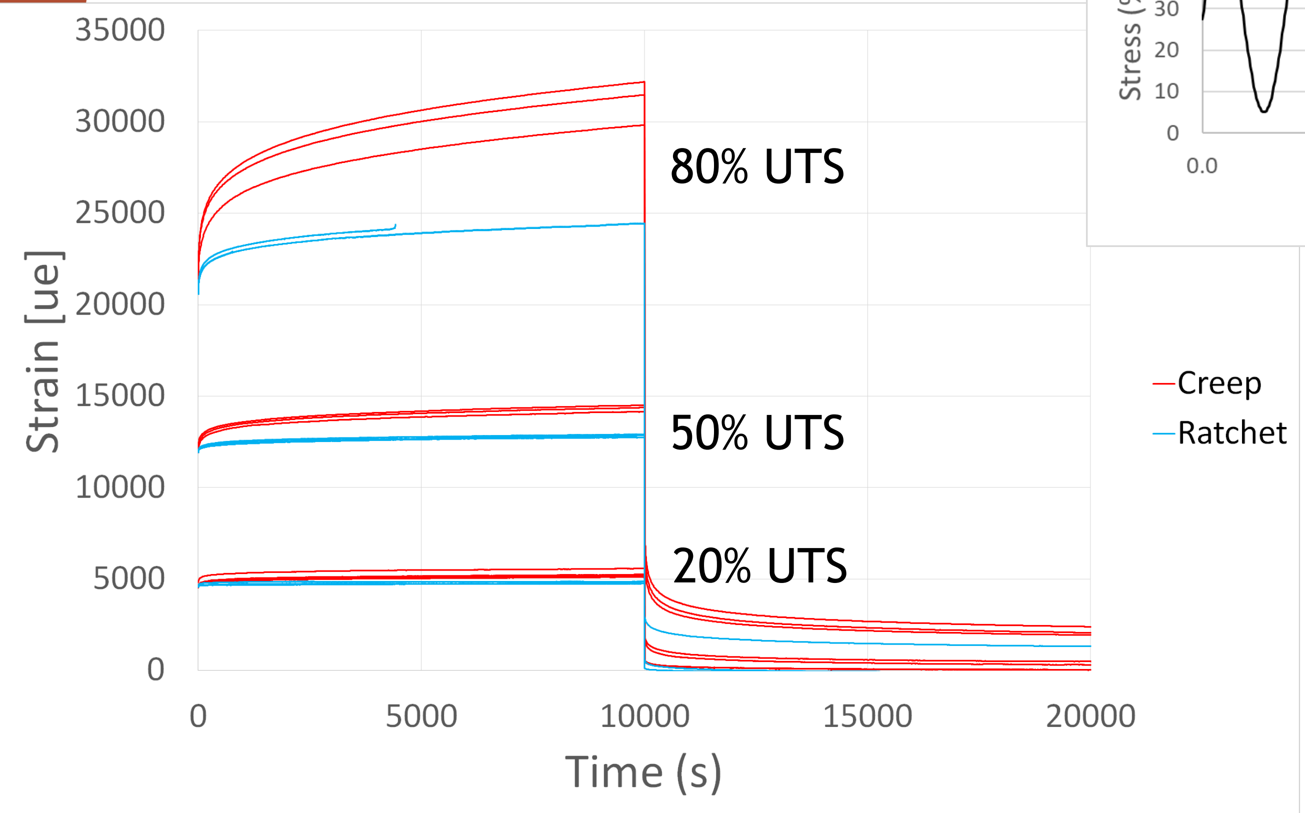
Bulk Coupon EA9696



Creep input

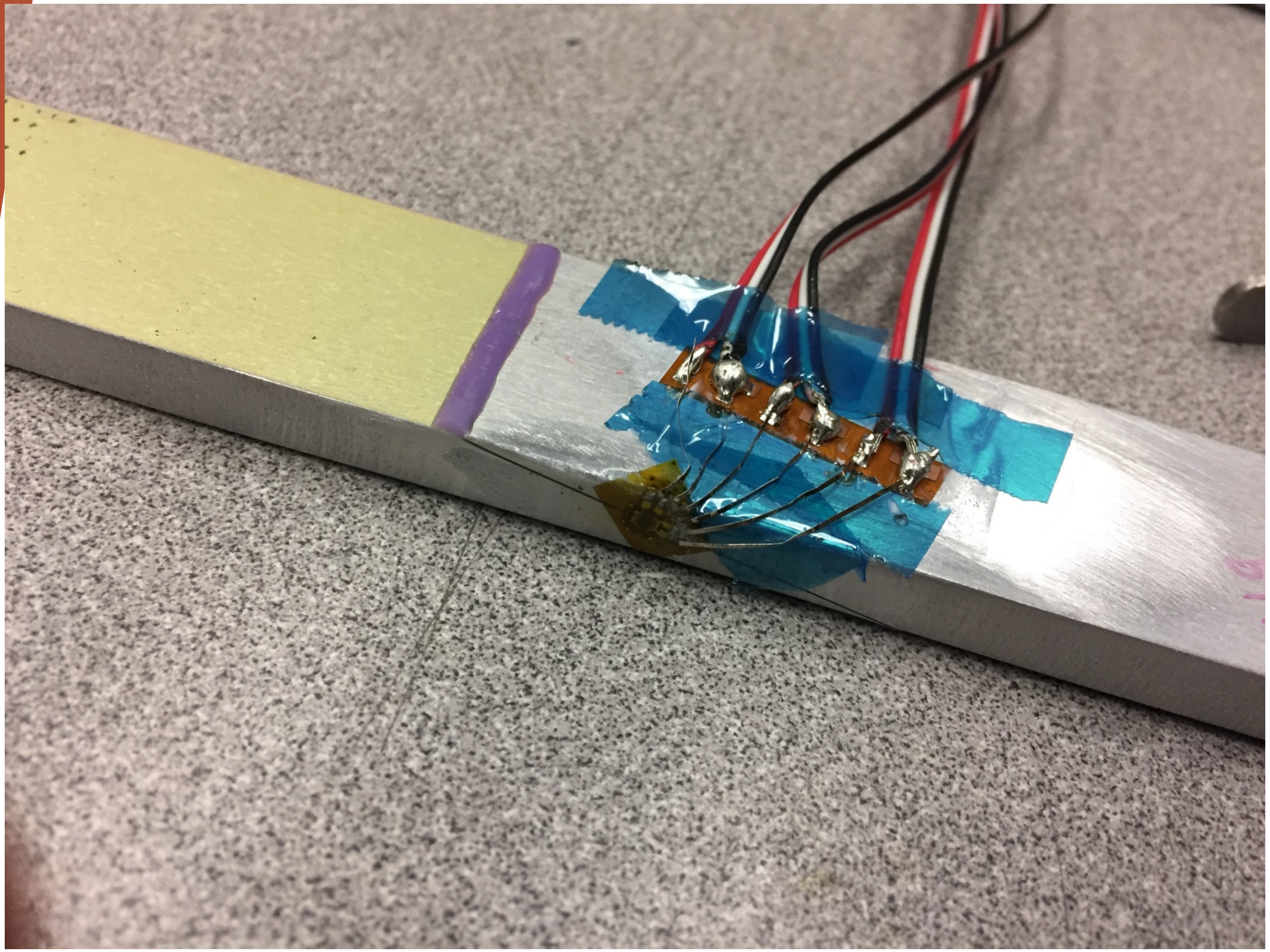


Ratchet input



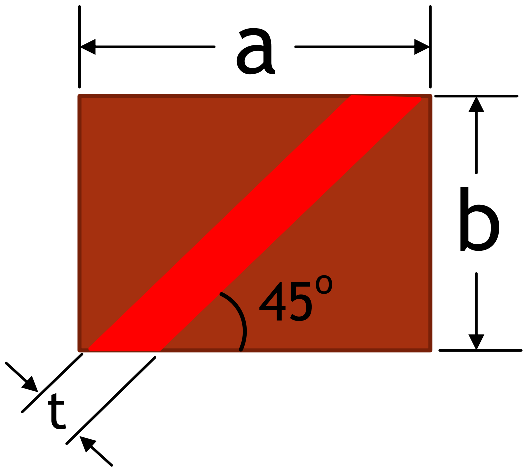
Scarf Joint

- Scarf joint coupon with strain gauge bonded over adhesive
- Scarf Angle: 10 degrees



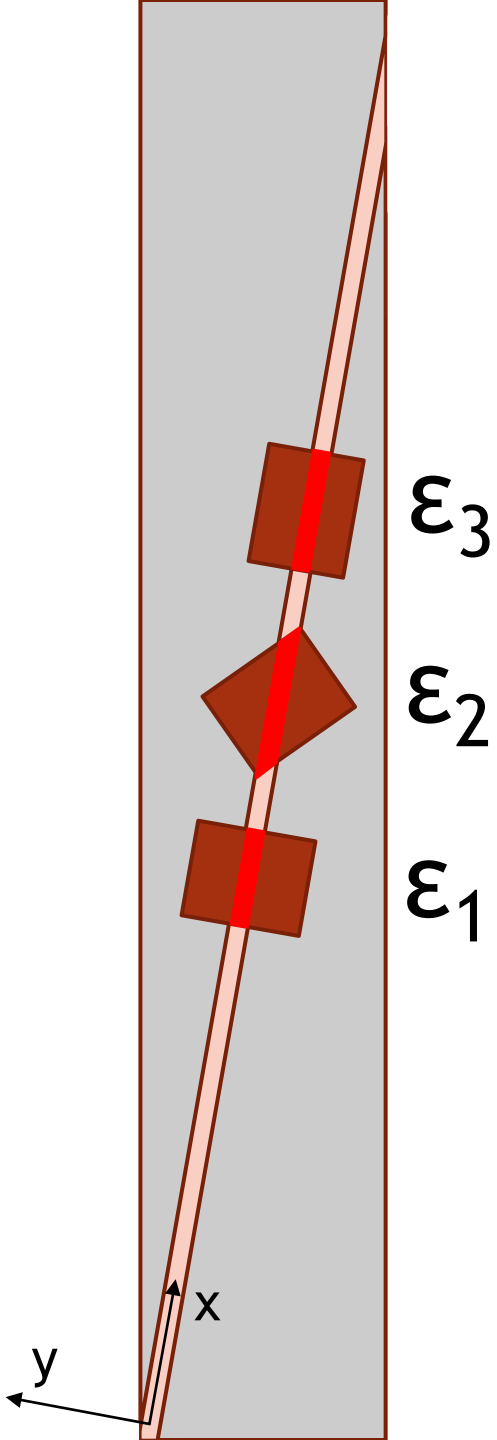
Measuring Strain

- Divided each strain by the percentage of the gage covering the adhesive
- Strain Gauge Area: 0.064in x 0.05in
- Adhesive Thickness: 0.008in



$\varepsilon'_1 = \varepsilon_1 * a/t$ $\varepsilon'_2 = \varepsilon_2 * a\cos(45^{o})/t$ $\varepsilon'_3 = \varepsilon_3 * b/t$

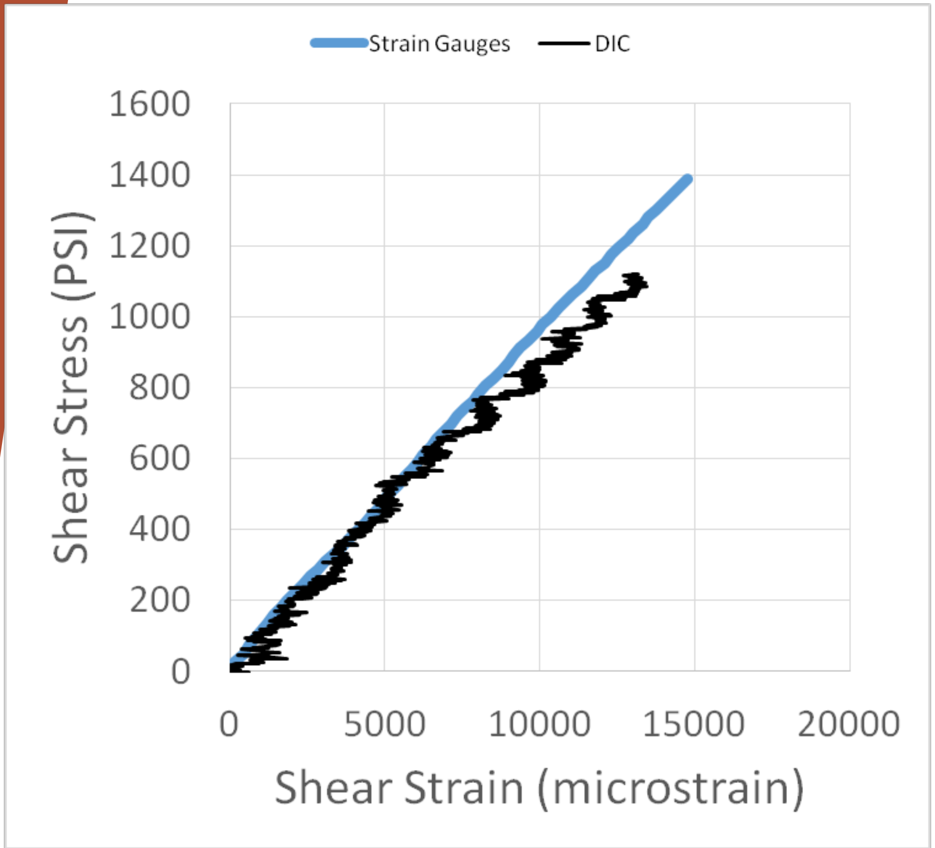
$$\gamma_{xy} = 2\varepsilon'_2 - \varepsilon'_1 - \varepsilon'_3$$



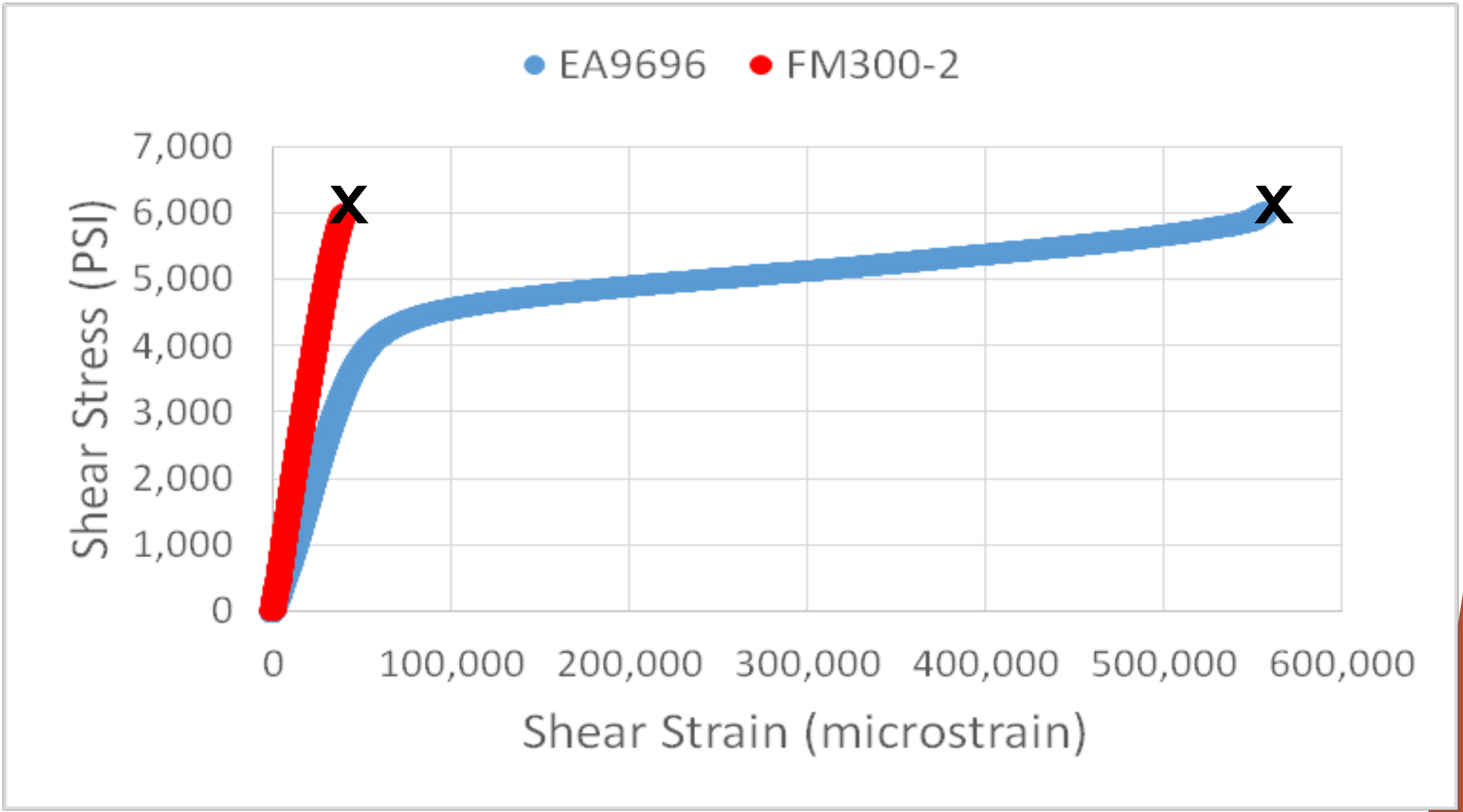
Monotonic Testing

Shear Modulus

	EA9696	FM300-2
Strain Gauge	88200 psi	122000 psi
Bulk Coupon data	88700 psi	129794 psi
Digital Imaging Correlation	87100 psi	

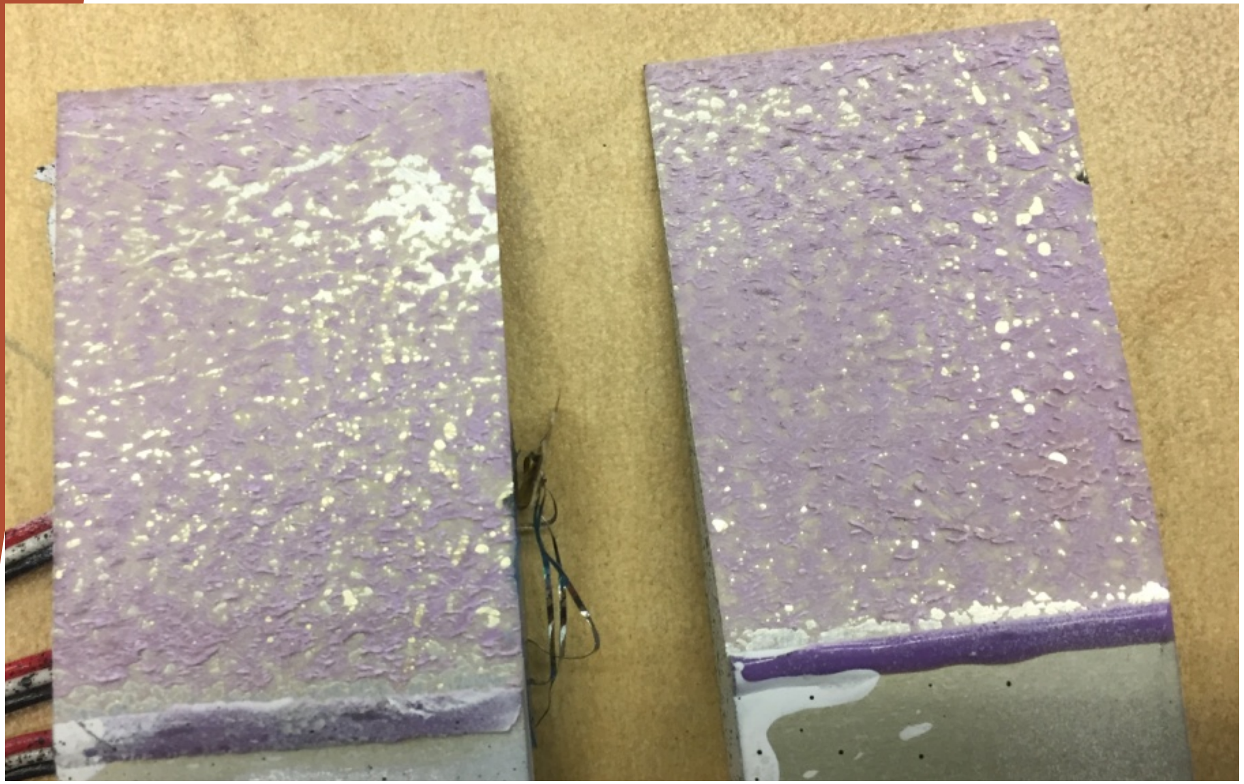


Elastic Region

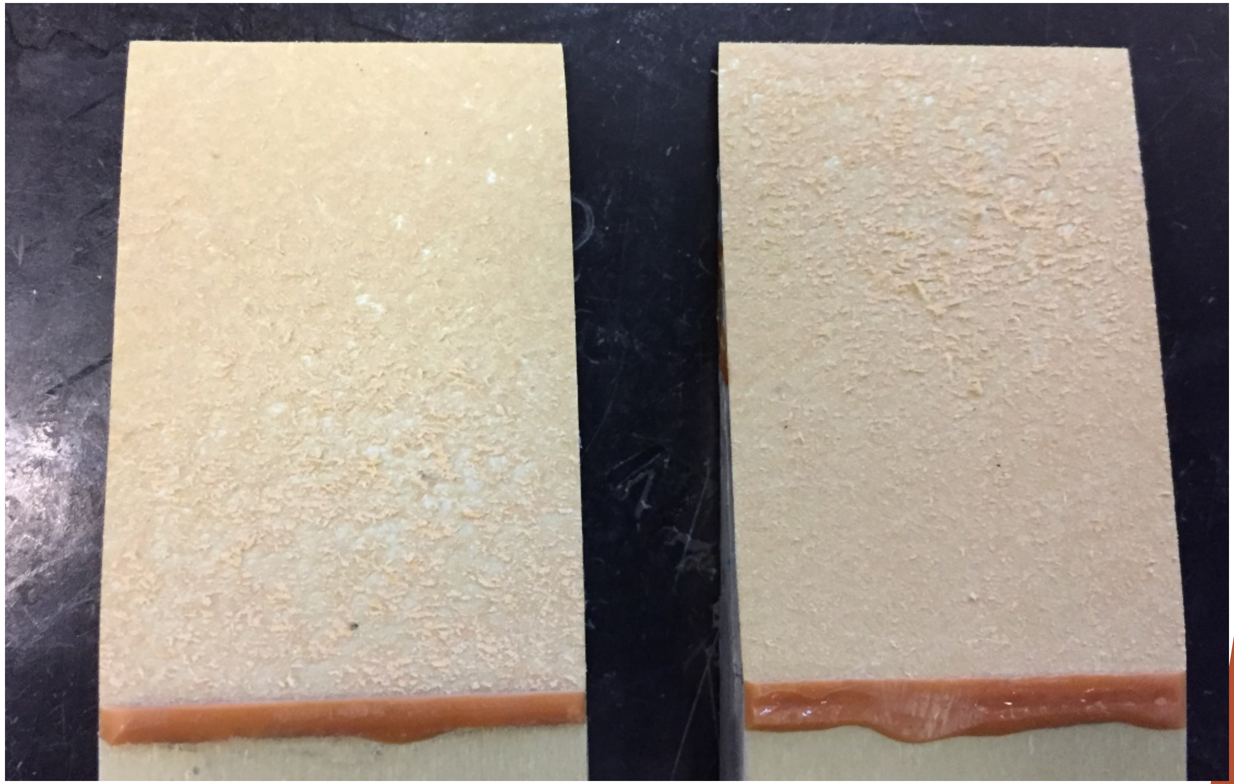


Failure surfaces

Monotonic Testing



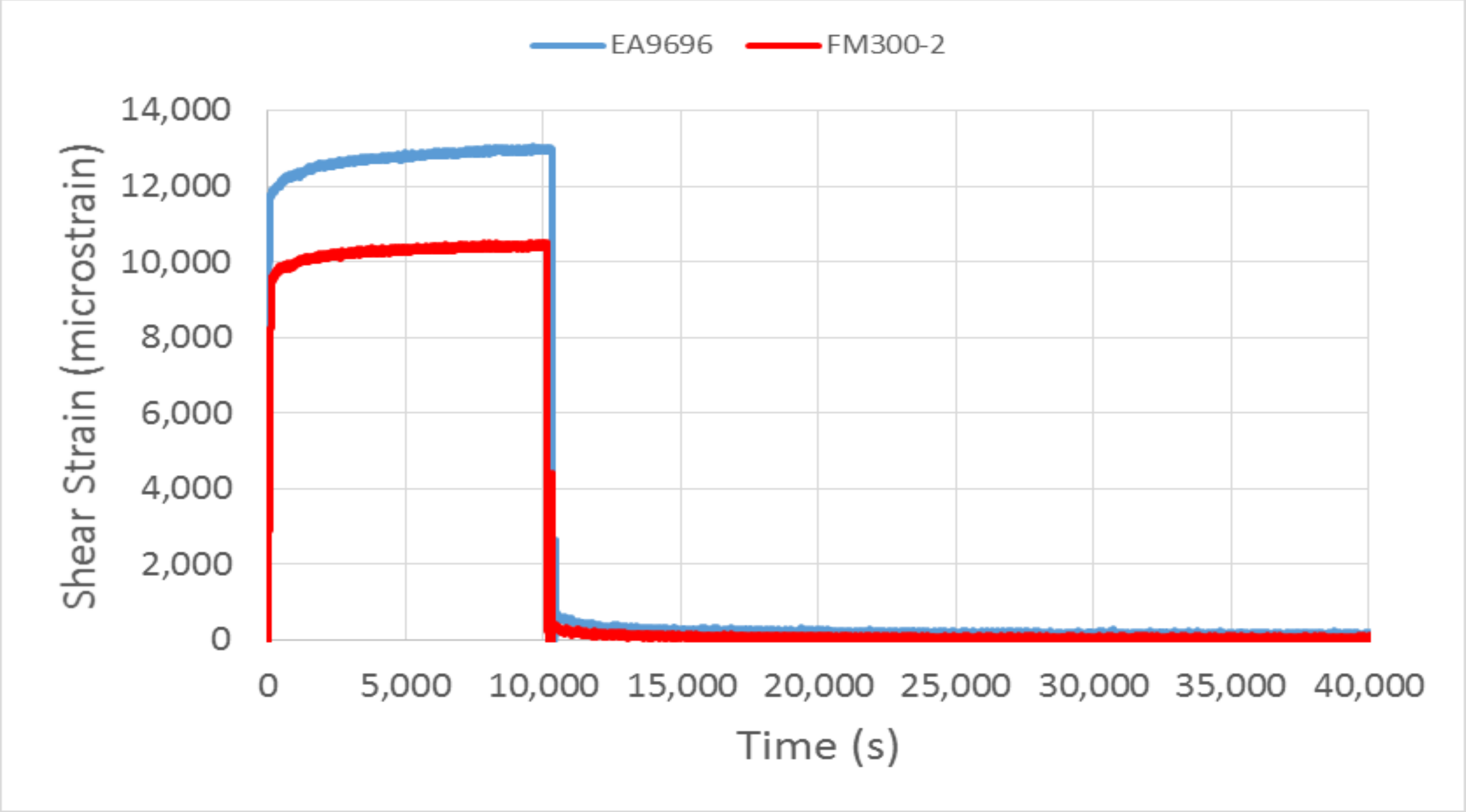
EA9696

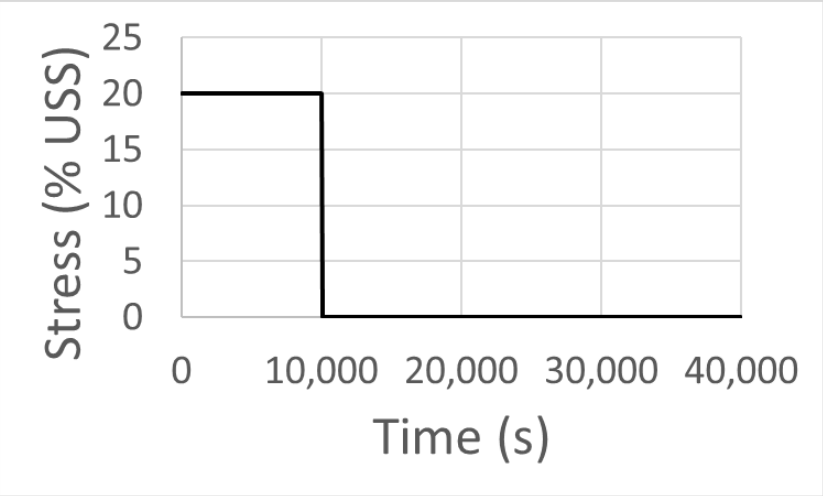


FM300-2

Creep Testing

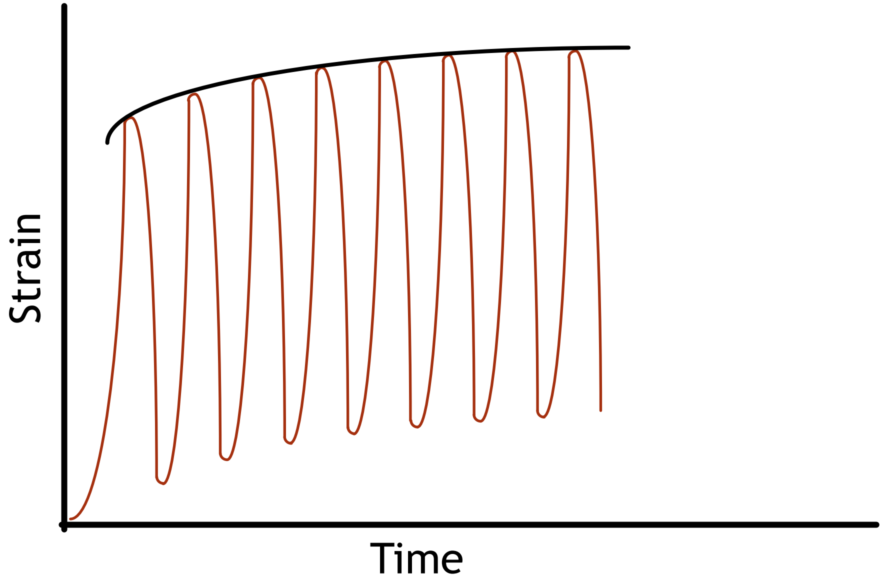
- 20% USS

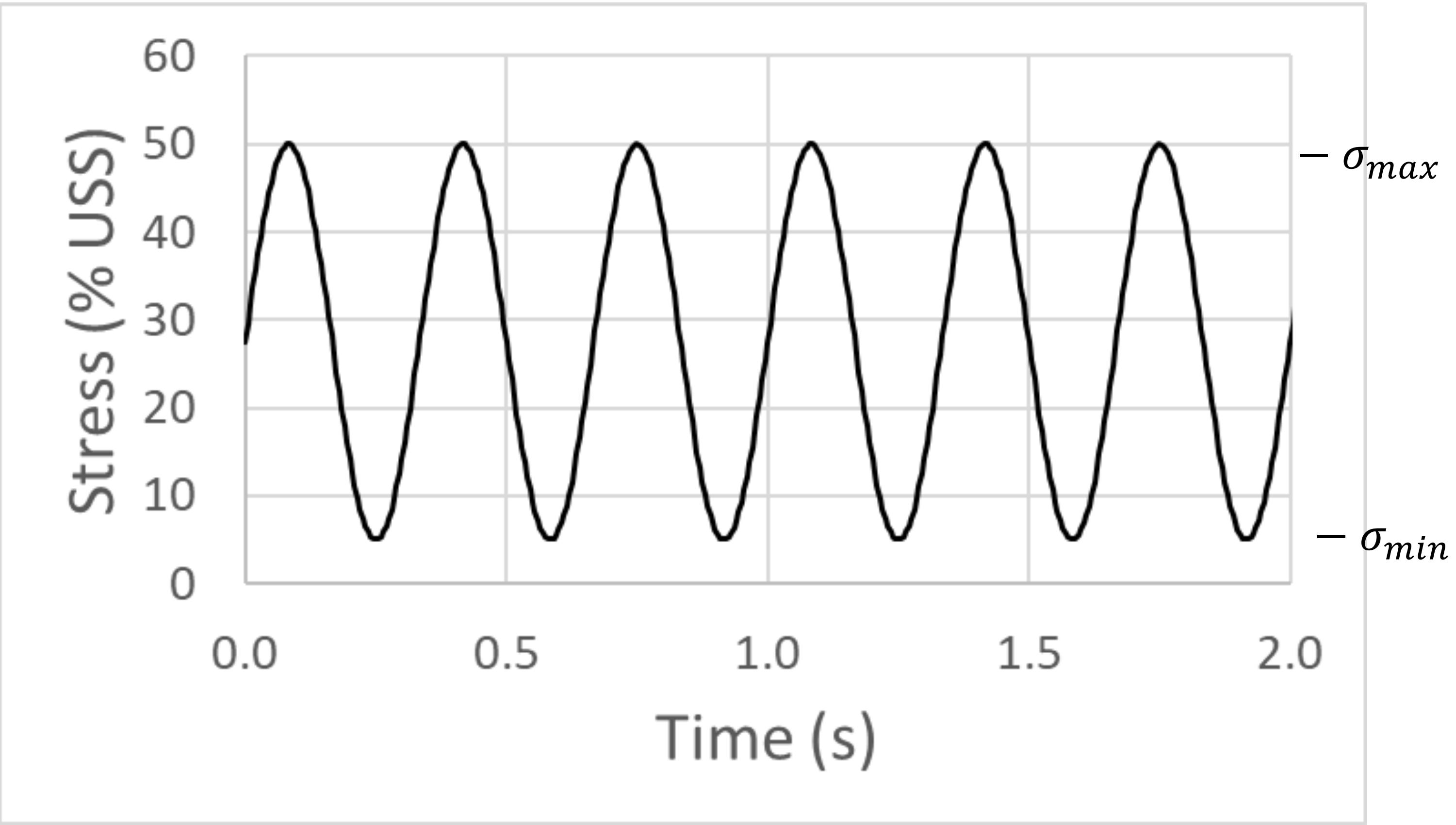




Cyclic Testing

- Sine Wave
- 10,000 Cycles
- Variables
  - Frequency
  - R Ratio



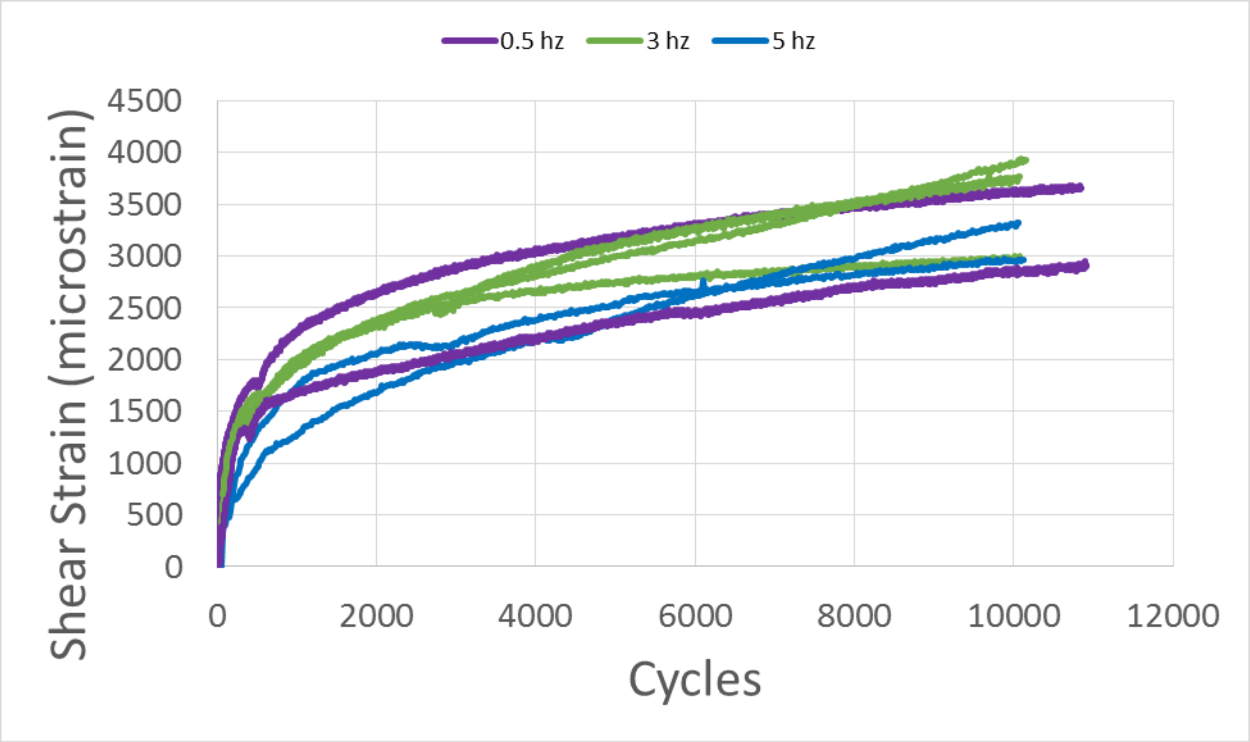


Stress Input for 3 Hz, 0.1 R, 50% USS

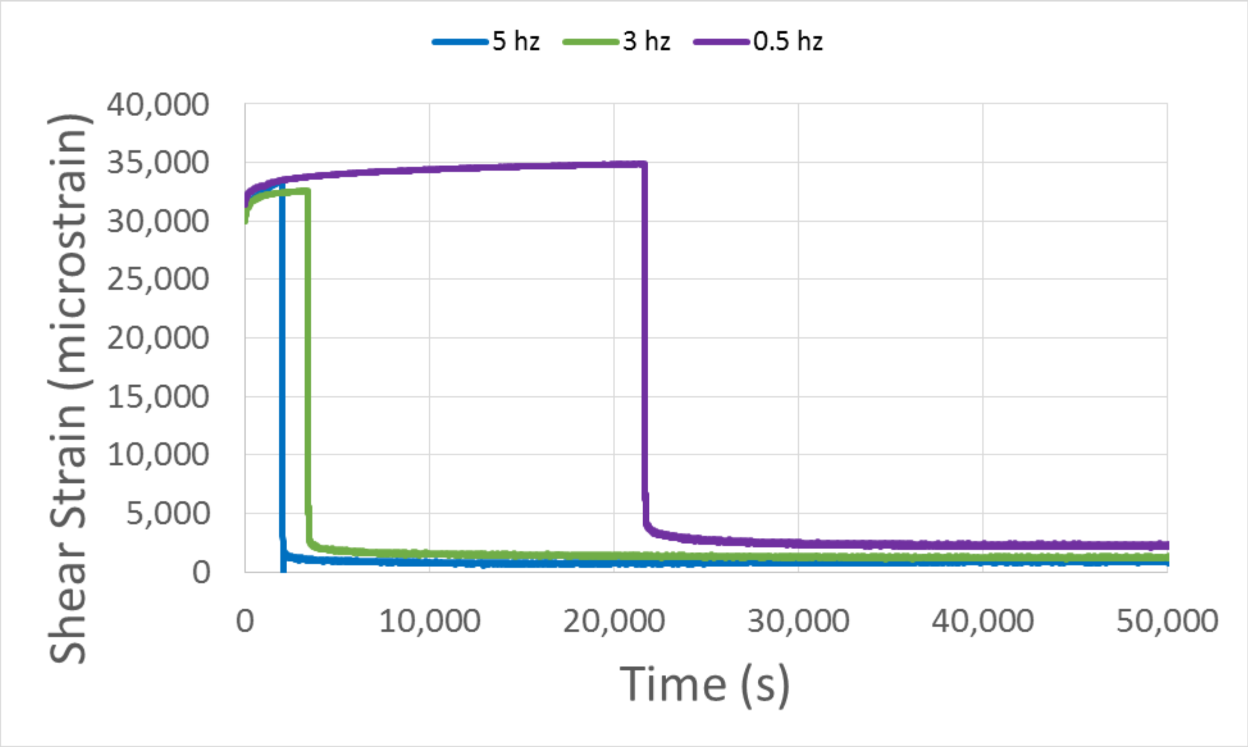
$$R = \frac{\sigma_{min}}{\sigma_{max}}$$

Change in Frequency

- 50% USS
- 0.1 R
- 10,000 cycles
- Sine Wave
- EA9696



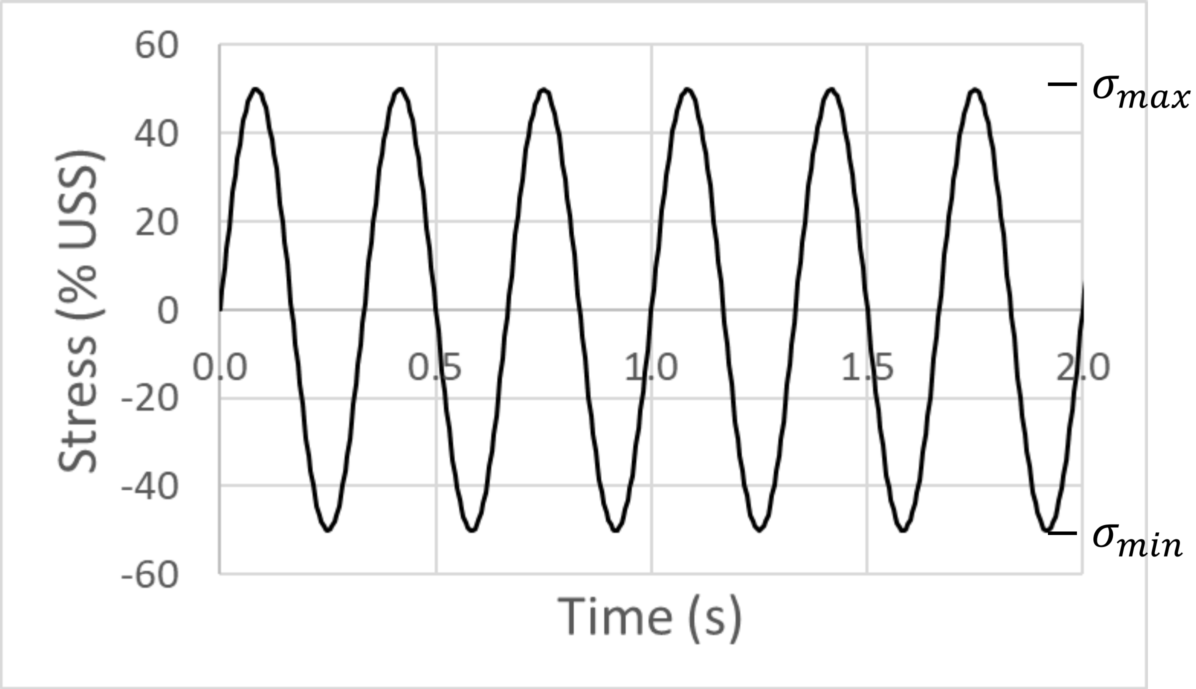
Strain Growth



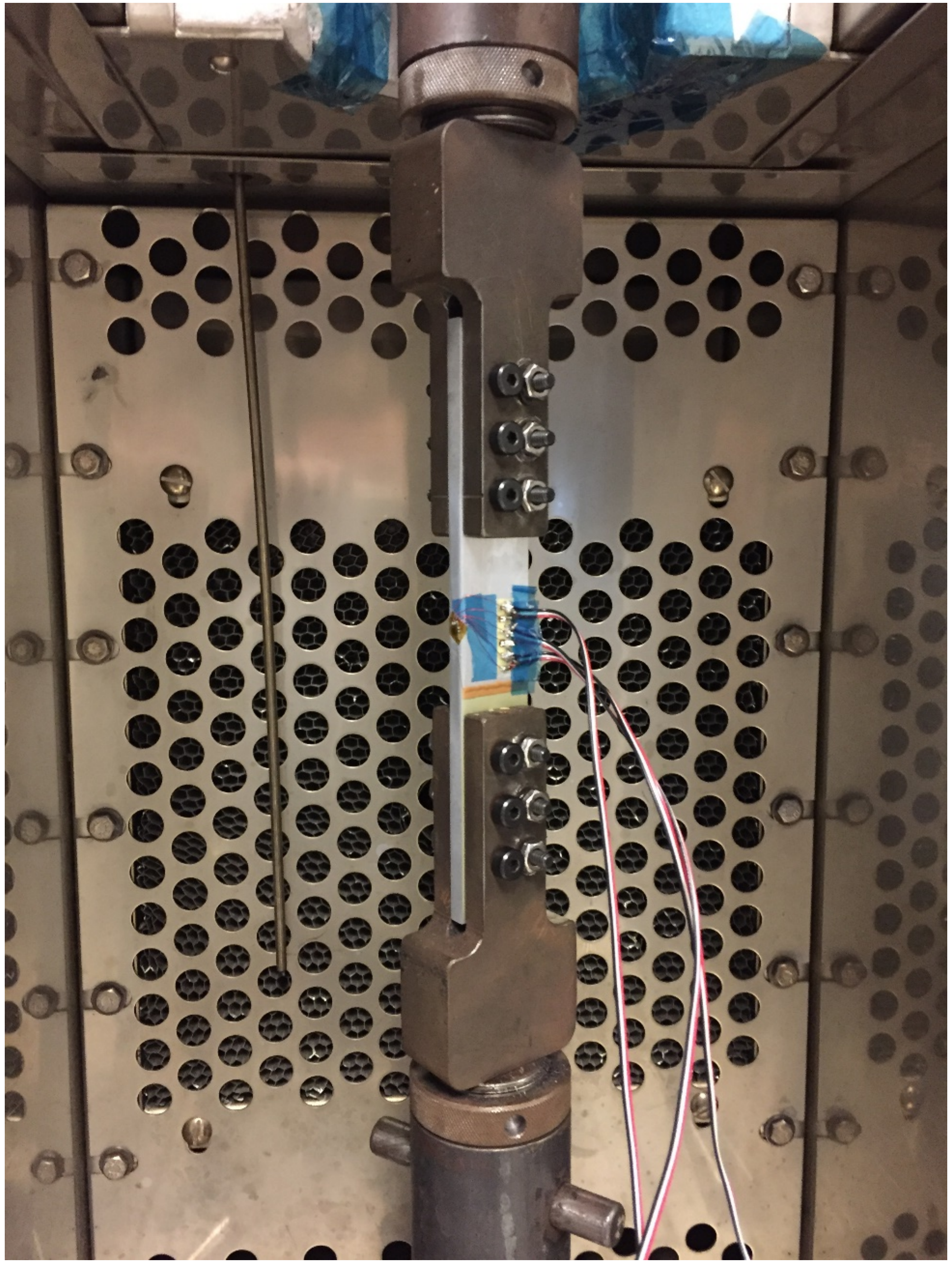
Ratcheting and Recovery

Change in R Ratio

- Sine Wave
- 10,000 Cycles
- 3 Hz
- $R = \frac{\sigma_{min}}{\sigma_{max}}$



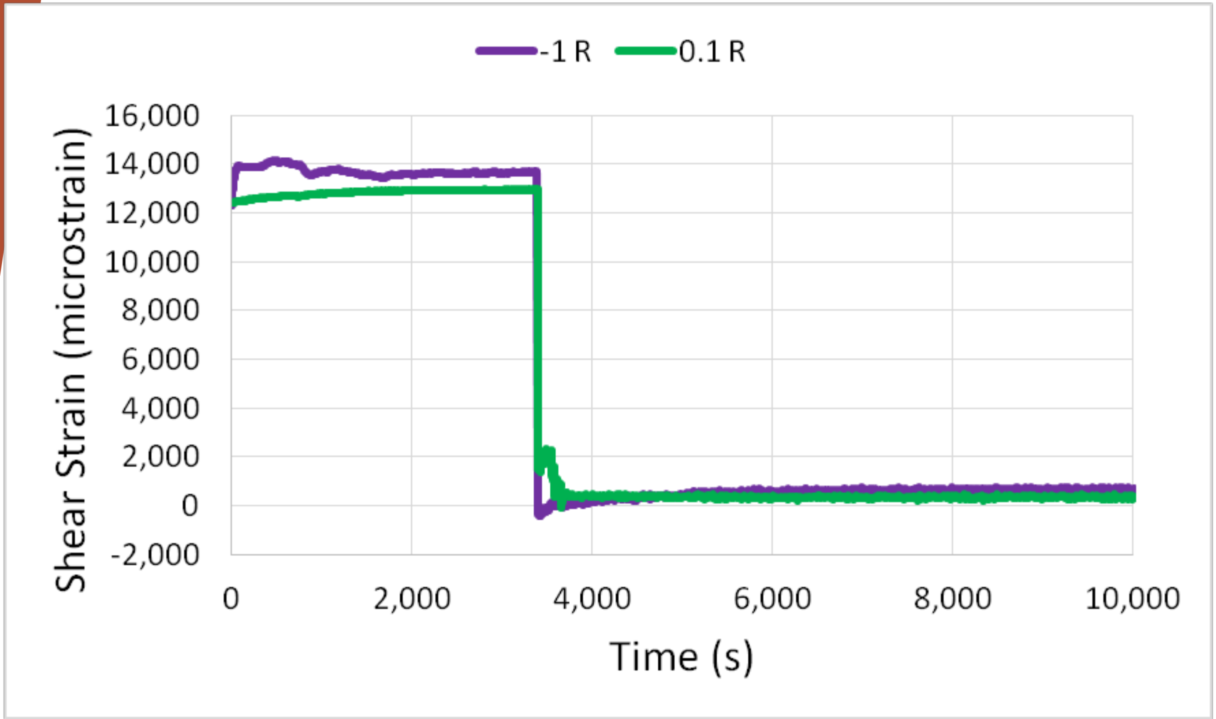
Stress Input for 3 Hz, -1 R, 50% USS



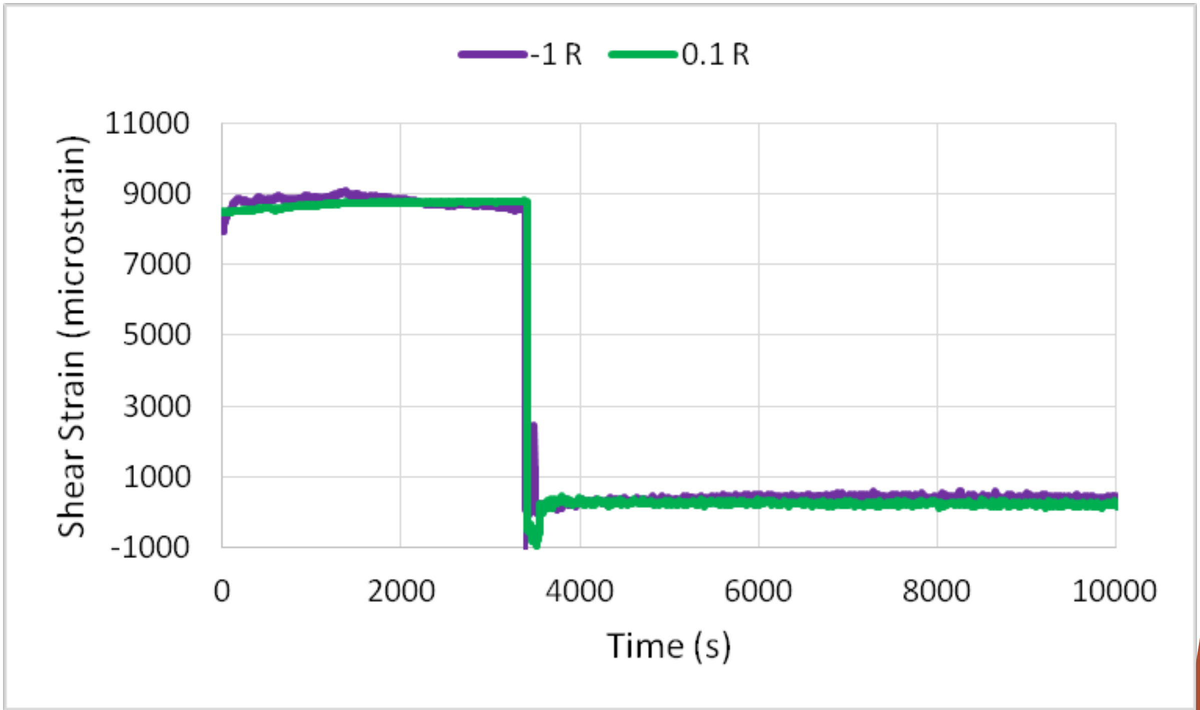
Compression Grips

Change in R Ratio

- 20% USS
- 3 Hz
- Sine Wave



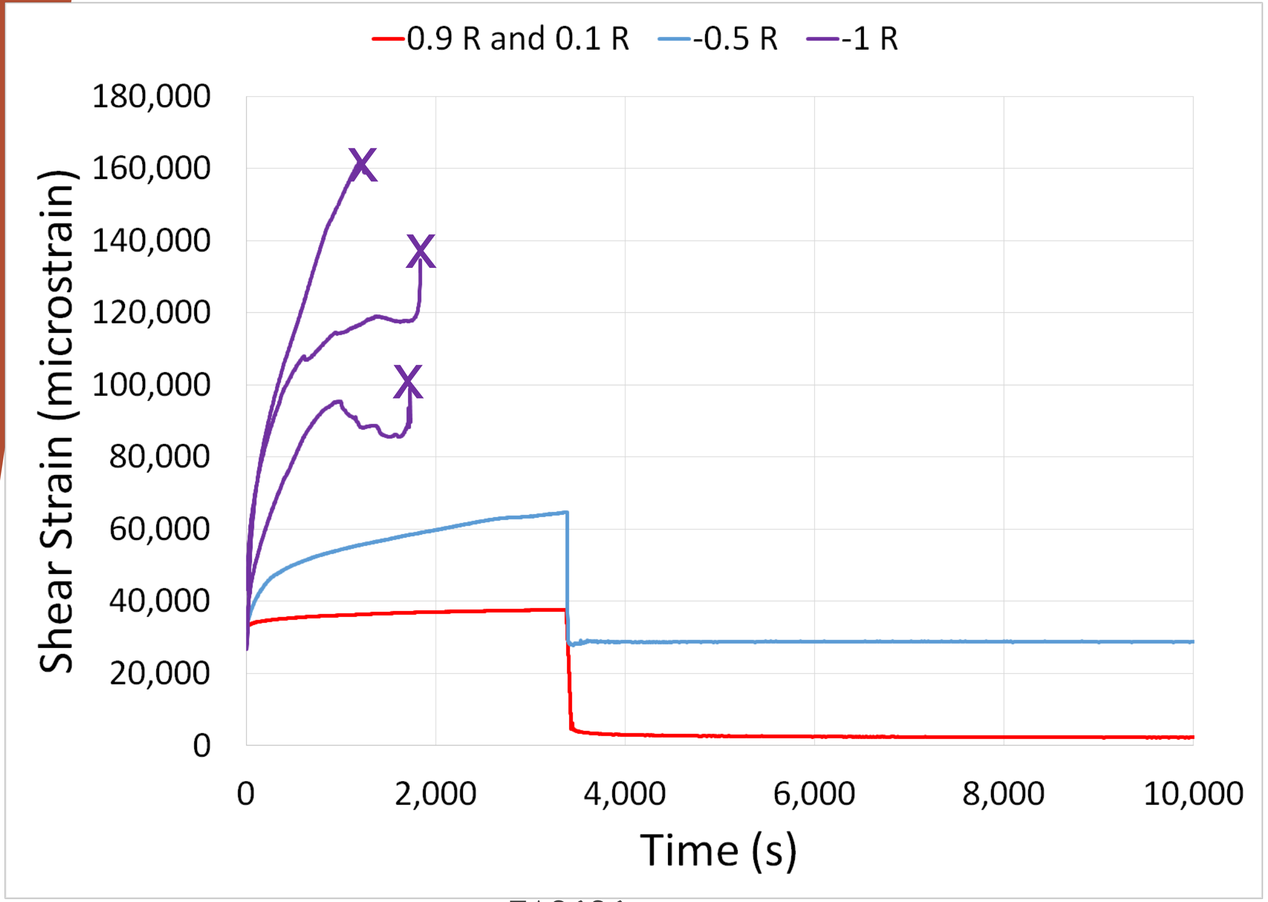
EA9696



FM300-2

Change in R Ratio

- 50% USS
- Sine Wave
- 3 Hz



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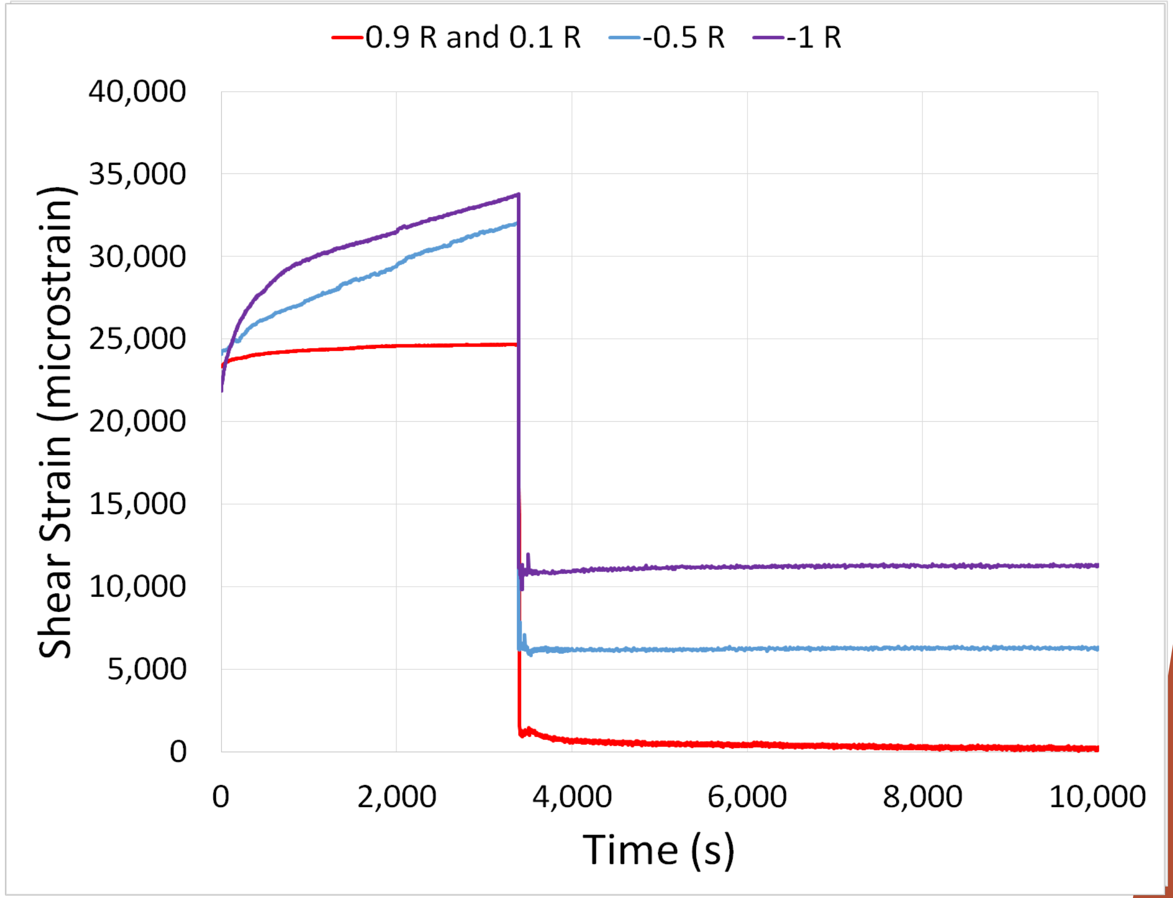
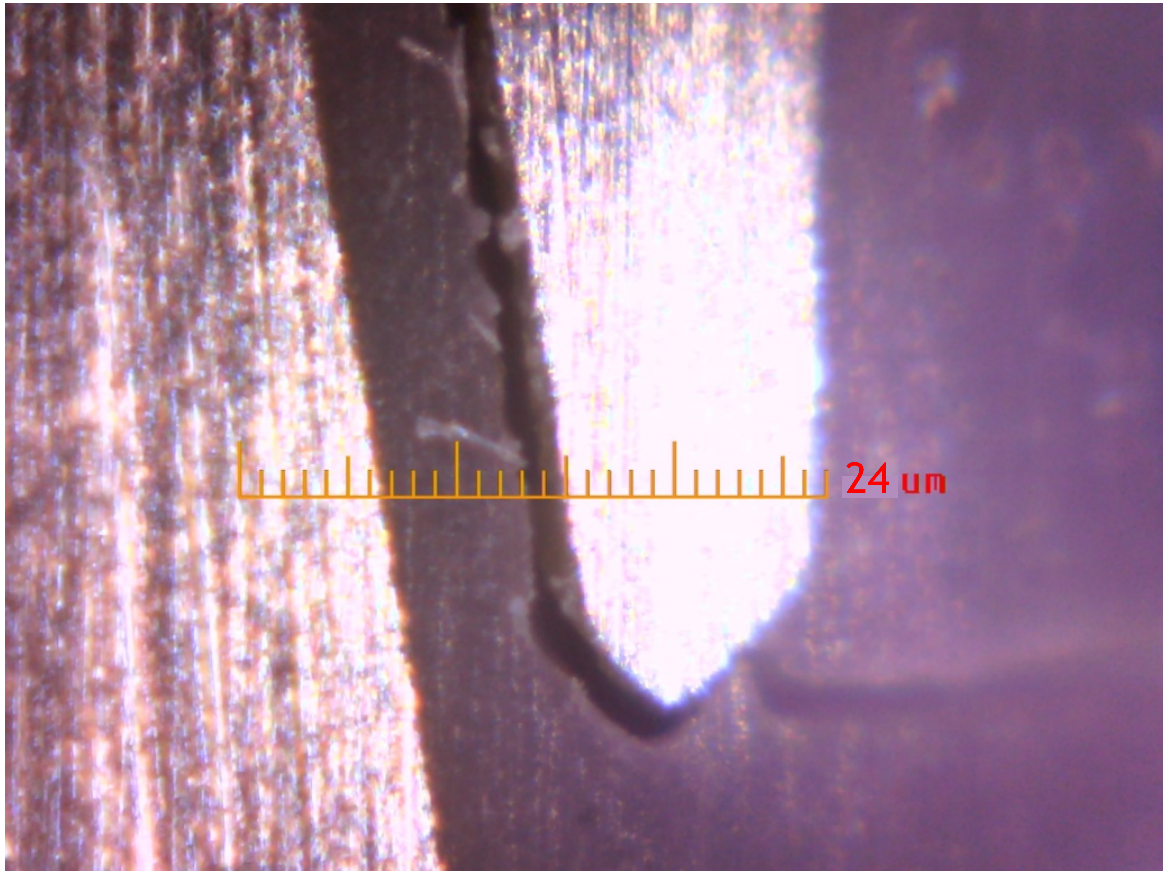
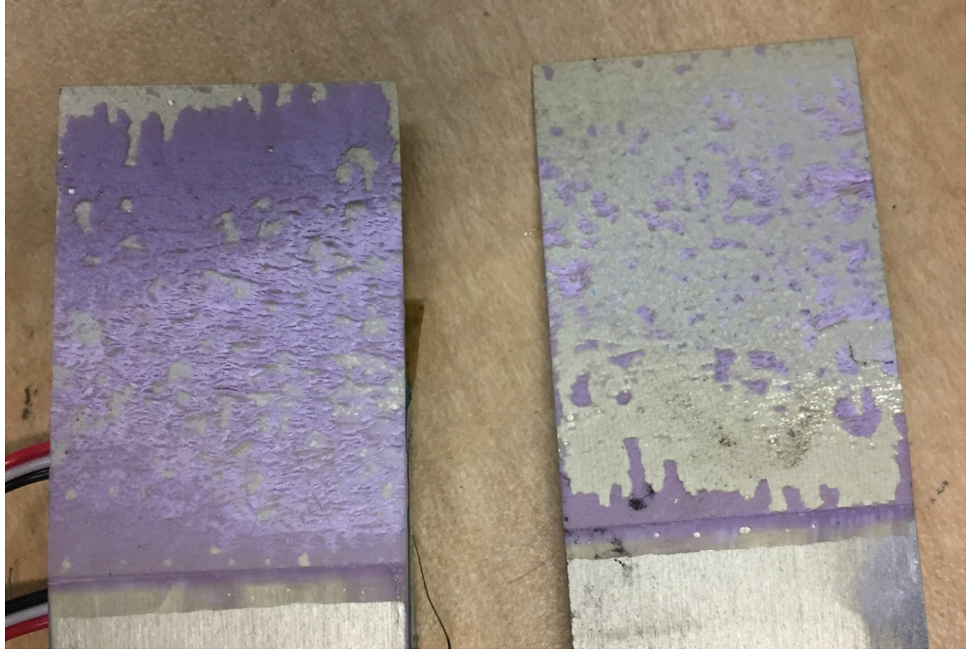
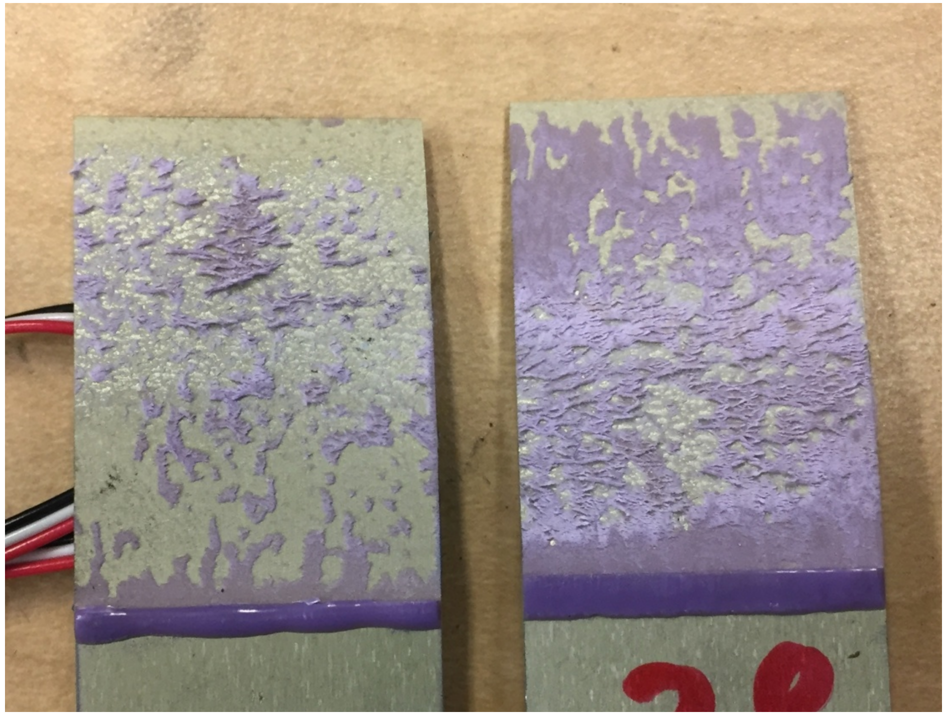


FM300-2

EA9696
50% USS
-1 R







Summary

- Thin bond adhesive behaves differently than bulk adhesive
- Strain gages can be used to measure strain over an adhesive bond
- Cyclic Testing
  - Cycle frequency has no effect on strain
  - Positive R ratio responds similar to creep
  - Negative R ratio creates considerable strain growth at 50% USS

Nonlinear Viscoelastic-Viscoplastic Model

Total Strain:

$$\varepsilon = \varepsilon^{ve} + \varepsilon^{vp}$$

Viscoelastic Model (Schapery)

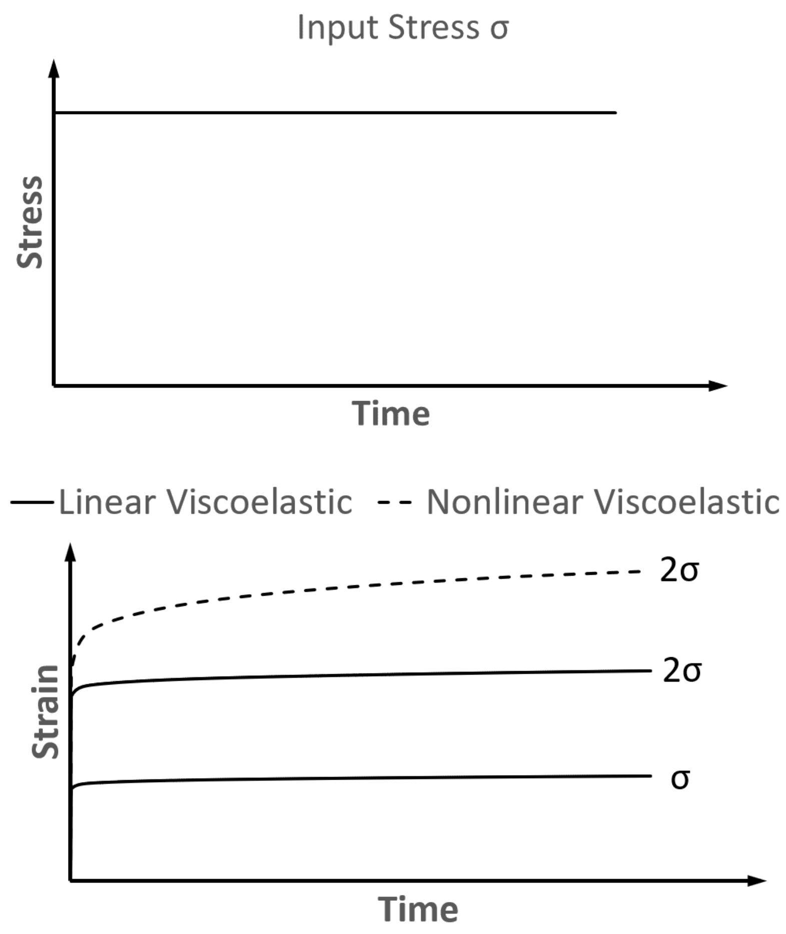
$$\varepsilon^{ve}(t) = g_0 D_0 \sigma^t + g_1 \int_0^t \Delta D^{(\psi^t - \psi^\tau)} \frac{d(g_2 \sigma^\tau)}{d\tau} d\tau$$

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

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

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 (n=7)



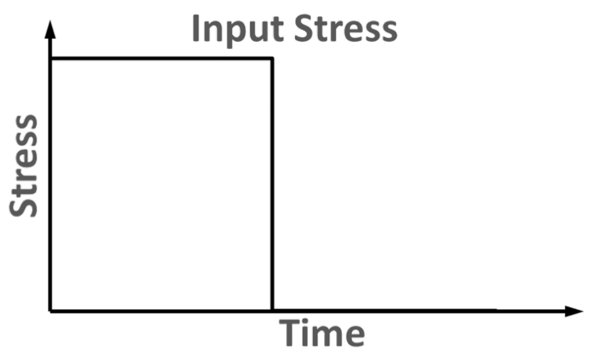
Nonlinear Viscoelastic-Viscoplastic Model

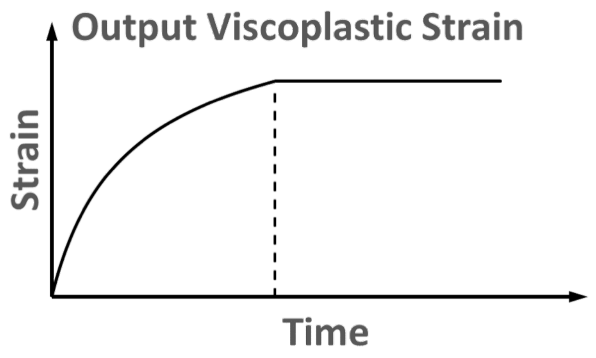
Viscoplastic Model (Perzyna)

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

η – viscosity parameter

N - constant





- ***f*** **Yield Function**

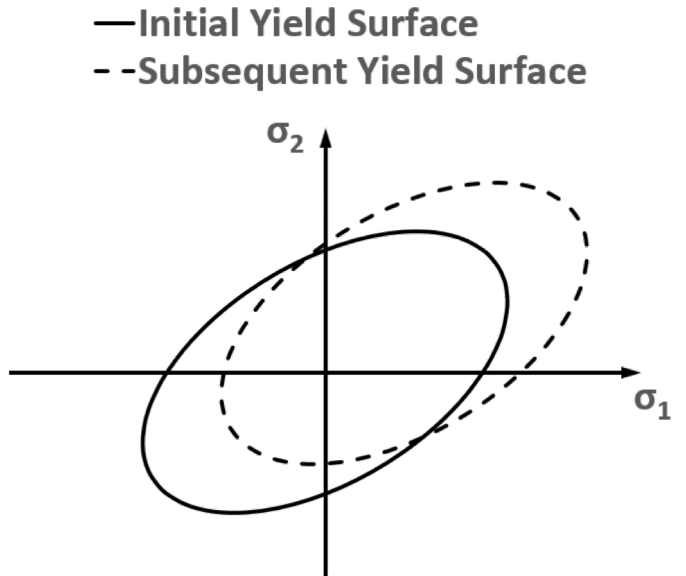
Von Mises Yield criterion + Nonlinear Kinematic Hardening

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

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

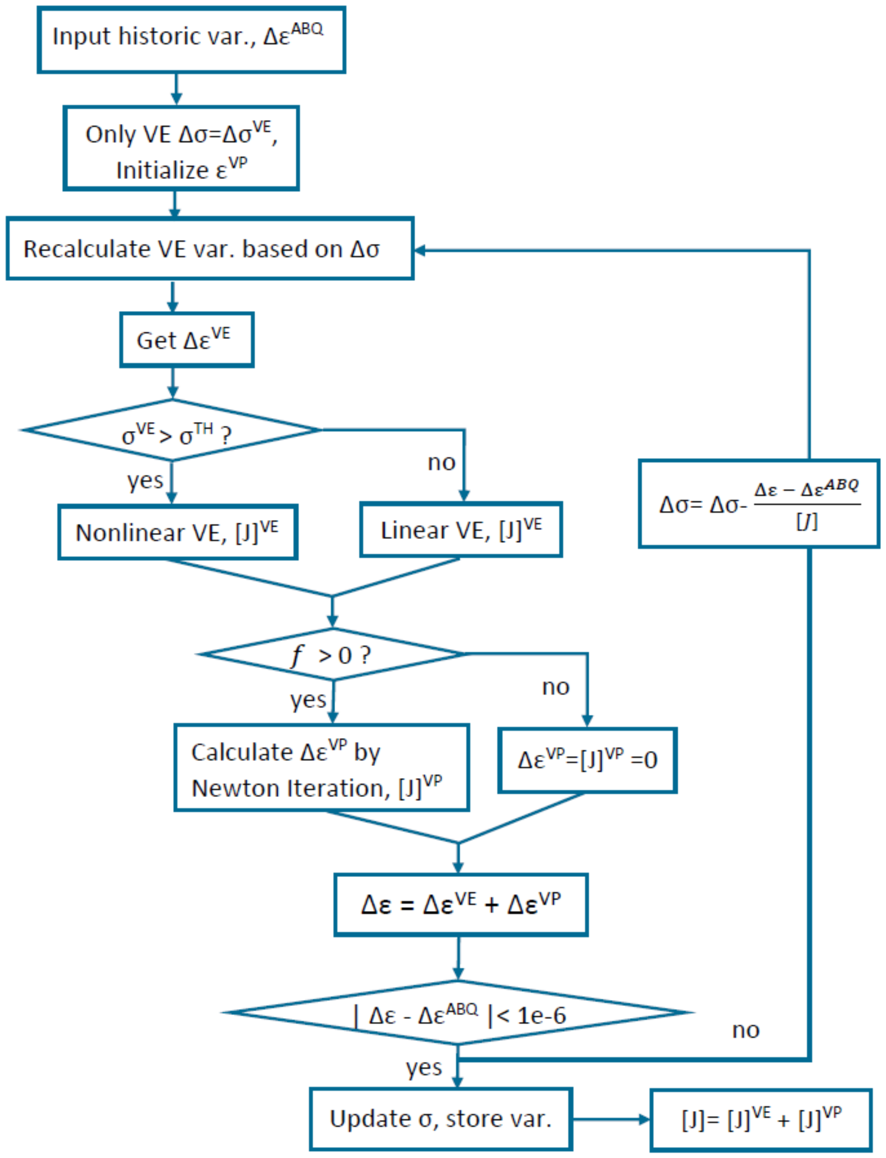
α_{ij} - back stress

ε_e^{vp} - effective viscoplastic strain



1D Model

- **Flowchart**



- **Parameters Calibration**

Creep Data without Permanent Strain ⇨
- Viscoelastic Parameters:
  Prony Series
  Nonlinear Parameters

↓

Uniaxial Tension Test ⇨
- Parameters in Yield Criterion and Hardening Rule

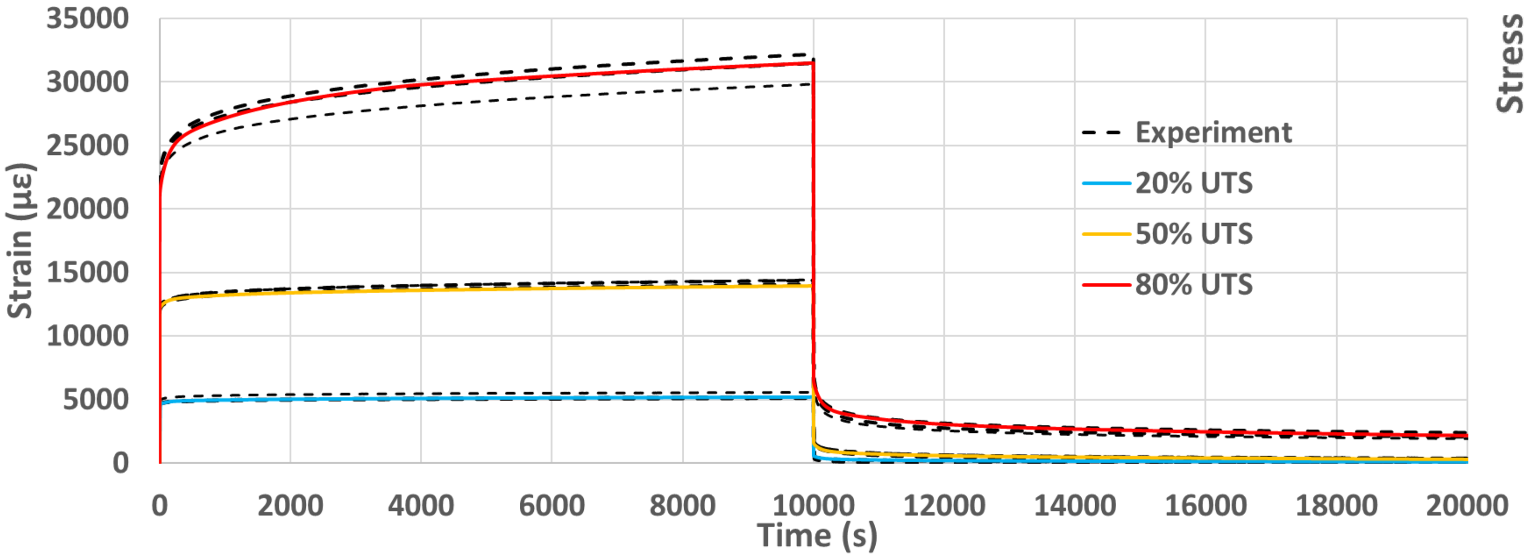
↓

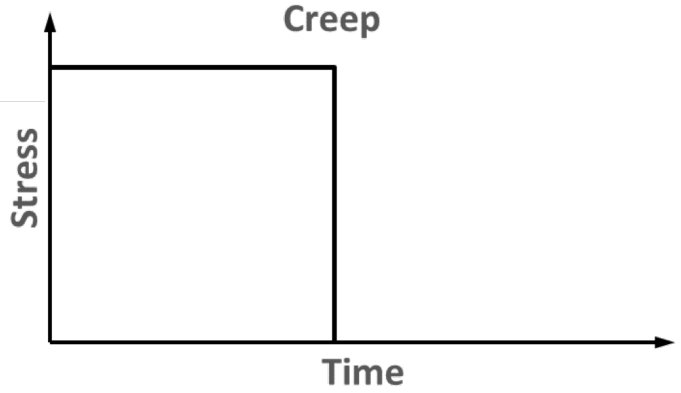
Creep data with Permanent Strain ⇨
- Viscosity Parameters

1D Model- Simulated For Bulk Coupons

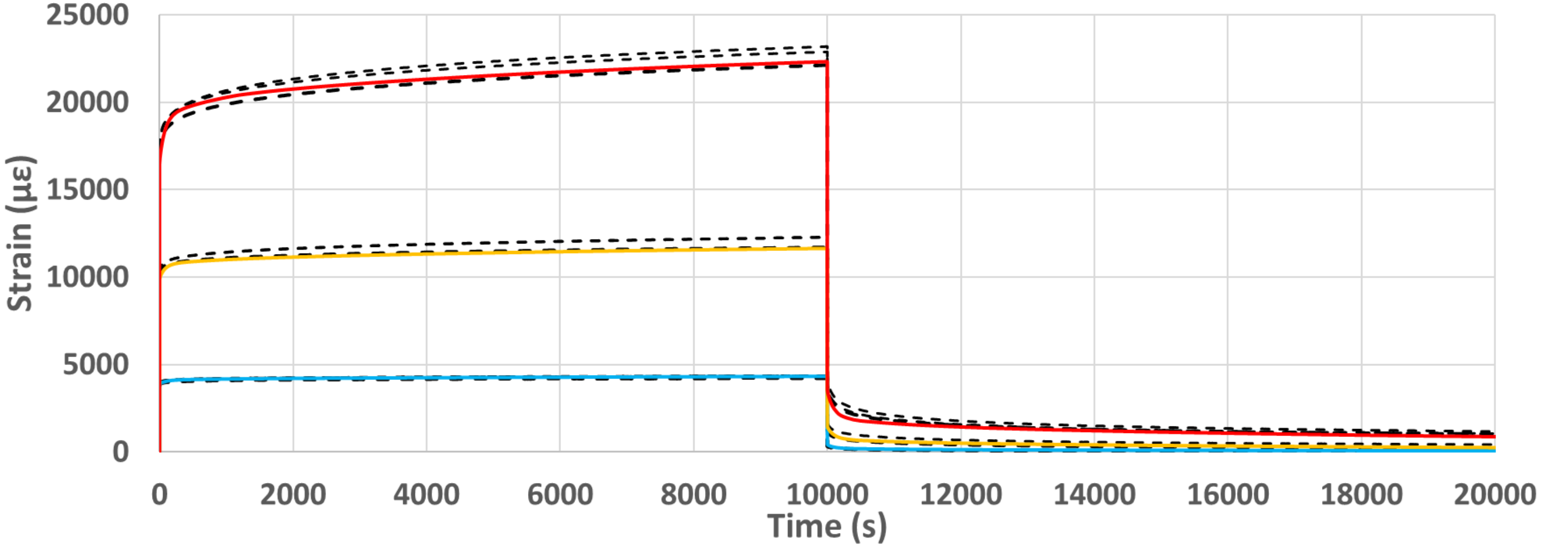
CREEP

EA9696



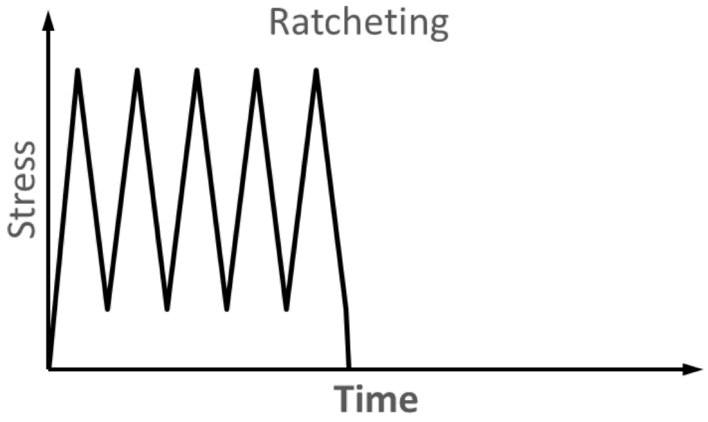


FM300-2

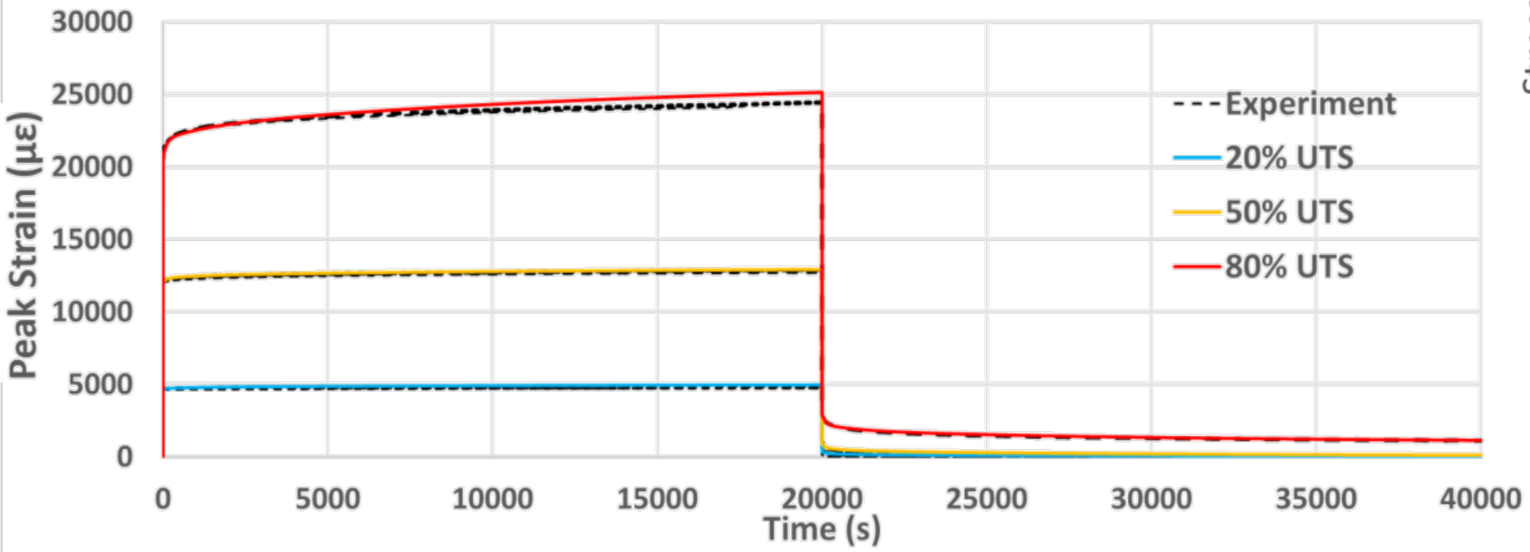


1D Model- Simulated For Bulk Coupons

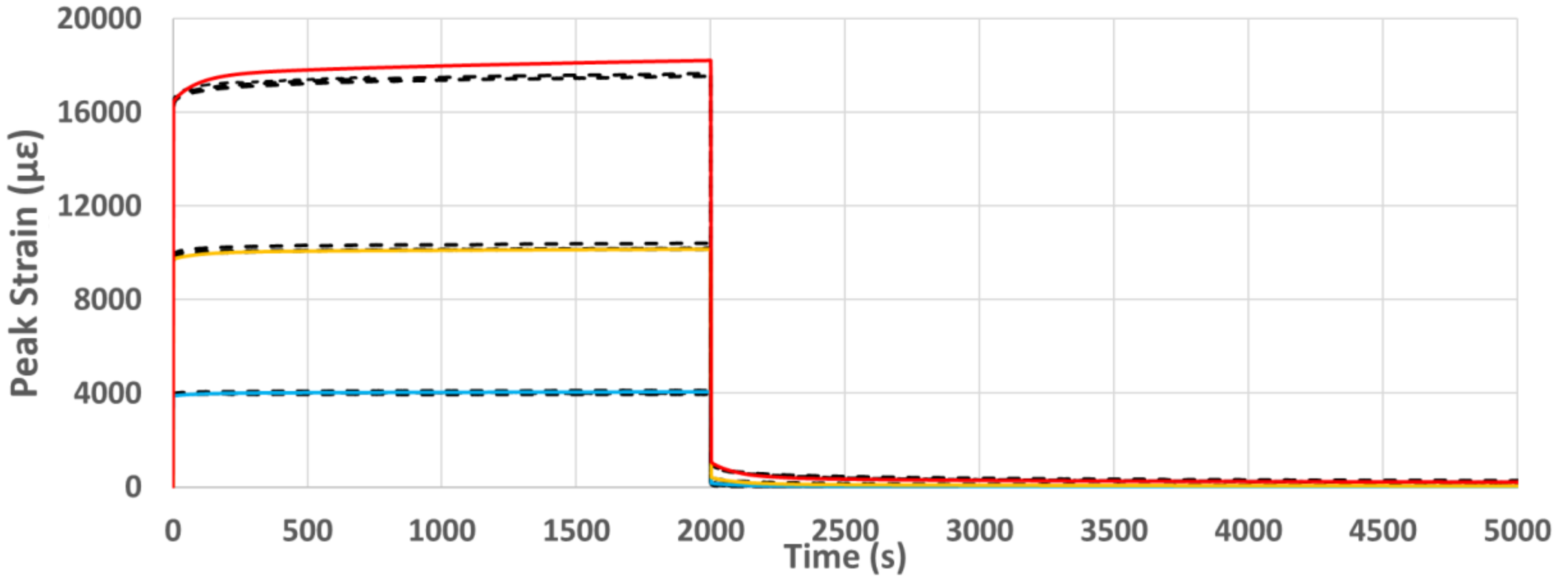
Ratcheting, 0.5 Hz, R=0.1, 10K Cycles



EA9696
10K Cycles



FM300-2
1K Cycles



3D Model-Algorithm-Stress Update

$$\left(\Delta\sigma_{ij}^{t}\right)^{k+1} = \left(\Delta\sigma_{ij}^{t}\right)^{k} - \left[\left(\frac{\partial R_{ij}^{t}}{\partial\sigma_{kl}^{t}}\right)^{k}\right]^{-1} (R_{kl}^{t})^{k}$$

$$\frac{\partial R_{ij}^{t}}{\partial\sigma_{kl}^{t}} = \frac{\partial\Delta\varepsilon_{ij}^{ve,t}}{\partial\sigma_{kl}^{t}} + \frac{\partial\Delta\varepsilon_{ij}^{vp,t}}{\partial\sigma_{kl}^{t}}$$

$$= \bar{J}^{t}\delta_{ik}\delta_{jl} + \frac{\partial\bar{J}^{t}}{\partial\sigma_{kl}^{t}}\frac{\partial\bar{\sigma}^{t}}{\partial\sigma_{kl}^{t}}\sigma_{ij}^{t} + \frac{1}{3}(\bar{B}^{t} - \bar{J}^{t})\delta_{kl}\delta_{ij} + \frac{1}{3}\sigma_{mm}^{t}\,\delta_{ij}\frac{\partial\bar{\sigma}^{t}}{\partial\sigma_{kl}^{t}}\left(\frac{\partial\bar{B}^{t}}{\partial\bar{\sigma}^{t}} - \frac{\partial\bar{J}^{t}}{\partial\bar{\sigma}^{t}}\right)$$

$$- \frac{\partial\bar{\sigma}^{t}}{\partial\sigma_{kl}^{t}}\left\{\frac{1}{2}\frac{\partial g_1^{t}}{\partial\bar{\sigma}^{t}}\sum J_n\left(e^{-\lambda_n\Delta\psi^{t}}q_{ij,n}^{t-\Delta t} - g_2^{t-\Delta t}S_{ij}^{t-\Delta t}\frac{1-e^{-\lambda_n\Delta\psi^{t}}}{\lambda_n\Delta\psi^{t}}\right)\right.$$

$$+ \frac{1}{2}\frac{\partial a^{t}}{\partial\bar{\sigma}^{t}}g_1^{t}\sum J_n\left[e^{-\lambda_n\Delta\psi^{t}}\frac{q_{ij,n}^{t-\Delta t}\lambda_n\Delta\psi^{t}}{(a^{t})^2} + g_2^{t-\Delta t}S_{ij}^{t-\Delta t}\left(\frac{e^{-\lambda_n\Delta\psi^{t}}}{a^{t}} - \frac{1-e^{-\lambda_n\Delta\psi^{t}}}{\lambda_n\Delta\psi^{t}}\right)\right]$$

$$+ \frac{1}{9}\frac{\partial g_1^{t}}{\partial\bar{\sigma}^{t}}\sum B_n\left(e^{-\lambda_n\Delta\psi^{t}}q_{mm,n}^{t-\Delta t} - g_2^{t-\Delta t}\sigma_{mm}^{t-\Delta t}\frac{1-e^{-\lambda_n\Delta\psi^{t}}}{\lambda_n\Delta\psi^{t}}\right)\delta_{ij}$$

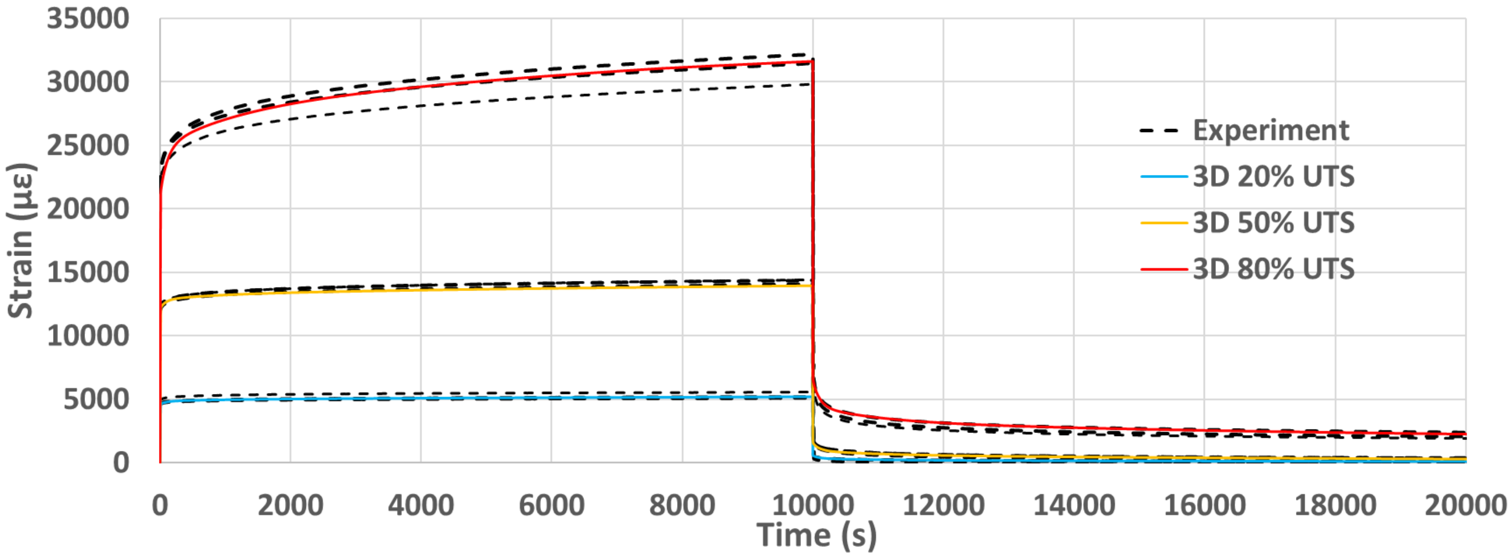
$$\left. + \frac{1}{9}\frac{\partial a^{t}}{\partial\bar{\sigma}^{t}}g_1^{t}\sum B_n\left[e^{-\lambda_n\Delta\psi^{t}}\frac{q_{mm,n}^{t-\Delta t}\lambda_n\Delta\psi^{t}}{(a^{t})^2} + g_2^{t-\Delta t}\sigma_{mm}^{t-\Delta t}\left(\frac{e^{-\lambda_n\Delta\psi^{t}}}{a^{t}} - \frac{1-e^{-\lambda_n\Delta\psi^{t}}}{\lambda_n\Delta\psi^{t}}\right)\right]\delta_{ij}\right\}$$

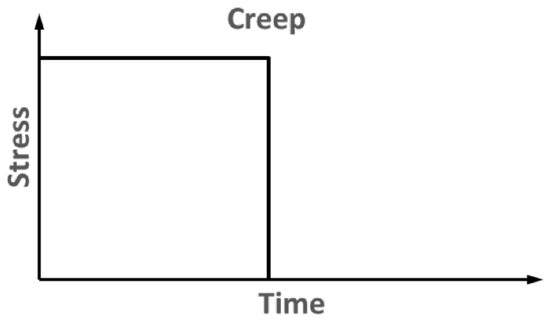
$$+ \Delta\mathrm{t}\,\eta\left(\frac{f}{\sigma_y^{0}}\right)^{N}\left(\frac{N}{f}\frac{\partial f}{\partial\sigma_{ij}^{t}}\frac{\partial f}{\partial\sigma_{kl}^{t}} + \frac{\partial^2 f}{\partial\sigma_{ij}^{t}\partial\sigma_{kl}^{t}}\right)$$

3D Model- Simulated For Bulk Coupons

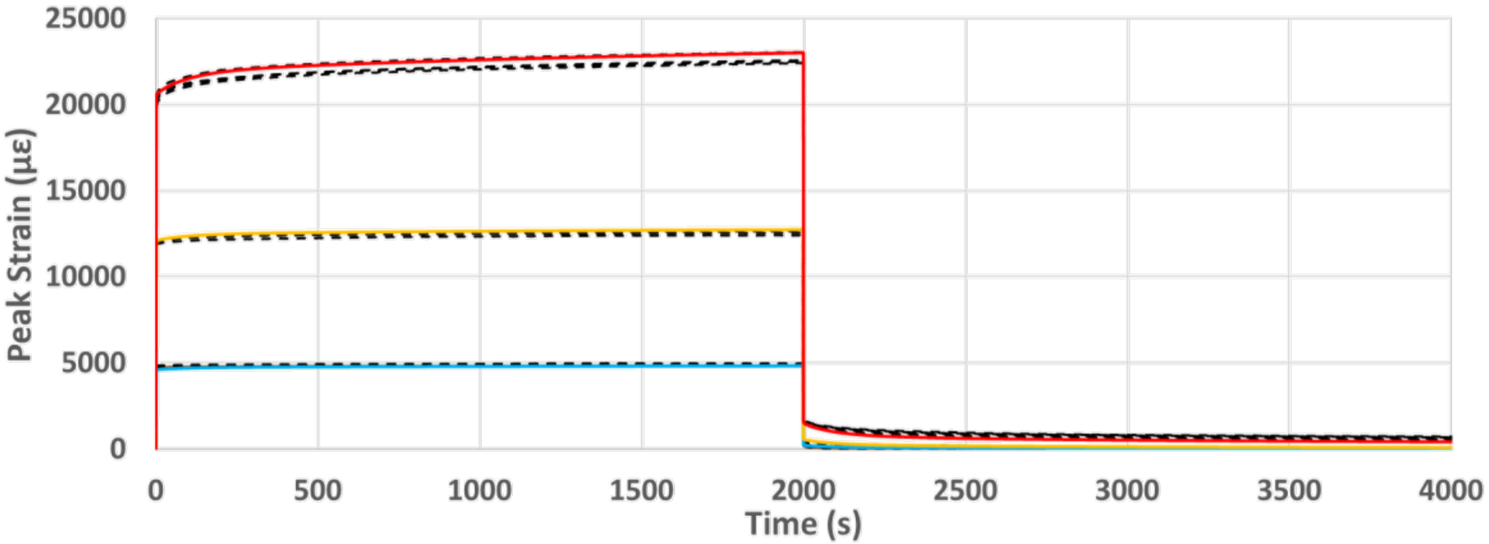
EA9696

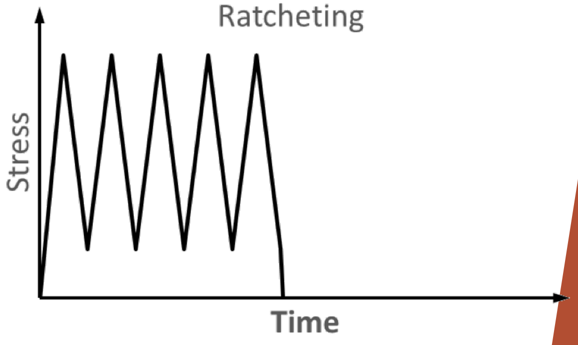
CREEP



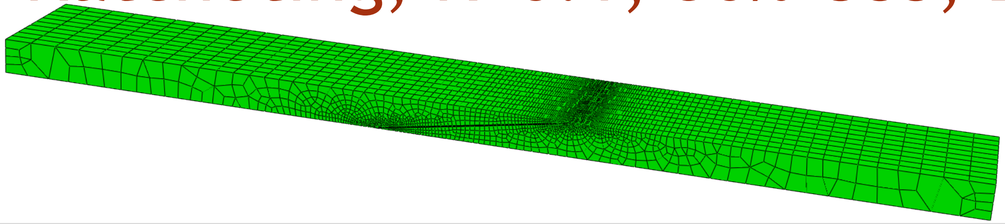


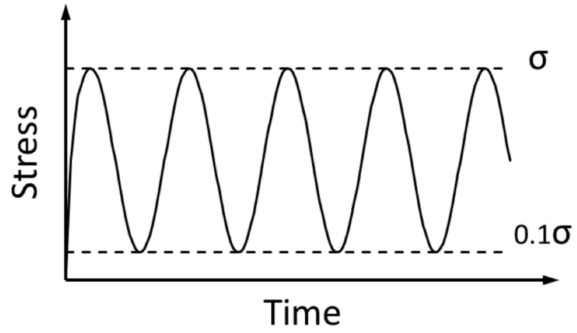
RATCHETING
0.5 Hz
R=0.1
1K Cycles

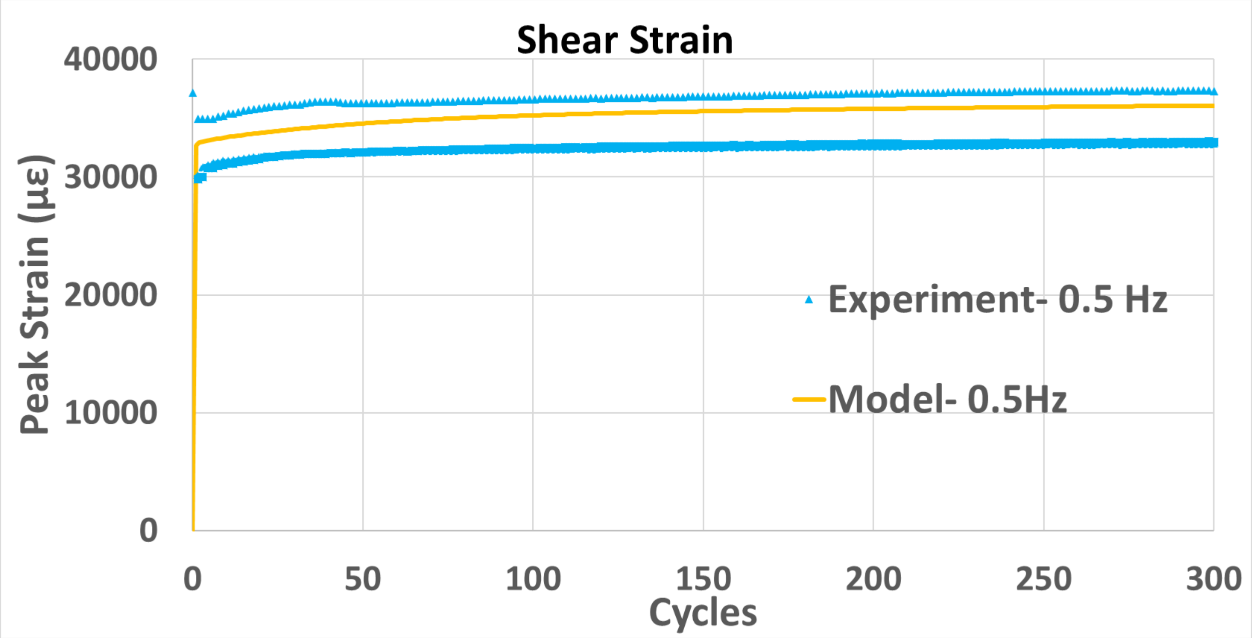


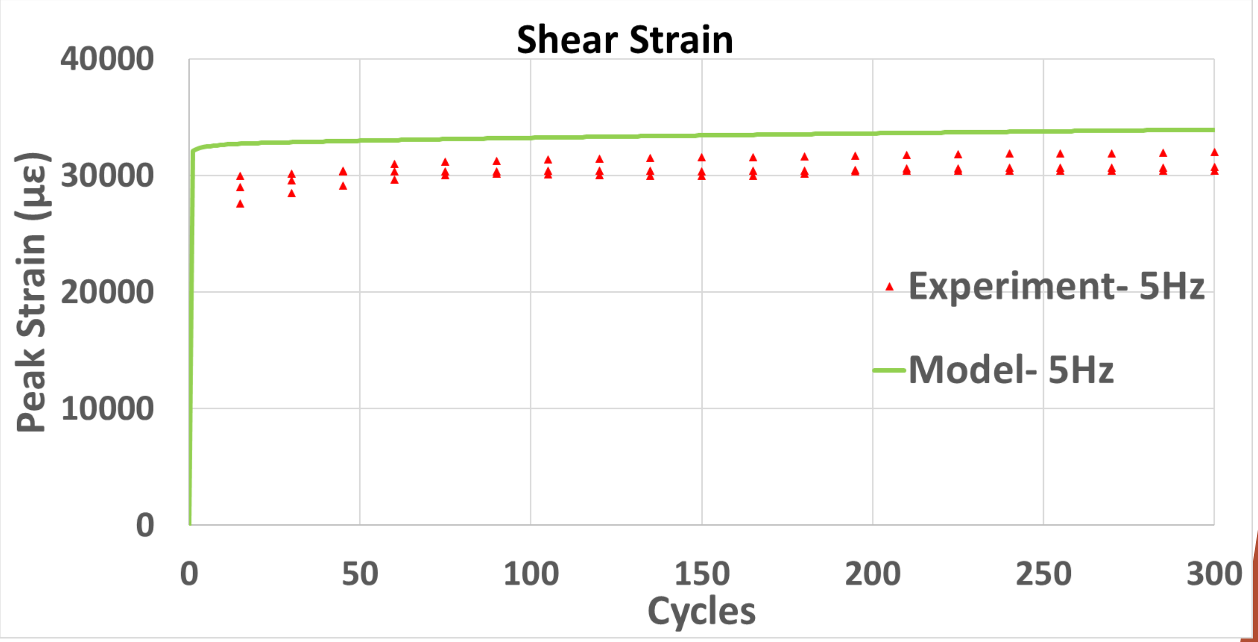


3D Model- Simulated For Scarf Joints Ratcheting, R=0.1, 50% USS, EA9696





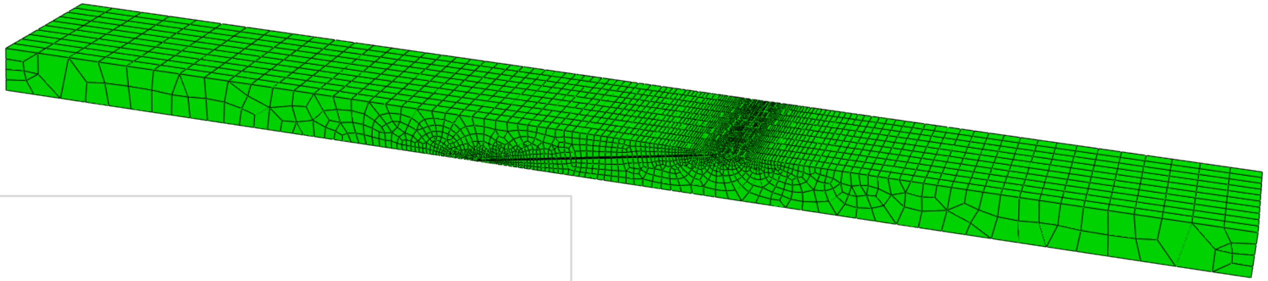


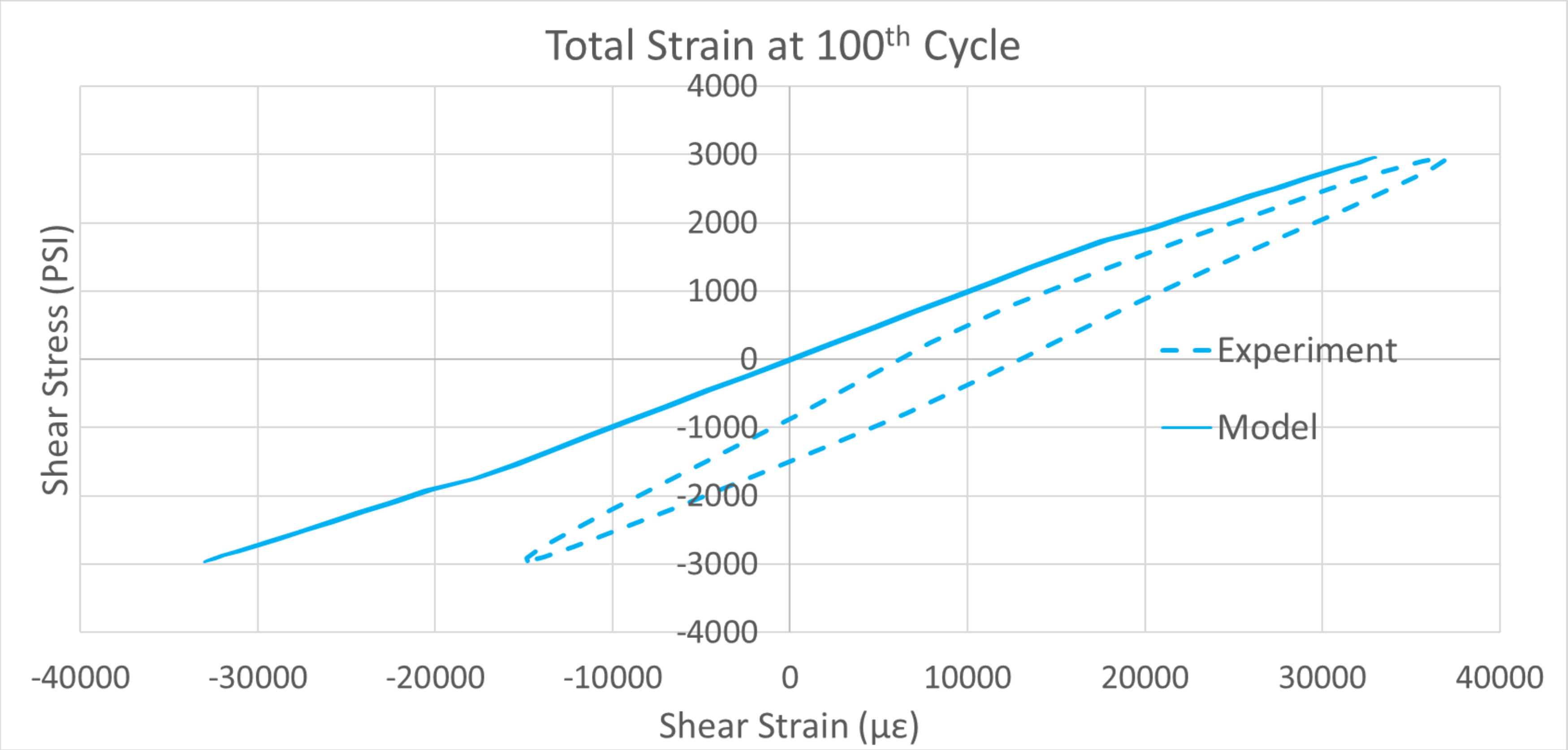


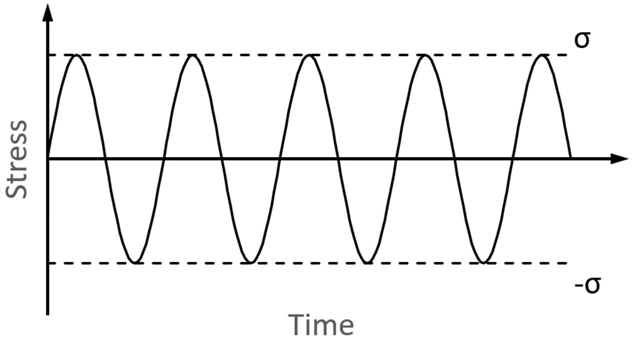
	Model (strain unit: με)				Experiment(strain unit: με)	
	Cycles	Permanent Strain	Cycles	Estimated Permanent Strain	Cycles	Permanent Strain
0.5 Hz	300	63	10 K	2100	10 K	2000
5 Hz		28		933		1300

3D Model- Simulated For Scarf Joints

Ratcheting, 3 Hz, R=-1, 50% USS, EA9696







Conclusion

- 1D model can predict the ratcheting behavior of bulk coupons with parameters from creep tests.
- 3D model can predict the ratcheting behavior (0.1R) of scarf joints with the recalibrated parameters.
- 3D model can not yet describe the hysteresis for scarf joints when R=-1.

Future Work

- Simulation of bonded joints under shear (-Dec 2020):

➢ Parameters Recalibration, Model Modification