WASHINGTON STATE UNIVERSITY

Durability of bonded aircraft structure

AMTAS Fall 2016 meeting
October 27th 2016
Seattle, WA

CECAM center of excellence for composites and advanced materials

JAMS JOINT ADVANCED MATERIALS & STRUCTURES CENTER OF EXCELLENCE

A Center of Excellence AMTAS Advanced Materials in Transport Aircraft Structures

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 static and 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.
  - Ratchetting in bulk tension and shear
- Approach
  - Coupons with varying amounts of peel stress
  - Bulk adhesives and thin bonds, plasticity models
  - Damage models
  - Non-linear viscoelasticty

Durability of Bonded Aircraft Structure

- Principal Investigators & Researchers
  - Lloyd Smith
  - Preetam Mohapatra, David Lemme, Reza Moheimani, Sayed Hafiz
- FAA Technical Monitor
  - Curt Davies
- Other FAA Personnel Involved
  - Larry Ilcewicz
- Industry Participation
  - Boeing: Will Grace, Peter VanVoast, Kay Blohowiak

Double Cantilever Beam (DCB)

🟪 EA9696

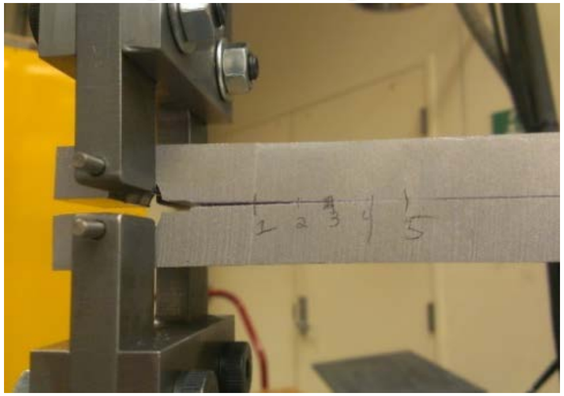
🟧 FM300-2

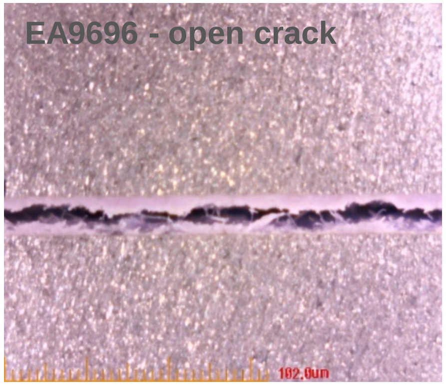
◼ EA9380.05

🟨 EA9394

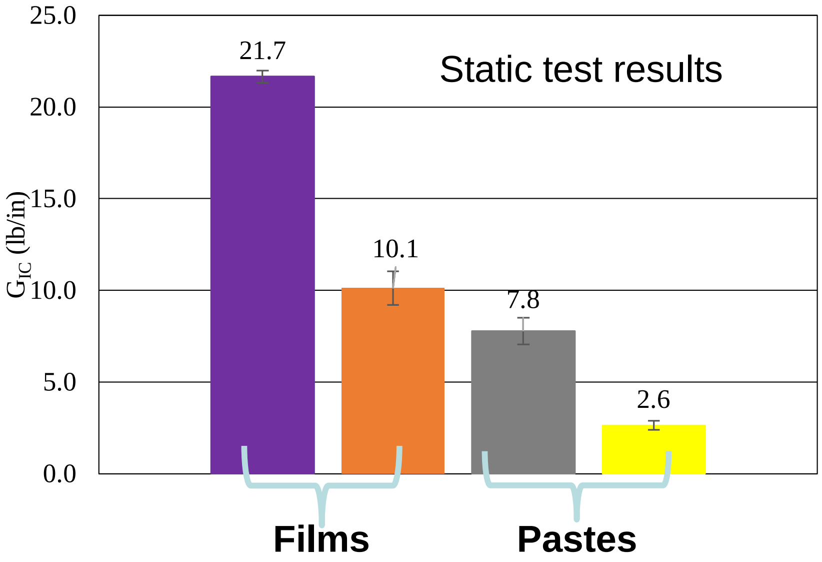
ASTM D3433

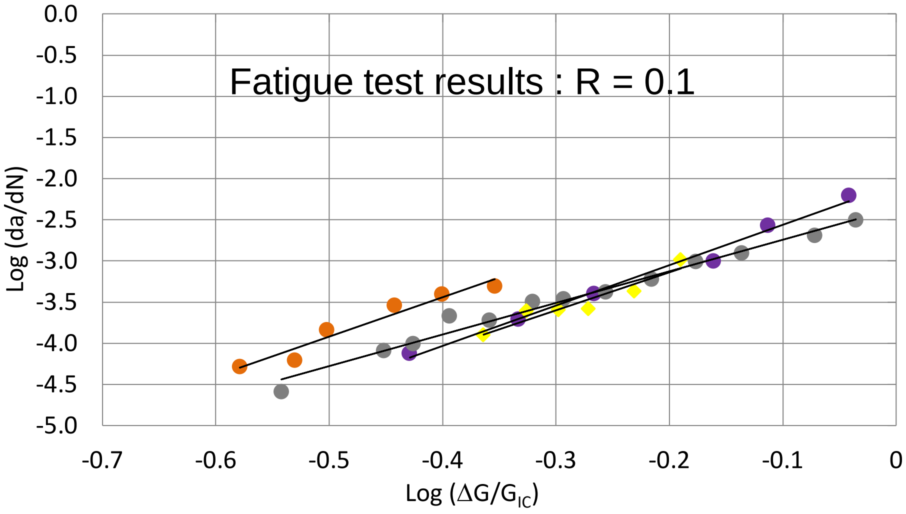
$$G_{1c} = \frac{[4L^2(\max)][3a^2+h^2]}{[EB^2h^3]}$$





EA9696 - open crack

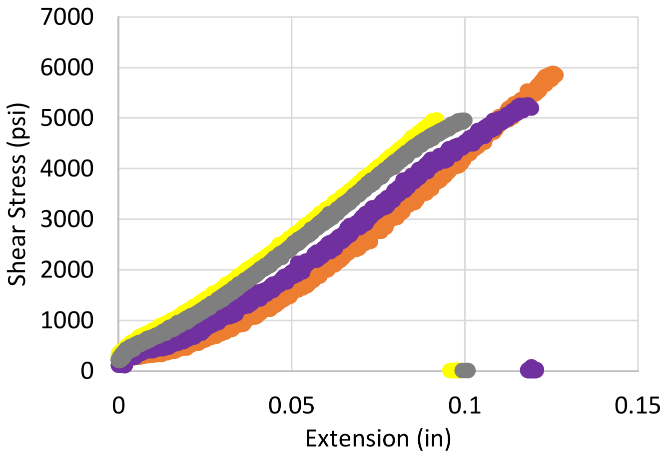


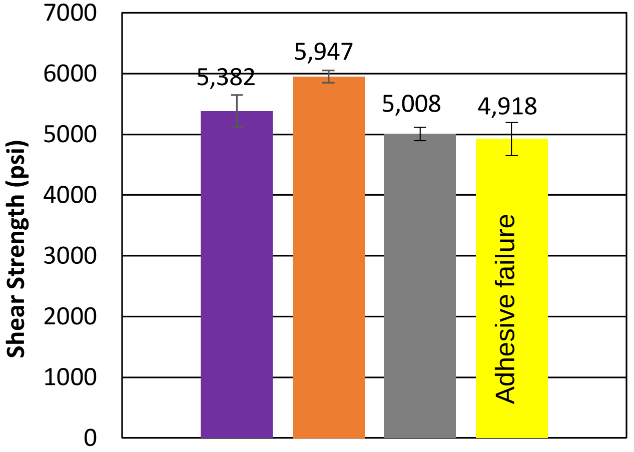


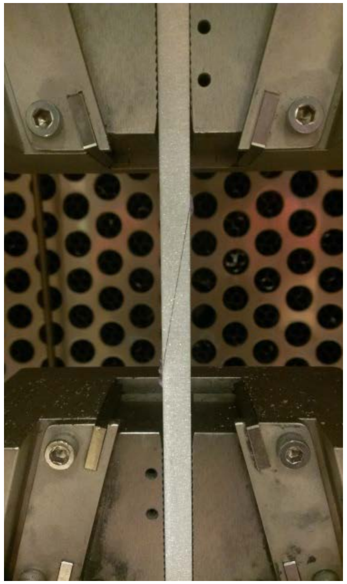
Observations :

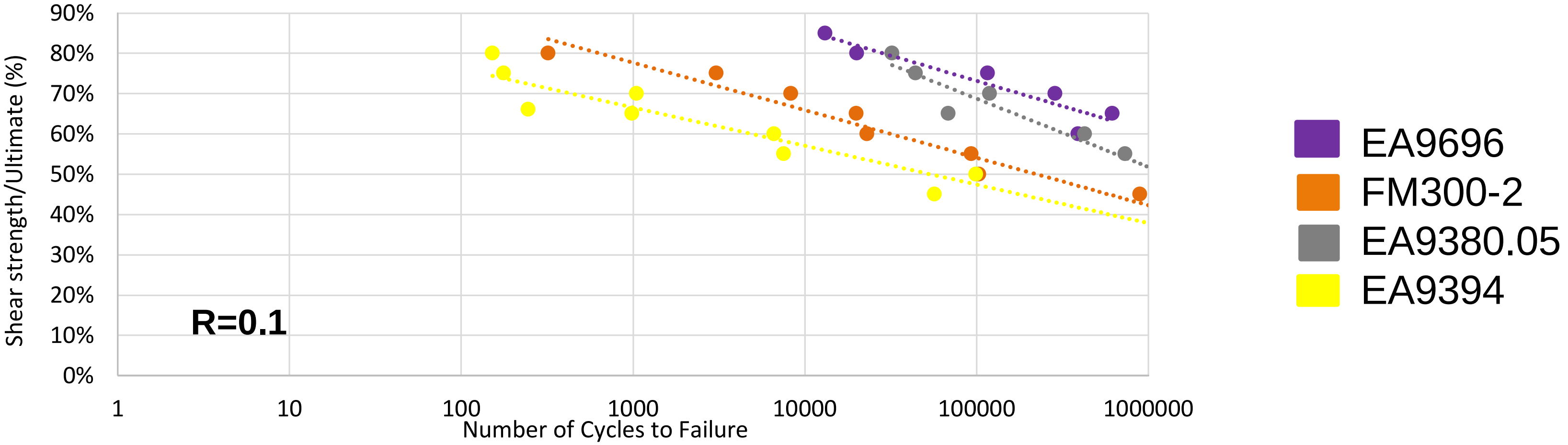
1. EA9696 – High toughness
2. FM300-2 ≈ EA9380.05
3. EA9394 – Low toughness (adhesive failure)

Scarf Joint









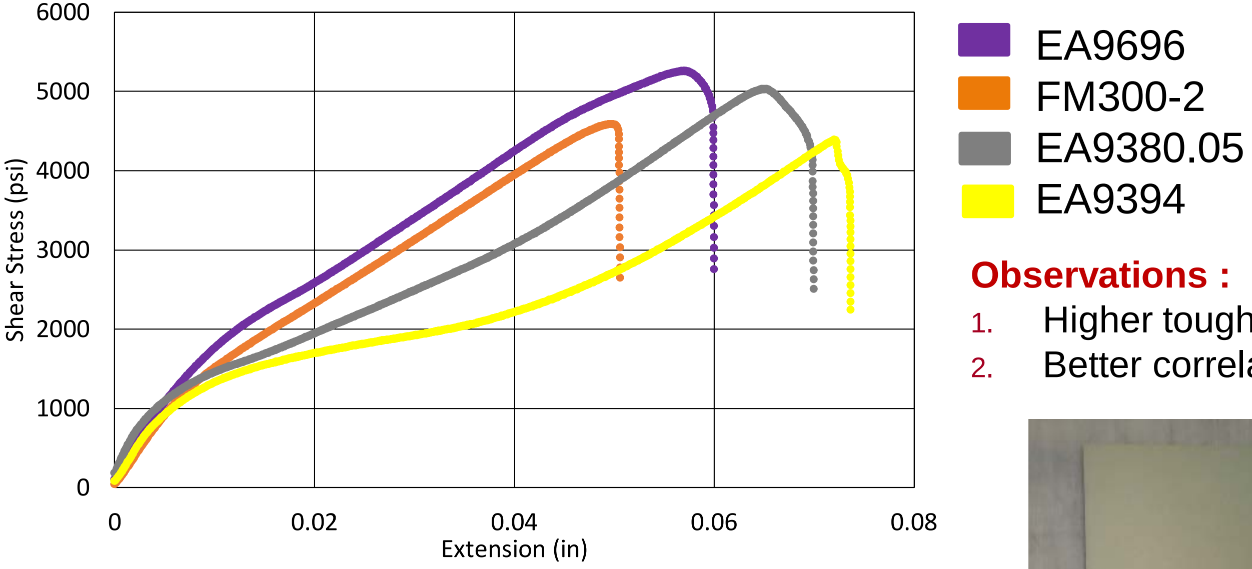
Static :

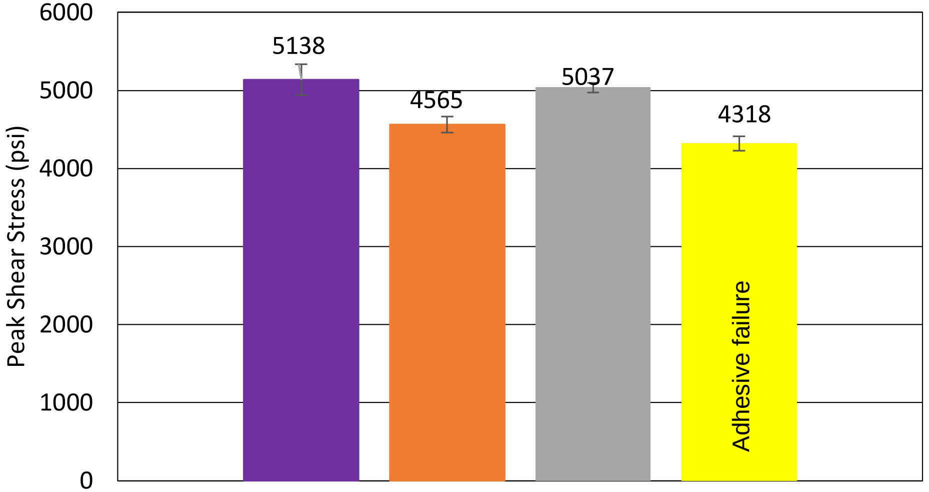
1. EA9696 and EA9380.05 show more softening
2. FM300-2 strongest
3. Static strength does not correlate well with G_{IC}

Fatigue :

1. EA9696 has highest fatigue life
2. EA9394 has shortest fatigue life
3. Fatigue life tends to correlate with G_{IC}

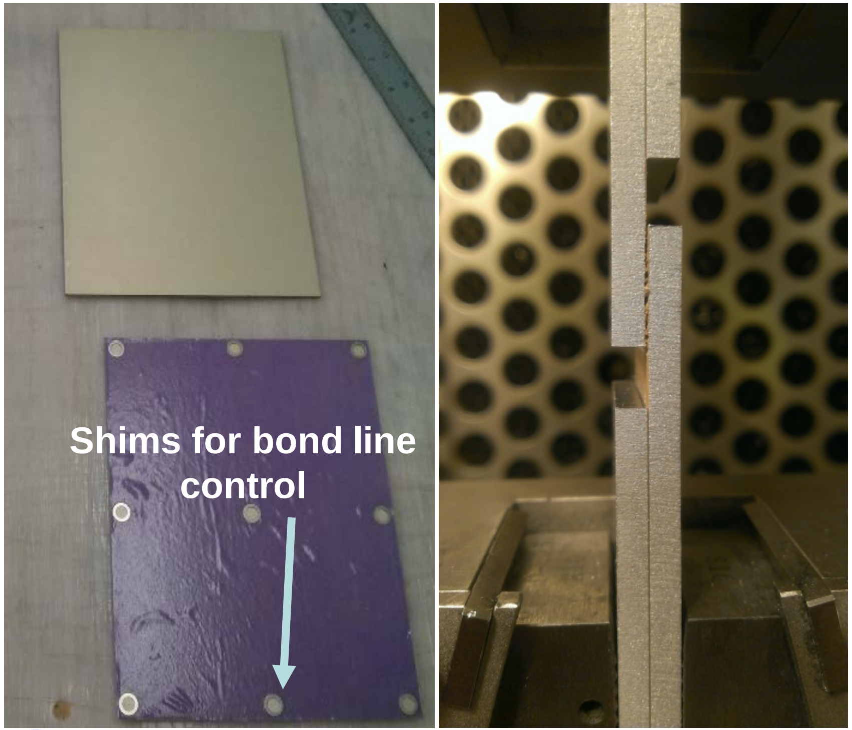
Wide Area Lap Shear - Static



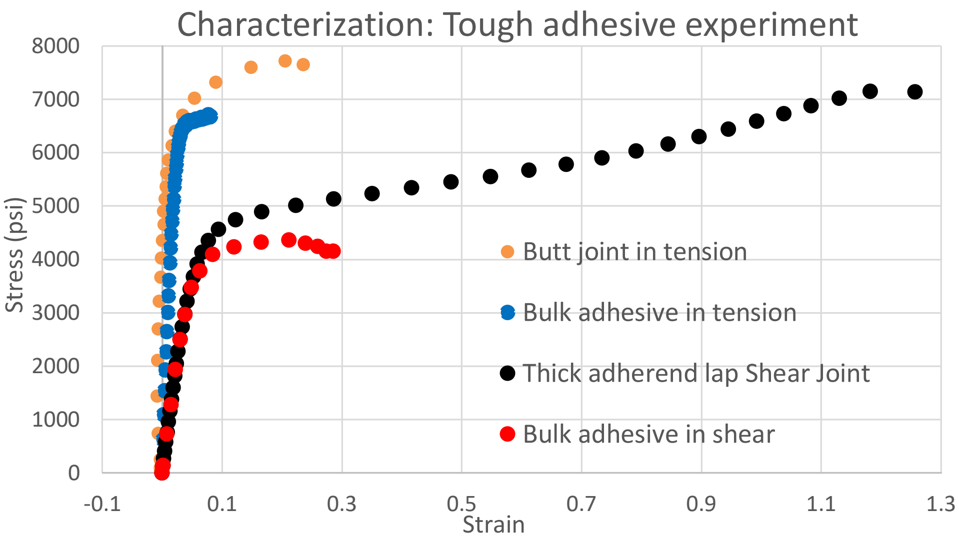


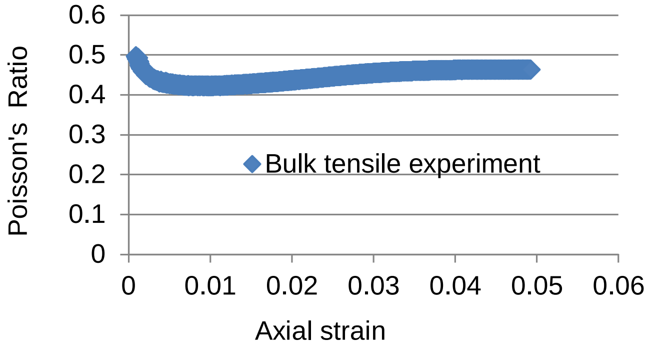
Observations :

1. Higher toughness than scarf
2. Better correlation with G_{IC} than scarf

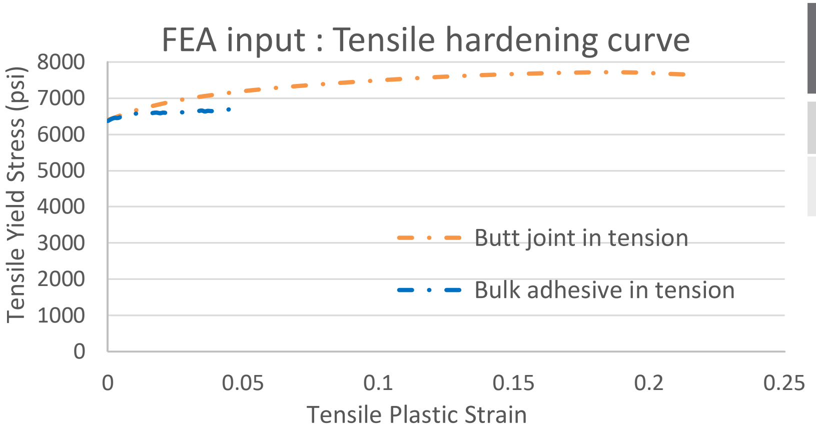


FEA Modeling of bulk adhesives and bonded joints





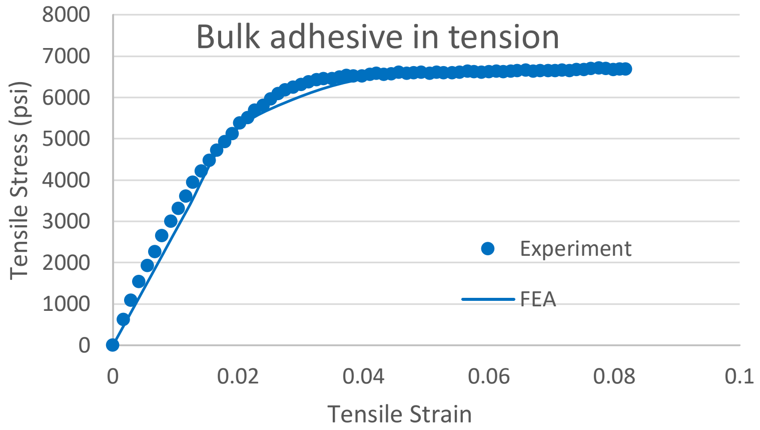
Elastic properties	Adhesive	Adherend
E (Psi)	277,000	10,600,000
υ_e	0.43	0.33

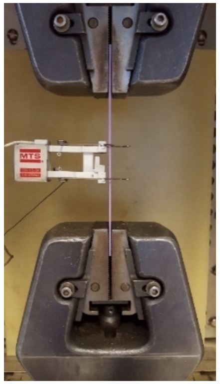


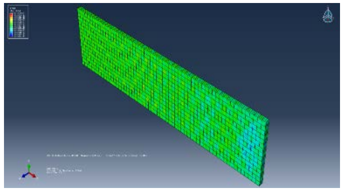
Yield criterion	Linear elastic	Hardening curve	Drucker Prager yield constants
von Mises	✓	✓	
Drucker Prager	✓	✓	✓

Exponent Drucker Prager model	
a (Psi^{-1})	0.00014
b	2
Ψ	3.50

FEA Modeling of bulk adhesives and bonded joints

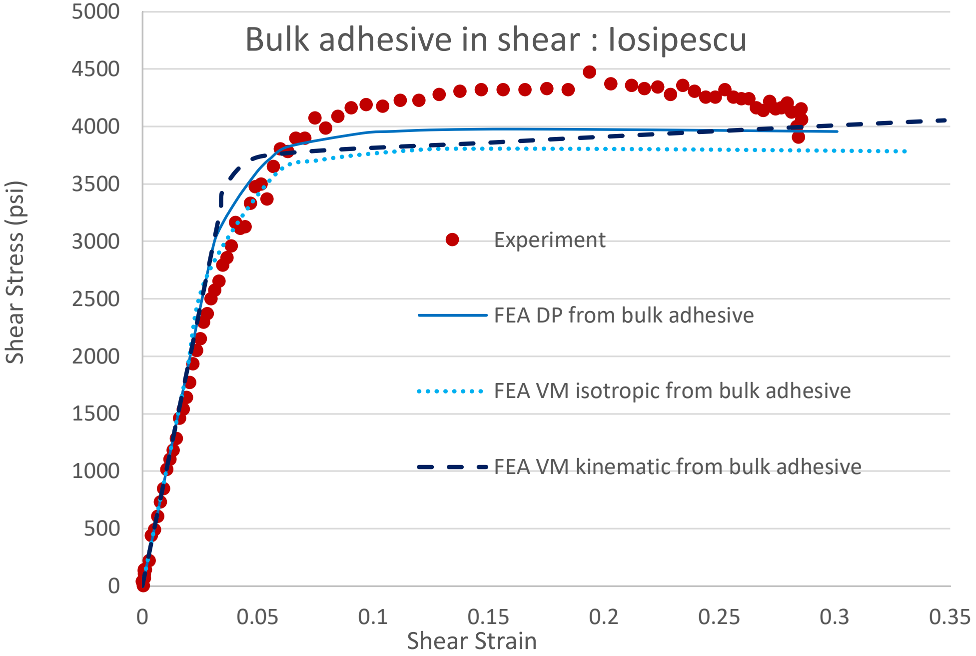


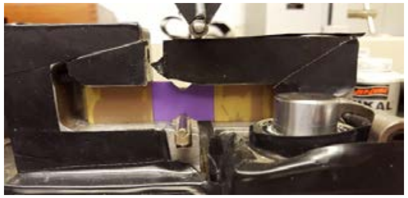


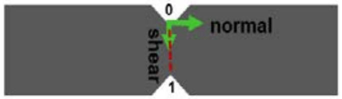


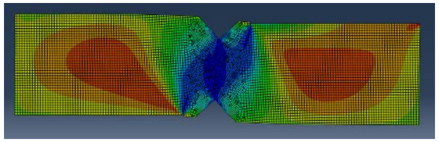
Observations :

1. Not sensitive to yield criteria or hardening model.









Observations :

1. Pressure sensitive > elastic plastic (4% better) with isotropic
2. Kinematic > Isotropic (4% better) with von Mises yielding
3. Less sensitive to yield criteria and hardening model

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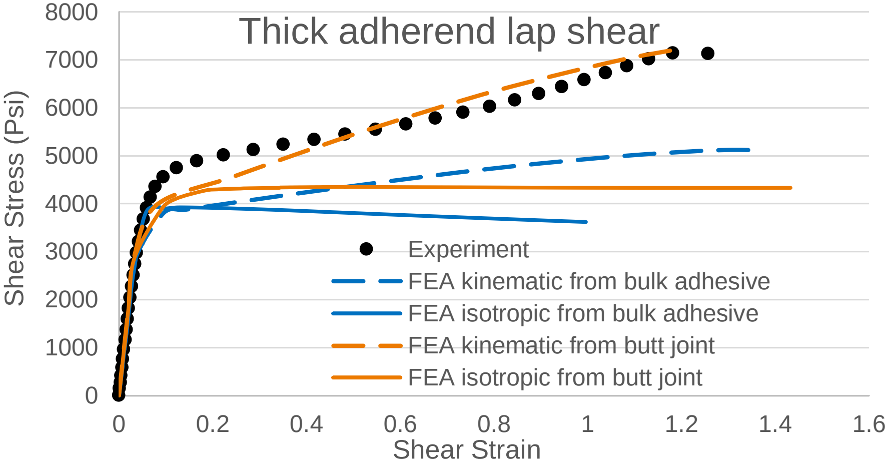
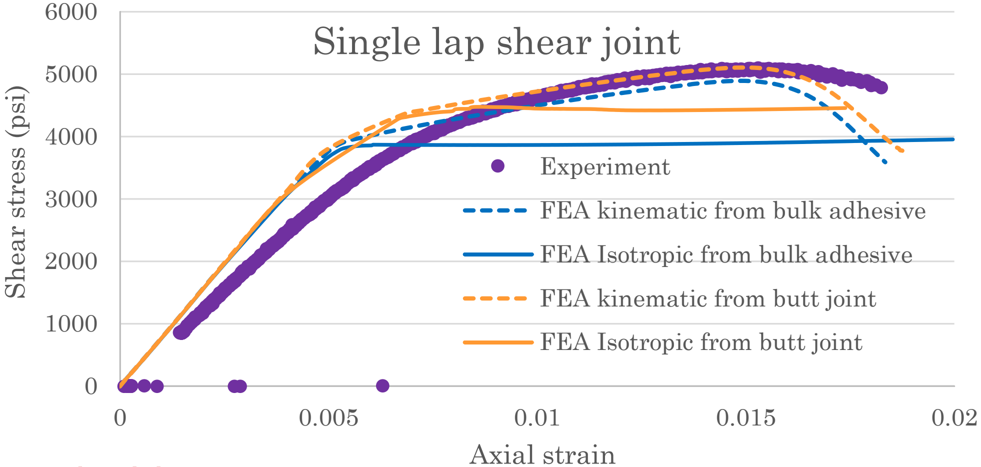
FEA Modeling of bulk adhesives and bonded joints



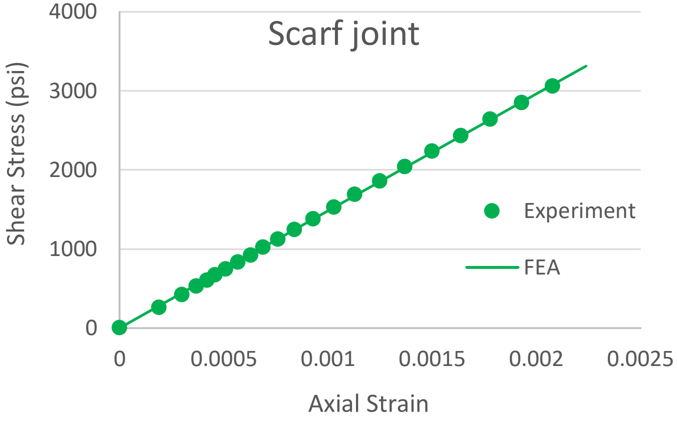
Stiff joint :

1. Kinematic > Isotropic, by 65%, for both thin film and bulk input
2. Thin film > Bulk form, by 40%, for both hardening type
3. Hardening model > Input property type > yield criteria



Compliant joint :

1. Thin film > Bulk form, better by (5% with Kinematic) and (13% by Isotropic)
2. Kinematic > isotropic , by 25% for both thin film and bulk form
3. Hardening model > input properties > yield criteria

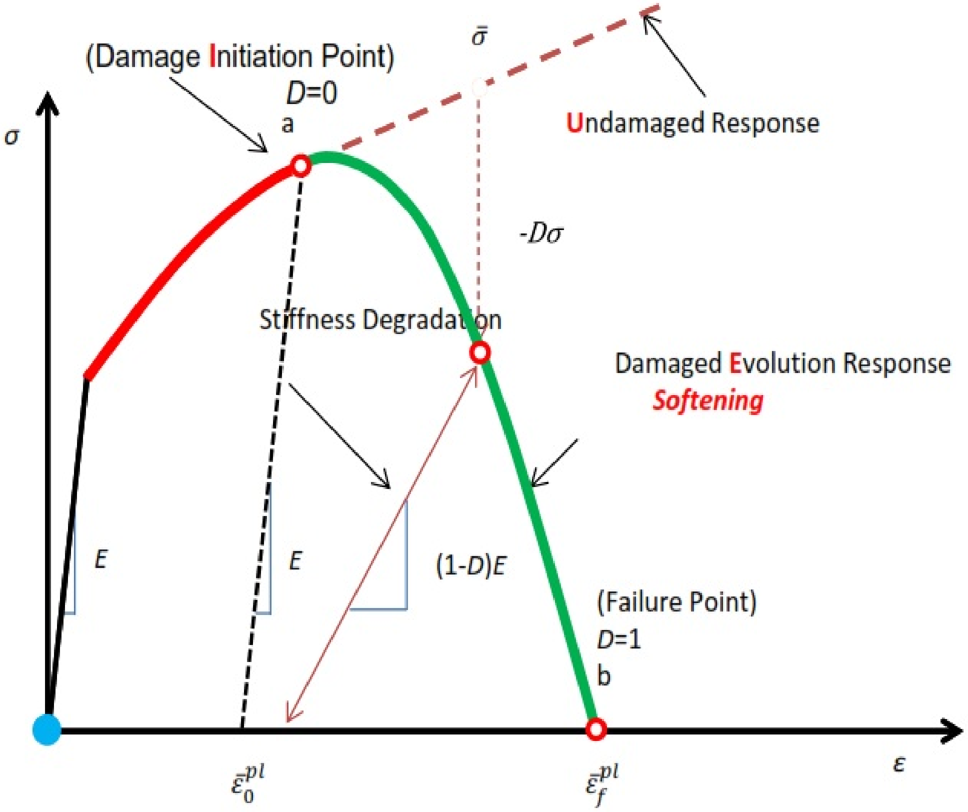


Joint in pure shear :

1. Toughened adhesive was linear in pure shear.
2. Independent of yield criteria or hardening model
3. Bulk input successful predictor.

Progressive damage modeling

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



Considerations:

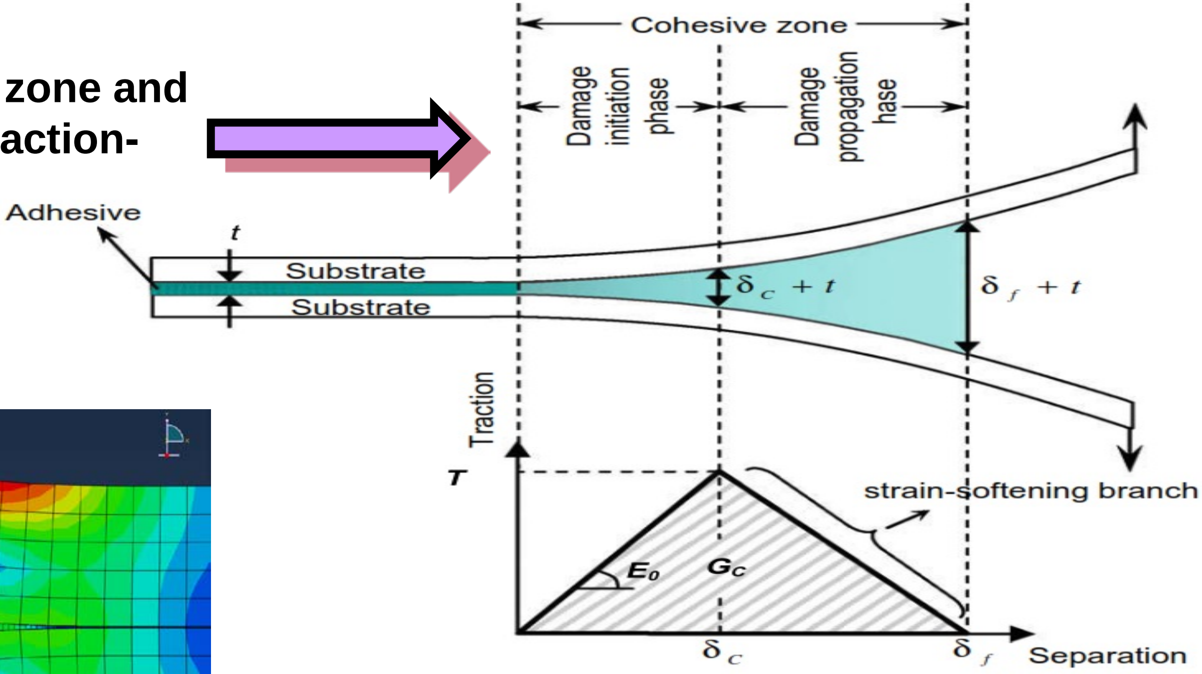
- 2D, plane strain
- Cohesive zone damage model with a traction-separation description of the interface element
- Compare load-displacement response with experiment and analytical results
- Analytical results are plotted based on Timoshenko beam theory(E is the substrate modulus)

$$P^{\text{Timo}} = \frac{b\,h}{2\,a}\sqrt{\frac{G_c\,E\,h}{3\left(1+\frac{(1+\nu)}{5}\left(\frac{h}{a}\right)^2\right)}} \qquad y^{\text{Timo}} = 4\,a^2\sqrt{\frac{G_c}{3\,E\,h^3}}\,\frac{\left(1+\frac{3(1+\nu)}{5}\left(\frac{h}{a}\right)^2\right)}{\sqrt{1+\frac{(1+\nu)}{5}\left(\frac{h}{a}\right)^2}}$$

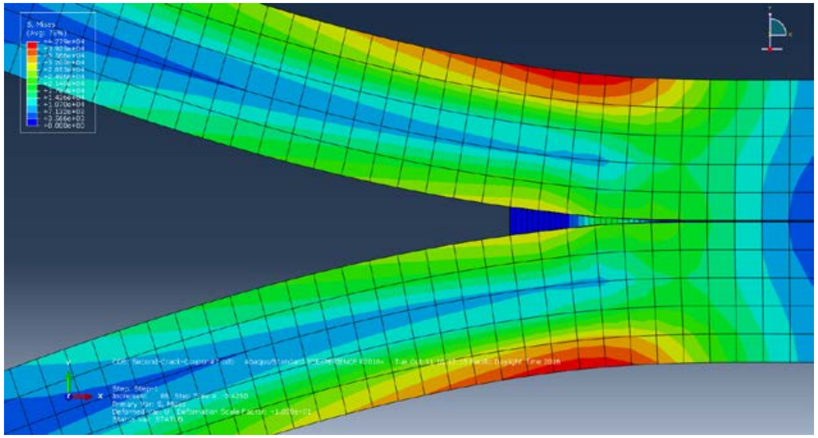
ABAQUS Inputs	
σ_y	Interface Strength
E	Interface Stiffness
G_{Ic}	Fracture Toughness

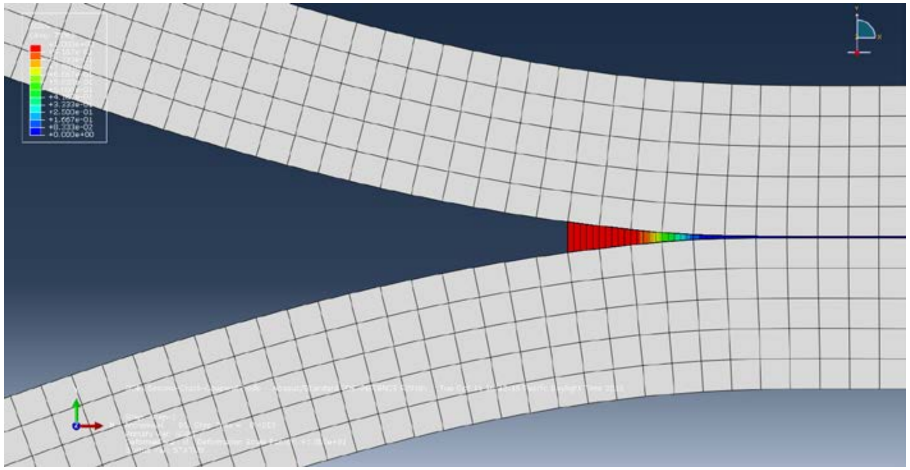
Damage modeling with cohesive elements in ABAQUS

Schematic damage process zone and corresponding bi-linear traction-separation law



von Mises stress Field





Displaying cohesive elements:

They are removed, while failing

SDEG (Scalar stiffness degradation)

0<D<1

Damage modeling with cohesive elements in ABAQUS

- ✓ CZM combines a strength based failure criterion to predict the **damage initiation** and a fracture mechanics-based criterion to determine the **damage propagation**.
- ✓ 2D meshing by using COH2D4(adhesive) and CPE4(adherends) four-node linear plane strain elements

- **Damage initiation**: (linear part)

❑ **Maximum nominal stress** (Pure Mode)

Damage initiates when either of the peel or shear components of traction exceeds the respective critical value.

$$max\left\{\frac{t_n}{t_n^0}, \frac{t_s}{t_s^0}\right\}=1, \qquad t_n^0 = \text{tensile strength}, \;\; t_s^0 = \text{shear strength}$$

Damage modeling with cohesive elements in ABAQUS

- **Damage evolution:** (Softening part)

Energy based evolution model:

❑ Pure Mode(Mode I or Mode II)

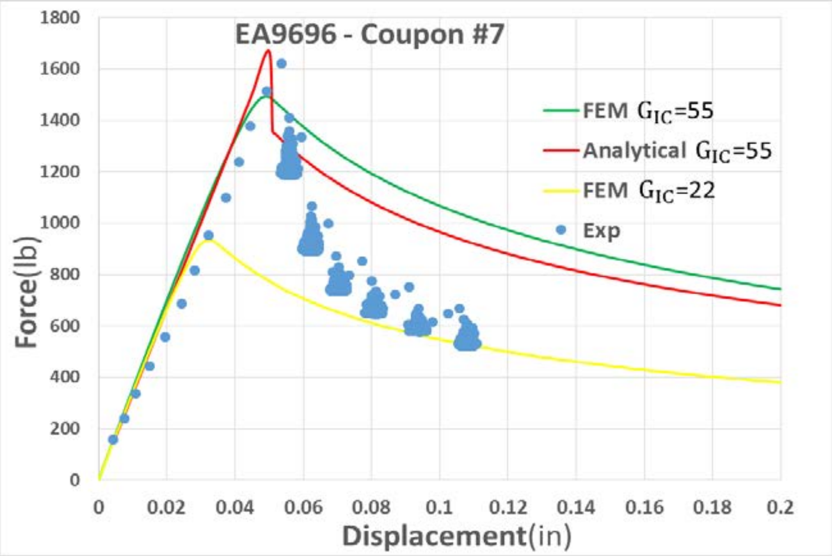
Damage propagates when either the normal or shear components of energy release exceeds the respective critical value.

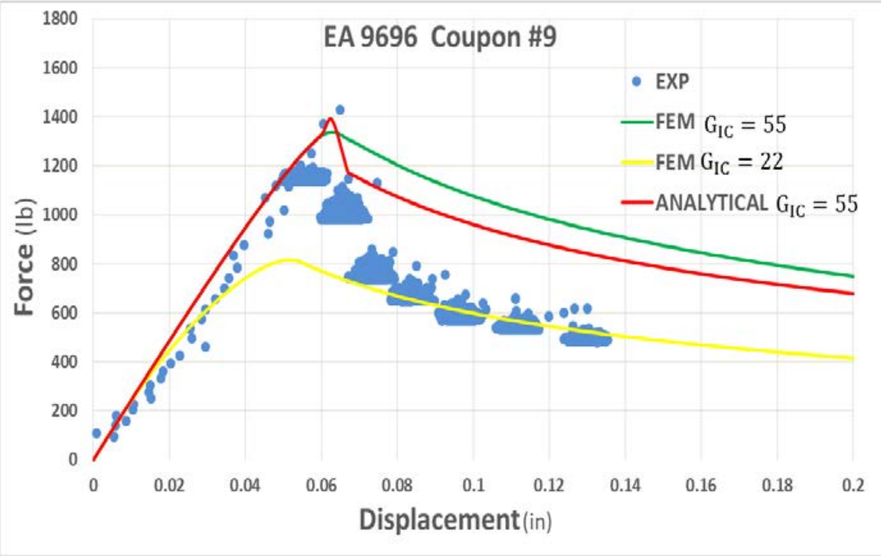
$\left\{\frac{G_I}{G_{Ic}}, \frac{G_{II}}{G_{IIc}}\right\}=1$, (*Fracture energy is equal to the area under the traction-separation curve)*

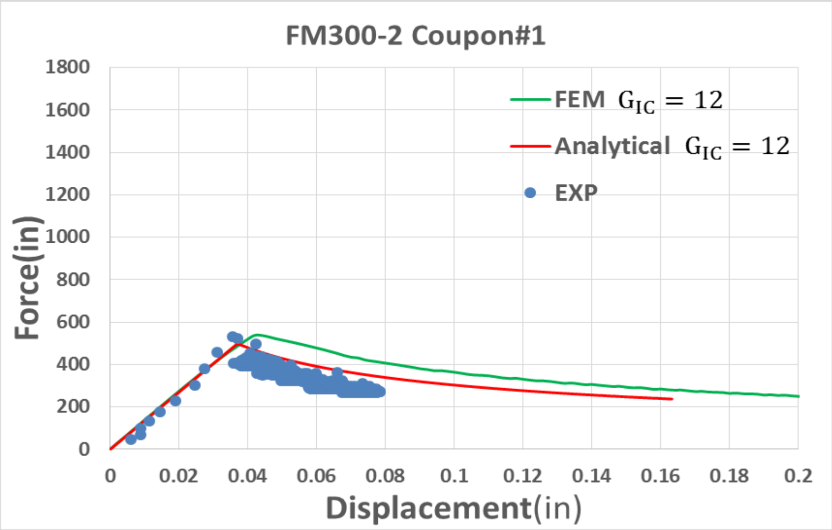
	Tensile Modulus E (ksi)	Tensile Strength σ_0 (Psi)	Fracture Toughness G_{Ic}(lb/in)
EA 9696	277	6660	22-55
FM300-2	400	7450	12
EA9394	615	6675	3
EA 9380.05	290*	7000*	10

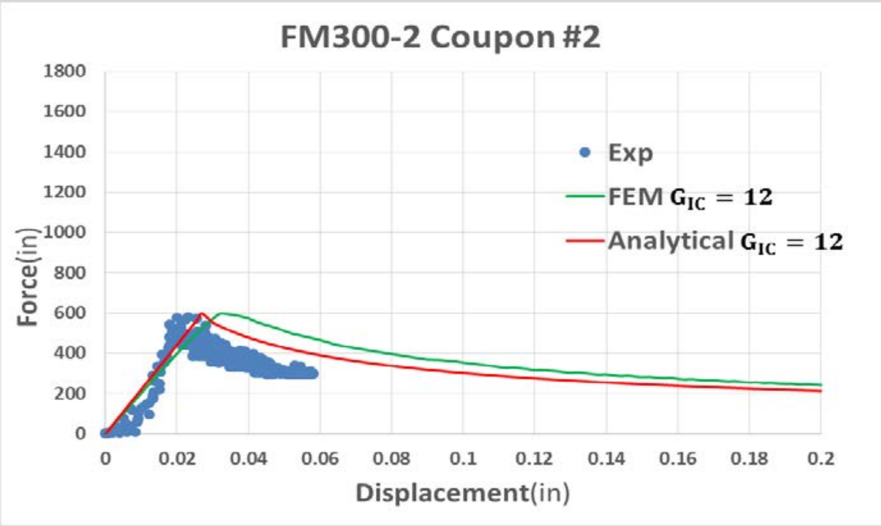
*** Found through iteration**

Static Test on DCB (2coupons per Adhesive)

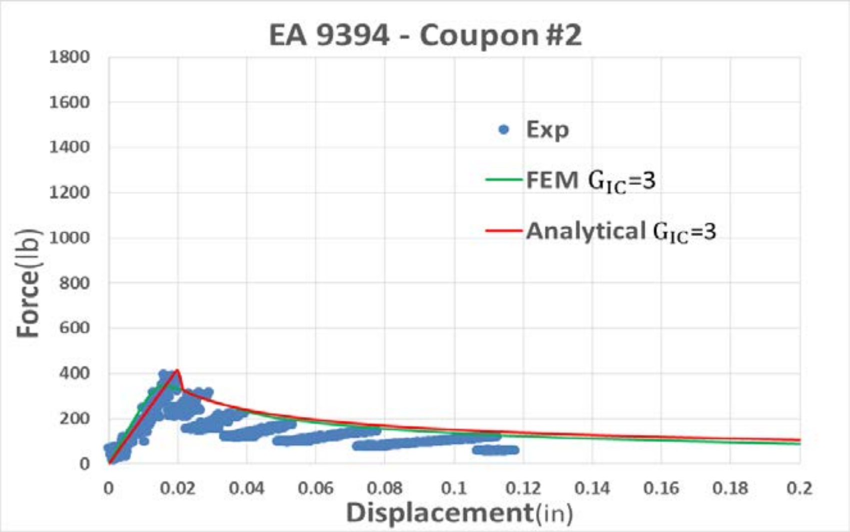

EA9696 - Coupon #7

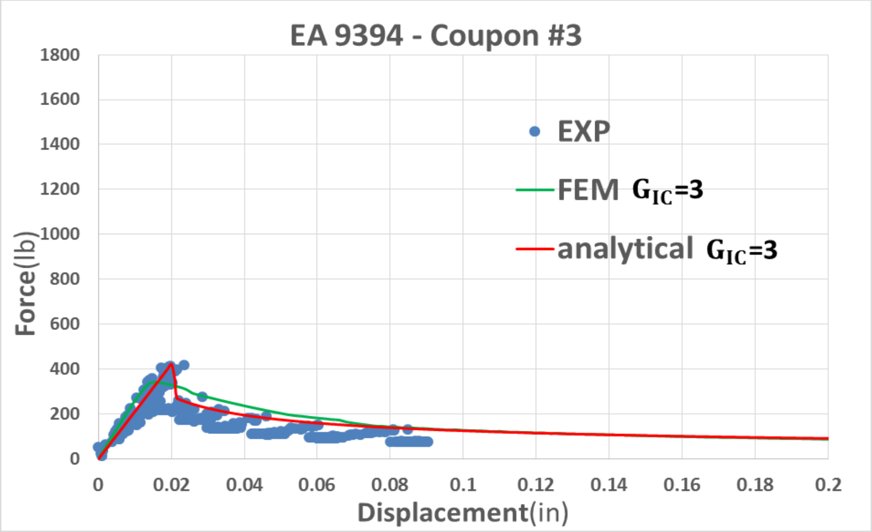

EA 9696 Coupon #9

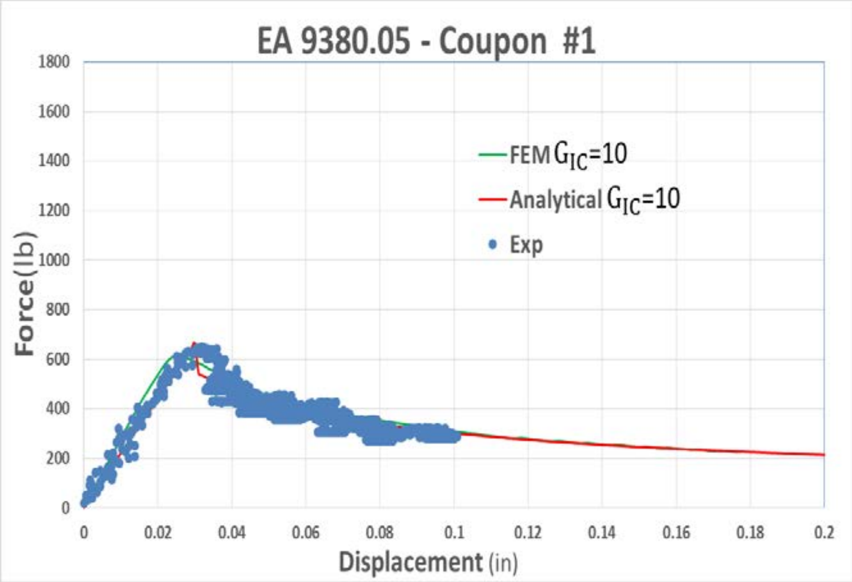

FM300-2 Coupon#1

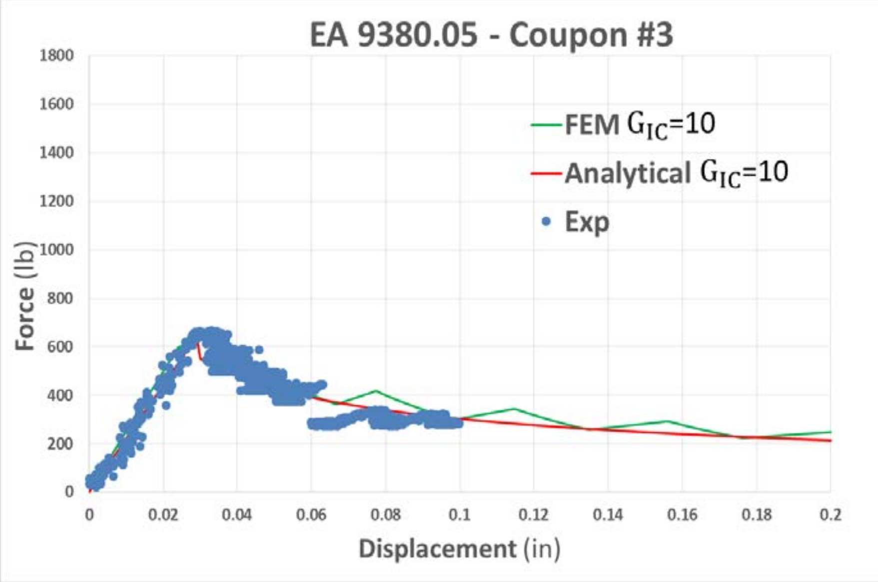

FM300-2 Coupon #2

Static Test on DCB (2coupons per Adhesive)





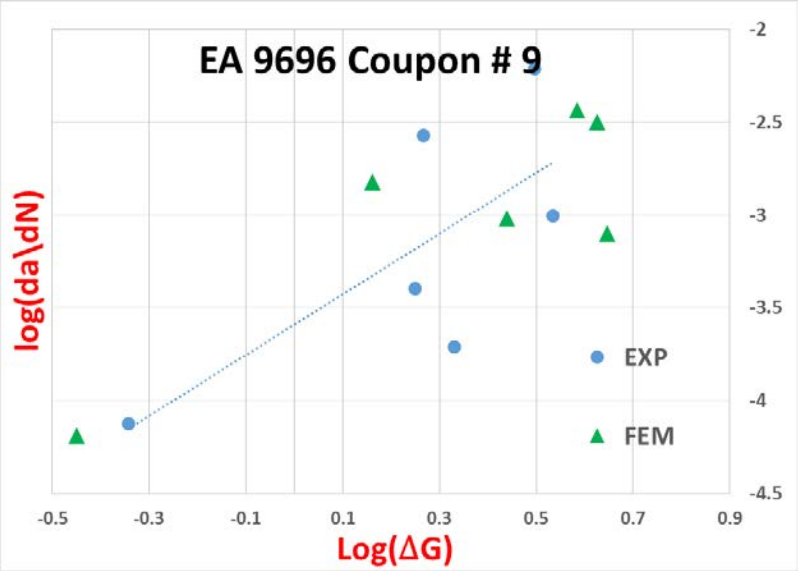


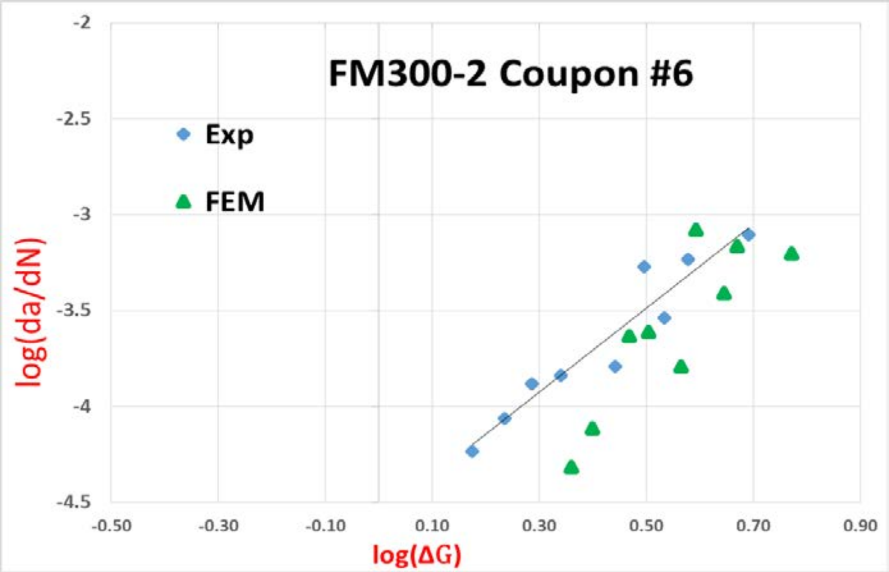


Fatigue Test on DCB – experiments and FEM models

- Paris law $\frac{da}{dN} = C\ G^{m}$

(da/dN-G) Plot	FM300-2	EA9696
EXP	C=3x10^{-5}, m=0.762	C=7x10^{-5}, m=1.0864





Time Dependence

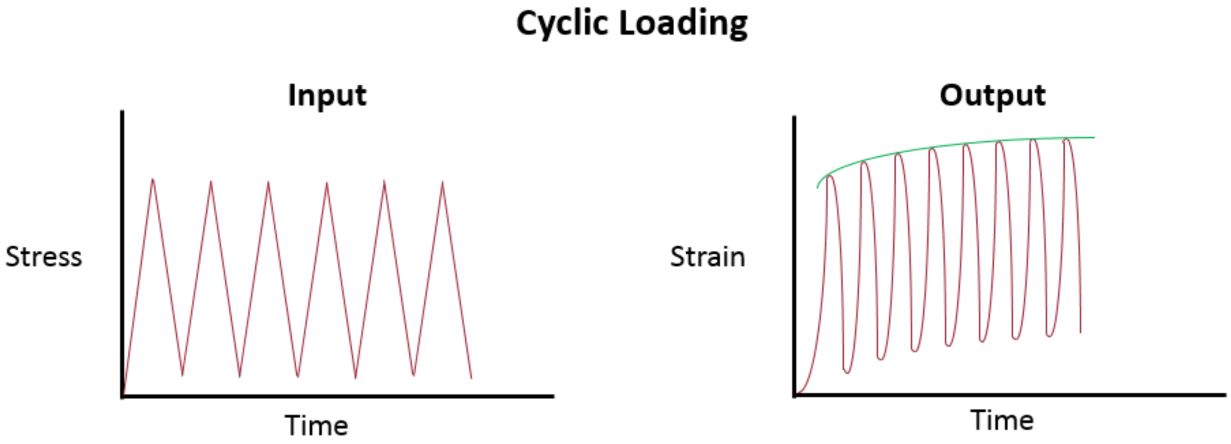
Aims:

- Influence of toughening agents
- Find nonlinear threshold.
- Determine how ratcheting behavior occurs under repeated loading.

Ratcheting: Increase in peak strain per cycle with repeated loading.

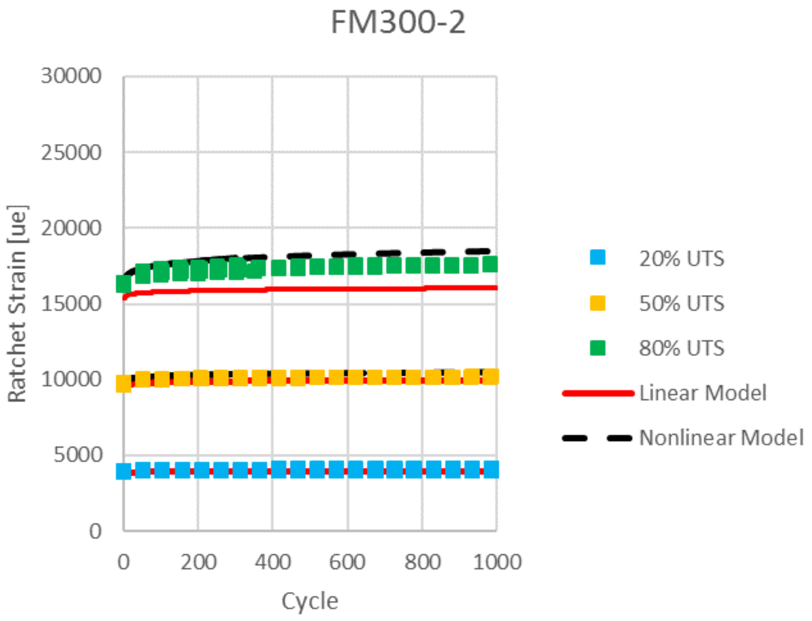
Approach:

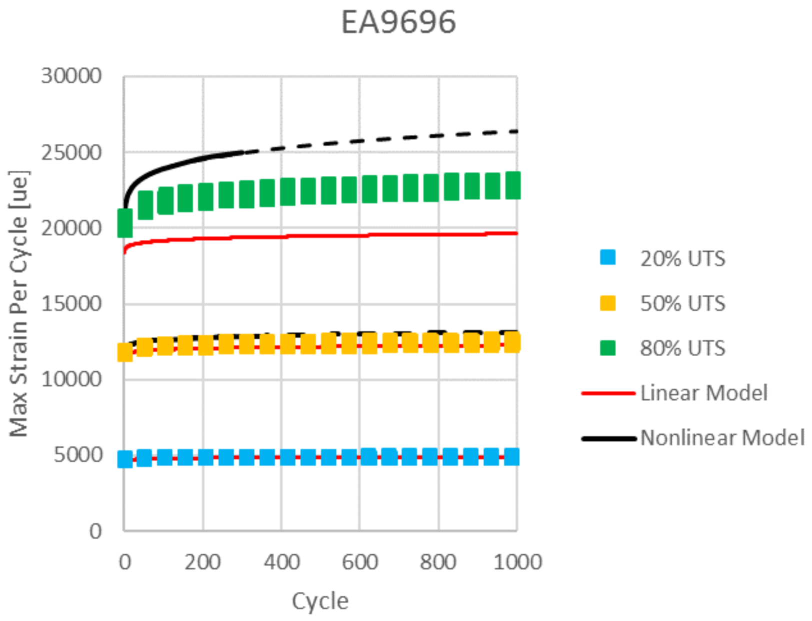
- Bulk adhesives
- Creep at different durations and stress levels.
- Fit response to linear and nonlinear viscoelastic models.
- Compare load response with linear model to find nonlinear and ratcheting thresholds and determine how nonlinear model predicts strain.



Nonlinear Ratcheting

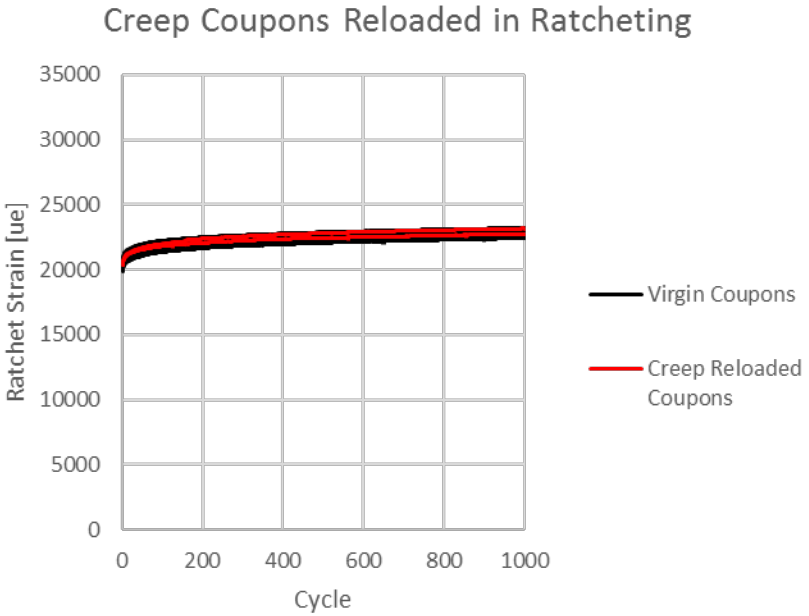
- Nonlinear viscoelastic model over predicts strain at high stress, while linear model under predicts strain.
- Why is nonlinearity higher in creep than ratcheting?

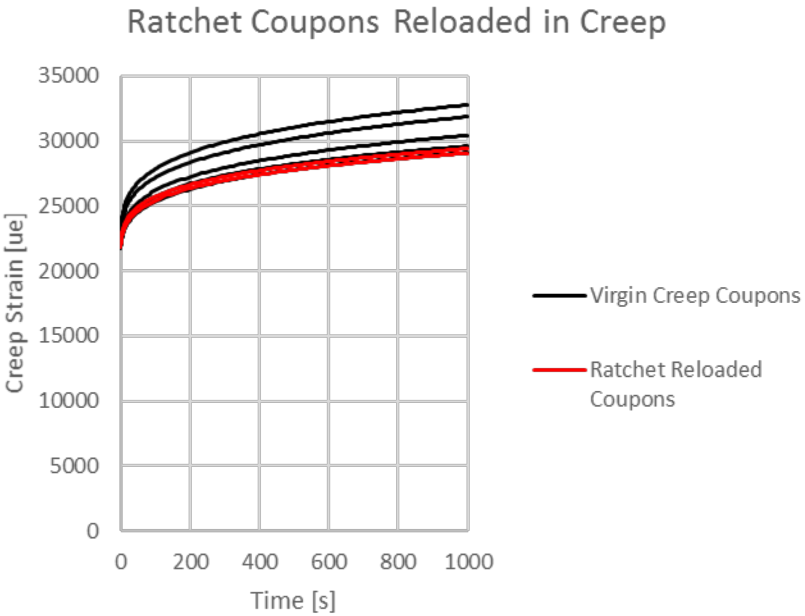




Reloading

- The difference in ratcheting is not due to variation in coupons but a difference in how the material behaves in static versus cycled loading.





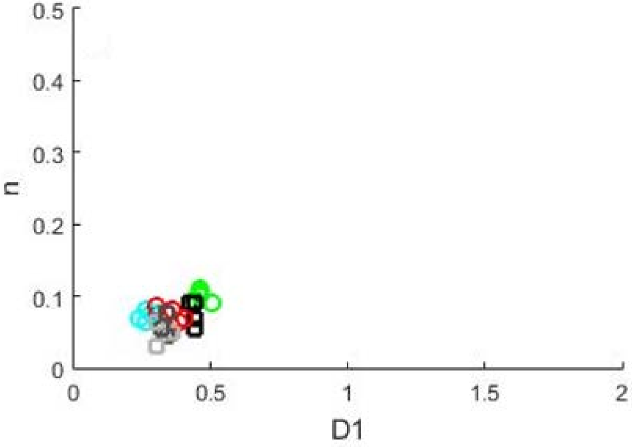
Power Law Model

Both creep and ratcheting were fit to a viscoelastic power law.

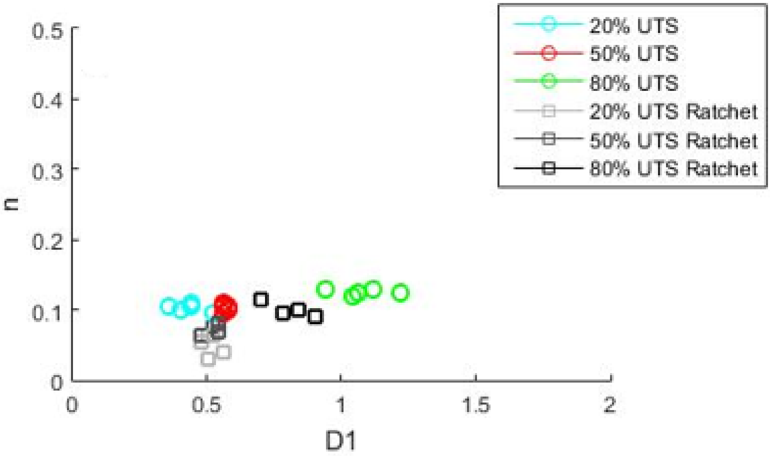
- Elastic compliance, D_0, was constant across all stress levels and for both creep and ratcheting.
- Creep and ratcheting showed a different time dependent response, shown by the coefficients D_1 and *n*, which was more significant in the toughened adhesive.

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

FM300-2



EA9696

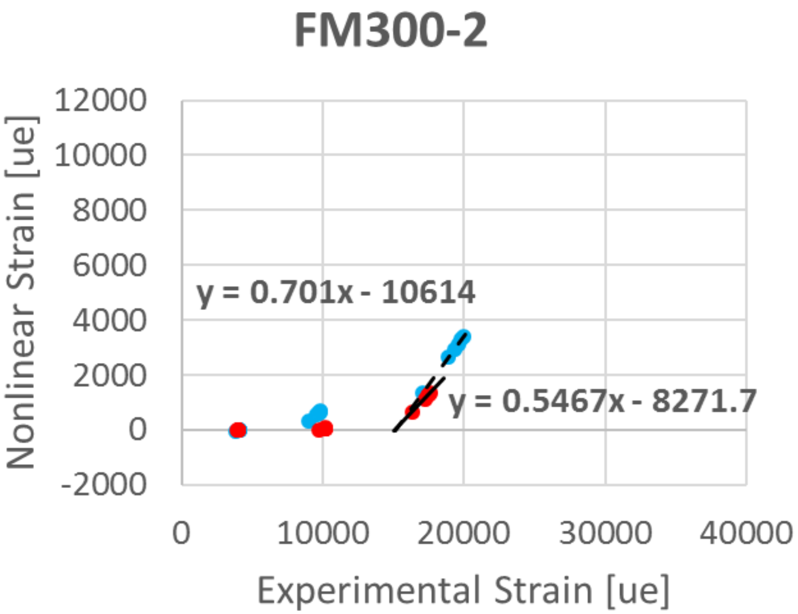


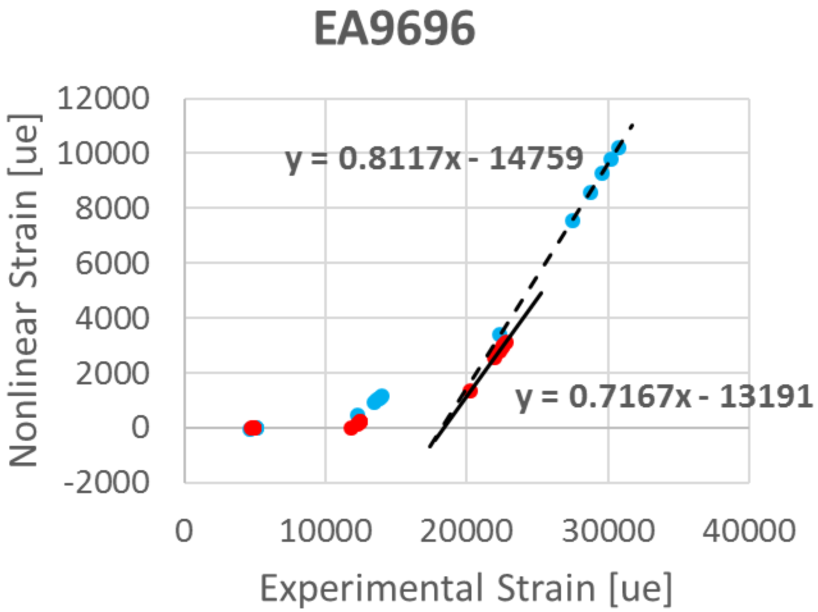
Nonlinear Strain

- Nonlinear strain was observed to increase linearly with total strain.
- Ratcheting had a smaller increase in nonlinear strain with total strain than creep
  - Why?

$$\varepsilon_{\text{nonlinear}} = \varepsilon_{\text{exp}} - \varepsilon_{\text{linear}}$$

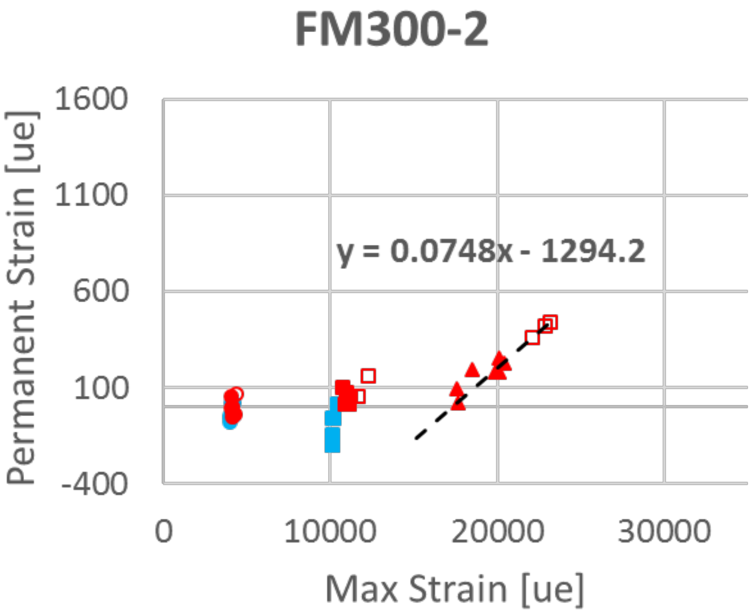
🟥 **Ratchet**
🟦 **Creep**

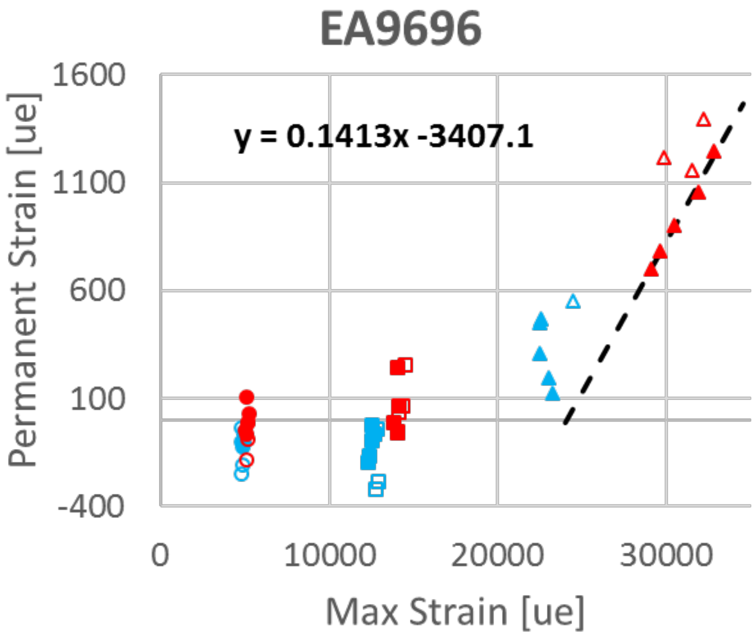




Permanent Strain

- The toughened adhesive showed significantly more permanent strain than the standard adhesive.
- Both adhesives showed lower permanent strain from ratcheting, and a linear relationship between permanent and total strain.





🟥 **Creep**
🟦 **Ratchet**

Schapery Nonlinear Model

A different approach to nonlinear viscoelasticity is being investigated.

Current Approach:

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

where F_1, F_1, and F_1 define the nonlinearity.

Schapery Approach, single integral with more nonlinear coefficients:

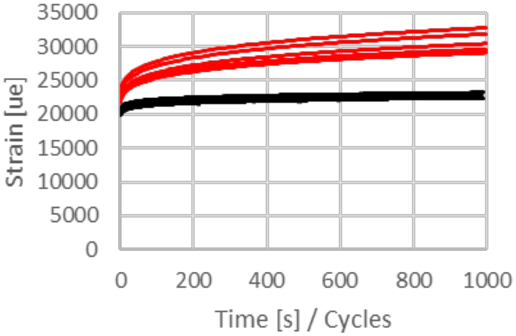
$$\varepsilon(t) = g_0 D_0 \sigma_0 + g_1 \int_0^t \Delta D(\varphi - \varphi') \frac{d(g_2\sigma_0)}{d\tau} d\tau$$

$$\varphi = \int_0^t \frac{dt'}{a_\sigma} \text{ and } \varphi' = \varphi(t) = \int_0^\tau \frac{dt'}{a_\sigma}$$

where g_0, g_1, g_2, and a_σ define the nonlinearity.

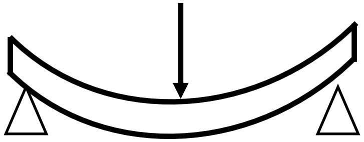
Viscoelastic Response in Shear

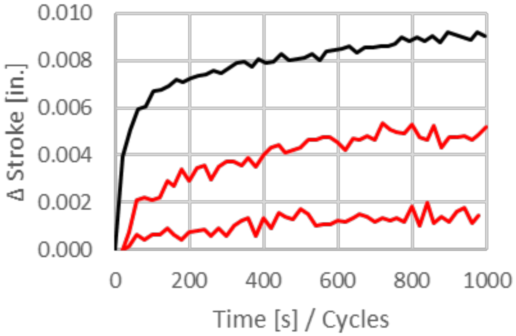
Bulk Tension



CECAM

End Notch Flexure (unnotched)





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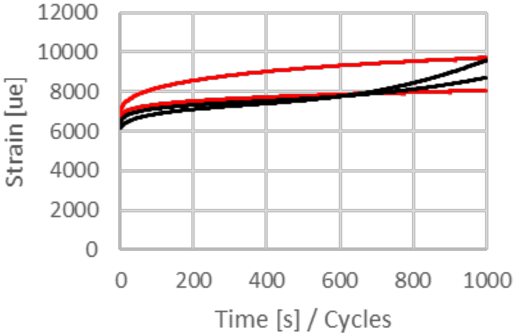
Wide Area Lap Shear



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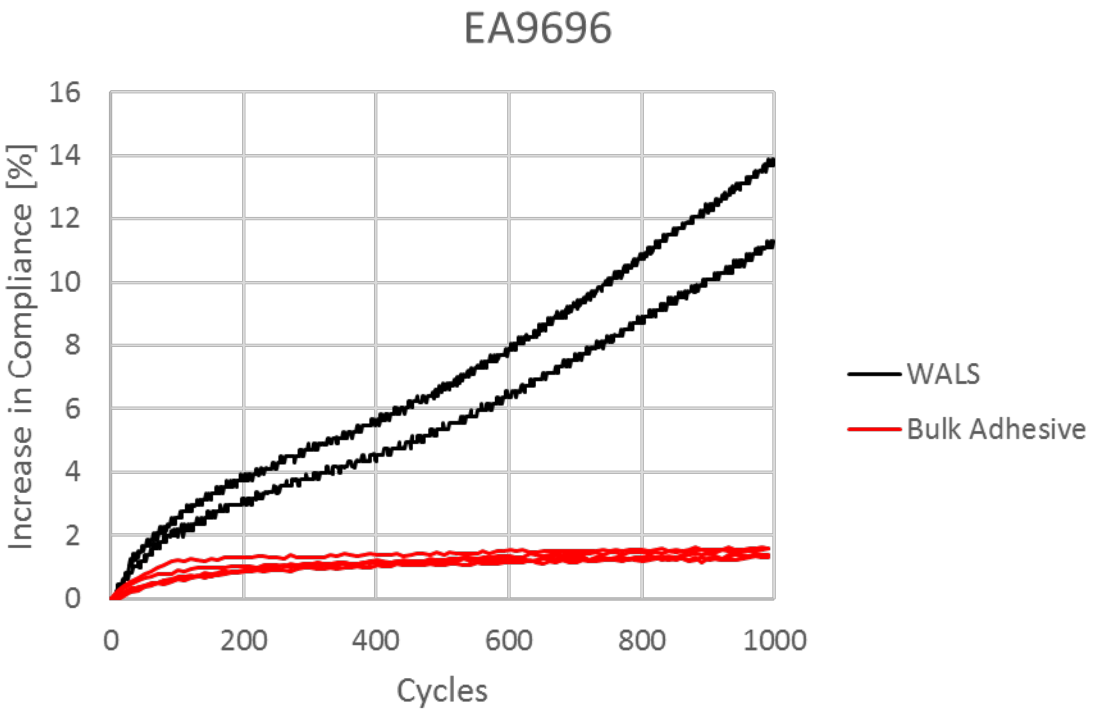
🟥 **Creep**
⬛ **Ratchet**

Viscoelastic Response in Shear

- Damage occurred in the WALS ratchet coupons while bulk resin coupons showed very little damage.



Observations

- G_{IC} tends to be a good indicator of fatigue performance
- Fatigue response depends more on adhesive toughness than bond thickness or temperature.
- Toughest adhesive (EA9696) did not have constant G_{IC}
  - Could not describe crack growth with linear fracture mechanics
- DCB crack growth followed Paris and were reproduced from FEA
- von Mises stress describes adhesive yield behavior
- Adherend void bridging increases plastic strain over bulk
- Adhesives tend to follow a kinematic hardening law
- Linear viscoelasticity under predicts ratchet strain while nonlinear model over predicts it.
- Nonlinear viscoelastic strain increased with total strain similar to permanent strain.
- Ratcheting in shear is more severe than bulk tension

Next Steps:

- Measure elastic and strength of EA 9380.05
- Static and Fatigue ENF simulation
- Consider a combined isotropic/kinematic hardening law
- Investigate ratcheting response in shear, numeric modelling
- Compare the nonlinear Schapery model with the triple integral model to determine if it fits the response in ratcheting better