Damage Tolerance and Durability of Adhesively Bonded Composite Structures

Thomas Siegmund

CT Sun

A Center of Excellence AMTAS Advanced Materials in Transport Aircraft Structures

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CECAM center of excellence for composites and advanced materials

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Adhesively Bonded Composite Structures

- Motivation and Key Issues
  - Contribute to the development of reliability of adhesively bonded structures
- Objective
  - Develop experimental and numerical methods to design and analyze design
- Approach
  - Nonlinear fracture mechanics methods (CTOA and cohesive zone models)
  - Develop related educational and training material

FAA Sponsored Project Information

- Principal Investigators & Researchers
  - **Thomas Siegmund** (PI, School of Mechanical Engineering)
  - **CT Sun** (Co-PI, School of Aeronautics and Astronautics)
- FAA Technical Monitor
  - Curt Davies
- Other FAA Personnel Involved
  - No current
- Industry Participation
  - No current

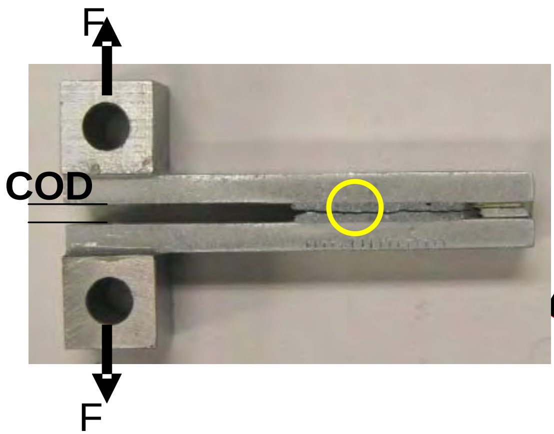
Adhesively Bonded Composite Structures – CZM Approach

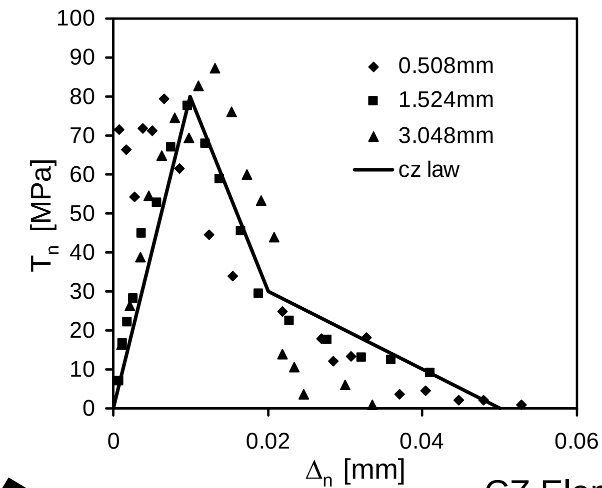
PI: Thomas Siegmund, Professor, School of Mechanical Engineering, siegmund@purdue.edu

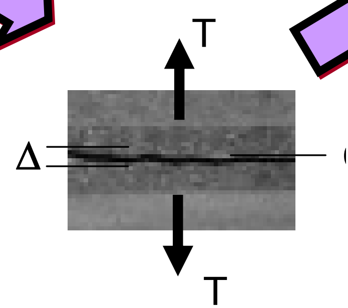
Objective: Demonstrate the use of the cohesive zone model approach in the analysis of adhesively bonded structures

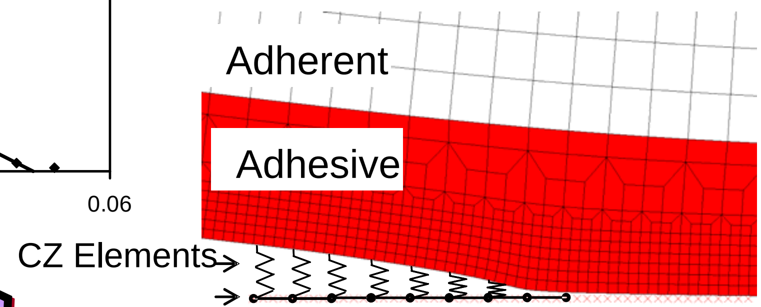
Approach: Employ previously developed data for Hysol EA9394 to typical structural joints

Cohesive Zone Model









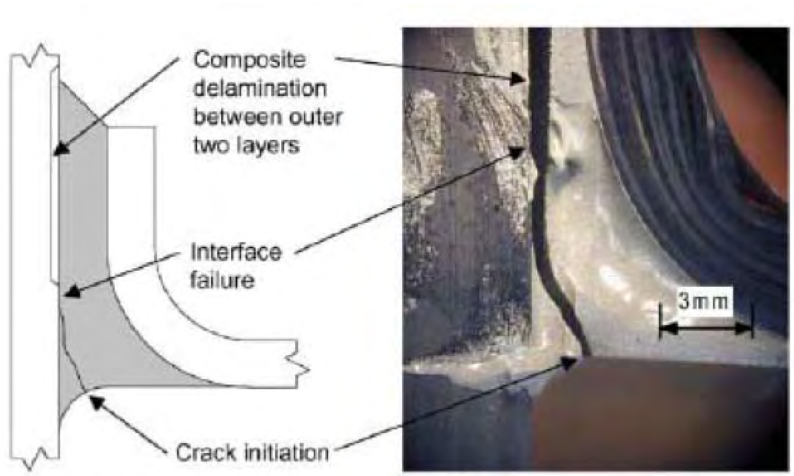
Finite element model with
Cohesive elements

Global Parameters

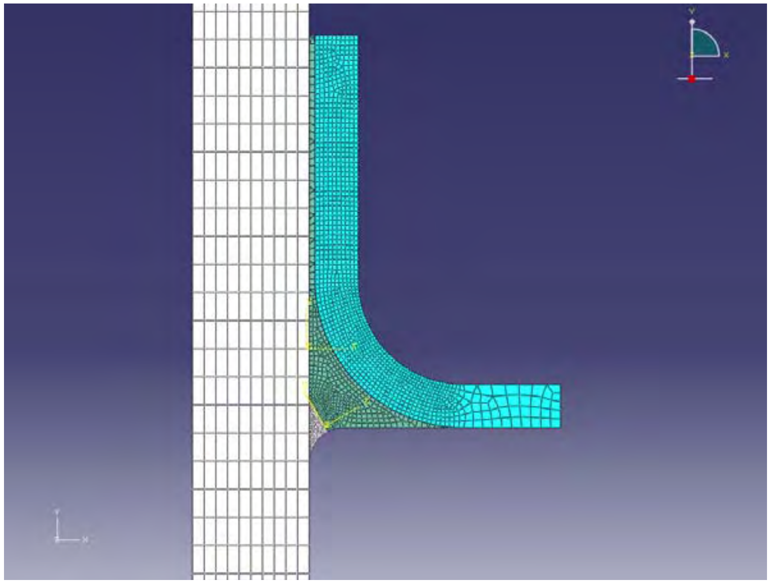
- Load, Displacement
- Environment
- Time
- Cycles

- Traction-Separation
- Damage

L-Joint



Feiha et al., *International Journal of Adhesion and Adhesives*, 2005, 47-59

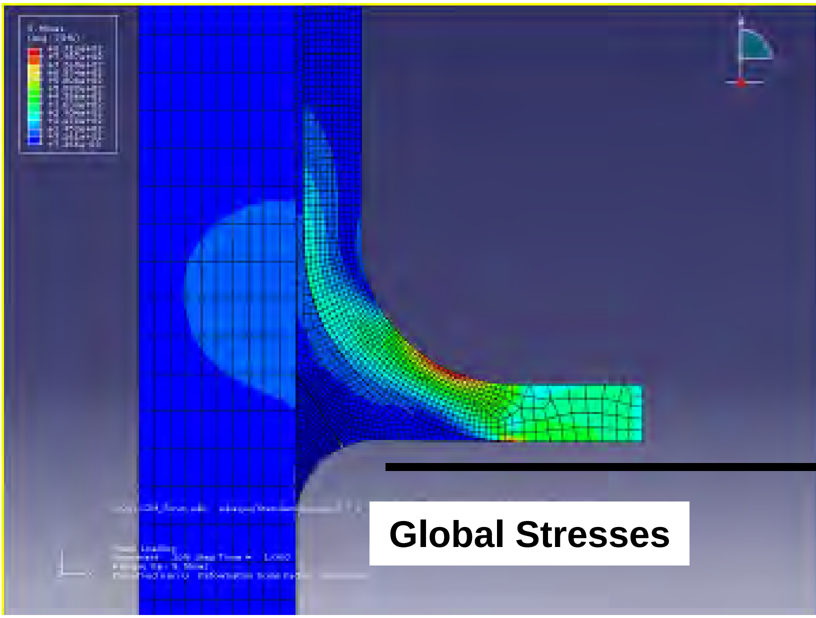


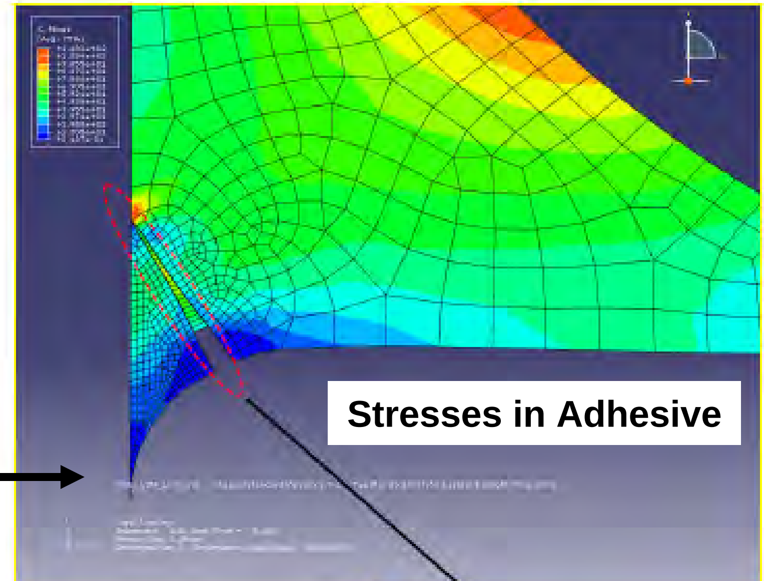
Model entirely with continuum elements

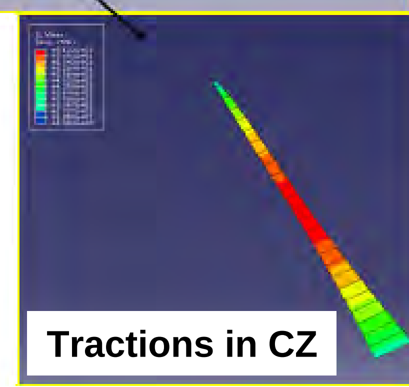
Adhesive with

continuum elements & cohesive elements

L-Joint







Fillet Radius (mm)	Failure Load (MPa)
1.5	405
3	465
5	570

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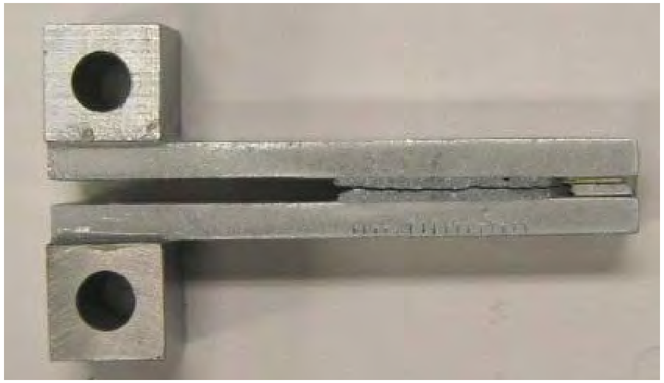
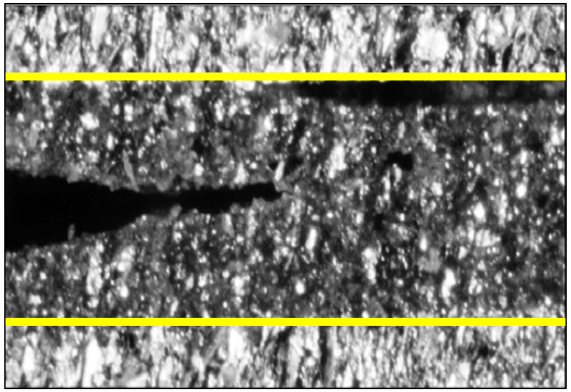
Joint Strength & Bondline Thickness

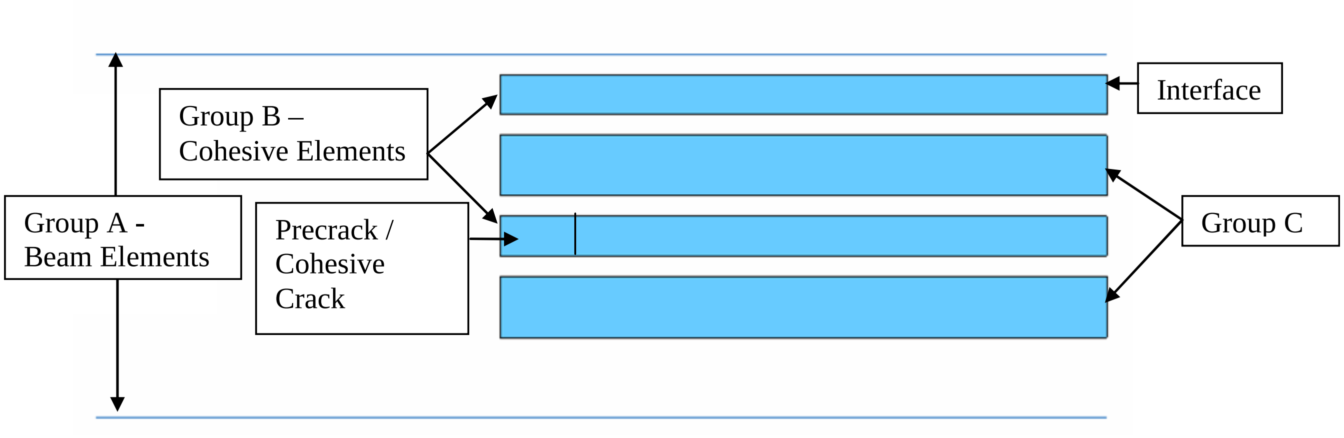




CAD to FEM strategy:

Define parts connected by tie constraints to form assembly

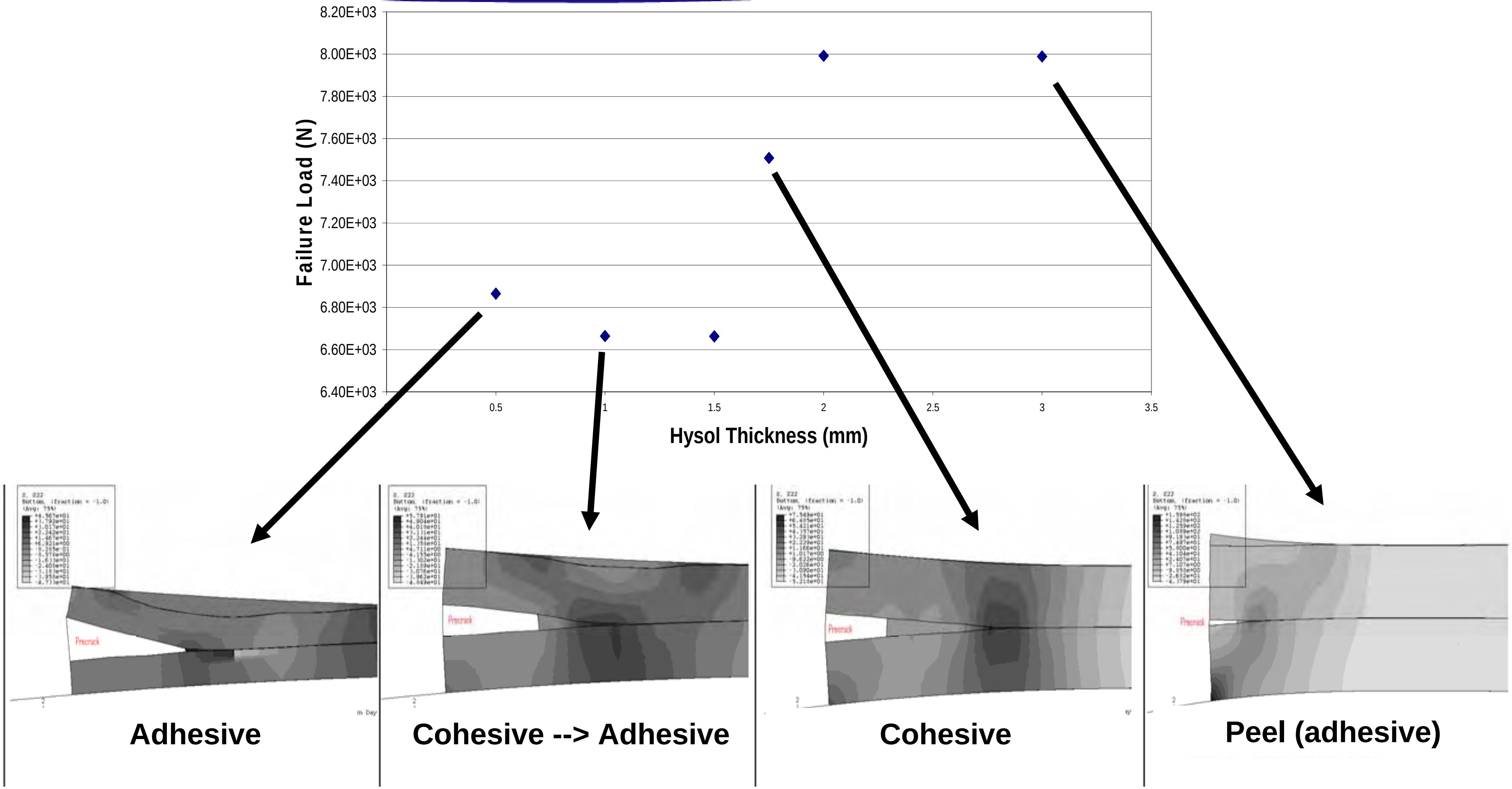
Mesh parts independently



Structural (beam) elements

Adhesive with continuum elements & cohesive elements

Joint Strength & Bondline Thickness



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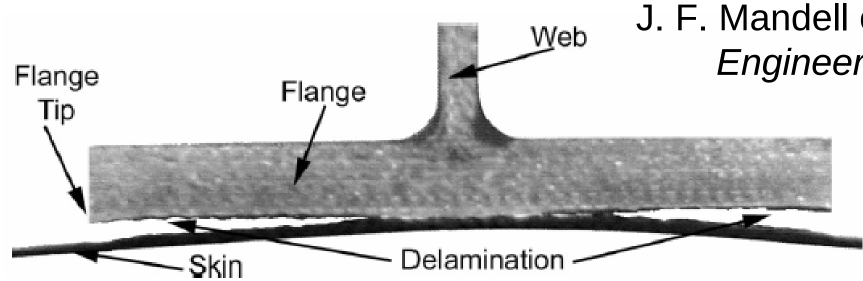
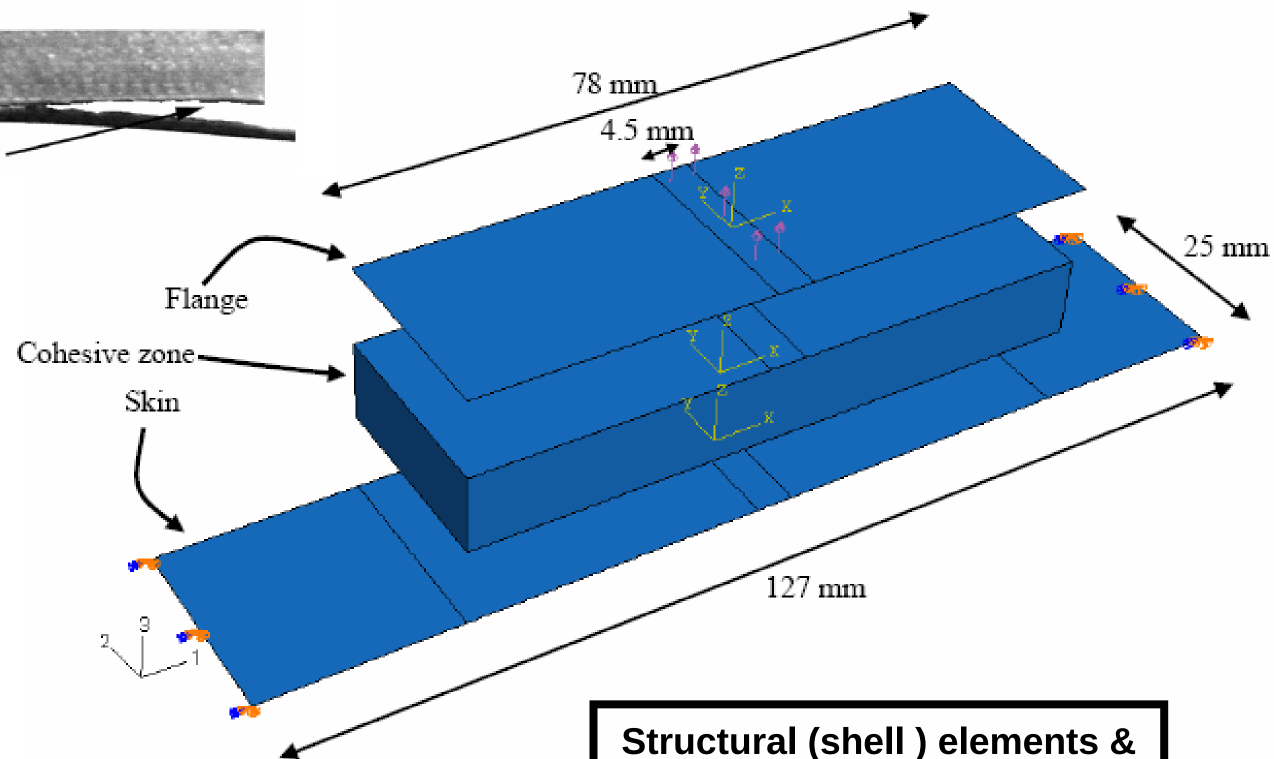
Skin – Stiffener Joint: Effect of Flange Thickness

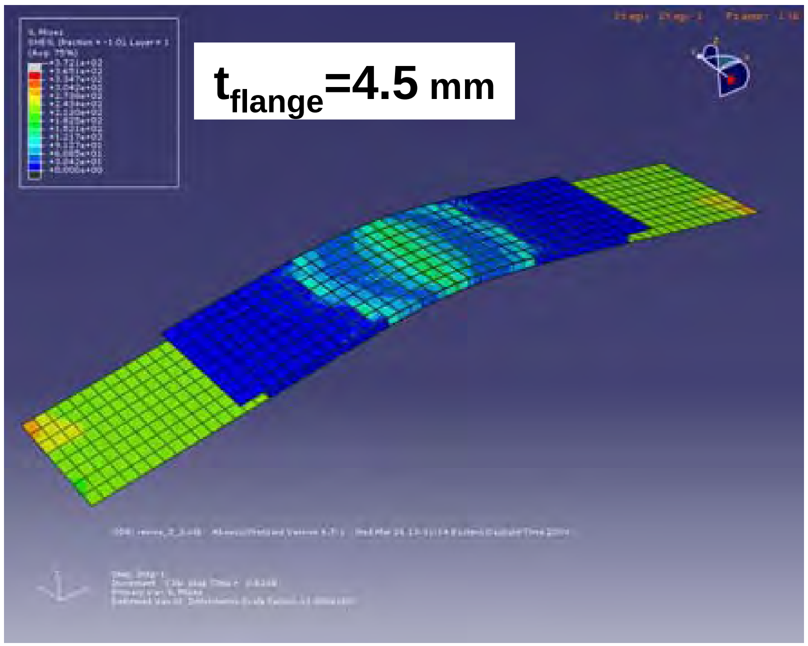


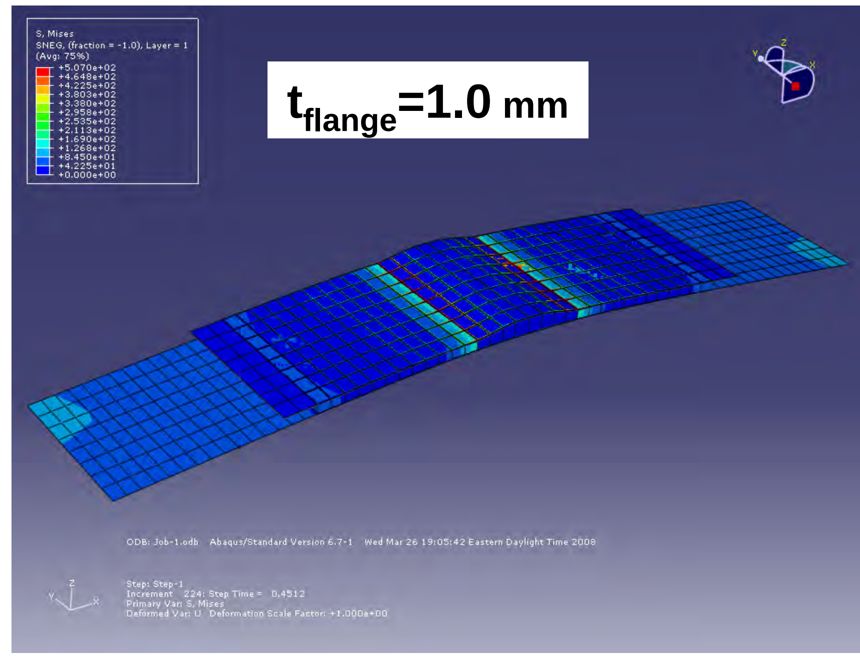
J. F. Mandell et al., *J. Solar Energy Engineering*, 125, 2003, 522-530.



Structural (shell) elements & Cohesive elements

Skin – Stiffener Joint: Effect of Flange Thickness



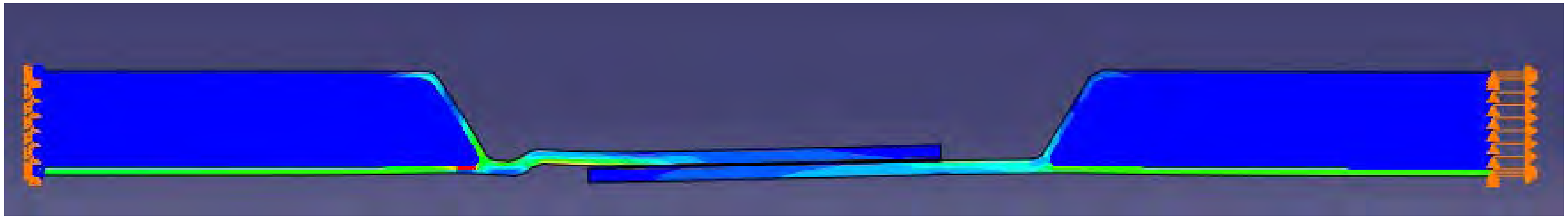


Delamination growth from flange free end

Delamination growth from flange center

Sandwich Panel Lap Joint

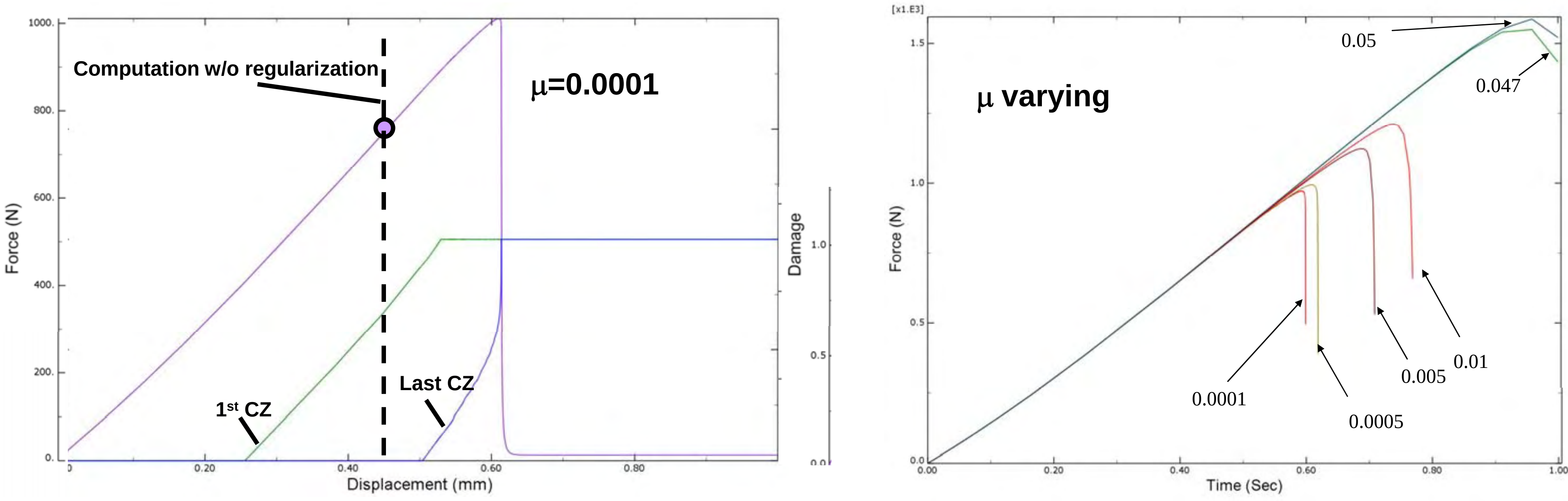
Solid elements for sandwich & Cohesive elements



Viscous Regularization of Damage in Cohesive Zone becomes essential in complex problems:

$$\dot{D}_v = \frac{1}{\mu}(D - D_v) \Rightarrow T = (1 - D_v)T_0$$

Sandwich Panel Lap Joint



Computation with regularization may well predict complete joint failure in a model
Convenience of obtaining a numerically converging solution must not be considered as a real failure load, and can only be considered as an upper bound.

Education & Training

Course: “Computational Fracture Mechanics”

(1) Review of classical fracture mechanics concepts for elastic materials; (K, J)

(2) Computational methods for classical fracture mechanics for elastic materials; (singular elements etc.)

(3) Computational methods of crack growth in elastic solids (including modeling with cohesive zone models, model generation, analysis, convergence criteria, fracture and fatigue);

(4) Review of classical fracture mechanics concepts for nonlinear material; (J, deformation theory vs. plasticity)

(5) Computational methods for nonlinear fracture mechanics (cohesive zone model, R curves);

(6) Continuum damage mechanics concepts and computational aspects (void growth models, localization, ductile fracture).

Numerical examples (ABAQUS CAE, ABAQUS Standard) for all chapters.

Project I: Conclusion to Date

- Developed tools to measure cohesive zone properties
- Explore various levels of model complexity
- Explore capabilities of commercial software (ABAQUS)
- Develop CAD to FEM modeling strategies

- Examples:
  - Bondline thickness dependence of joint strength
    - Solid model
  - Fillet radius influence on L-joint strength
    - Structural – solid model
  - Shell – stiffener structure
    - Structural model
  - Sandwich panel joint
    - Convergence of solution

Project I: A Look Forward

- Benefit to Aviation:
  - Response to increase in need for understanding adhesive bonding processes and their reliability
  - Novel analysis approaches to aerospace structures
  - Address to fundamental issues in bonded structures
  - Provide related training and education material
- Future needs
  - Long term response of adhesively bonded structures: fatigue & environment, variable amplitude loading
  - Further understanding of nonlinear failure processes

Project II: Prediction of Adhesive Lap Joint Strength Using CTOA

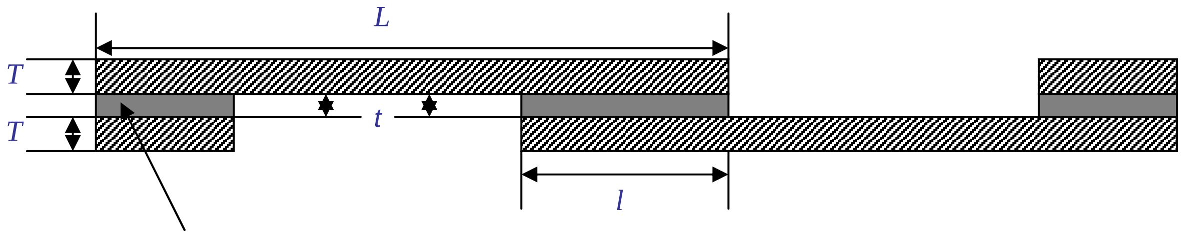
C.T. Sun, Professor sun@purdue.edu, School of Aeronautics & Astronautics, Purdue University

Haiyang Qian, Ph.D. Student

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

Approach – Conduct fracture experiments using DCB and single lap specimens of 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 of Lap Joints



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

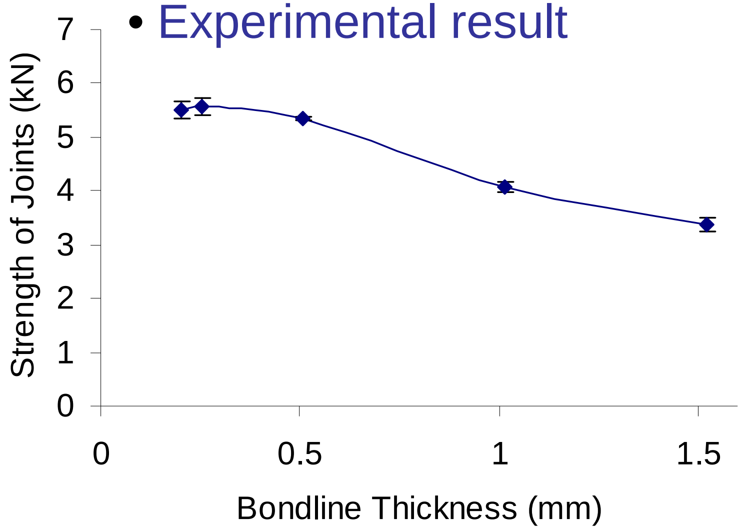
t=0.008in, 0.01in, 0.02in, 0.06in

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



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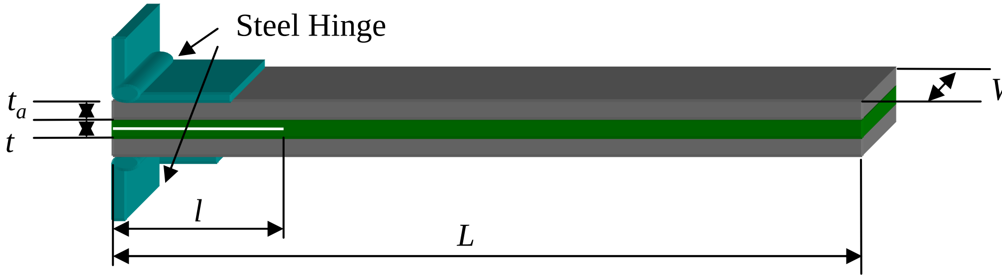
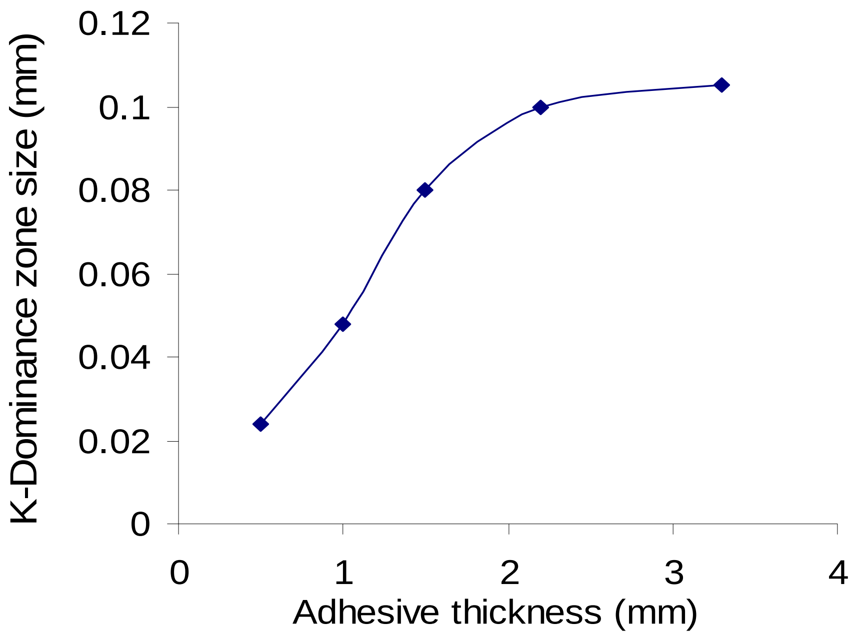
Size of K-Dominance Zone in DCB

$$\sigma_{yy} = \frac{K_I}{\sqrt{2\pi x}} + 0\,(1)$$

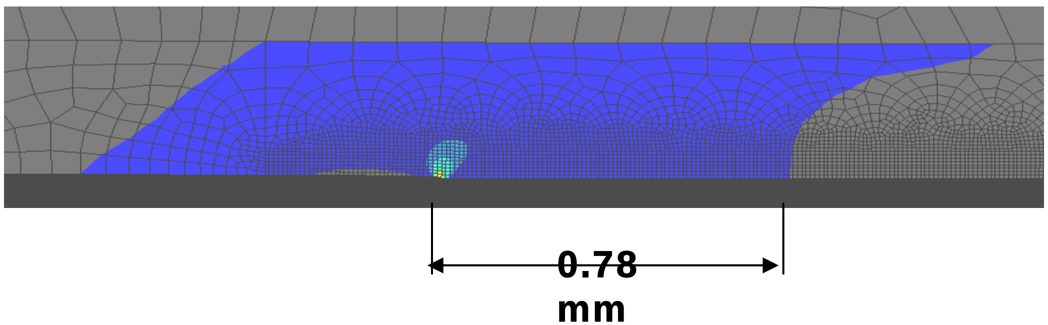


Degree of K-Dominance

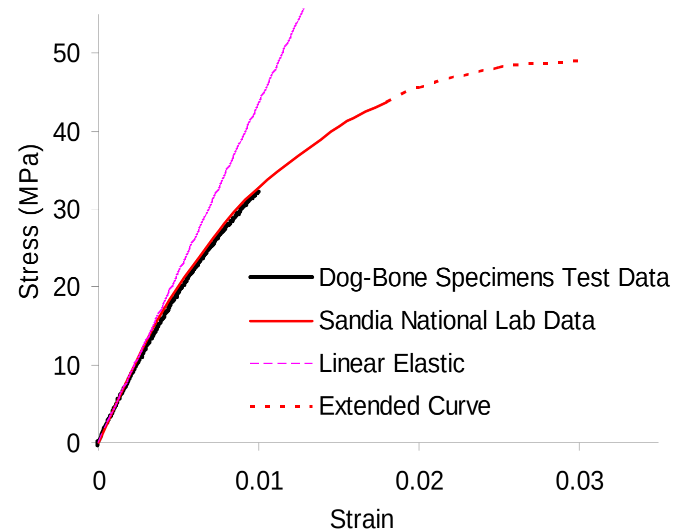
$$\Lambda = \frac{\sigma_{yy}^{Singular}}{\sigma_{yy}^{Singular} + \left|\sigma_{yy}^{Non-Singular}\right|}$$



Plastic Zone Size in DCB Hysol EA9394

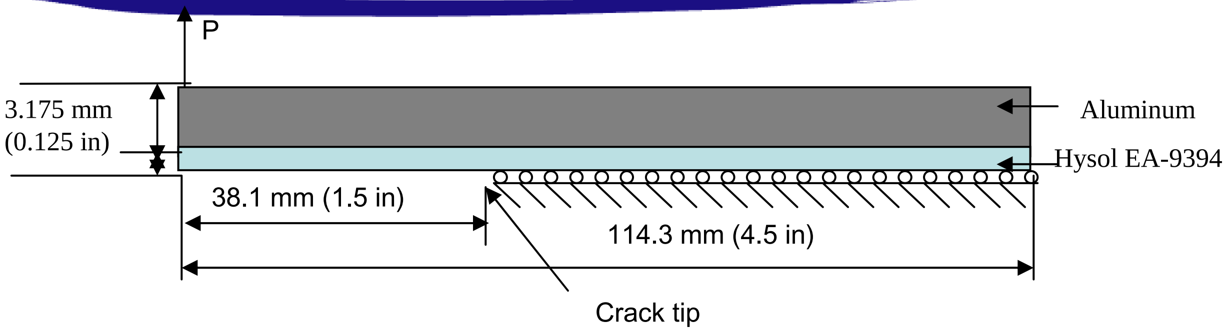


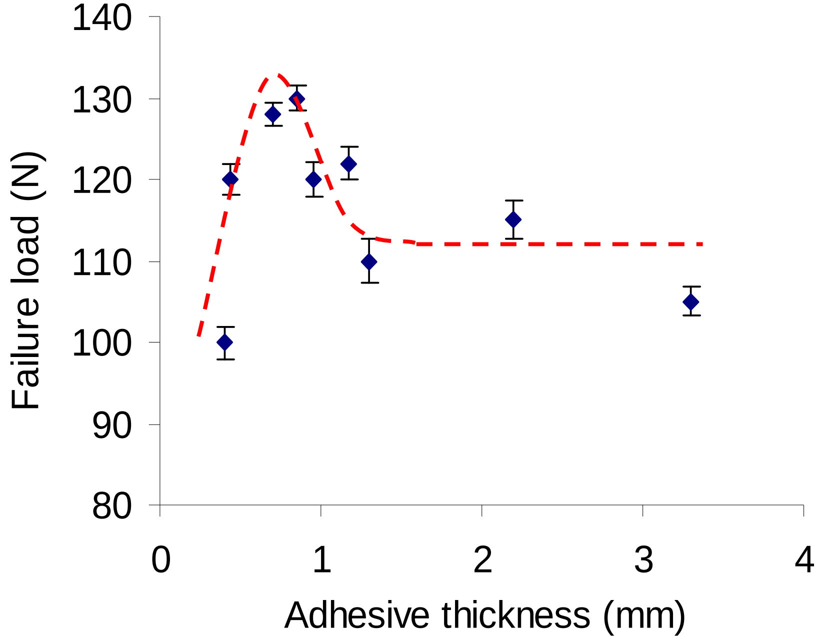
Adhesive Thickness: 0.8 mm
Plastic Zone Size: 0.78 mm
90% K-Dominance: 0.04 mm

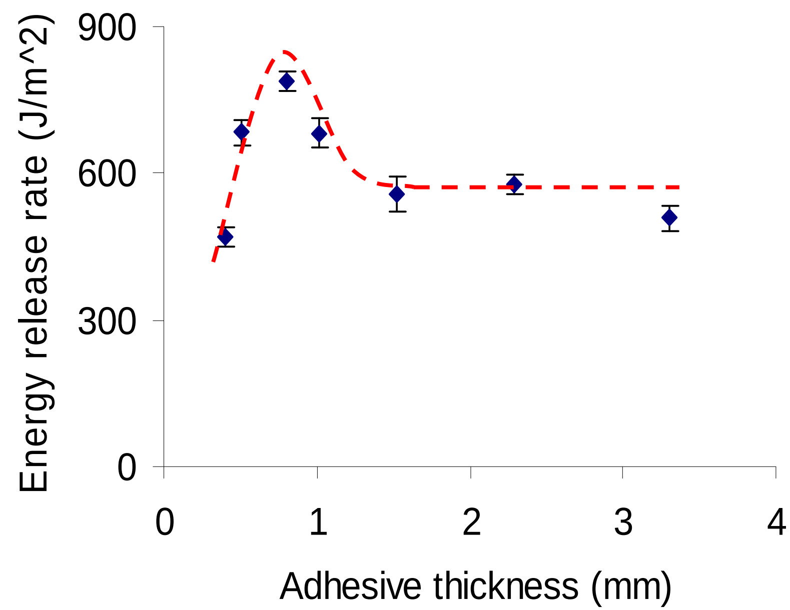


Small scale yielding assumption is violated

DCB Test Result for Hysol EA9394 by LEFM

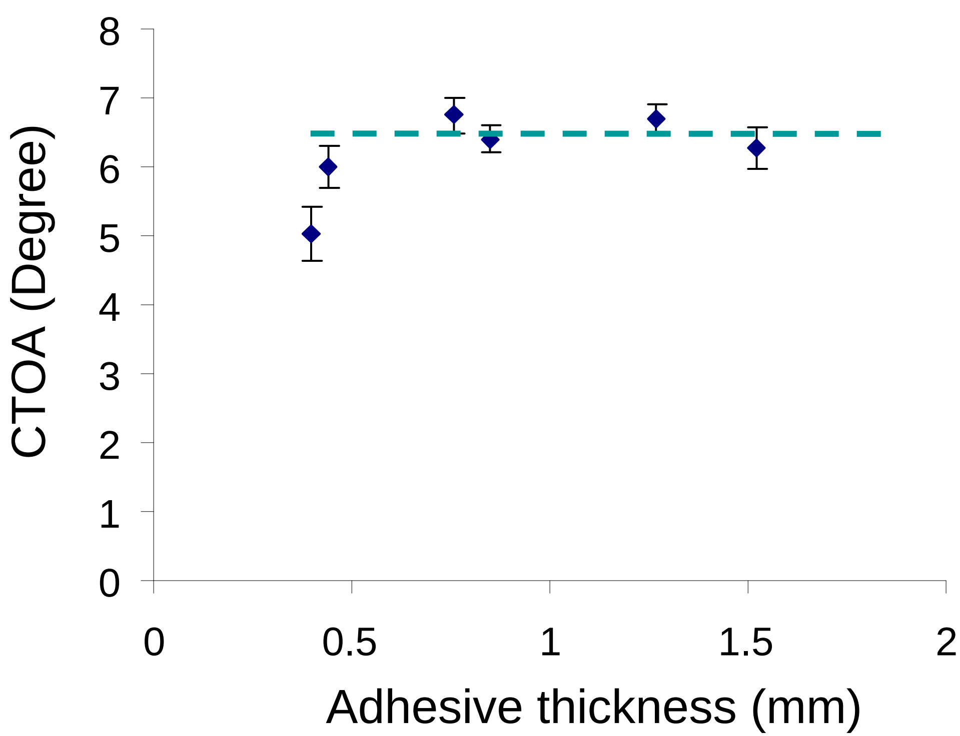


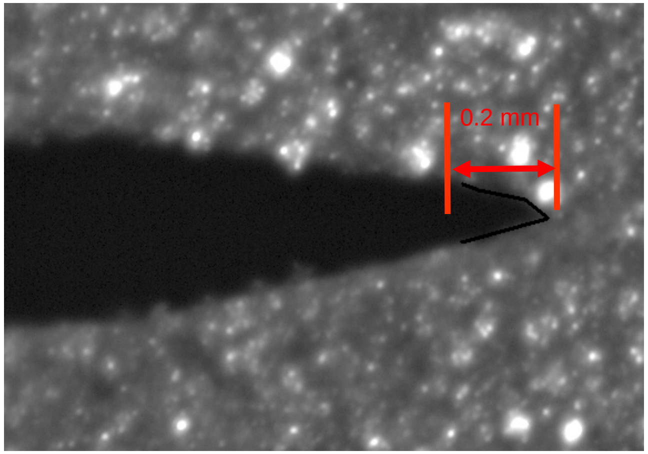


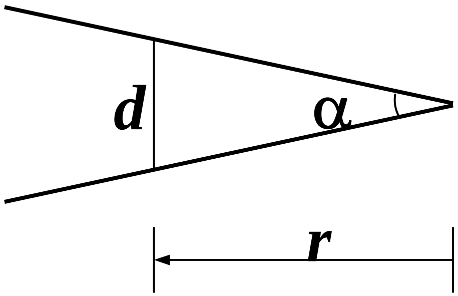


CTOA as Fracture Criterion in DCB

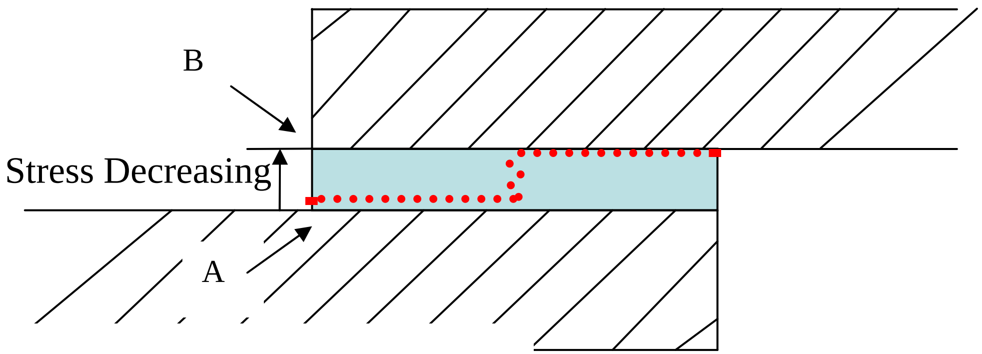
Measured CTOA

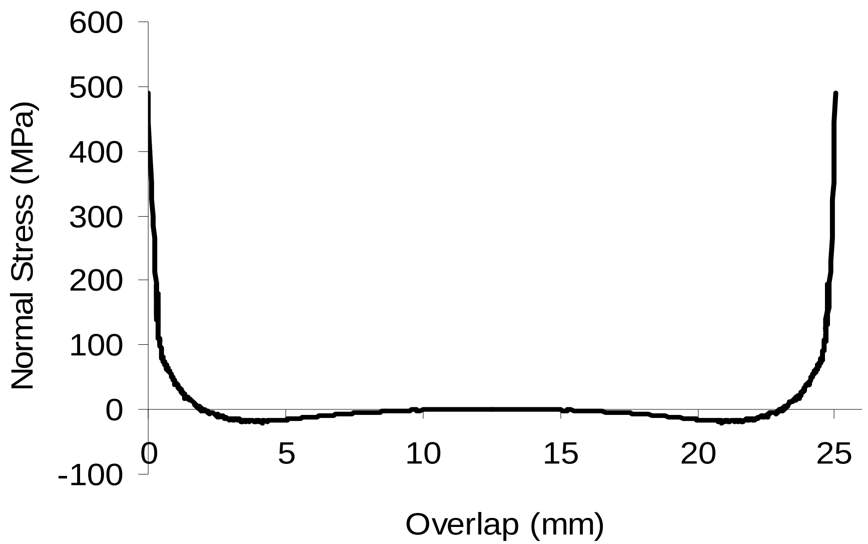


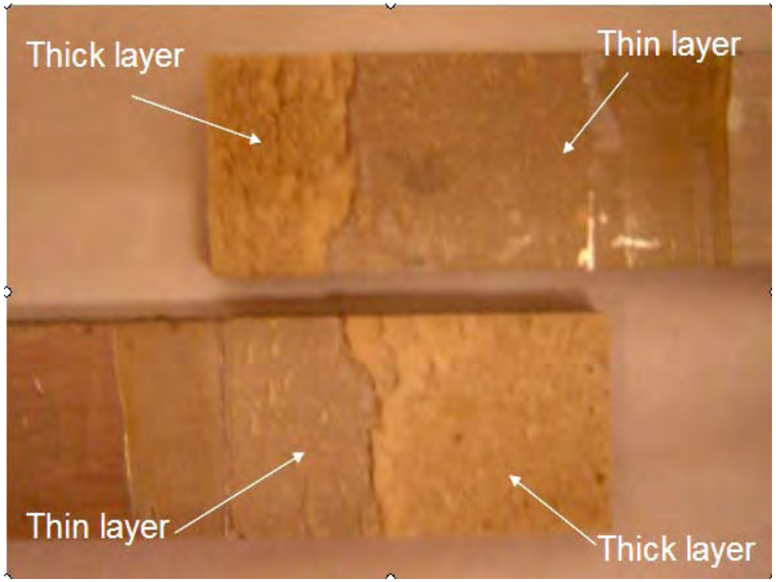




Fracture Path in Single Lap Joint







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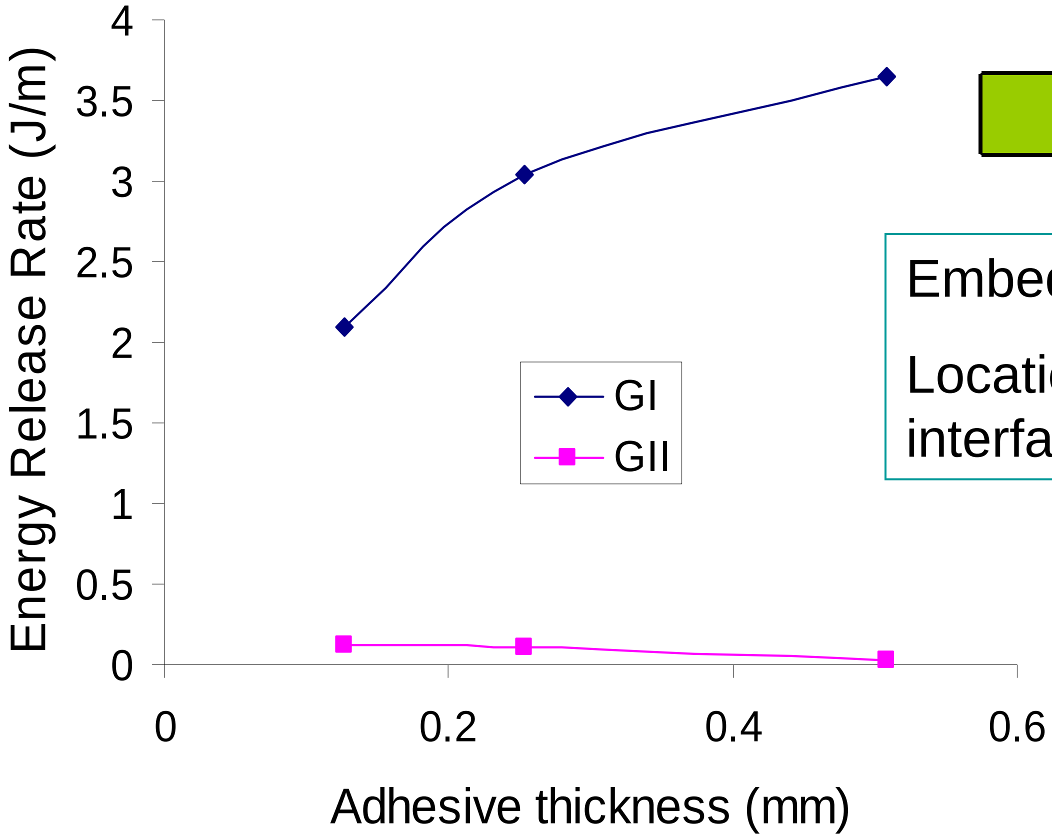
Embedded Crack for Failure Prediction in Single Lap Joints

Mode I dominated

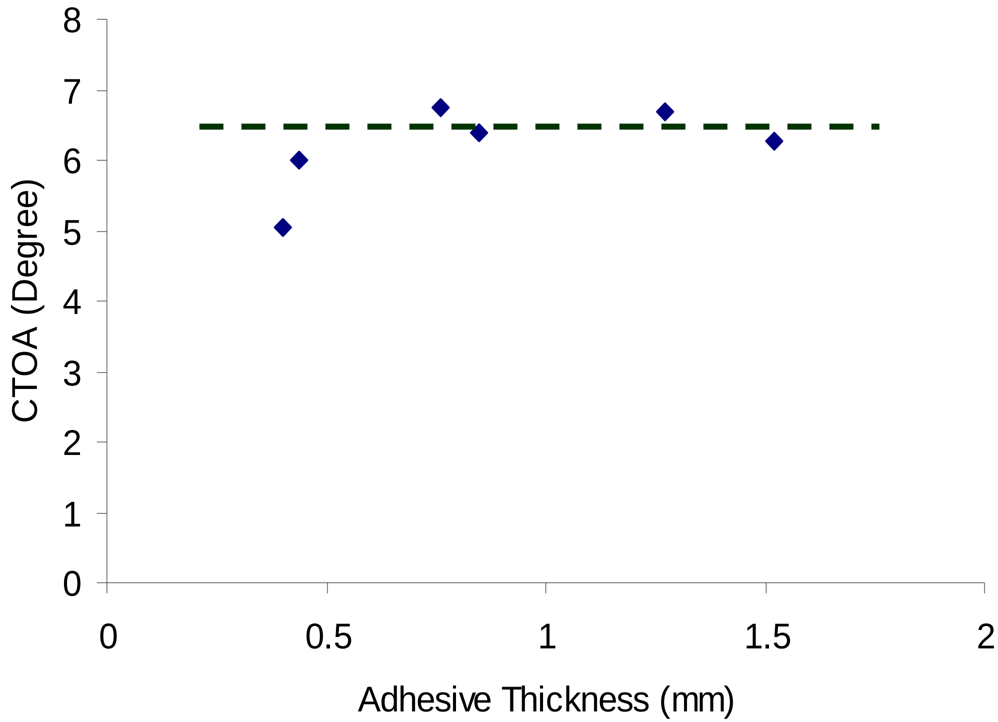


Embedded crack length: 0.3-0.7 mm

Location: 0.05 mm above the lower interface

CTOA under Failure Load for Single Lap Joints

- CTOA is independent of adhesive thickness before failure mode change



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Project II: Conclusions to Date

- LEFM is not suitable for predicting fracture in DCB adhesive specimens because of large plastic zone relative to the K-dominance zone size
- A single CTOA value can be used to predict fracture in DCB specimens with different adhesive thicknesses.
- Failure loads of lap joints can be predicted using the CTOA measured with DCB specimens in conjunction with an assumed crack embedded near the adhesive/adherend interface.

Project II: 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
  - 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
  - Extend the CTOA fracture criterion to include bonded plates or shells under general loading conditions
  - Conduct experiments to verify the proposed fracture criterion