JAMS

Damage Tolerance and Durability of Adhesively Bonded Composite Structures

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Center of Excellence for AMTAS Advanced Materials in Transport Aircraft Structures

PURDUE UNIVERSITY

CECAM center of excellence for composites and advanced materials

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**
  - **C. T. Sun**
  - **Thomas Siegmund**
  - Post-Doc: Steffen Brinkmann
  - Graduate Students: Haiyang Qian, Jungmin Lee, Richard Khoo, Hee Seok Roh, Jibin Han (grad. 12/05)

- FAA Technical Monitor
  - **Peter Shyprykevich**

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 and bondline thickness on joint fracture

Project I

Adhesive Constitutive Behavior in Bonded Joints

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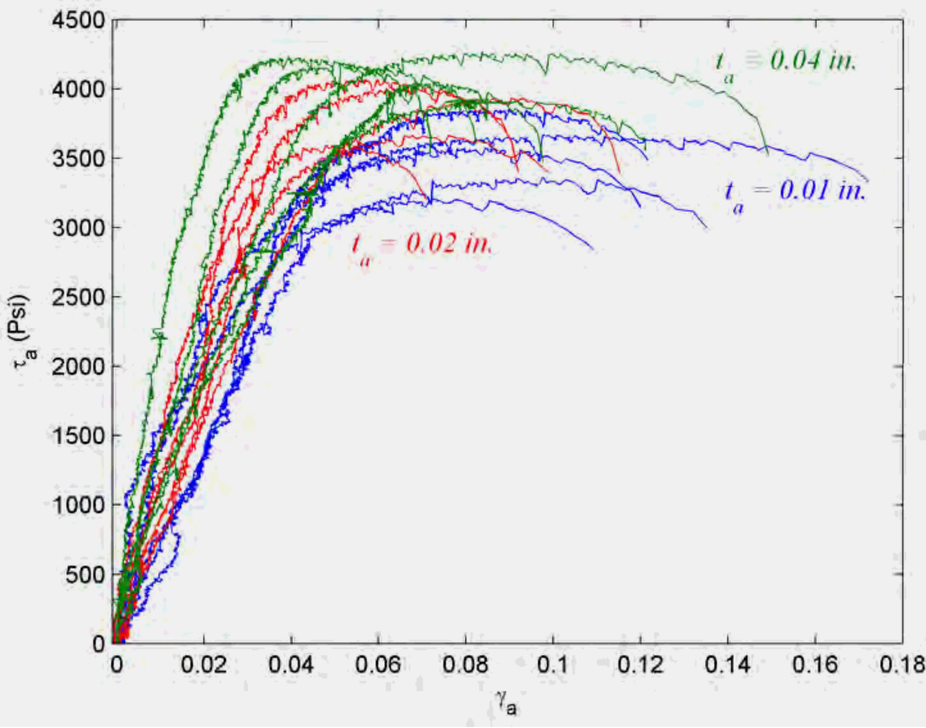
Jungmin Lee and Hee Seok Roh, Graduate Students

Background and Objectives

Background

- nonlinear adhesive constitutive behavior is needed to conduct modeling/analysis – e.g., FEA
  - choice of constitutive curve is not clear
- adhesive τ vs γ measured by ASTM D5656:
  - exhibits 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)
- ***material property*** **should be geometry independent**



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

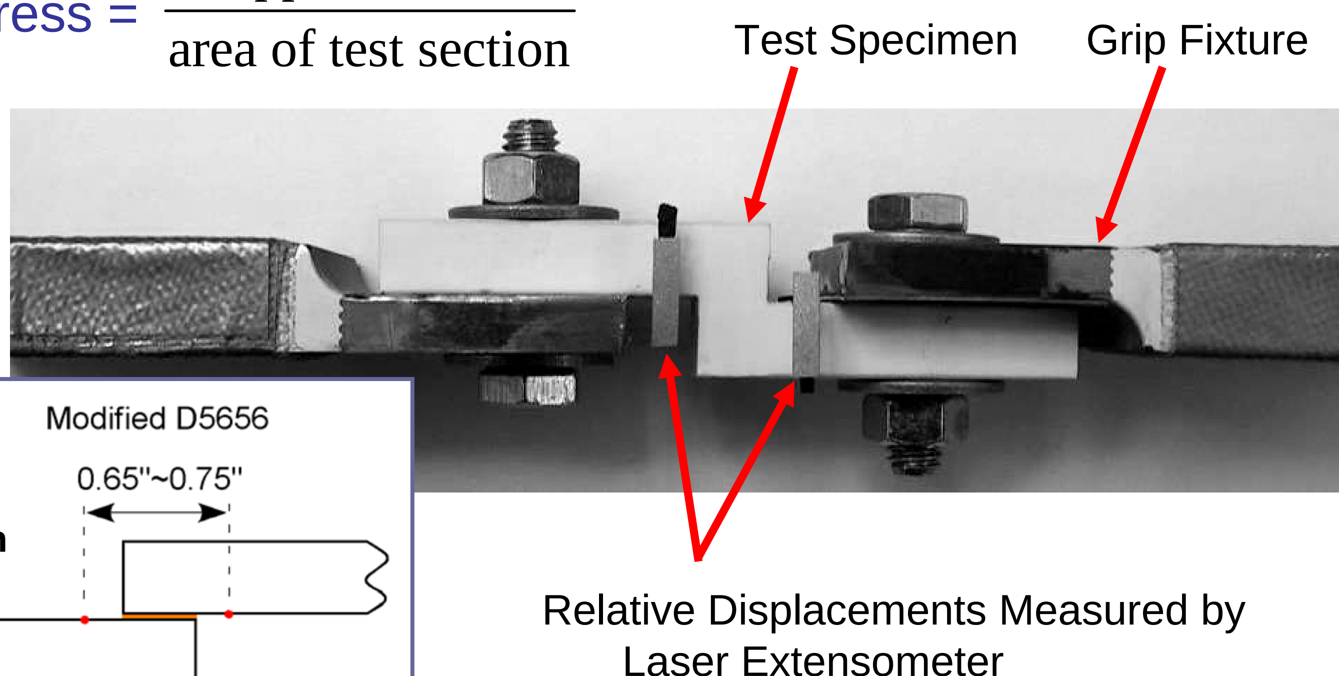
Objectives:

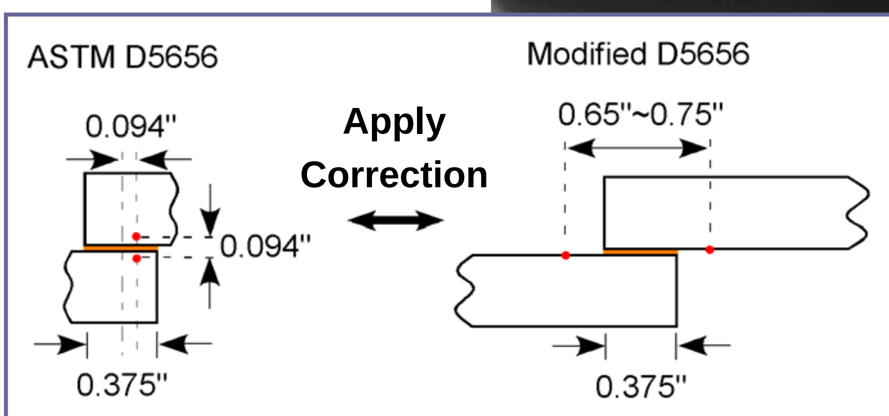
- understand why ASTM D5656 behavior is bondline-thickness dependent
- establish more direct and simple test method for determining constitutive behavior: tensile dogbone, t.b.d. method
- resolve differences observed between tensile dogbone test & ASTM D5656

Modified ASTM D5656 Joint Tests

- Average shear strain = $\dfrac{\text{relative displacement}}{\text{adhesive thickness}}$

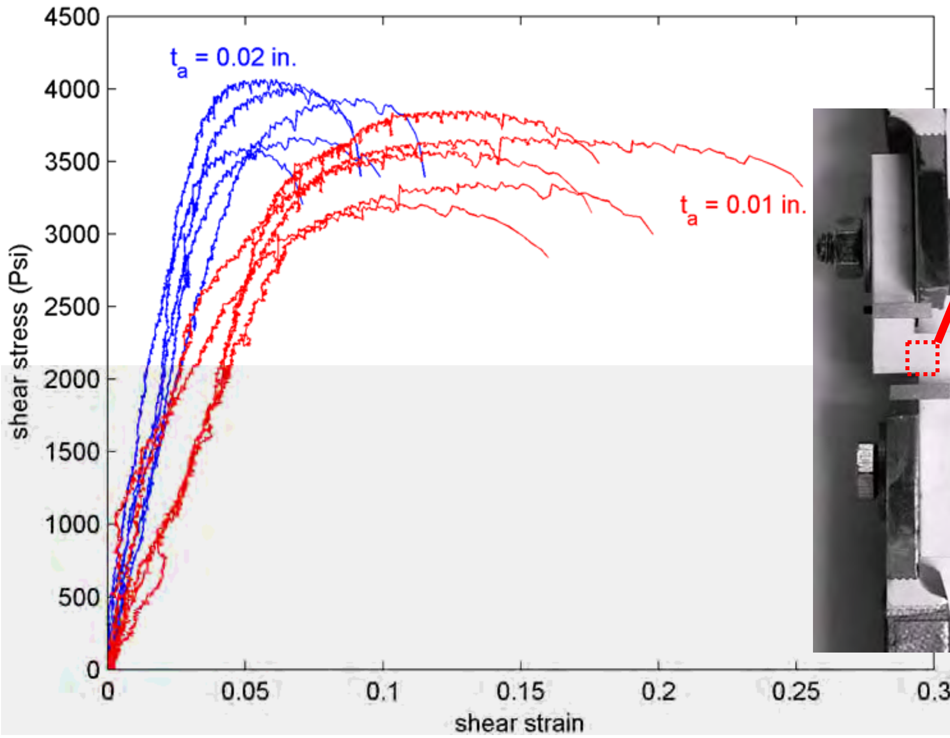
- Average shear stress = $\dfrac{\text{applied load}}{\text{area of test section}}$

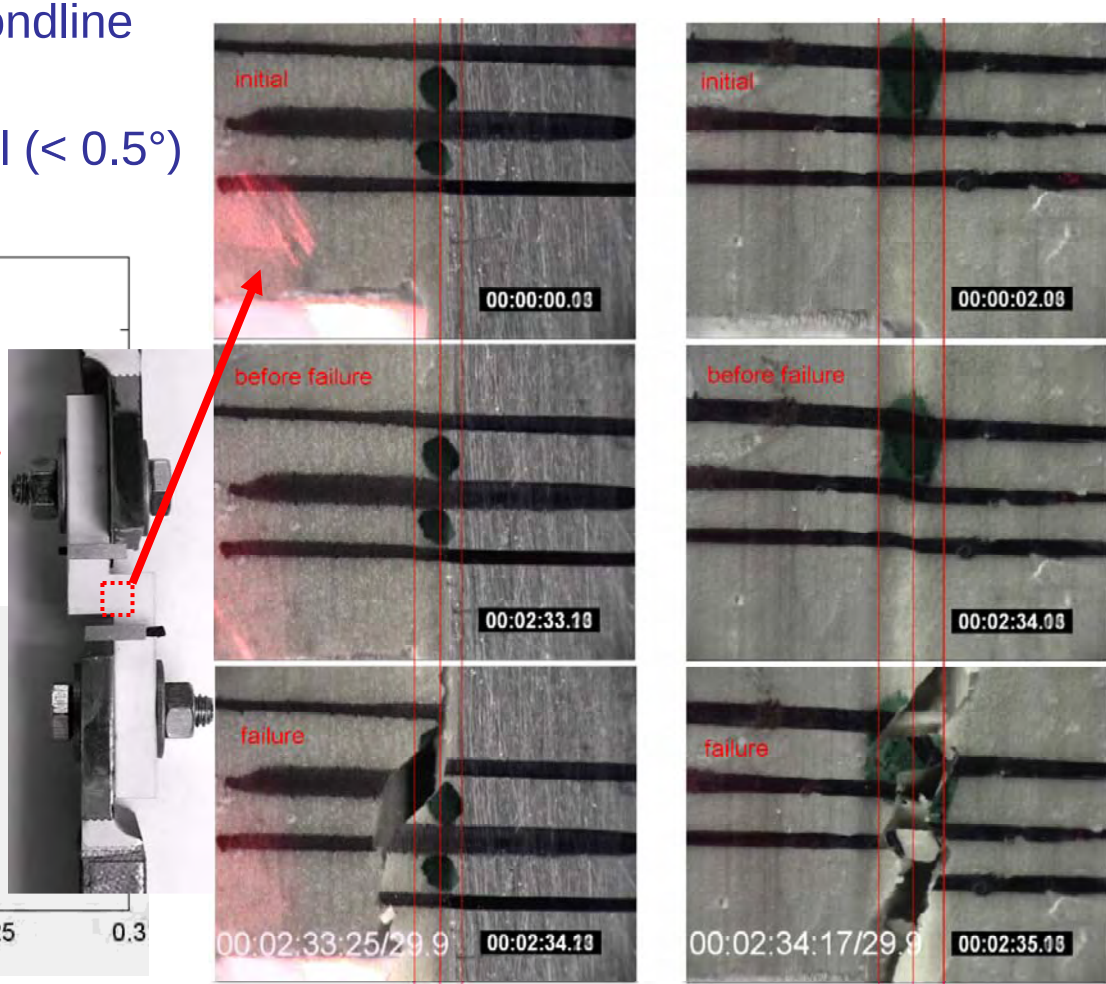




D5656 Test Results

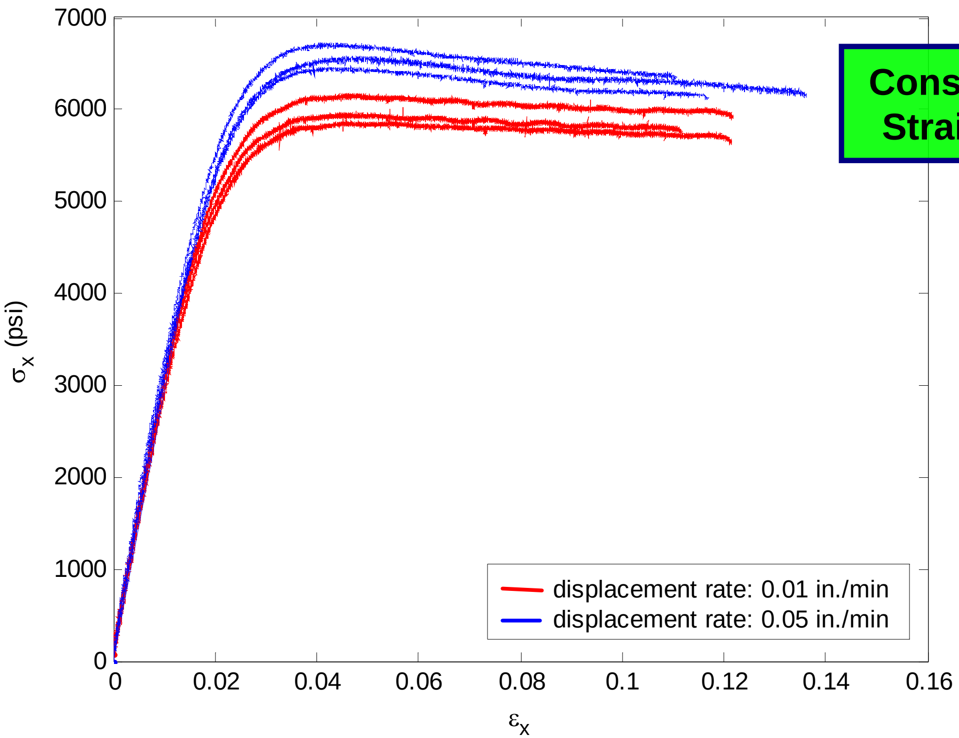
- D5656 test data show strong bondline thickness dependency
- global rotation of joint is minimal (< 0.5°)

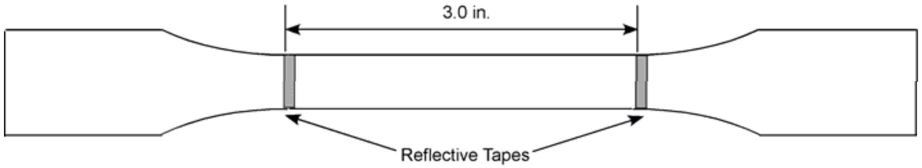




Bulk Adhesive Constitutive Behavior – Tensile Dogbone Tests

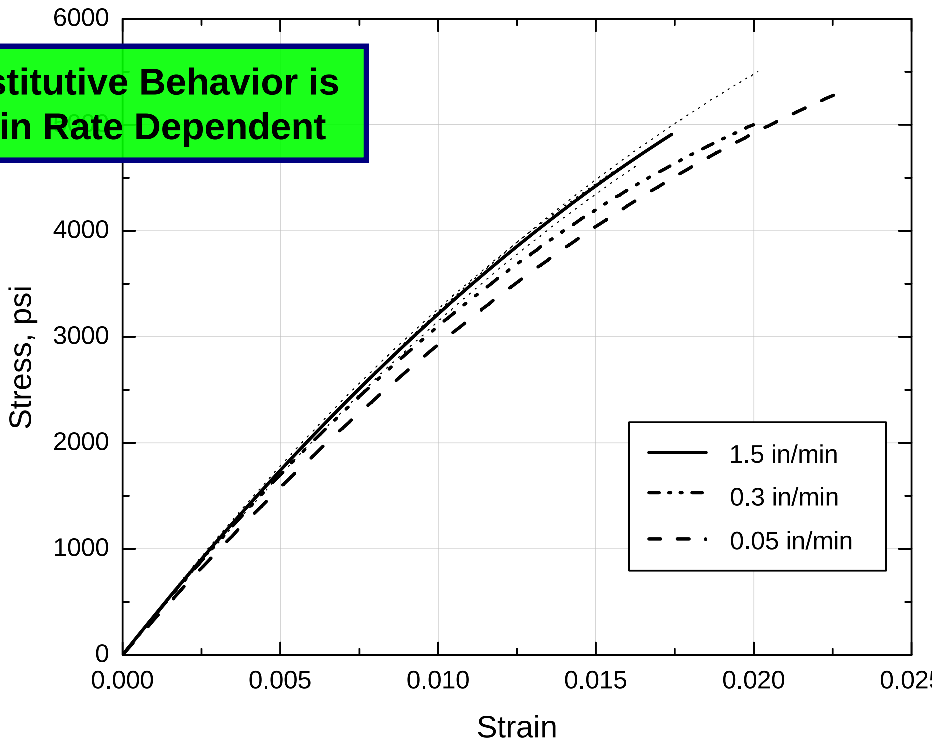
Cytec FM 73 film adhesive

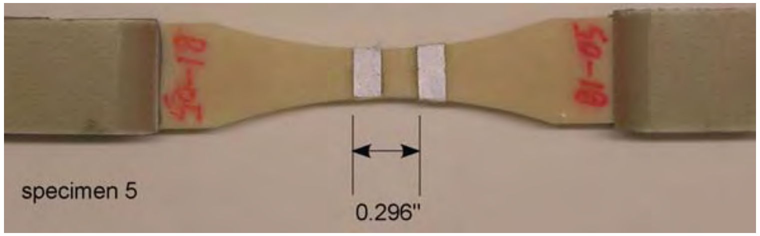




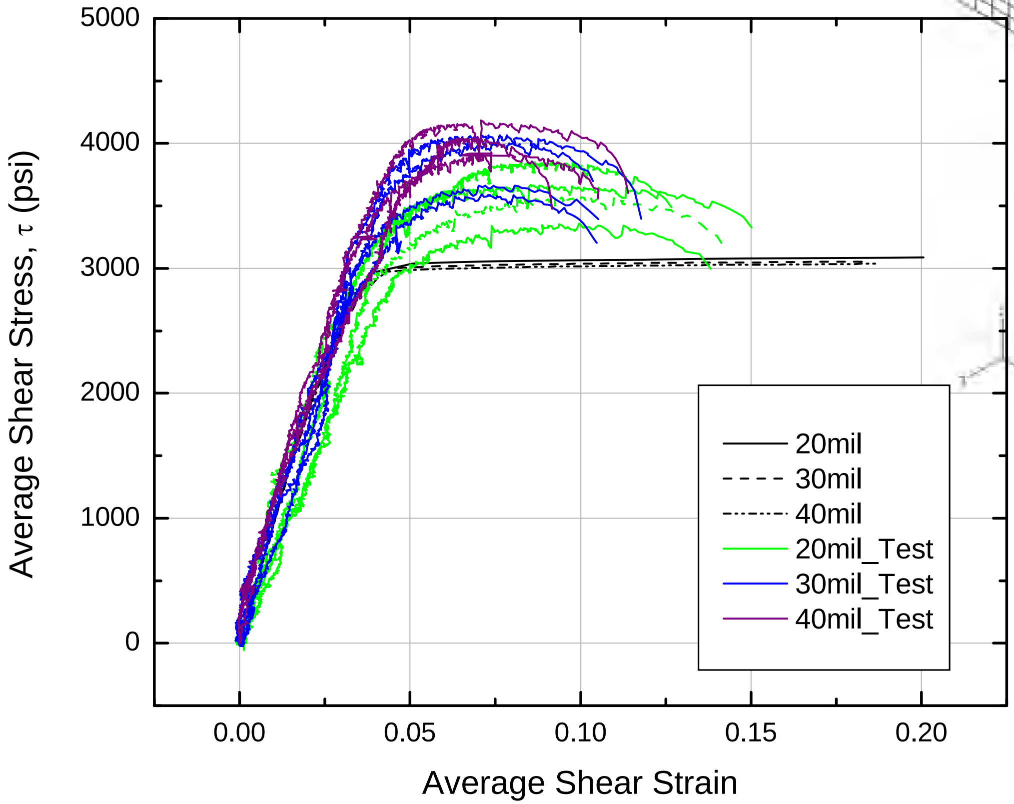
PTM&W ES6292 epoxy paste adhesive

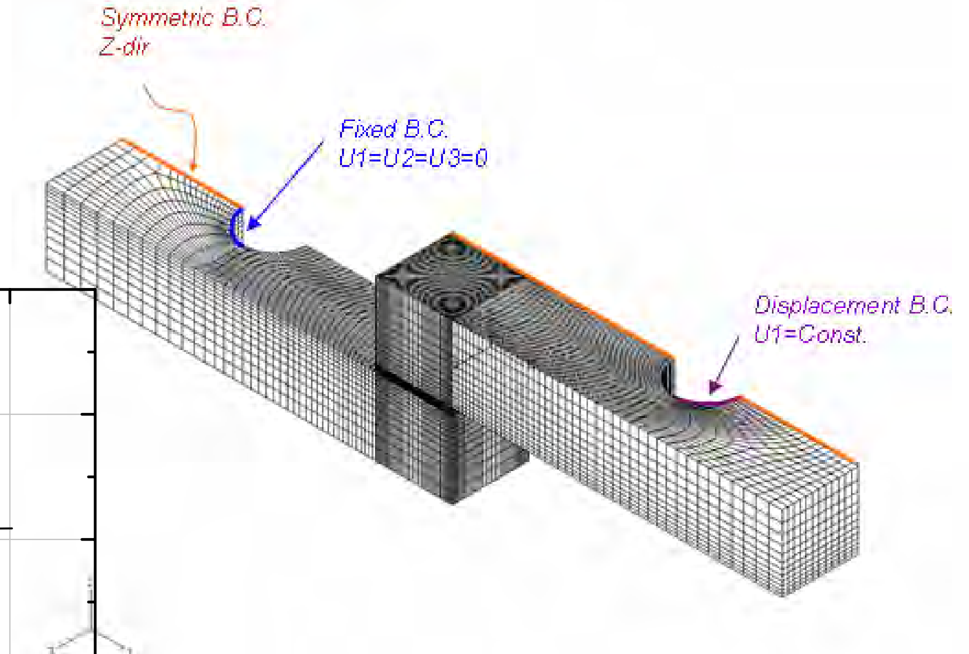
Constitutive Behavior is Strain Rate Dependent





Finite Element Modeling



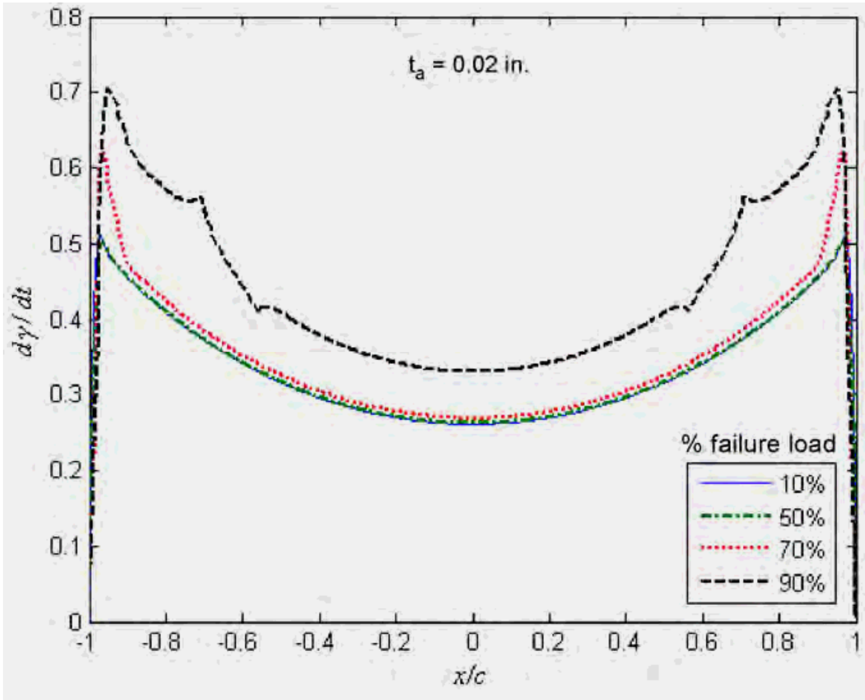


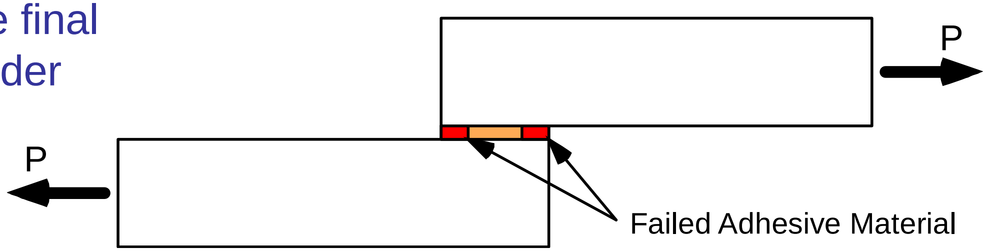
- bulk tensile coupon constitutive data used to model D5656 test
- FEA models not showing bondline thickness dependency
  - need to account for strain rate dependency and damage evolution

Discussion

- strain rate dependency:
  - adhesive exhibits strain rate dependency
  - strain rate in joint ~ 10^{-1} s^{-1}
  - strain rate in bulk tensile coupon less than ~10^{-3} s^{-1}
  - must model adhesive using viscoplastic material (Zgoul M. and Crocombe 2004)

- localized damage evolution:
  - highly constrained bondline permits localized failure prior to joint final failure
  - increased compliance – effectively showing plastic “plateau” and large final failure strain in D5656 tests run under displacement control
  - FEA models must capture this phenomenon





Summary

- D5656 thick adherend data measured for PTM&W ES 6292 adhesive
  - show strong bondline thickness dependency
- bulk tensile coupons tested to measure adhesive constitutive behavior directly
- FEA models of D5656 specimens using bulk-measured tensile data predicts only initial portion of specimen behavior
- issues exist:
  - premature failure of bulk tensile specimens – not measuring entire constitutive behavior
    - improved test is needed
  - to replicate D5656 data using bulk tensile coupon data, FEA modeling must account for
    - strain rate dependency
    - localized damage evolution

Project II

Effect of Adhesive Thickness on Mixed Mode Fracture of Joints

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Richard Khoo, Graduate Student

Background and Objectives

Background

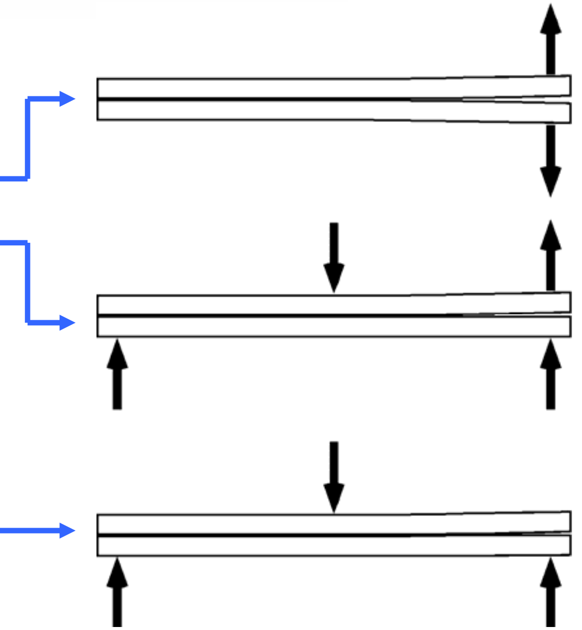
- fracture mechanics is capable tool for damage tolerance analysis
- need mixed mode strain energy release rate (SERR) data

Objectives

- measure mixed mode SERR for range of bondline thickness
  - Mixed Mode Bending (MMB), DCB, ENF
- observe processes occurring at crack tip
- use modeling/analysis to understand bondline effect in measured data – establish fracture criteria in joints that accounts for bondline thickness dependent G_{IC} and G_{IIC}

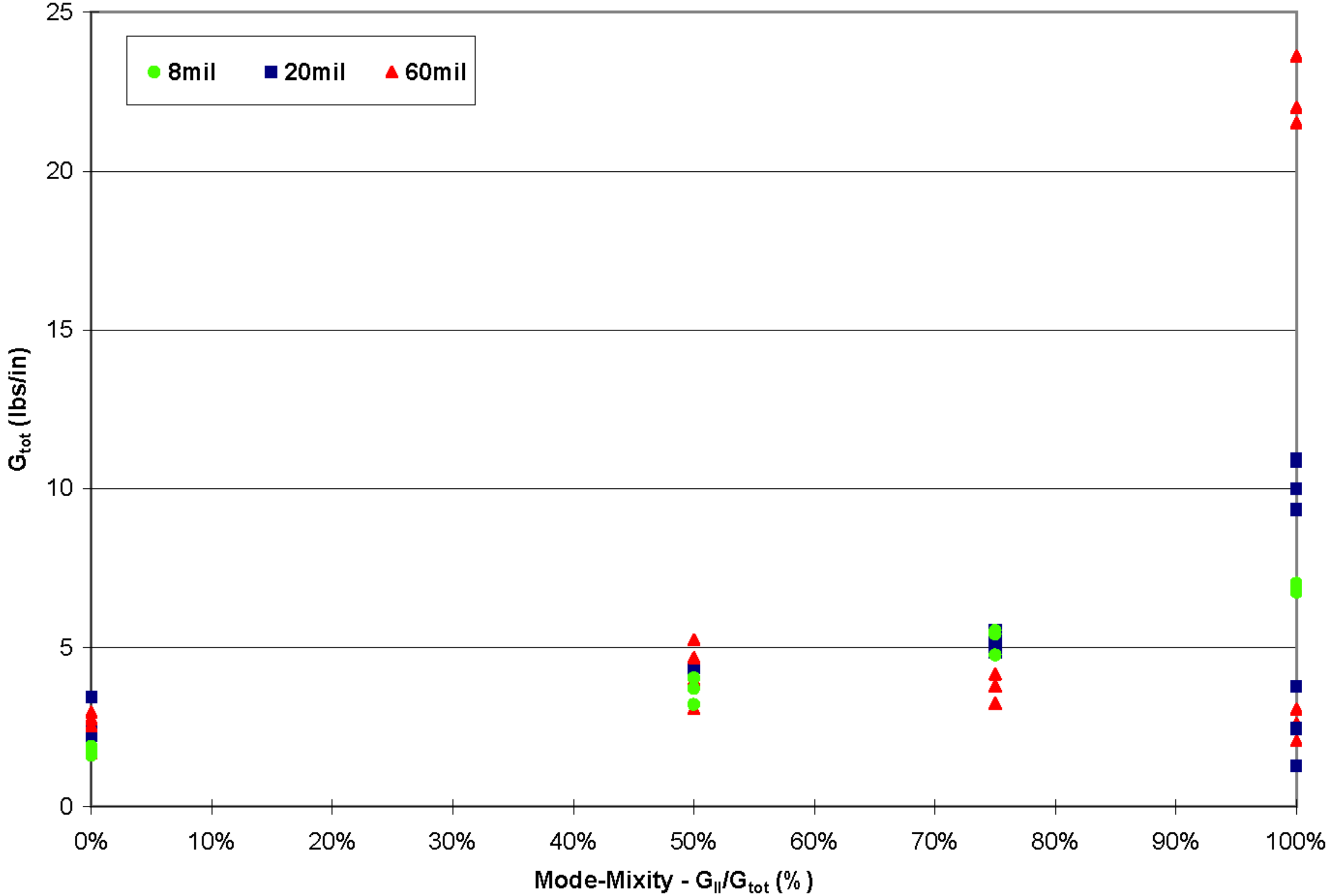
Experiments

- G_c measured for range of mode I and mode II mix ratios
  - Double Cantilever Beam (DCB) – pure mode I
  - Mixed Mode Bending (MMB)
  - End Notched Flexure (ENF) – pure mode II
- test specimen details
  - adherends: 2024-T4 Al alloy, 0.25 x 1.0 x 6.0 in.
  - adhesive: PTM&W ES6292 epoxy paste adhesive
  - bondline thickness range: 0.008 to 0.060 in.
- test matrix

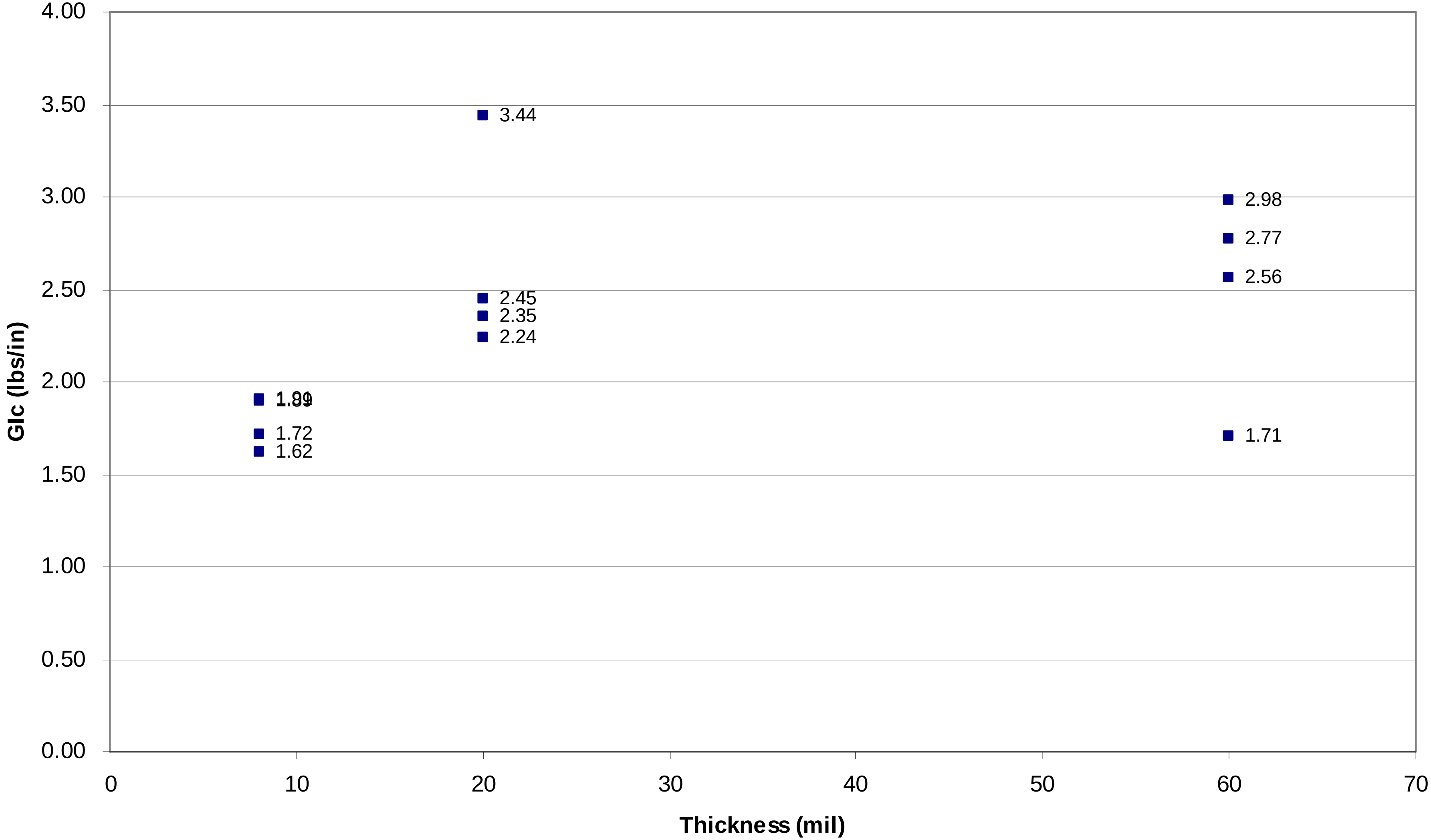


Mode Mix (% mode II)	t_a = 0.008 in.	t_a = 0.020 in.	t_a = 0.040 in.	t_a = 0.060 in.
0	done	more tests	to-do	done
50	done	done	to-do	more tests
75	done	done	to-do	more tests
100	done	done	to-do	done

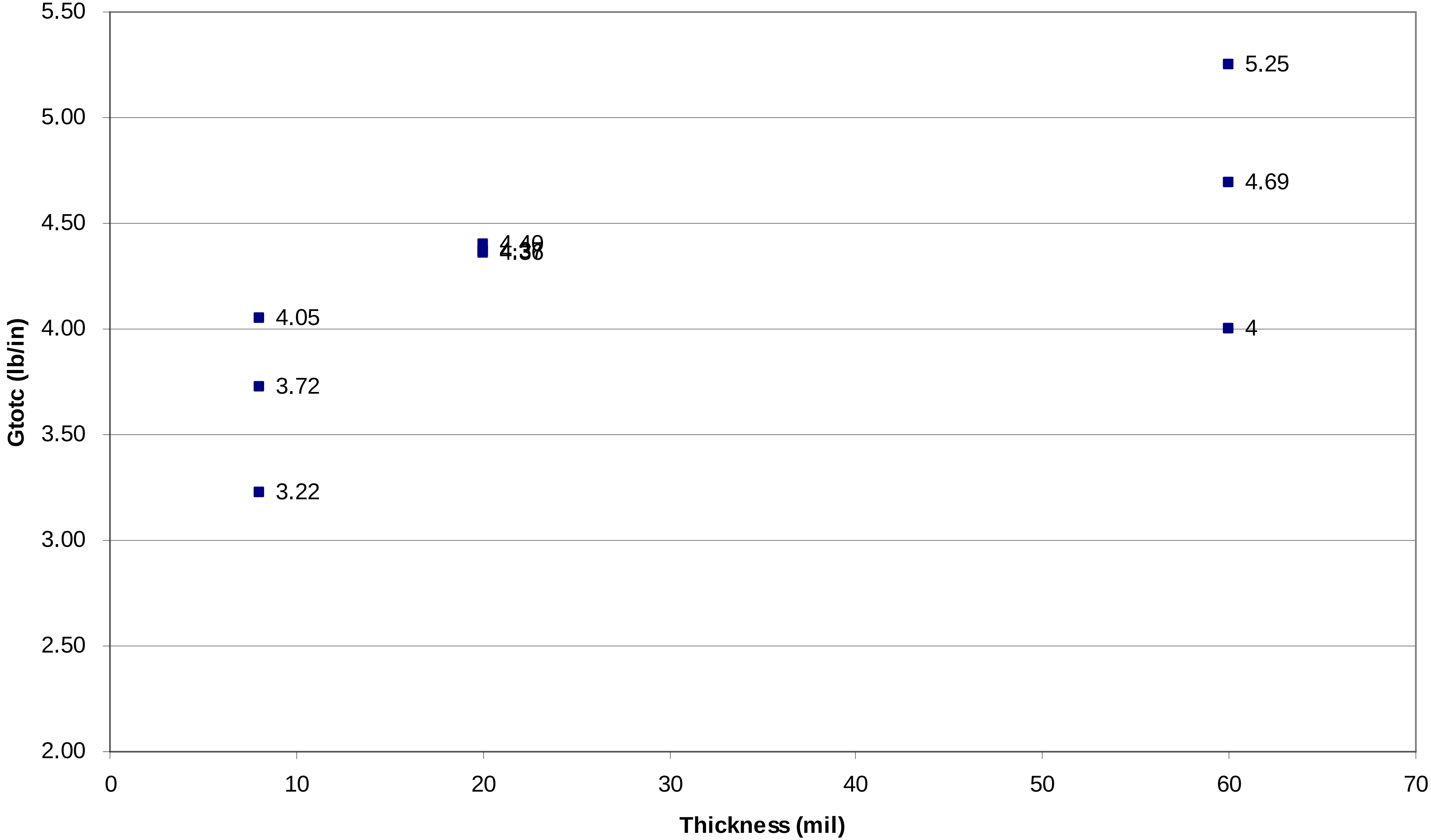
Results I – Overall G_C Trend



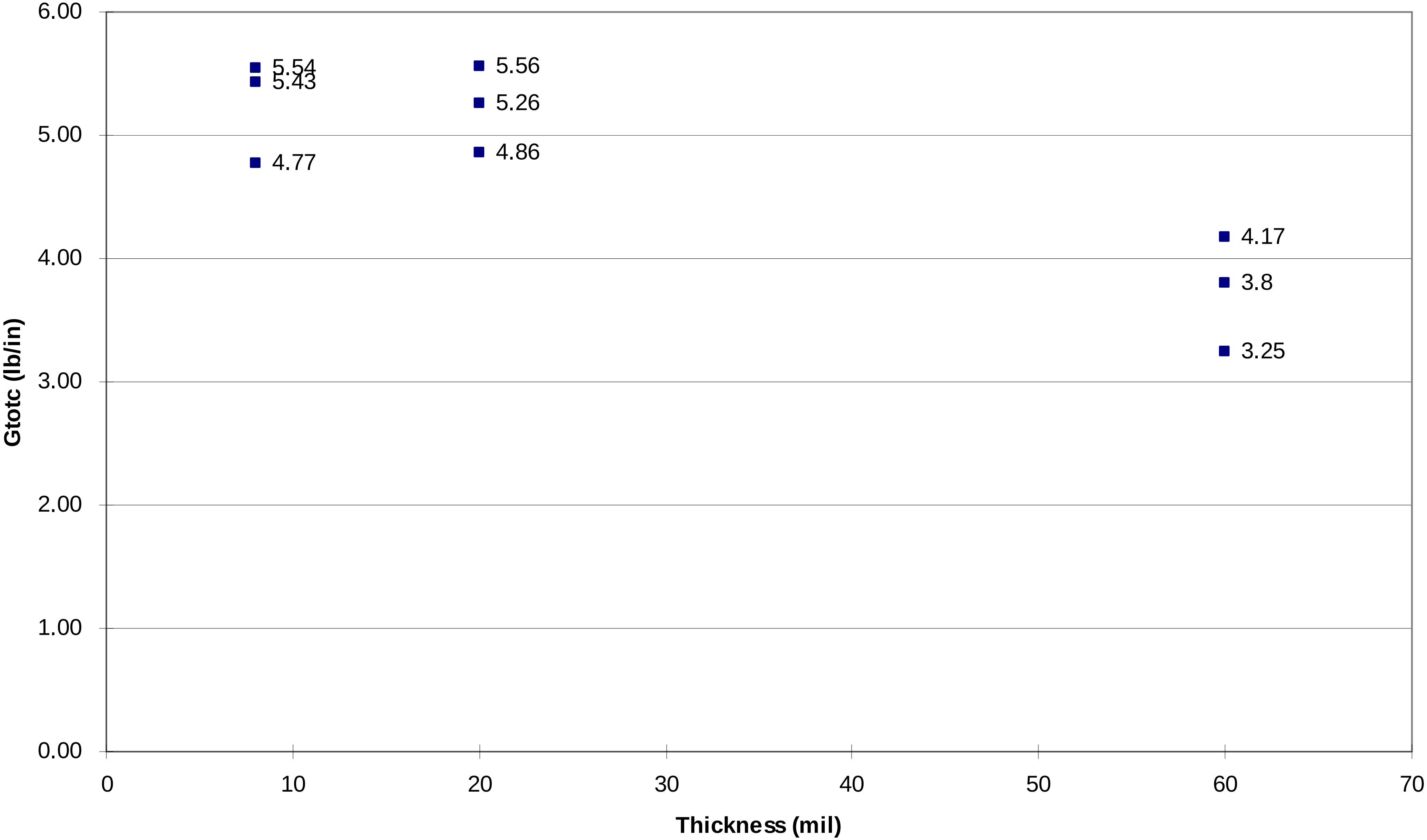
Results II – G_{IC} vs. t_a



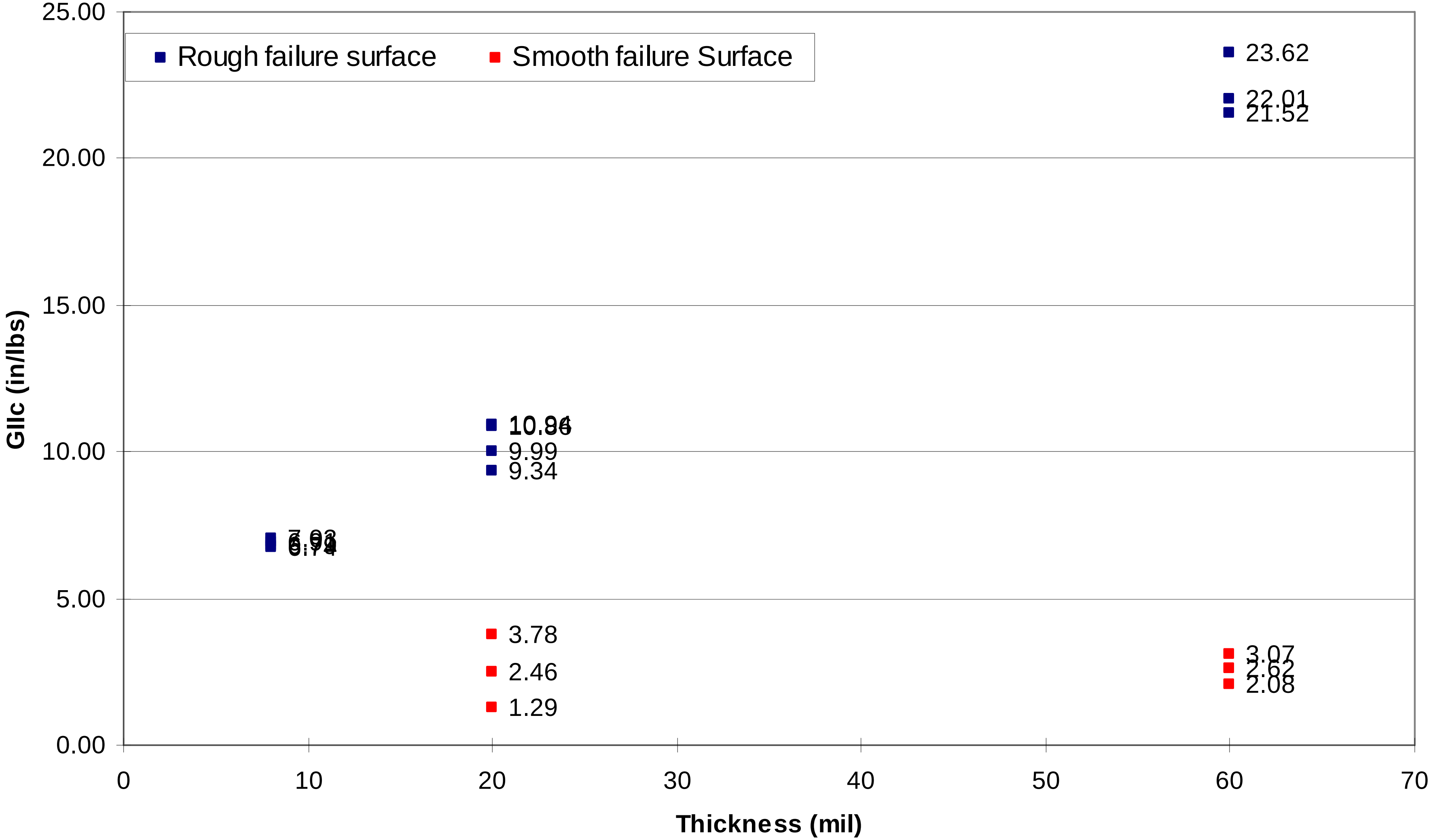
Results III – 50% Mode II G_C vs. t_a



Results IV – 75% Mode II G_C vs. ta

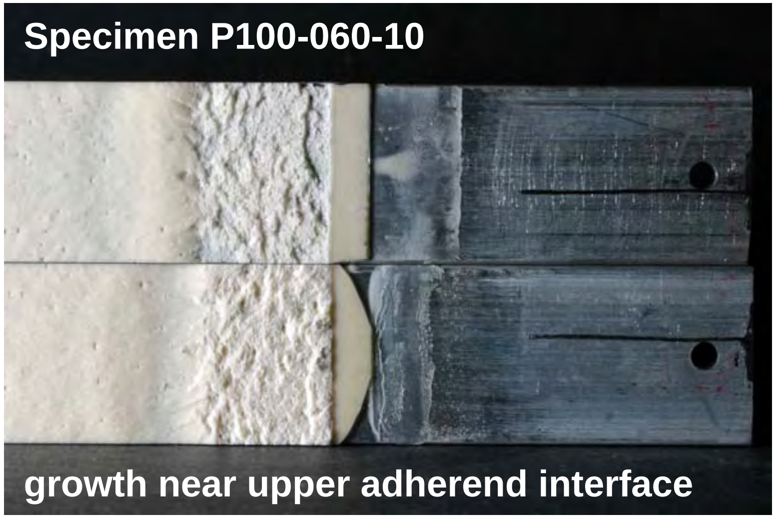


Results V – G_{IIC} vs. t_a



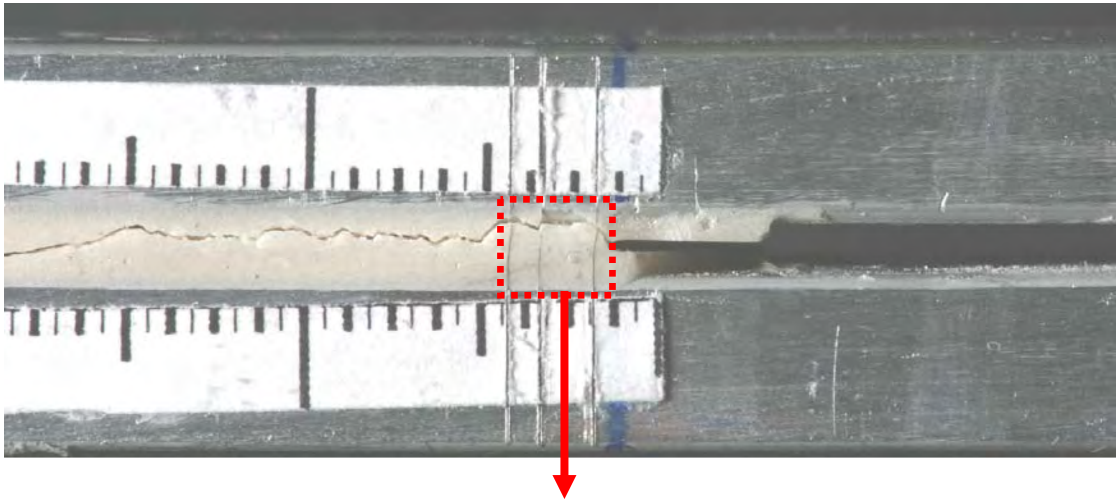
Discussion

- failure modes
  - all specimens exhibited cohesive failure
    - data omitted if any amount of adhesion (clean interface) failure observed
  - stable crack growth – leaves behind rough fracture surface
- pure mode II: 20 and 60 mil bondline specimens exhibited bimodal behavior
  - stable growth – rough fracture surface; G_{IIC} ~ 10 - 22 lb/in
  - unstable growth – smooth fracture surface ; G_{IIC} ~ 2.5 lb/in



Plastic Zone Development

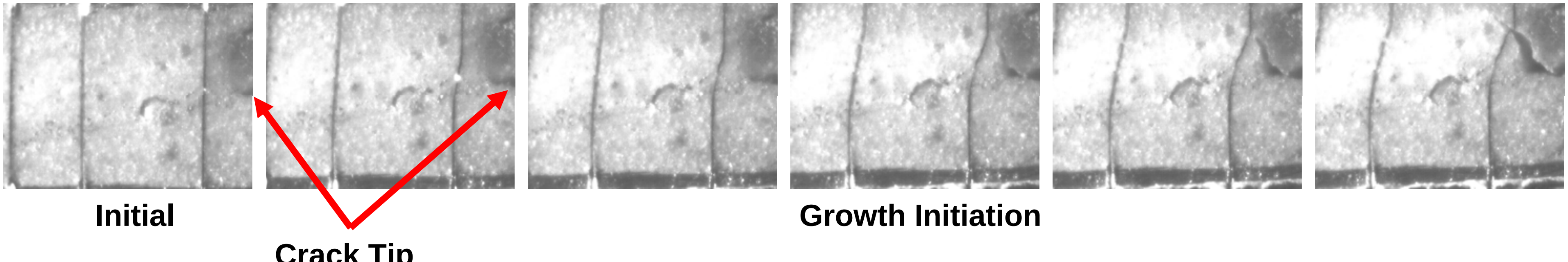
- significant plastic strain developed ahead of crack tip prior to growth
- confinement of plastic zone by adherends known to play key role in fracture



Pure Mode II Loading

Bondline Thickness: 0.060 in.

Microscope Field of View:



Summary

- G_C measured as function of mode mixity (modes I and II), and bondline thickness
- 8 mil bondline exhibits monotonically increasing G_C for higher mode II content
- 20 and 60 mil bondlines exhibit bimodal behavior for 100% mode II
  - stable growth / rough fracture surface – high G_{IIC}
  - unstable growth / smooth fracture surface –low G_{IIC}
- large plastic deformation observed to develop ahead of crack tip
- FEA modeling of fracture tests is under-way to quantify plastic zone size and confinement/interaction with adherends
  - validation to be achieved via comparison with image-analysis measurements of shear strain

Effect of Bondline Thickness on Strength of Adhesively Bonded Joints

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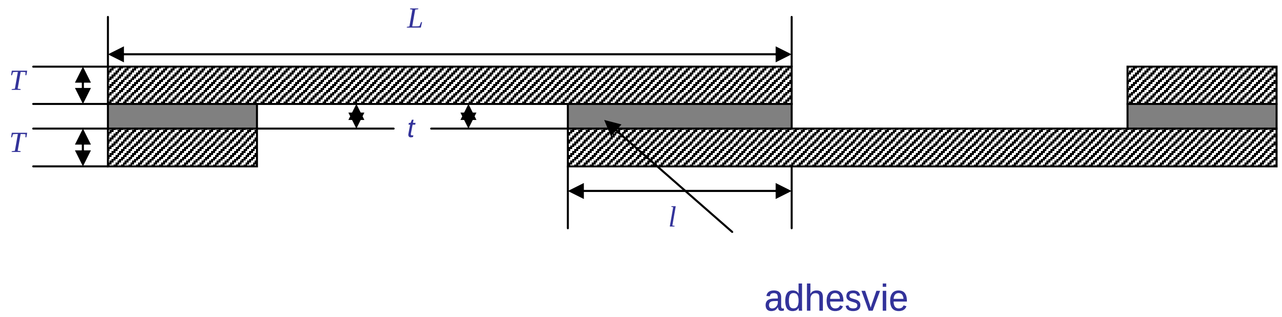
Hiayang Qian, Graduate Student

Objectives

- To understand the mechanism that effects the thickness-dependent joint strength behavior in adhesively bonded joints
- To develop a CTOA approach for predicting crack growth in bonded joints with the capability of accounting for the effect of bondline thickness

Single Lap Joint Specimen Configuration for Strength Test



L=3in

l=1in

T=0.125in

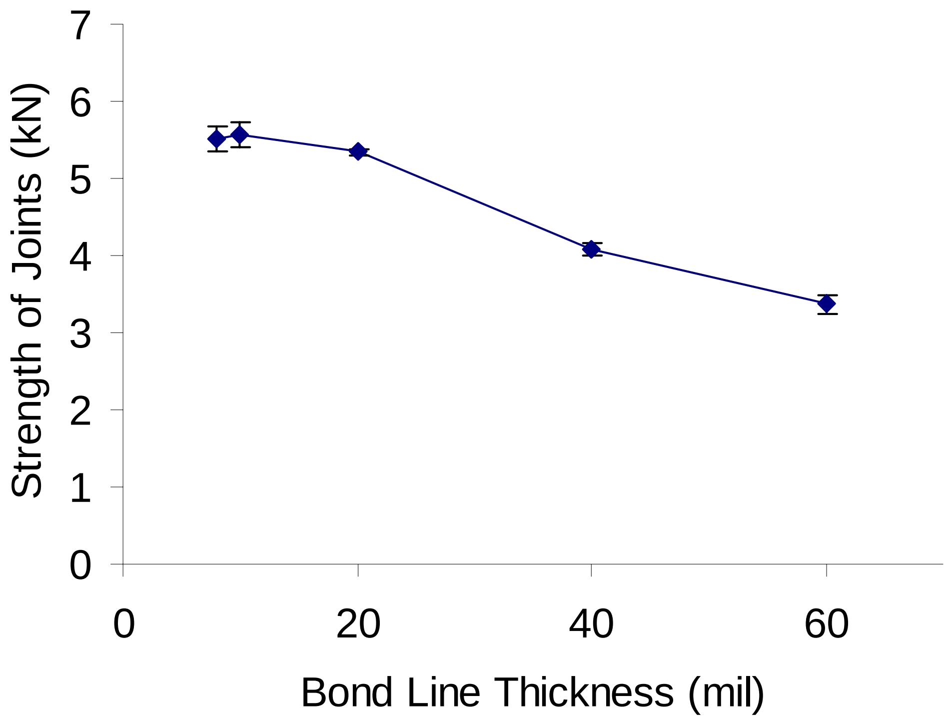
t=0.008in, 0.01in, 0.02in, 0.06in

Adherend: Aluminum Alloy 7075

Adhesive: PTM&W ES6292

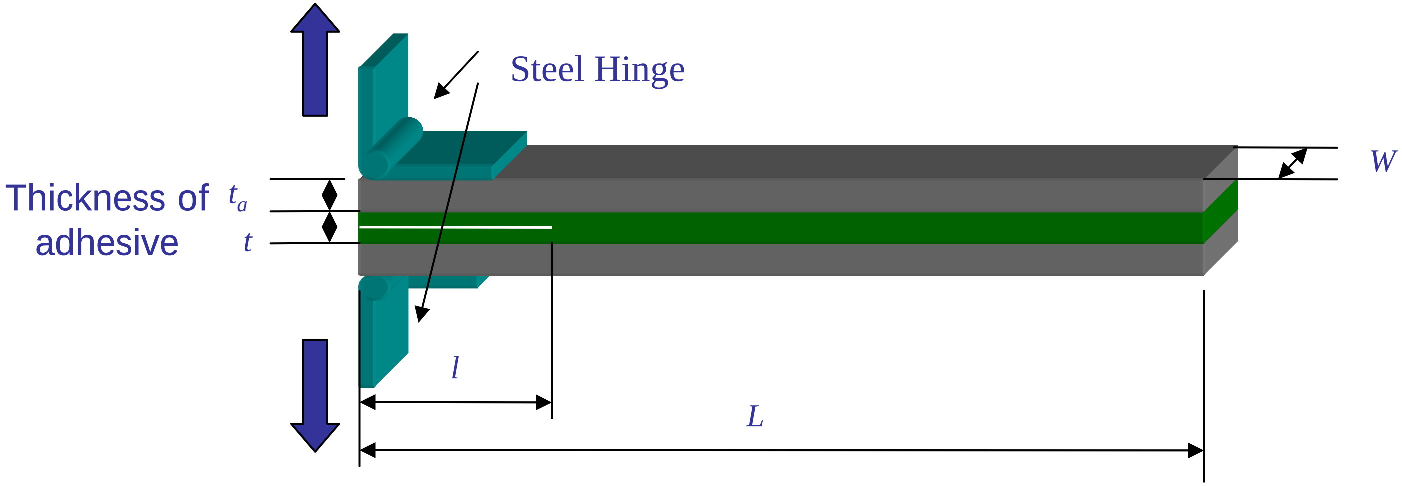
Surface Treatment: Semco Pasa-Jell 105 (etching method)

Single Lap Joint Strength vs. Adhesive Thickness



The joint strength decreases as the adhesive thickness increases

DCB Specimen for Fracture Test



Total length of the specimen: 4 in

Pre-crack length: 1.5 in

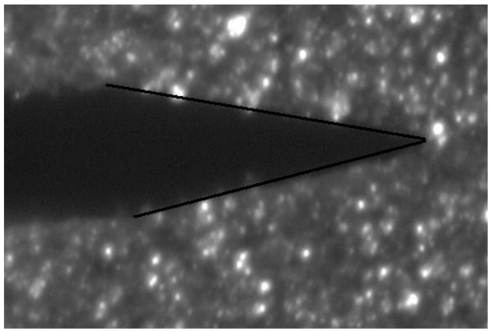
Adherend: Aluminum 7075

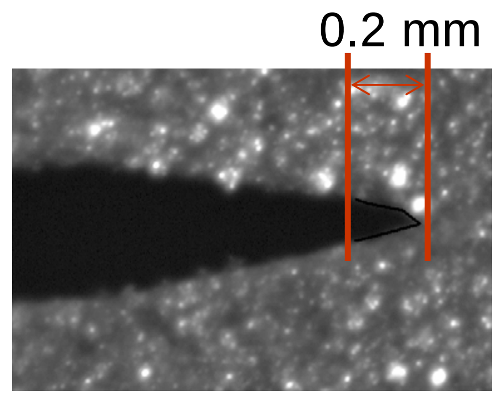
Adherend thickness: 125mil (0.125 in)

Adhesive: Hysol EA9394

Thickness range: 27mil-120mil

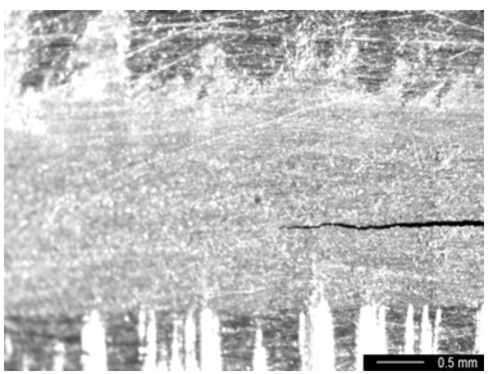
CTOA Measuring with Crack Propagation

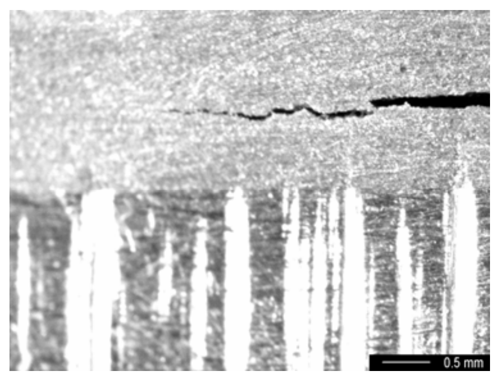


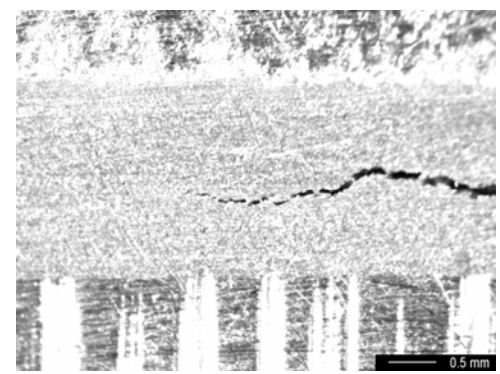


Initial State

Before crack initiation

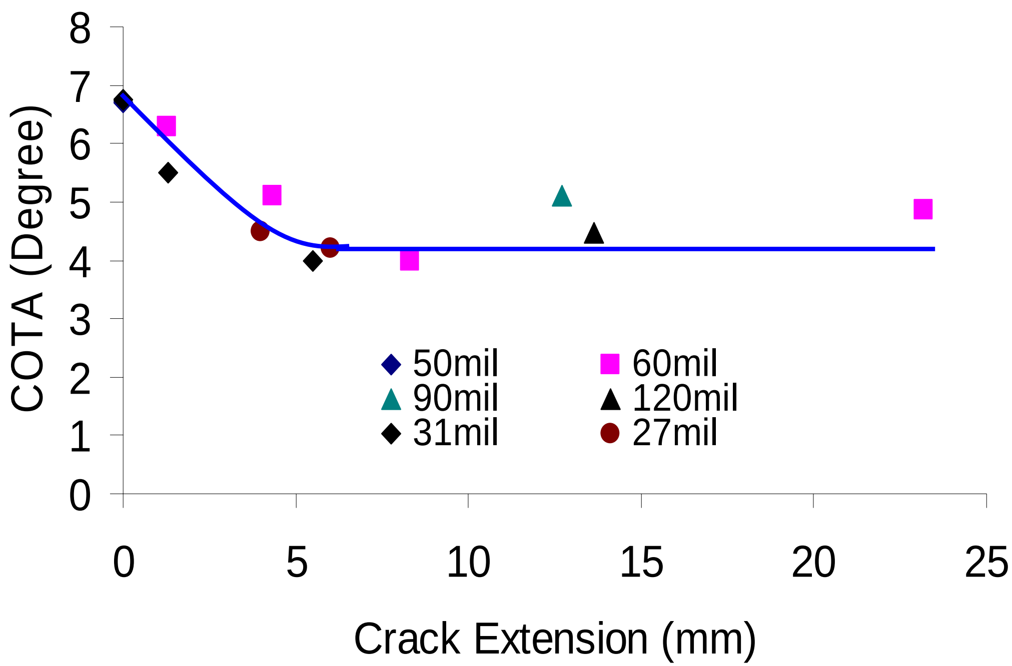






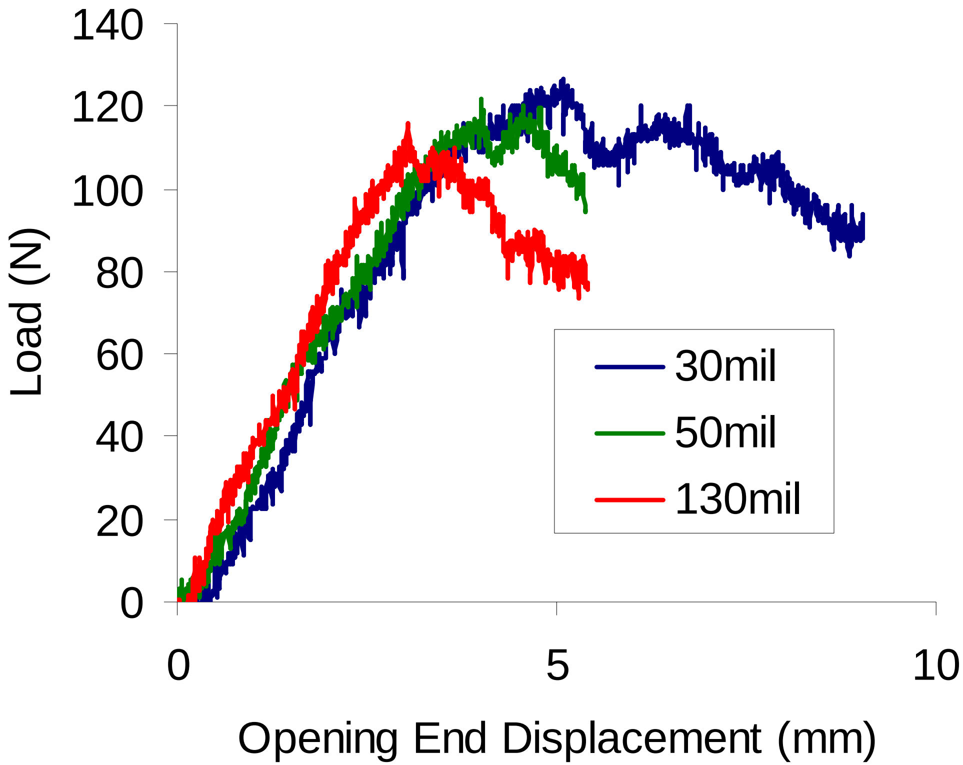
Crack Propagation

CTOA Curve is Independent of Bondline Thickness



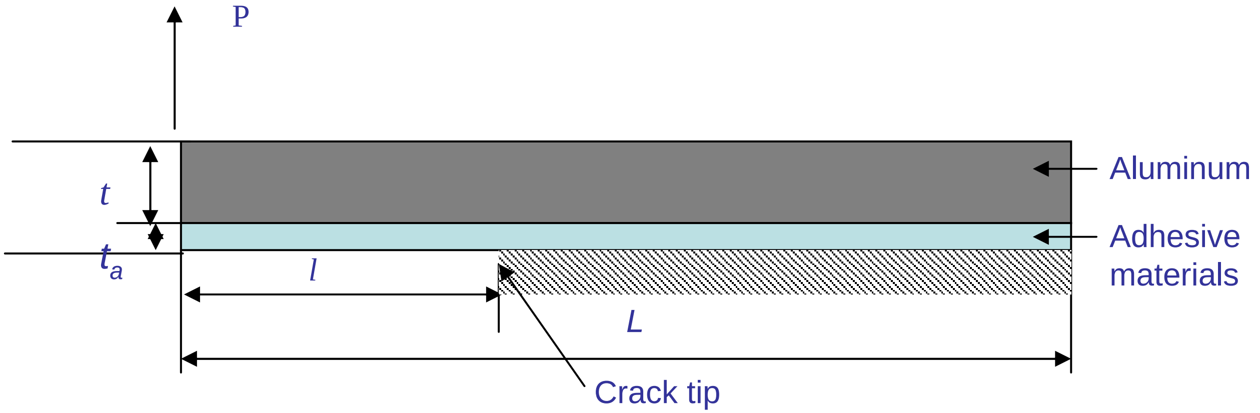
$$CTOA = \begin{cases} 0.0003x^4 - 0.01x^3 + 0.1253x^2 - 0.8303x + 6.74 & (x \le 5.7) \\ 4.2 & (x \ge 5.7) \end{cases}$$

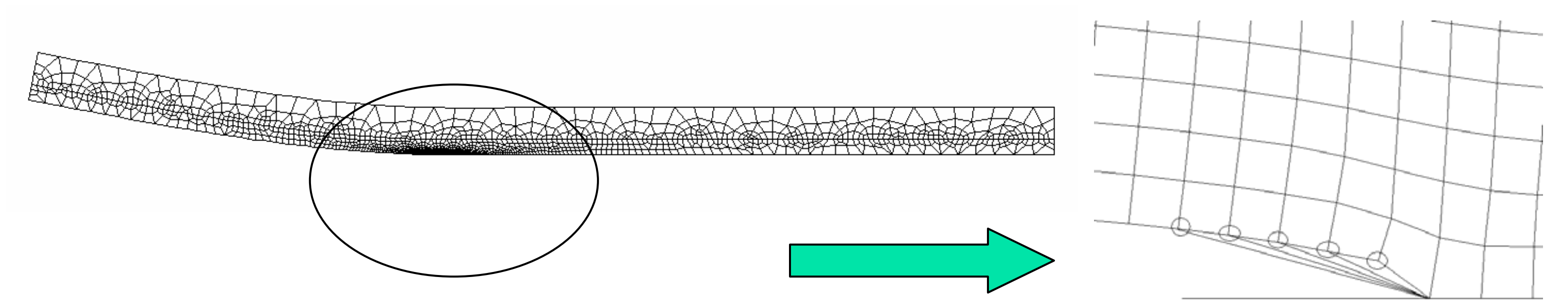
Effect of Bondline Thickess on DCB Fracture Load



Load and Displacement at the Opening End of the Specimens

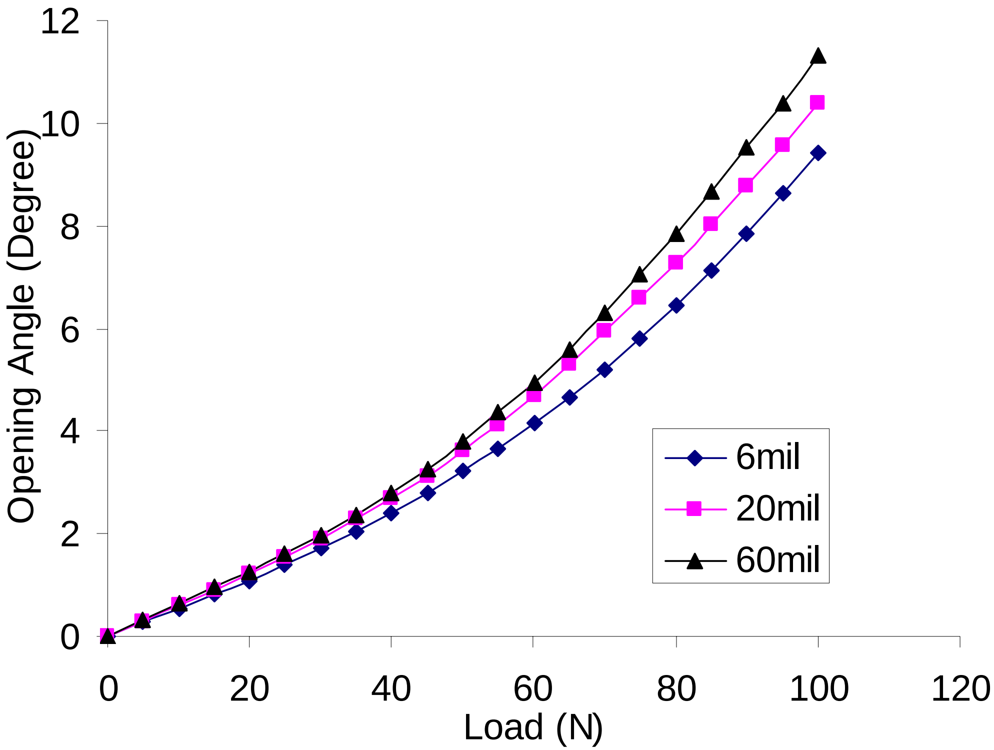
DCB Model and CTOA Calculation



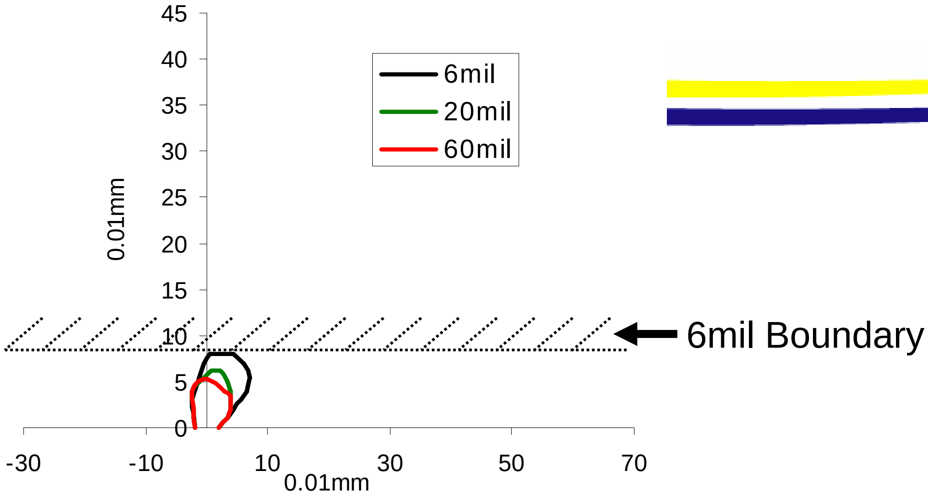


CTOA Calculation

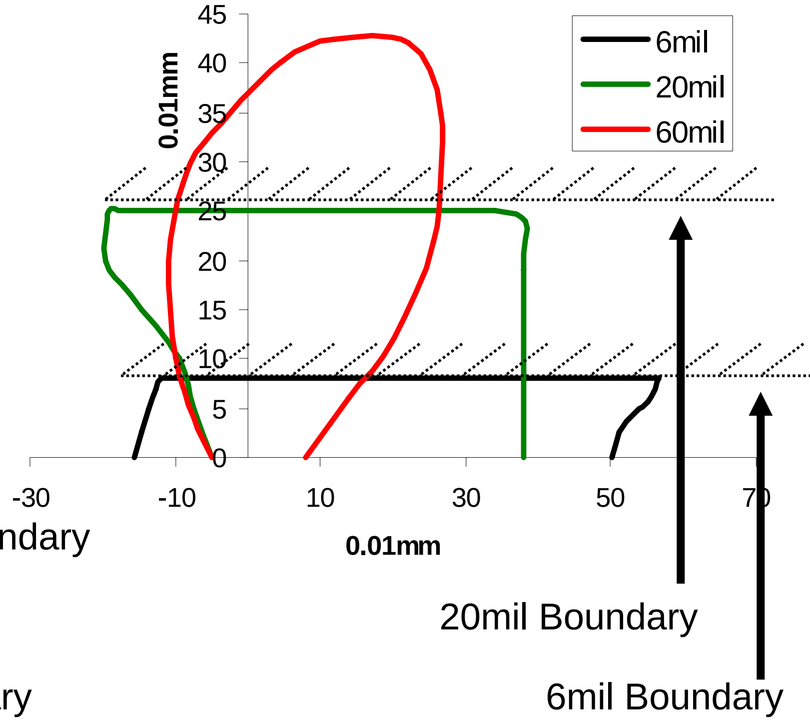
Effect of Bondline Thickness on CTOA



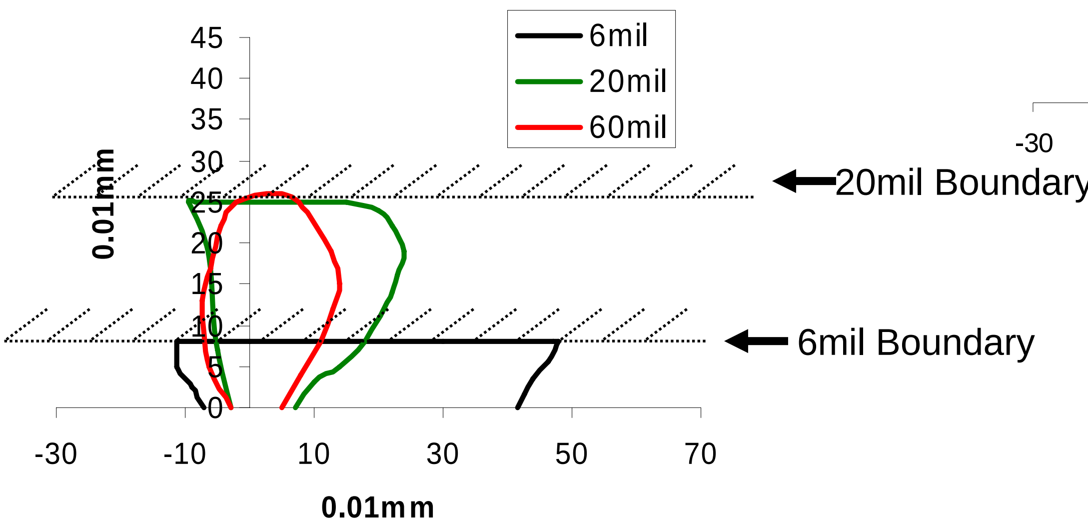
Confinement of Plastic Zone



Plastic Zone under 35N

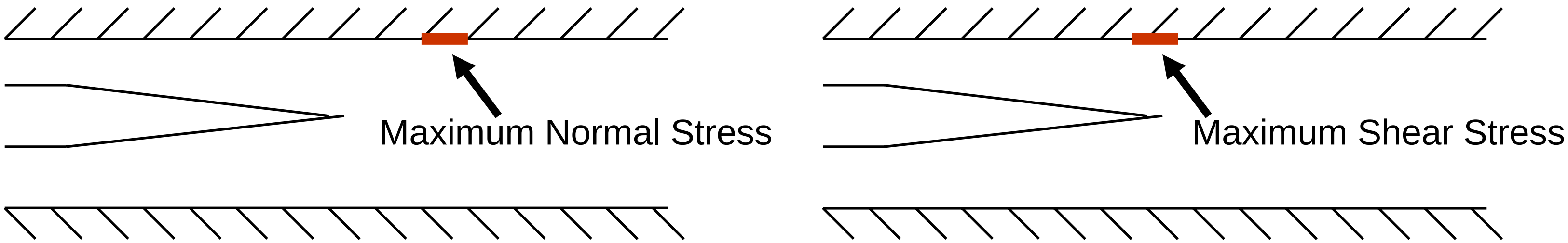


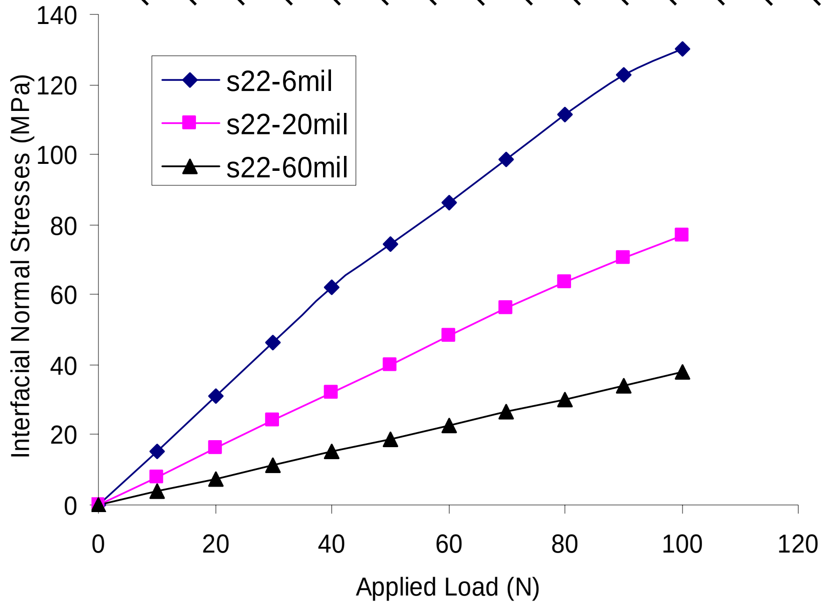
Plastic Zone under 100N



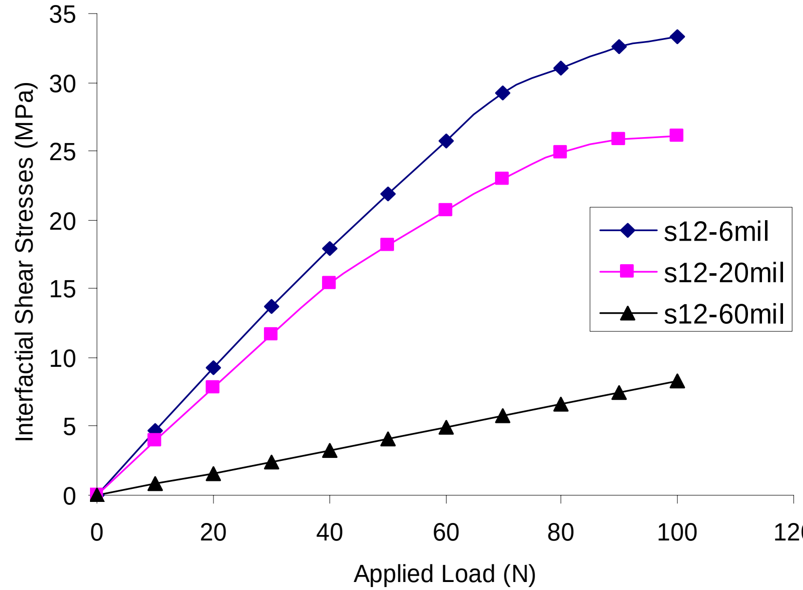
Plastic Zone under 75N

Interfacial Stresses Increase as Thickness Decreases





Maximum Normal Stresses



Maximum Shear Stresses

Summary of Results

- Strength of single lap joint increases as bondline thickness increases
- CTOA for crack growth in adhesive is independent of bondline thickness
- In DCB fracture test, toughness increases as bondline thickness decreases. This result may be explained in terms of greater confinement of crack tip plastic zone in thinner bondline case
- For thinner bondlines the interfacial stresses between the adhesive and adherend are higher than those for thicker bondlines. It is possible that interfacial strength failure may precede crack extension leading to a lower failure load in joints with thinner bondlines.

Project IV

Influence of Bondline Thickness and Moisture on Joint Fracture

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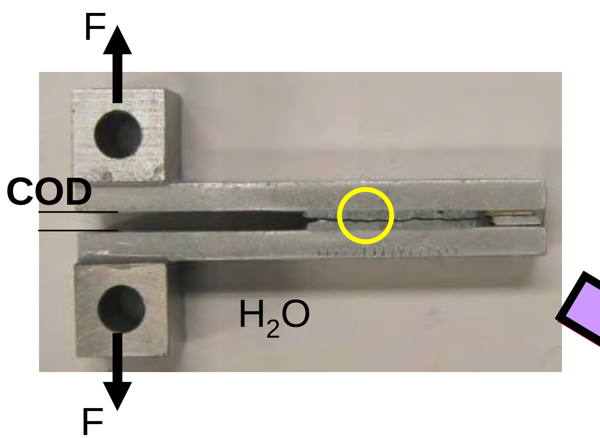
Steffen Brinckmann, Post Doctoral Research Associate
Jibin Han, (PhD 12/2005)
Eric Anderson, SURF Summer Student

Damage Tolerance and Durability of Adhesively Bonded Composite Structures

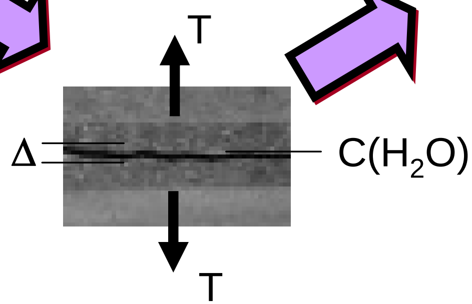
- **Project goals:**
  - Develop and employ the cohesive zone model approach to fracture to the analysis of adhesive joint failure
- **Major achievements/conclusions to date:**
  - ☑ Test procedure to determine cohesive zone model parameters under monotonic loading
  - ☑ Transferability of test data between independent crack growth tests
  - ☑ Test procedure for moisture degradation
  - ☑ Coupled cohesive zone model for moisture/load interaction
  - ☑ 3D model implementation
- **Benefits the aviation industry:**
  - CZ model approach well established in e.g. microelectronics, civil engineering
  - Aid in establishing approach to aviation industry
  - Establish approach to long term problems (fatigue, environmental degradation) to reduce testing time

Influence of Bondline Thickness and Moisture on Joint Fracture

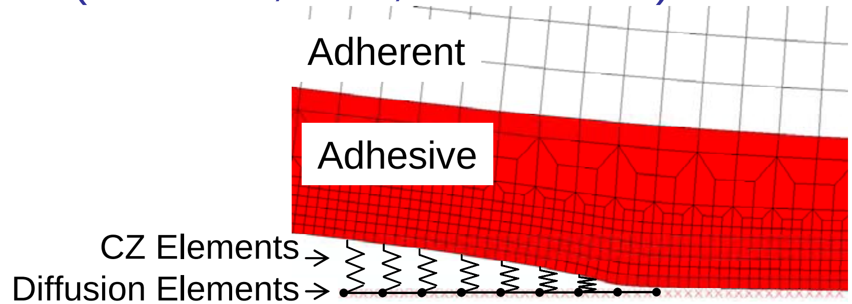
- **The Cohesive Zone Model:**
  - Describes local energy dissipation during fracture and fatigue
  - Is conveniently coupled to other fields (moisture, heat, electrical…)



Global Parameters:
- Force (F) – Displacement (COD)
- Environment (H_2O)



Local Parameters:
- Traction (T) – Separation (Δ)
- H_2O Concentration C(H_2O)

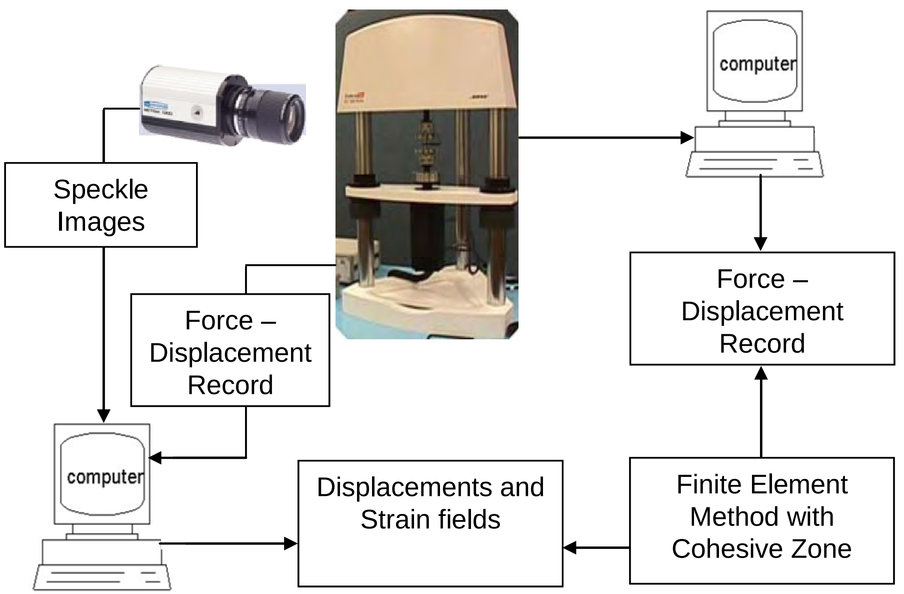


Finite element model with cohesive elements & H_2O transport

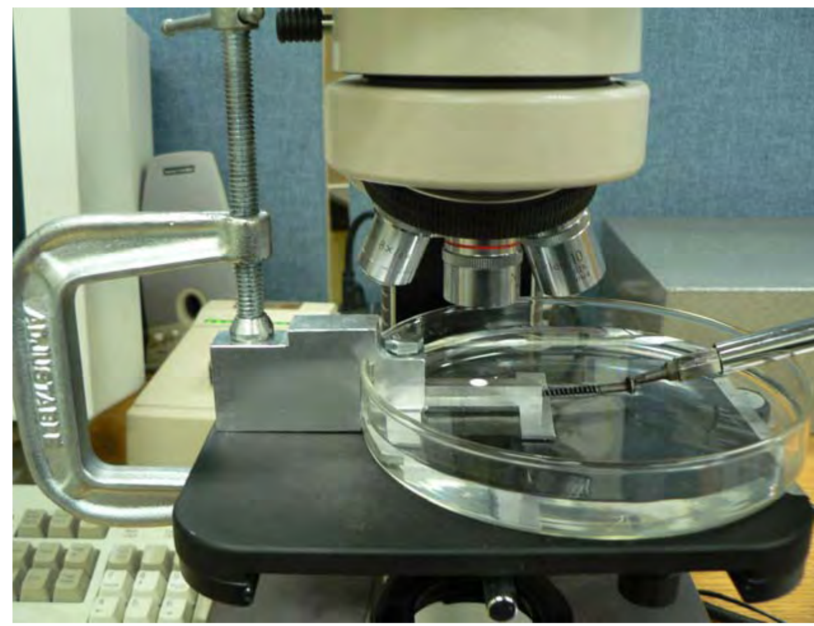
Influence of Bondline Thickness and Moisture on Joint Fracture

Experimental Set-up

Crack Growth Resistance

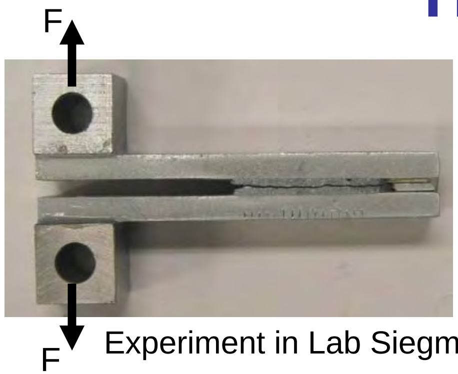


Environmental Degradation



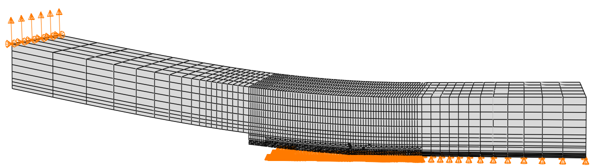
Influence of Bondline Thickness and Moisture on Joint Fracture

Transferability of CZ Model



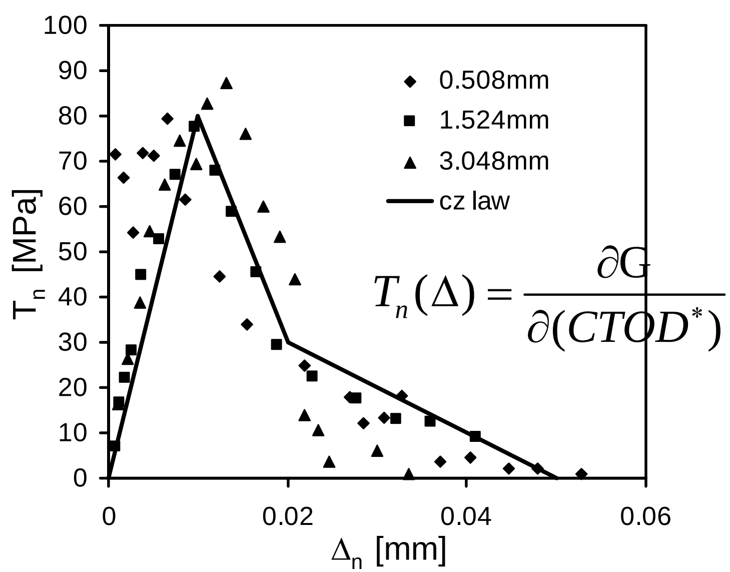
L=50 mm
b=10 mm
t=3.175 mm
a_0=25 mm

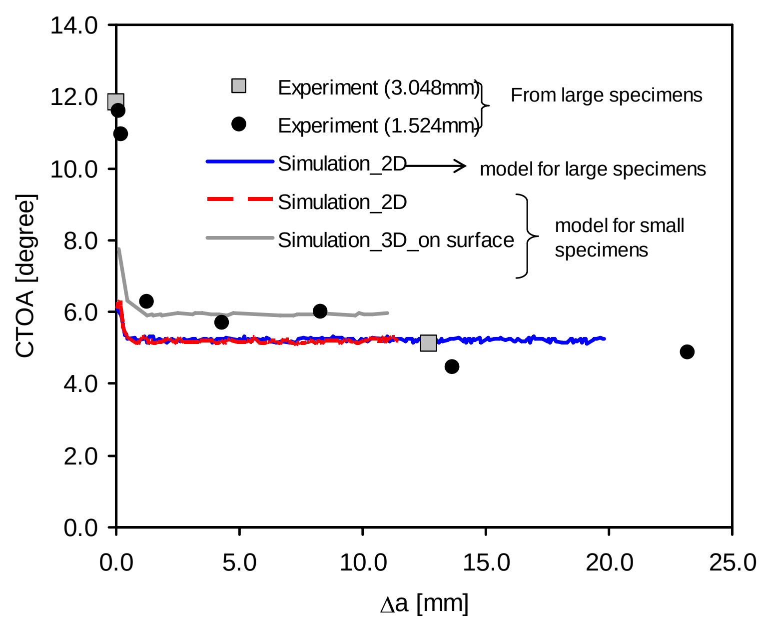
Experiment in Lab Siegmund



L=125 mm
b=17 mm
t=3.175 mm
a_0=38 mm

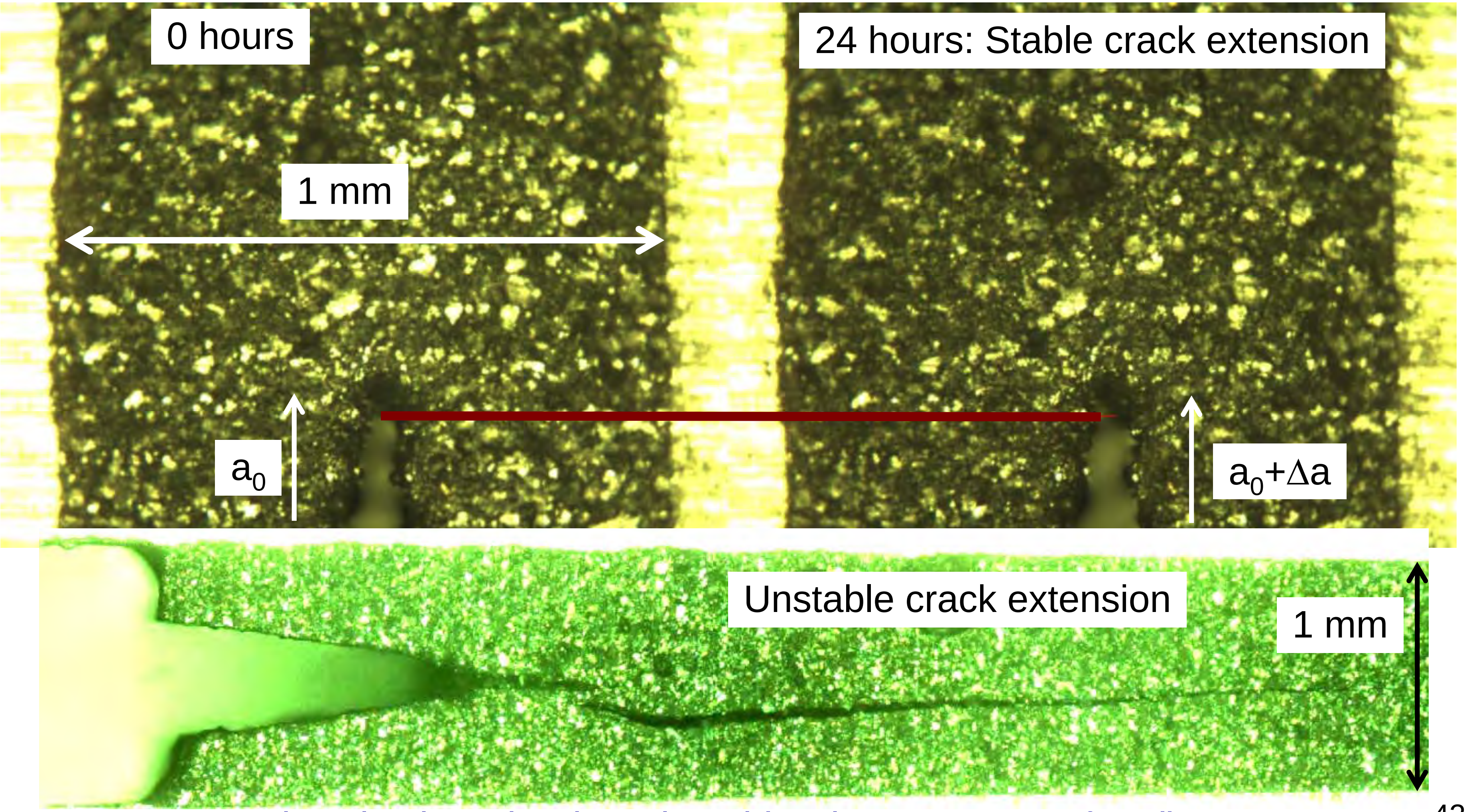
Experiment in Lab Sun





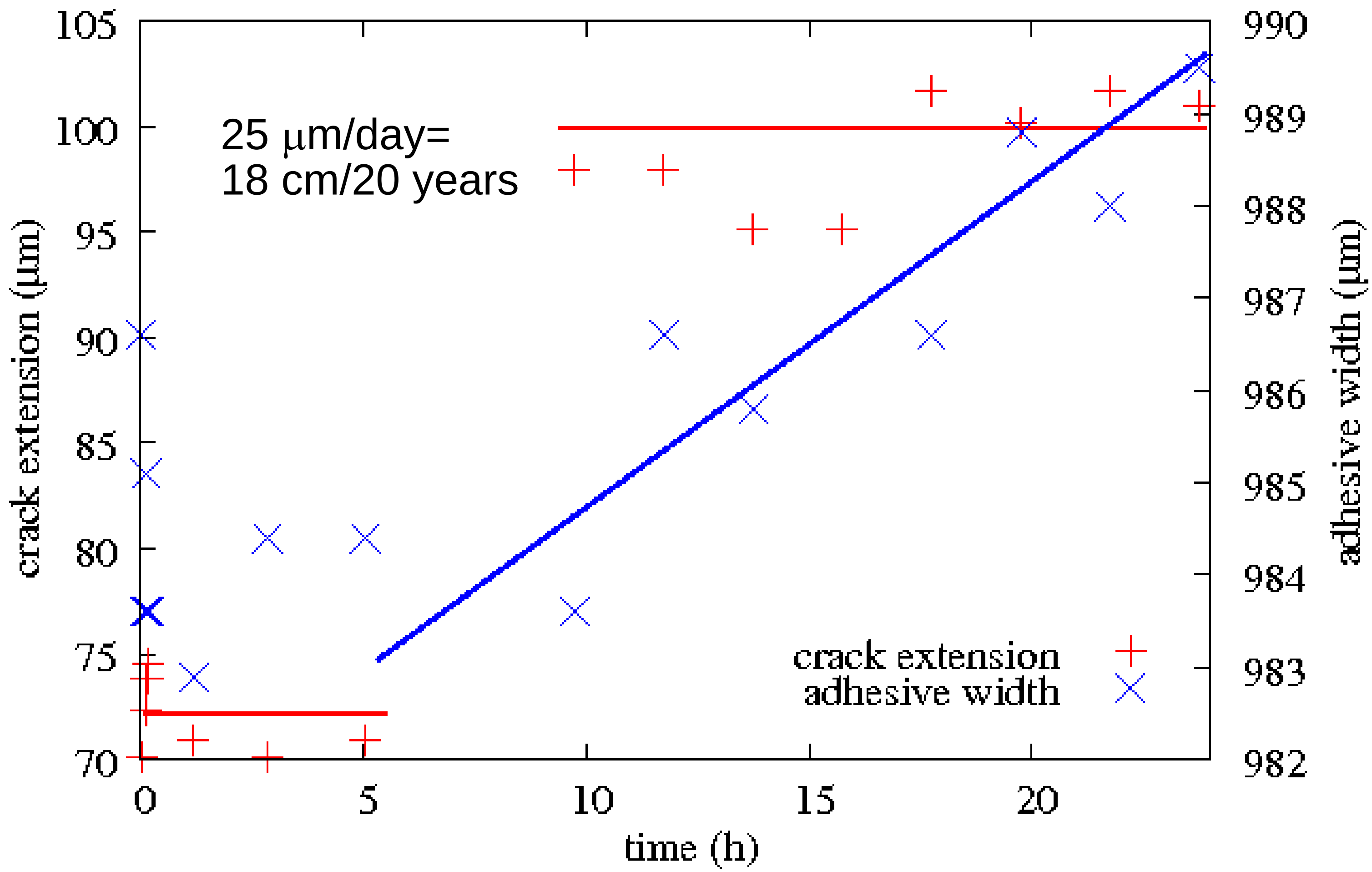
Influence of Bondline Thickness and Moisture on Joint Fracture

Moisture Degradation: Experiments



Influence of Bondline Thickness and Moisture on Joint Fracture

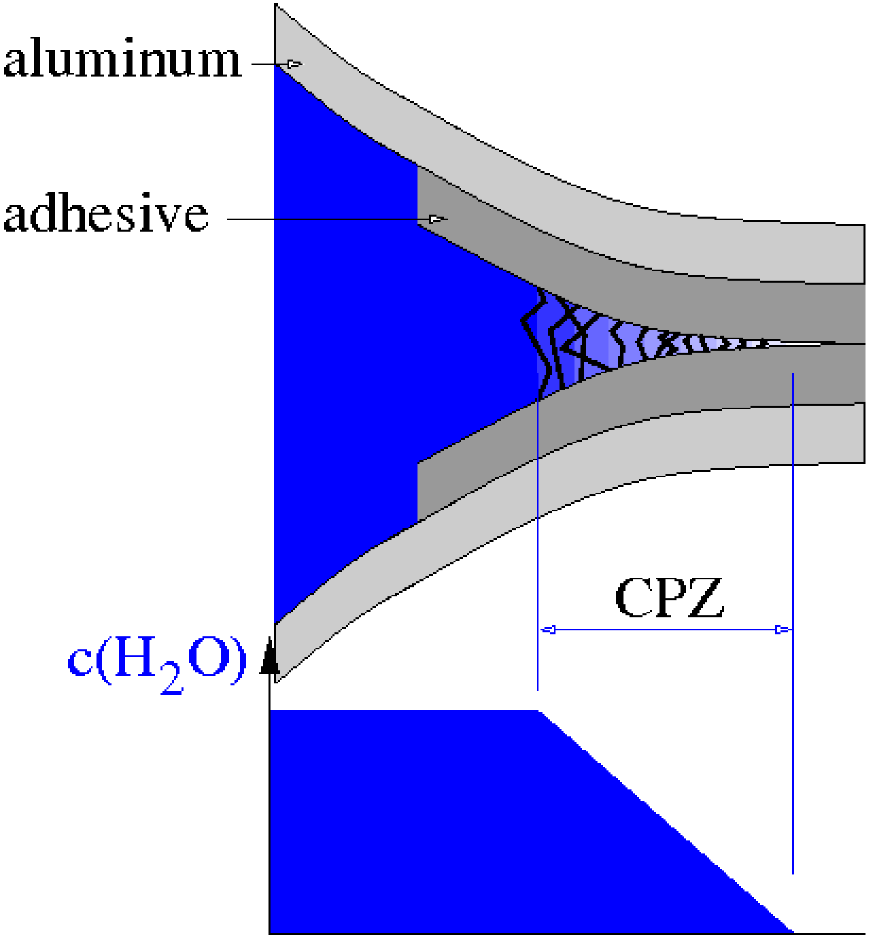
Moisture Degradation: Experiments



Influence of Bondline Thickness and Moisture on Joint Fracture

Moisture Degradation: Simulation

As aggressive environment (moisture) enters the crack, it enhances the crack growth.



Diffusion of water:

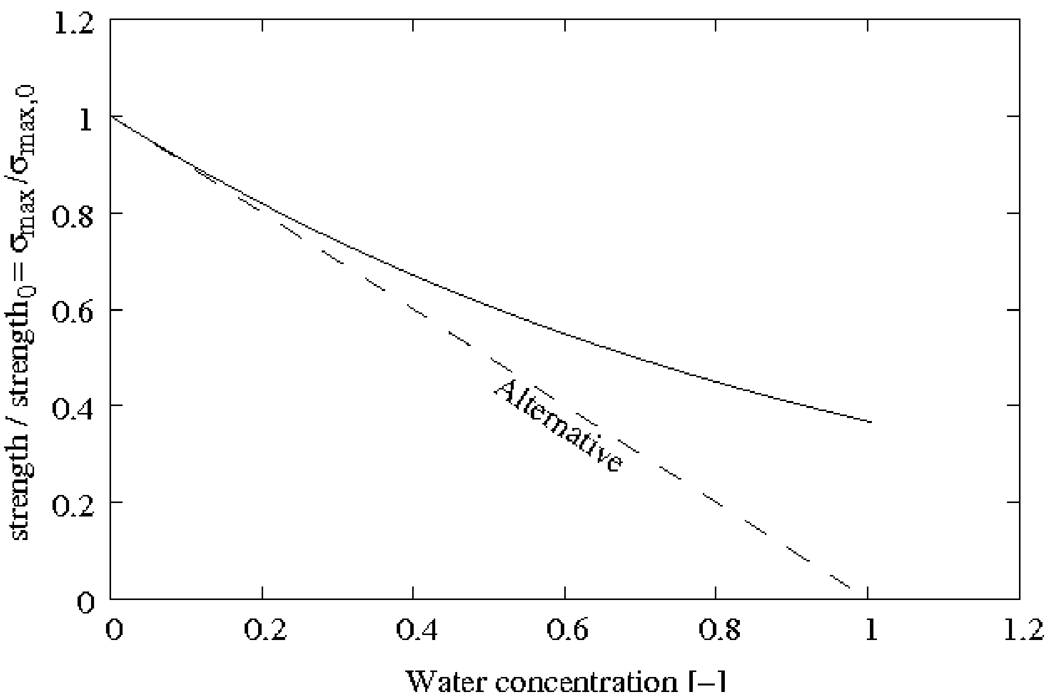
- In the crack the water concentration is 100%.
- In the Crack Process Zone (CPZ) the water concentration reduces.
- In the virgin material the water concentration is 0%.

The diffusion depends on the opening of the crack in the CPZ. At sites where the crack is wide open, water diffuses fast. And vice versa.

Influence of Bondline Thickness and Moisture on Joint Fracture

Moisture Degradation: Simulation

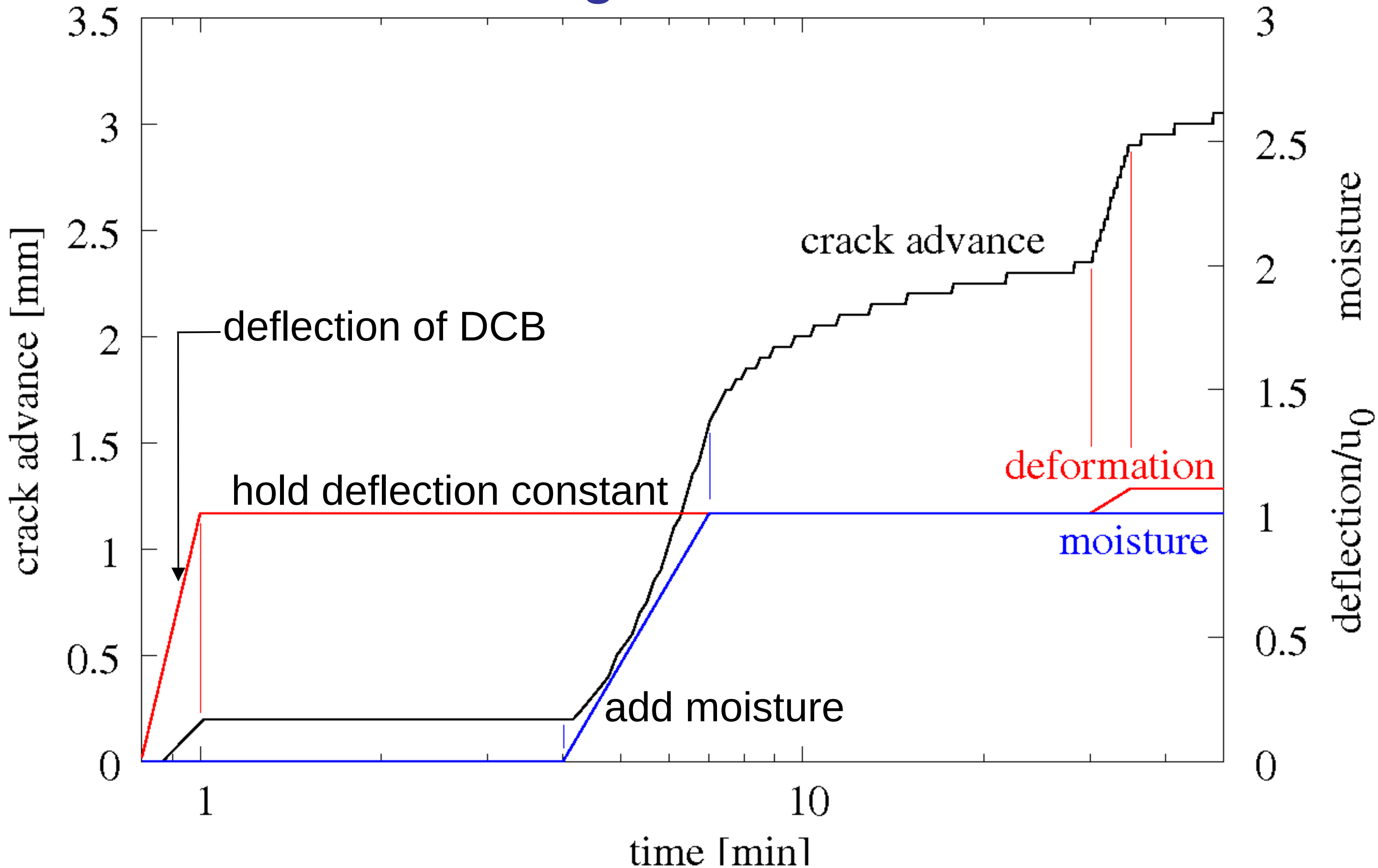
As moisture enters the crack process zone, the polymer ligaments loose their strength. In the current model they retain 36% of their strength at full saturation with moisture.



Implementation: Coupled mechanical – transport solution using ABAQUS

Influence of Bondline Thickness and Moisture on Joint Fracture

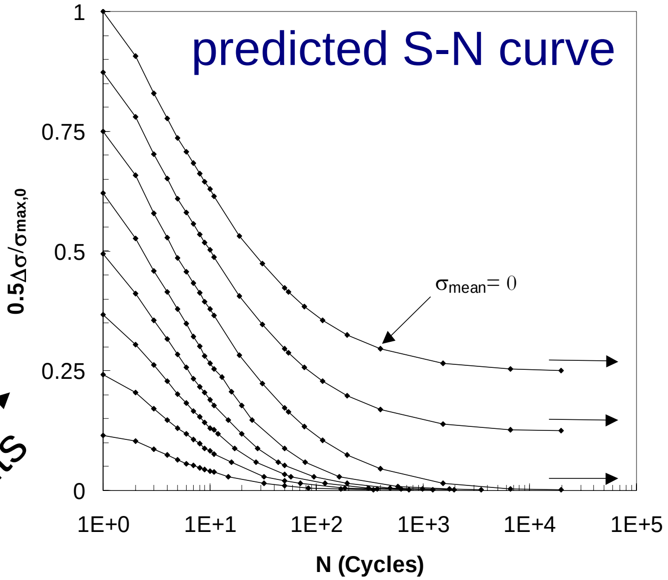
Moisture Degradation: Simulation



Influence of Bondline Thickness and Moisture on Joint Fracture

- **A Cohesive Zone Model for Fatigue Failure**

B-737 composite stabilizer after 18 years of service (CECAM Bulletin)

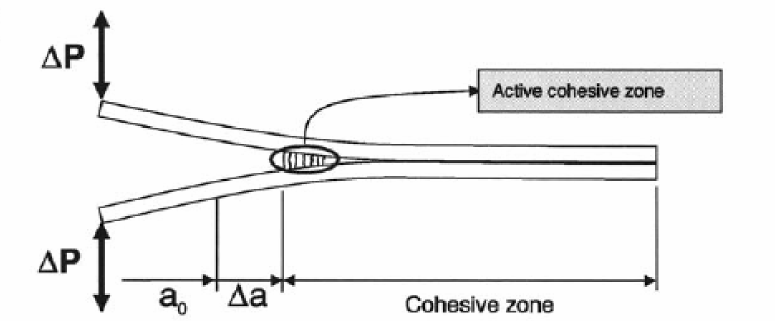


Damage law

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

Previous Results

Goal Year #3



A Look Forward

- **Benefit to Aviation** *– in response to increasing use of adhesive bonding*
  - supports use of more sophisticated computation-based design and analysis tools
    - ***failure process*** prediction, including adhesive plasticity
    - CTOA criterion simple to implement
    - VCCT and cohesive zone (cracked & un-cracked) now available in commercial codes
    - simulation tools can reduce time to conduct extensive environmental degradation tests
  - 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
  - simpler test methods to obtain fracture and constitutive data
    - seeking to define simpler tests and remove necessity to collect data as function of bond thickness

A Look Forward

- **Future Needs**
  - account for strain rate dependency and localized failure evolution in constitutive modeling of adhesive – demonstrate transferability to joints of generic configuration
  - quantify mixed mode fracture tests via local criterion – e.g., CTOA or CZ
  - experimentally characterize the interfacial strength between the adhesive and adherends
  - fatigue crack growth characterization
  - **investigate other adherend (namely composite) and adhesive types and failure modes: interfacial (a.k.a. adhesion) and mixed interfacial/cohesive failure + composite failure**
  - use the developed CTOA and CZ approaches to further investigate the competing nature of interfacial strength and fracture toughness of the adhesive in determining performance of bonded joints
  - theoretically study the adhesive properties and bondline thickness for optimal performance of bonded joints