Durability of Adhesive Joints
-cyclic loading
-viscoplasticity

2019 JAMS Annual Meeting

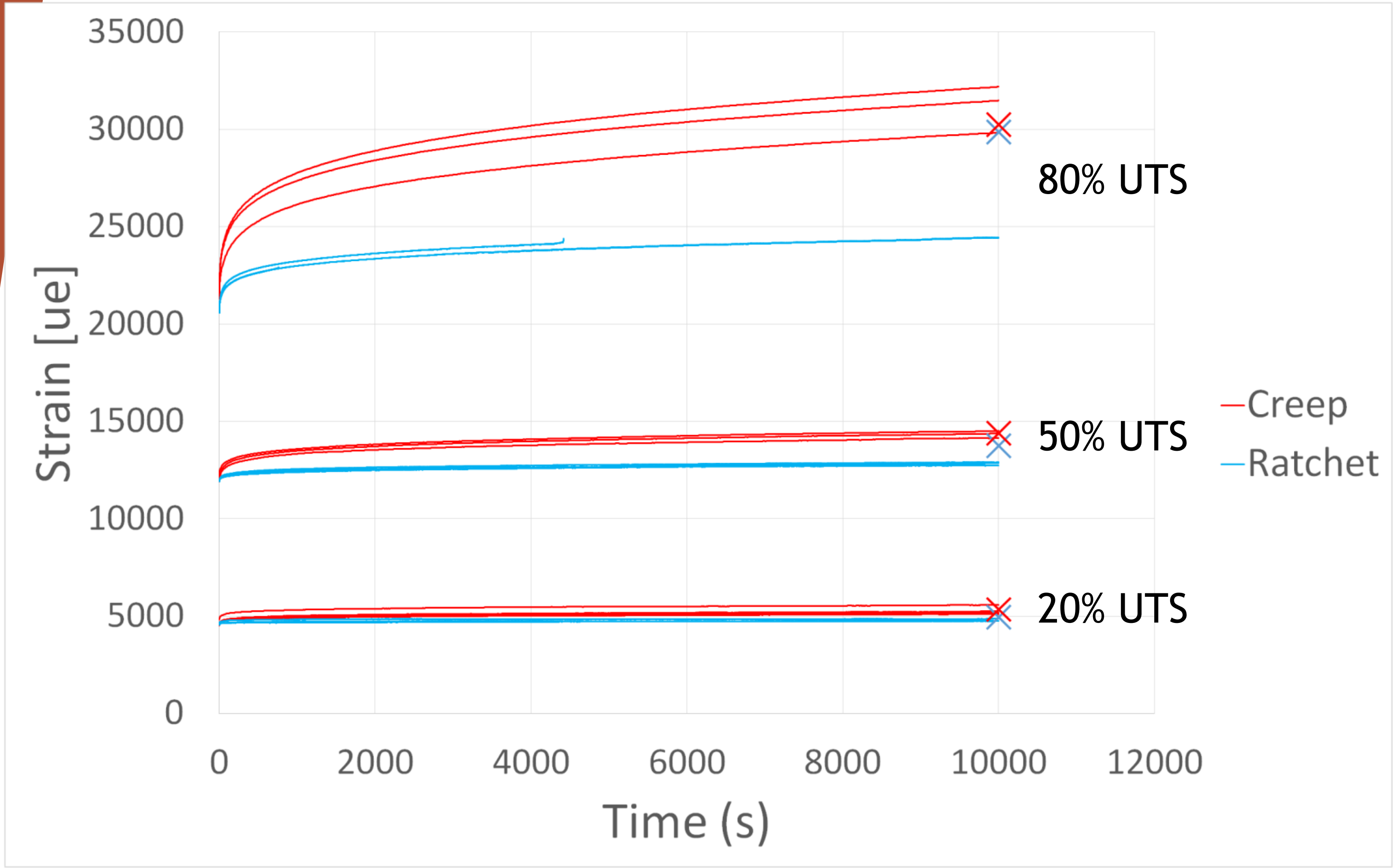
5/22/19

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

- 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
  - Explore cyclic response of adhesive joints.
  - Develop predictive models describing adhesive time and plastic response.
- Approach
  - Experiments designed to clarify constitutive relations.
  - Develop FEA Models of adhesive bonds.
  - Compare models with experiments that are unlike constitutive tests.

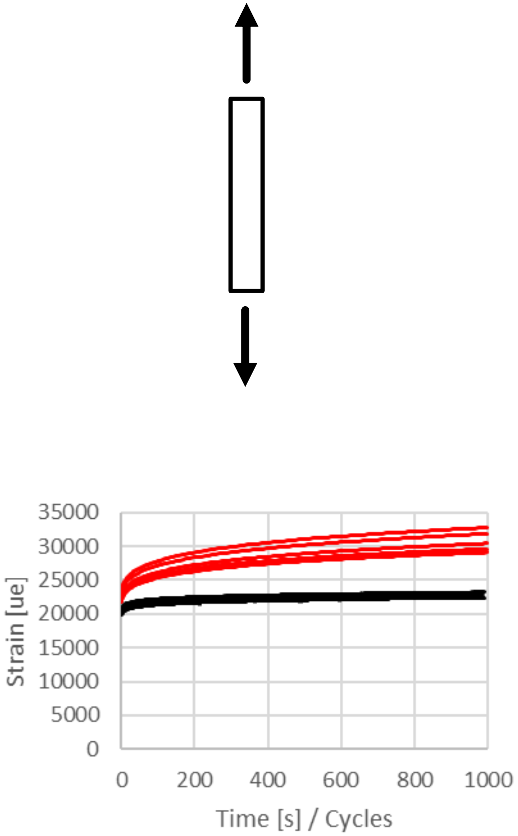
Review: Bulk Coupon, EA9696

Ratcheting triangle wave

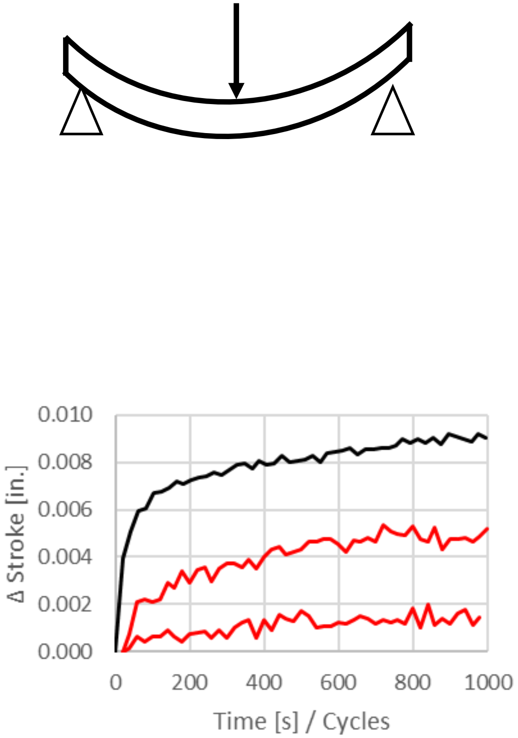


Viscoelastic Response in Shear

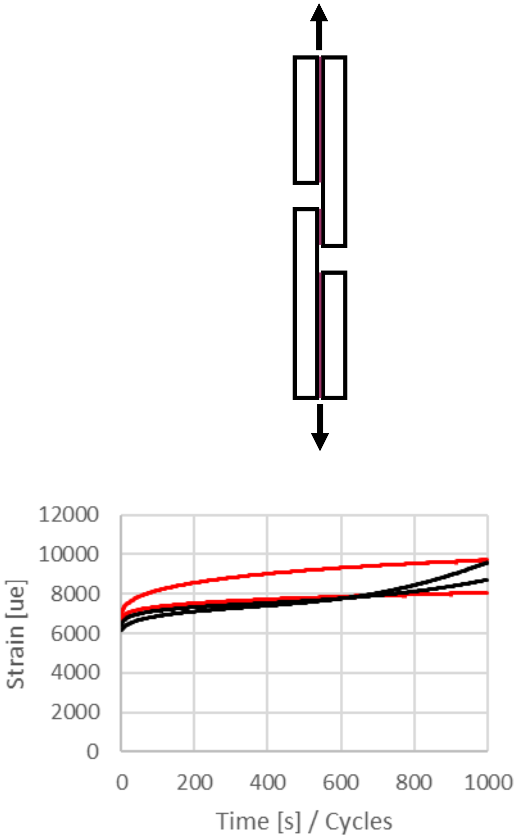
Bulk Tension



End Notch Flexure
(unnotched)



Wide Area Lap Shear

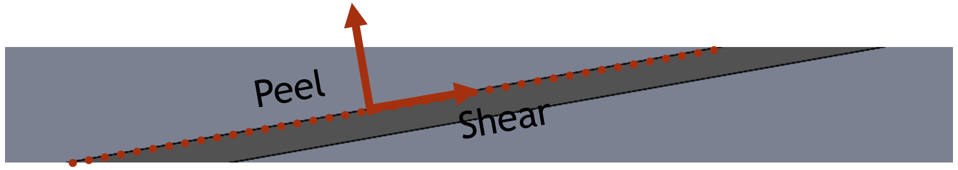


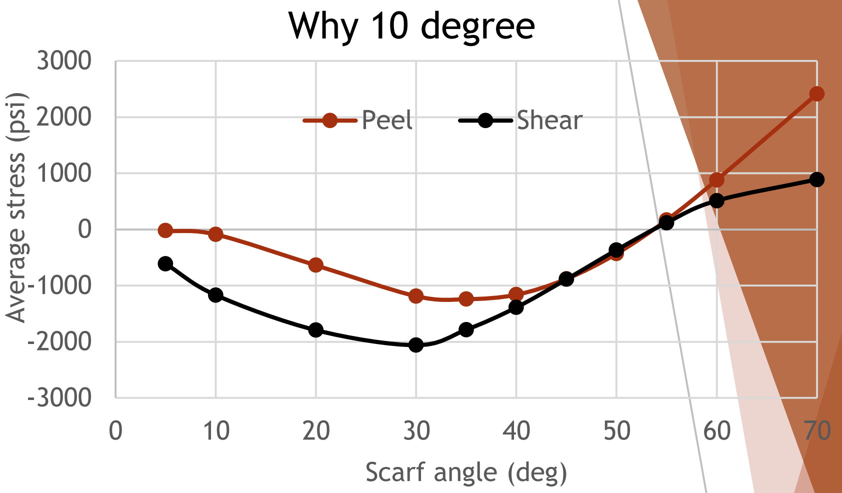
🟥 Creep
■ Ratchet

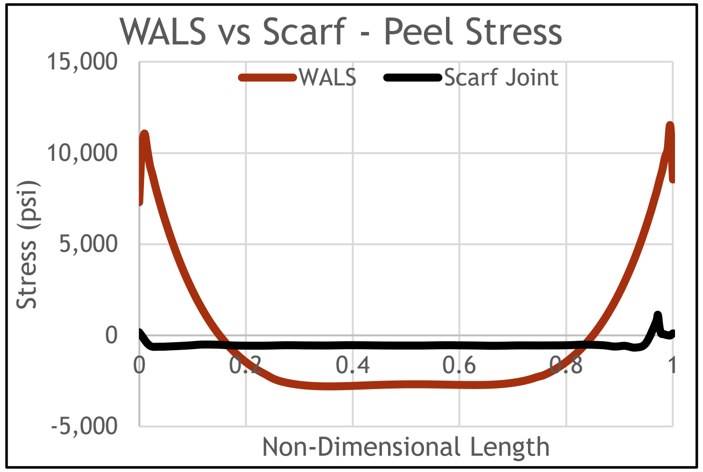
Why Scarf Joint?

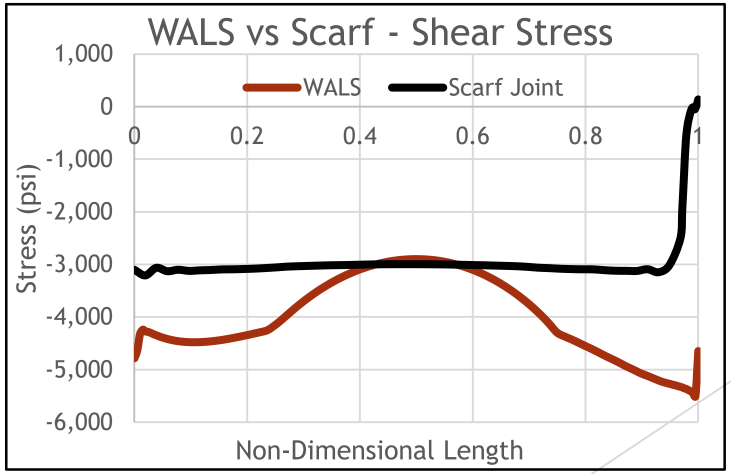
FEA Results :

- Scarf has no load eccentricity
- Scarf has a uniform distribution of shear stress
- Scarf has minimal peel stress



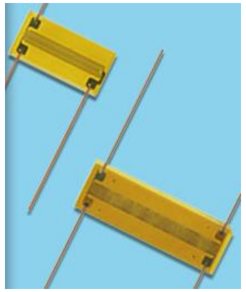




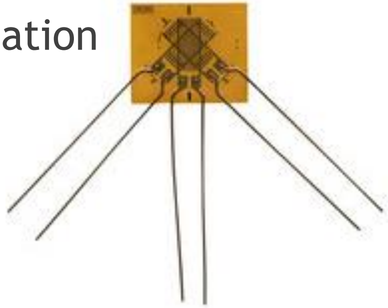


Measuring Cyclic strain

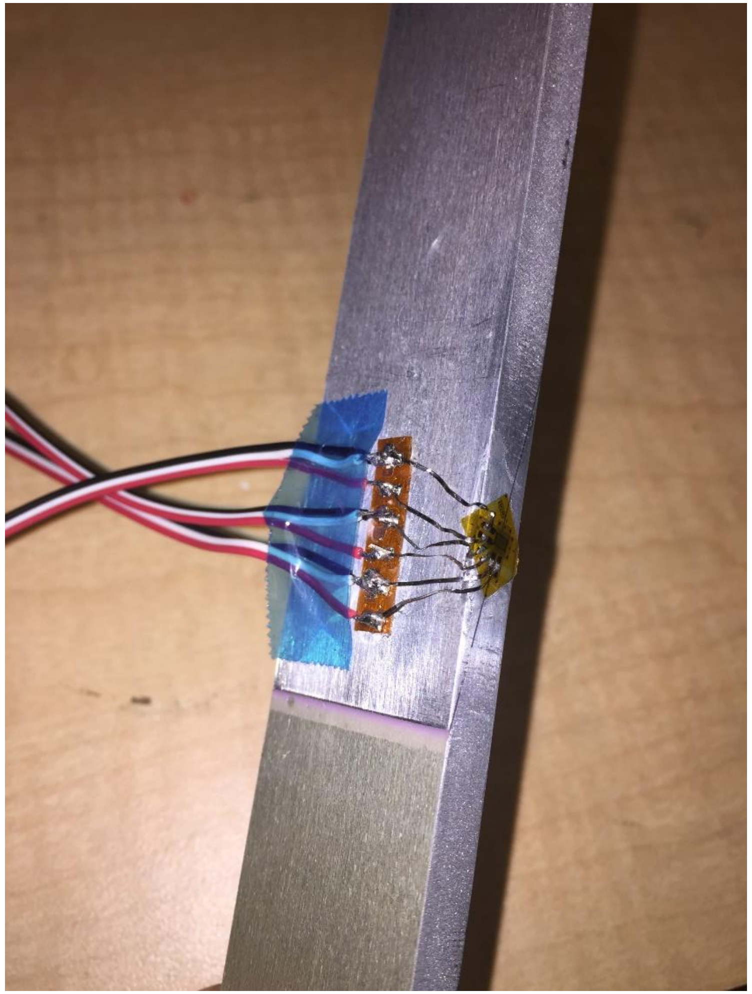
- Thin bond prevents traditional direct methods
- Extensometer tends to drift with cyclic loading
- DIC is computationally expensive
- Shear modulus gage not available



- Considered a stacked rosette
  - Maximum strain not sensitive to gage orientation

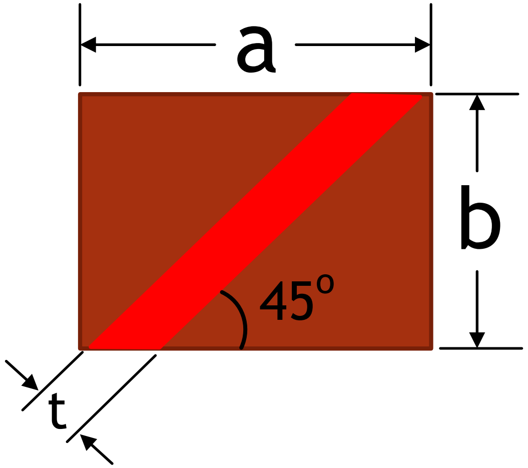


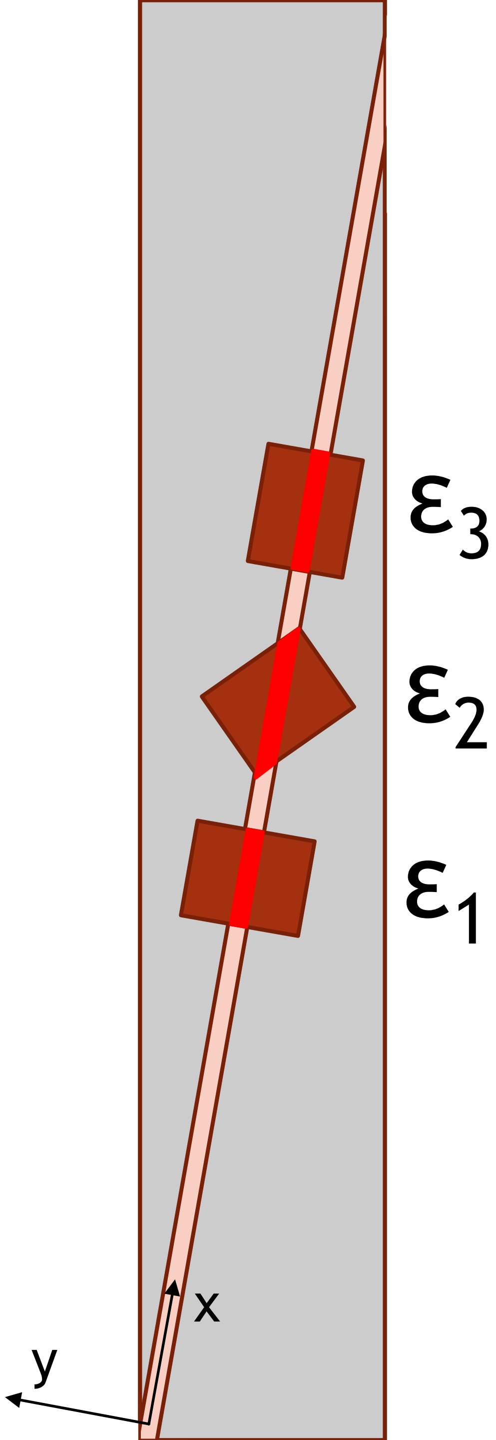
Scarf Coupon
EA9696



Strain Modifications

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



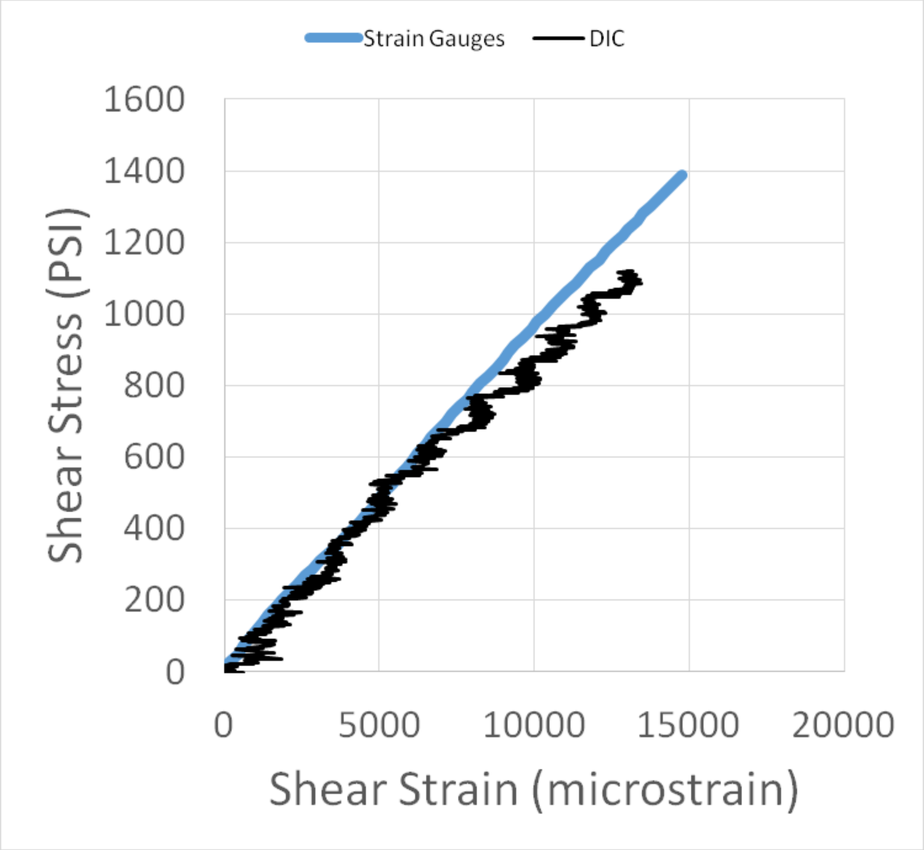


$$\varepsilon'_1 = \varepsilon_1 a/t \qquad \varepsilon'_2 = \varepsilon_2 a\cos(45^{o})/t \qquad \varepsilon'_3 = \varepsilon_3 b/t$$

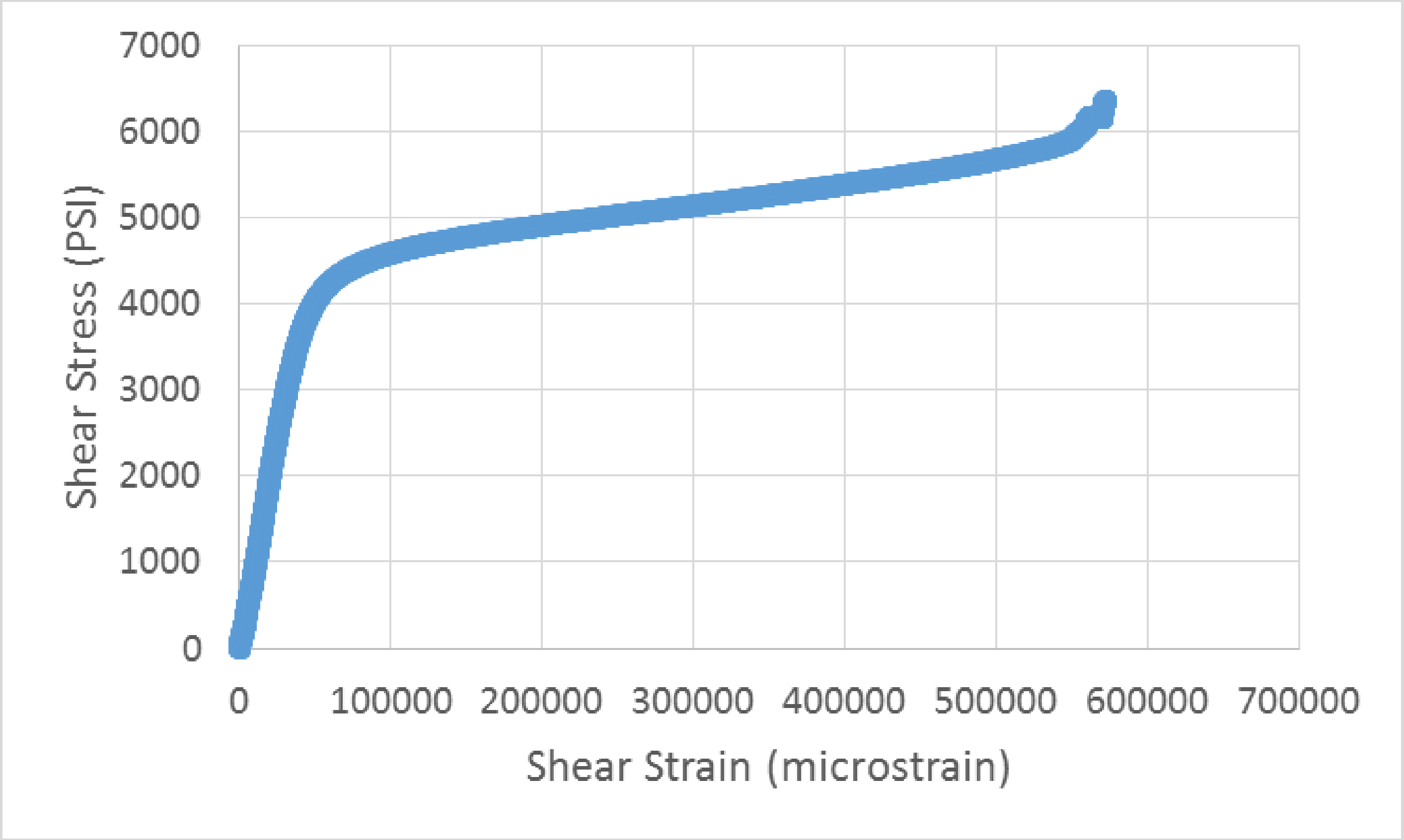
$$\gamma_{xy} = 2\varepsilon'_2 - \varepsilon'_1 - \varepsilon'_3$$

Monotonic Testing Results

- Ultimate Shear Strength (USS): 6 ksi
- Adhesive Shear Modulus: 88.5 ksi
  - Verified through digital imaging correlation

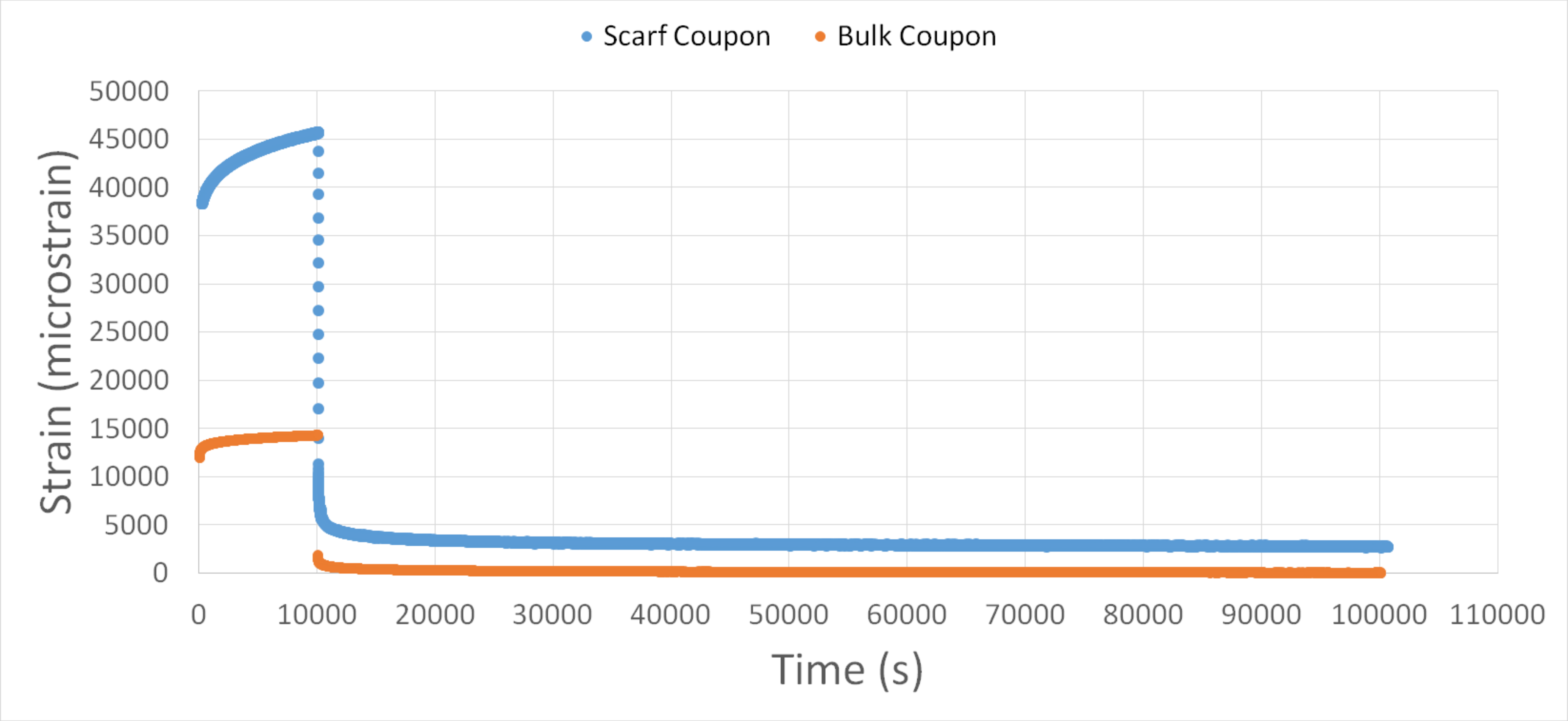


Elastic Region



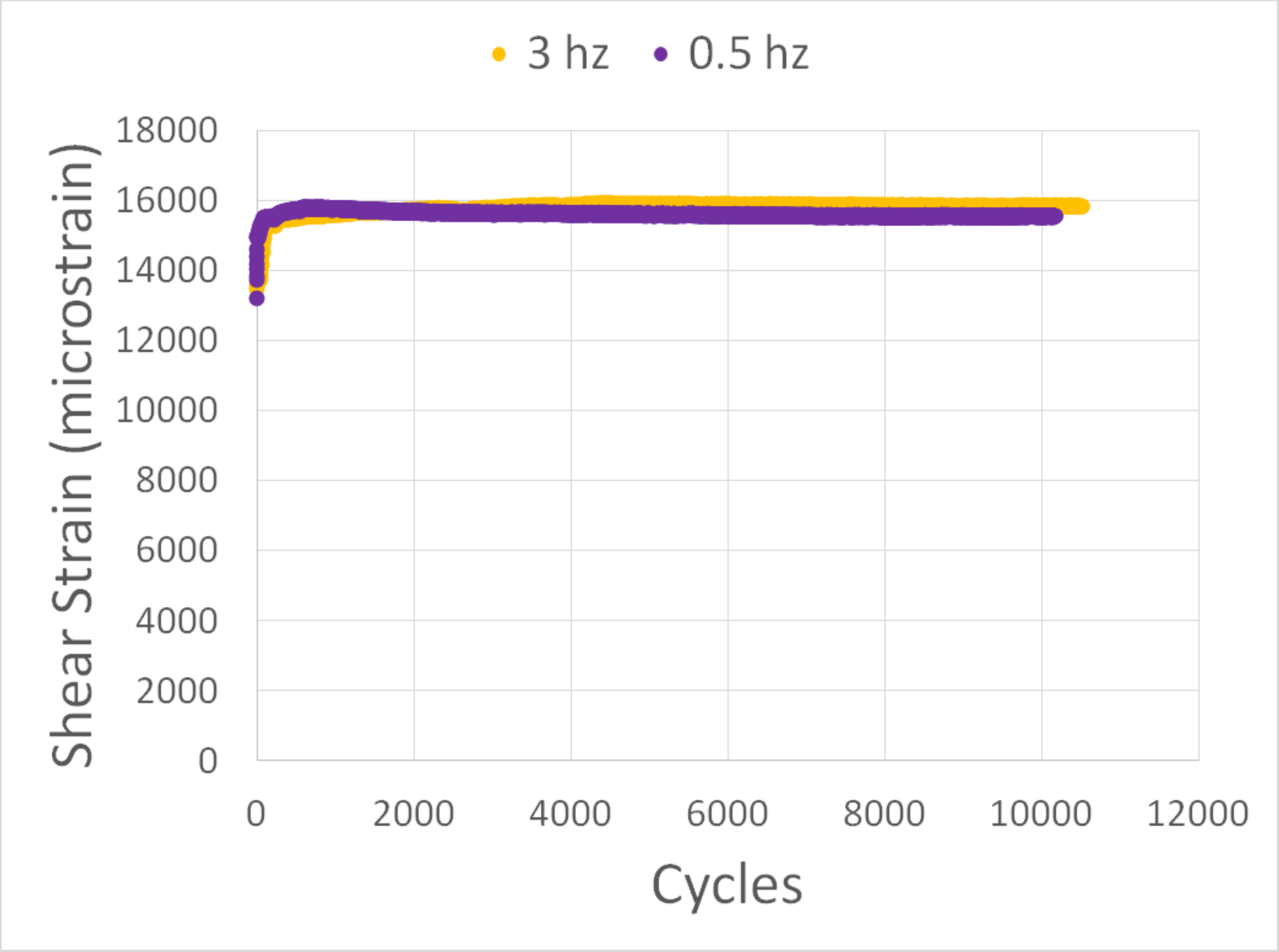
Creep Testing

- 50% USS

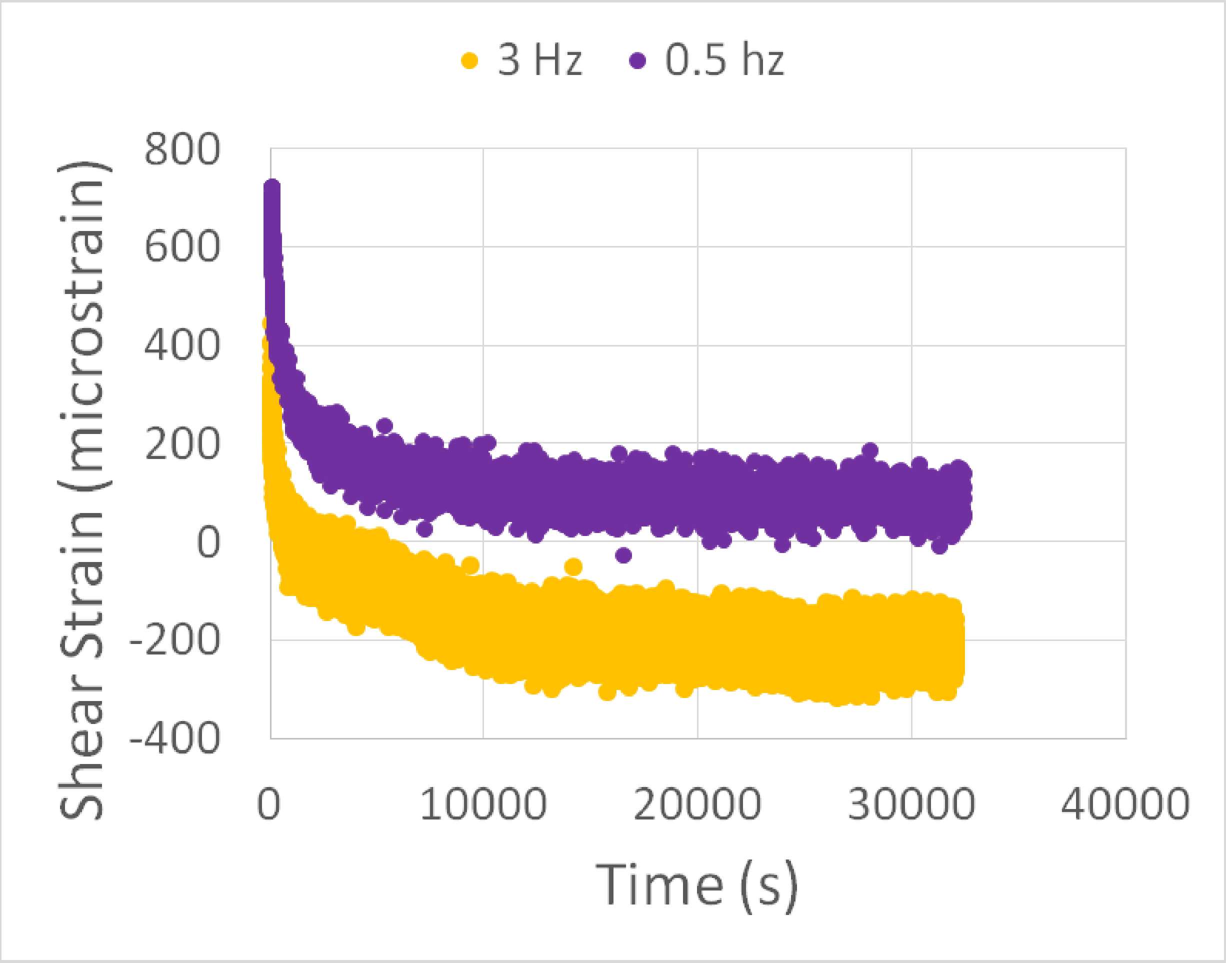


Change in Frequency

- 20% USS
- 0.1 R
- Sine Wave



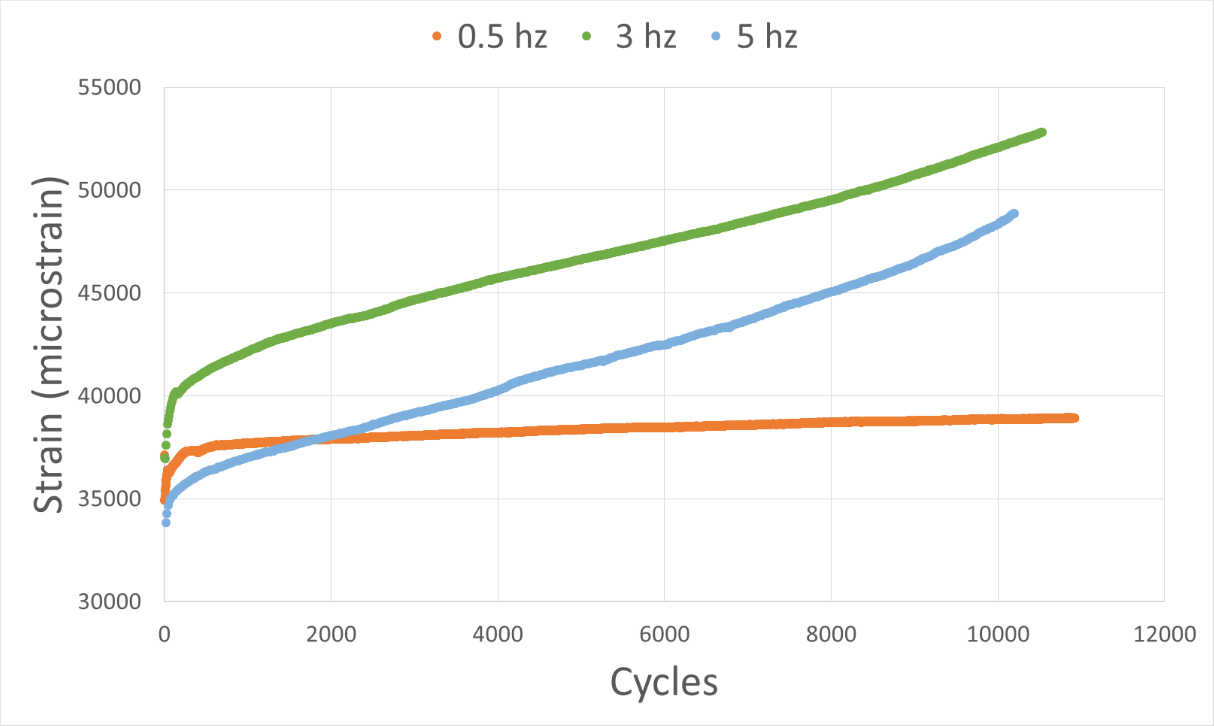
Ratcheting



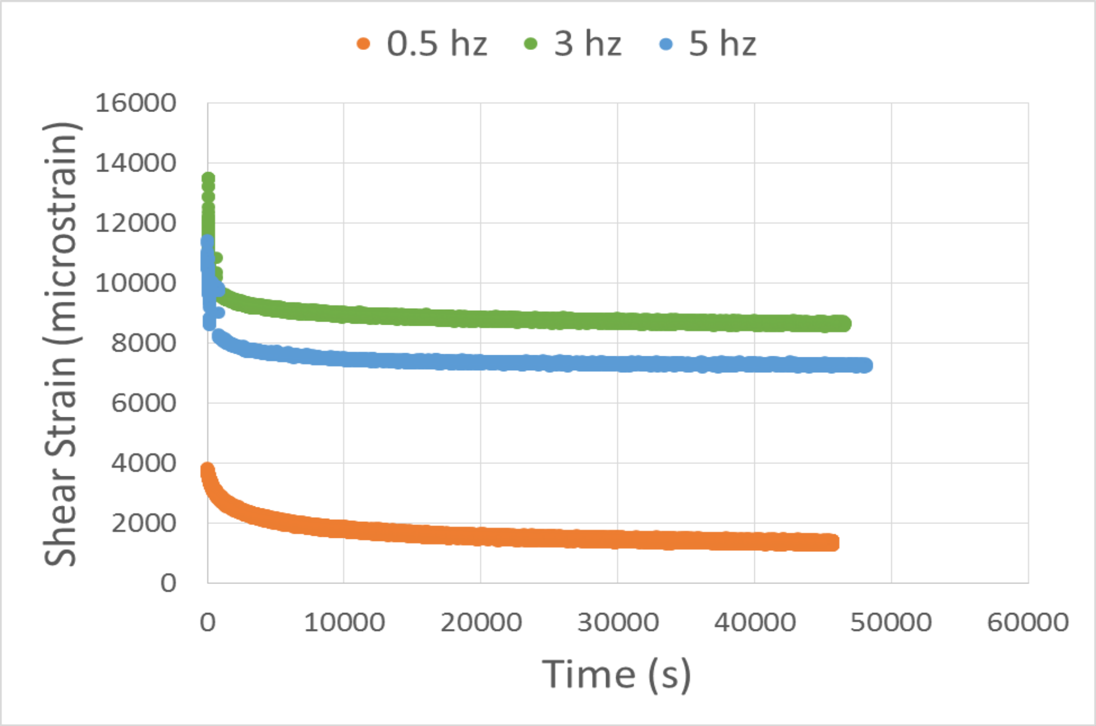
Recovery

Change in Frequency

- 50% USS
- Sine Wave
- 0.1 R



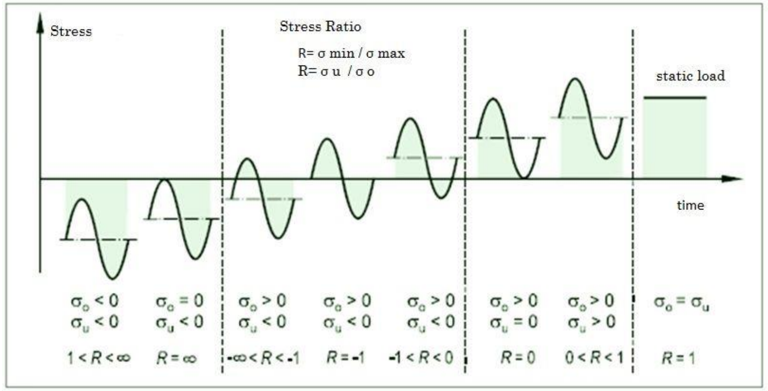
Ratcheting

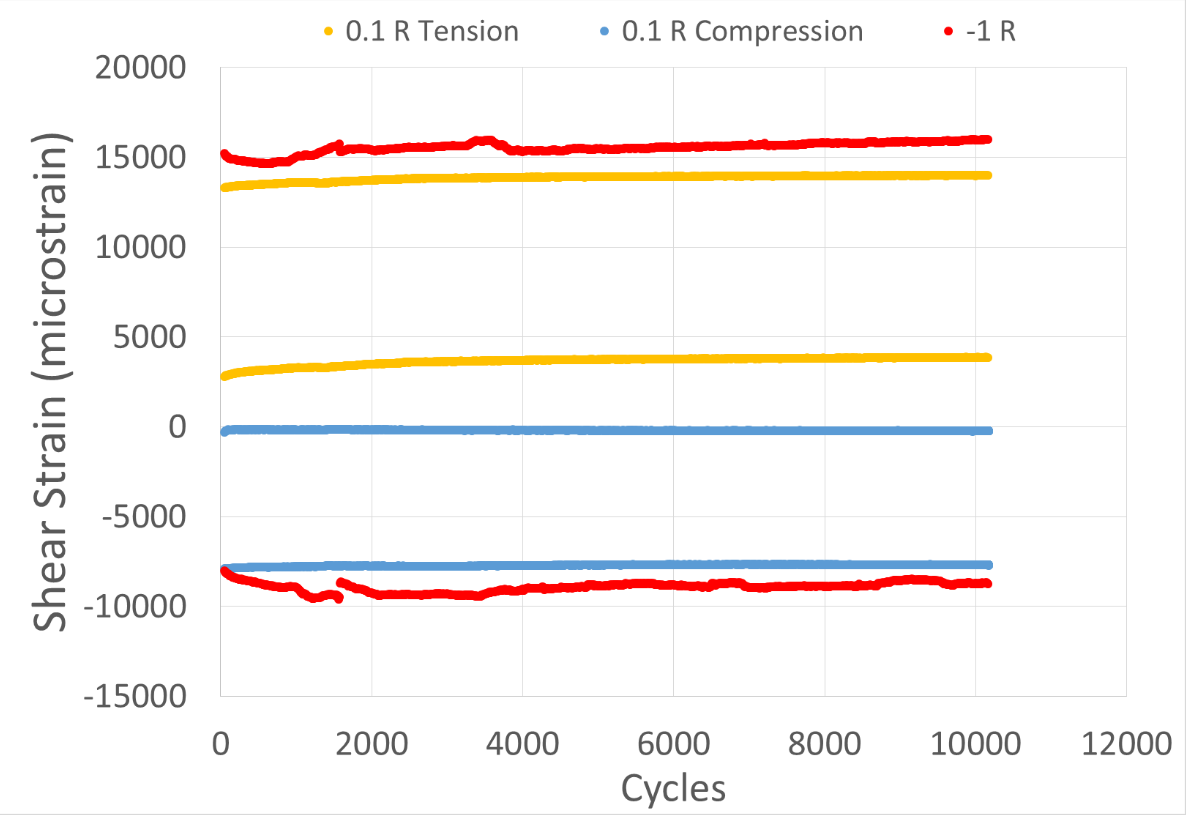


Recovery

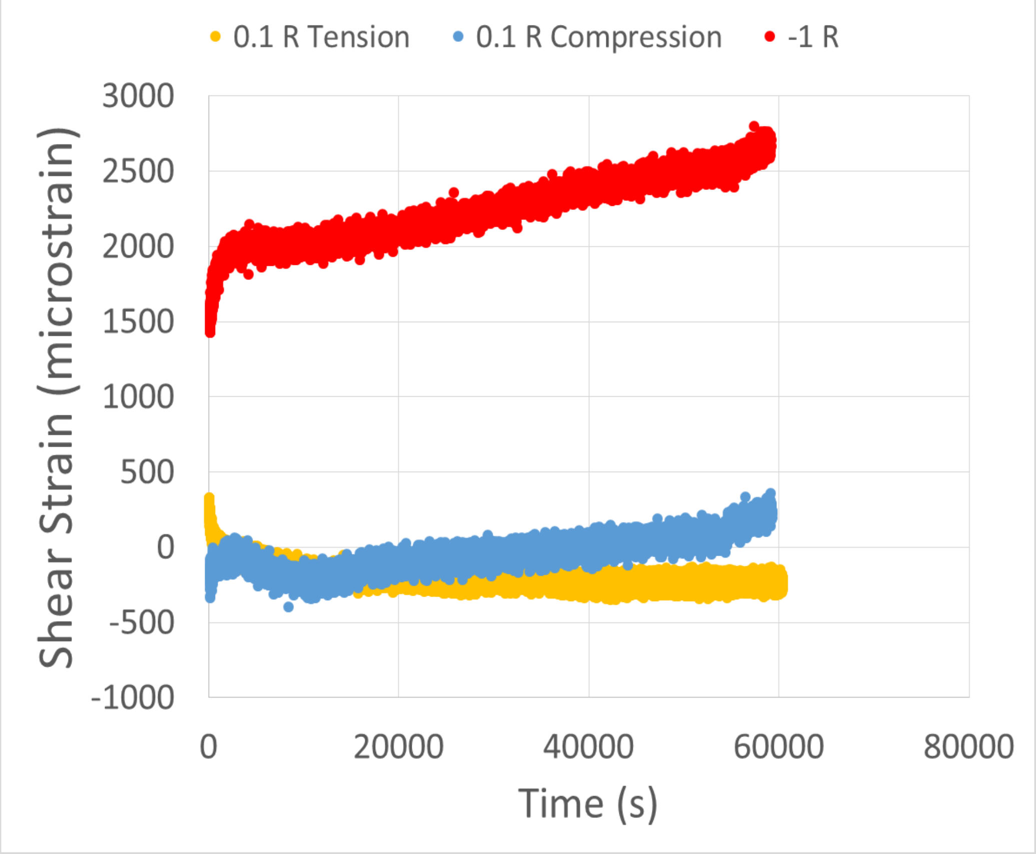
Change in R Ratio

- 20% USS
- 3 Hz
- Sine Wave





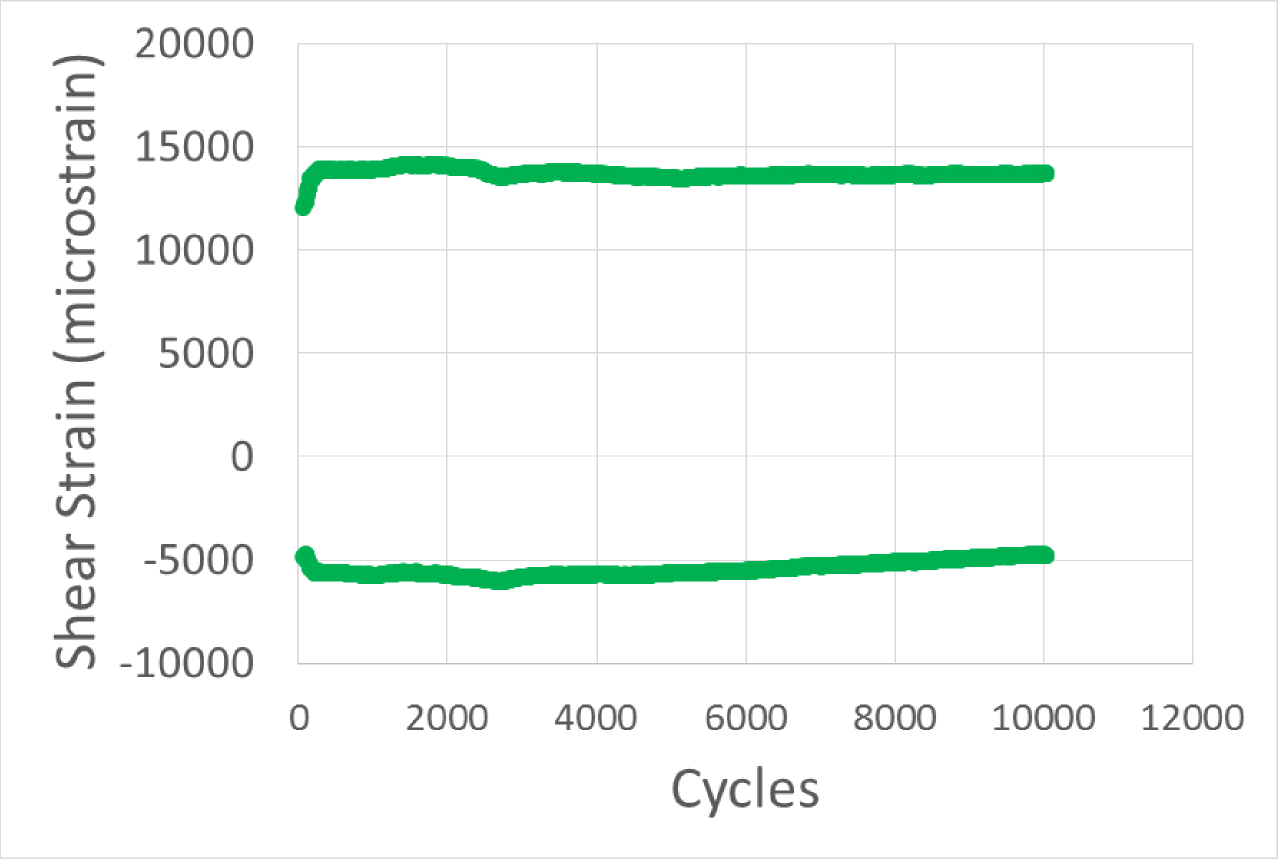
Ratcheting



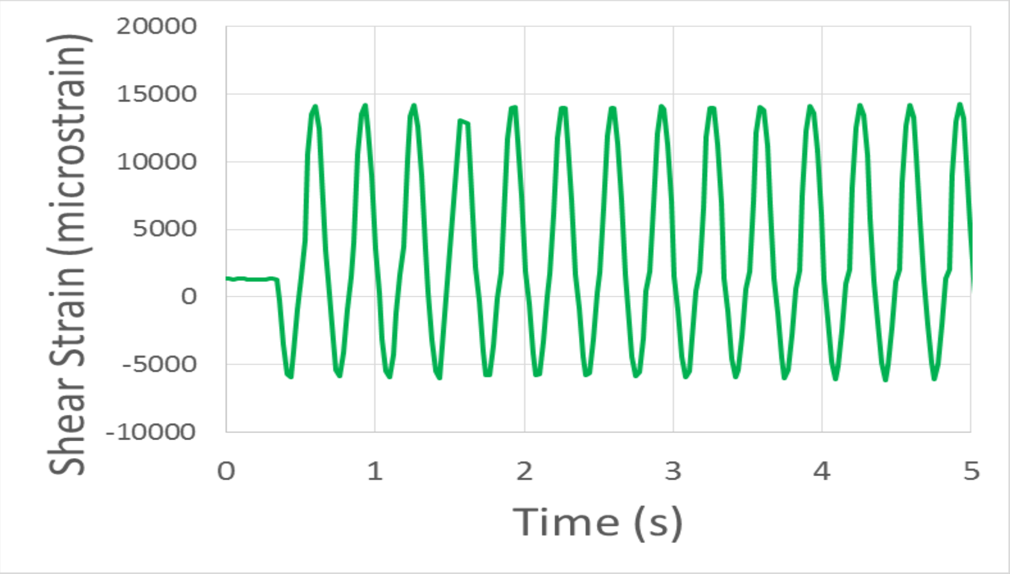
Recovery

Inverted Sine Wave

- 20% USS
- 3 Hz
- -1 R



Ratcheting



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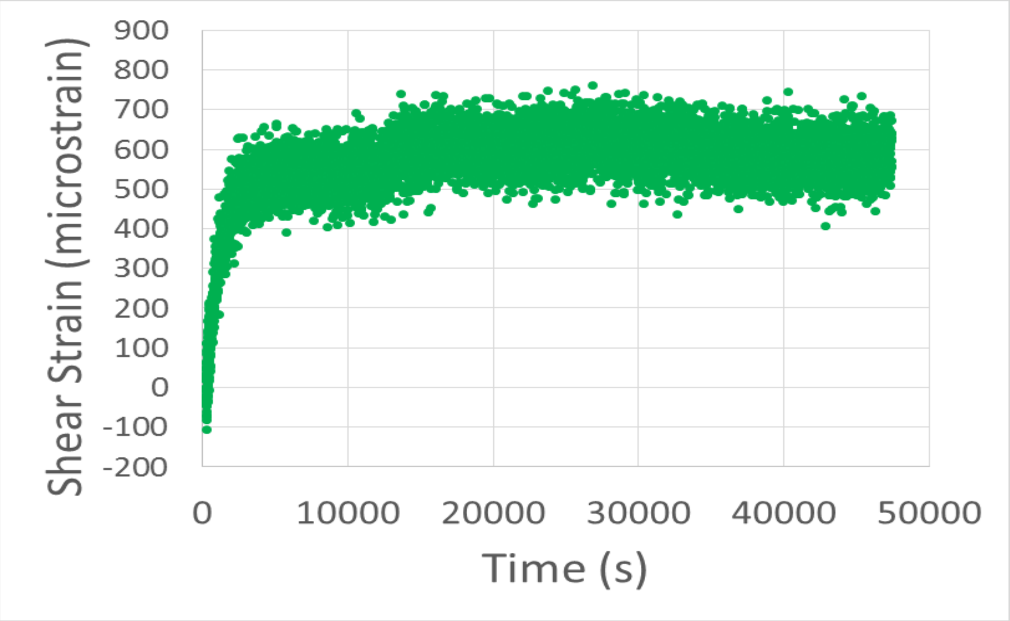
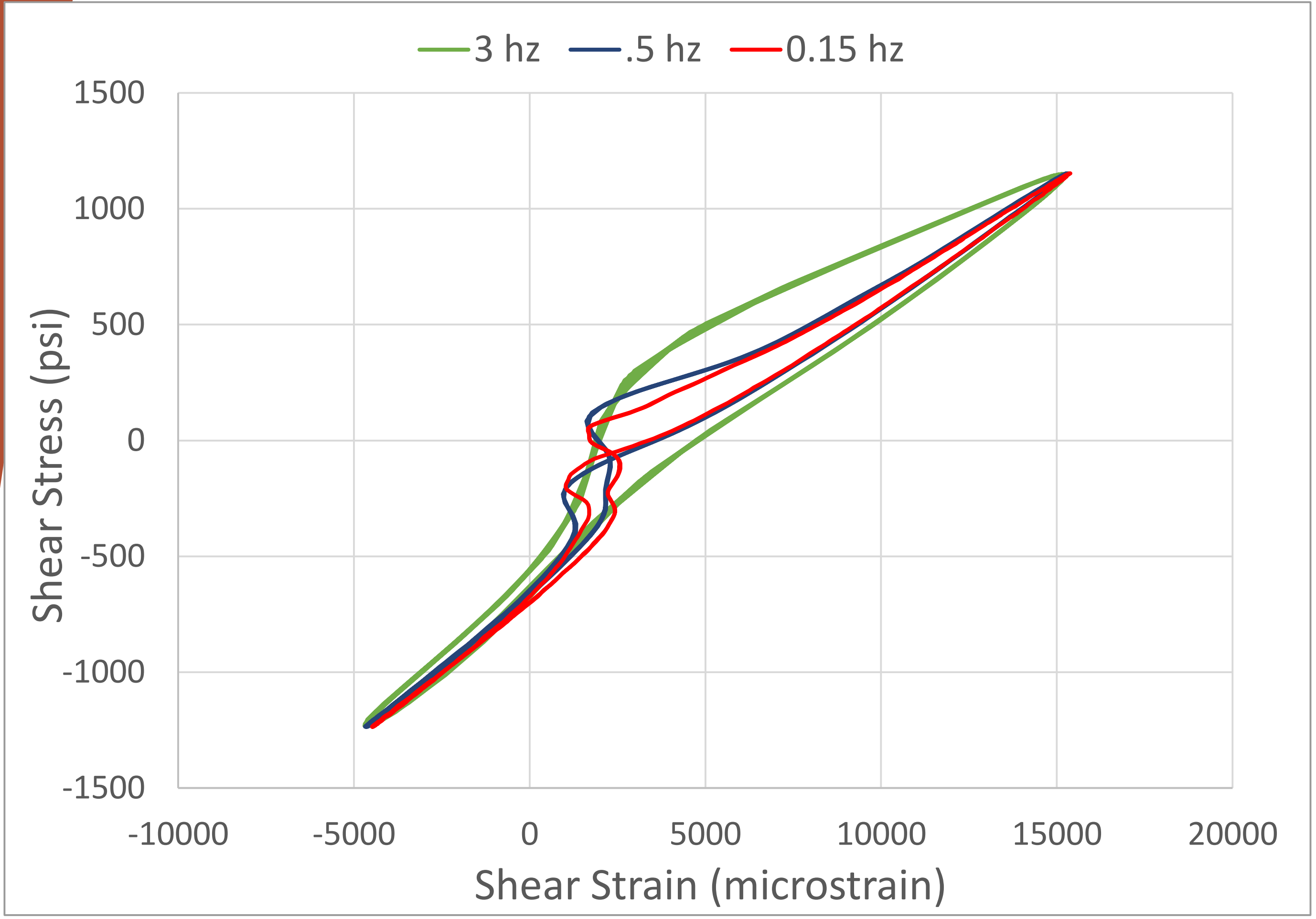


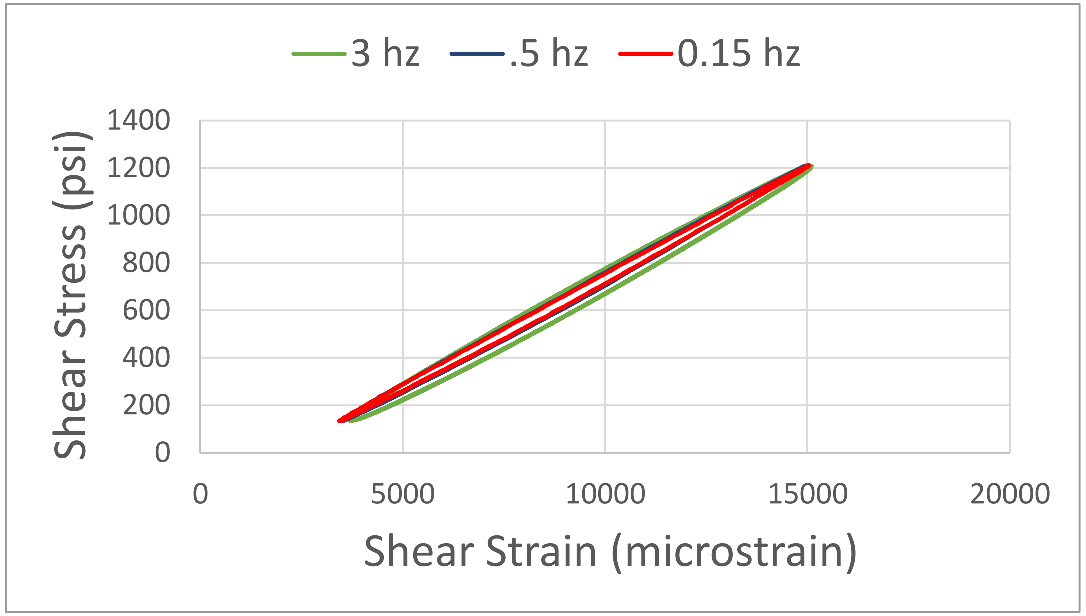
Recovery

Stress-Strain Hysteresis Loop

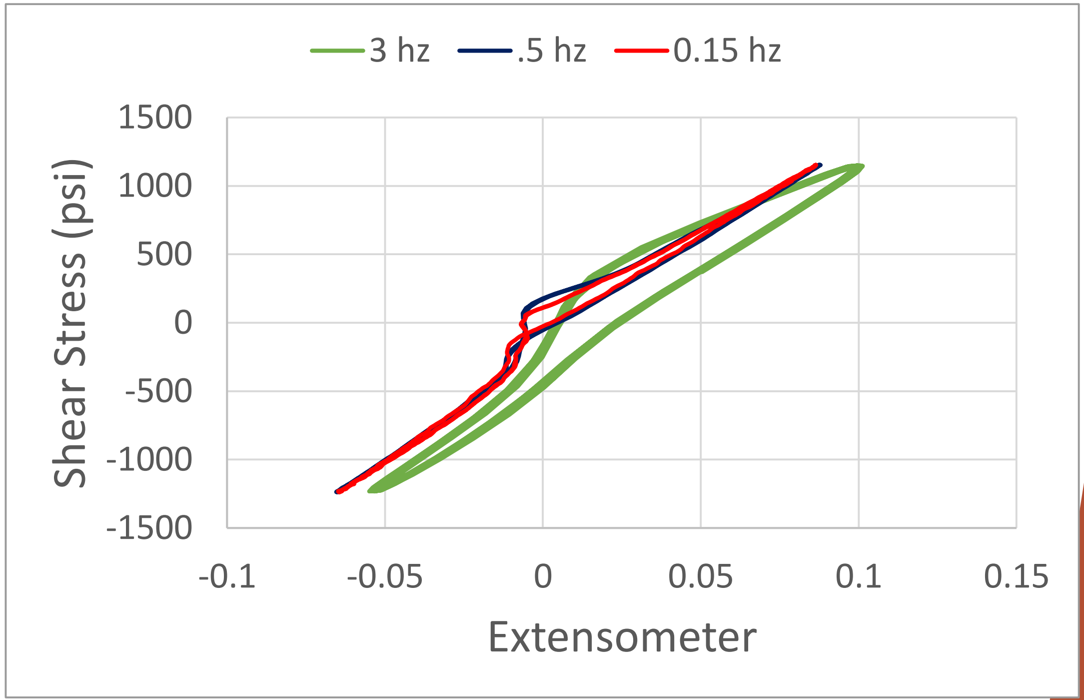
- 20% USS
- Sine Wave



-1 R



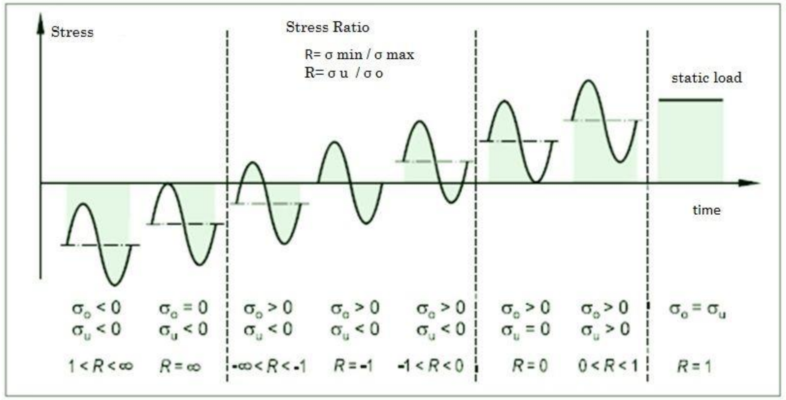
0.1 R

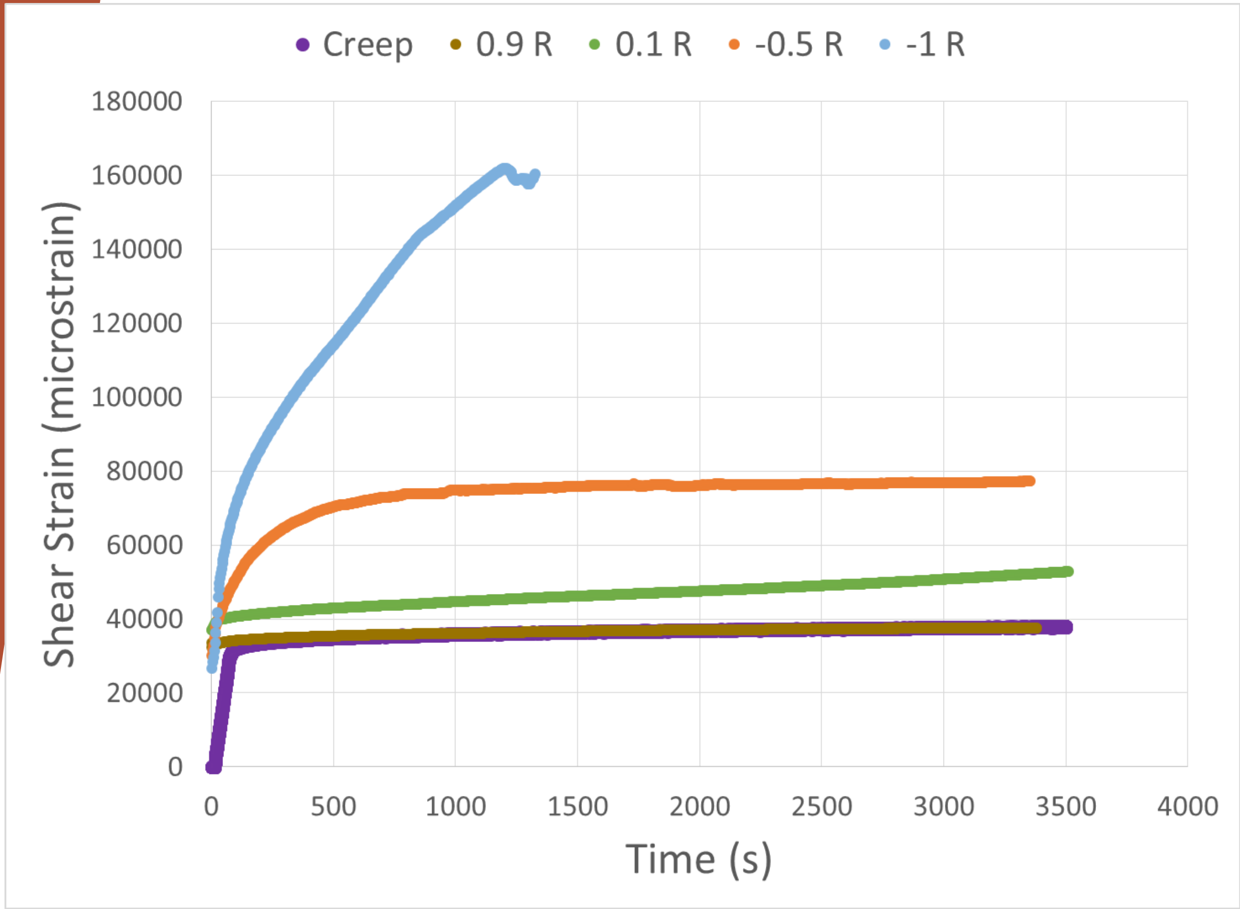


-1 R

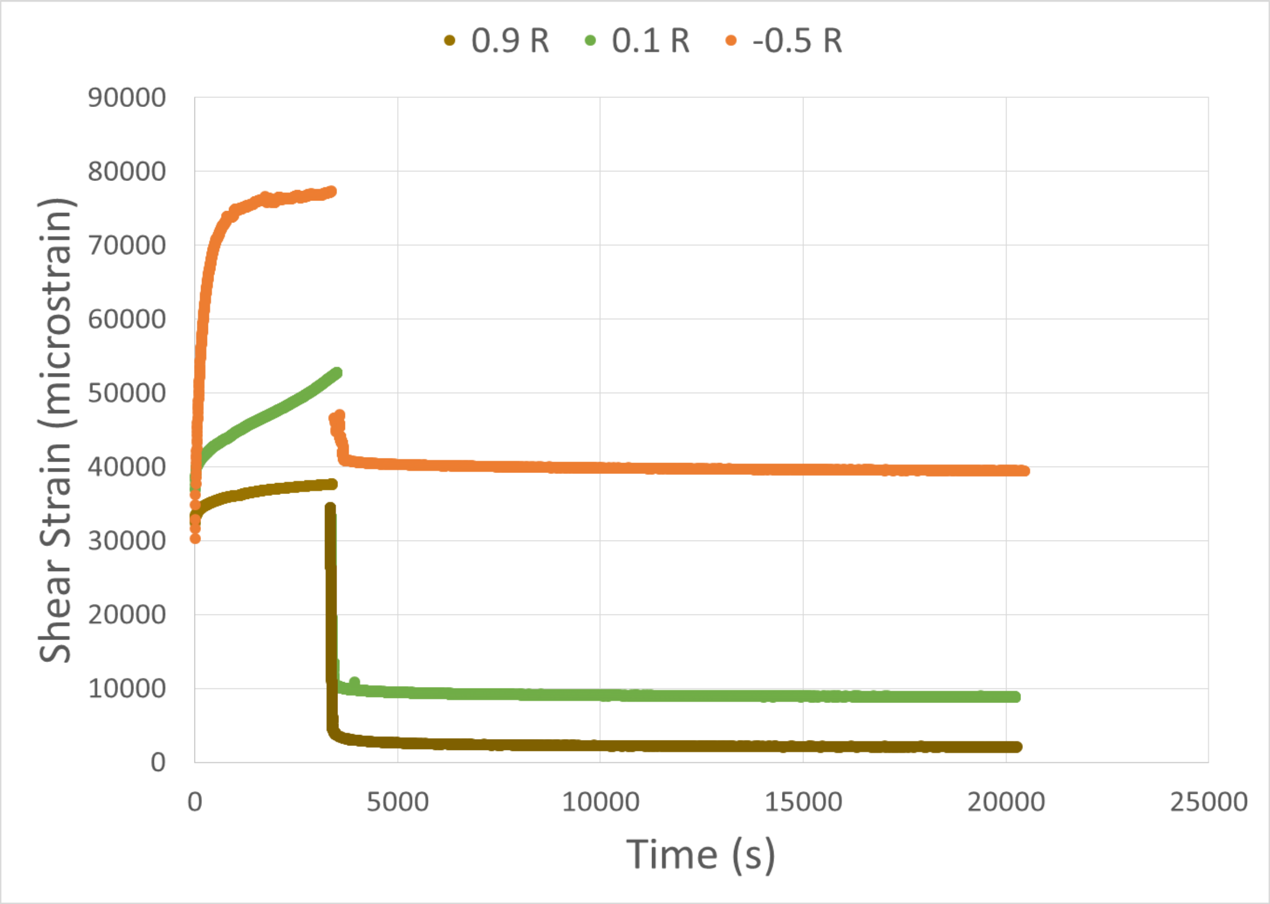
Change in R Ratio

- 50% USS
- Sine Wave
- 3 Hz





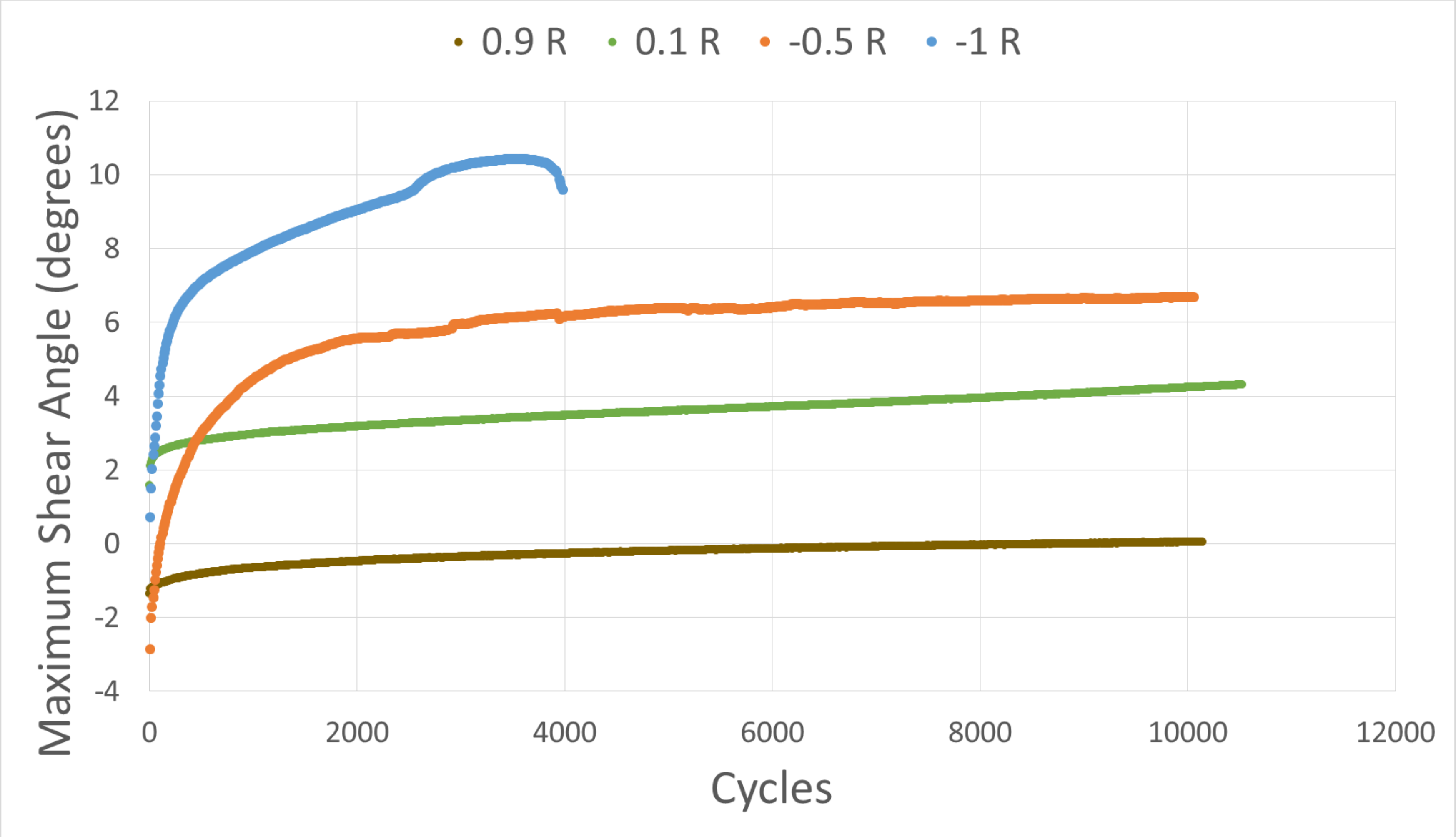
Ratcheting

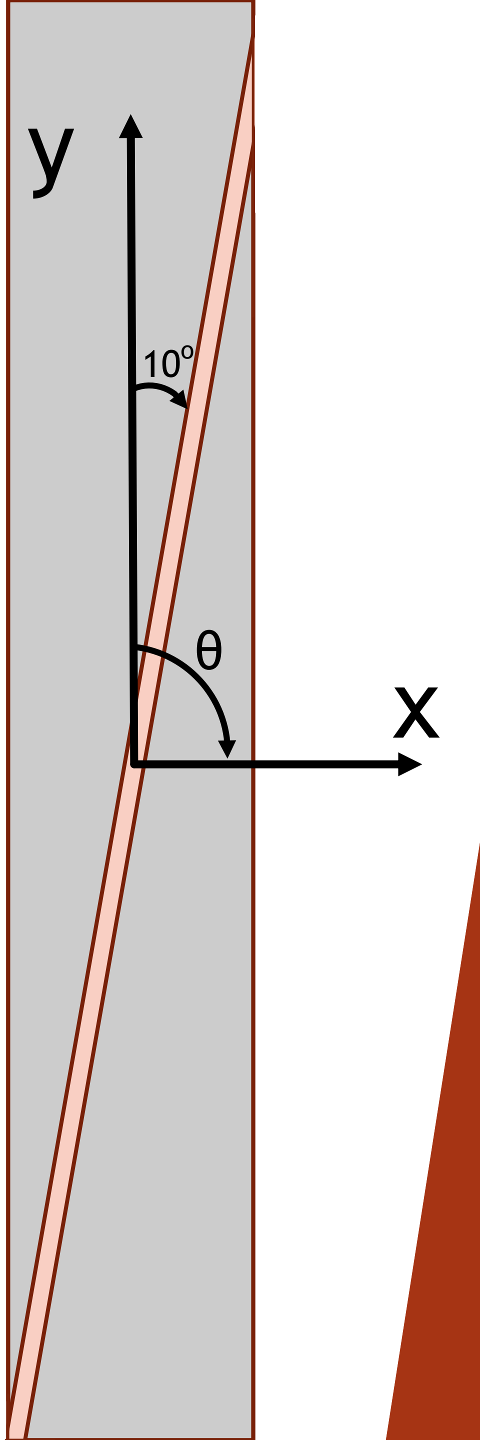


Ratcheting and Recovery

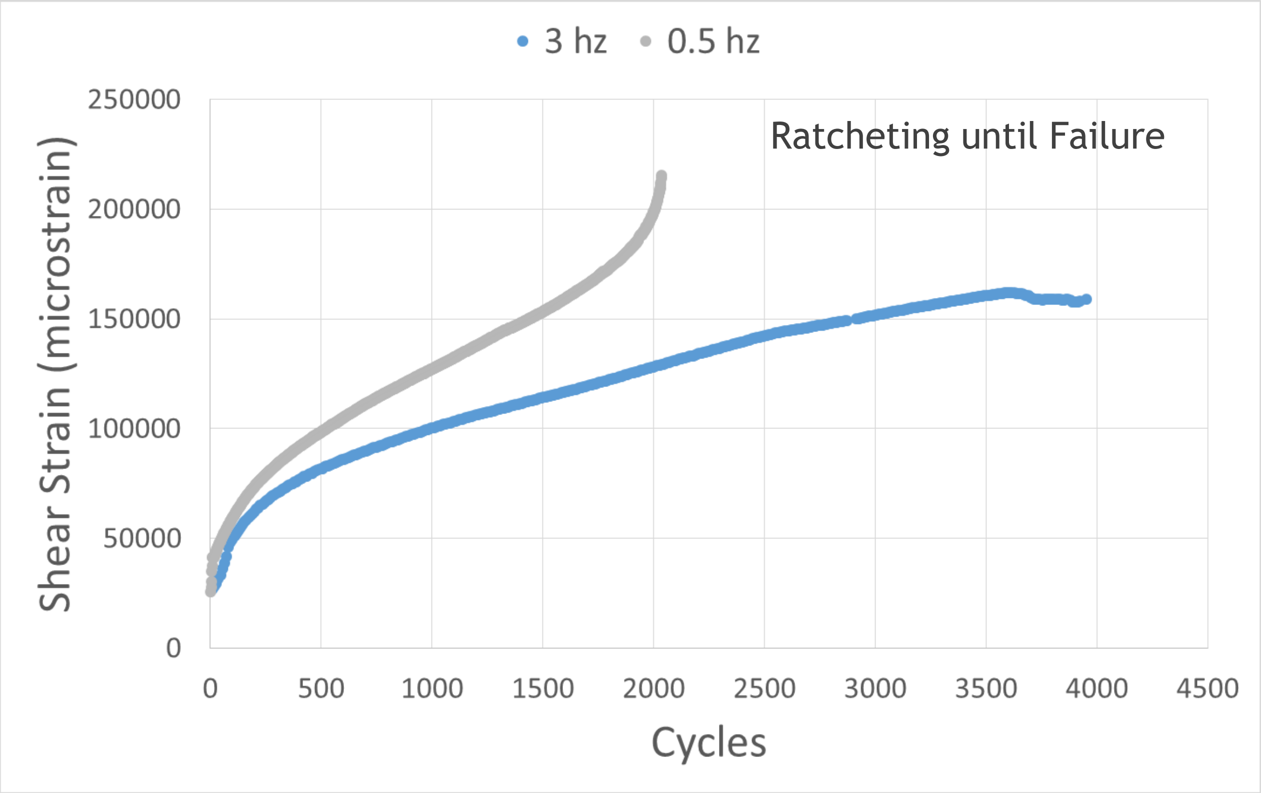
Maximum Shear Angle

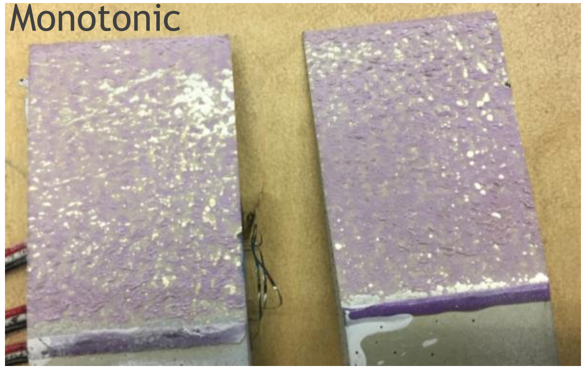
- 50% USS
- Sine Wave
- 3 Hz

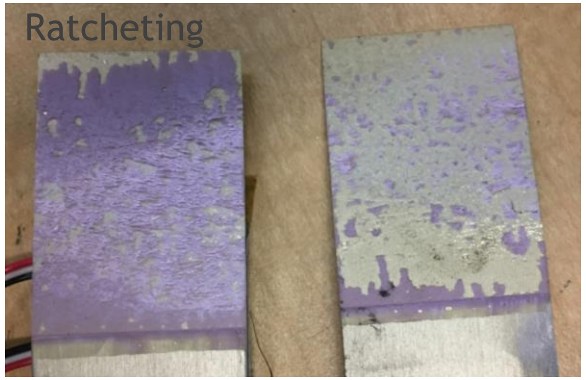


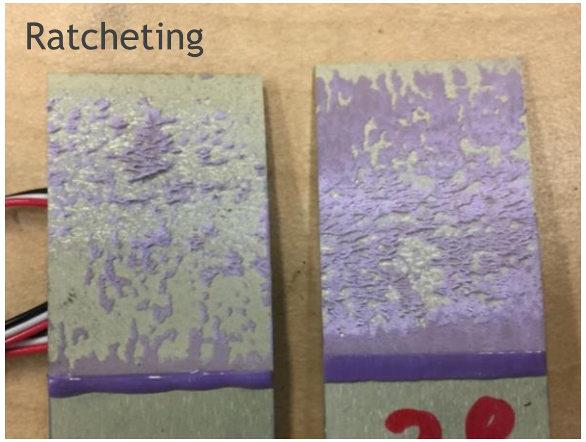


50% USS
-1 R




Monotonic


Ratcheting


Ratcheting

Questions

- 50% UTS, R=0.1 (compression)
  - Similar cyclic and permanent strain as in tension?
- Do WALS coupons have response similar to scarf joints?
  - They also have tension at free edges
- Is strain growth associated with material softening (i.e. damage)?
  - We can now measure modulus during a cyclic test
- Is the maximum shear angle a measure of damage?
  - We need more data
- What can the failure surface tell us?
  - Adhesive failure vs. primer failure

Test Matrix

EA9696   0.1 R   10,000 Cycles

		Frequency (Hz)		
		0.05	3.00	5.00
Stress (% Ultimate Shear Strength)	80%	0/3	0/3	0/3
	50%	2/3	2/3	1/3
	20%	1/3	2/3	

EA9696   3 Hz 10,000 Cycles

		R ratio			
		-1.00	-0.50	0.10	0.90
Stress (% Ultimate Shear Strength)	50%	2/3	1/3	2/3	1/3
	20%	3/3		2/3	

FM300-2   0.1 R 10,000 Cycles

		Frequency (Hz)		
		0.05	3.00	5.00
Stress (% Ultimate Shear Strength)	80%	0/3	0/3	0/3
	50%	0/3	0/3	0/3
	20%	0/3	0/3	

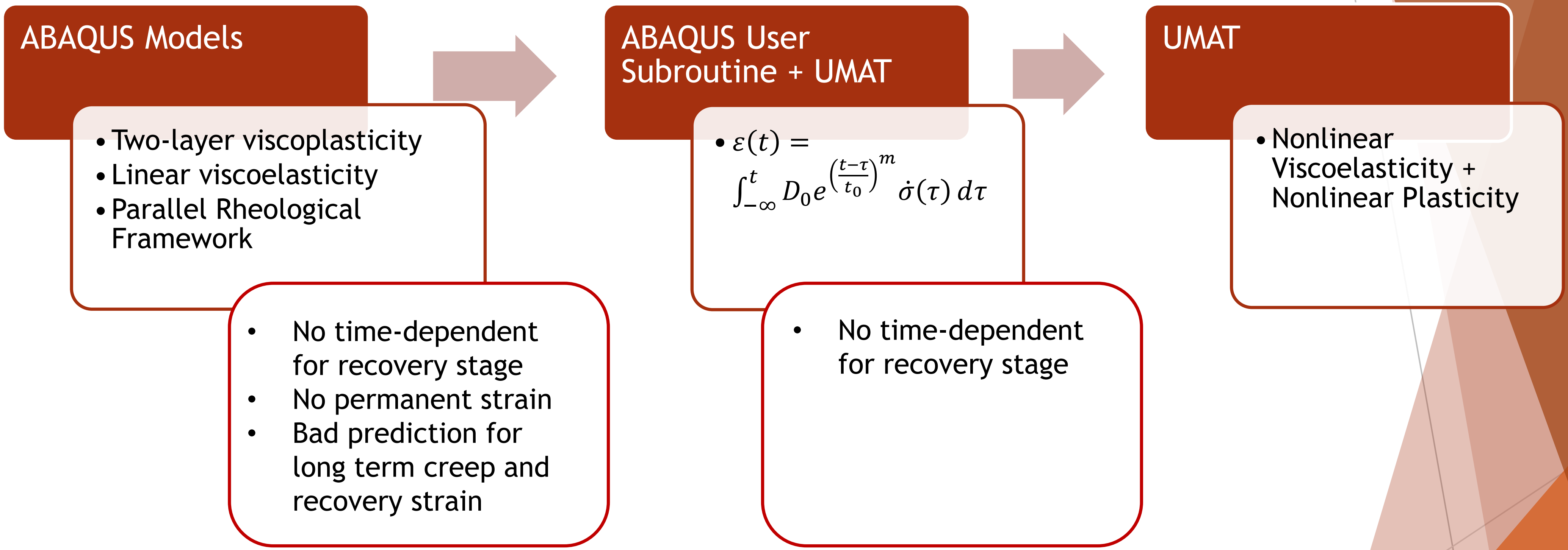
FM300-2   3 Hz   10,000 Cycles

		R ratio			
		-1.00	-0.50	0.10	0.90
Stress (% Ultimate Shear Strength)	50%	0/3	0/3	0/3	0/3
	20%	0/3		0/3	

🟩 Finished	🟨 In Progress	🟧 Not Started

Nonlinear Viscoplastic Model

- **History Models**



ABAQUS Models

- Two-layer viscoplasticity
- Linear viscoelasticity
- Parallel Rheological Framework

- No time-dependent for recovery stage
- No permanent strain
- Bad prediction for long term creep and recovery strain

ABAQUS User Subroutine + UMAT

- $\varepsilon(t) = \int_{-\infty}^{t} D_0 e^{\left(\frac{t-\tau}{t_0}\right)^m} \dot{\sigma}(\tau)\, d\tau$

- No time-dependent for recovery stage

UMAT

- Nonlinear Viscoelasticity + Nonlinear Plasticity

Popular Nonlinear Viscoplastic Models

Viscoplastic Models Comparison

- **Raghava Model**

$$f = \frac{(\eta-1)I_1 + \sqrt{(\eta-1)^2 I_1^2 + 12\eta J_2}}{2\eta} - \sigma_t - R(k)$$

η – viscosity parameter
σ_t - yield stress in uniaxial tension
$R(k)$ - hardening rule

- **Zapas- Crissman Model**

$$\varepsilon^{vp} = \left(C \int_0^t \sigma^N \, d\tau\right)^M$$

C, N, M – temperature dependent parameters

- Both models had limited ability to describe plasticity.

Nonlinear Viscoplastic Model

Total Strain:

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

VE- Schapery Model

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

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

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

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, here this project has 7 branches in Prony (i.e. n=7)

Nonlinear Viscoplastic Model

VP- Perzyna Model

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

Where,

η – viscosity parameter

N - constant

- ***f* yield stress**

Model 1:

$$f = \tau - \alpha I_1 - \kappa\left(\varepsilon_e^{vp}\right) = \sqrt{\frac{3}{2}S_{ij}S_{ij}} - \alpha I_1 - \kappa\left(\varepsilon_e^{vp}\right)$$

$$\kappa\left(\varepsilon_e^{vp}\right) = \kappa_0 + \kappa_1\left(1 - e^{-k\varepsilon_e^{vp}}\right)$$

Model 2:

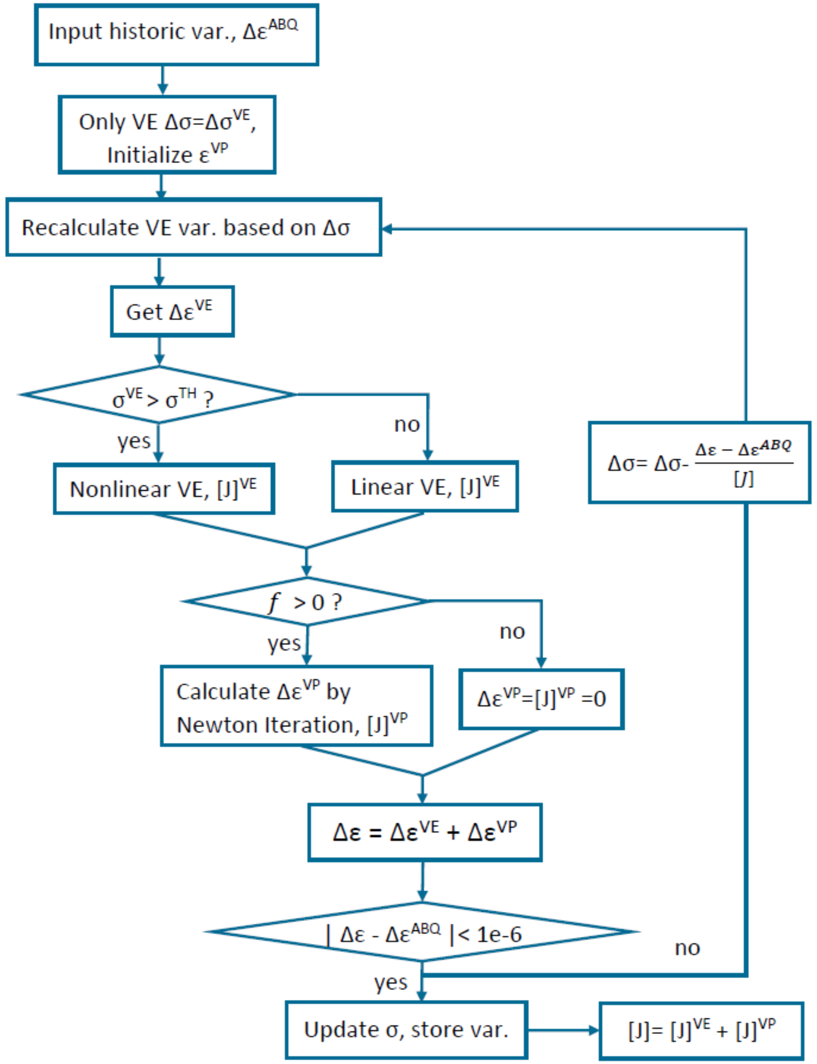
$$f = \sigma_e - \sigma_y^0 = \sqrt{\frac{3}{2}\left(S_{ij} - \alpha\right)\left(S_{ij} - \alpha\right)} - \sigma_y^0$$

$$\alpha = \frac{c}{k}\left(1 - e^{-k\varepsilon_e^{vp}}\right)$$

	Yield Surface	Hardening	Associated/Non Associated
Model 1	Drucker-Prager	Nonlinear Isotropic	Associated (f=g)
Model 2	Von Mises	Nonlinear Kinematic	Associated (f=g)

Nonlinear Viscoelastic-Viscoplastic Model

- **Flowchart**



Input historic var., $\Delta\varepsilon^{ABQ}$

Only VE $\Delta\sigma=\Delta\sigma^{VE}$, Initialize ε^{VP}

Recalculate VE var. based on $\Delta\sigma$

Get $\Delta\varepsilon^{VE}$

$\sigma^{VE} > \sigma^{TH}$?

yes

no

Nonlinear VE, $[J]^{VE}$

Linear VE, $[J]^{VE}$

$\Delta\sigma = \Delta\sigma - \frac{\Delta\varepsilon - \Delta\varepsilon^{ABQ}}{[J]}$

$f > 0$?

yes

no

Calculate $\Delta\varepsilon^{VP}$ by Newton Iteration, $[J]^{VP}$

$\Delta\varepsilon^{VP}=[J]^{VP}=0$

$\Delta\varepsilon = \Delta\varepsilon^{VE} + \Delta\varepsilon^{VP}$

$|\Delta\varepsilon - \Delta\varepsilon^{ABQ}| < 1e\text{-}6$

no

yes

Update σ, store var.

$[J]=[J]^{VE}+[J]^{VP}$

- **Parameters Calibration**

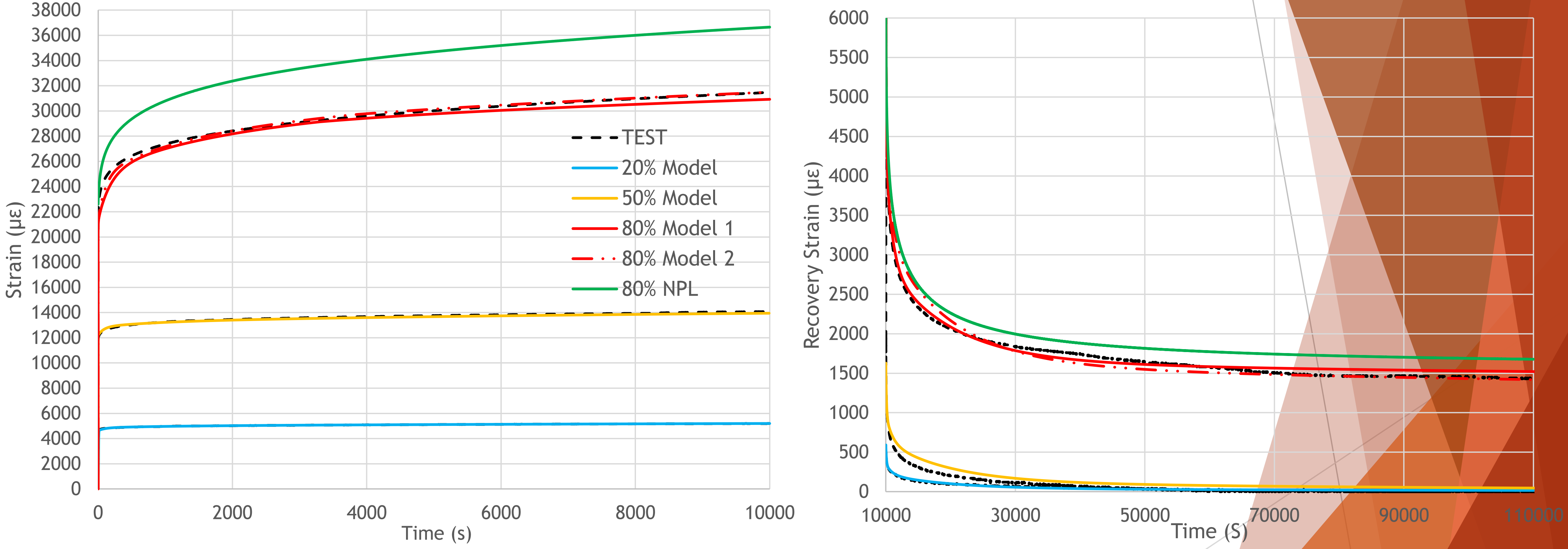
Creep data without permanent strain
- Prony series
- VE nonlinear parameters

Uniaxial tension test
- Yield surface and hardening rule

Creep data
- VP parameters

Bulk Coupon EA9696

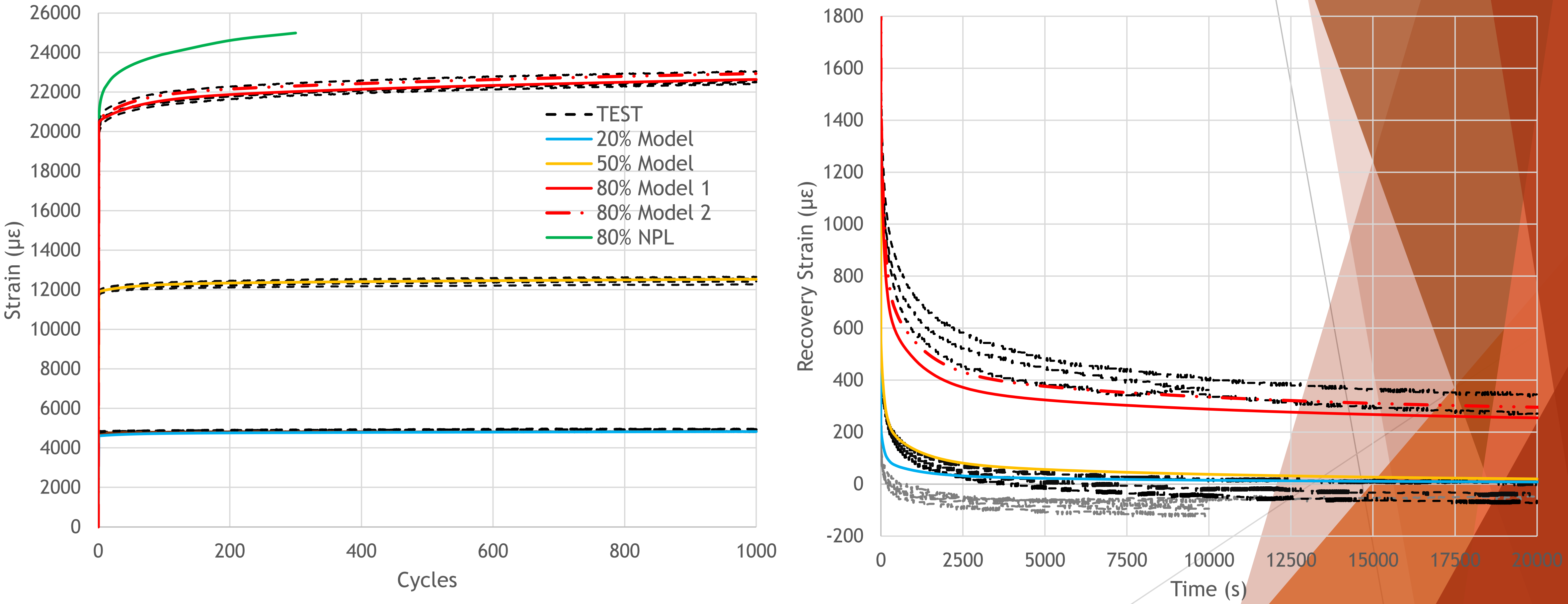
Creep



Bulk Coupon EA9696

Ratcheting

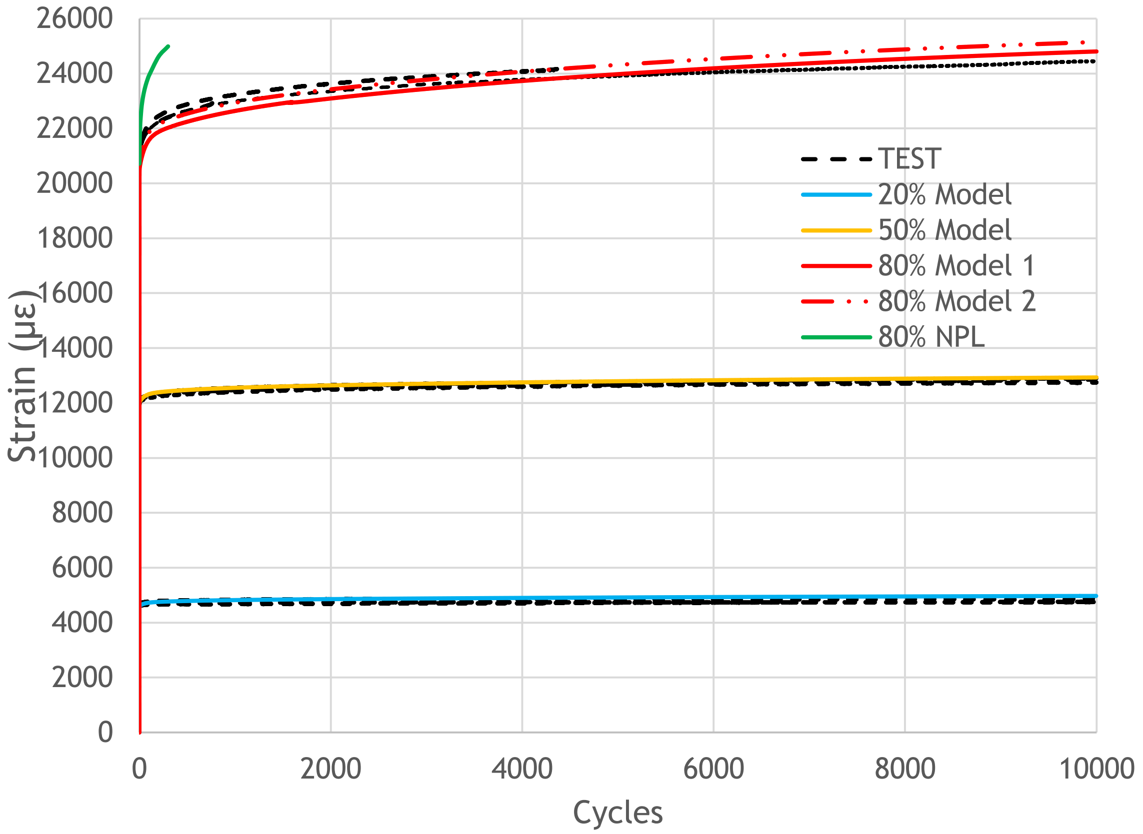
0.5Hz, R=0.1, 1K Cycles

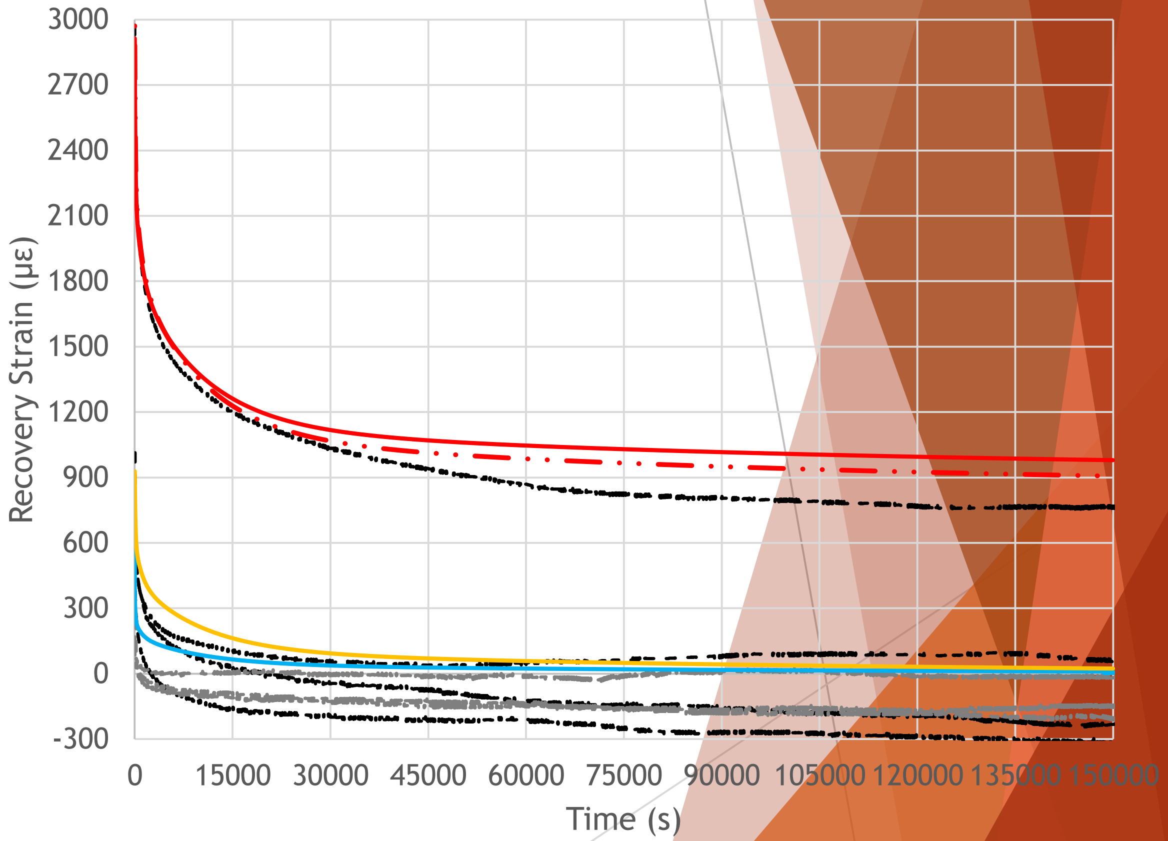


Bulk Coupon EA9696

Ratcheting

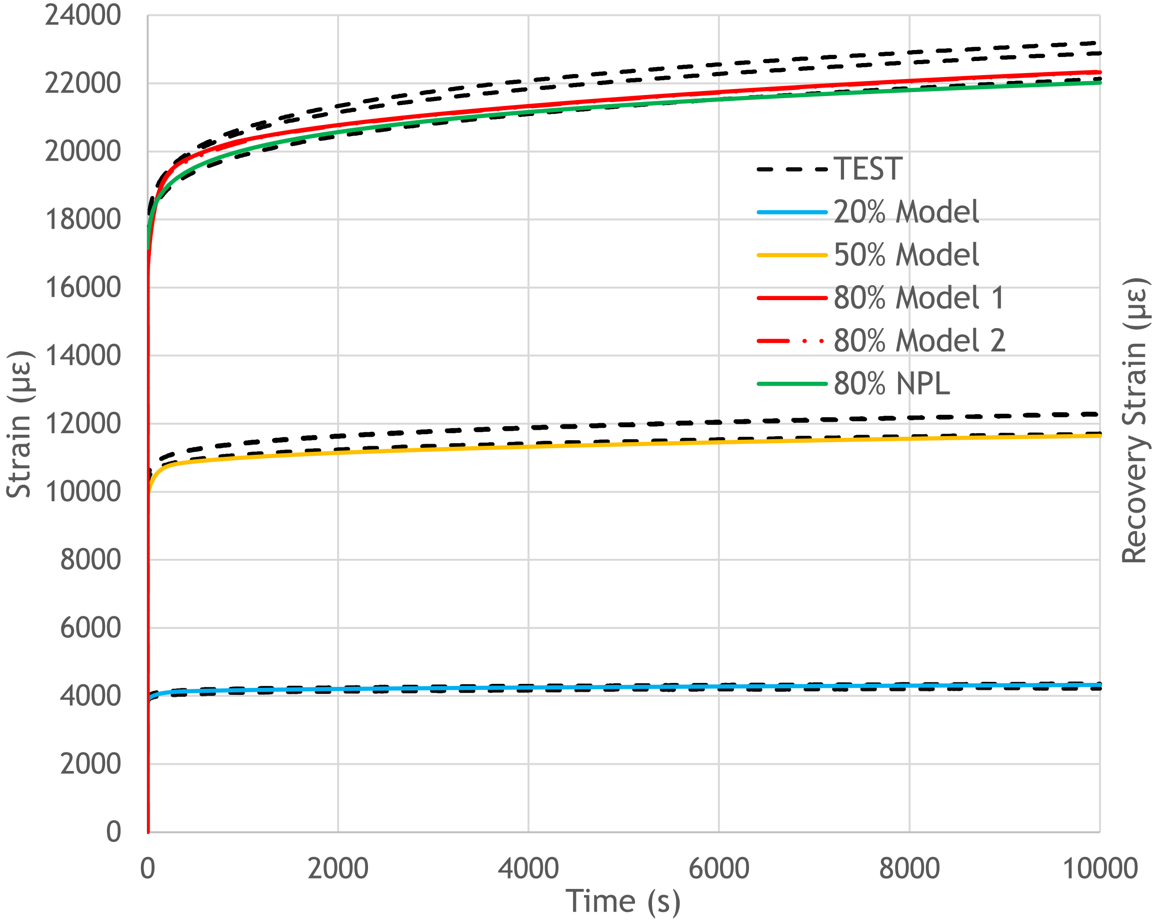
0.5Hz, R=0.1, 10K Cycles

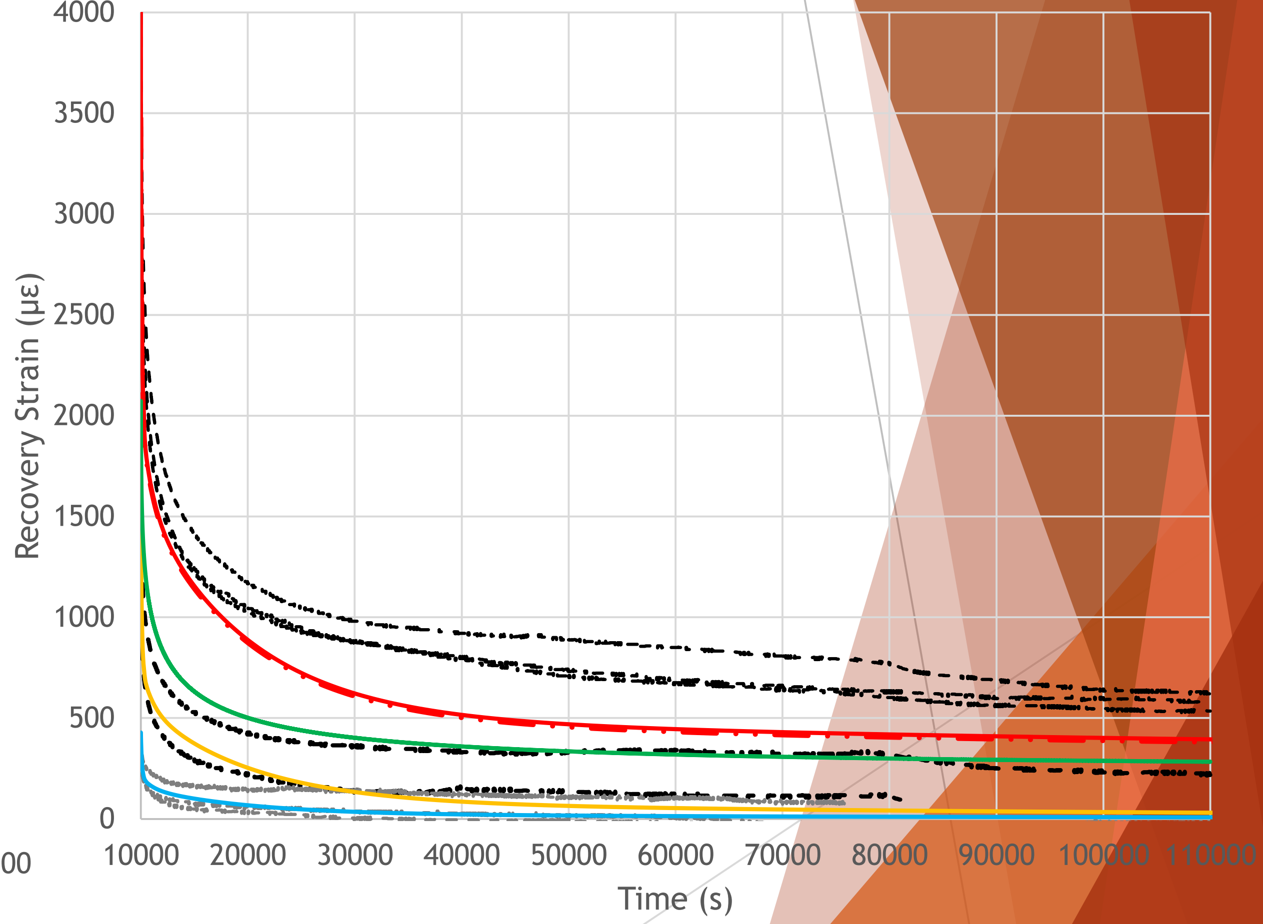




Bulk Coupon FM300-2

Creep

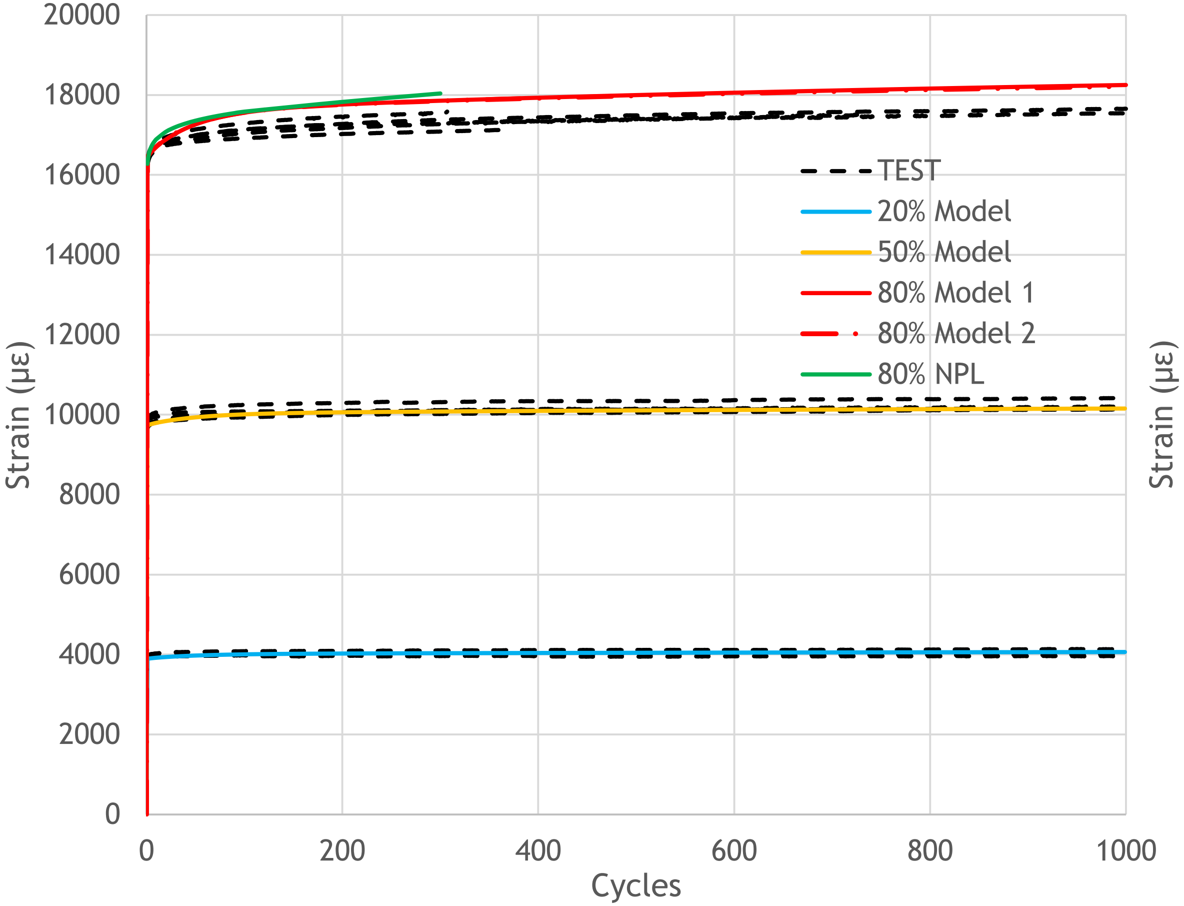


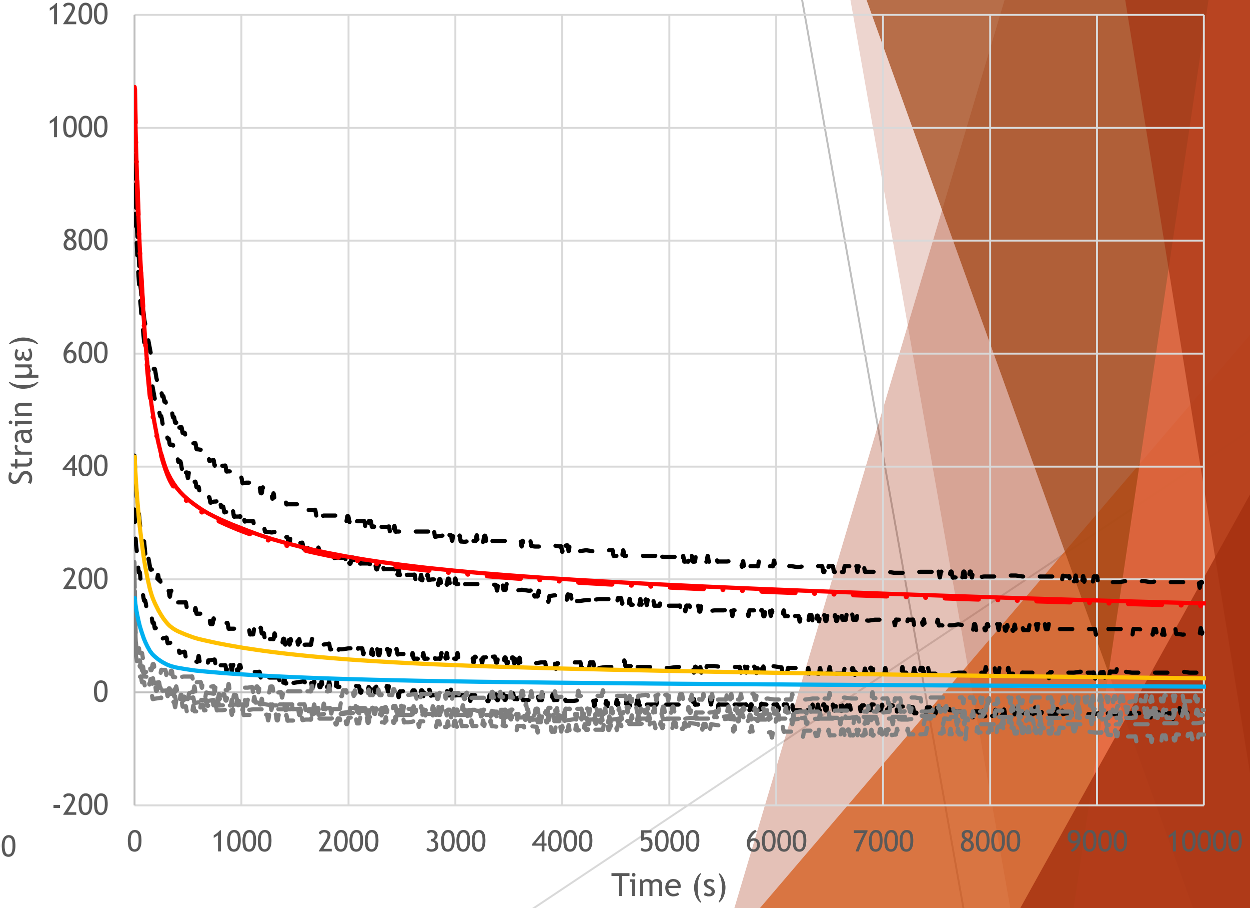


Bulk Coupon FM3000-2

Ratcheting

0.5Hz, R=0.1, 1K Cycles

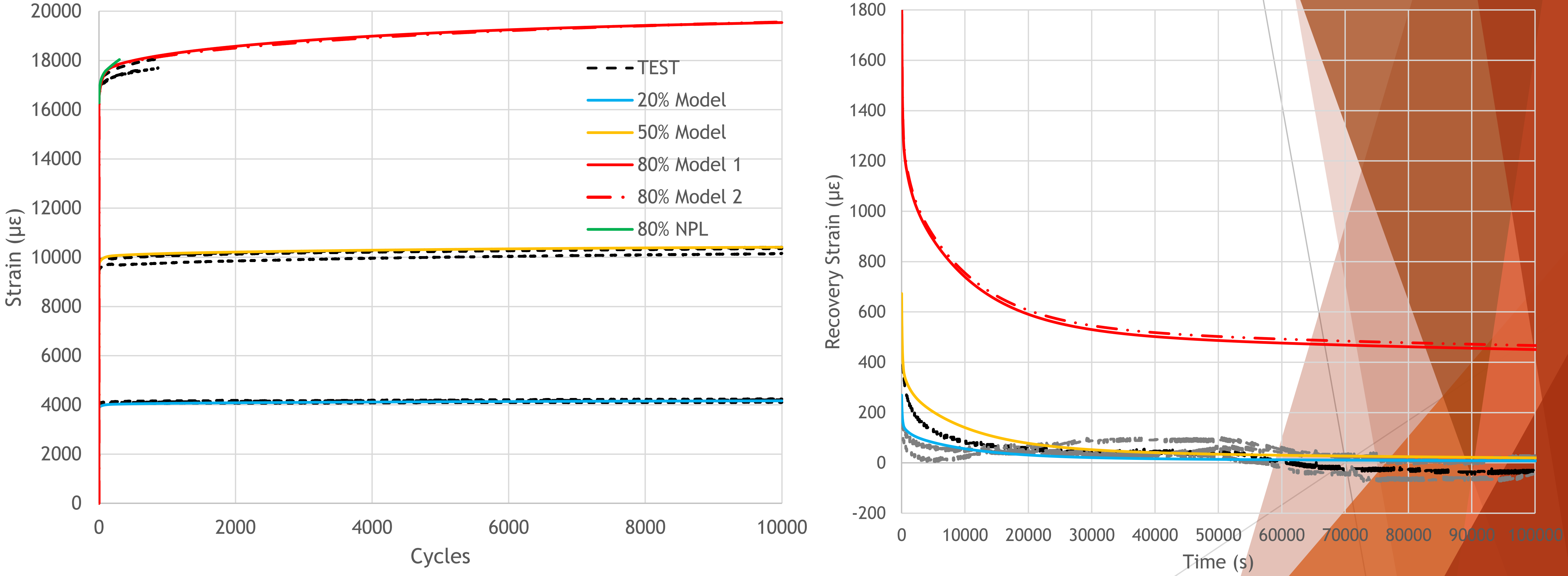




Bulk Coupon FM300-2

Ratcheting

0.5Hz, R=0.1, 10K Cycles



Conclusion

- Strain gages work surprisingly well in measuring thin bond adhesive strain
- Some adhesives exhibit more cyclic plasticity in shear than normal stress
- Plastic strain can accumulate at low stress (20% UTS)
- Adhesives exhibit viscoelastic and viscoplastic response.
- Parameters calibrated from creep test can predict ratcheting response.
- Plastic rule is more important for multiaxial stress.

Looking Forward

- Benefit to Aviation
  - Methodology to characterize adhesive plasticity
  - Improved models of adhesive time and plastic response
  - Adhesive ratcheting behavior
- Future needs
  - Experiment
    - Shear with compression, WALS
    - Shear angle, softening, failure surface examination
  - Simulation of bonded joints under shear
    - Extend current model to 2D plane strain.
    - Consider plastic flow rule as non-associated.
    - Apply to scarf and WALS adhesive joints.