Damage Tolerance and Durability of Adhesively Bonded Composite Structures

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The Joint Advanced Materials and Structures Center of Excellence

Damage Tolerance and Durability of Adhesively Bonded Composite Structures

- **Motivation and Key Issues**
  - failure prediction of composite adhesive joints remains a difficult problem
    - multiple failure modes and complex failure processes
    - damage initiation and growth influenced by geometry, loading, and environmental factors such as moisture, temperature, etc.
  - damage in joints is difficult to detect – must design structures to be tolerant to reasonably-sized flaws
    - accurate models are needed to ***predict failure*** and ***assess damage tolerance***
- **Objectives**
  - investigate physical phenomena and processes leading to failure in adhesively bonded joints
  - account for bondline thickness and environmental conditions
  - develop models describing these phenomena
- **Approach:**
  - combined experimental/analytical investigations supporting development of models

FAA Sponsored Project Information

- Principle Investigators & Researchers
  - **Hyonny Kim (now at UCSD)**
  - **C. T. Sun**
  - **Thomas Siegmund**
  - Post-Doc: Steffen Brinkmann
  - Students: *Haiyang Qian*, Nicholas Girder, Matt Wan
    - former students: Jibin Han (Dec 2005), J. Lee (May 2006), T.T. Khoo (Dec. 2006), Hee Seok Roh
- FAA Technical Monitor
  - Curt Davies
- Industry Participation
  - ABAQUS

Focus Areas Towards Achieving Objectives:

– Adhesive constitutive behavior for use in bonded joint analyses

– Effect of adhesive thickness on mixed mode fracture of joints

– Effect of bondline thickness on strength of adhesively bonded joints – CTOA approach

– Influence of moisture, cyclic loading and time dependence on joint fracture – Cohesive zone model approach

Project I. Adhesive Constitutive Behavior Measurement and Bondline Thickness Dependent Mixed Mode Fracture

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Students: Jungmin Lee (PhD May 2006), Richard Khoo (MS Dec 2006), Hee Seok Roh

Objective:

- support analysis tools used for design and damage tolerance
- use of nonlinear FEA and fracture mechanics based analyses has become more routine
  - VCCT and cohesive-zone incorporated into commercial FEA codes

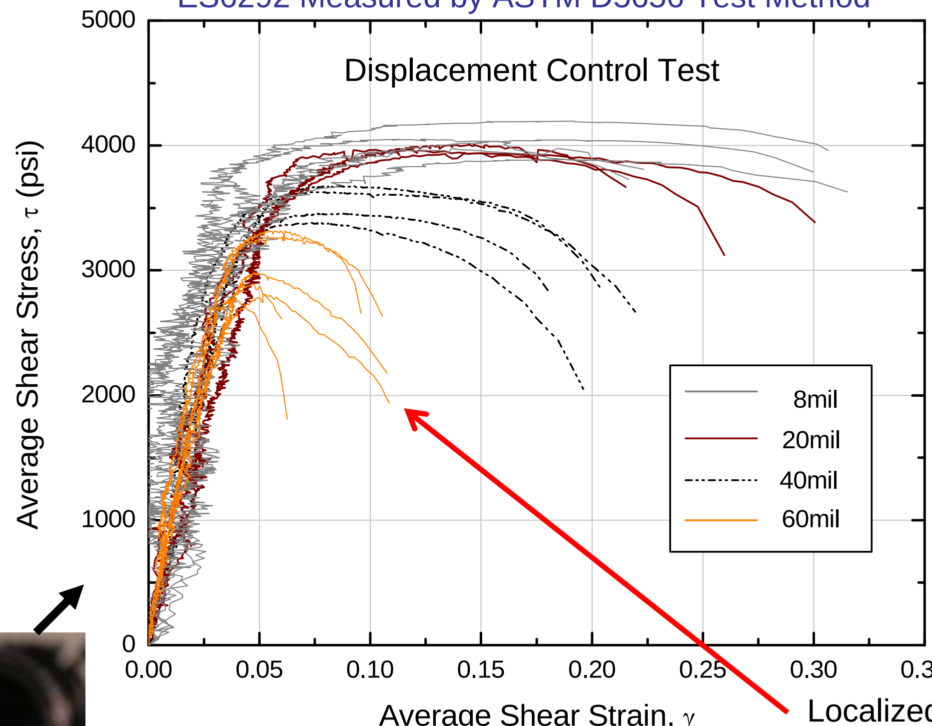
Approach

- Accurately measure material property data as crucial ingredients to increasingly capable and available modeling tools
- defining improved methods for constitutive curve measurement
- investigate bondline thickness dependent mixed mode fracture envelope

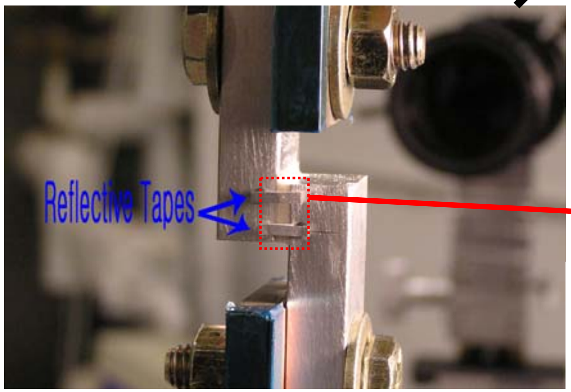
Adhesive Constitutive Behavior in Bonded Joints

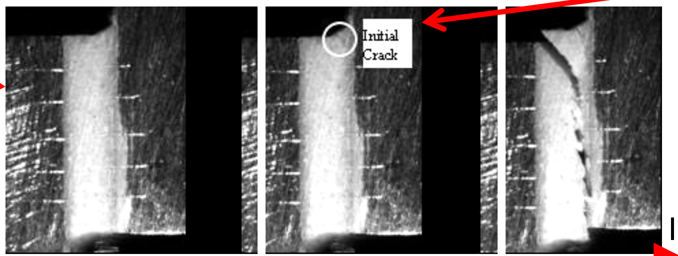
- choice of constitutive curve is not clear
- adhesive τ vs γ measured by ASTM D5656:
  - exhibits strong bond thickness dependency
  - criticized as being inconsistent at ASTM *Symposium on Joining and Repair of Composites* (March 2003), and at FAA Adhesive Joints Workshop (June 2004)
- ***true material property*** **should be geometry independent**
- establish more direct and simple test method for determining constitutive behavior:
  - bulk-adhesive tensile dogbone
  - t.b.d. new method

Shear Stress vs. Shear Strain Relationship for PTM&W ES6292 Measured by ASTM D5656 Test Method



Modified D5656 Test Specimen
- less rotation
- laser displ. measurement



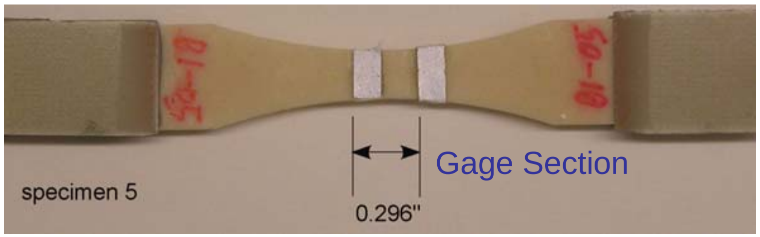


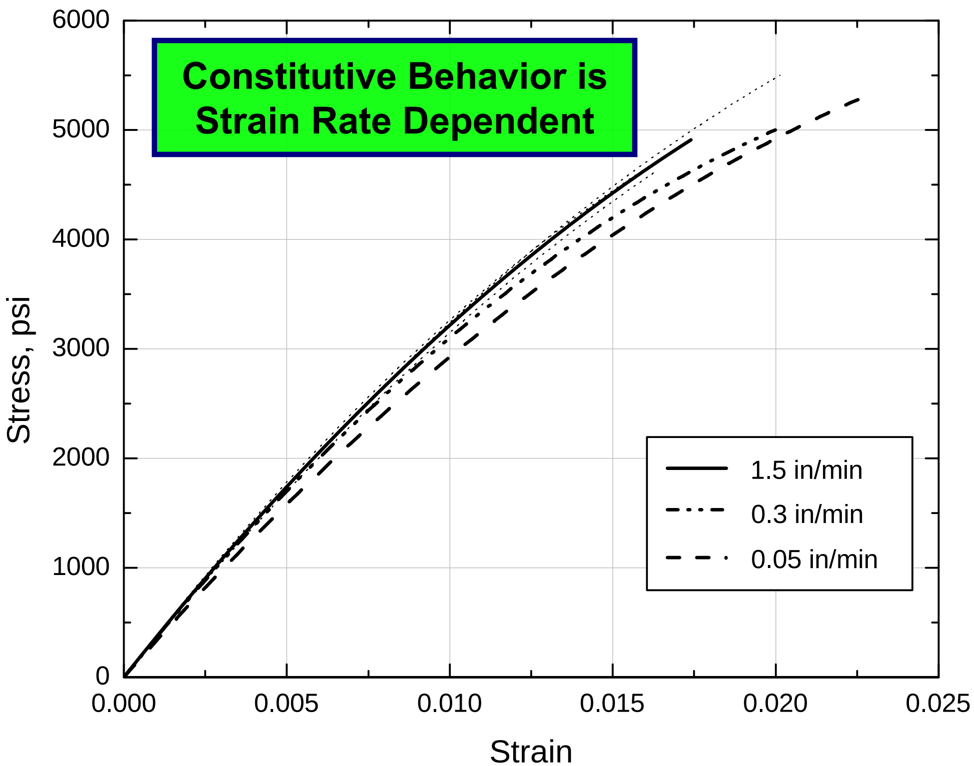
Localized Damage Evolution Causing Apparent Softening

Increasing Time

Bulk Adhesive Constitutive Behavior – Tensile Dogbone Tests

PTM&W ES6292 epoxy paste adhesive

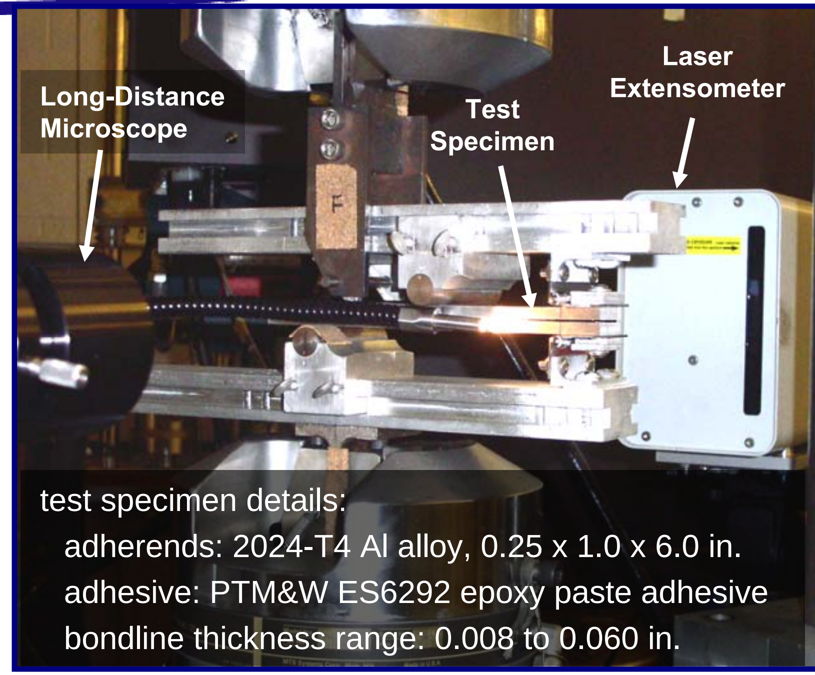


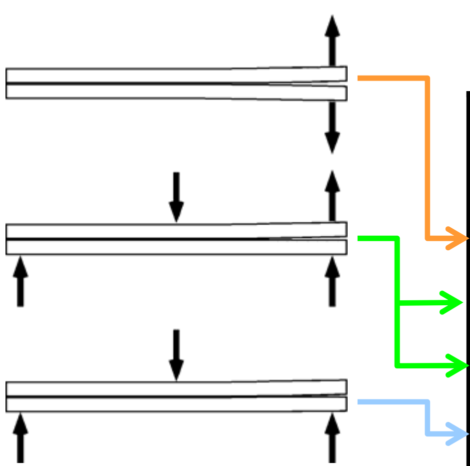


- bulk dogbone *partially* successful
- main issues:
  - premature failure – not measuring entire constitutive curve
    - voids always present due to manufacturing method (casting)
    - initiation of failure leads to immediate cross-width fracture and thus can not develop significant plastic deformation
  - does not include effects of:
    - adherend constraint on adhesive layer
    - possible material micro-structural differences between thin adhesive layer vs. thick bulk

Bondline Thickness Dependent Mixed Mode Fracture

- motivation:
  - fracture mechanics is capable tool for dam. tolerance analysis
  - need mixed mode strain energy release rate (SERR) data
- approach:
  - SERR measured for range of bondline thickness to establish mixed mode fracture envelope database
  - observed processes occurring at crack tip
  - use nonlinear FEA to understand bondline effect in measured data
  - establish fracture criteria in joints that accounts for bondline thickness dependent G_{IC} and G_{IIC}

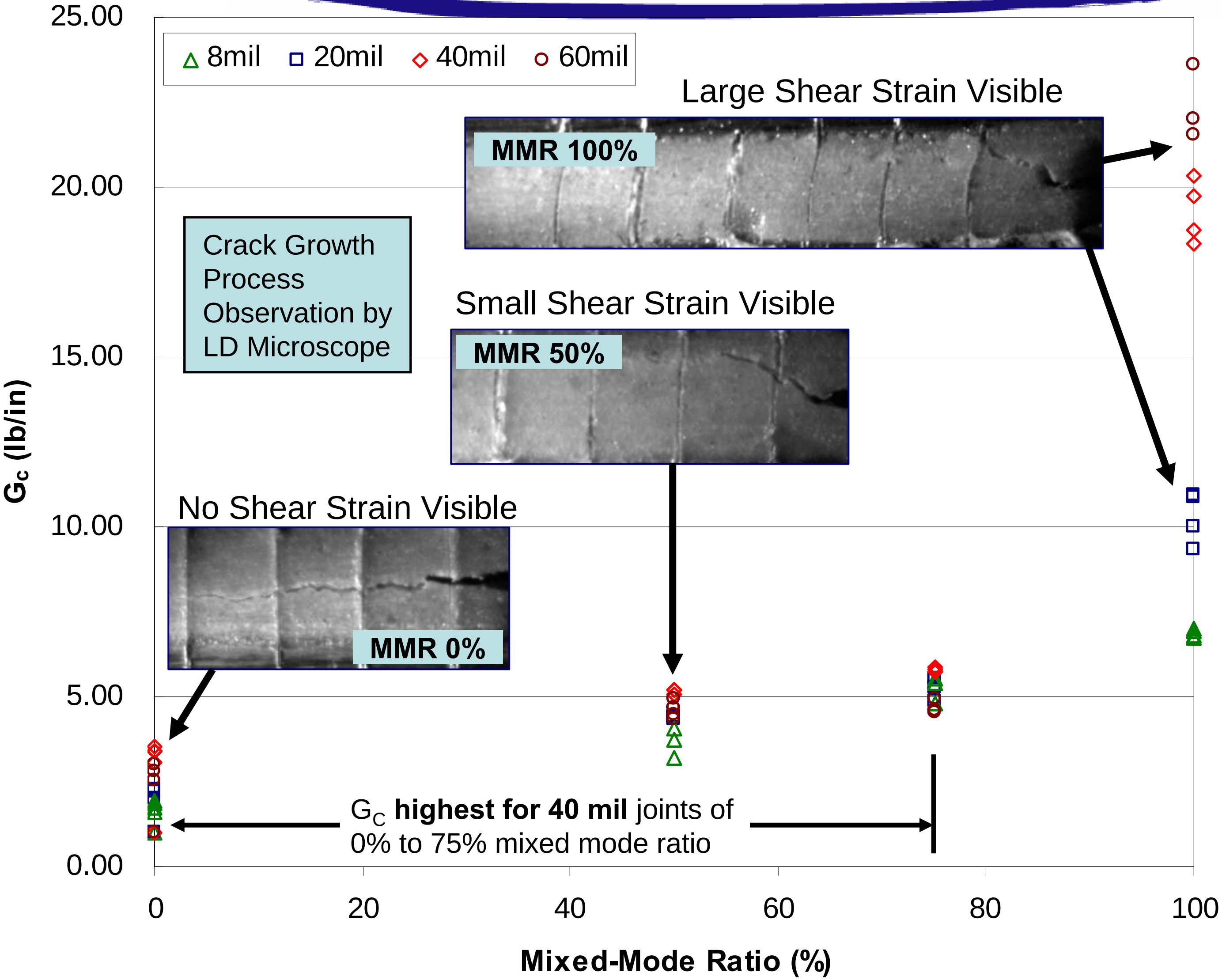




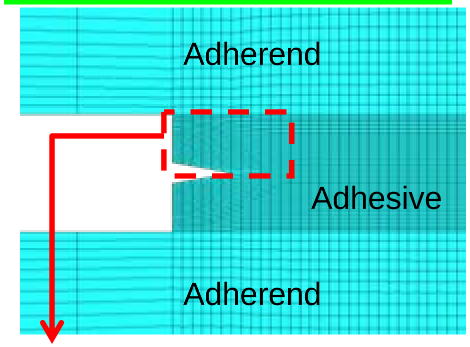
Matrix of Completed Tests (all tests at RT ambient):

Mode Mix (% mode II)	t_a = 0.008 in.	t_a = 0.020 in.	t_a = 0.040 in.	t_a = 0.060 in.
0	4	5	6	4
50	3	3	3	5
75	3	3	3	3
100	4	7	4	6

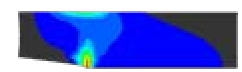
Results – Mixed Mode G_C Envelope



FEA Plastic Zone Predictions – Mode I

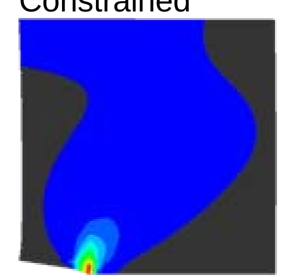


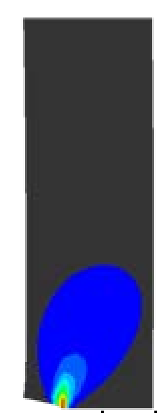
Plastic Zone (PZ) Contours at Growth Initiation:



8 mil. – PZ Highly Constrained

40 mil. – PZ Moderately Constrained

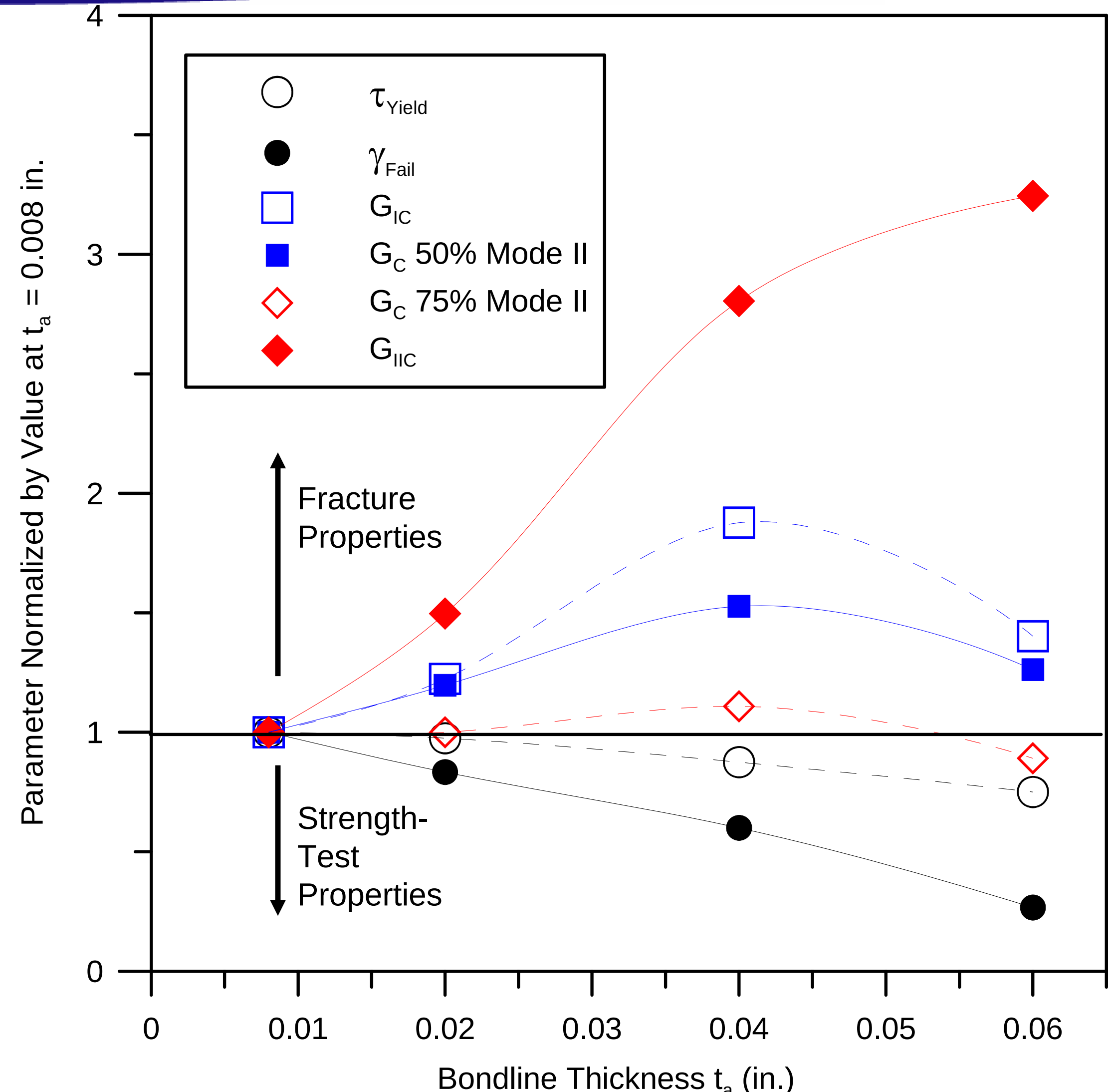




60 mil. – PZ Unconstrained

Summary: Comparison of Shear Strength Test and Fracture Properties

- Fracture properties and shear strength test properties show opposite trend over bondline thickness range 0.008 to 0.06 in.
- Fracture Tests:
  - G_{IC} and G_C at 50% Mode II optimum for t_a = 0.04 in.
  - G_C at 75% Mode II relatively insensitive to t_a
  - G_{IIC} increasing (could plateau and go down for higher t_a than investigated)
  - optimal constraint of plastic zone gives highest G_C
- D5656 Shear Strength Tests:
  - shear yield strength decreasing for higher t_a
  - shear failure strain decreasing for higher t_a
  - related to localization of plastic and failure process zone for higher t_a



Project I: Conclusions to Date & Benefits to Aviation Industry

- **Tools and Protocols**:
  - modified shear strength tests: localized damage/fracture develops for thick bonds – this should be accounted for in data processing and analyses
  - dogbone test for constitutive curve partially successful
  - new specimen is being designed that is easy to test like dogbone but accounts for confinement of adhesive layer
- **Data**
  - strong bondline thickness effect observed for fracture and shear strength tests
  - fracture properties and strength test properties show opposing trends over range of bondline thickness
- **Analysis**
  - plastic zone confinement shown via FEA to affect critical SERR dependency on bondline thickness

Project II: Modeling Thickness Effect on Strength of Adhesive Lap Joint Using CTOA

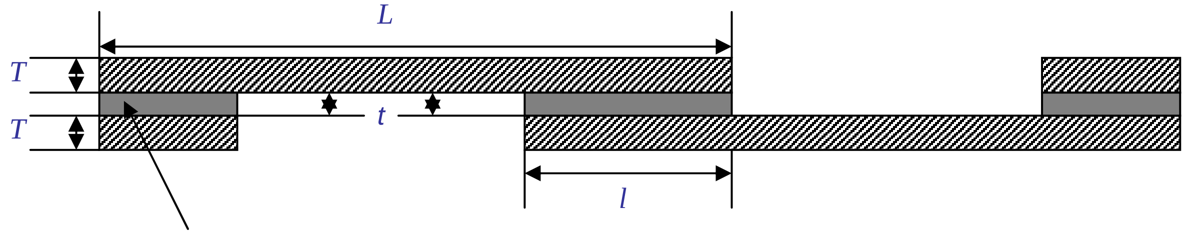
C.T. Sun, Professor sun@purdue.edu, School of Aeronautics & Astronautics, Purdue University

Haiyang Qian, Ph.D. Student

Objective – Develop a CTOA fracture criterion to model adhesive thickness-dependent lap joint strength

Approach – Conduct fracture experiments using DCB specimens with various adhesive thicknesses to validate the proposed CTOA approach and to determine the limitation on its applicability with finite element analyses of the experiments

Adhesive Thickness Effect on the Strength Lap Joints



L=3in, l=1in, T=0.125in

t=0.008in, 0.01in, 0.02in, 0.06in

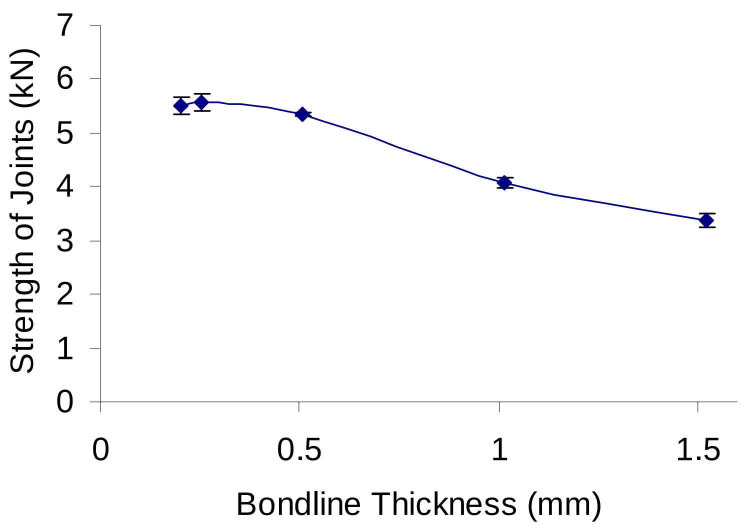
Adherend: Aluminum Alloy 7075

Adhesive: HYSOL EA9394

Surface Treatment: Semco Pasa-Jell 105 (etching method)

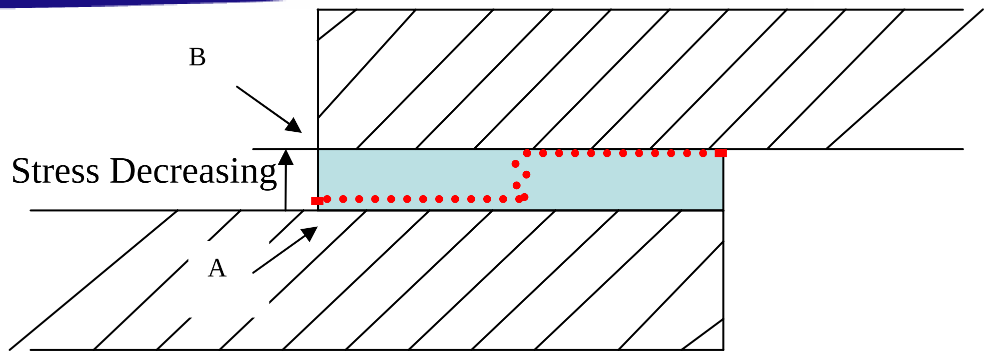
- Joint strength increases as the bondline thickness decreases up to 0.25 mm

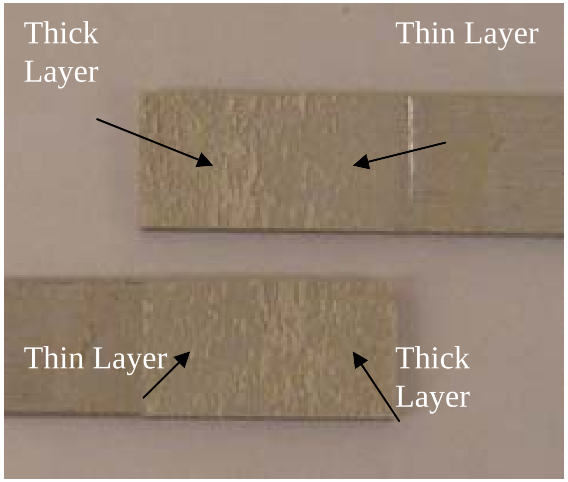
- Experimental result



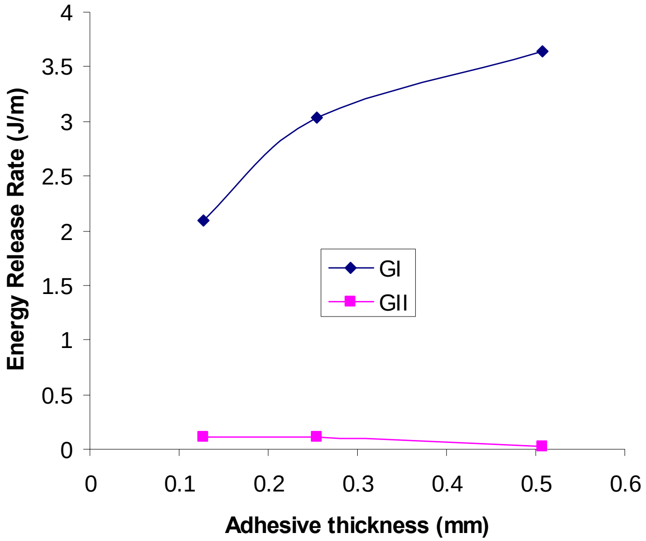
Fracture Initiation is Mode I Dominant in Lap Joints

- Stress concentration near the joint edge and near the interface
- Initial flaw (crack) is under mode I loading
- Crack growth is along the interface (red line)



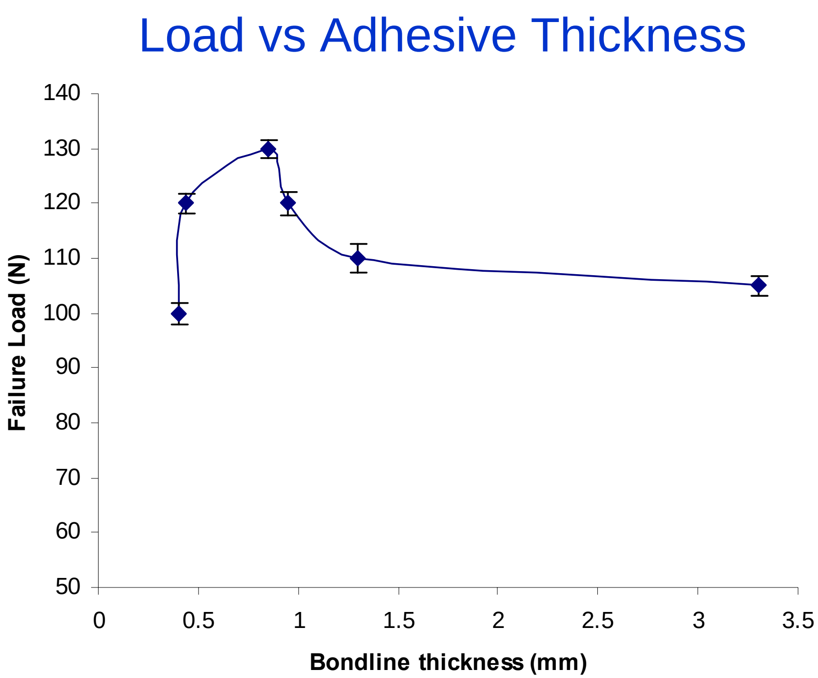


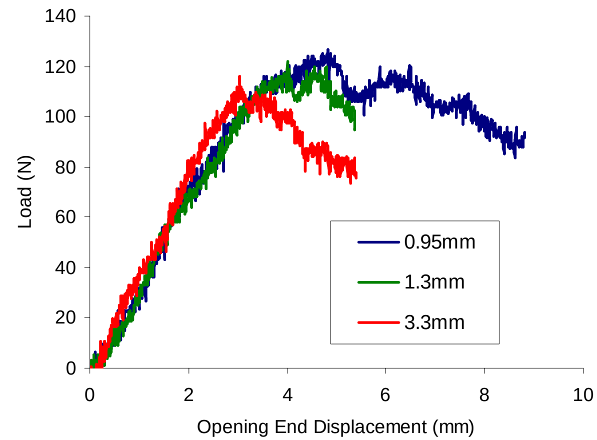
Initial crack mode mixity

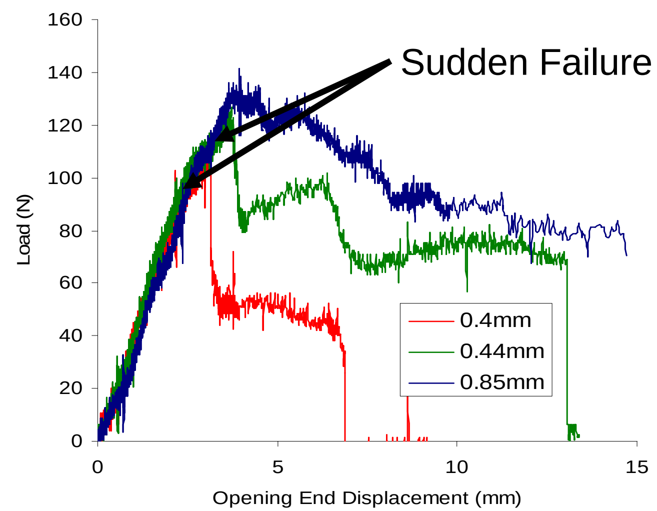


DCB Test Results

failure modes transition from mode I fracture to interfacial failure as adhesive thickness decreases below a certain level

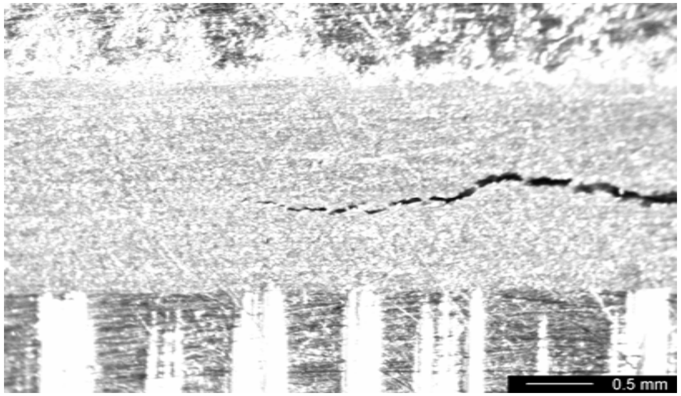


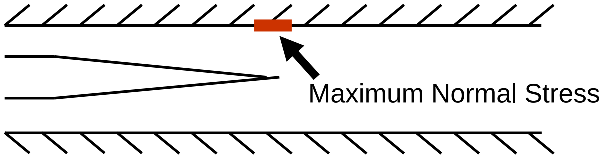




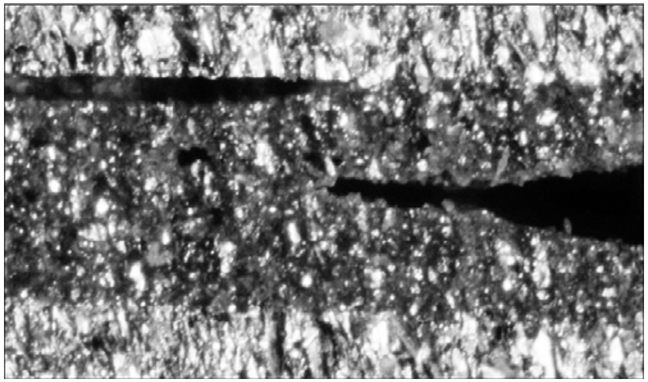
Effect of Adhesive Thickness on Failure Mode

- Mode I crack propagates in thicker adhesive

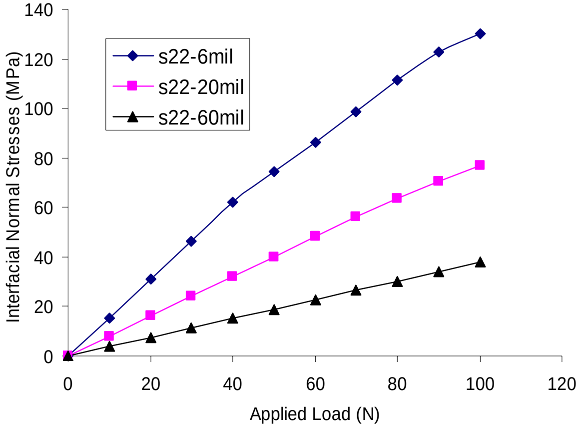




- Transition of failure mode in thinner adhesive

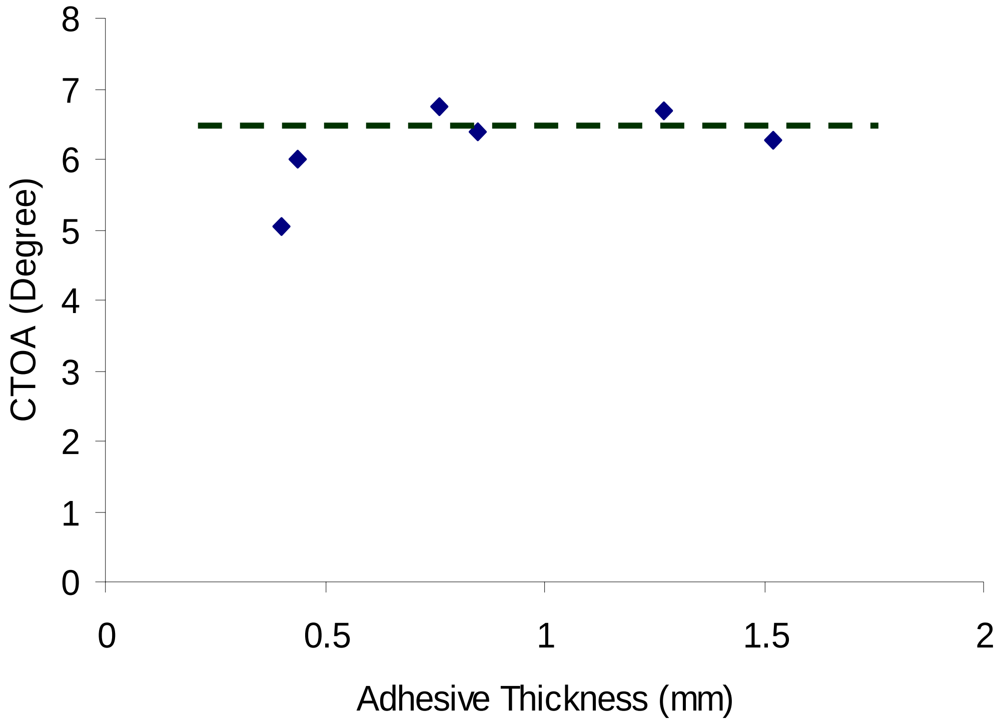


Normal stress at the interface



CTOA Criterion for Hysol EA9394

- CTOA is independent of adhesive thickness before failure mode change



Project II: Conclusions to Date & Benefits to Aviation Industry

- **<u>Tools and Protocols</u>**:
  - Critical CTOA concept: CTOA is a fracture criterion that is independent of adhesive thickness if failure mode remains mode I. This is the case for thicker bondlines
- **<u>Data</u>**
  - Critical CTOA data determined in dependence of bond line thickness
- **<u>Analysis</u>**
  - FEA analysis predictions using critical initial CTOA and failure mode transition due to high interfacial stress between adherend and adhesive layer

Project III: Influence of Bondline Thickness, Moisture, Load History

Thomas Siegmund, Associate Professor, siegmund@purdue.edu

Steffen Brinckmann, Post Doctoral Research Associate

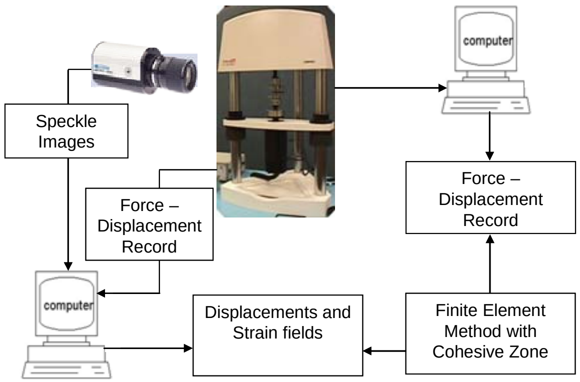
Jibin Han, (PhD 12/2005)

Eric Anderson, Nicolas Girder, Matt Wan (SURF Summer Students)

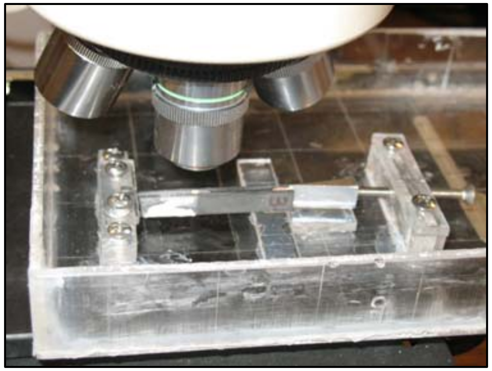
- **Objective:**
  - Develop and employ the cohesive zone model approach to fracture to the analysis of adhesive joint failure
- **Approach:**
  - Crack growth experiments: monotonic, fatigue, time-dependence, environmental degradation
  - Models: cohesive zone models in 3D, monotonic, fatigue, coupled for moisture/load interaction
  - Image analysis: Digital image correlation for strain fields, quantitative fracture surface analysis and fracture reconstruction

Experimental Facilities

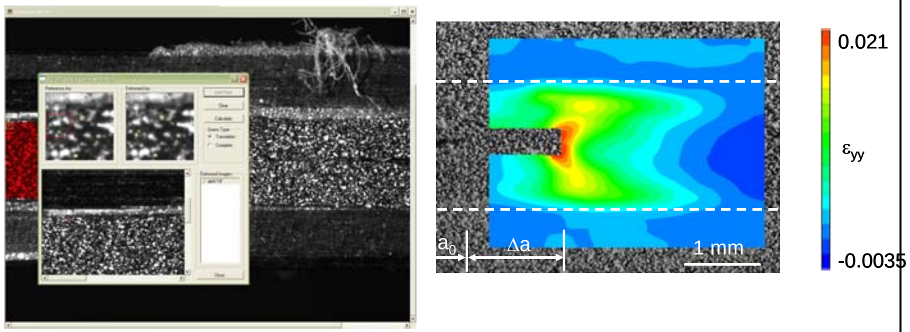
Crack Growth Resistance



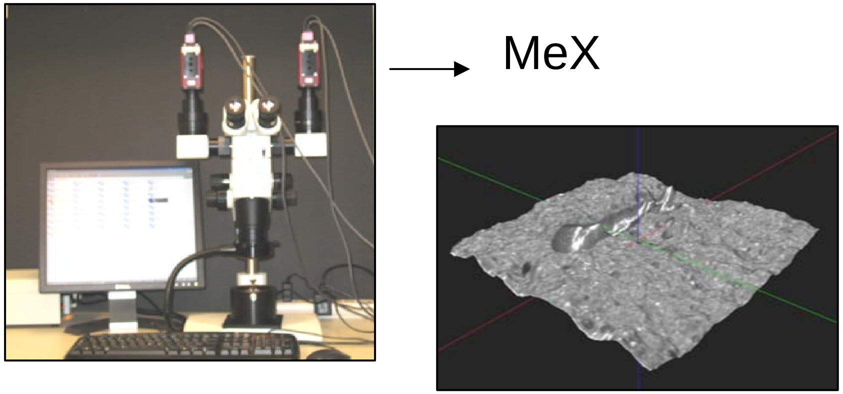
Environmental Degradation



Digital Image Correlation

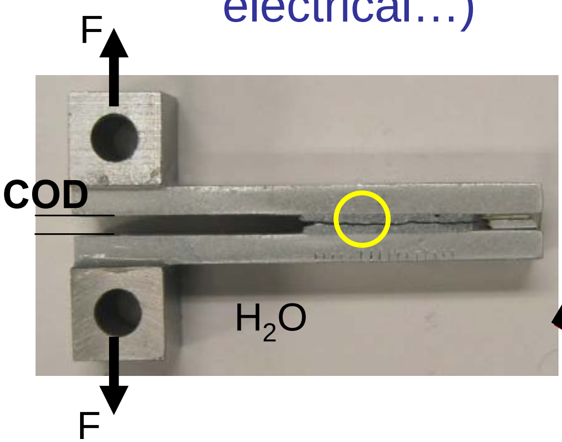


Stereo-Fractography



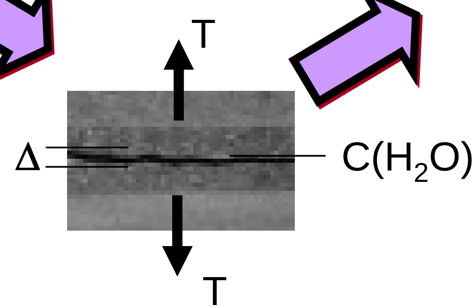
Computational Modeling

- **The Cohesive Zone Model:**
  - Describes local energy dissipation during fracture and fatigue
  - Is conveniently coupled to other fields (plasticity, moisture, heat, electrical…)



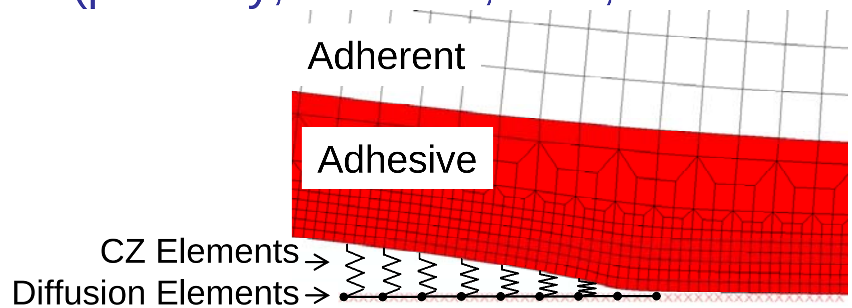
Global Parameters:

- Load, Displacement
- Environment
- Time
- Cycles



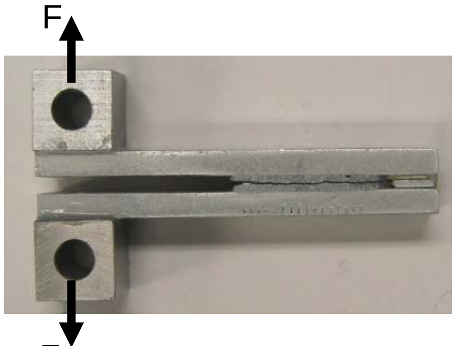
Local Parameters:

- Traction-Separation
- Concentration
- Damage

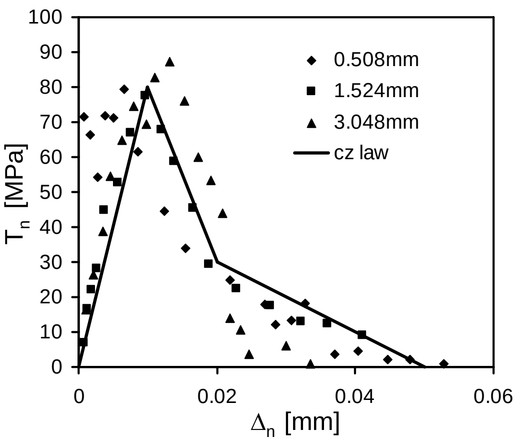


Finite element model with Cohesive elements, moisture transport, and cyclic damage

Monotonic Loading

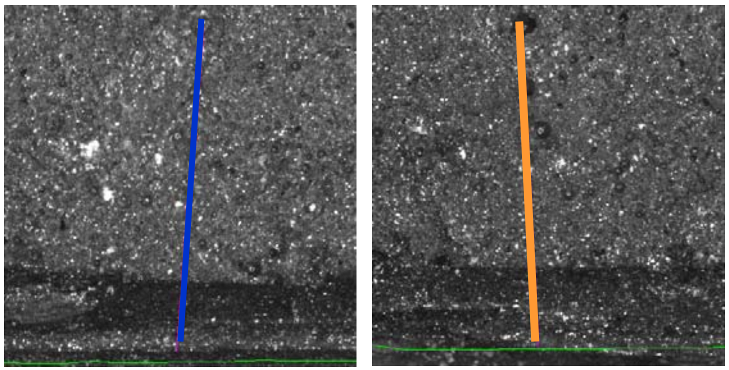


$$T_n(\Delta) = \frac{\partial G}{\partial (CTOD^*)}$$

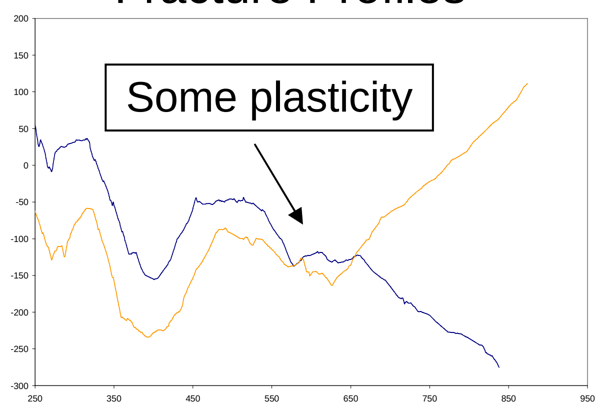


$\sigma_{max}, \delta, \Gamma$

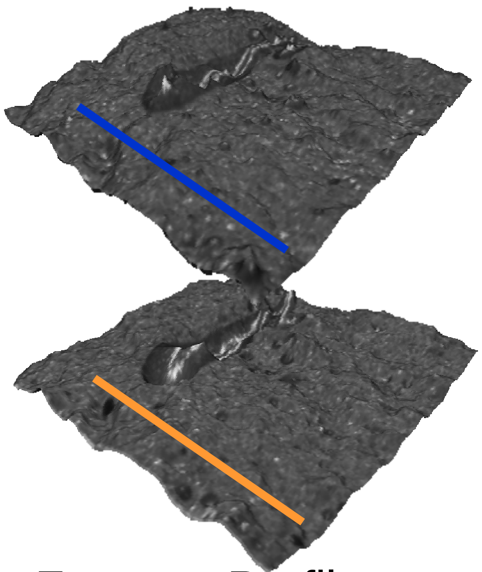
Stereo Images Pair
Left -- Right



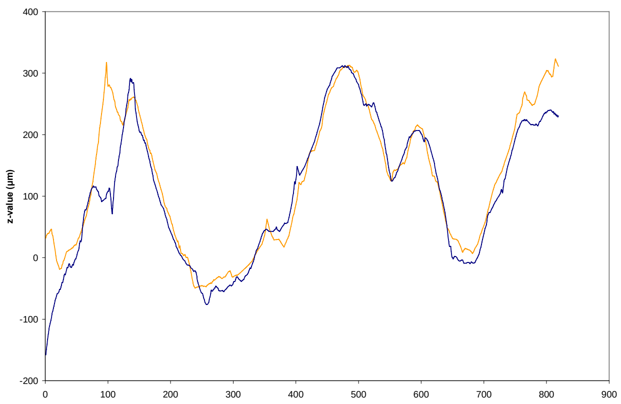
Fracture Profiles



Digital Elevation Maps

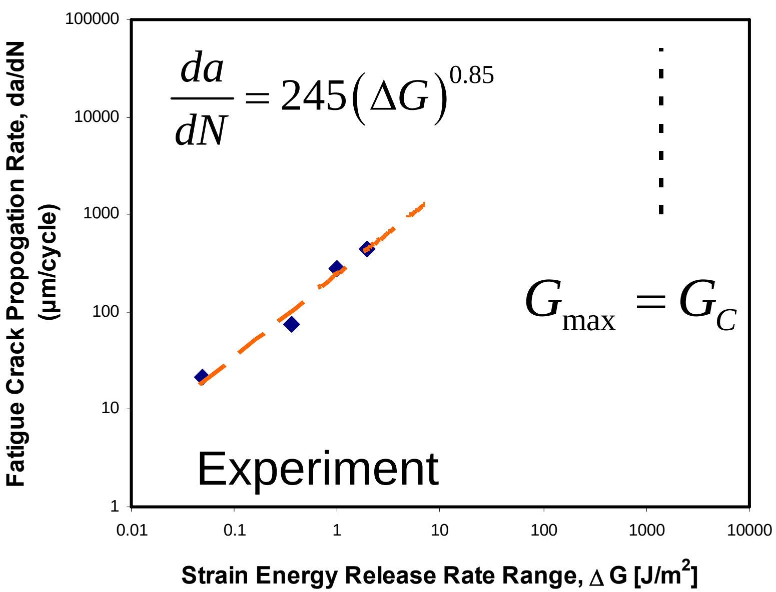


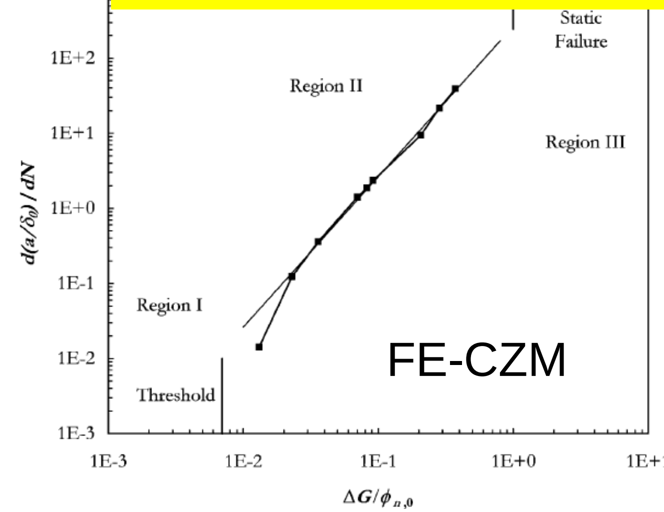
Fracture Profiles

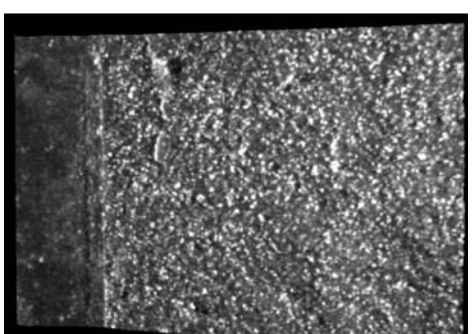


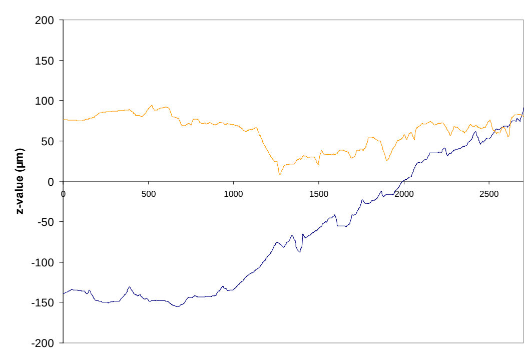
Fatigue Loading

$$\sigma_{\max} = \sigma_{\max,0}(1-D), \delta, \Gamma$$





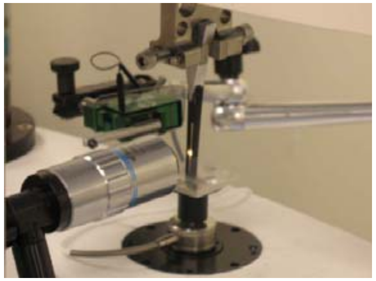




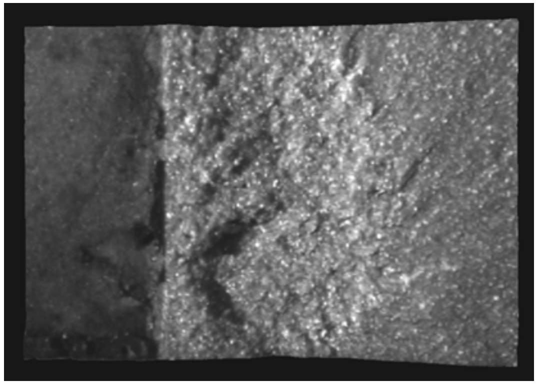
Fractography

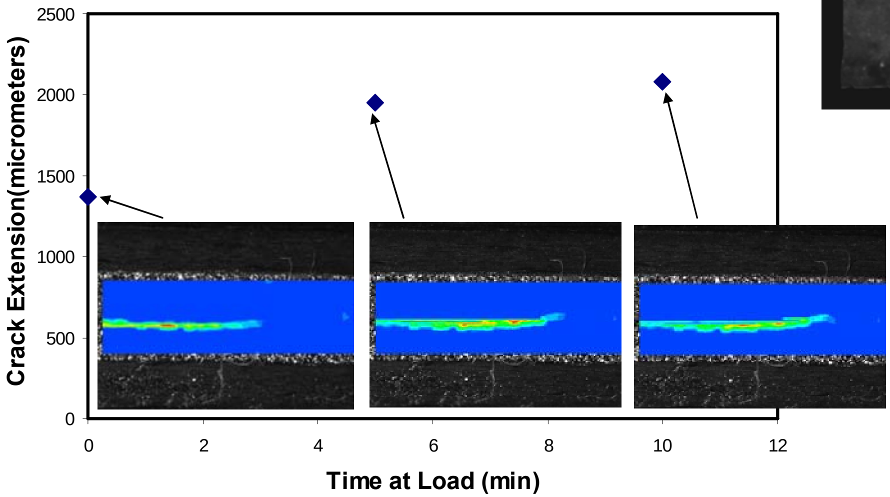
Time Dependence

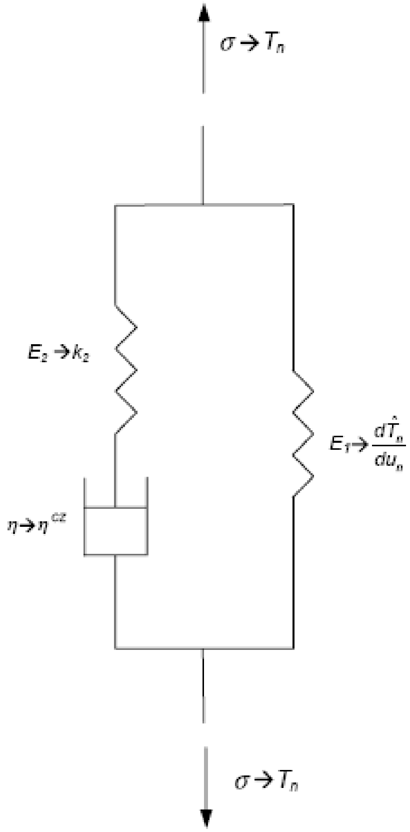
Wedge test with constant loading



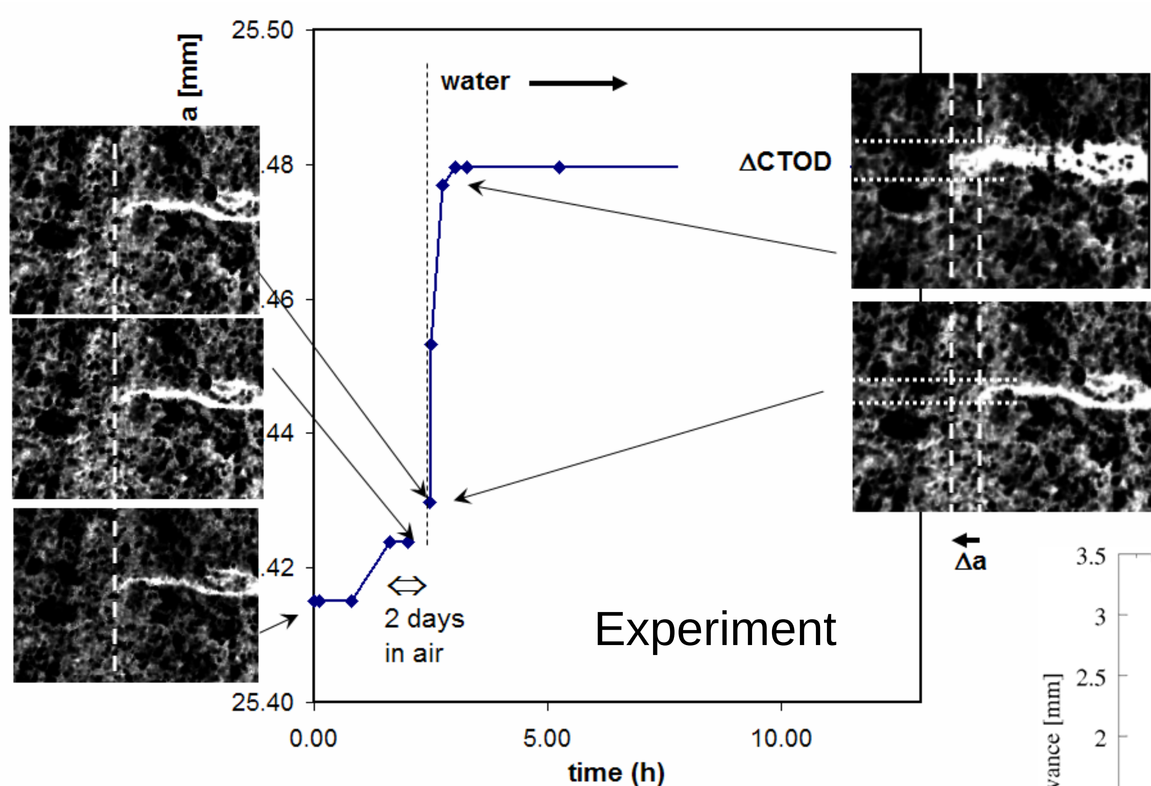
Precrack → Stable → Unstable

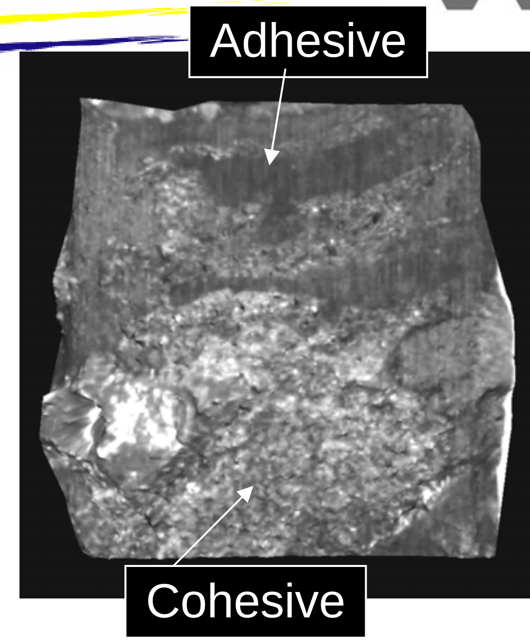


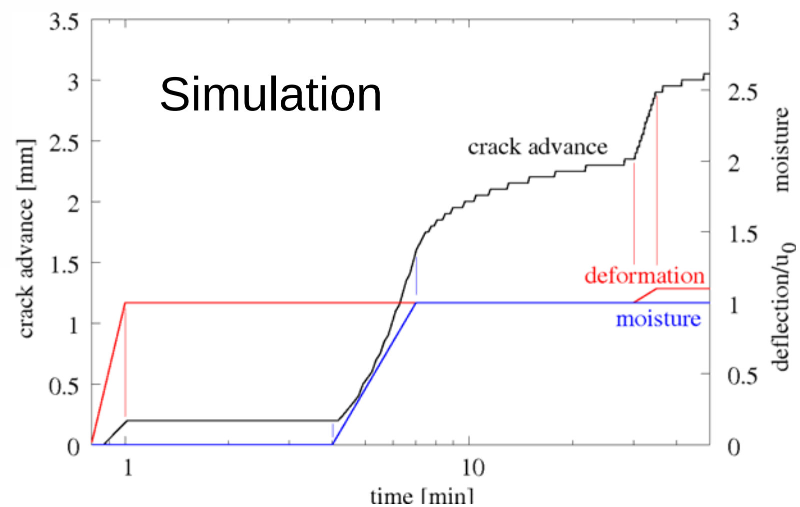




Moisture Effects on Joint Fracture







Project III: Conclusions to Date & Benefits to Aviation Industry

- **Analysis**
  - Cohesive zone models: fracture – fatigue – rate dependence – moisture degradation
- **Tools and Protocols**:
  - In-situ crack growth
  - Digital image correlation applied to adhesives
  - Quantitative fractography
  - Environmentally assisted crack growth with wedge test
  - Time dependent crack growth with wedge test
- **Data**
  - Preliminary data on fatigue crack growth resistance and moisture assisted crack growth

A Look Forward

- **Benefit to Aviation**
  – in response to increasing use of adhesive bonding
  - **Analysis Tools:** supports sophisticated computation-based design
    - ***failure process*** prediction, including adhesive plasticity
    - CTOA, VCCT, Cohesive Zone model
    - now available in commercial codes
    - simulation tools can reduce time to conduct extensive environmental degradation tests
  - **Data:** addressing important issues of bondline thickness
    - quantify phenomena governing why “properties” seemingly depend on bondline thickness
    - definition and use of local failure criteria that are not bondline thickness dependent
  - **Protocols:** test methods to obtain fracture and constitutive data
    - seeking to define simpler tests and remove necessity to collect data as function of bond thickness
    - Fractography

A Look Forward

- **Future Needs**
  - results to date concentrated on adhesive using metal adherends – future work needed to investigate other adherend (namely composite) and adhesive types and failure modes: interfacial (a.k.a. adhesion) and mixed interfacial/cohesive failure + composite failure
  - investigate combined loading (simultaneous effects of temperature, humidity, cyclic loading) for range of bondline thickness and mode mix ratio
  - establish mixed mode fracture criteria that accounts for bondline thickness
  - integrate aspects of individual crack growth models into cohesive zone approach
  - development of improved test specimen for constitutive curve measurement
  - account for localized failure evolution in modeling of shear tests – demonstrate transferability to joints of generic configuration
  - use the developed fracture models to find optimized adhesive thicknesses for different adhesives
  - develop a embedded crack concept in conjunction with the developed fracture models to predict general bonded joint strength