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Durability of Bonded Aircraft Structure

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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
- Improve our understanding of adhesive response under fatigue loading.
  - Effect of peel stress on static and fatigue response.
  - Response in tension and shear, in bulk and thin bonds.
  - Effect of joint toughness on fatigue life.
  - Visco-elastic response in static and cyclic loading.
- Approach
  - Coupons with varying amounts of peel stress
  - Bulk adhesives and thin bonds, plasticity models
  - Bond thickness and temperature
  - Non-linear viscoelasticty

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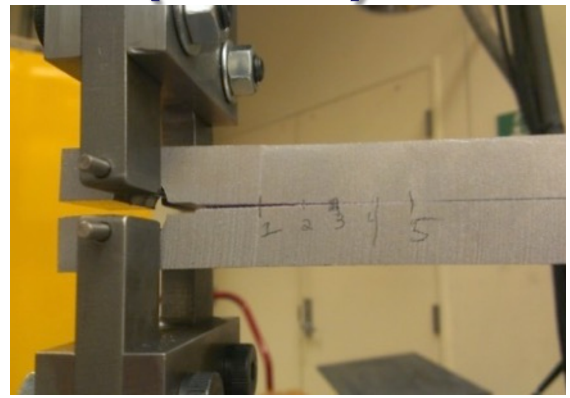
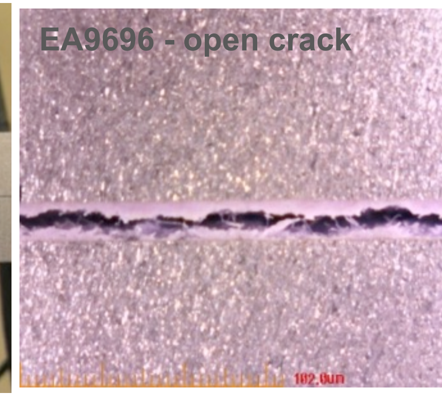
Double Cantilever Beam (DCB)

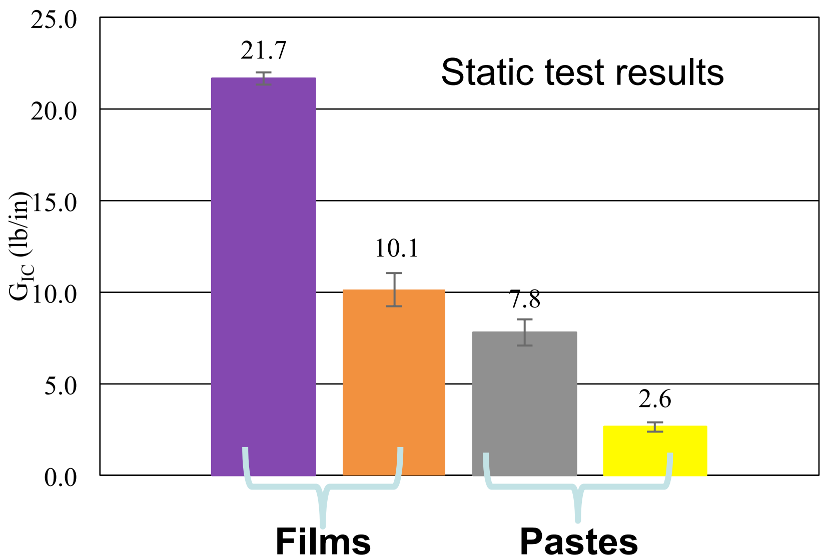


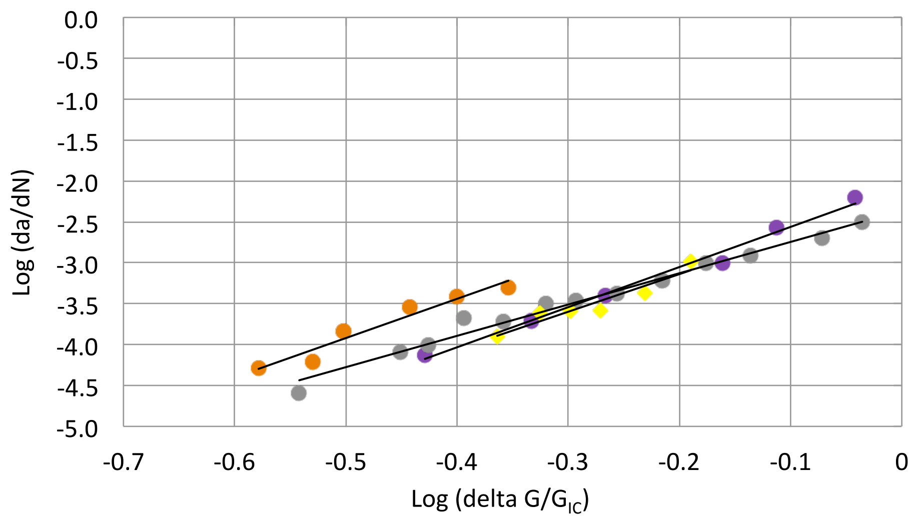


- EA9696
- FM300-2
- EA9380.05
- EA9394

ASTM D3433

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





- **EA9696 – High toughness**
- **FM300-2 ≈ EA9380.05**
- **EA9394 – Low toughness (adhesive failure)**

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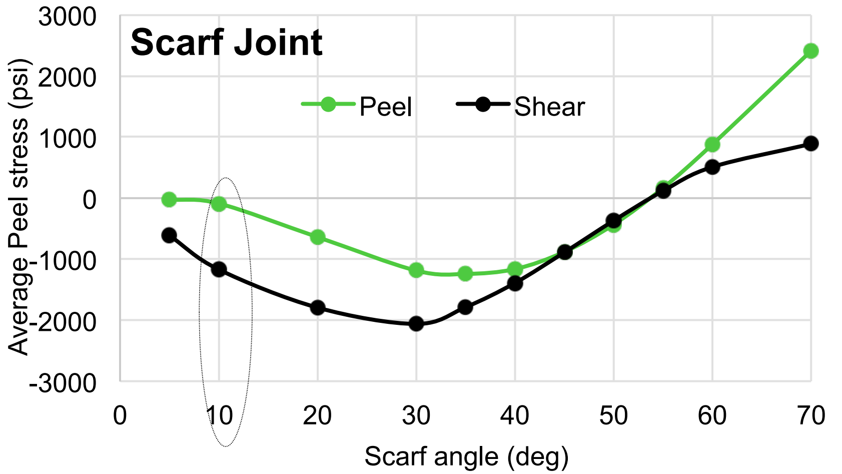
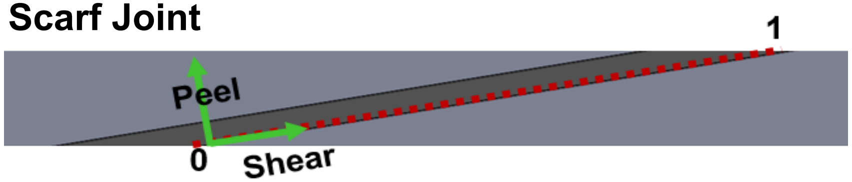
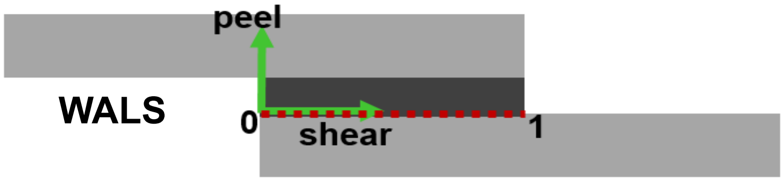
Coupon Peel Stress

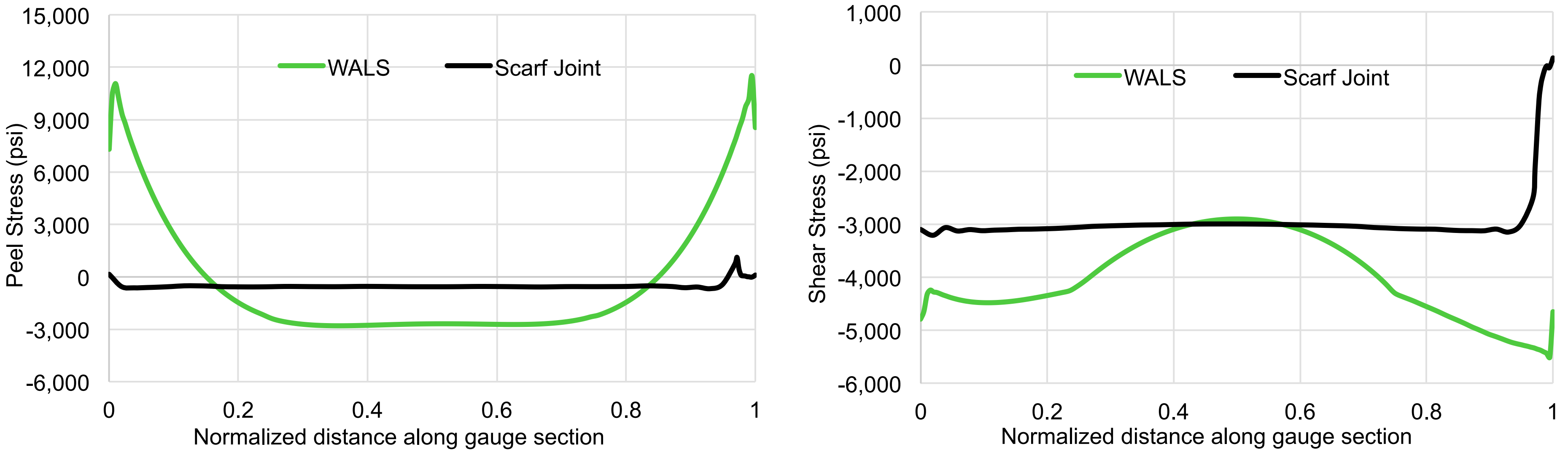
FEA Results :

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









Scarf Joint - Static

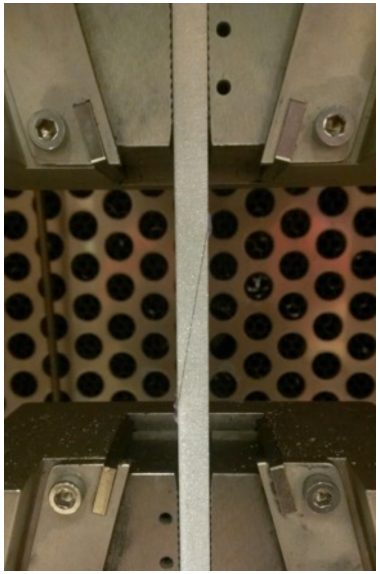
- EA9696 and EA9380.05 show more softening
- FM300-2 strongest
- Static strength does not correlate well with G_{IC}

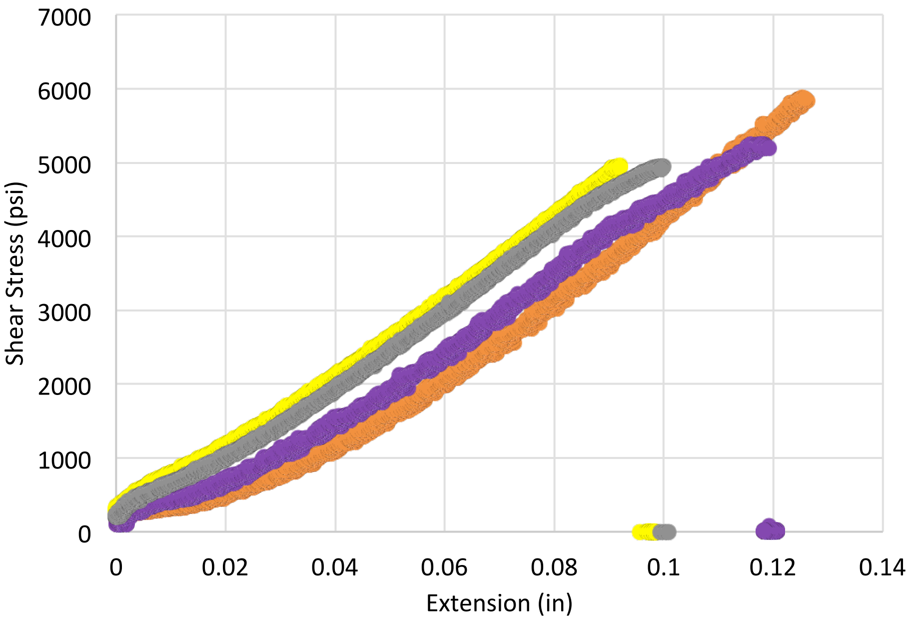
EA9696

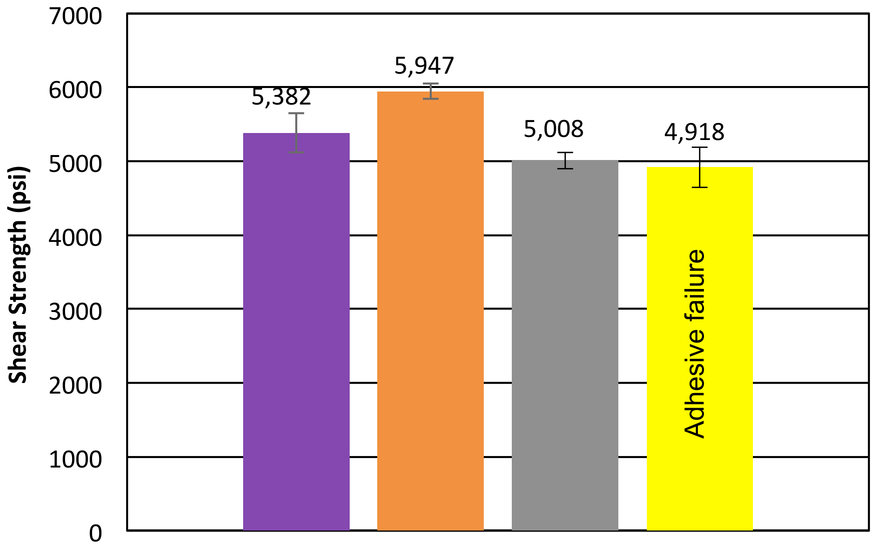
FM300-2

EA9380.05

EA9394







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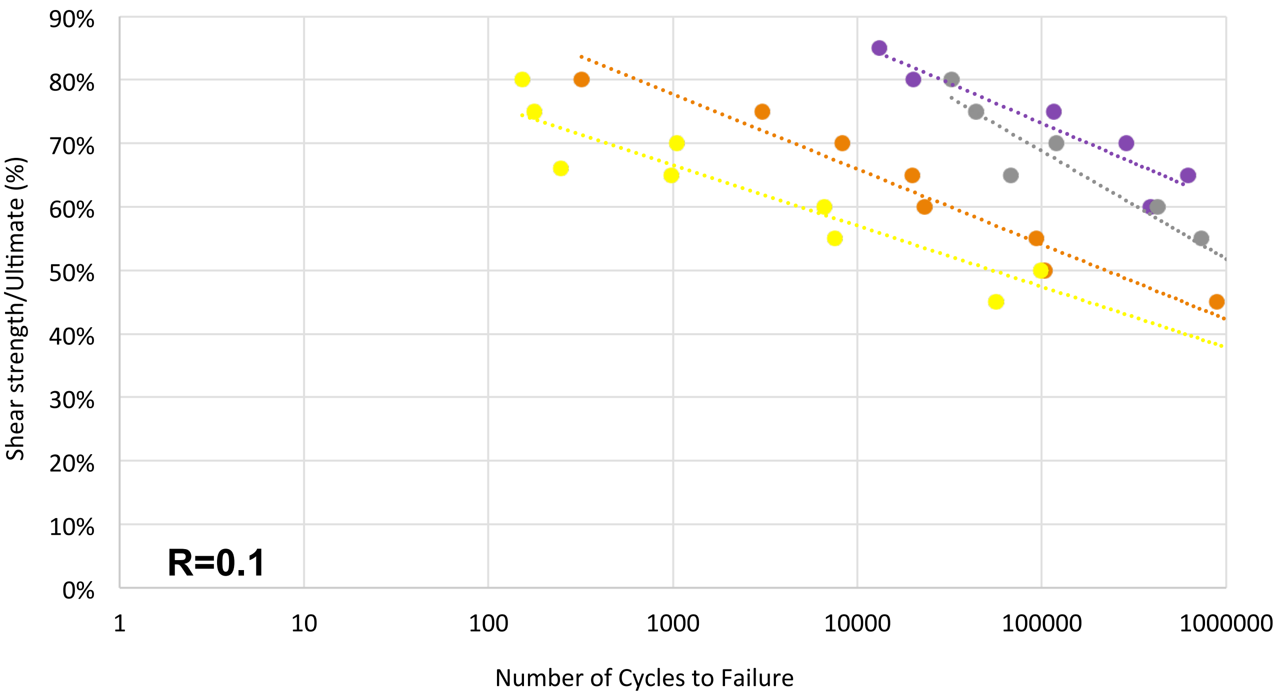
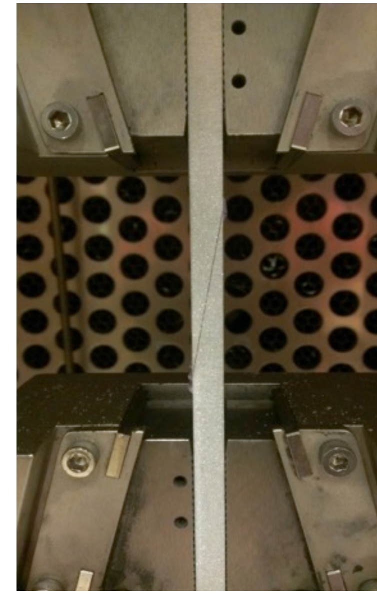
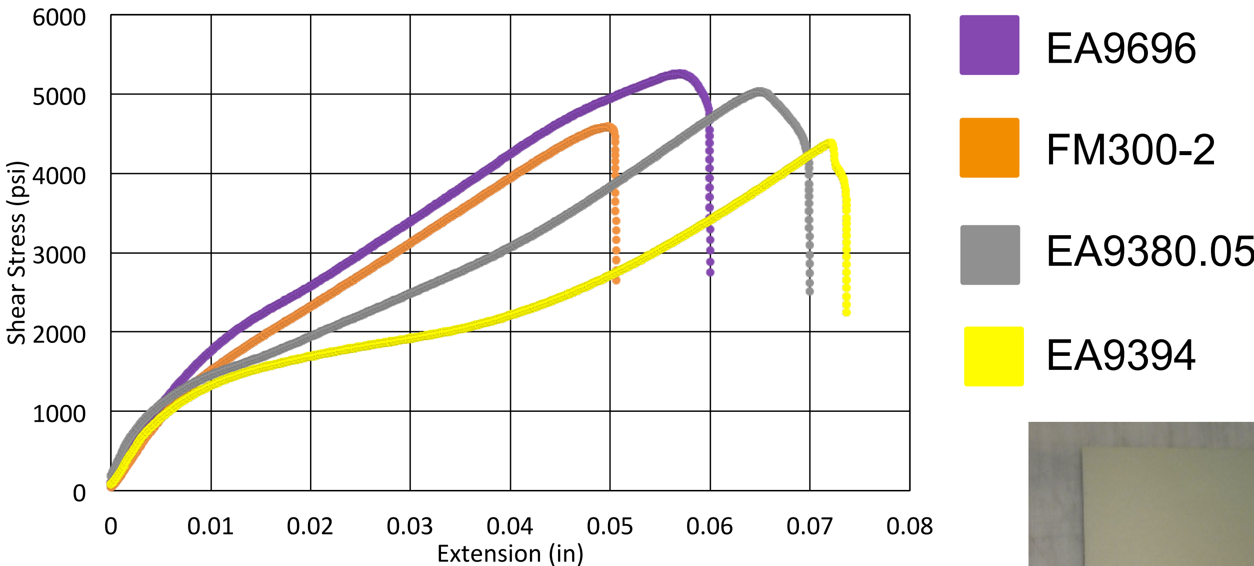
Scarf Joint - Fatigue

- EA9696 has highest fatigue life
- EA9394 has shortest fatigue life
- Fatigue life tends to correlate with G_{IC}

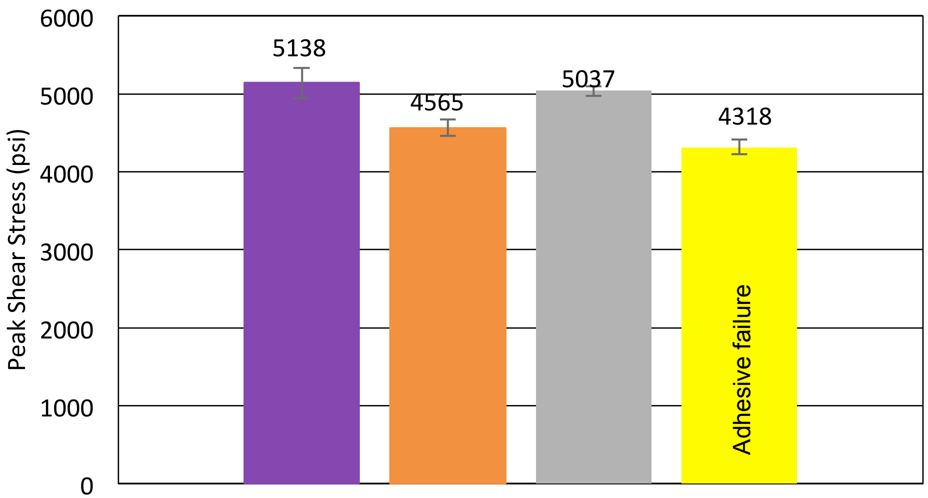


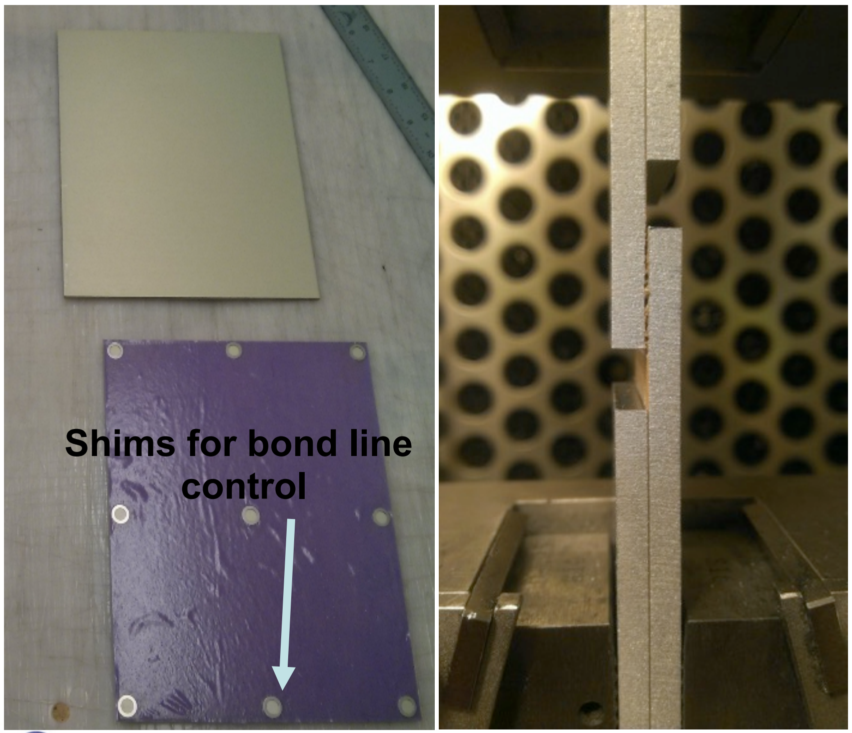


Wide Area Lap Shear - Static

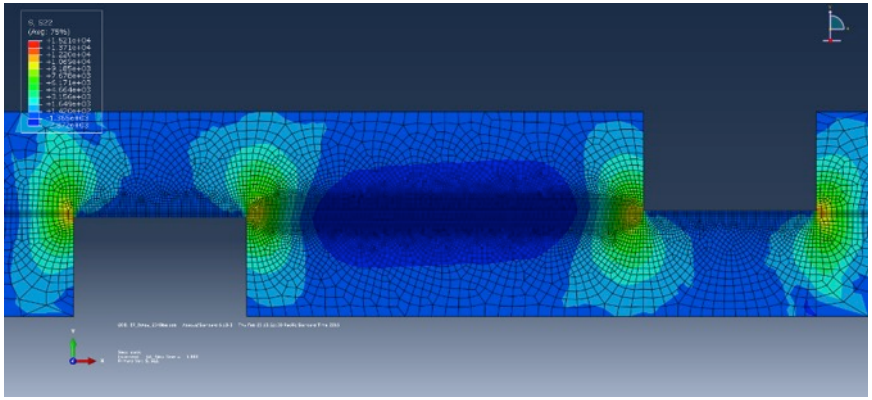


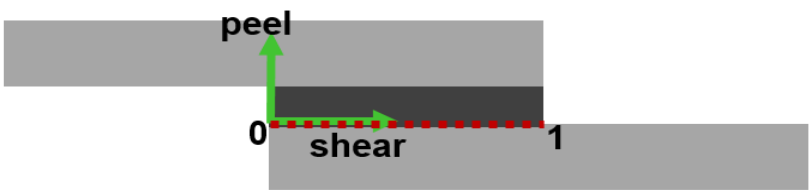
- Higher toughness than scarf
- Better correlation with G_{IC} than scarf

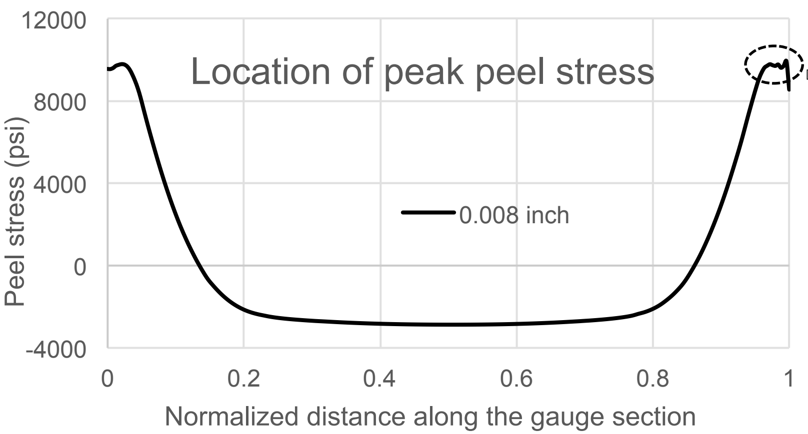


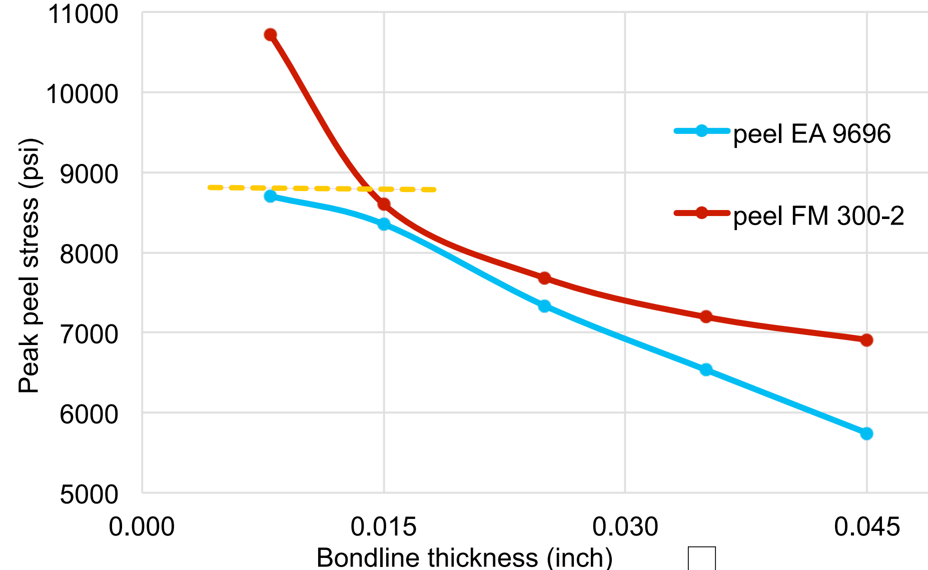


Wide Area Lap Shear – Bond Thickness









Peak peel stress vs. bondline thickness

- Loaded at 70% of their respective peak static strength.
- Thickness affects peel stress more than shear stress
- 0.008” EA 9696 ≈ 0.014” FM 300-2 (comparable thickness)

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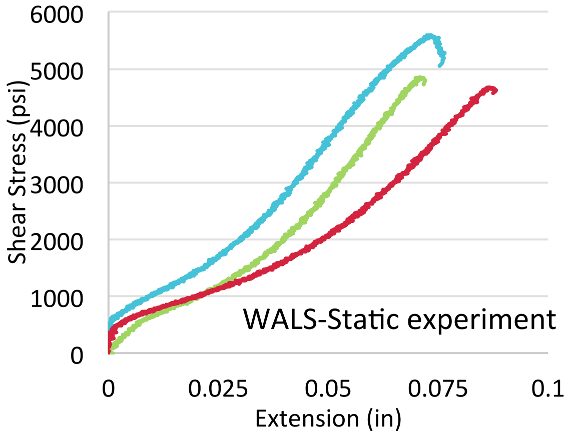
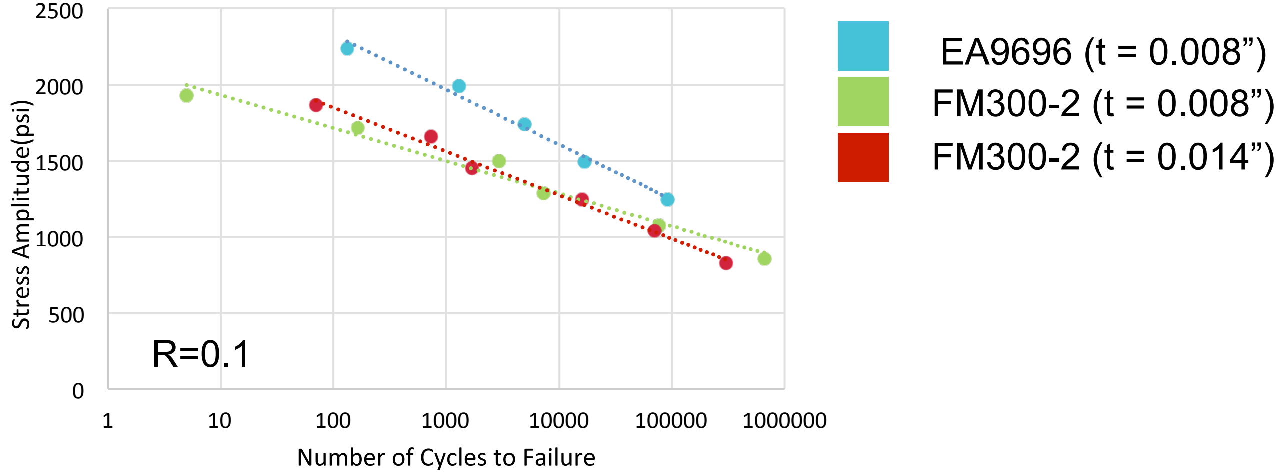
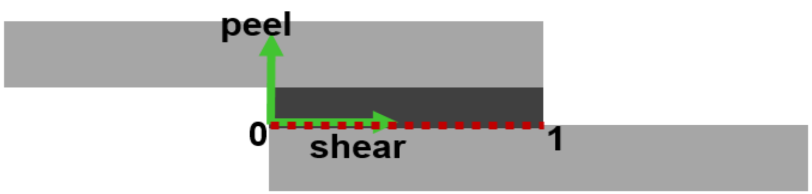
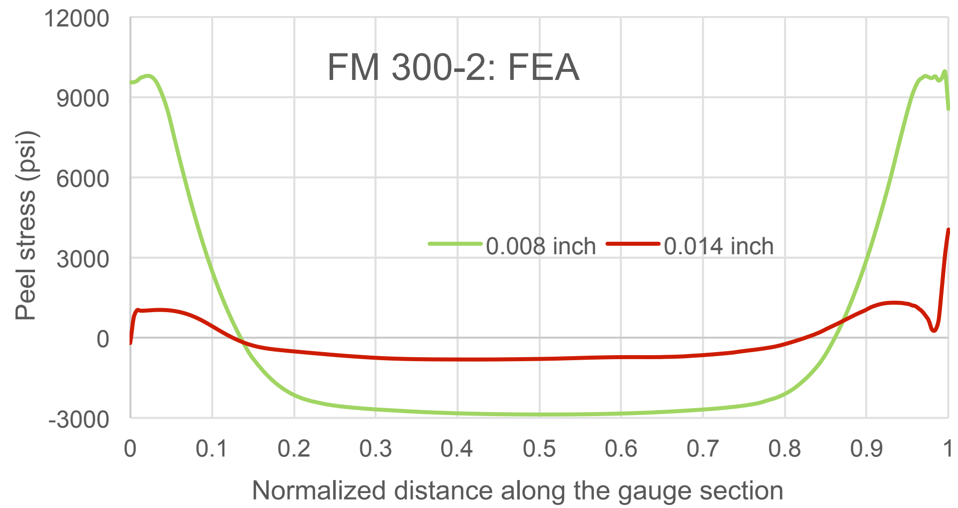
Wide Area Lap Shear: Bond Thickness





- Experimentally observed load applied to elastic plastic models to compare peel stress





Observations

- Increase in thickness increases ductility of the joint.
- Bond thickness had negligible effect on fatigue life
- In fatigue, adhesive toughness is more important than peel stress.

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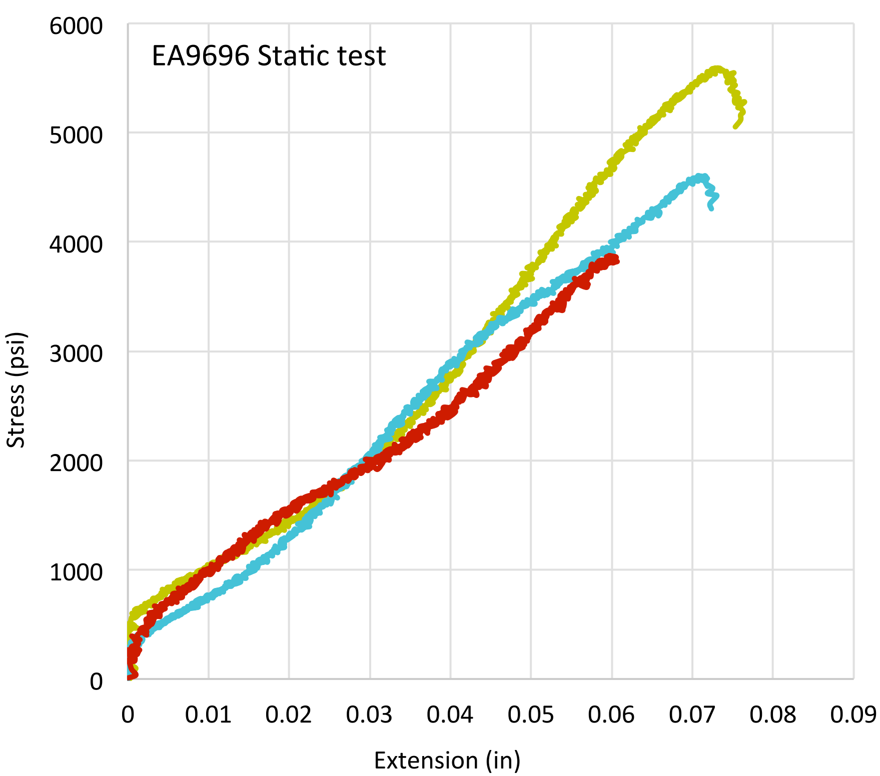
Wide Area Lap Shear: Temperature

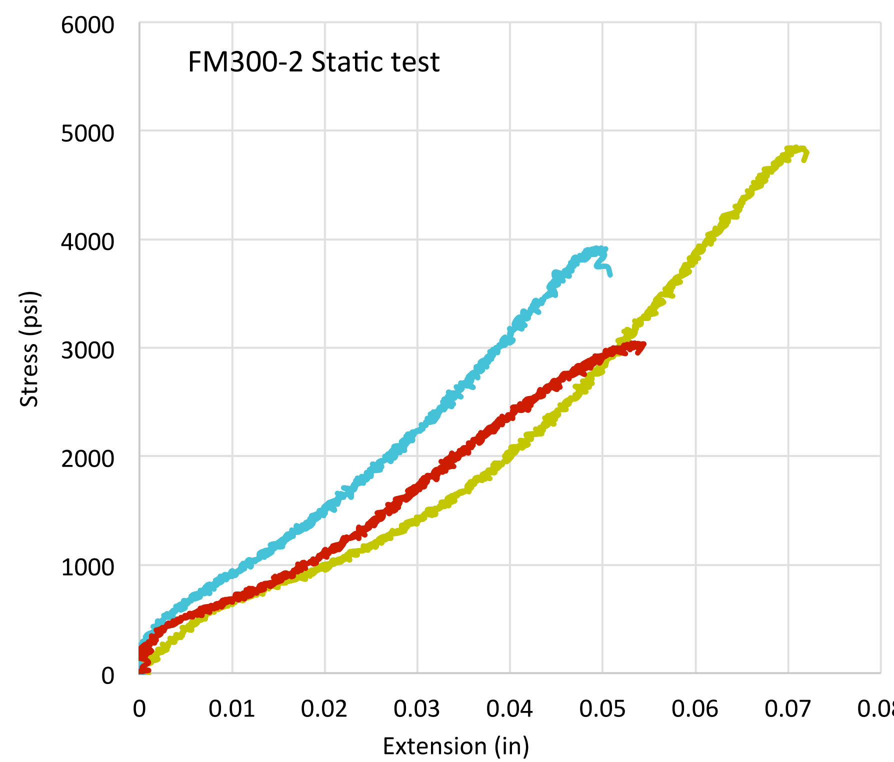
- Static strength reduces as temperature increases
- Toughness is not significantly affected by temperature

77F/25°C

149F/65°C

212F/100°C





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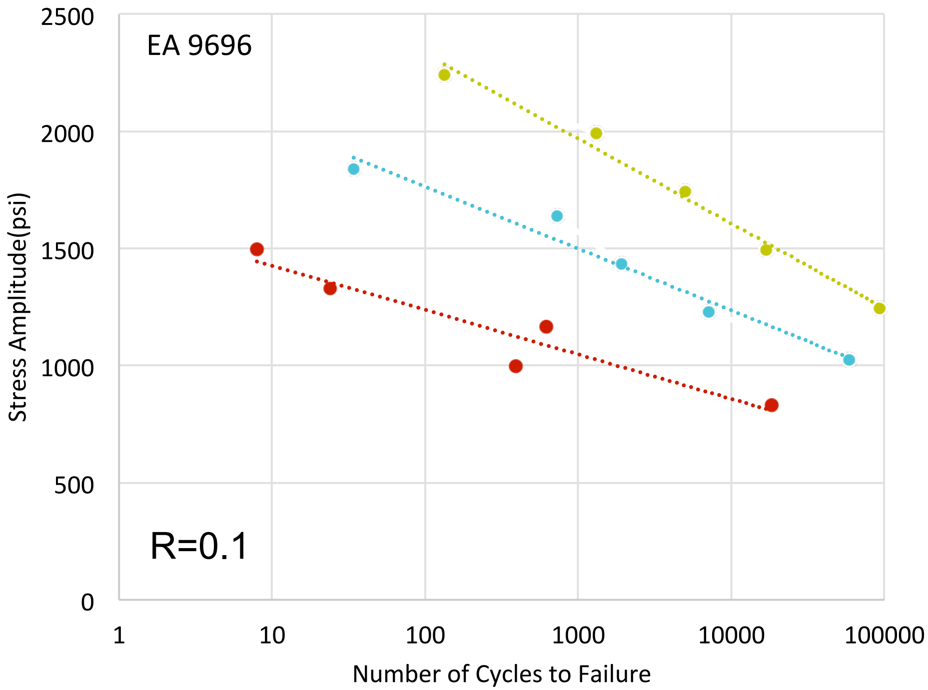
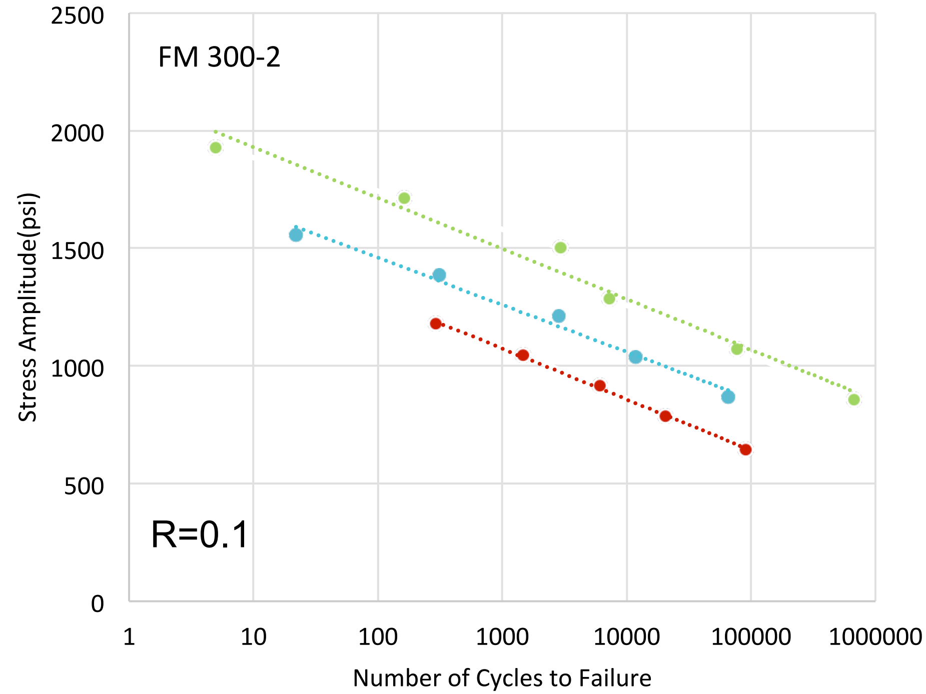
Wide Area Lap Shear: Temperature

- Fatigue life decreases as temperature increases
- Fatigue response strongly affected by static strength

77F/25°C
149F/65°C
212F/100°C





Observations from experiment

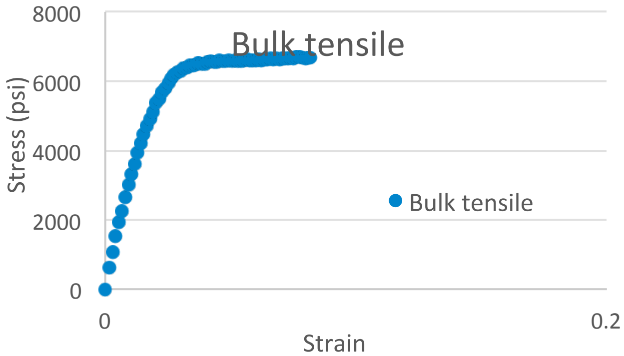
1. G_{IC} tends to be a good indicator of fatigue performance

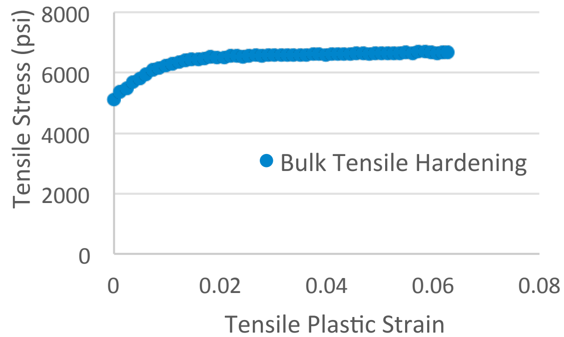
2. Joint toughness increases with peel stress and bond thickness, but not with increasing temperature

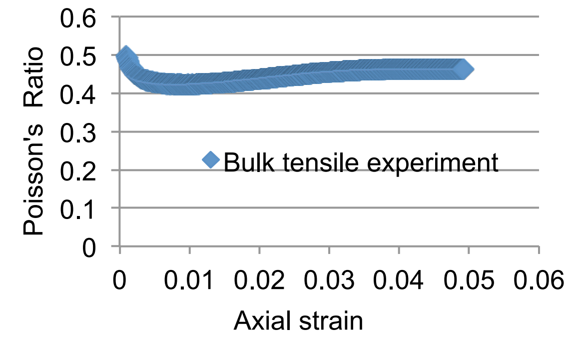
3. Fatigue response depends more on adhesive toughness than bond thickness or temperature.

FEA adhesive models: EA9696

- Model inputs







Linear Elastic	Adhesive	Adherend
E (Psi)	277000	10600000
υ_e	0.43	0.33

- Elastic-plastic:
  - Not sensitive to hydrostatic stress
  - von Mises
- Input:
  - Linear elastic properties
  - Tensile hardening curve

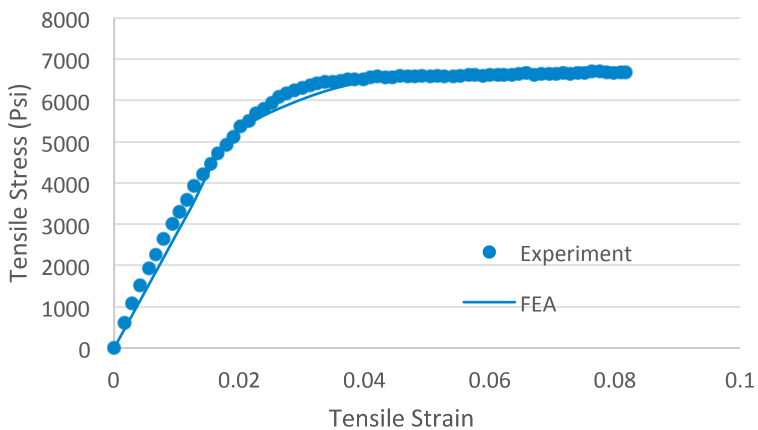
- Drucker Prager:
  - Sensitive to hydrostatic stress
  - Exponent > linear (better describes non associated flow of adhesive)
- Input:
  - Linear elastic properties
  - Tensile hardening curve
  - Drucker Prager parameters

Exponent Drucker Prager	Adhesive
a ( )	0.0008
b	2
Ψ	3.5

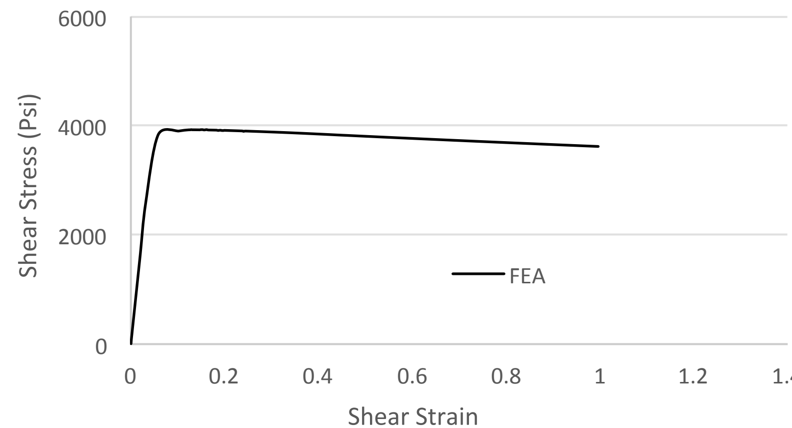
- Can use shear input (not usually done)
- Did not improve correlation with current results

FEA adhesive models: EA9696

- Bulk adhesive in tension (input)



- Thick adherend lap shear



- Good agreement
- von Mises and Drucker Prager predicted same result

- Good agreement only for linear elastic portion
- Von Mises and Drucker Prager predicted similar results

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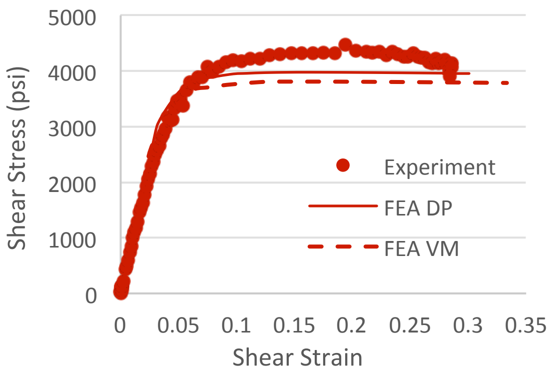
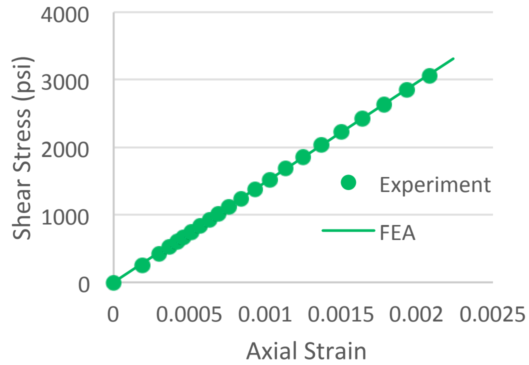
FEA adhesive models: EA9696

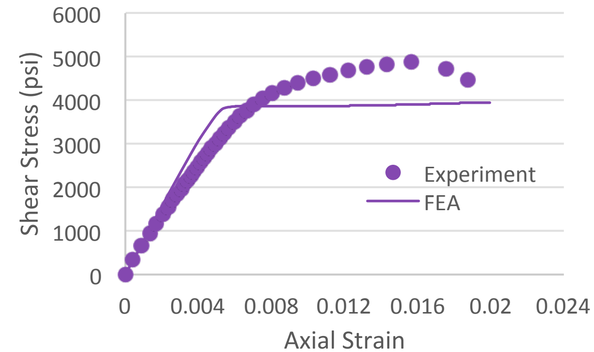
- Bulk shear specimen

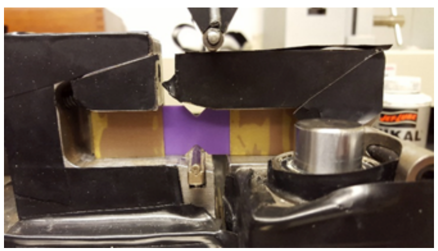


- Scarf joint



- WALS





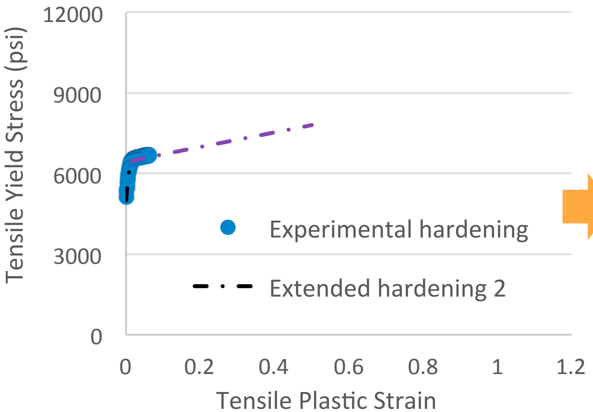
- Good agreement
- Drucker Prager exceeded von Mises by 4%

- Good agreement
- No non-linear response

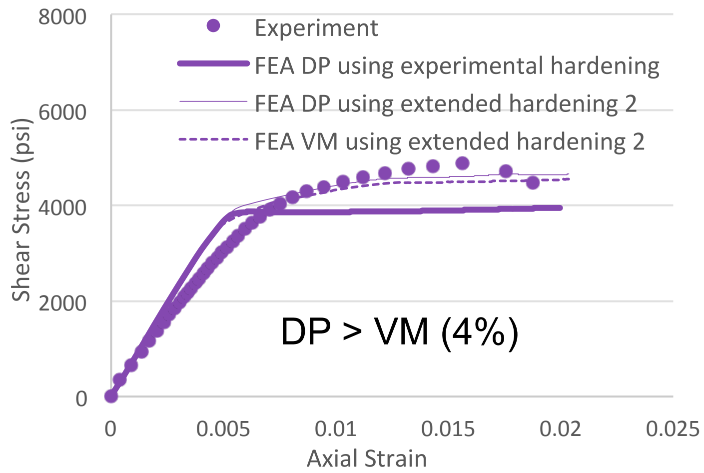
- Good agreement
- Von Mises and Drucker Prager predicted similar results

FEA adhesive models: EA9696

- Bulk adhesive Material model



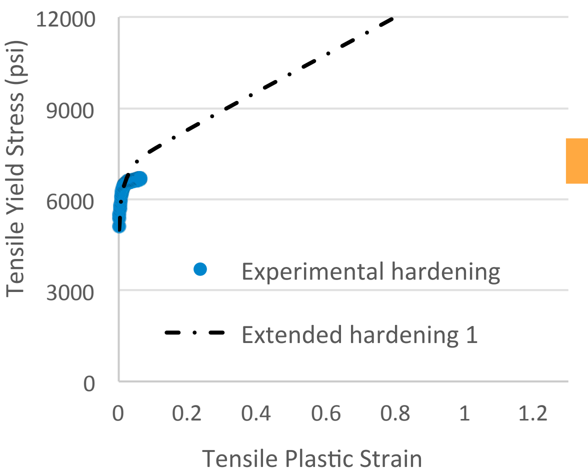
- Wide area lap shear



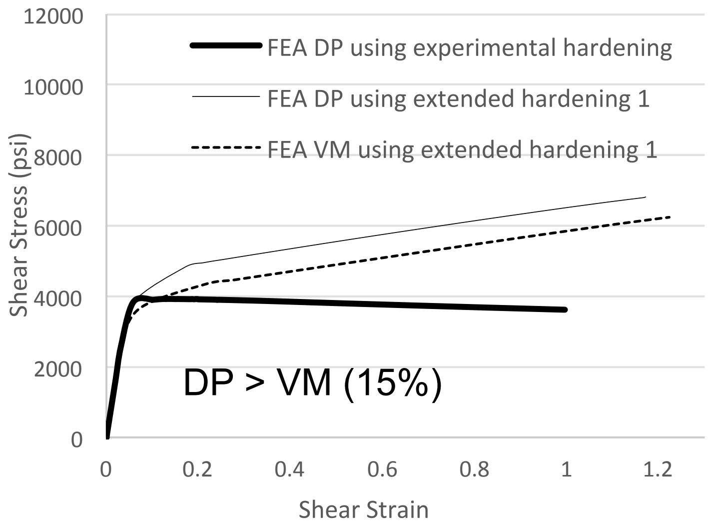
Referrence: Zgoul M. "Characterising the rate dependent response of adhesively bonded structures." Doctoral dissertation, School of Engineering, University of Surrey, Guildford, UK, 2002.

One tension hardening curve could not describe WALS and thick adherend shear

- Bulk adhesive Material model



- Thick adherend lap shear



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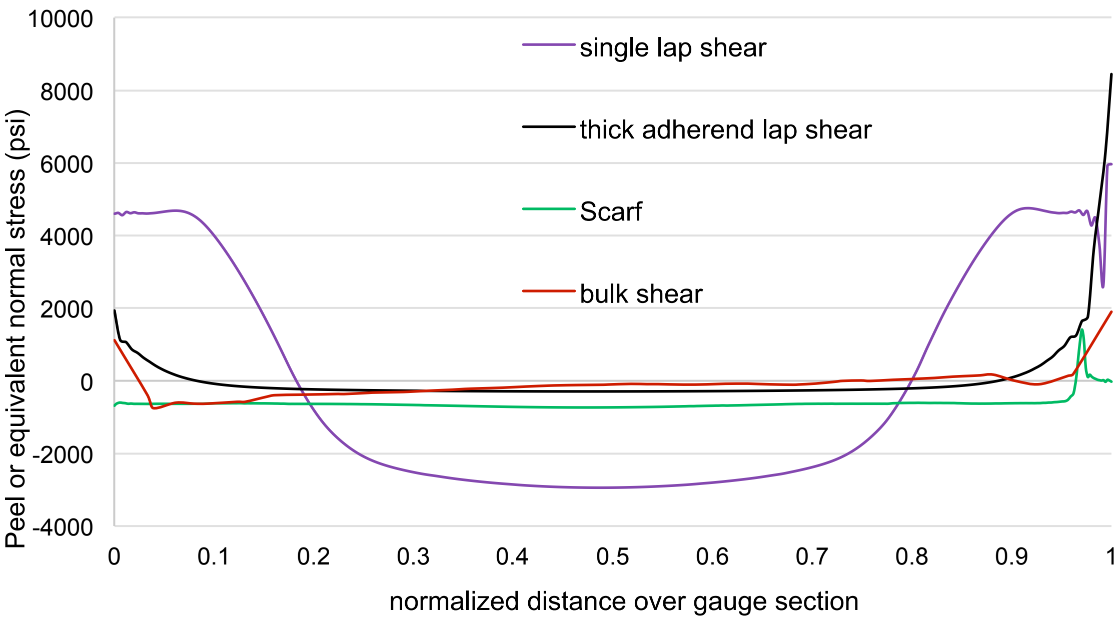
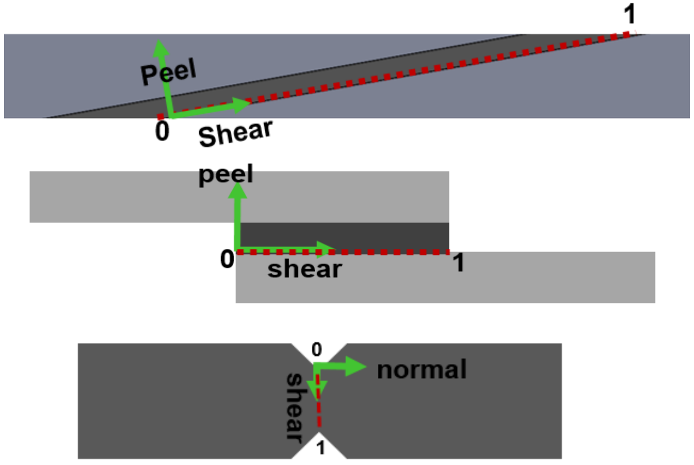
FEA adhesive models: EA9696

- **Comparison of shear configurations: Peel stress analogy**





Observations

1. Joints with low peel stress had low toughness and were readily modeled using elastic response
2. Joints with high peel stress could not be modeled from constituent properties
   - Required tailored hardening curve (extended) for each configuration
3. Drucker Prager model agreed slightly better than von Mises elastic plastic model

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Progressive damage modeling

Aim: Identify failure criterion for adhesive joints under cohesive damage and validate with experimental results.

Material degradation and failure (no pre-crack needs to be defined)	**Adhesive type**	**Mechanism**
Cohesive zone model: CZM • Uses traction separation law • Based on interface Finite Element	High ductility	LEFM & EPFM
Continuum damage Model :CDM • Material degradation occurs inside of solid element • when damage propagation onset & path are not known a priori	Brittle or moderately ductile	LEFM & EPFM

Advantages of CDM over CZM

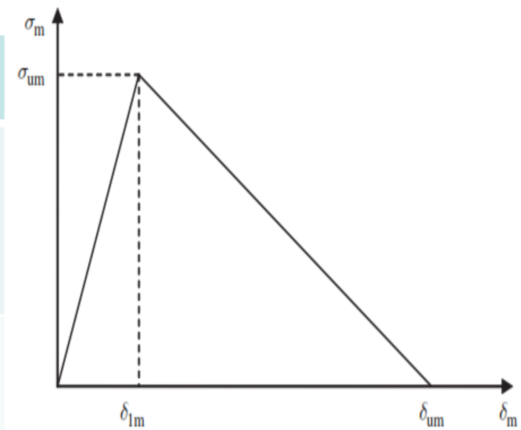
- ❑ Predict mode-mixity even when one of modes predominates
- ❑ Capture the influence of asymmetrical propagation and crack path along adhesive thickness
- ❑ Size and shape of fracture process zone (FZP) and its evolution during crack growth is well managed

Progressive damage modeling

Development of a numerical fracture model incorporating CZM,CDM - ABAQUS

- ✓ Use DCB and ENF (Damage for pure mode I & II)

Constitutive softening law	$\sigma=(1-D)E\delta_r$
Cohesive/Damage parameter 0<D<1	$D=\delta_{um}(\delta_m-\delta_{1m})/\delta_m(\delta_{um}-\delta_{1m})$
Critical Fracture Energy (mode I, II)	$G_I=\sigma\delta_{u,Im}/2$ $G_{II}=\tau\delta_{u,IIm}/2$



Future Work

- ❖ **Fatigue damage of adhesives – experiments and models**
- ❖ **Composite adherends**
  - ✓ CDM and CZM can be used to simulate the failure of adherends and adhesive
  - ✓ Failure is combination of cohesive and delamination of substrate
  - ✓ Simulation of delamination development in fiber composites and failure of adhesive joints

Time Dependence

Aims:

- Identify the influence of toughening agents on adhesive time dependent response.
- Find nonlinear threshold.
- Determine if ratcheting behavior occurs under repeated loading.

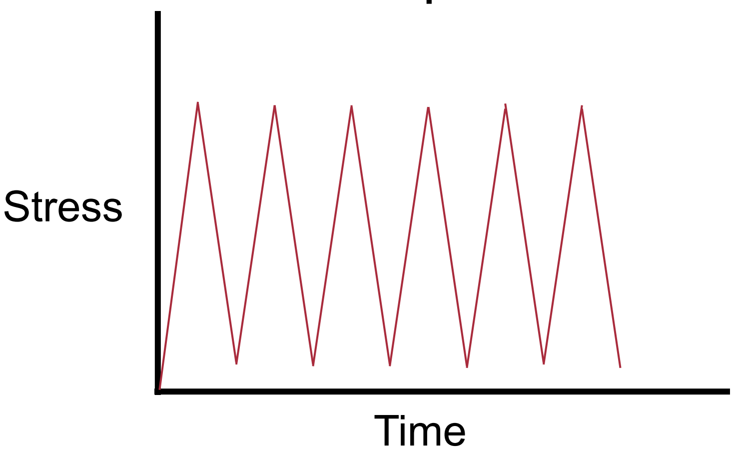
Ratcheting: cyclic accumulation of inelastic deformation.

Approach:

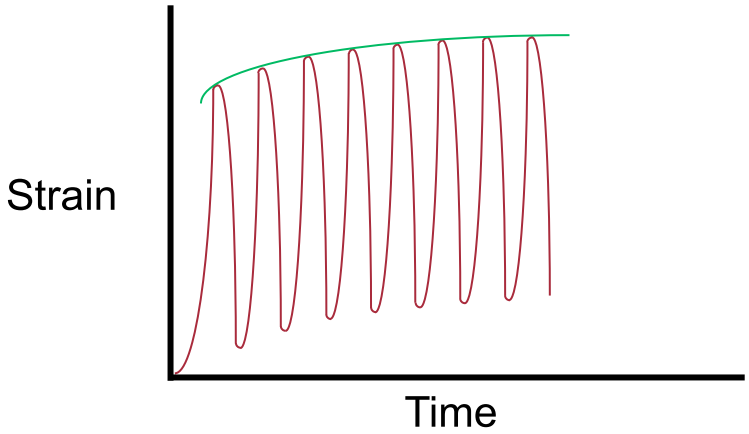
- Creep tests at different durations and stress levels.
- Fit response to linear and nonlinear viscoelastic models.
- Compare load response with linear model to find nonlinear and ratcheting thresholds and determine how nonlinear model predicts strain.

Cyclic Loading

Input



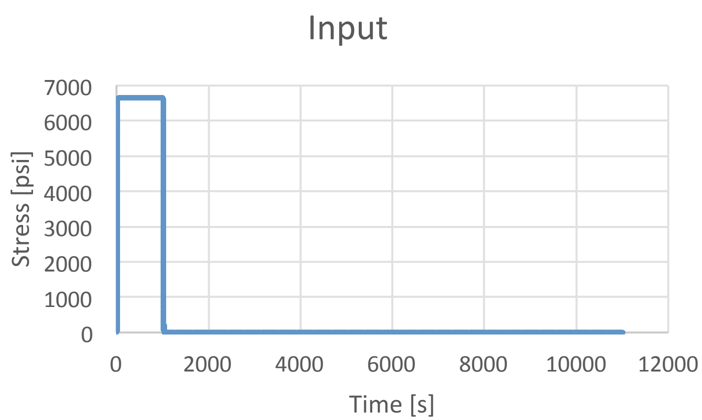
Output

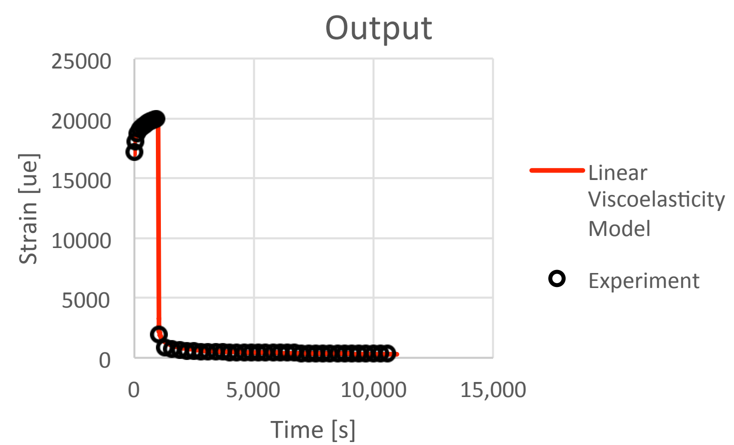


Linear Viscoelasticity

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

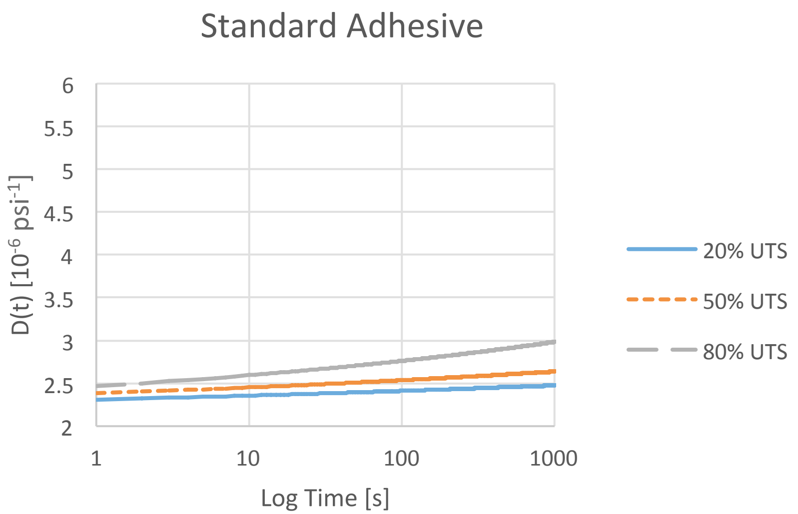
$$D(t)=D_0+D_1 t^n$$

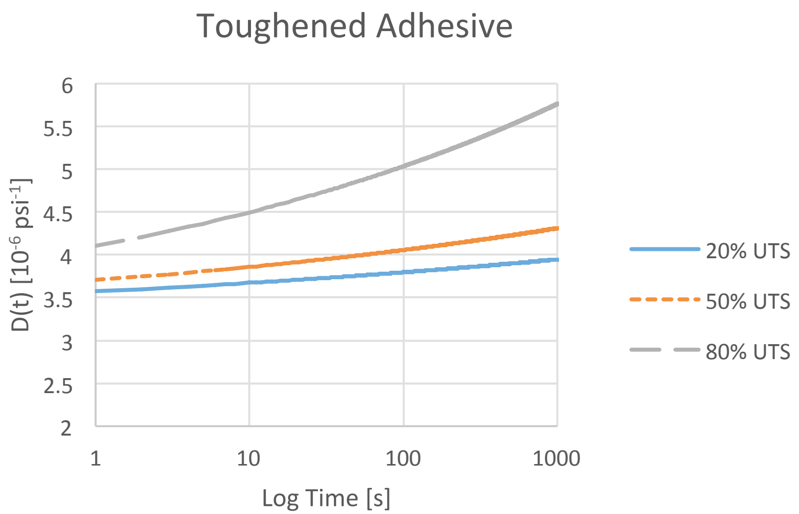




Linear Viscoelasticity

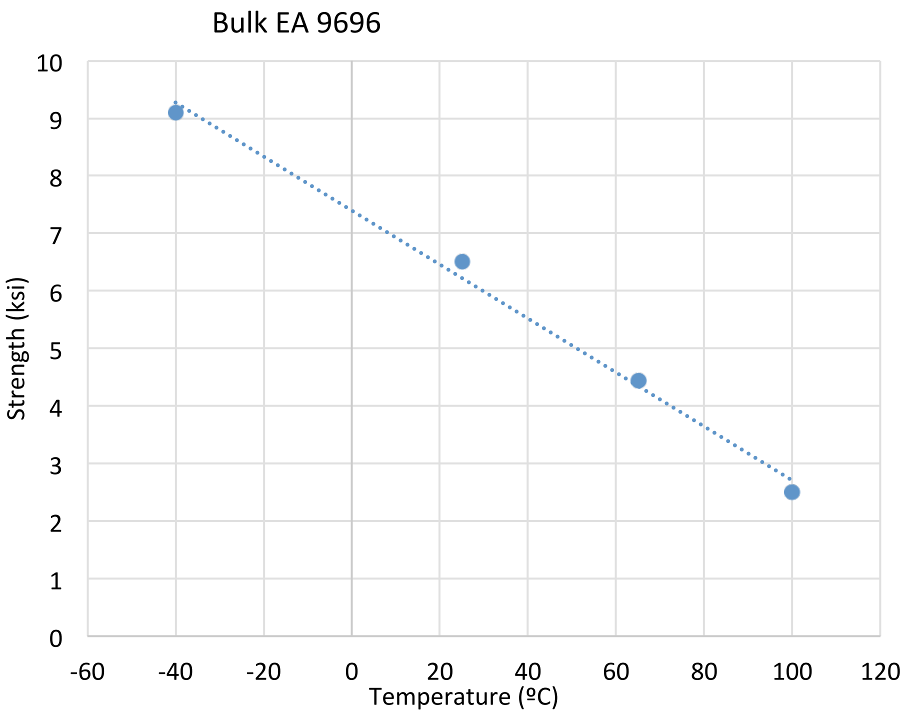
- Adhesives behave nonlinearly
  - Initial compliance
  - Compliance over time

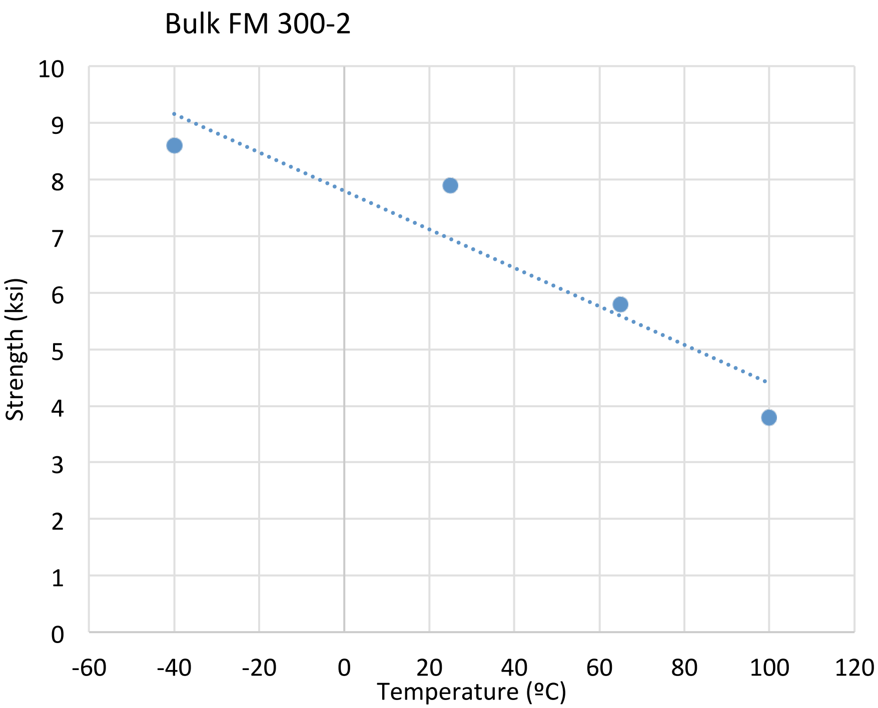




Linear Viscoelasticity: Temperature

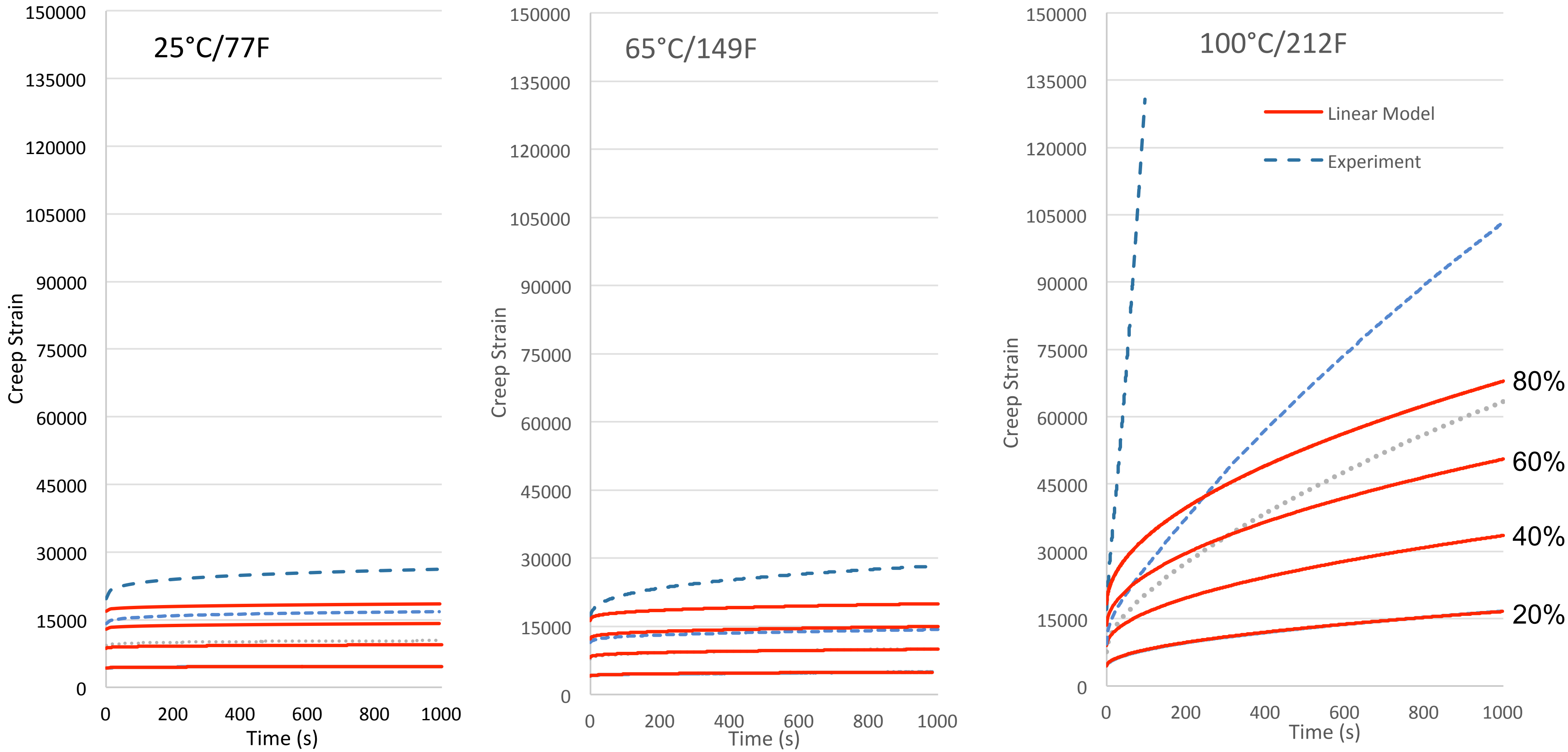
- Strength decreases almost linearly with increasing temperature





Linear Viscoelasticity: Temperature

- EA 9696 increased nonlinearity and creep with increasing temperature.



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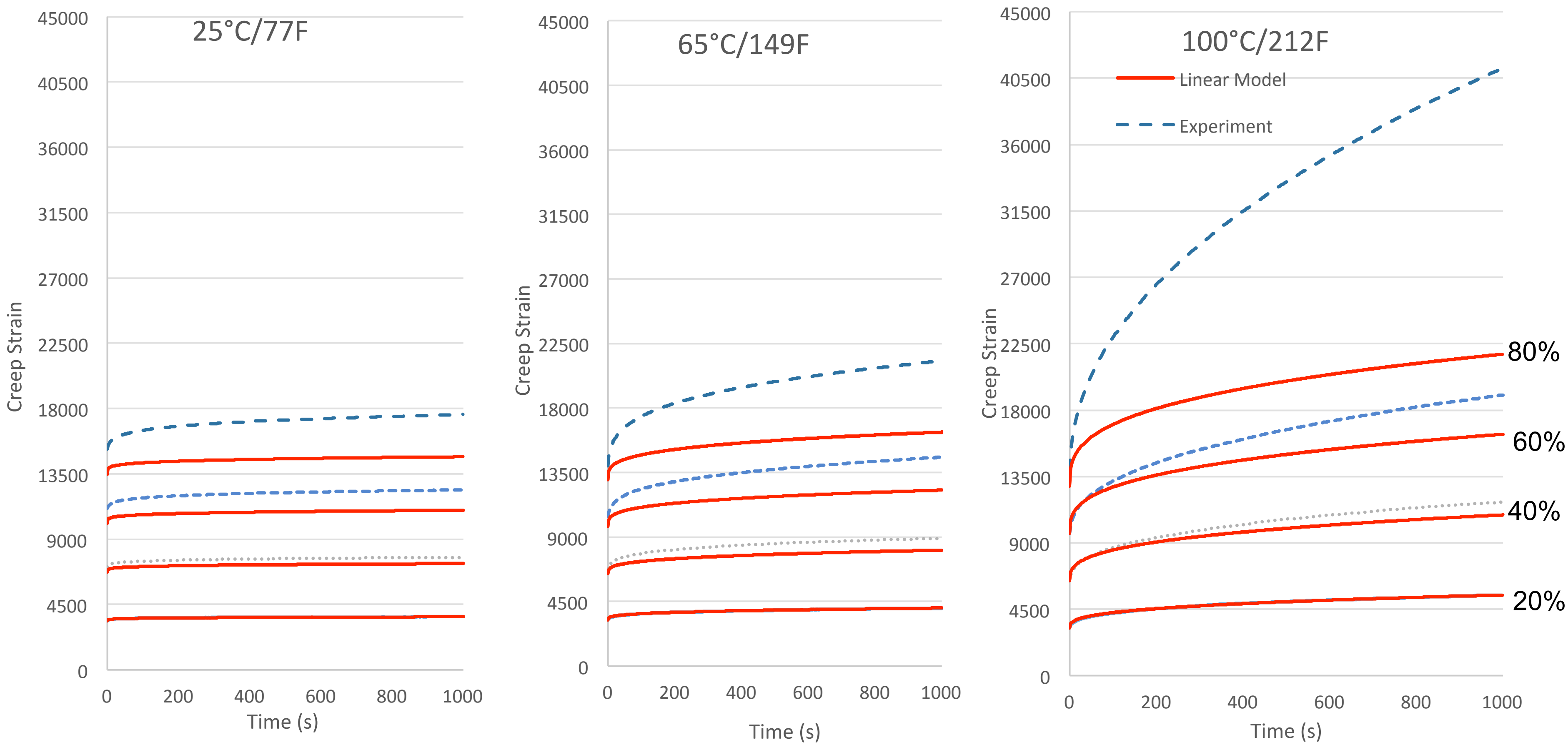
Linear Viscoelasticity: Temperature

- FM300-2 increased nonlinearity and creep with increasing temperature.



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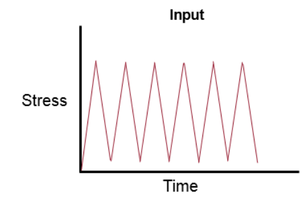
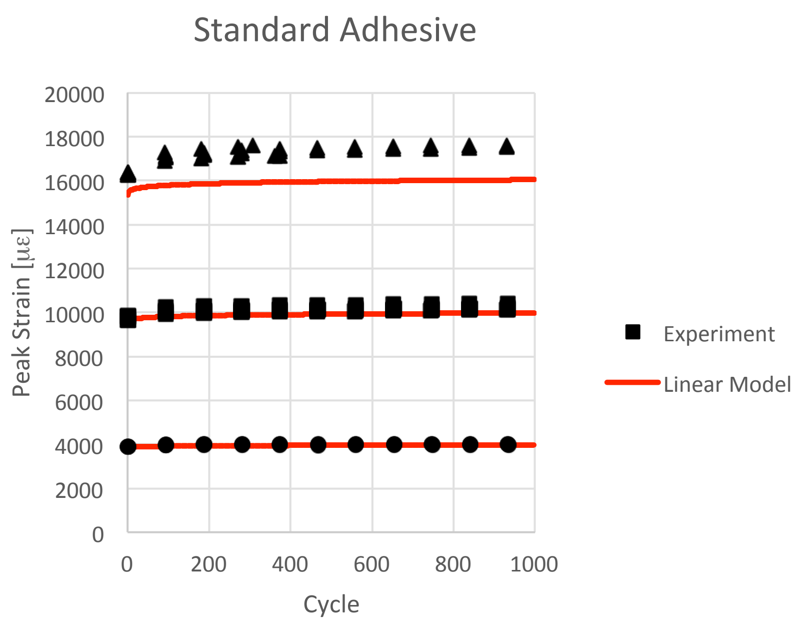
Linear Viscoelasticity: Temperature

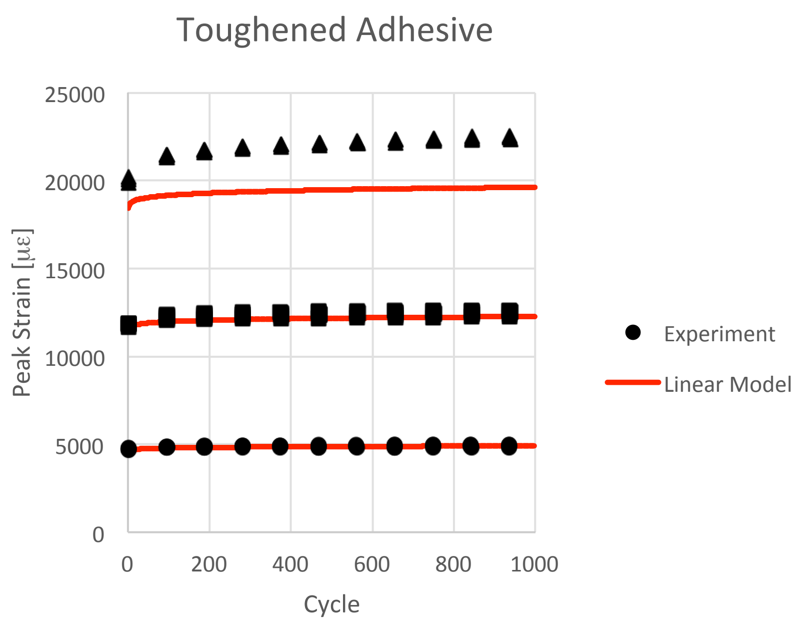


Strain input

$$\varepsilon(t)=\frac{9f\sigma_{max}}{5}\left\{D_0 t+\frac{D_1 t^{n+1}}{n+1}+\sum_{i=1}^{m}2(-1)^{i+1}\left[D_0(t-t_i)+\frac{D_1 (t-t_i)^{n+1}}{n+1}\right]H(i-1)\right\}$$

N





Nonlinear Viscoelasticity

Nonlinear viscoelastic strain to an arbitrary stress input

$$\varepsilon(t)=\int_0^t F_1(t-\xi_1)\sigma(\xi_1)d\xi_1+\int_0^t\int_0^t F_2(t-\xi_1)\sigma(\xi_1)\sigma(\xi_2)d\xi_1 d\xi_2+\int_0^t\int_0^t\int_0^t F_3(t-\xi_1)\sigma(\xi_1)\sigma(\xi_2)\sigma(\xi_3)d\xi_1 d\xi_2 d\xi_3$$

For uniaxial creep, this becomes

$$\varepsilon(t)=F_1\sigma+F_2\sigma^2+F_3\sigma^3$$

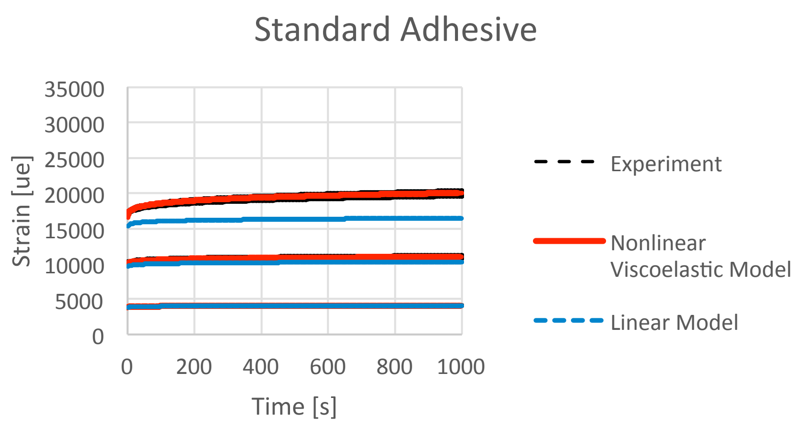
F_1, F_2, and F_3 are found from creep tests at three stress levels, σ_A, σ_B, and σ_C,

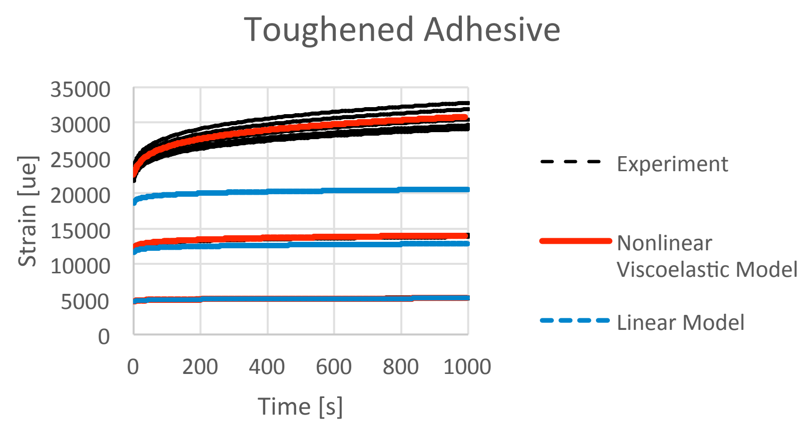
$$D_{0A}+D_{1A}t^{n_A}=F_1+F_2\sigma_A+F_3\sigma_A^2$$

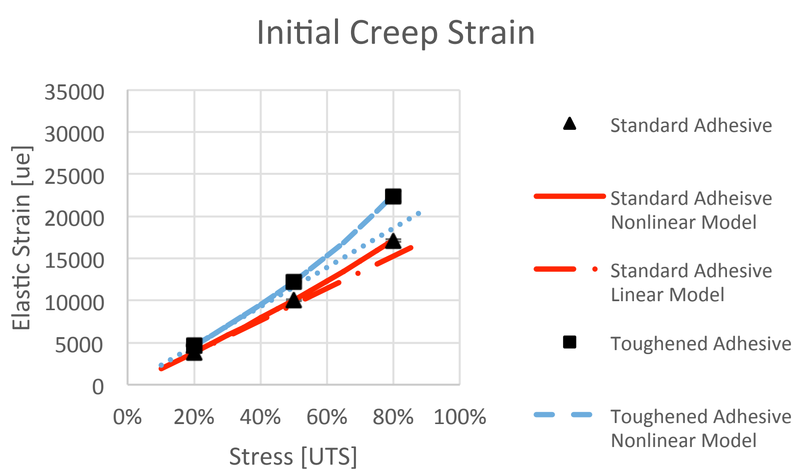
$$D_{0B}+D_{1B}t^{n_B}=F_1+F_2\sigma_B+F_3\sigma_B^2$$

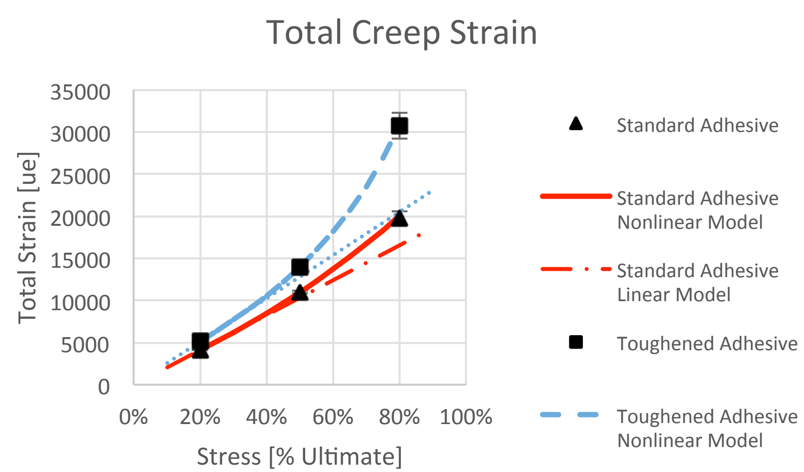
Nonlinear Creep

Good agreement under creep









Nonlinear Ratcheting

For a cycled stress input in ratcheting, nonlinear strain is given by,

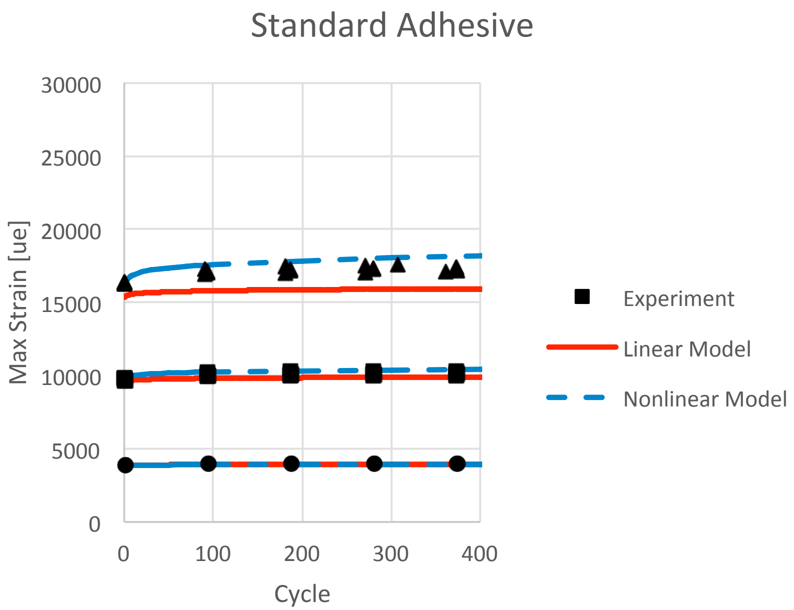
$$\varepsilon(t)=\frac{9f\sigma_{max}}{5(\sigma_A-\sigma_B)(\sigma_A\sigma_B-\sigma_A\sigma_C-\sigma_B\sigma_C+\sigma_C^2)}\left[L_1(A)(\sigma_B\sigma_C^2-\sigma_B^2\sigma_C)+L_1(B)(\sigma_C\sigma_A^2-\sigma_C^2\sigma_A)+L_1(C)(\sigma_A\sigma_B^2-\sigma_A^2\sigma_B)\right]+\frac{81f^2\sigma_{max}^2}{25(\sigma_A-\sigma_B)(\sigma_A\sigma_B-\sigma_A\sigma_C-\sigma_B\sigma_C+\sigma_C^2)}\left[L_2(A)(\sigma_C^2-\sigma_B^2)+L_2(B)(\sigma_A^2-\sigma_C^2)+L_2(C)(\sigma_B^2-\sigma_A^2)\right]+\frac{729f^3\sigma_{max}^3}{125(\sigma_A-\sigma_B)(\sigma_A\sigma_B-\sigma_A\sigma_C-\sigma_B\sigma_C+\sigma_C^2)}\left[L_3(A)(\sigma_C-\sigma_B)+L_3(B)(\sigma_A-\sigma_C)+L_3(C)(\sigma_B-\sigma_A)\right]$$

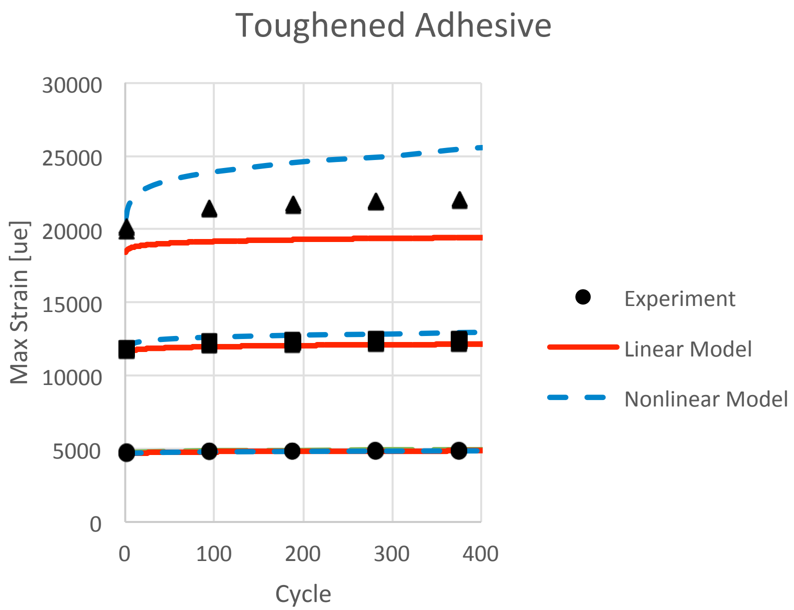
$$L_1=D_0t+\frac{D_1t^{n+1}}{n+1}+\sum_{i=2}^{m}2(-1)^{i+1}\left[D_0(t-t_i)+\frac{D_1(t-t_i)^{n+1}}{n+1}\right]$$

$$L_2=D_0t^2+\frac{D_1t^{n+2}}{n+1}+\sum_{i=2}^{m}2(-1)^{i+1}\left[2D_0t(t-t_i)+\frac{D_1t(t-t_i)^{n+1}}{n+1}+D_1(t-t_i)\right.$$

Nonlinear Ratcheting

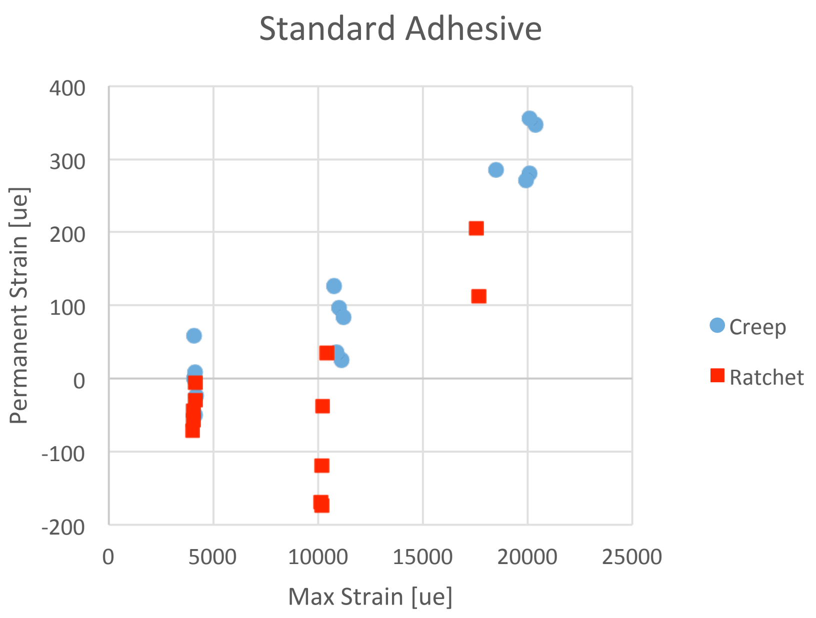
Nonlinear viscoelastic model over predicts strain at high stress

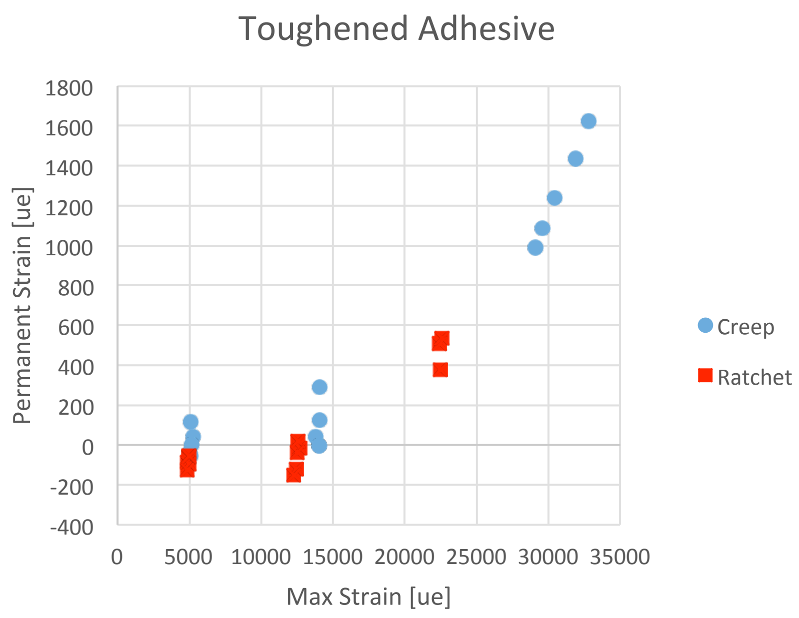




Permanent Strain

- Max strain: strain after 9000s of recovery
- Both adhesives showed lower permanent strain from ratcheting





Time Depedence

Observations

- Both adhesives show a nonlinear creep and ratcheting response.
- Creep experiments can be used to predict ratcheting response.
- Nonlinearity appears to begin after 50% which corresponds to permanent formation
- Permanent strain is small (3% of the total strain)
- A nonlinear model improves correlations, but becomes unstable after 400 cycles

Next Steps

- Test 10,000 second creep and 10,000 cycle ratcheting
- Develop strategies to improve nonlinear model
- Consider effect of low temperature creep

Looking forward

- Benefit to Aviation
  - Improved (accelerated) certification procedures for bonded structure
  - Guidance for adhesive joint design under fatigue loading
- Future needs
  - Improved understanding of adhesive non-linear adhesive response
    - Viscoelastic, plastic/damage, environment.

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