Durability of Bonded Aircraft Structure

JAMS Technical Review

3/31/2015 to 4/1/2015, Baltimore MD

WASHINGTON STATE UNIVERSITY

World Class. Face to Face.

Durability of Bonded Aircraft Structure

- Motivation and Key Issues
  - Bonded joints contribute to the weight savings of composite materials
  - The degradation of composite adhesives has received less attention than their adherends
- Objective
  - Improve understanding of adhesives in fatigue
  - Consider effect of adhesive toughness
  - Identify environments leading to ratcheting response
- Approach
  - Fatigue testing of normal, shear and mixed mode coupons
  - Account for time dependence
  - Consider the effects of temperature

Durability of Bonded Aircraft Structure

- Principal Investigators & Researchers
  - Lloyd Smith, Sayed Hafiz, David Lemme, Preetam Mohapatra, Harrison Scarborough
- FAA Technical Monitor
  - Curt Davies
- Other FAA Personnel Involved
  - Larry Ilcewicz
- Industry Participation
  - Kay Blohowiak, Pete VanVoast, Will Grace (Boeing)

Outline

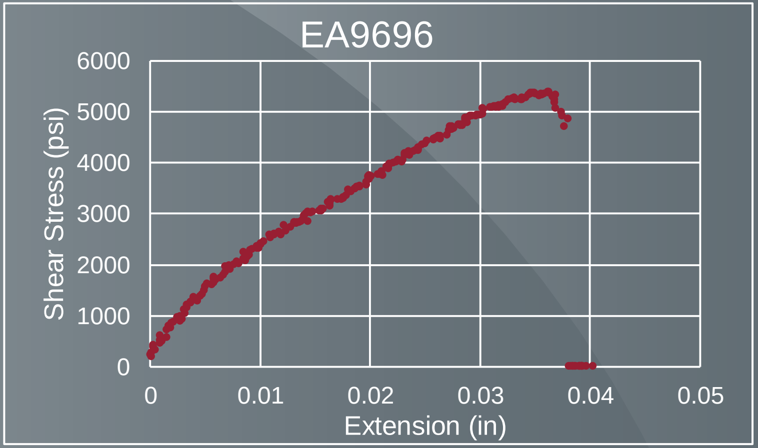
- Fatigue, Experiment
- Fatigue, Modelling
- Ratcheting
- Temperature

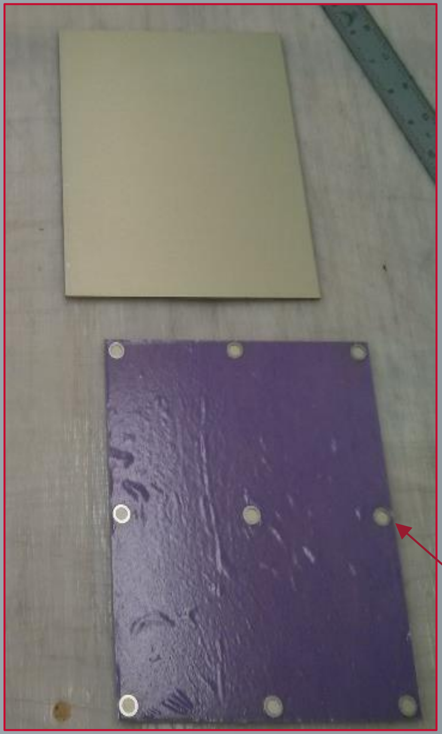
Fatigue, Harrison Scarborough

- Aim: compare the effect of adhesive ductility on fatigue response
- Test coupons
  - WALS
  - DCB
  - Scarf
- Materials
  - EA9696 (film)
  - FM300-2 (film)
  - EA9394 (paste)
  - EA9380 (paste)

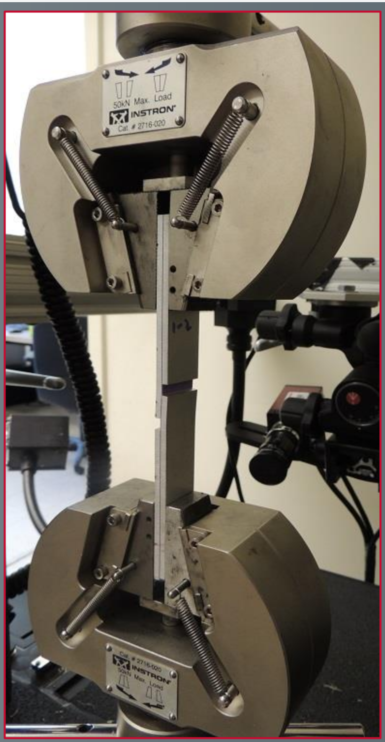
Wide Area Lap Shear

Status: Static testing of film adhesives complete.



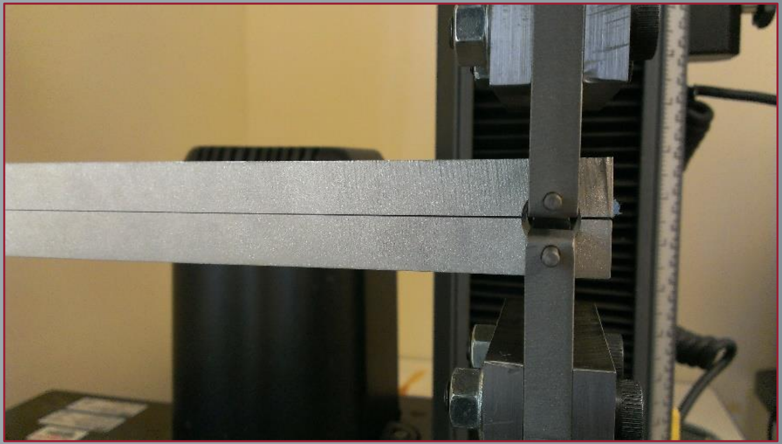


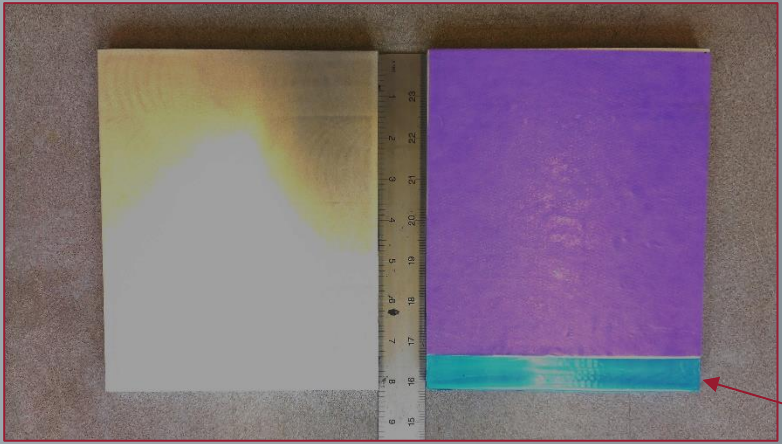
Shims for bond line control



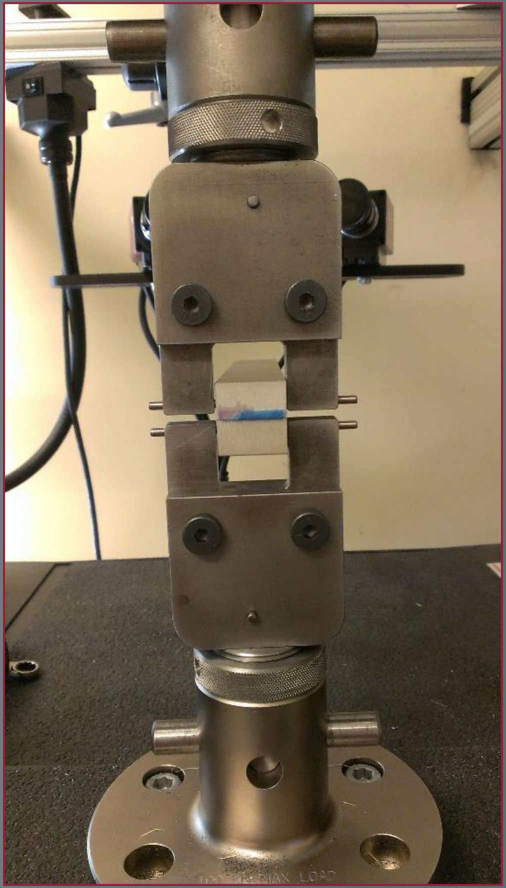
Double Cantilever Beam

Status: Two coupons of each film adhesive has been tested. More coupons are in process.





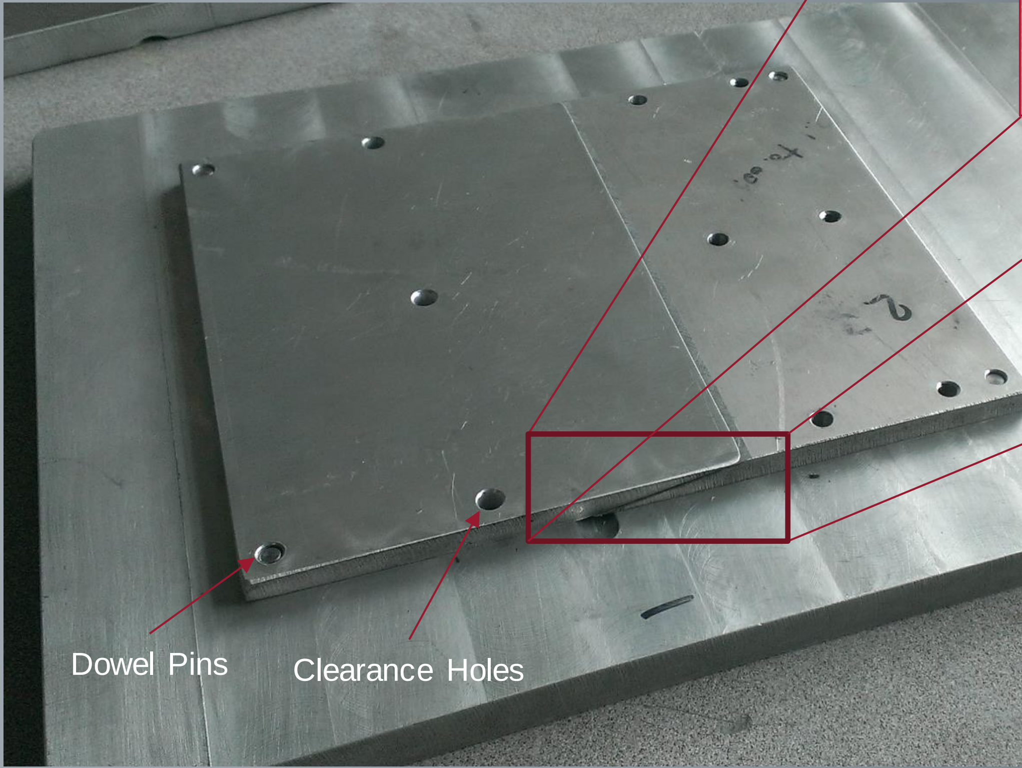
Teflon precrack

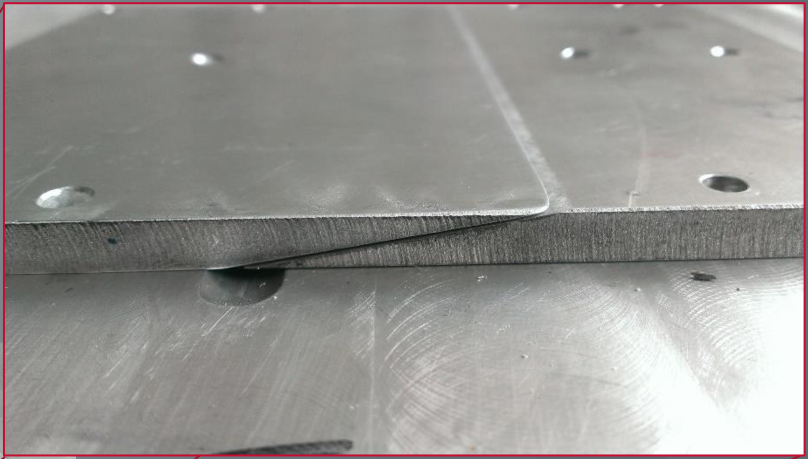


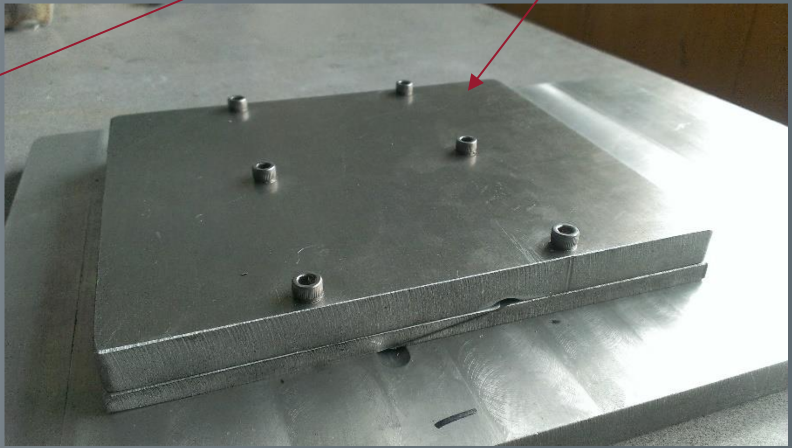
Scarf Fixture

Status: Static testing of film adhesives has been completed. Fatigue testing is currently underway.

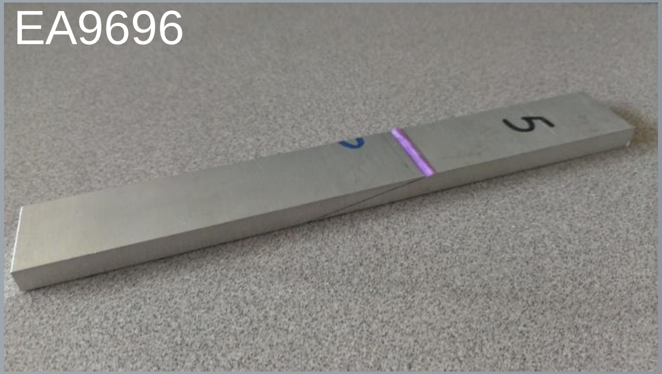
Cure Plate



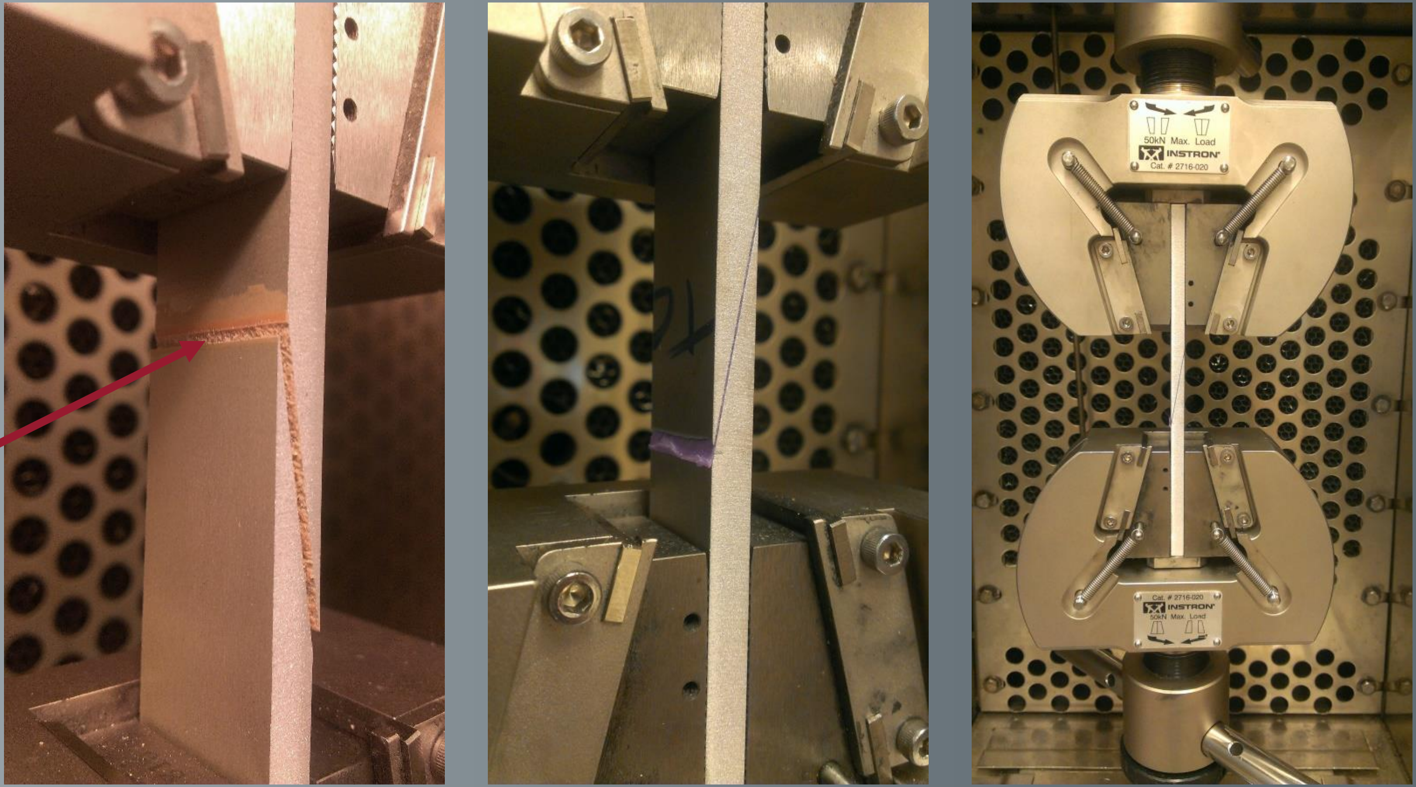




Scarf Joint



Tooling

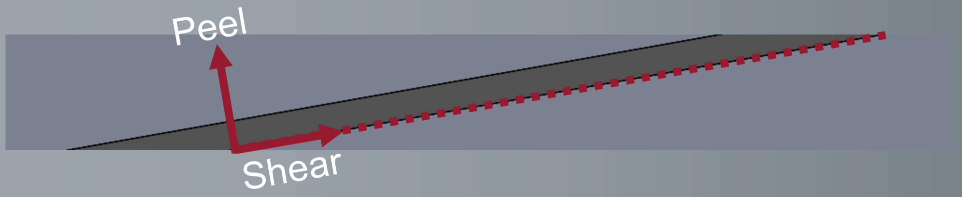


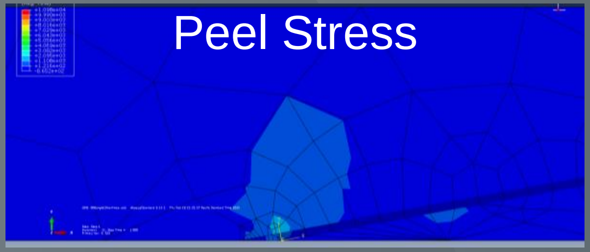
Filet machined flat for consistency

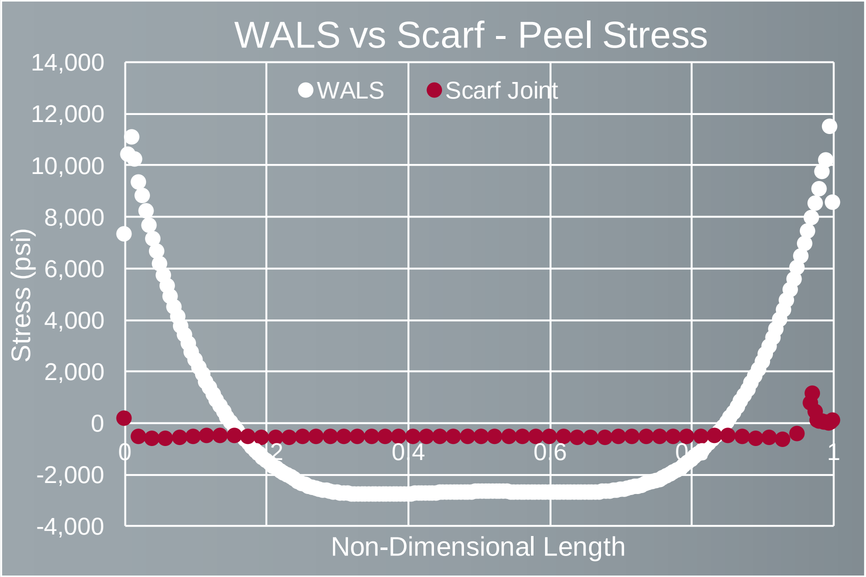
Why Scarf Joint?

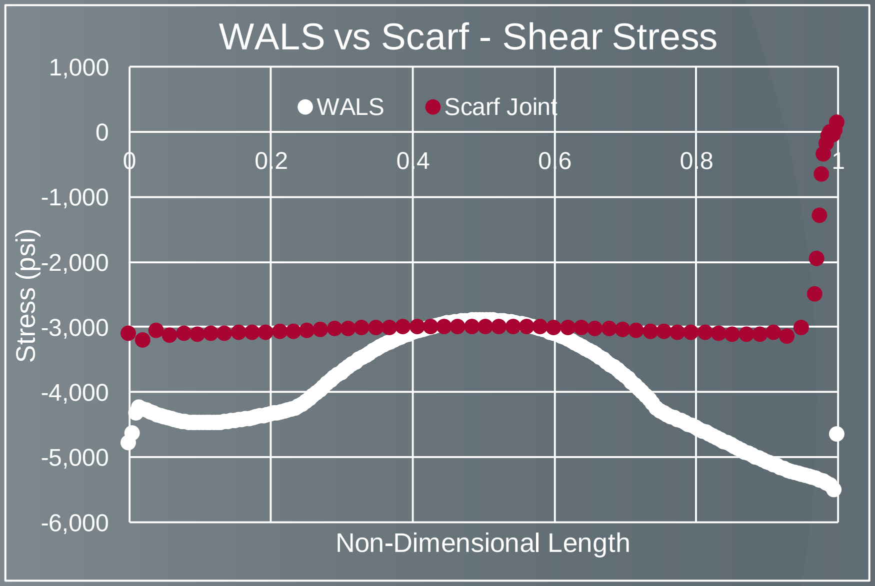
FEA Results :

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









Double Cantilever Beam (DCB)

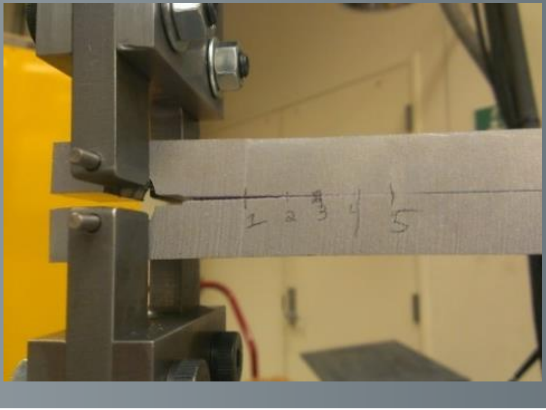
BSS7208, ASTM D3433

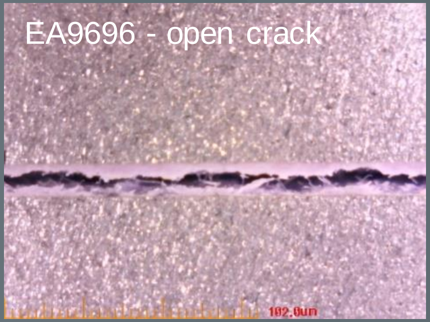
Used to evaluate toughness in peel

- EA9696 tougher in peel
- FM300-2 less tough in peel

BSS7208

$$G_I = \frac{p^2}{2b}\,\frac{2}{3EI}\,[3\,(a + 0.6h)^2 + h^2\,]$$

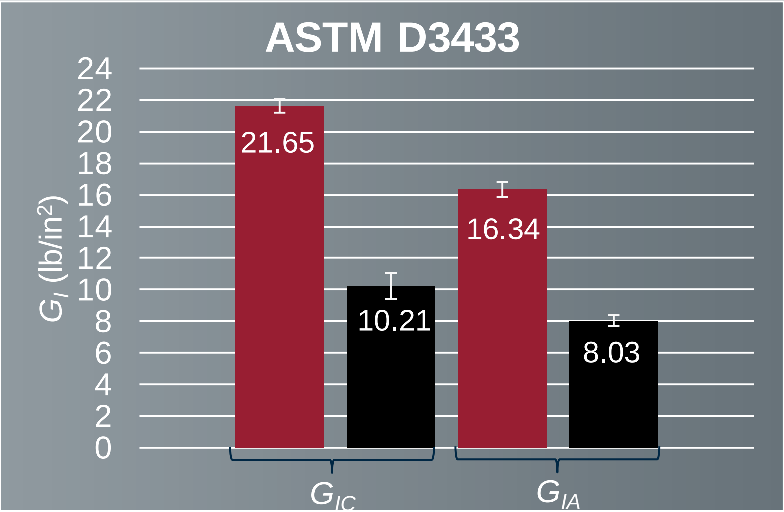




ASTM D3433

$$G_{1c} = \frac{[4L^2(\max)][3\,a^2+h^2]}{[E\,B^2h^3]}$$

$$G_{1a} = \frac{[4\,L^2(\min)][3\,a^2+h^2]}{[E\,B^2h^3]}$$

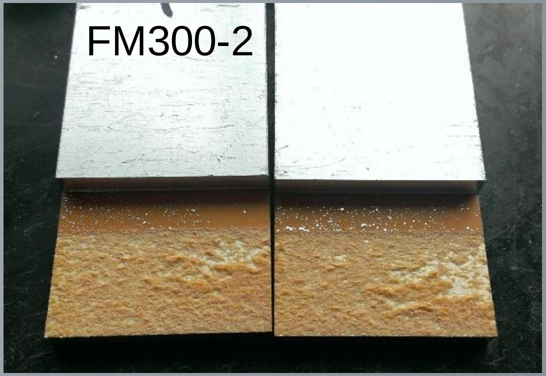


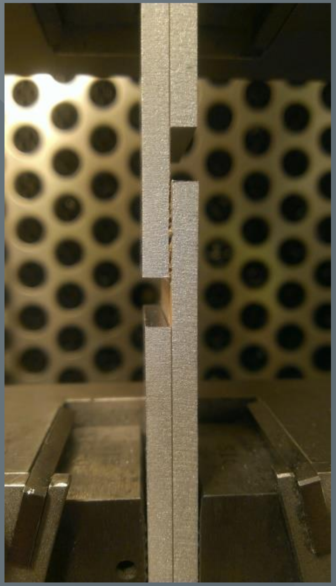
🟥 EA9696

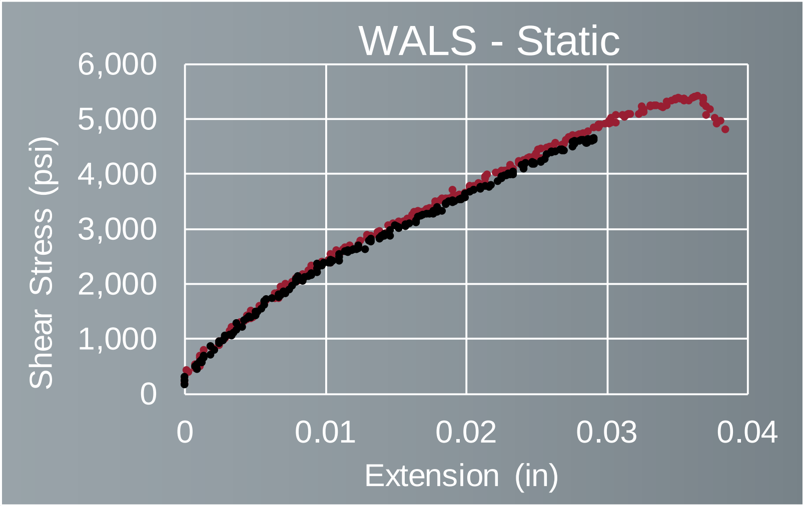
⬛ FM300-2

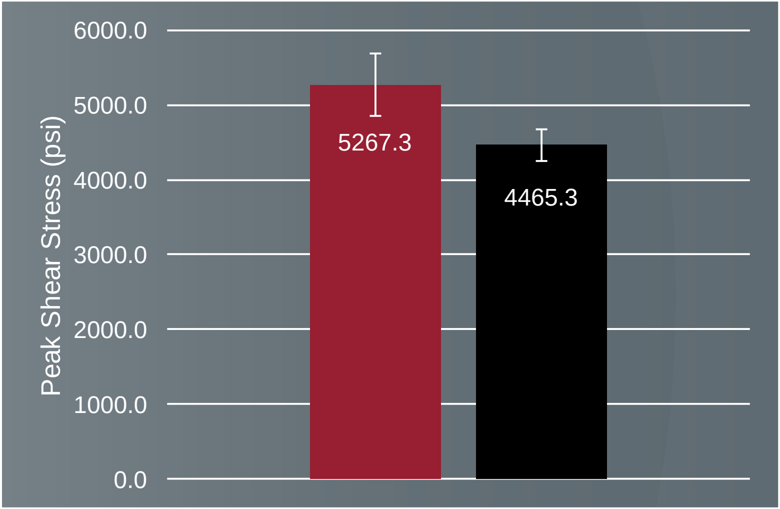
Wide Area Lap Shear

- EA9696 more tough
- FM300-2 less tough









🟥 EA9696

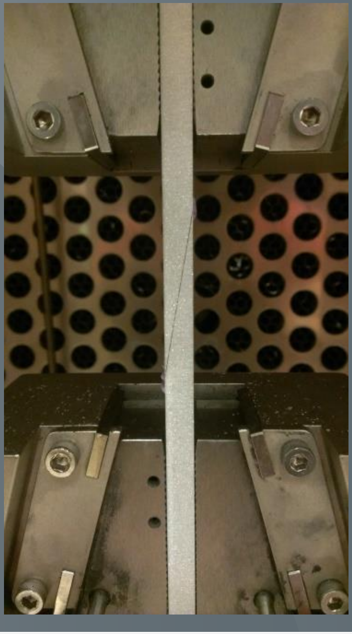
⬛ FM300-2

Scarf Joint – Static

In shear test.

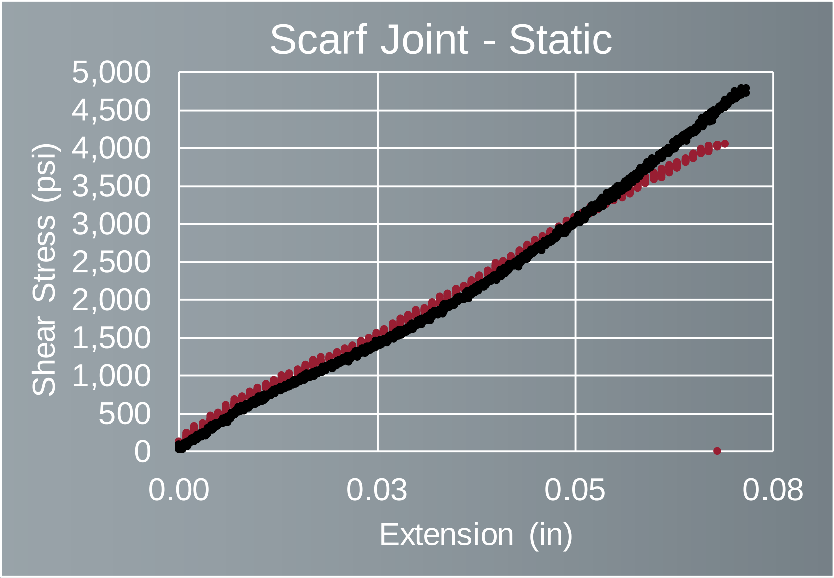
- EA9696 brittle
- FM300-2 brittle

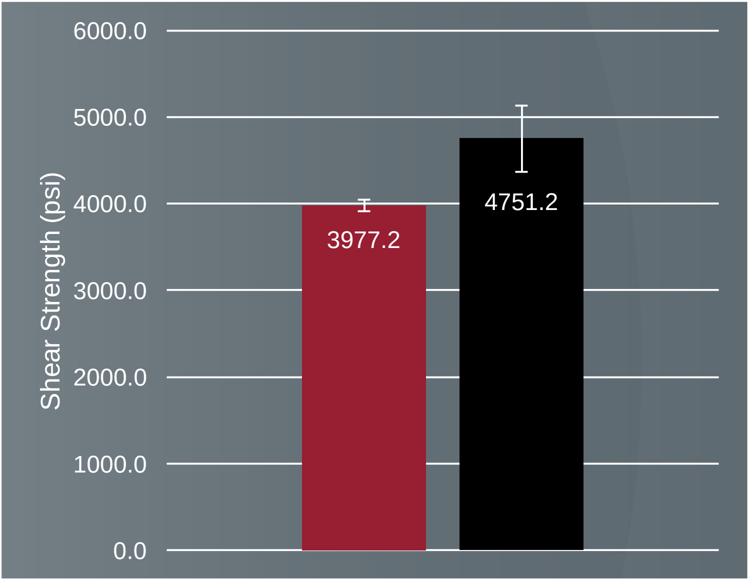
These adhesives tougher in peel than in shear



🟥 EA9696

⬛ FM300-2





FEA RESULTS

Scarf Joint – Fatigue

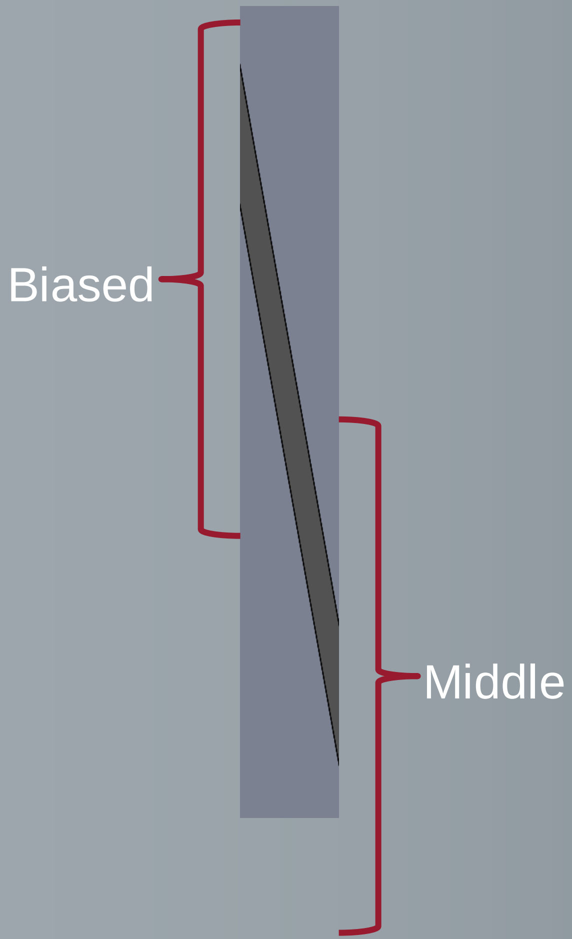
$G = 140{,}000\ psi$

$t =\ .008$ in

$e = extensometer\ displacement$

$\tau = 2850\ psi\ (60\%\ peak)$

Extensometer Locations



Average Shear Strain

$\gamma = .020$

Strain using Biased Location

$\gamma = .218$

Strain using Middle Location

$\gamma =\ .239$

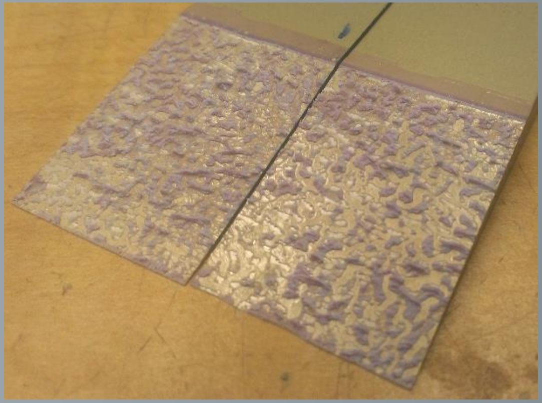
8.5% difference

RESULTS

Scarf Joint – Fatigue

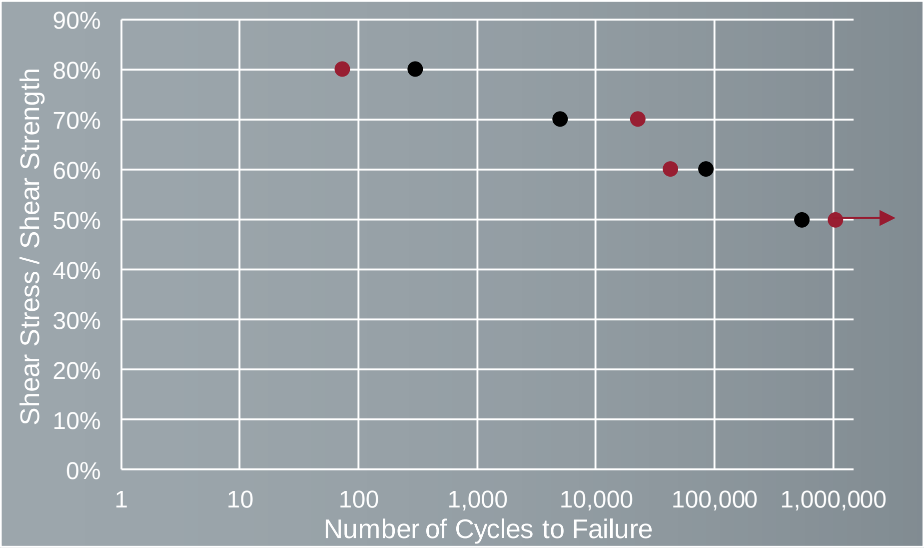
Preliminary results:

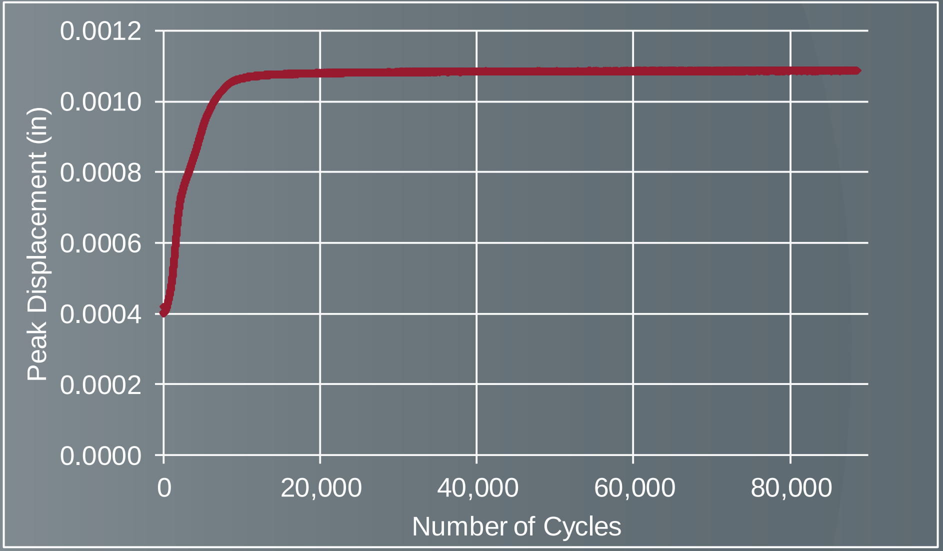
- Endurance limit for EA9696 ~50% UTS
- Elongation measured using extensometer



🟥 EA9696

⬛ FM300-2

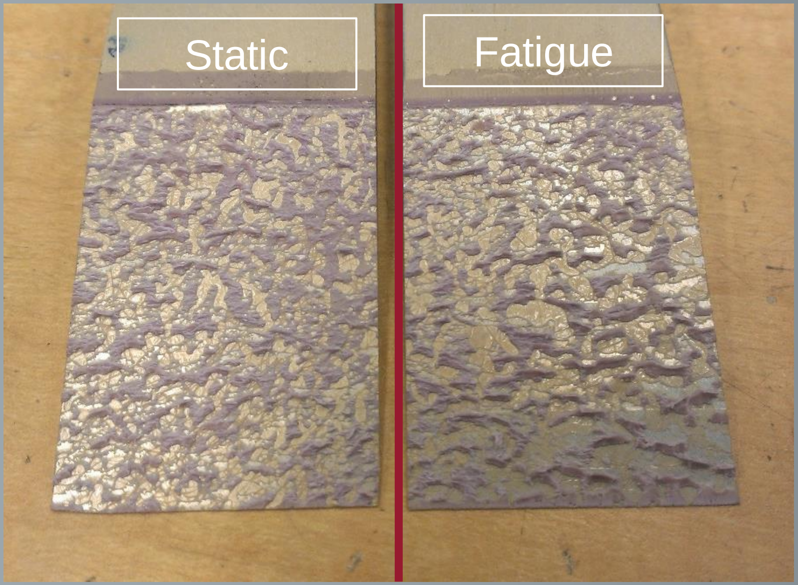


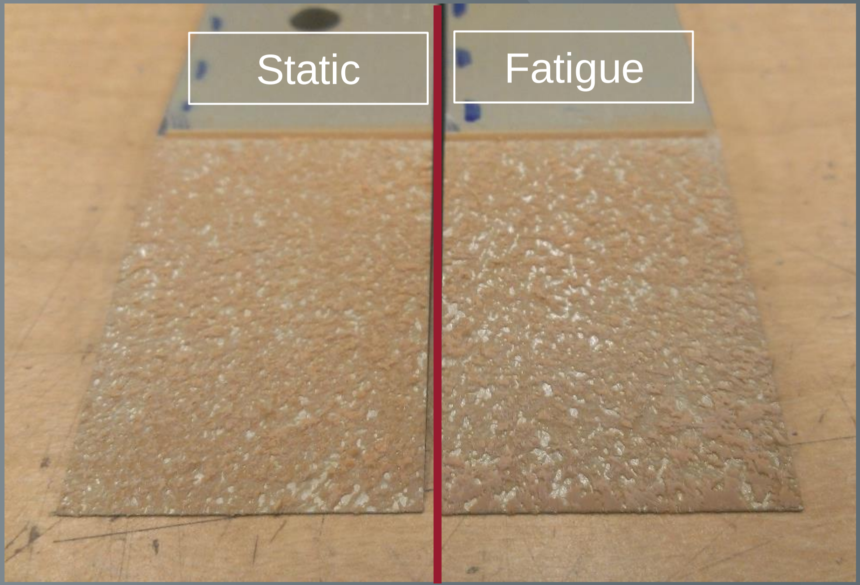


RESULTS

Scarf Joint – Fatigue

Failure Surfaces

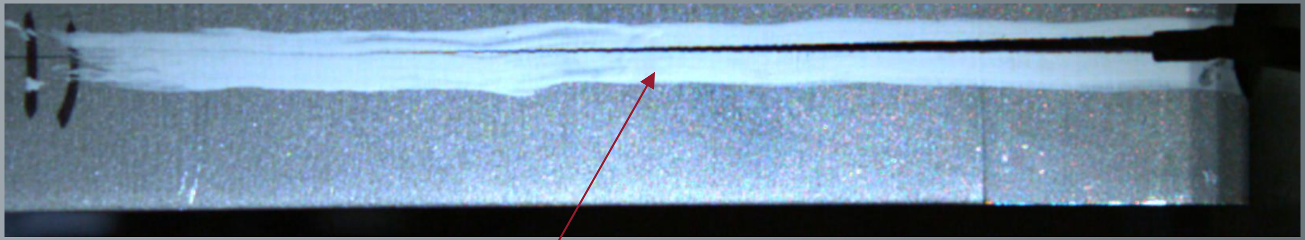




Double Cantilever Beam (DCB) – Fatigue

Status:

- Testing two methods of measuring crack length
  - Camera monitoring
  - Coupon compliance
- Testing edge treatment for color contrast



Liquid paper (white-out)

Next Steps

1. Complete static DCB testing
2. Finalize procedure for DCB testing in fatigue
3. Continue building S-N curve for scarf joints
4. Finalize bonding procedure for paste adhesives.
5. Investigate ratcheting of the scarf joint

Fatigue, Preetam Mohapatra

Aims

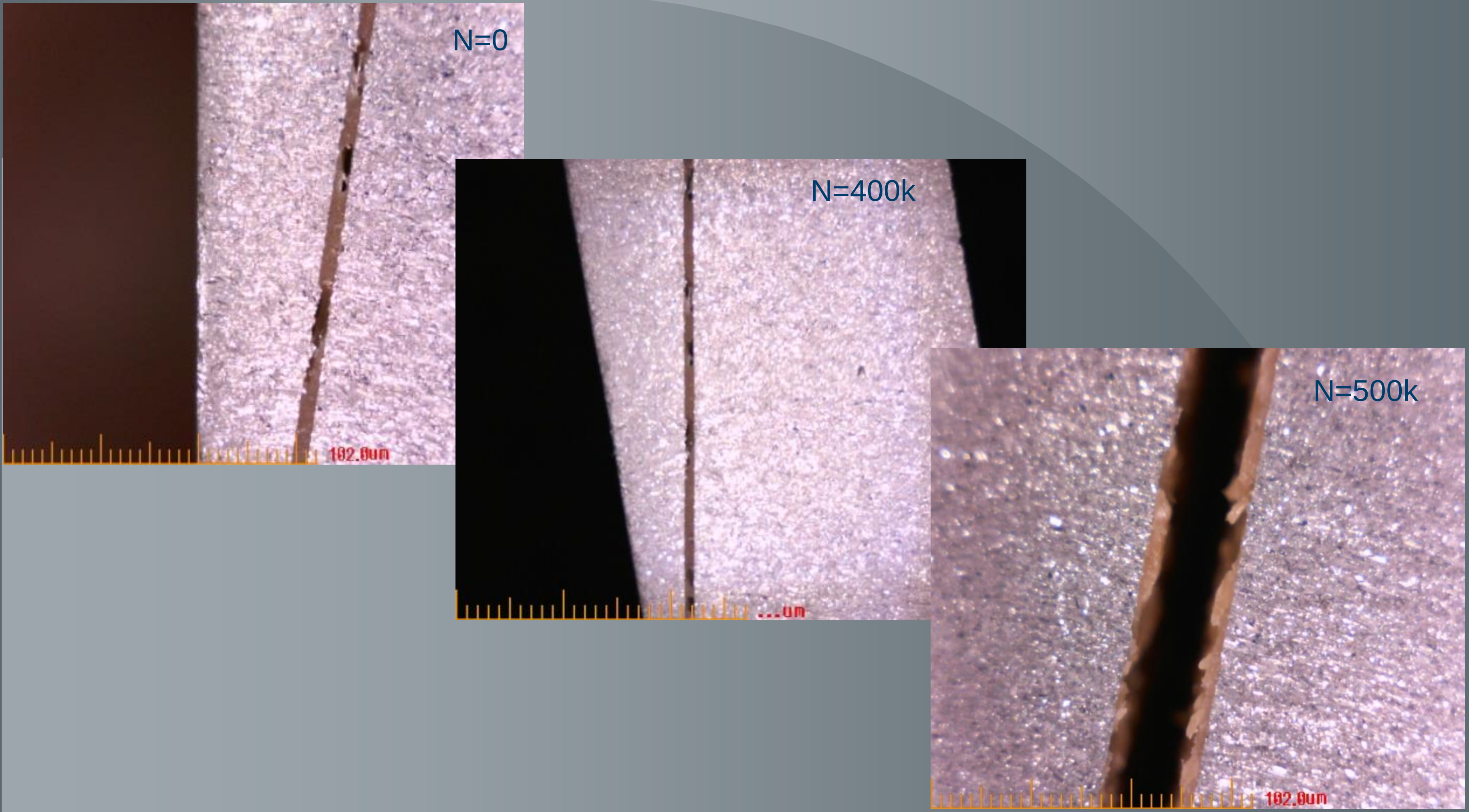
- ➢ Investigate the correlation between the static strength and FATIGUE LIFE of scarf joints
  - Identify fracture criterion for adhesive fatigue failure
  - Analyze the crack growth rate with different load cycles and adhesives
  - Estimate the fatigue life numerically with FEA
  - Validate with experimental results

Geometries

- ➢ Crack opening modes related to different coupon configurations
- DCB : Mode I
- ENF : Mode II
- Scarf : Mixed mode (I+II)

Status: investigating fatigue damage criteria for WALS, scarf, and DCB

Scarf fatigue failure: FM 300-2

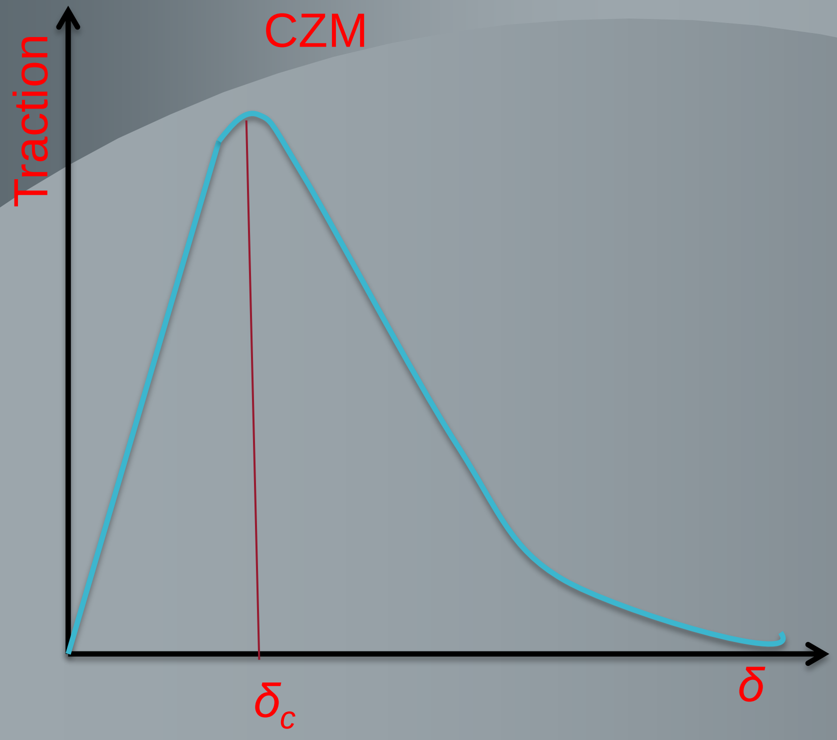


- Half a million cycle with 3Hz, Load ratio 0.1
- 3443 lbs – 344 lbs (Sin curve)
- No fatigue crack initiation or propagation was evident

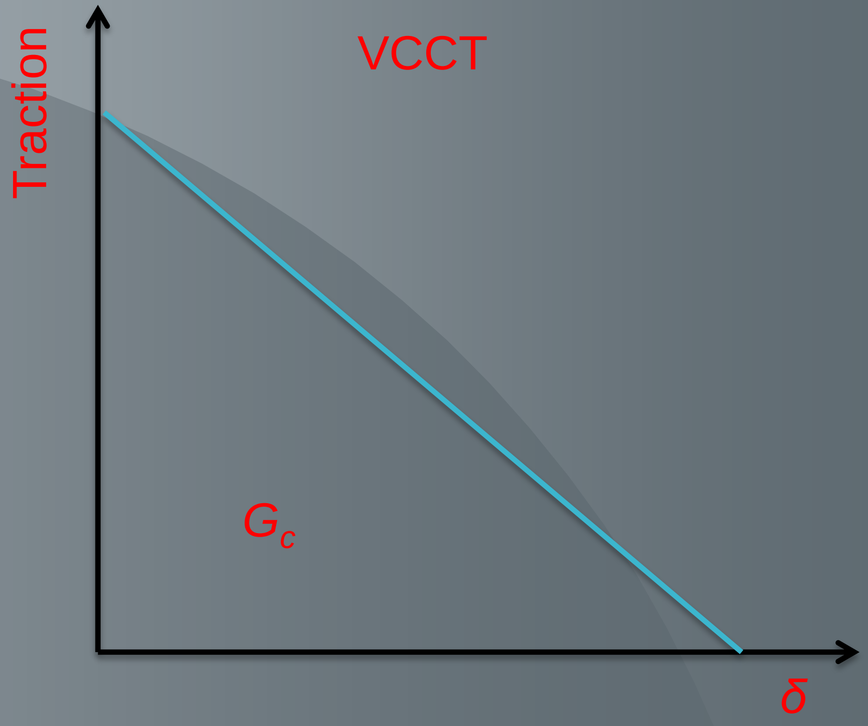
Fracture criteria: FEA

1. Material degradation and failure (no pre-crack)	Adhesive type	Mechanism
Cohesive zone model: CZM (traction separation law)	High and low ductility	LEFM & EPFM

2. De-bonding (pre-crack)	Adhesive type	Mechanism
Critical stress	Low ductility	LEFM
Crack Tip Opening Displacement	High ductility	EPFM
Virtual Crack Closure Technique or Enhanced VCCT (energy release failure criterion)	Low ductility	LEFM
Direct Cycle Fatigue (for cyclic loading)	Low ductility	LEFM



- Onset of failure: when traction force reaches maximum value (surfaces are elastically bonded)
- Crack propagation: failing cohesive elements from maximum traction to zero traction
- Complete failure: when the bond reaches max allowable displacement with zero traction force



- Onset of failure: when traction force reaches maximum value (surfaces are rigidly bonded)
- Crack propagation: once propagation started, the de-bonded nodes are released
- Complete failure: when the bond reaches maximum allowable strain energy release rate, G_c

Assumptions: Direct Cycle Fatigue

- **Material is Non-linear elastic**
- **Unloading follows the same path as that of loading**
- **Stable crack propagation (in Paris region)**
- **Plastic zone << LEFM zone (in Paris region)**

Direct Cyclic Fatigue: ABAQUS

- $G_{Ceq} = combined\ equivalent\ (G_{CI}, G_{CII}, G_{CIII})$ by BK, Power law or Reeder model
- $R = \frac{G_{min}}{G_{max}}$

Onset of Fatigue crack (region I)

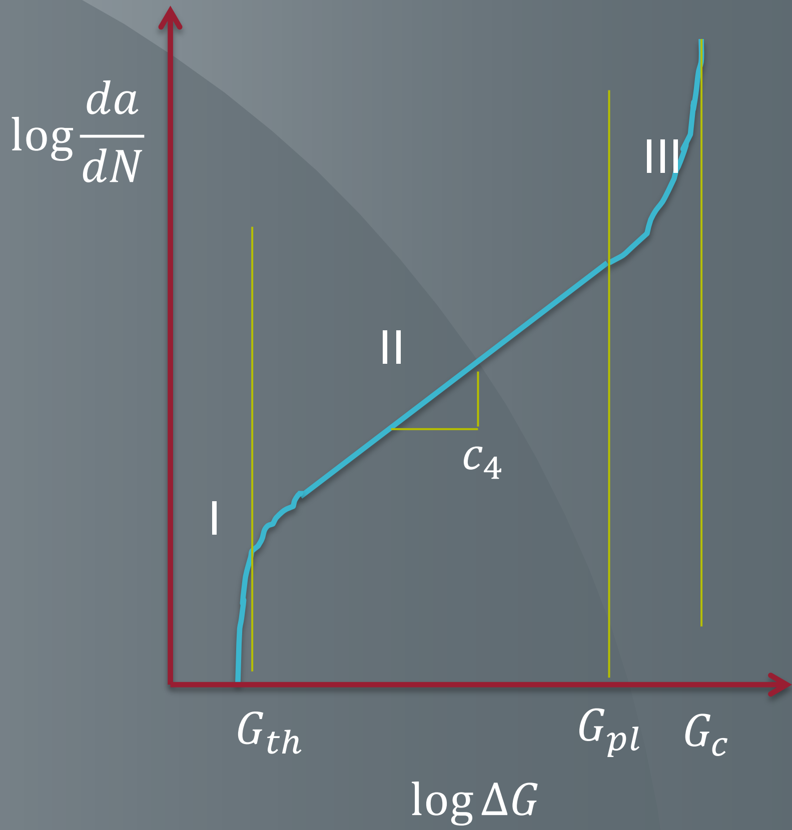
- $\frac{N}{c_1 \Delta G^{c_2}} \geq 1$
- $G_{max} > G_{threshold}$
- $G_{threshold} = r_1 G_{Ceq}$
- $\Delta G = G_{max} - G_{min}$

Stable crack propagation (Paris region II)

- $\frac{da}{dN} = c_3 \Delta G^{c_4}$
- $G_{pl} > G_{max} > G_{threshold}$
- $G_{pl} = r_2 G_{Ceq}$

Unstable fracture and failure (region III)

- $G_{pl} < G_{max} < G_c$ rapid crack propagation
- $G_{max} \geq G_c$ failure



- $G_{CI}, G_{CII}, G_{CIII}, c_1, c_2, c_3, c_4, r_1$ and r_2 are material constants (obtained from experiment)
- r_1 and r_2 depend on the load ratio R
- N is number of cycles

Next step

- ➢ Validate the numerical fatigue life with experiment (under cyclic loading)
- DCB (fatigue parameters for pure mode I)
- ENF (fatigue parameters for pure mode II)

- ➢ Compare scarf and WALS
- Crack propagation in Mode I or II or mixed mode (de-bonding)
- Continuum damage due to material degradation (CZM)

- ➢ Fatigue life vs. adhesive toughness and strength
- Different adhesive systems
- Temperature effects

Ratcheting, David Lemme

Aim: Study the adhesive’s viscoelastic effects in fatigue.

Ratcheting

Inputs:
- Mean Stress
- Stress Amplitude
- Strain Rate
- Peak Hold Time

Outputs:
- Cycles to Failure
- Strain at n Cycles

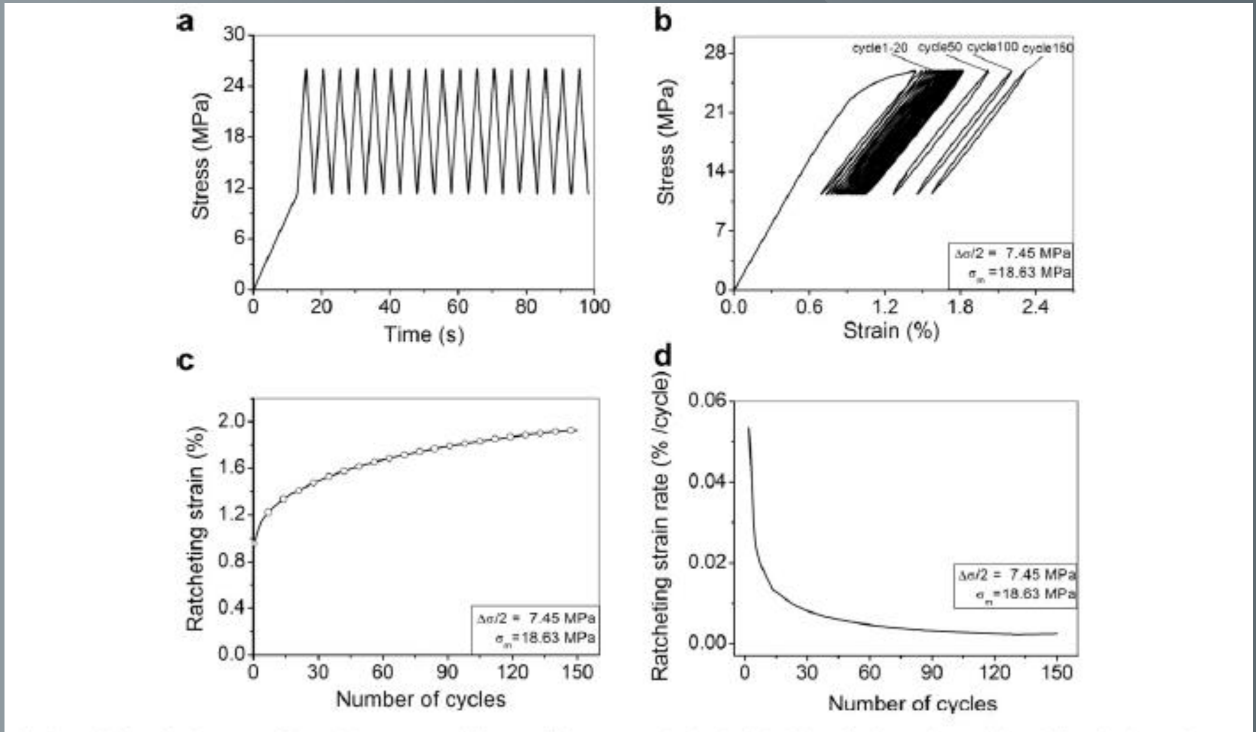


Fig. 3. Uniaxial ratchetting test of ACF: (a) stress control diagram; (b) stress–strain relationship; (c) ratchetting strain evolution; (d) ratchetting strain rate evolution.

Lin, Y.C., Xiao-Min Chen, and Jun Zhang. “Uniaxial ratchetting behavior of anisotropic conductive adhesive film under cyclic tension.” *Elsevier* (2010). Print.

Adhesive: Hitachi AC-8955YW-23

Viscoelasticity Plan

Study the effects of creep, relaxation, and ratcheting in adhesives.

Ratcheting

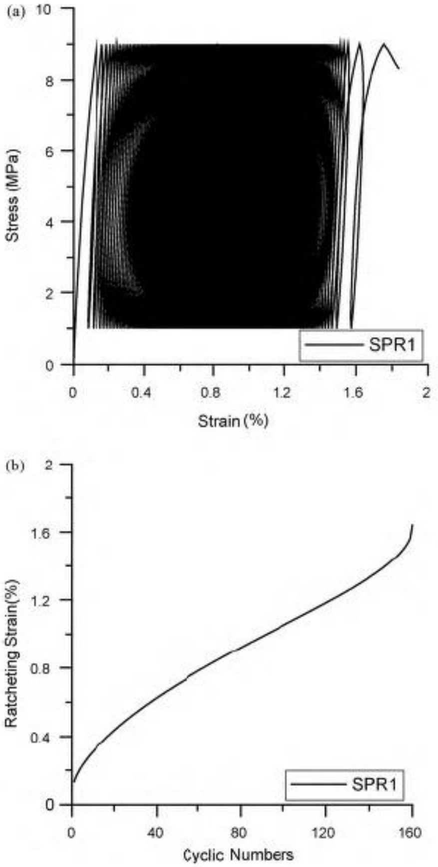


Fig. 5. Ratcheting behavior of sintered silver film specimen SPR1 (a) axial stress–strain response; (b)ratcheting strain with cycles.

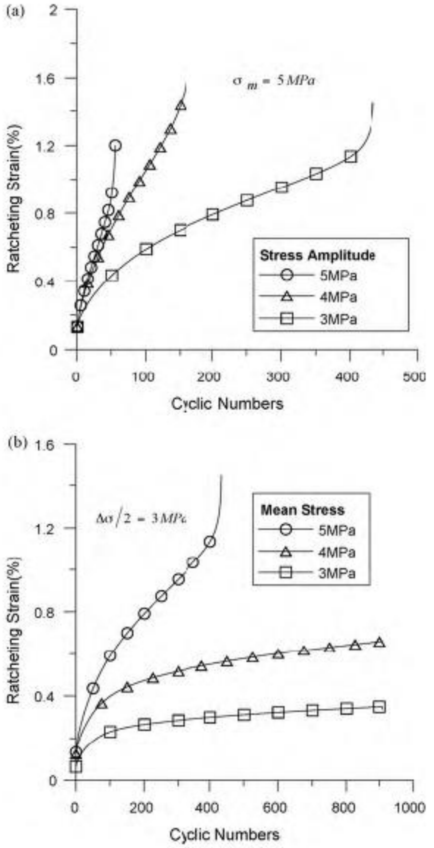


Fig. 6. Ratcheting behavior of sintered silver film (a) at the same mean stress and different stress amplitudes; (b) at the same stress amplitude and different mean stresses.

Tao Wang, Gang Chen, Yanping Wang, Xu Chen, and Guo-quan Lu. “Uniaxial ratcheting and fatigue behaviours of low-temperature sintered nano-scale silver paste at room and high temperatures.” Elsevier (2010). Print.

Creep Testing

Goal: determine the viscoelastic properties of EA9696 and FM300-2 and compare to a power law model.

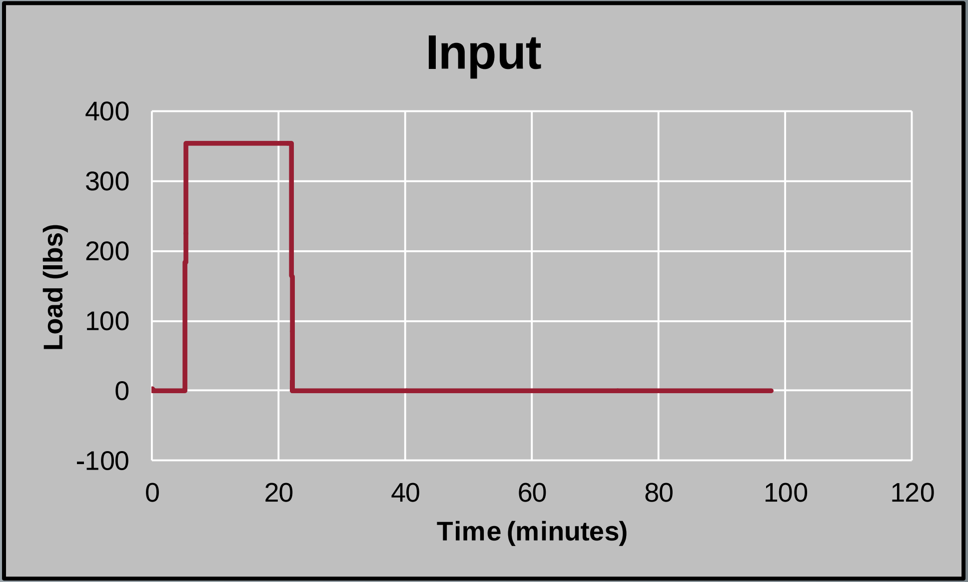
Bulk adhesive coupons:

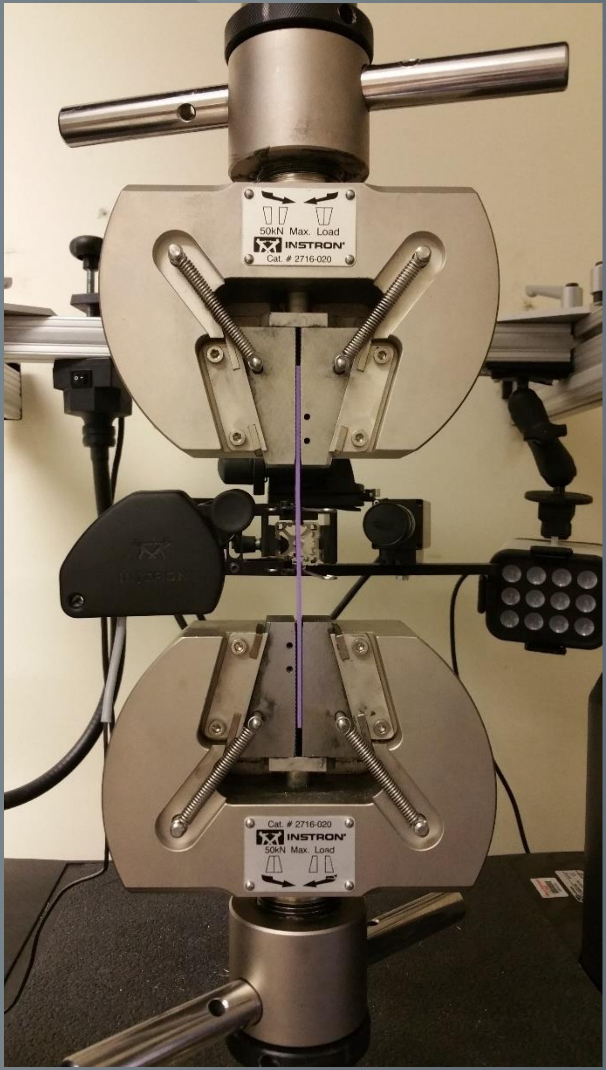
- 8 layers of film adhesive
- Sandwiched between two steel plates and vacuum bagged.
- 1 x 6 x 0.068 in

Creep Testing

Status:

Test:

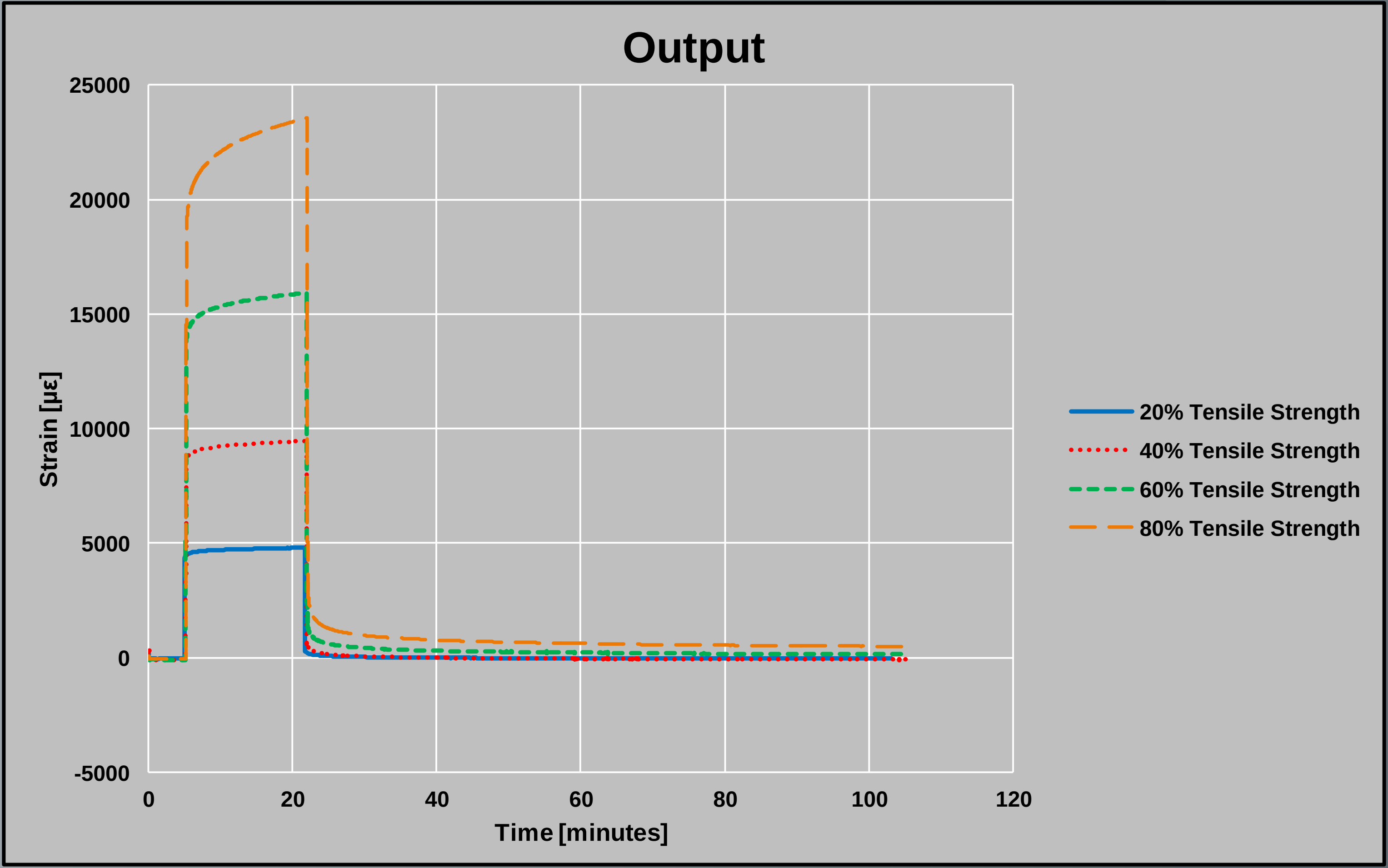




Creep Testing

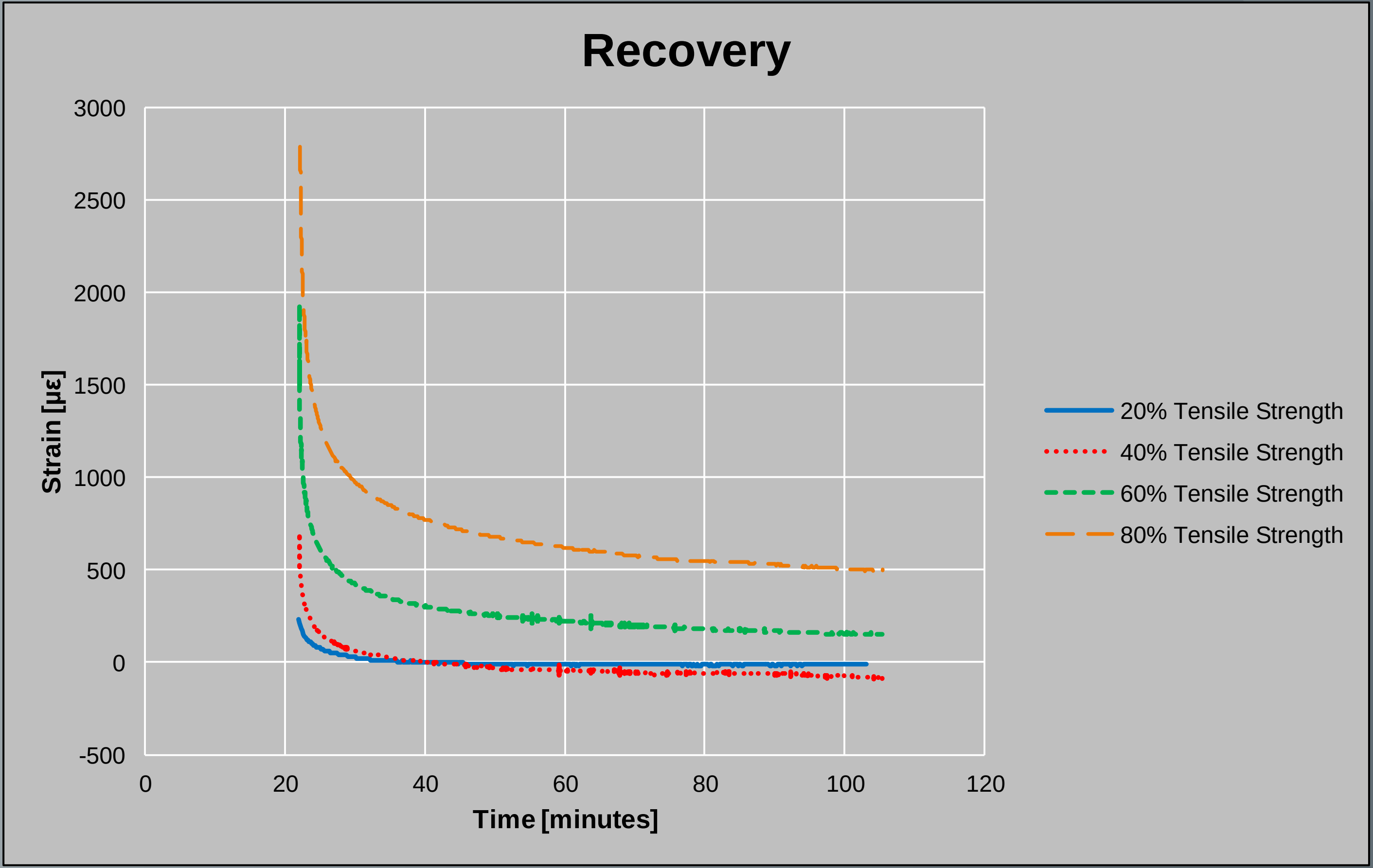
EA9696 results:

$$\sigma_t = 6500\ psi$$



Creep Testing

EA9696 results:



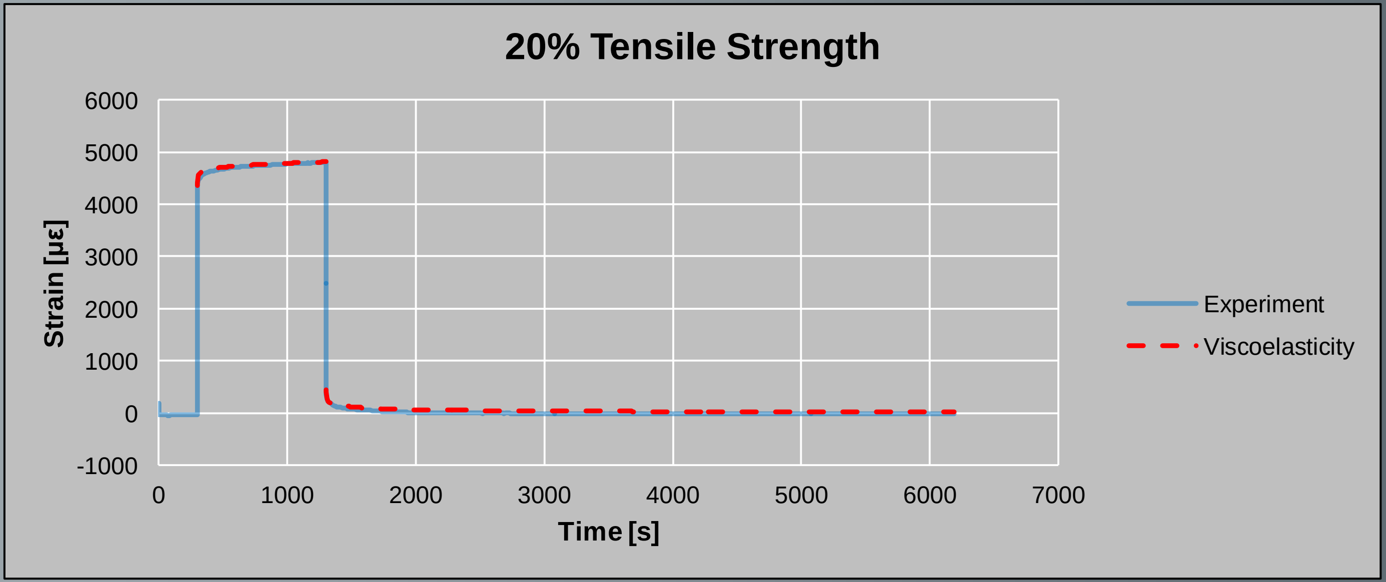
Creep Testing

Where does nonlinearity occur? Compare with power law model.

$$Creep\ Compliance = D(t) = D_0 + D_1 t^n$$

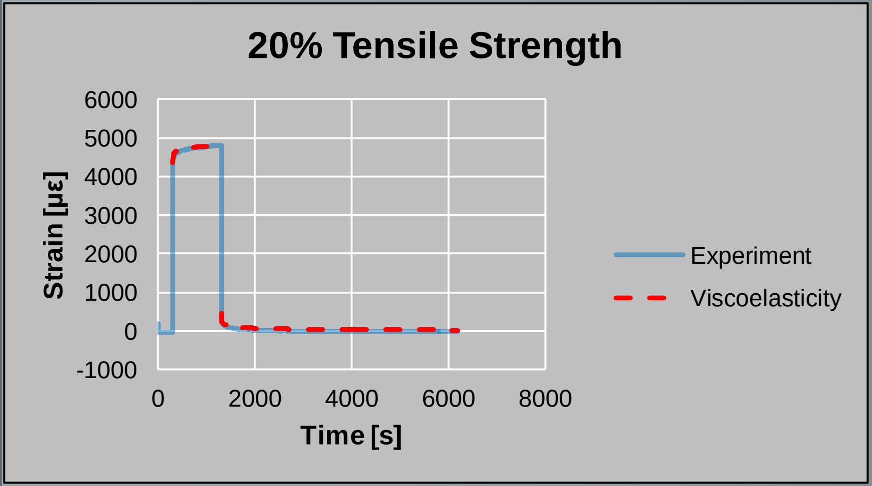
Using 20% tensile strength strain,

$$D_0 = 1/0.31\ Msi$$
$$D_1 = 0.11$$
$$n = 0.16$$

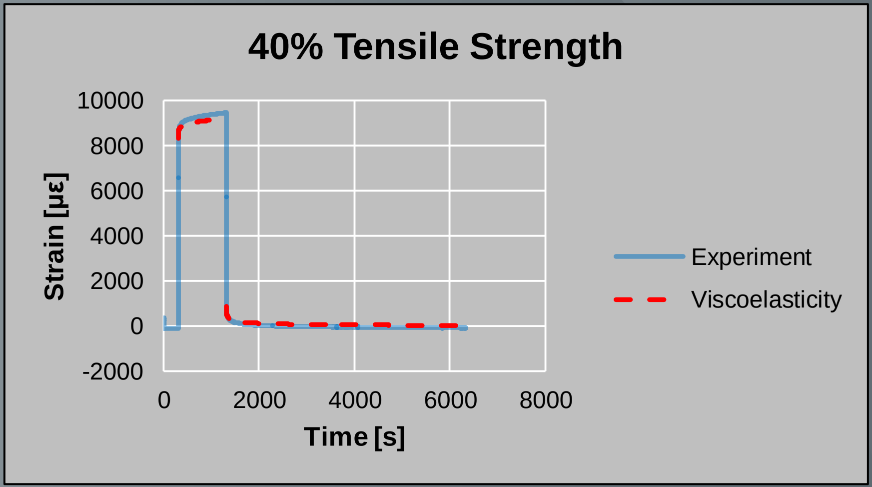


Creep Testing

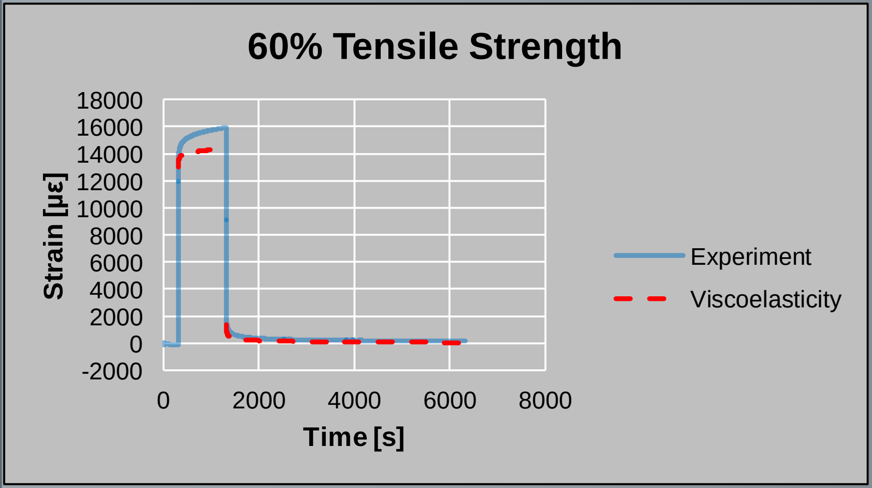
EA9696 results:



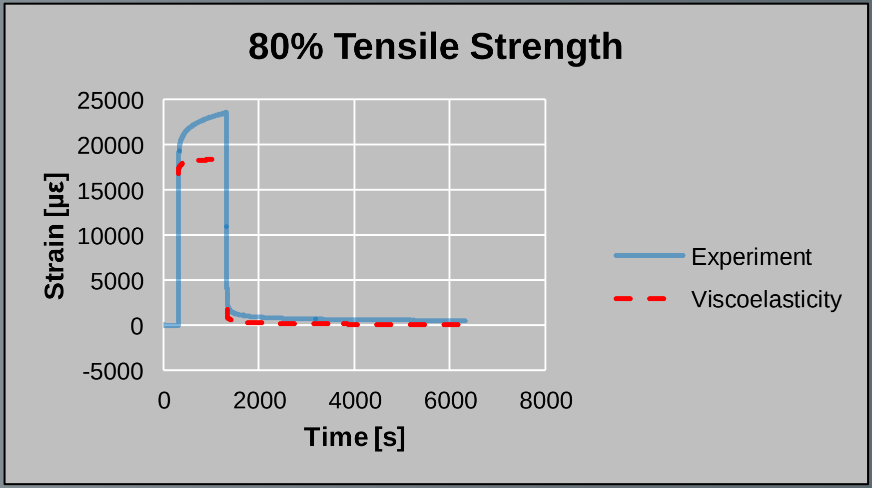
20% Tensile Strength



40% Tensile Strength



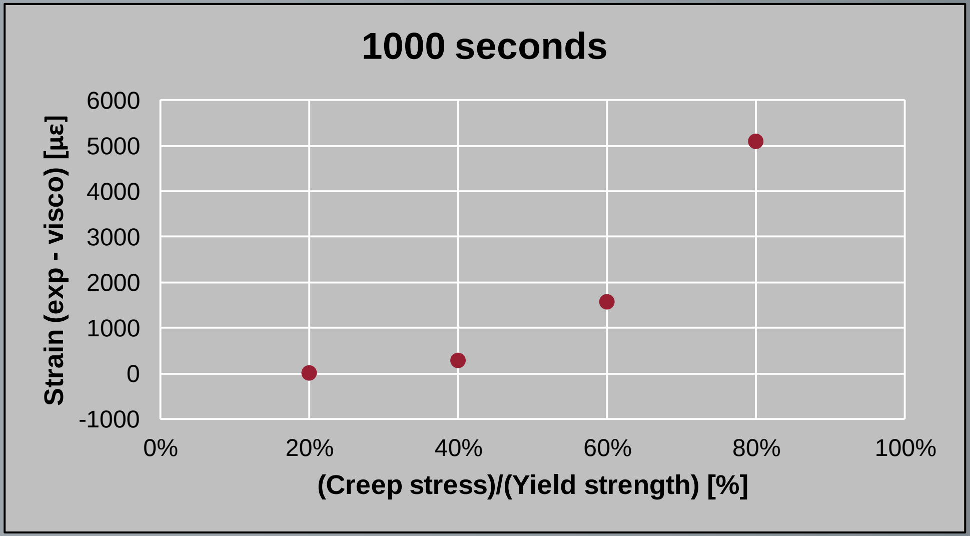
60% Tensile Strength

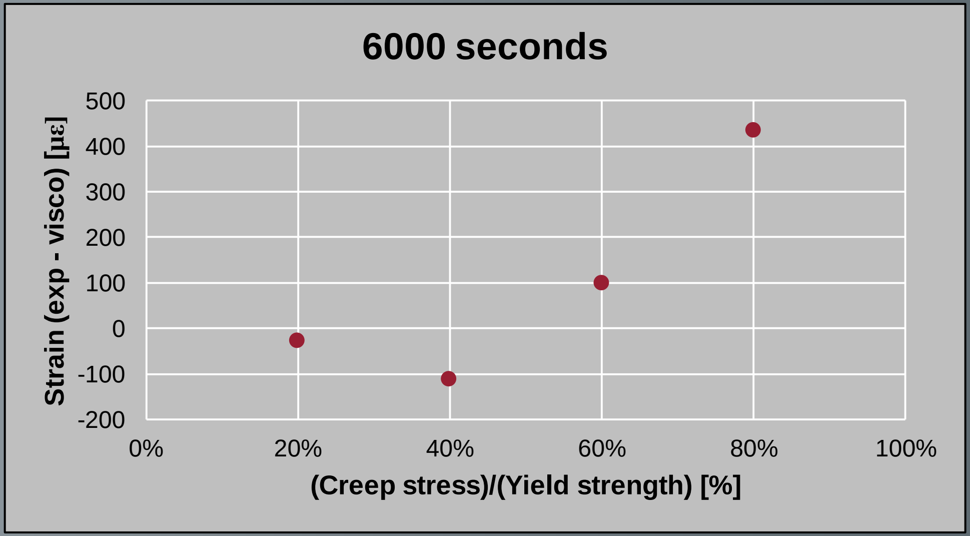


80% Tensile Strength

Creep Testing

EA9696 results:

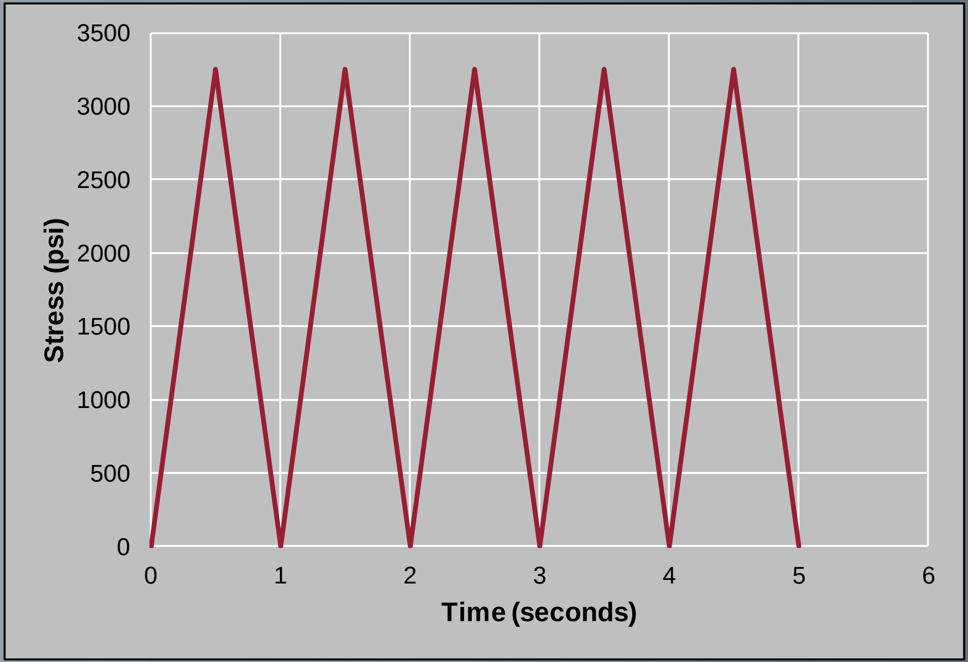




Viscoelastic Ratchetting Model

Goal: Model ratchetting strain based on linear viscoelastic model.

Stress is modeled as a triangular wave.



Viscoelastic Ratchetting Model

Strain is found from the convolution integral.

$$\epsilon(t) = \int_{-\infty}^{t} D(t-\tau)\dot{\sigma}(\tau)\,d\tau$$

$$D(t) = D_0 + D_1 t^n$$

Inputs:

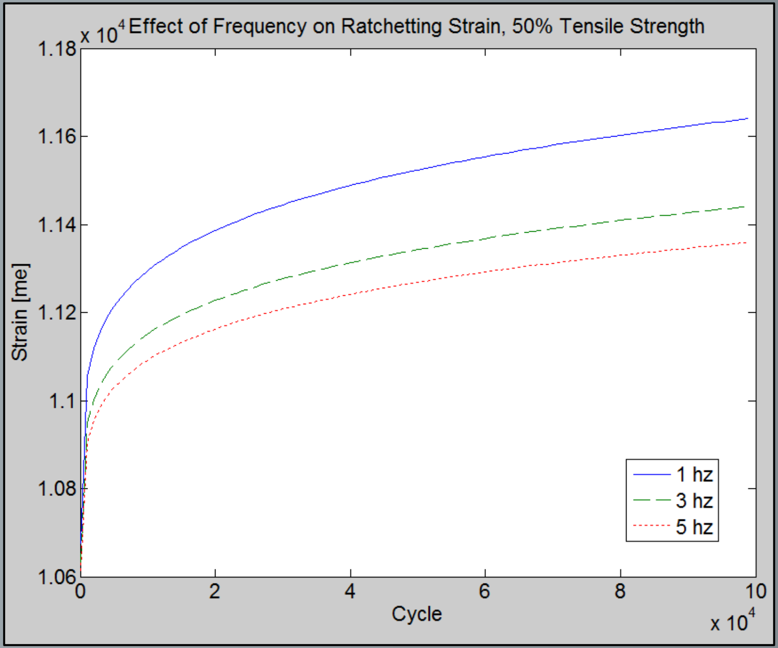
- Max stress, σ
- Frequency, f
- Cycle, N
- Time, t

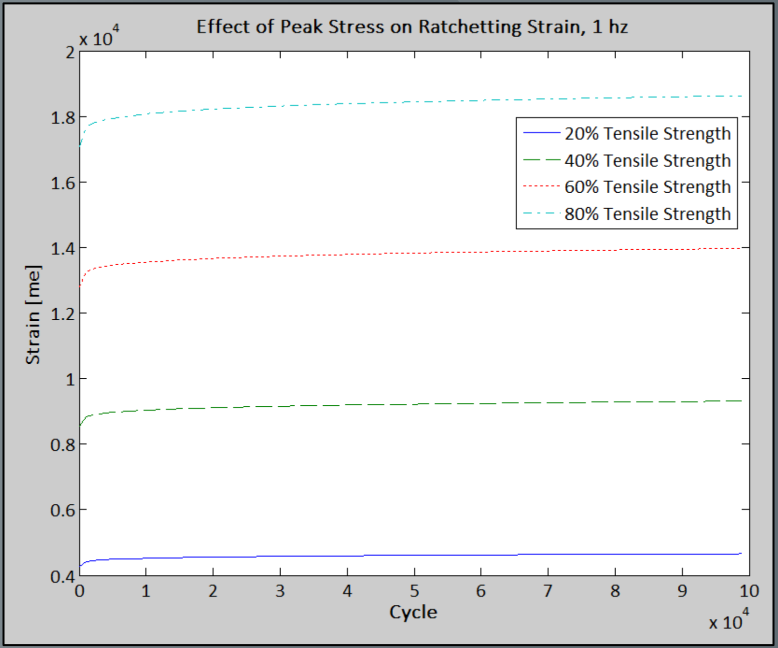
Output:

- Max strain at cycle

$$\varepsilon(t) = 2D_0\sigma_{max}(N-ft) + \frac{2D_1\sigma_{max}f}{n+1}\left[t^{n+1} + \sum_{i=1}^{2N-1} 2(i)^{-1}(t-\frac{i}{2f})^{n+1}\right]$$

Viscoelastic Ratchetting Model





Next Steps

- Creep tests for 10,000s and 100,000s durations.
- Creep tests for FM300-2.
- Relaxation tests for EA9696 and FM300-2.
- Ratchetting model based on viscoelastic properties.

Temperature, Sayed Hafiz

- Aim: determine if temperature induced changes in ductility have the same effect as room temperature differences in ductility

Status: 12 neat resin, 8 WALS coupons made

Temperature Effects on Adhesive Fatigue and Creep

- An adhesive joint loses its strength and fatigue resistance when exposed to hostile environments.
- We are interested in how toughness is affected by temperature and as a result fatigue resistance of adhesives.
- Creep experiments have shown nonlinear behavior at 60% of ultimate strength. Does it remain the same at elevated temperature?

Scope of Work

The experimental work for this project will involve placing wide area lap shear (WALS) joints in fatigue at different temperatures.

Temperature	**-5°C**	**30°C**	**65°C**	**100°C**
EA 9696	25 WALS	25 WALS	25 WALS	25 WALS

Temperature	**-5°C**	**30°C**	**65°C**	**100°C**
FM 300-2	25 WALS	25 WALS	25 WALS	25 WALS

Scope of Work

Also creep test of neat resin coupons at 70 °C/160F.

Adhesives
EA 9696
FM 300-2

Duration	1000 sec	10000 sec	100000 sec
20% of UTS			
40% of UTS			
60% of UTS			
80% of UTS			

Next Steps

Develop creep test method in the servo hydraulic load frame inside the environmental chamber.

- Benefit to Aviation
  - Improved (accelerated) certification procedures for bonded structure
  - Guidance for adhesive joint design
- Future needs
  - Adhesive fatigue predictive capability
  - Fatigue response of adhesive joints
  - Effect of temperature on adhesive response