A SELECTION OF COMPOSITES SIMULATION PRACTICES AT NASA LANGLEY RESEARCH CENTER

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MSC Software
Composites Consortium Meeting

May 3 – May 4, 2007
Santa Ana, CA

NATIONAL
INSTITUTE OF
AEROSPACE

OUTLINE

- **National Institute of Aerospace (NIA) overview**
- **NASA Langley (LaRC) overview**
- **Examples of composites simulation:**
  - Thermo-mechanical material model
  - Damage analyses of composites
    - Progressive damage material model
    - Virtual crack closure technique (VCCT)
    - Decohesion element
  - Flight 587 structures investigation
  - Rotorhub flexbeam analysis
  - Mixed-mode delamination failure criterion
  - Delamination in z-pin reinforced laminates
- **Concluding remarks**

NATIONAL INSTITUTE OF AEROSPACE

- An Independent Non-profit Research and Graduate Education Institute formed in 2002 by a Consortium of Six Universities and the AIAA Foundation
- Conceived by NASA Langley Research Center and established to serve as LaRC's Collaborative Partner
- Conducts Collaborative ***Research*** in Engineering and Science relevant to Aerospace
  - Georgia Tech
  - Virginia Tech
  - University of Virginia
  - University of Maryland
  - North Carolina A&T State University
  - Old Dominion University
  - College of William & Mary
  - Hampton University

COMPOSITE RESEARCH ACTIVITIES AT NASA LANGLEY

- Computational materials
- Crash worthiness of composite structures
- Structural tailoring with composites
- Manufacturing and fabrication technology
- Health monitoring using embedded sensors
- Residual strength and damage propagation
- Influence of generalized imperfections on composite shell response
- Delamination and crack growth
- Thermo-mechanical material response
- Multidisciplinary design environments
- Uncertainty quantification for composite designs
- Impact response and strain rate sensitivity

SIMULATION ISSUES FOR COMPOSITES

- Variabilities in composite design (fiber placement, fiber angle, thickness, volume fraction, failure modes, etc)
- Visualization of composite simulation results
- Micro-mechanics through macro-mechanics - Problem of scale (global local analysis requirements)
- Computational models for new and evolving materials
- Computational models for incorporating mechanical-based failure models
- Failure initiation and damage propagation of different composite architectures (sandwich construction, integrally-stiffened sections, etc)
- Corroborating experimental program for validation of analysis

At NASA Langley, these issues are addressed by researchers using:

1. User-defined material models
2. User-defined element routines
3. User-developed pre and post-processing software

Research Technology Directorate (RTD) consists of 21 branches:

Configuration Aerodynamics Branch	Advanced materials and Processing Branch	Aeroacoustics Branch	Safety-Critical Avionics Systems Branch
Computational Aerosciences Branch	Aeroelasticity Branch	Applied Technologies and Testing Branch	Structural Acoustics Branch
Flow Physics and Controls Branch	Durability, Damage Tolerance and Reliability Branch	Dynamic Systems and Controls Branch	Structural Dynamics Branch
Advanced Sensing and Optical Measurement Branch	Gas, Fluid and Acoustics Research Support Branch	Flight Dynamics Branch	
Aerothermodynamics Branch	Structural Mechanics and Concepts Branch	Crew Systems and Aviation Operations Branch	
Hypersonic Airbreathing Propulsion Branch	Nondestructive Evaluation Sciences Branch	Electromagnetics and Sensors Branch	

THERMO-MECHANICAL MATERIAL MODEL

TRAVIS TURNER

STRUCTURAL ACOUSTICS BRANCH
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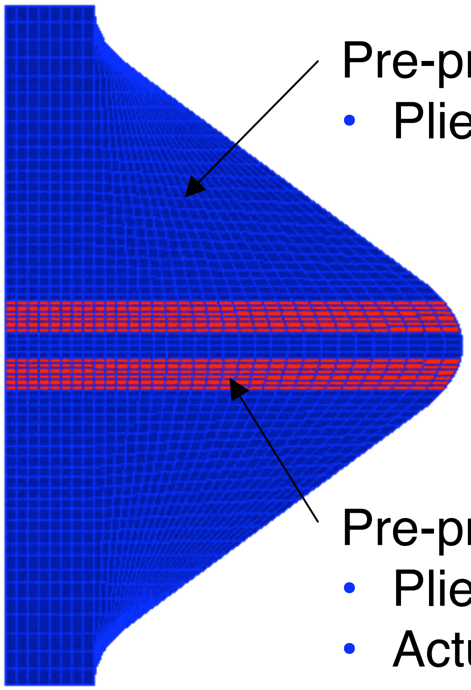
NUMERICAL MODEL

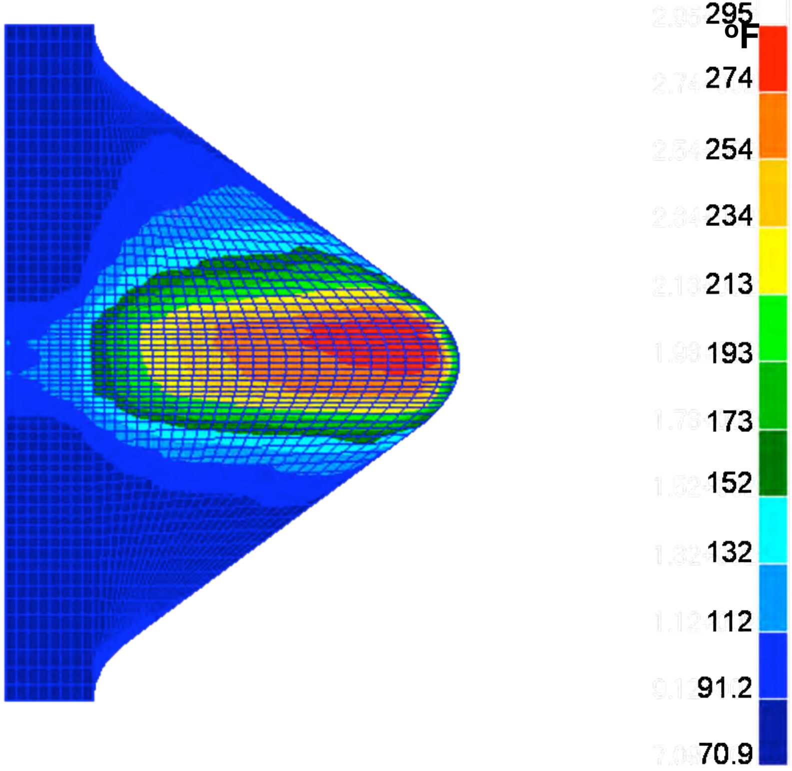
Shell Element Mesh



Pre-preg only
- Plies 0.0036” thick

Pre-preg & actuators
- Plies 0.0032” thick
- Actuators 0.006” thick

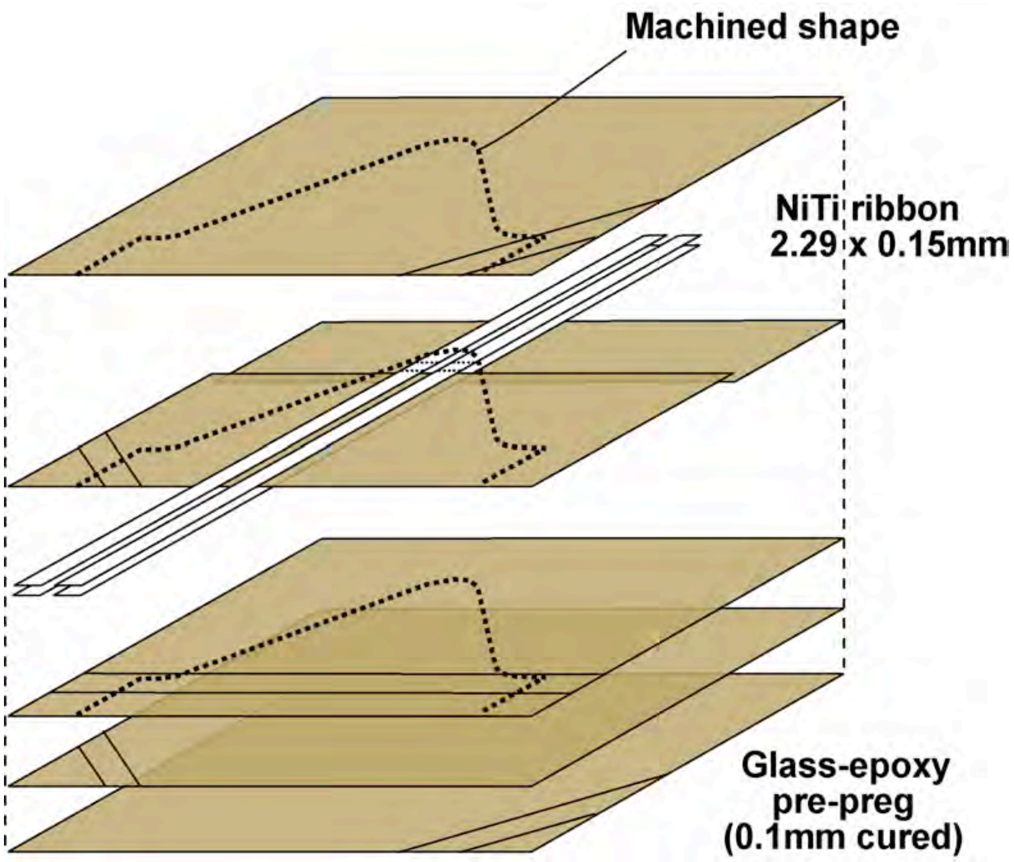
Meas. Thermal Load Applied



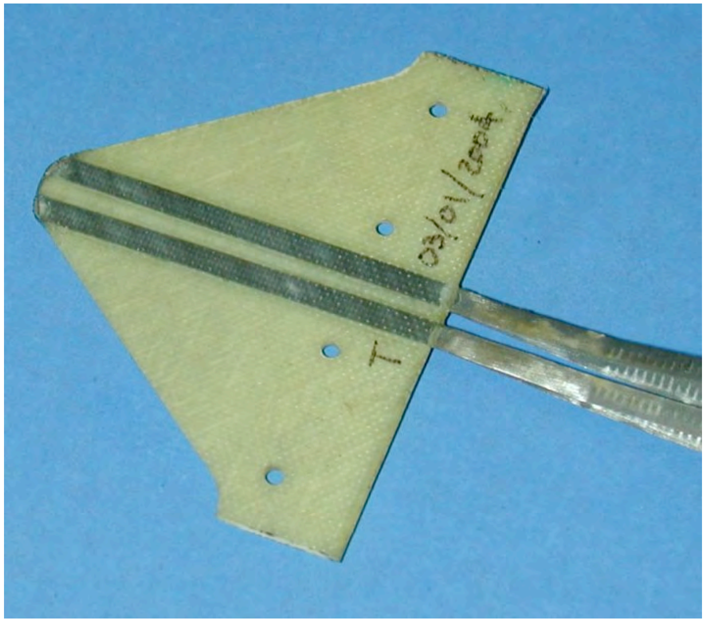
- Developed thermo-mechanical FE model based upon LaRC-developed constitutive model implemented in MSC.Nastran and ABAQUS
- Shell element mesh separates glass-epoxy-only and SMAHC element types
- Nonlinear static solution performed with imposed temperature load specified by experimental measurements at critical temperatures

STRUCTURAL DEFLECTION CONTROL

Actuators embedded within layers of a laminated composite structure



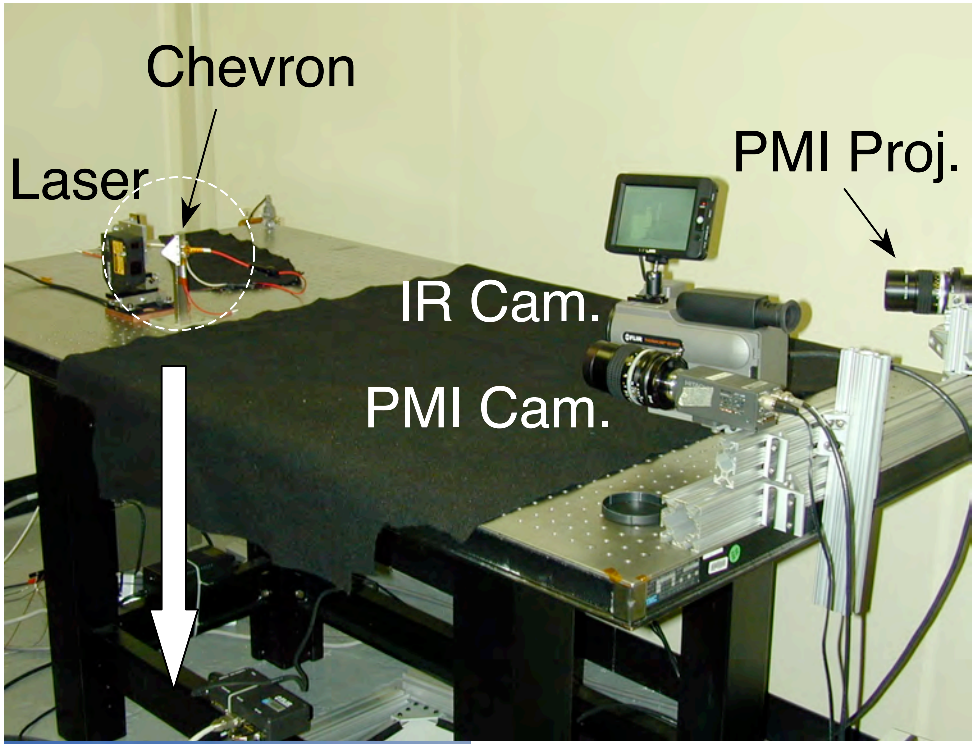
Completed Flow Effector

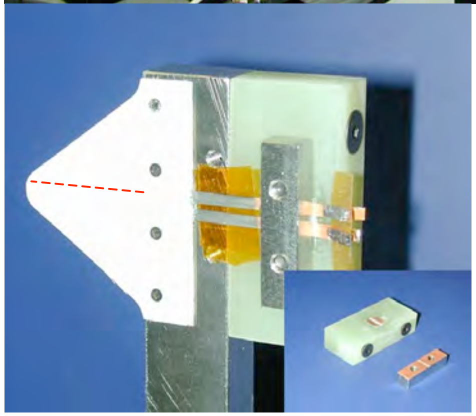


- Discrete actuator “inclusion”
- Non-uniform consolidated pre-preg ply thickness
- Non-uniform temperature distribution in service

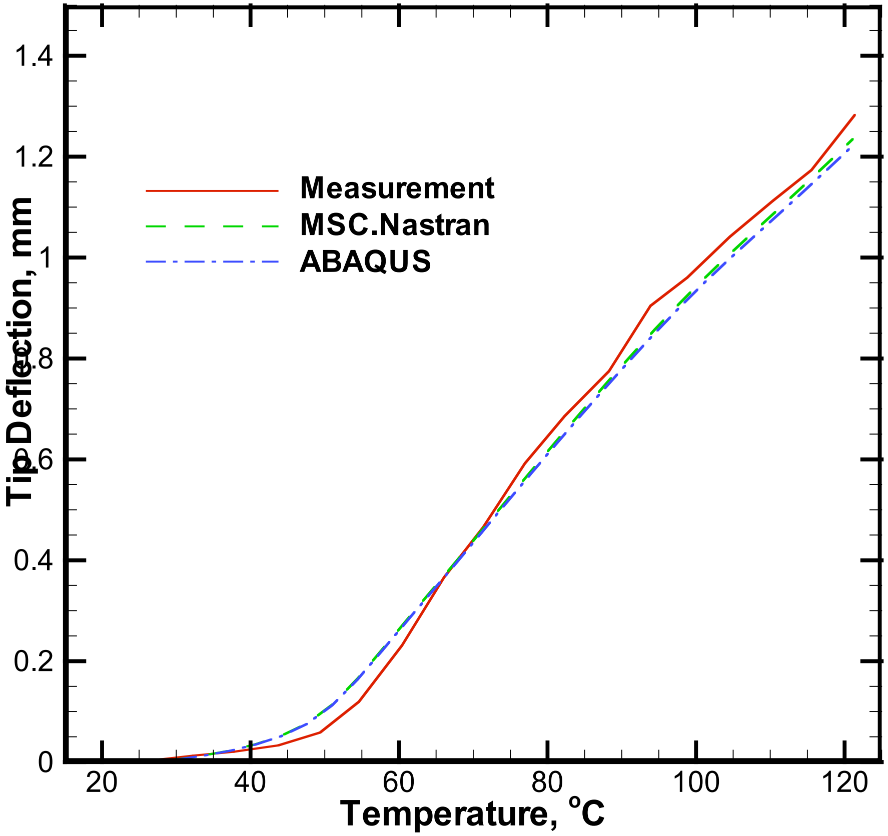
Flow Effector Deflection Control

Bench Top Test System



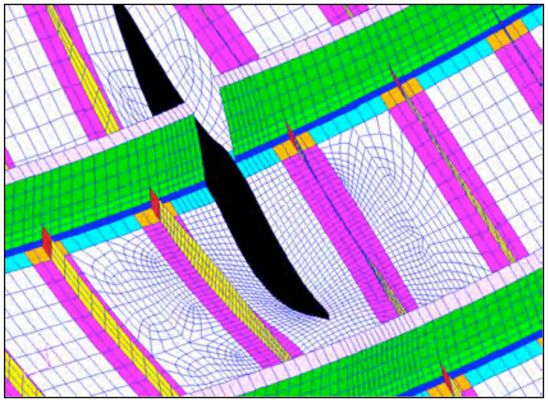


Tip Deflection Comparison



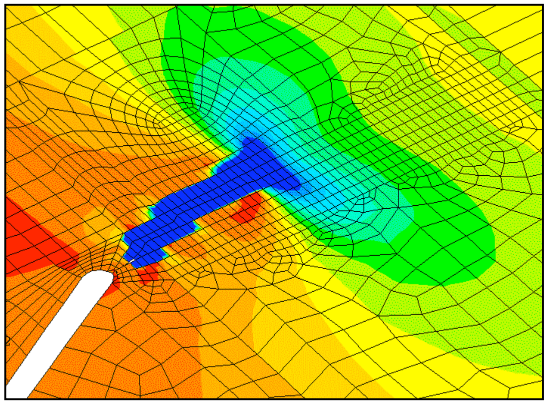
- Excellent numerical-experimental agreement
- Numerical design tool validated

DAMAGE ANALYSES OF COMPOSITES



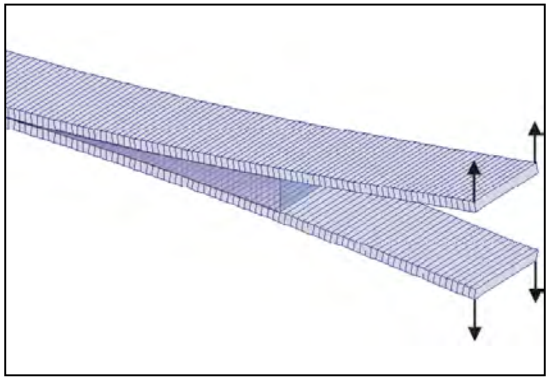
Through-the-thickness crack

- fracture mechanics and modifications
- strain softening



Ply Damage

- continuum damage modeling (CDM)
- strength-based methods (criteria)
- micromechanics approach



Delamination/Debonding

- fracture mechanics approaches (VCCT)
- decohesion elements

Slide provided by C. Davila

PROGRESSIVE FAILURE MATERIAL MODEL

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GENERAL DYNAMICS
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Resident at Durability, Damage Tolerance and Reliability Branch, NASA Langley Research Center

PFA/PDA SIMULATIONS

- Develop user-defined material subroutine UMAT for PFA and user-defined element subroutine UEL for PDA using ABAQUS/Standard
- UMAT features linear elastic, bimodulus, orthotropic material model for a composite laminate
- Failure initiation based on material allowable values using:
  - Maximum stress criteria
  - Maximum strain criteria
  - Hashin criteria
  - Tsai-Wu polynomial failure criterion
- Material degradation based on degrading elastic material stiffness coefficients for a particular failure direction resulting in near zero stress for that component - rather than degrading engineering properties
- Material degradation can be instantaneous or recursive over several solution steps
- Delamination and crack growth modeling using Boeing fracture interface element (VCCT approach) using user-defined element subroutine UEL

TYPICAL FAILURE INITIATION CRITERIA

- **Maximum stress criteria**

$$\frac{\sigma_{11}}{X_T} \le 1 \text{ for } \sigma_{11} \ge 0; \quad \frac{|\sigma_{11}|}{X_C} \le 1 \text{ for } \sigma_{11} \le 0$$

$$\frac{\sigma_{22}}{Y_T} \le 1 \text{ for } \sigma_{22} \ge 0; \quad \frac{|\sigma_{22}|}{Y_C} \le 1 \text{ for } \sigma_{22} \le 0$$

$$\frac{\sigma_{33}}{Z_T} \le 1 \text{ for } \sigma_{33} \ge 0; \quad \frac{|\sigma_{33}|}{Z_C} \le 1 \text{ for } \sigma_{33} \le 0$$

$$\frac{|\tau_{12}|}{S_{XY}} \le 1; \quad \frac{|\tau_{23}|}{S_{YZ}} \le 1; \quad \frac{|\tau_{13}|}{S_{XZ}} \le 1$$

- **Tsai-Wu polynomial failure criterion**

$$\begin{aligned}\phi = {} & F_1\sigma_{11} + F_2\sigma_{22} + F_3\sigma_{33} + F_{11}(\sigma_{11})^2 + F_{22}(\sigma_{22})^2 + F_{33}(\sigma_{33})^2 \\ & + 2F_{12}\sigma_{11}\sigma_{22} + 2F_{23}\sigma_{22}\sigma_{33} + 2F_{13}\sigma_{11}\sigma_{33} \\ & + F_{44}(\sigma_{13})^2 + F_{55}(\sigma_{23})^2 + F_{66}(\sigma_{12})^2 \ge 1\end{aligned}$$

TYPICAL MATERIAL DEGRADATION

- 3D stress-strain relations

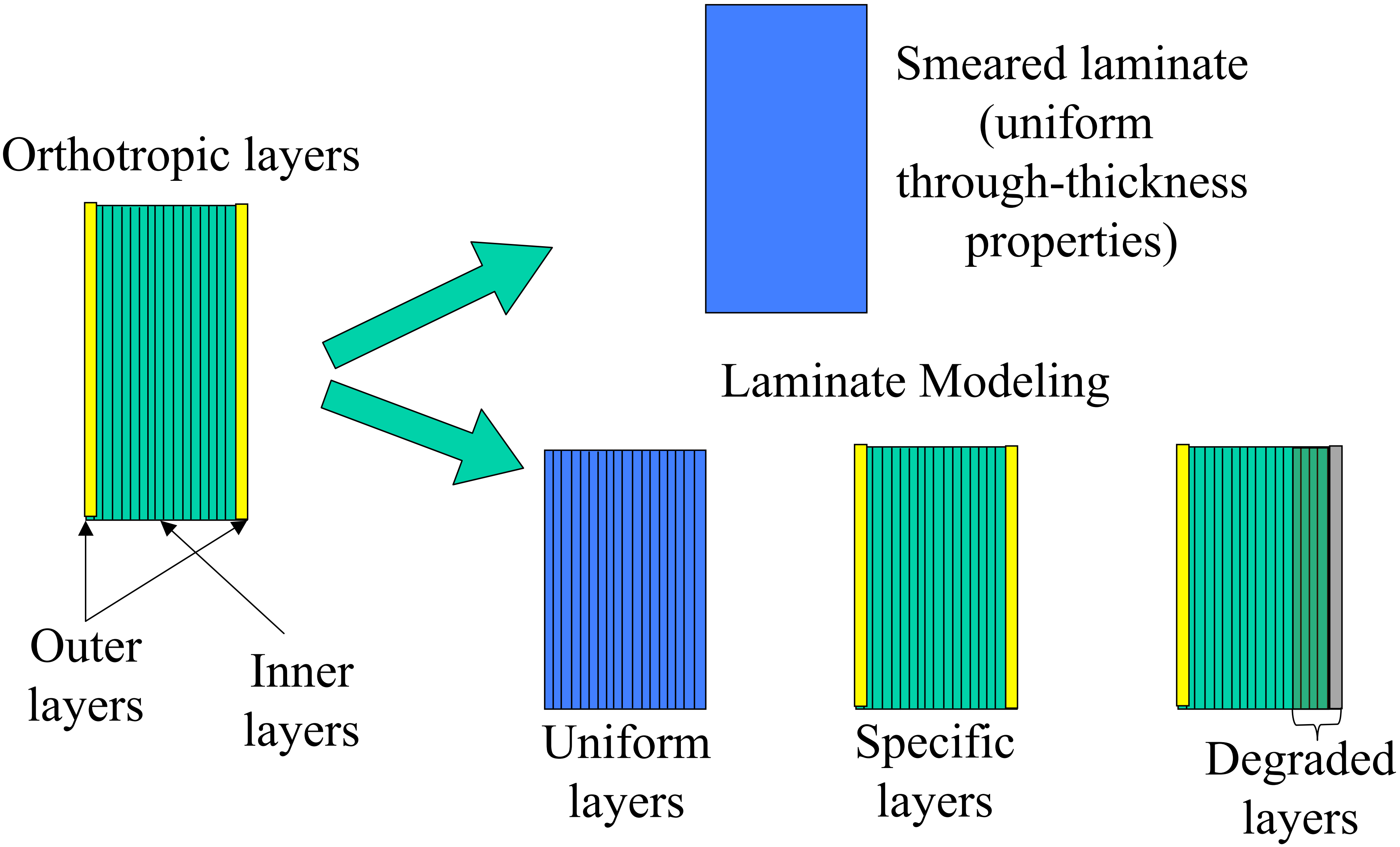
$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{13} \\ \sigma_{23} \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \gamma_{12} \\ \gamma_{13} \\ \gamma_{23} \end{Bmatrix}$$

- Material degradation of the i^{th} row and column of the constitutive matrix [C] when the i^{th} stress component indicates failure
- Off-diagonal terms set to zero; diagonal term degraded by factor b_i

$$C_{ij}^{\text{degraded}} = C_{ji}^{\text{degraded}} = 0 \text{ for i} \neq \text{j}$$

$$C_{ii}^{\text{degraded}} = \beta_i C_{ii}$$

MATERIAL MODELING OPTIONS



Orthotropic layers

Outer layers

Inner layers

Smeared laminate (uniform through-thickness properties)

Laminate Modeling

Uniform layers

Specific layers

Degraded layers

THE VIRTUAL CRACK CLOSURE TECHNIQUE

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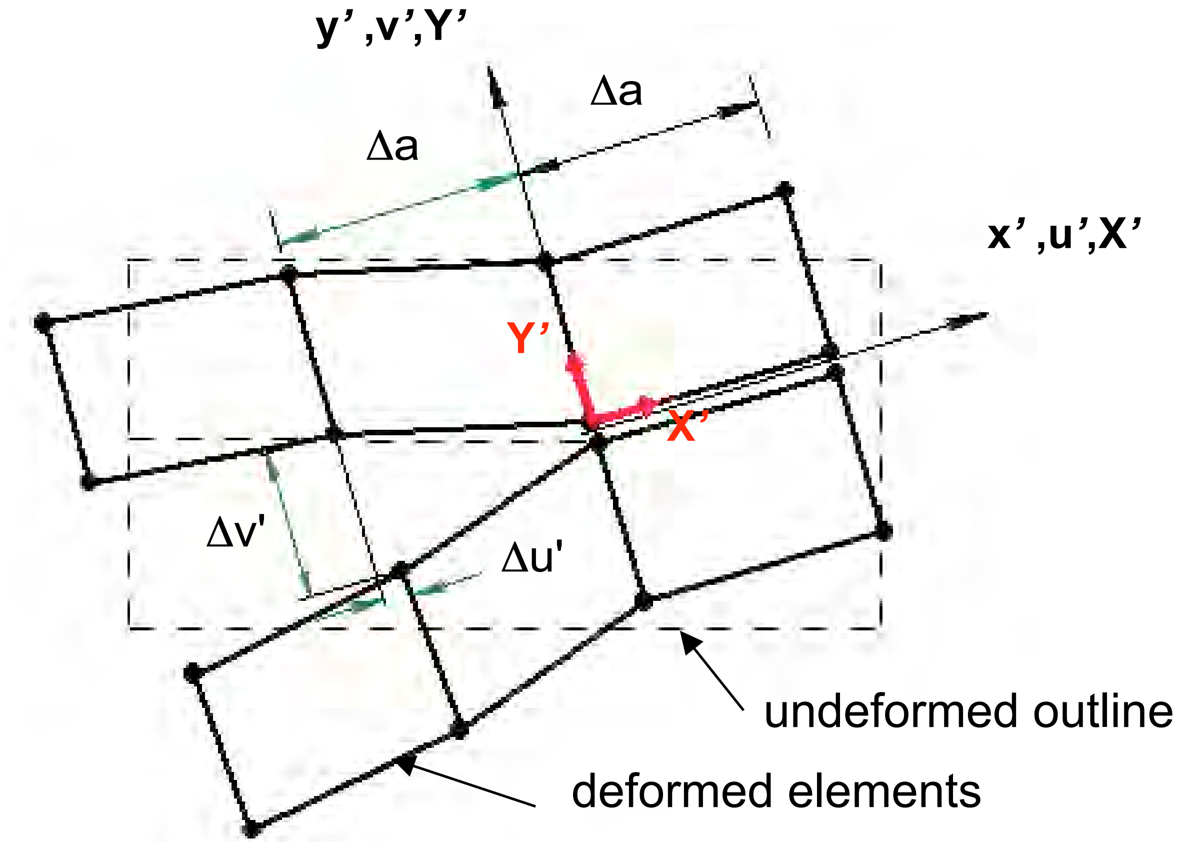
VIRTUAL CRACK CLOSURE TECHNIQUE (VCCT)*

- Two and three-dimensional analysis
- Nonlinear analysis
- Arbitrarily shaped delamination front
- 2D Finite Element Analysis

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

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

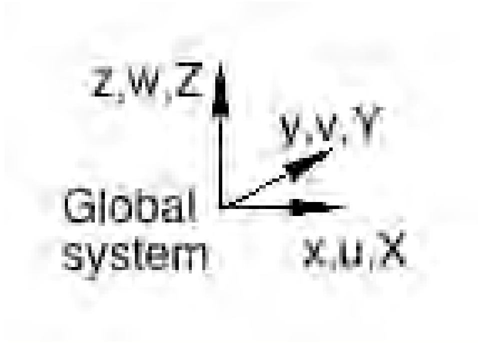
$$G_T = G_I + G_{II}$$

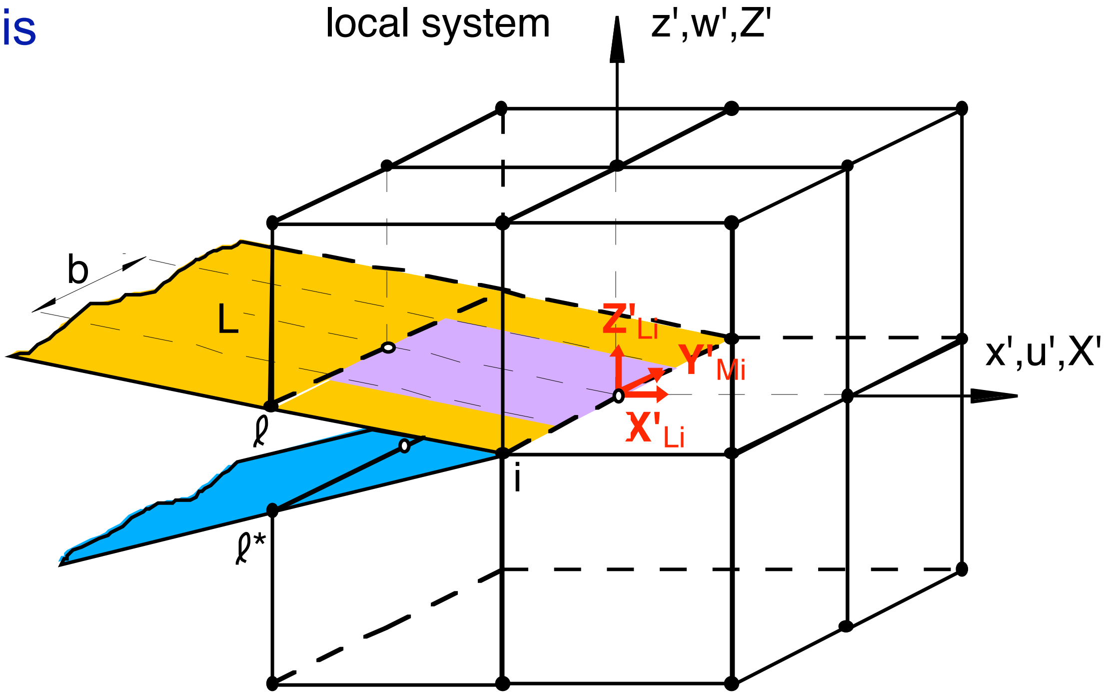


*Rybicki and Kanninen, Engineering Fracture Mechanics, 1977

VIRTUAL CRACK CLOSURE TECHNIQUE - CONTINUED

- 3D Finite Element Analysis





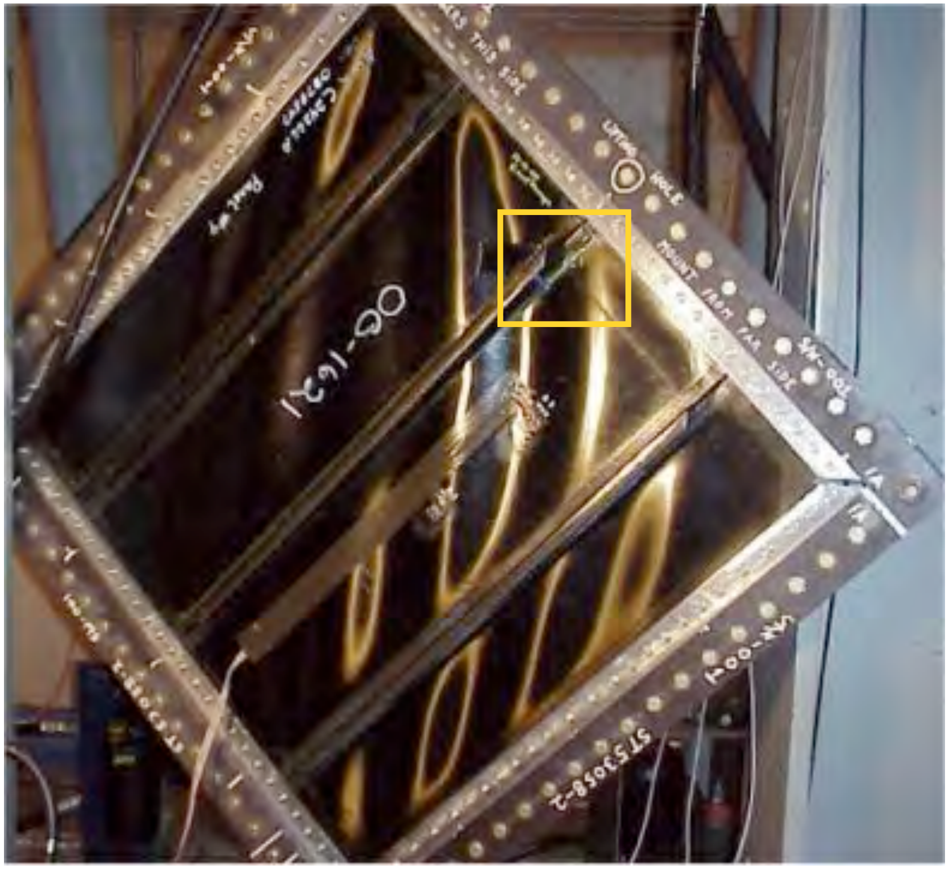
$$G_I = \frac{1}{2\Delta ab} \cdot Z'_{Li} \cdot \left(w'_{L\ell} - w'_{L\ell^*} \right)$$

$$G_{II} = \frac{1}{2\Delta ab} \cdot X'_{Li} \cdot \left(u'_{L\ell} - u'_{L\ell^*} \right)$$

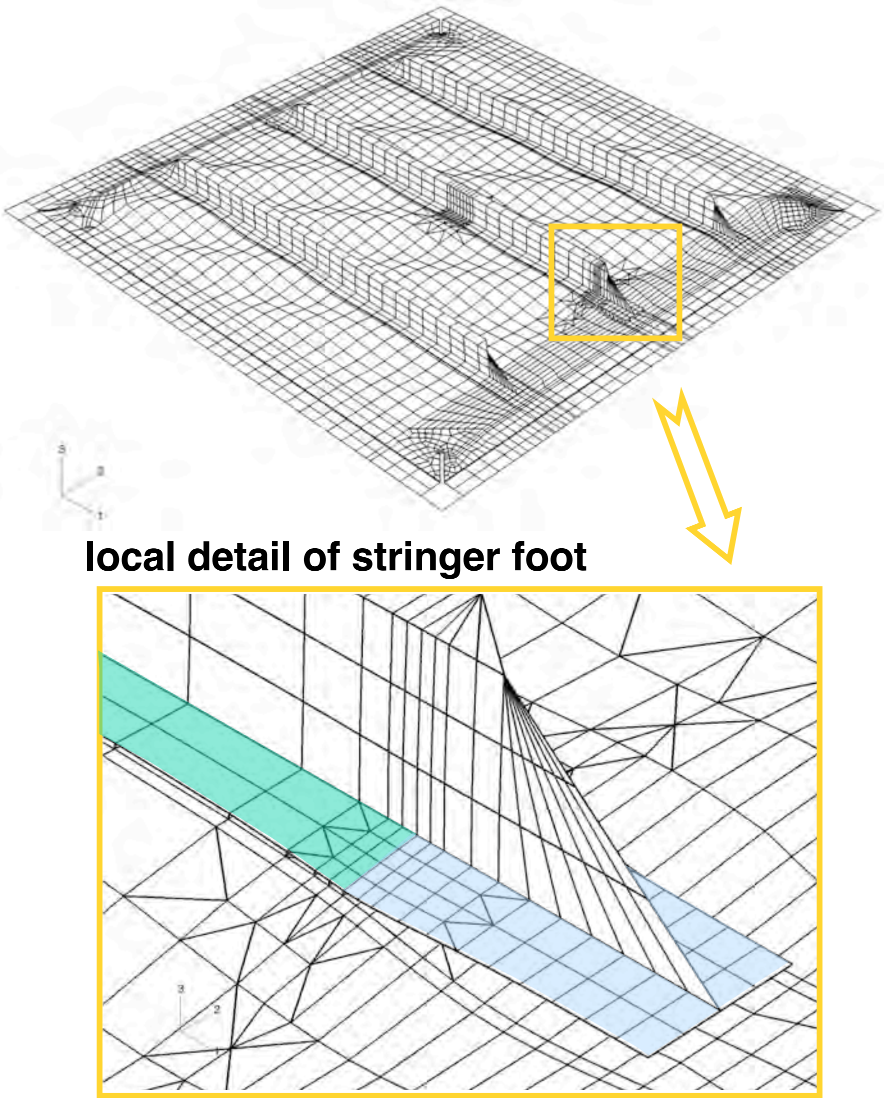
$$G_{III} = \frac{1}{2\Delta ab} \cdot Y'_{Li} \cdot \left(v'_{L\ell} - v'_{L\ell^*} \right)$$

STRINGER STIFFENED PANEL SUBJECTED TO SHEAR LOADING

- Testing of Stiffened Shear Panel Boeing, Philadelphia*



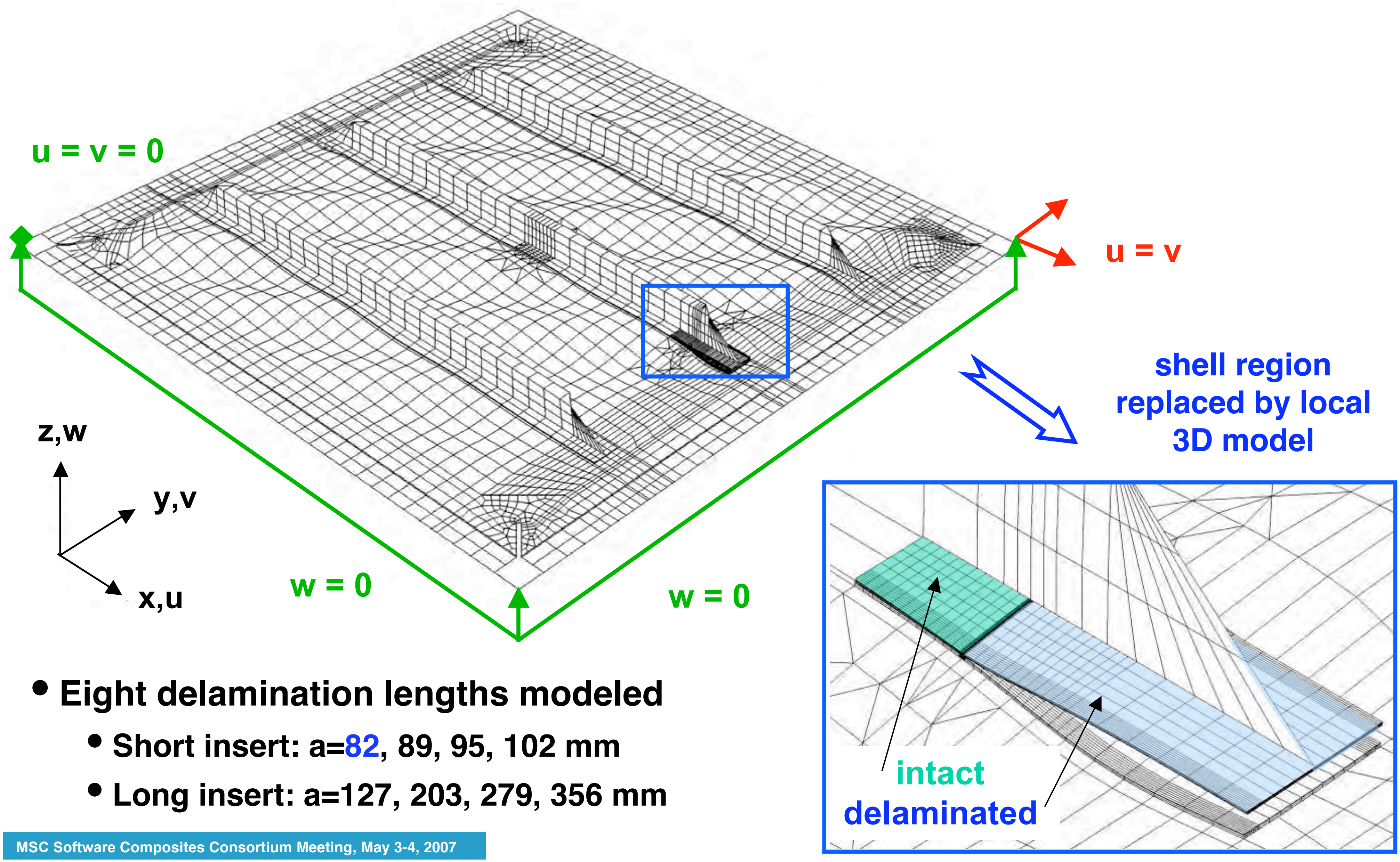
- Original Boeing ABAQUS Shell Model*



local detail of stringer foot

*Pierre Minguet, Boeing

SHELL FE-MODEL WITH LOCAL 3D MODEL

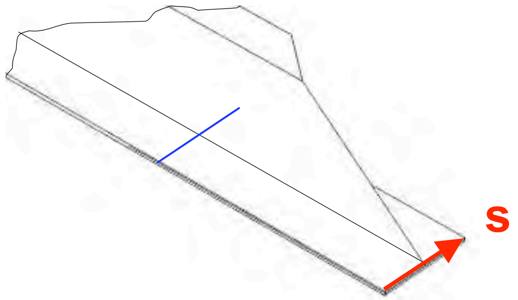


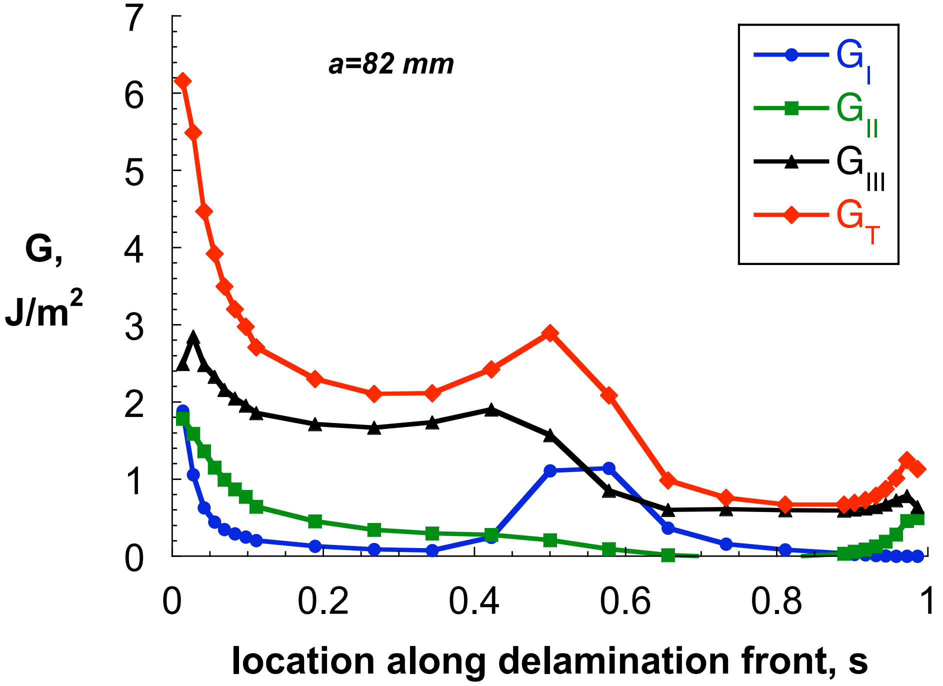
shell region replaced by local 3D model

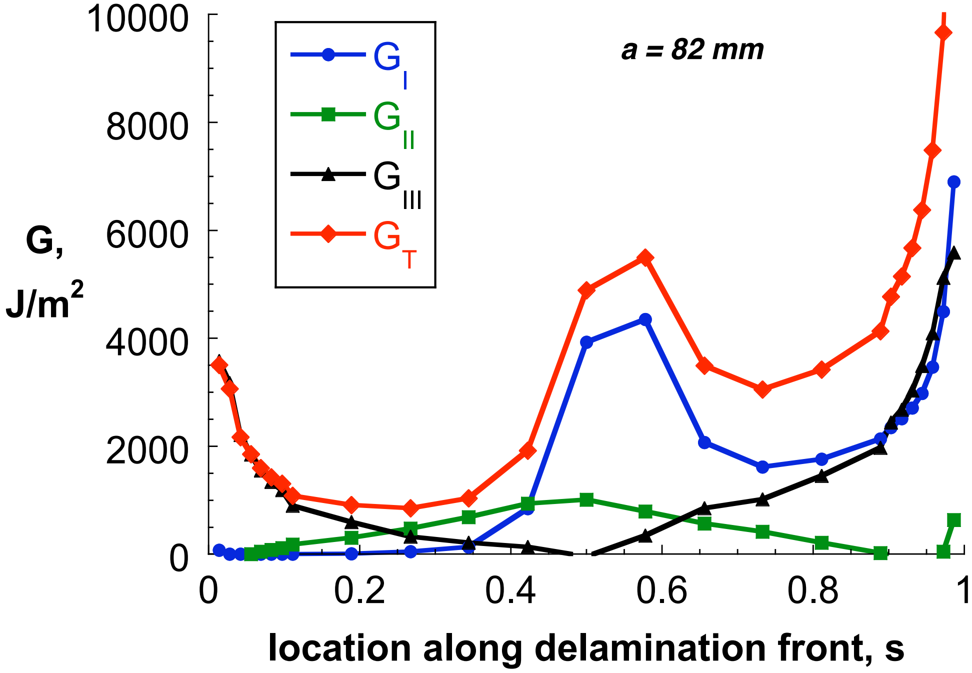
- **Eight delamination lengths modeled**
  - **Short insert: a=82, 89, 95, 102 mm**
  - **Long insert: a=127, 203, 279, 356 mm**

COMPUTED ENERGY RELEASE RATES

- **Increment 5, u = v = 0.2 mm, 3.3 %**
- **Increment 41, u = v = 6.35 mm, 100%**





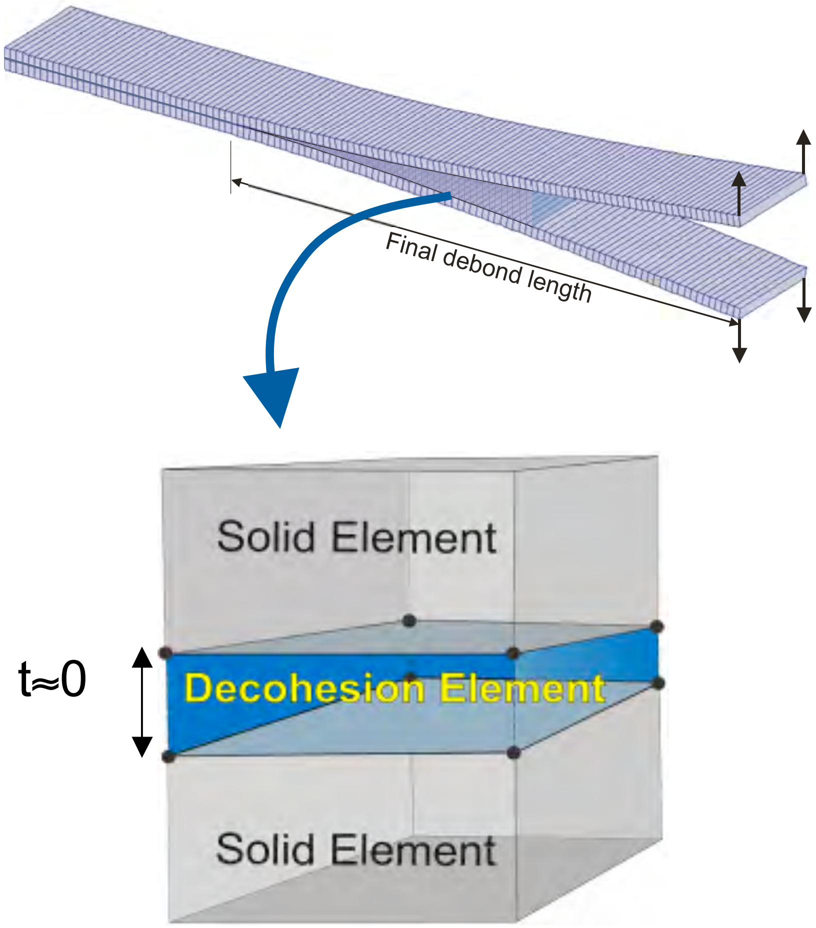


DECOHESION ELEMENTS FOR SIMULATING DELAMINATION

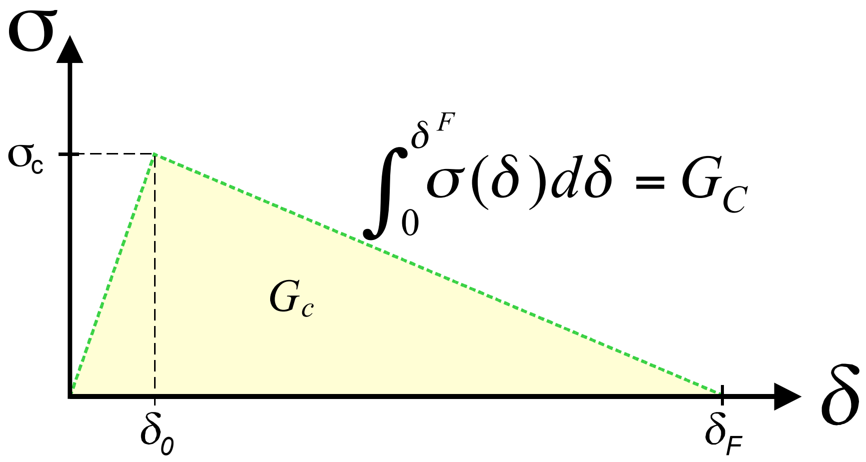
CARLOS DAVILA

DURABILITY, DAMAGE TOLERANCE AND
RELIABILITY BRANCH
NASA LANGLEY RESEARCH CENTER
HAMPTON, VA

DECOHESION FINITE ELEMENT



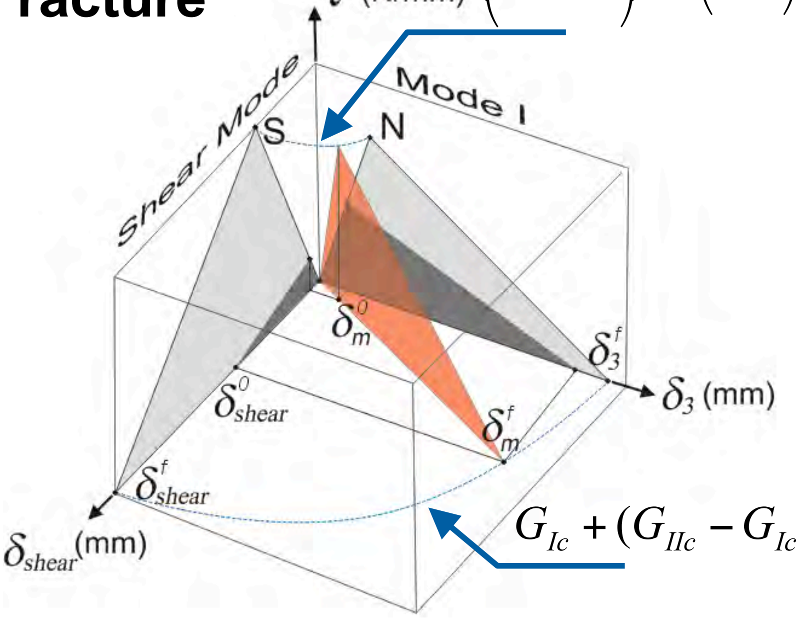
Bilinear Traction-Displacement Law



$$\int_0^{\delta^F}\sigma(\delta)d\delta = G_C$$

Mixed-Mode Fracture

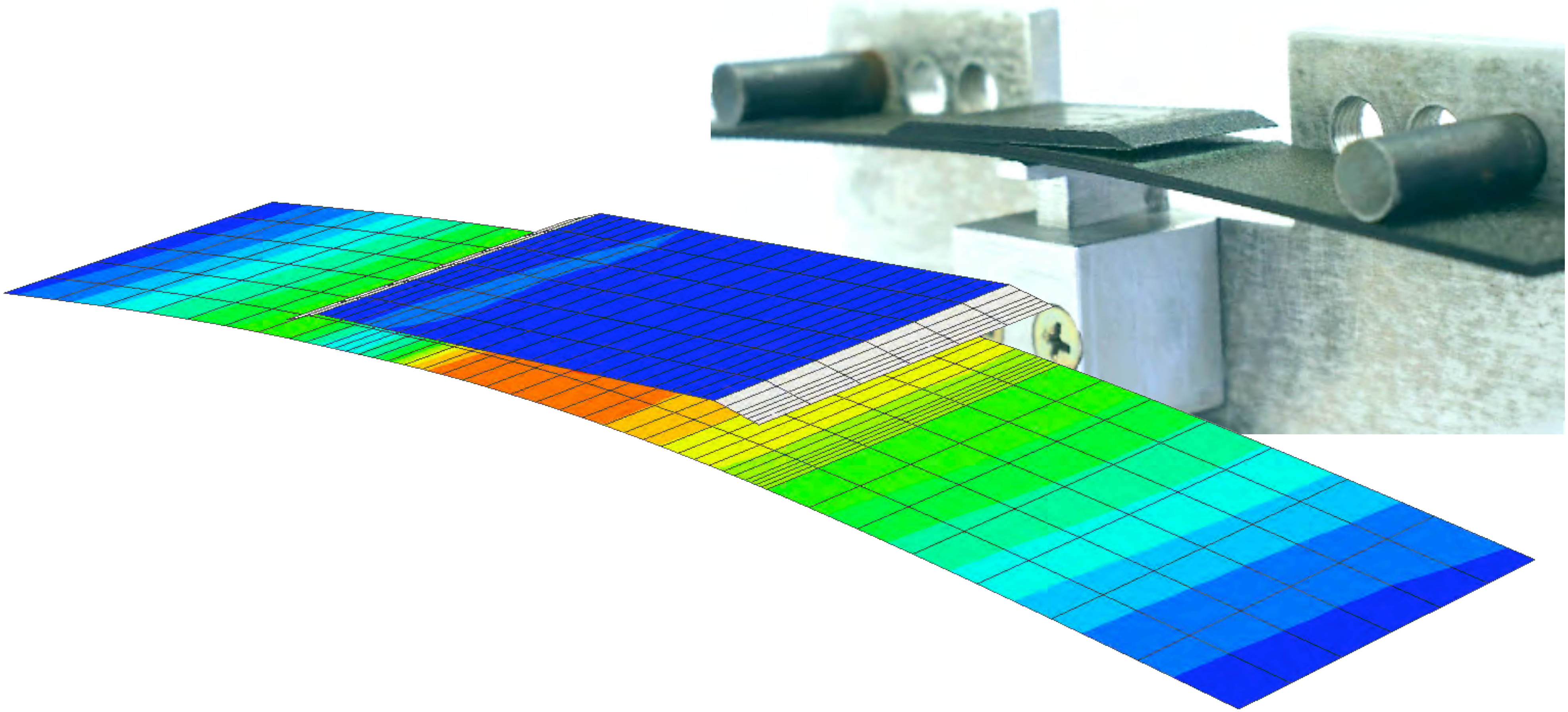
$$\left(\frac{\langle\sigma_z\rangle_+}{T}\right)^2+\left(\frac{\tau_{xz}}{S}\right)^2+\left(\frac{\tau_{yz}}{S}\right)^2=1$$



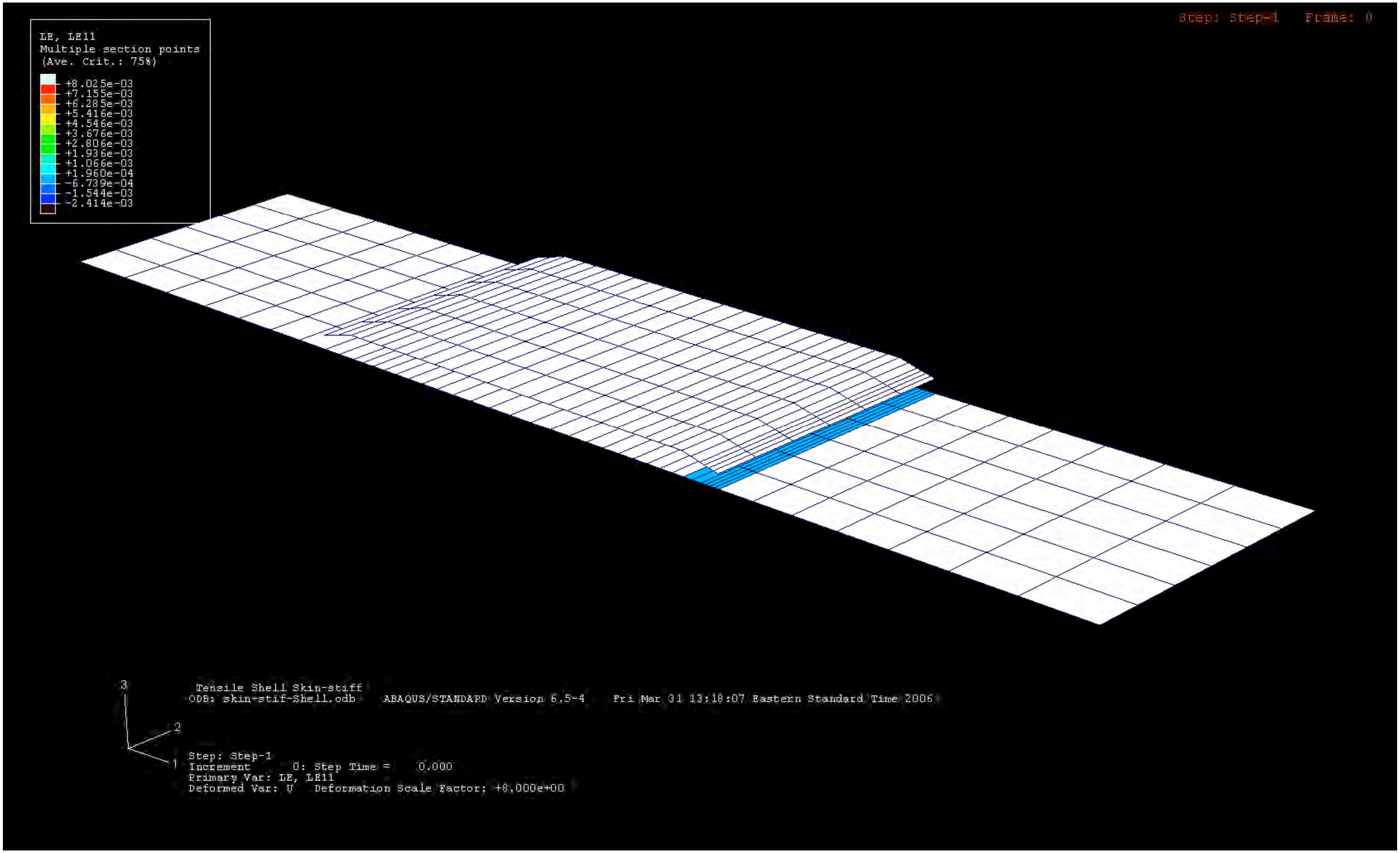
$$G_{Ic}+(G_{IIc}-G_{Ic})\left(\frac{G_{II}}{G_I+G_{II}}\right)^{\eta}$$

SKIN / STRINGER SEPERATION SPECIMEN

Decohesion elements used to predict delamination in skin / stringer specimen



SKIN / STRINGER SEPERATION SPECIMEN



```
LE, LE11
Multiple section points
(Ave. Crit.: 75%)
  +8.025e-03
  +7.155e-03
  +6.285e-03
  +5.416e-03
  +4.546e-03
  +3.676e-03
  +2.806e-03
  +1.936e-03
  +1.066e-03
  +1.960e-04
  -6.739e-04
  -1.544e-03
  -2.414e-03
```

```
Step: Step-1    Frame: 0
```

```
 Tensile Shell Skin-stiff
ODB: skin-stif-Shell.odb    ABAQUS/STANDARD Version 6.5-4    Fri Mar 31 13:18:07 Eastern Standard Time 2006

Step: Step-1
Increment      0: Step Time =    0.000
Primary Var: LE, LE11
Deformed Var: U   Deformation Scale Factor: +8.000e+00
```

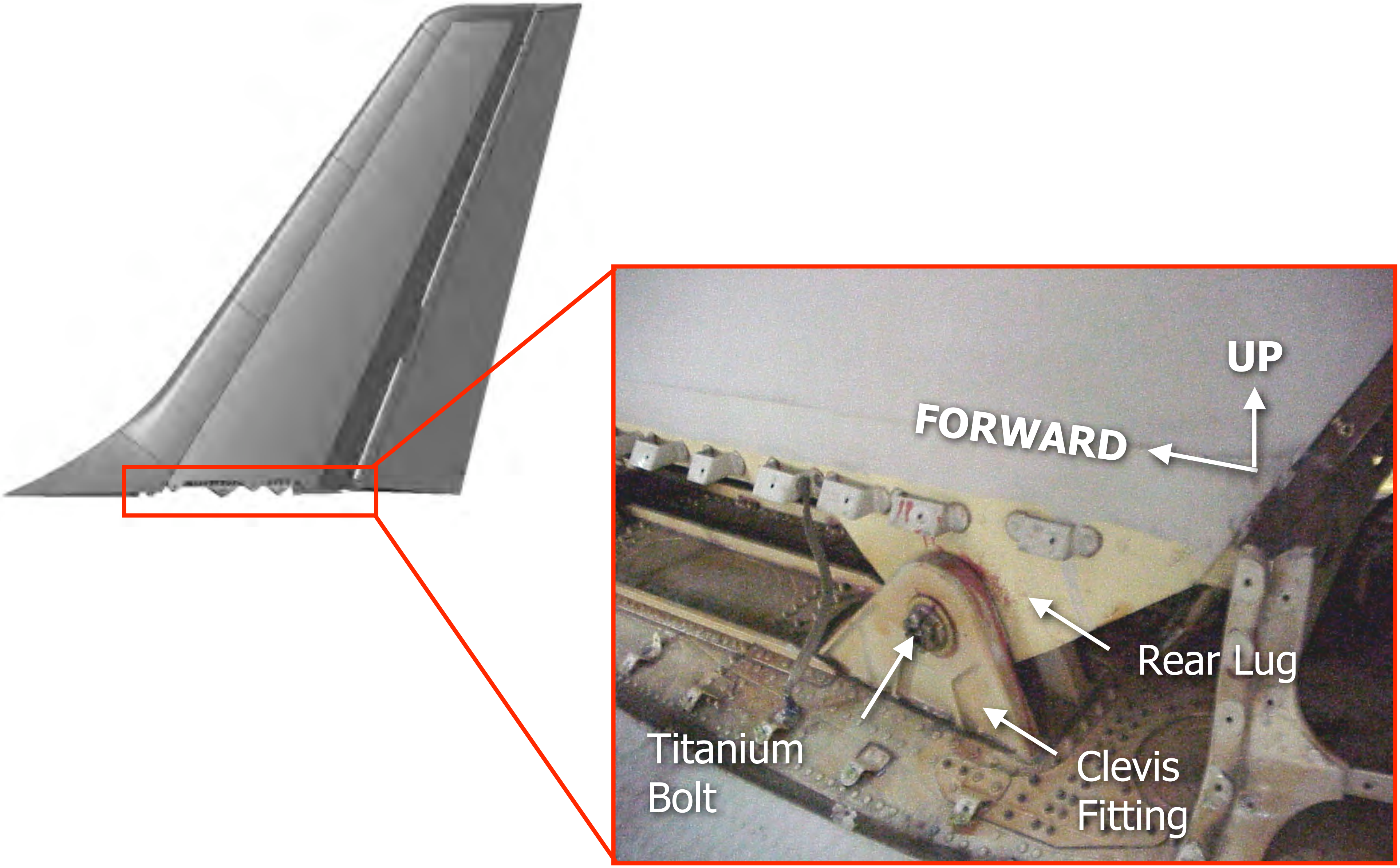
NTSB Board Meeting
AA Flight 587

Structures Investigation

Brian K. Murphy - NTSB

Detailed Lug Analysis Team -
NASA LaRC

MAIN ATTACHMENT FITTINGS

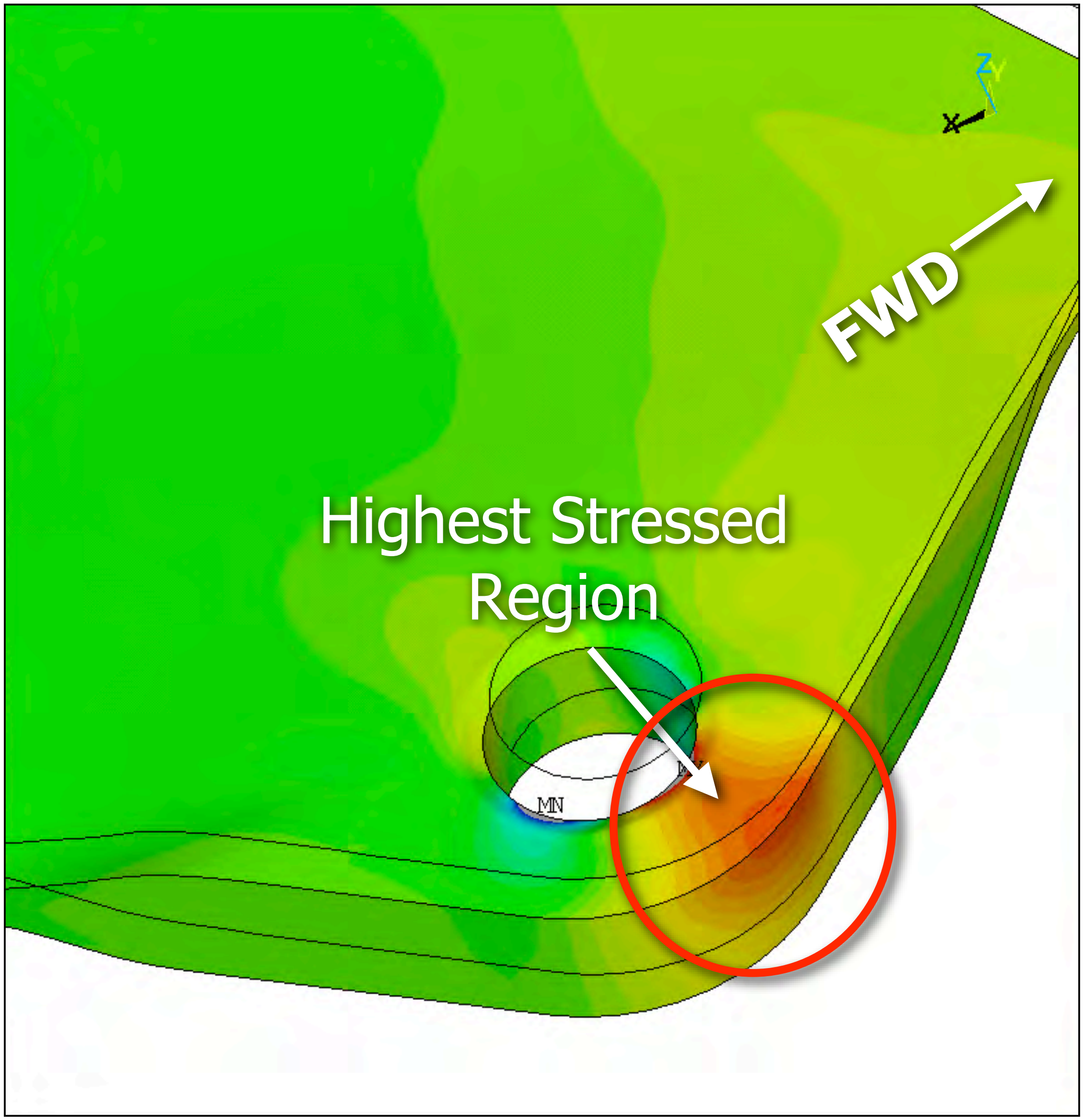


LUG STRENGTH DETERMINATION

The strength of the lug was determined by:

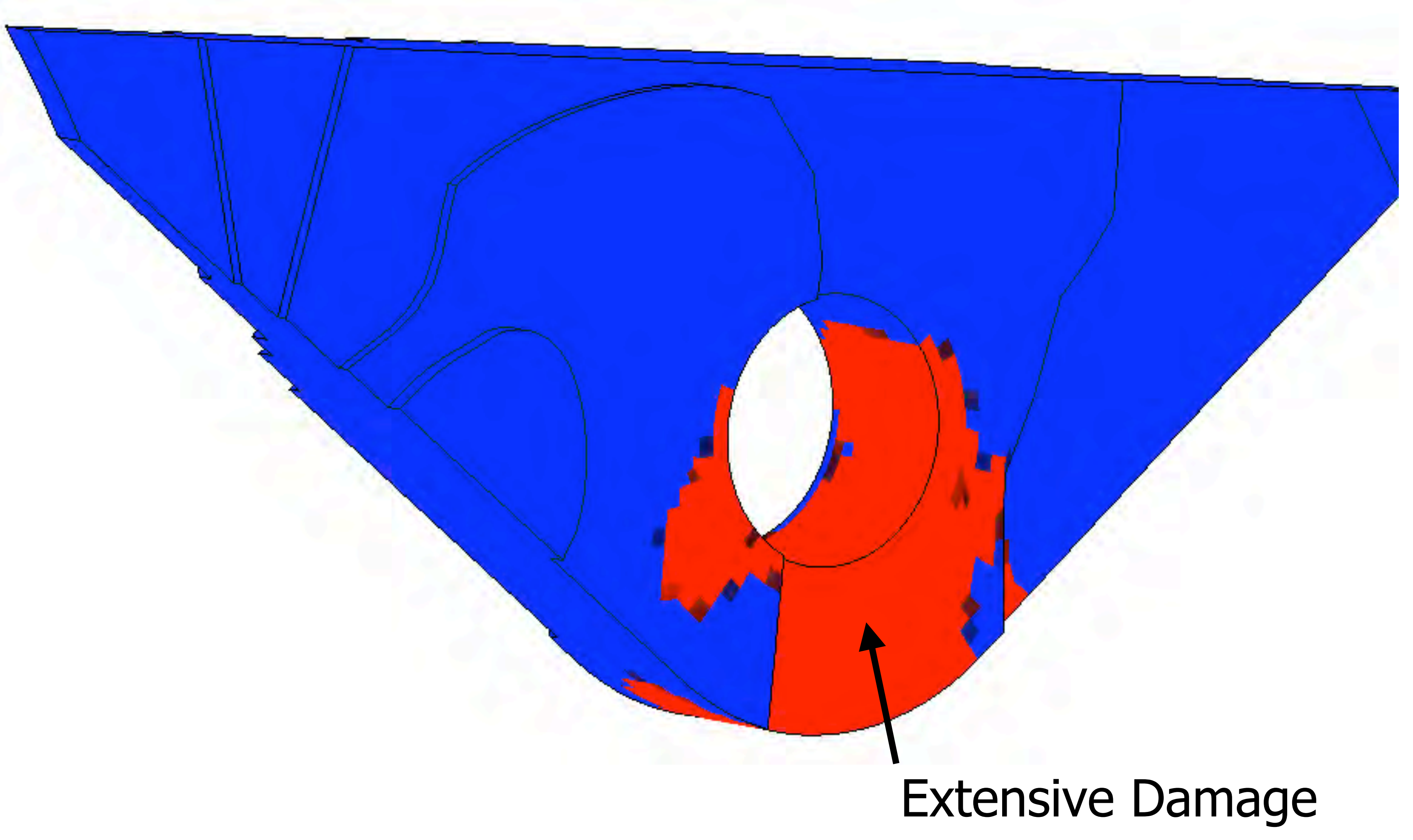
- Finite element analysis
- Progressive failure analysis
- Post accident lug tests

FINITE ELEMENT ANALYSIS OF THE LUG



Highest Stressed Region

PROGRESSIVE FAILURE ANALYSIS



FINITE ELEMENT MODEL OF DELAMINATION IN A ROTORHUB FLEXBEAM

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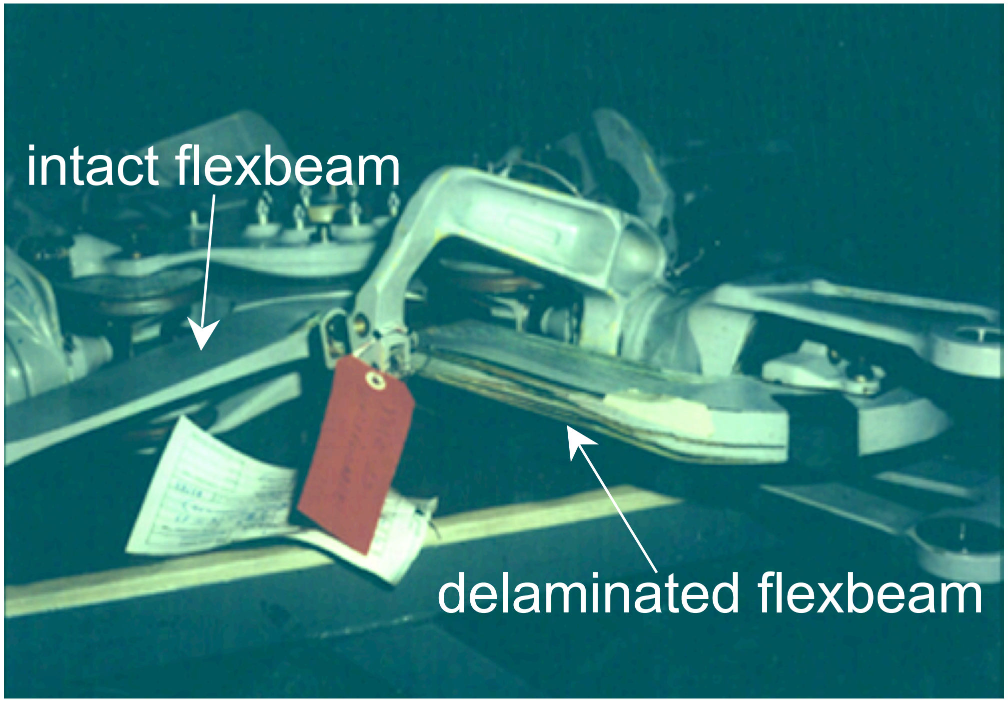
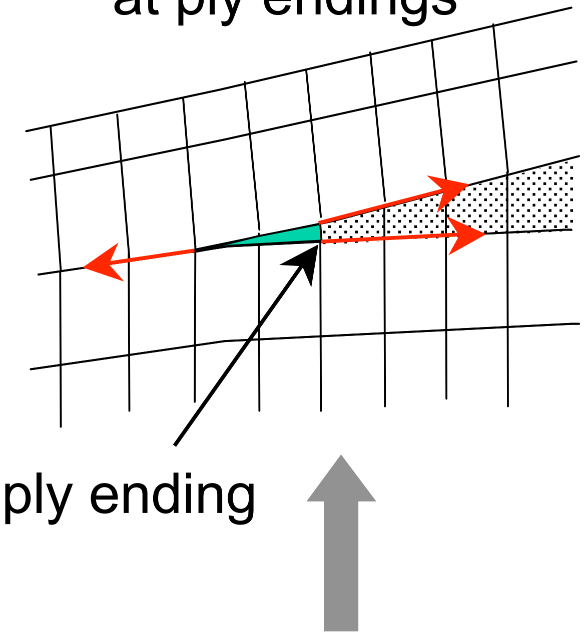
Resident at Durability, Damage Tolerance and Reliability Branch, NASA Langley Research Center

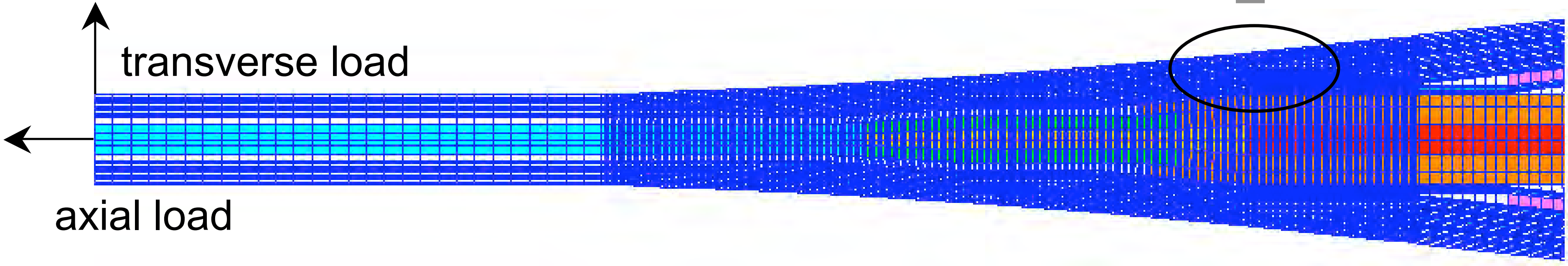
FINITE ELEMENT MODEL OF DELAMINATION IN A ROTORHUB FLEXBEAM



Helicopter Rotorhub

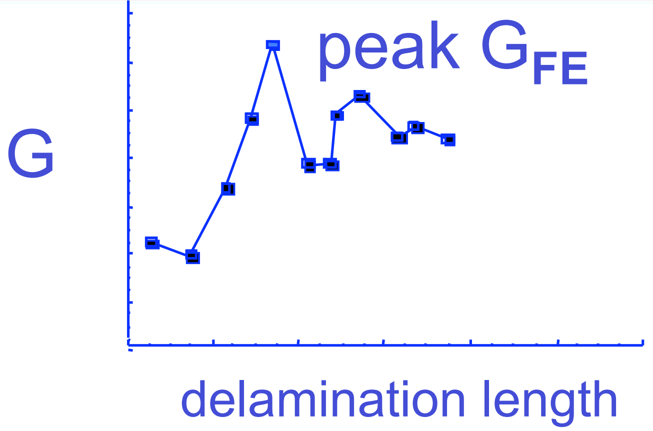
Delaminations initiate at ply endings



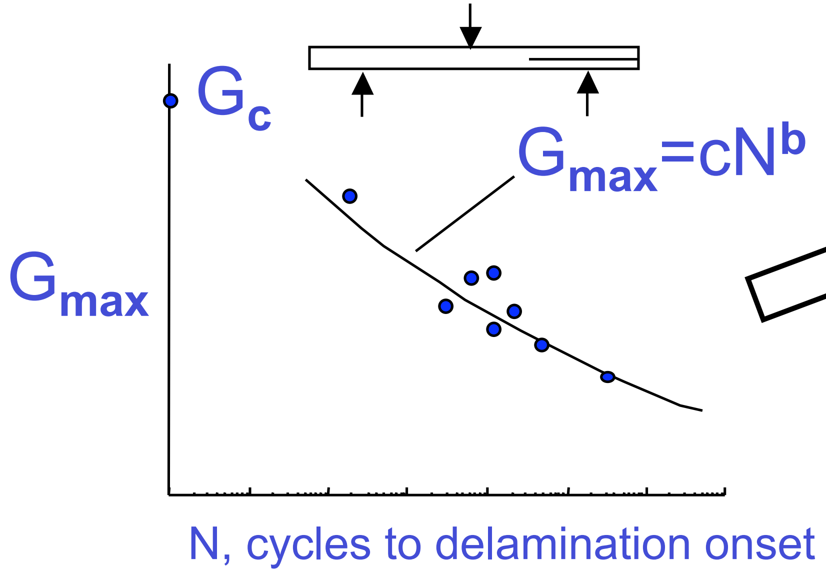


Finite element model of flexbeam with internal ply-drops

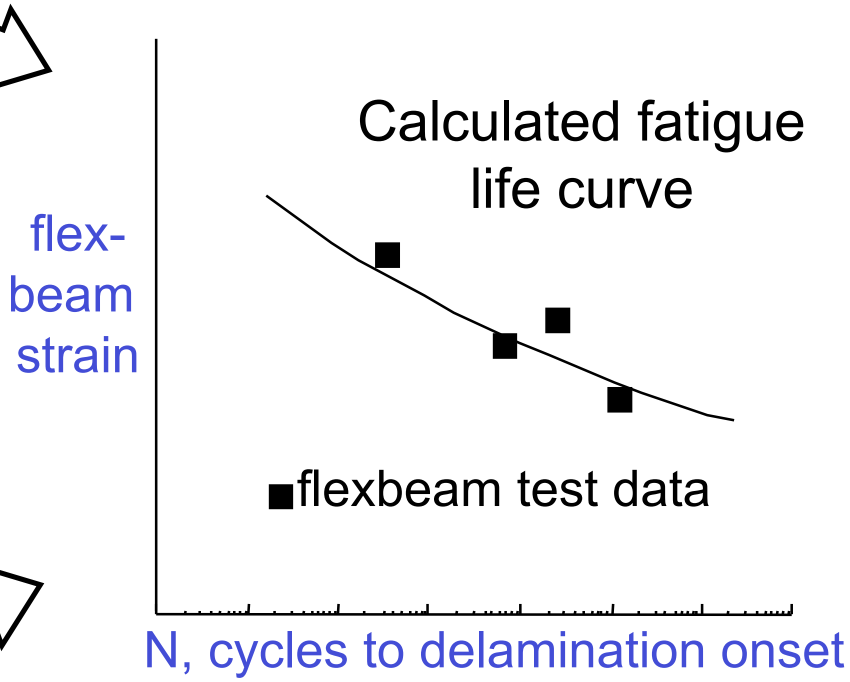
FLEXBEAM FATIGUE LIFE METHODOLOGY



VCCT used to calculate G as delamination grows



Fatigue toughness data for modeled material



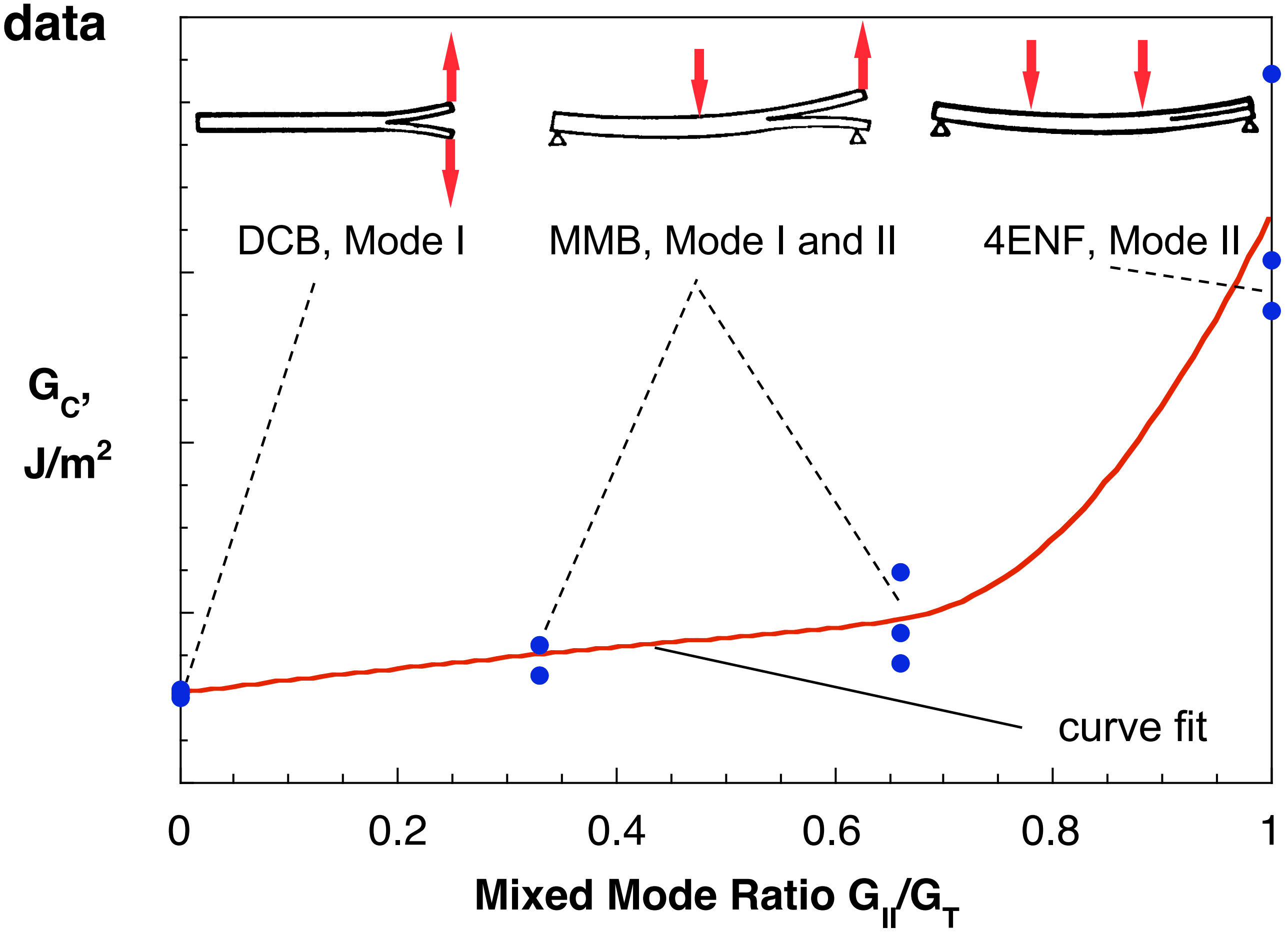
MIXED-MODE FAILURE CRITERIA FOR DELAMINATION IN COMPOSITE LAMINATES

JAMES REEDER

NASA LANGLEY RESEARCH CENTER
HAMPTON, VA

2D MIXED MODE FRACTURE CRITERION

- **Experimental data**

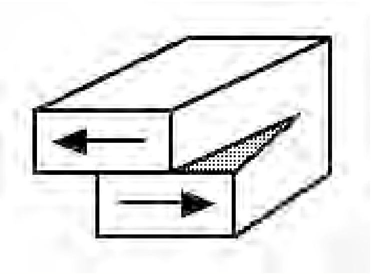


- **Curve fit equation by Benzeggagh and Kenane, 1996**

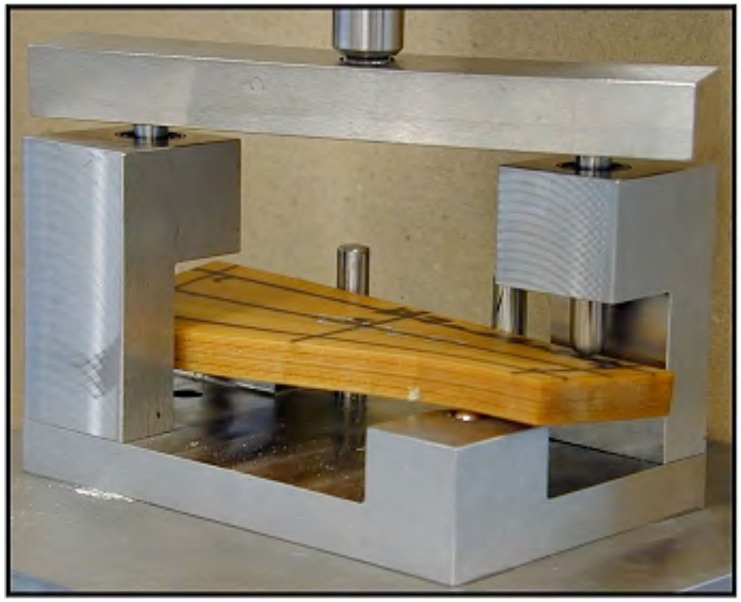
$$G_c = \left(G_{Ic} + \left(G_{IIc} - G_{Ic} \right) \cdot \left(\frac{G_{II}}{G_T} \right)^{\eta} \right)$$

PROPOSED 3D MIXED MODE FRACTURE CRITERION

- Mode III - ECT Specimen



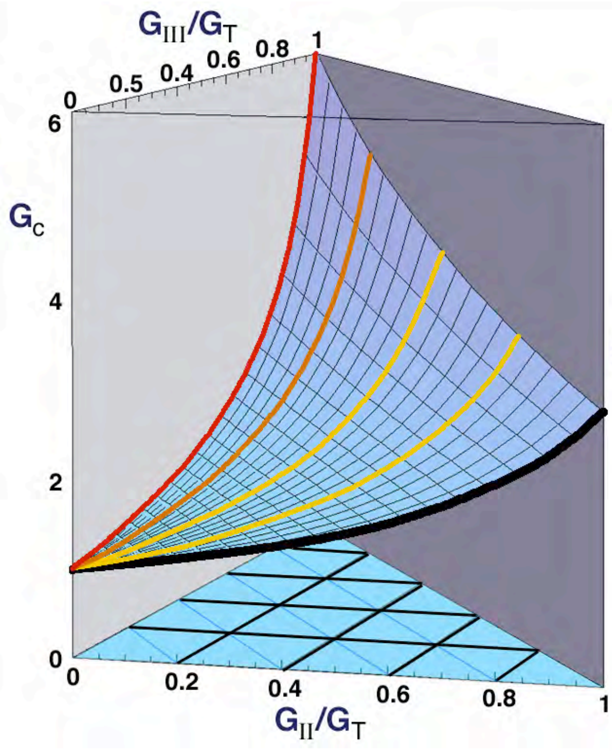
tearing mode III



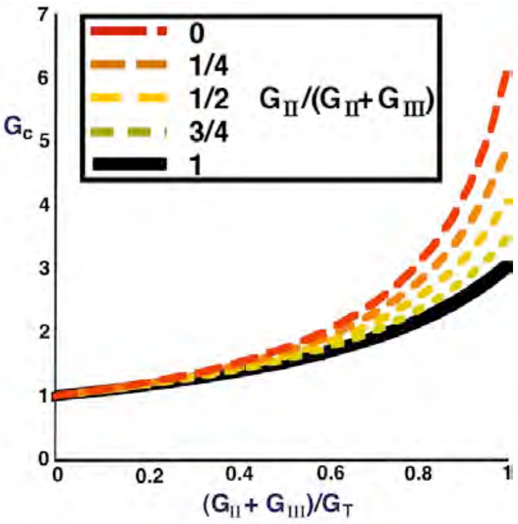
- Proposed 3D failure criterion**

$$\frac{G_T}{G_{Ic}+\left(G_{IIc}-G_{Ic}\right)\left(\frac{G_{II}+G_{III}}{G_T}\right)^{\eta}+\left(G_{IIIc}-G_{IIc}\right)\frac{G_{III}}{G_{II}+G_{III}}\left(\frac{G_{II}+G_{III}}{G_T}\right)^{\eta}}\geq 1$$

- Surface representation



- 2D plot representation to obtain values



**James Reeder, NASA Langley Research Center

ANALYSIS TO PREDICT DELAMINATION IN Z-PIN REINFORCED LAMINATES

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Z-PIN TECHNOLOGY

Definition

- Pultruded graphite rods positioned through-thickness (z-direction) of a composite laminate
- Pins are 0.2-0.5mm diameter rods
- Typical range of areal density between 0.5% and 4%
- Inserted into uncured laminate using ultrasonic hammer

Purposes

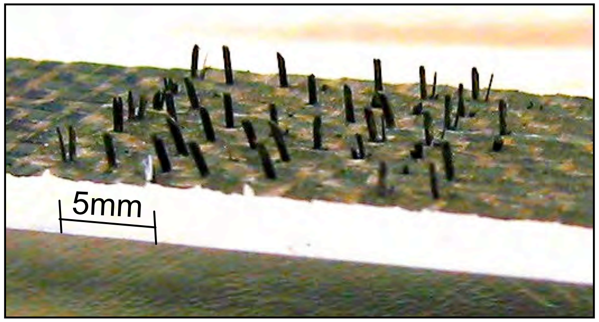
- Improve composite laminate transverse strength
- Prohibit delamination

Drawbacks

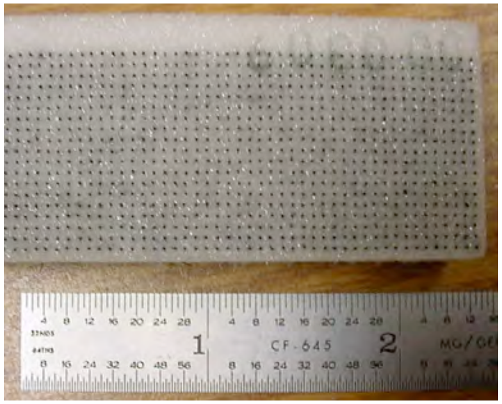
- Degrade laminate (in-plane) properties

Applications

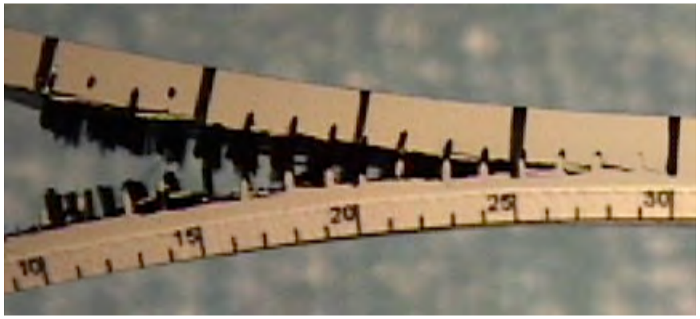
- F/A 18 inlet ducts, X-cor^{TM}, Formula 1 auto racing



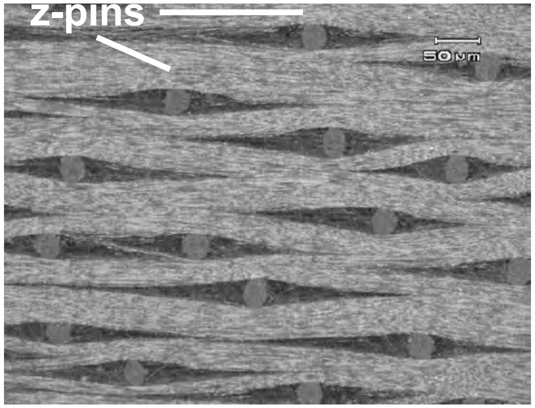
Z-Pins protruding from laminate



Z-Pin preform: Insertion side*



Z-pin bridging mode I delamination



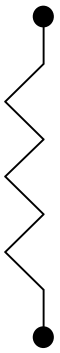
Fiber misalignment from z-pins**

*Pierre Minguet, Boeing. **Jeffery Schaff, Sikorsky Aircraft.

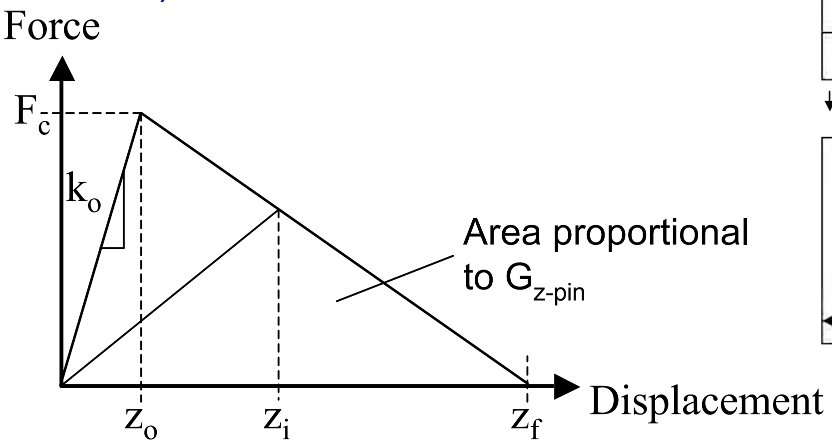
FINITE ELEMENT ANALYSIS

1 Discrete spring used to represent individual z-pins

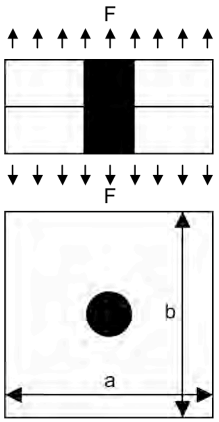
(Traction law assigned for representing z-pin failure)



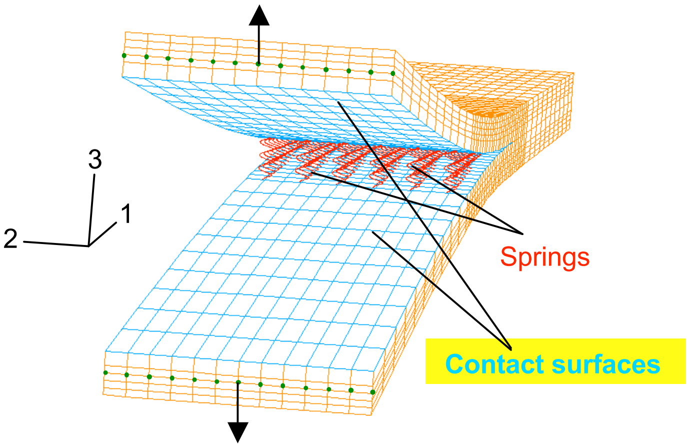
$$k_i = \begin{cases} k_o & \Leftarrow z_i \le z_o \\ (1 - d)k_o & \Leftarrow z_o \le z_i \le z_f \\ 0 & \Leftarrow z_i \ge z_f \end{cases}$$



Area proportional to $G_{z\text{-pin}}$



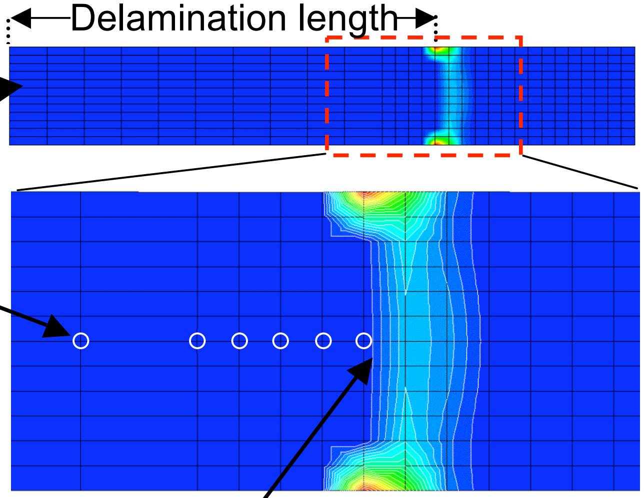
2 Springs inserted into finite element model



Springs

Contact surfaces

3 Delamination growth tracked using contact pressure



Delamination length

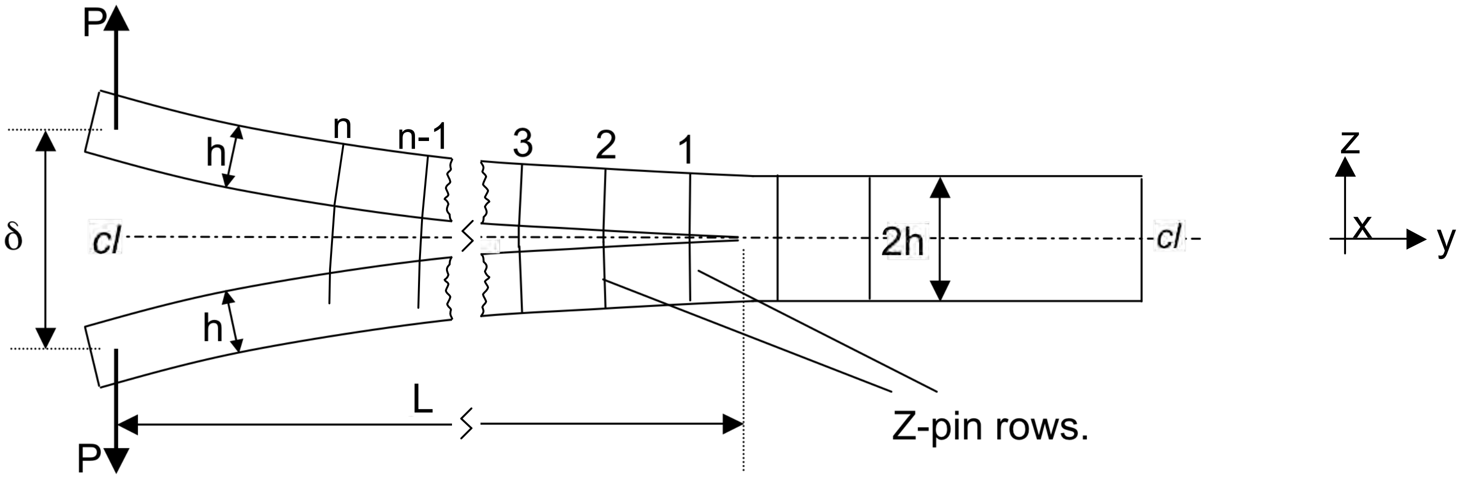
Delamination surface

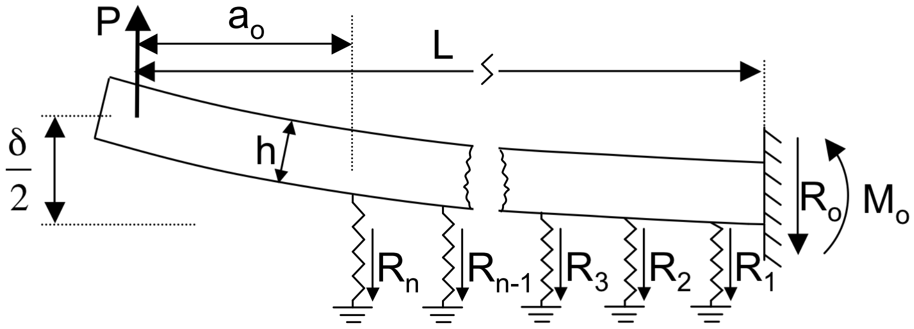
Nodes at which contact pressure is monitored

Dark blue = no contact pressure

Estimated delamination front

BEAM THEORY ANALYSIS



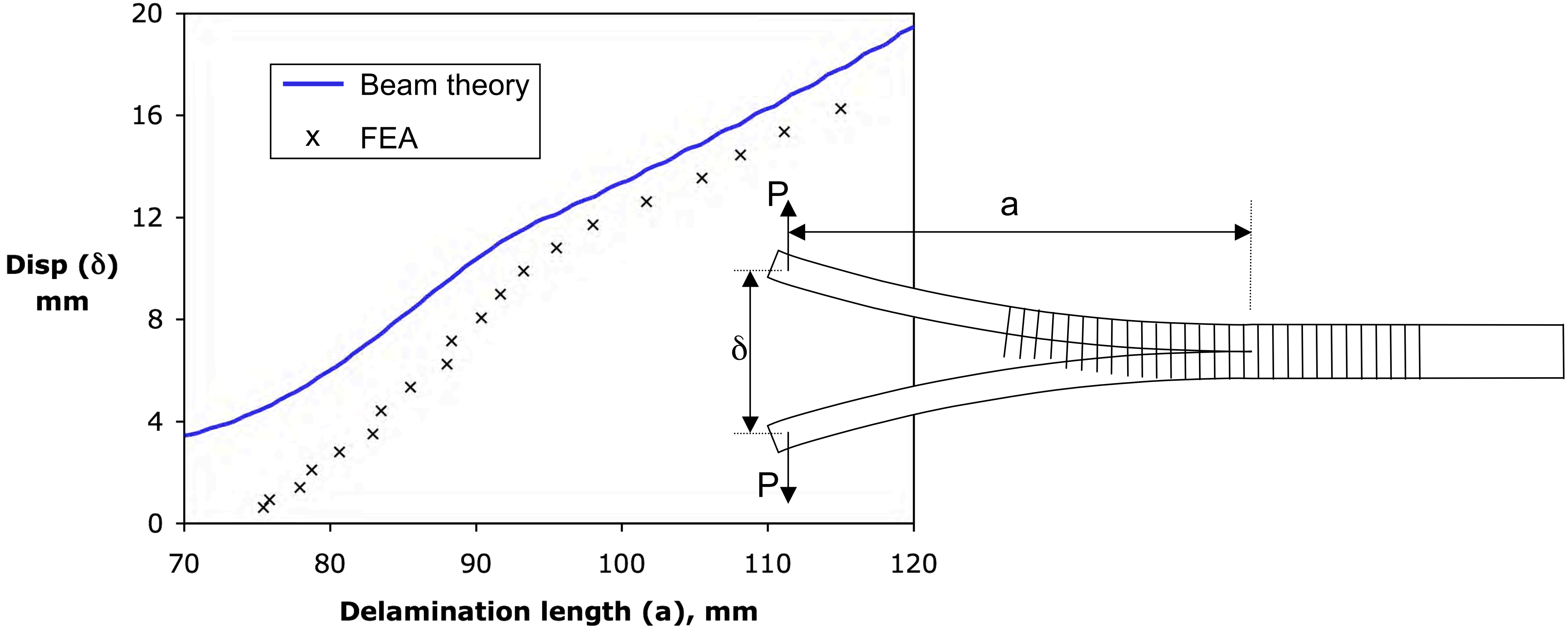


$$C_i = \frac{\delta_i}{P} = 2\left[\frac{a_o^3}{3EI} + \frac{L^3 - a_o^3}{3E_{zp}I}\right] + \frac{1}{3PE_{zp}I}\left[\sum_{i=1}^{n} k_i z_i a_i^2 (a_i - 3L)\right]$$

- **Half specimen modeled**
- **Specimen arms represented as cantilever beams**
- **Spring represents z-pin row**
- **Traction law to represent z-pin pull out**
- **Closed-form solutions for specimen compliance**
- **Algorithm to predict delamination growth**

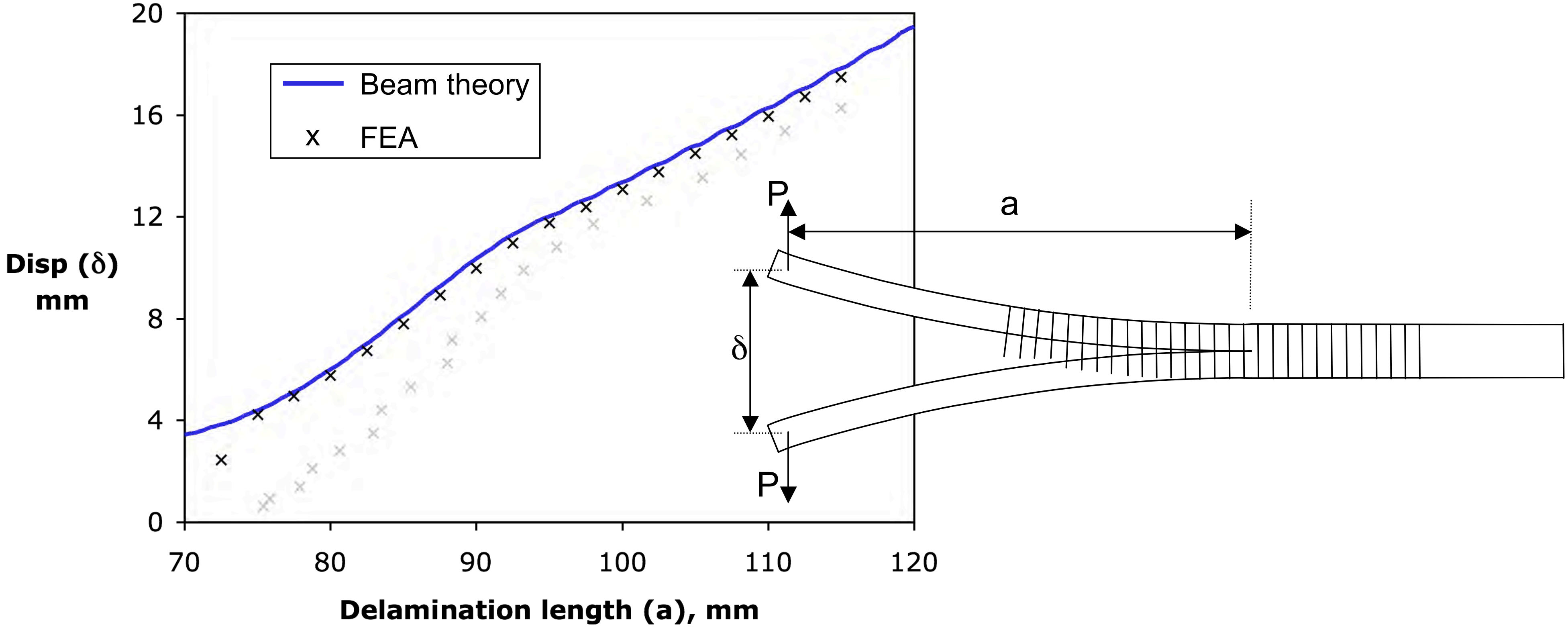
COMPARISON WITH BEAM THEORY

- Finite element analysis overestimates delamination length for a given displacement



COMPARISON WITH BEAM THEORY

- Finite element analysis results in better agreement with beam theory when decohesion elements used for delamination



CONCLUDING REMARKS

- Many analysis studies involve a low Technology Readiness Level (TRL). Therefore, specialized tools are required which are not always commercially available

- In many cases the finite element analysis software has to provide input to specialized user subroutines. An adequate interface is required to enable appropriate communication with the user subroutines.

- The specialized analysis tools are often computationally expensive