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Durability of adhesive bonded joints in aerospace structures

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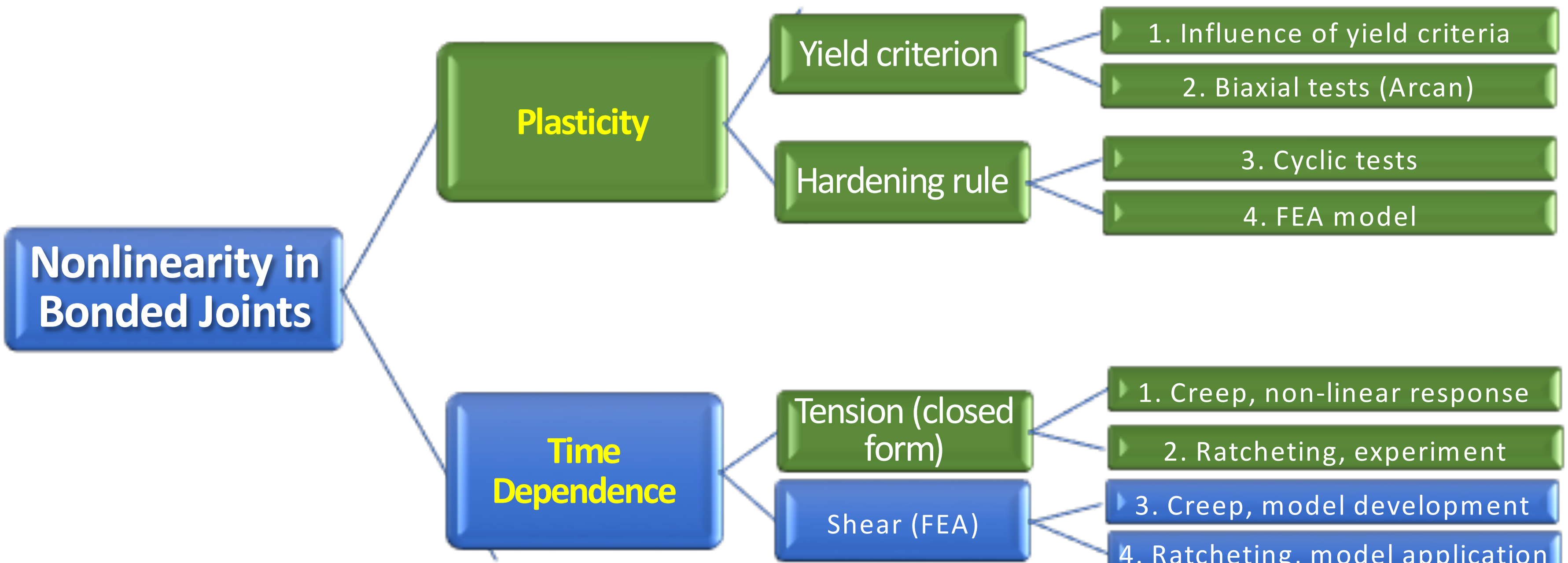
Durability of adhesive bonded joints in aerospace structures

- Principal Investigators & Researchers
  - Lloyd Smith
  - Preetam Mohapatra, Yi Chen, Trevor Charest
- FAA Technical Monitor
  - Ahmet Oztekin
- Other FAA Personnel Involved
  - Larry Ilcewicz
- Industry Participation
  - The Boeing Company: Will Grace, Peter VanVoast, Kay Blohowiak

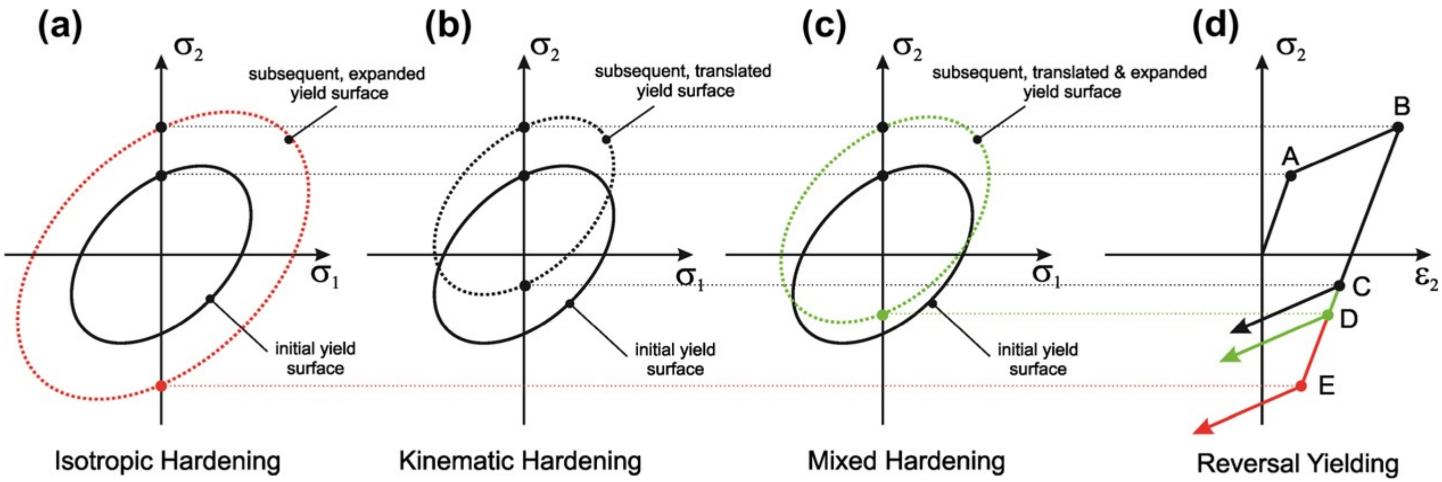
Durability of bonded aircraft structure

- 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
  - Describe plastic adhesive response.
  - Develop time-dependent adhesive models.
- Approach
  - Experiments designed to clarify constitutive relations.
  - Develop FEA Models of adhesive bonds.
  - Compare models with experiments that are unlike constitutive tests.

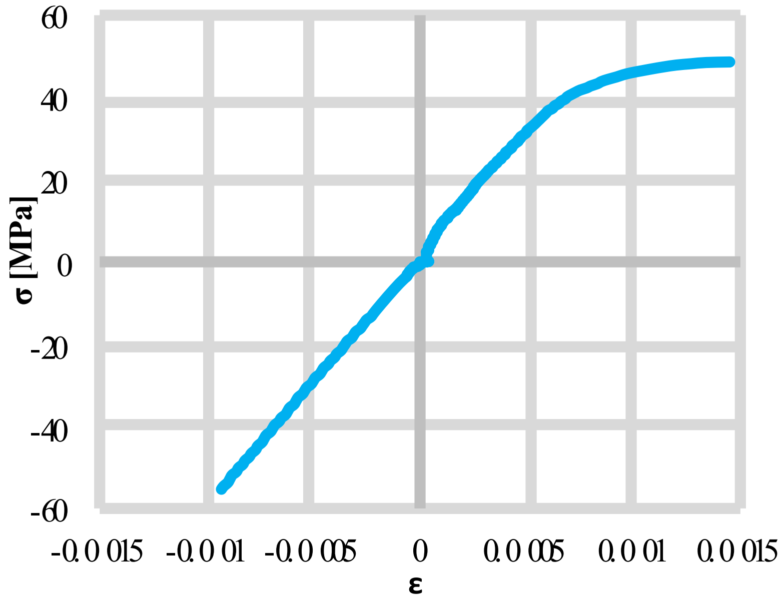
Durability of adhesive bonded joints in aerospace structures



Plasticity : Hardening Rule: Challenges



Ref: Muransky O. et al [Metal Plasticity]



What we found:

To quantify hardening in thin film adhesives we need to load and unload in a shear stress state

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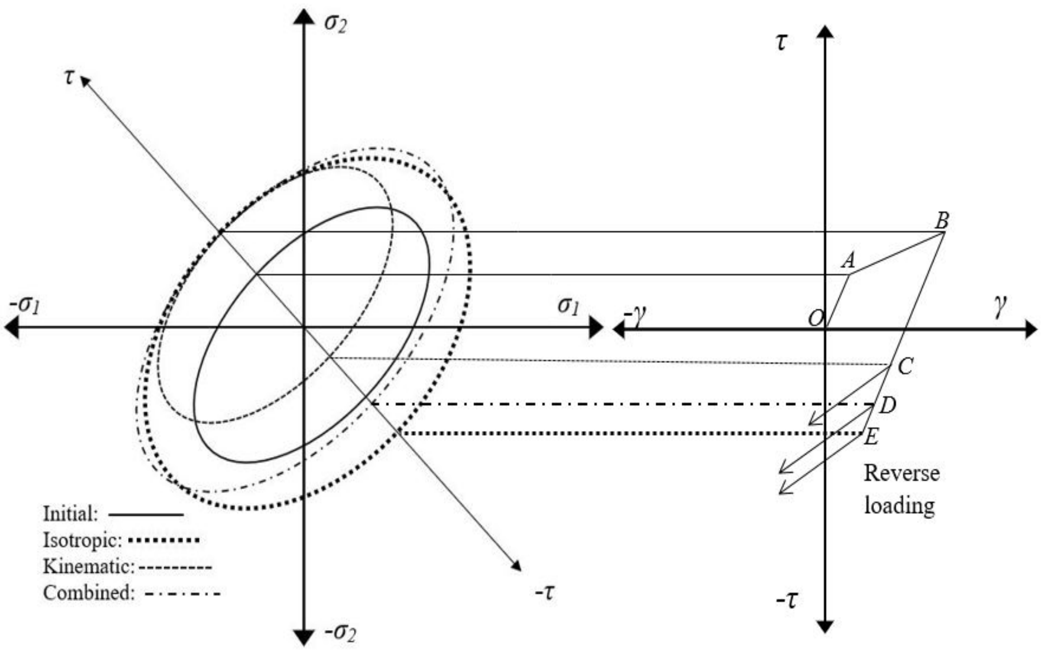
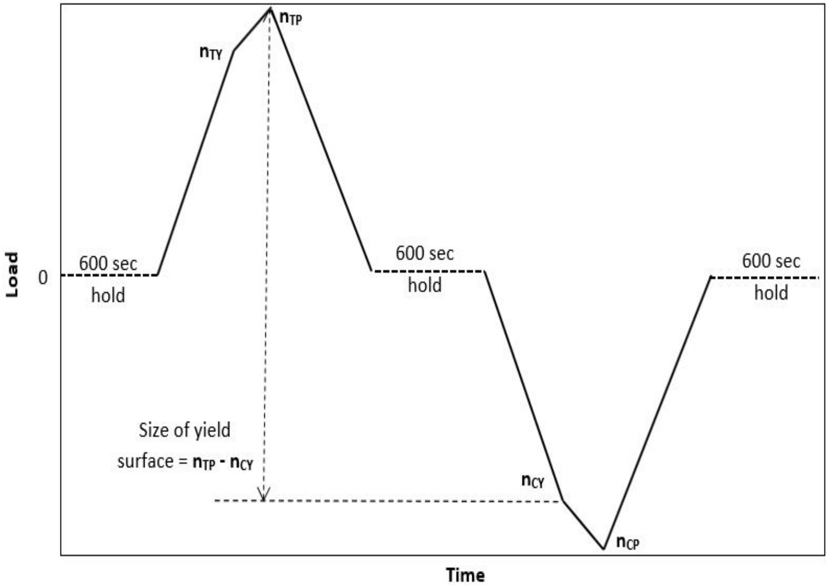
Plasticity : Hardening Rule: in Shear





- Initial size : $Y_o = 2\tau_A$
- Kinematic: $Y_k = \tau_B - \tau_C = 2\tau_A$
- Isotropic: $Y_i = \tau_B - \tau_E = 2\tau_B$
- Combined: $2\tau_A < Y_c = (\tau_B - \tau_D) < 2\tau_B$
- $k = \frac{\tau_B + \tau_D}{2(\tau_B - \tau_A)}$

Schematic presentation of cyclic shear loading

- tensile yield (n_{TY})
- tensile peak (n_{TP})
- compressive yield (n_{CY})
- compressive peak (n_{CP})

Size of yield surface at Nth cycle: $n_{TP} - n_{CY}$

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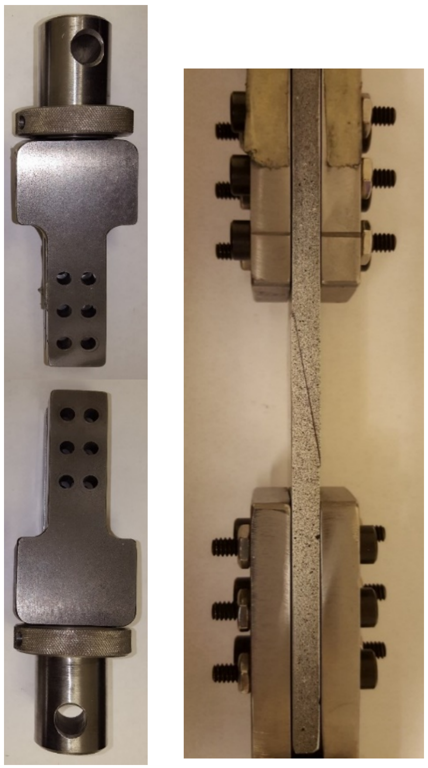
Plasticity : Hardening Rule: Testing



Scarf fixture for tension-compression testing and assembly

Cyclic testing of scarf joint on an Instron to quantify adhesive hardening

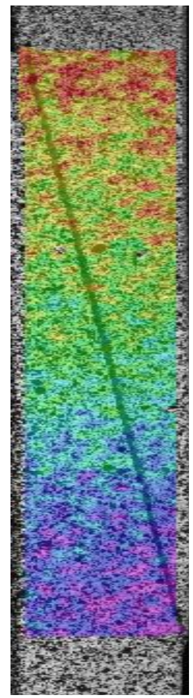
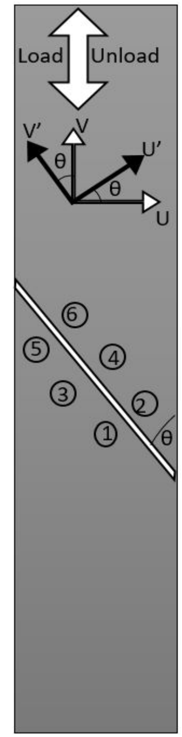


Image analysis software (Vic 3D) used to analyze speckle images for strain calculation



Schematic locations of points tracked to calculate strain

$$\tau_{avg} = \frac{F\cos\theta}{A}$$

$$\gamma_{12} = \frac{dV'_{1-2} - \left(\frac{\tau_{avg}(D-t)}{G}\right)}{t}$$

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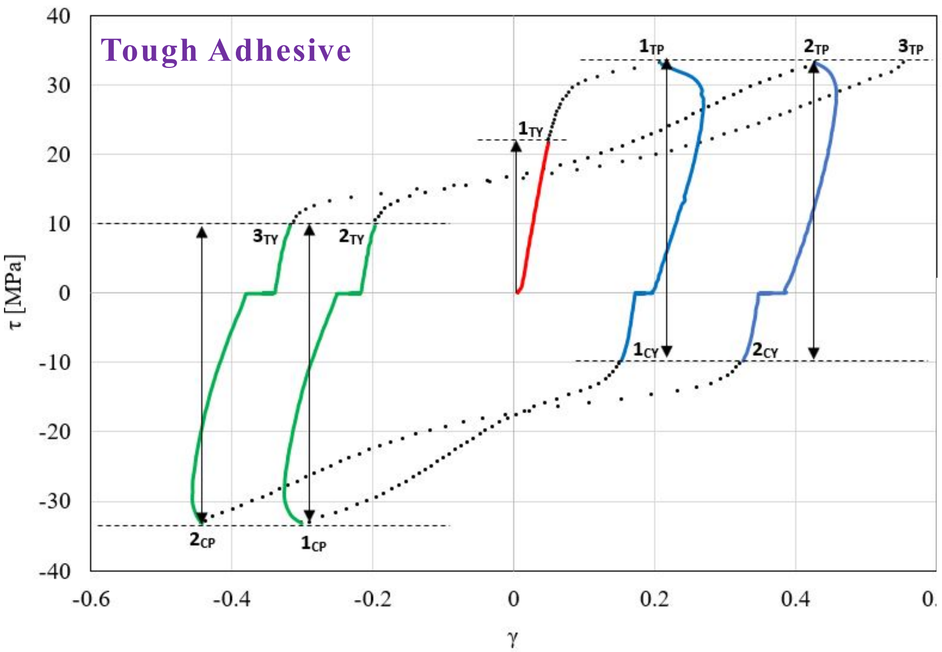
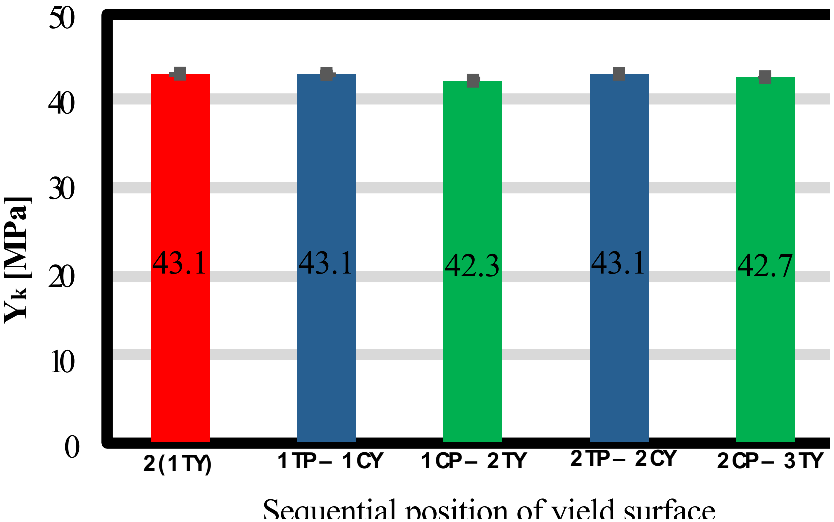
Plasticity : Hardening Rule: Quantification



- 0.2% offset criterion used to determine yield point
- $Y_k \sim 43.1$ MPa

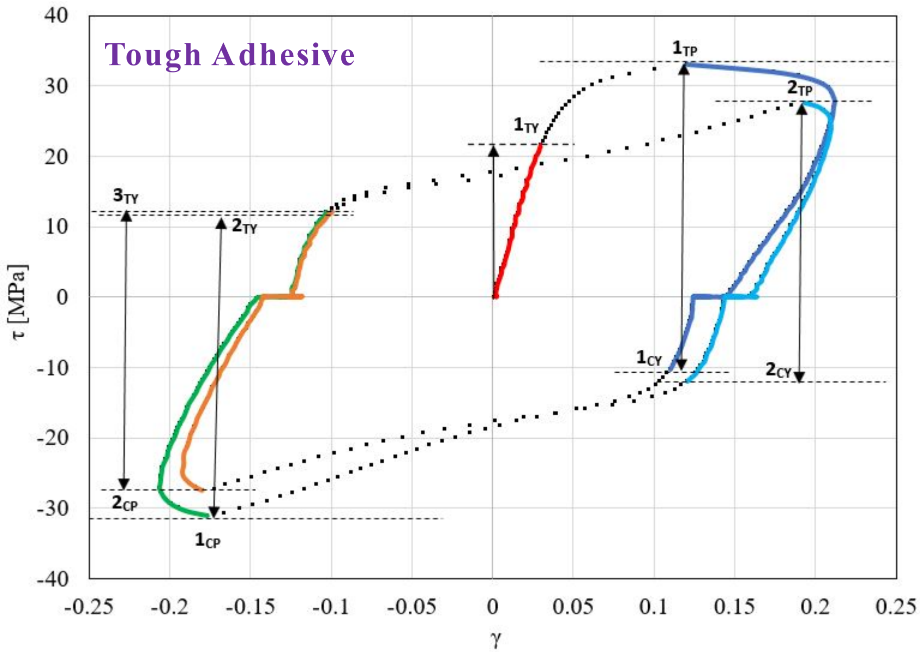


Initial size : $Y_o = 2\tau_A = 43.1$

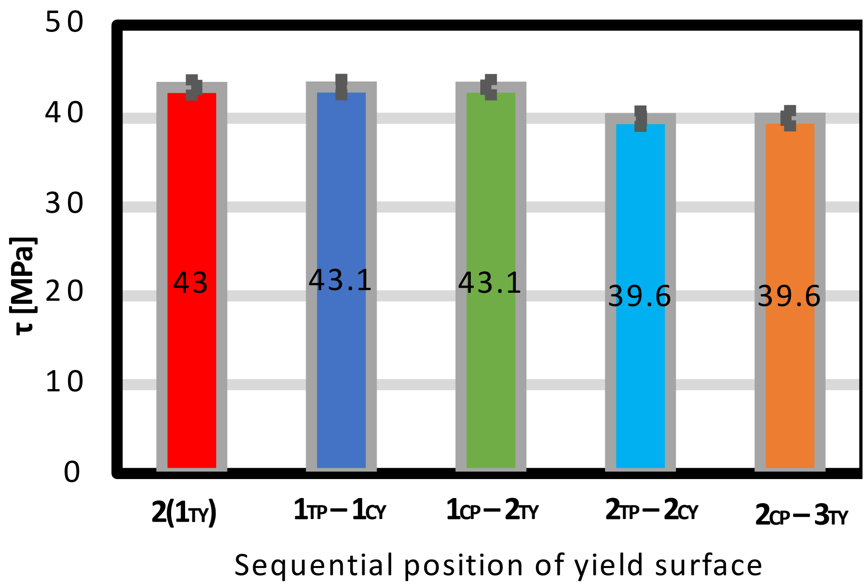
$$Y_k = \tau_B - \tau_C = 43.1$$

What we found: kinematic behavior dominated hardening mechanism of tough adhesive.

Plasticity : Hardening Rule: Quantification



- 0.2% offset criterion used to determine yield point
- Y_k ~ 43.1 MPa -> 39.6 MPa



Initial size : $Y_o = 2\tau_A = 43$

$$Y_k = \tau_B - \tau_C = 43.1, 39.6$$

What we found: Tough adhesive demonstrated kinematic hardening behavior

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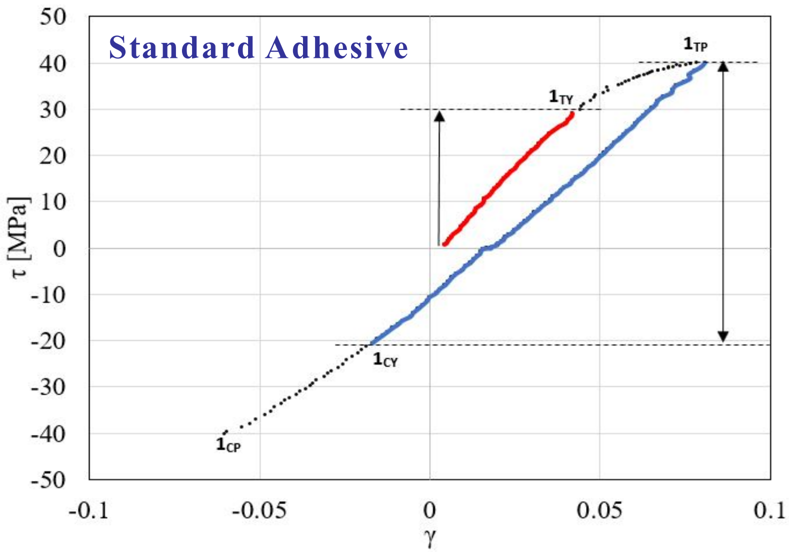
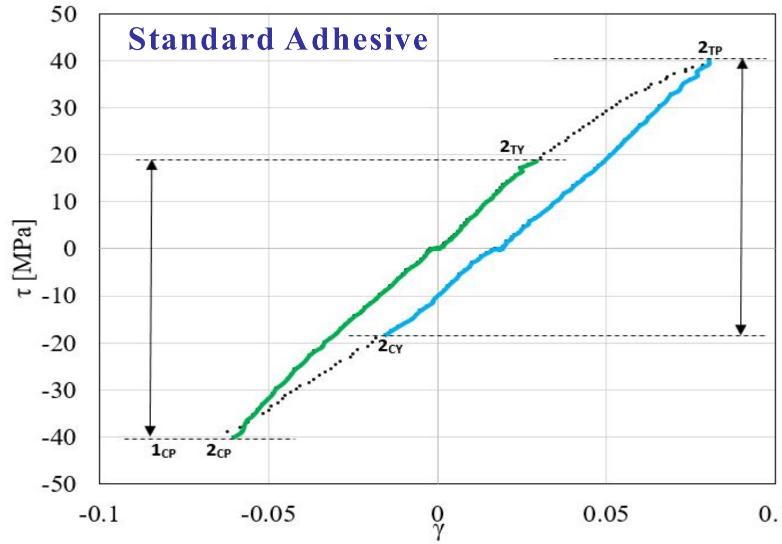
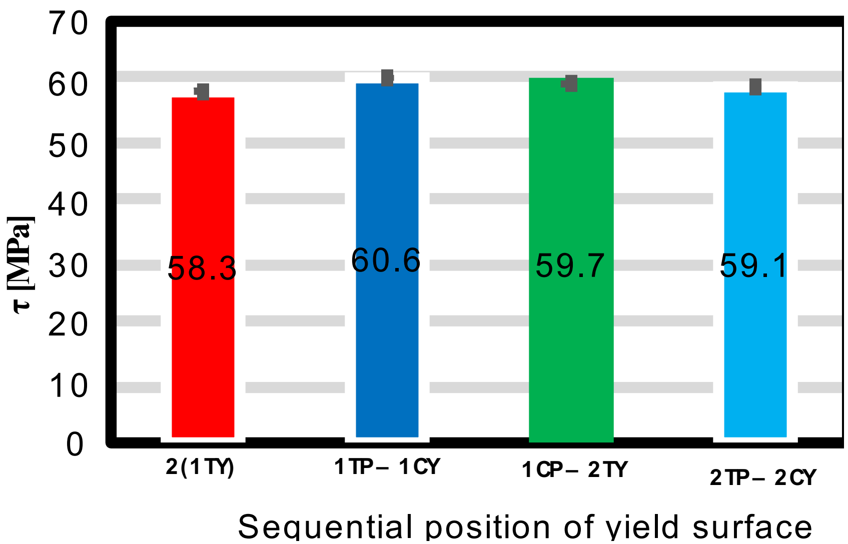
Plasticity : Hardening Rule: Quantification







- 0.2% offset criterion used to determine yield point
- 80.18 (isotropic) > 60.36 (actual size) > 58.28 (kinematic)

$$k = 91\%$$

(91% kinematic & 9% isotropic)

What we found:

Standard adhesive demonstrated combined hardening

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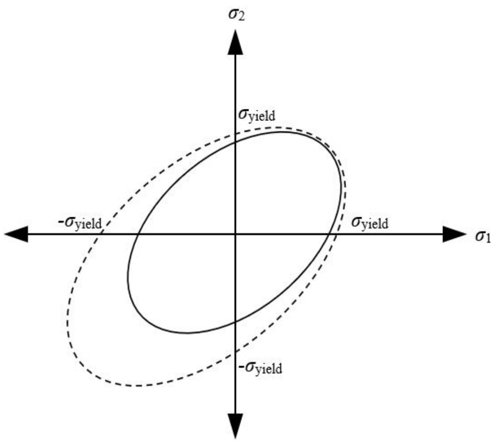
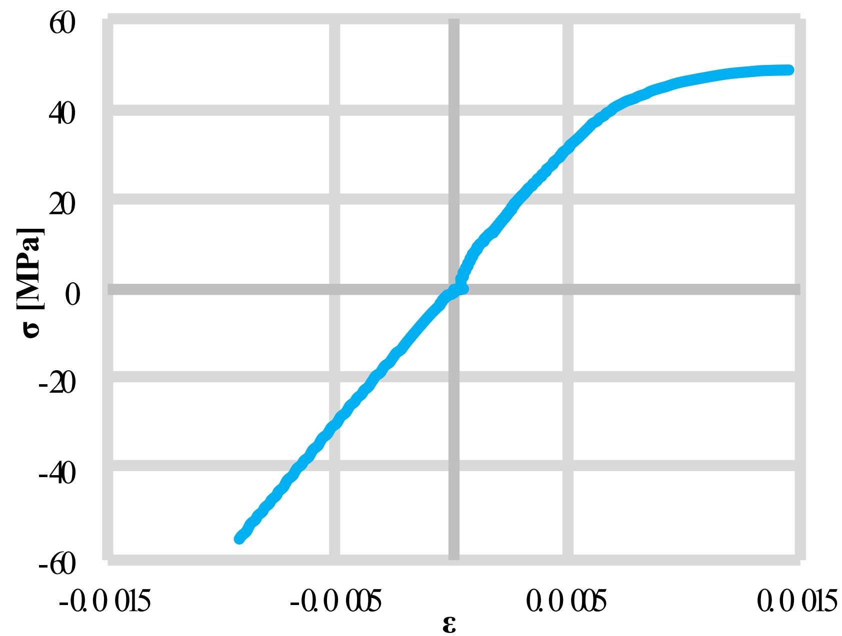
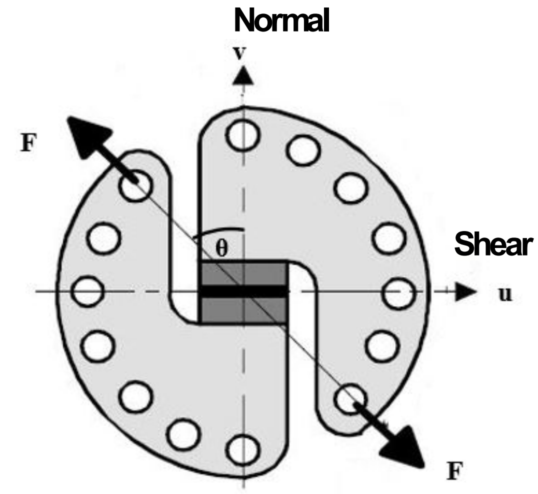
Plasticity: Yield Criterion: Challenges



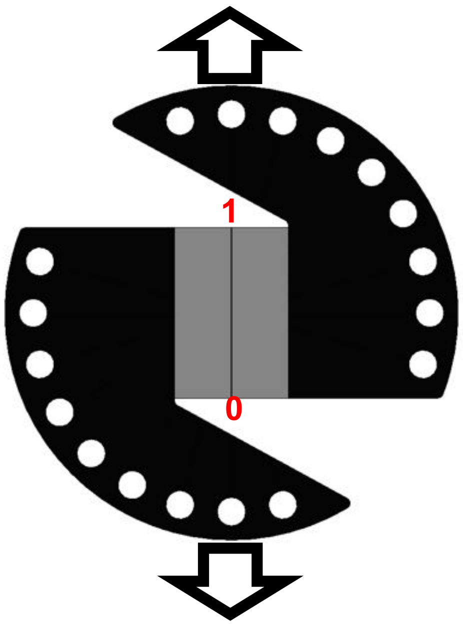




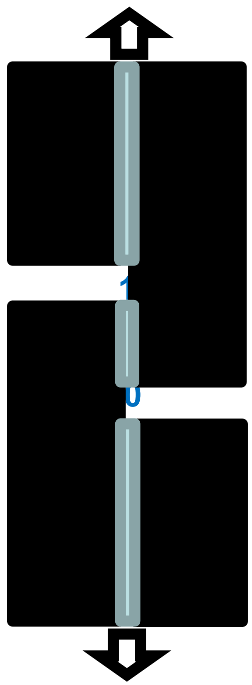
Schematic yield surface in normal-normal stress state:
Solid line = von Mises (typically used for metals)
Dotted line = Drucker-Prager (typically used for rocks, concrete, soil)

- Adhesive joints don't soften at yield in compression.
- Consider normal-shear

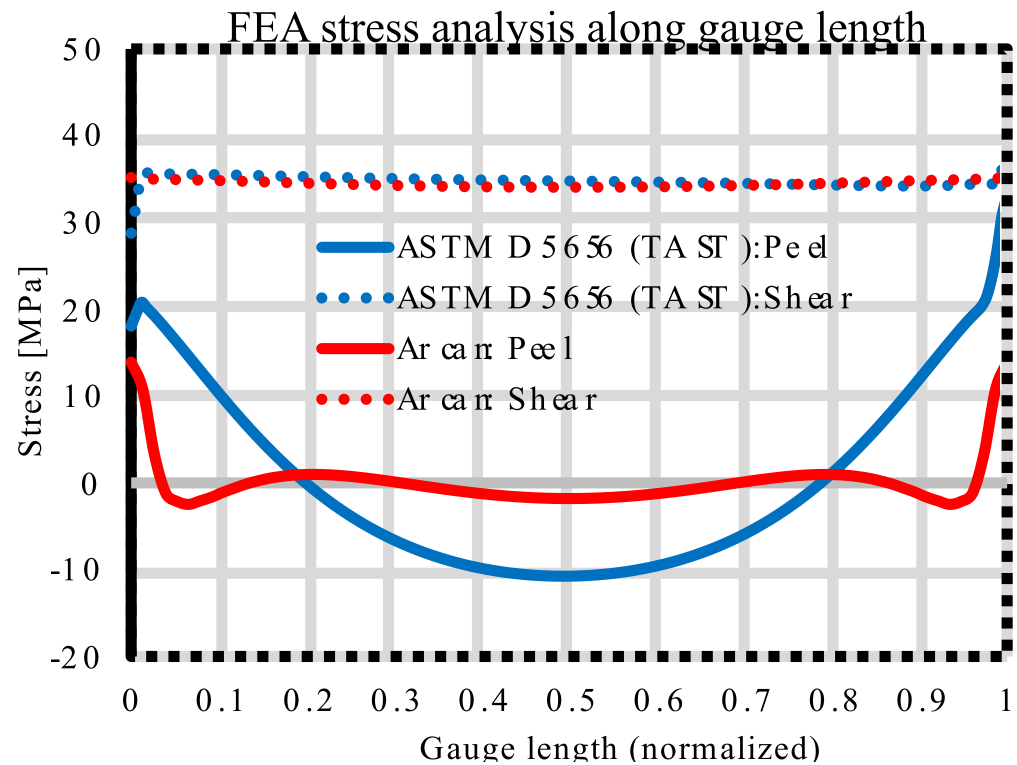
Plasticity: Yield Criterion: Mixed-Mode Fixture Design



Arcan



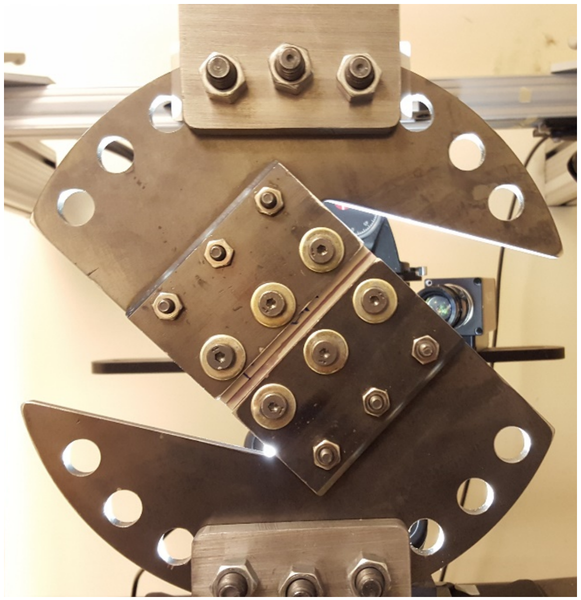
ASTM D 5656 (TAST)

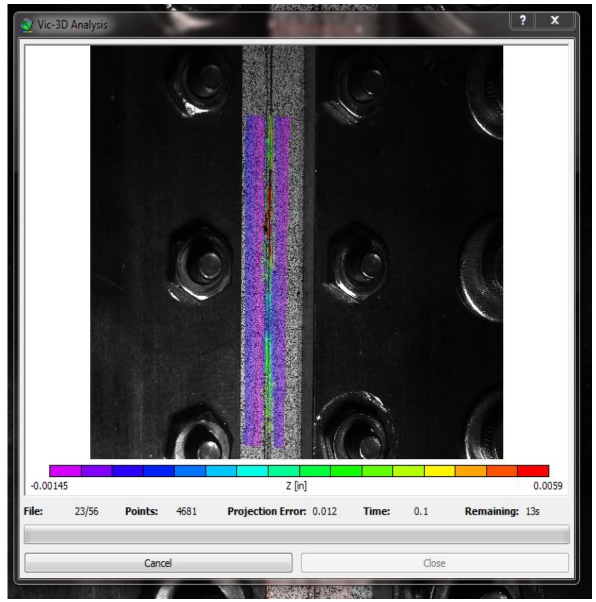


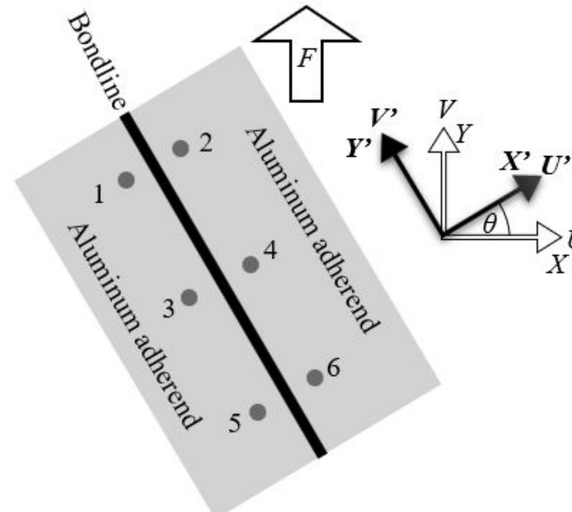
Arcan vs.TAST (ASTM D 5656)

- More uniform stress state
- Higher Shear/peel stress ratio

Plasticity: Yield Criterion: Testing in Normal-Shear







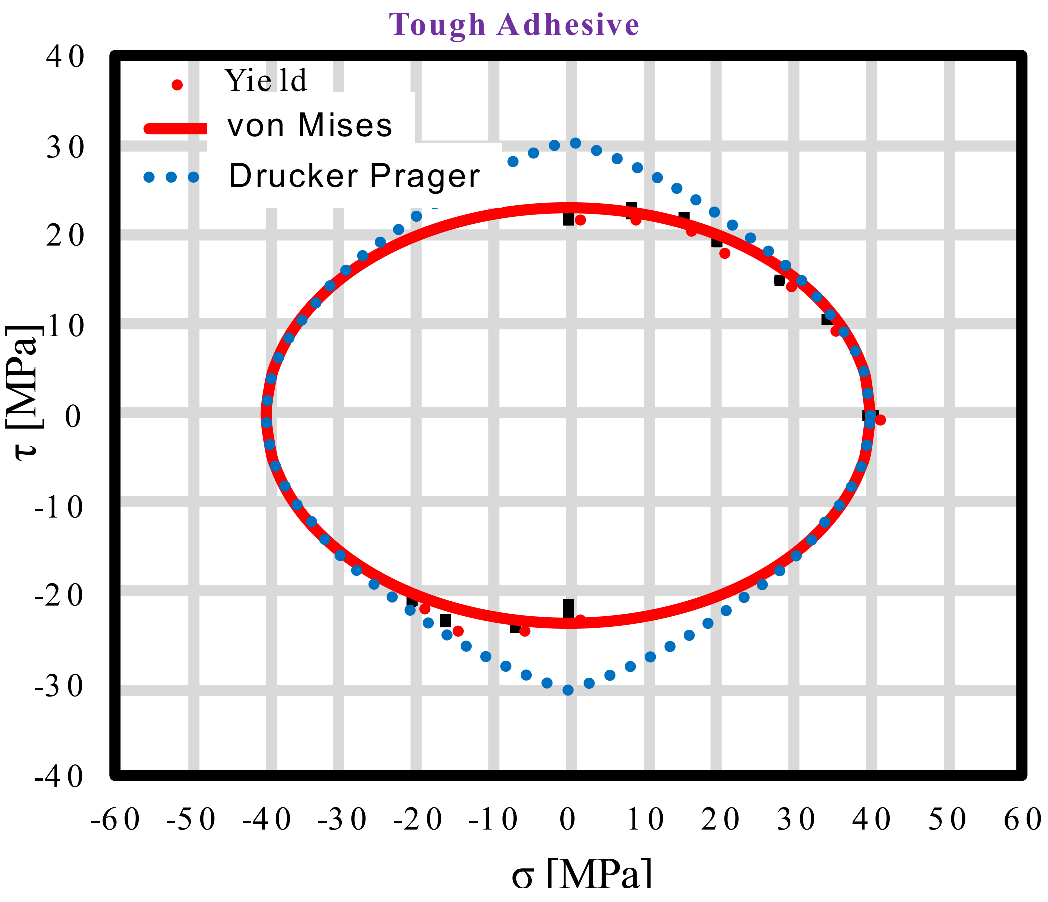
- Designed our own Arcan fixture for conducting biaxial testing
- Testing at 45 degree angle in progress on an Instron load frame

Image analysis software (Vic 3D) used to analyze speckle images for strain calculation

Normal stress: $\sigma_{w'} = \frac{F \sin\theta}{A}$

Shear stress: $\tau_{u'v'} = \frac{F \cos\theta}{A}$

Plasticity: Yield Criterion: Test Results



What we found:

von Mises: best fit

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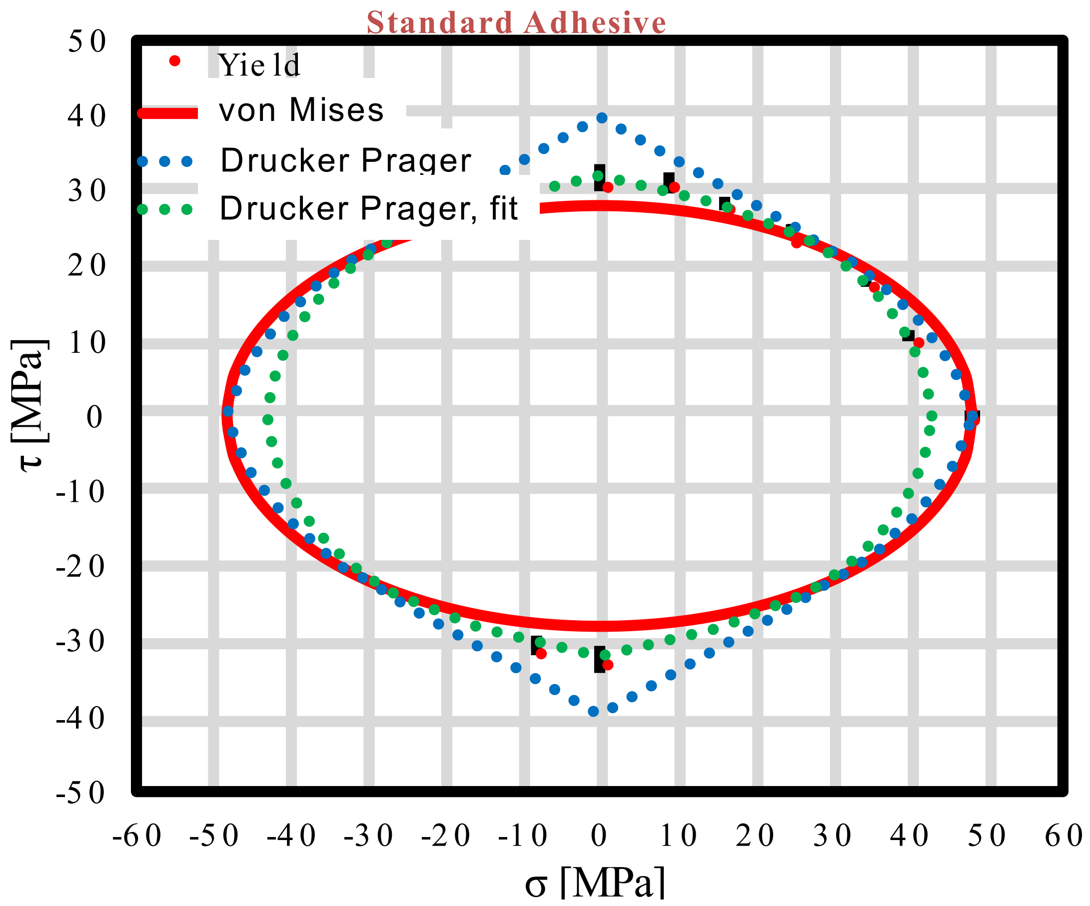
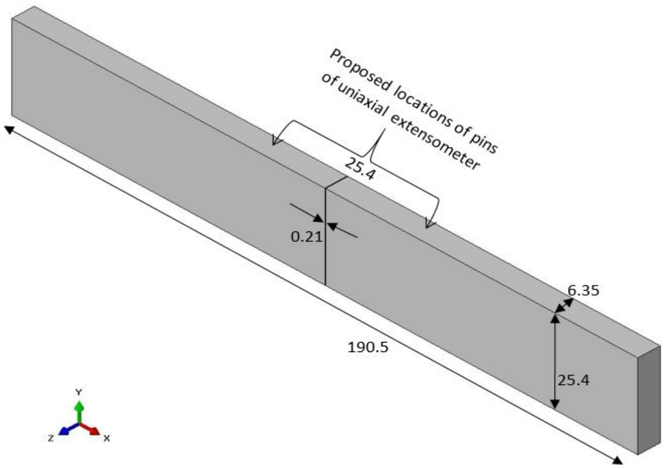
Plasticity: Yield Criterion: Test Results



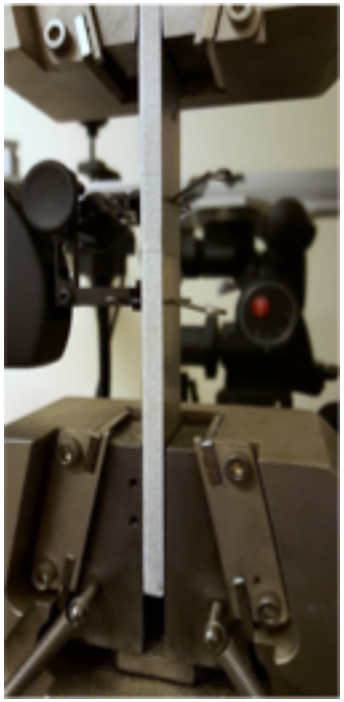
What we found:

von Mises: generally best fit

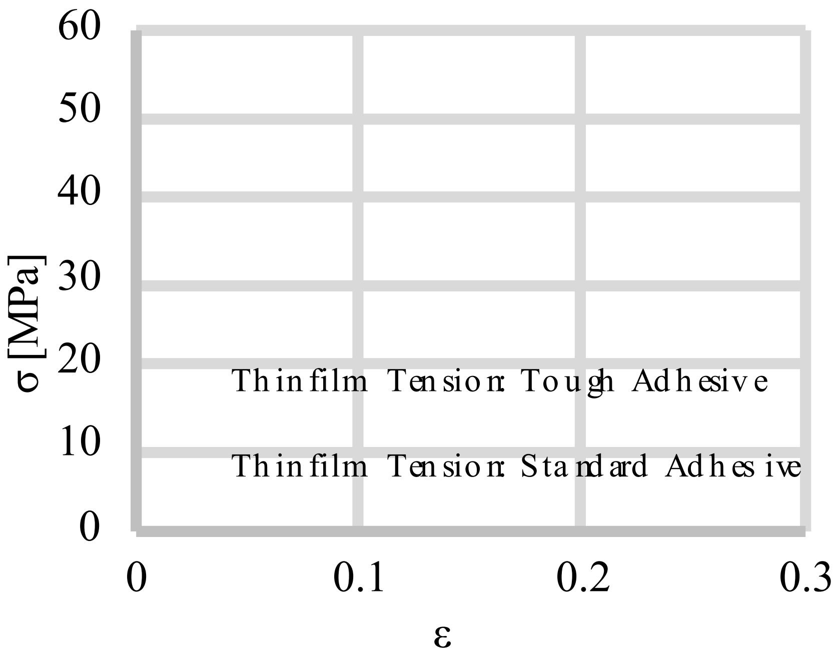
Plasticity: Numerical Modeling: Tensile Input Properties



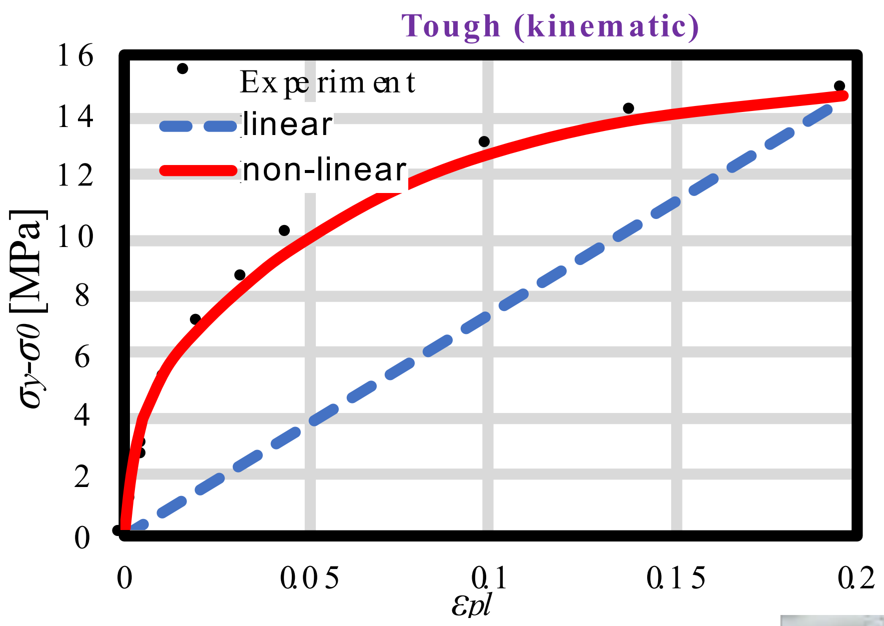
Schematic butt joint with dimensions, load applied in the X direction

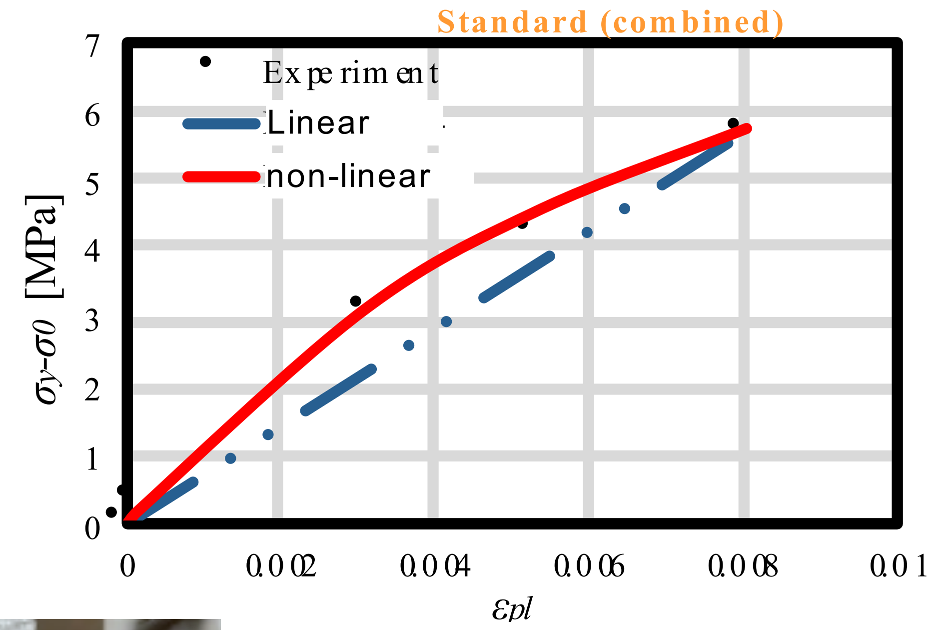


Butt joint being tested on an Instron load frame



Plasticity: Numerical Modeling: Tensile Input Properties





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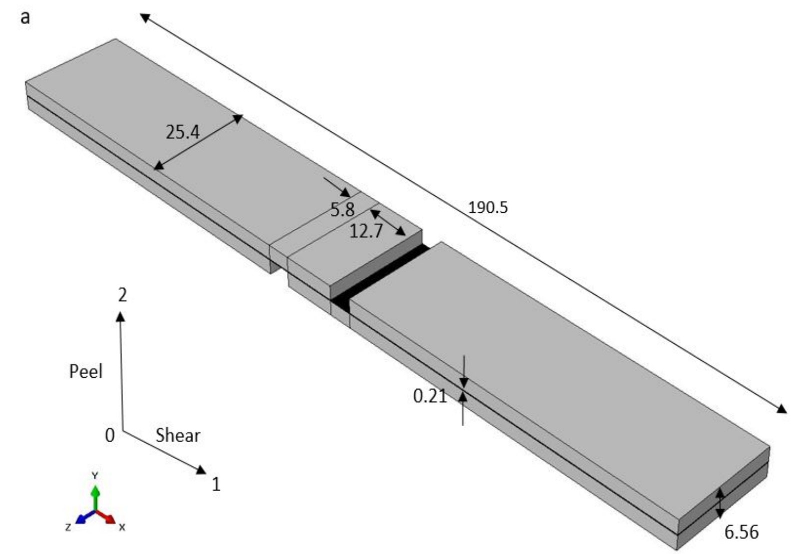
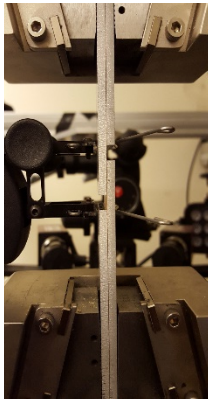
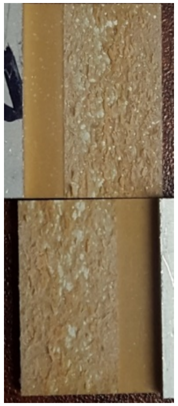
Plasticity: Numerical Modeling: Shear Joints

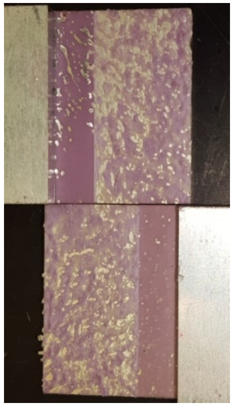




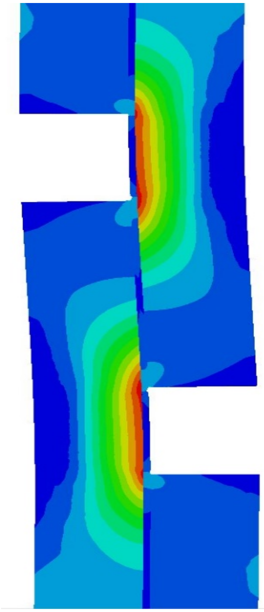
Testing on Instron



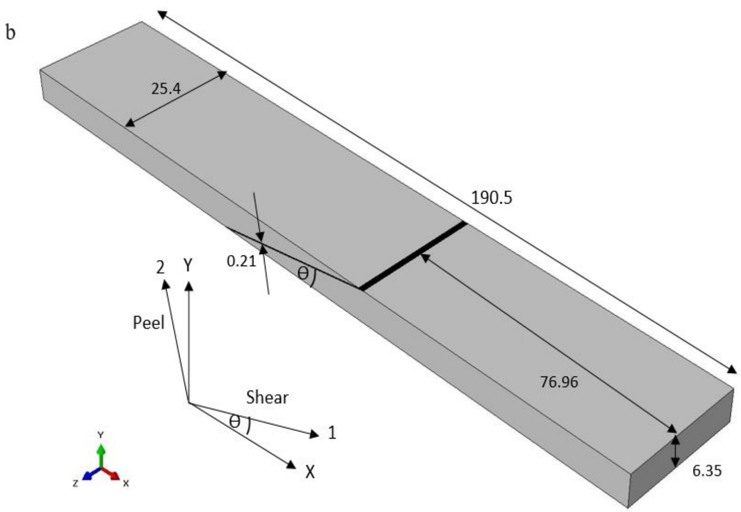
Standard adhesive

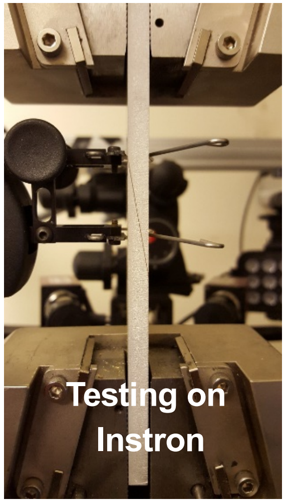


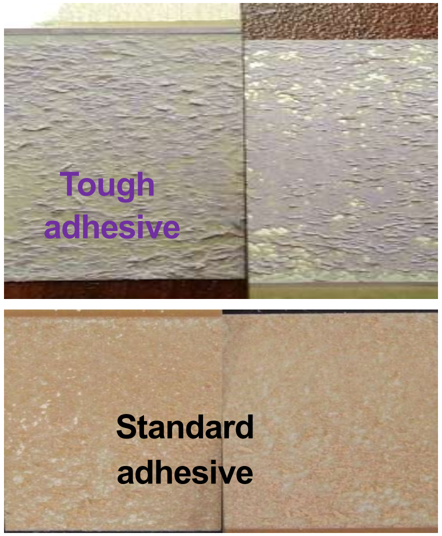
Tough adhesive

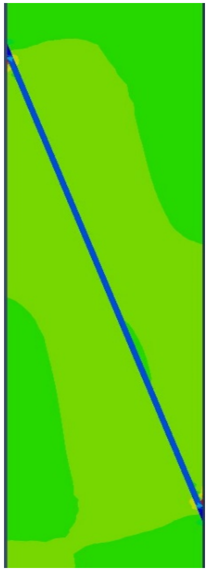


FEA









FEA

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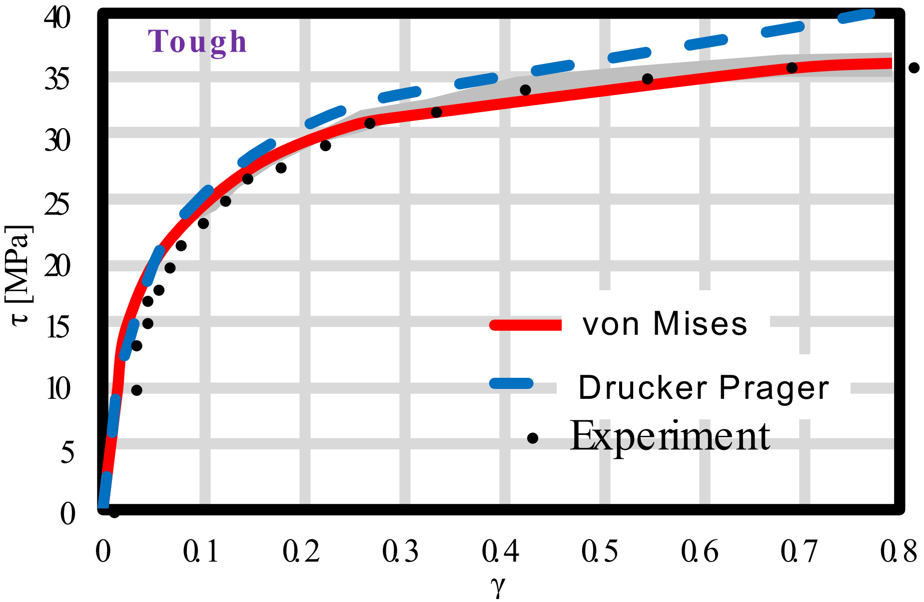
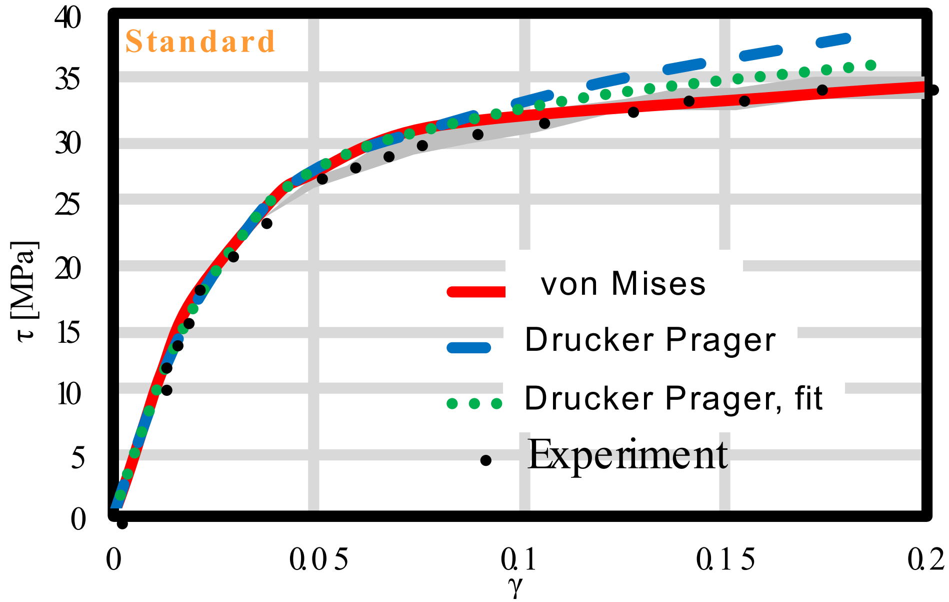
Plasticity: Validation of Yield Criterion (lap shear coupon)

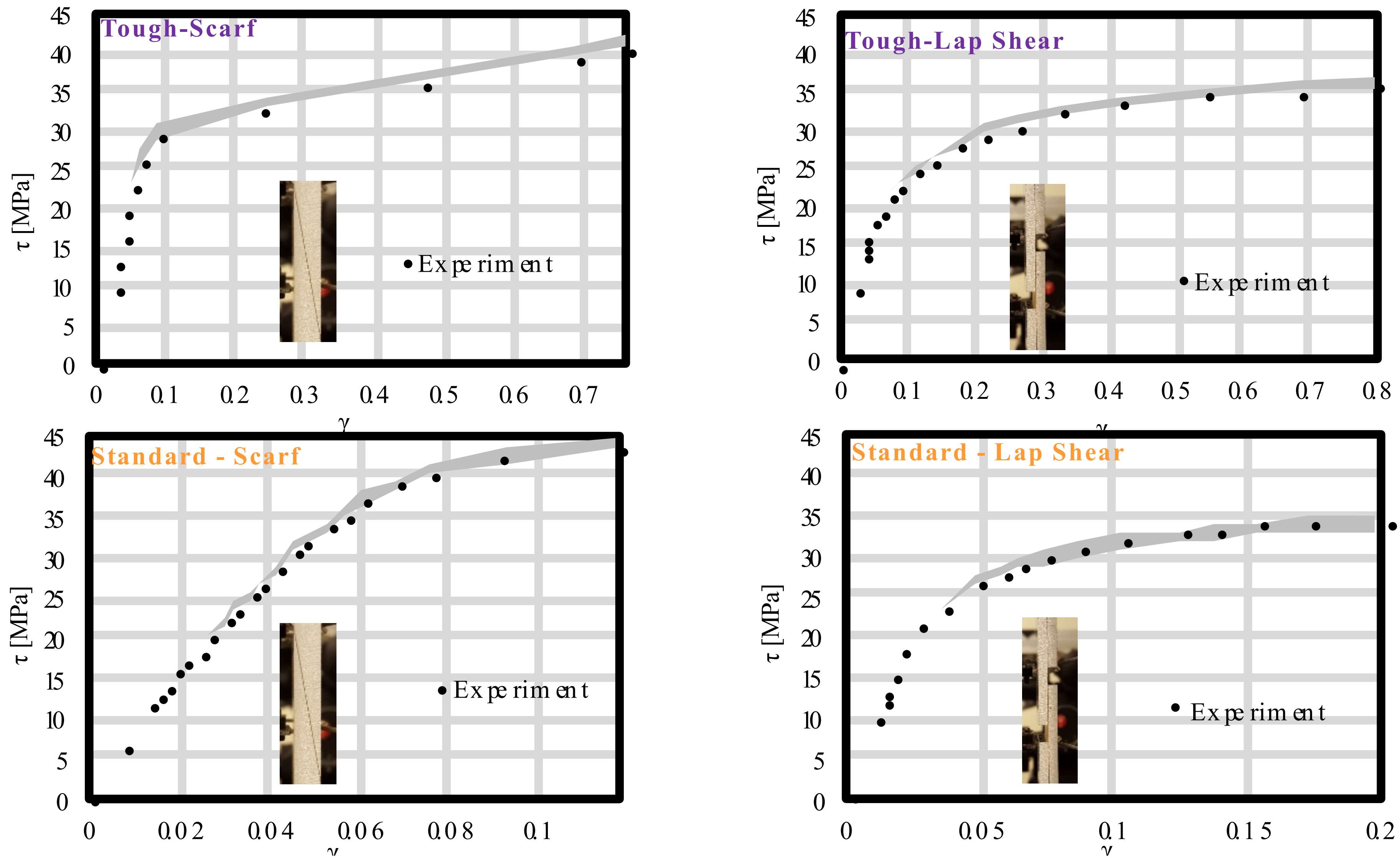




What we found: use of mixed mode lap-shear joint

- von Mises criterion better explains adhesive yielding
- Adhesive yielding is not sensitive to hydrostatic pressure.

Plasticity: Validation of Hardening Rule



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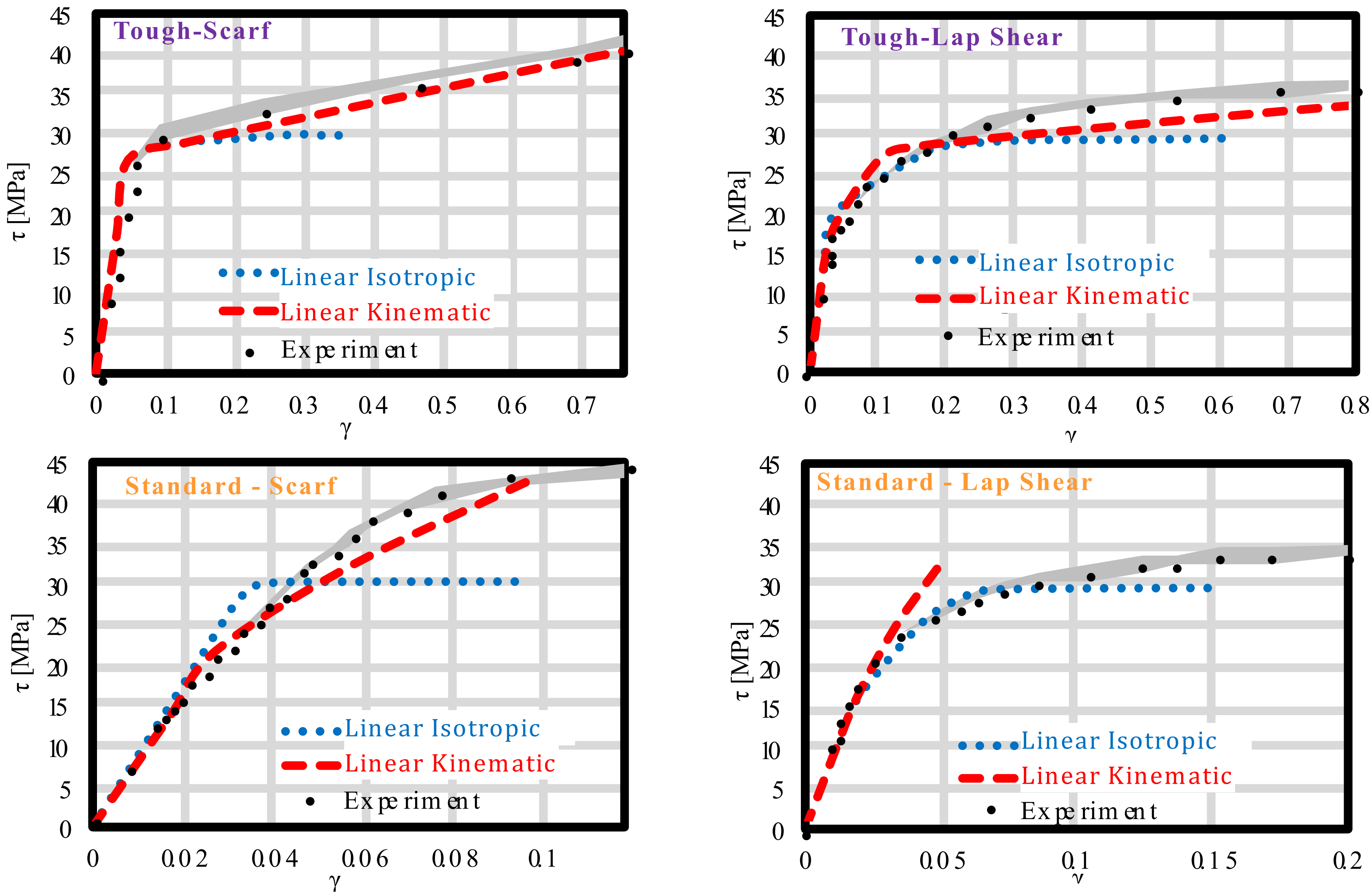
Plasticity: Numerical Modeling: Validation of Hardening Rule



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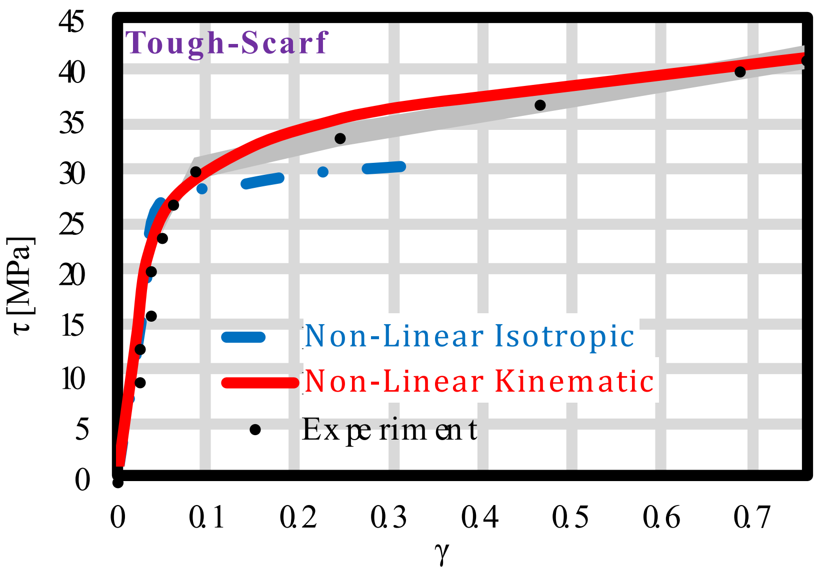
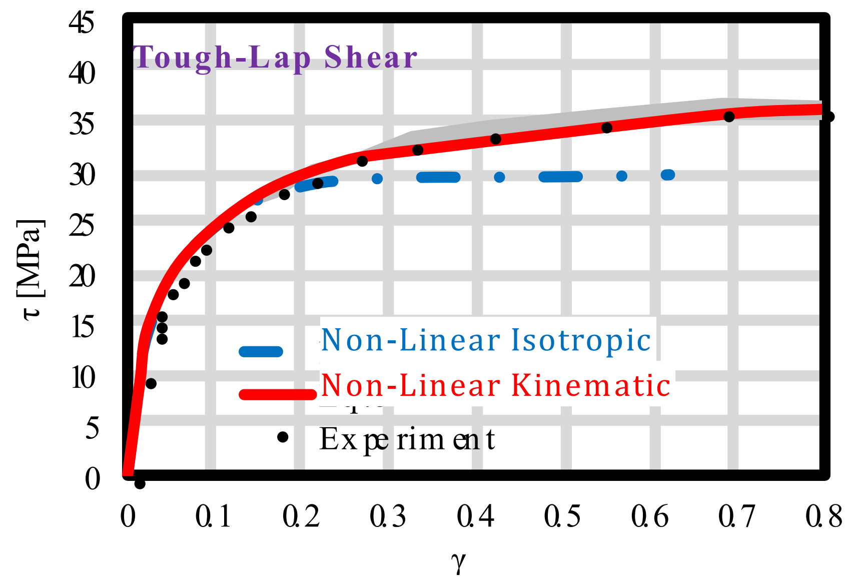
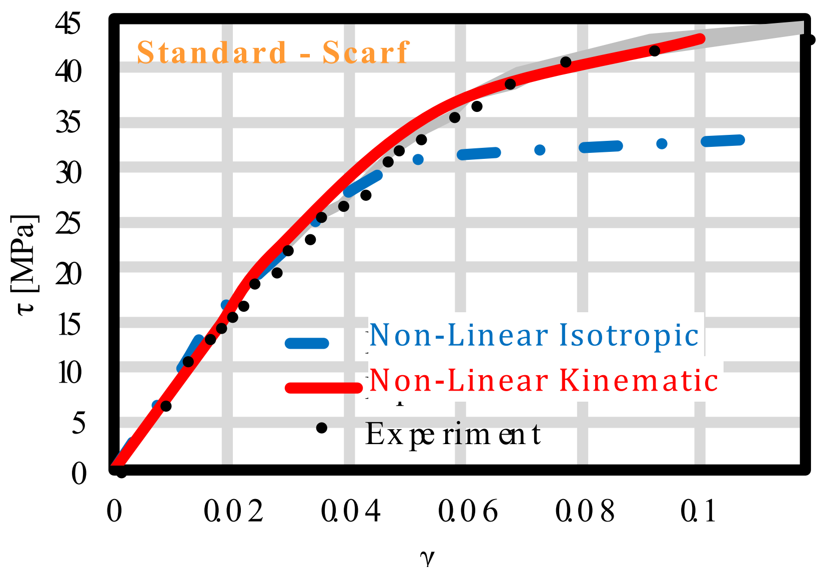
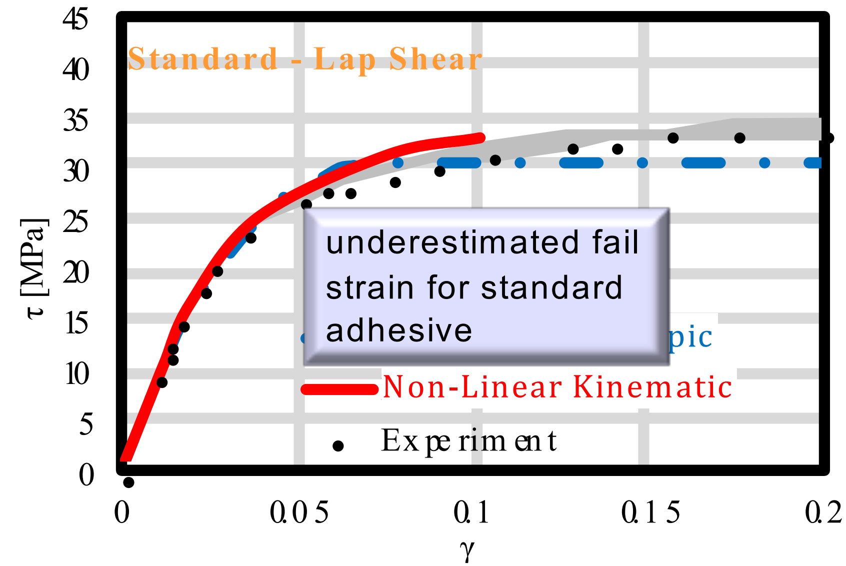
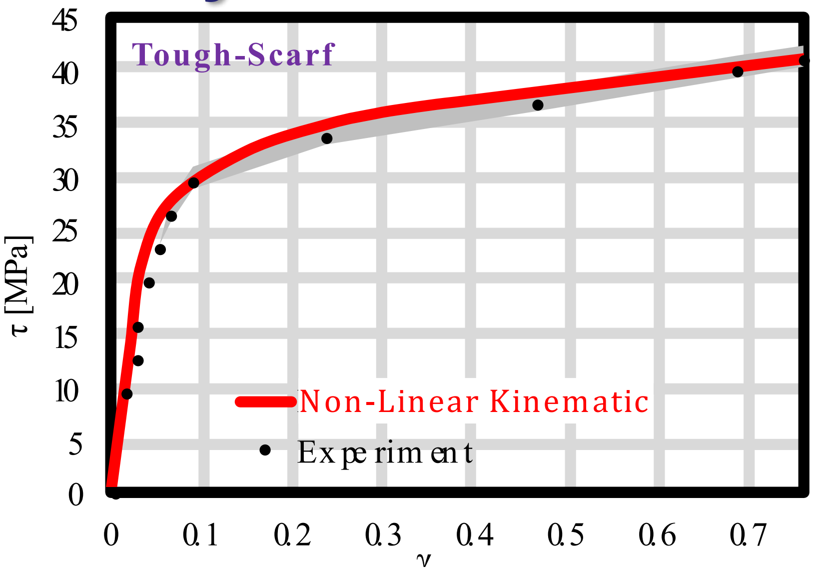


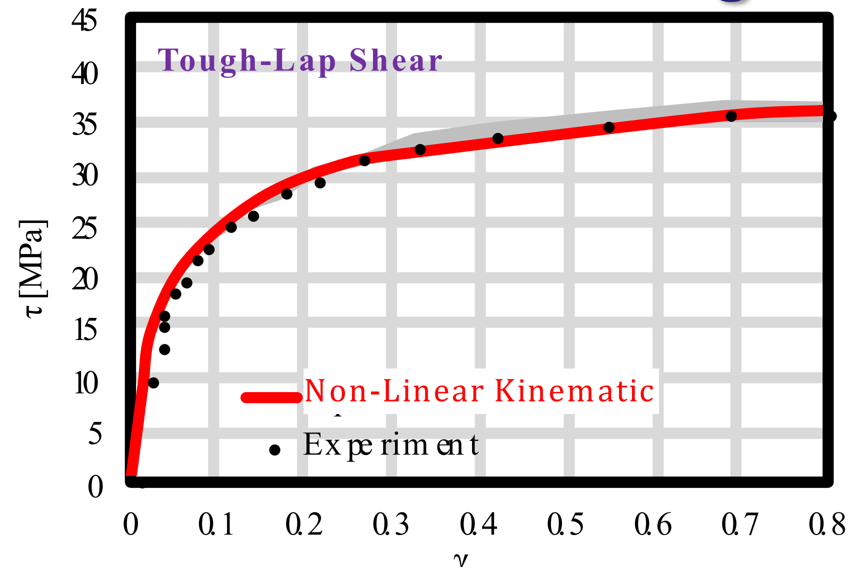


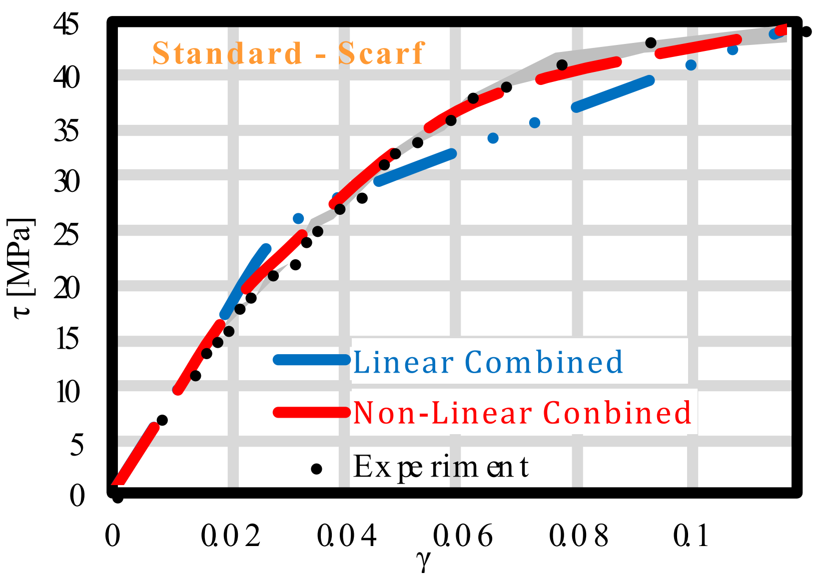


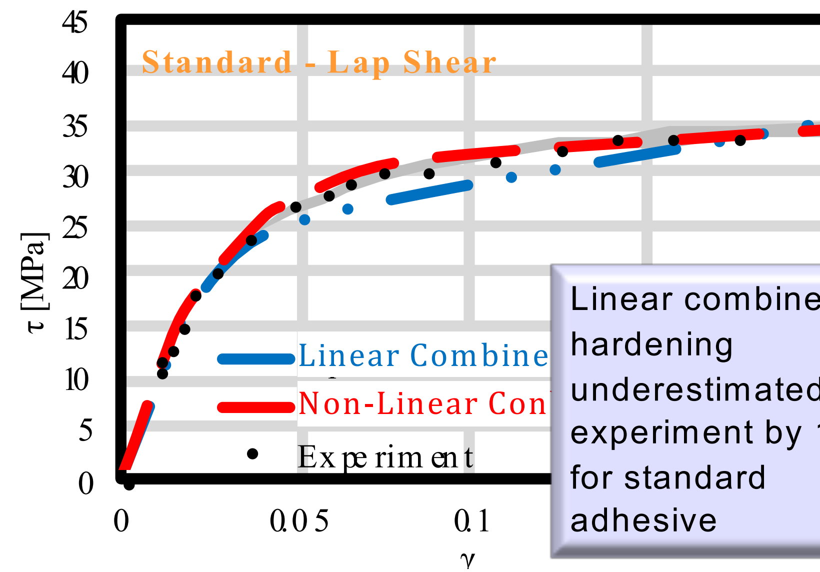


Plasticity: Numerical Modeling: Validation of Hardening Rule









Linear combined hardening underestimated experiment by 13% for standard adhesive

Plasticity : Summary

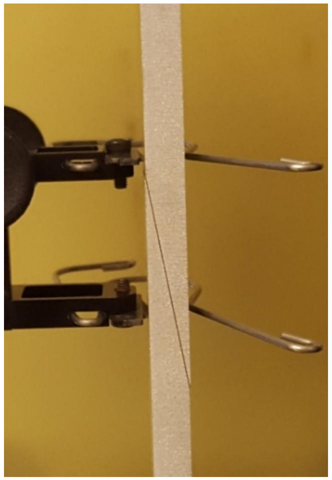
- Assuming plastic properties can lead to error in numerical modeling.
  - Little has been done to characterize adhesive plastic response
- Arcan fixture was effecting in creating uniform shear with minimal peel stress.
- Adhesives considered here followed von Mises yielding
  - not influenced by hydrostatic pressure.
- Adhesives in this work tended to follow kinematic hardening
  - Isotropic hardening is commonly assumed
  - Nonlinear kinematic hardening governed the tough adhesive behavior.
  - Nonlinear combined hardening (90% kinematic) described standard adhesive.

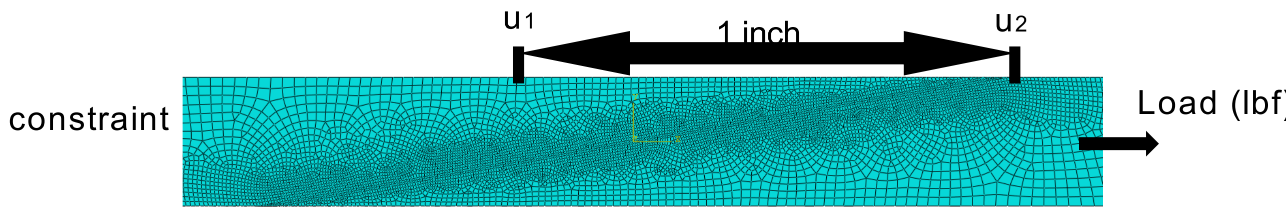
Viscoelasticity

- Effect of prior loadings on adhesive
  - Modulus
  - Strength
  - Failure strain

Approach- strain in scarf joints & PRF model

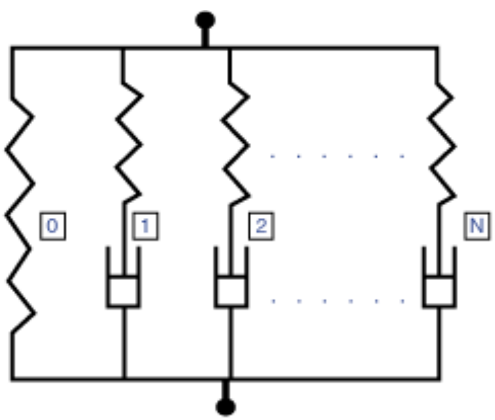
Strain detect for scarf joints





- For scarf joints, extensometer is used to get the displacement u_1 & u_2 at two points;
- $\Delta = u_2 - u_1$, it can be seen as an engineering strain as well as the displacement. In this presentation, the strain for scarf joints is Δ.
- $slope = \frac{load}{\Delta}$ is used as a system stiffness since the shear strain of the adhesive can not be obtained by extensometer.

Parallel Rheological Framework



- Hyperelastic & 3-branch Viscoelastic networks
- Viscous part:

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

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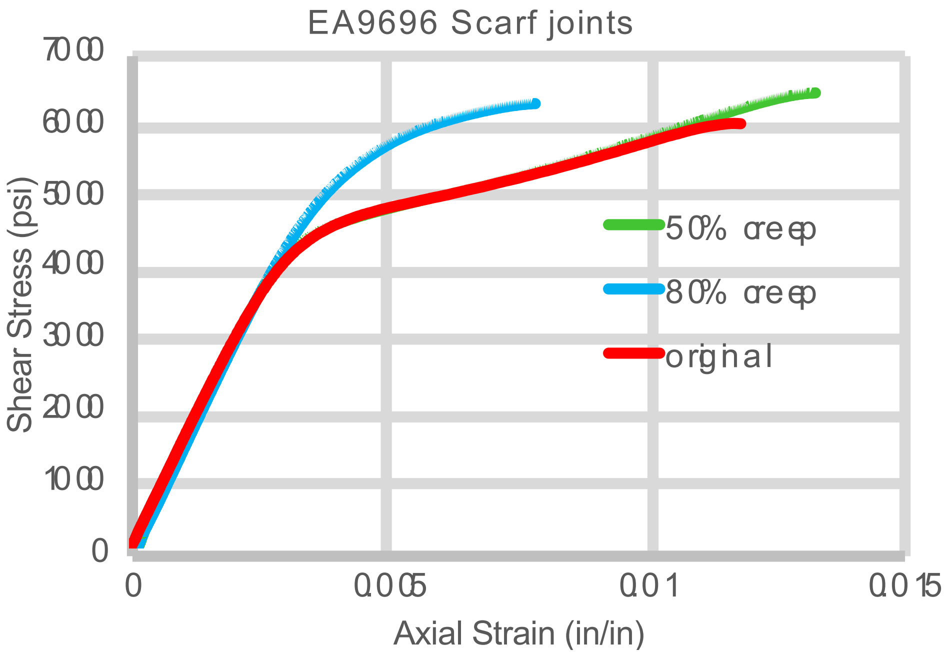
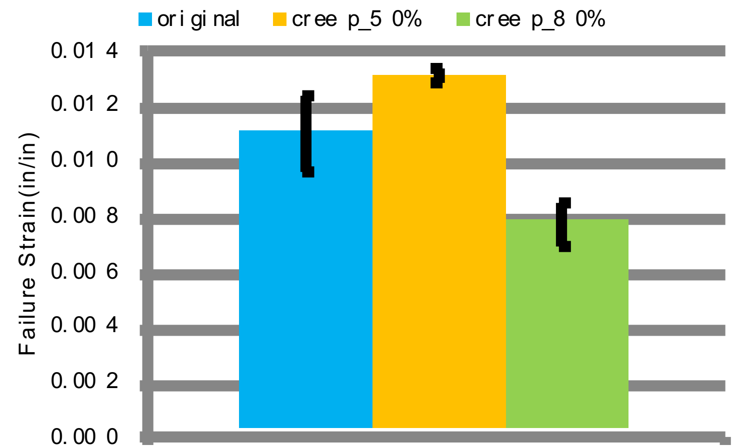
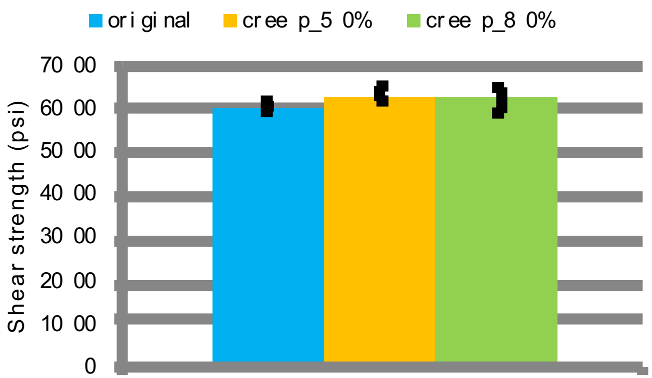
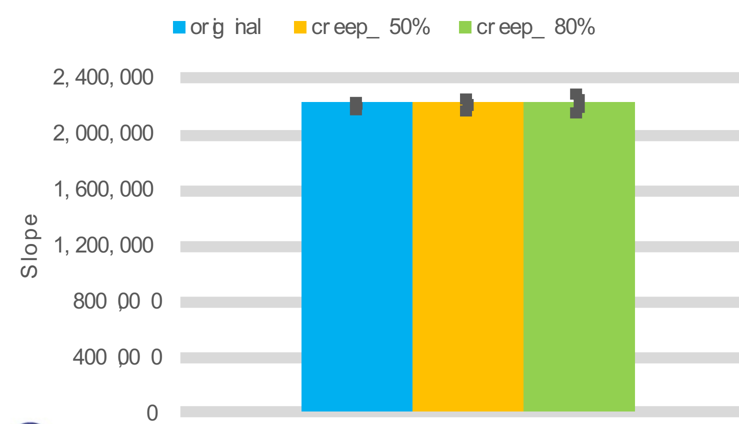
Approach- Failure Test

Failure Comparison between Scarf Joints with and without Prior Load









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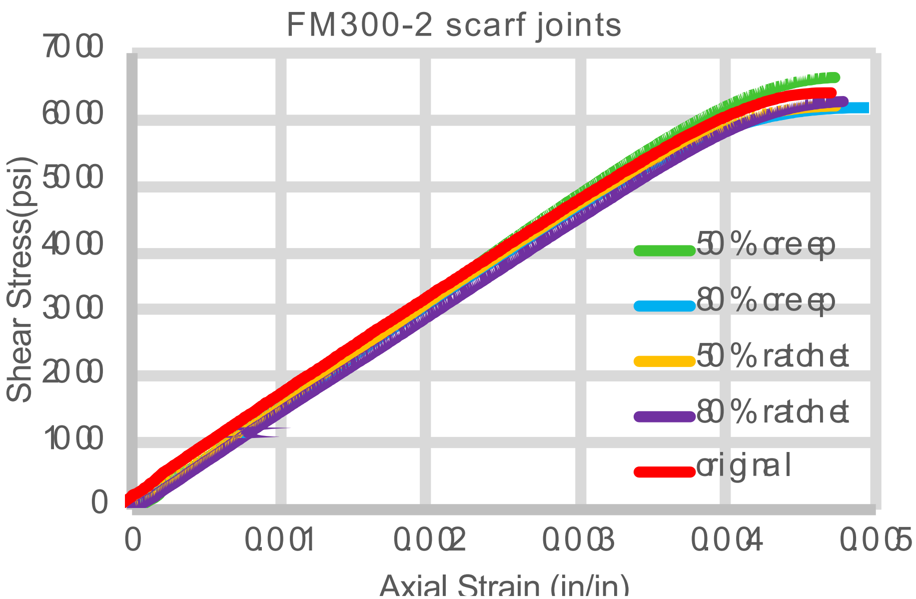
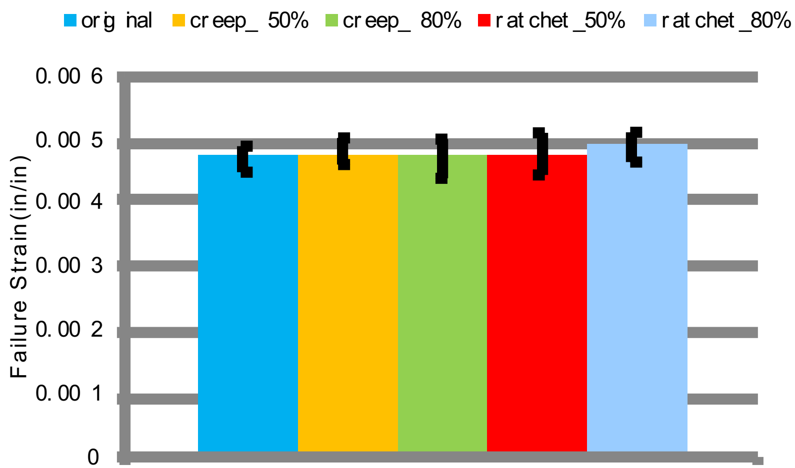
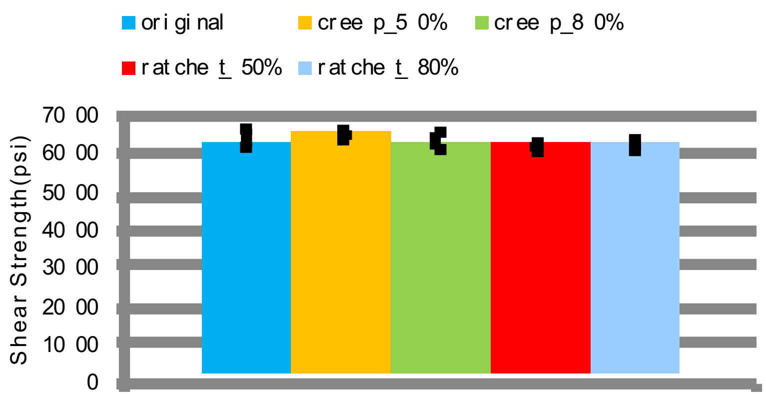
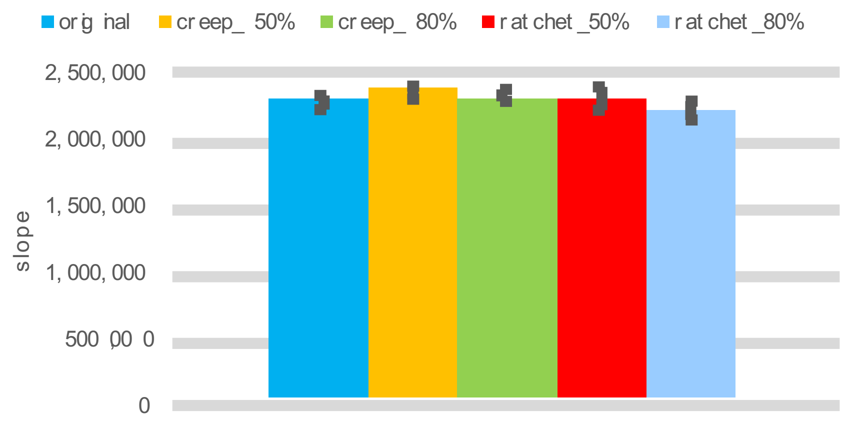
Approach- Failure Test

Failure Comparison between Scarf Joints with and without Prior Load





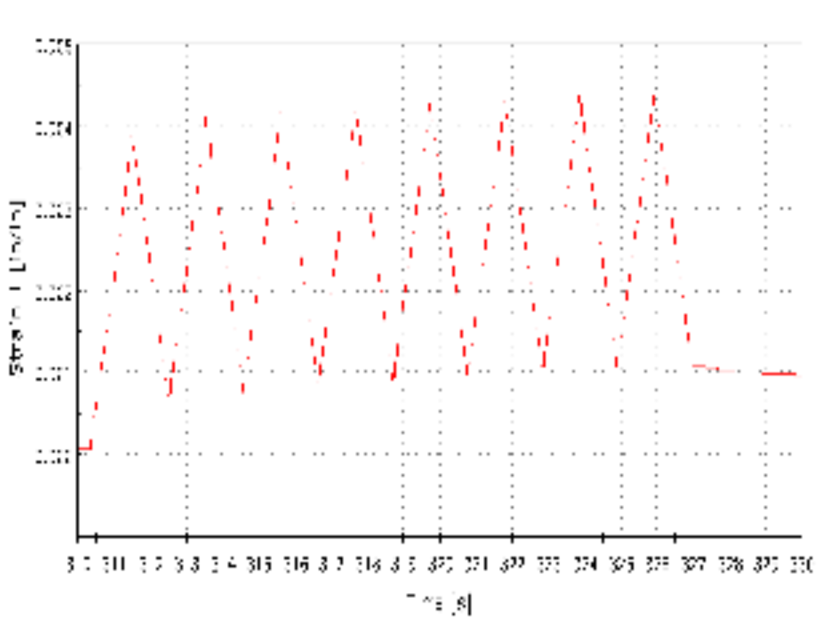


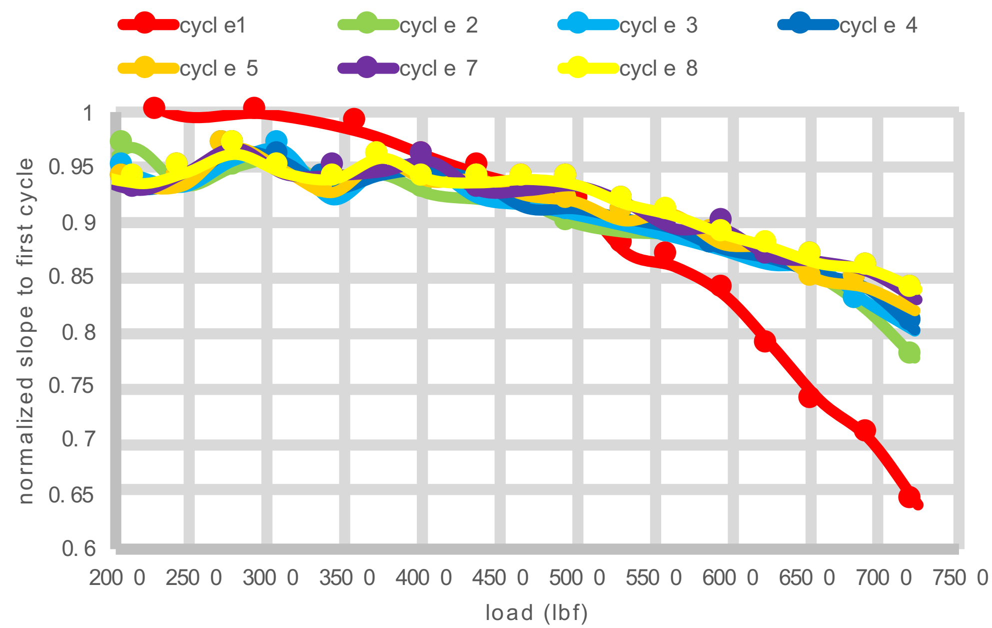


Approach- Cyclic Loading Test

Slope Changes at Loading Stage

- EA9696 Scarf Joints Ratcheting Test at 80% USS



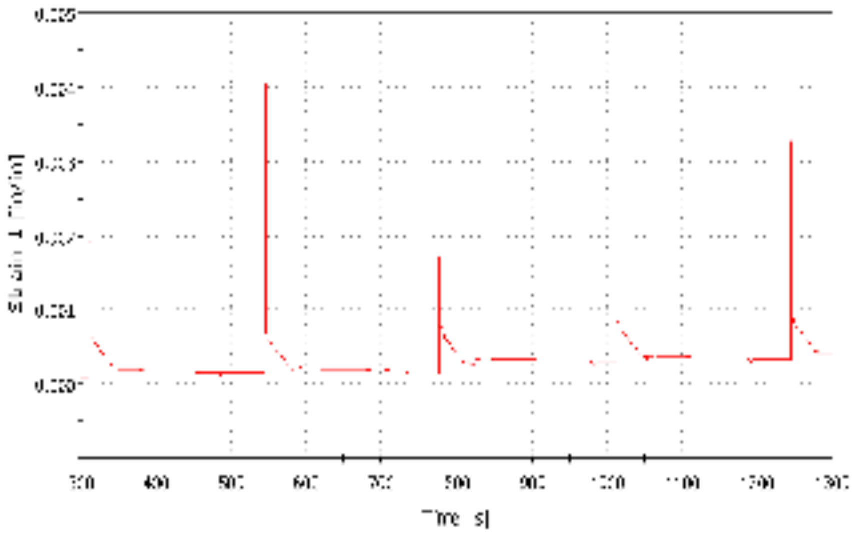


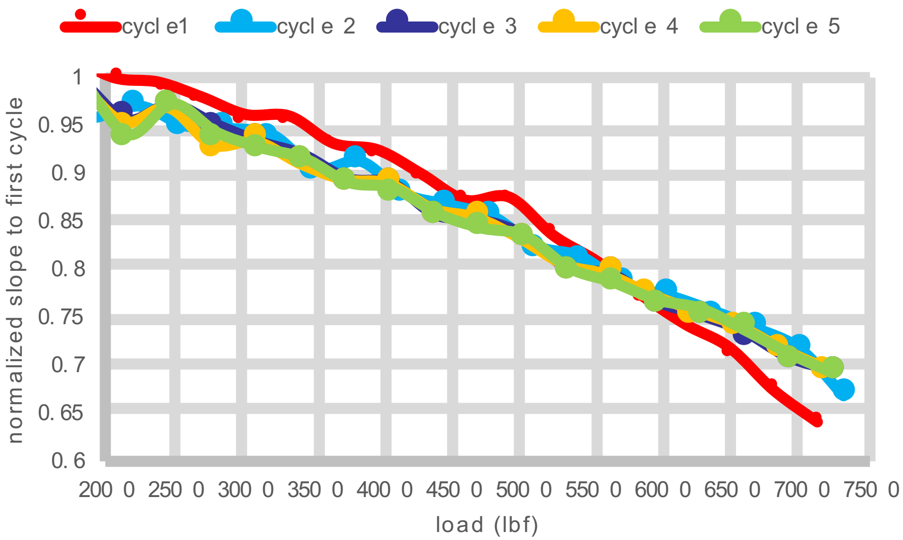
- Coupon was loaded for 8 cycles without failure;
- Another coupon failed after 20th cycle;
- The stiffness at the fist cycle loading is softer than remaining cycles;
- Most of the stiffness change is due to time dependence.

Approach- Cyclic Loading Test

Slope Changes at Loading Stage

- EA9696 Scarf Joints: Ratcheting Test with Recovery Per Cycle at 80% USS



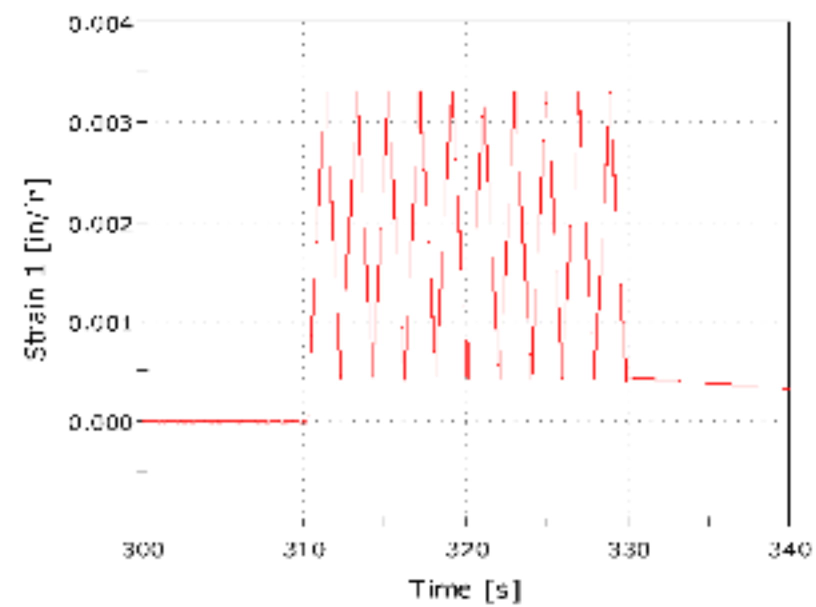


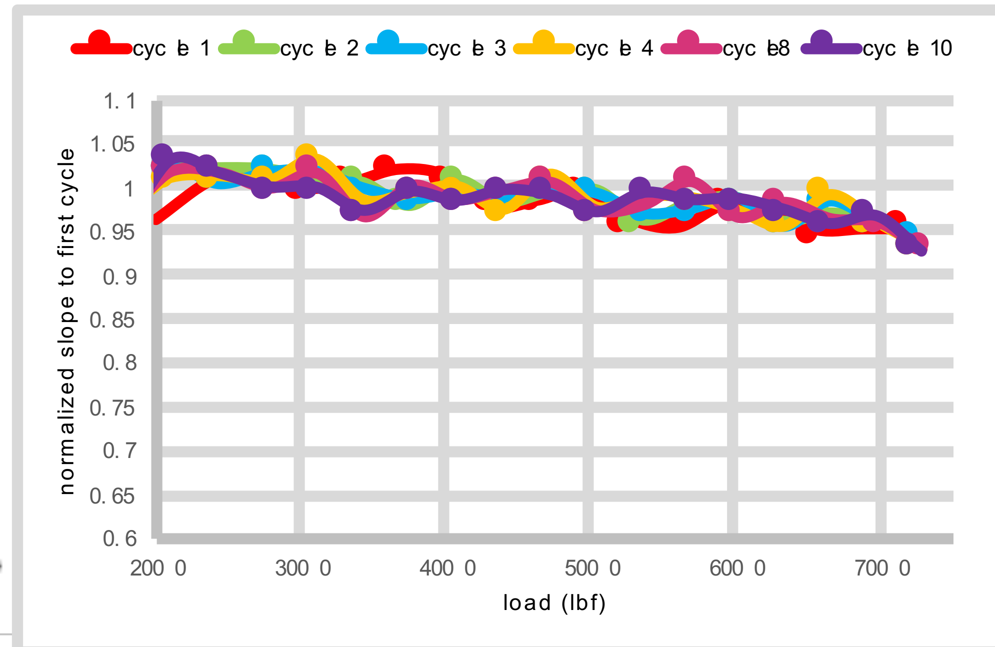
- Recovery between load cycles reduces the difference in stiffness between cycles.

Approach- Cyclic Loading Test

Slope Changes at Loading Stage

- FM300-2 Scarf Joints Ratcheting Test at 80% USS





- FM300-2 is more linear (constant slope) than EA9696

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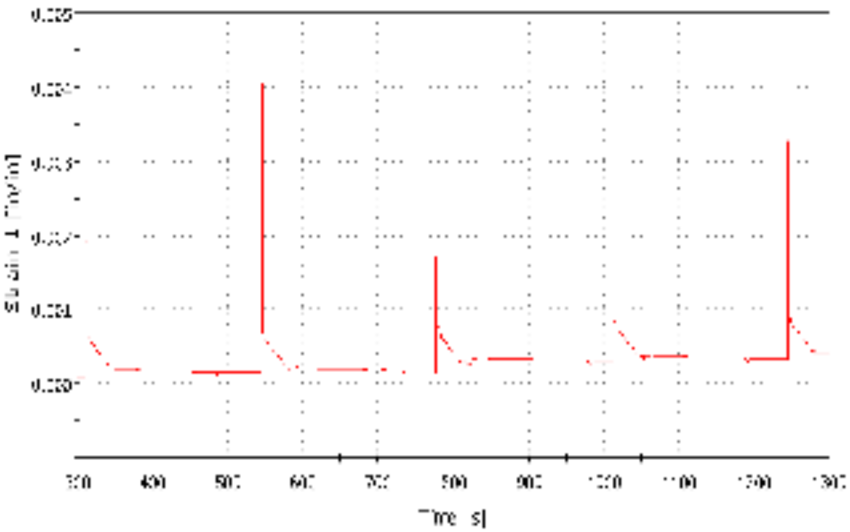
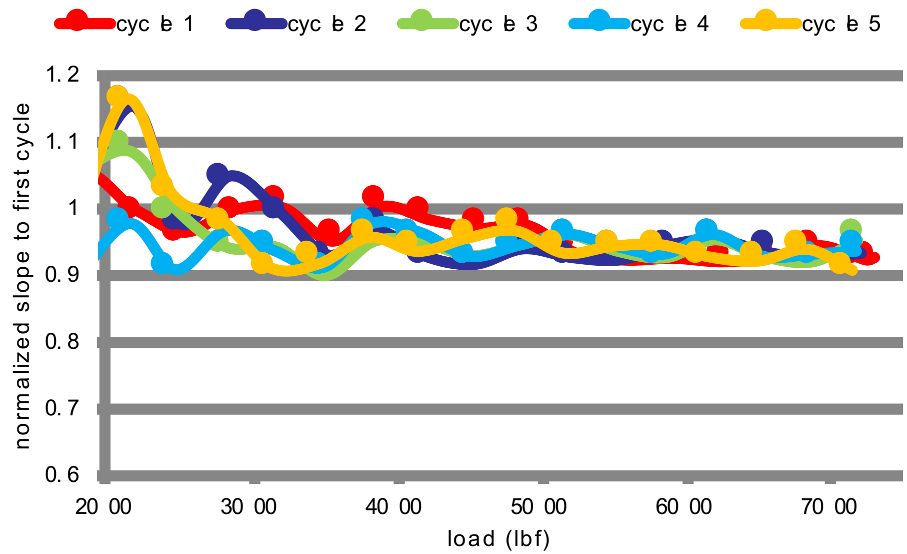
Approach- Cyclic Loading Test

Slope Changes at Loading Stage

- FM300-2 Scarf Joints: Ratcheting Test with Recovery Per Cycle at 80% USS

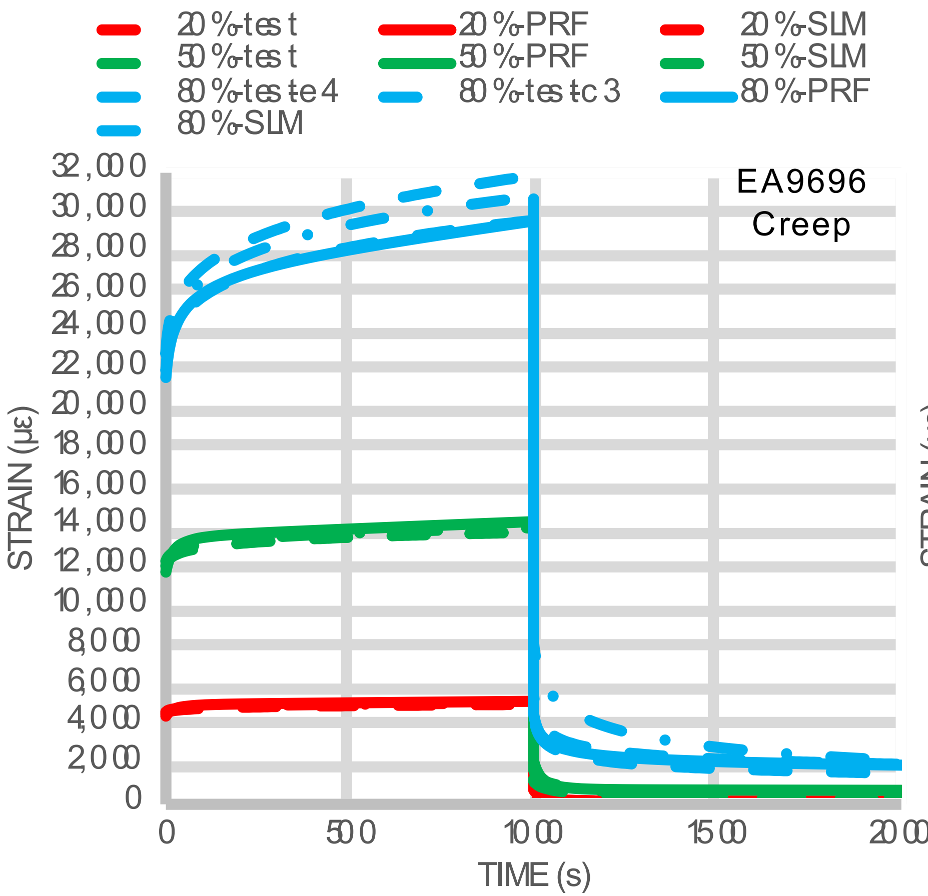


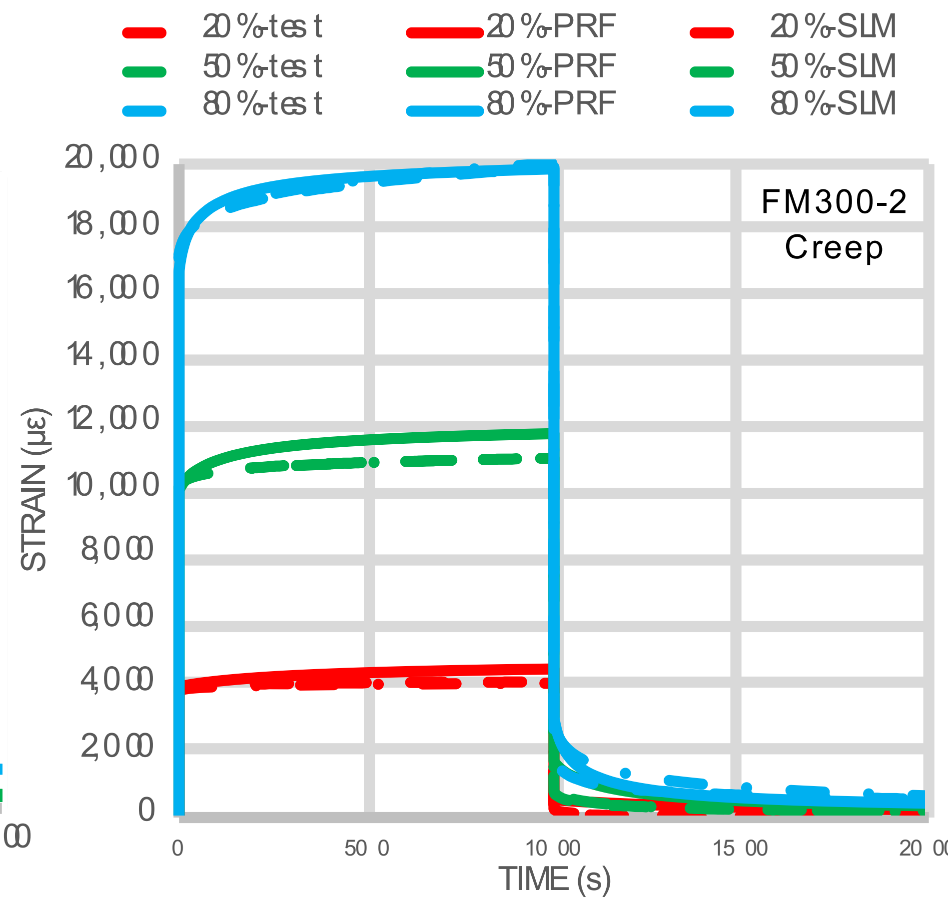


- Recovery caused some scatter in stiffness at low load, otherwise had little effect on stiffness.

Approach- Parallel Rheological Framework in ABAQUS

Bulk resin





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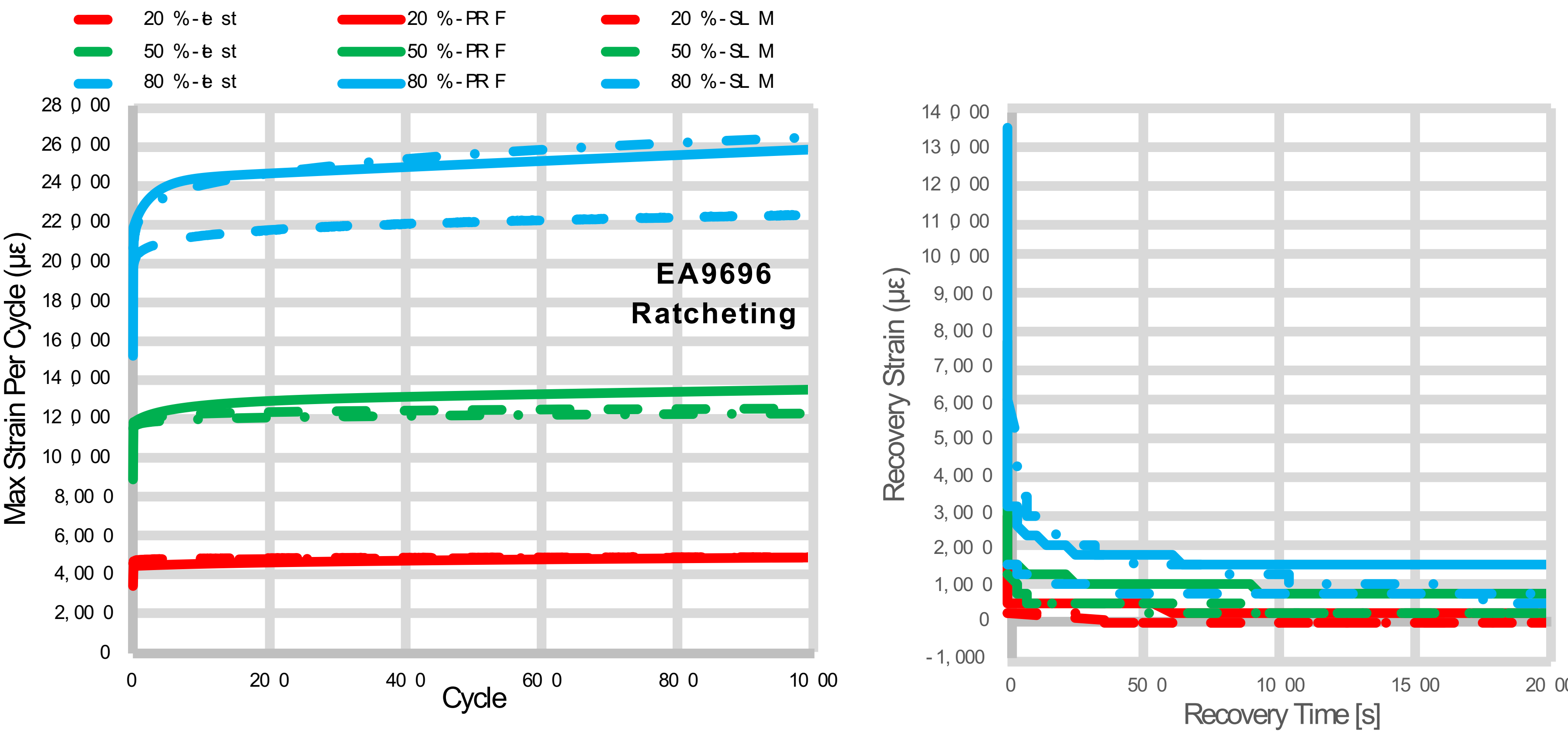
Approach- Parallel Rheological Framework FE Model

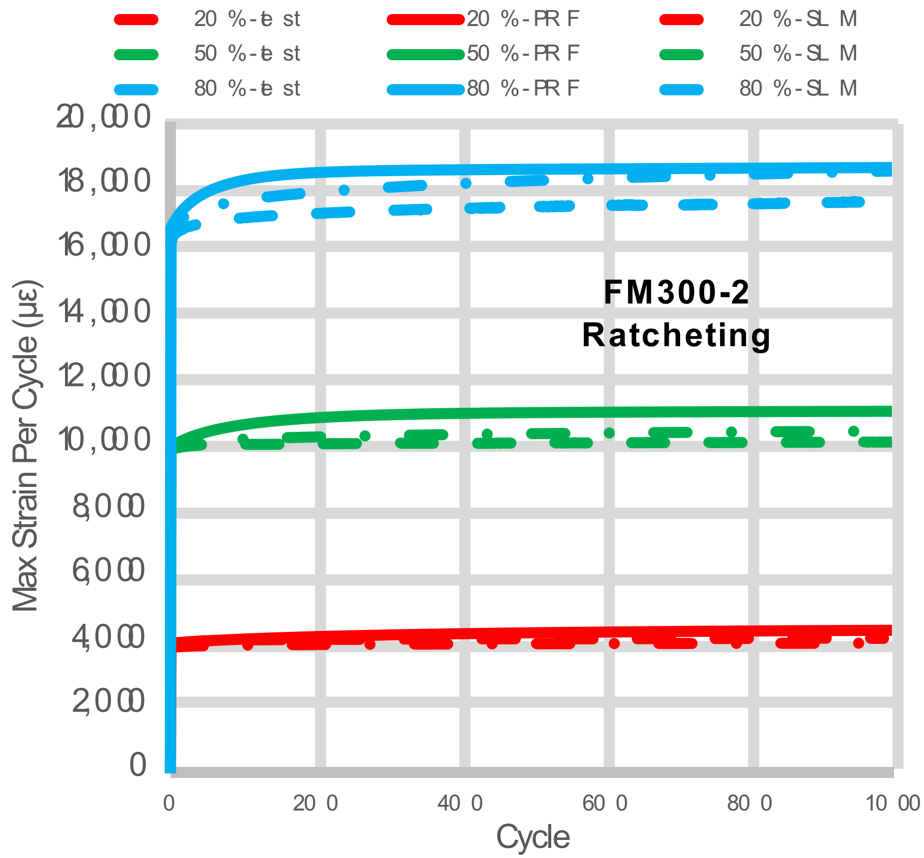
Bulk resin

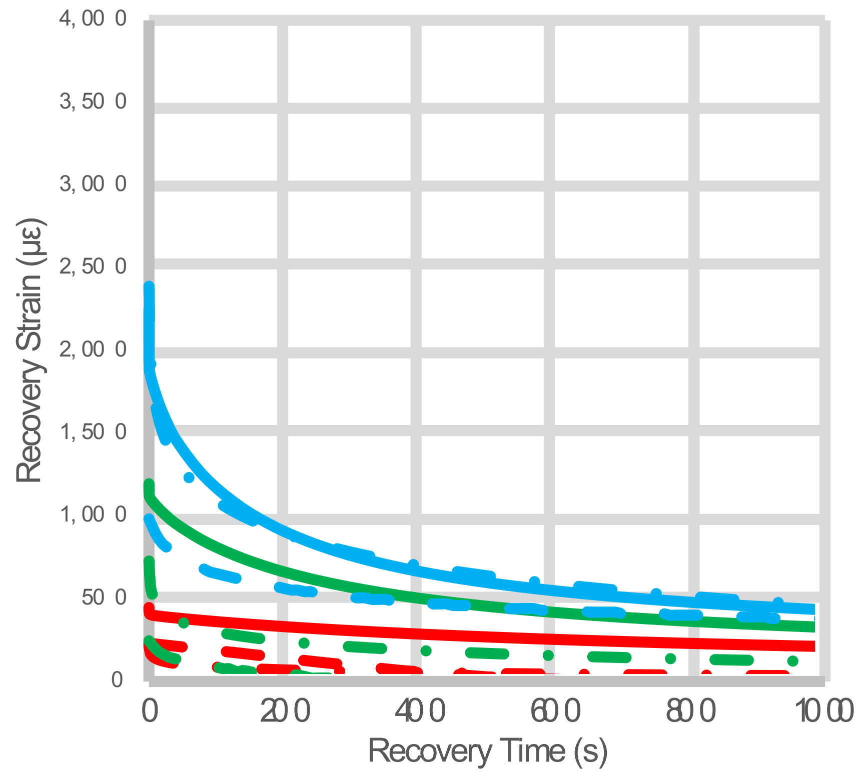


- For ratcheting at 80% UTS, the cycle compliance is too high.

Approach- Parallel Rheological Framework FE Model

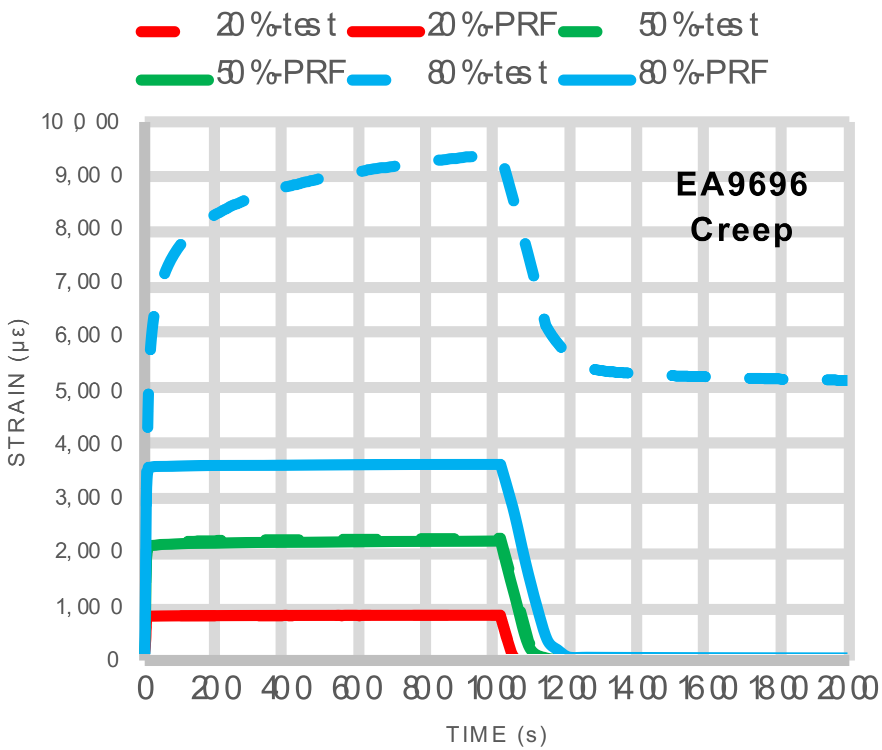
Bulk resin

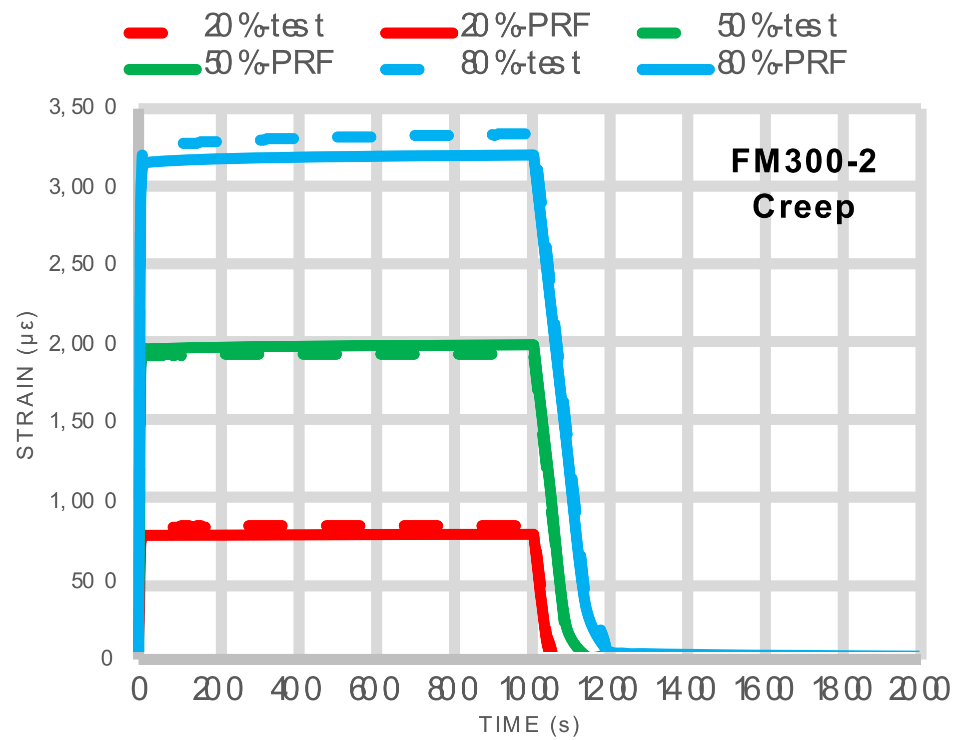




Approach- Parallel Rheological Framework FE Model

Scarf Joints





EA9696				FM300-2			
Bulk		scarf		Bulk		scarf	
UTS (psi)	yield stress % of UTS	USS (psi)	yield stress % of USS	UTS (psi)	yield stress % of UTS	USS (psi)	yield stress % of USS
6500	92%	6000	75%	8300	86%	6100	98%

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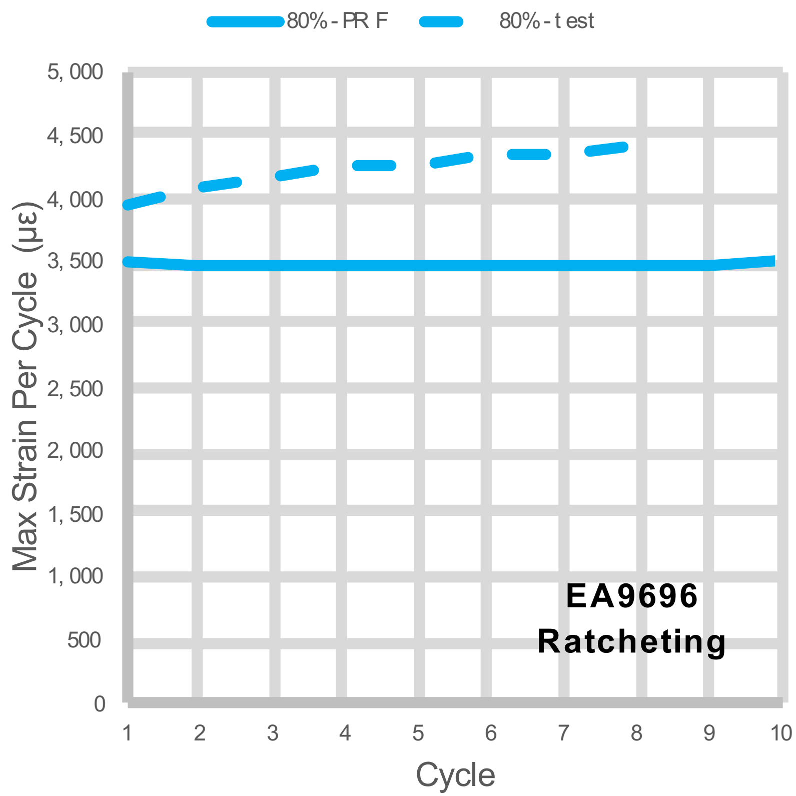
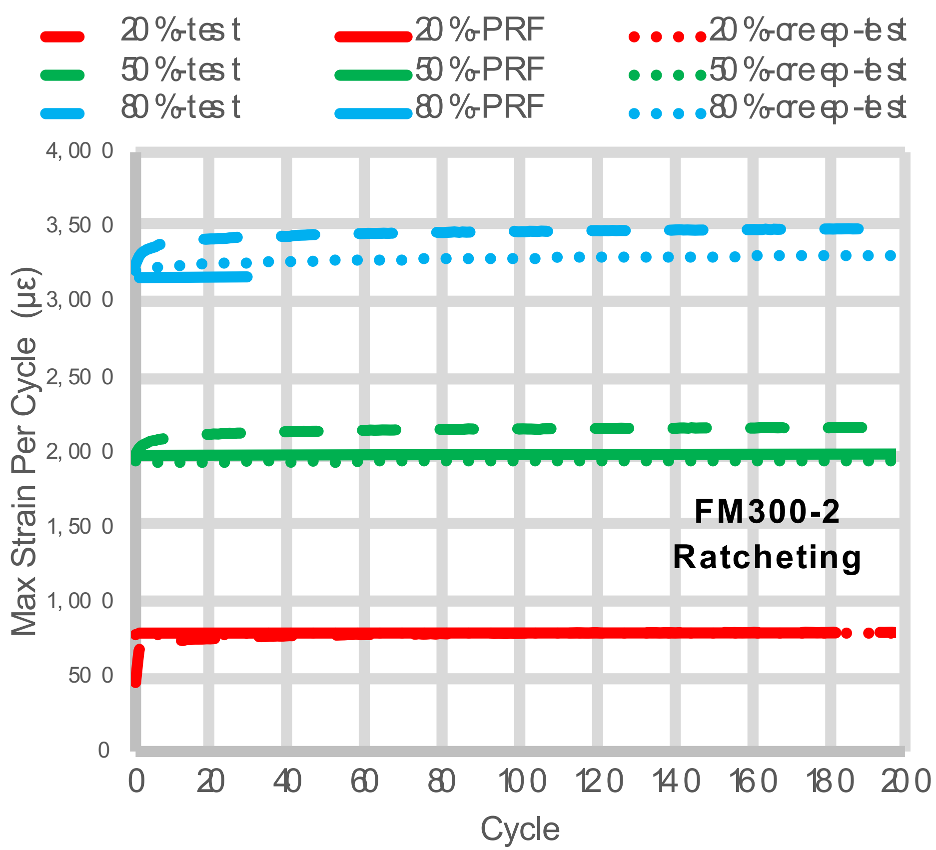
Approach- Parallel Rheological Framework FE Model

Scarf Joints





- PRF doesn't accumulate strain with cycles for scarf joints.

Viscoelasticity : Summary

- Prior loading has a small effect on subsequent adhesive material response.
  - A reduction in failure strain and strain hardening was only observed with prior loading above the yield strength
- Repeated loading had little effect on adhesive modulus
  - Tension/compression work is ongoing
- Repeated loading found generally good agreement with experiment for tensile, bulk coupon tests
  - Agreement reduced in shear ratcheting tests

Looking forward

- Benefit to Aviation
  - Methodology to characterize adhesive plasticity
  - Improved models of adhesive plastic response
  - Adhesive ratcheting behavior
- Future needs
  - Numeric models of time dependent behavior
    - Strain measurement in cyclic tests (scarf joints)
    - Time dependence of cyclic behavior

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