Damage Tolerance and Durability of Adhesively Bonded Composite Structures

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The Joint Advanced Materials and Structures Center of Excellence

FAA Sponsored Project Information

- Principle Investigators & Researchers
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  - **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

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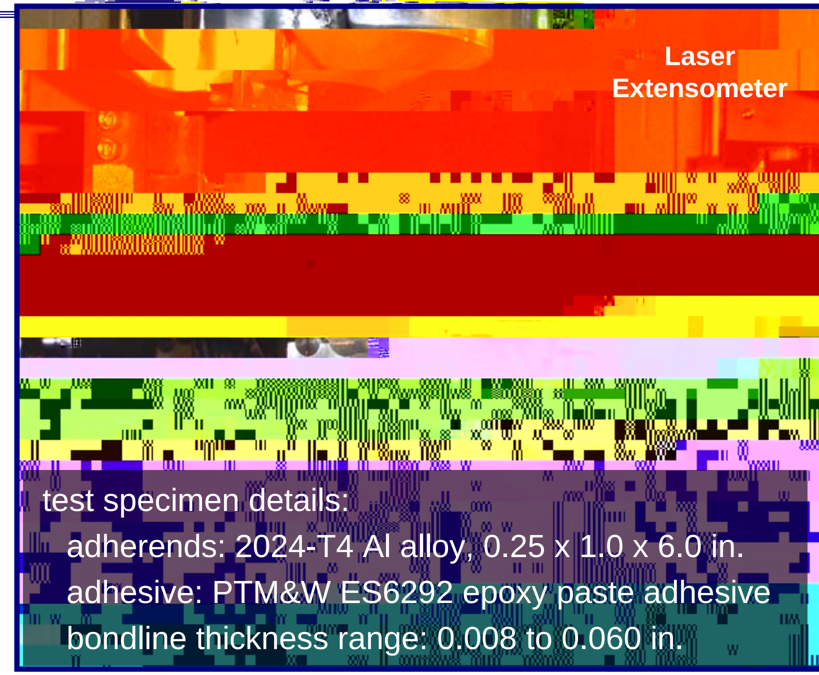
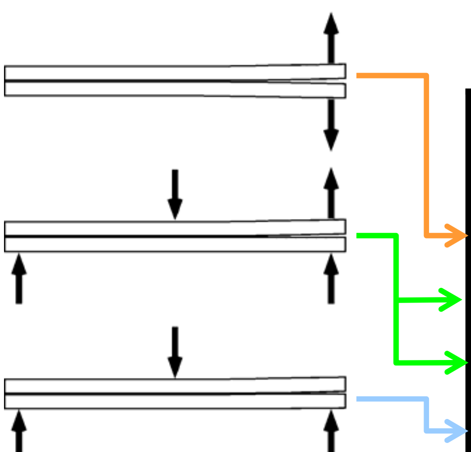
Bondline Thickness Dependent Mixed Mode Fracture

- 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}





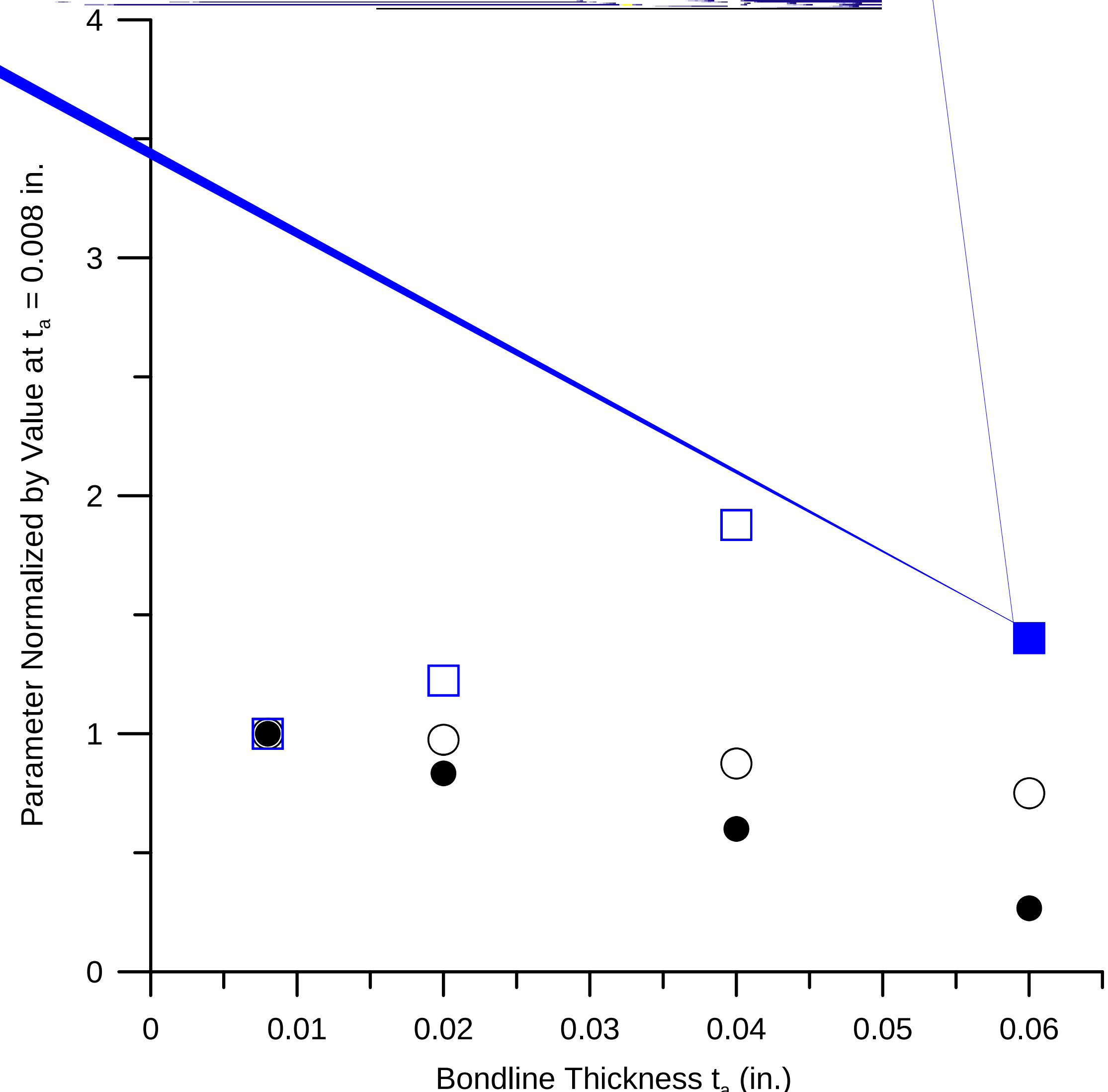
Matrix of Completed Tests (all tests at RT ambient):

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**

ummary: 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
- 6 Shear Strength Tests:
  - ear yield strength decreasing higher t_a
  - ar failure strain decreasing for er t_a
  - ed to localization of plastic ailure process zone for r t_a



Project I: Conclusions to Date & Benefits to Aviation Industry

- **<u>Tools and Protocols</u>**:
  - 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 th

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

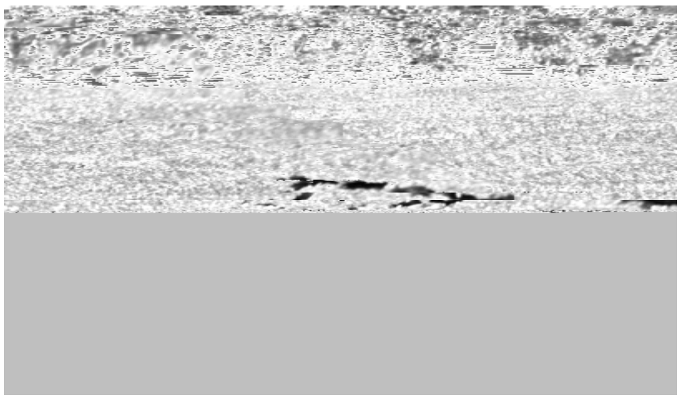
Approach – Conduct fracture experiments using DCB specimens with various adhesive thicknesses to validate the proposed CTOA approach and to determine the limitation on its applicability with finite element analyses of the experiments

DCB Test Results

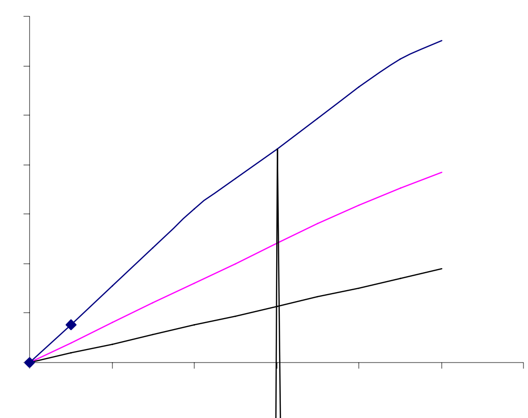
failure modes transition from mode I fracture to interfacial failure as adhesive thickness decreases below a certain level

Effect of Adhesive Thickness on Failure Mode

- Mode I crack propagates in thicker adhesive

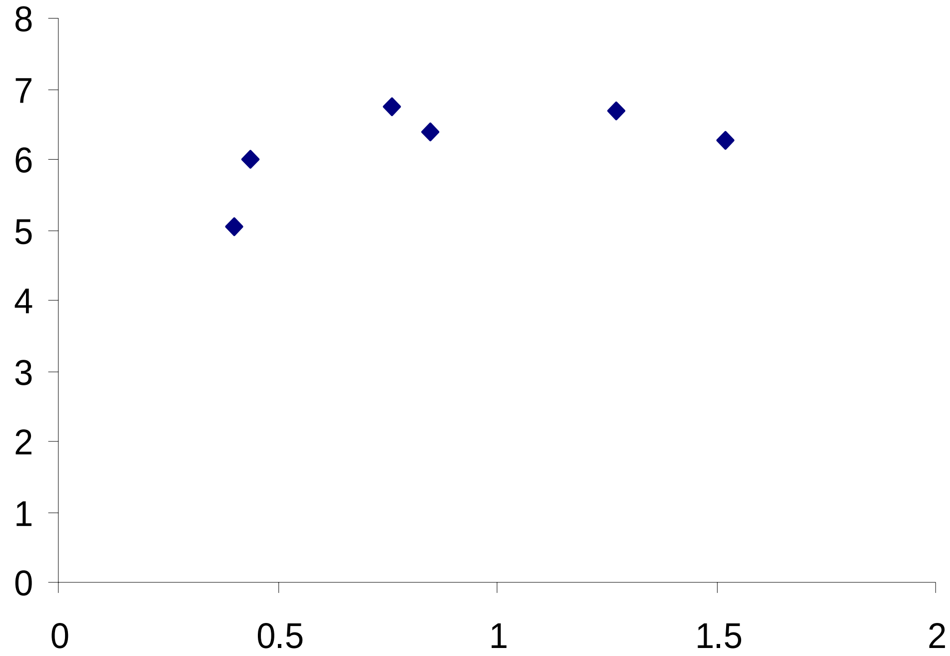


- Transition of failure mode in thinner adhesive



CTOA Criterion for Hysol EA9394

- CTOA is independent of adhesive thickness before failure mode change



Project II: Conclusions to Date & Benefits to Aviation Industry

- **Tools and Protocols**:
  - 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
- **Data**
  - Critical CTOA data determined in dependence of bond line thickness
- **Analysis**
  - 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

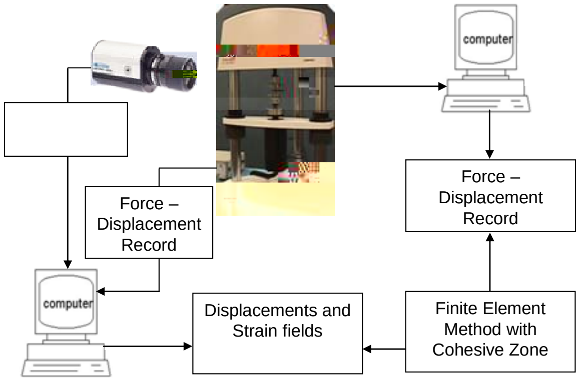
Steffen Brinckmann, Post Doctoral Research Associate

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

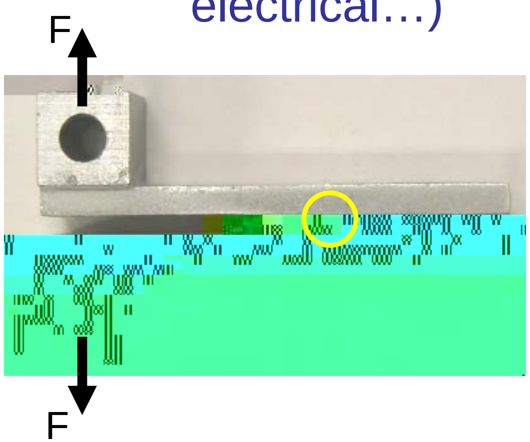
Crack Growth Resistance



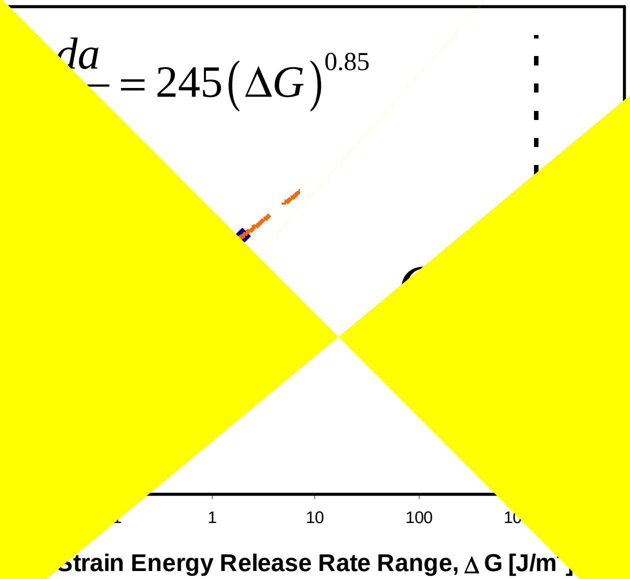
Environmental Degradation

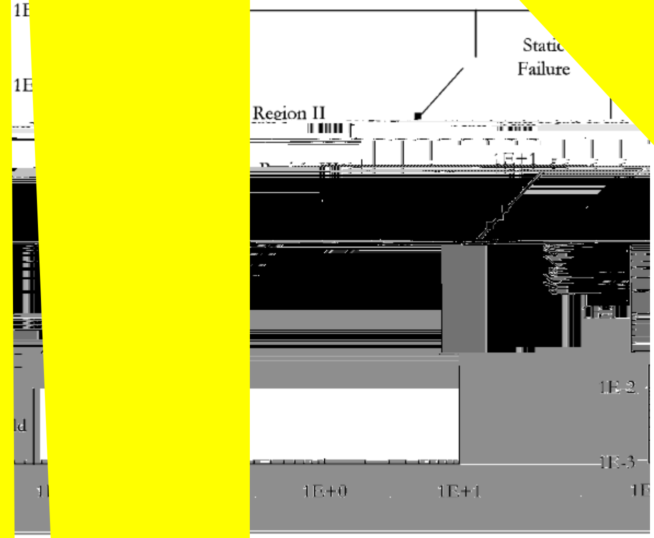
Computational Modeling

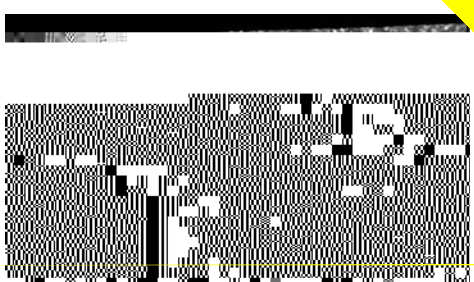
- **The Cohesive Zone Model:**
  - Describes local energy dissipation during fracture and fatigue
  - Is conveniently coupled to other fields (plasticity, moisture, heat, electrical…)

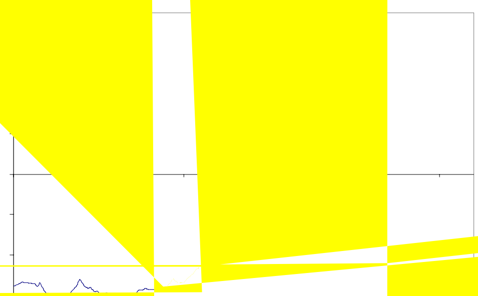


Global Parameters:
- Force (F) – Dis


da
= 245(ΔG)0.85
1
10
100
Strain Energy Release Rate Range, Δ G [J/m

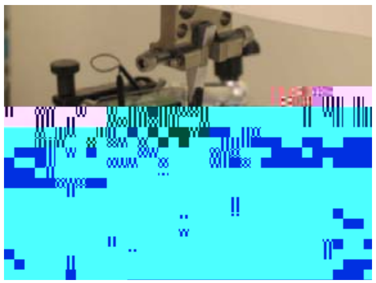

Static
Failure
Region II



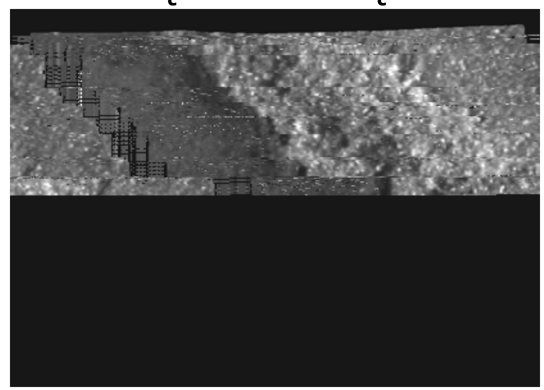


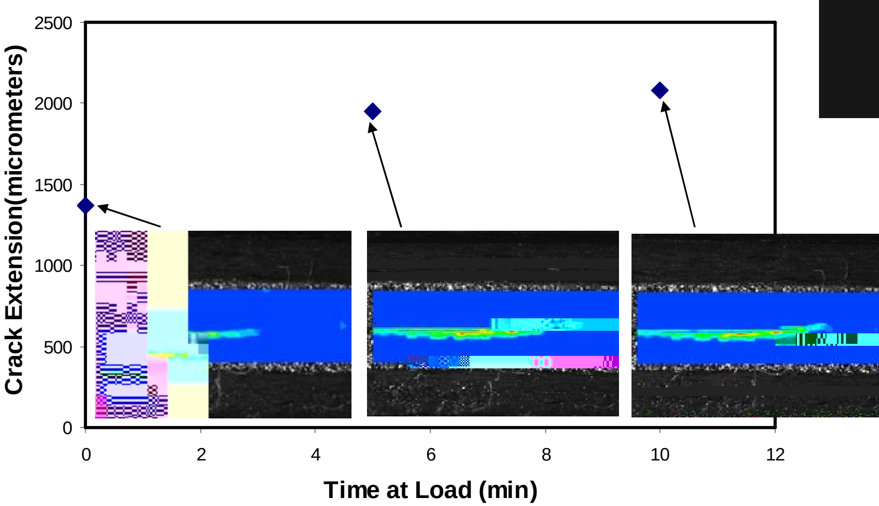
Time Dependence

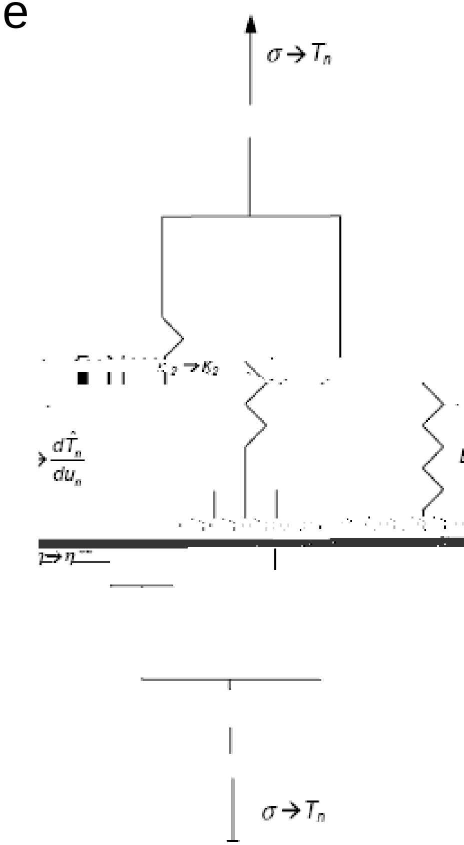
Wedge test with constant loading



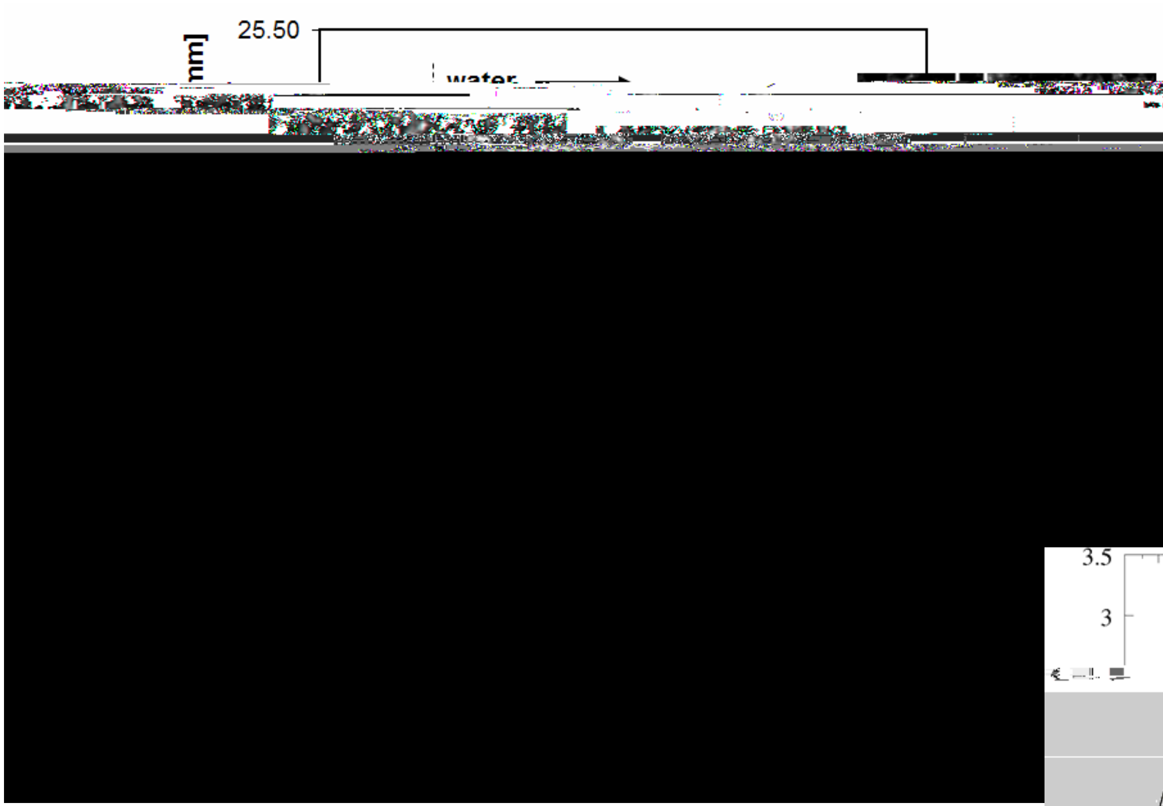
Precrack Ą Stable Ą Unstable

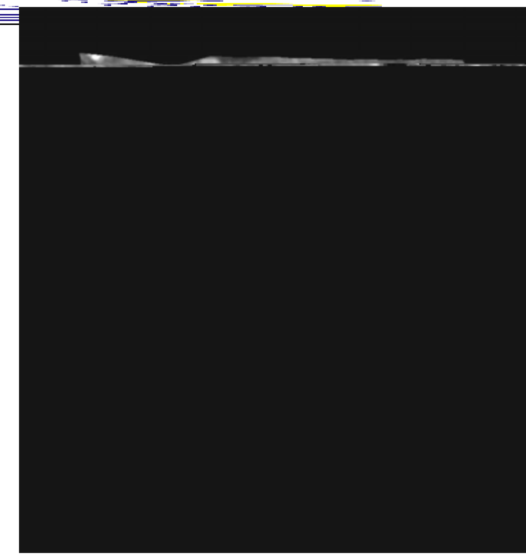


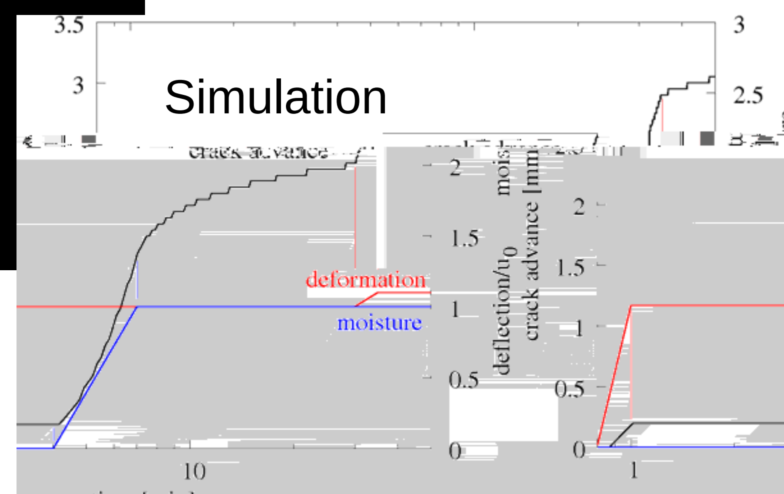




Moisture Effects on Joint Fracture







Project III: Conclusions to Date & Benefits to Aviation Industry

- **Analysis**
  - Cohesive zone models: fracture – fatigue – rate dependence – moisture degradation
- **Tools and Protocols**:

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