COMPUTATIONAL FRACTURE MECHANICS FOR COMPOSITES

STATE OF THE ART AND CHALLENGES

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NIA - Senior Staff Scientist

CAA/FAA Workshop on Adhesive Bonding, Gatwick, UK, October 2004

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OUTLINE

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- Delamination sources at geometric and material discontinuities
- History of skin-stiffener debonding testing and analysis
- Fracture mechanics methodology for delamination onset prediction
  - Experiments to determine fracture toughness
  - Finite element analysis to compute mixed-mode energy release rate
- Past studies on skin/stringer debonding
  - A shell/3D modeling technique
  - Application of Fracture Mechanics Methodology
- Summary
- Outlook
- Summary of FAA/ASTM D30 Workshop
- Remaining challenges

DELAMINATION SOURCES AT GEOMETRIC AND MATERIAL DISCONTINUITIES

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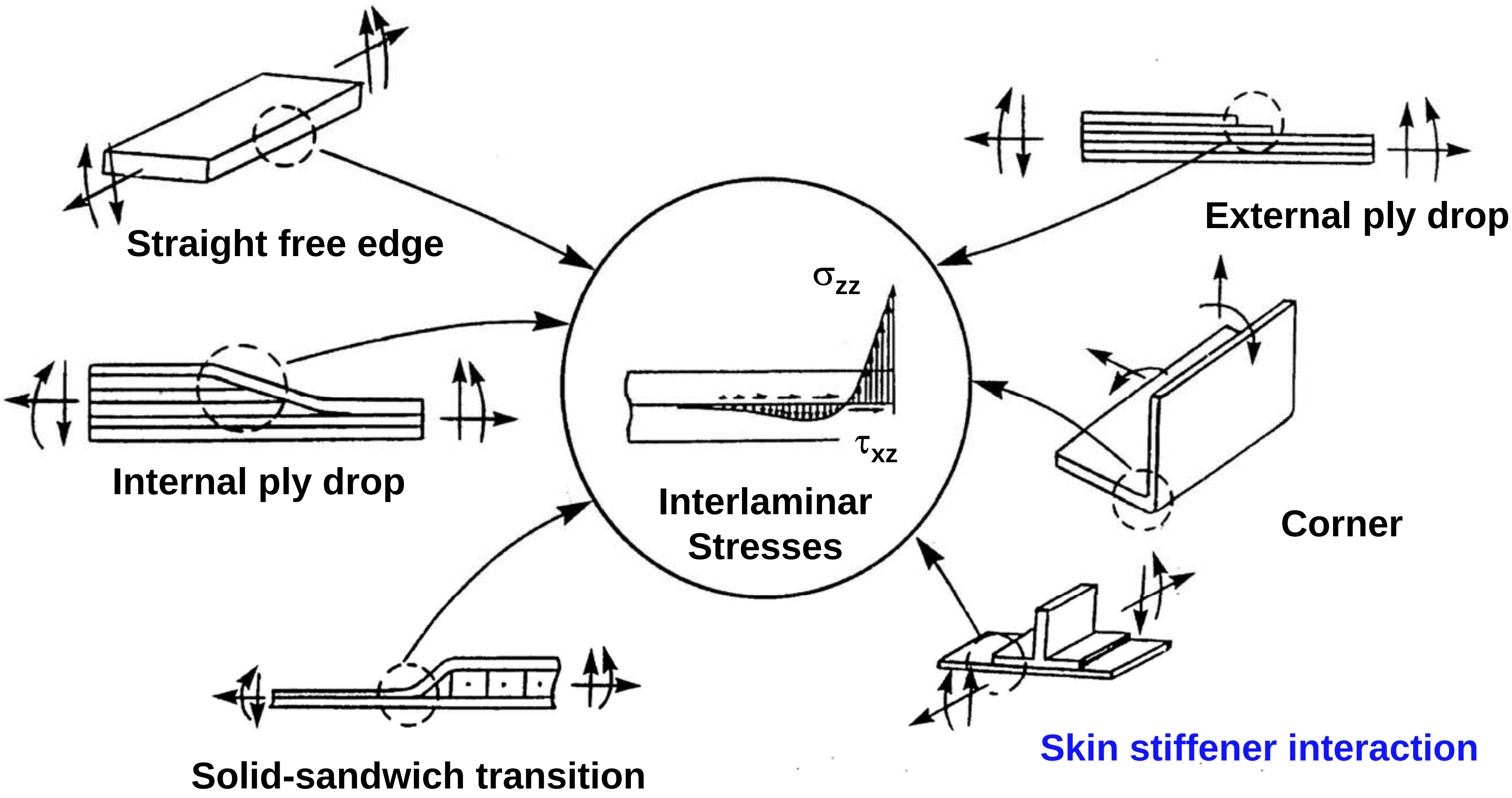

HISTORY OF SKIN/STIFFENER DEBONDING
PRESSURIZED COMPOSITE FUSELAGE

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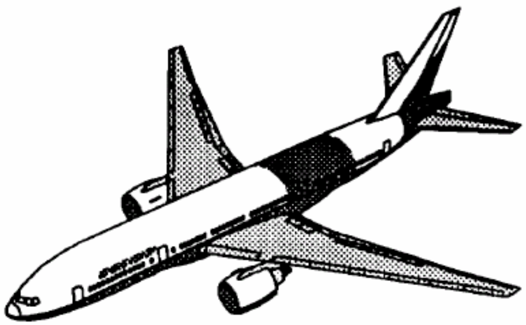
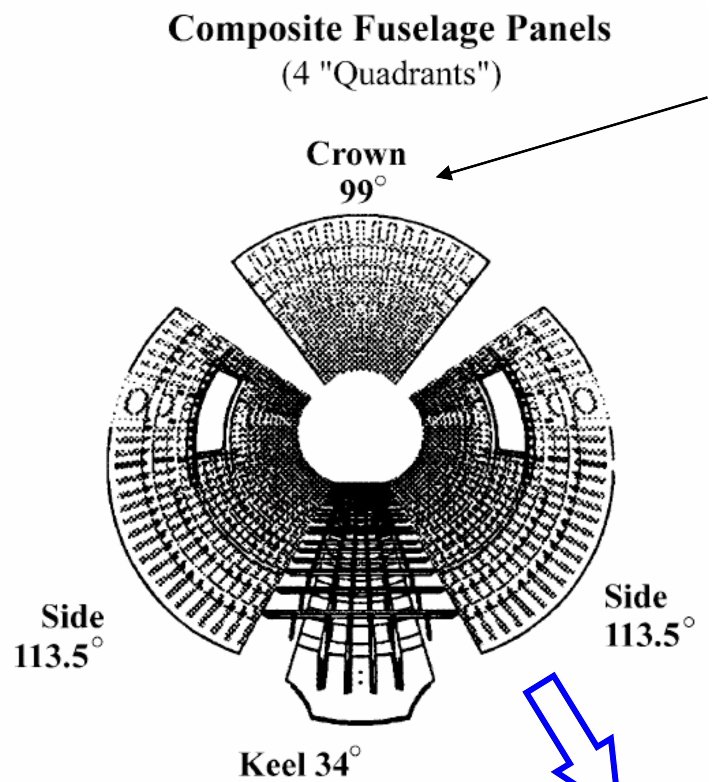
- **Composite Fuselage Technology Development***



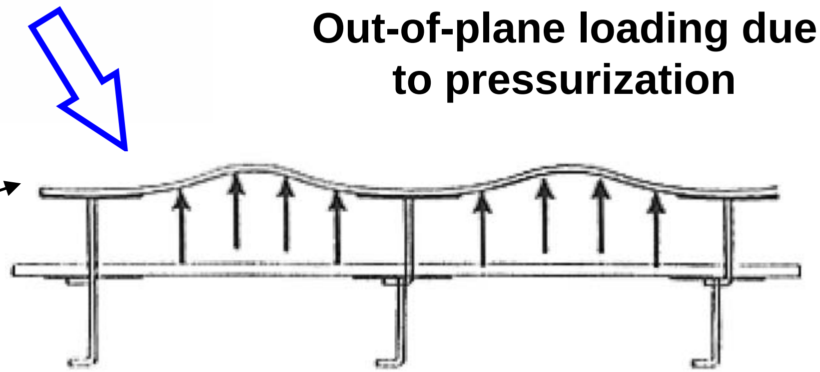
An equivalent metal fuselage section has 10 panels



Crown panel
frame bonded onto skin to reduce manufacturing costs

Out-of-plane loading due to pressurization

deformed shape



*L.B. Ilcewicz, Composite Technology Development for Commercial Airframe Structures

HISTORY OF SKIN/STIFFENER DEBONDING
POST-BUCKLED THIN-SKIN ROTORCRAFT FUSELAGE

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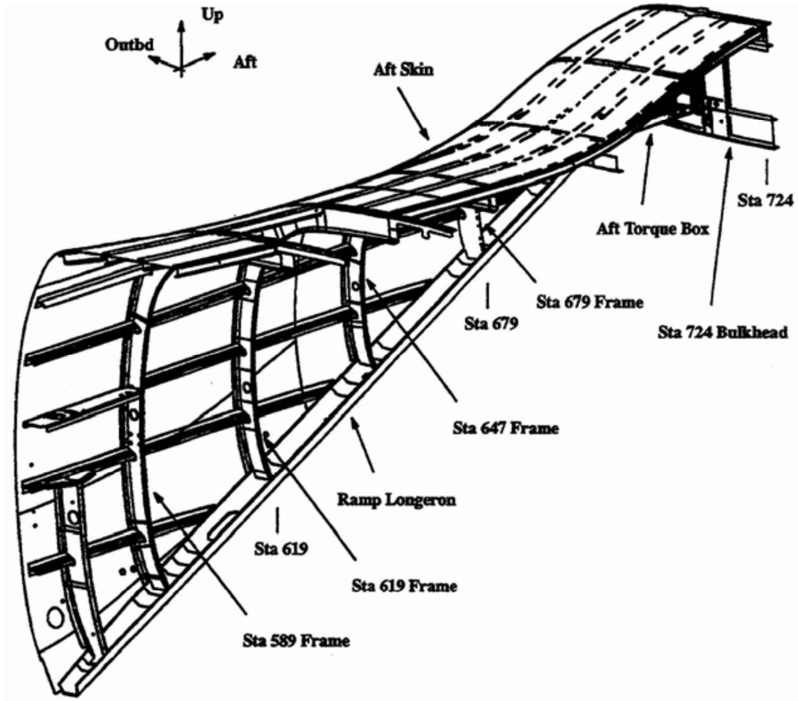
V-22 Osprey Tiltrotor aircraft

- **Composite fuselage stiffened skin***



- **Post-buckling behavior drives weight in thin-skin rotorcraft fuselage**
- **Buckling generates severe stresses on the bondline between skin and stiffeners**

*Pierre Minguet, Boeing

HISTORY OF SKIN/STIFFENER DEBONDING
POST-BUCKLED THIN-SKIN ROTORCRAFT FUSELAGE

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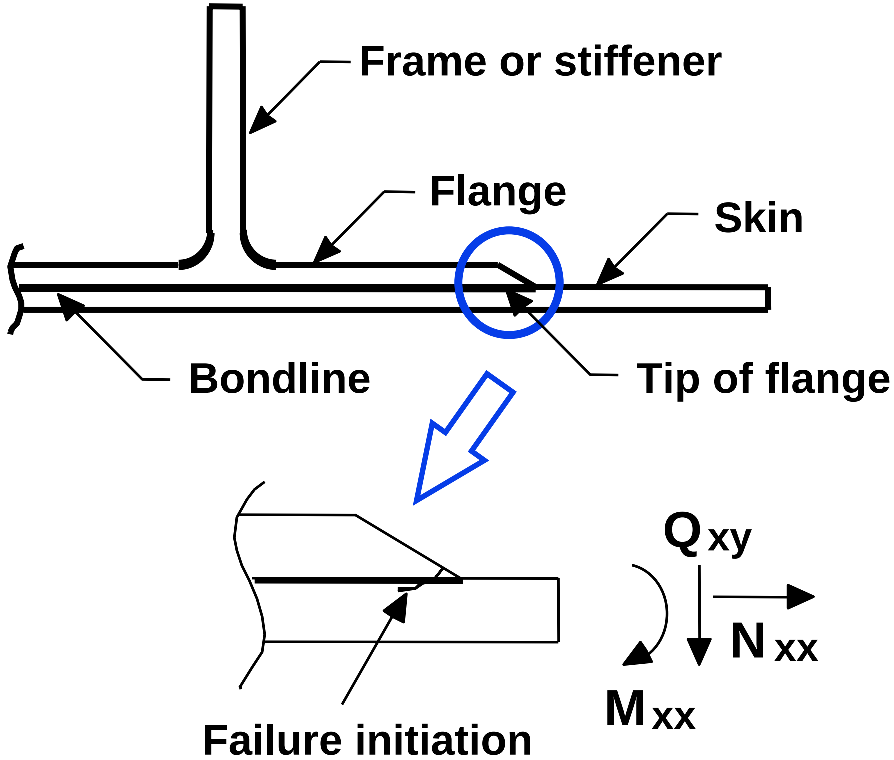
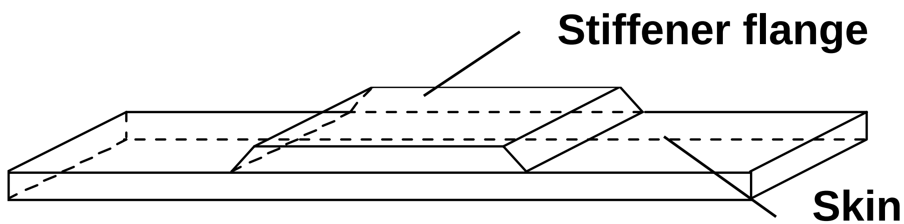
- **Testing of Stiffened Shear Panel**
  Boeing, Philadelphia*

*Pierre Minguet, Boeing

- **Debonding Mechanism**



- **Simplified Specimen**



CURRENTLY USED FAILURE METHODOLOGIES

- **Stress-Based Failure Criteria**
- **Damage Mechanics**
  - Decohesion element (interface elements) Carlos Davila, Pedro Camanho, to be implemented in ABAQUS 6.5 released in December 2004
- **Linear Elastic Fracture Mechanics**
  - **Captures discontinuity of interlaminar disbonds or delaminations**
  - **Stress singularities not an issue**
  - **Characteristic material data can be generated using simple specimens and tests**

FRACTURE MECHANICS METHODOLOGY

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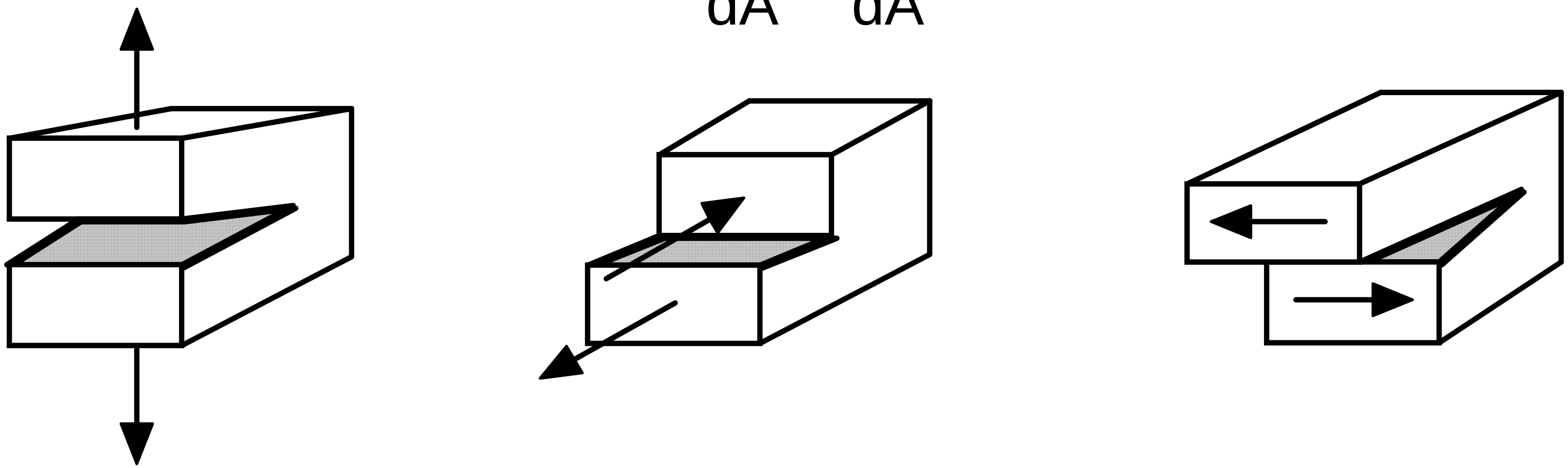
Energy Release Rate

$$G = \frac{dW}{dA} - \frac{dU}{dA}$$



crack opening
mode I

in plane shear
mode II

tearing
mode III

$$G = G_I + G_{II} + G_{III}$$

Failure occurs if local mixed mode energy release rate exceeds a critical value !

EXPERIMENTS TO DETERMINE FRACTURE TOUGHNESS

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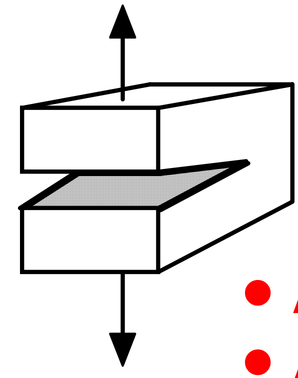
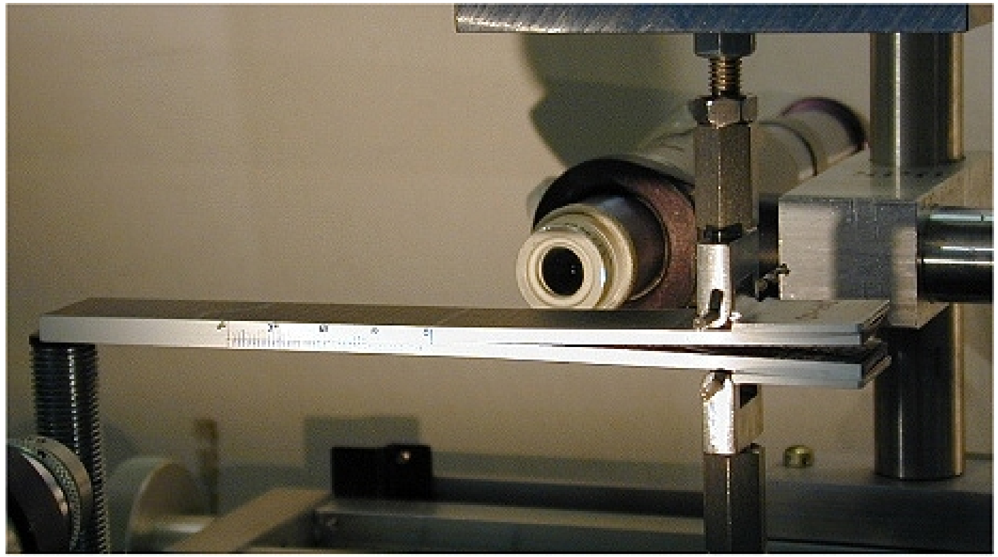
- **Mode I - DCB Specimen**

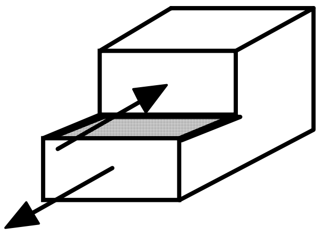


crack opening mode I

- **ASTM D5528 - static**
- **ASTM D6615 - fatigue**

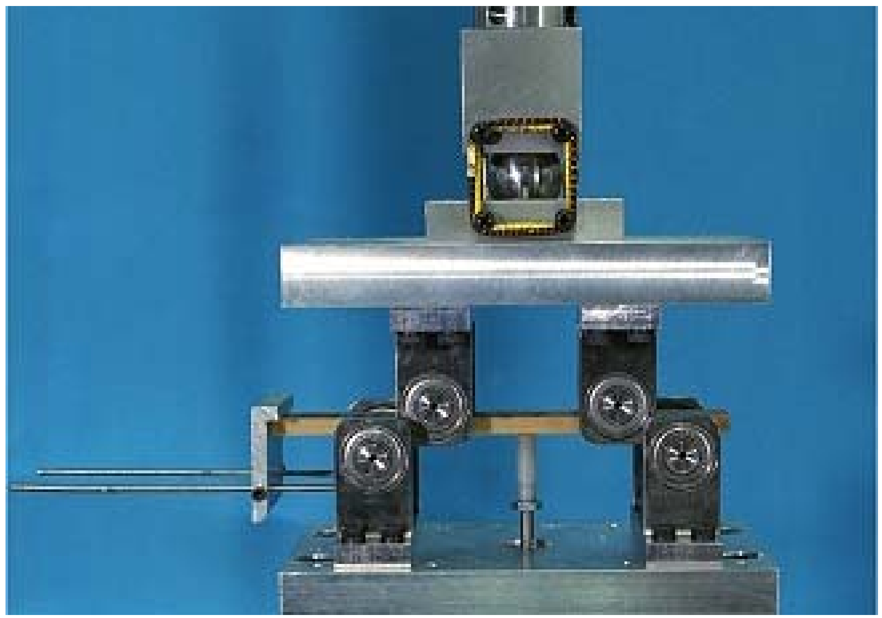


- **Mode II - 4ENF Specimen***



in plane shear mode II

- **Standard in development**



*Rod Martin, MERL - Barry Davidson, Syracuse University

EXPERIMENTS TO DETERMINE FRACTURE TOUGHNESS - continued

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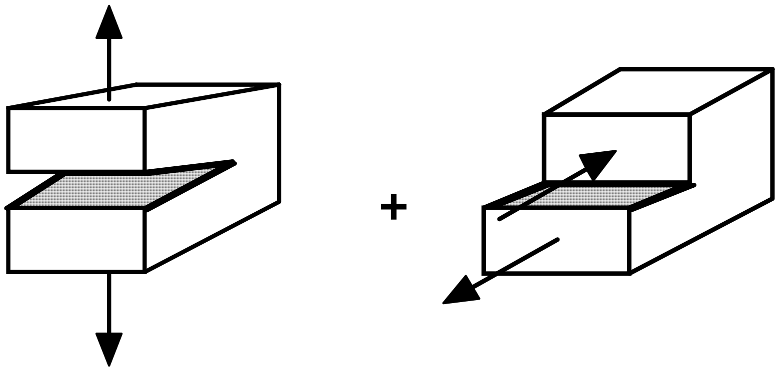
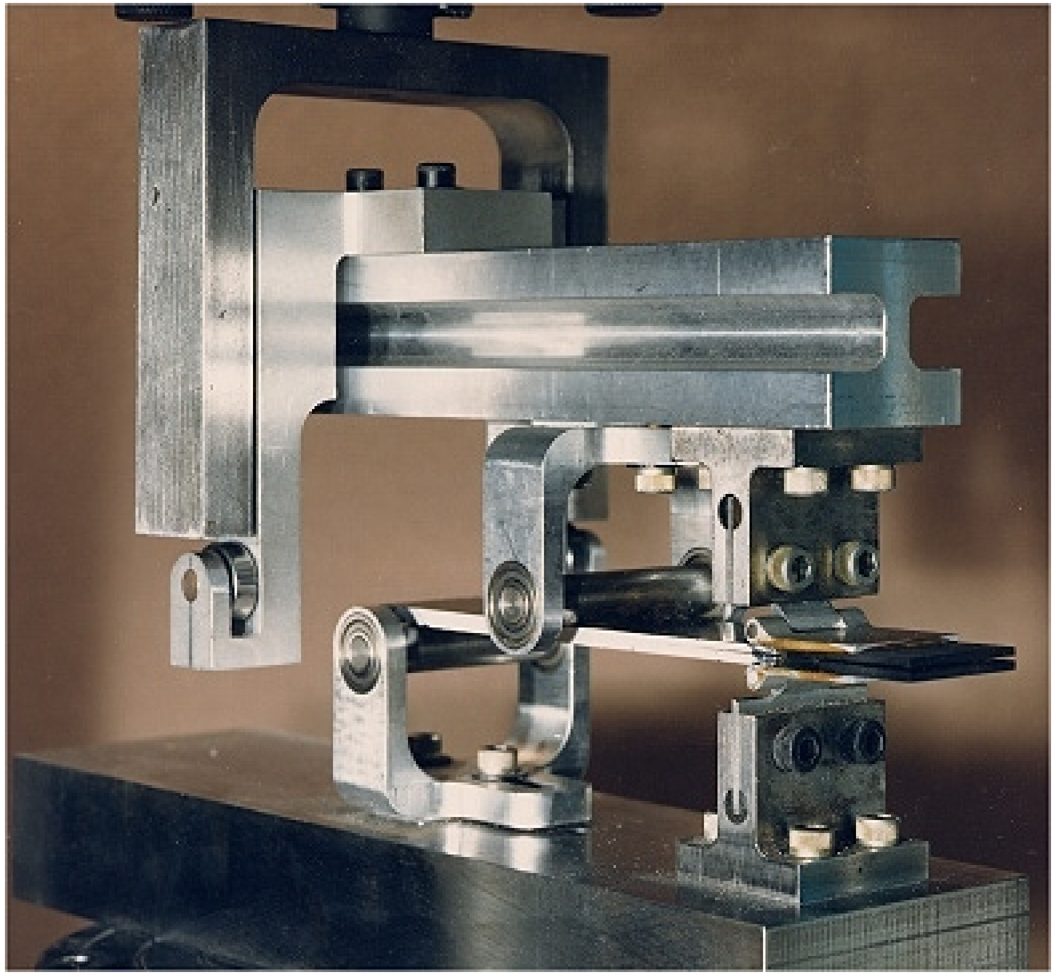
- **Mixed Mode I/II - MMB Specimen***



crack opening mode I + **in plane shear mode II**

- **ASTM D6671**



*James Reeder, NASA Langley Research Center

2D MIXED MODE FRACTURE CRITERION IS STATE OF THE ART

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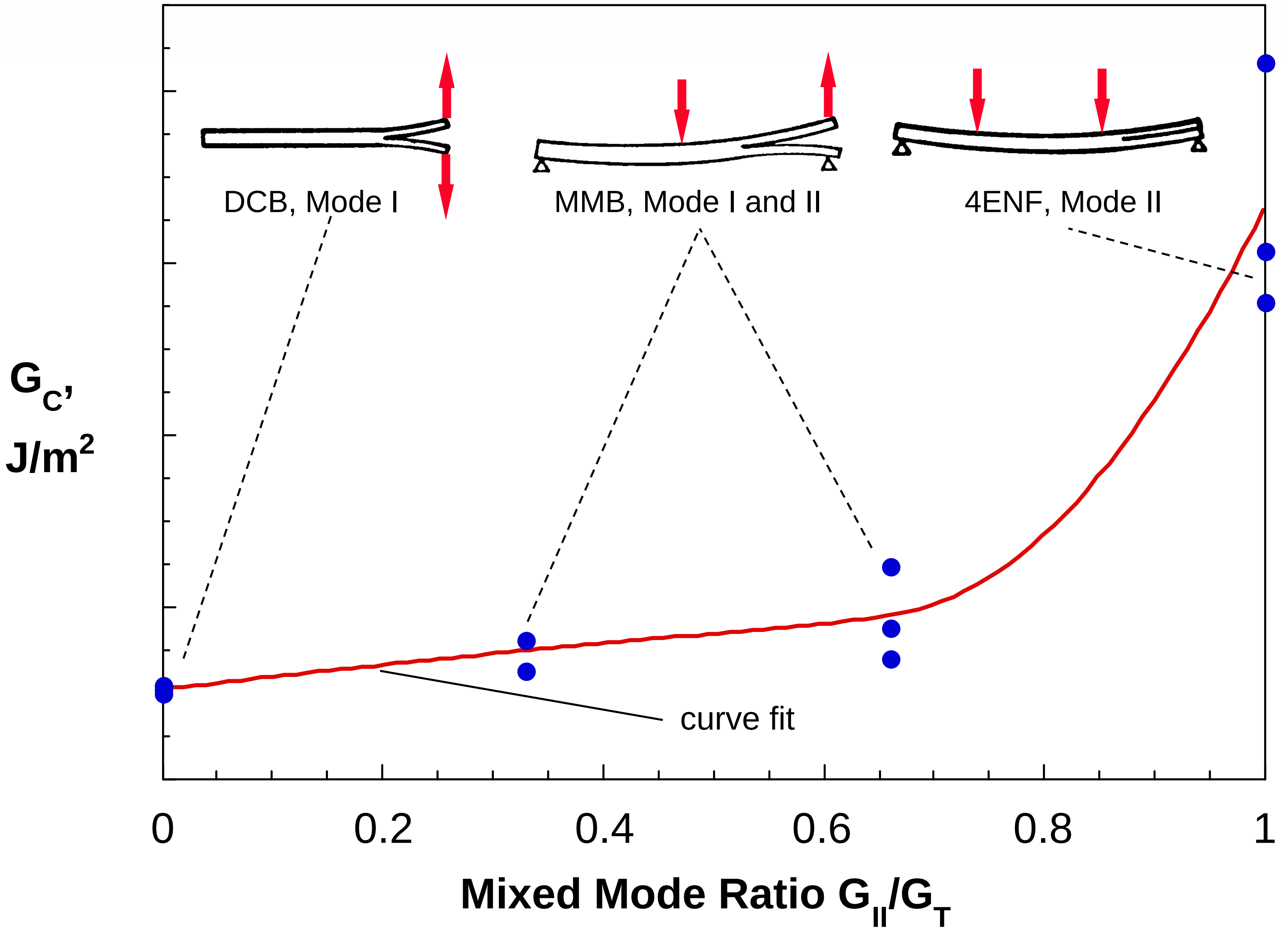

3D MIXED MODE FRACTURE CRITERION IS MISSING TODAY

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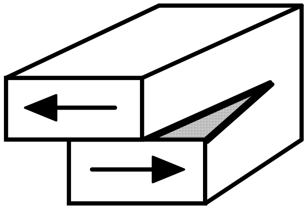
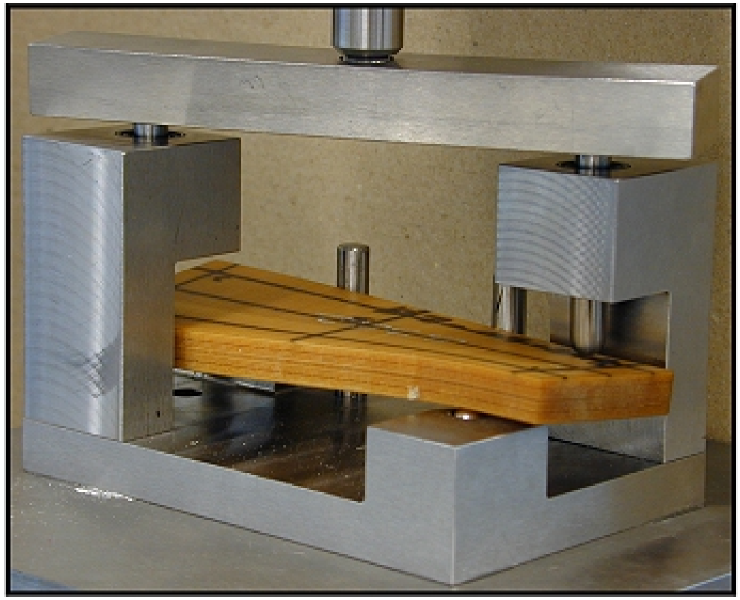
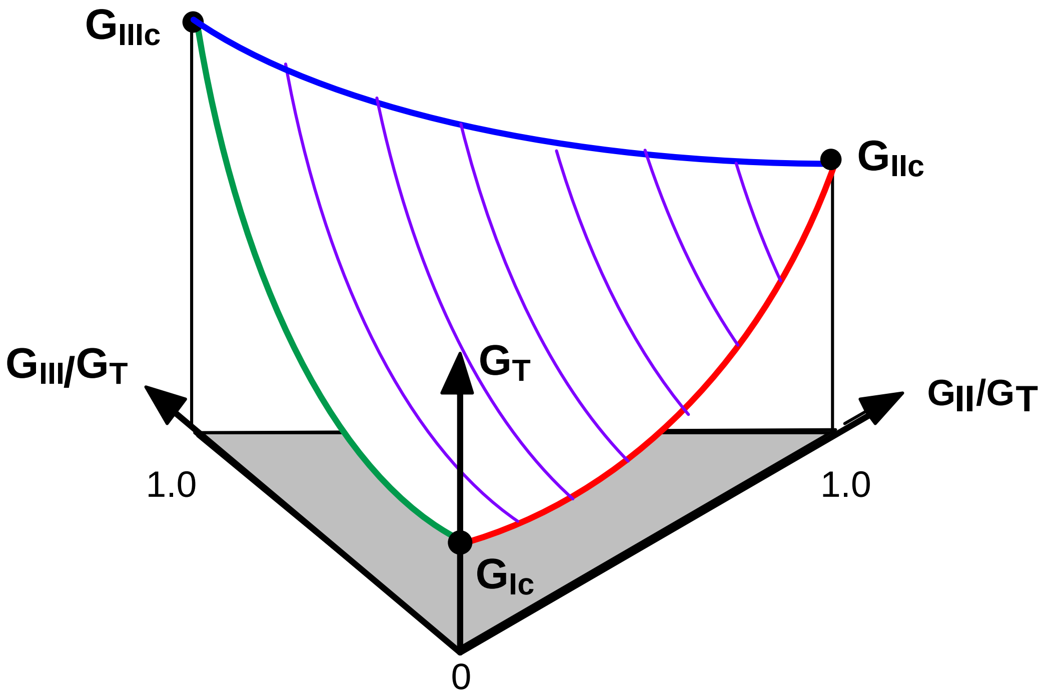
- **Mode III - ECT Specimen***





- **Failure surface $G_c = G_c(G_{Ic}, G_{IIc}, G_{IIIc})$****



- **Standard in development**

*James Ratcliffe,NRC at NASA Langley Research Center

**James Reeder, NASA Langley Research Center

STATUS OF FRACTURE TOUGHNESS TESTING
FATIGUE ONSET VALUES

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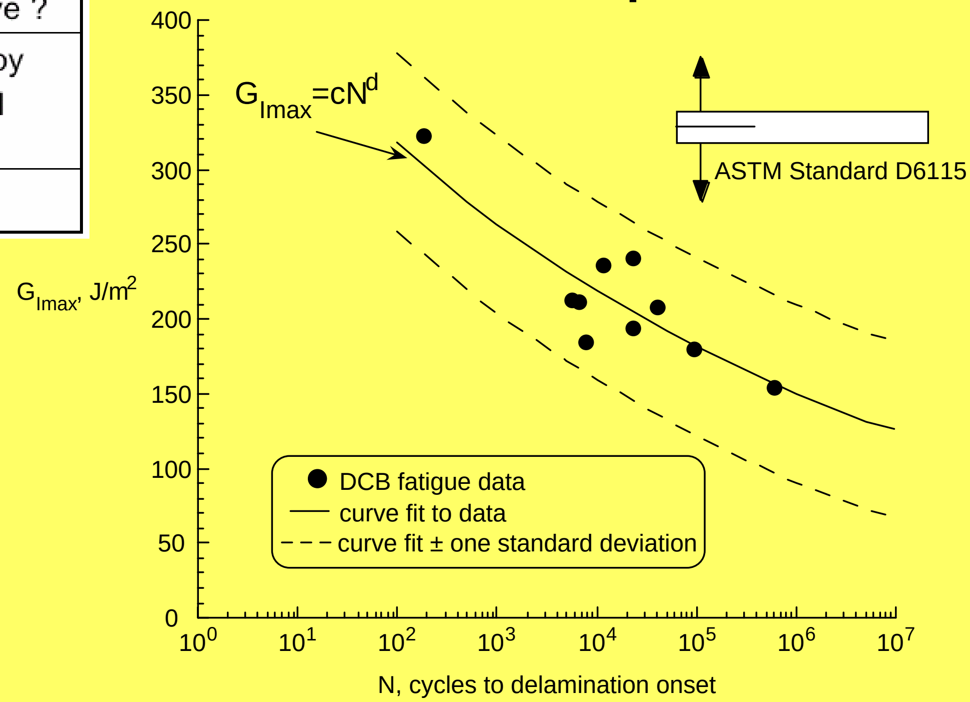
Mode	Specimen	Static	G_c vs. N	da/dN
I - opening	DCB	✔ D5528	✔ D6615	normalized by static R-curve
II - shear	4ENF	✍ stable	✘ small displacement	small dG/dA ?
	3ENF	✘ unstable (JIS 7086)	✘ small displacement	✘ small dG/dA ?
	ELS	✘ unstable (ESIS)		normalized by static R-curve ?
I + II	MMB	✔ D6671		normalized by static mode I R-curve
III - tearing	ECT	✍		

Isabelle Paris, Composites Innovations Inc. - Montreal

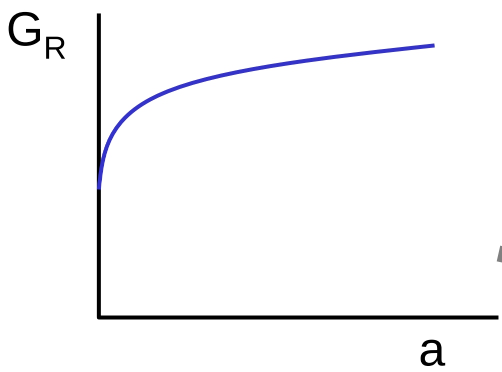
Fatigue Delamination Onset in S2/E7T1 DCB Specimens



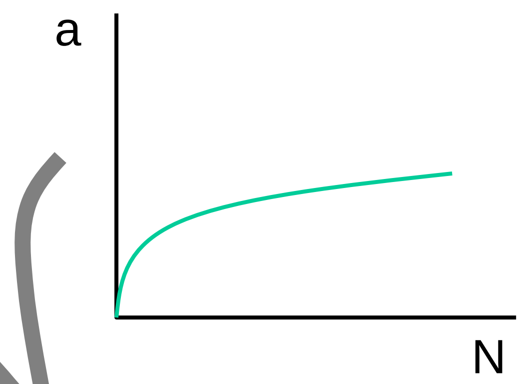
Kevin O'Brien, ARL/VTD at NASA LaRC

STATUS OF FRACTURE TOUGHNESS TESTING
FATIGUE PROPAGATION VALUES

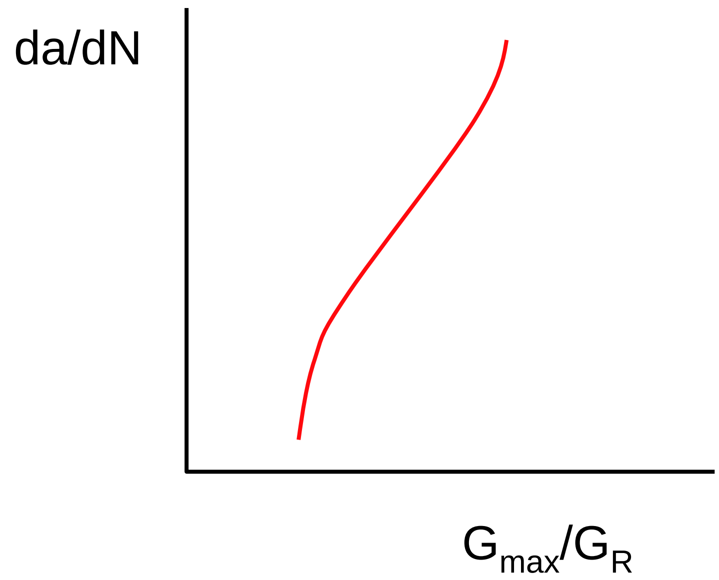
- **Proposed Fatigue Delamination Growth Characterization: Normalizing by the Static R-Curve***



Static delamination R-curve



$$\frac{da}{dN} = A\left(\frac{G_{max}(a)}{G_R(a)}\right)^n$$

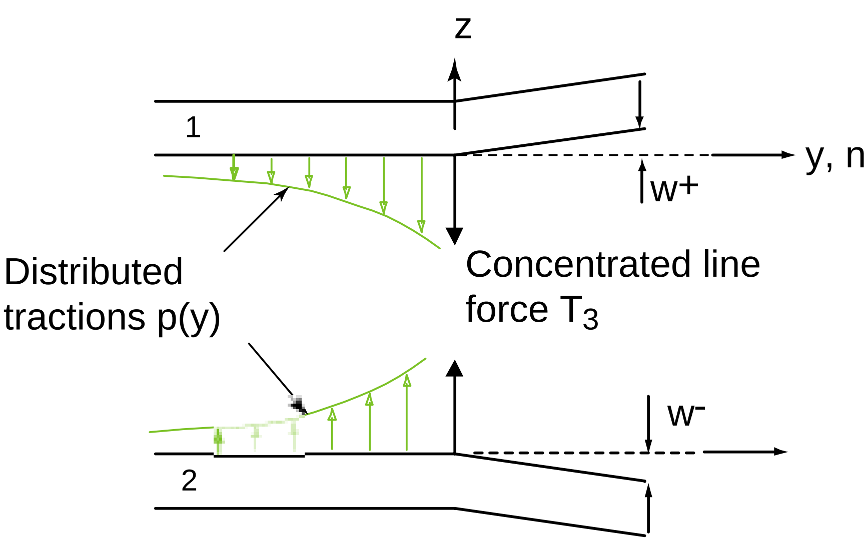


*Isabelle Paris, Kevin O’Brien, Rod Martin

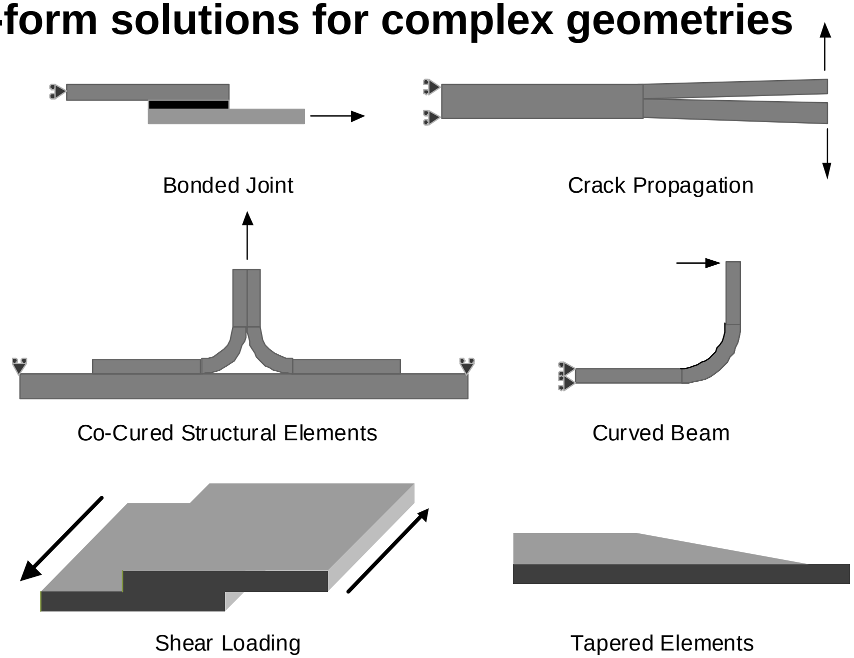
ANALYSIS TOOLS
OVERVIEW

- **Analytical Closed Form Solutions for Simple Configurations**
  - **Edge delamination - Kevin O'Brien**
  - **SUBLAM**
    - Georgia Tech, Erian Armanios
    - Developed by Material Science Corporation under SBIR contract with the FAA for use with General Aviation bonded joints - Gerald Flanagan
    - Can be used to calculate SERR as a function of disbond length

Single-Step SERR Calculation



Closed-form solutions for complex geometries



ANALYSIS TOOLS
OVERVIEW - continued

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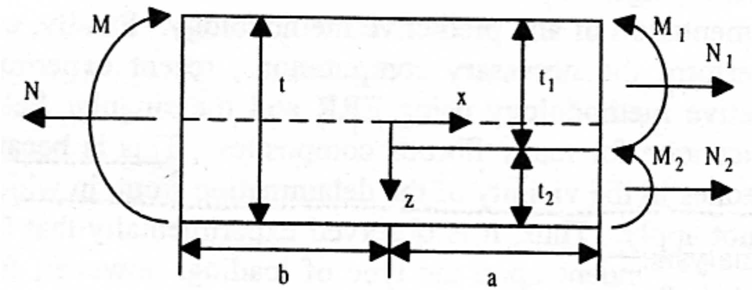
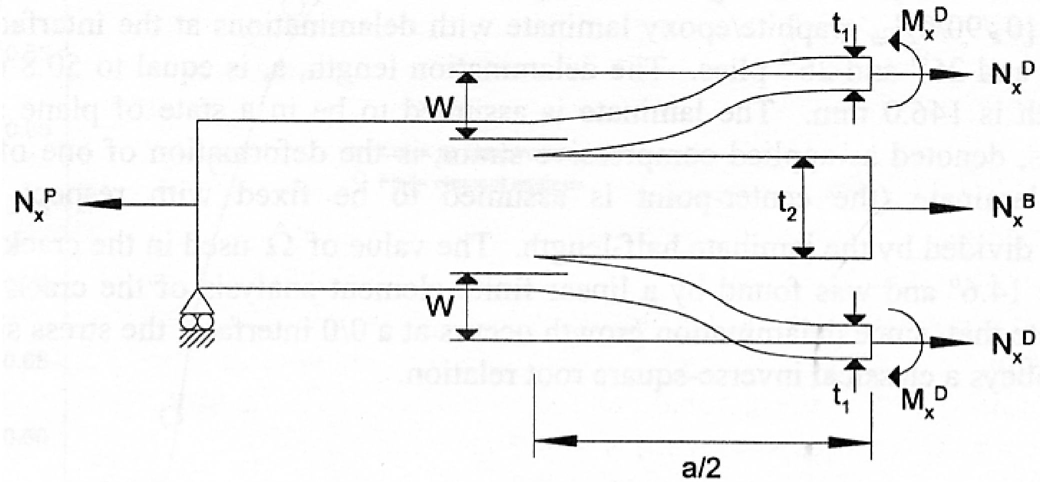
- **“Crack Tip Element” - Barry Davidson**
  - Closed-form linear-elastic solution aimed at overcoming computational difficulties in determining strain energy release rate and mode mix.
  - Obviates need for locally detailed 2D and 3D FEMs
  - Limited to linear analysis



Post-buckled delaminations

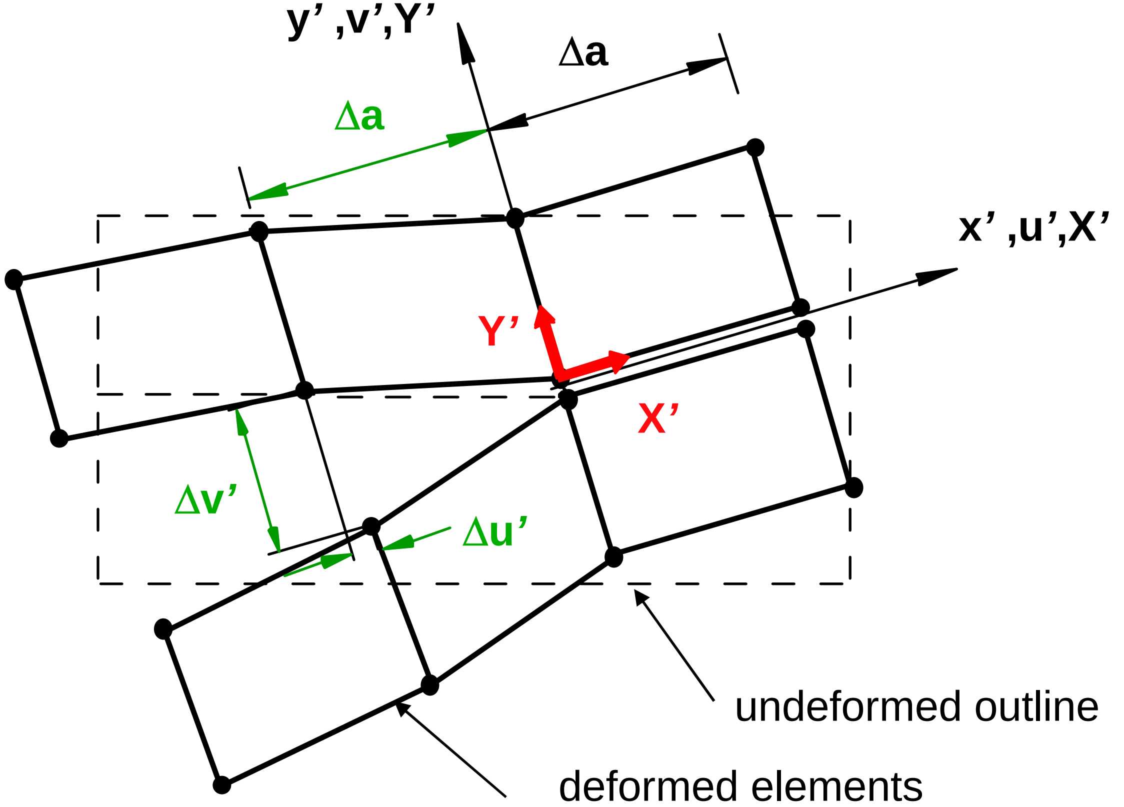


- **Virtual Crack Closure Technique (VCCT)**
  - Two and three-dimensional analysis
  - Nonlinear analysis
  - Arbitrarily shaped delamination front

$$G_I = \frac{1}{2\Delta a} \cdot Y' \cdot \Delta v'$$

$$G_{II} = \frac{1}{2\Delta a} \cdot X' \cdot \Delta u'$$

$$G_T = G_I + G_{II}$$



ANALYSIS TOOLS

Boeing 2D VCCT Interface Element - Formulation

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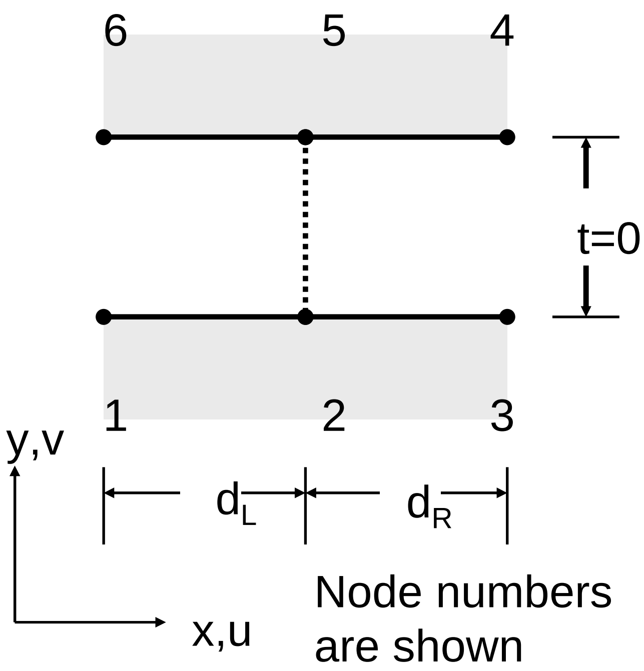
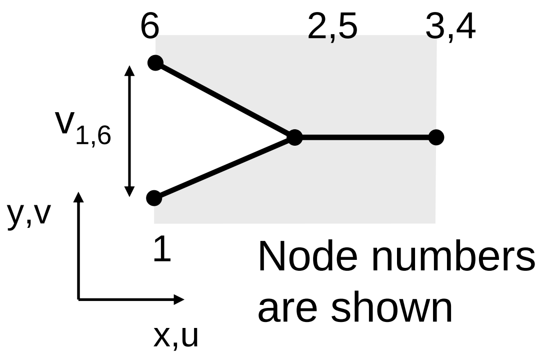
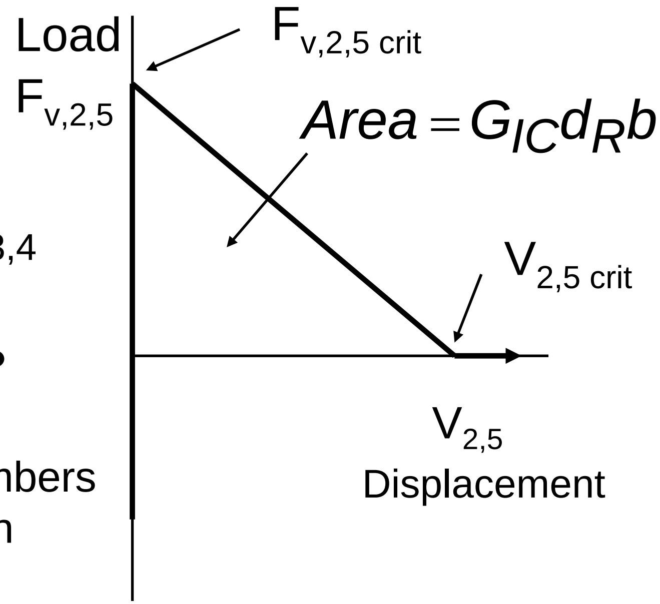
- **Interface Element for Mixed Mode Fracture Analysis***



Pure Mode I

Modified VCCT





- Node pair 2,5 are initially bound together
- Node pairs 1,6 and 3,4 are unconstrained and act to sense approaching crack

Nodes 2 and 5 will start to release when:

$$\frac{1}{2}\frac{v_{1,6}F_{v,2,5}}{bd_L} = G_I \geq G_{IC}$$

Mode II treated similarly

$G_I =$ mode I energy release rate

$G_{IC} =$ Critical mode I energy release rate

* G. Mabson, Boeing, Patent Pending

ANALYSIS TOOLS

Boeing 2D VCCT Interface Element - Propagation

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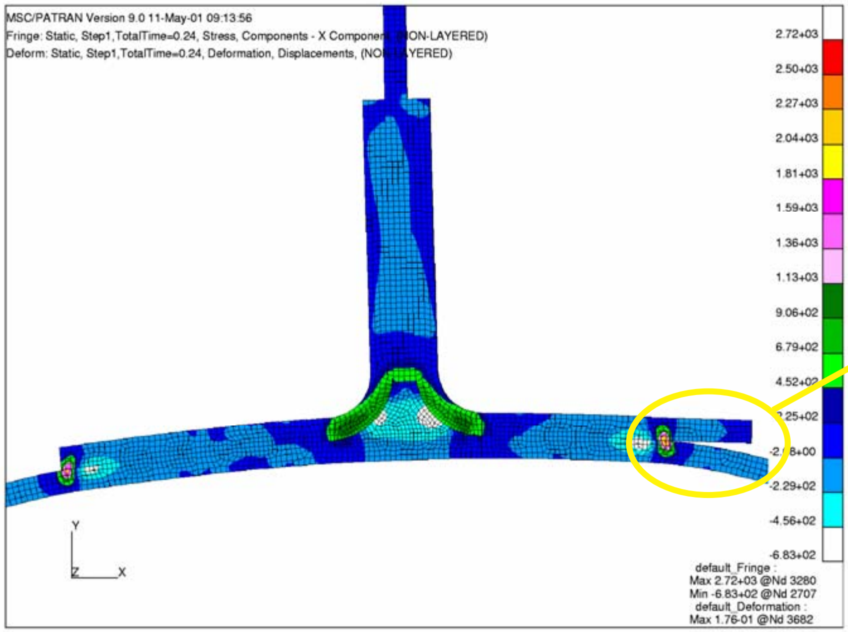
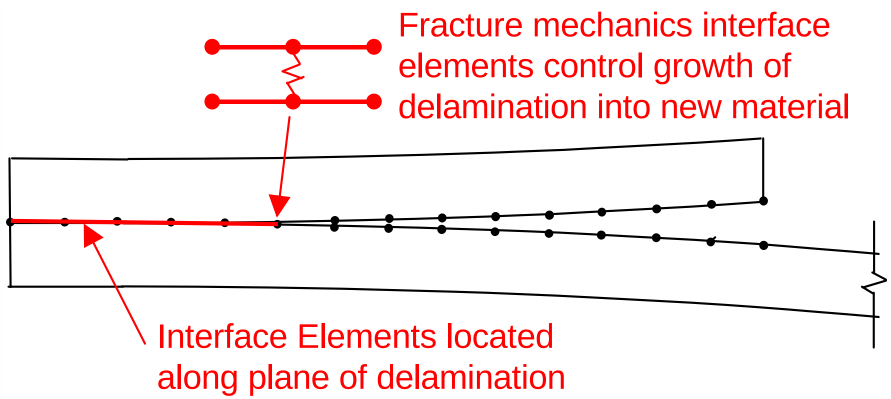
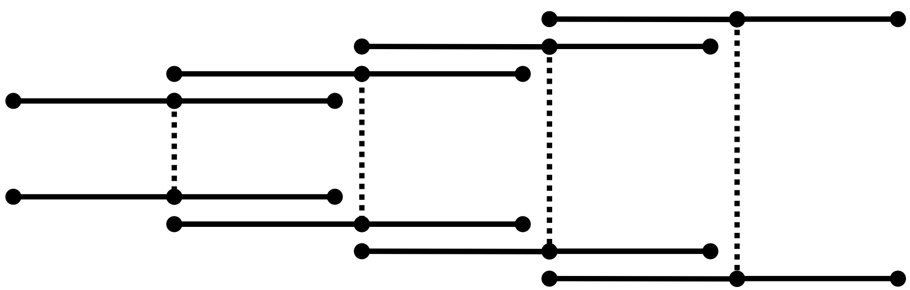
- **Fracture Interface Elements Along Crack Plane***







- **By using a series of overlapping interface elements, delaminations can be propagated along a predefined path.**
- **Direction of propagation is not pre-specified.**
- **Propagation is integral part of the analysis.**
- **3D VCCT interface element for delamination available.**
- **ABAQUS implementation expected for December 2004.**

* G. Mabson, Boeing, Patent Pending