Durability of Bonded Aircraft Structure

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WASHINGTON STATE UNIVERSITY
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Durability of Bonded Aircraft Structure

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

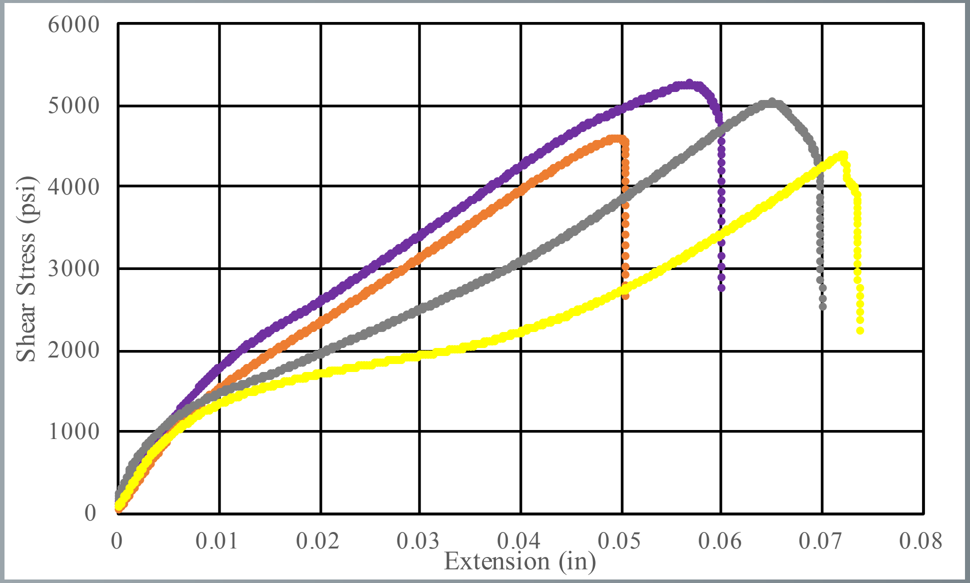
Outline

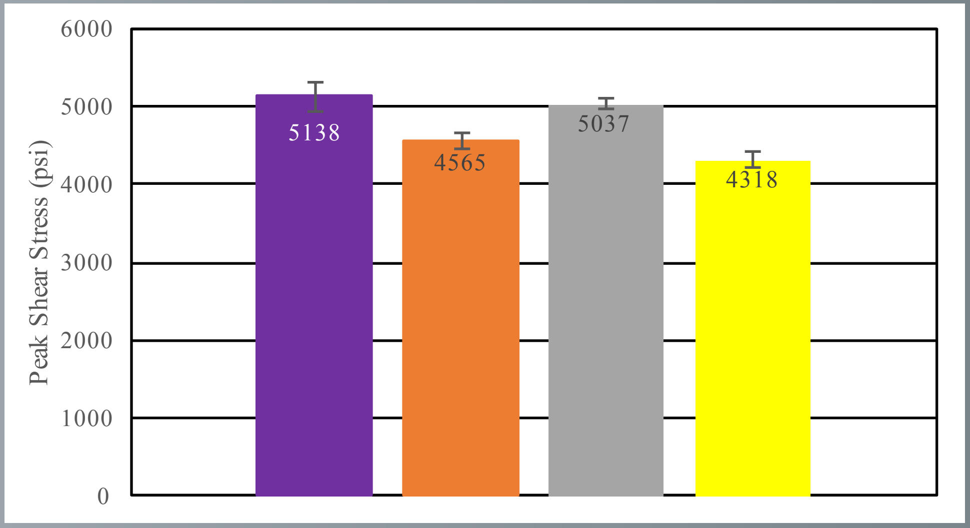
- Aim: Understand the effect of static performance on fatigue life of adhesive joints

- Joint performance is influenced by:
  - Type (tough, less tough, brittle)
  - Form (film, paste)
  - Environment (temperature effects)
  - Thickness of bonded joint
  - Adhesive characteristics
    - Ratcheting behavior
    - Viscoelastic response

Wide Area Lap Shear - Static

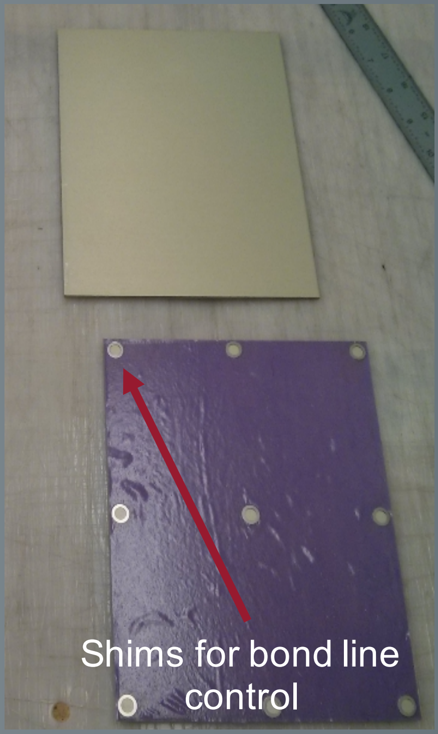
Status: Complete

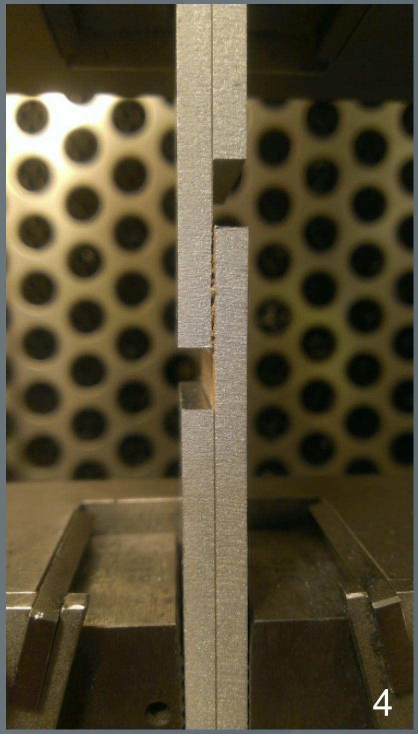




- EA9696
- FM300-2
- EA9380.05
- EA9394

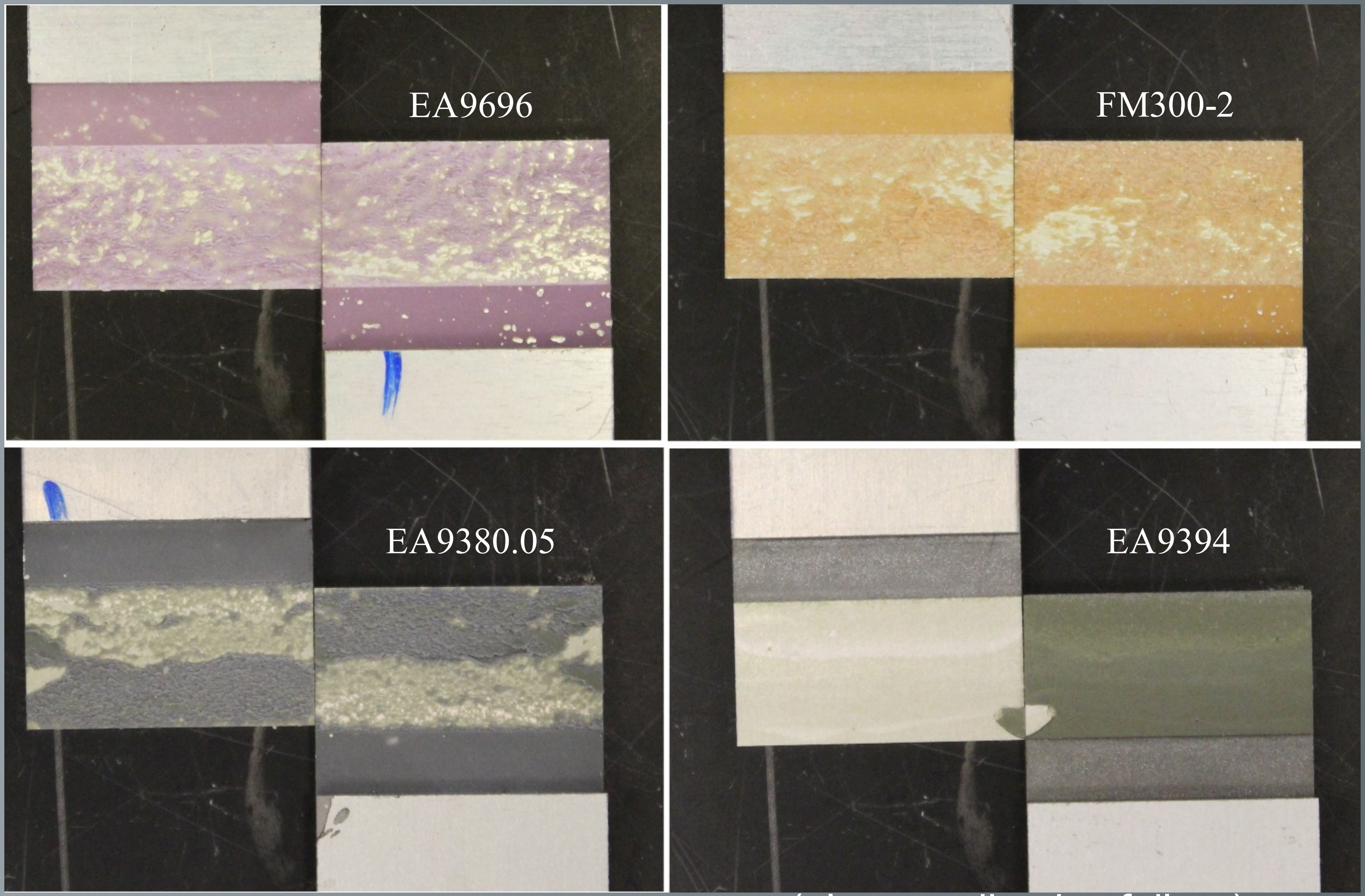
- FM300-2 and EA9394 appear brittle
- EA9696 and EA9380.05 appear tough





Wide Area Lap Shear - Static

Failure Surfaces

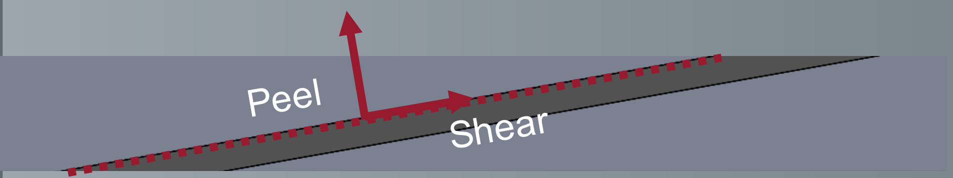


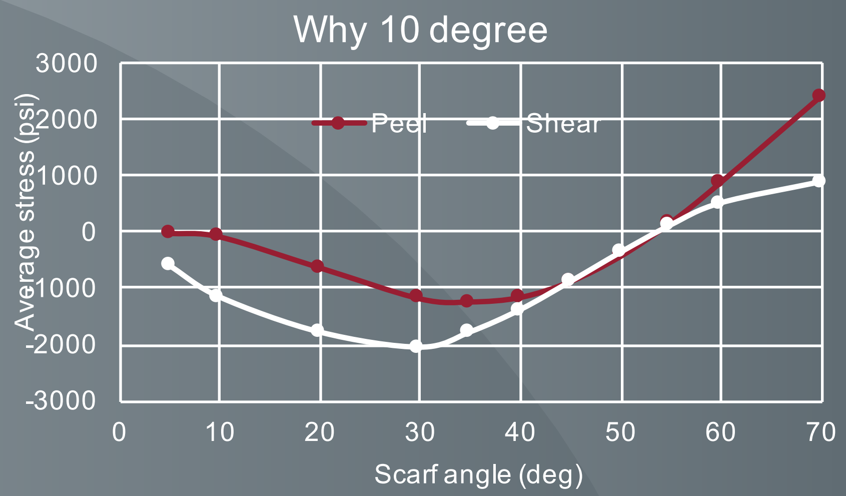
(always adhesive failure)

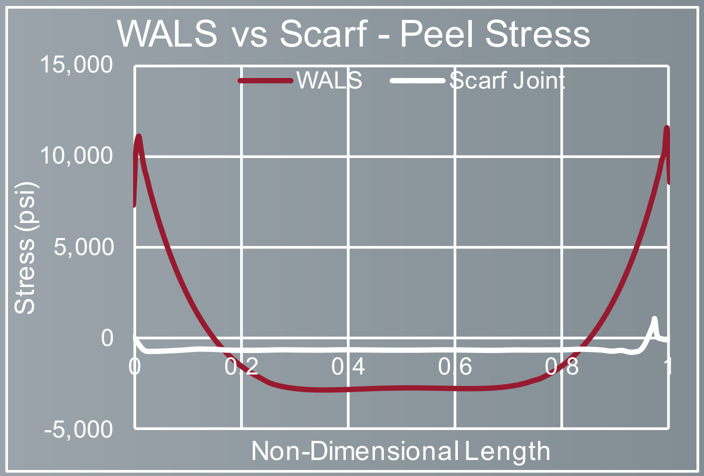
Why Scarf Joint?

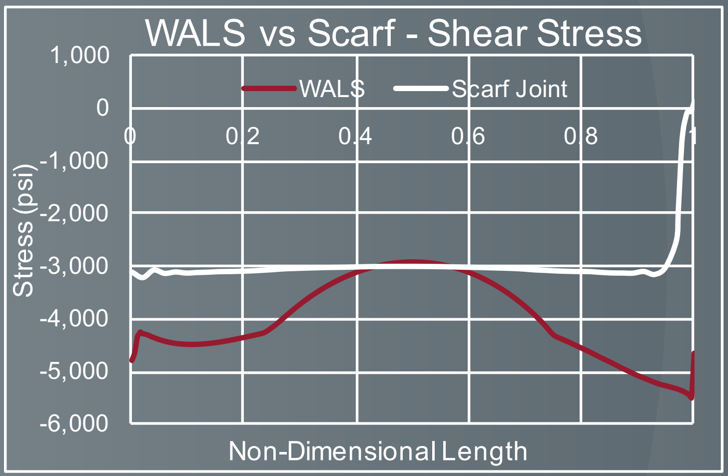
FEA Results :

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









Scarf Joint - Static

In static shear test.

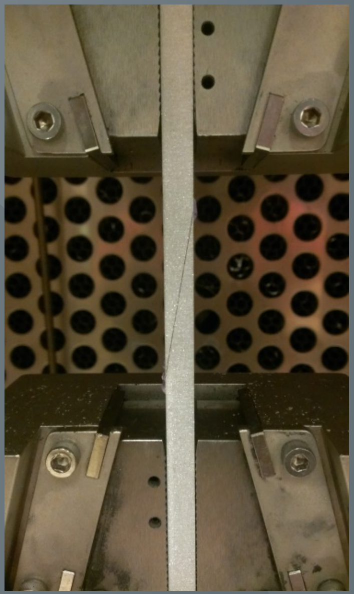
- EA9696 and EA9380.05 show a "knee point", similar to the KGR experiment at same stress level
- FM300-2 and EA9394 show no change in slope
- FM300-2 strongest

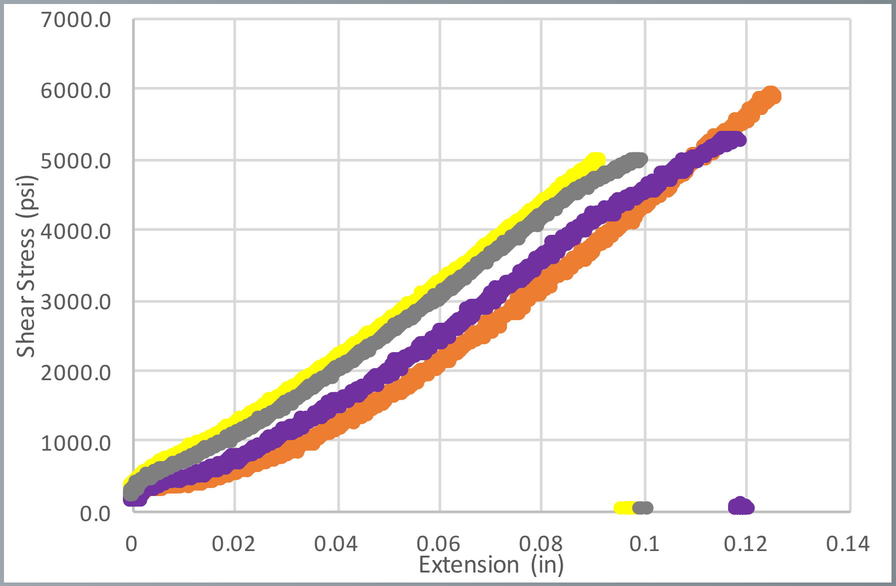
EA9696

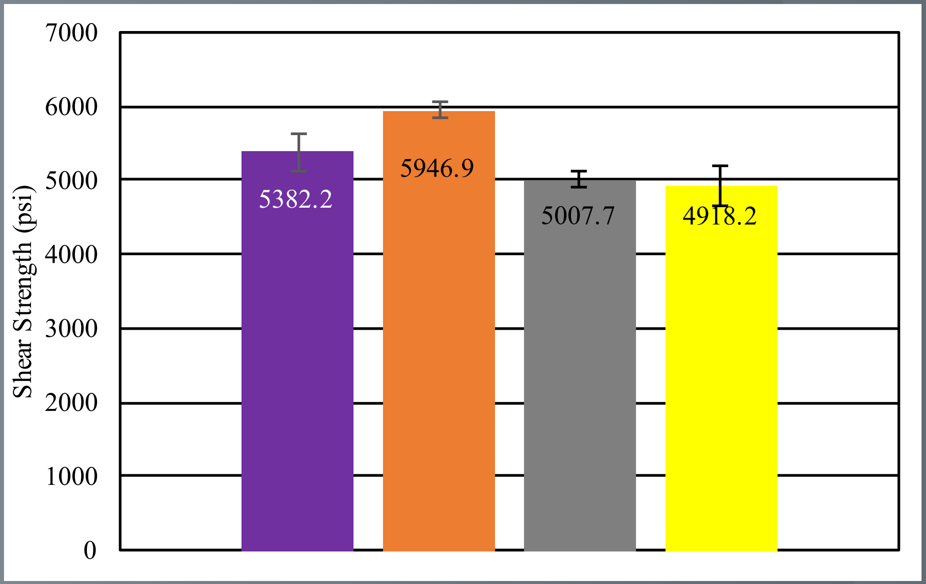
FM300-2

EA9380.05

EA9394





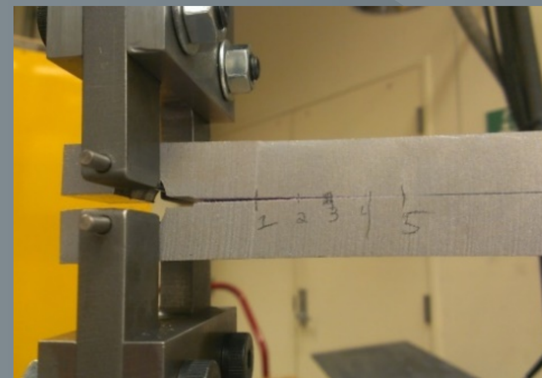


Double Cantilever Beam (DCB) - Static

BSS7208, ASTM D3433

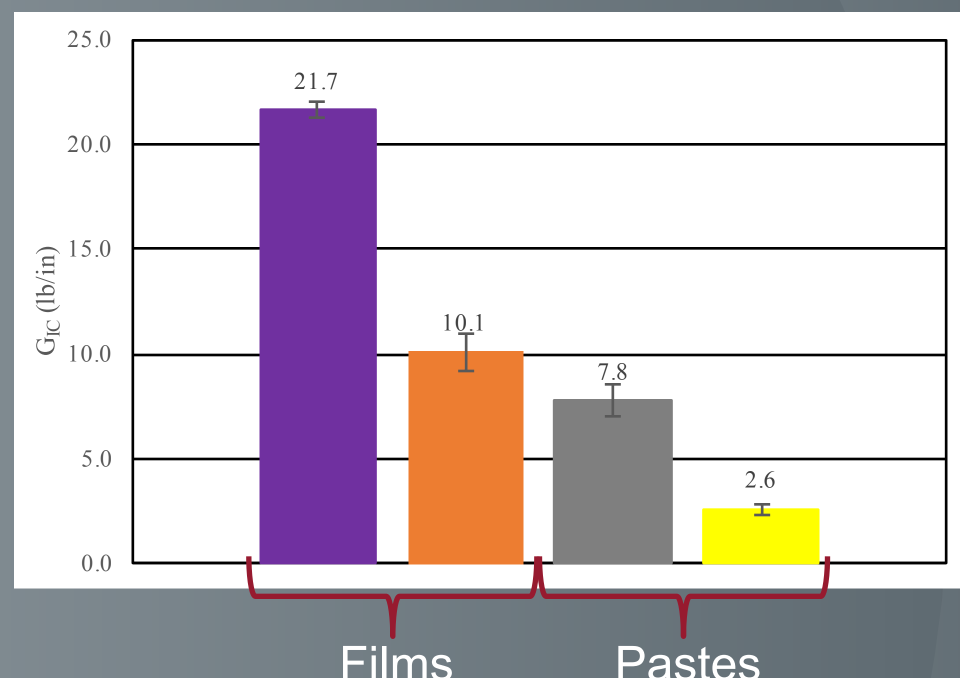
Status: Complete

- EA9696 – Highly Tough
- FM300-2 – More brittle
- EA9380.05 – More tough
- EA9394 – Very Brittle



ASTM D3433

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

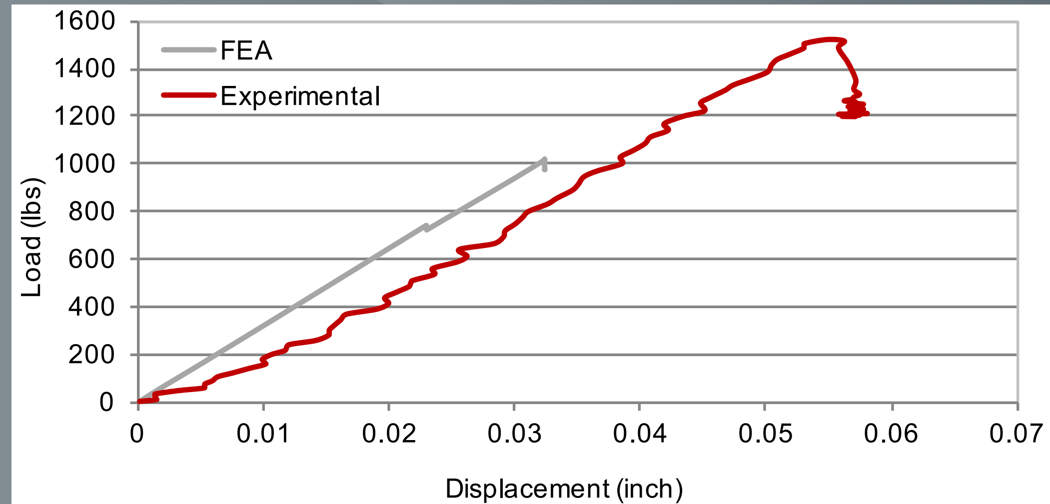


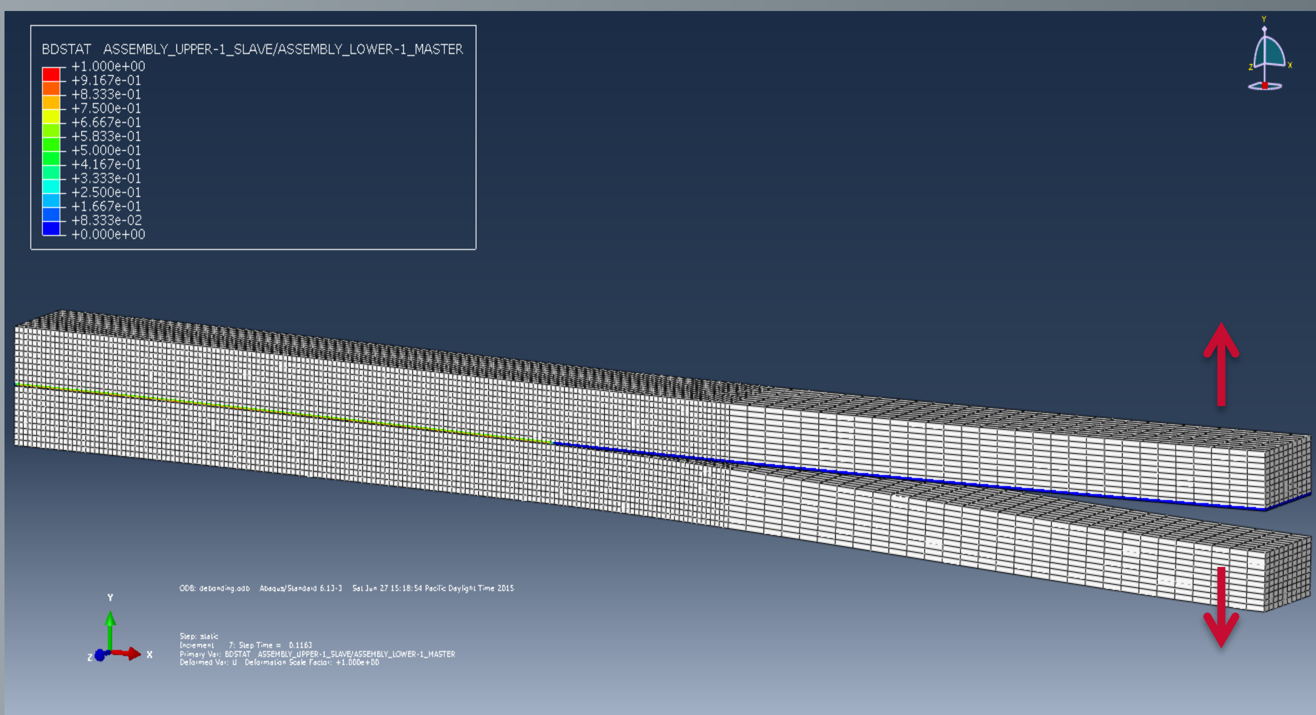
EA9696 | EA9380.05

FM300-2 | EA9394

Double Cantilever Beam (DCB) – Static FEA

- Virtual crack closure technique (VCCT)





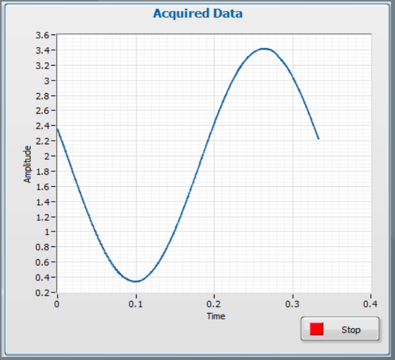
Scarf Joint - Fatigue

Status: Complete

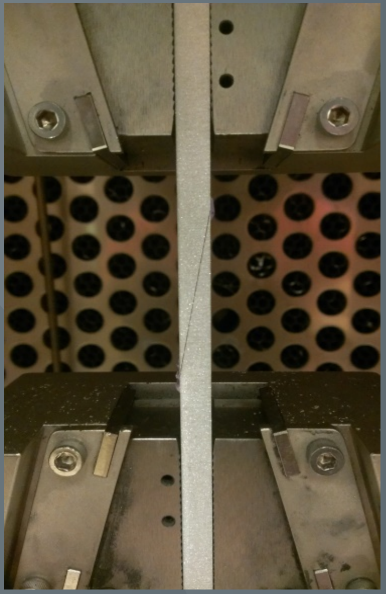
In fatigue shear test:

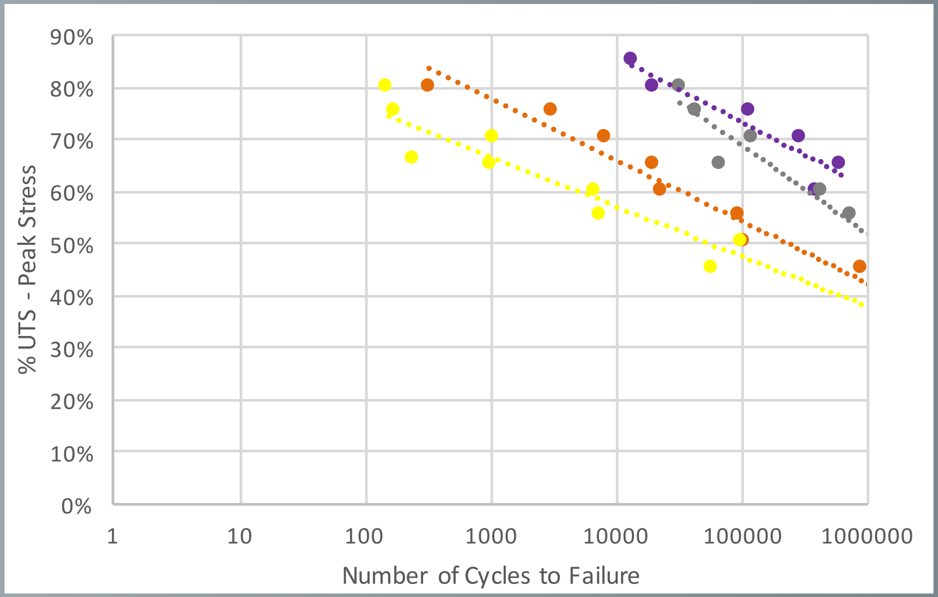
- EA9696 has highest fatigue life at all stress levels
- EA9394 has shortest fatigue life at all stress levels
- EA9380.05 has longer fatigue life than FM300-2

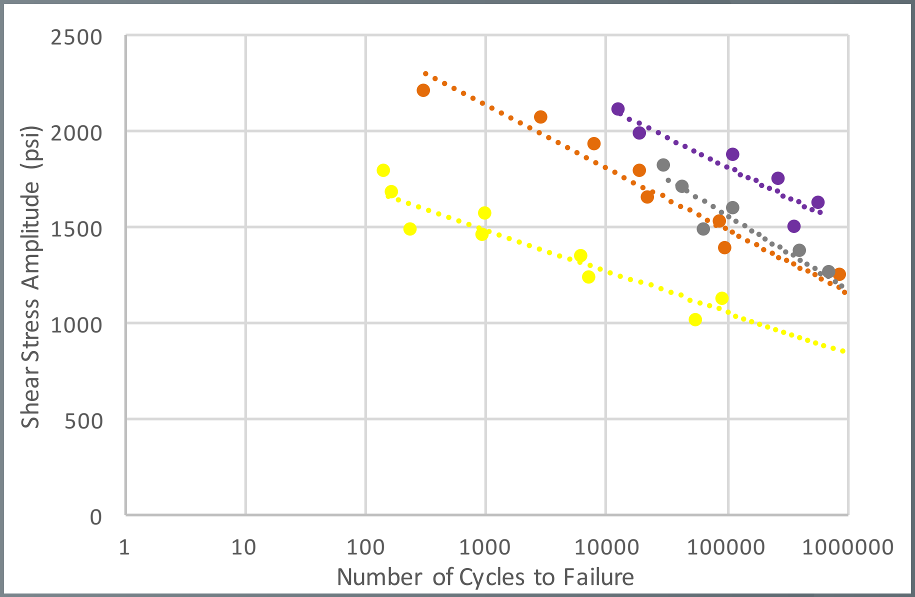
- EA9696
- FM300-2
- EA9380.05
- EA9394



- Sine function
- Load control
- R ratio 0.01



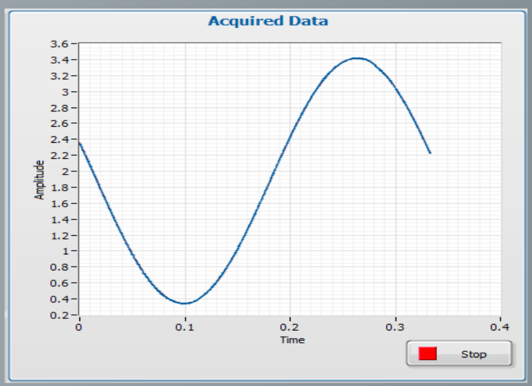




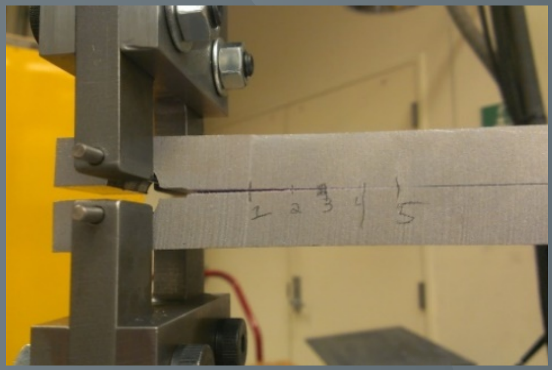
Double Cantilever Beam (DCB) - Fatigue

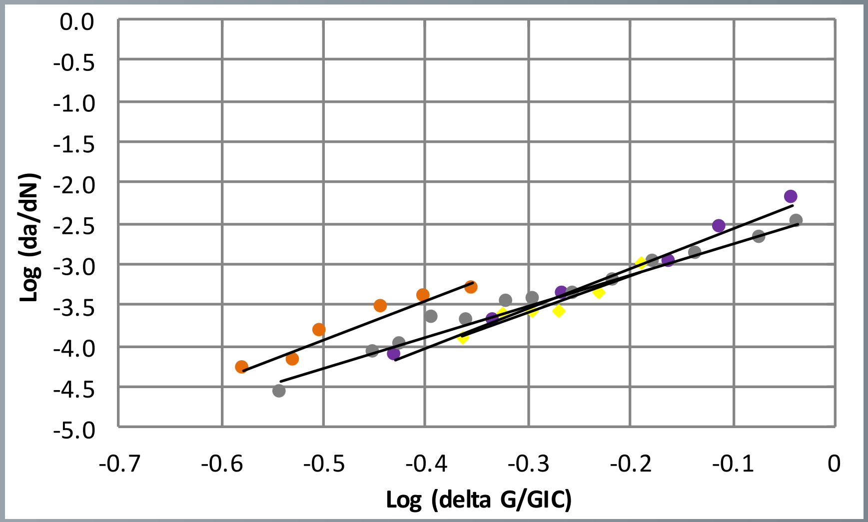
Status: Complete

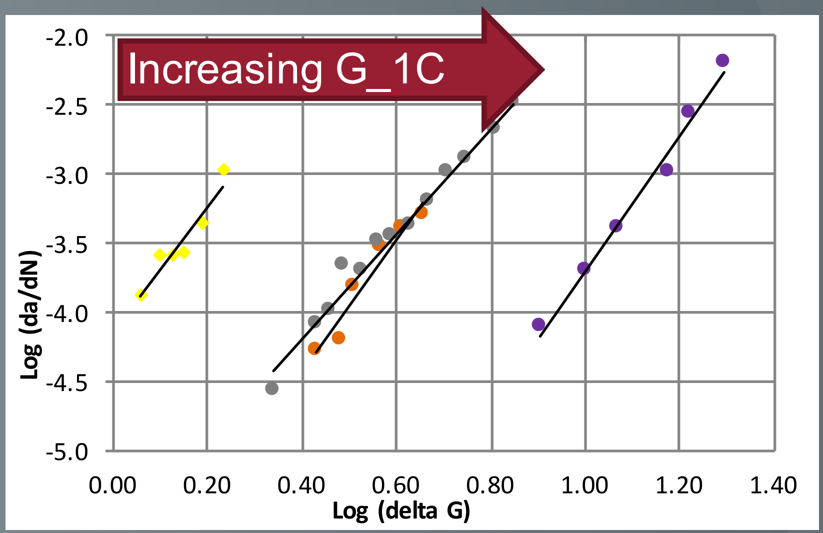
- EA9696 – Tough
- FM300-2 similar to EA9380.05
- EA9394 – Brittle



EA9696
FM300-2
EA9380.05
EA9394







Conclusions: Experiment

1. DCB in static is a good measure of DCB fatigue performance since the results are directly proportional to the G_{IC} constants.

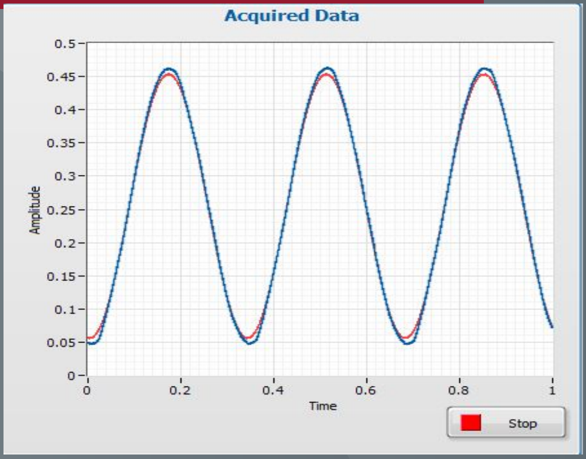
2. Static Scarf is not an efficient measure of shear performance in fatigue unless small changes in slope are investigated.

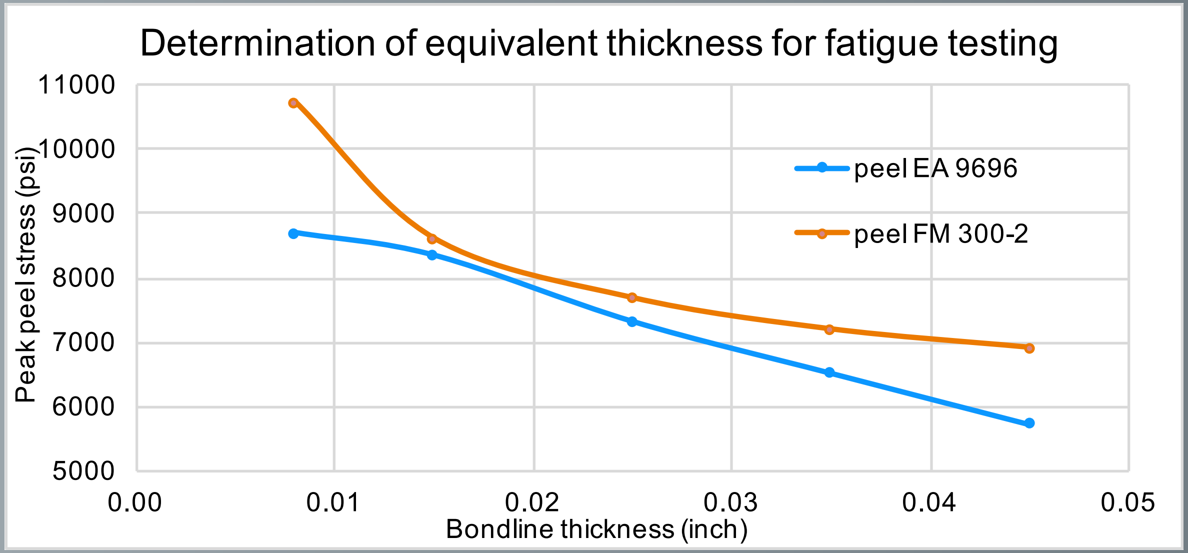
3. Static WALS is an efficient predictor of fatigue behavior in both shear and peel stress.

Wide Area Lap Shear - Fatigue

Aim:
Determine the effects of temperature and joint thickness on strength and fatigue performance.

Approach:
Placing wide area lap shear in the grips of servo hydraulic load frame under sinusoidal loading.

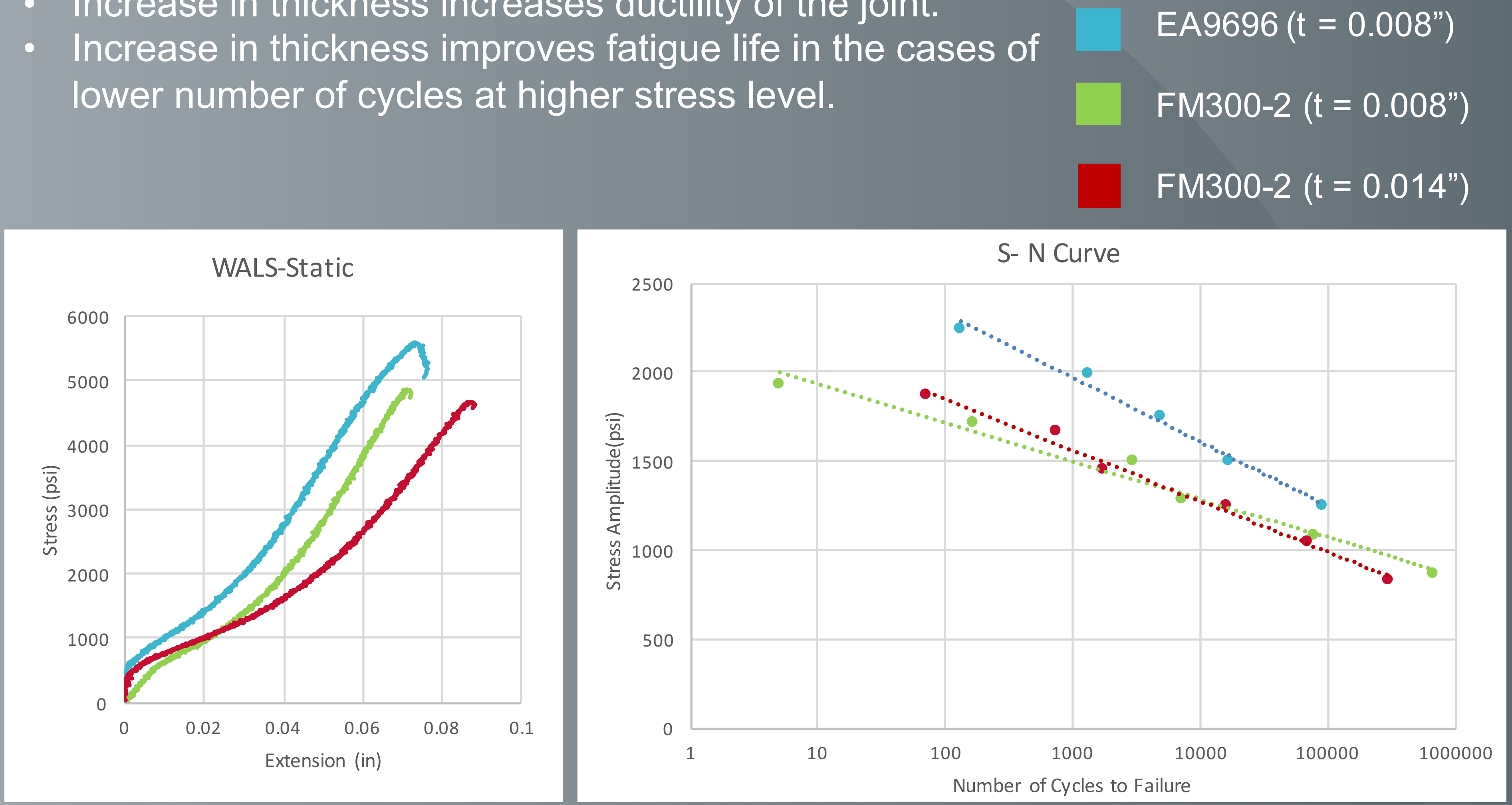




- Loaded at 70% of their respective peak static strength.
- Peel stress is the failure criteria.
- 0.008" tough adhesive ~ 0.014" thick less tough adhesive

Thickness

- Increase in thickness increases ductility of the joint.
- Increase in thickness improves fatigue life in the cases of lower number of cycles at higher stress level.



Load Ratio is 0.1, Peak Stress going from 90% to 40% of respective Strength.

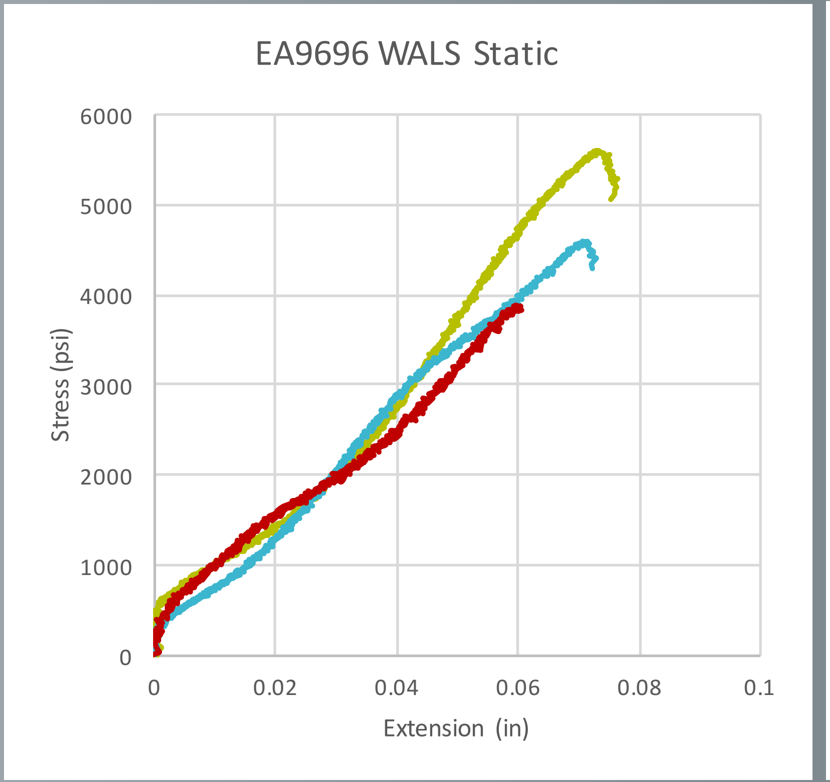
Temperature

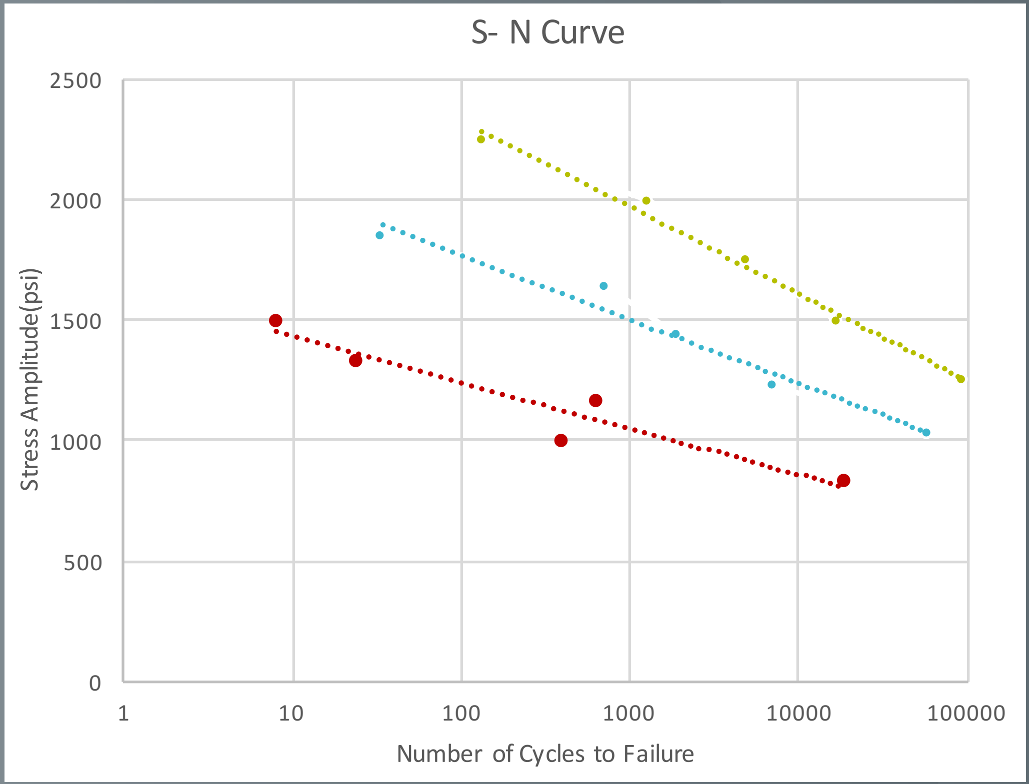
- For EA9696 strength reduces 30% from room temperature to 212F.
- Fatigue performance worsen with increase in temperature.

77F/25°C

149F/65°C

212F/100°C

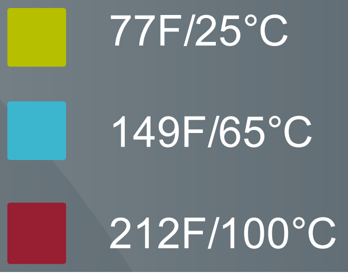


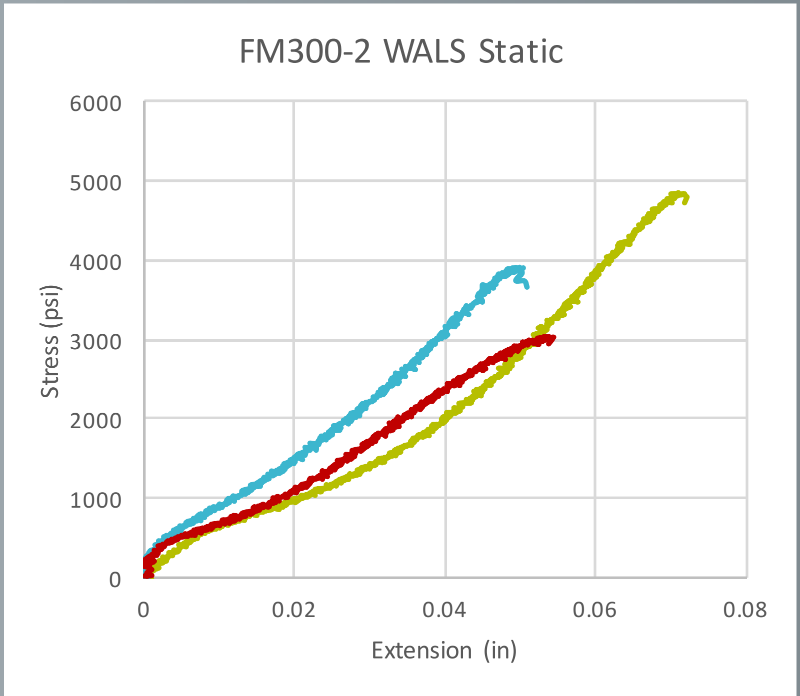


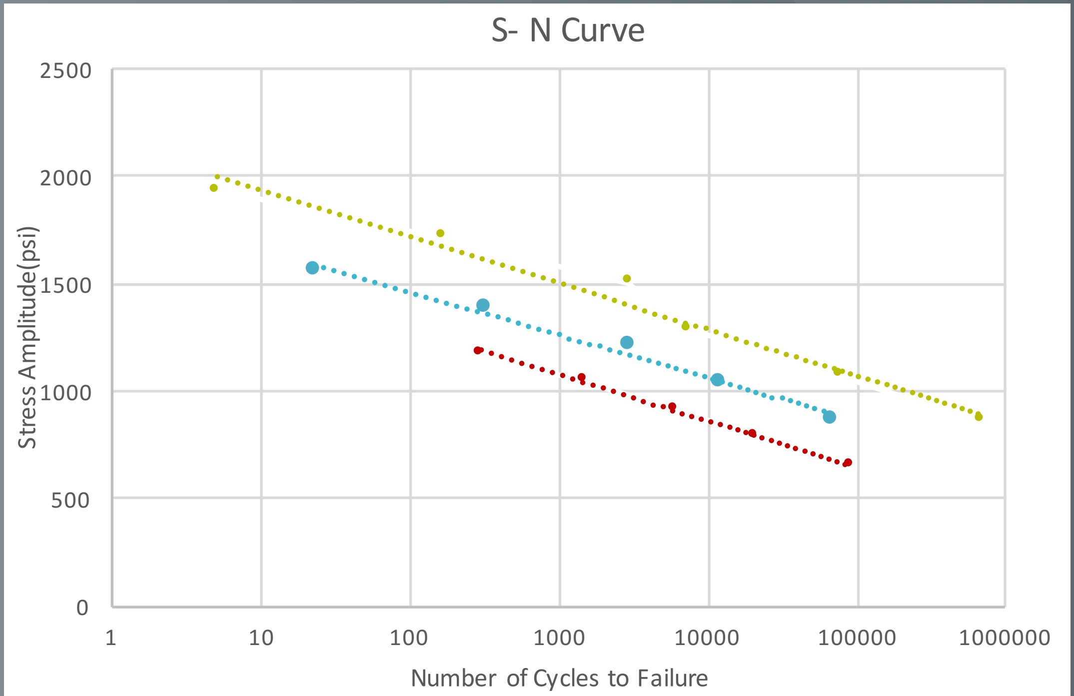
Load Ratio is 0.1, Peak Stress going from 90% to 50% of respective Strength.

Temperature

- For FM300-2 strength reduces 40% from room temperature to 212F.
- Fatigue life increases (with respect to its own stress level) with increase in temperature.







Load Ratio is 0.1, Peak Stress going from 90% to 50% of respective Strength.

Fatigue vs Static – FEA approach

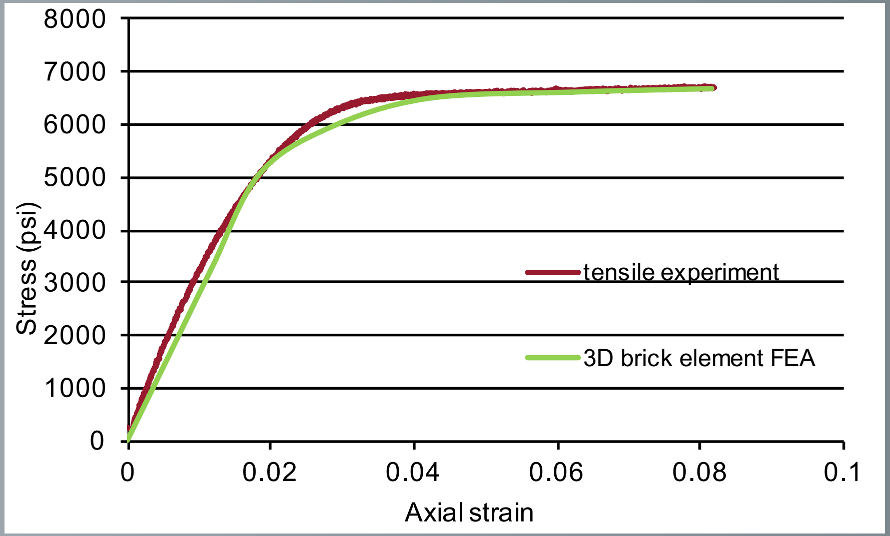
- Static: WALS and scarf
1. Elastic plastic yield criteria
2. Hydrostatic pressure dependent yield criteria
3. Visco elastic material response, Next step

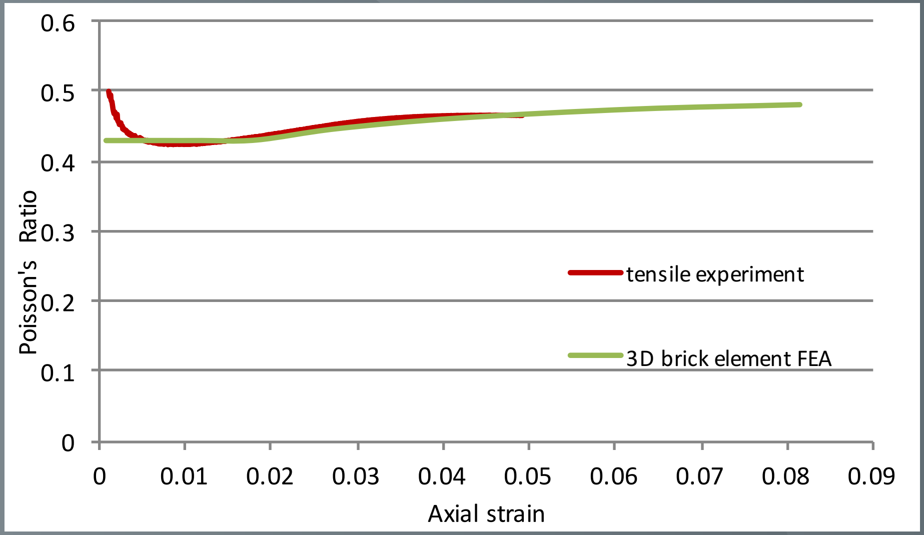
- Static: DCB
1. Virtual crack closure technique (VCCT)

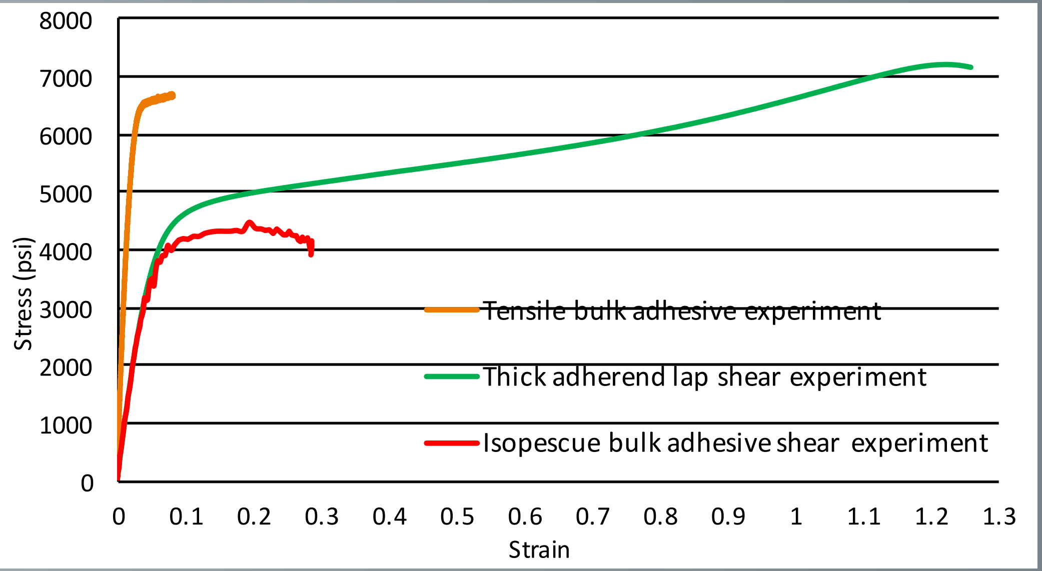
- Fatigue: WALS, scarf and DCB
1. Virtual crack closure technique (VCCT)
2. Cohesive zone modeling (CZM), Next step

Adhesive characterization: needed for FEA

- Bulk adhesive specimen of the toughened adhesive: Experiment vs FEA







- Comparison of tensile and shear response

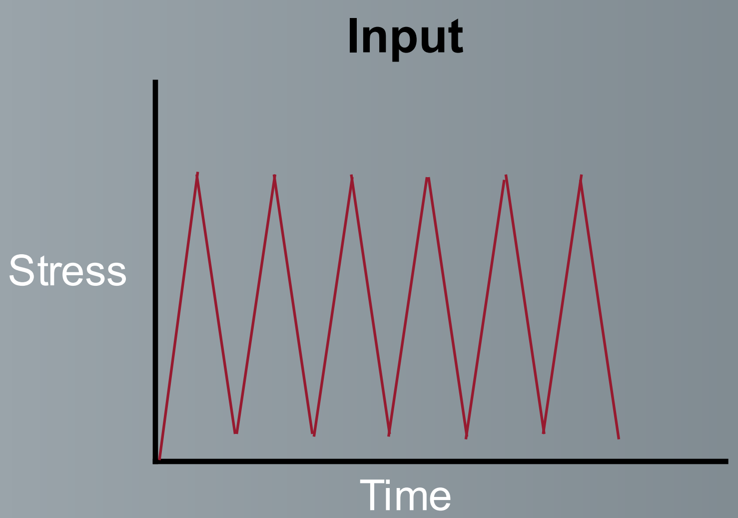
1. ASTM D 638-10: Bulk adhesive tested in pure tension
2. ASTM D 5656: Thick adherend lap shear (KGR extensometer), provided by The Boeing Company
3. ASTM D537: Isopescue test (DIC)

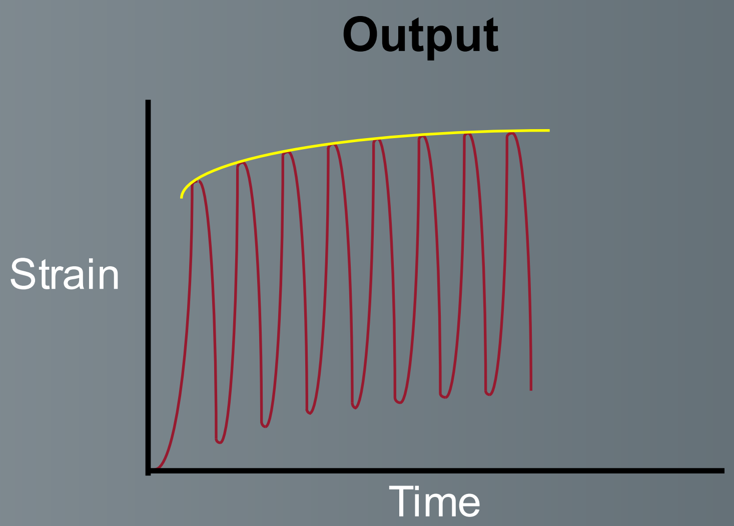
Time Dependence

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

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

Ratcheting





Time Dependence

Modeling Ratcheting

Linear viscoelastic strain for an arbitrary stress history can be modeled with the convolution integral:

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

Where

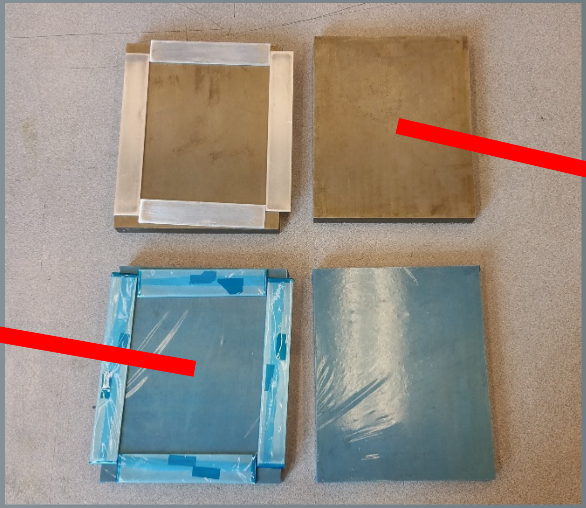
$$D(t) = D_0 + D_1 t^n$$

- D_o, D_1, and n are viscoelastic constants found from creep experiments.
- $\dot{\sigma}$ is the derivative with respect to τ of the stress history.

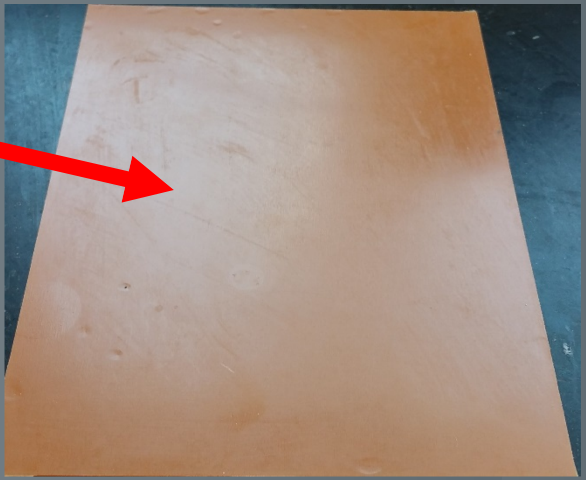
Coupon Fabrication

8 layers of film adhesive were laminated together and cured in to a bulk resin coupon, and then cut to 1” wide by 6” long. Thickness was around 0.064” to 0.068”. Coupons cured between steel plates originally wrapped in Teflon, however in FM300-2 this produced a textured surface shown below. Coupons fabricated with Teflon were found to have a smaller viscoelastic response. As a result of the surface condition, steel plates were released instead of wrapped in Teflon.

Teflon

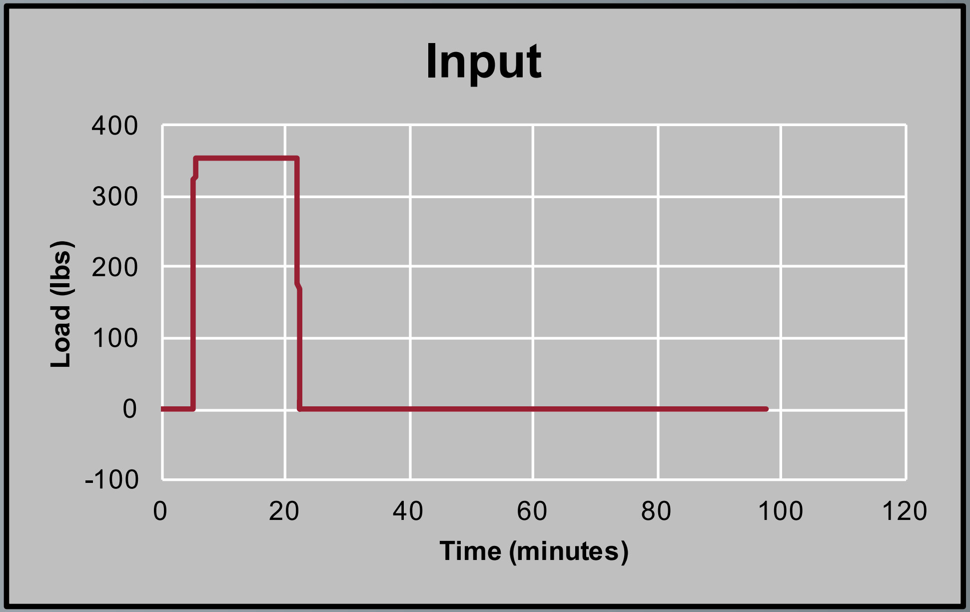


Release



Creep Testing

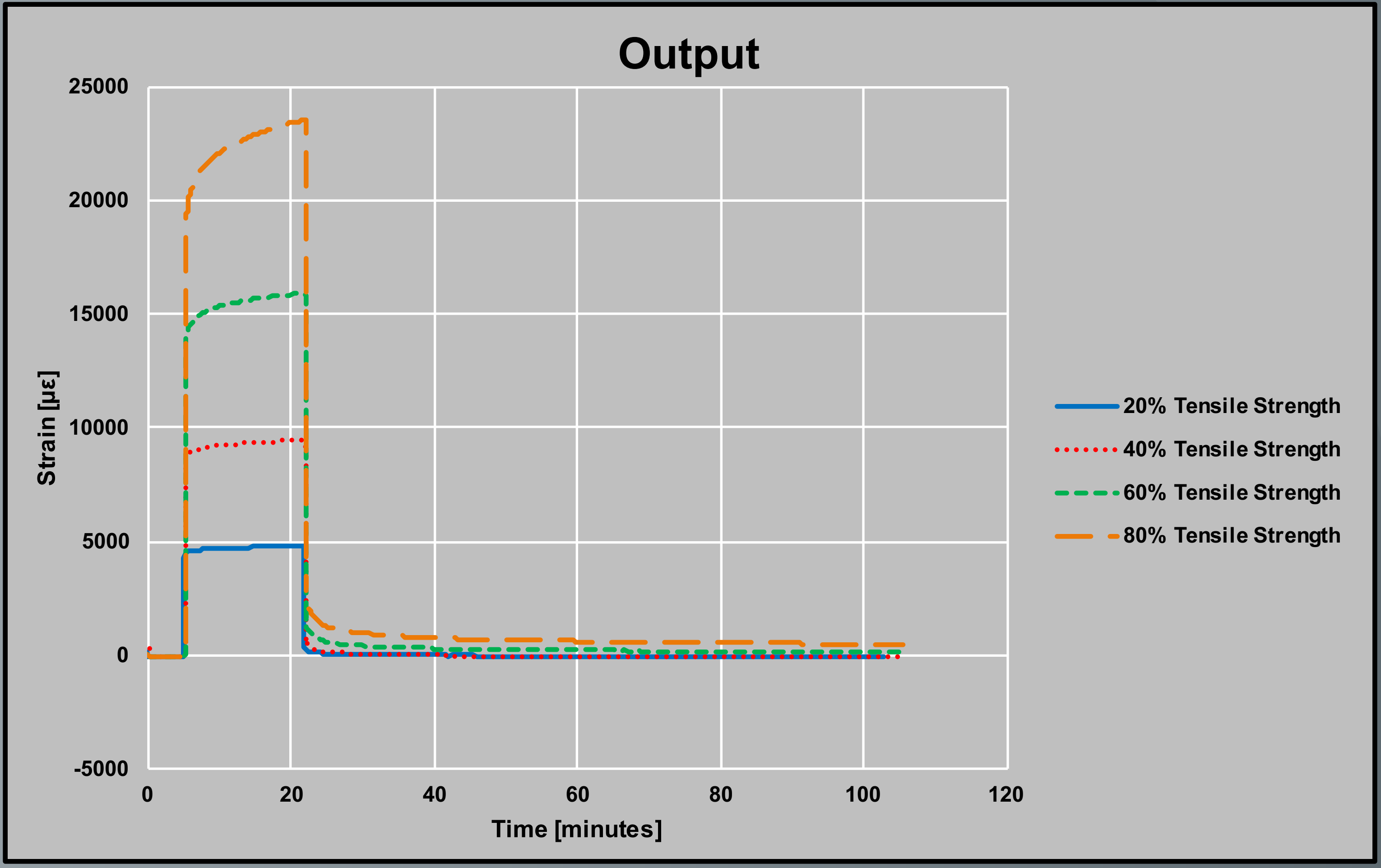
Apply a constant load in uniaxial tension to bulk resin coupons.



Creep Testing

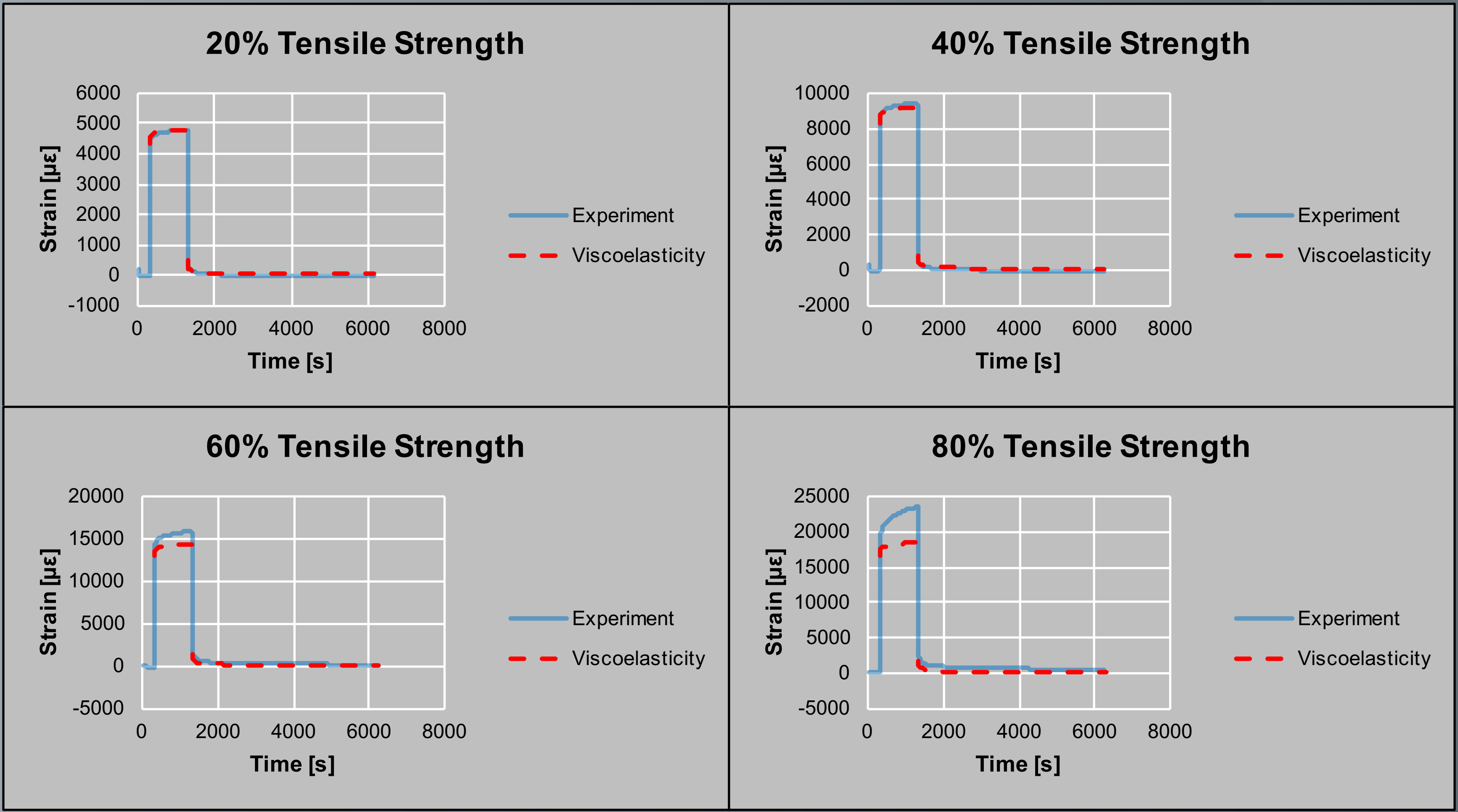
EA9696 results:

$$\sigma_t = 6500\ psi$$



Time Dependence

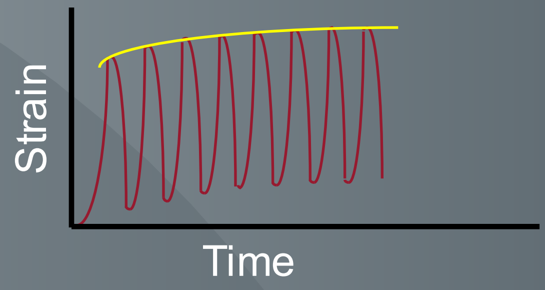
Viscoelastic constants were fit to a 20% tensile strength creep test and then used to predict higher stresses. This under predicted experimental creep showing that the adhesives are nonlinear viscoelastic.

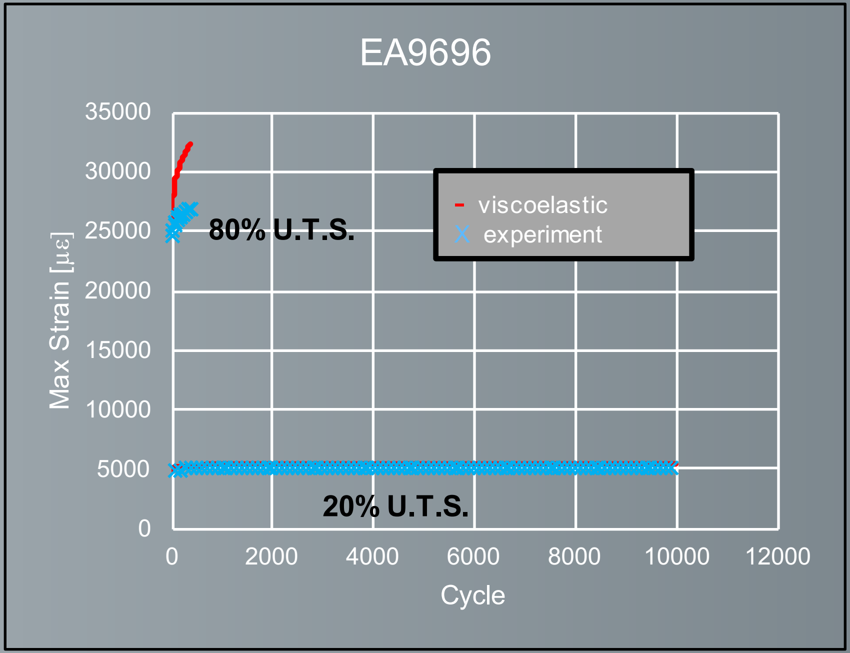


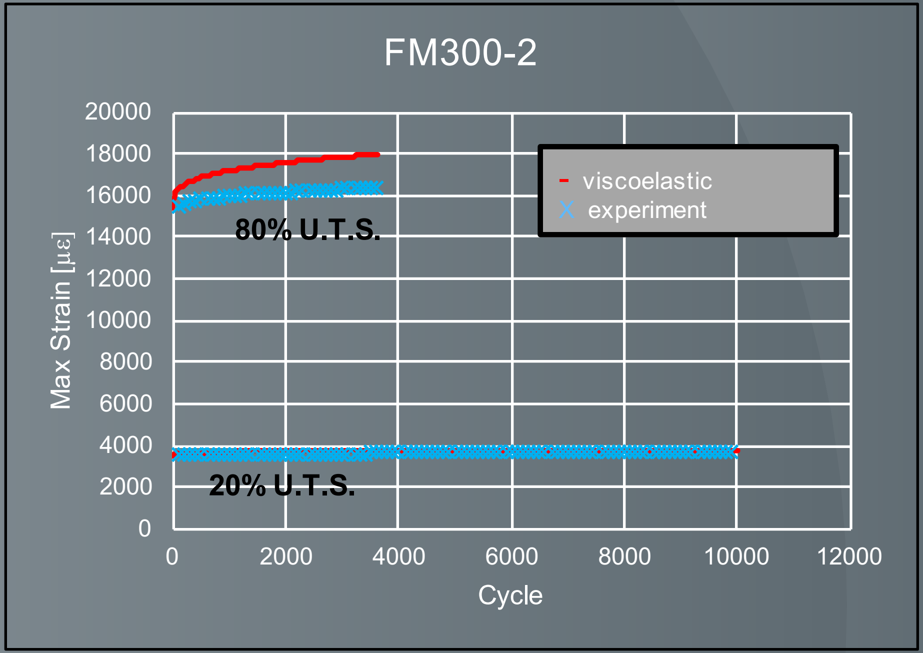
Time Dependence

A linear viscoelastic model was then used to predict ratcheting strain for 20% and 80% tensile strength. Model coefficients were determined from creep tests of the same stress so nonlinearity was removed as a variable.

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





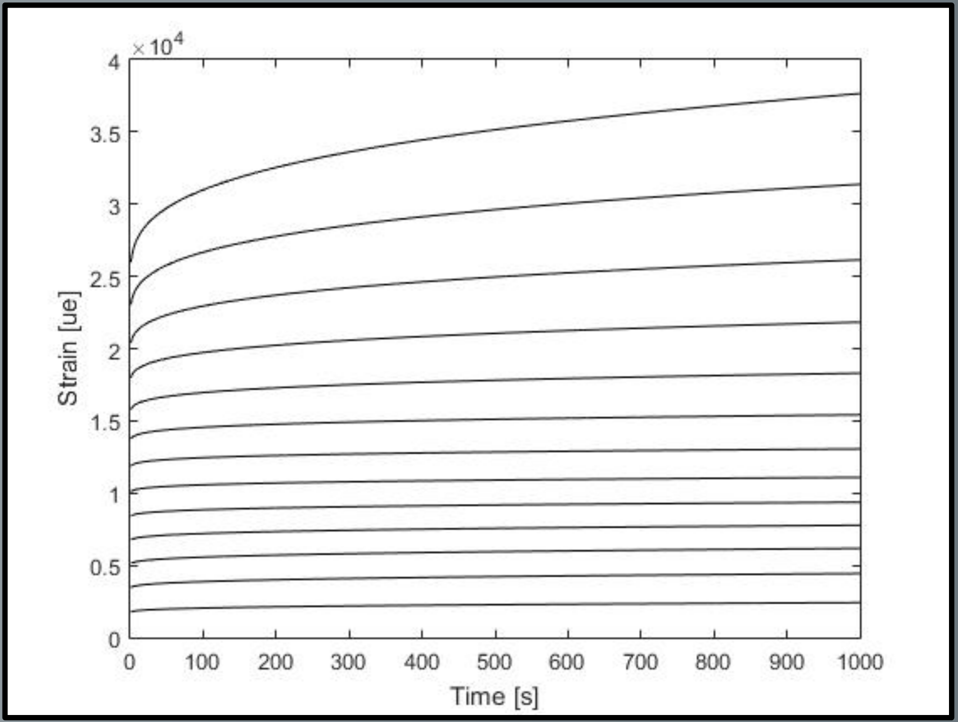


Time Dependence

Nonlinear creep can be modeled with:

$$\varepsilon_{11}(t) = F_1\sigma + F_2\sigma^2 + F_3\sigma^3$$

F_1, F_2, and F_3 are found experimentally from creep tests at three different stresses. The nonlinearity can be seen below.



Time Dependence

Modeling Ratcheting

Nonlinear viscoelastic strain can be modeled as:

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

Where F_1, F_2, and F_3 are determined from three creep tests at different stresses:

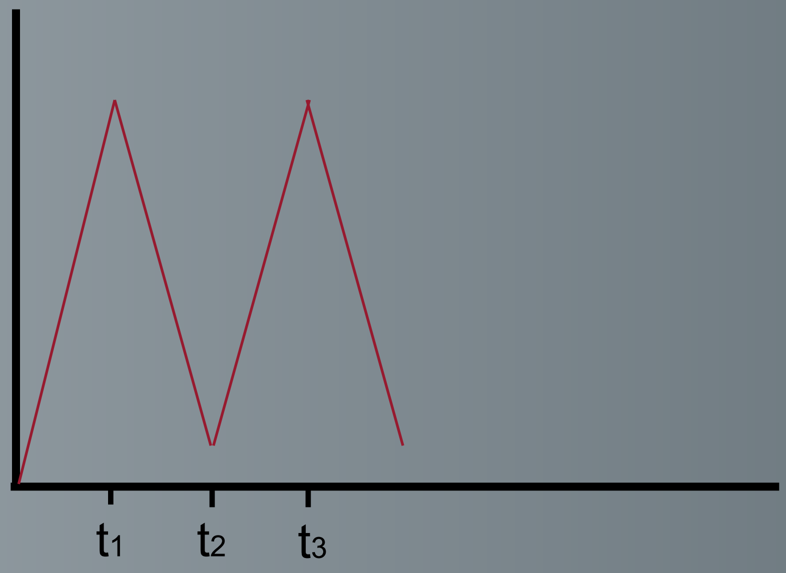
$$\varepsilon_{0_A} + \varepsilon_{1_A} t^{n_A} = F_1\sigma_a + F_2{\sigma_A}^2 + F_3{\sigma_A}^3$$
$$\varepsilon_{0_B} + \varepsilon_{1_B} t^{n_B} = F_1\sigma_B + F_2{\sigma_B}^2 + F_3{\sigma_B}^3$$
$$\varepsilon_{0_C} + \varepsilon_{1_C} t^{n_C} = F_1\sigma_C + F_2{\sigma_C}^2 + F_3{\sigma_C}^3$$

Time Dependence

Modeling Ratcheting

For a triangular wave, the stress is:

$$\sigma(t) = \frac{9f\sigma_{\max}}{5}\left[tH(t) + \sum_{i=2}^{\text{ramp}} 2(-1)^{i+1}(t - t_{i-1})H(t - t_{i-1})\right]$$



Time Dependence

Modeling Ratcheting

Plugging this in to convolution integral, we get:

$$
\begin{aligned}
\varepsilon(t) &= \frac{9f\sigma_{max}}{5\sigma_A(-\sigma_B{}^2 + \sigma_A\sigma_B)(\sigma_A\sigma_C{}^2 + \sigma_B\sigma_C{}^2 - \sigma_C{}^3 - \sigma_A\sigma_B\sigma_C)}\big[(\sigma_B^2\sigma_C^3 - \sigma_B^3\sigma_C^2)\boldsymbol{L_1}(\boldsymbol{A}) + (\sigma_A^3\sigma_C^2 - \sigma_A^2\sigma_C^3)\boldsymbol{L_1}(\boldsymbol{B}) + (\sigma_A^2\sigma_B^3 - \sigma_A^3\sigma_B^2)\boldsymbol{L_1}(\boldsymbol{C})\big] \\
&- \frac{81f^2\sigma_{\max}^2}{25\sigma_A(-\sigma_B{}^2 + \sigma_A\sigma_B)(\sigma_A\sigma_C{}^2 + \sigma_B\sigma_C{}^2 - \sigma_C{}^3 - \sigma_A\sigma_B\sigma_C)}\big[(\sigma_B\sigma_C^3 - \sigma_B^3\sigma_C)\boldsymbol{L_2}(\boldsymbol{A}) + (\sigma_A\sigma_C^3 - \sigma_A^3\sigma_C)\boldsymbol{L_2}(\boldsymbol{B}) + (\sigma_A\sigma_B^3 - \sigma_A^3\sigma_B)\boldsymbol{L_2}(\boldsymbol{C})\big] \\
&+ \frac{729f^3\sigma_{\max}^3}{125\sigma_A(-\sigma_B^2 + \sigma_A\sigma_B)(\sigma_A\sigma_C{}^2 + \sigma_B\sigma_C{}^2 - \sigma_C{}^3 - \sigma_A\sigma_B\sigma_C)}\big[(\sigma_B\sigma_C^2 - \sigma_B^2\sigma_C)\mathbf{L_3}(\mathbf{A}) + (\sigma_C\sigma_A^2 - \sigma_A^2\sigma_C)\mathbf{L_3}(\mathbf{B}) + (\sigma_A\sigma_B^2 - \sigma_B^2\sigma_A)\mathbf{L_3}(\mathbf{C})\big]
\end{aligned}
$$

Time Dependence

Modeling Ratcheting

Where

$$L_1 = \varepsilon_0 t + \frac{\varepsilon_1 t^{n+1}}{n+1} + \sum_{i=2}^{ramp} 2(-1)^{i+1}\left[\varepsilon_0(t-t_i) + \frac{\varepsilon_1(t-t_i)^{n+1}}{n+1}\right]$$

$$\begin{aligned} L_2 = (-1)^{ramp+1}&\left[\varepsilon_0 t^2 - \frac{\varepsilon_1 t^{n+2}}{(n+1)(n+2)} + \sum_{i=2}^{ramp} 2(-1)^{i+1}\left[\varepsilon_0 t(t-t_i) - \frac{\varepsilon_1(t-t_i)^{n+2}}{(n+1)(n+2)}\right]\right] \\ &- \left[(-1)^{ramp-1}\frac{\varepsilon_1 t^{n+2}}{(n+1)(n+2)} - \frac{\varepsilon_1(2t)^{n+2}}{(n+1)(n+2)} + \sum_{i=2}^{ramp} 2(-1)^{i}\frac{\varepsilon_1(2t-t_i)^{n+2}}{(n+1)(n+2)}\right] \\ &+ \sum_{i=2}^{ramp} 2(-1)^{i}\left[\varepsilon_0 t t_i + (-1)^{\mathrm{ramp}-1}\frac{\varepsilon_1(t-t_i)^{n+2}}{(n+1)(n+2)} - \frac{\varepsilon_1(2t-t_i)^{n+2}}{(n+1)(n+2)} + \sum_{j=2}^{\mathrm{ramp}} 2(-1)^{j+1}\left[\varepsilon_0(t-t_j)t_i - \frac{\varepsilon_1(2t-t_j-t_i)^{n+1}}{(n+1)(n+2)}\right]\right] \end{aligned}$$

Time Dependence

Modeling Ratcheting

$$
\begin{aligned}
L_3 = (-1)^{\mathrm{ramp}+1} \Bigg\{ & (-1)^{\mathrm{ramp}+1} \Bigg[\varepsilon_0 t^3 + \frac{\varepsilon_1 t^{n+3}}{(n+1)(n+2)(n+3)} + \sum_{i=2}^{\mathrm{ramp}} 2(-1)^{i+1} \left[\varepsilon_0 t^2 (t - t_i) + \frac{\varepsilon_1 (t - t_i)^{n+3}}{(n+1)(n+2)(n+3)} \right] \Bigg] \\
& - \left[\frac{\varepsilon_1 (2t)^{n+3}}{(n+1)(n+2)(n+3)} + (-1)^{\mathrm{ramp}} \frac{\varepsilon_1 t^{n+3}}{(n+1)(n+2)(n+3)} + \sum_{i=2}^{\mathrm{ramp}} 2(-1)^{i+1} \frac{\varepsilon_1 (2t - t_i)^{n+3}}{(n+1)(n+2)(n+3)} \right] \\
& + \sum_{j=2}^{\mathrm{ramp}} 2(-1)^{j} \Bigg[\varepsilon_0 t^2 t_j + \frac{\varepsilon_1 (2t - t_j)^{n+3}}{(n+1)(n+2)(n+3)} (-1)^{\mathrm{ramp}} \frac{\varepsilon_1 (t - t_j)^{n+3}}{(n+1)(n+2)(n+3)} + \sum_{i=2}^{\mathrm{ramp}} 2(-1)^{i+1} \left[\varepsilon_0 t t_j (t - t_i) + \frac{\varepsilon_1 (2t - t_i - t_j)^{n+3}}{(n+1)(n+2)(n+3)} \right] \Bigg] \Bigg\} \\
& - \Bigg\{ (-1)^{\mathrm{ramp}+1} \left[\frac{\varepsilon_1 (2t)^{n+3}}{(n+1)(n+2)(n+3)} + (-1)^{\mathrm{ramp}} \frac{\varepsilon_1 t^{n+3}}{(n+1)(n+2)(n+3)} + \sum_{i=2}^{\mathrm{ramp}} 2(-1)^{i+1} \frac{\varepsilon_1 (2t - t_i)^{n+3}}{(n+1)(n+2)(n+3)} \right] \\
& - \left[\frac{\varepsilon_1 (3t)^{n+3}}{(n+1)(n+2)(n+3)} + (-1)^{\mathrm{ramp}} \frac{\varepsilon_1 (2t)^{n+3}}{(n+1)(n+2)(n+3)} + \sum_{i=2}^{\mathrm{ramp}} 2(-1)^{i+1} \frac{\varepsilon_1 (3t - t_i)^{n+3}}{(n+1)(n+2)(n+3)} \right] \\
& + \sum_{j=2}^{\mathrm{ramp}} 2(-1)^{j} \left[\frac{\varepsilon_1 (3t - t_j)^{n+3}}{(n+1)(n+2)(n+3)} + (-1)^{\mathrm{ramp}} \frac{\varepsilon_1 (2t - t_j)^{n+3}}{(n+1)(n+2)(n+3)} + \sum_{i=2}^{\mathrm{ramp}} 2(-1)^{i+1} \frac{\varepsilon_1 (3t - t_i - t_j)^{n+3}}{(n+1)(n+2)(n+3)} \right] \Bigg\} \\
& + \sum_{k=2}^{\mathrm{ramp}} 2(-1)^{k} \Bigg\{ (-1)^{\mathrm{ramp}+1} \Bigg[\varepsilon_0 t^2 t_k + \frac{\varepsilon_1 (2t - t_k)^{n+3}}{(n+1)(n+2)(n+3)} + (-1)^{\mathrm{ramp}} \frac{\varepsilon_1 (t - t_k)^{n+3}}{(n+1)(n+2)(n+3)} \\
& + \sum_{i=2}^{\mathrm{ramp}} 2(-1)^{i+1} \left[\varepsilon_0 t t_k (t - t_i) + \frac{\varepsilon_1 (2t - t_i - t_k)^{n+3}}{(n+1)(n+2)(n+3)} \right] \Bigg] \\
& - \left[\frac{\varepsilon_1 (3t - t_k)^{n+3}}{(n+1)(n+2)(n+3)} + (-1)^{\mathrm{ramp}} \frac{\varepsilon_1 (2t - t_k)^{n+3}}{(n+1)(n+2)(n+3)} + \sum_{i=2}^{\mathrm{ramp}} 2(-1)^{i+1} \frac{\varepsilon_1 (3t - t_i - t_k)^{n+3}}{(n+1)(n+2)(n+3)} \right] \\
& + \sum_{j=2}^{\mathrm{ramp}} 2(-1)^{j} \Bigg[\varepsilon_0 t t_j t_k + \frac{\varepsilon_1 (3t - t_j - t_k)^{n+3}}{(n+1)(n+2)(n+3)} + (-1)^{\mathrm{ramp}} \frac{\varepsilon_1 (2t - t_j - t_k)^{n+3}}{(n+1)(n+2)(n+3)} \\
& + \sum_{i=2}^{\mathrm{ramp}} 2(-1)^{i+1} \left[\varepsilon_0 t_j t_k (t - t_i) + \frac{\varepsilon_1 (3t - t_i - t_j - t_k)^{n+3}}{(n+1)(n+2)(n+3)} \right] \Bigg] \Bigg\}
\end{aligned}
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Time Dependence

Summary:

- Both adhesives show a nonlinear creep and ratcheting response.
- Creep experiments can be used to predict ratcheting response.
- Nonlinearity appears to begin after 40% which corresponds to when permanent strain begins to be observed
- At high stress the power law over predicts ratcheting strain.

Next Steps:

- Account for variations in creep response at the same stress level by doing multiple tests.
- Complete ratcheting test matrix and apply nonlinear model.
- Investigate causes of ratcheting strain due to plasticity.