Durability of adhesive bonded joints in aerospace structures

Washington State University

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AMTAS Fall meeting Seattle, WA

Durability of Bonded Aircraft Structure

- Principal Investigators & Researchers
  - Lloyd Smith
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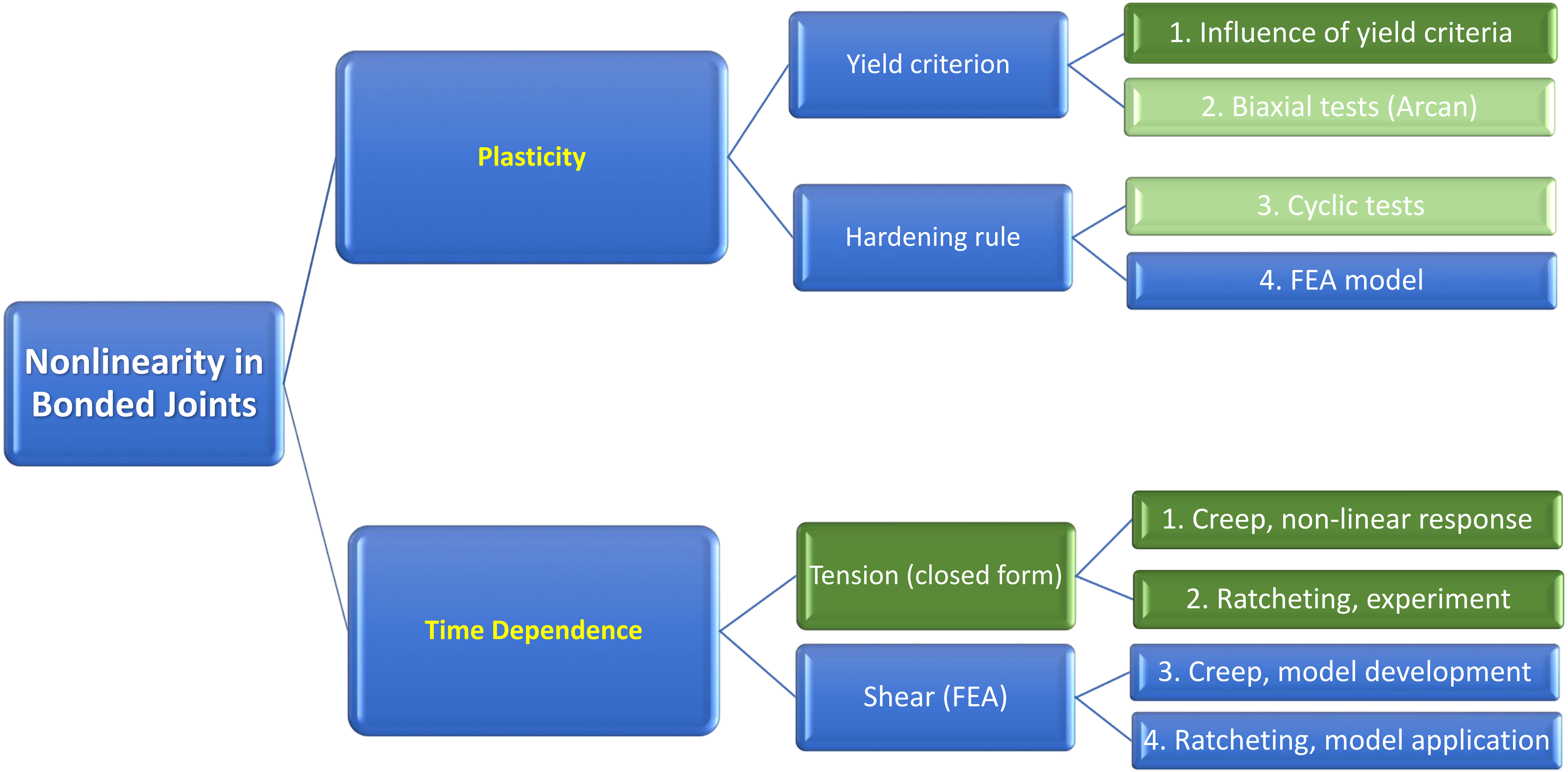
- FAA Technical Monitor
  - Ahmet Oztekin
- Other FAA Personnel Involved
  - Larry Ilcewicz
- Industry Participation
  - Boeing: Will Grace, Peter VanVoast, Kay Blohowiak

Durability of adhesive bonded joints in aerospace structures



Approach: Plasticity

❖ **Primary Research Aim:** Modeling of adhesive plasticity to describe nonlinear stress-strain response.

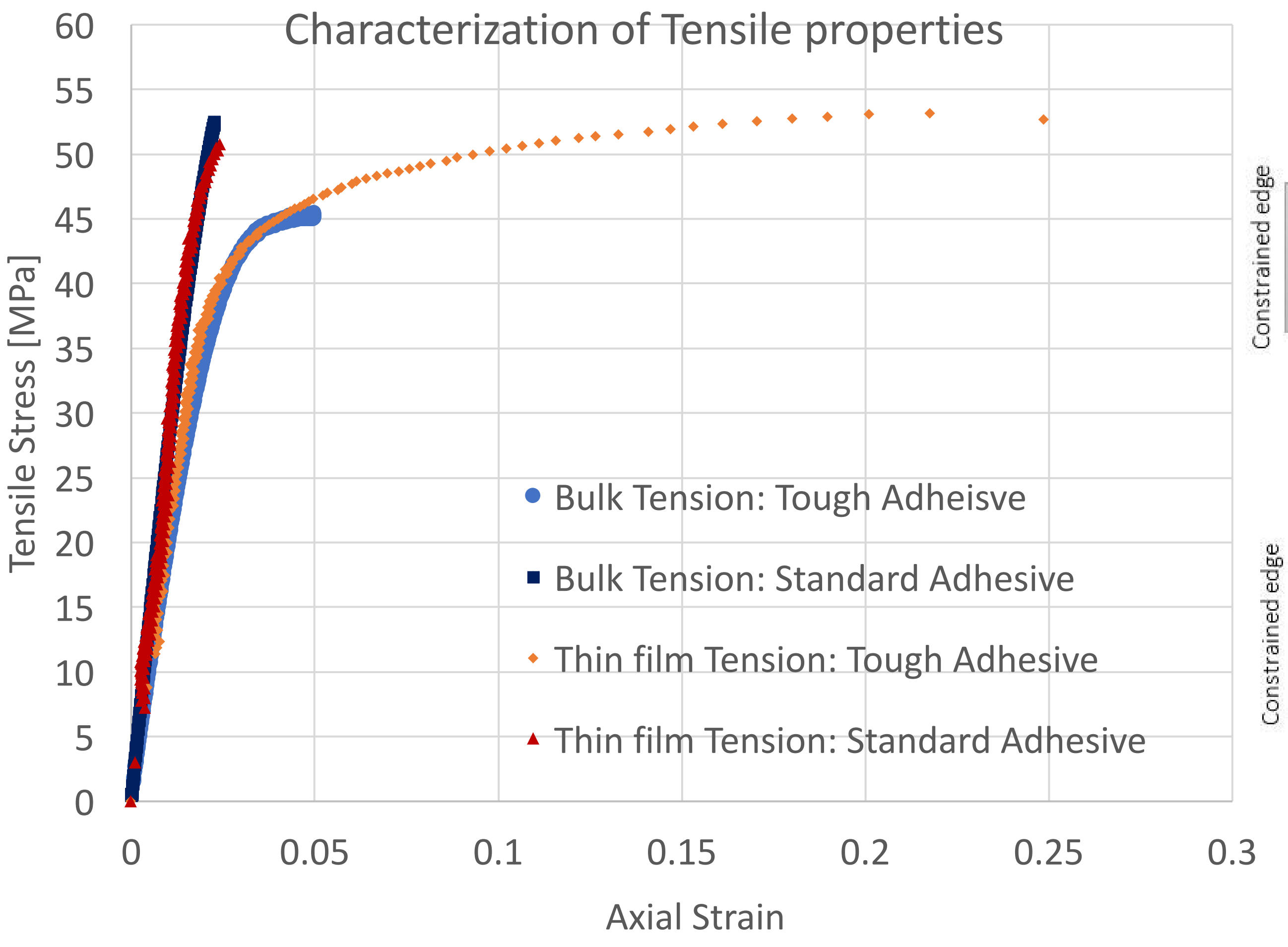
➢ **Sub Task:**

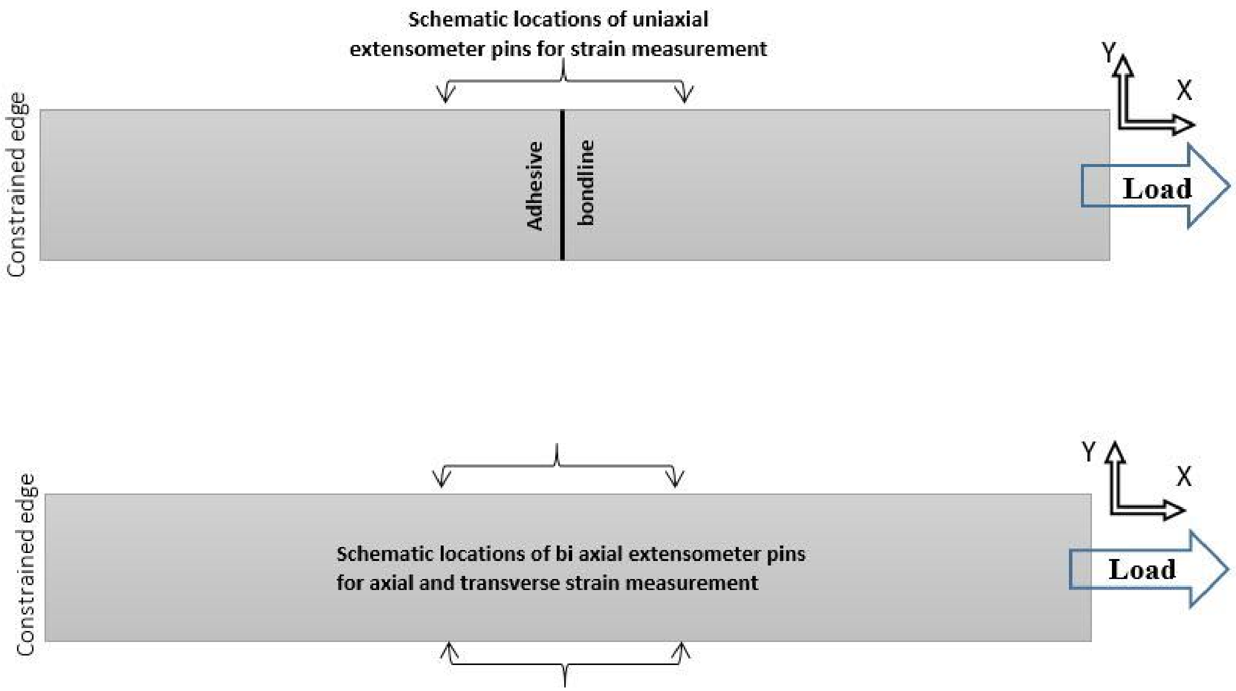
1. Identify the influence of yield criterion and hardening rule on bonded joints (complete)
2. Characterizing hardening rule (complete Dec 2017)
3. Characterizing yield criterion (complete Dec 2017)
4. Numerically combining hardening rule and yield criterion (complete Feb 2017)

Approach: Plasticity

1. Identify yield criterion and hardening rule of bonded joints

- **Input properties**: Bulk and Thin film adhesive properties in Tension.

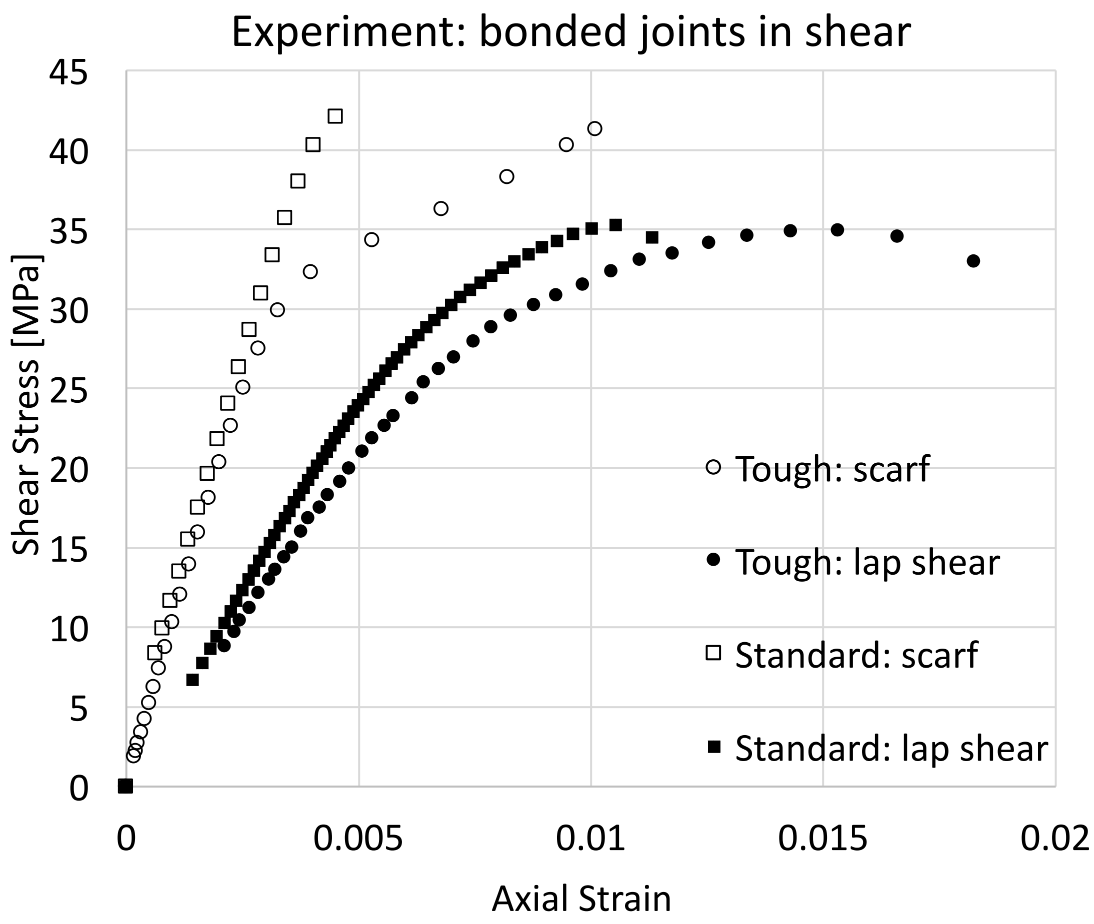


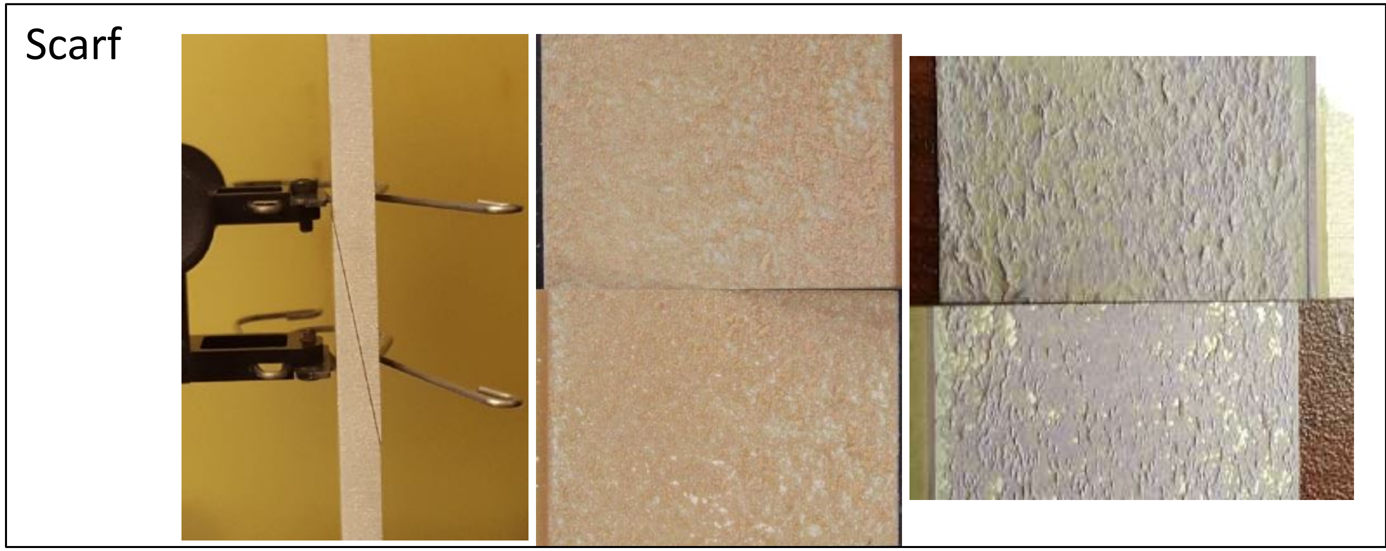


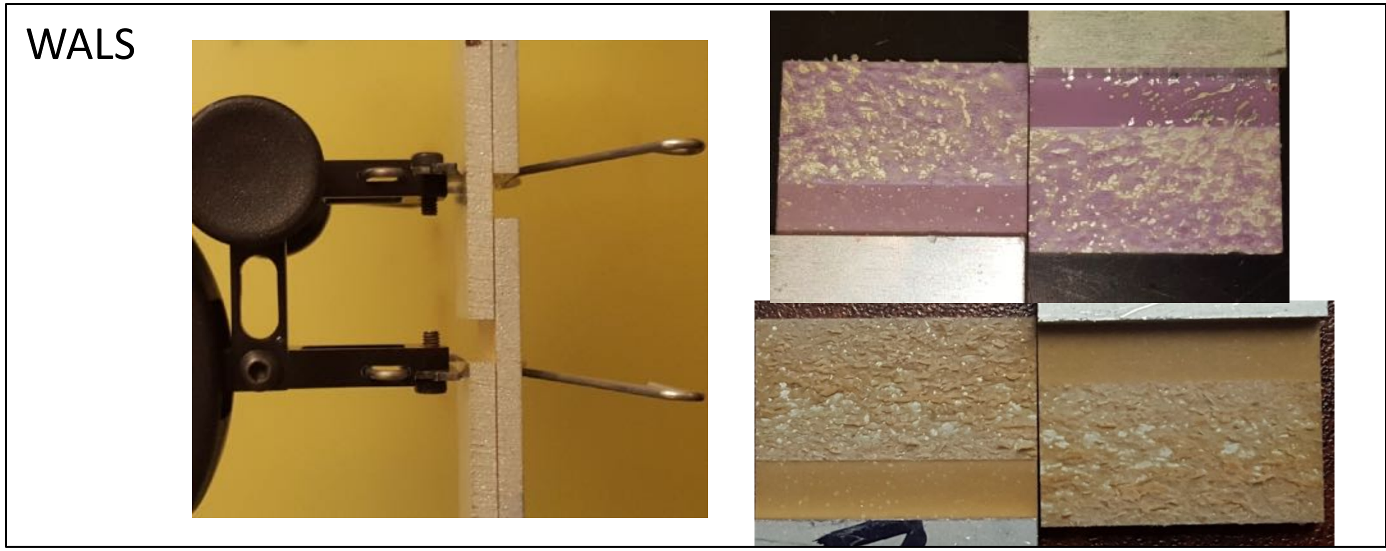
Approach: Plasticity

1. Identify the influence of yield criterion and hardening rule on bonded joints

- **Background**: Investigate yield criterion and hardening rule of bonded joints.
- **Outcome type**: Comparison of Test results vs different FEA models

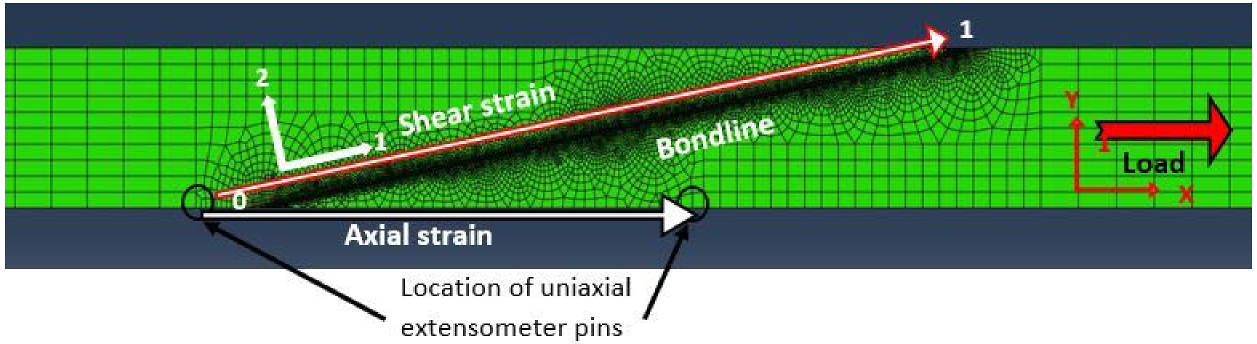


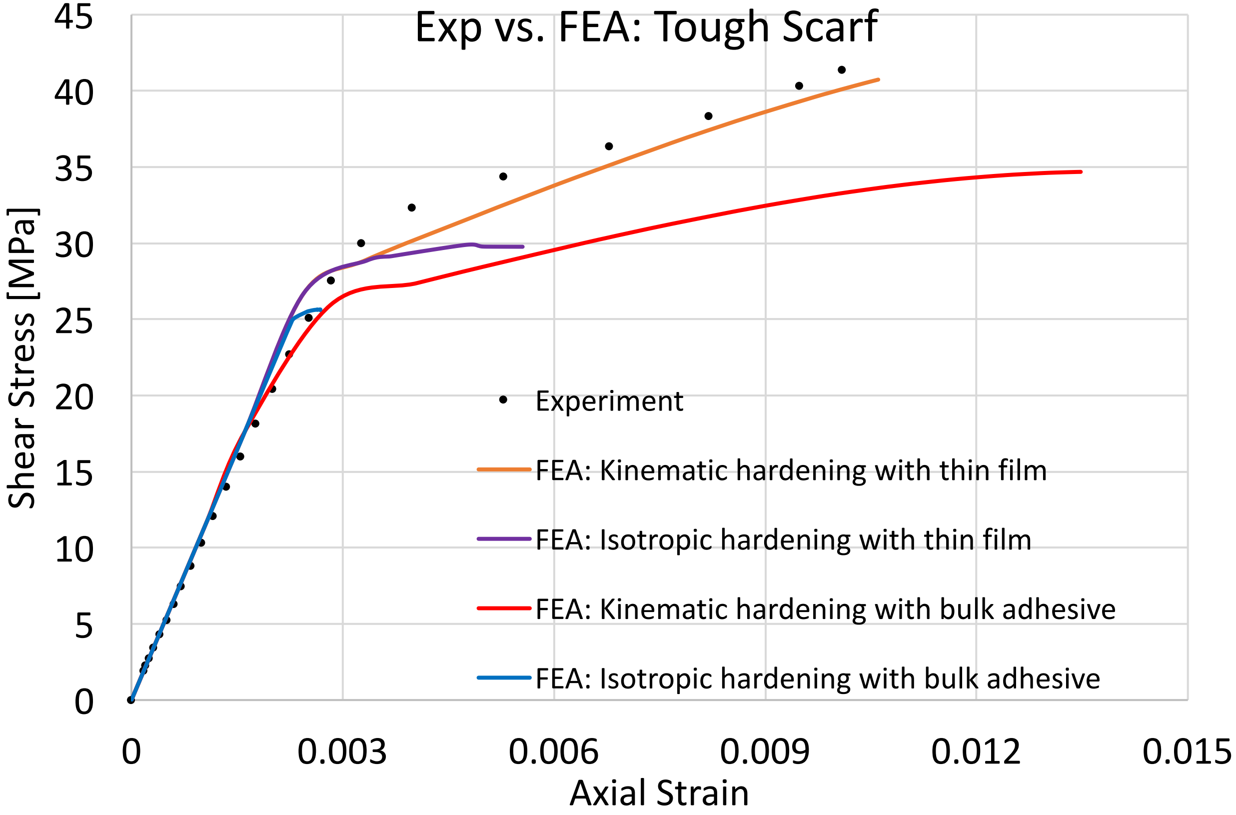


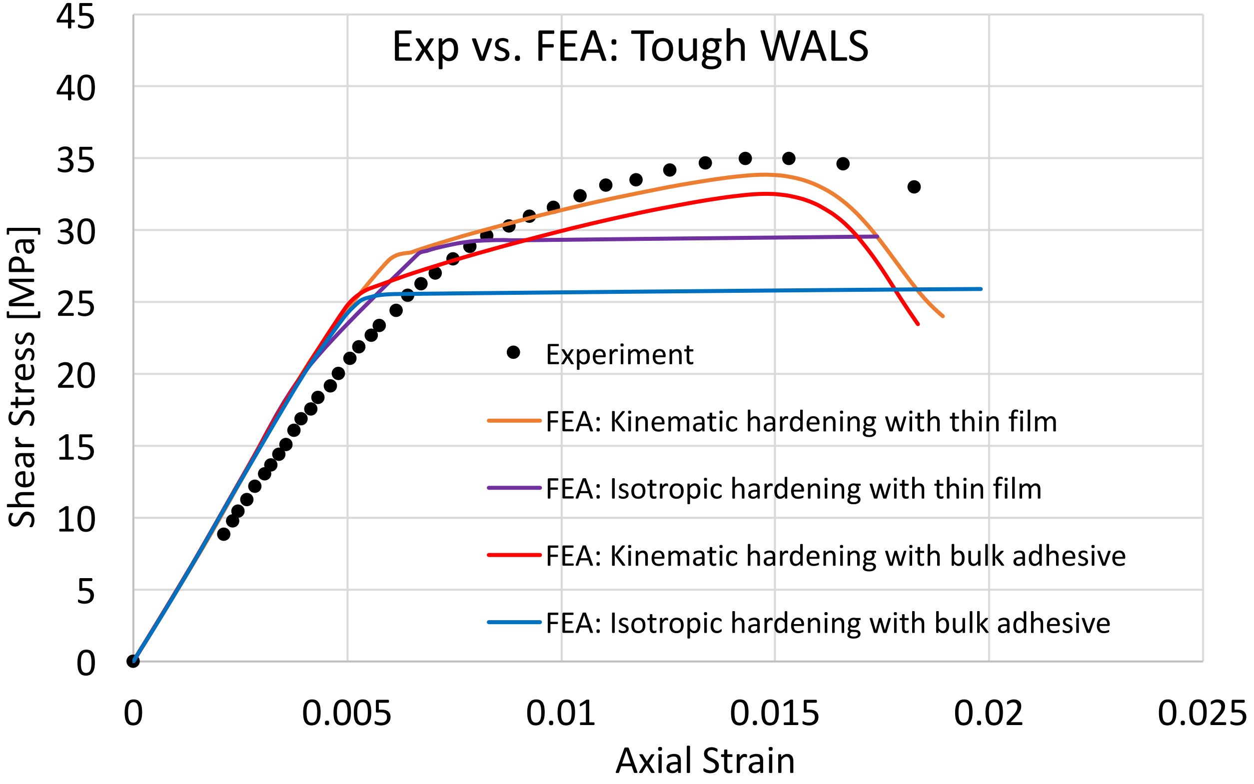


Approach: Plasticity

- Validation of Material model: Isotropic vs Kinematic hardening
- Choice of Input property: Bulk vs. Thin film



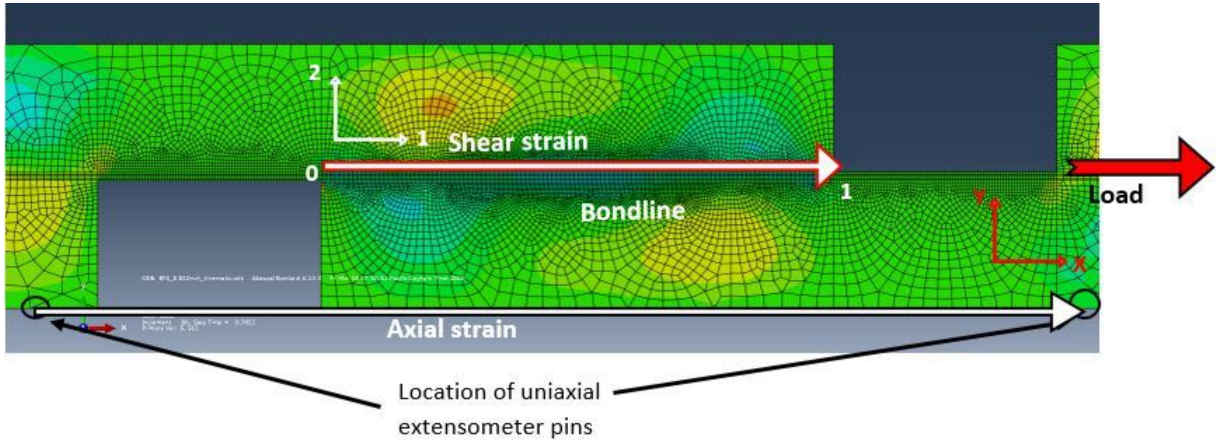


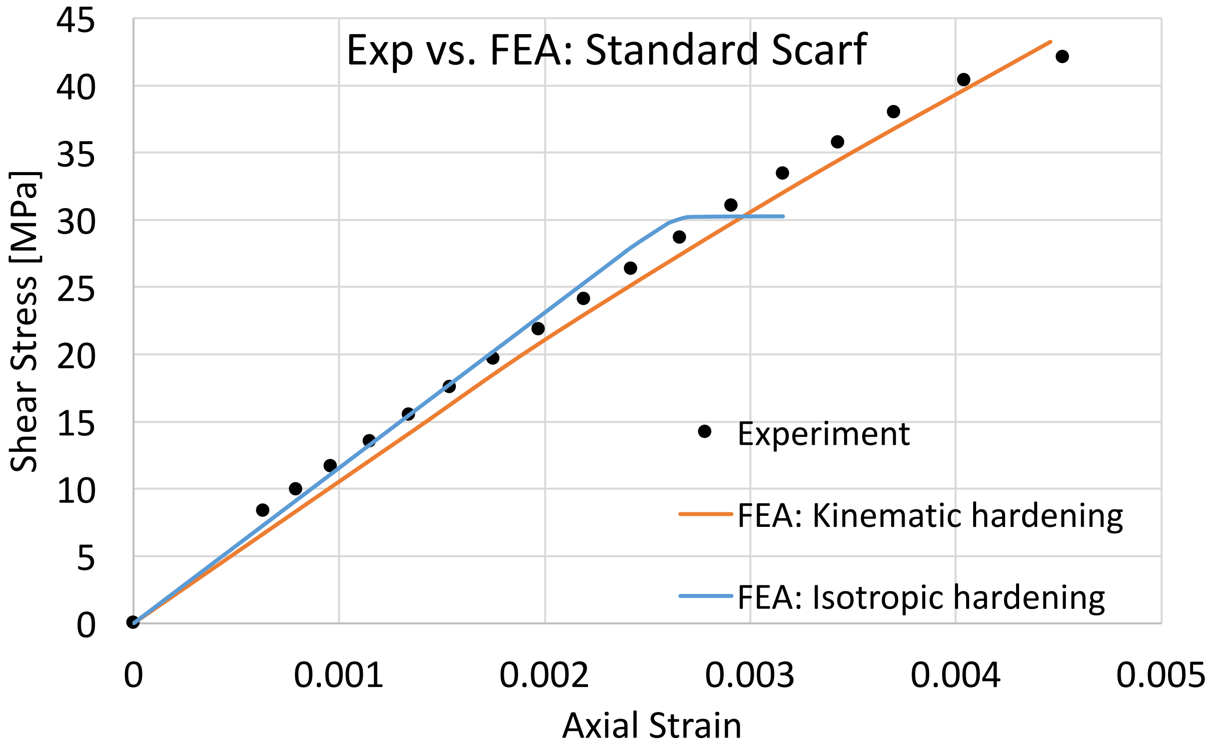


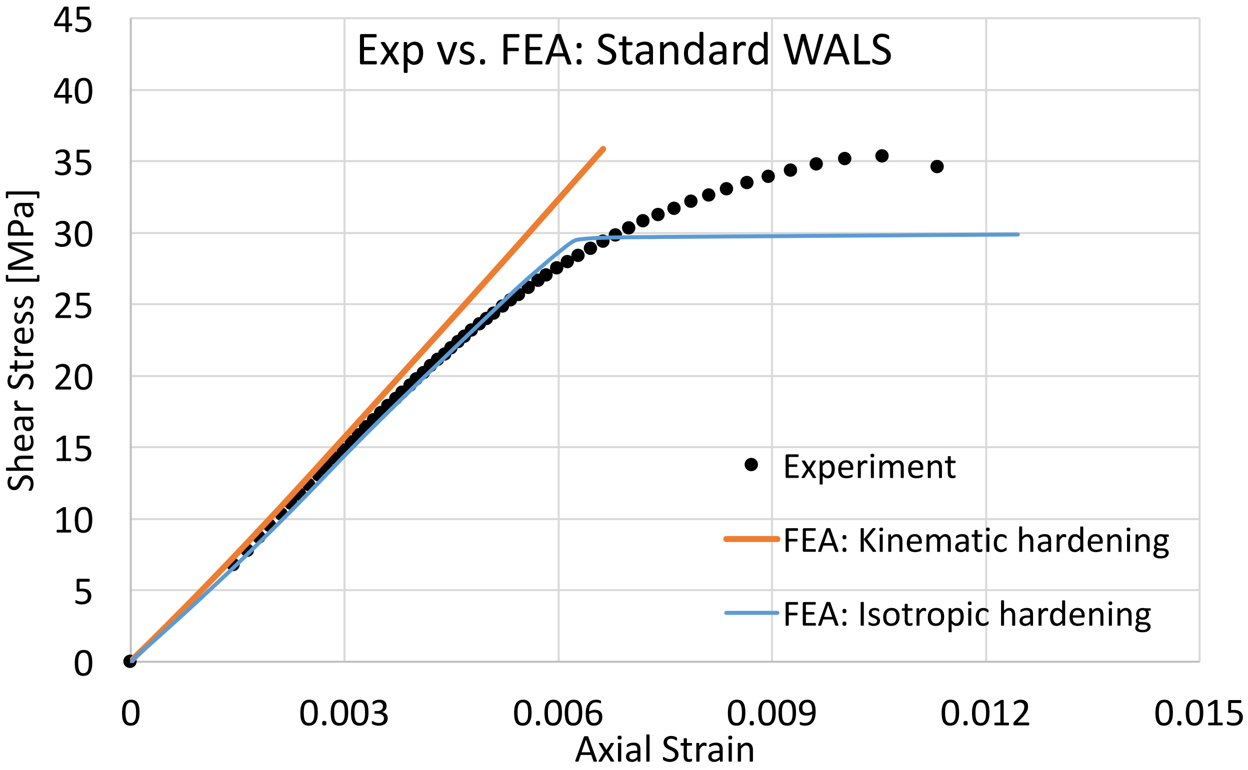
- **Status**: Completed, Journal paper submitted
- **Task outcome**: Adhesive follows a von Mises yield criterion and kinematic hardening

Approach: Plasticity

- Validation of Material model: Isotropic vs Kinematic hardening
- Choice of input property: Bulk = thin film (for Standard adhesive)





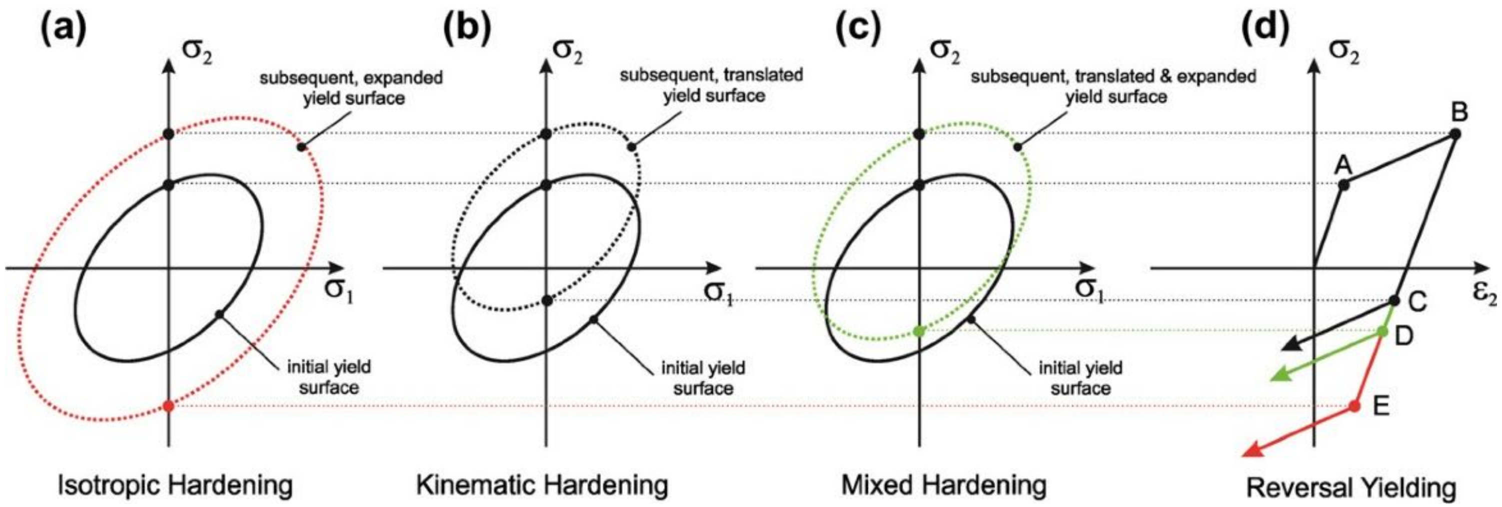


- **Status**: Completed, Journal paper submitted
- **Task outcome**: Adhesive follows a von Mises yield criterion and kinematic hardening

Approach: Plasticity

2. Characterize hardening rule

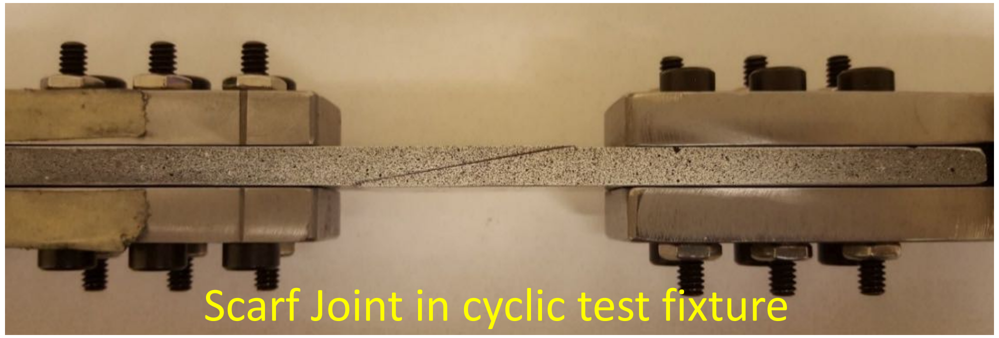
- **Background**: Similar to metals, adhesives could follow isotropic, kinematic or combined hardening rule.
- Lot of research done with metals, but none with bonded joints.
- This has to be verified by studying the movement of the yield surface under cyclic tension compression loading in a biaxial stress space.

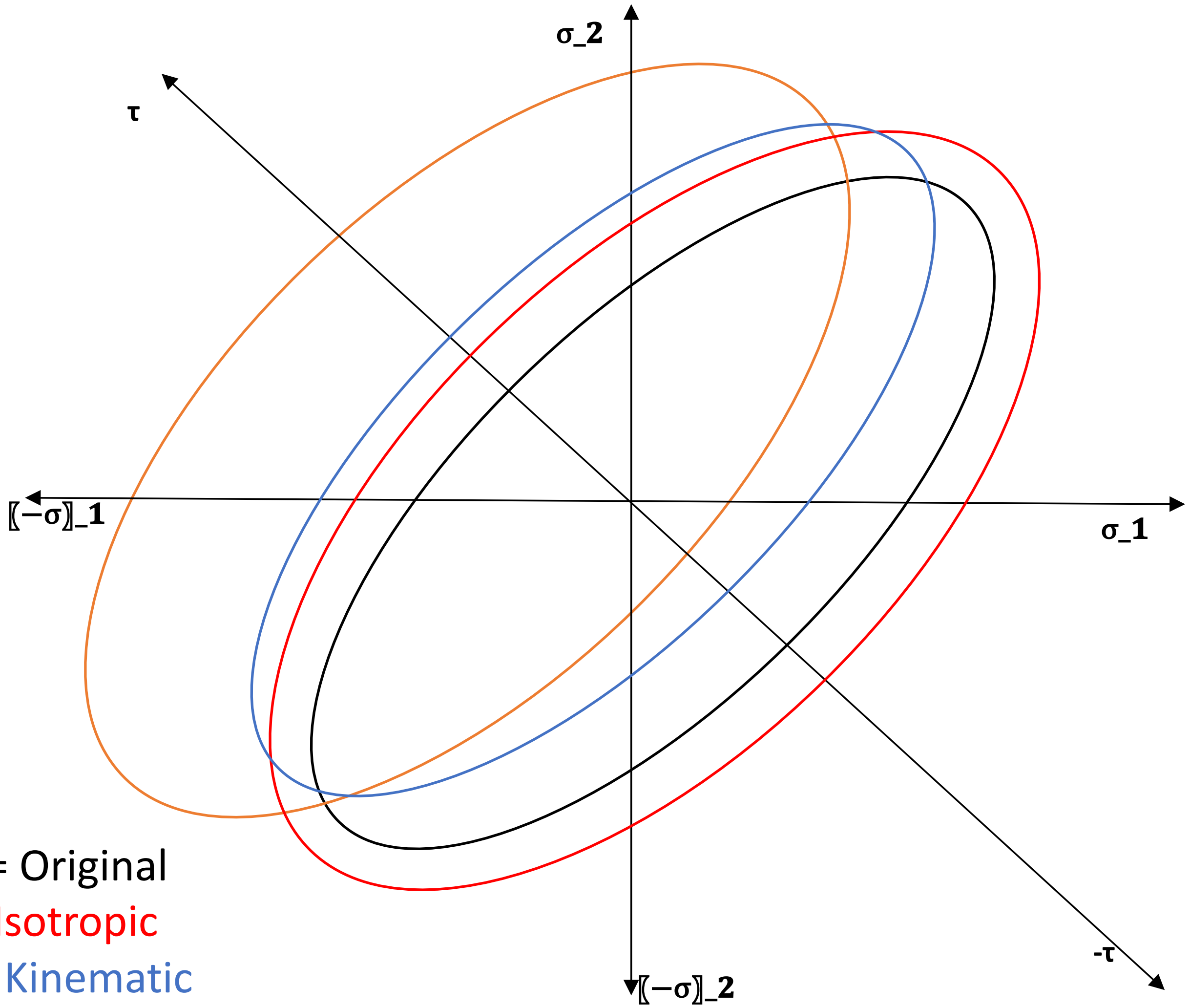


Ref: Muransky O. *et al* [Metal Plasticity]

Approach: Plasticity

- **Outcome type**: Cyclic ten-comp tests for scarf joint. Plot of yield surface translation/expansion/both, Journal paper

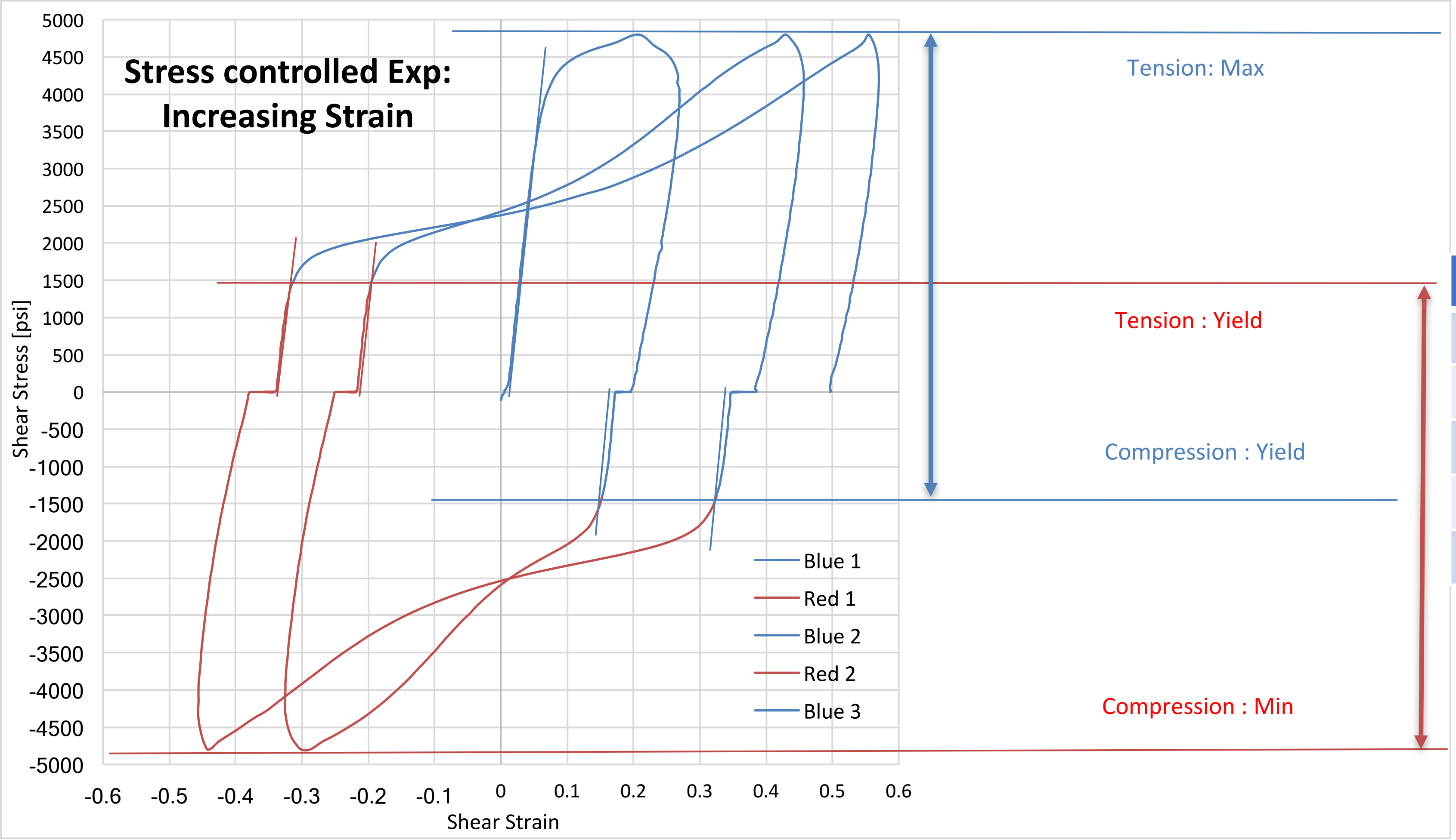




Black = Original
Red = Isotropic
Blue = Kinematic
Orange = Combined

Approach: Plasticity

- **Outcome type**: Cyclic ten-comp tests for scarf joint. Plot of yield surface translation/expansion/both, Journal paper



Blue = Red (all cycles)
Peaks [+4800 to -4800 psi]

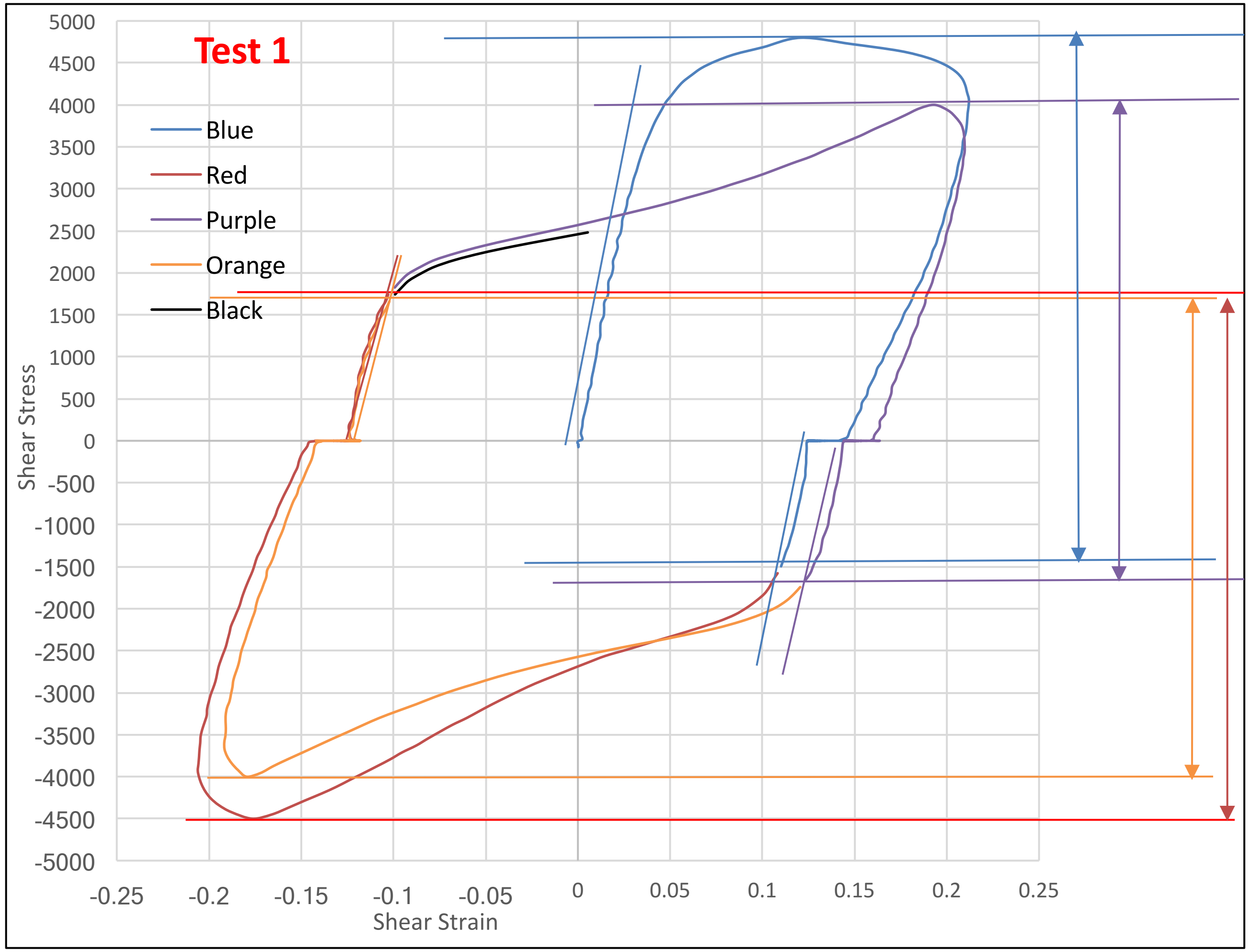
Cycle #	Yield surface size [psi]	
1 (Blue: ten peak)	6250	+4800 to -1450
2 (Red: comp peak)	6250	-4800 to +1450
3 (Blue: ten peak)	6250	+4800 to -1450
4 (Red: comp peak)	6250	-4800 to +1450
5 (Blue: ten peak)	6250	+4800 to -1450

- **Status**: Documentation in progress

- **Task outcome**: Yield surface showed translation (kinematic hardening).

Approach: Plasticity

- **Outcome type**: Cyclic ten-comp tests for scarf joint. Plot of yield surface translation/expansion/both, Journal paper



Blue ~ Red (1st and 2nd cycle)

Purple = Orange (3rd and 4th cycle)

Virtual Strain Controlled: Stress peaks [psi]	Test 1 Cycles# (presented here)	Yield surface size [psi]	
4800	1 (Blue: ten peak)	6300	+4800 to -1500
-4500	2 (Red: comp peak)	6250	-4500 to +1750
4000	3 (Purple: ten peak)	5750	+4000 to -1700
-4000	4 (Orange: comp peak)	5750	-4000 to +1700

Decreasing Stress: Stress peaks [psi]	Test 2 Cycles#	Yield surface size [psi]	
4800	1 (Blue: ten peak)	6200	+4800 to -1400
-4500	2 (Red: comp peak)	6160	-4500 to +1660
3425	3 (Purple: ten peak)	4756	+3425 to -1330
-3500	4 (Orange: comp peak)	4800	-3500 to +1300

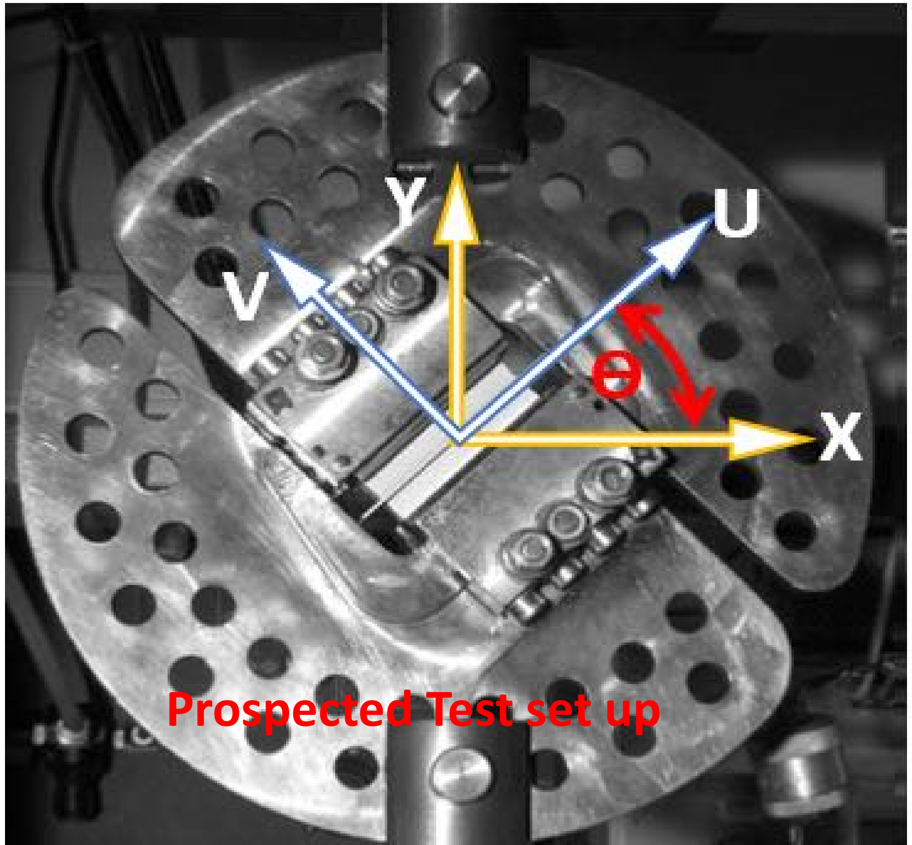
- **Status**: Documentation in progress

- **Task outcome**: Yield surface showed translation after stabilizing cycles in a strain controlled/decreasing stress experiment (Kinematic hardening).

Approach: Plasticity

3. Characterizing yield criterion

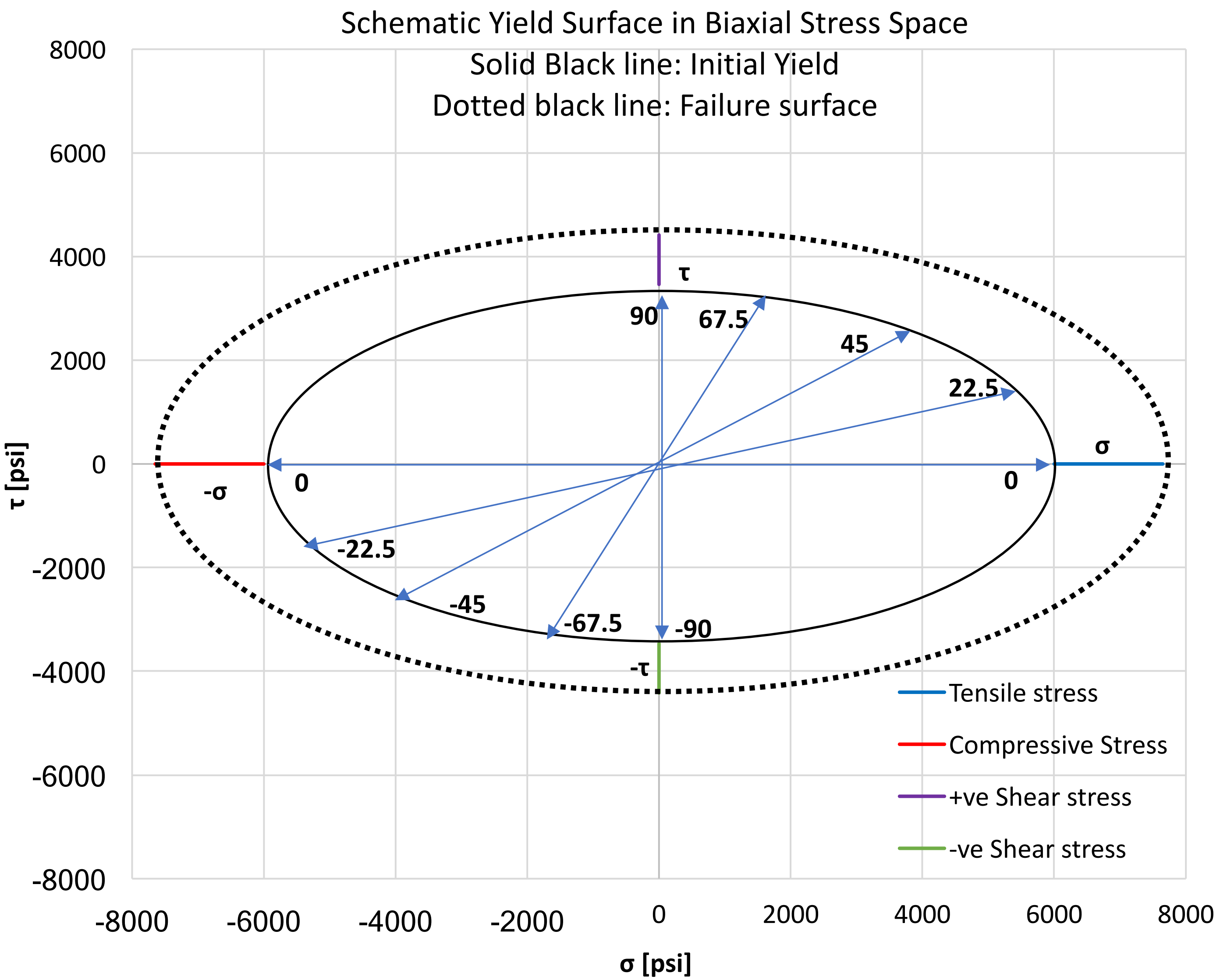
- **Background**: Assumption of yield criteria to avoid complex characterization with thin bonded joints
- Test bonded joints with mixed mode Arcan fixture to plot yield surface in biaxial stress space to identify shape of yield surface.
- **Outcome type**: Test results, Journal paper

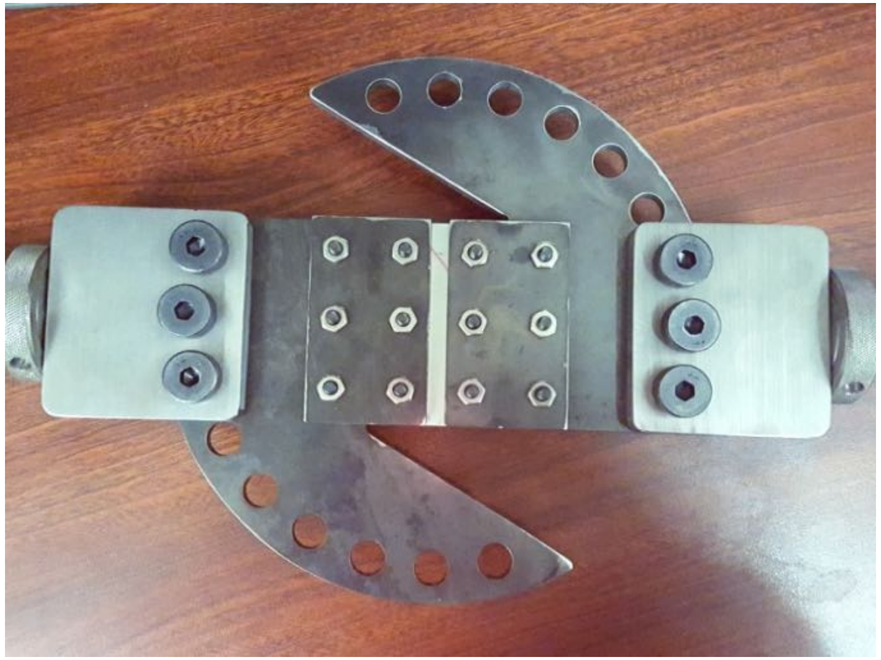


Normal component: $\sigma_V = \frac{F \cos\theta}{A}$

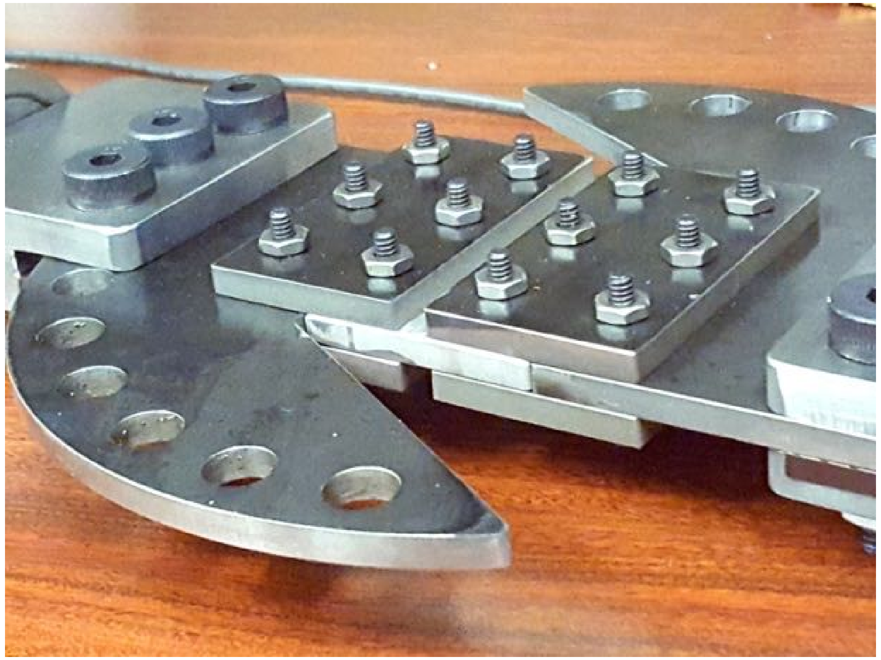
Shear Component: $\sigma_U = \frac{F \sin\theta}{A}$

Approach: Plasticity

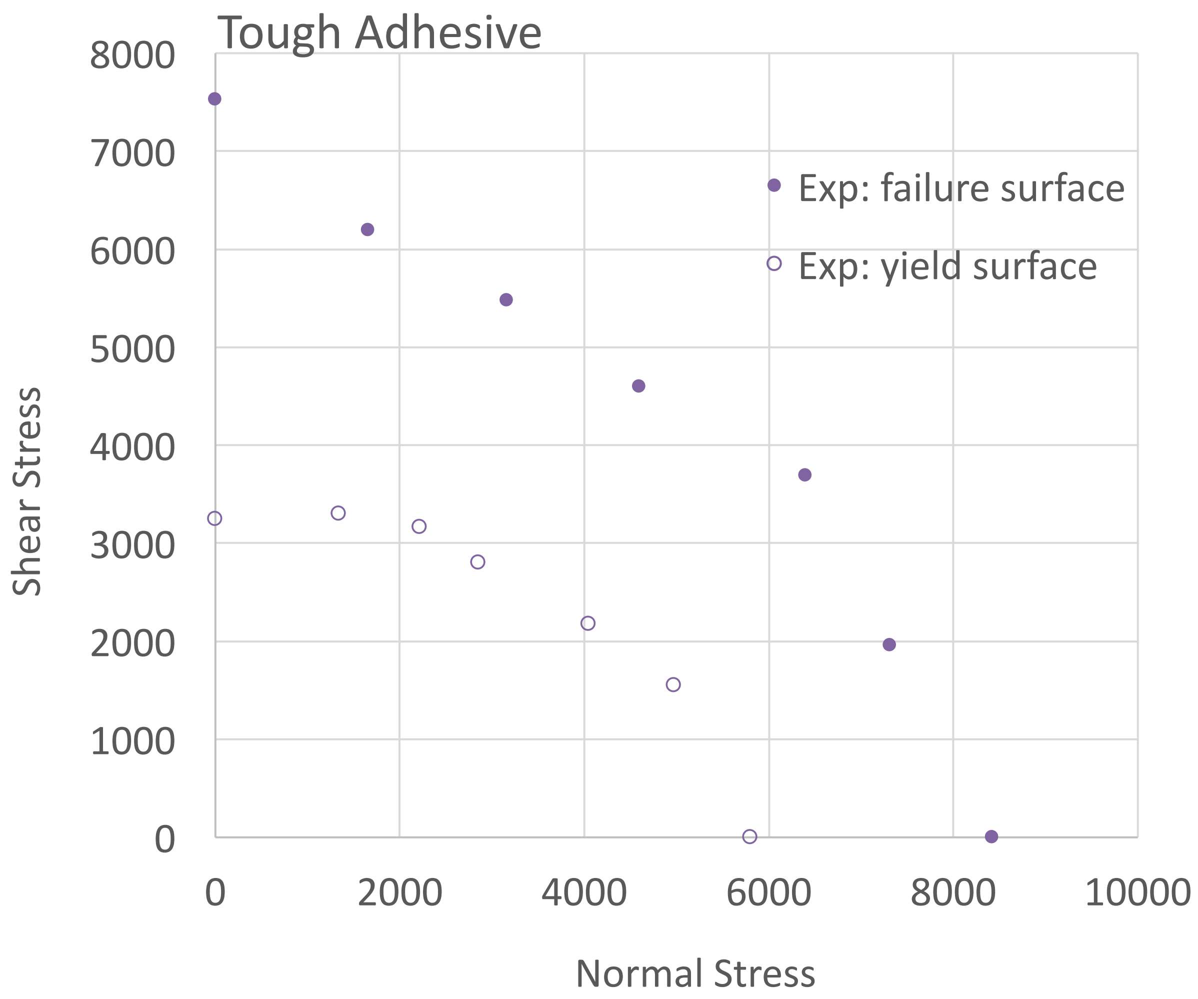


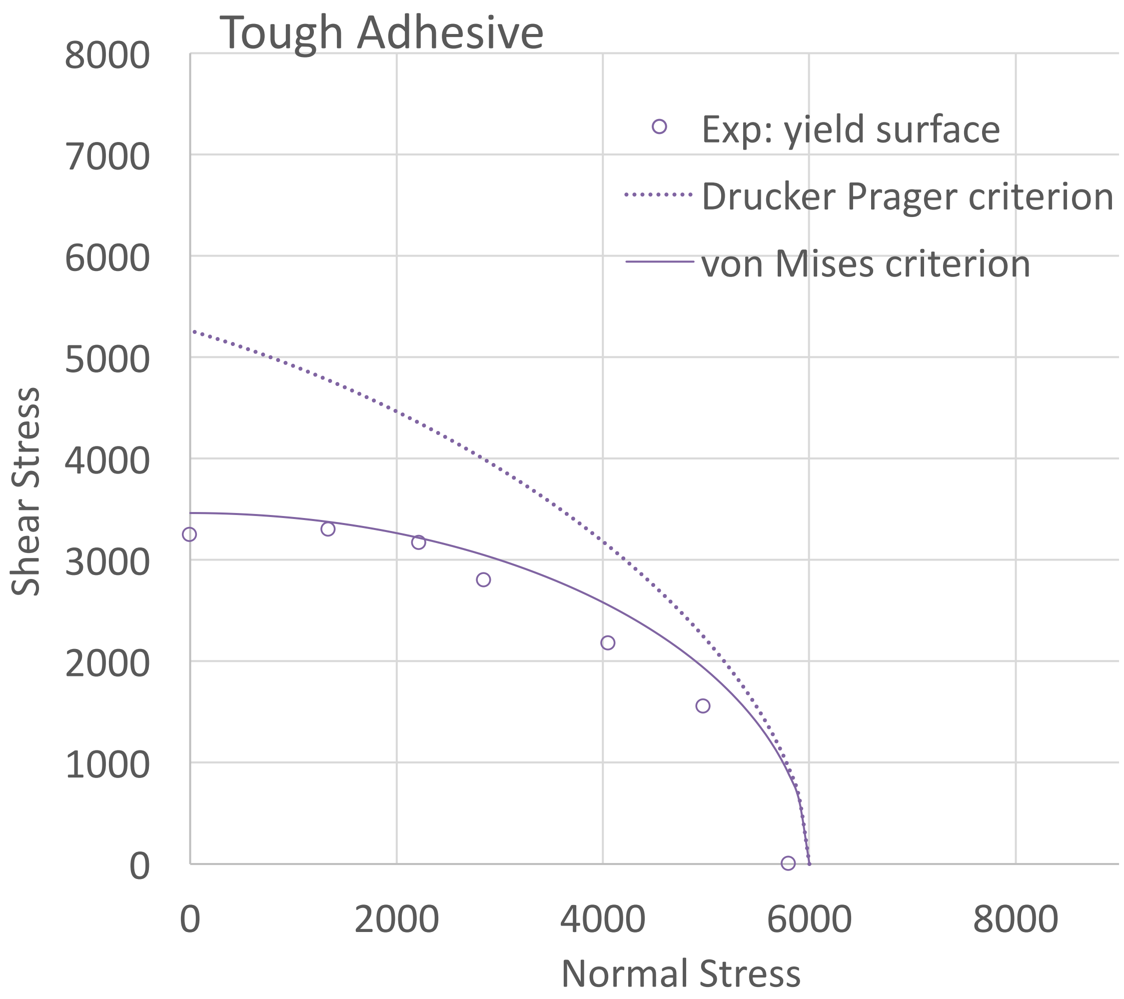


Assembly: fixture and coupon



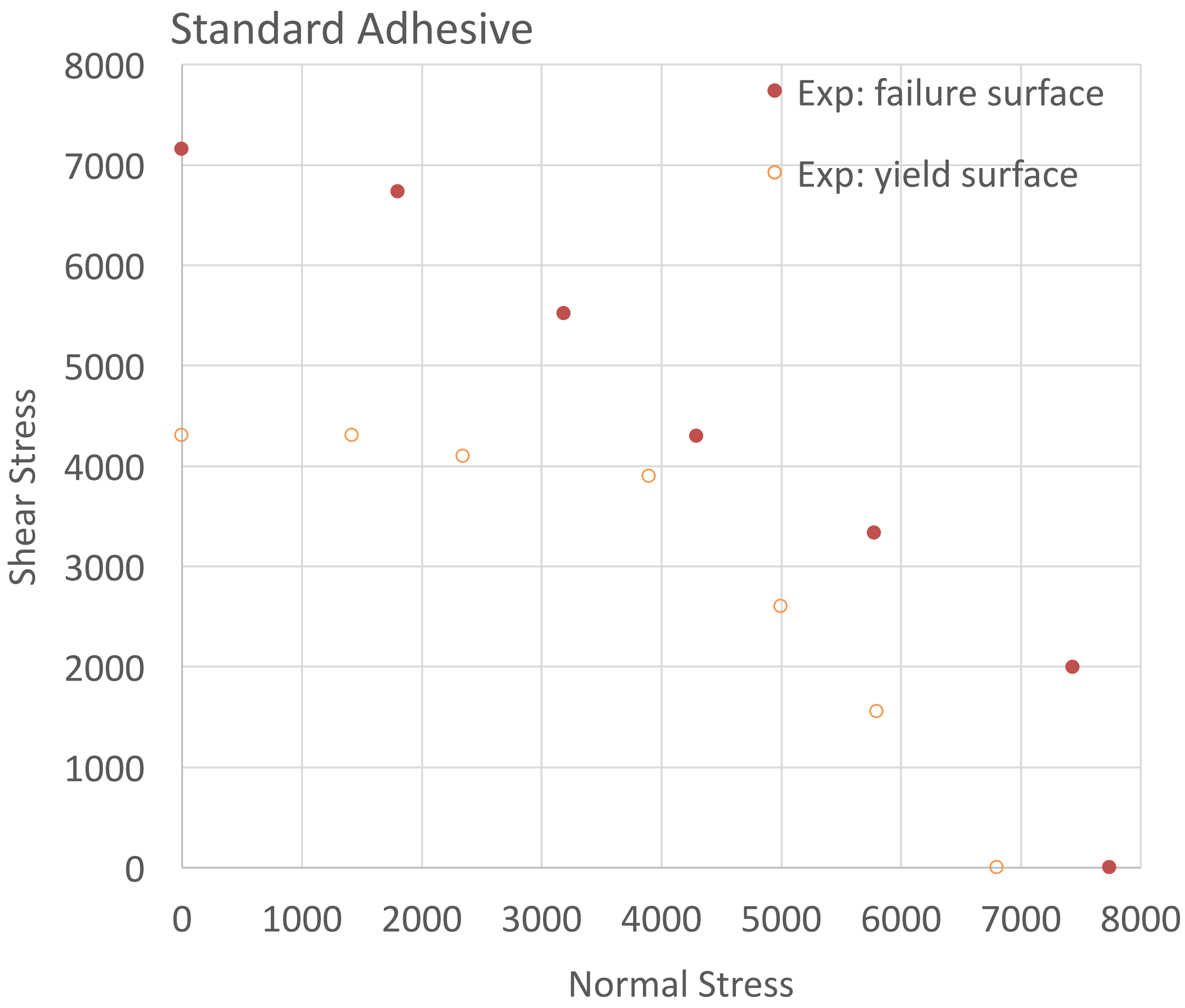
Approach: Plasticity

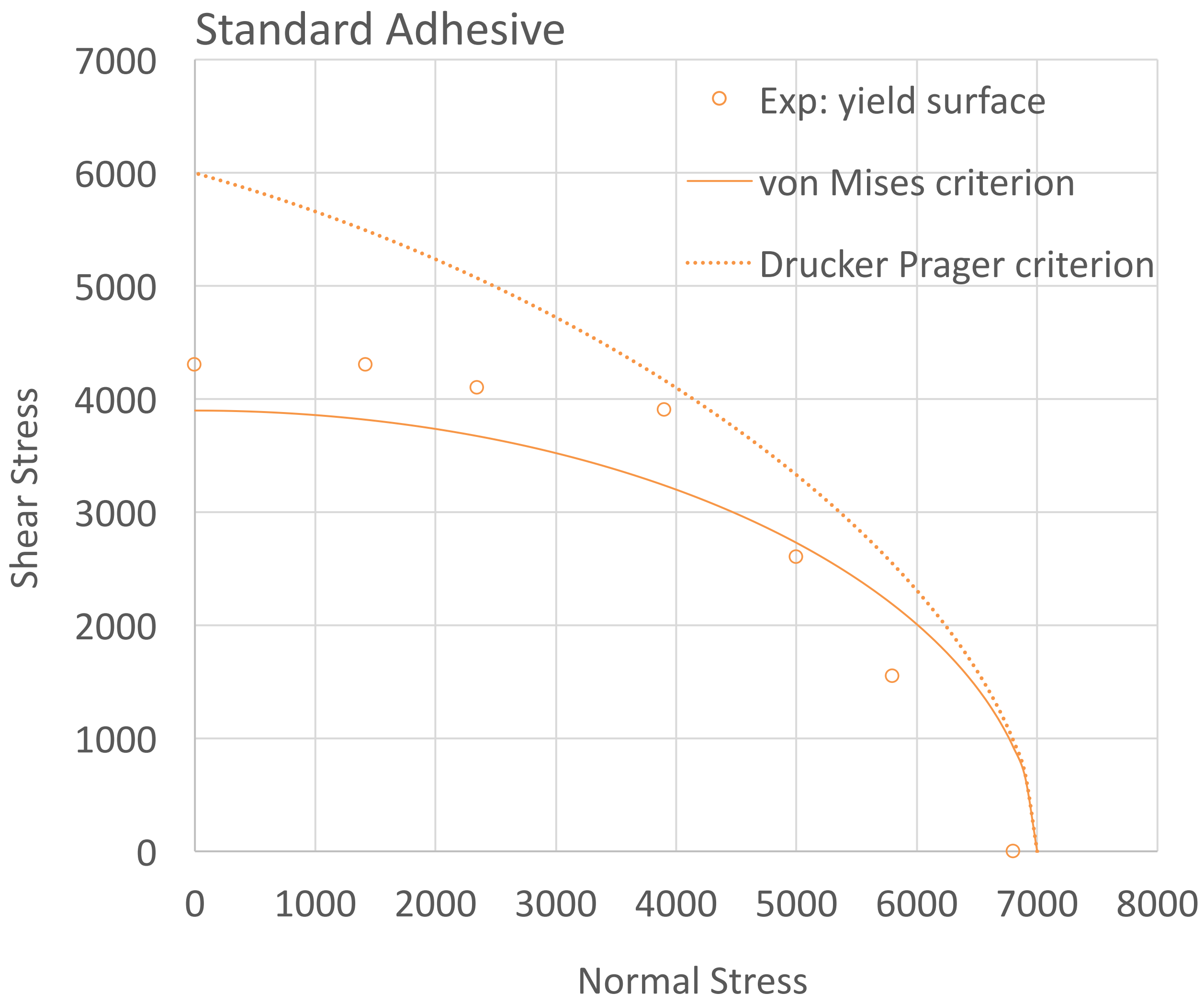




- **Status**: Documentation in progress
- **Task outcome**: yield surface shape and size to be plotted from experimental data.

Approach: Plasticity





- **Status**: Documentation in progress
- **Task outcome**: yield surface shape and size to be plotted from experimental data.

Approach: Plasticity

4. Numerically modeling nonlinear hardening rule.

- **Background**: Modeling of nonlinear hardening is common in metals.
- Nonlinear hardening has not been characterized for bonded joints due to experimental complexities, assumed to be linear.
- To model nonlinear hardening by including possible effects form both Isotropic and or kinematic hardening.
- **Outcome type**: Numerical modeling, comparison of experiment and simulation, Journal paper
- **Status**: Identified the modeling technique to use cyclic scarf test data to extract nonlinear hardening parameters by separating isotropic and kinematic hardening components (estimated Feb 2018)
- **Task outcome**: Numerical modeling-FEA simulation of nonlinear hardening

Approach: Time dependence (viscoelasticity/viscoplasticity)

Background

- The time-dependent behavior of adhesives is important for the durability
- Seldom accurate models for adhesives to predict the ratcheting
- The response of shear coupons is more complicated to test

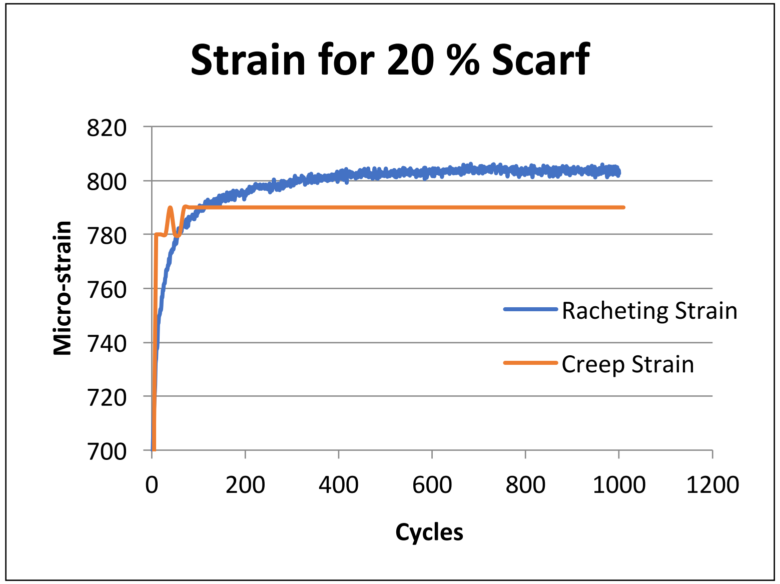
Objectives

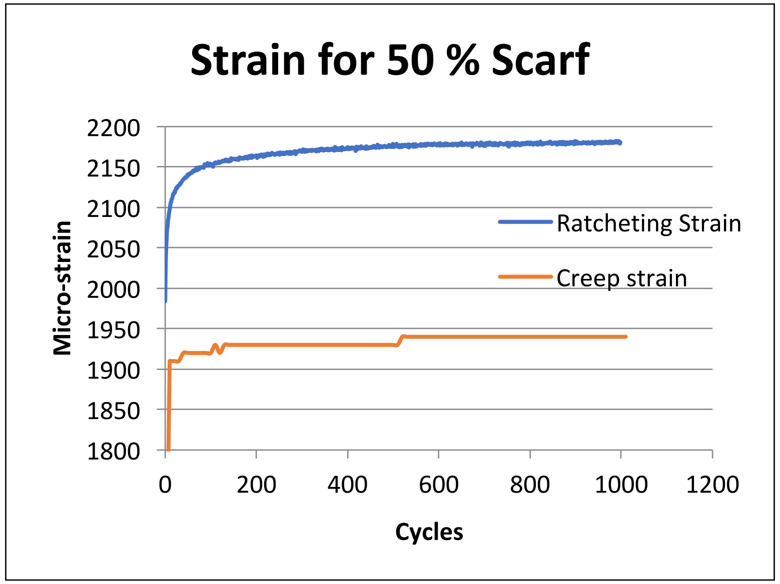
The final objective is to build a shear viscoelastic modeling on bonded joints for ratcheting.:

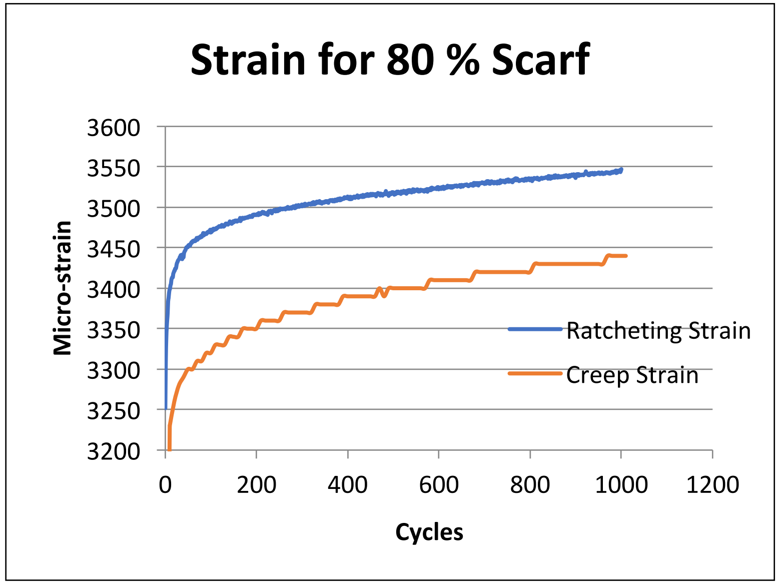
- Viscoelastic response of bulk resin, closed form model (complete)
- FEA Viscoelasticity model of bulk Resin (12/31/2017)
- FEA viscoelastic model of bonded joints in creep (05/31/2018)
- FEA viscoelastic model of bonded joints in ratcheting (12/31/2018)

Approach: Time dependence (viscoelasticity/viscoplasticity)

- FM300-2

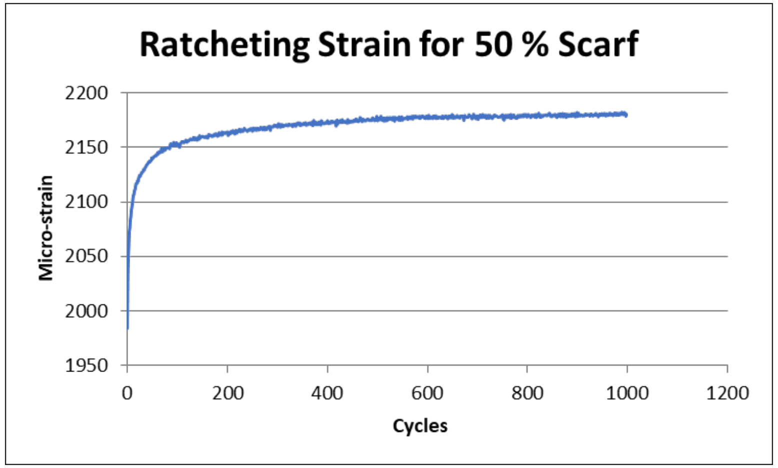




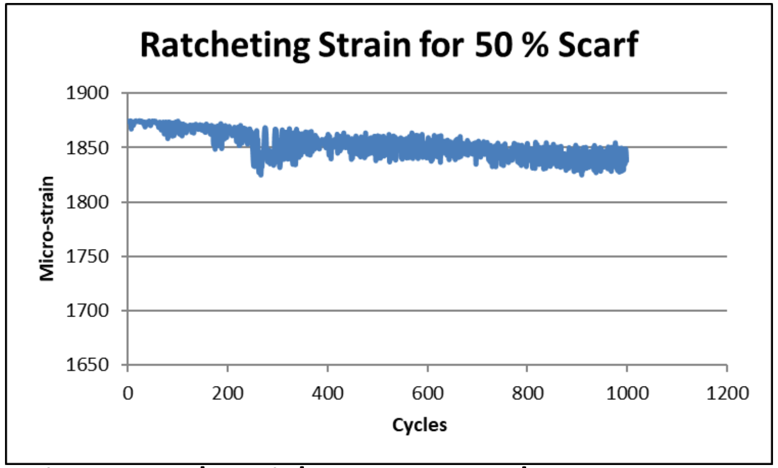


Ratcheting Efforts (Extensometer)

- Extensometer can slip during ratcheting
- Used Digital Image Correlation to try to capture peak strains
  - DIC does not sample fast enough
- Shear strain gauge measurement will begin next week



Good ratcheting result from extensometer



Ratcheting result with suspected extensometer slippage

Approach: Time dependence (viscoelasticity/viscoplasticity)

- Tensile Viscoelasticity Modeling on Bulk Resin

Material Type	Material Model	Components of Model	Nonlinear	Time-Dependent	Tried	Results
Elasticity	22.2 Linear Elasticity	Elastic				
	22.3 Porous Elasticity	Porous Elastic	●			
	22.4 Hypoelasticity	Hypoelastic	●			
	22.5 Hyperelasticity	Hyperelastic	●			
Plasticity	23.2.1 Classical Metal Plasticity	Plastic	●			
	23.2.4 Rate-Dependent Plasticity	Creep: time hardening	●	●	●	No viscoelastic strain in recovery stage.
	23.2.6 Anisotropic Yield/Creep	Plastic or Creep	●	●		
	23.2.11 Two-Layer Viscoplasticity	Elastic Plastic Viscous: time hardening	●	●	●	Difference in creep stage of 80% loading.
Viscoelasticity	22.7 Linear Viscoelasticity	Viscoelastic		●	●	No permanent strains in recovery.
	22.8.1 Hysteresis in Elastomers	Hysteresis Hyperelastic	●	●	●	Can not fit for three kinds loading simultaneously.
	22.8.2 Parallel Rheological Framework	Hyperelastic Viscous: strain hardening	●	●	●	Difference in creep and recovery stages of 80% loading.

Simulate the tensile creep-recovery behaviors of EA9696 bulk coupons under loading of 20% UTS, 50%UTS and 80% UTS.

Approach: Time dependence (viscoelasticity/viscoplasticity)

- 23.2.4 Rate Dependent Plasticity

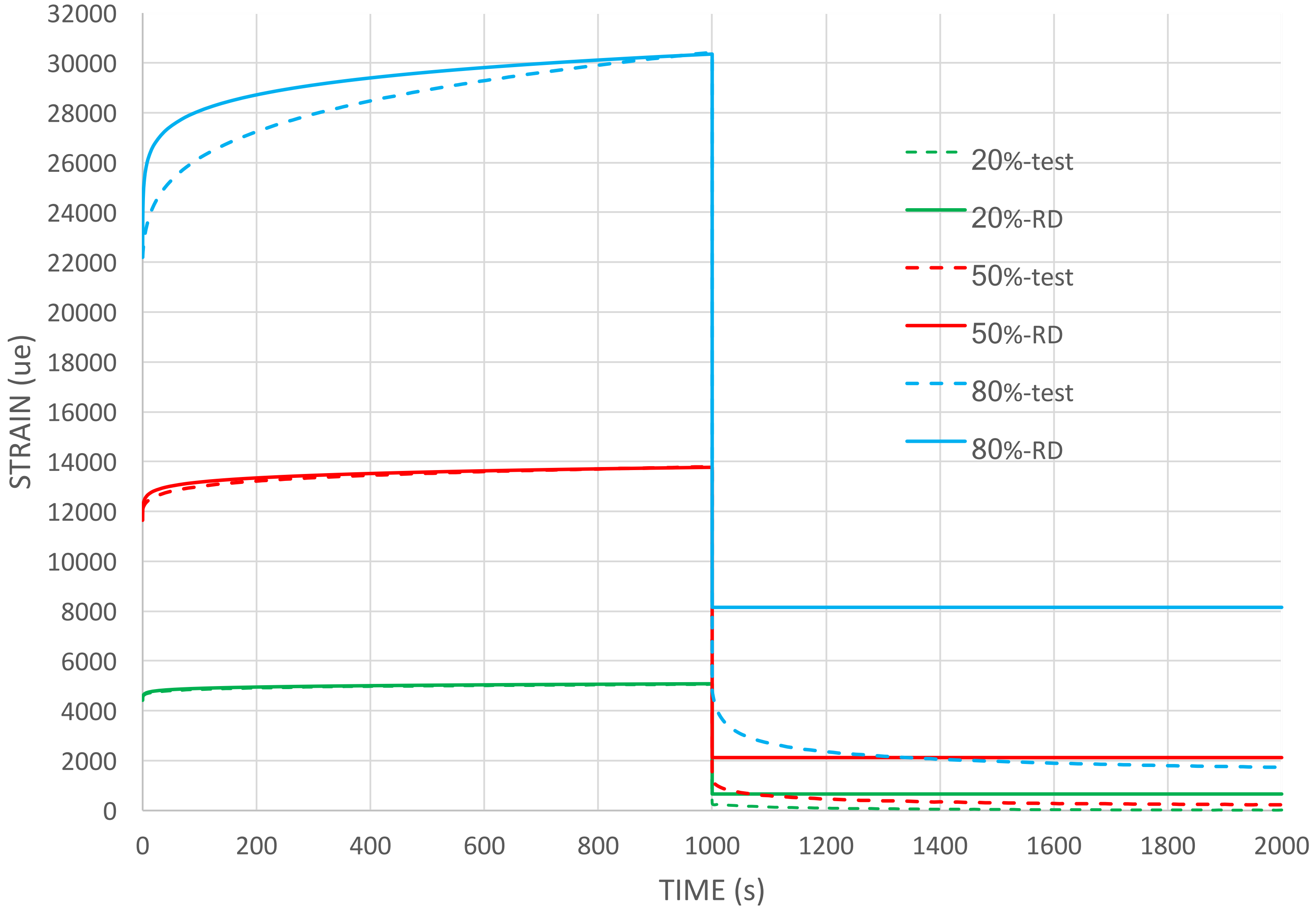


Fig.1 comparison between simulation and test

- Time hardening:
  $\dot{\varepsilon}^{cr} = A\sigma^{n} \cdot t^{m}$

Parameter	20%	50%	80%
E0(MSI)	283842.8	269043.2	234234.2
A	3.8e-8	3.8e-8	2.8e-8
n	1	1	1.17
m	-0.92	-0.92	-0.92

Approach: Time dependence (viscoelasticity/viscoplasticity)

- 23.2.11 Two-Layer Viscoplasticity

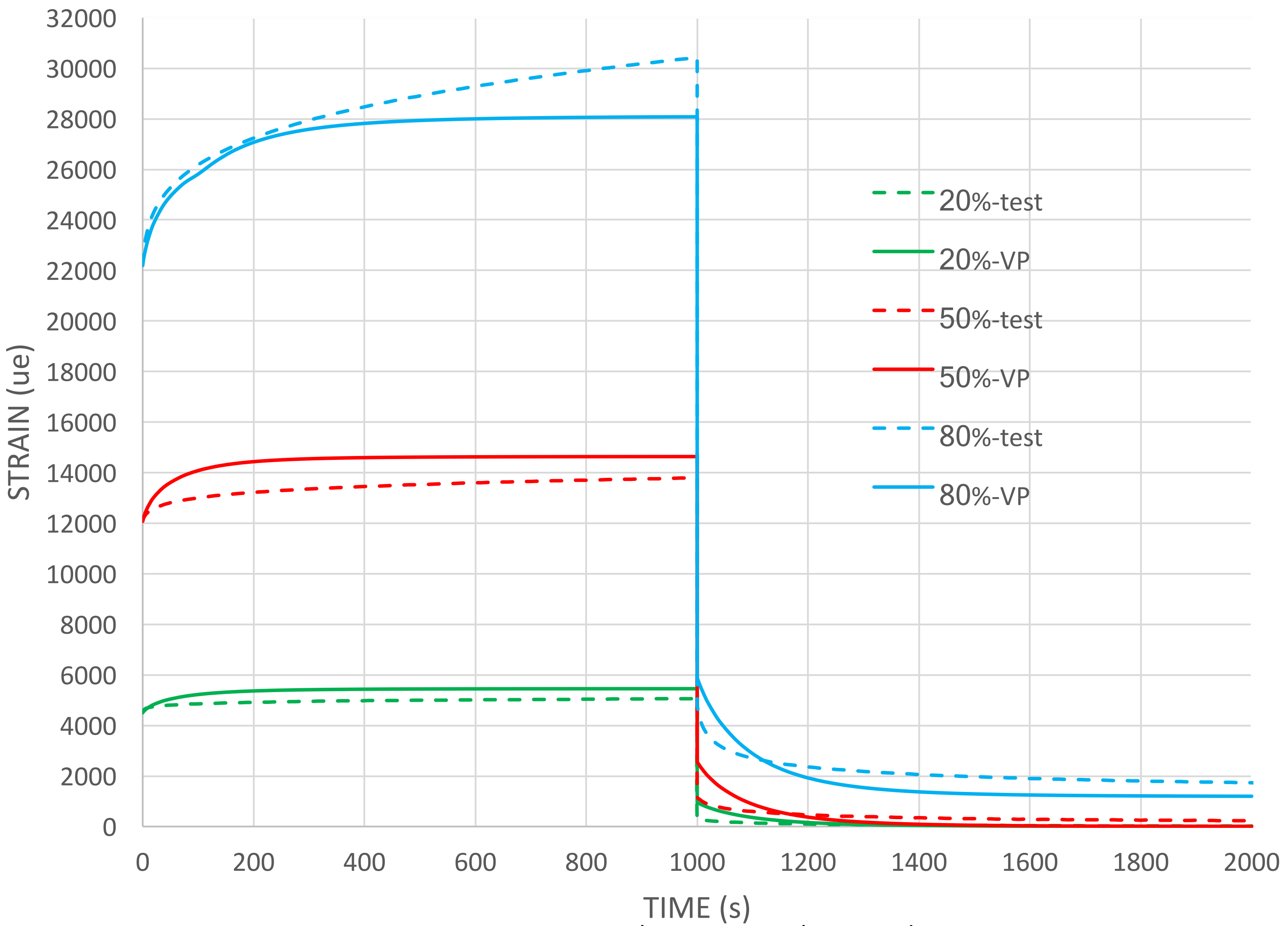


Fig.2 comparison between simulation and test

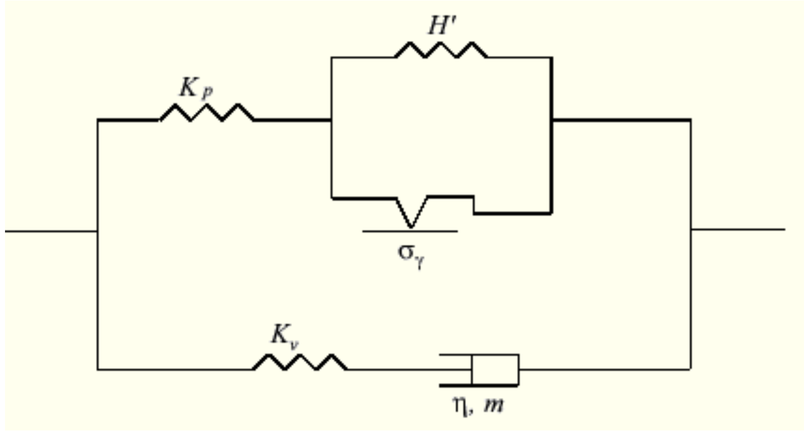


Fig.3 Model Sketch

- Viscous part: $\dot{\varepsilon}_{ev}^{v} = A \cdot {\sigma_{ev}}^{n} \cdot t^{m}$

Parameter	Value
A	2.496e-7
n	1.1809
m	-0.12968

Approach: Time dependence (viscoelasticity/viscoplasticity)

- 22.7 Linear Viscoelasticity

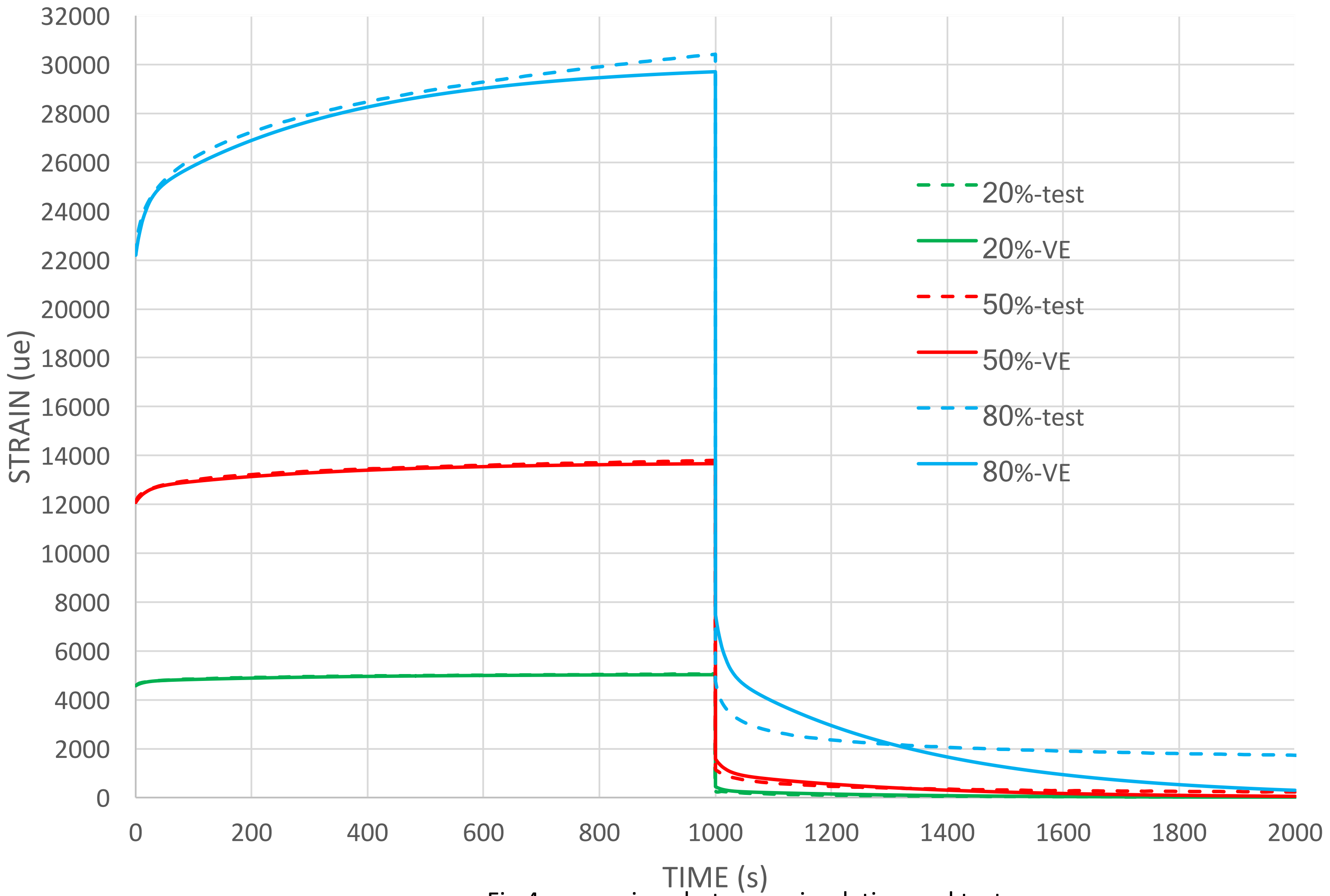


Fig.4 comparison between simulation and test

- 2-branch Prony series

Parameter	20%	50%	80%
E0(MSI)	283842.8	269043.2	234234.2
G1	0.0398	0.0511	0.0487
τ1(S)	13.228	20.654	16.6
G2	0.057	0.0733	0.0758
τ2(S)	306.47	318.44	308

Approach: Time dependence (viscoelasticity/viscoplasticity)

- 22.8.1 Hysteresis in Elastomers

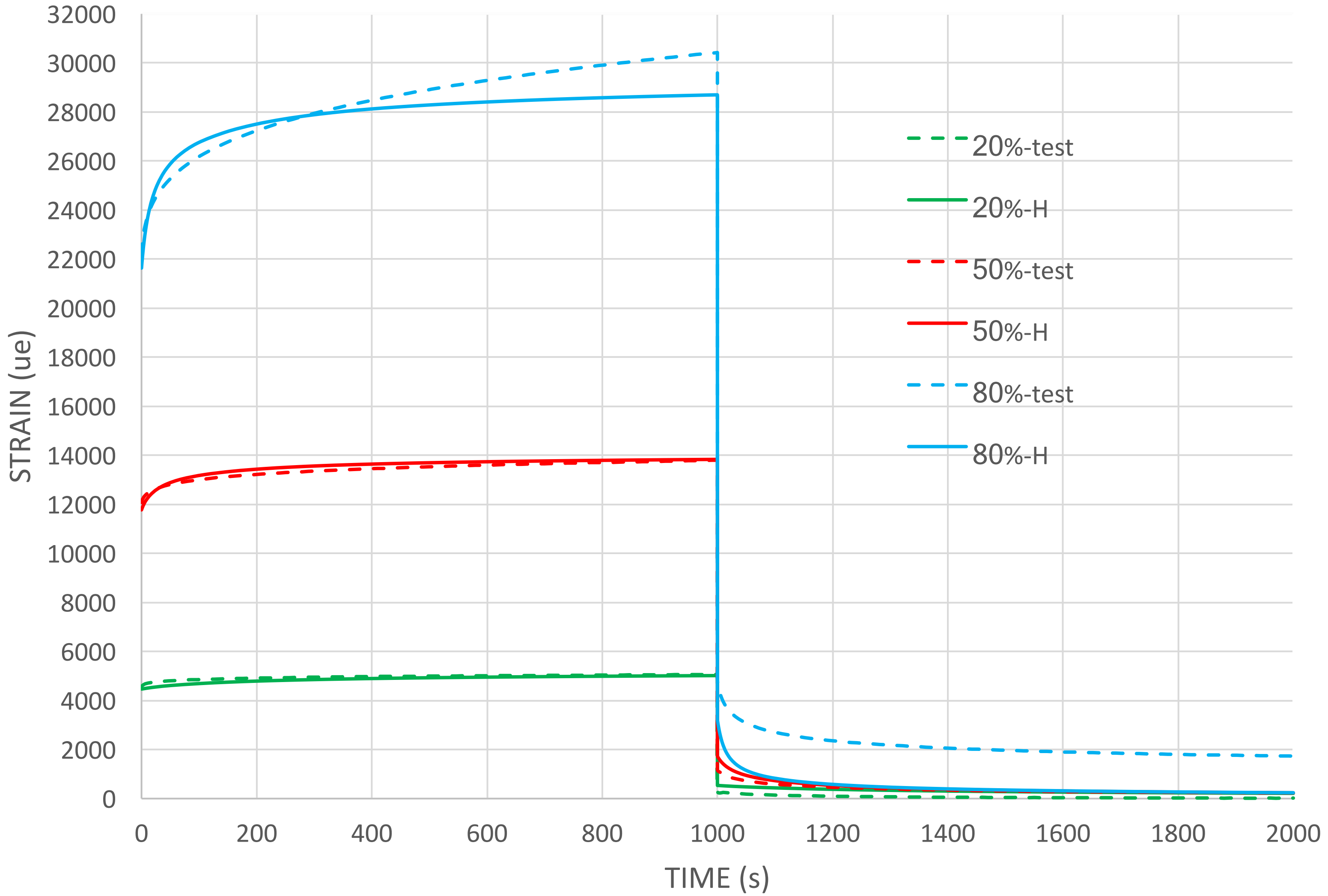


Fig.7 comparison between simulation and test

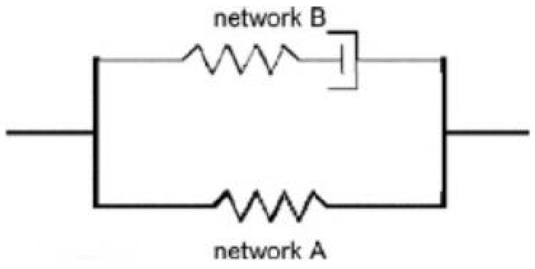


Fig.8 Model Sketch

- Network B: $\dot{\epsilon}_B^{cr} = A \cdot (\epsilon^{cr})^C \cdot \sigma_B{}^m$

Parameter	Value
A	3.8969e-3
m	3
c	-0.082312

Approach: Time dependence (viscoelasticity/viscoplasticity)

- 22.8.1 Hysteresis in Elastomers

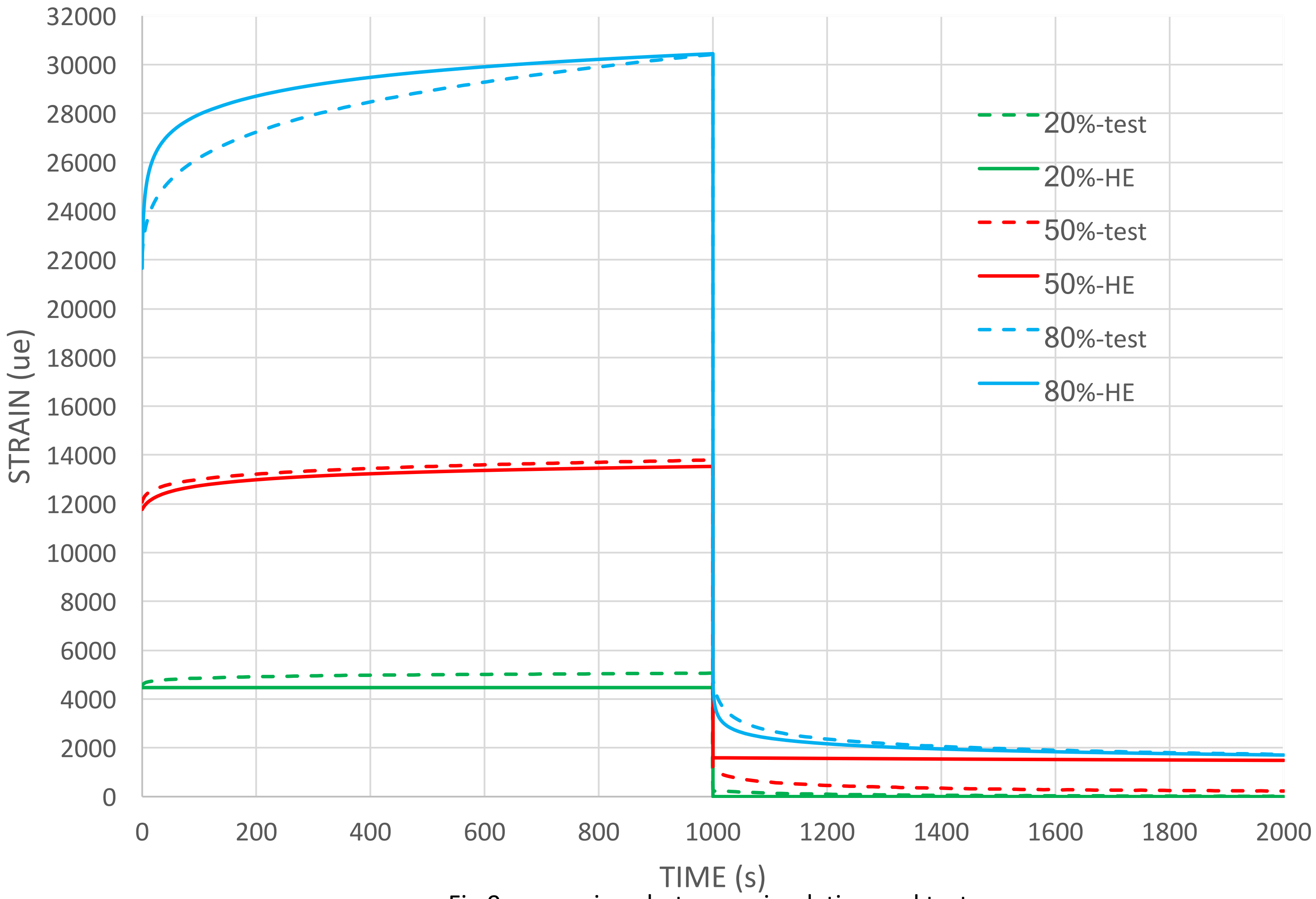


Fig.9 comparison between simulation and test

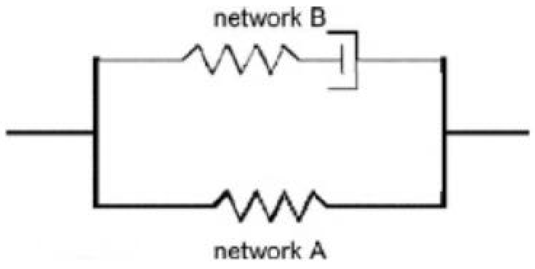


Fig.10 Model Sketch

- Network B: $\dot{\epsilon}_B^{cr} = A \cdot (\epsilon^{cr})^C \cdot \sigma_B{}^m$

Parameter	Value
A	3.8696e-3
m	8.4
c	-0.02312

Approach: Time dependence (viscoelasticity/viscoplasticity)

- 22.8.2 Parallel Rheological Framework

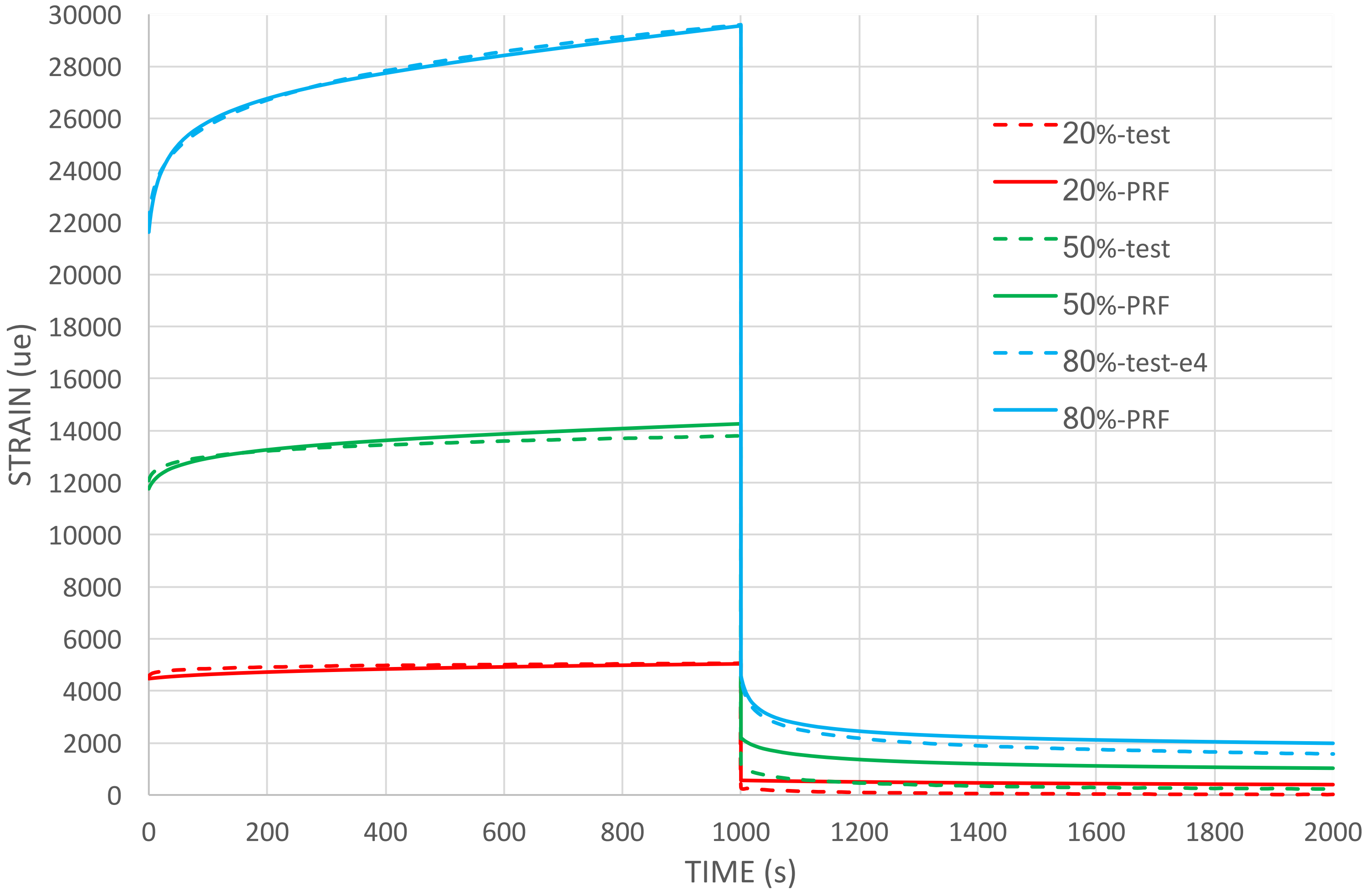


Fig.5 comparison between simulation and test

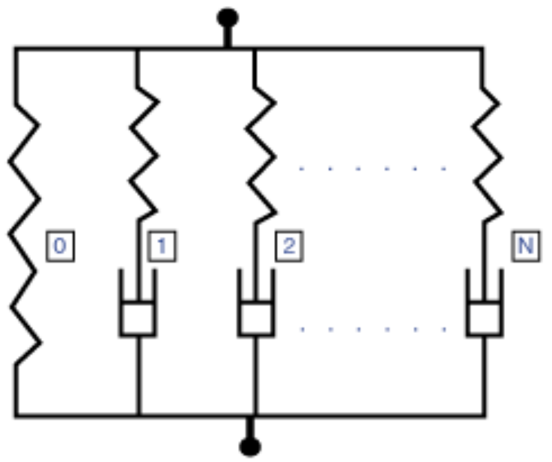


Fig.6 Model Sketch

- Viscous part:

$$\dot{\epsilon}^{cr} = \left(Aq^n[(m+1)\epsilon^{cr}]^m\right)^{\frac{1}{m+1}}$$

Parameter	Branch-1	Branch-2	Branch-3
A	2.01e-12	9.7e-14	2.94e-11
n	3.1284	1.4683	1.6875
m	-0.04	-0.09	-0.007

Approach: Time dependence (viscoelasticity/viscoplasticity)

- 22.8.2 Parallel Rheological Framework-Ratcheting

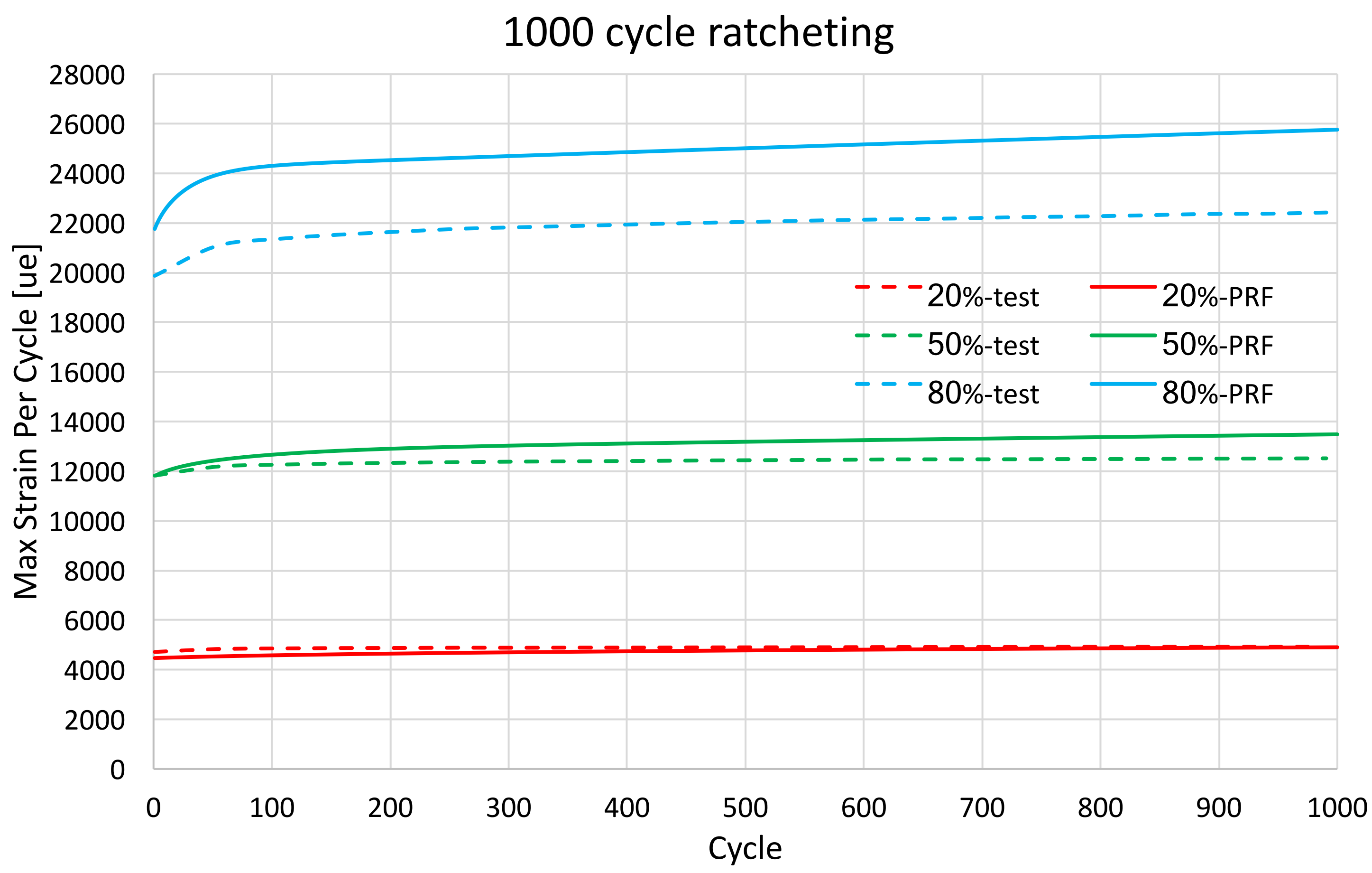
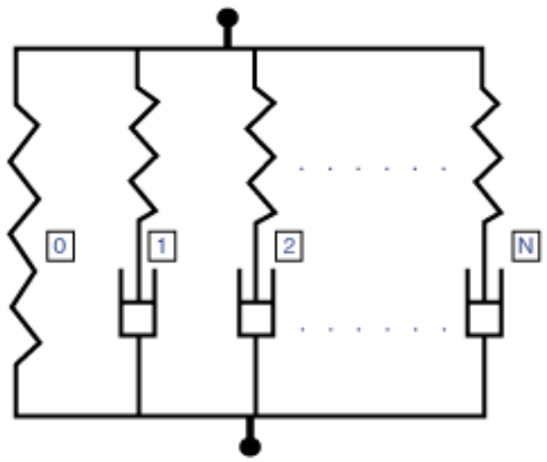


Fig.5 comparison between simulation and test



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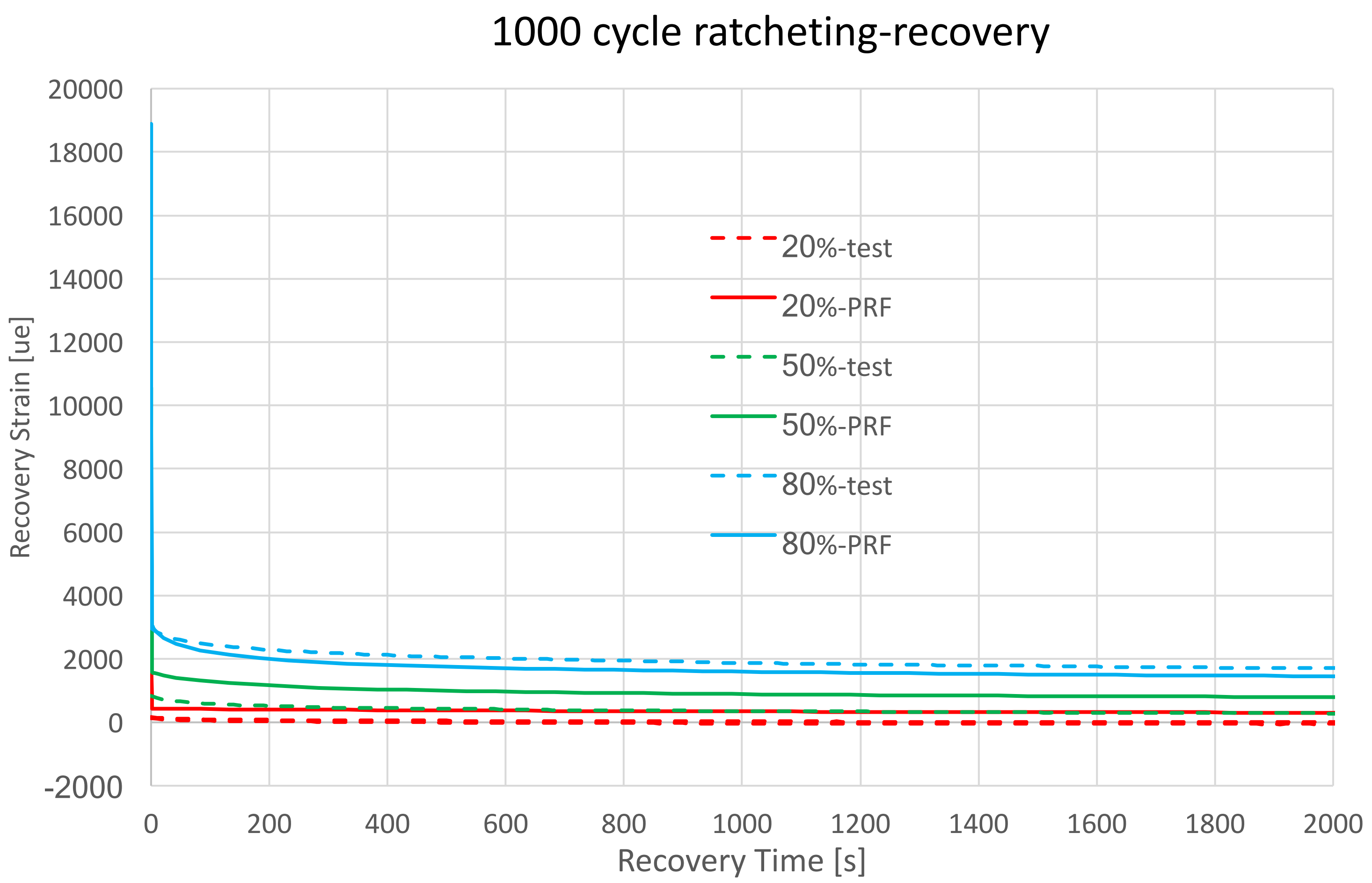

Fig.5 comparison between simulation and test

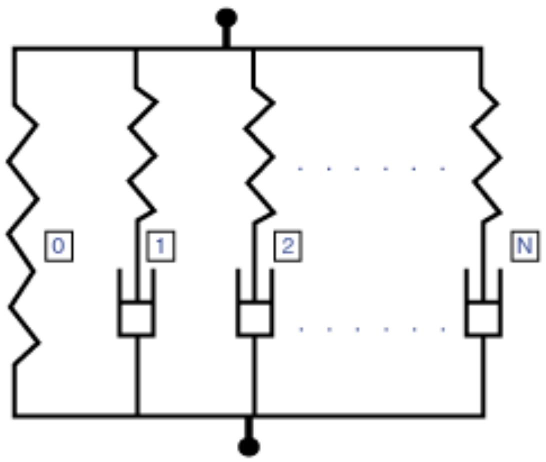

Fig.6 Model Sketch

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Approach: Time dependence (viscoelasticity/viscoplasticity)

- Further Work

➢ Tensile Viscoelasticity Modeling on Bulk Resin (12/31/2017)

- Optimize parameters in mentioned Parallel Rheological Framework Model and Two-Layer Viscoplasticity Model
- Modify the viscous equations(exponents expression) in PRF and Two-Layer Viscoplasticity Models which have effect on the slope of creep curve and permanent strain
- A model with higher strain rate for 80% loading
- UMAT

➢ Shear Viscoelastic Modeling on Bonded Joints for Creep (05/31/2018)

- Simulate the creep/recovery behavior of WALS coupons, scarf joints.
- Verify the linear/ nonlinear model by comparison with the test data.

➢ Shear Viscoelastic Modeling on Bonded Joints for Ratcheting (12/31/2018)

- Simulate the ratcheting/recovery behavior of WALS coupons, scarf joints.
- Verify this model by comparison with the test data.

Summary

- Plasticity
  - Adhesives we’ve tested follow a von Mises yield criterion
  - Adhesives we’ve tested follow a kinematic hardening rule

- Viscoelasticity
  - Adhesives become non-linear about 50% UTS
  - Ratcheting response is greater in shear than in normal stress

Future work

- Plasticity
  - Complete yield and hardening tests
  - Incorporate yield and hardening results in a predictive FEA model

- Viscoelasticity
  - Complete ratcheting experimental tests
    - Include strength and fracture toughness changes with ratcheting
  - Develop FEA model of non-linear viscoelastic response under creep
  - Apply model to shear and ratcheting loading environments