

Modeling Response and Integrity of Aerospace Structures

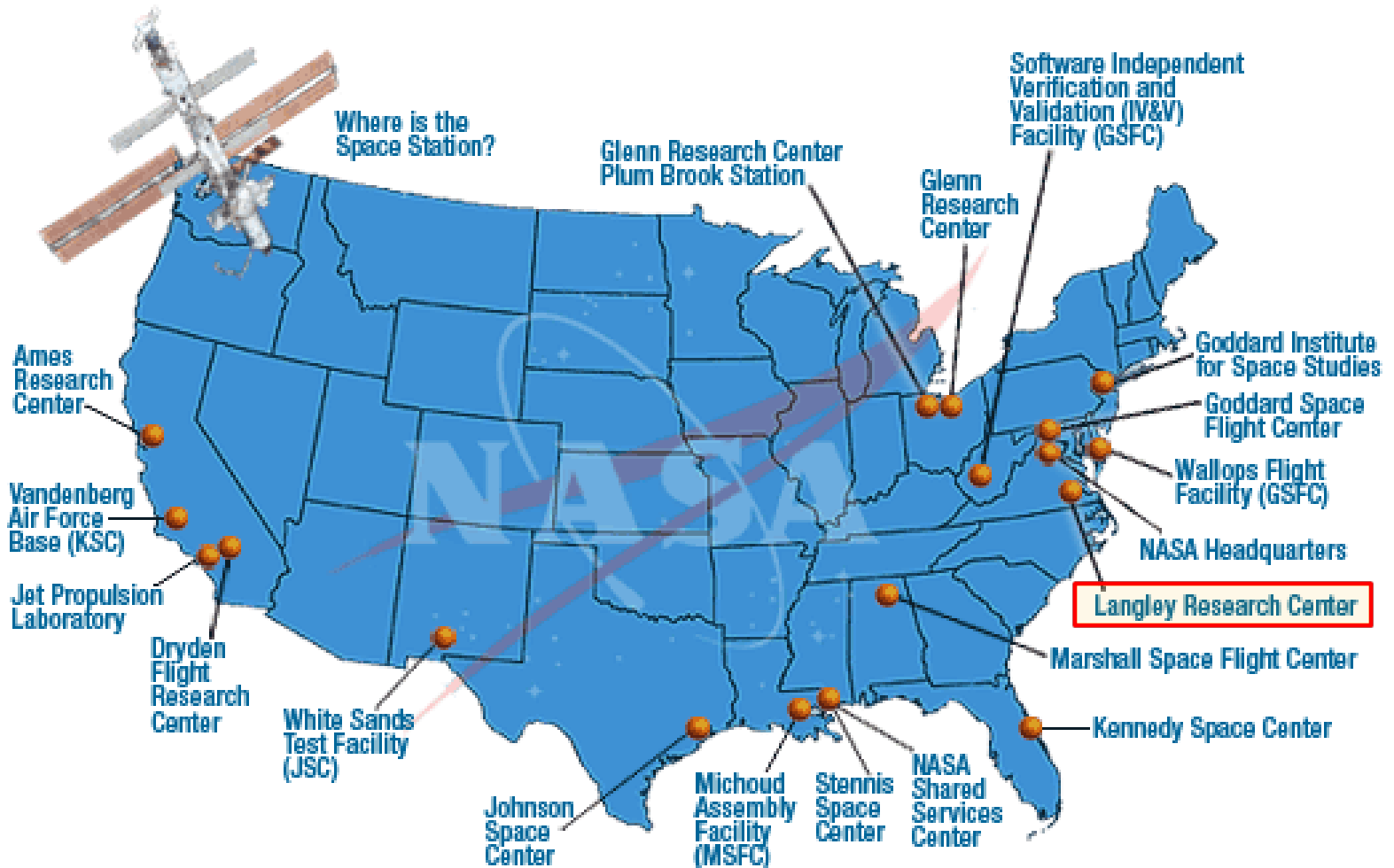
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March 5, 2010

Outline

- **Introduction**
- **Research in space structures**
- **Research in damage tolerance of composite aircraft structures**
- **Research in fracture mechanics**
- **Concluding remarks**

NASA Centers and Facilities



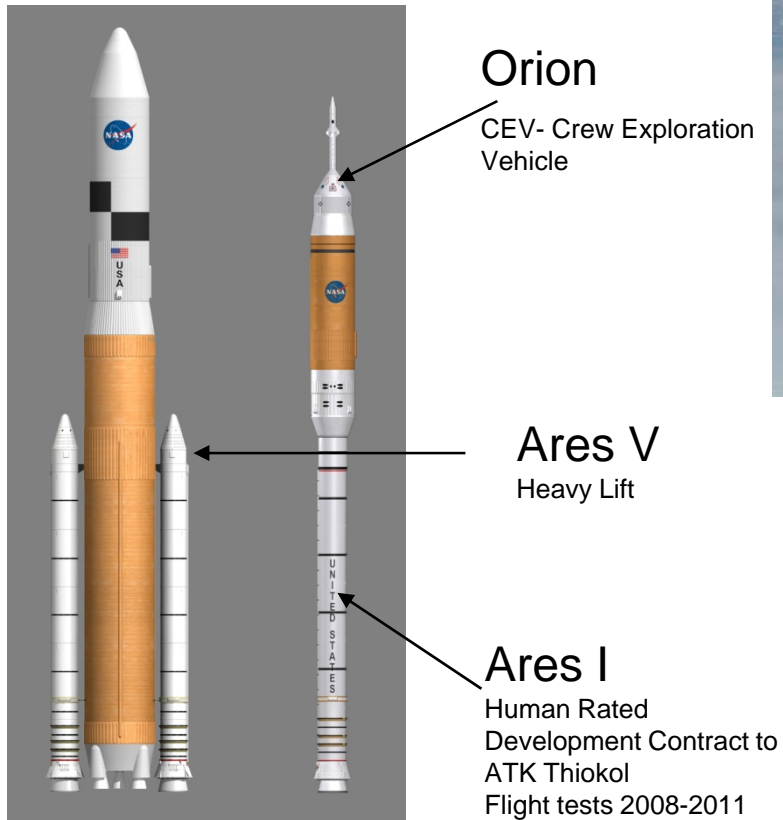
NASA Langley Research Center established in 1917 has pioneered many key research and technology developments in aeronautics, space exploration, and scientific discovery. This center employs more than 3000 engineers, scientists, and management staff.

Space Structures

- Crew exploration vehicle water landing simulation
- Inflation deployment structures

Crew Exploration Vehicle Water Landing

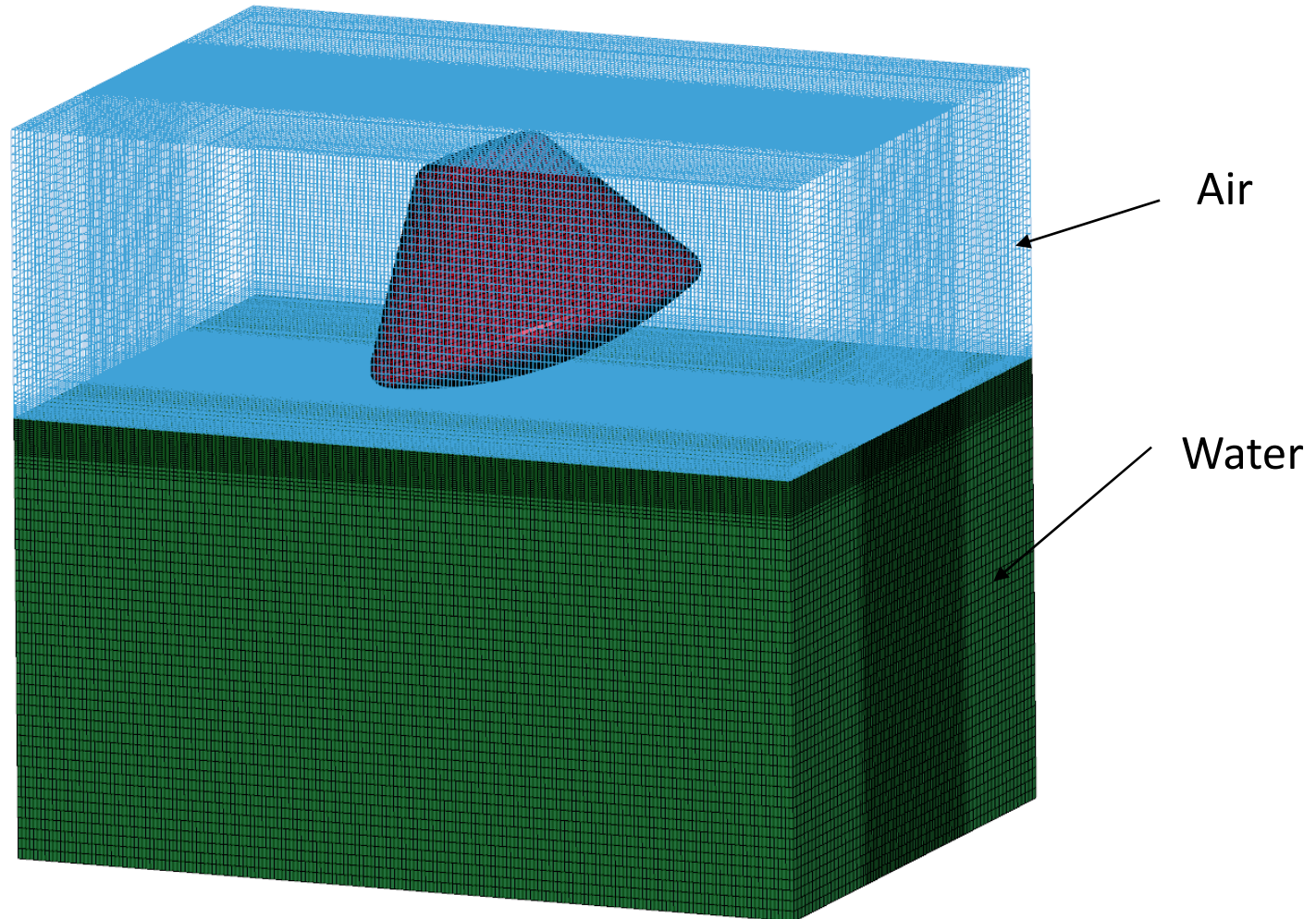
Constellation Program



- NASA Orion spacecraft landing system development

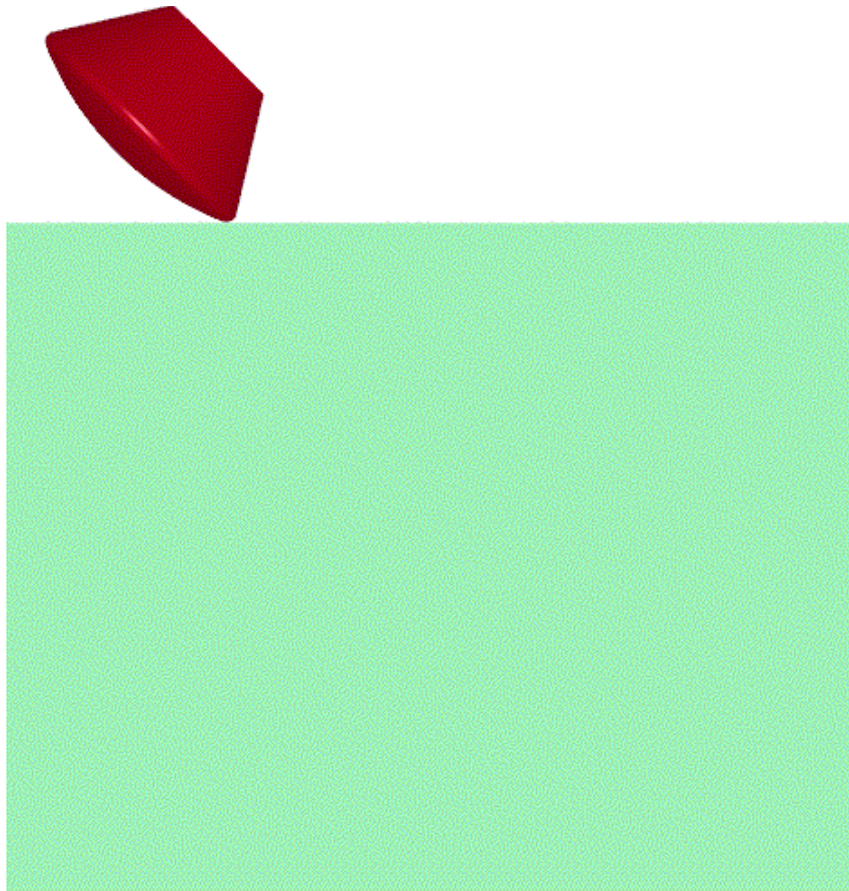
Crew Exploration Vehicle
Water Landing

Arbitrary-Lagrangian-Eulerian Finite Element Model

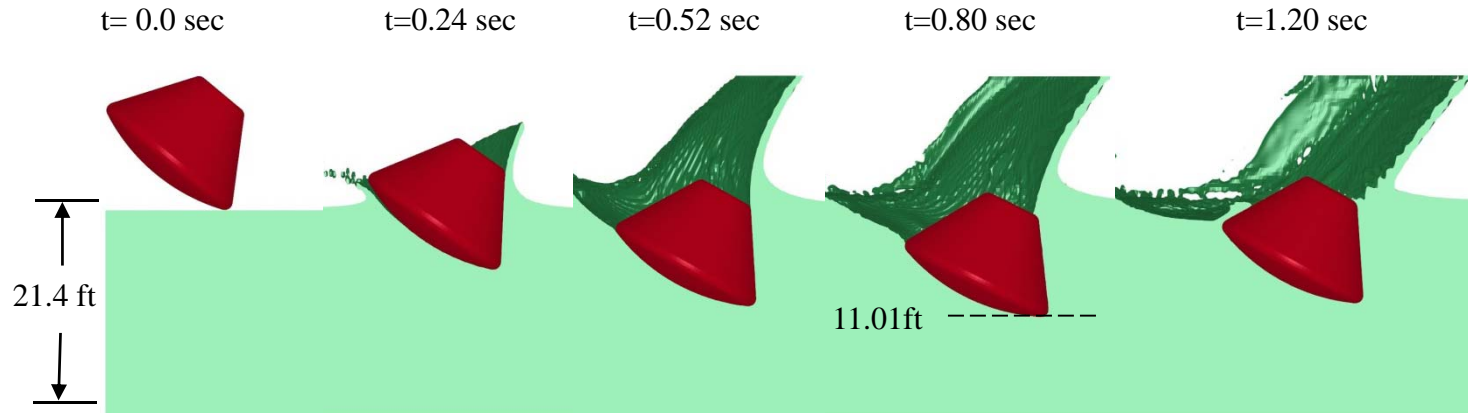


Capsule Water Diving Characteristics

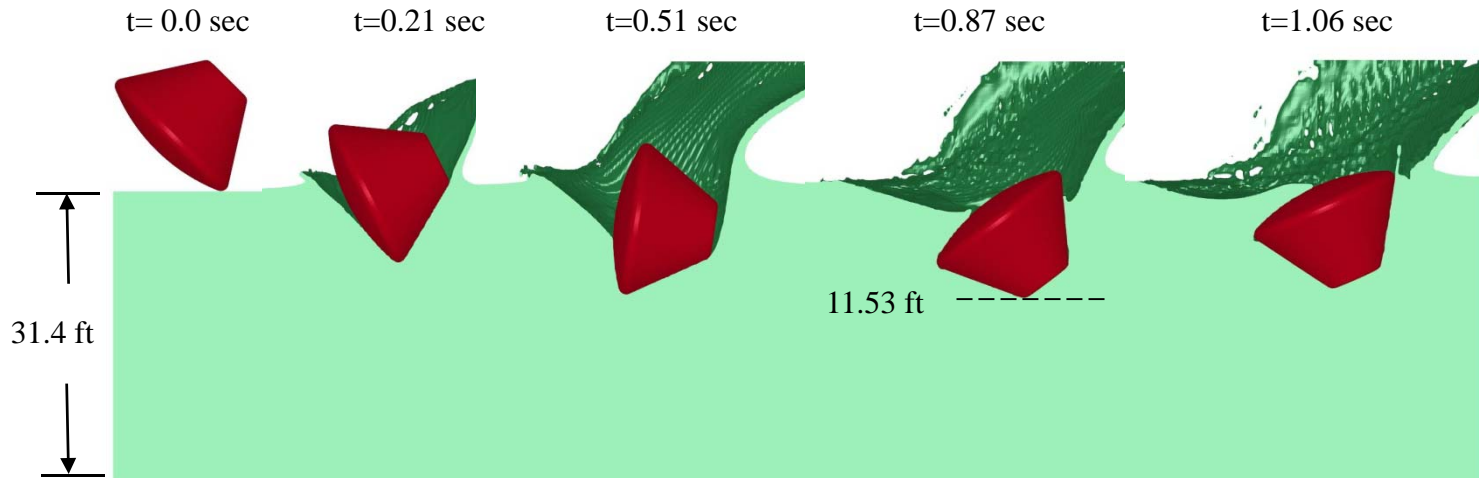
Pitch angle: 45-deg, Vertical velocity: 31 ft/s, Horizontal velocity: 47 ft/s



Snap Shots of Water Diving Characteristics

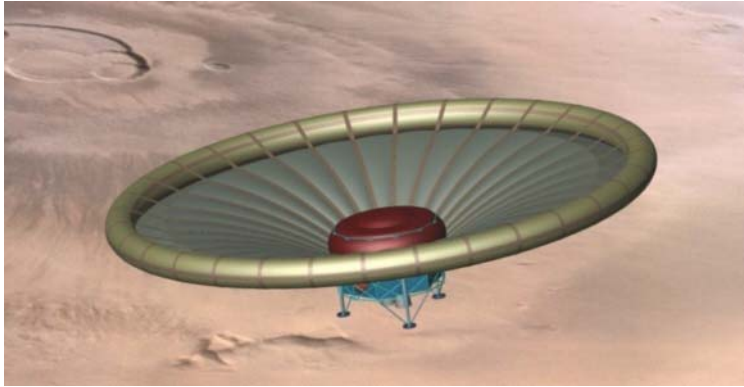


Pitch angle: 40-deg, Vertical velocity: 35 ft/s, Horizontal velocity: 30 ft/s

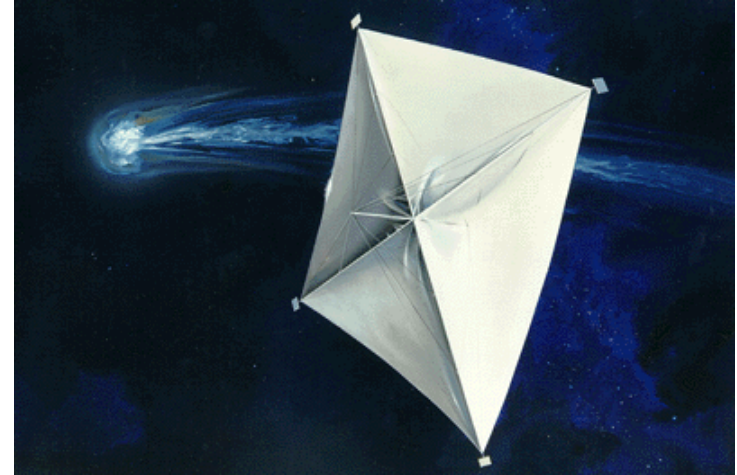


Pitch angle: 45-deg, Vertical velocity: 31 ft/s, Horizontal velocity: 47 ft/s

Inflatable Structures



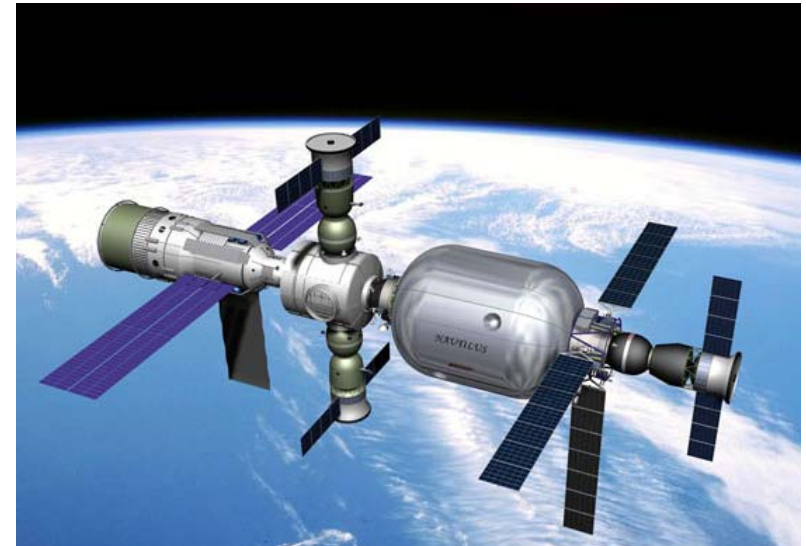
Inflatable Dish Antenna



Solar Sail with Inflatable Booms



Inflatable Wing

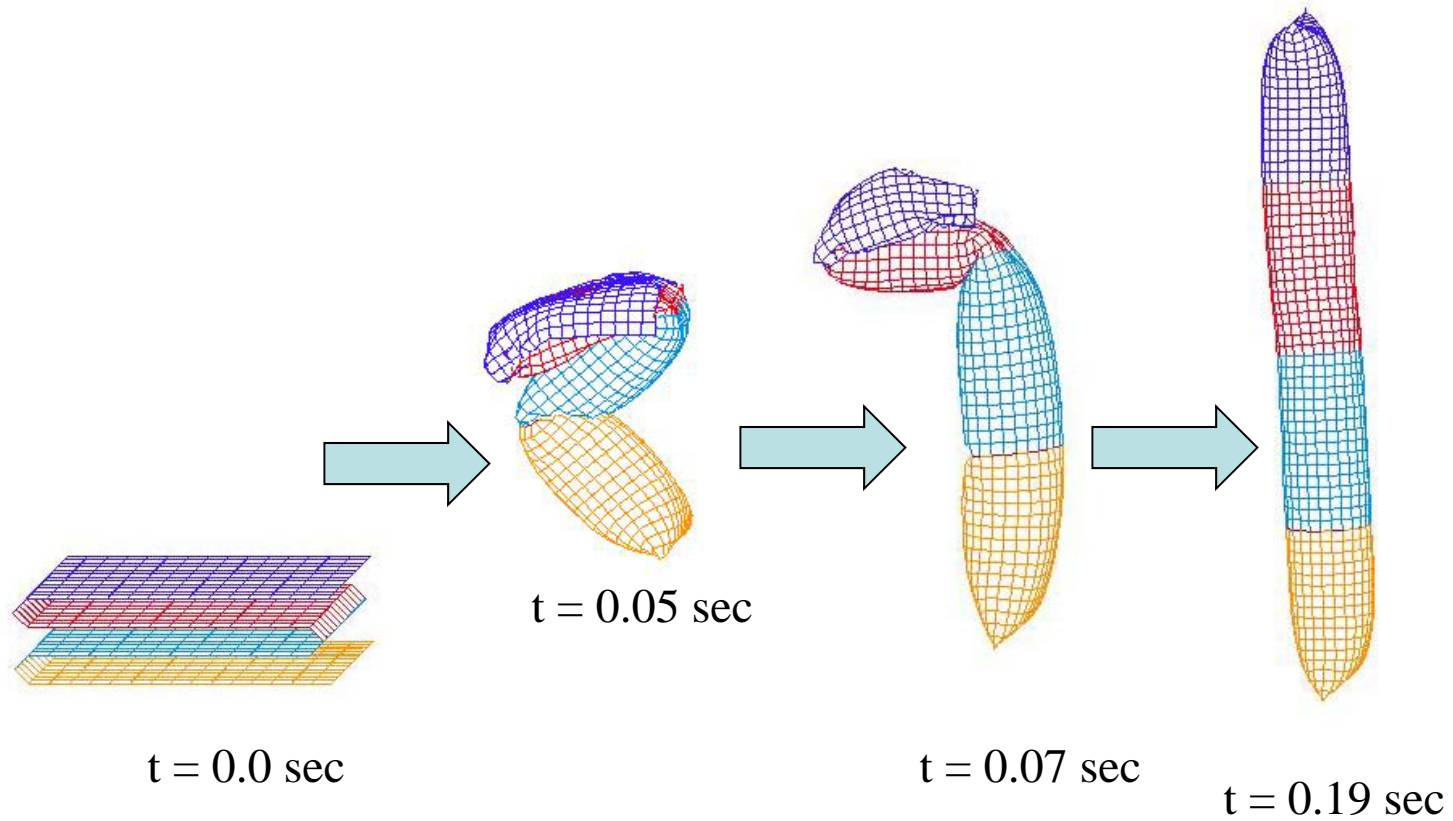


Inflatable Space Habitat

Technical Challenges for Analyzing Inflatable Structures

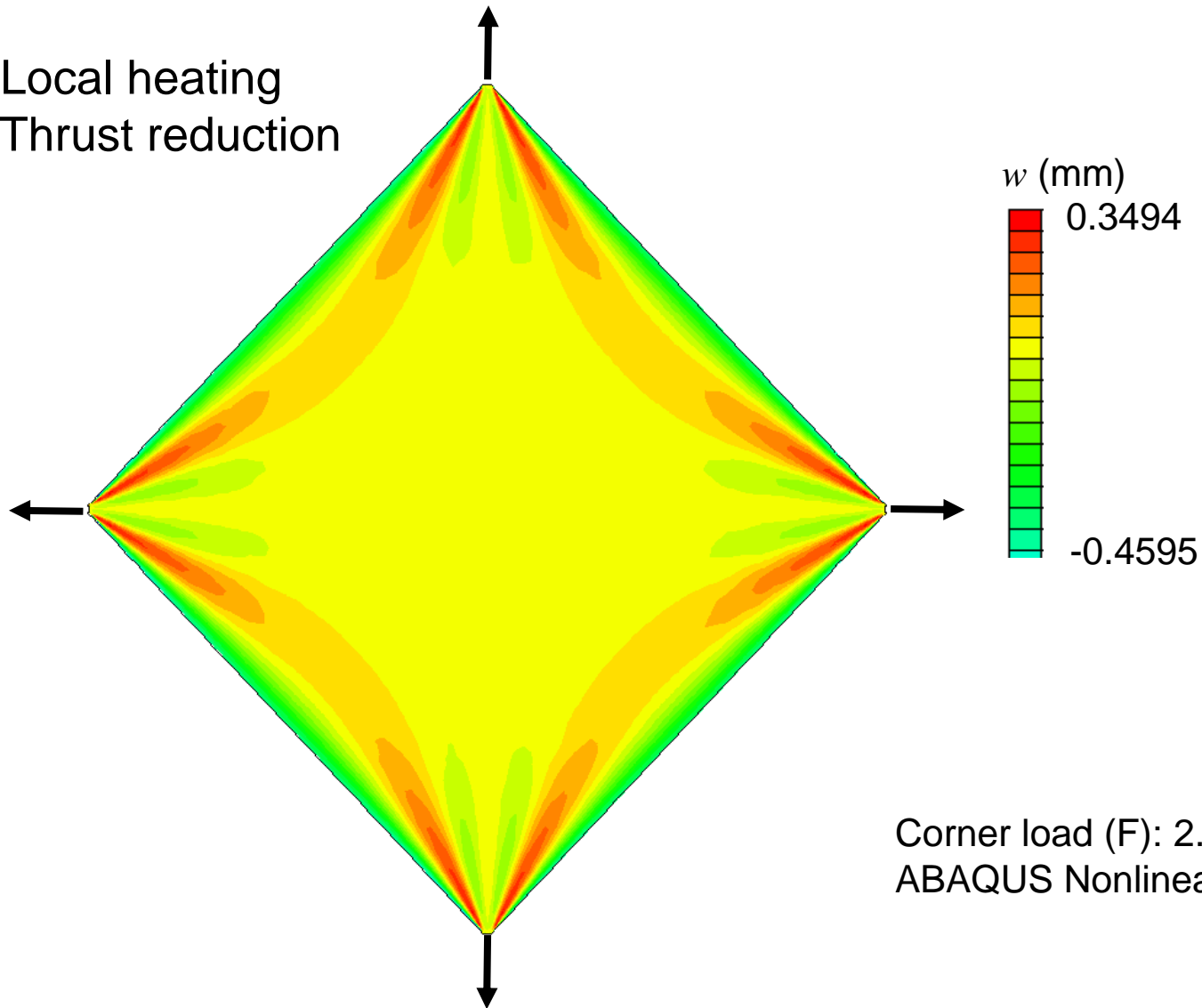
- Highly nonlinear flexible structures
- Lengthy computational time for simulating contacts and gas-structure interactions in inflation deployment process

Inflation Deployment of Folded Tube

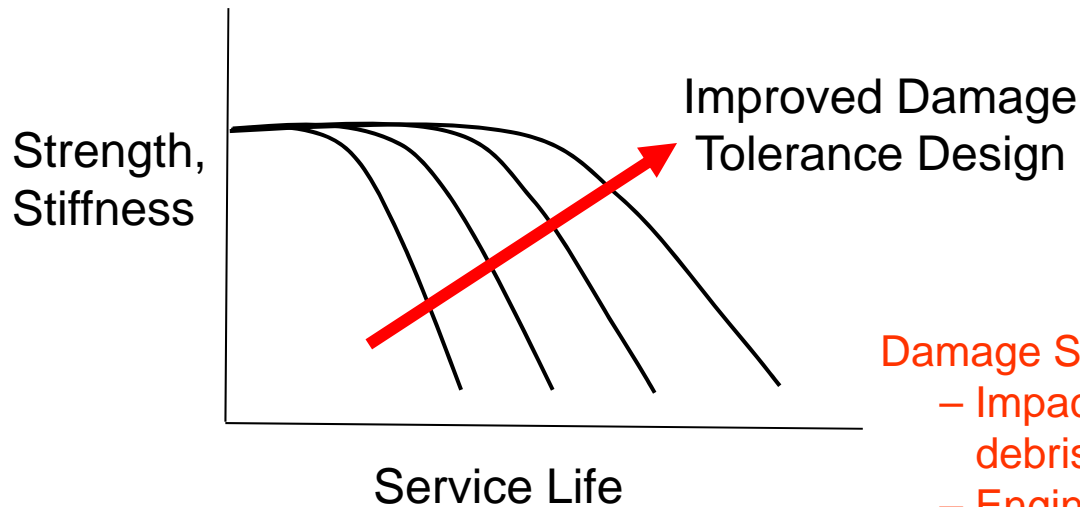


Wrinkling Deformations

- Local heating
- Thrust reduction



Damage Tolerance of Composite Aircraft Structures

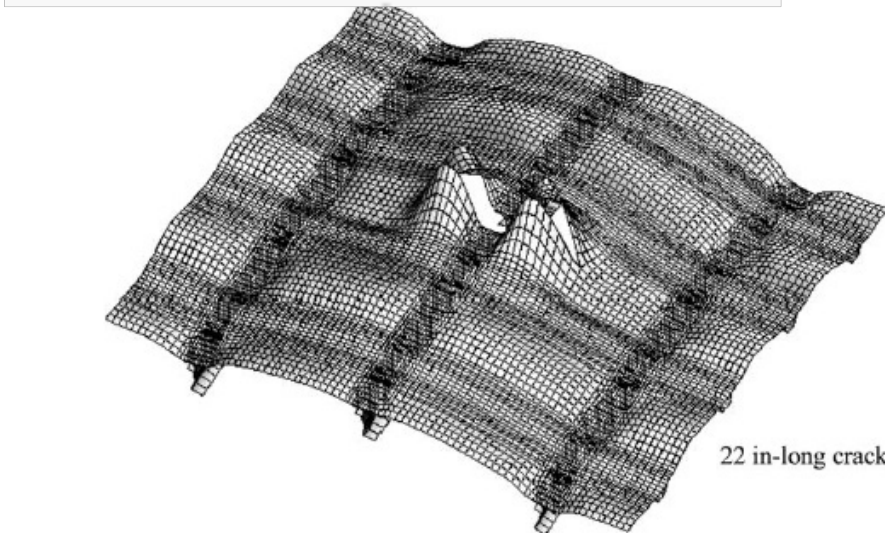
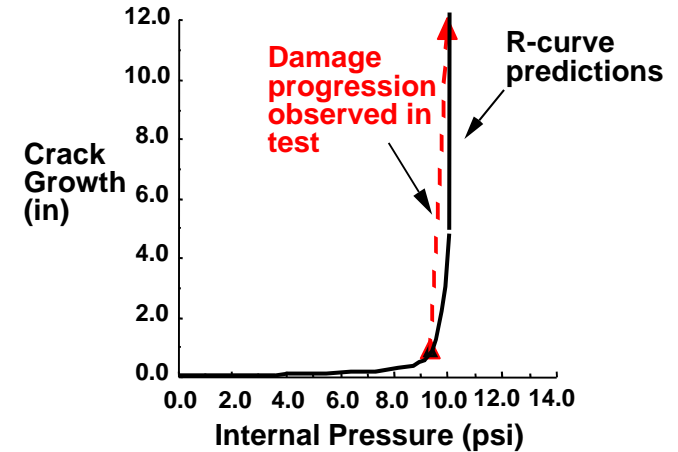
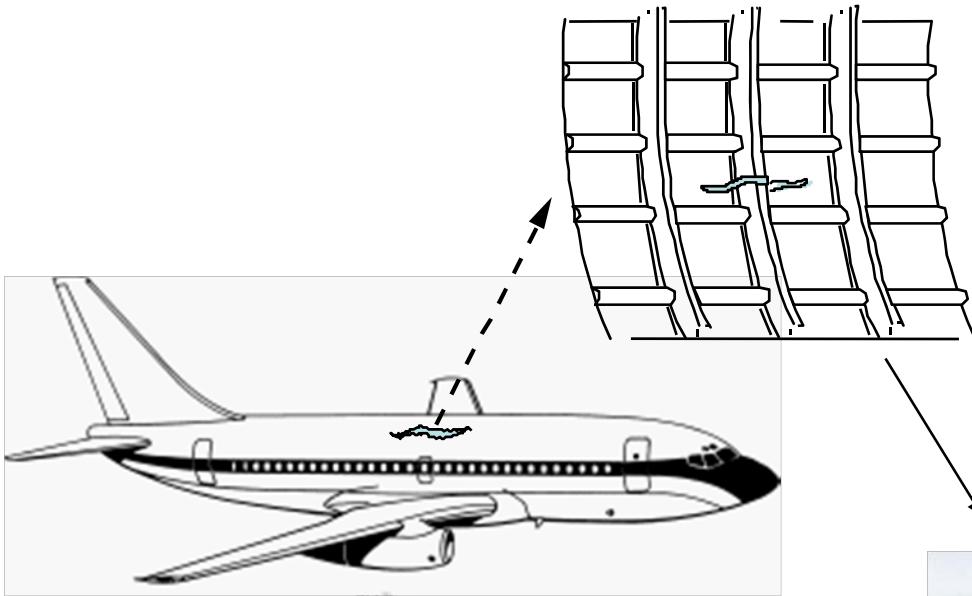


Damage Sources:

- Impact damage (tools, tool box, runway debris, service carts, hailstones, etc)
- Engine failure (rotor disk fragments, blades, etc)
- Fatigue
- Manufacturing and assembly defects
- Environmental effects (temperature, moisture, etc)

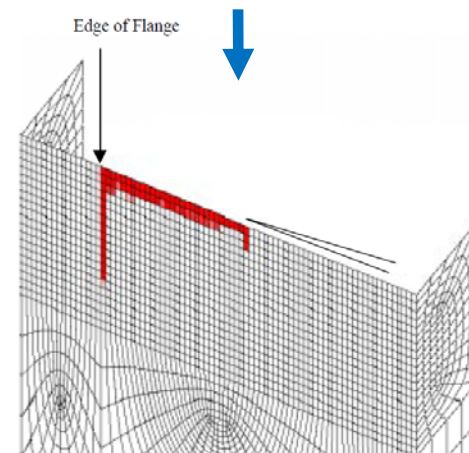
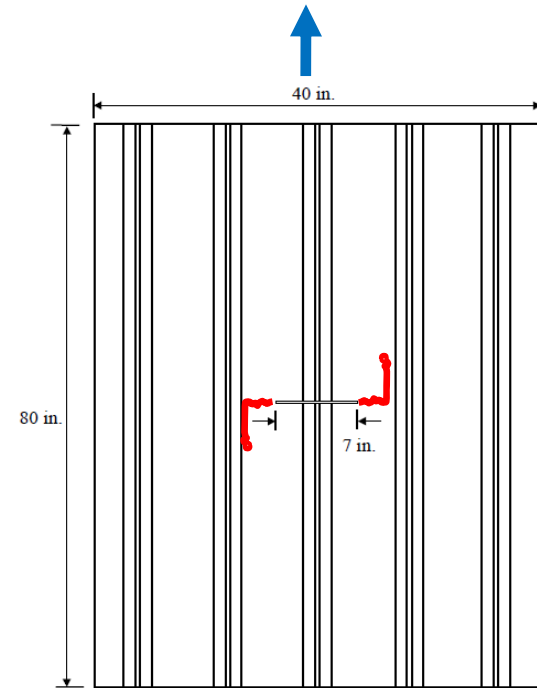
- Damage tolerance analyses of cracked panels
- Composite wing box test and analysis data correlation
- Effects of residual strain on the bridging stress in cracked fiber-metal laminates

Fuselage Panel With Discrete Source Damage



Panels tested in LaRC pressure box

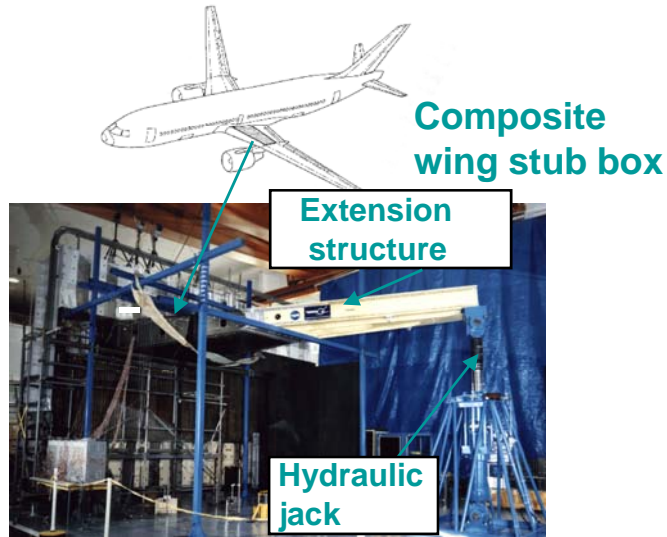
Progressive Failure Analysis



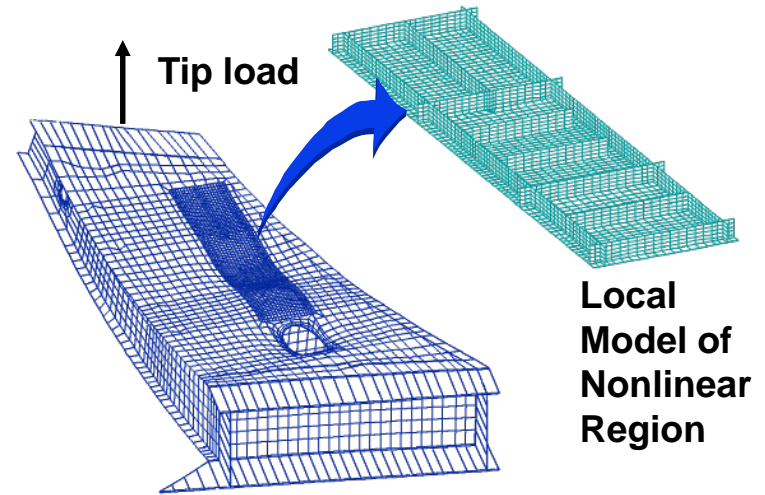
Composite Wing Tested at Langley



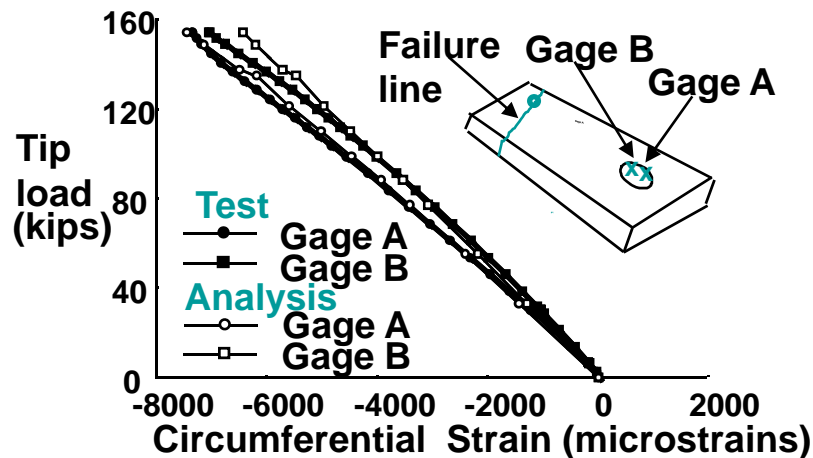
Analysis of Wing Stub Box



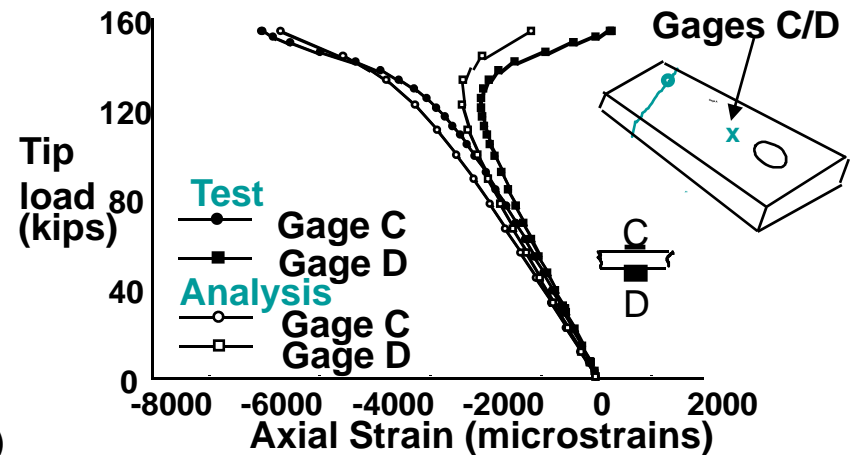
Experimental Setup



Deformed Shape



Access Door Cutout



Nonlinearly Deformed Unstiffened Bay

Boeing 787 (50% Composites)



Benefits

- Reduces structural weight
- Uses 20% less fuel
- Increases range



Improving Aircraft Durability and Efficiency with Fiber Metal Laminates

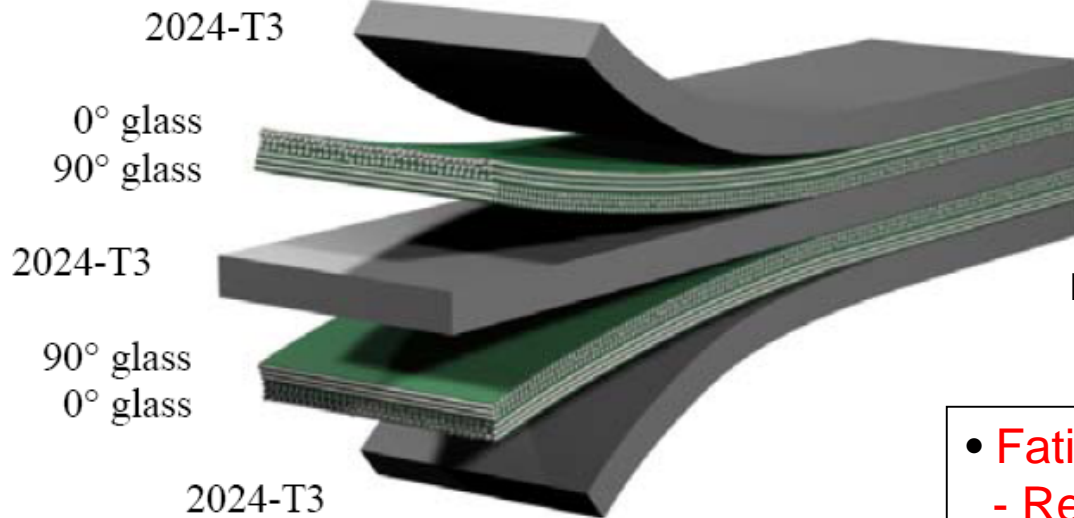
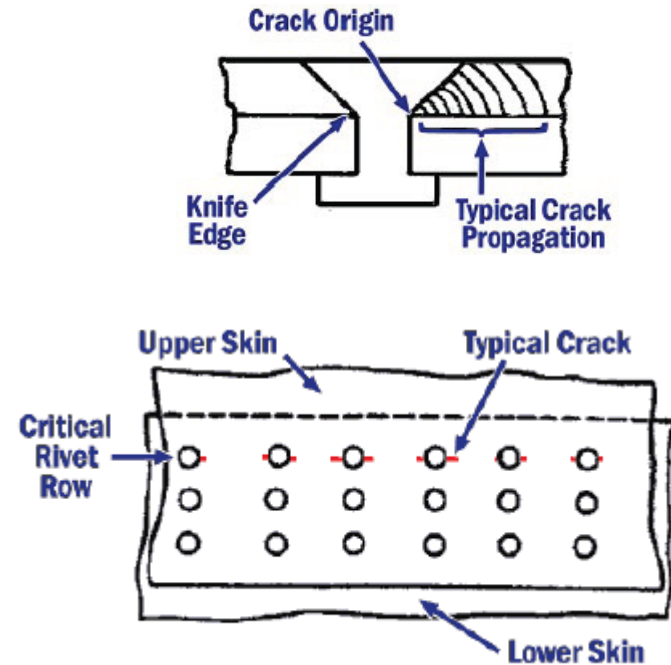


Illustration of Glare 3-3/2-0.4 [from Alderliesten]

- **Fatigue and impact resistance**
 - Reduce weight
 - Lower maintenance cost



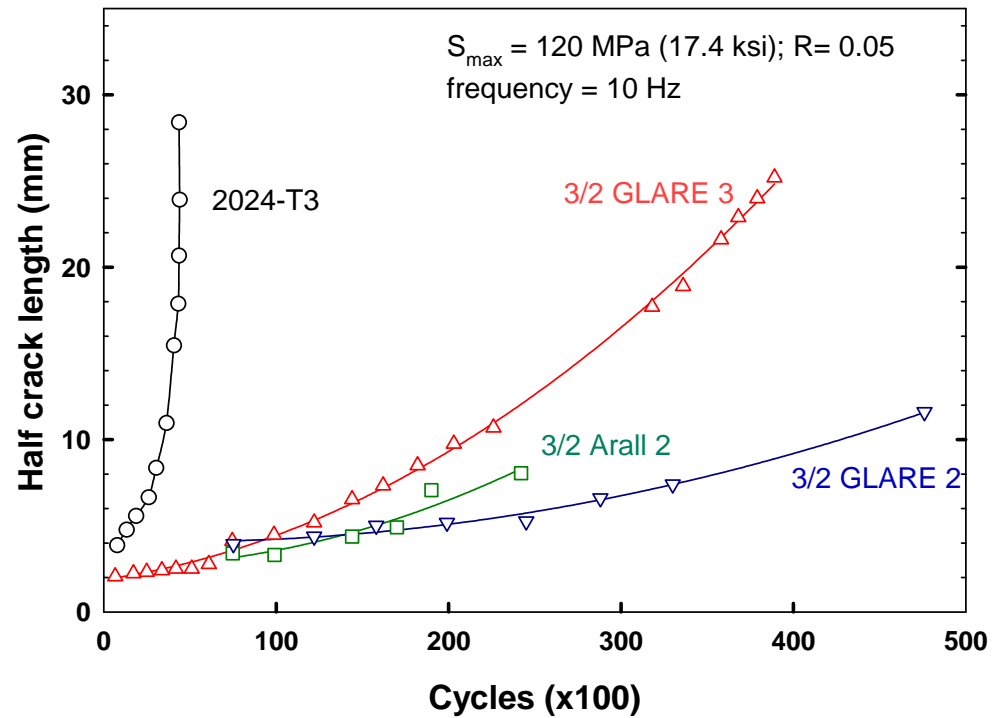
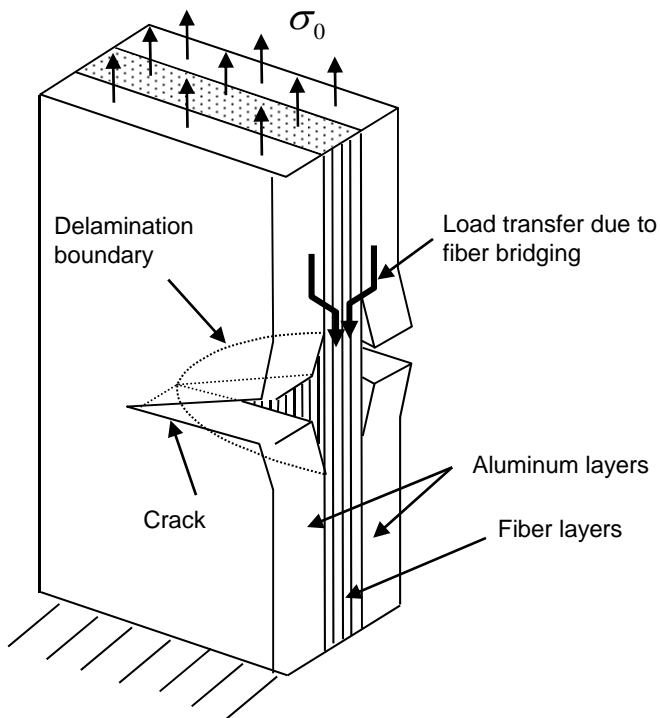
Fatigue Crack Initiation and Coalescence



Aloha Airline 243
Boeing 737-200
April 28, 1988
Honolulu, HI

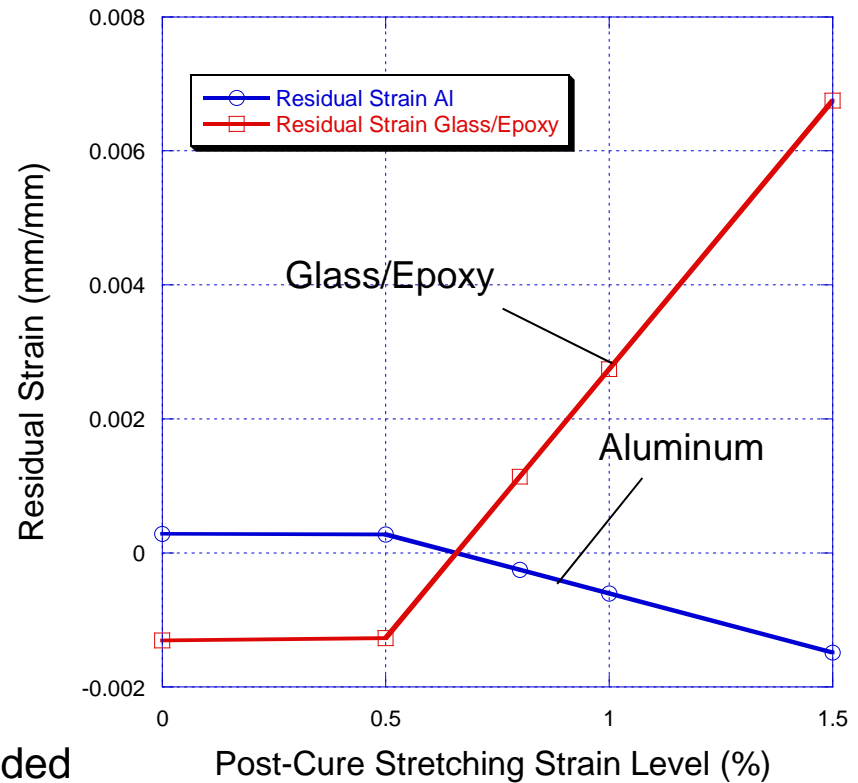
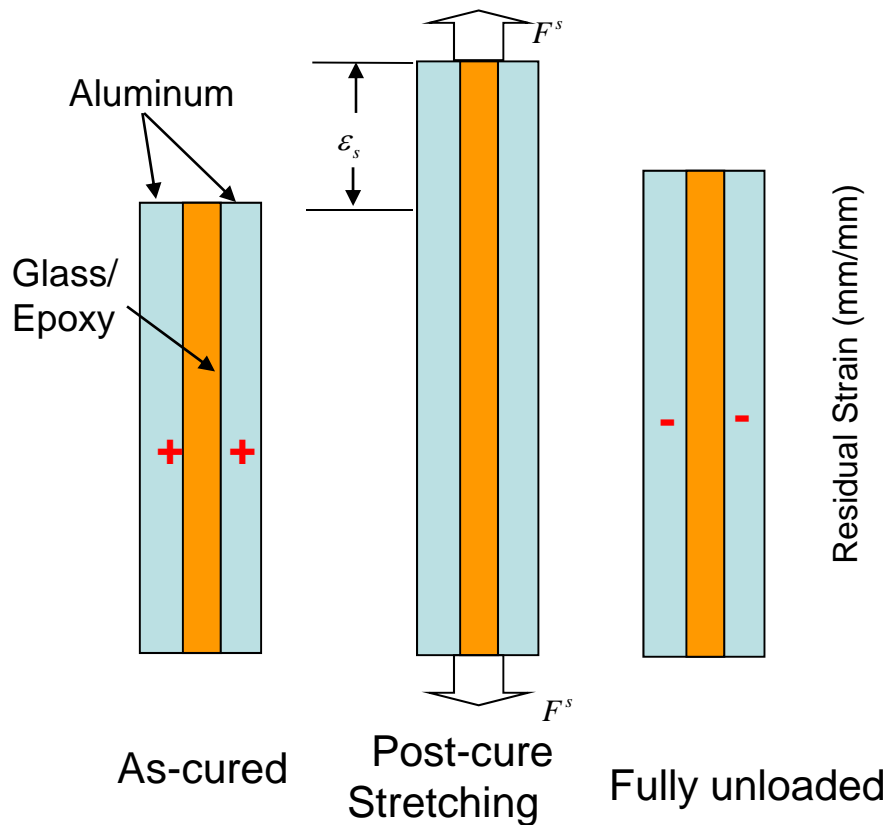
Fatigue Crack Growth Behavior of FML's

- FML's show significant improvement in fatigue crack growth resistance



Source: Vogelesang et al. (1995)

Residual Strains after Post-Cure Stretching

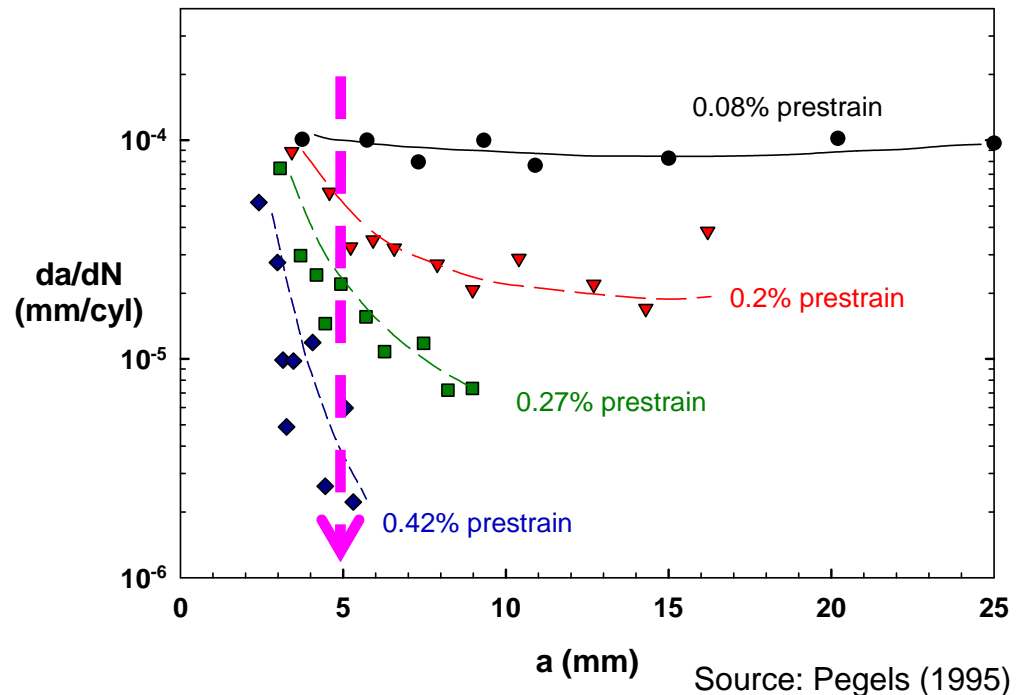
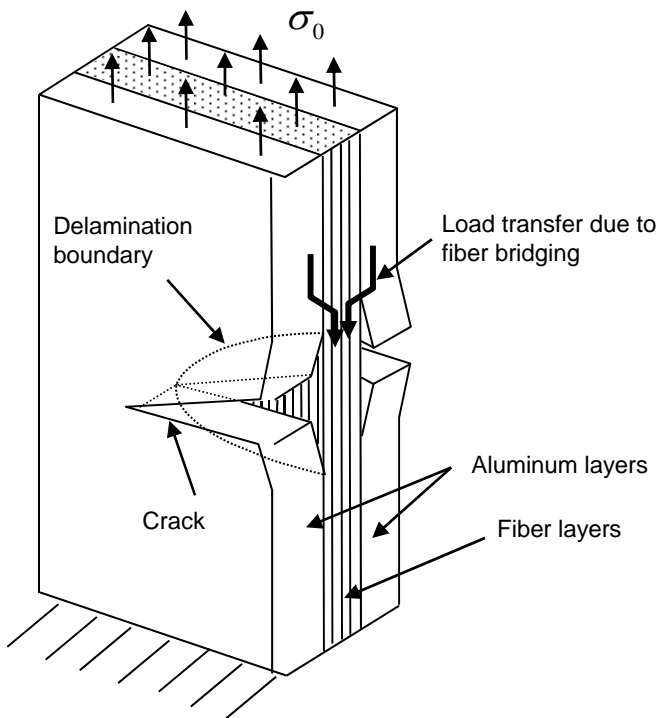


**Residual Strain
in Aluminum**

Tension  **Compression**

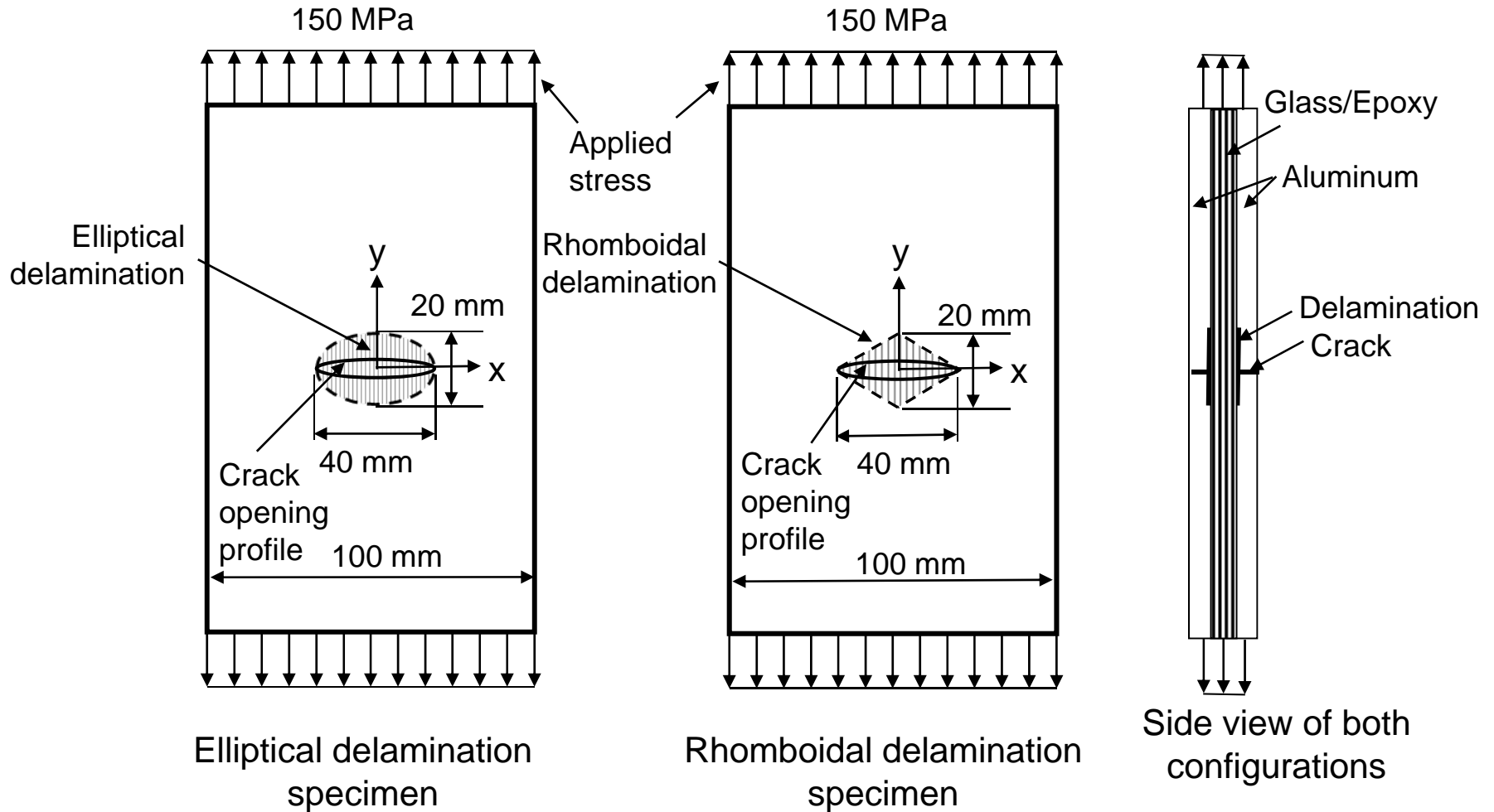
Post Cure Stretching Reducing Crack Growth Rate

- Post cure stretching can result in improved fatigue crack growth resistance

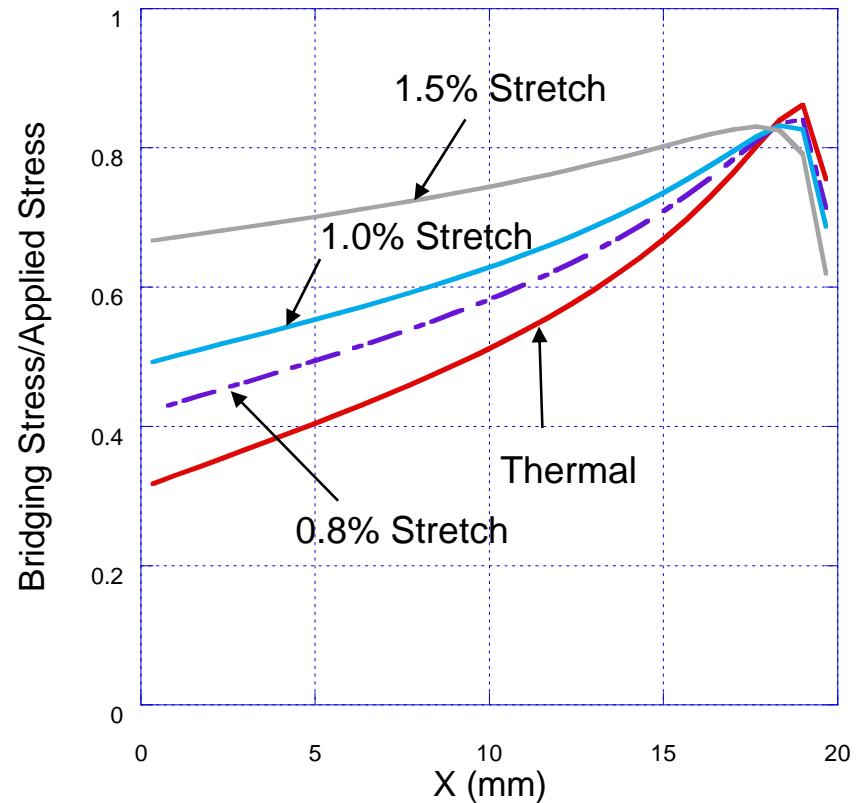
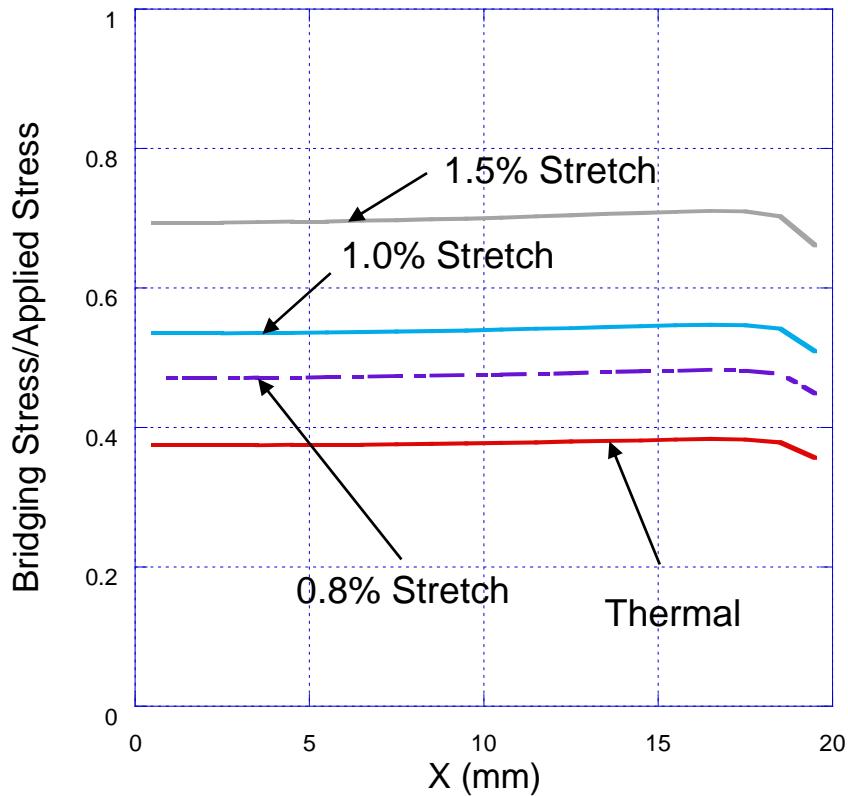
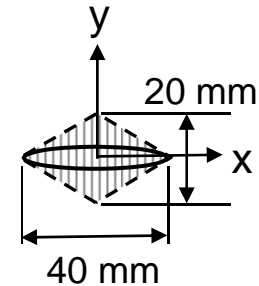
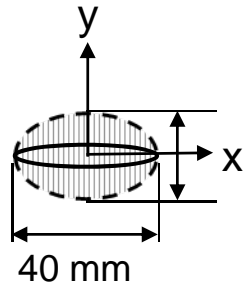


- Post cure stretching can result in improved fatigue crack growth resistance

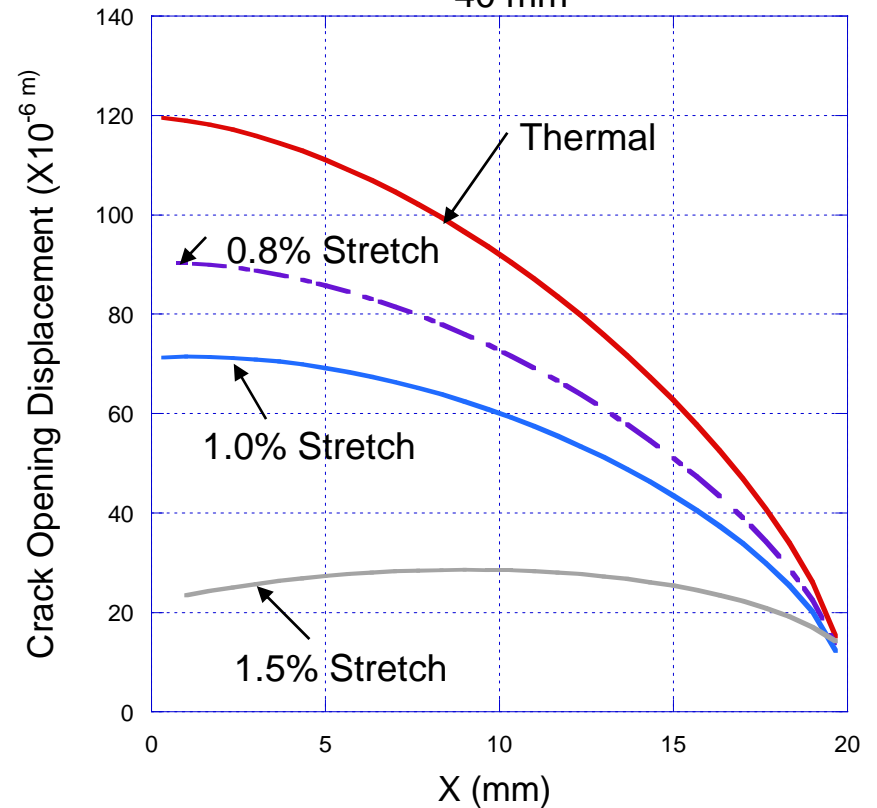
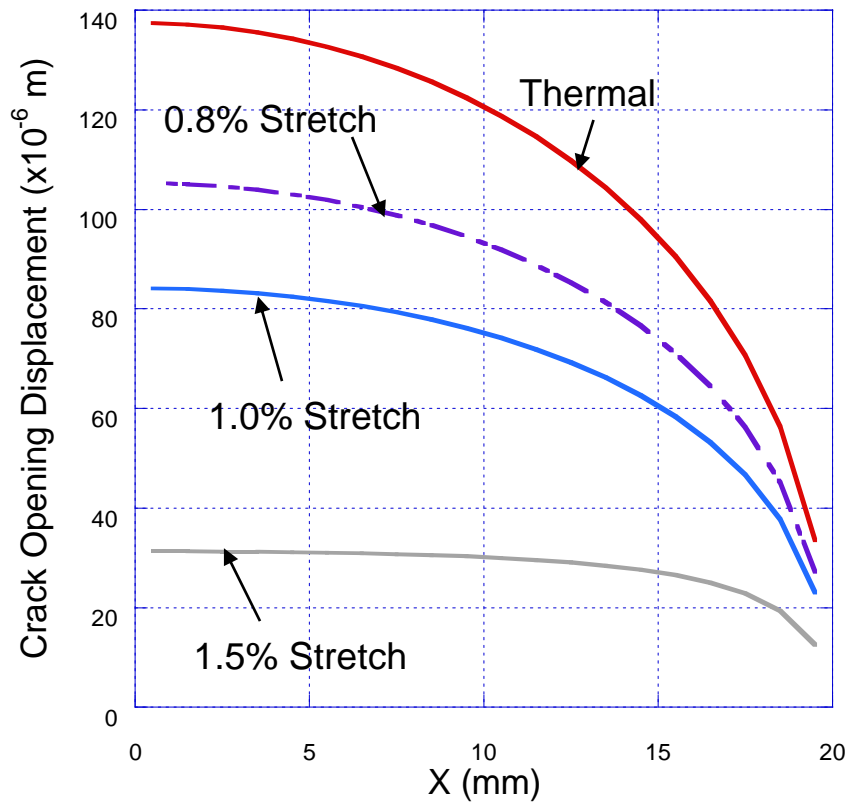
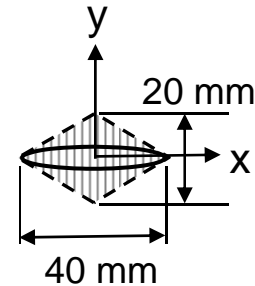
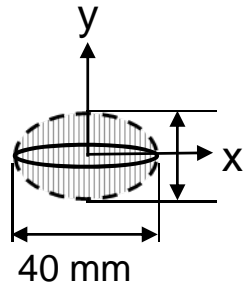
Specimens with Elliptical or Rhomboidal Delaminations



Effects of Residual Stain on Bridging Stress



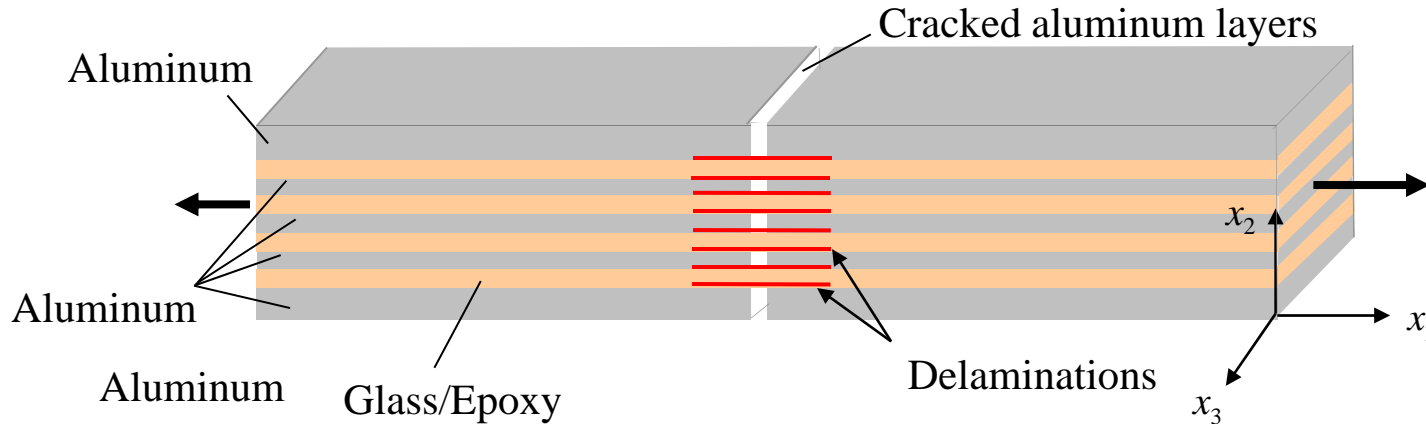
Effect of Residual Strains on CODs



Fracture Mechanics Related Research

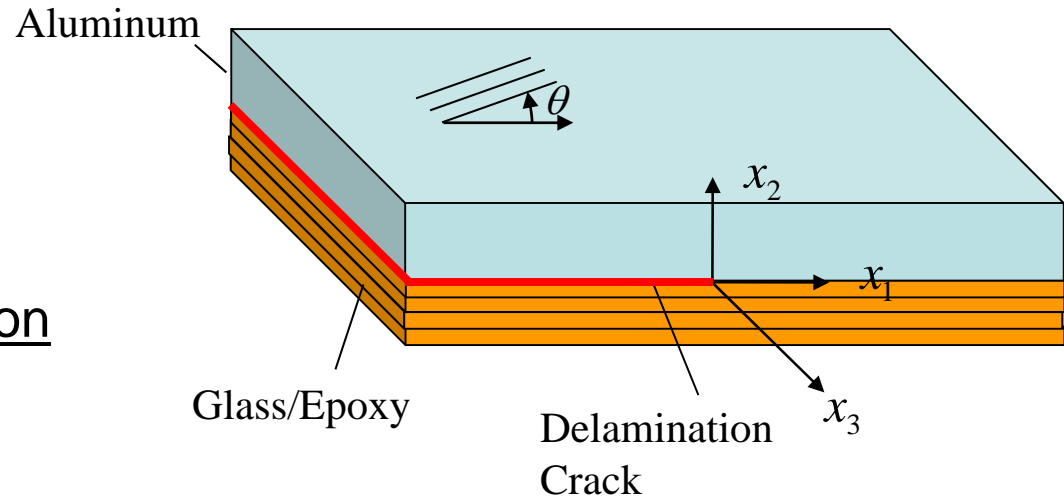
- Stress intensity factors for interfacial cracks
- Conditions for the equivalence of cohesive zone models and linear fracture mechanics

Delaminated FML Configurations

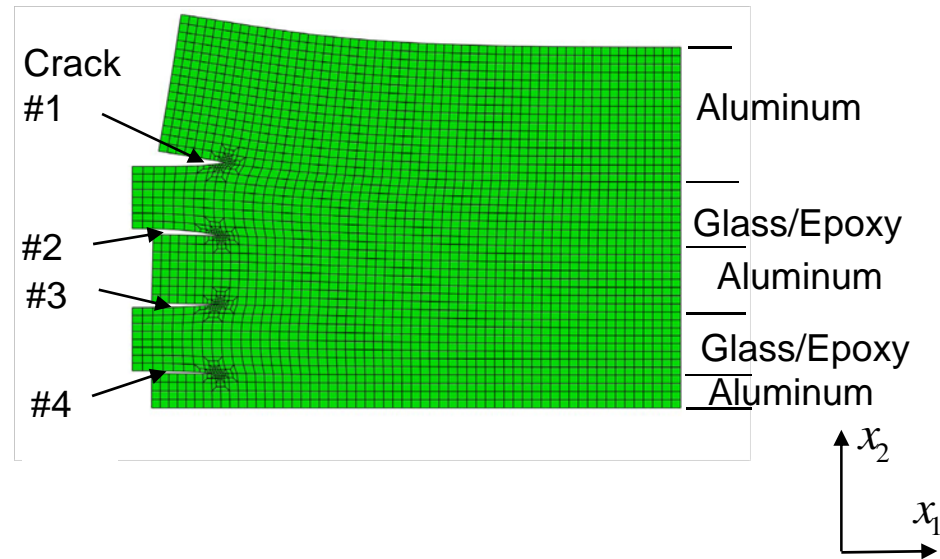


FML with multiple cracks and interfacial delaminations

FML with single interfacial delamination



Calculation of Stress Intensity Factors for Interfacial Cracks

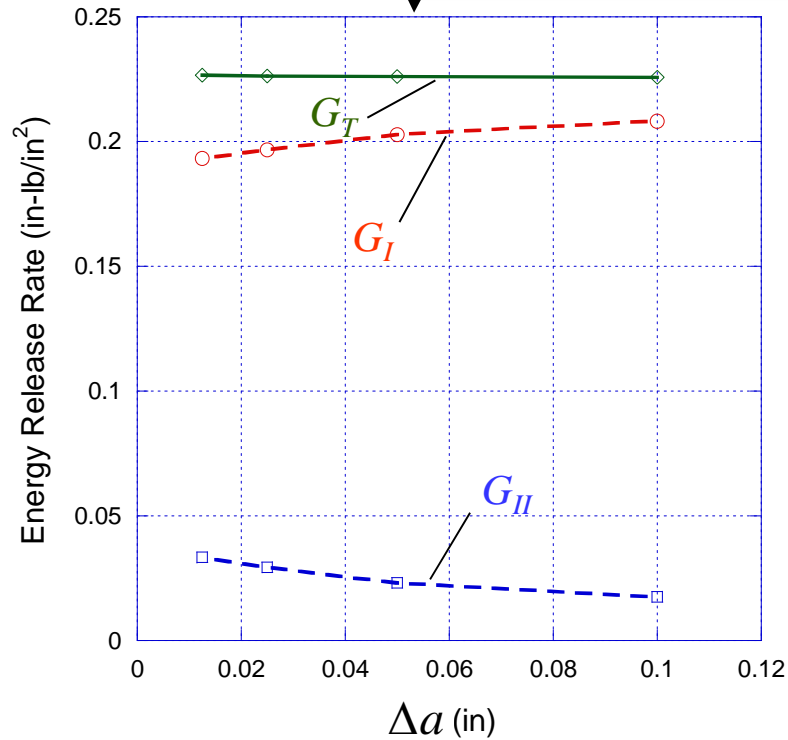
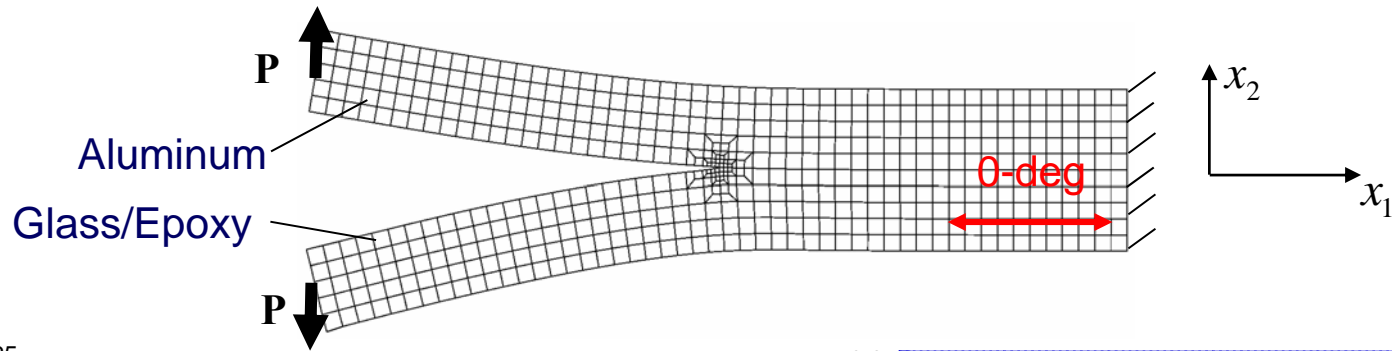


Objectives

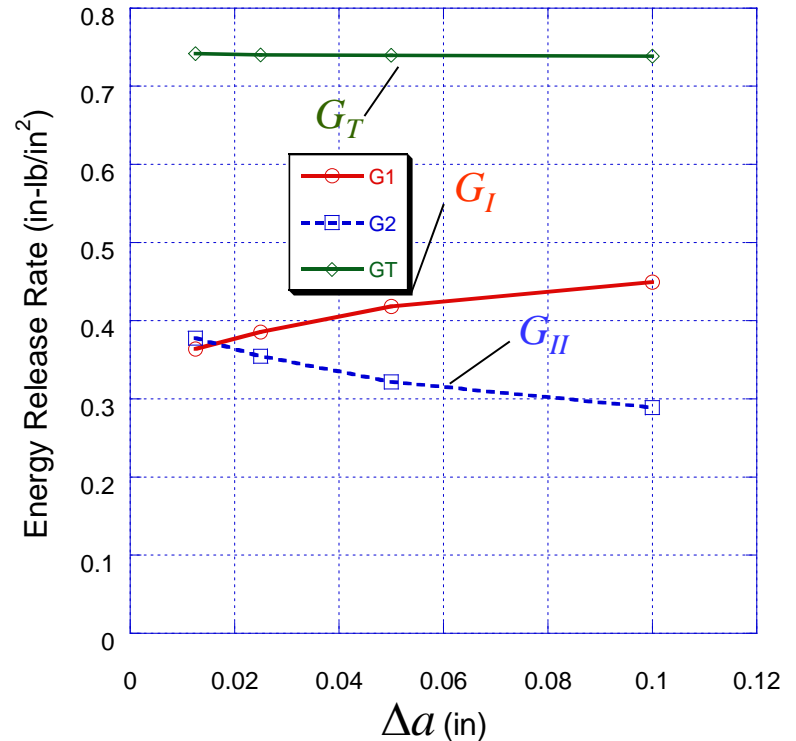
- Obtain mesh-size-independent stress intensity factors for interfacial cracks
- Explore the use of stress intensity factors to establish interfacial crack failure (growth) criterion

Ref. John T. Wang , 50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 4 -7 May 2009.

Energy Release Rates



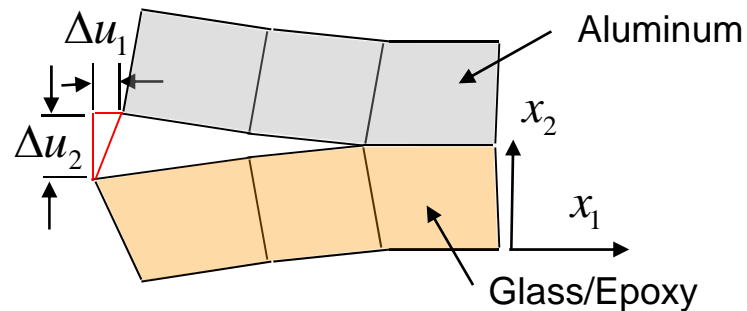
0-deg unidirectional Glass/Epoxy Layer



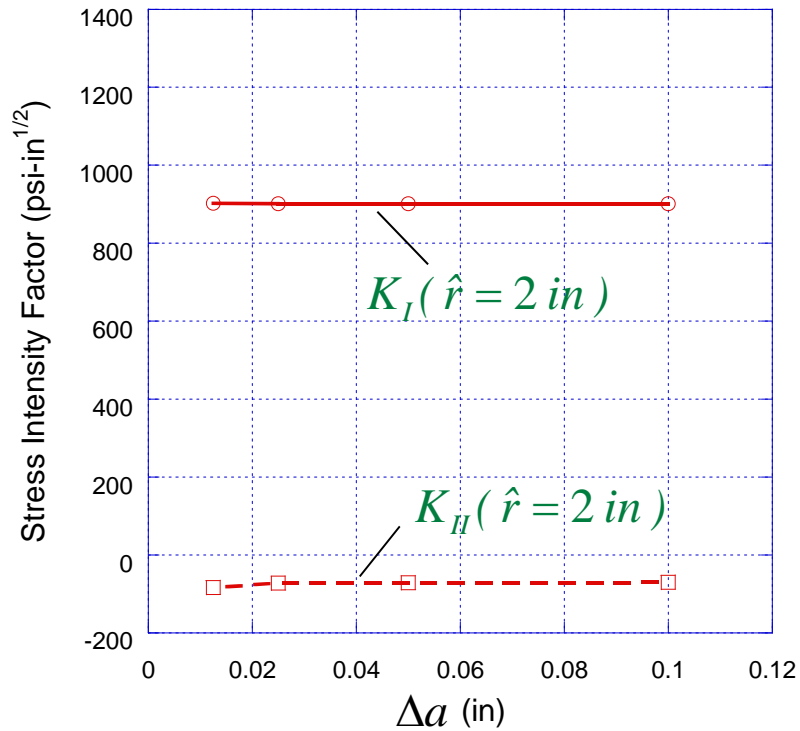
90-deg unidirectional Glass/Epoxy Layer

Displacement Ratio Method

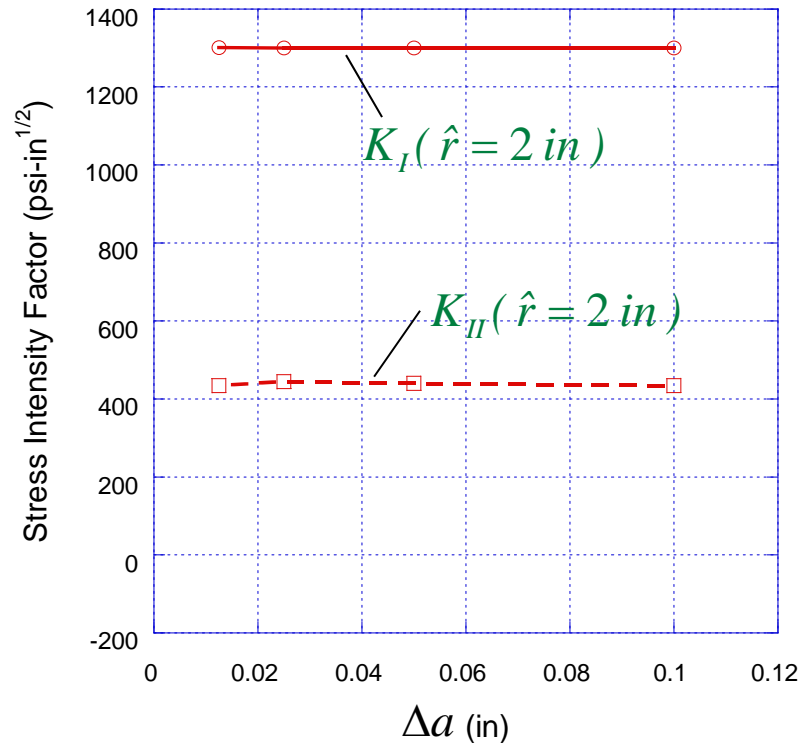
- Definition of stress intensity factors proposed by Wu (1990) and Hwu (1993)
- Stress intensity factors determined with the total energy release rate and ratios of relative interfacial crack surface displacements (Sun and Qian, 1997)



Stress Intensity Factors



0-deg unidirectional Glass/Epoxy Layer

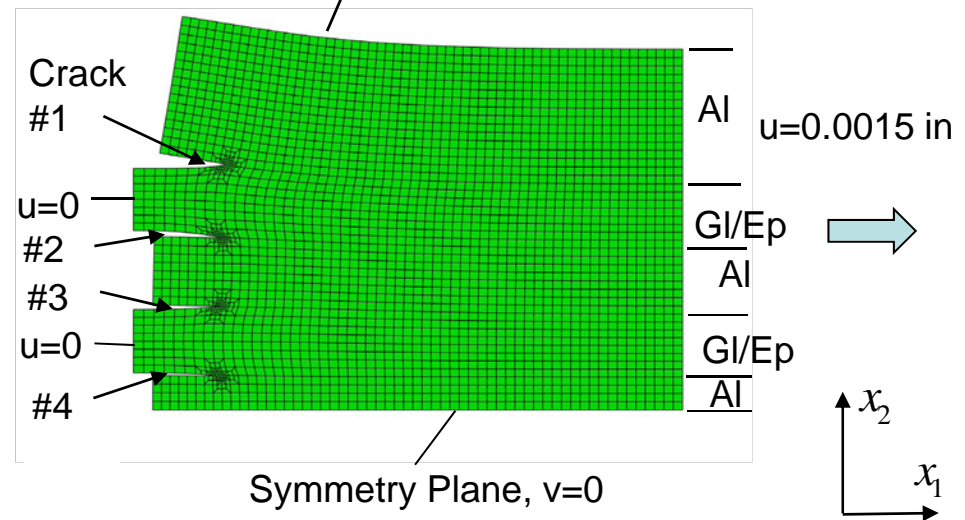
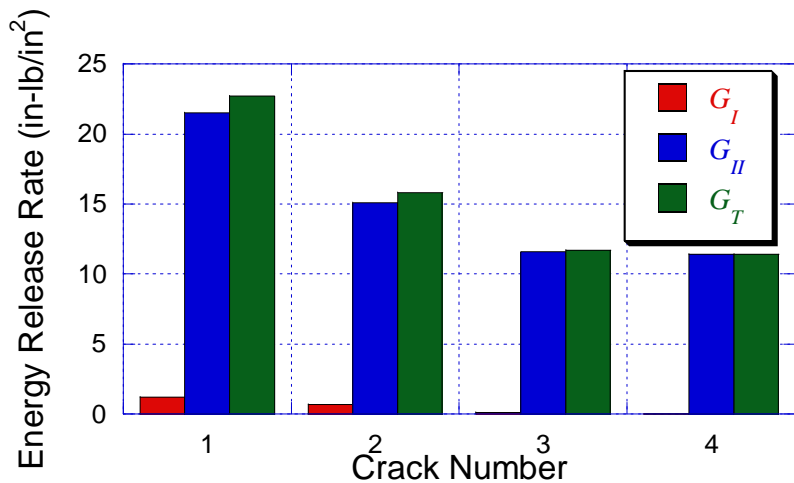
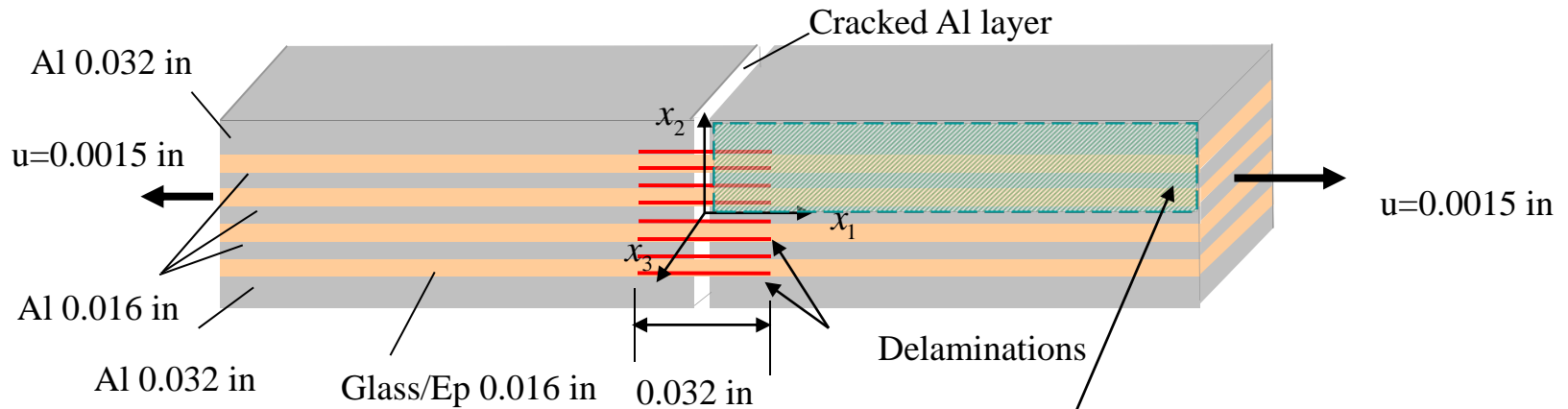


90-deg unidirectional Glass/Epoxy Layer

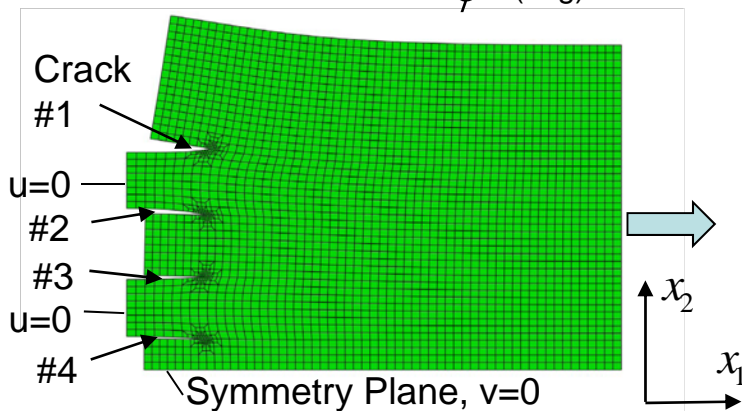
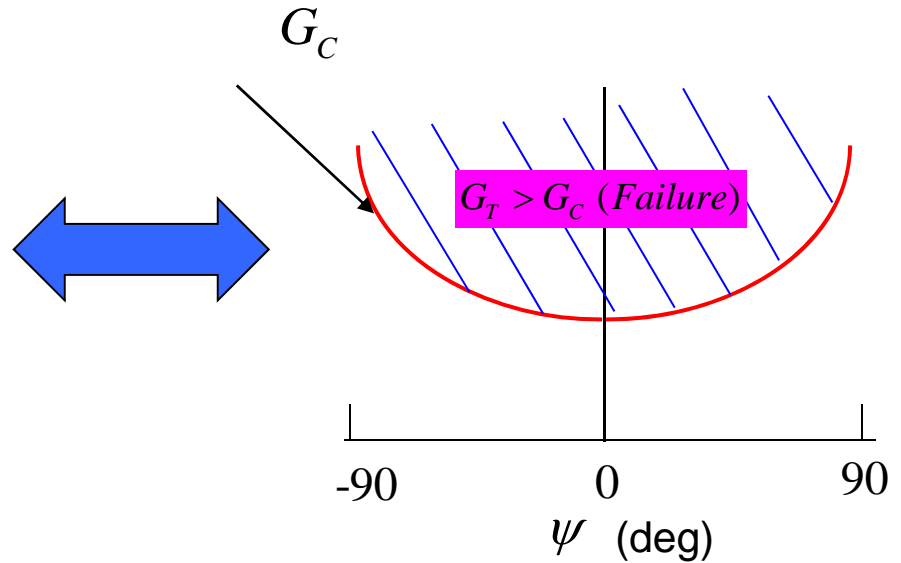
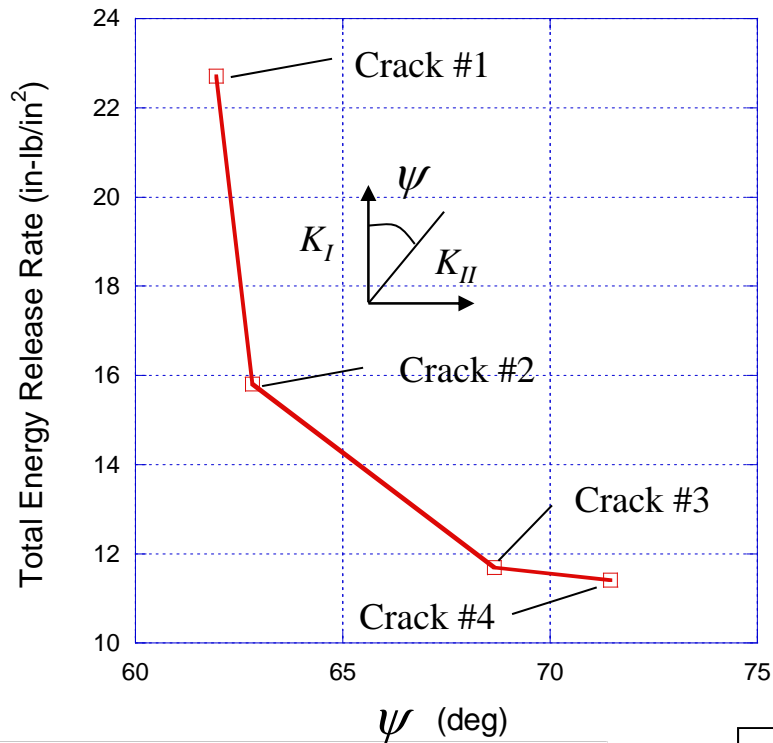
- **Not sensitive to mesh size**
- Converting to another reference length using

$$\mathbf{K}(\hat{r}_2) = \mathbf{\Lambda} \left\langle \left\langle (\hat{r}_1 / \hat{r}_2)^{-i\varepsilon_\alpha} \right\rangle \right\rangle \mathbf{\Lambda}^{-1} \mathbf{K}(\hat{r}_1)$$

Energy Release Rates for FML with Multiple Cracks



FML Interfacial Crack Failure Criterion



- Mode mixity angles defined as

$$\psi = \tan^{-1} \frac{K_{II}}{K_I}$$

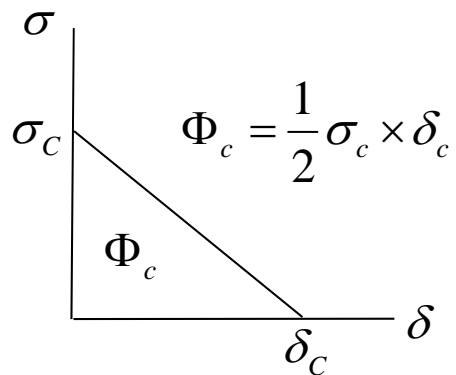
- Mixed mode failure criterion

$$G_T(\psi) \geq G_C(\psi)$$

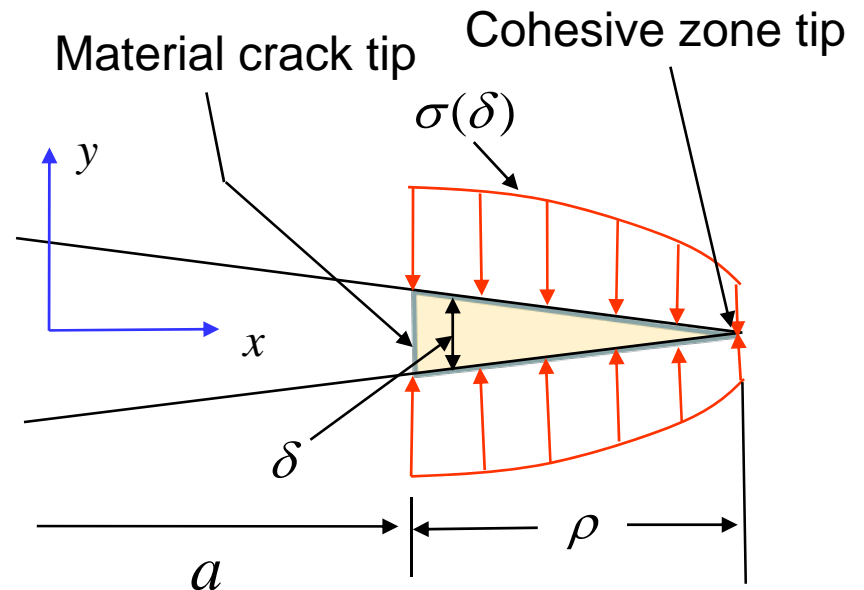
- Experimental procedure not well established

Cohesive Zone Model (CZM)

- CZM essentially models fracture process zone by a line or a plane ahead of the crack tip subjected to cohesive traction
- The constitutive behavior is given by traction-separation relationship



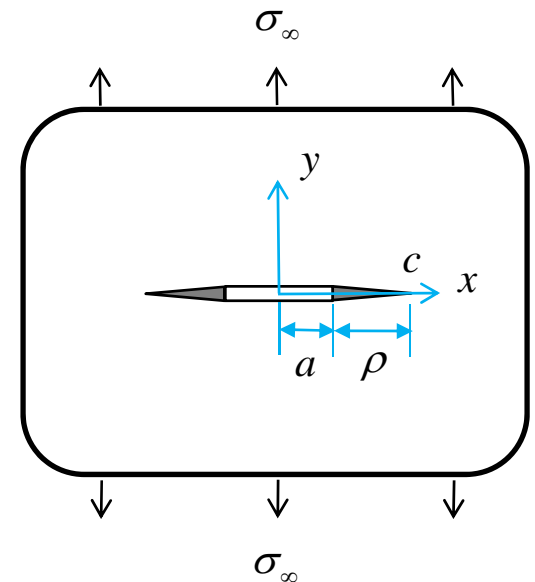
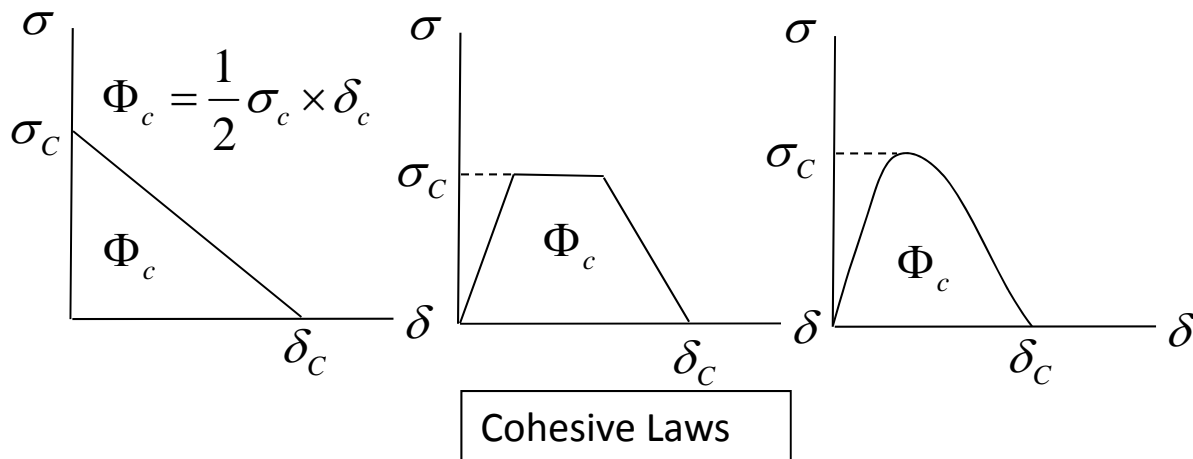
Cohesive Law



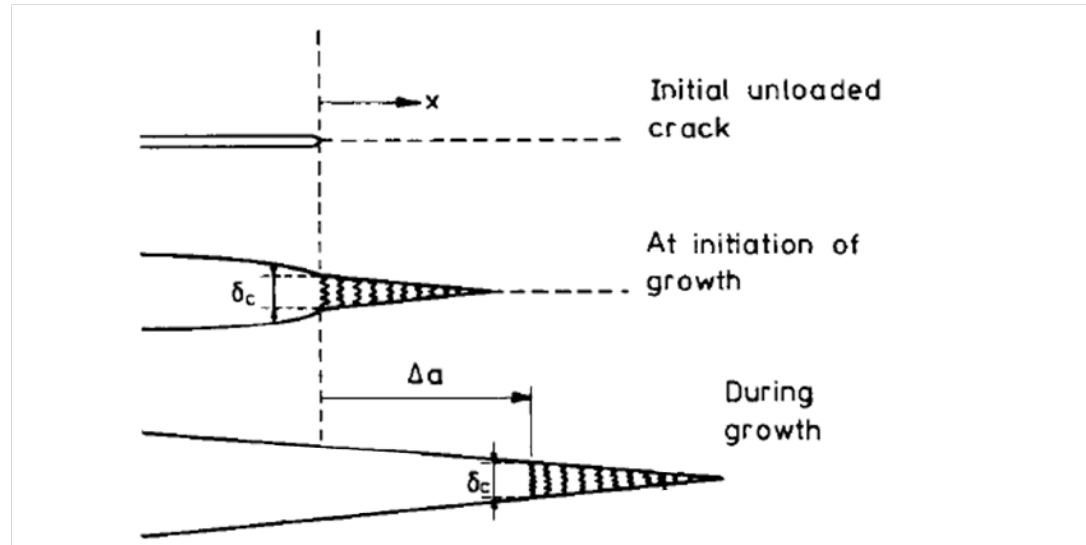
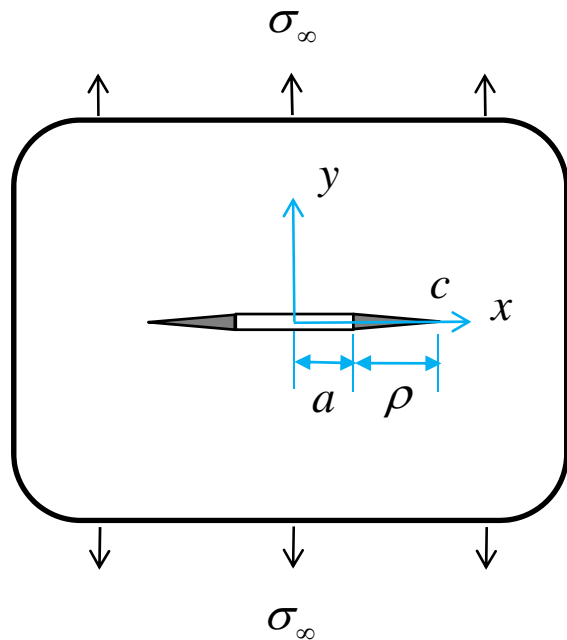
Cohesive zone models (continued)

- Cohesive zone models (CZMs) also known as “Dugdale-Barrenblatt model”
- Widely accepted as a computationally convenient fracture analysis tool
- Many different cohesive laws used and similar failure load predicted for the same cracked structure

Φ_c : Cohesive energy
release rate (CERR)

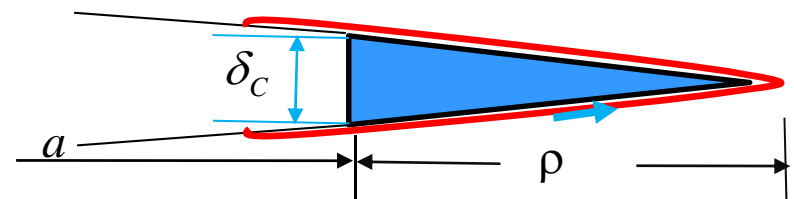
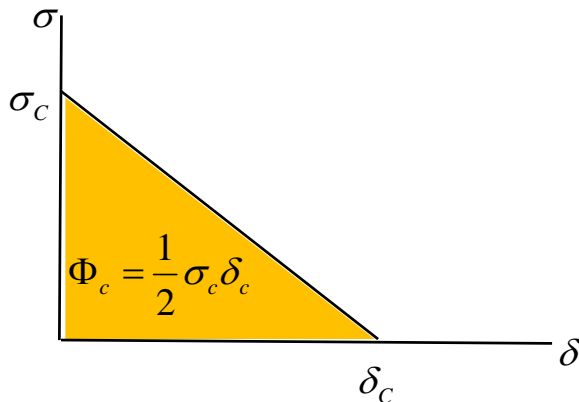


Fully Developed Cohesive Zone



$$J = \Phi_c$$

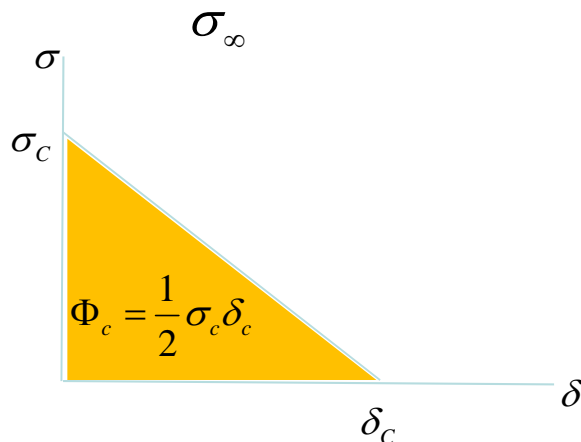
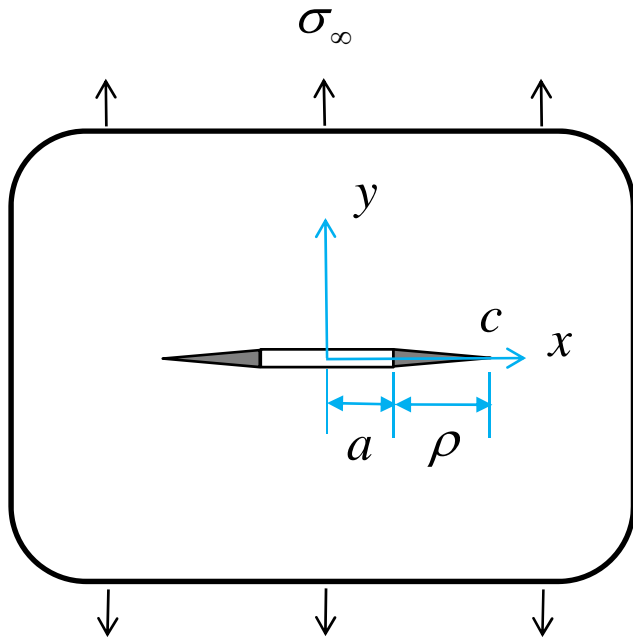
$$\delta(a) = \delta_c$$



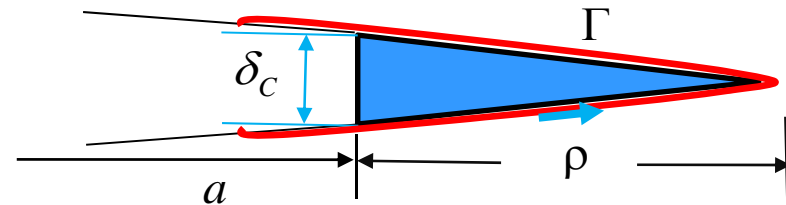
$$J = -\int_a^{a+\rho} \sigma \frac{\partial \delta}{\partial x} dx = \int_0^{\delta_c} \sigma(\delta) d\delta = \Phi_c$$

$$J = G_c \text{ for brittle fracture}$$

Equivalence of LEFM and CZM



- Remote applied stress for a fully developed cohesive zone: σ_∞



$$J = \Phi_c$$

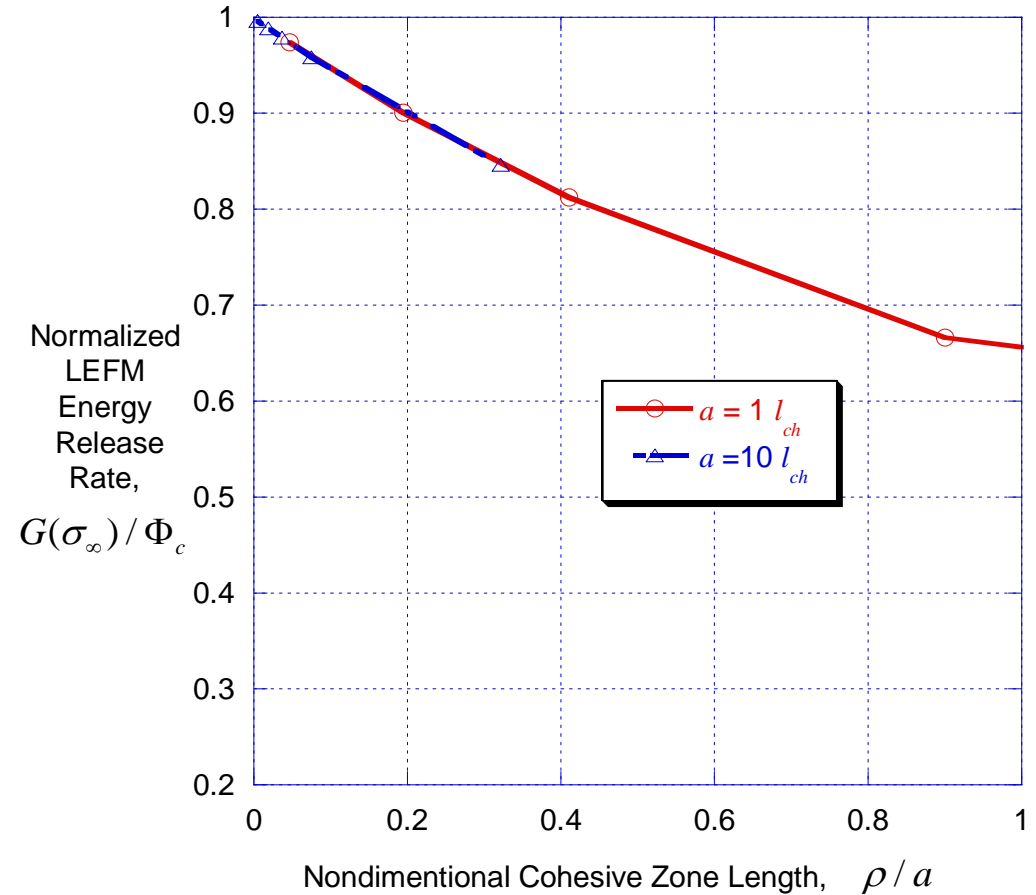
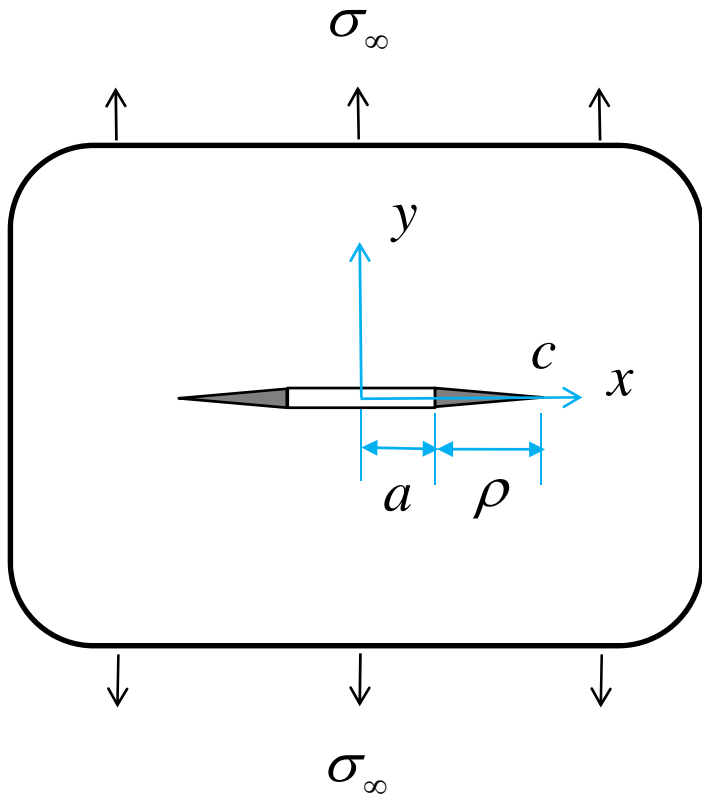
$$\delta(a) = \delta_c$$

- LEFM energy release rate at crack tip

$$G(\sigma_\infty) = \frac{(\sigma_\infty)^2 \pi a}{E}$$

- Is the ratio $G(\sigma_\infty) / \Phi_c \approx 1$?

LEFM Energy Release Rate vs. Cohesive Zone Length



$$\text{Characteristic Length: } l_{ch} = \frac{\Phi_c}{E\sigma_c^2}$$

Concluding Remarks

- Results of three research areas related to modeling the response and integrity of aerospace structures presented
- In the area of damage tolerance of composite aircraft structures, methods for predicting the damage progression in cracked composite panels, composite wing box test and analysis data correlation, and effects of residual strain on the bridging stress in cracked fiber-metal laminates discussed
- In the area of response prediction of space structures, crew module water landing, and techniques for modeling inflatable structures included
- In the area of current fracture mechanics research, stress intensity factors for interfacial cracks, and cohesive zone models addressed