FAA Bonded Structure Research Projects

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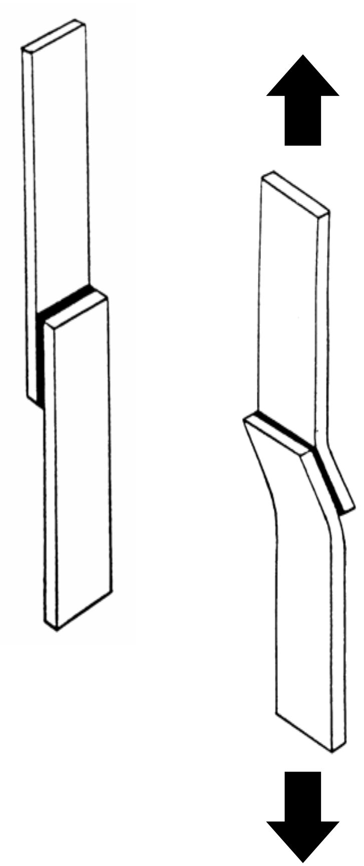
26 October 2004

Session Purpose

- Give understanding of FAA involvement in bonded structures
- Show areas addressed by FAA research
- Provide material for discussion of needs in bonded structure research.

Motivation

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



Areas of Research

- Analysis of bonded joints
- Surface preparation
- Adhesive qualification and characterization
- Effects of thick and variable bondlines
- Larger scale testing including damage tolerance.

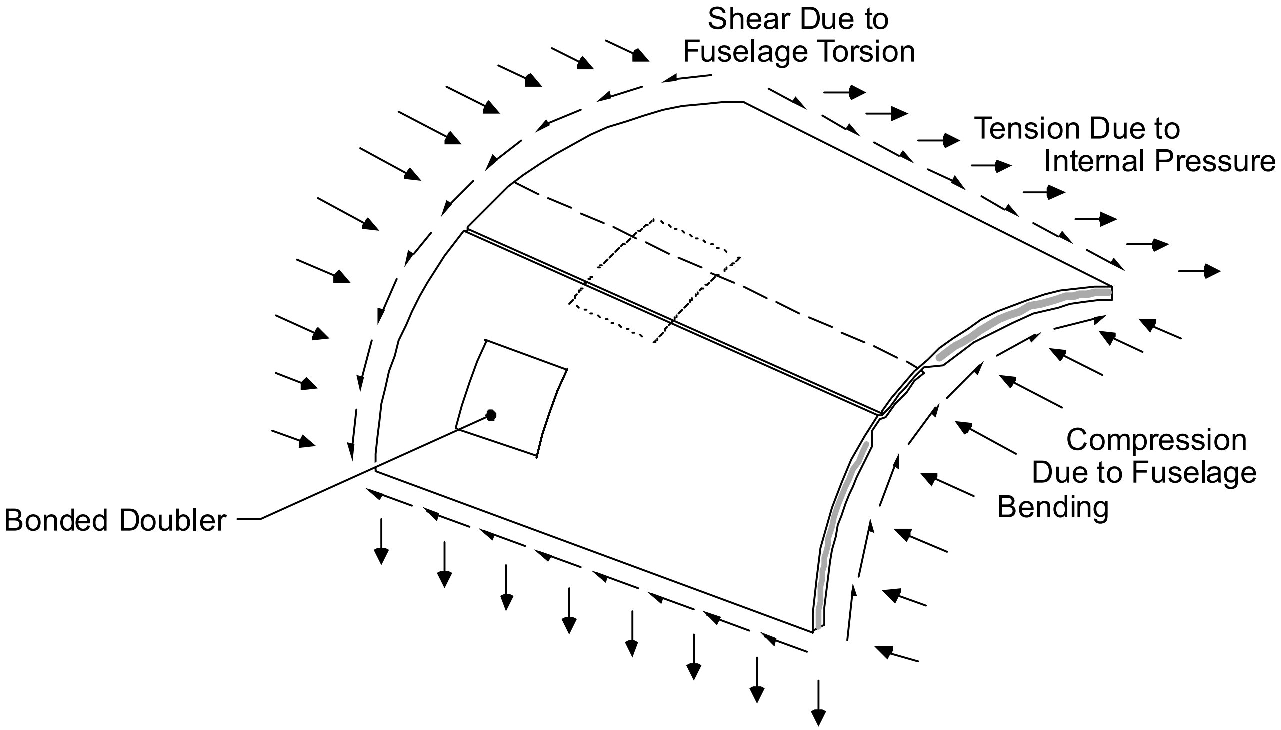
Analysis

- Closed form solutions
  - Hyonny Kim, Purdue University
  - Keith Kedward, University of California Santa Barbara
- Code based on plate theory suitable for General Aviation community and others
  - Materials Sciences Corporation
  - Gerry Flanagan, Rachael Andrulonis

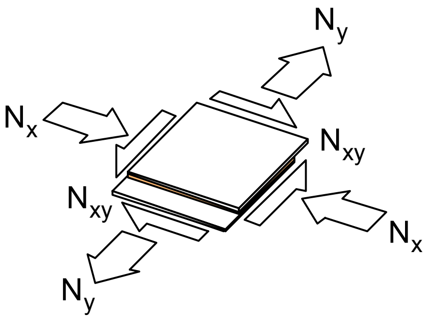
Bonded Joint Stress Analyses

- Closed form model
- In-plane shear loading
  - Combined shear + tension loading
  - Plastic strain-based ultimate load
  - Variable bondline thickness
  - Tension loading in general unbalanced single lap joint
- Reports
  - "Stress Analysis of In-plane Shear-Loaded Adhesively Bonded Composite Joints and Assemblies" DOD/FAA/AR-01/7
  - "Characterization of In-plane, Shear-Loaded Adhesive Lap Joints: Experiment and Analysis" DOD/FAA/AR-03/21

General Joint Loading

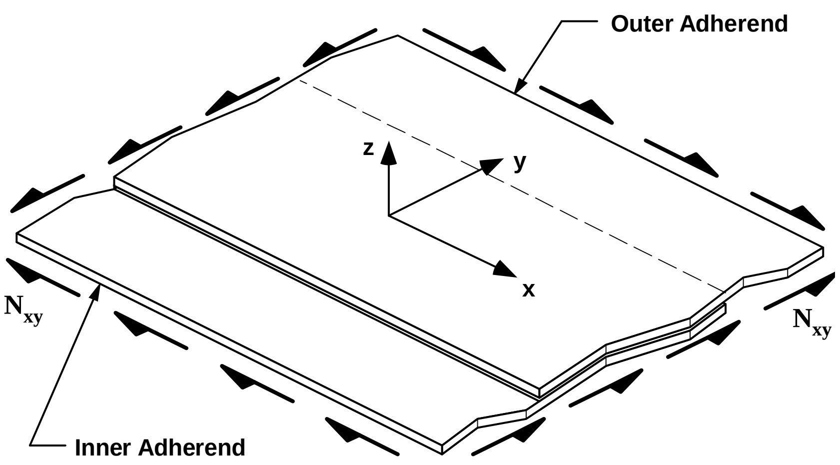


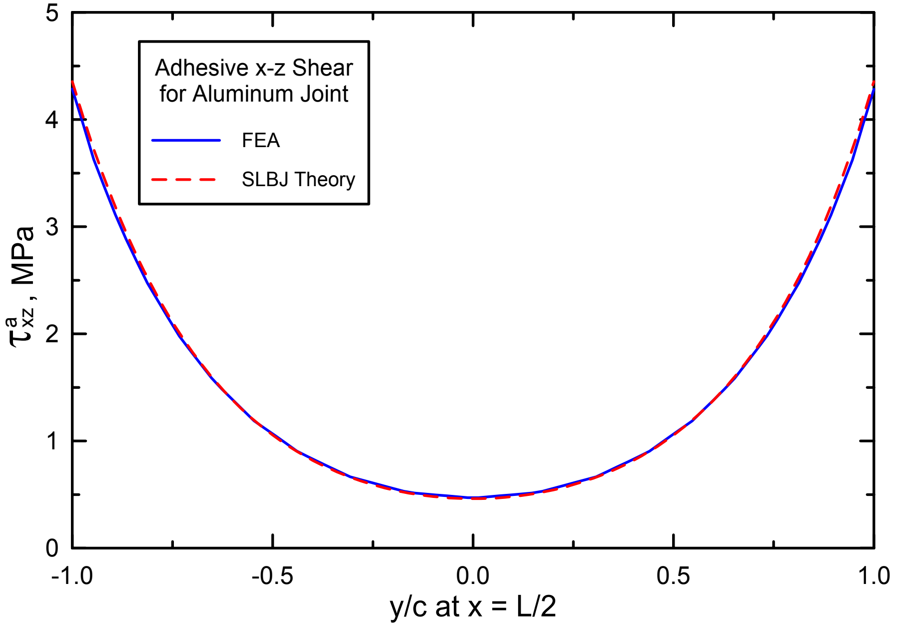
Segment of Joint Loaded by Biaxial Tension/Compression and Shear



In-plane shear + tension produces adhesive shear stress

In-Plane Shear Loaded Lap Joint



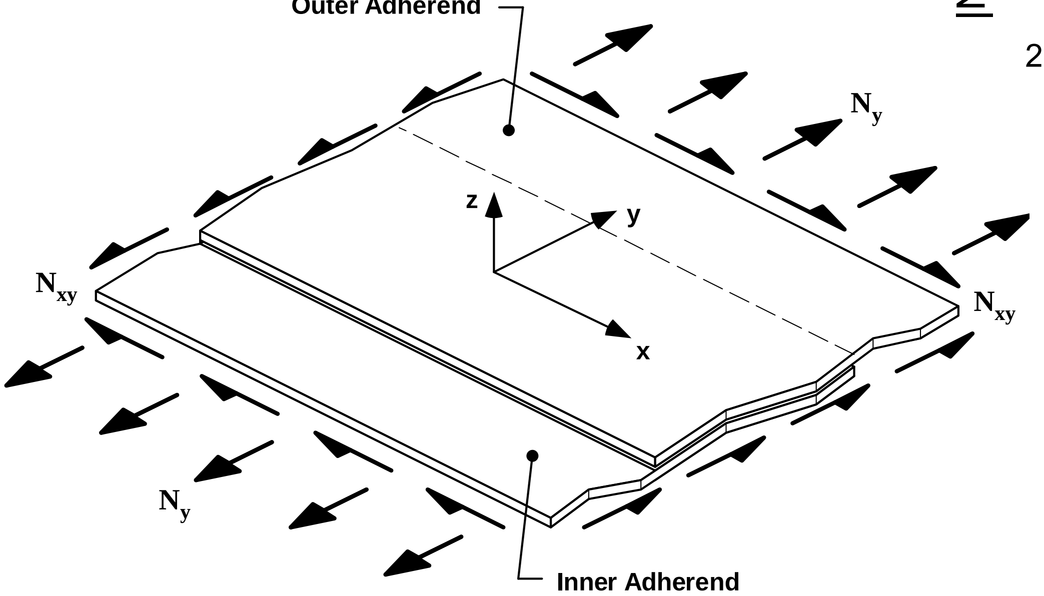


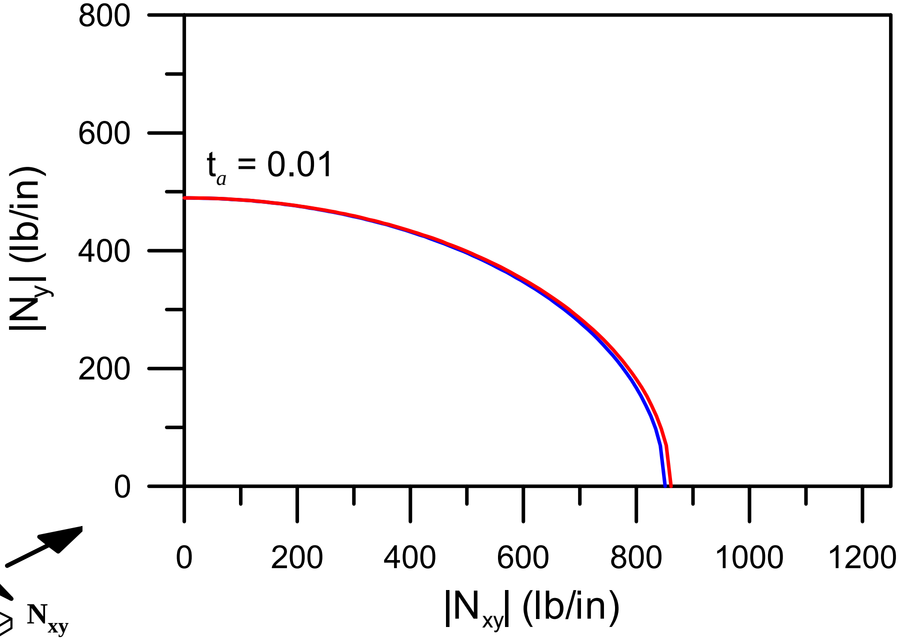
In-plane shear load transfer across joint produces τ_{xz} shear stress in adhesive

Kim, H. and Kedward, K.T., "Stress Analysis of Adhesive Bonded Joints Under In-Plane Shear Loading," *Journal of Adhesion*, Vol. 76, No. 1, 2001, pp. 1-36.

Combined Loading: Shear + Tension

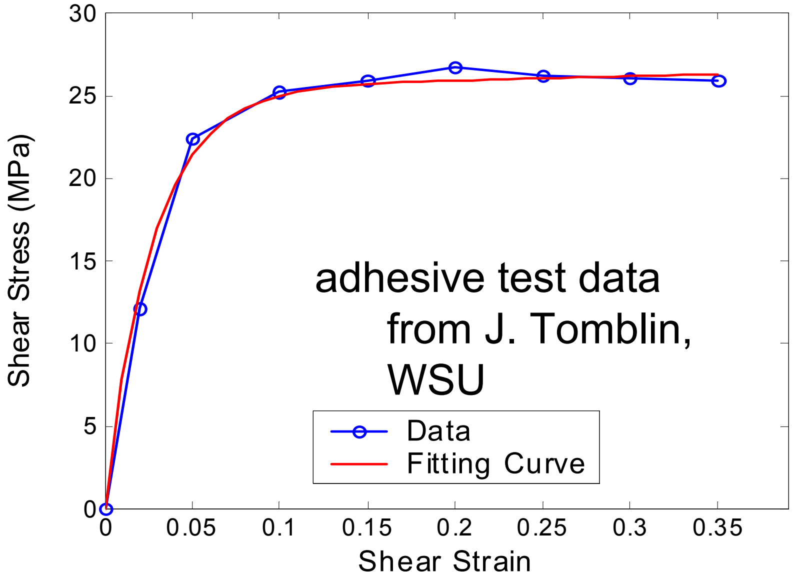
Von-Mises Based Failure Envelope



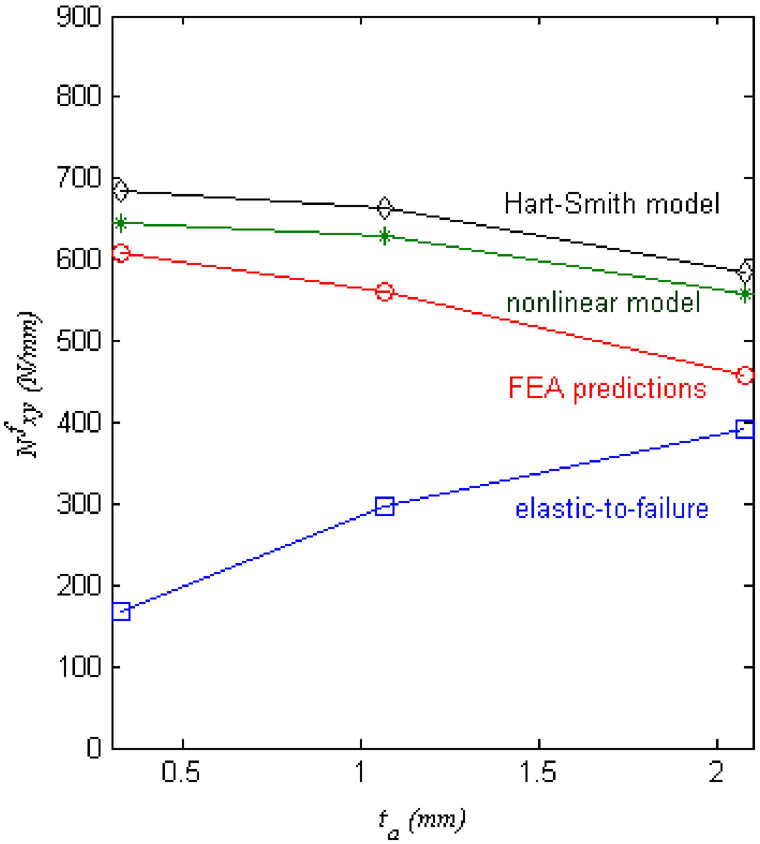


Plastic Strain-Based Ultimate Load

- In-plane shear loading
- Ductile adhesive joint carries greater load than elastic-limit design
- More conservative than Hart-Smith elastic-perfectly plastic model

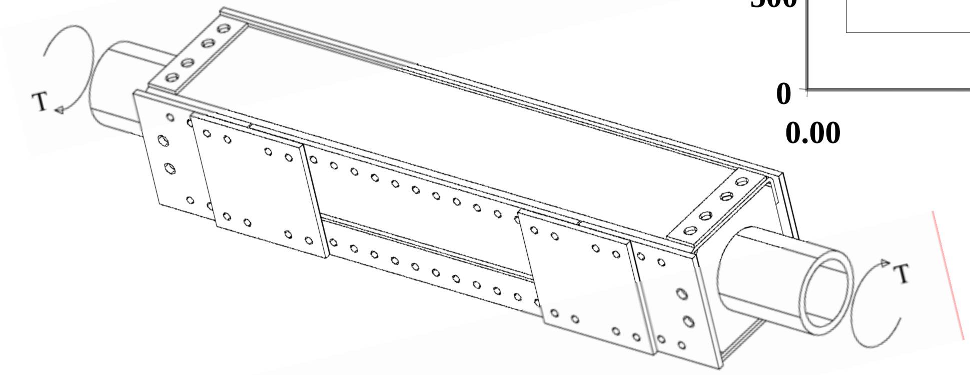


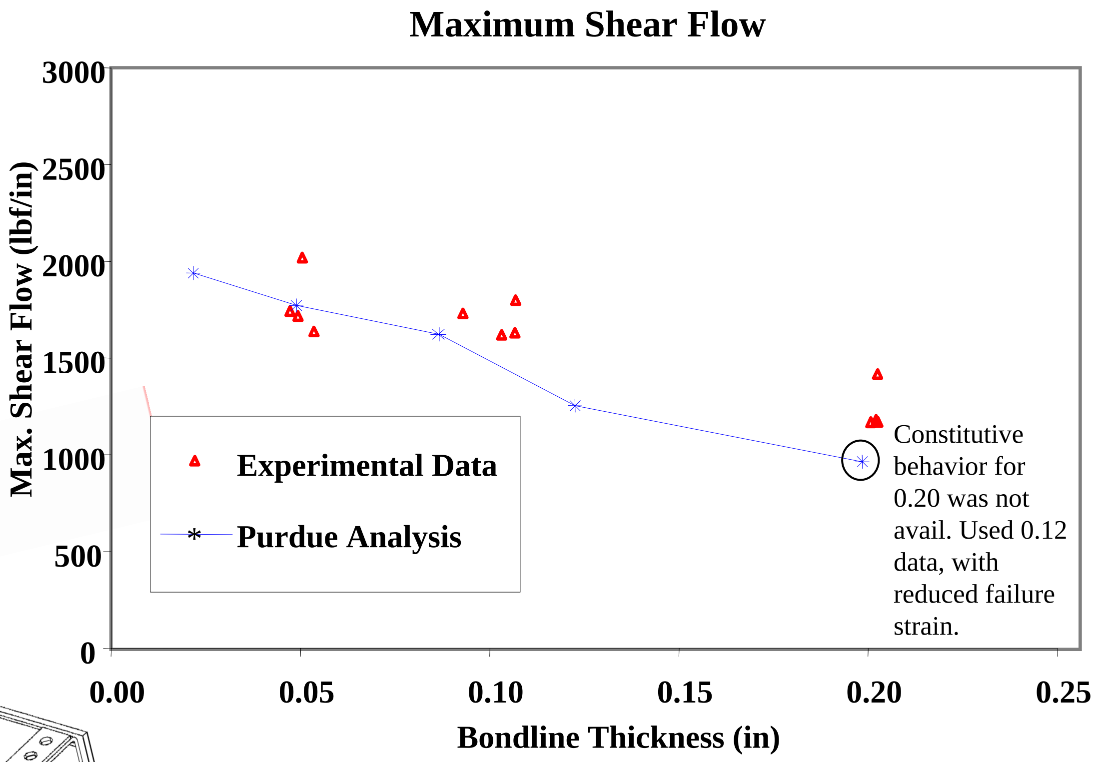
adhesive test data from J. Tomblin, WSU



Failure Prediction vs. Test Data

- Box-beam torsion lap shear coupon
- Experiments conducted by Wichita State University (John Tomblin)





Constitutive behavior for 0.20 was not avail. Used 0.12 data, with reduced failure strain.

New Analysis Code

- Create a new bonded joint analysis standard
  - Replace A4EI as a referenced standard
  - Much broader class of problems
  - Handle bending, peel, and general adhesive nonlinearity
- Handle adhesive mechanics in a rigorous fashion
  - Adhesive as a 3D material
  - Thickness effects, including thickness variability
- Provide intelligent failure criteria
  - Adhesive and adherends
  - Stress/strain based and fracture mechanics capability
- Release a commercial quality code
  - Modern, Windows based GUI
  - Documentation
- Perform validation tests.

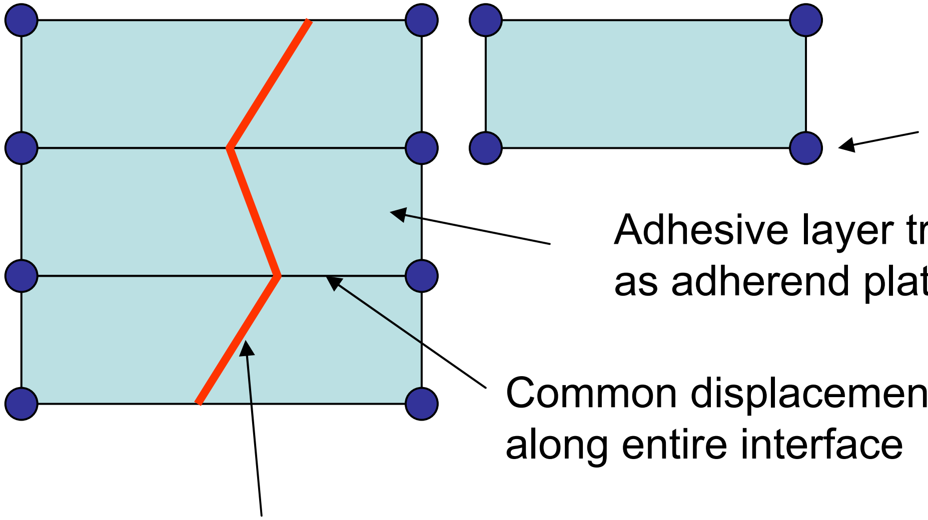
Analysis Approach

- Modify an existing code that handles interlaminar stress and fracture for composite laminates
- Wrap a graphical user interface around analysis code
  - Parametric models for most possible joint topologies
  - Database management for material properties and user models
  - Graphical display of output
  - VB.net based
- Build failure models on top of analysis code
  - Highly modular system
  - User customization

Existing Code: SUBLAM

- Originally developed by G. Flanagan under NASA funding
- Continued development by MSC and Navy
- Modern, well documented FORTRAN 95 code
- Allows for general, finite-element-like modeling, but is designed to yield accurate interlaminar stress components with extremely coarse models
- Added material nonlinearity to code.

Some Concepts from SUBLAM



“Elements” may be joined at nodes

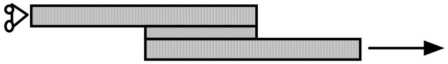
Force and displacement boundary conditions applied at nodes

Adhesive layer treated with same mechanics as adherend plates

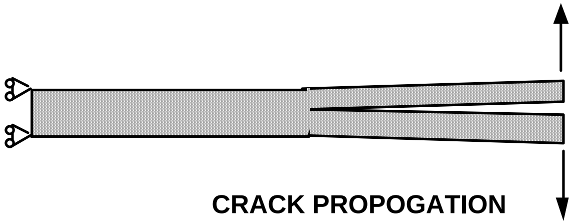
Common displacement and tractions along entire interface

Zig-Zag type theory
Linear distribution for u & v
Quadratic for w

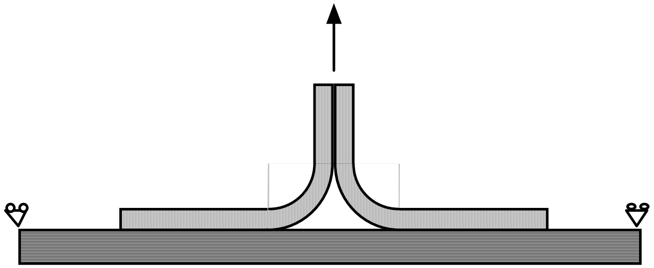
Classes of Problems Solved by SUBLAM



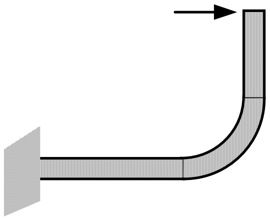
BONDED JOINT



CRACK PROPOGATION

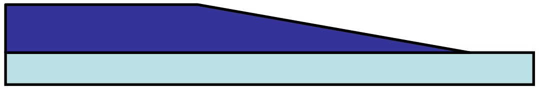


STIFFENER ELEMENT



CURVED BEAM

Shear Loading



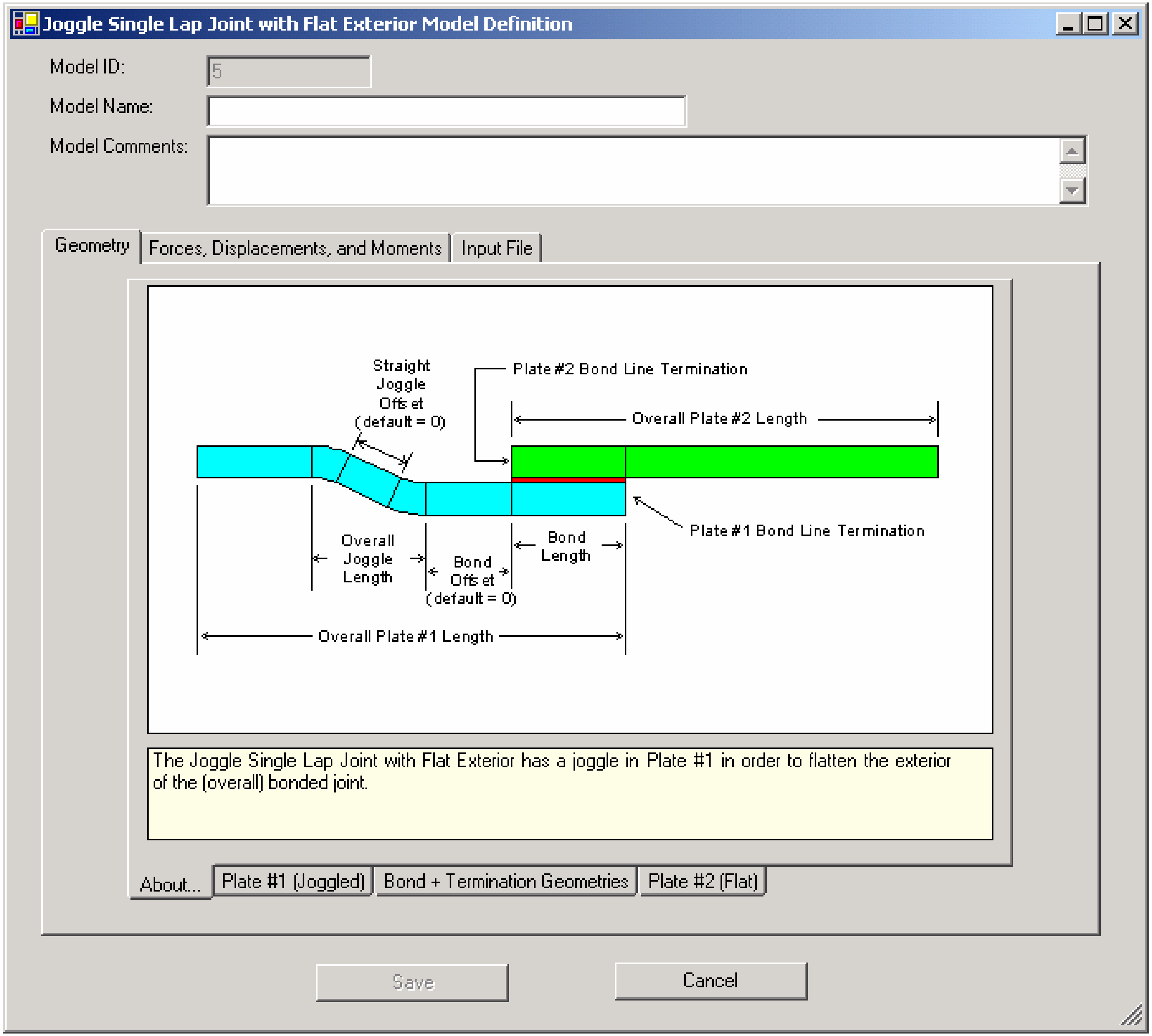
Tapered Elements

SUBLAM Approach

- Stacked, high-order plates
  - Plates are laminated, with full material information captured
  - For uniform plates, governing differential equations solved in closed-form
  - Plate equilibrium equations used to compute interfacial tractions
- Plates joined end-to-end to form complex structures
- Tapered and nonlinear elements handled using P-element approach
  - Legendre polynomial series
  - Equilibrium equations used as with exact solution
- Generalized plane-strain
  - Prismatic structures

Graphical User Interface

- Standard Microsoft Windows features
- Extensive use of database concepts
  - Storage of material properties
  - Store user models
- Interactive parametric modeling
- Graphical output and report generation.



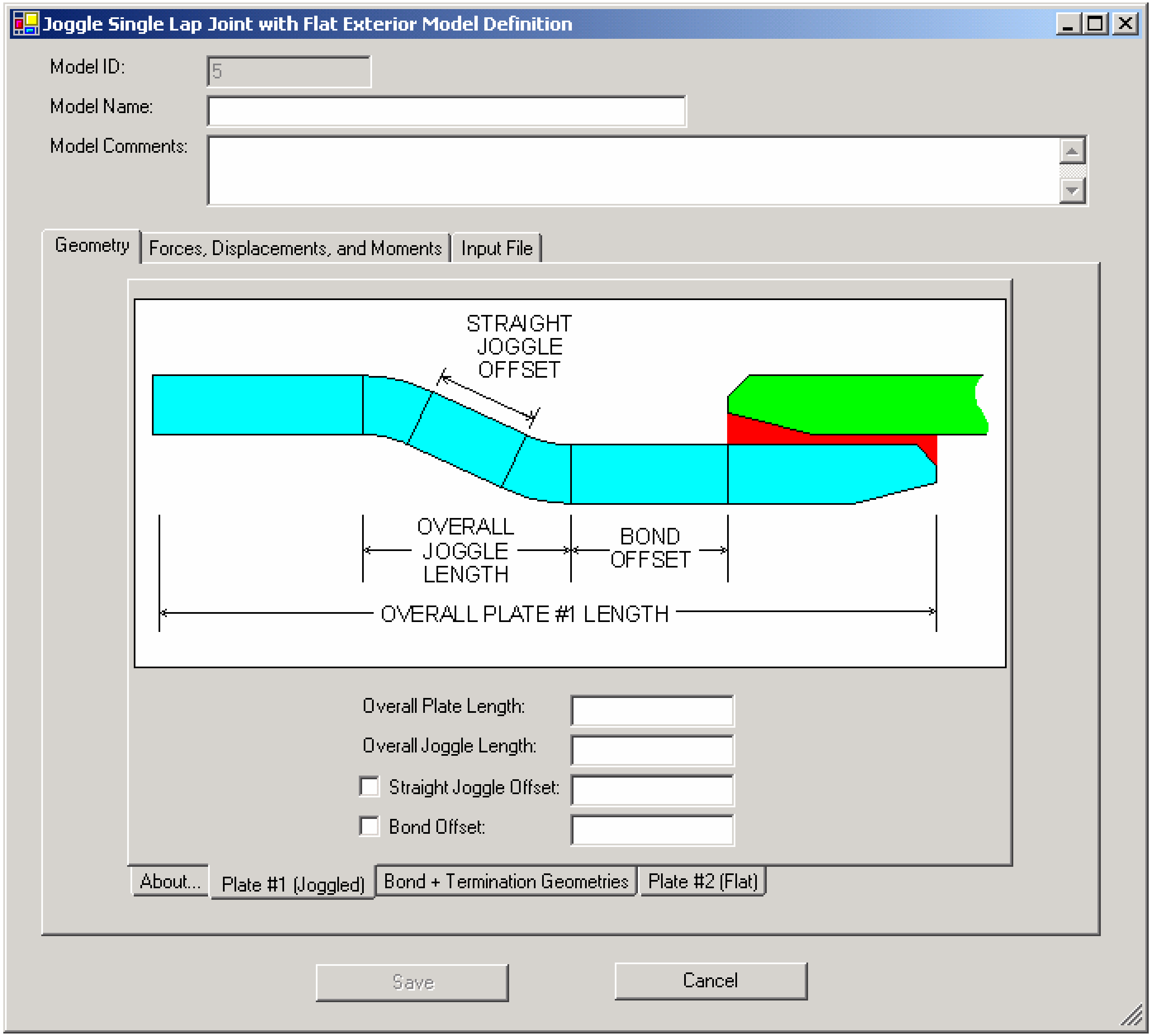
Joggle Single Lap Joint with Flat Exterior Model Definition

Model ID: 5

Model Name:

Model Comments:

The Joggle Single Lap Joint with Flat Exterior has a joggle in Plate #1 in order to flatten the exterior of the (overall) bonded joint.



Joggle Single Lap Joint with Flat Exterior Model Definition

Model ID: 5

Model Name:

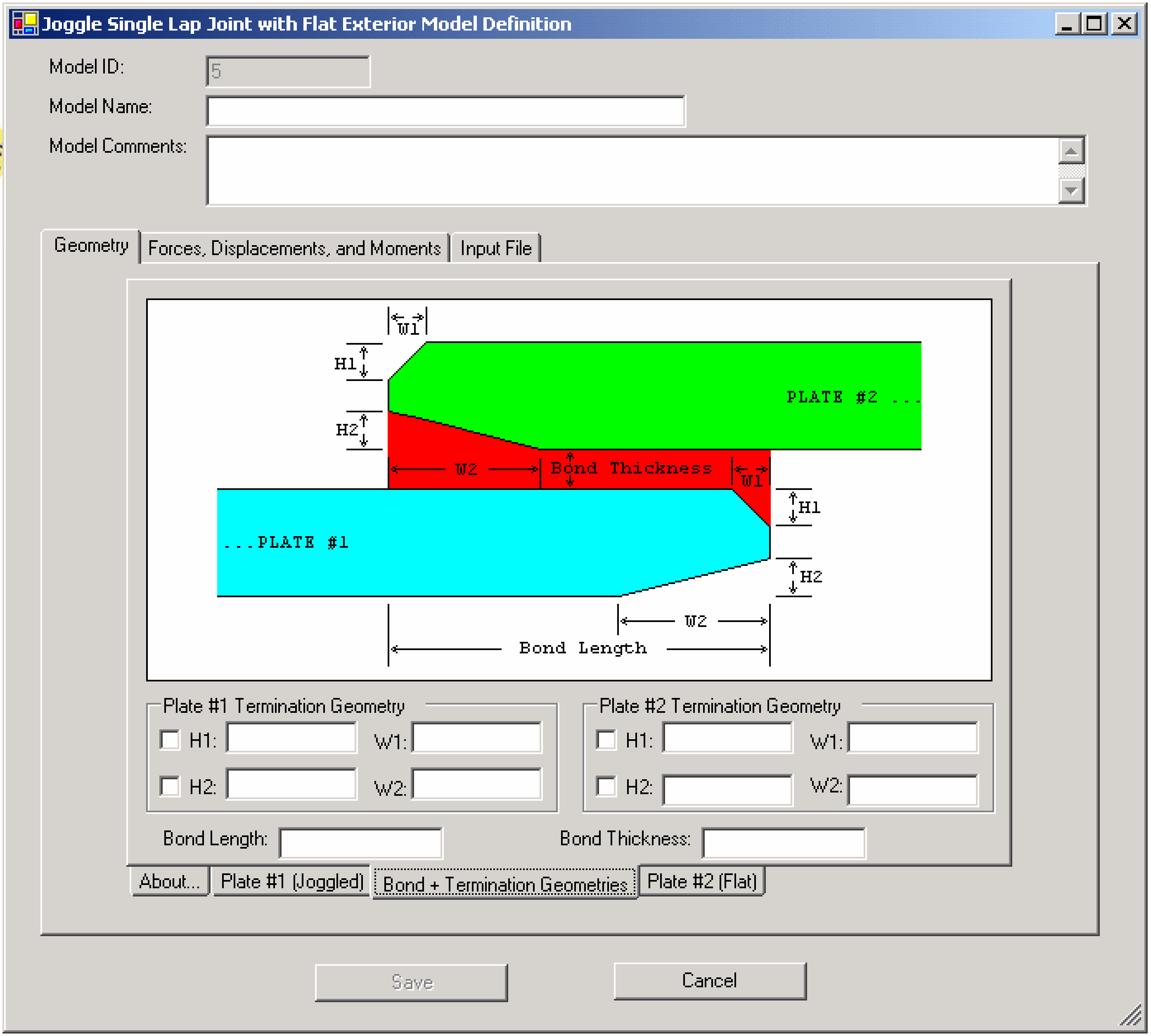
Model Comments:

Overall Plate Length:

Overall Joggle Length:

☐ Straight Joggle Offset:

☐ Bond Offset:



Joggle Single Lap Joint with Flat Exterior Model Definition

Model ID: 5

Model Name:

Model Comments:

Plate #1 Termination Geometry

☐ H1:

W1:

☐ H2:

W2:

Plate #2 Termination Geometry

☐ H1:

W1:

☐ H2:

W2:

Bond Length:

Bond Thickness:

Analysis Code - Summary

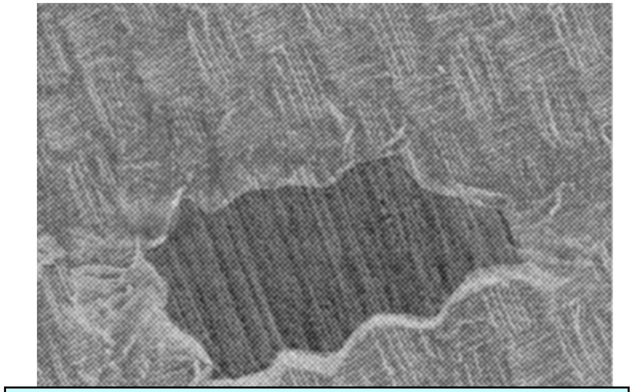
- A commercial quality, very general bonded joint analysis code is being created
  - Built on a proven, accurate, analysis engine
  - Graphical interface for productivity and ease-of-introduction
- Code is being combined with advanced mechanics concepts for adhesive behavior
- Beta testing - next month
- Technical Contact at MSC
  - Gerry Flanagan, flanagan@materials-sciences.com

Surface Preparation

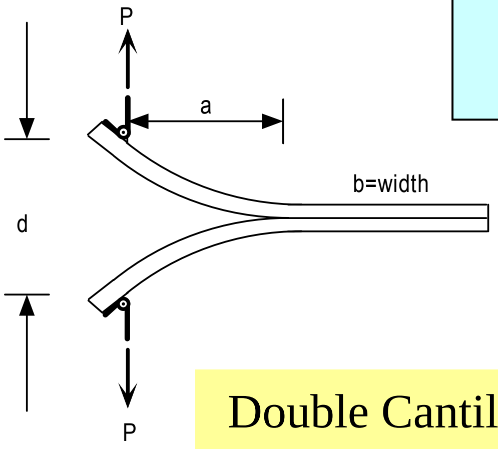
- Peel-ply effects, sanding, and mechanical test evaluations
  - Jason Bardis and Keith Kedward at University of California Santa Barbara
  - Reports
    - “Effects of Surface Preparation on Long-term Durability of Composite Adhesive Joints” DOT/FAA/AR-01-7
    - “Effects of Surface Preparation on Long-term Durability of Adhesively Bonded Composite Joints” DOT/FAA/AR-03-53
- Started four grants to develop chemical test(s) for adequacy of surface preparation, moisture effects, and aging
  - Wichita State, U. of Washington, Washington State, Florida International

Surface Preparation and Peel Ply Studies

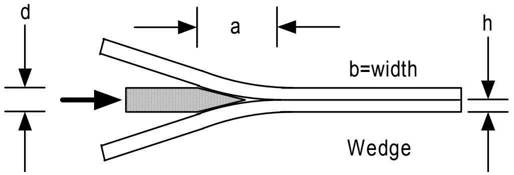
- University of California Santa Barbara Objectives: Develop guidance and supporting engineering practice to minimize or prevent interfacial failure in composite bonded joints
  - Material nomenclature (peel ply vs. release fabric)
  - Recommended fabrication practices
  - Quantitative methods to substantiate bond processes (chemical & mechanical testing during fabrication)
- Technical considerations in initial UCSB work
  - Chemical contamination of removable plies
  - Abrasion for surface preparation
  - Mechanical quality control tests



Chemical contamination from a nylon release fabric causes interfacial failures
(Ref: Hart-Smith, Brown, Wong)



Double Cantilever Beam (DCB) Test

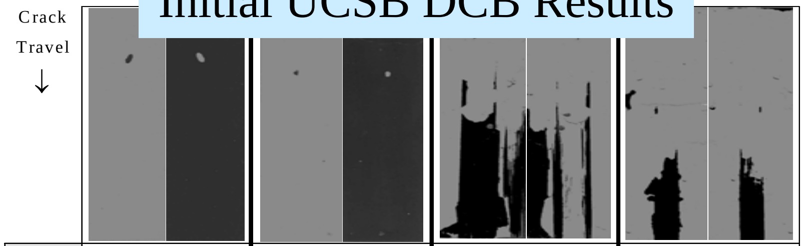


Composite equivalent of the Boeing wedge test

UCSB Bonding Results

- Improper use of removable layers has led to AD
- Removable plies or layers that leave chemical contamination on bonding surfaces include release fabrics and release films
  - Surface abrasion (grit blasting) will not guarantee the elimination of contaminates and potential, undesirable adhesive (interfacial) failures
  - Ongoing efforts to establish standard terminology for removable plies and update product labels & technical literature to warn of potential bonding problems

Initial UCSB DCB Results



Bond	release fabric - release fabric	release fabric – release fabric	vac bag – vac bag	vac bag – vac bag
Blast	no	yes	no	yes
Failure	purely interfacial	purely interfacial	cohesive/interlaminar	cohesive/interlaminar

Black is IM7/8552 adherend, gray is EA9394 adhesive

- The terminology “peel ply” will be used only for those removable plies that contain no chemical treatment to aid release
  - More research is needed to establish guidance for peel ply use in bonding

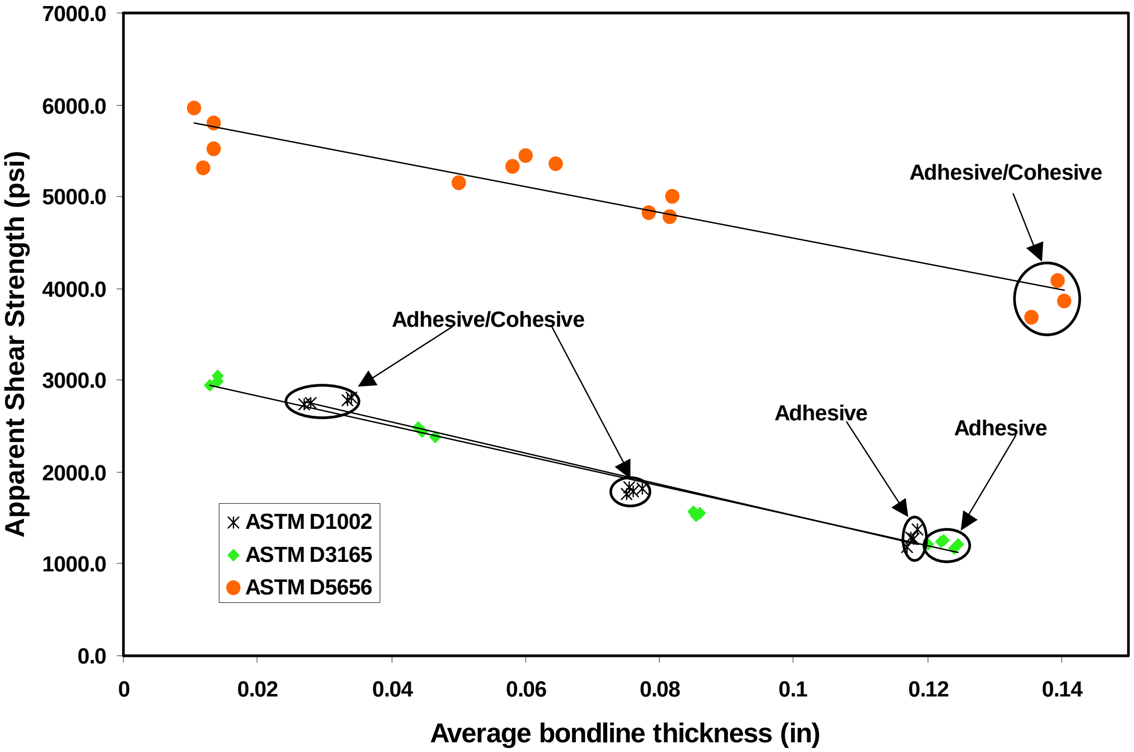
Adhesive Qualification and Characterization

- Adhesive qualification
  - – FAA Survey
    - John Tomblin, Wichita State University
  - – Test method development
    - Charles Yang, Wichita State University
    - Dan Adams, University of Utah
- Adhesive characterization
  - – Static properties
    - John Tomblin et al, Wichita State University
  - – Fatigue and creep
    - John Tomblin et al, Wichita State University

Adhesive Qualification

- FAA Survey
  - Results of survey were discussed at the US Workshop
- Test method development
  - Lap shear test methods
    - "Investigation of Adhesive Behavior in Aircraft Applications" DOT/FAA/AR-01/57
    - "Analytical Modeling of ASTM Lap Shear Adhesive Specimens" DOT/FAA/AR-02/130
  - Bulk adhesive testing
    - Use recently developed University of Utah V-Notch Rail Shear Test for bulk shear property
    - "Development and Evaluation of the V-Notched Rail Shear Test for Composite Laminates" DOT/FAA/AR-03/63

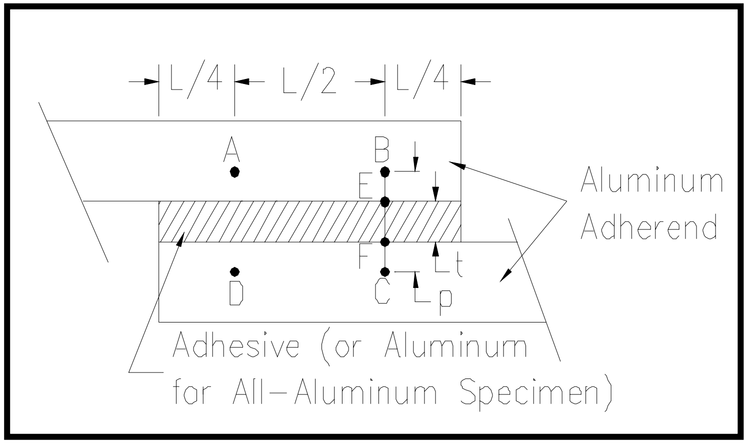
Adhesive Test Methods



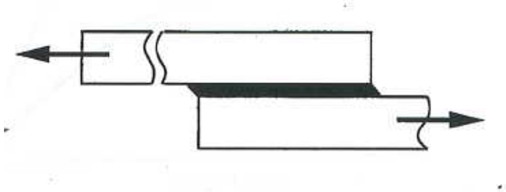
- ASTM D1002 & D3165 for joint characterization
- ASTM D5656 for adhesive characterization

ASTM D5656 Test Method

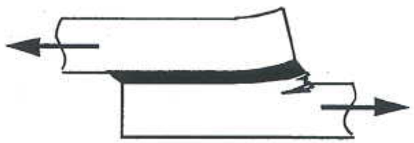
- Thick adherend
  - ***Adhesive*** characterization rather than ***Joint*** characterization
  - Elastic Limit & Plastic Strain
  - Design & Analysis
  - Reduces peel stresses
- Correction for metal deformation
- Four-Pin Configuration
  - Reduces errors due to rotation and slippage
  - Reduces scatter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



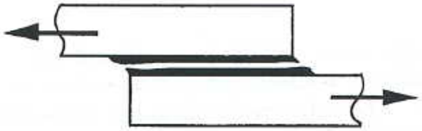
Failure Modes



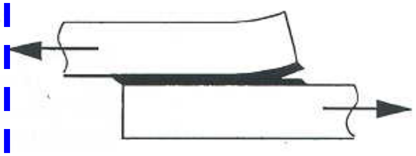
a. Adherend Failure
(Outside of Joint)



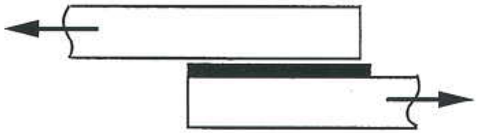
b. Adherend Failure
(Composite Interlaminar Fracture)



c. Cohesive Failure
(Shear)



d. Cohesive Failure
(Peel)



e. Adhesive Failure
(Shear)

f. Adhesive Failure
(Peel)

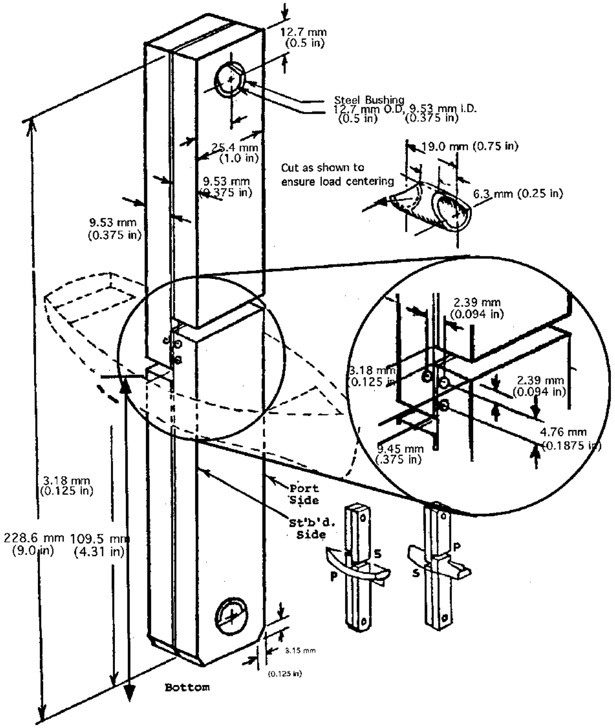
ASTM D5656

Adhesive Characterization

- Static properties
  - “Shear Stress-Strain Data for Structural Adhesives” DOT/FAA/AR-02/97
- Fatigue and creep
  - “Fatigue and Stress Relaxation of Adhesives in Bonded Joints” DOT/FAA/AR-03/56

Test Matrix for Determination of Shear Properties 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”

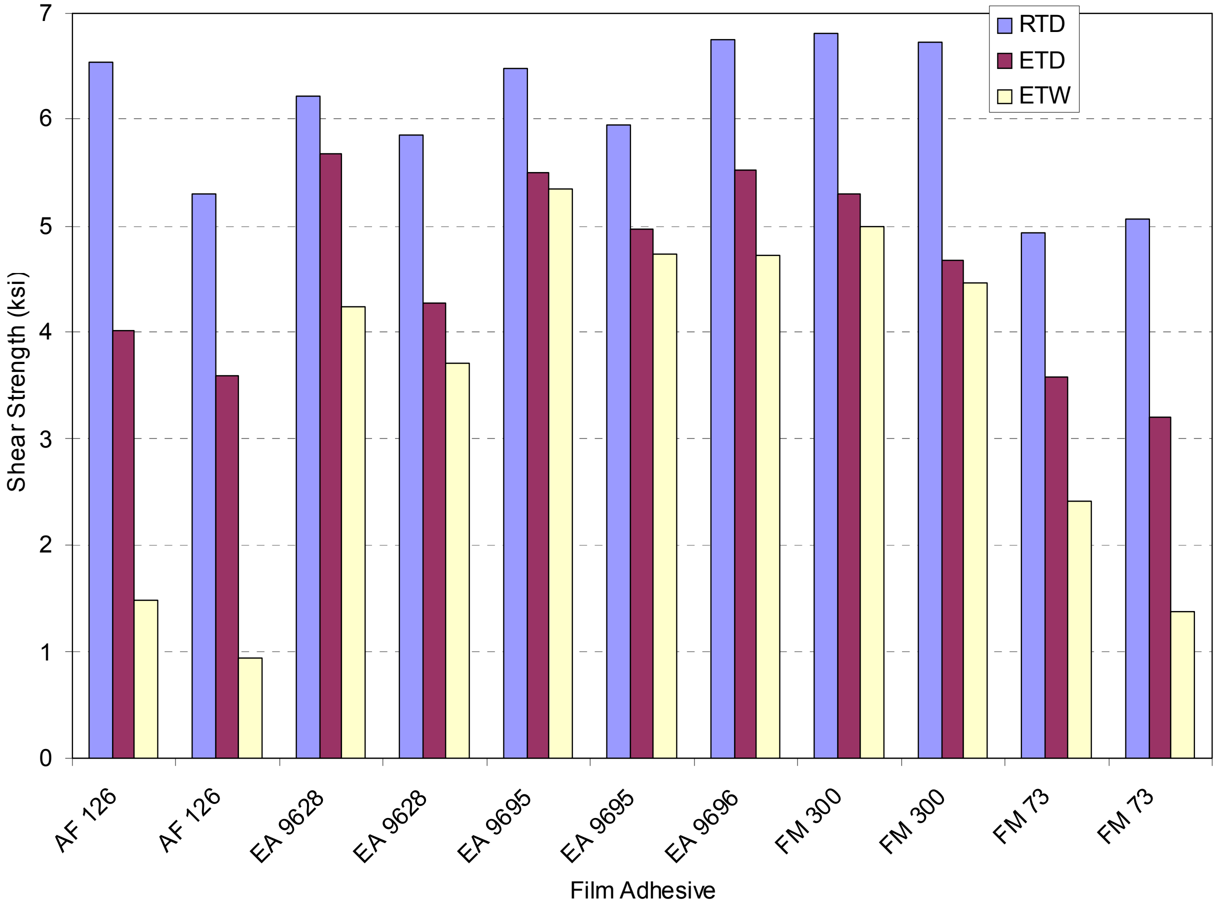


Adhesive Types Investigated

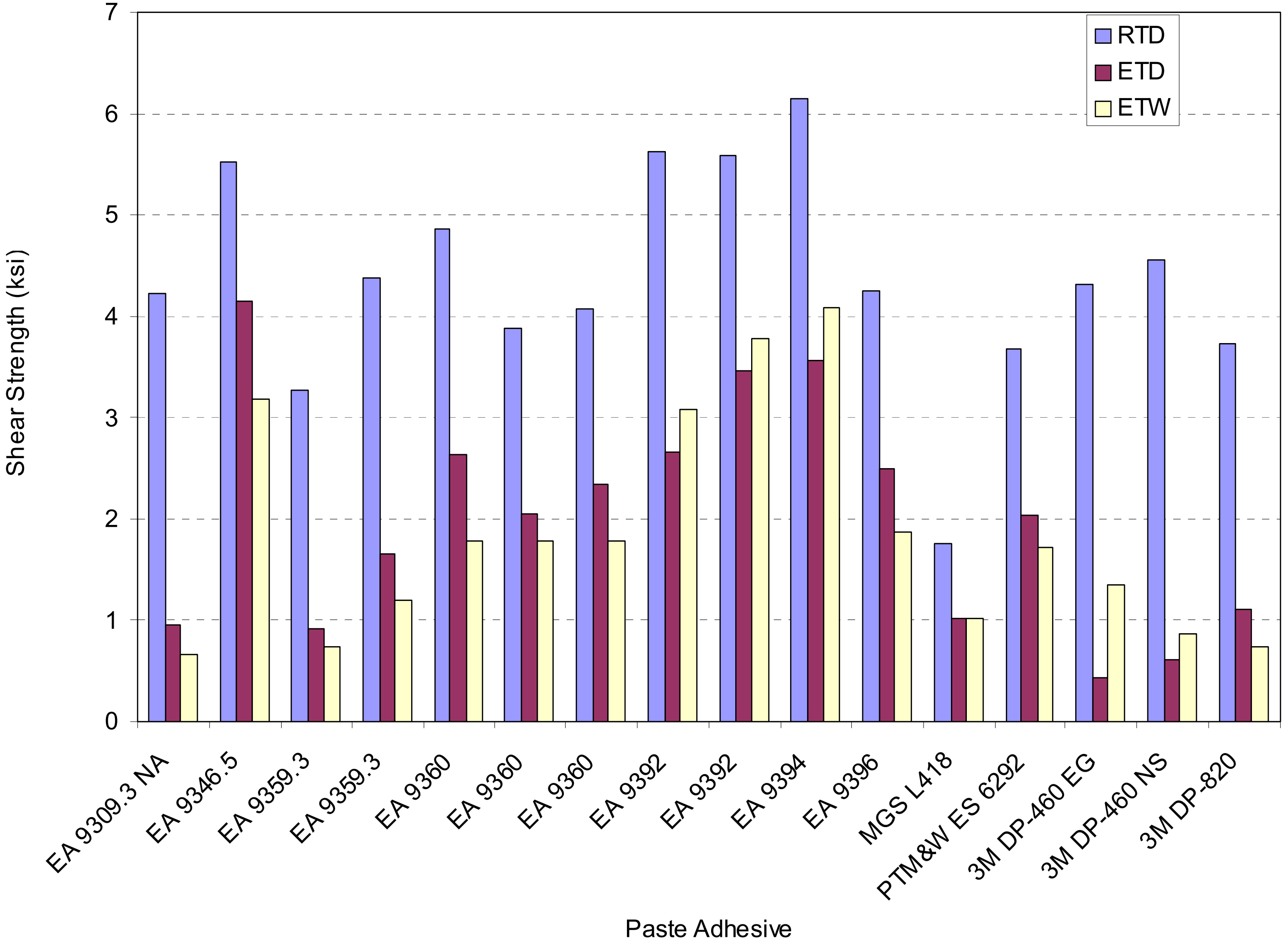
- Film Adhesives (6)
  - AF 126
  - EA 9628
  - EA 9695
  - EA 9696
  - FM 300
  - FM 73
- Paste Adhesives (12)
  - EA 9309.3 NA
  - EA 9346.5
  - EA 9359.3
  - EA 9360
  - EA 9392
  - EA 9394
  - EA 9396
  - MGS L418
  - PTM&W ES 6292
  - 3M DP-460 EG
  - 3M DP-460 NS
  - 3M DP-820

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

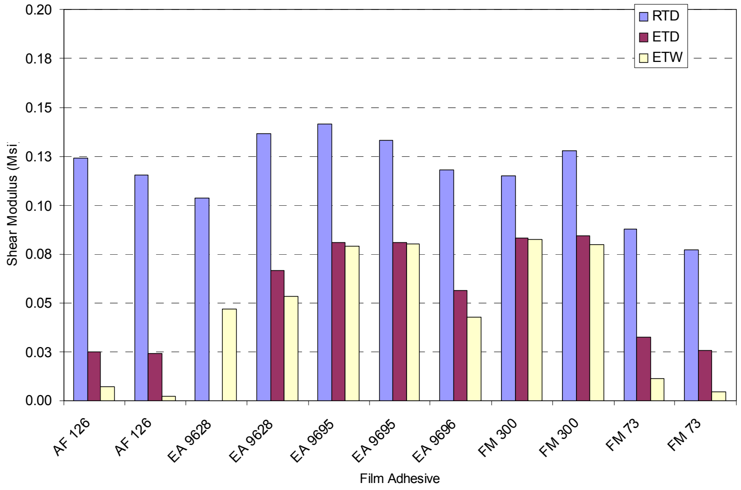
Apparent Shear Strength Comparison



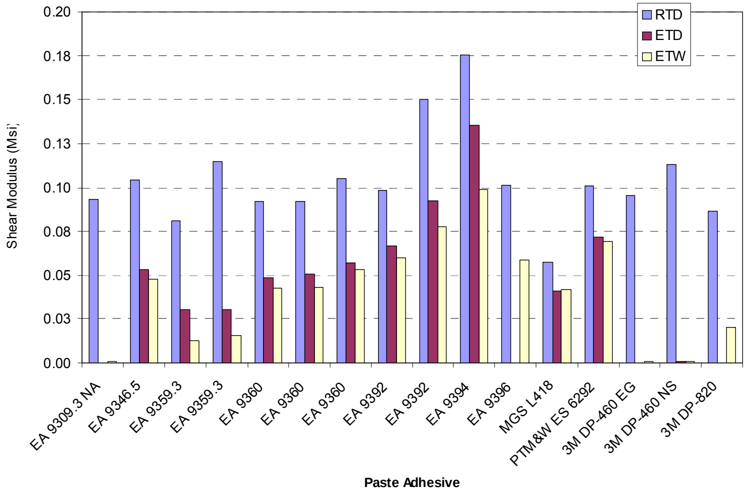
Apparent Shear Strength Comparison



Initial Shear Modulus Comparisons



Film Adhesive



Paste Adhesive

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

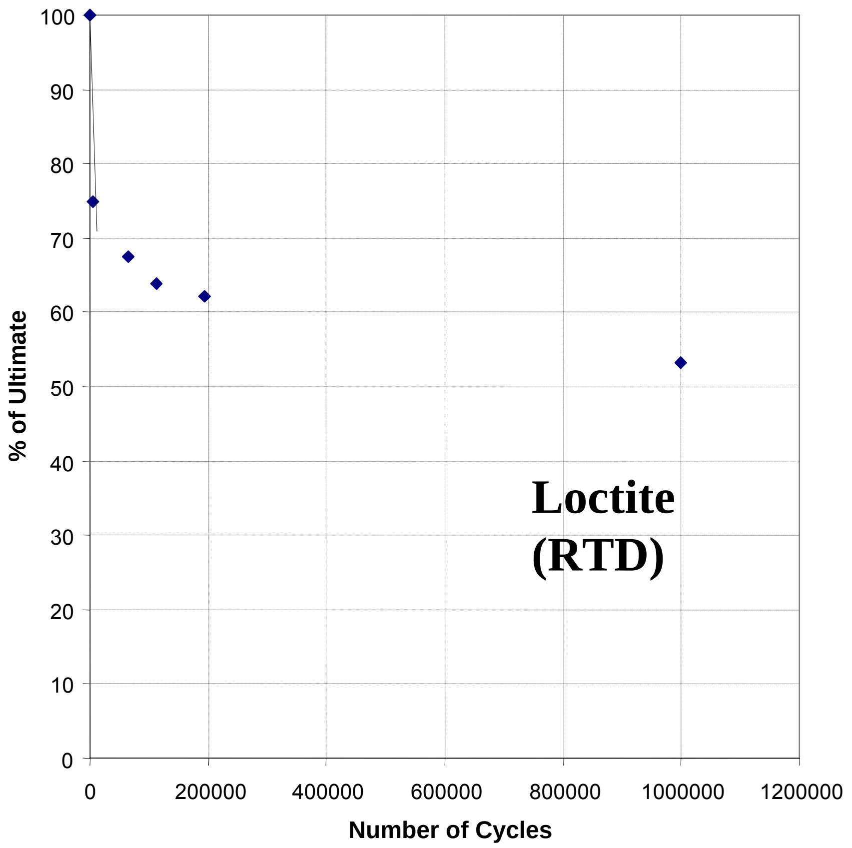
y=-3.227*ln(x)+100.96

100000Cy SL1≈65% UL ≈183% LL

10000Cy SL2≈72% UL ≈202% LL

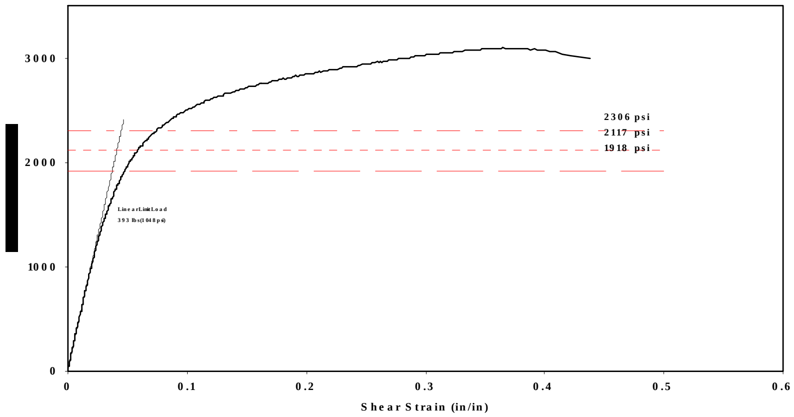
1000Cy SL3≈78% UL ≈220% LL

Note: For RTW and CTD, %UL are different

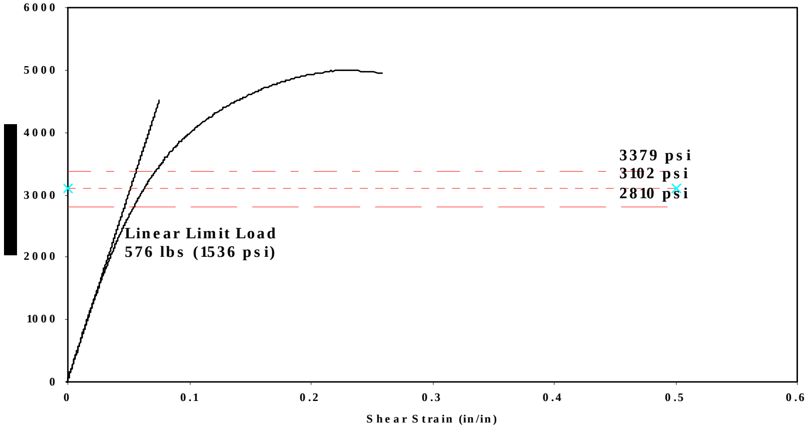


Loctite Stress Levels

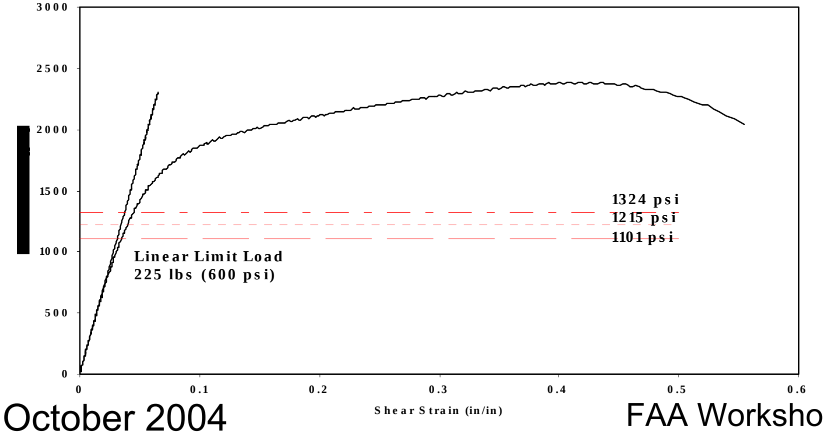
Loctite RTD



Loctite CTD



Loctite RTW

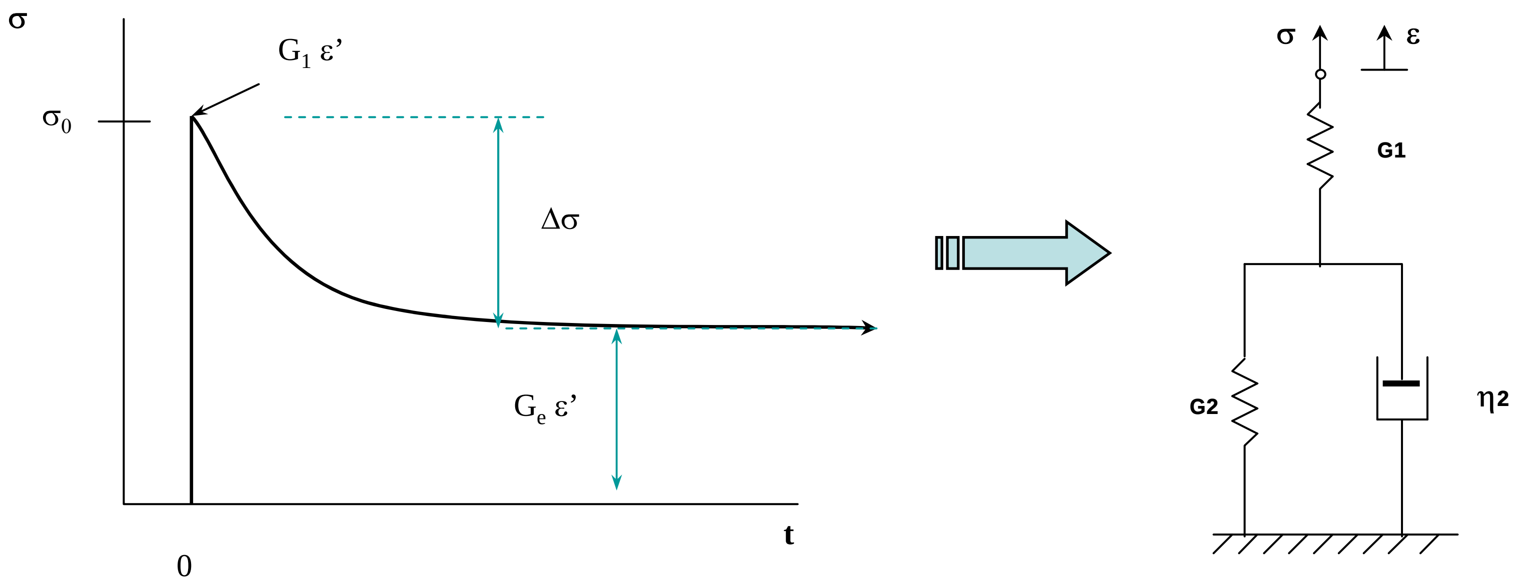


Fatigue life in a range below knee point and above linear limit point.

Fatigue Behavior of Adhesives

- *‘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 content in bondline equals longer fatigue life
- Film adhesive indicates better resistance to moisture (less voids?)
- Low frequencies resulted in shorter life, probably due to creep effects: high frequencies did not result in temperature increase during testing

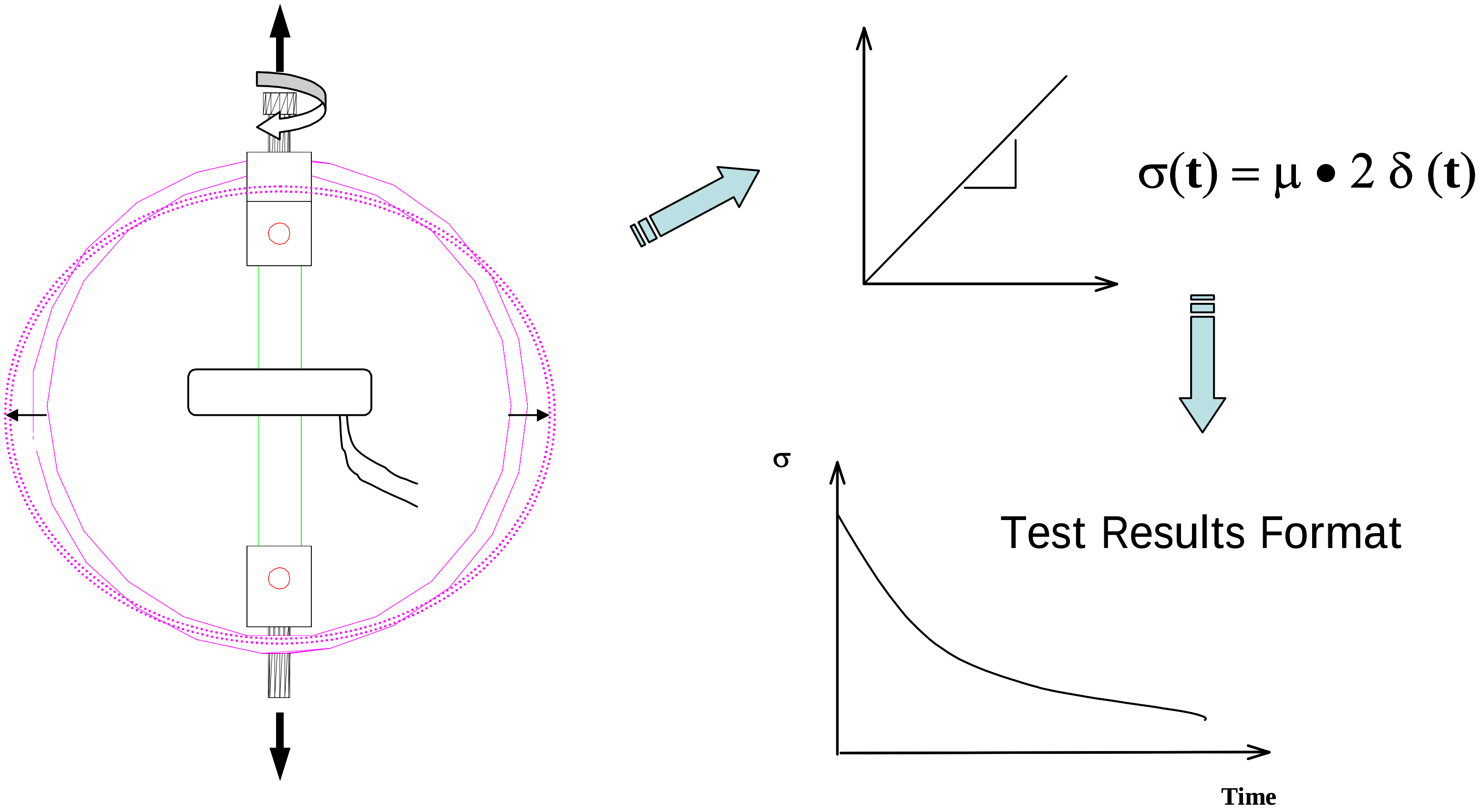
Stress Relaxation of Adhesive Joints



- 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

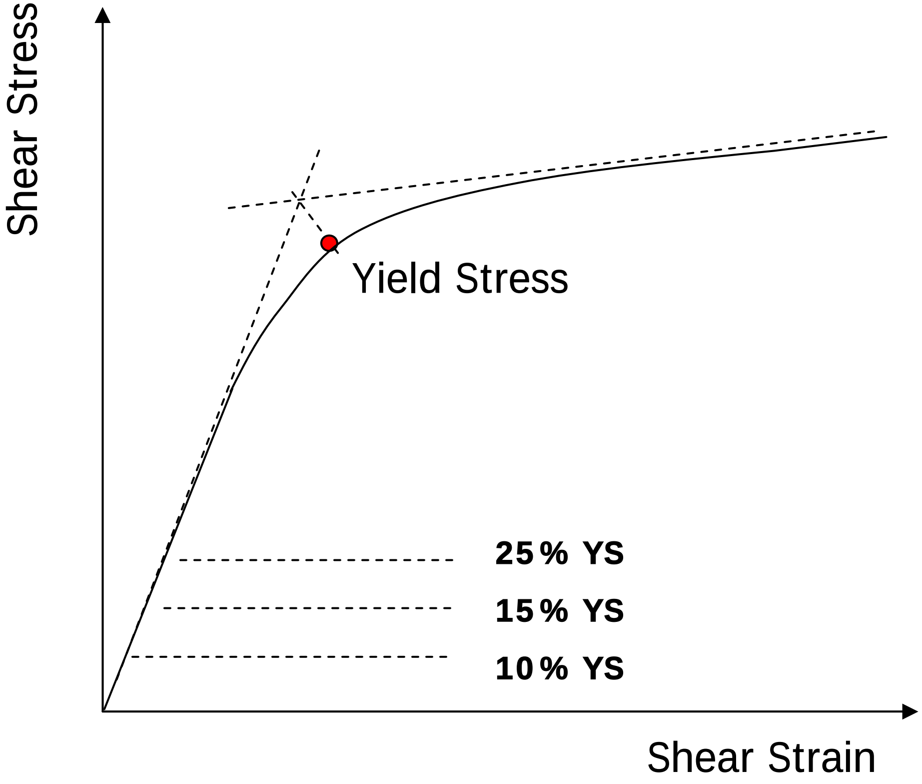
Calibration for each environmental condition



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

Test Results Format

Stress Level Determination



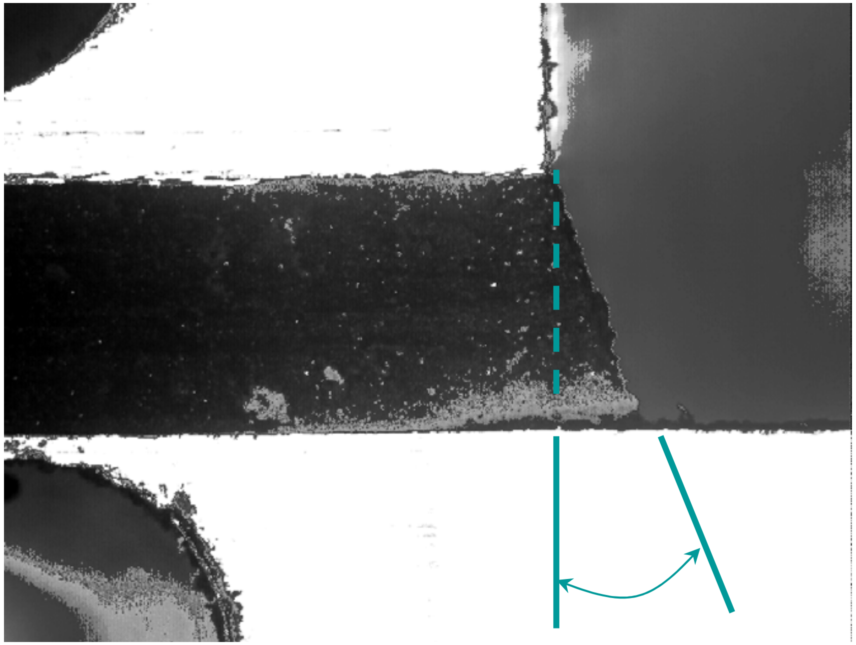
Test Temperatures

150°F

180°F

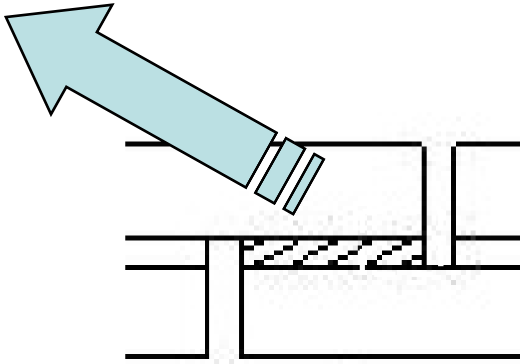
210°F

Creep Deformation

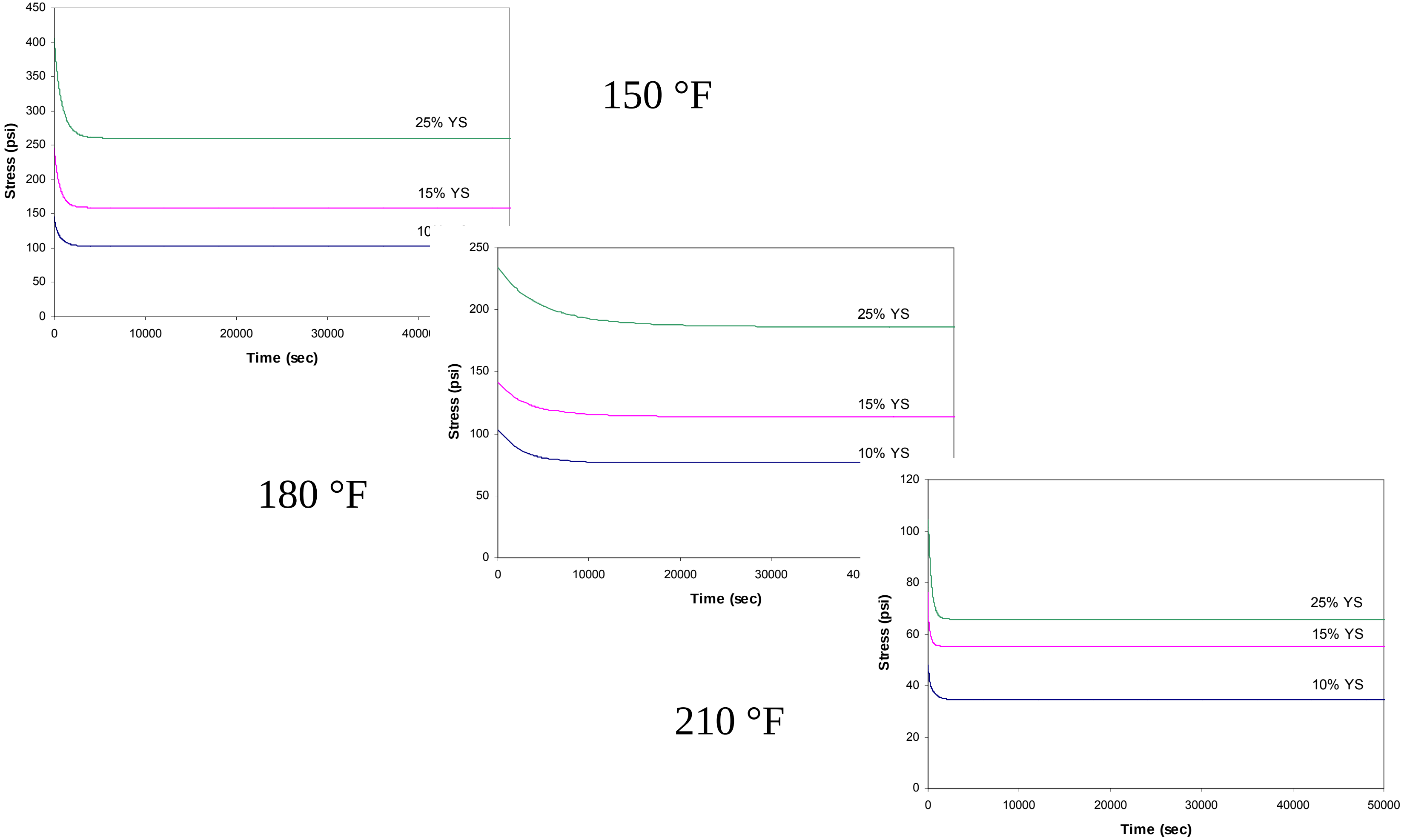


[50X magnification]

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



Loctite Stress Relaxation Results



150 °F

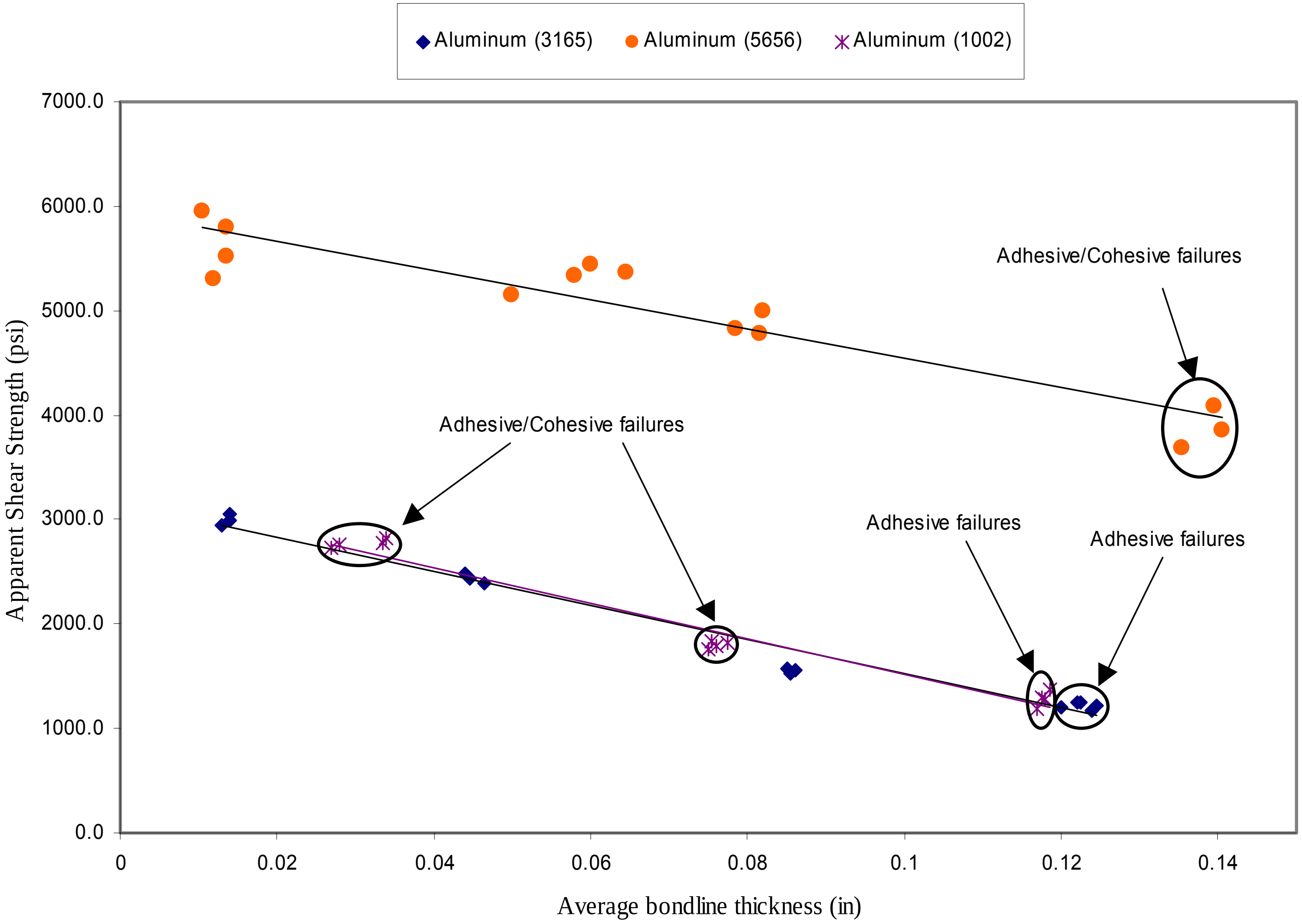
180 °F

210 °F

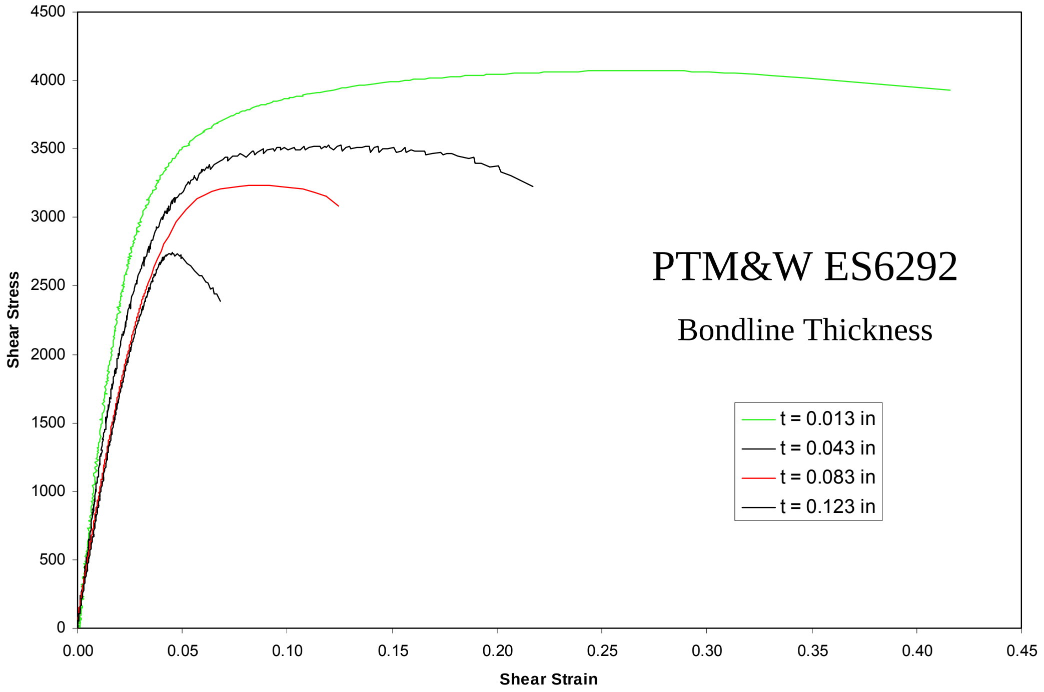
Thick and Variable Bondline Effects

- Thickness effects on strength
  - Different ASTM test methods
  - John Tomblin, Wichita State University
  - “Investigation of Thick Bondline Adhesive Joints” DOT/FAA/AR-01/33
- Variable bondline effects
  - Length and width tapers
  - Yuqiao Zhu and Keith Kedward, University of California Santa Barbara
  - “Methods of Analysis & Failure Predictions for Adhesively Bonded Joints of Uniform and Variable Thickness”, to be published

Shear Strength Results vs Bondline Thickness

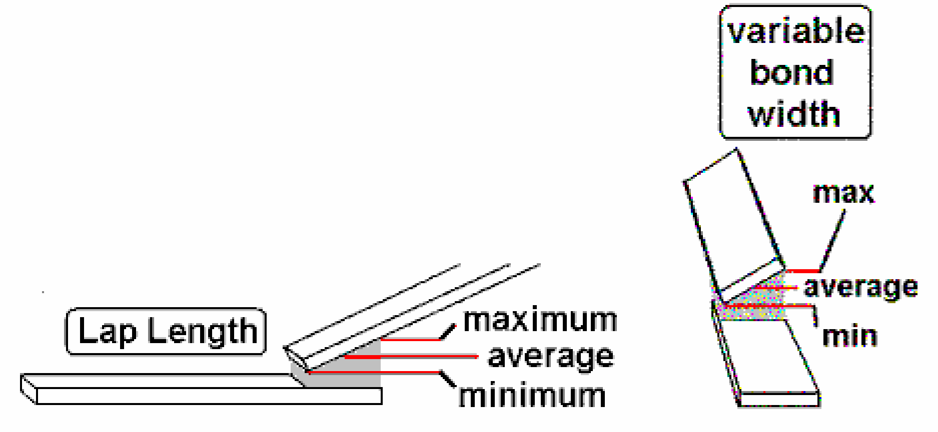


Bondline Thickness Effects



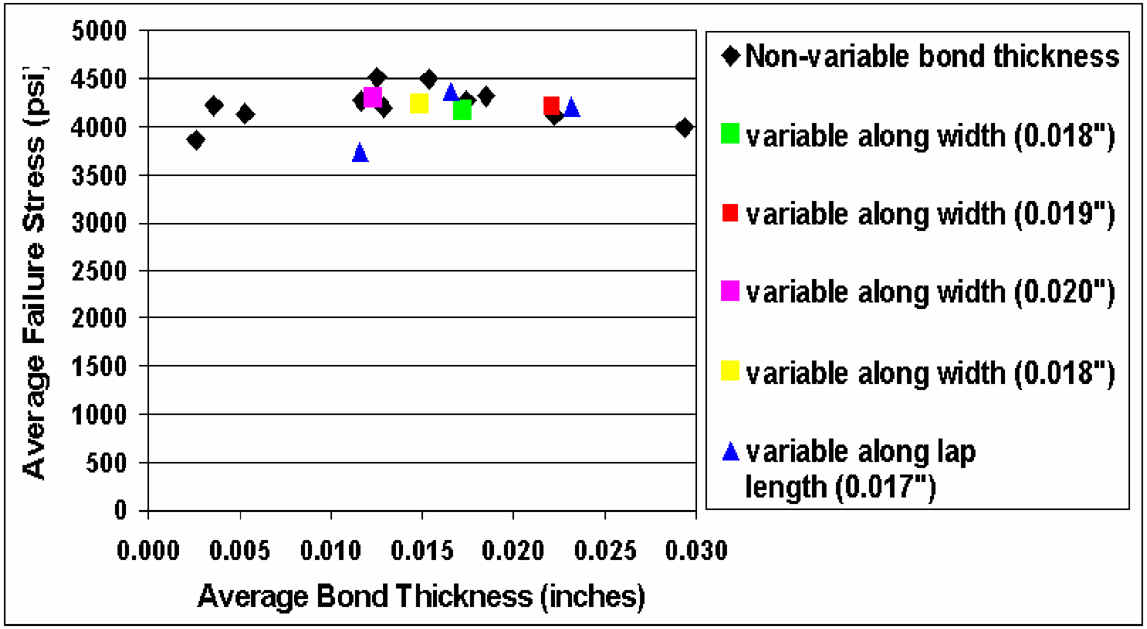
- Increasing bondline thickness resulted in reduced plastic strain and lower yield stress

Bondline Variability Effects



- Average thickness varied from 0.012 to 0.024 inches
- Minimum thickness varied from 0.0035 to 0.0155 inches
- Maximum thickness varied from 0.0205 to 0.0325 inches
- Changes in thickness were ~ 0.018 from the thinnest to the thickest

Bondline Variability Effects



- Adhesive: DP460 (brushed), Cured at 180° F for 1 hour,
- Adherends: Titanium, tested at room temperature
- ASTM D1002-99 single lap joint

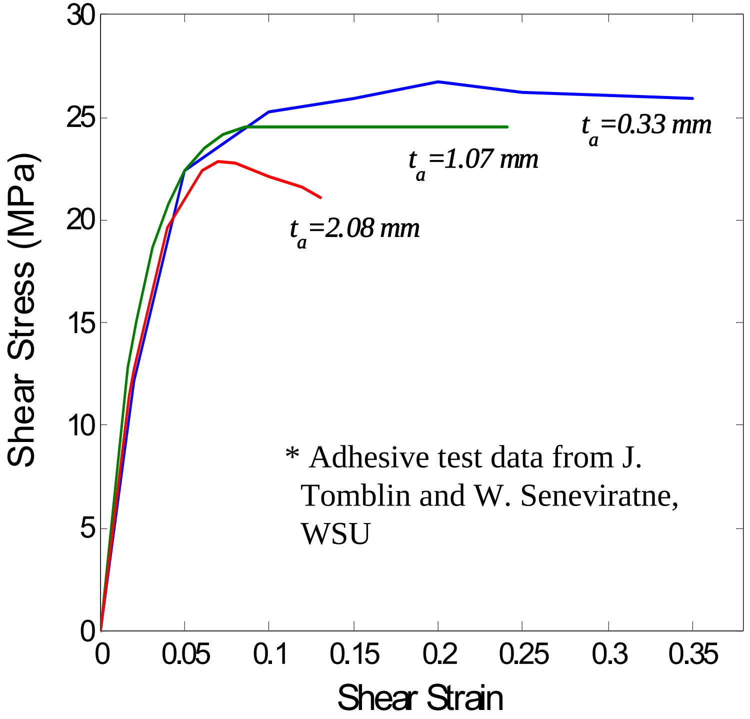
Thick and Variable Bondline Effects (continued)

- Basic understanding of the behavior of thick adhesive joints
  - Hyonny Kim and C.T. Sun, Purdue University
  - Adhesive constitutive relationships
  - Fracture criteria
- Effect of moisture on thick bondlines
  - Thomas Siegmund, Purdue University
  - Diffusivity along the bondline
  - Gradients in moisture content

Intrinsic Material Properties vs. Joint Behavior

- Understand relationship between intrinsic material properties vs. “properties” inferred from structural (joint) behavior
  - **Intrinsic** material properties should be independent of joint configuration, e.g., bondline thickness, mode of loading

- Resolve differences observed from different test methods:
  - Tensile test dogbone
  - Napkin ring
  - ASTM 5656
  - Bulk adhesive

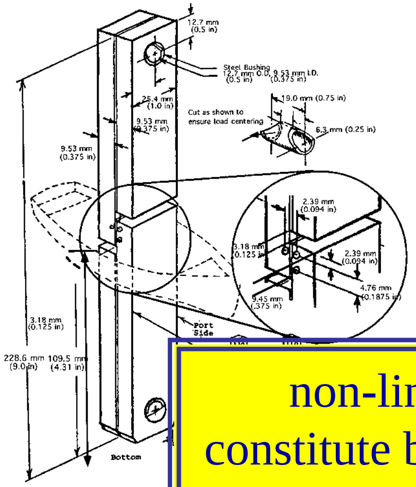


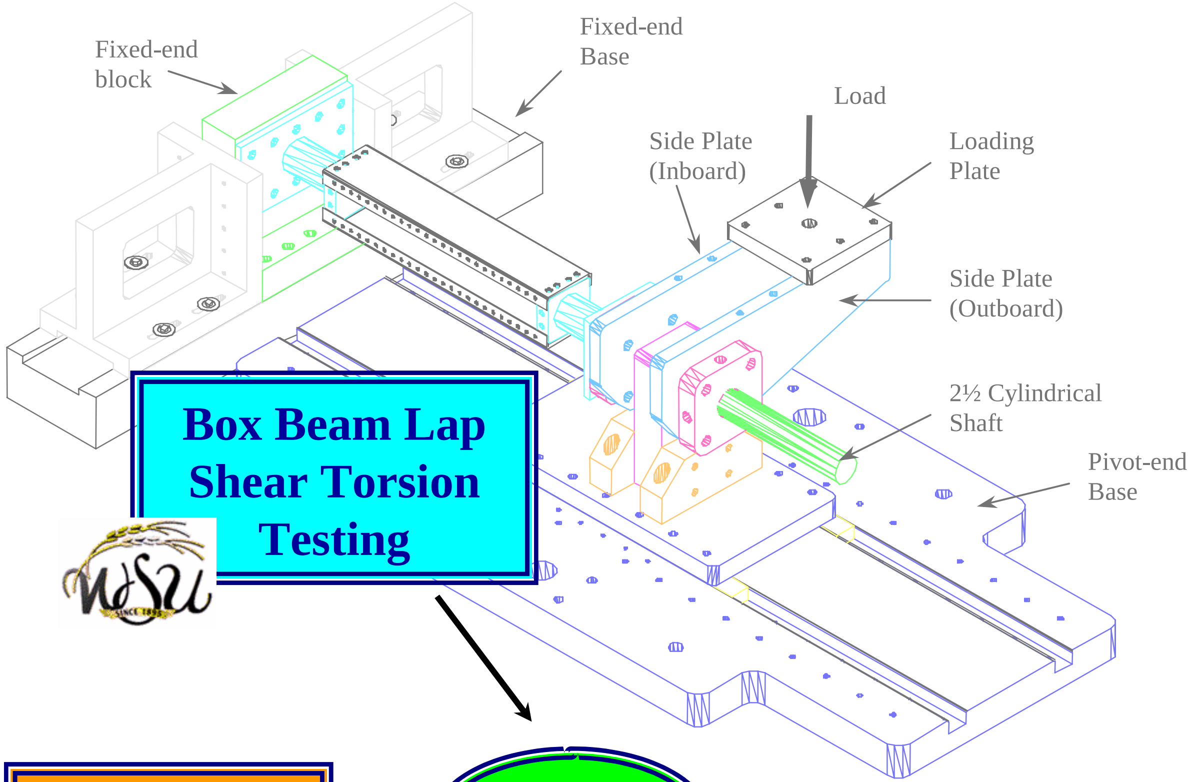
* Adhesive test data from J. Tomblin and W. Seneviratne, WSU

Element Testing

- Torsion beam testing
  - John Tomblin, Wichita State University
  - “Characterization of In-plane, Shear-Loaded Adhesive Lap Joints: Experiment and Analysis” DOD/FAA/AR-03/21
  - Additional tests with disbonds
- Picture frame testing
  - John Tomblin, Wichita State University
  - Disbonds

Box Beam Lap Shear Torsion Test





non-linear constitute behavior of adhesive

Shear Loaded Bonded Joint (SLBJ) Theory

Joint Failure Prediction

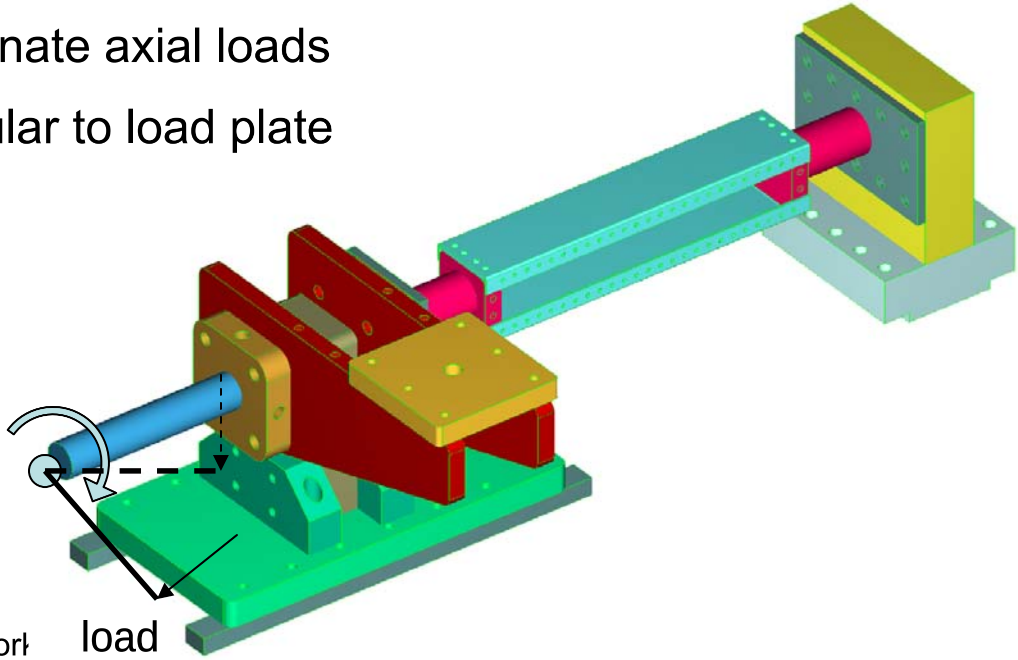
Box Beam Lap Shear Torsion Testing

Validation

Design Guidelines & Certification

Box Beam Torsion Lap Shear Test –Test Setup

- Adhesive: PTM&W ES6292
- Sub-panels: NEWPORT NB321 7781
- Capacity: 56 000 in-lbs [torsion only]
- Specimen Size: 4” x 12” Lap Joint
- Axial Float is allowed to eliminate axial loads
- Measure the load perpendicular to load plate to calculate the torque

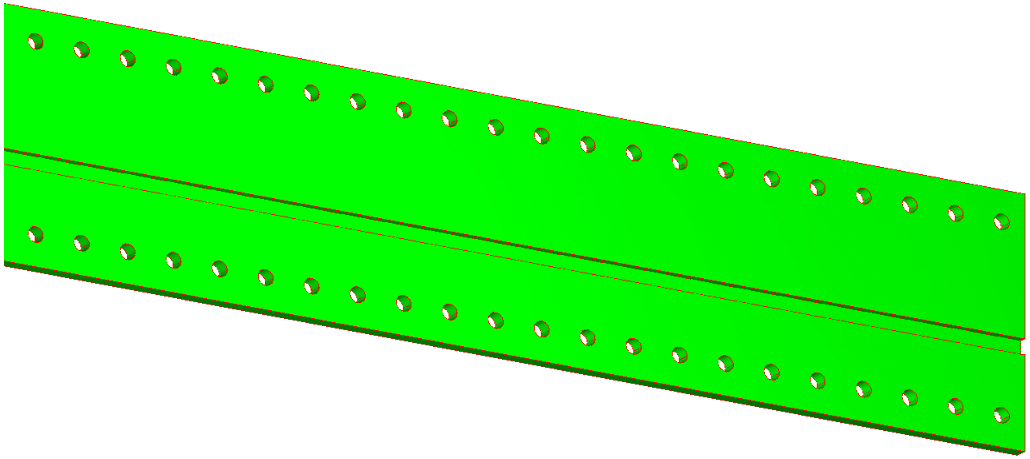


Materials

- 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]

Adhesive Lap Joint Specimen



Gage width ~ 0.5”

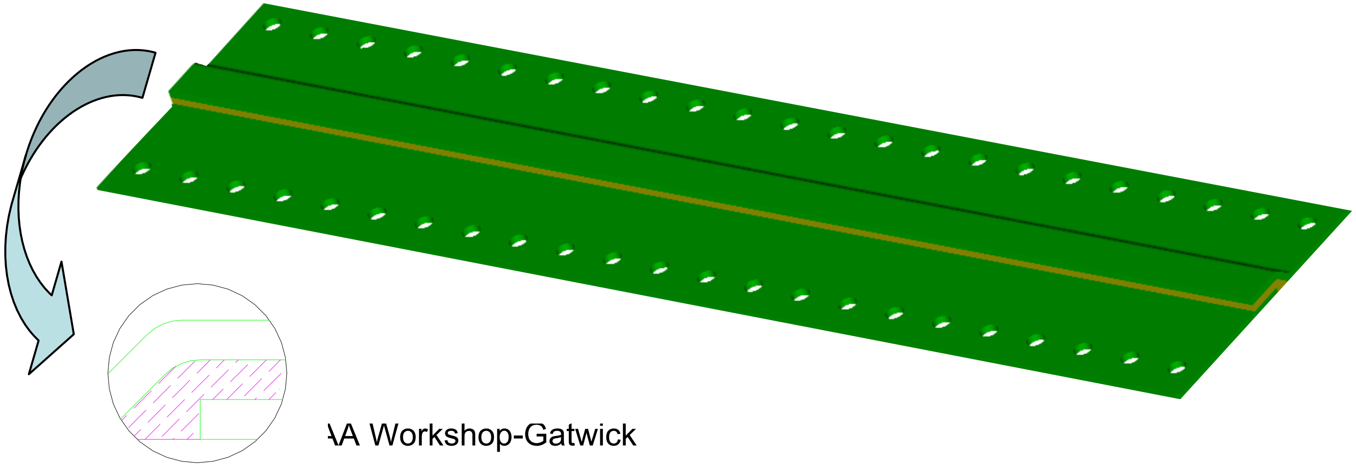
Gage section ~ 17.25”

Flat Joint

PTM&W

EA9360

Loctite

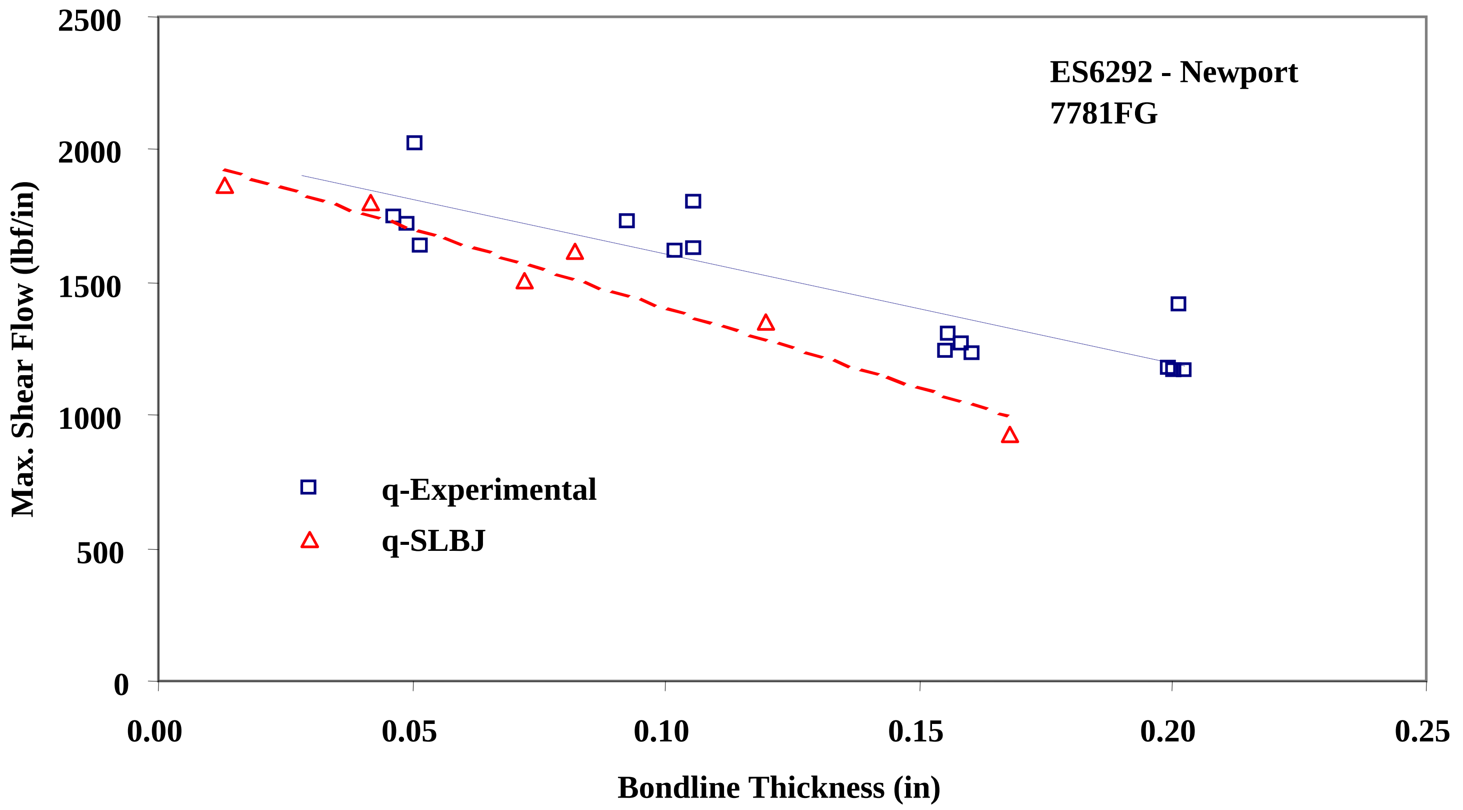


Joggle Joint

PTM&W

EA9360

Test Results



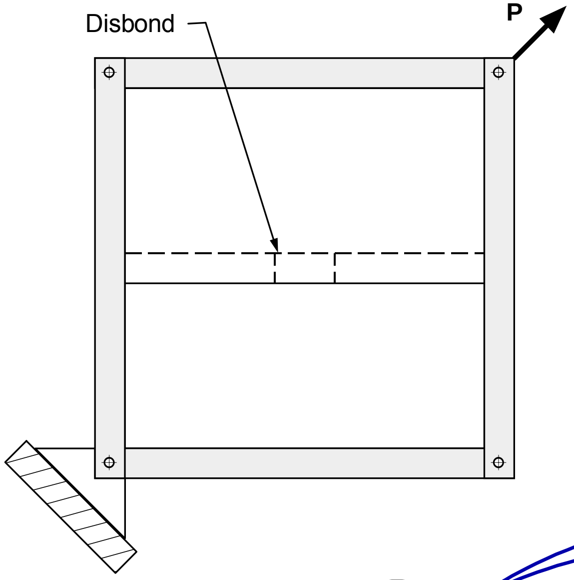
Constitutive behavior for
0.20 was not available

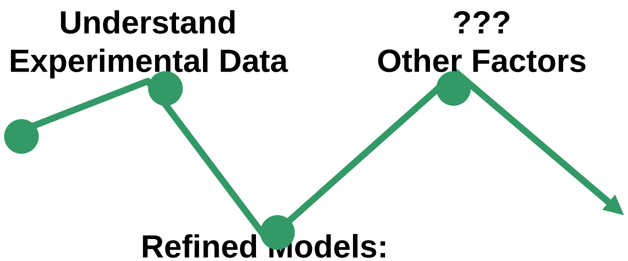
Box Beam Lap Shear Torsion Conclusions

- Load carrying capabilities of adhesive joints decreases as bondline thickness increases, the reduction being the same as for small test coupons
- Purdue Analysis predictions 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

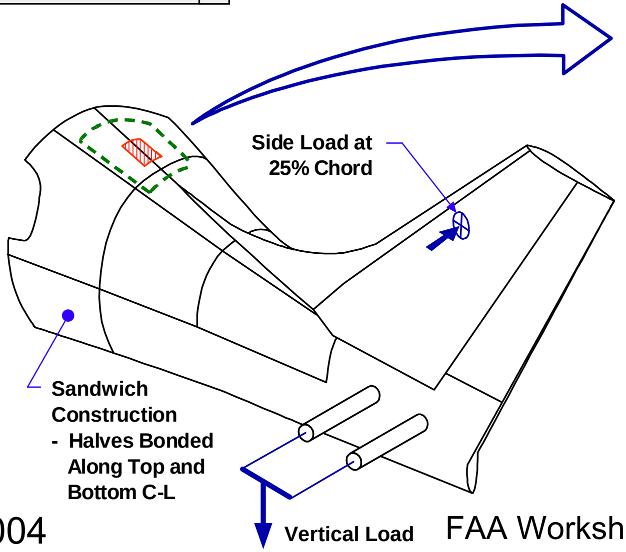
Full-Scale Behavior
Including Damage Tolerance

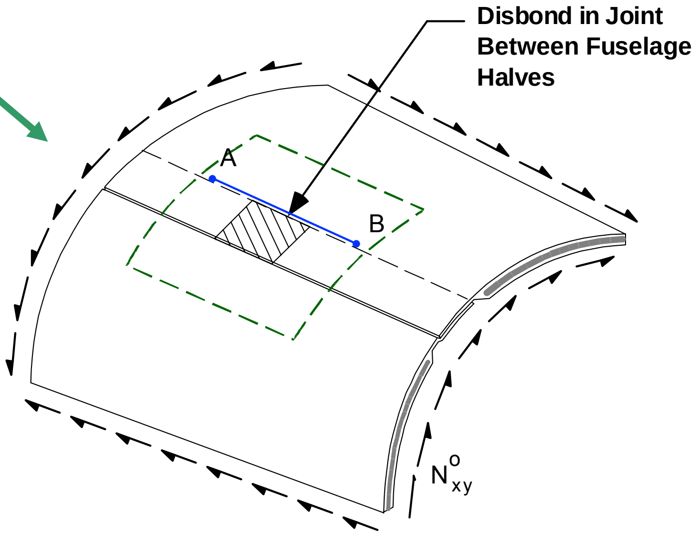
Path to get from Coupons & Elements to Full Scale Component Level





Refined Models:
Adhesive Plasticity, Peel Stress
Failure Under Multiaxial Stress,
Fracture Mechanics

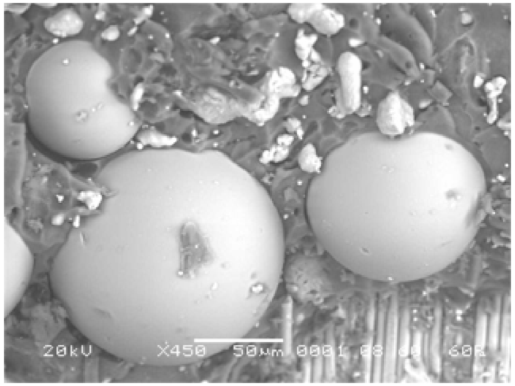




Develop predictive models: maintain balance between simplicity and complexity

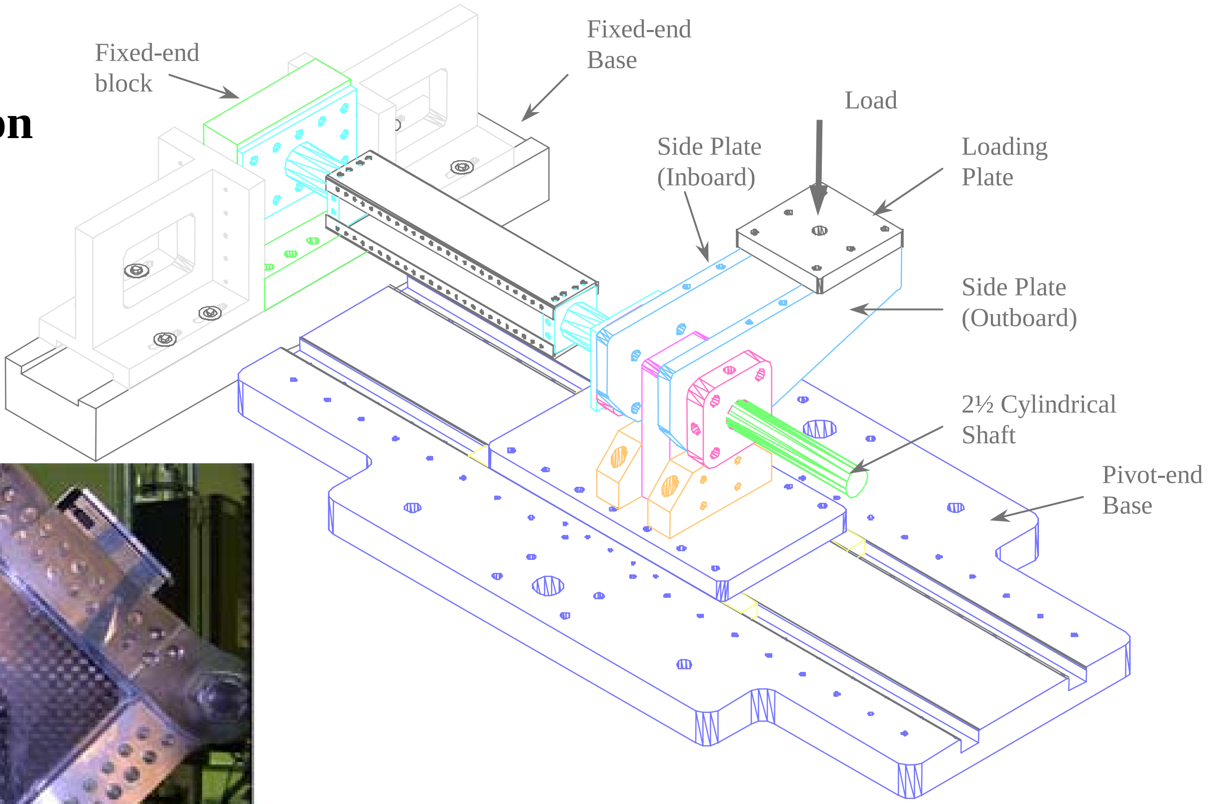
Effects of Defects

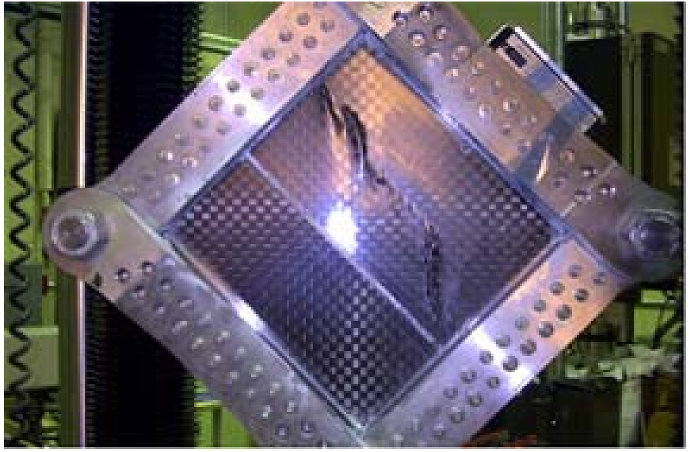
- Variable bondline thickness
- Disbonds/Flaws
  - Effects of different disbond geometries
  - Effectiveness of fasteners to provide fail safety and to prevent catastrophic unzipping of bonds
- Low-velocity impact damages
  - Different impactor diameters
  - Different gage lengths
  - Bondline thicknesses
- Wichita State University



Element Testing

Box Beam Torsion

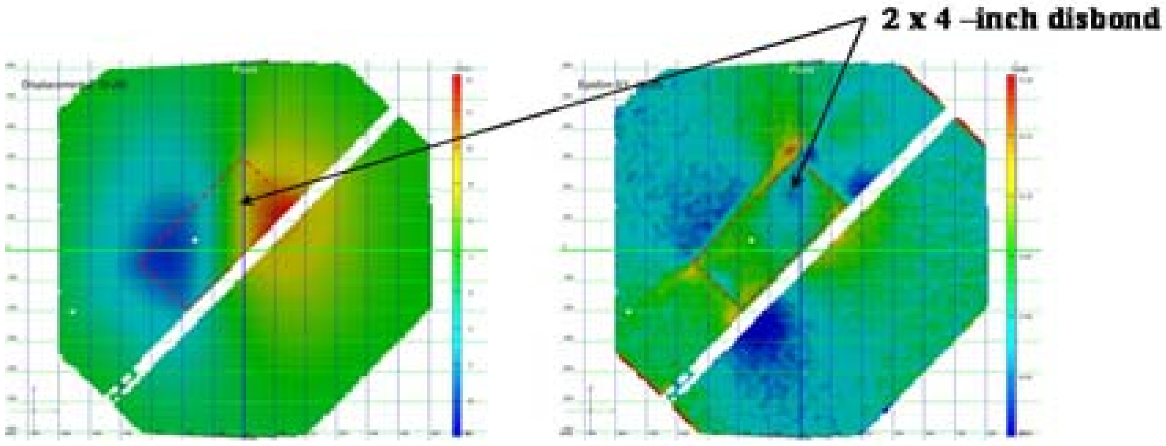




Picture Frame

Picture Frame Shear

- 11.5 x 11.5 –inch test section
- Full-field strain-displacement techniques to detect damage growth



2 x 4 –inch disbond

(a) Z-displacement

(b) In-plane shear strain

Program Results

- There is a decrease in strength for thicker bondlines
- Adhesive strength as a function of environment is highly dependent on glass transition temperature
- Characterized shear stress-strain response of 18 adhesives that can be used by industry for design and analysis and for FAA personnel in certification
- ASTM D5656 is recommended for adhesive characterization
- Thin adherend methods should only be used for quality control
- Taxonomy of peel and release plies has been agreed upon and will be documented in MIL-HDBK-17
- Mechanical tests to determine whether a good bond exists are cumbersome and unreliable - the industry must turn to chemical characterization
- Reports are available at http://actlibrary.tc.faa.gov