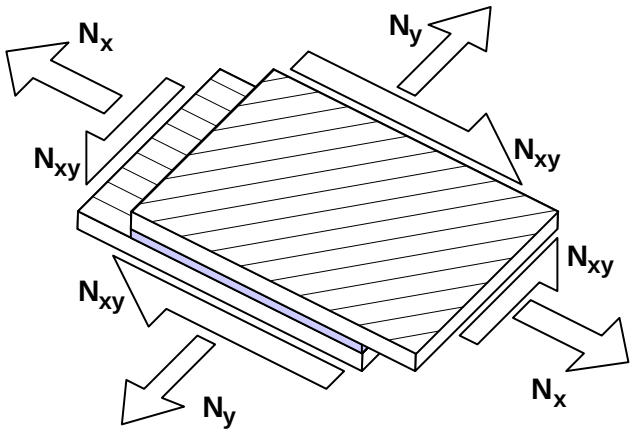
RESEARCH / DESIGN / TESTING / CERTIFICATION

Adhesive Behavior in Aircraft Applications



John Tomblin
Waruna Seneviratne
Paulo Escobar
Yoon-Khian Yap
Pierre Harter

National Institute for Aviation Research
Wichita State University

FAA Workshop on
Key Characteristics for Advanced Material Control
September 16 – 18, 2003

Program Overview

- Coupon Level Testing
  - Investigation of Thick Bondline Adhesive Joints
    - Adhesive test methods
    - Bondline thickness effects
    - Environmental effects

      [FAA Report: DOT/FAA/AR-01/33]
  - Characteristic Shear Responses of Structural Adhesives

    [FAA Report: DOT/FAA/AR-02/97]
  - Fatigue & Stress Relaxation of Adhesive Joints

    [FAA Report: Submitted to FAA]

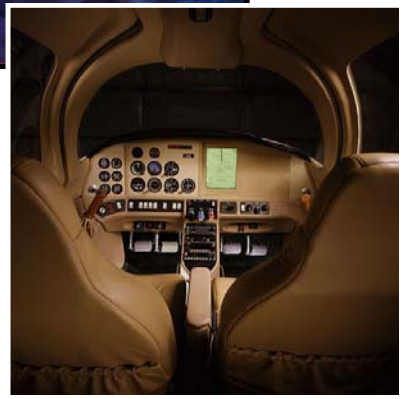
- Subcomponent Testing & Analysis
  - Box Beam Torsion Lap Shear Test
  - Shear Loaded Bonded Joint (SLBJ) Theory [Purdue University]

    [FAA Report: DOT/FAA/AR-03/21]

Available electronically at http://actlibrary.tc.faa.gov

Research Effort

Funded by
FAA



Industry Partners

Cessna
A Textron Company

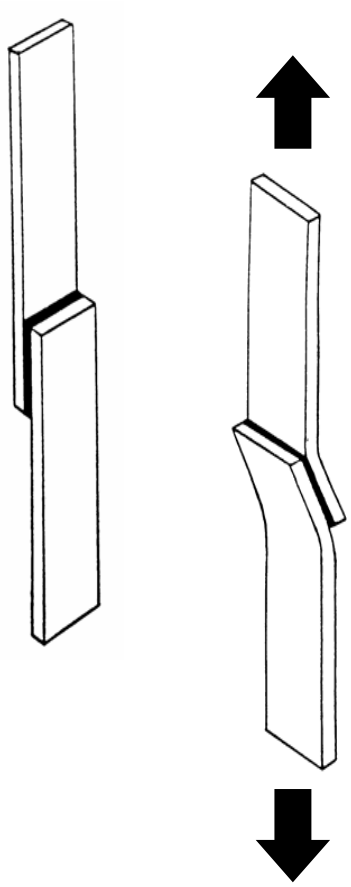
CIRRUS DESIGN

LANCAIR

Partnered with
Purdue University

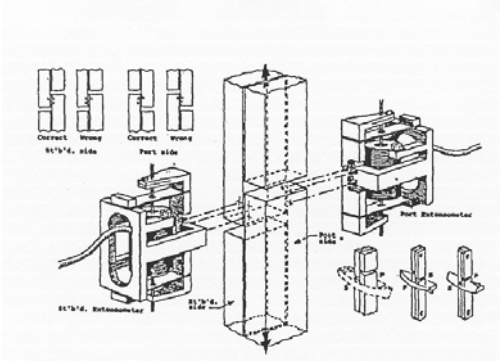
Motivation

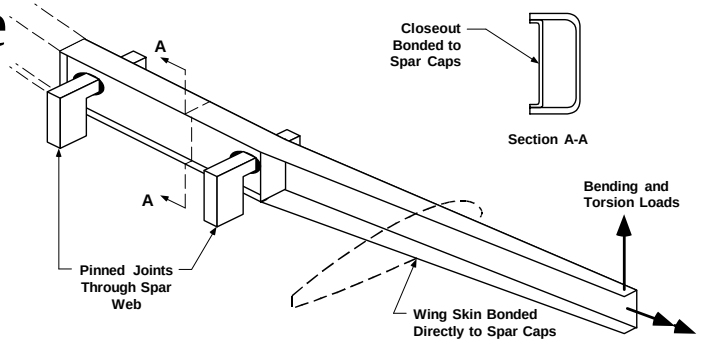
- Number of certification programs involve a large range of adhesive bonding applications
- Migration from secondary to primary structure
- Limited guidance material existed
- Limited experimental analytical models that can be effectively used in design



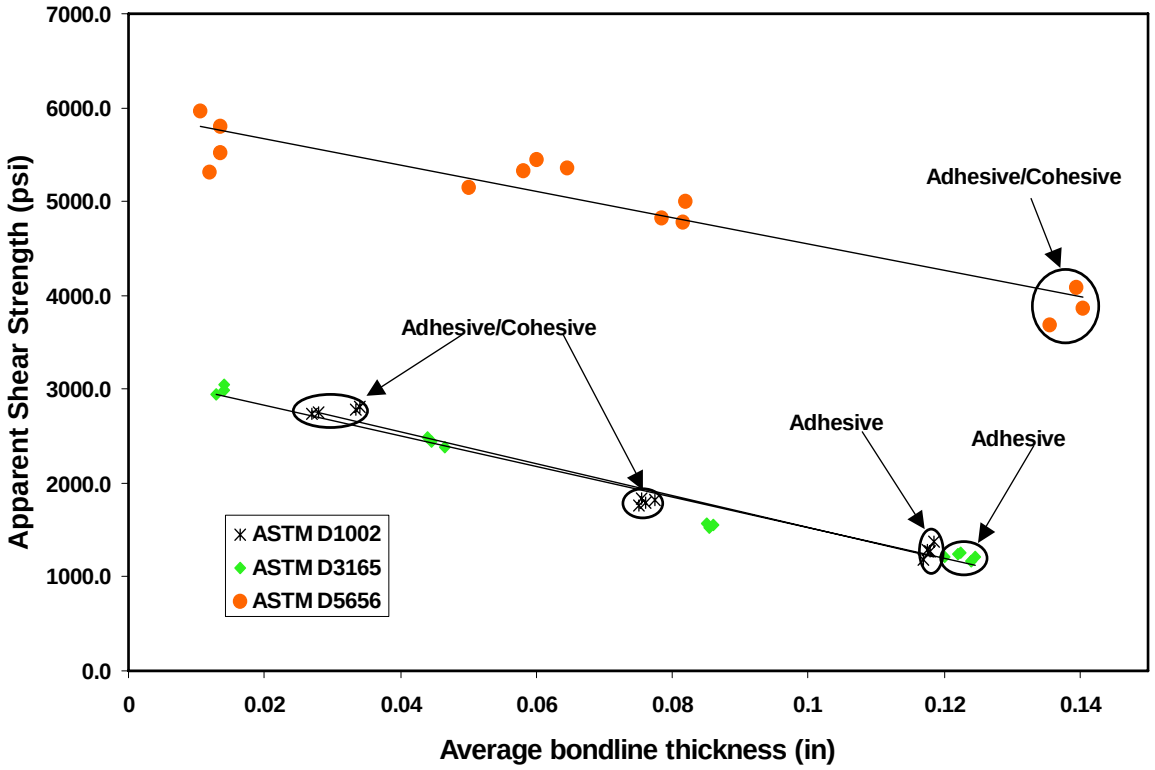
Motivation (contd..)

- Traditional bondline thicknesses used : less than 0.010”
- Current bondline thicknesses : up to 0.140”
- Generate data regarding the effects of thick bondlines
- Long term durability of adhesive joint (fatigue/creep) needs to be addressed with respect to thick bondline joints





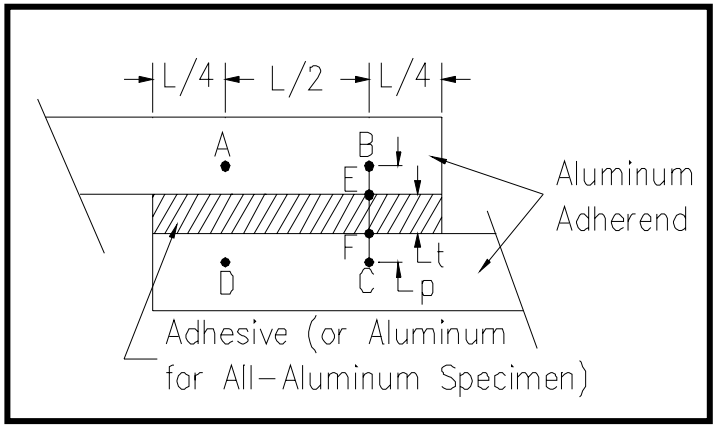
Adhesive Test Methods



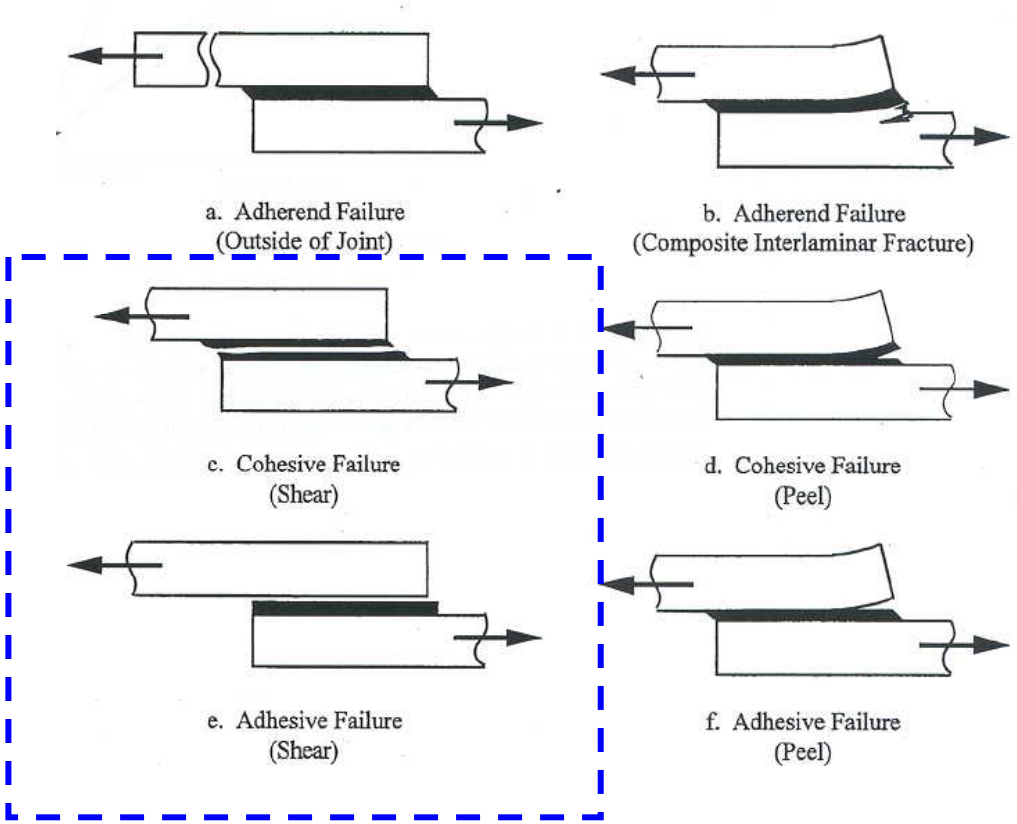
- ASTM D1002 & D3165 for joint characterization
- ASTM D5656 for adhesive characterization

ASTM D5656 Test Method

- Thick adherend
  - ***Adhesive*** characterization rather than ***Joint*** characterization
  - Elastic Limit & Plastic Strain
  - Design & Analysis
  - Reduced peel stresses
- Correction for metal deformation
- Four-Pin Configuration
  - Reduces errors due to rotation and slippage
  - Reduced scatter in data

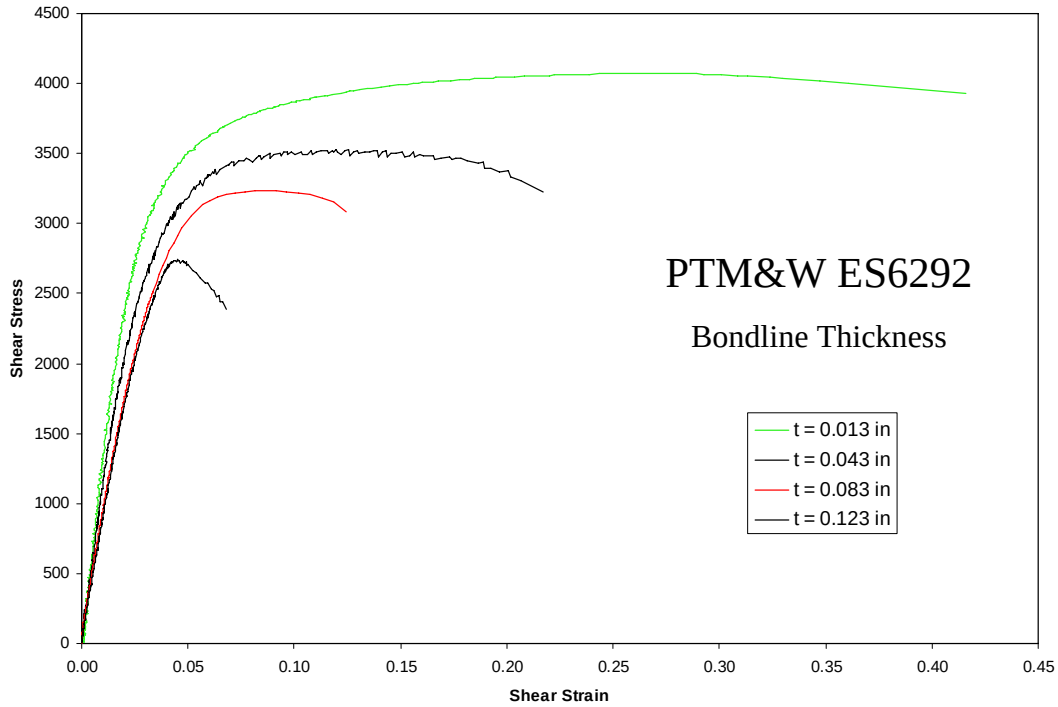


Failure Modes



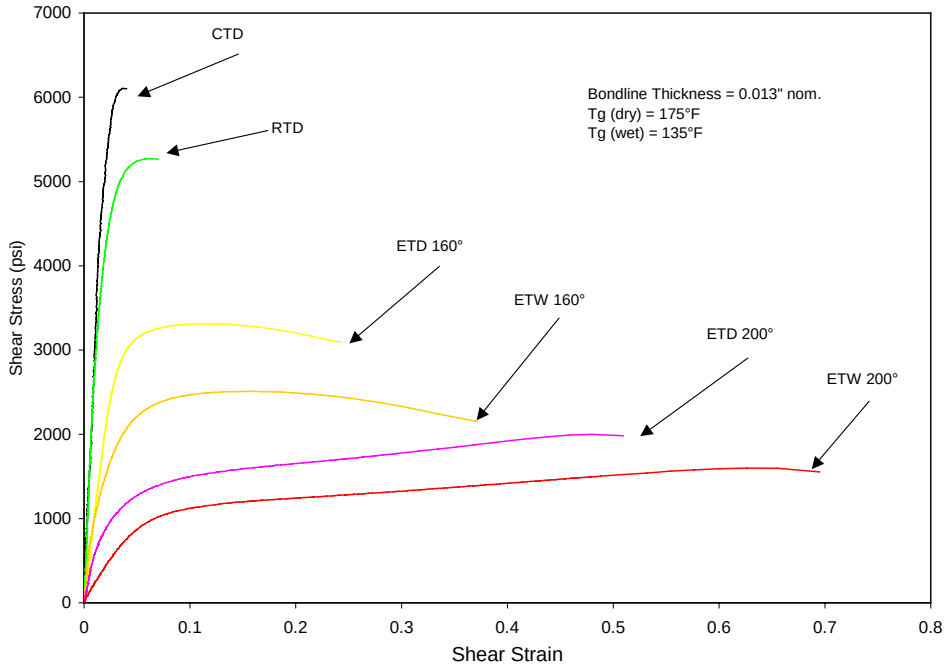
ASTM D5656

Bondline Thickness Effects



- Increasing bondline thickness resulted in reduced plastic strain and lower yield stress

Environmental Effects

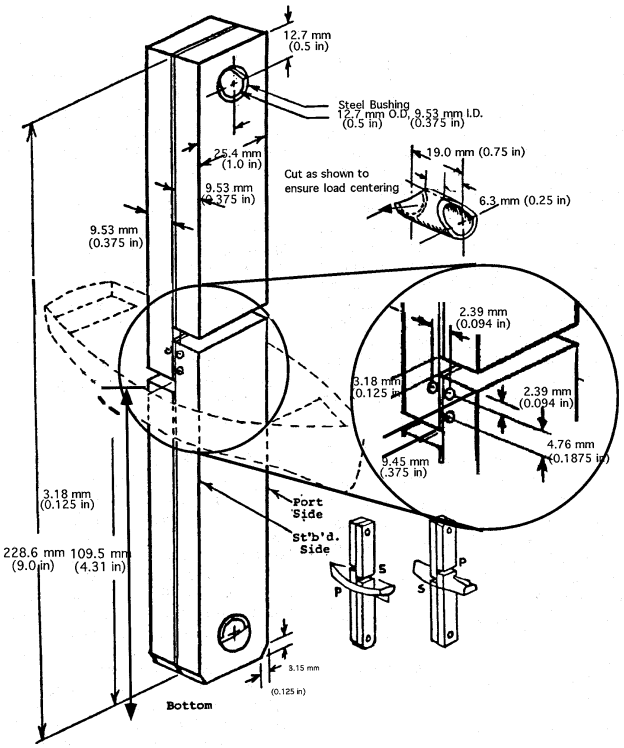


MGS
A100/B100

- Yield stress and stiffness decreased with increasing temperature and humidity
- Environmental condition affects failure mode

Characteristic Shear Responses of Structural Adhesives

- 18 Adhesive Types
  - 6 Film Adhesives
  - 12 Paste Adhesives
- ASTM D5656 [4 pin holes]
- Three Environmental Conditions
  - Room Temp. ambient [RTD]
  - Elevated Temp. (180°F) dry [ETD]
  - Elevated Temp. (180°F) wet [ETW]
    - 145 °F and 85% relative humidity for 1000 hrs
- Bondline Thickness
  - Film Adhesives: 0.01” – 0.03”
  - Paste Adhesives: 0.03” – 0.05”



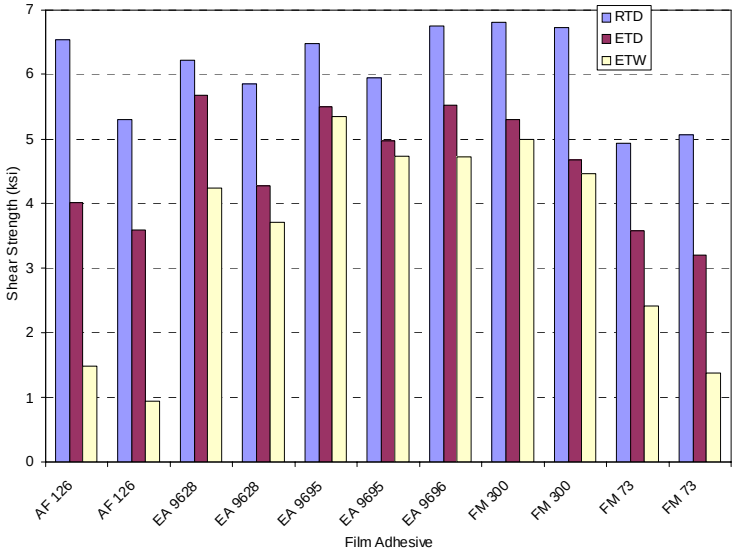
Adhesive Types Investigated

- Film Adhesives (6)
  - AF 126
  - EA 9628
  - EA 9695
  - EA 9696
  - FM 300
  - FM 73

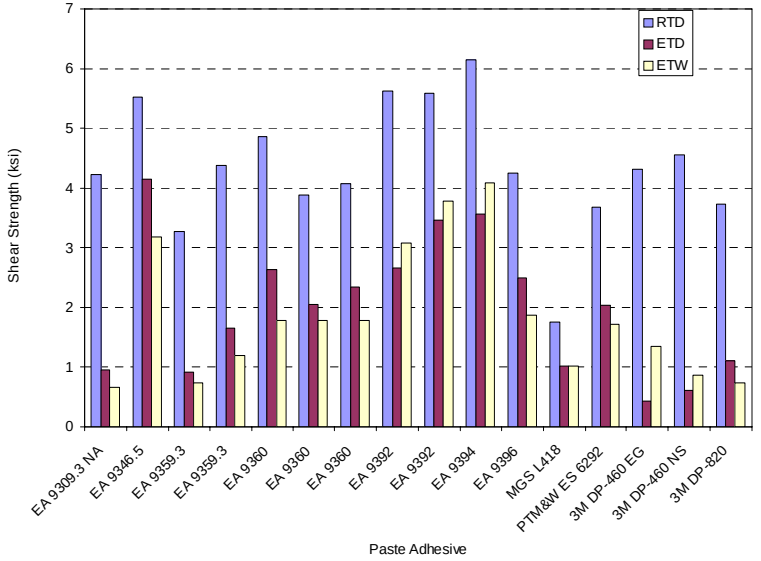
- Paste Adhesives (12)
  - EA 9309.3 NA
  - EA 9346.5
  - EA 9359.3
  - EA 9360
  - EA 9392
  - EA 9394
  - EA 9396
  - MGS L418
  - PTM&W ES 6292
  - 3M DP-460 EG
  - 3M DP-460 NS
  - 3M DP-820

Adhesives & Aluminum sub-panels (Phosphoric Anodized) were provided by Cessna Aircraft, Wichita, KS

Apparent Shear Strength Comparison

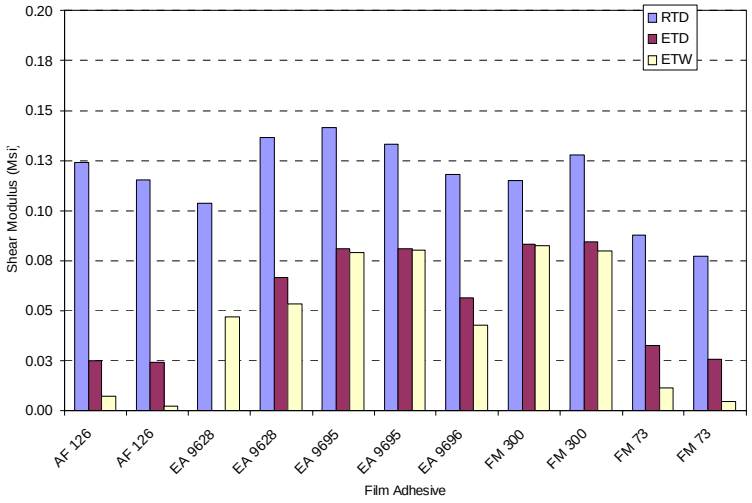


Film Adhesive

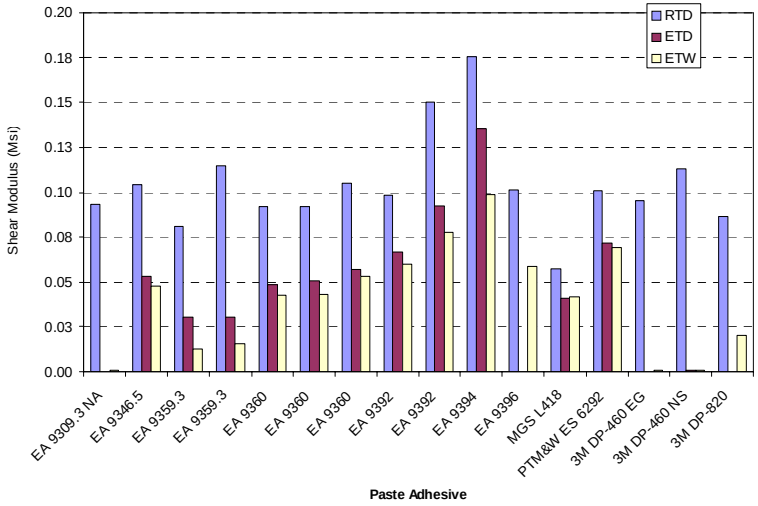


Paste Adhesive

Shear Modulus Comparison



Film Adhesive



Paste Adhesive

FAA Final Report: DOT/FAA/AR-02/97

Fatigue of Thick Bondline Adhesive Joints

Modified ASTM D3166-99
[Aluminum Adherend of 0.375”]

- Three Adhesives
  - PTM&W [0.060” & 0.160”]
  - Loctite [0.032”]
  - EA9696 [0.02”]
- Three Stress Levels
  - 10^3, 10^4 and 10^5 cycles
- Three Frequencies
  - F=2 Hz, 5 Hz and 10 Hz
- Three Environmental Conditions
  - RTD, RTW
  - CTD (-40°F)

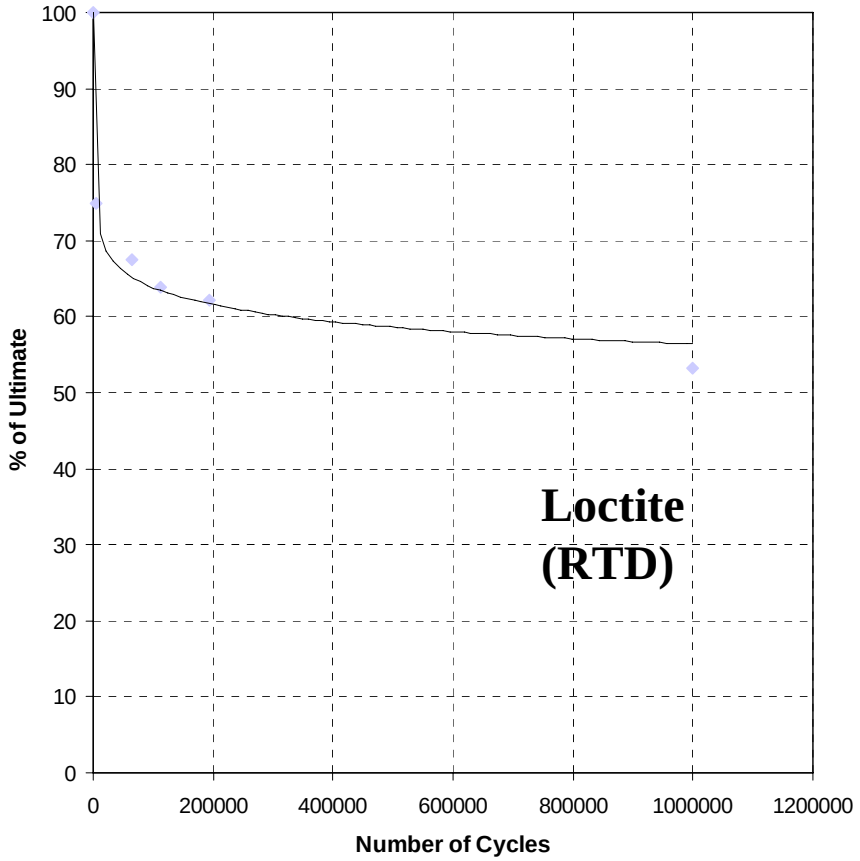
Stress Level Determination

Based on the initial SN Curve

y=-3.227*ln(x)+100.96

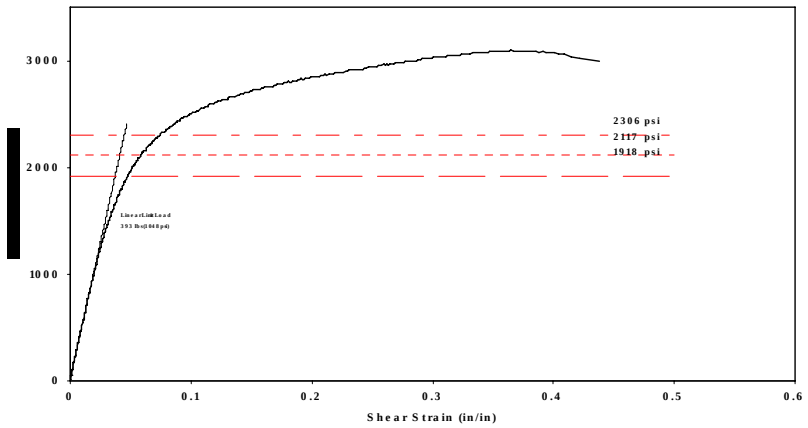
100000Cy SL1≈65% UL ≈183% LL
10000Cy SL2≈72% UL ≈202% LL
1000Cy SL3≈78% UL ≈220% LL

Note: For RTW and CTD, %UL are different

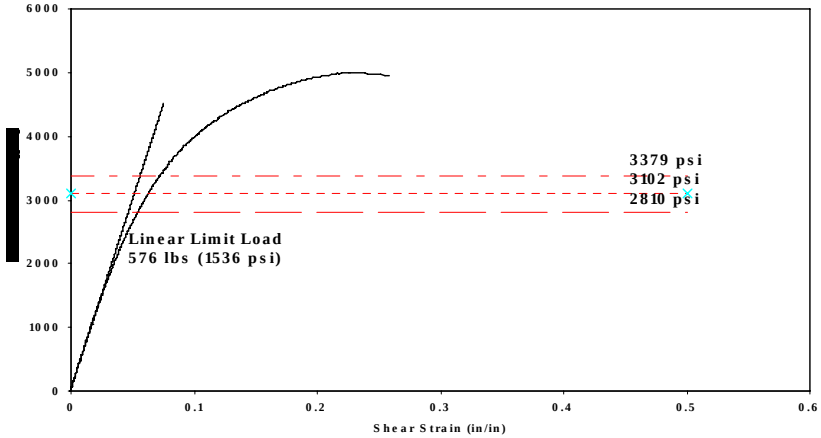


Loctite Stress Levels

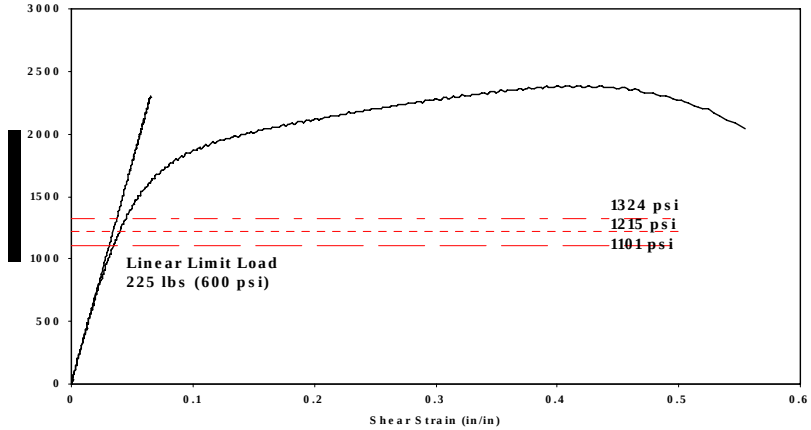
Loctite RTD



Loctite CTD

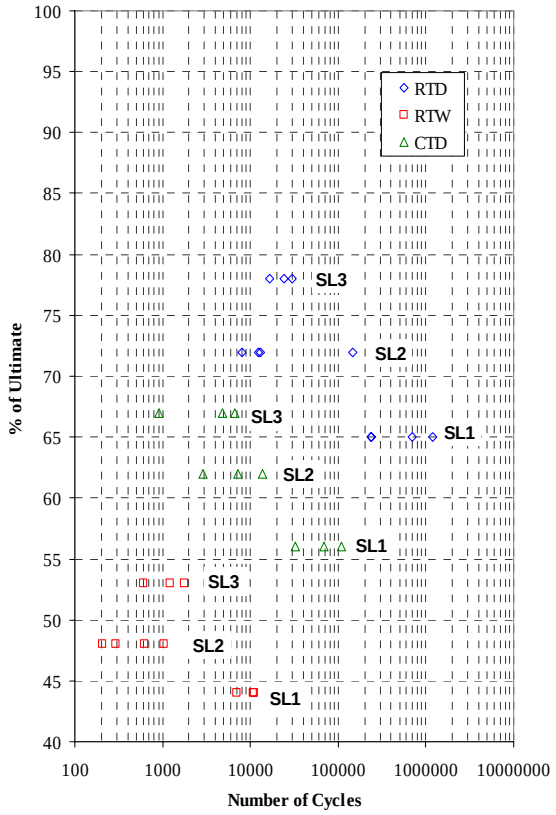


Loctite RTW

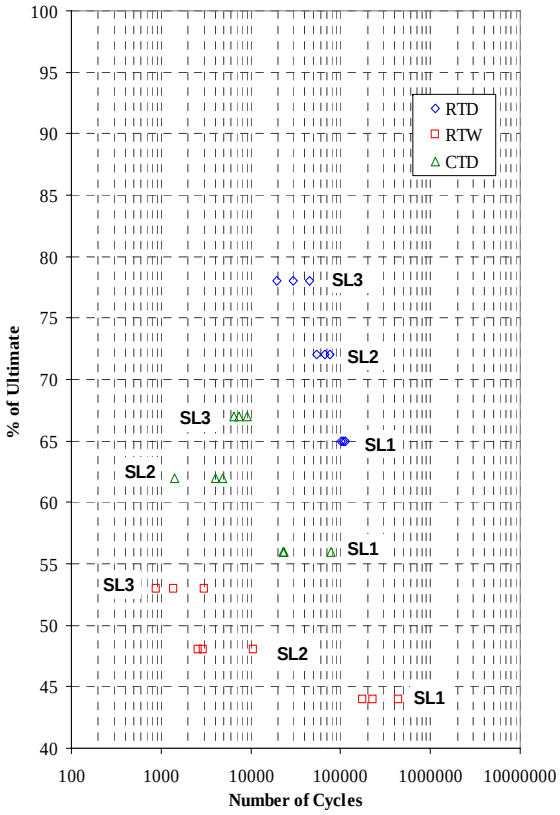


Fatigue life in a range below knee point and above linear limit point.

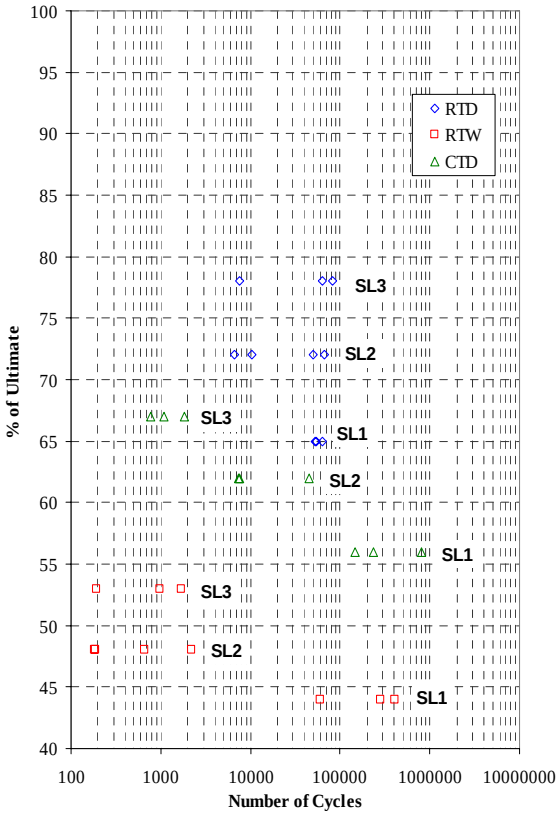
Fatigue Behavior of Adhesives



2 Hz

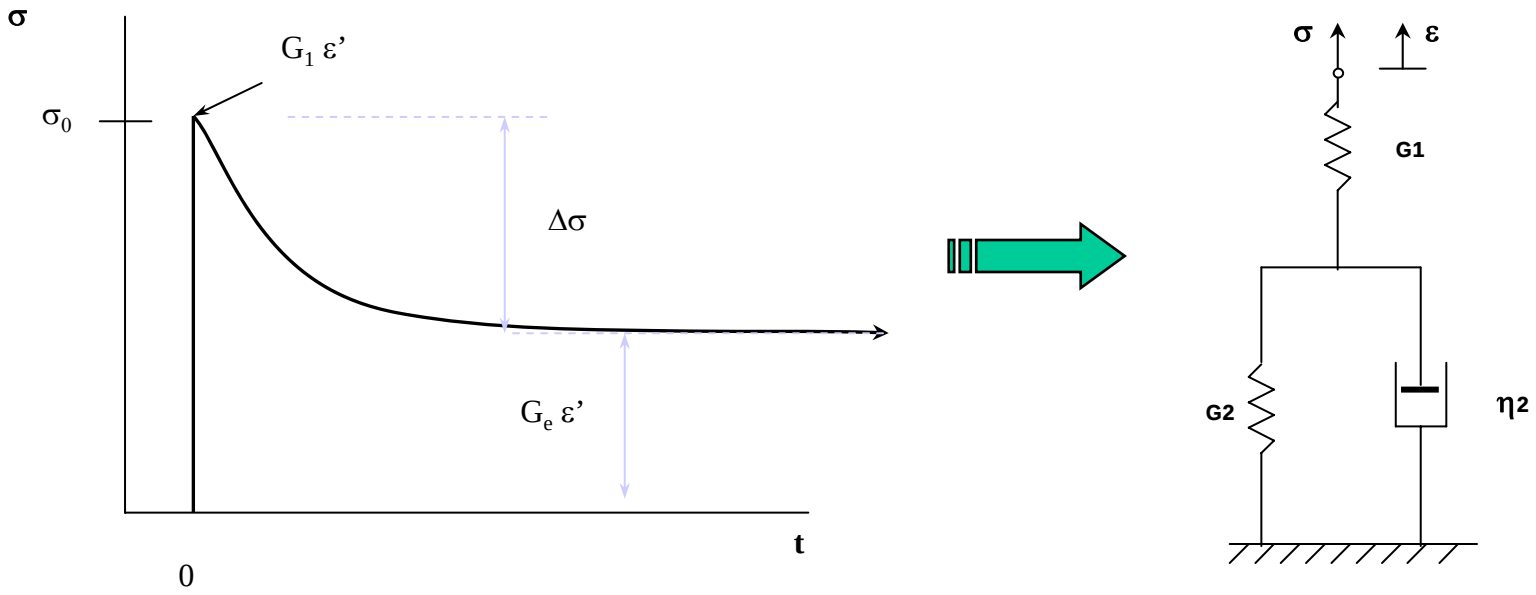


5 Hz



10 Hz

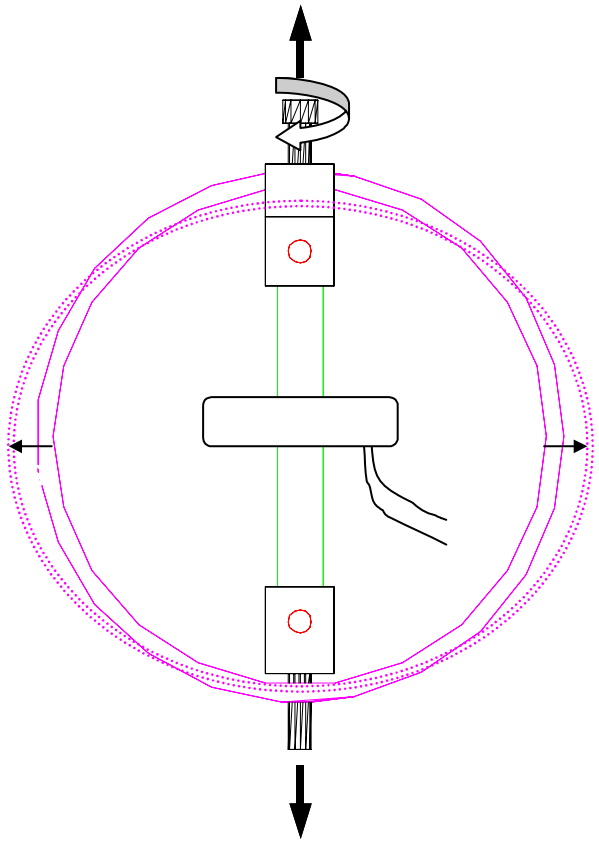
Stress Relaxation of Adhesive Joints

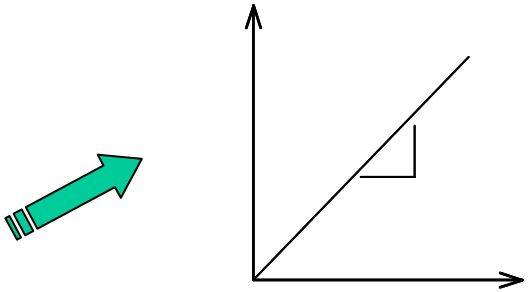


- Applied stress gradually decreases to a stable value over time
- Elastic strain that appears during initial rapid loading is slowly replaced by creep strain, with the total of the two being constant
- Steady-state creep and linear viscoelastic material behavior

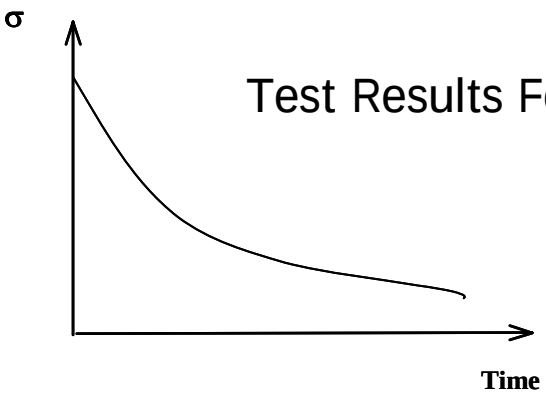
Modified ALCOA Stressing Fixture

Calibration for each environmental condition



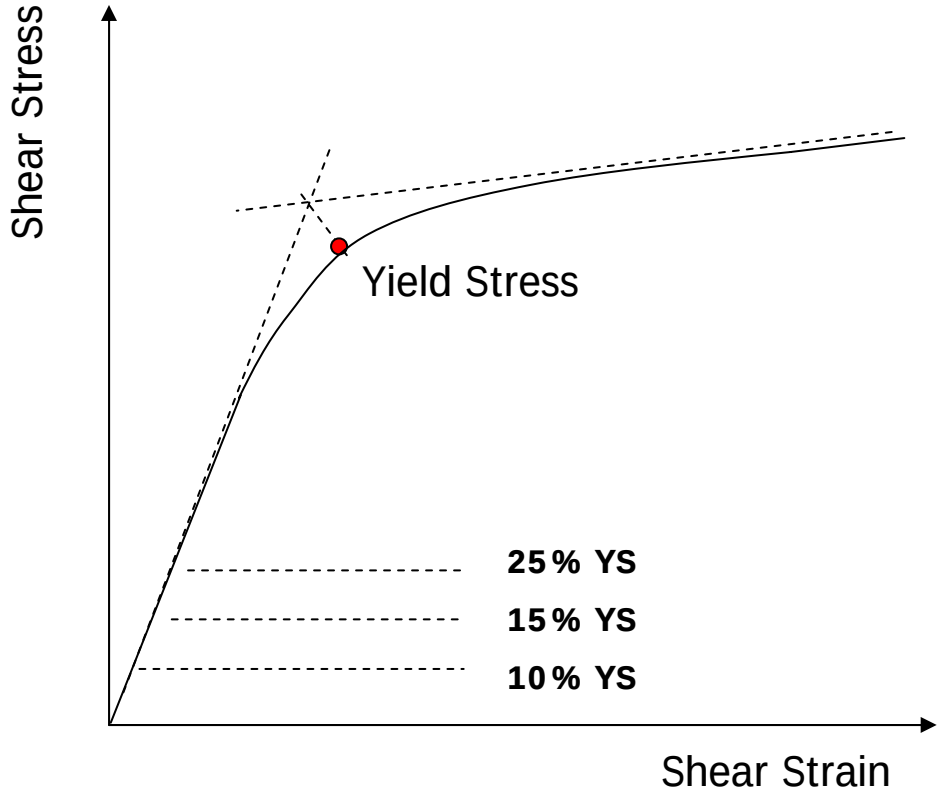


$$\sigma(t) = \mu \bullet 2\,\delta\,(t)$$



Test Results Format

Stress Level Determination



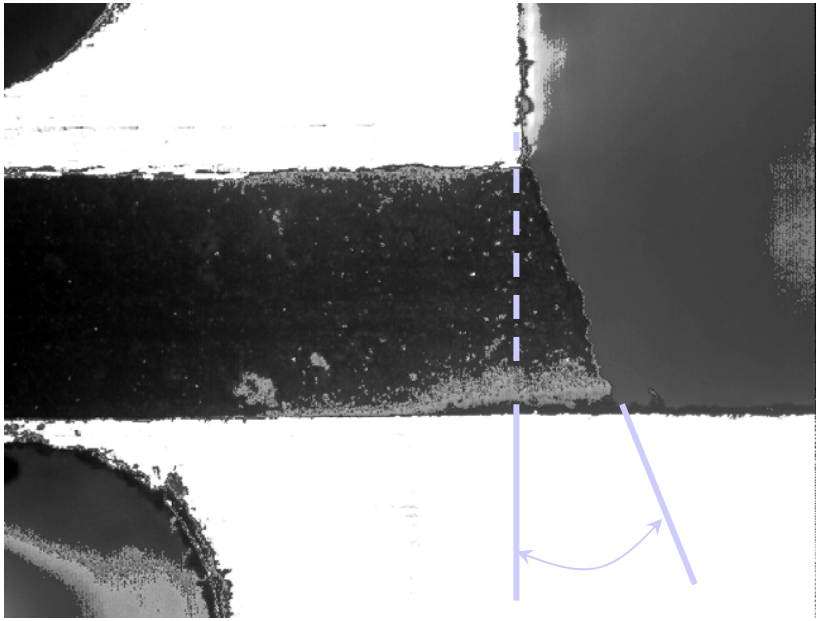
Test Temperatures

150°F

180°F

210°F

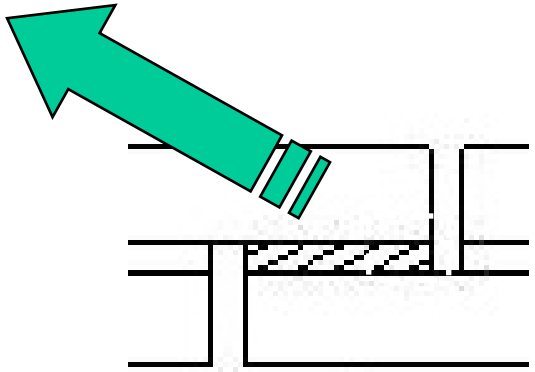
Creep Deformation



~18°

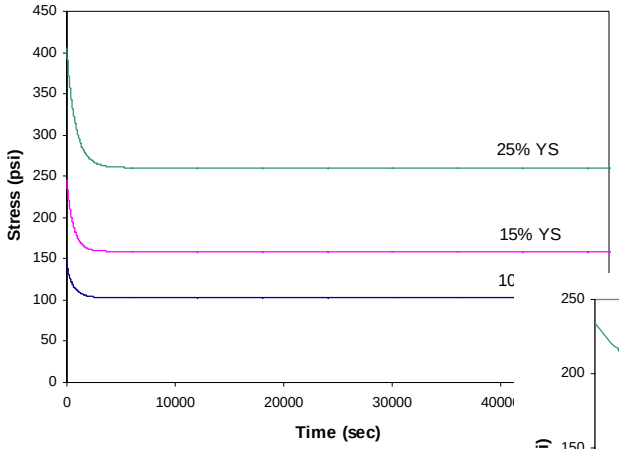
[50X magnification]

- Loctite
  - 25% YS
  - 180 °F
  - 167 hours

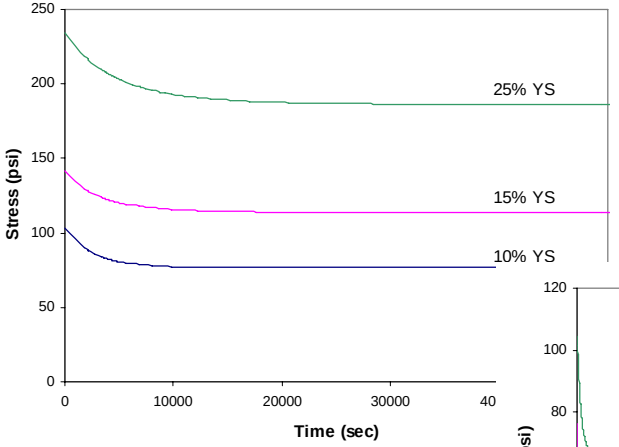


Loctite Stress Relaxation Results

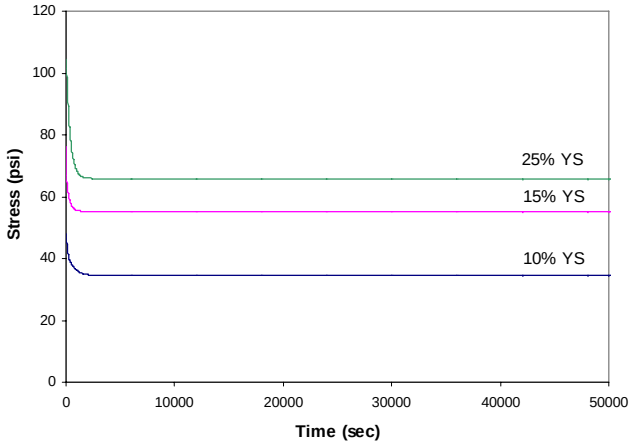
150 °F



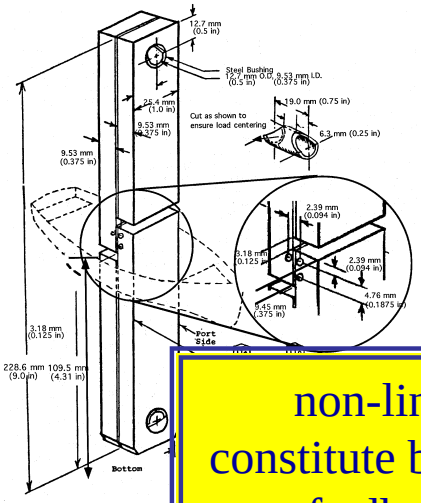
180 °F

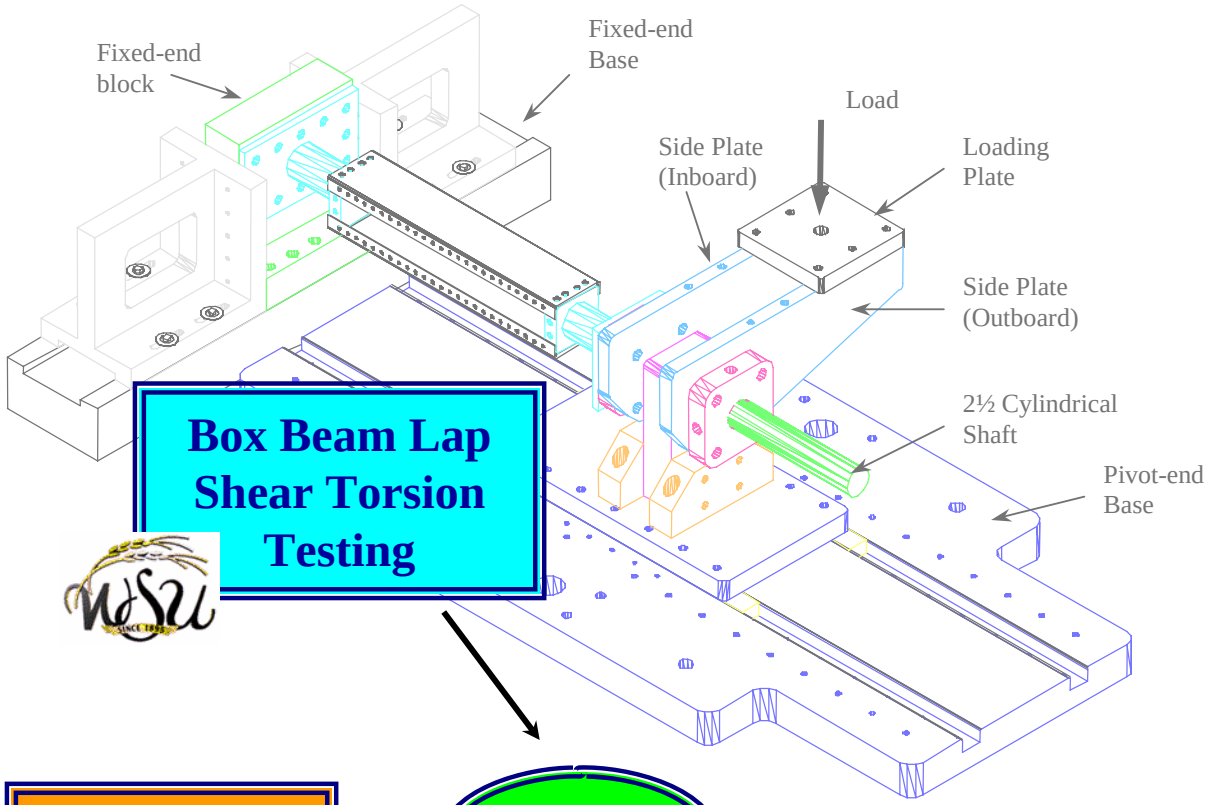


210 °F



Box Beam Lap Shear Torsion Test





non-linear constitute behavior of adhesive

Box Beam Lap Shear Torsion Testing

Shear Loaded Bonded Joint (SLBJ) Theory

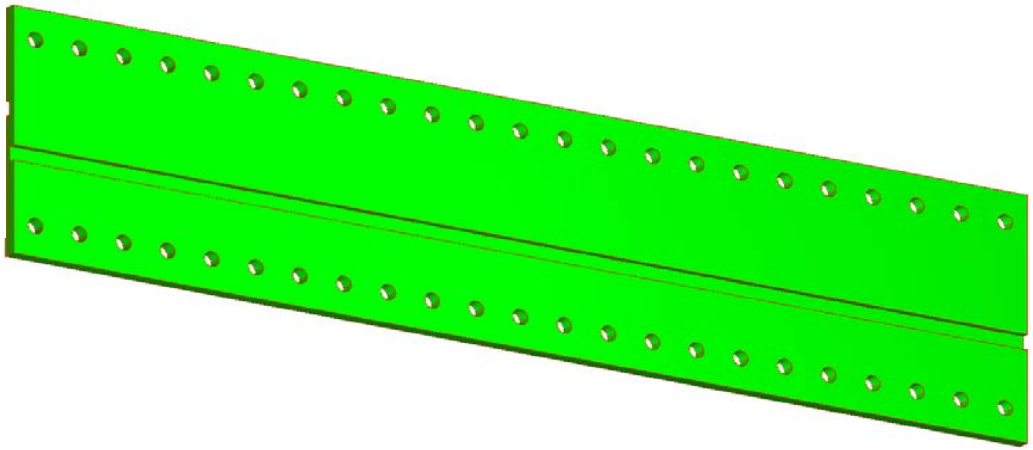
Joint Failure Prediction

Validation

Design Guidelines & Certification

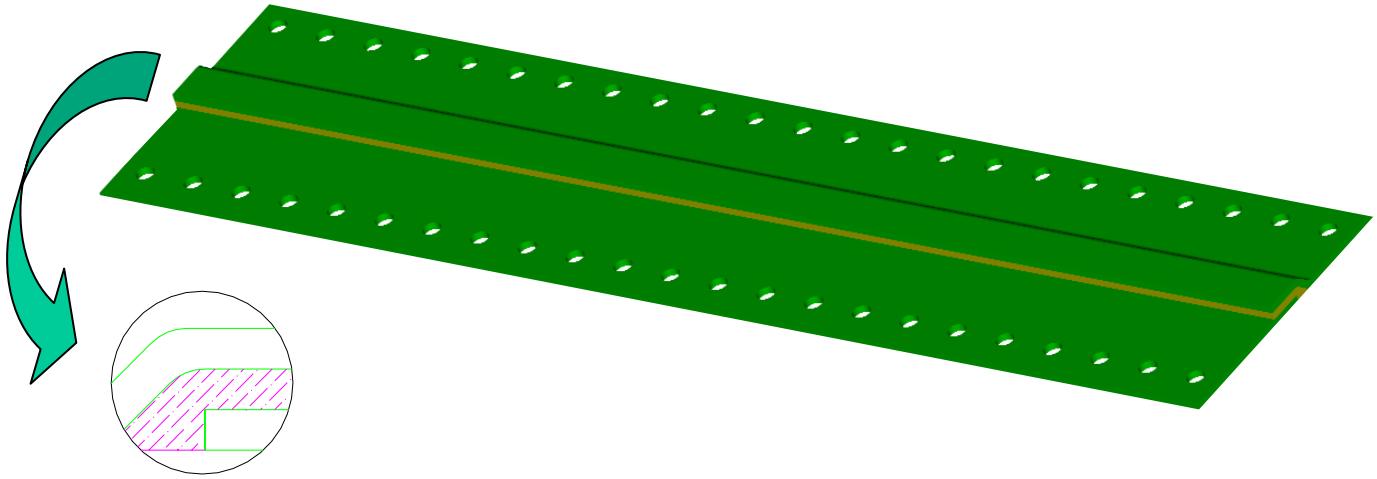
Adhesive Lap Joint Specimen

Gage width ~ 0.5”
Gage section ~ 17.25”



Flat Joint

PTM&W
EA9360
Loctite



Joggle Joint

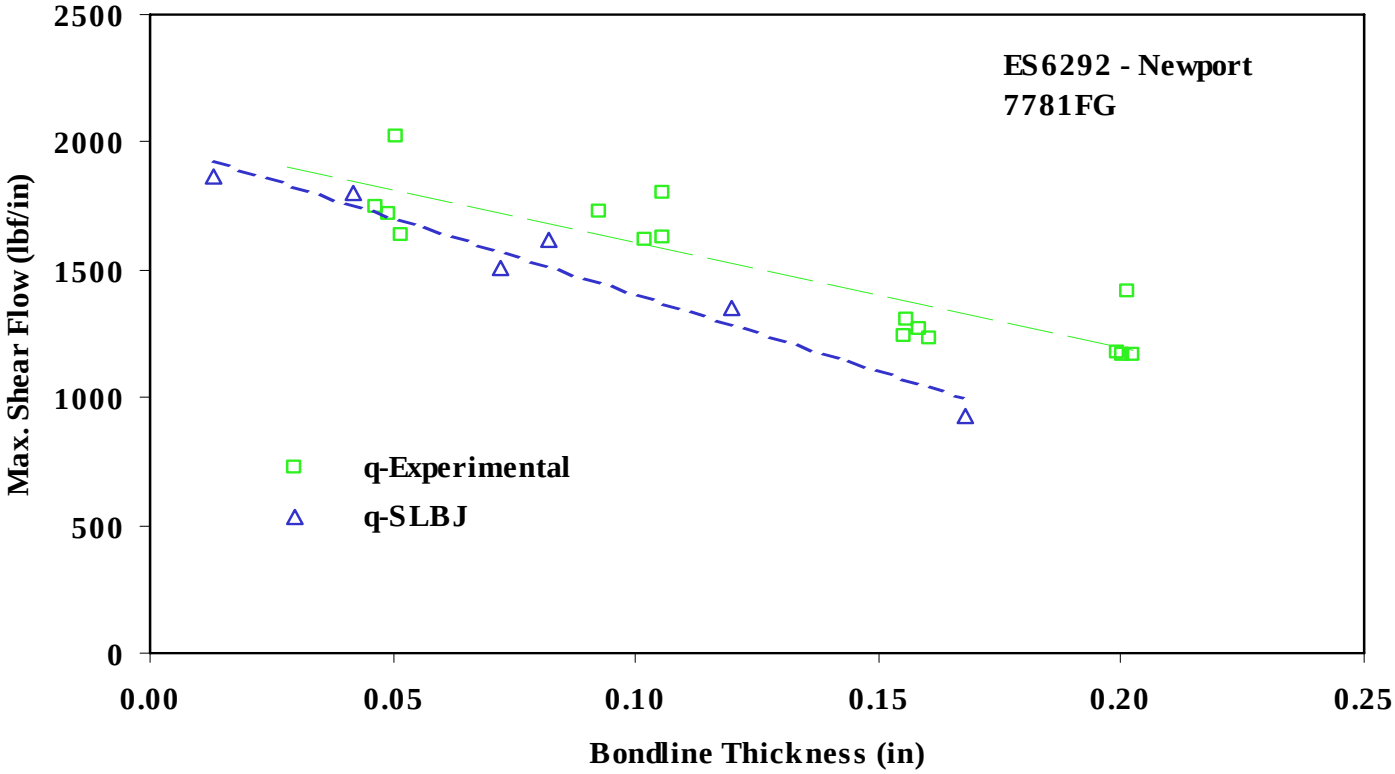
PTM&W
EA9360

Materials

- Adhesives
  - PTM&W ES6292 [t = 0.05” ~ 0.20”]
  - EA 9360 [t = 0.10”]
  - Loctite (CESSNA Proprietary) [t = 0.05”]

- Adherend
  - NEWPORT E-Glass Fabric 7781 / NB321
  - NEWPORT NB321/3K70P Carbon Cloth
    - Fiberglass/Carbon Layup Schedule – $[0_4/45/-45/0_4]$
  - Aluminum 2024-T3 Clad
    - Phosphorus Anodized & Bond Primed
      [CESSNA Aircraft, Wichita, Kansas]

Maximum Shear Flow (Comparison)



Constitutive behavior for 0.20 was not available

Conclusions

Environmental Effects

- Adhesives become weak and ductile at high temperatures and brittle at low temperatures.
- Yield stress and modulus of all adhesives decrease with increasing temperature and humidity
- The plastic behavior of adhesives at elevated temperatures caused significant shear deformation
- Mechanical properties of adhesives can be substantially degraded by the absorption of moisture
- Environmental condition affects the failure mode as well as the mechanical properties

Conclusions (Contd..)

Fatigue

- *'High stress'* fatigue life of adhesive exists in a range below *Knee point* and above *linear limit point*
- Failure modes indicate that moisture affects adhesive bulk instead of the adhesive-adherend interface (RTW cohesive failures)
- Observation – lower void in bondline = longer fatigue life
- Film adhesive indicates better resistance to moisture (less voids?)

Stress Relaxation

- Stress relaxation was increased as the stress level and temperature was increased

Conclusions (Contd…)

Box Beam Lap Shear Torsion

- Load carrying capabilities of adhesive joints decreases as bondline thickness increases
- Purdue Analysis predictions (SLBJ Theory) comparable with box beam test results
- Increasing bondline thickness affects the failure mode of bonded joints
- Accumulation of large plastic strains in thin bondlines resulted in high adherend interlaminar strains and caused substrate (first-ply) failure
- Unstable damage development of thick bondlines (lower plastic strain development) resulted in adhesive cracking in multiple locations with a cohesive type failure and lower failure strengths