Durability of bonded aerospace structure

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World Class. Face to Face.

Durability of Bonded Aircraft Structure

• Motivation and Key Issues:

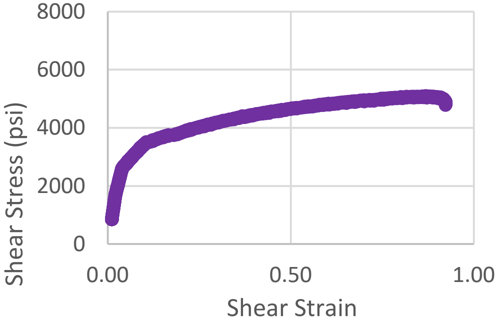
- Adhesive bonding is a key path towards reduced weight in aerospace structures.
- Certification requirements for bonded structures are not well defined.

• Objective

- Predict adhesive response in static and repeated loading
  - Stress components
  - Bulk vs. thin bonds
  - Adhesive toughness
  - Visco-elastic response in static and cyclic loading
  - Ratchetting in bulk tension and shear

• Approach

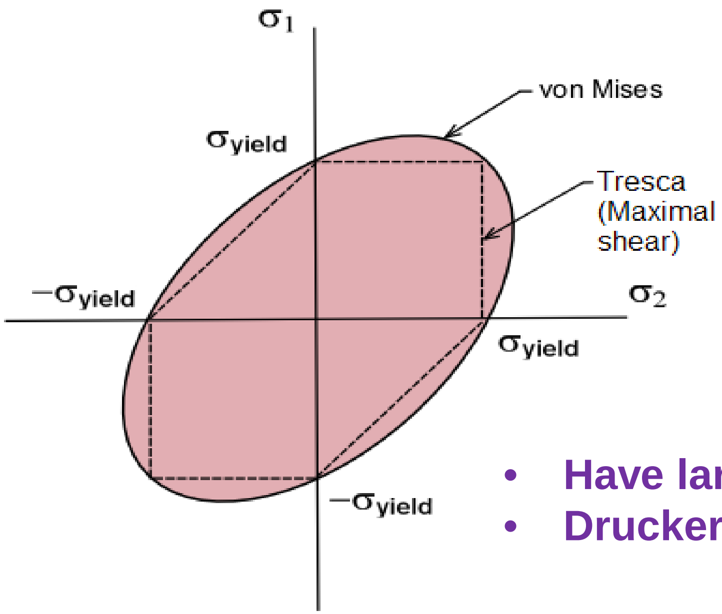
- Control stress state through coupon design
- Bulk adhesives and thin bonds, plasticity models
- Ratcheting, non-linear viscoelasticty



Durability of Bonded Aircraft Structure

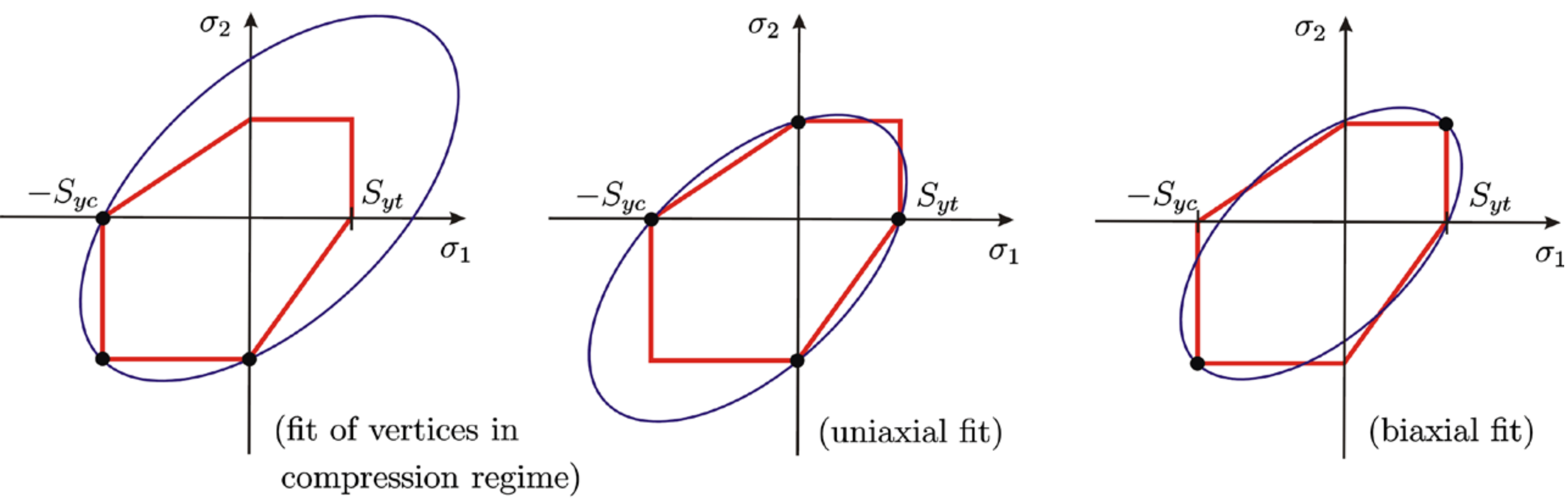
- Principal Investigators & Researchers
  - Lloyd Smith
  - Preetam Mohapatra, David Lemme, Reza Moheimani, Sayed Hafiz
- FAA Technical Monitor
  - David Westlund
- Other FAA Personnel Involved
  - Larry Ilcewicz
- Industry Participation
  - Boeing: Will Grace, Peter VanVoast, Kay Blohowiak

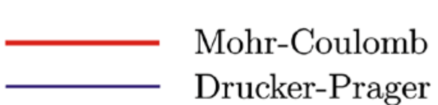
Existing plasticity model: yield criteria



- **Developed for metals**

- **Have largely been assumed to work for polymer materials**
- **Drucker-Prager considers only first quadrant**





- **Developed for concrete, soil and other porous material**

Existing plasticity model: yield criteria

1. Elastic-plastic yielding: Von Mises:

$$\sigma_y = \sqrt{3}\sigma_S = \sqrt{\frac{1}{2}[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2]}$$

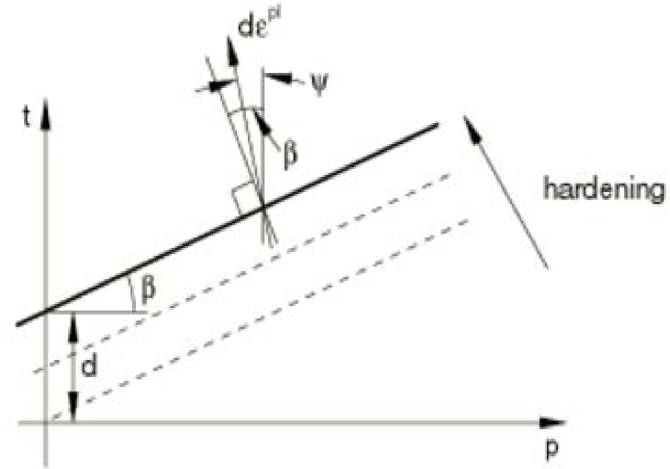
2. Elastic plastic yielding sensitive to Hydrostatic stress :

i. Linear Drucker Prager : $\sigma_y = t = \sqrt{3}\sigma_S - \mu p$

where; $\mu = 3\,(\frac{\sigma_C}{\sigma_T}-1)/(\frac{\sigma_C}{\sigma_T}+1)$

$$p = \frac{\sigma_1+\sigma_2+\sigma_3}{3}$$

When $p = 0$, $\sigma_y = t = \sqrt{3}\sigma_S$



ii. Modified linear Drucker Prager : $\frac{\sigma_y^2}{3\sigma_S^2} = \left(1-\frac{\mu p}{\sqrt{3}\sigma_S}\right)^2 + (q_1 f)^2 - 2q_1 f \cosh\frac{\sqrt{3}p}{2\sigma_S}$

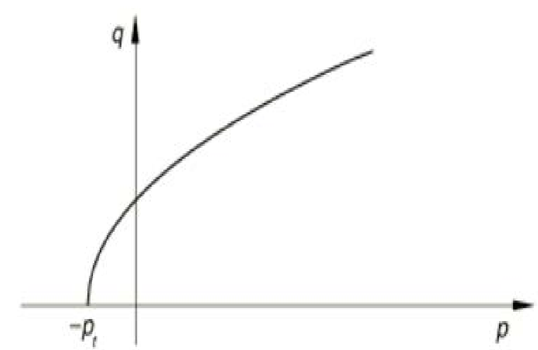
Where; q_1 = void interaction parameter

f = effective volume fraction of cavities,

when *f*= 0, $\sigma_y = t = \sqrt{3}\sigma_S - \mu p$

iii. Exponent Drucker Prager : $\sigma_y^b = q^b = \lambda\sigma_T^2 - 3(\lambda-1)\sigma_T p$

where; $\lambda = \frac{\sigma_C}{\sigma_T}$, *b=2*



Existing plasticity model: hardening rule

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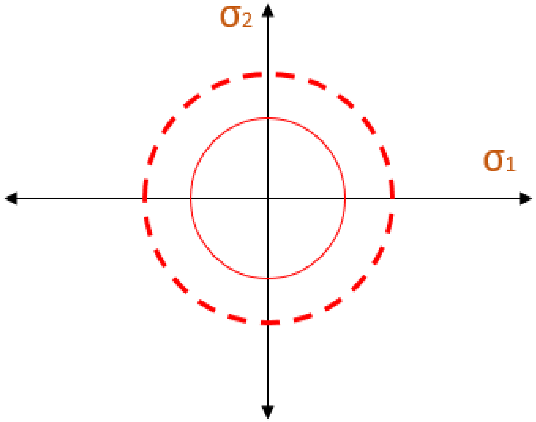
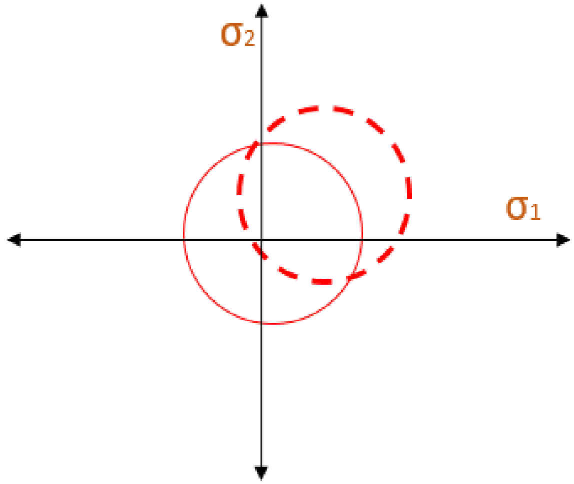
1. Nonlinear Isotropic hardening: (change in size)

- **Developed for metals with experimental characterization**
- **Often assumed for adhesives and polymers**
- **No significant effort on experimental characterization**



2. Nonlinear Kinematic hardening: (change in location)

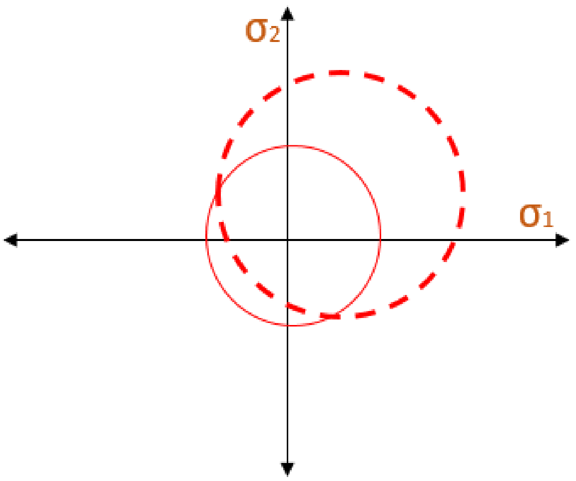
- **Used as linear form to avoid complexity**
- **FEA codes allow only von Mises criterion to be modeled**



Existing plasticity model: hardening rule

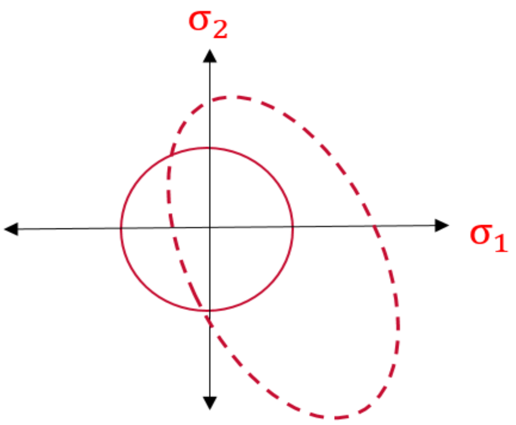
3. Nonlinear combined hardening: (change in size and location)

- **Developed for metals with experimental characterization**
- **Rarely used for polymers or adhesives**
- **Not included in commercial FEA codes**



4. Anisotropic hardening: (change in size, location and shape)

- **Developed for metal sheets with experimental characterization**
- **Never used for polymers or adhesives**



Existing plasticity model: input

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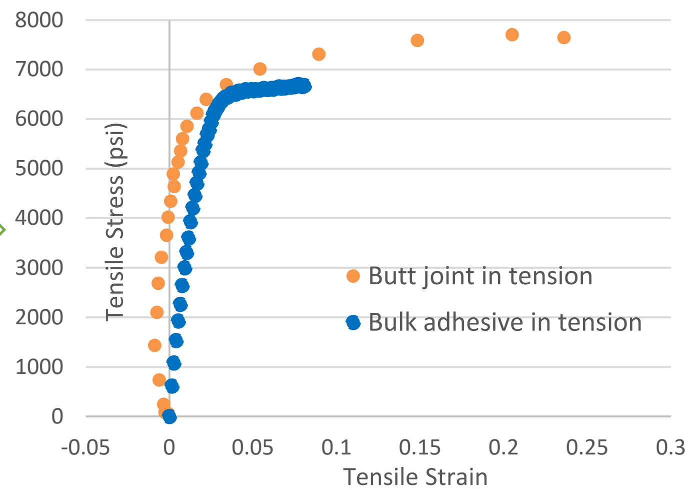
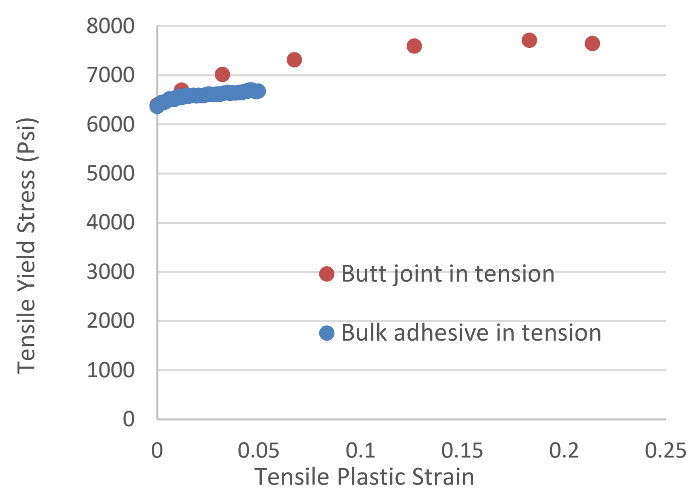
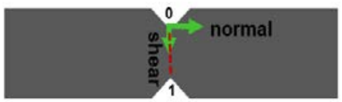
Tensile Input: material model

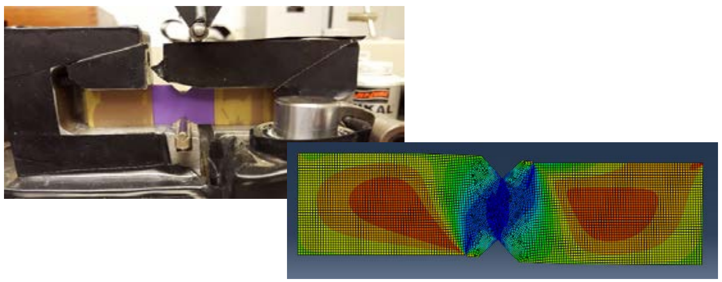


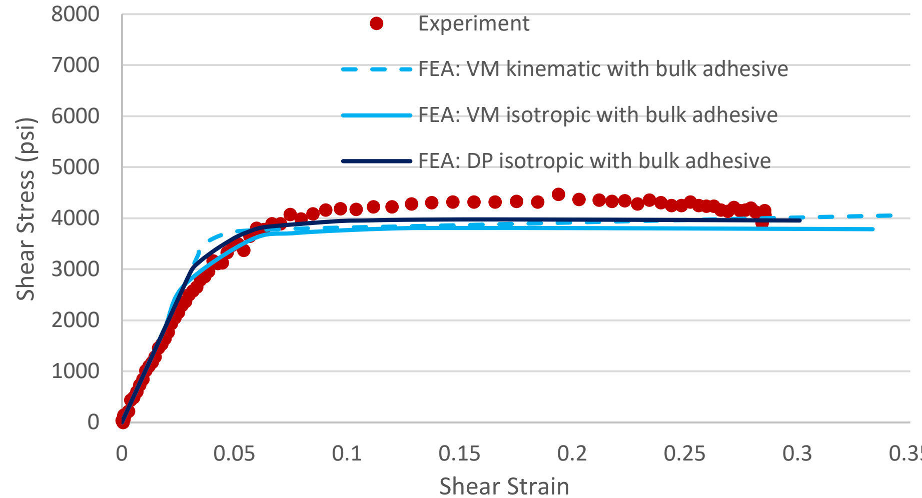


Existing plasticity model: prediction

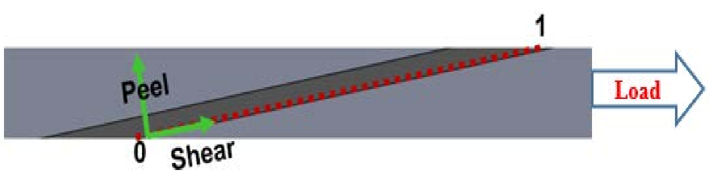
FEA Prediction:
bulk adhesive in shear

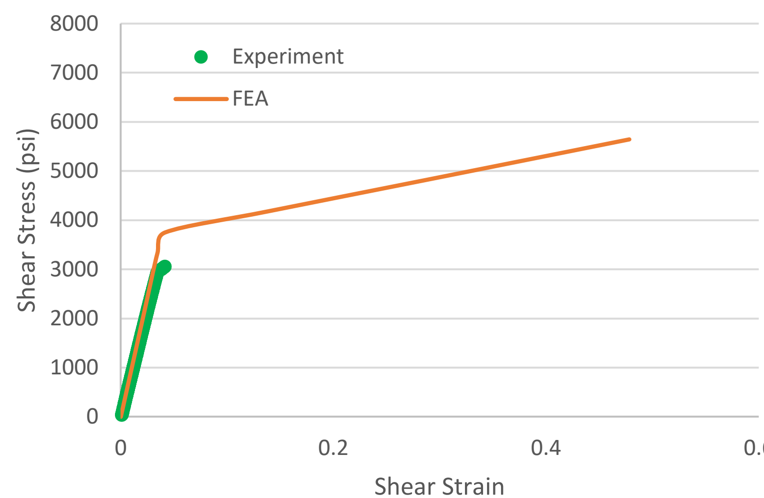






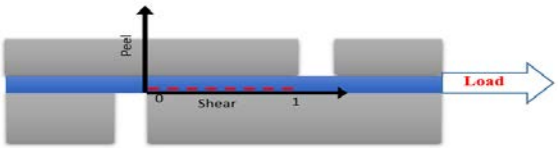
FEA Prediction:
Scarf joint (pure shear)

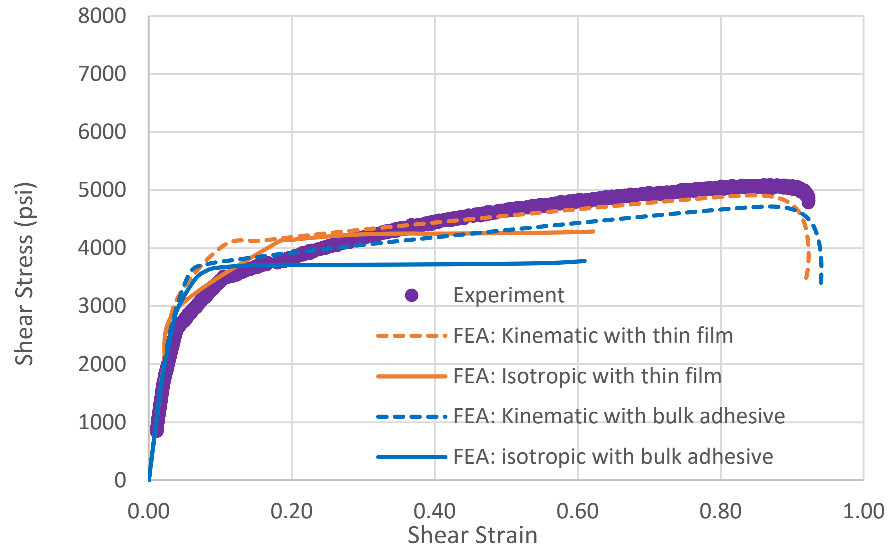




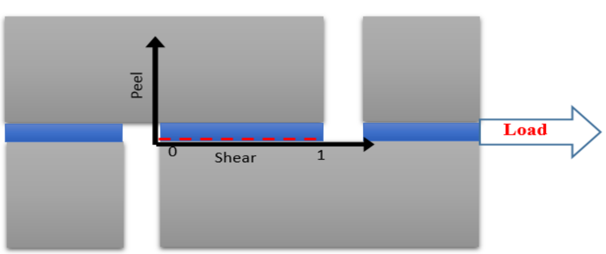
Existing plasticity model: prediction

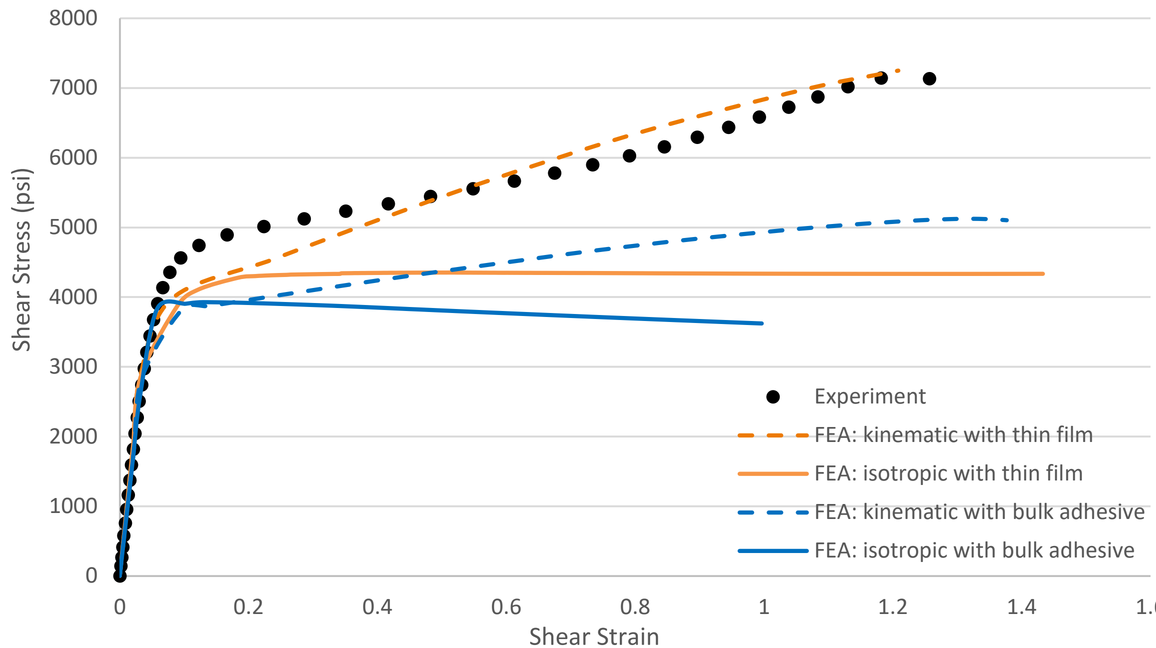
FEA Prediction:
Single lap shear
(compliant joint)



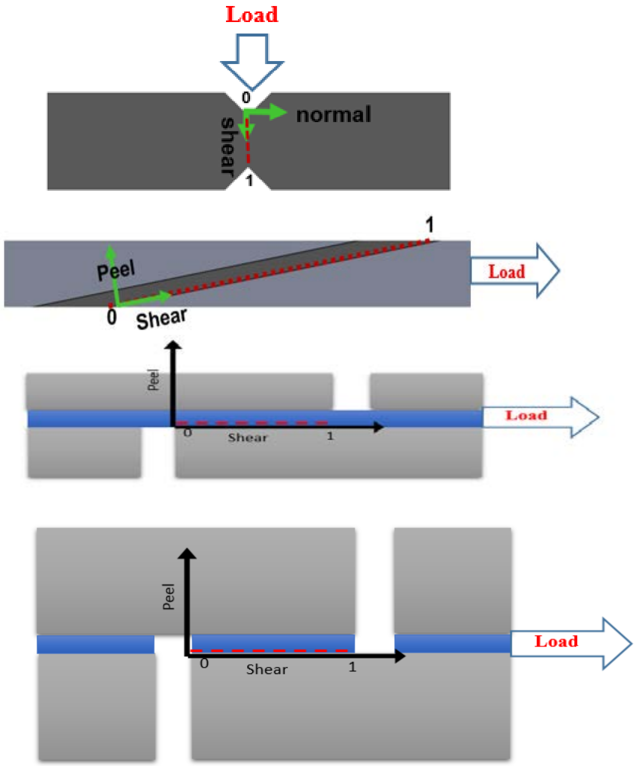


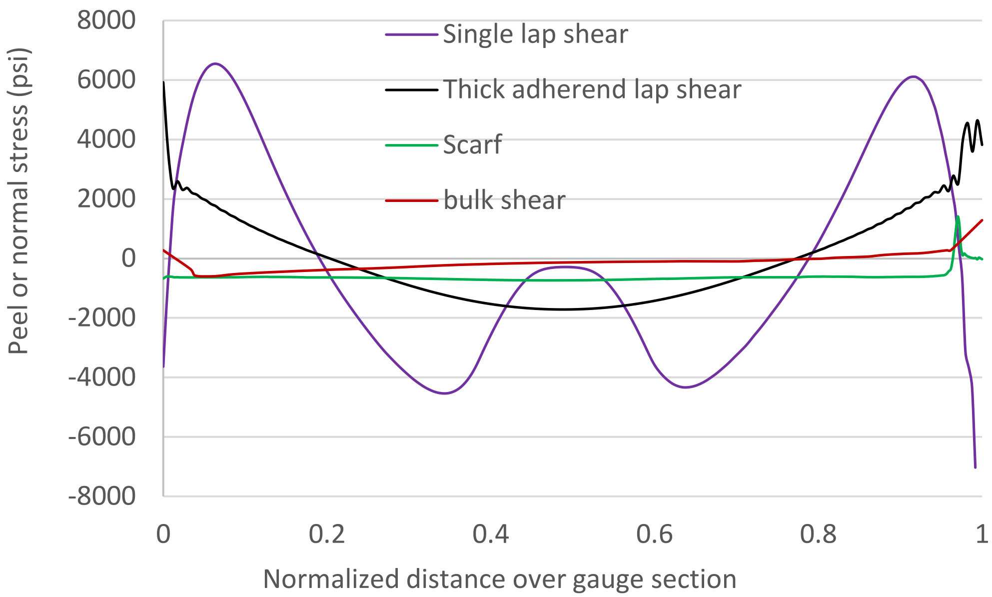
FEA Prediction:
Thick adherend lap shear
(stiff joint)





Existing plasticity model: peel stress analogy



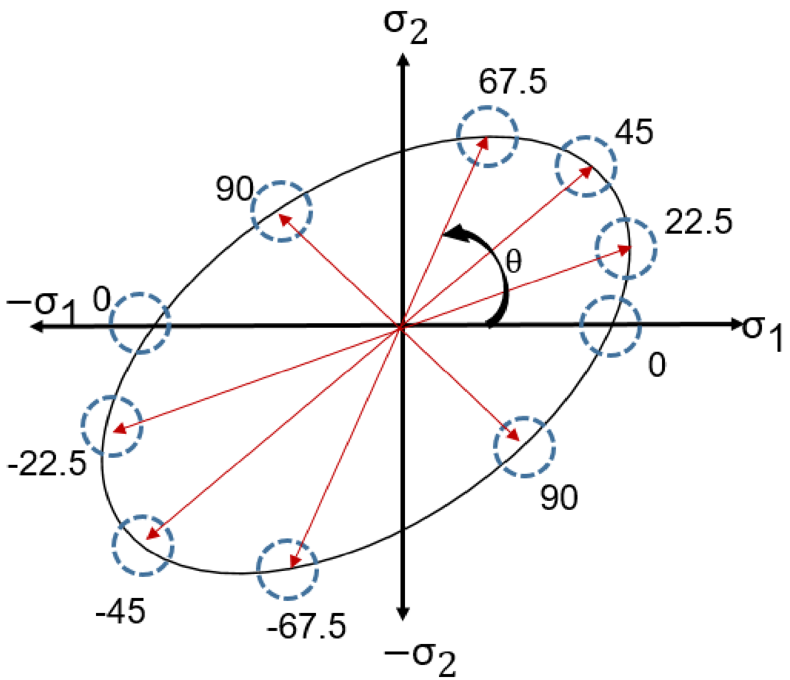


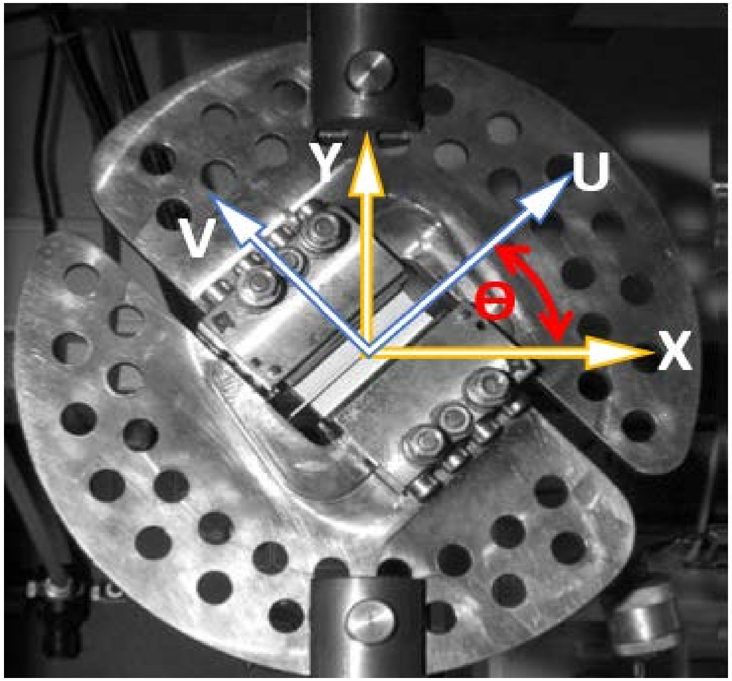
Advanced plasticity model: requirement

1. Dedicated user-defined plasticity model
2. Combined hardening input possible (isotropic + kinematic)
3. Combined hardening can be incorporated with pressure sensitive (Drucker Prager) or deviatoric (von Mises) criterion
4. Experimentally determined yield surface and its movement in biaxial stress space. (NO assumption)

Advanced plasticity model: yield criteria

- Need to determine initial and final yield stress
- Measure difference in compressive shear and tensile shear





- + : tension
- - : compression

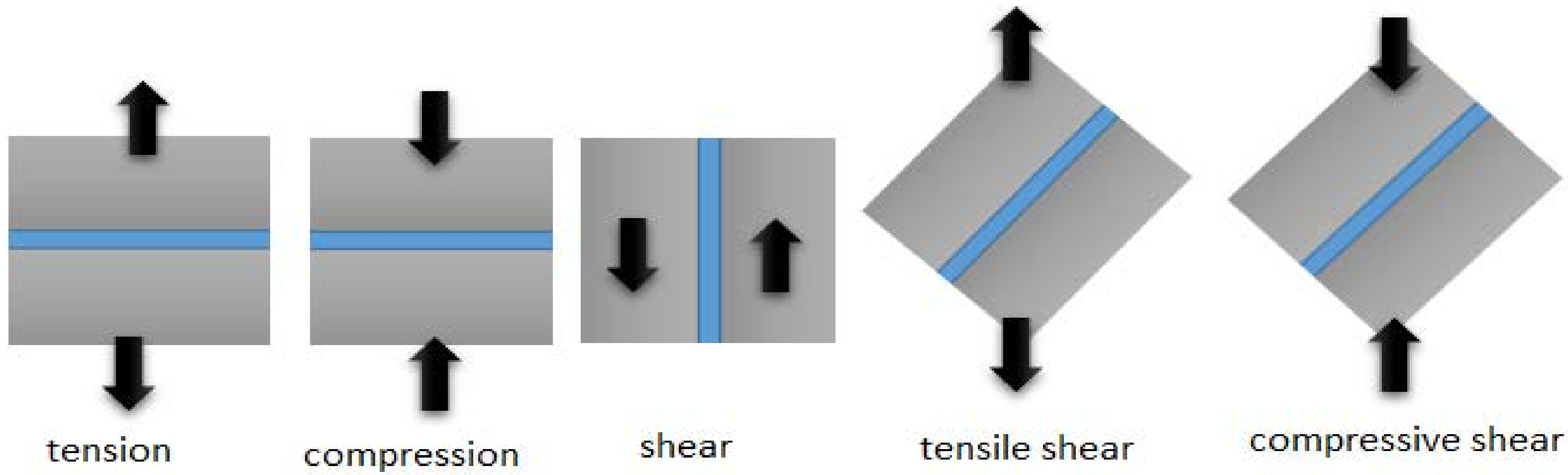
$$\sigma_U = \sigma_Y (\sin\theta)^2$$

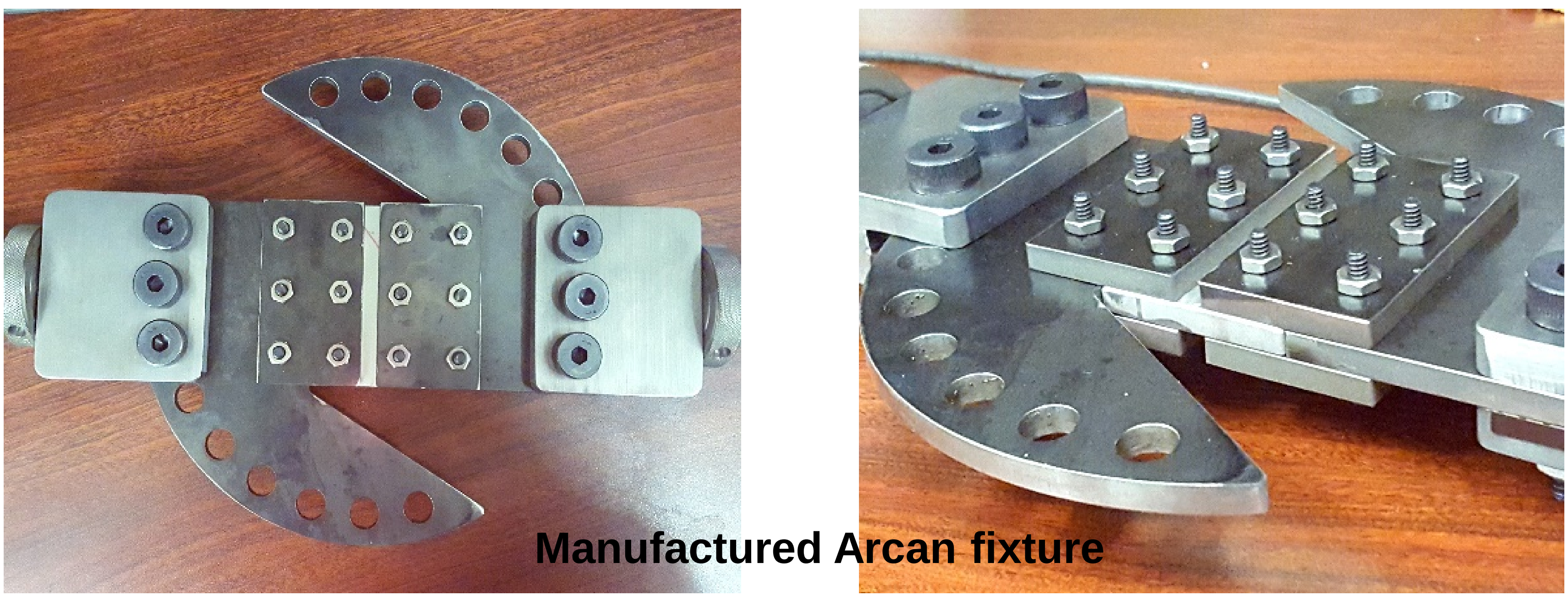
$$\sigma_V = \sigma_Y (\cos\theta)^2$$

Configuration to be tested

- θ=0 : pure tension and compression
- θ =90 : pure shear
- 0<θ<90 : mixed mode (tensile and compressive)

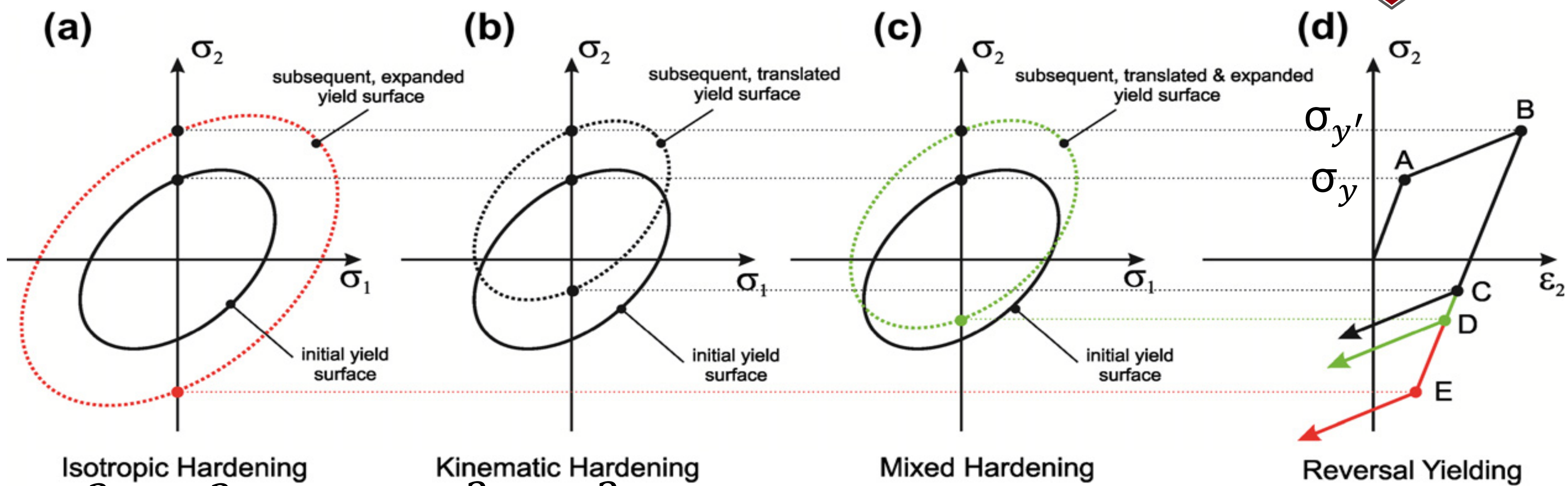
Advanced plasticity model: yield criteria





Manufactured Arcan fixture

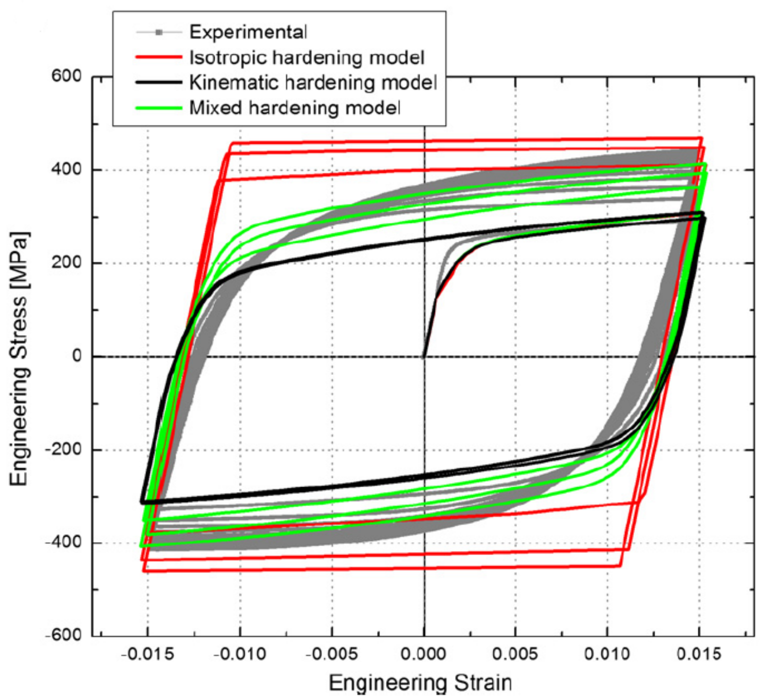
Advanced plasticity model: hardening rule



$2\sigma_i = 2\sigma_{y'}$

$2\sigma_y = 2\sigma_i$

$2\sigma_y < 2\sigma_i < 2\sigma_{y'}$

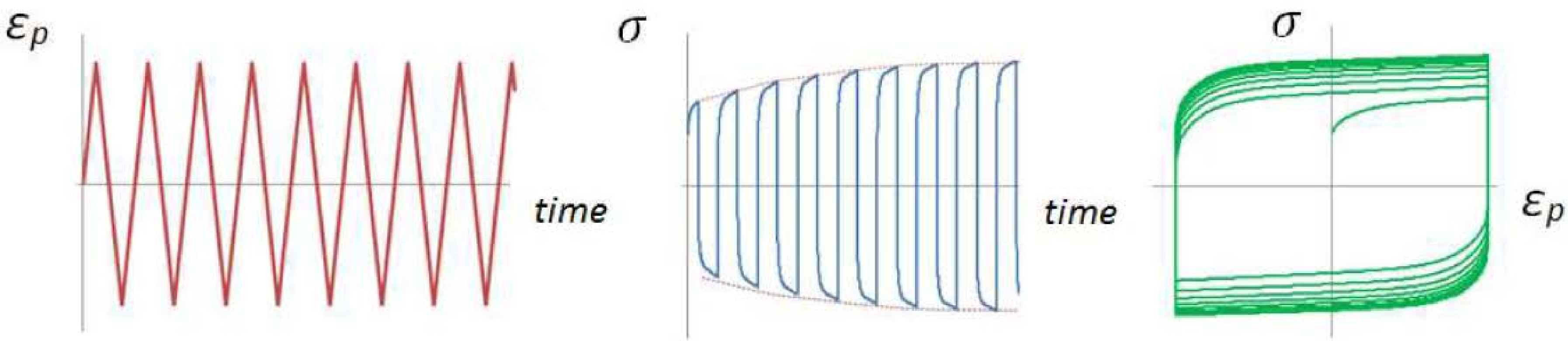


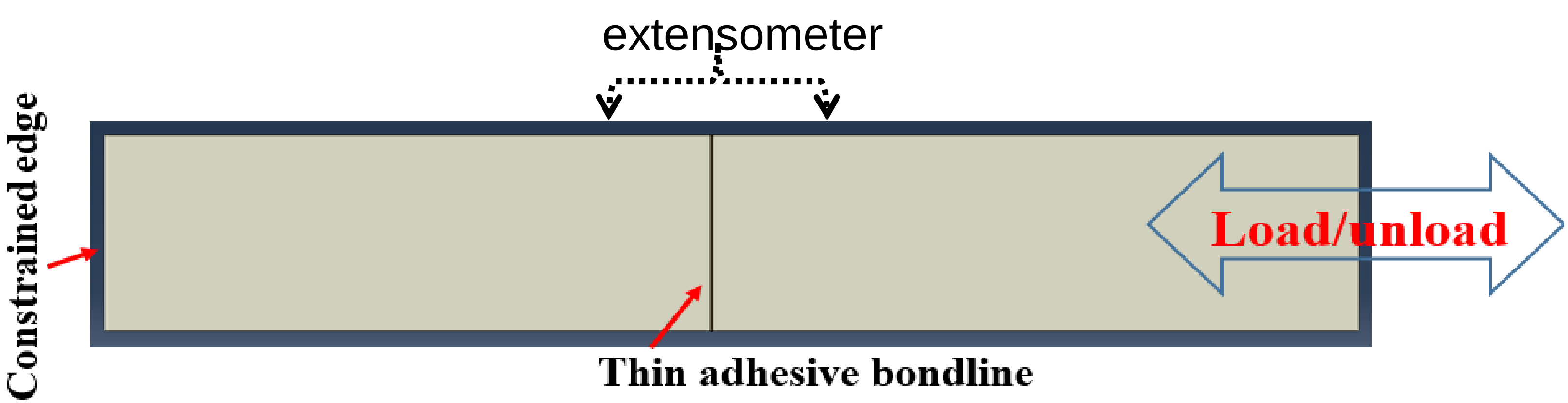
- Common procedure for experimental characterization of hardening in steel
  - Muransky O. *et al.* “The effect of plasticity theory on predicted residual stress fields in numerical weld analyses”

Advanced plasticity model: hardening rule

Example of hardening

- Input: Strain cycles
- Output: Stress cycles



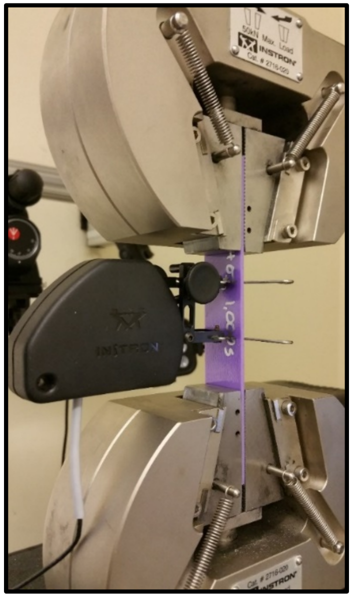


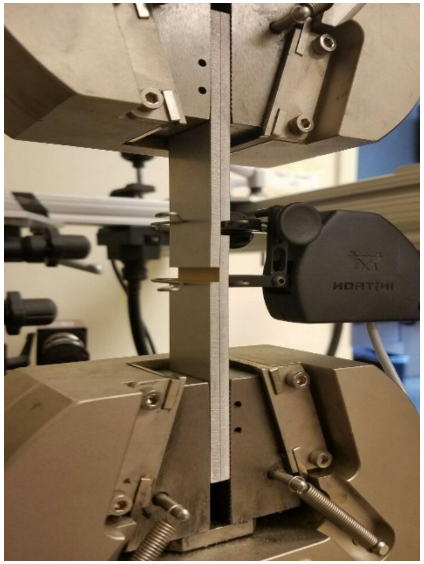
- Extensometer with transfer function
- 0.5 Hz for cyclic testing. Low frequency ~ quasi static

Time Dependence

Aims:
- Influence of toughening agents
- Nonlinear threshold
- Ratcheting behavior

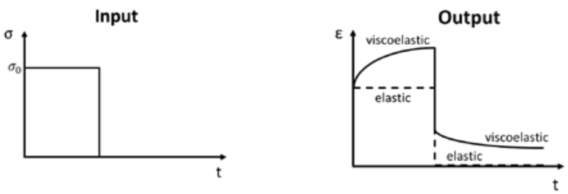
Approach:
- Bulk (tension) and film (shear)
- Durations and stress level
- Linear and nonlinear viscoelastic models.
- Creep and repeated loading



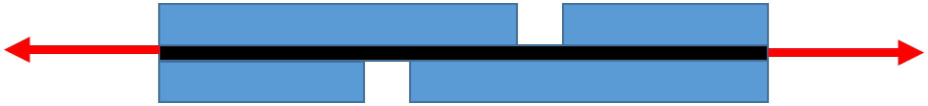


Approach

1. **Creep:** Static creep tests at 20%, 50%, and 80% of the ultimate shear strength.



2. **Cycled Ramp Loading:** Cycled loading tests at 20%, 50%, and 80% of the ultimate shear strength.



Wide Area Lap Shear (WALS) – ASTM D3165

	Stress [% Ultimate Shear Strength]		
	20%	50%	80%
1,000 second / cycle	5 coupons	5 coupons	5 coupons

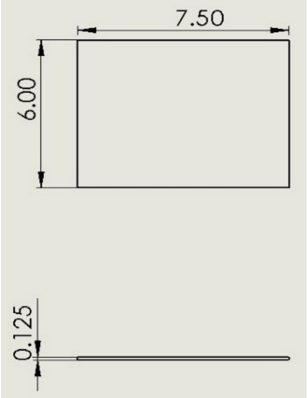
Adhesive	Ultimate **Shear** Strength [psi]
Toughened- EA 9696	5300
Standard – FM300-2	4500

Adhesive	Ultimate **Tensile** Strength [psi]
Toughened	6500
Standard	8300

Methods

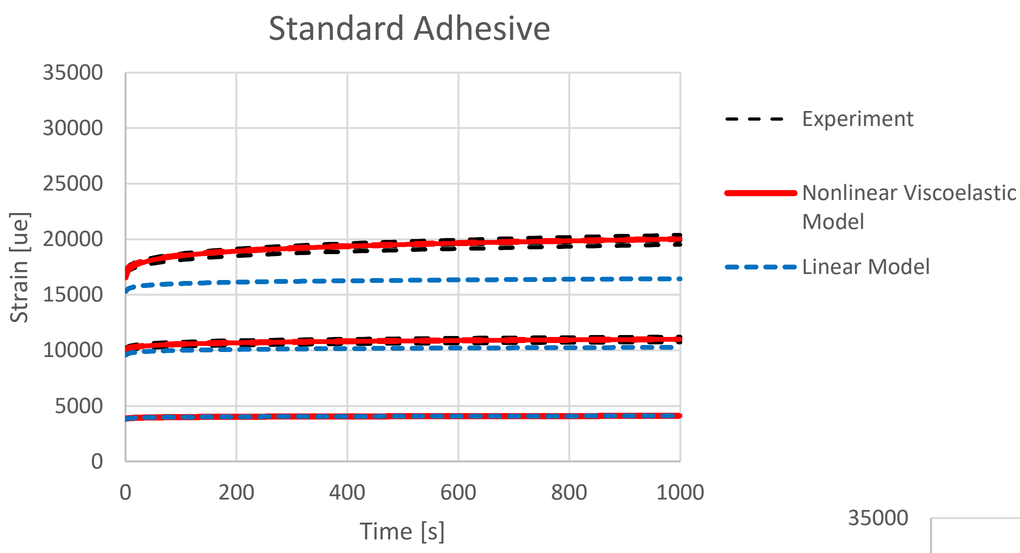
Coupon Fabrication

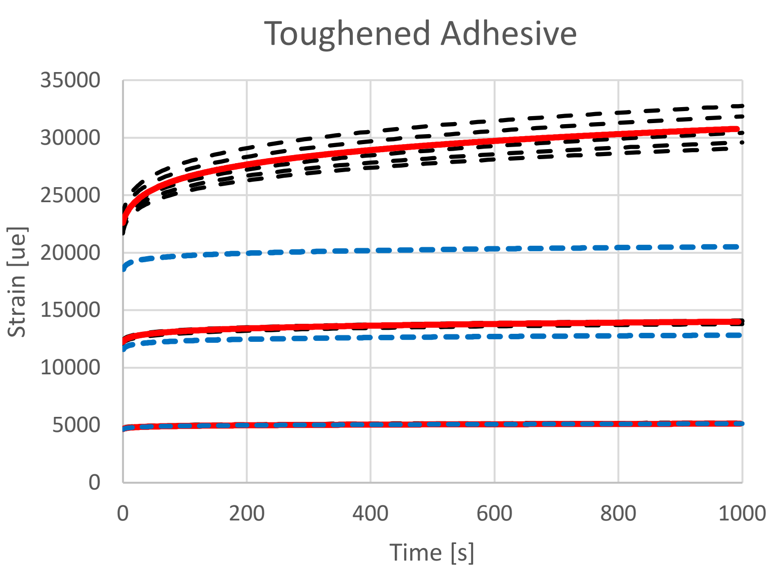
- Two film adhesives were used, came as a roll of material approximately 0.010 inches thick.
- one layers of the film were used to create WALS coupons.
- Aluminum plates with 0.010 shims were used to control thickness and released with Frekote 770NC
- Coupons were vacuum bagged and cured in an autoclave at 250 °F.
- After curing, the plate was waterjet in to four, 1 inch wide by 6 inch long



Nonlinear Creep

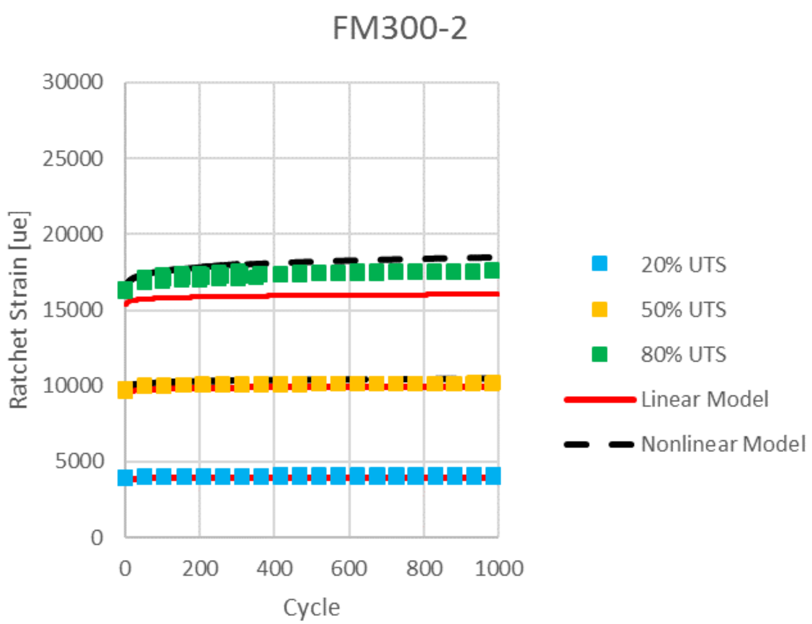
Good agreement under creep

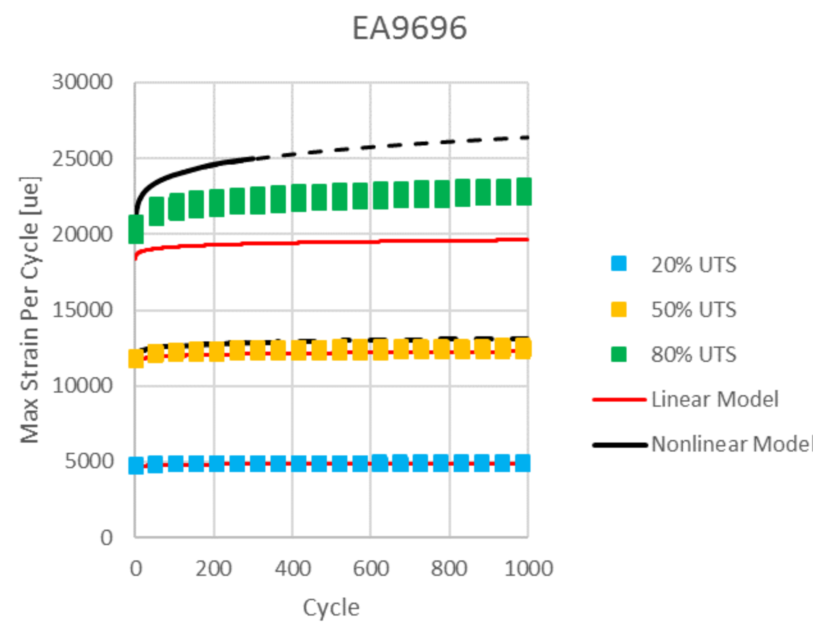




Nonlinear Ratcheting

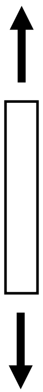
- Nonlinear viscoelastic model over predicts strain at high stress, while linear model under predicts strain.
- Why is nonlinearity higher in creep than ratcheting?

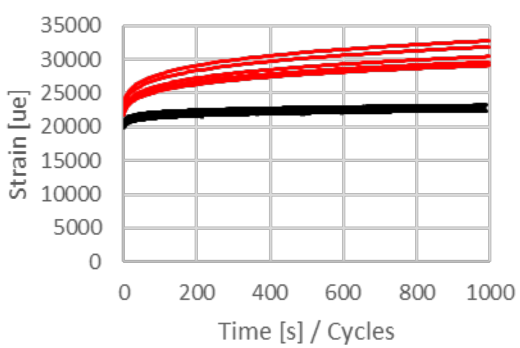




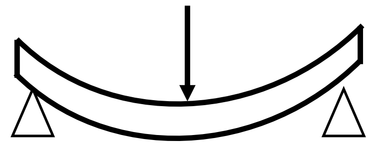
Viscoelastic Response in Shear

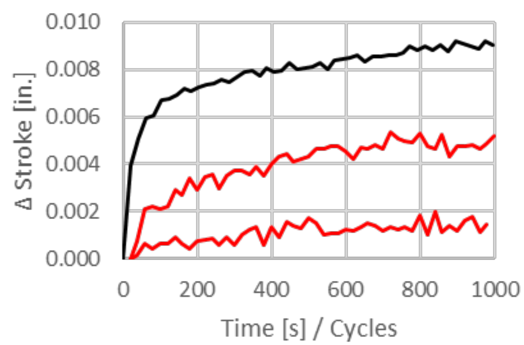
Bulk Tension



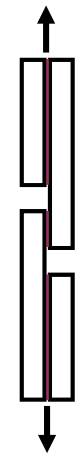


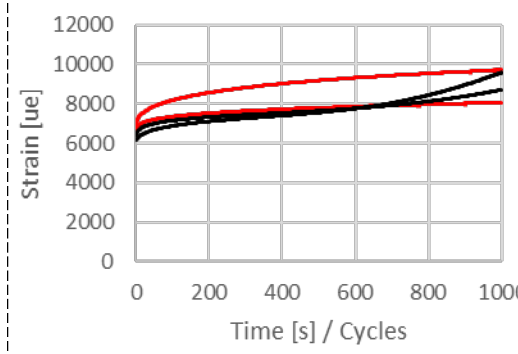
End Notch Flexure
(unnotched)





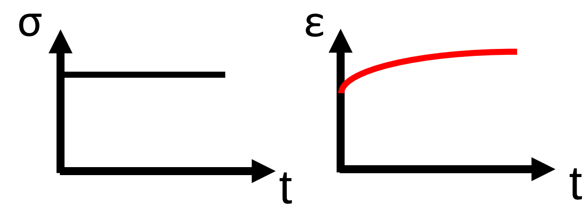
Wide Area Lap Shear





Creep
Ratchet

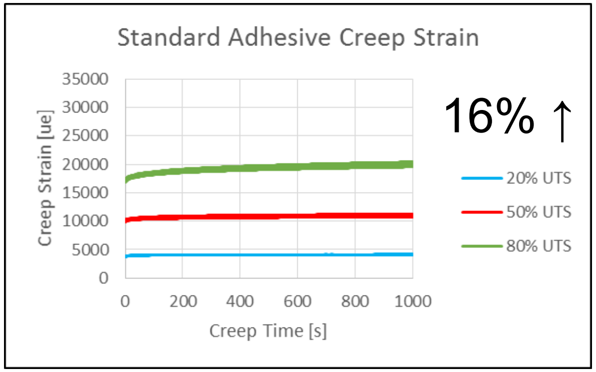
Results



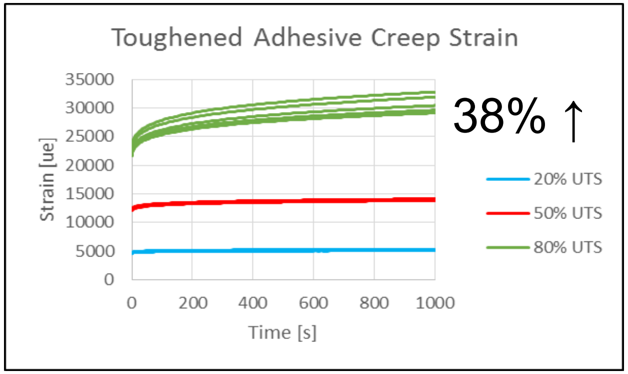
Creep Tests

- The toughened adhesive had higher elastic and viscoelastic strain.
- Both adhesives appeared to behave nonlinear both in the elastic response and the viscoelastic response.
- Large variation in the response between coupons occurred at 80% UTS
- Increase of creep strain for bulk tension is higher than in joints in shear

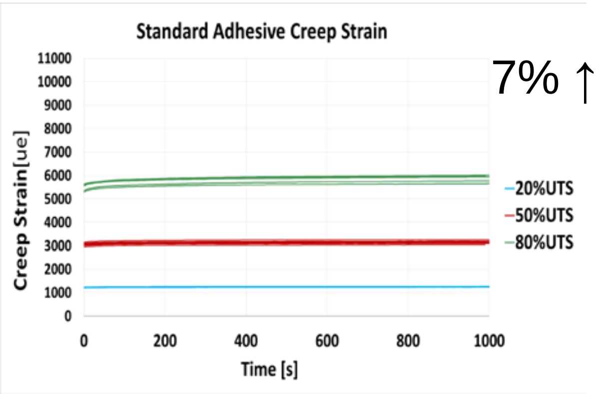
Bulk Resin



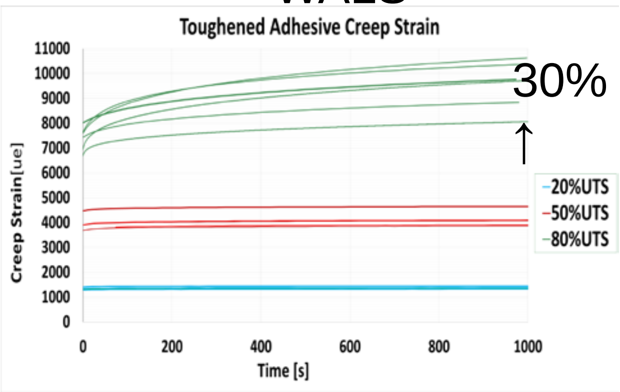
Bulk Resin



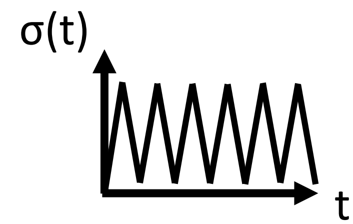
WALS

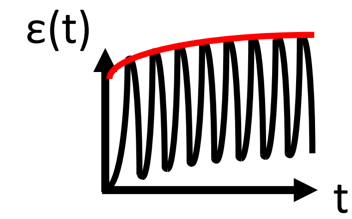


WALS



Results

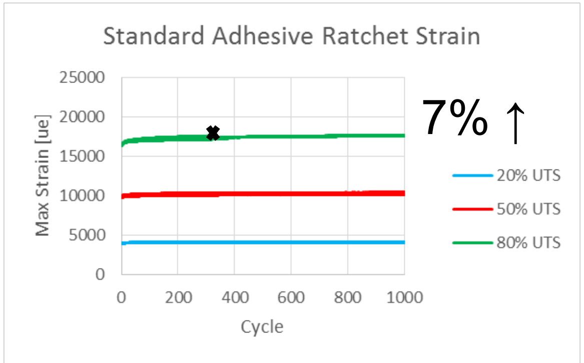




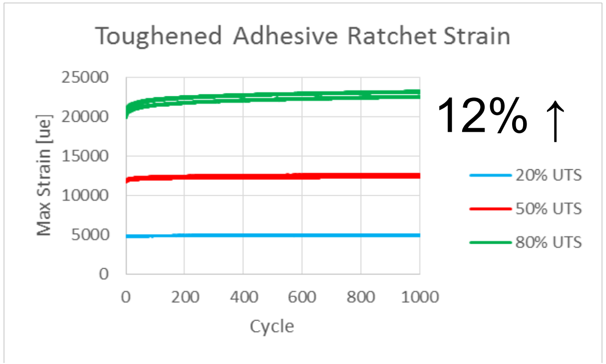
Cycled Loading

- Testing done at 0.5 Hertz. Ratchet tests cycle the load between a set maximum and ten percent (load ratio of 0.1)
- Ratchet strain was lower than creep strain.
- Both adhesives showed linear response in ratcheting at 20% and 50% UTS and a nonlinear response at 80% UTS.
- At 80%UTS of WALS, the ratcheting increases quickly, and the failure of the material is controlled by the increasing ratcheting strain.(All coupons failed for standard adhesive)

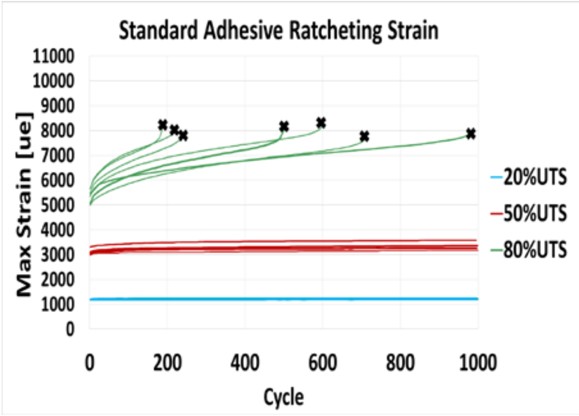
Bulk Resin



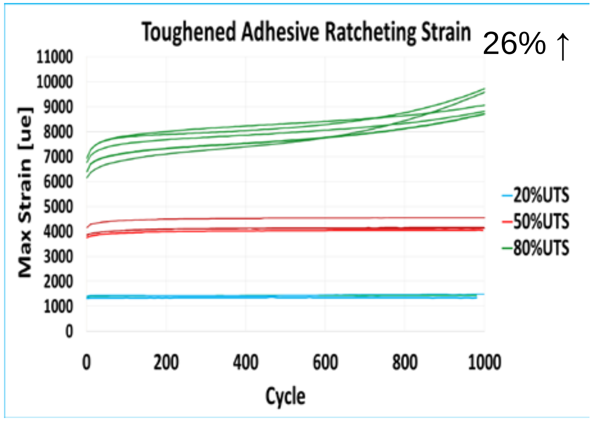
Bulk Resin



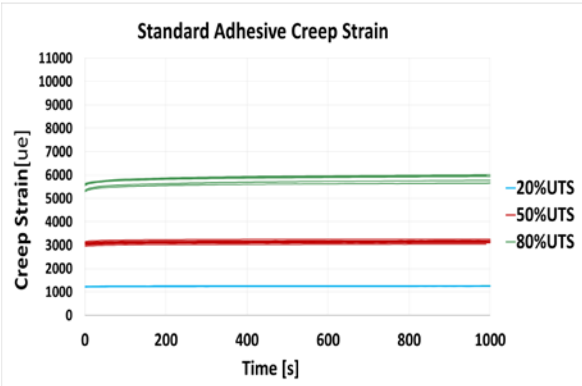
WALS

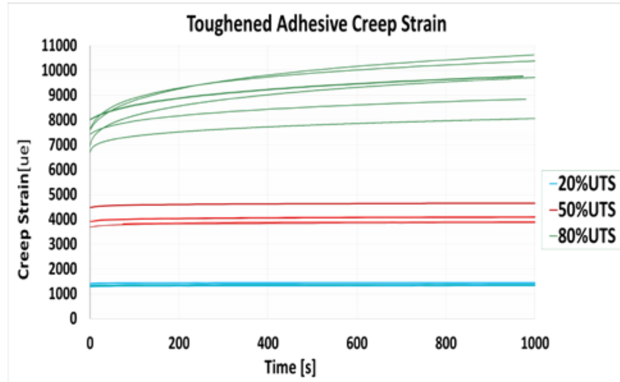


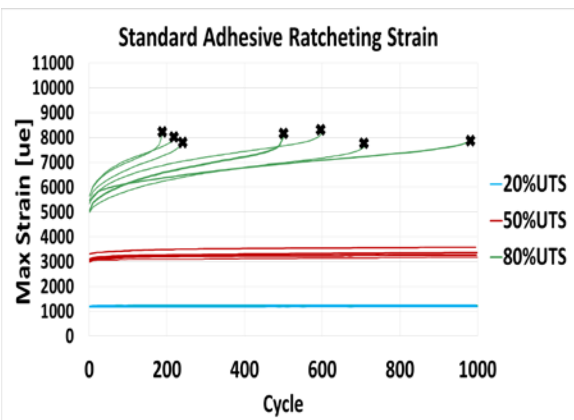
WALS

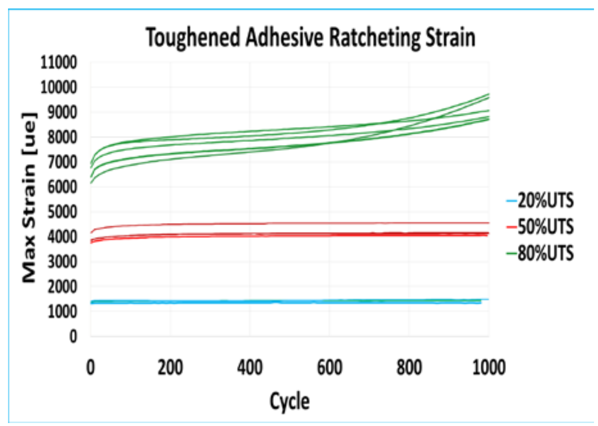


Creep vs. Ratcheting









Observations

- von Mises stress and Drucker-Prager describe adhesive yield behavior
- Adherend void bridging increases plastic strain over bulk
- Adhesives tend to follow a kinematic hardening law
- In tension linear viscoelasticity under predicts ratchet strain while nonlinear viscoelasticity over predicts it.
- Ratcheting in shear is more severe than bulk tension

Next Steps:

- Examine yield criteria by testing adhesive joints in biaxial stress
- Examine hardening law through tension/compression of adhesive joints
- Investigate ratcheting response in shear
  - Complete test matrix of joints in shear and tension with four adhesives
- Compare adhesive damage from tension and shear loading
- FEA model of mixed-mode tension-shear in adhesive joint
- Consider alternative non-linear visco-elastic models
- Identify adhesives with shear toughness

			Bulk				Bonded Joint																		
			Tension			Shear	Tension				Shear									Mixed					
	Adhesive	Test	Neat Resin			Iosepescu	Butt Joint			DCB	Scarf			ENF			KGR			WALS			Arcan		
Film	EA9696	Static	3/3			4/4	5/5										Boeing						0/56		
Film	EA9696	Fatigue					0/10										0/10								
Film	EA9696	Creep	5/5	5/5	5/5		0/5	0/5	0/5		0/5	0/5	0/5	0/5	0/5	2/5	0/5	0/5	0/5	5/5	5/5	5/5			
Film	EA9696	Ratchet	5/5	5/5	5/5		0/5	0/5	0/5		0/5	0/5	0/5	0/5	0/5	2/5	0/5	0/5	0/5	5/5	5/5	5/5			
Film	FM300-2	Static	3/3			0/4	0/5										0/5						0/56		
Film	FM300-2	Fatigue					0/10										0/10								
Film	FM300-2	Creep	5/5	5/5	5/5		0/5	0/5	0/5		0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5	5/5	5/5	5/5			
Film	FM300-2	Ratchet	5/5	5/5	5/5		0/5	0/5	0/5		0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5	5/5	5/5	5/5			
Paste	EA9394	Static	3/3			0/4	0/5										0/5						0/56		
Paste	EA9394	Fatigue					0/10										0/10								
Paste	EA9394	Creep	5/5	5/5	2/5		0/5	0/5	0/5		0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5			
Paste	EA9394	Ratchet	5/5	5/5	2/5		0/5	0/5	0/5		0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5			
Paste	EA9380.05	Static	0/3			0/4	0/5										0/5						0/56		
Paste	EA9380.05	Fatigue					0/10										0/10								
Paste	EA9380.05	Creep	1/5	1/5	5/5		0/5	0/5	0/5		0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5			
Paste	EA9380.05	Ratchet	0/5	0/5	0/5		0/5	0/5	0/5		0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5	0/5			

Complete
Potential
In Progress

Type of plates
AL-2024-T3 Bare