# NASA Langley Damage Tolerance Experiences

**by**

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**presented at the**

**FAA Symposium on**
**Composite Damage Tolerance**
**And Maintenance**
**Chicago**
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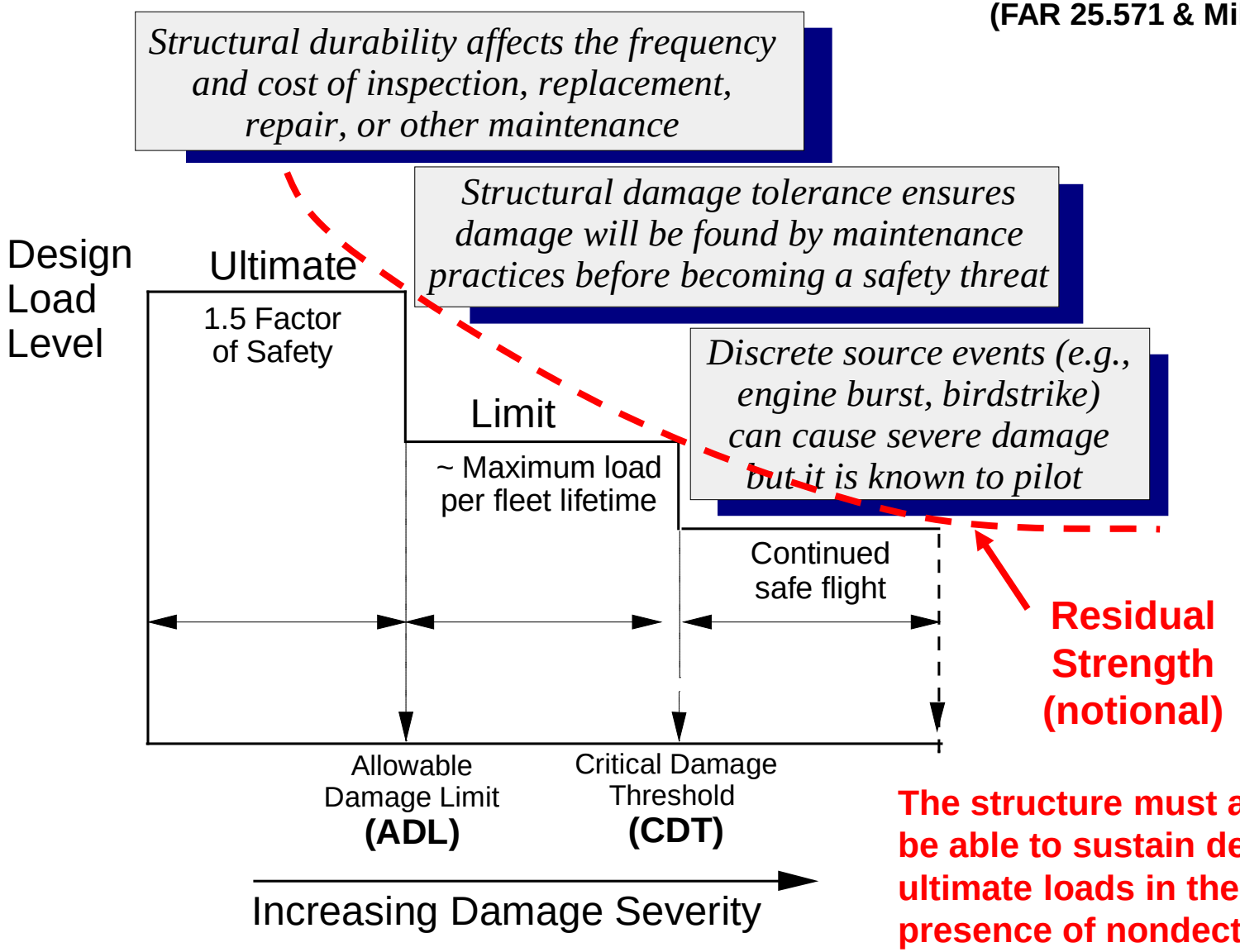
# Outline

- NASA Langley's Composites Programs
- SOA Analysis
- Emerging Continuum Methods
- Future Directions

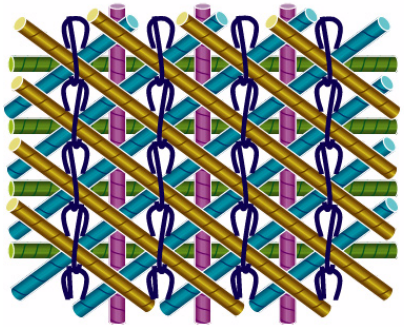
# Durability and Damage Tolerance Requirements

**(FAR 25.571 & Mil-17)**

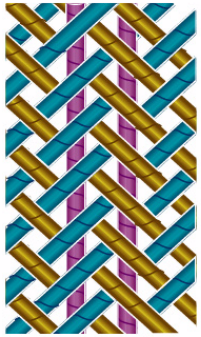



**The structure must always be able to sustain design ultimate loads in the presence of nondectable damage.**

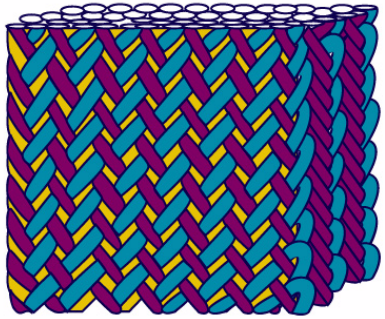
# Textile Materials



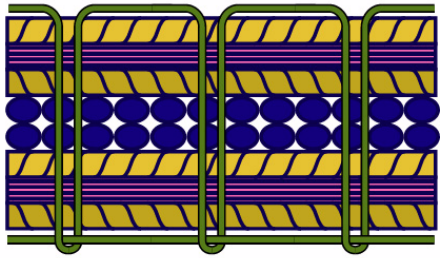
Multiaxial warp knit
(stitched & unstitched)



2-D triaxial braid
(stitched & unstitched)



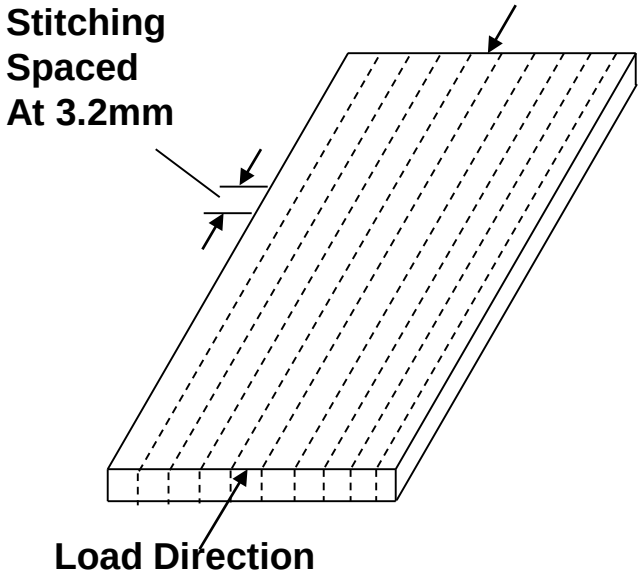
3-D braid



Knitted/stitched

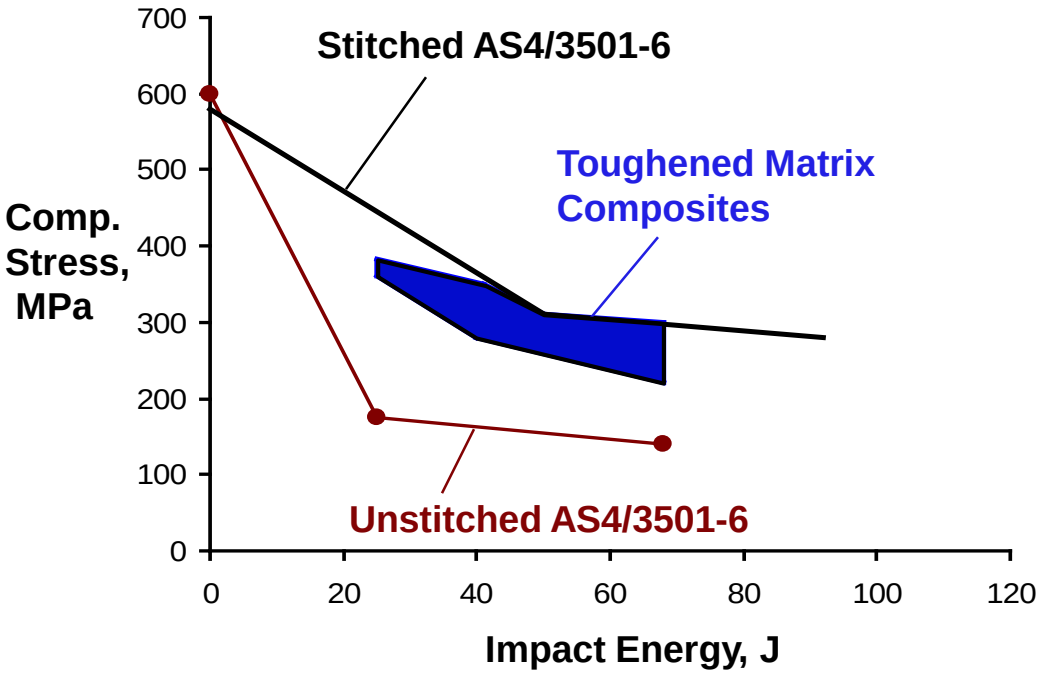
# Stitching Improves Damage Tolerance

## Details of Stitched Plates




**48 ply stitched laminate**
**$[+45/0/-45/90]_{6s}$**

## Compression After Impact Strength



# NASA ACT Program – Full Scale Wing Box Test (2000)


**AS4/3501-6 and IM7/3501-6 in textile preform**

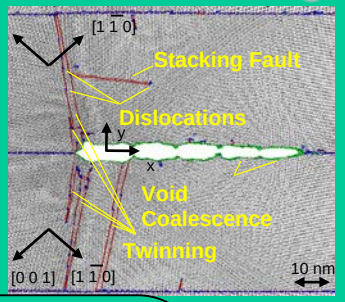
- **No damage or permanent deformation at DLL**
- **Test Article with repair of simulated damage failed at 97% of DUL**

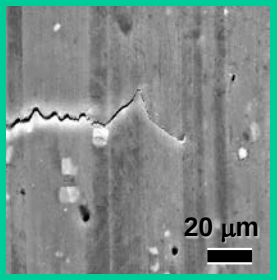
# Evolution of Damage Tolerance at NASA Langley (1999-)

Complexity, Computational Expense

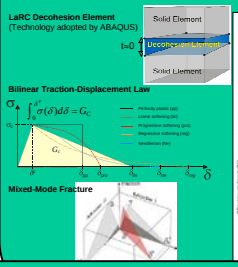
Time

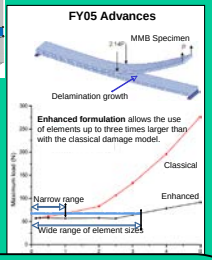
## Damage Science

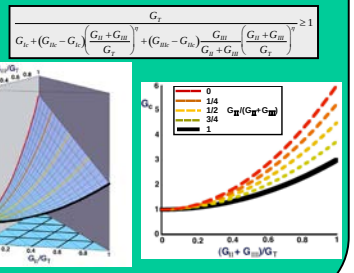



## Emerging Continuum Methods

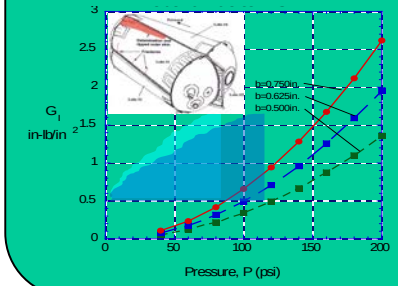


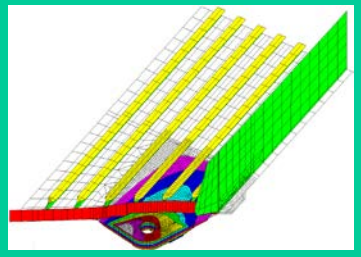



Spin-Offs

## Current State-of-the-Art



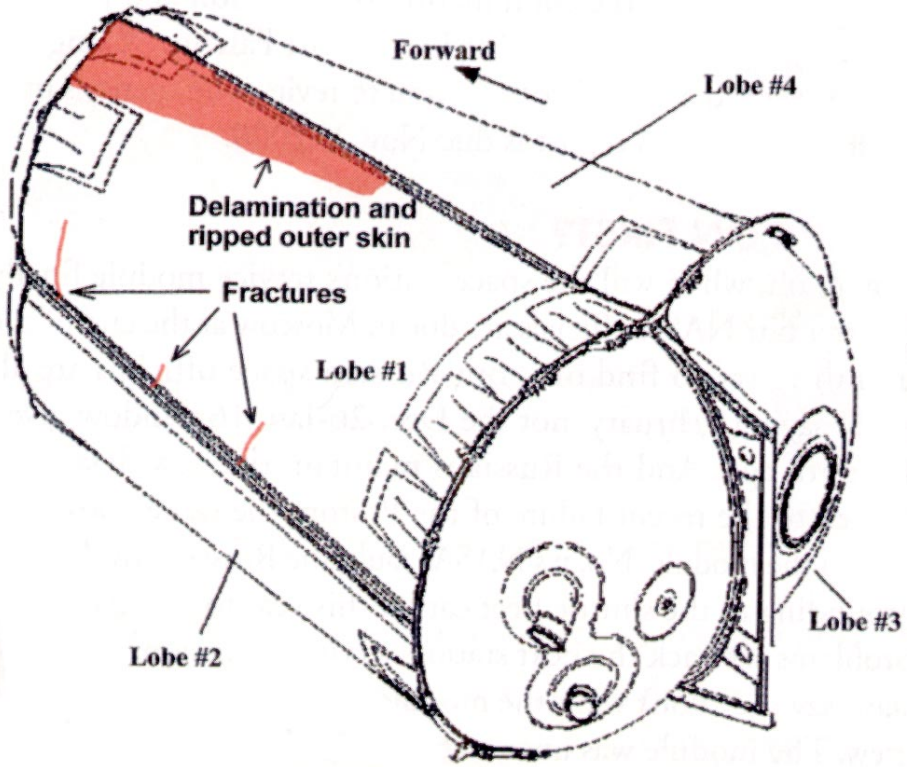



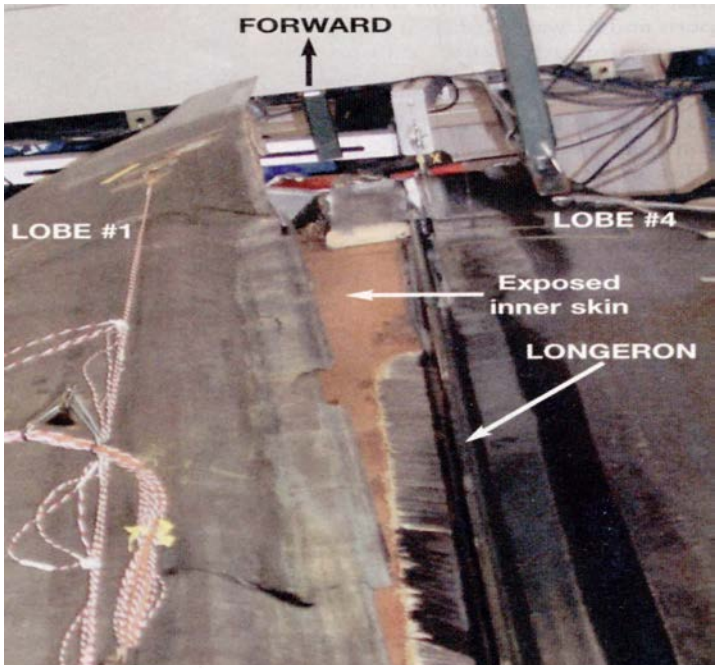
Spin-Offs

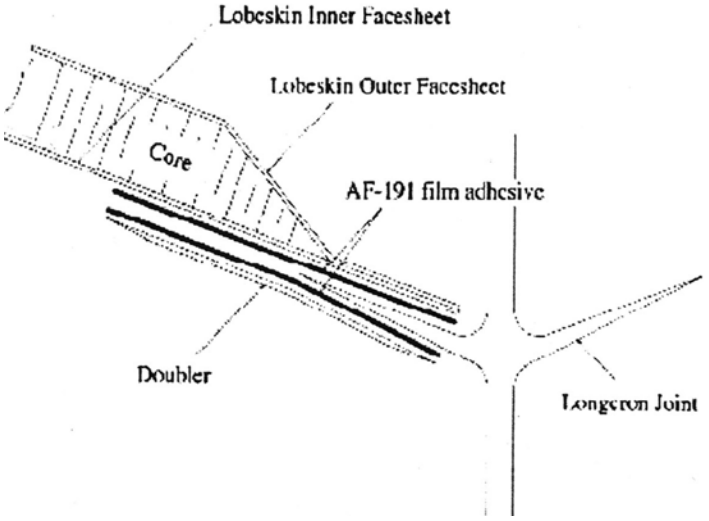
# Hypersonic Experimental Vehicle (X-33 Program)

**The liquid hydrogen composite tank failed during the protoflight ground test.**

# X-33 Composite Liquid Hydrogen Tank Failure



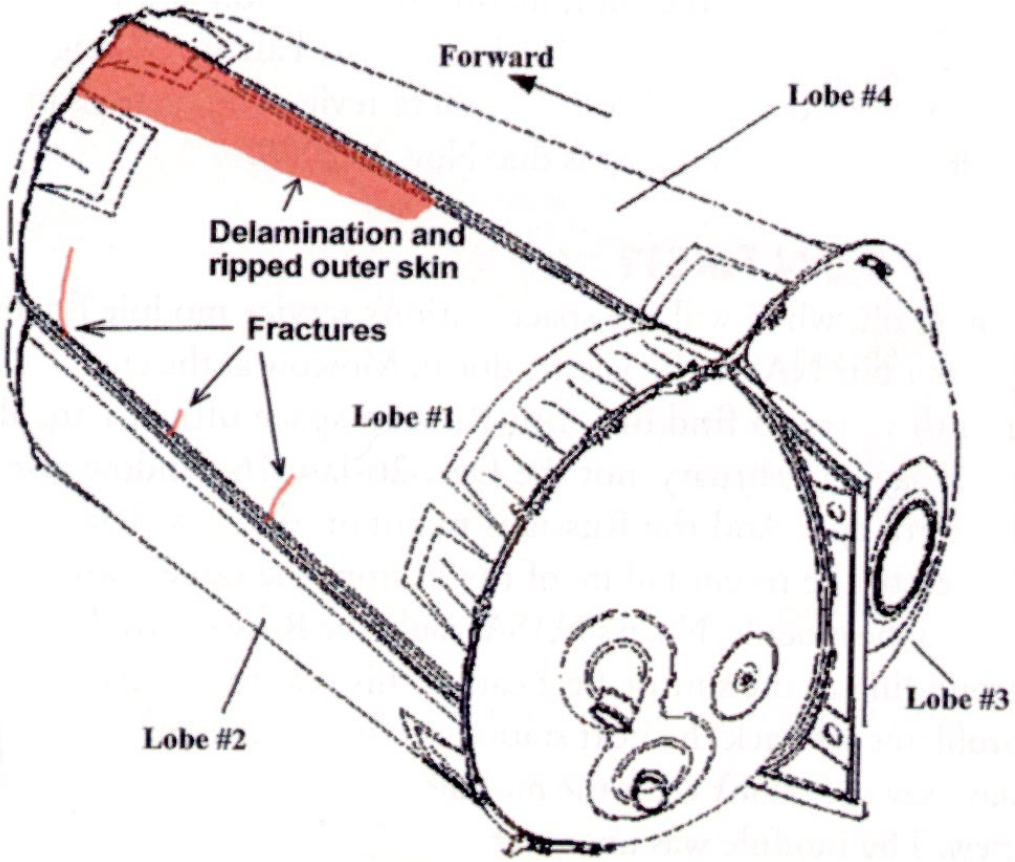



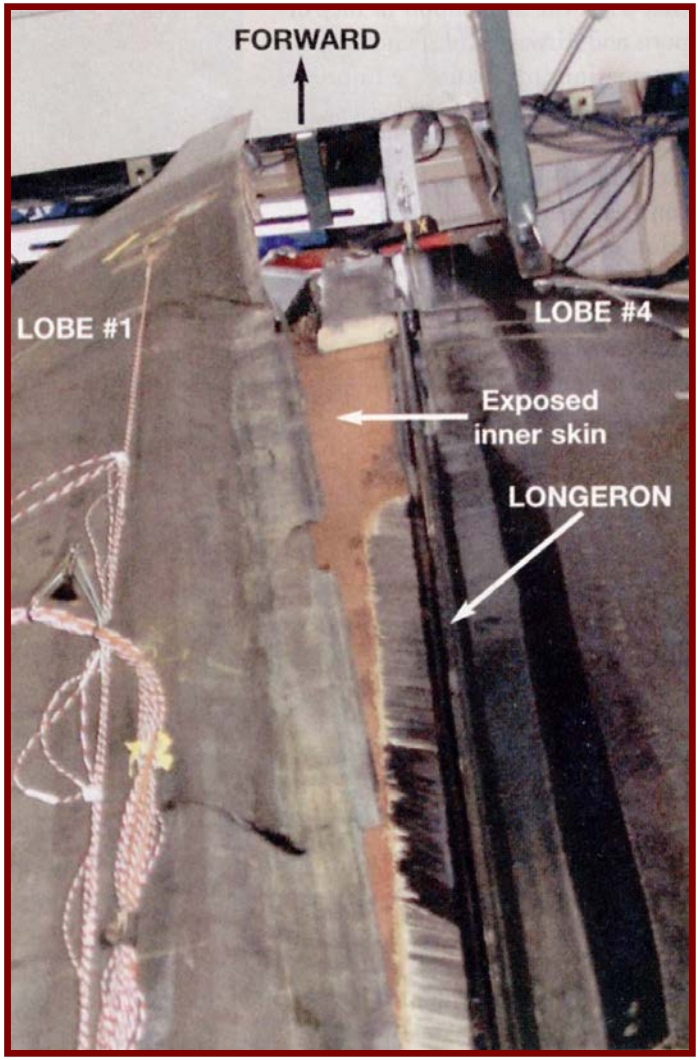




**The lobes are sandwich construction:**

- **The inner face sheet is $[45/90_3/-45/0_3/-45/90_3/45]_T$**
- **The outer face sheet is $[65/0/-65/90/-65/0/65]_T$**
- **The face sheets are IM7/977-2 laminates.**
- **The core is a honeycomb Korex 3/16 - 3.0 (1.5 in. thick).**
- **The adhesive is AF-191.**

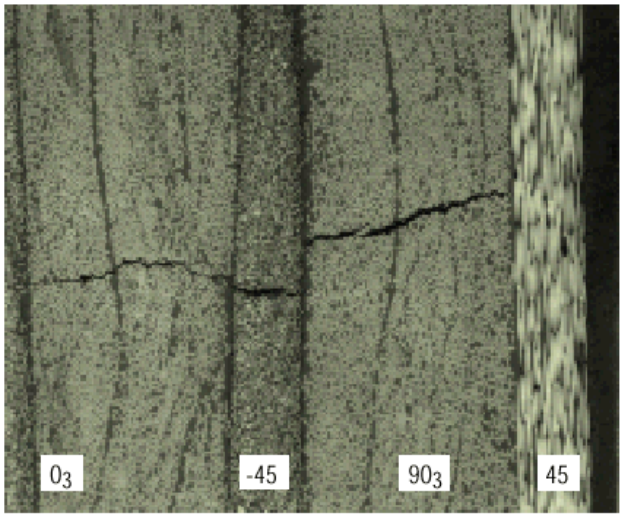
# X-33 Composite Liquid Hydrogen Tank Failure



# Causes of the X-33 Composite Tank Failure

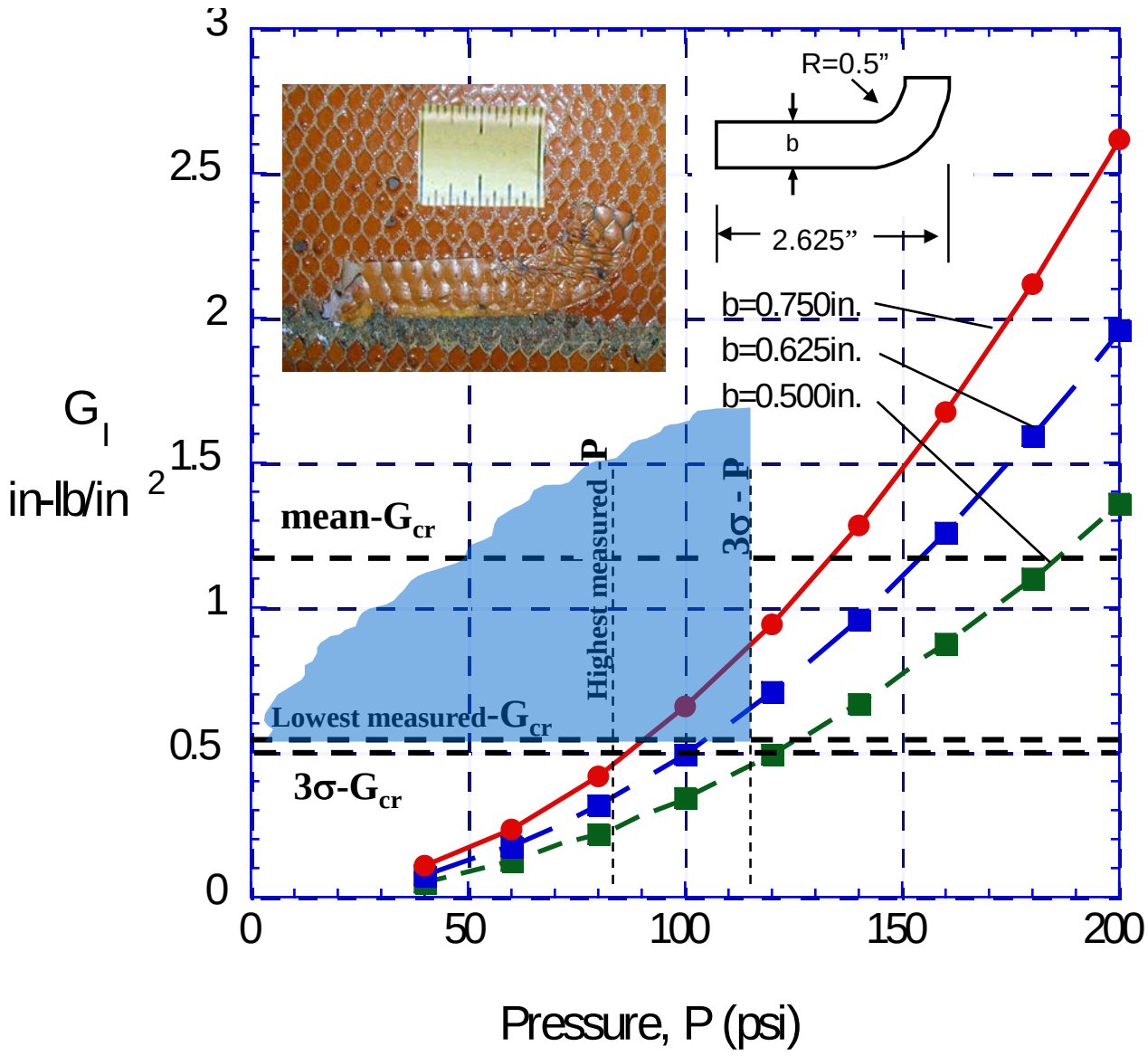
## Inner Skin Microcracking



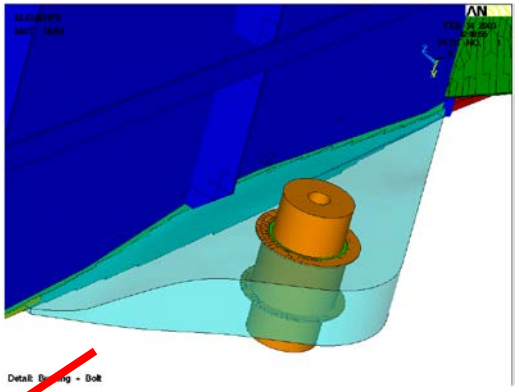

## Teflon Tape in Core

## Weak Core to Face Sheet Bond Strength/Toughness

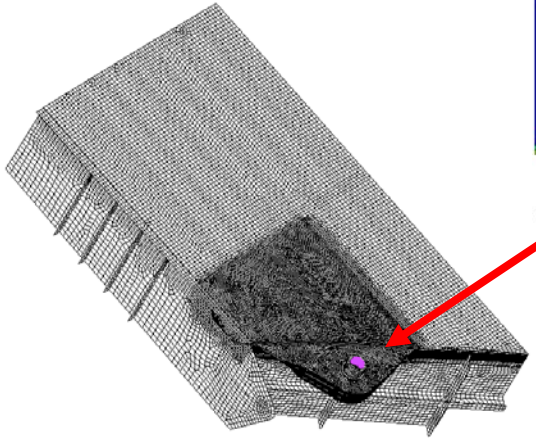
# Strain Energy Release Rates for an F.O.D. Debond



# Rear Fuselage and Tail Configuration



Lug and Pin

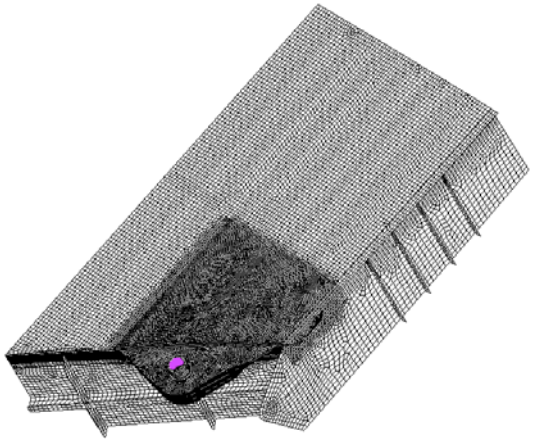


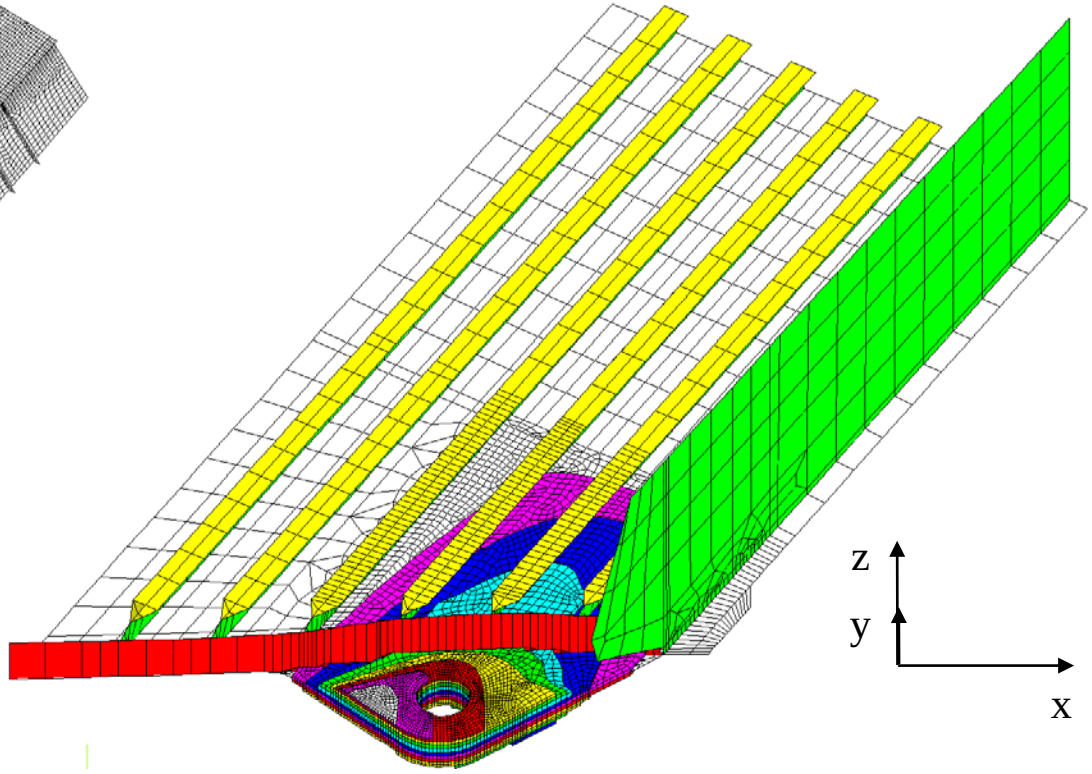
Local FE Model




Global FE Model

# 3D-Shell Finite Element Model

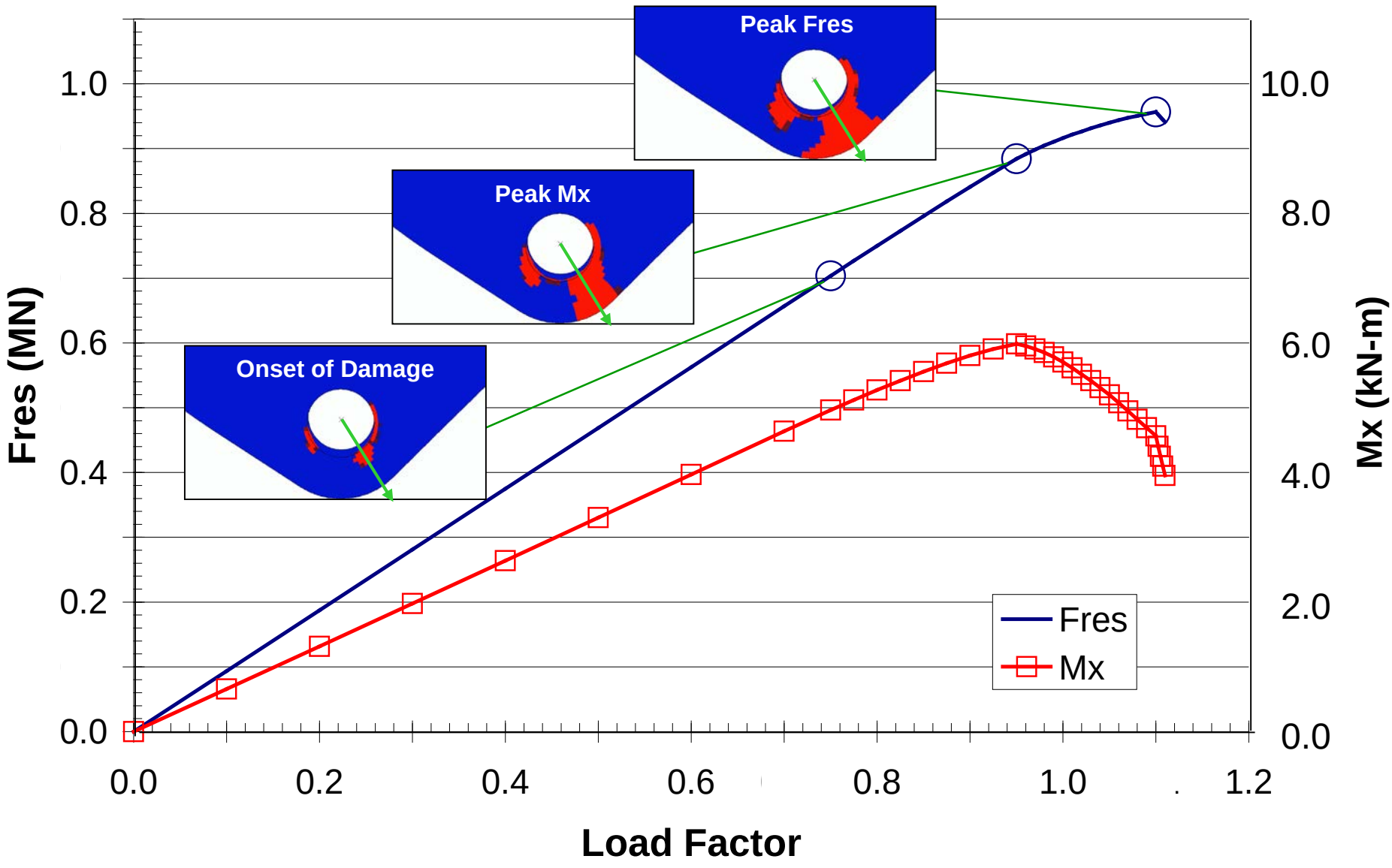




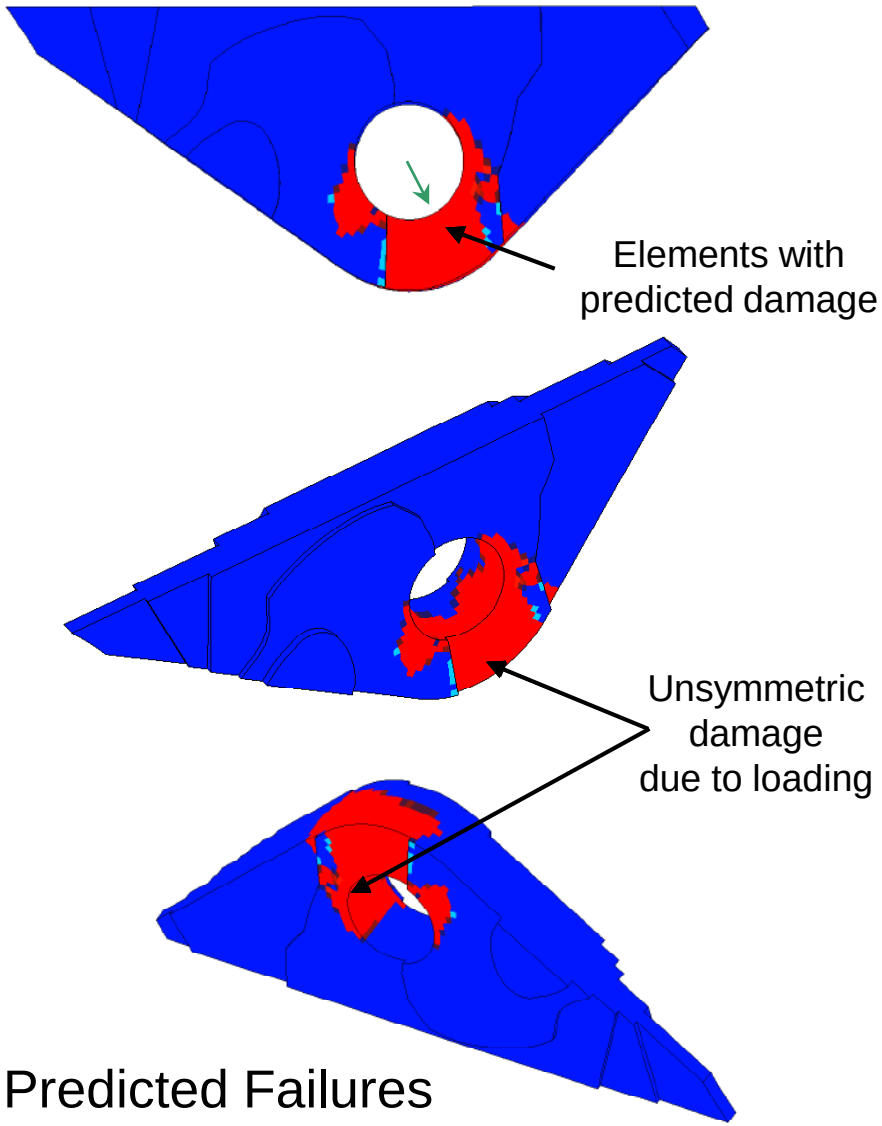

**Attributes**

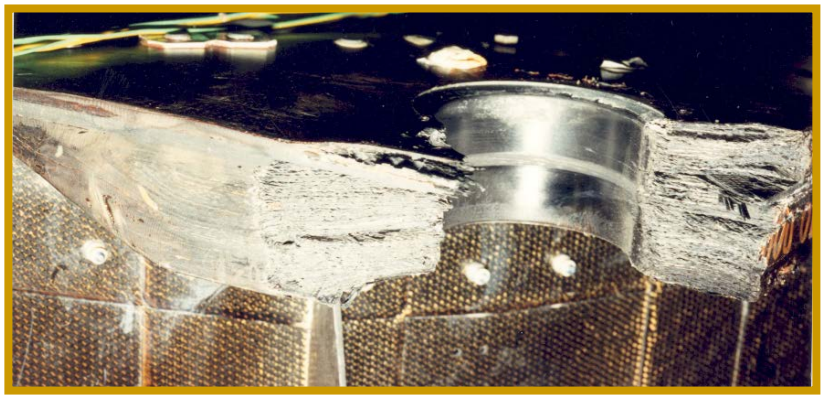
25,931 nodes
21,519 elements
Contact modeled
200 plies in lug
Global-local coupled analysis
Damage monitored as load incremented

# Damage Propagation from PFA



# Comparison of Predicted and Test Results

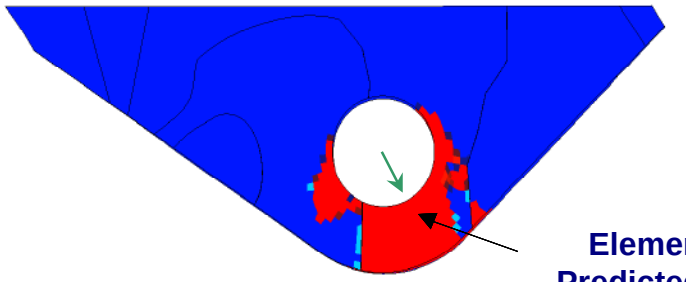


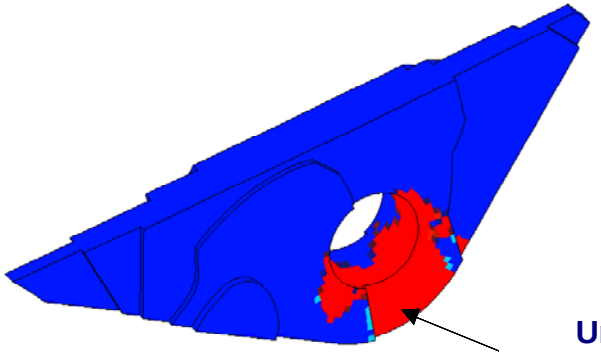
Failed Test Lug

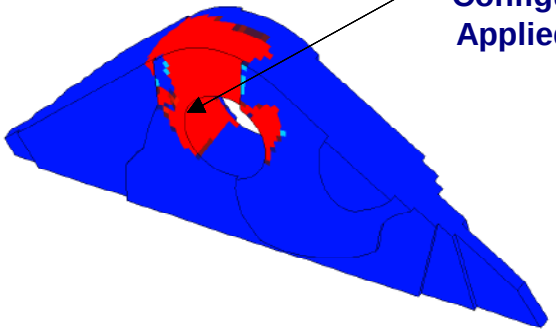
| | |
|---|---|
| **Test Failure Load** | **907 kN** |
| **Predicted Failure Load** | **896 kN** |

# W375 Accident Conditions – Damage

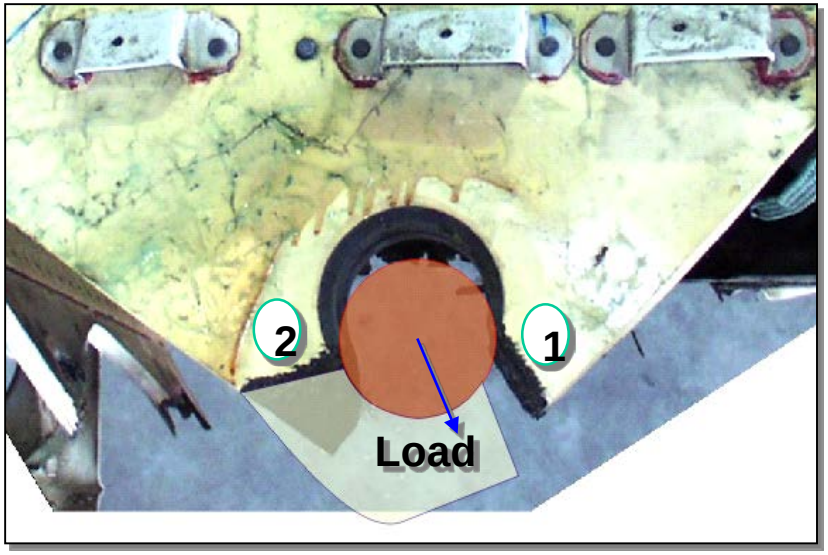


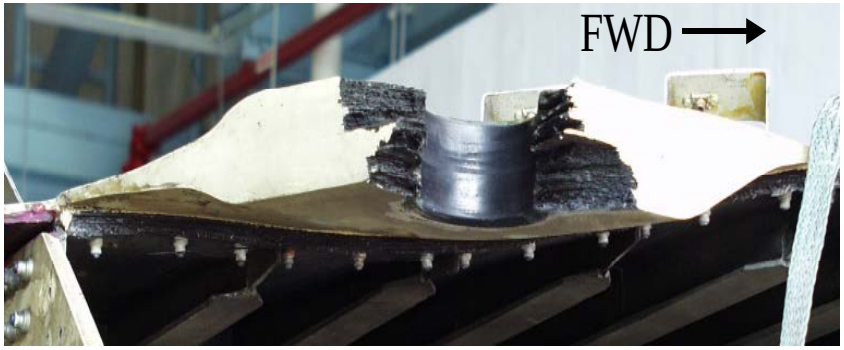
Elements with Predicted Damage



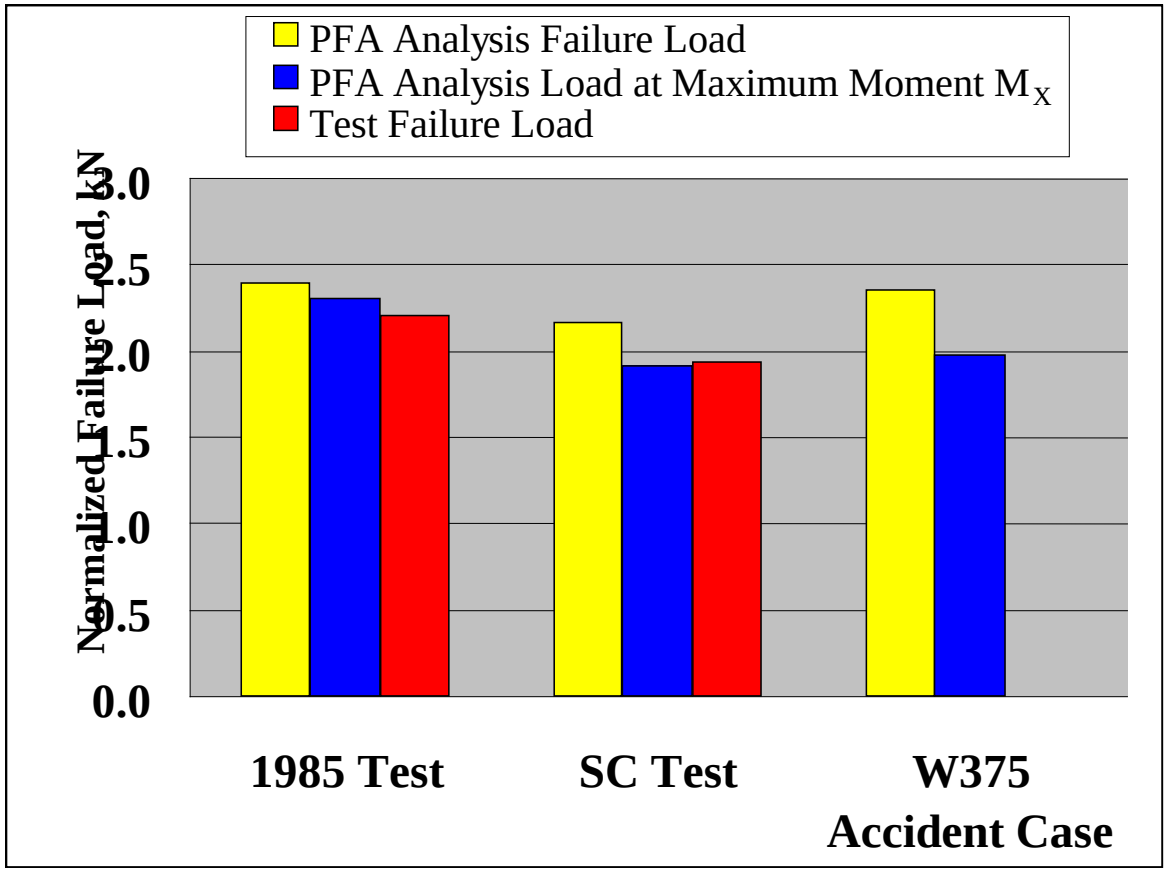


Unsymmetric Damage Due to Configuration and Applied Moments



# Normalized Failure Load for 1985-Certification Test, 2003-Subcomponent Test and W375 Accident Condition



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Complexity, Computational Expense

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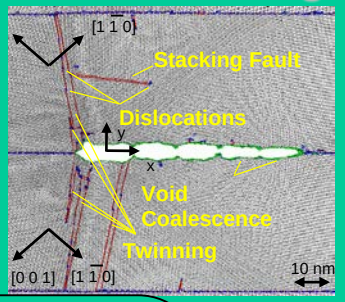
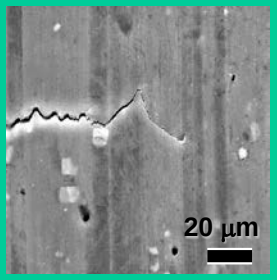
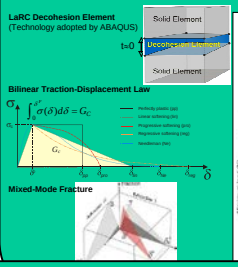
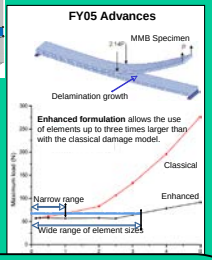
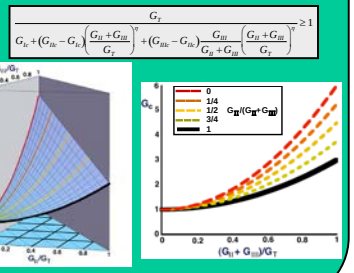



## Emerging Continuum Methods

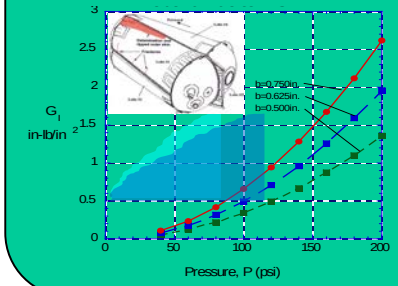


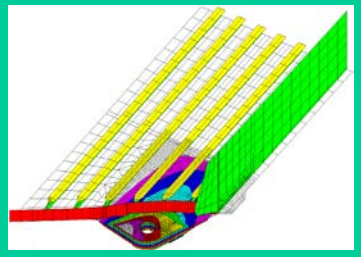



Spin-Offs

## Current State-of-the-Art



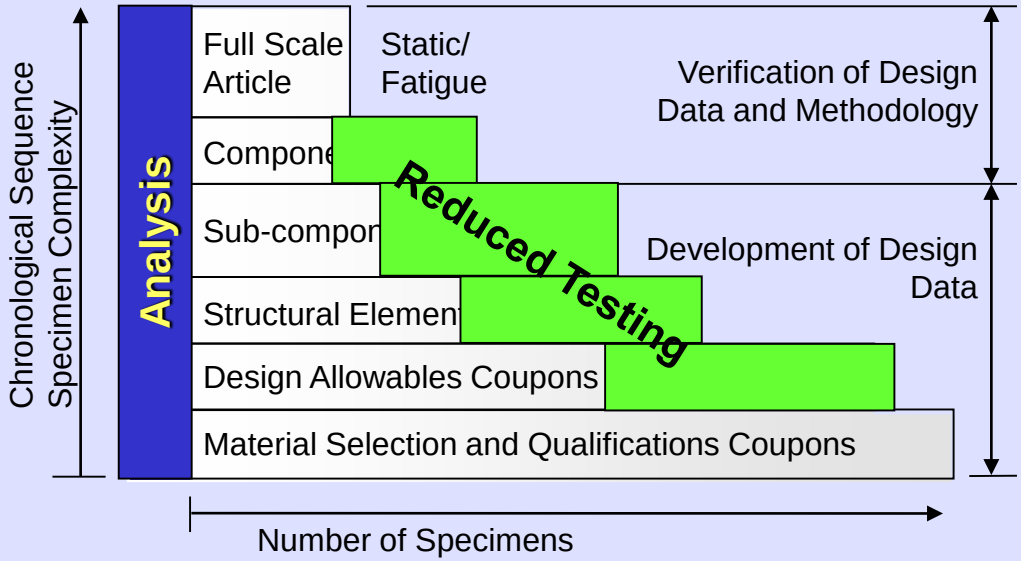



Spin-Offs

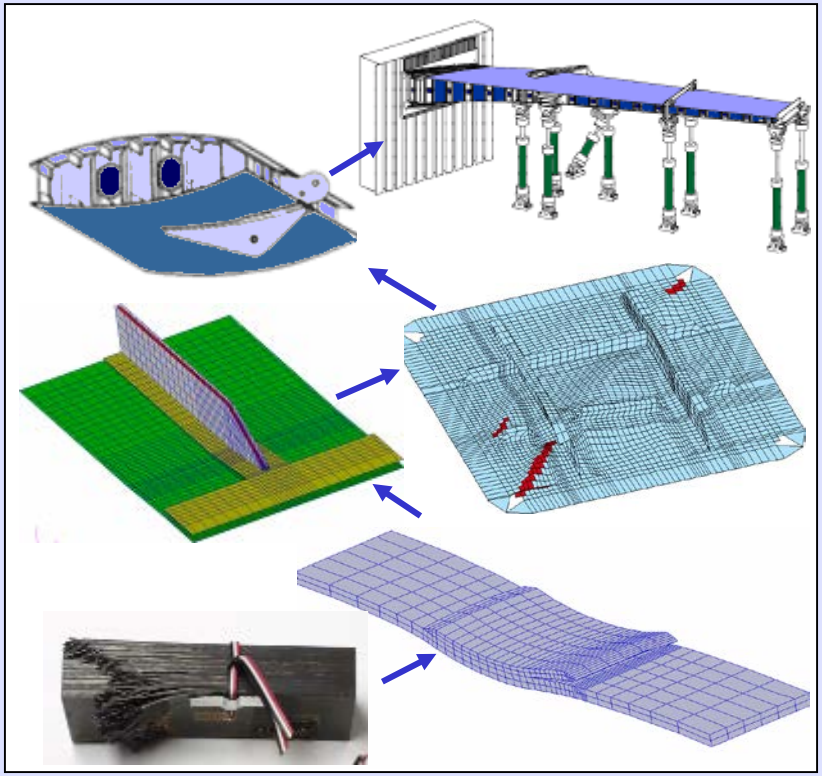
# Building Block Approach

## Building Block Integration.

*Certification Methodology (Mil-Hbk.-17)*




## Structural Levels of Testing & Analysis

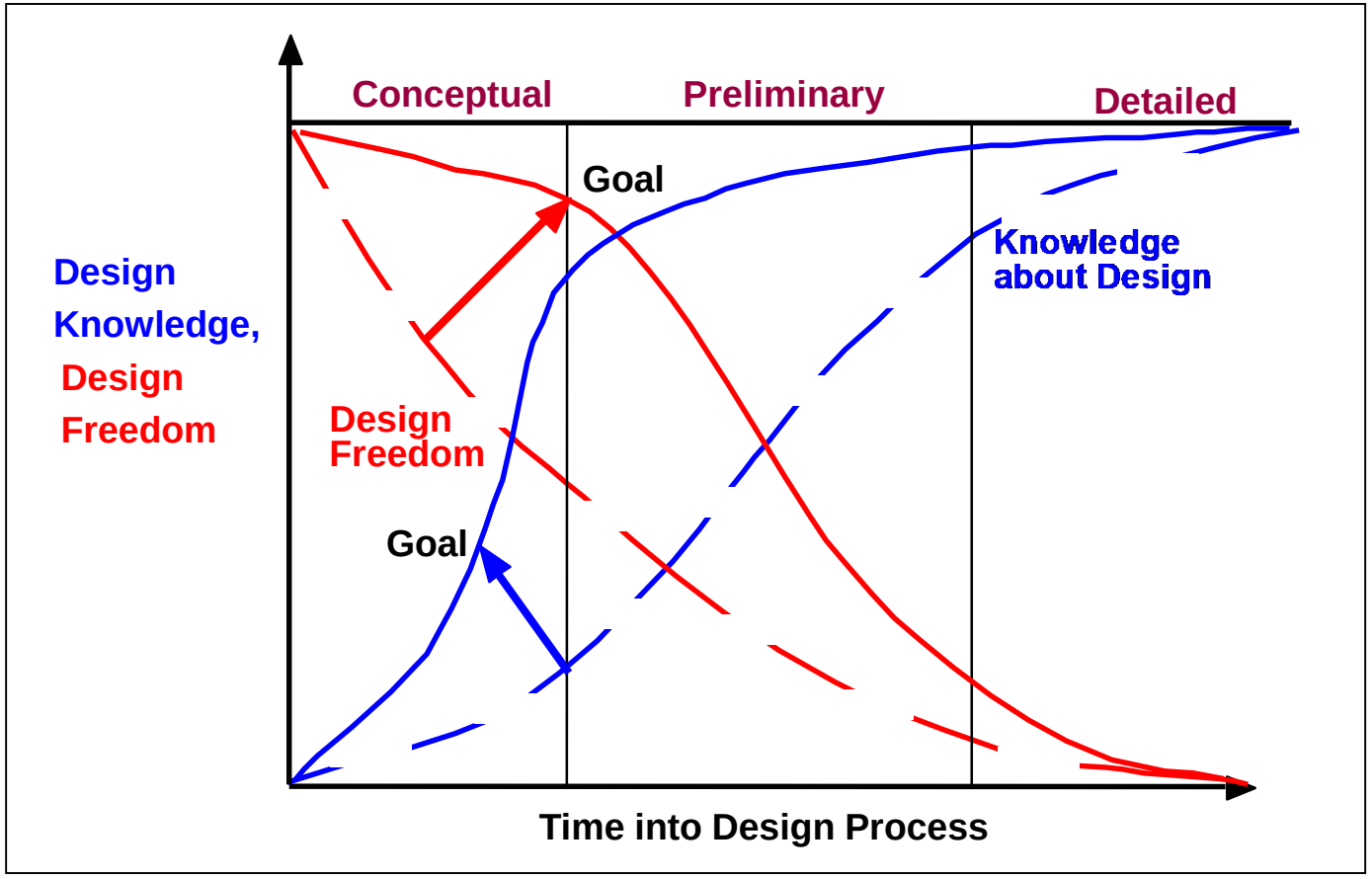


- **High-Fidelity Progressive Failure Analysis**
  - **Reduced reliance on testing**
  - **Faster design process**

  } ➡ **reduced non-recurring costs**

  - **More accurate design tools** ➡ **reduced recurring costs**

# Design Freedom vs. Knowledge



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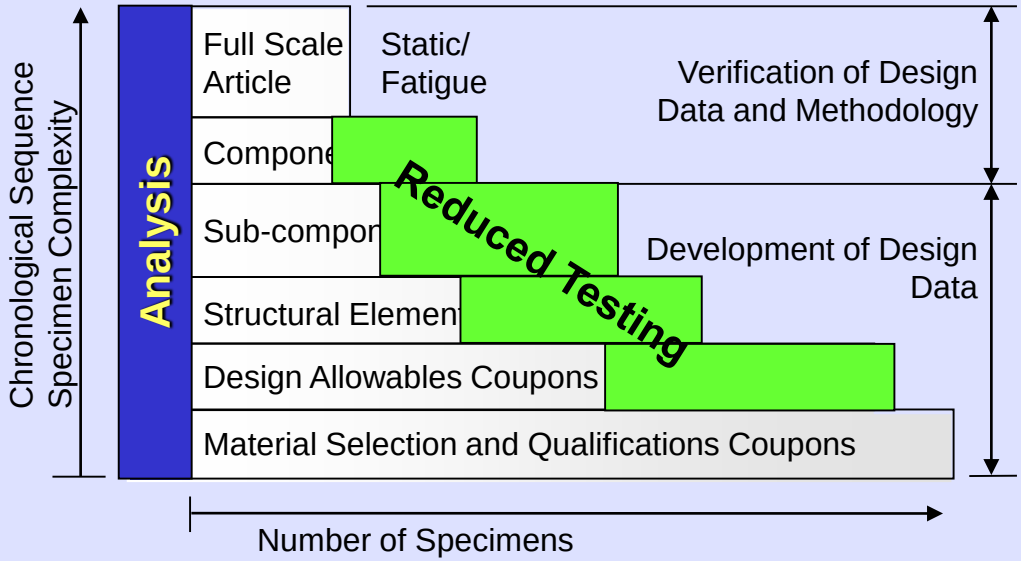
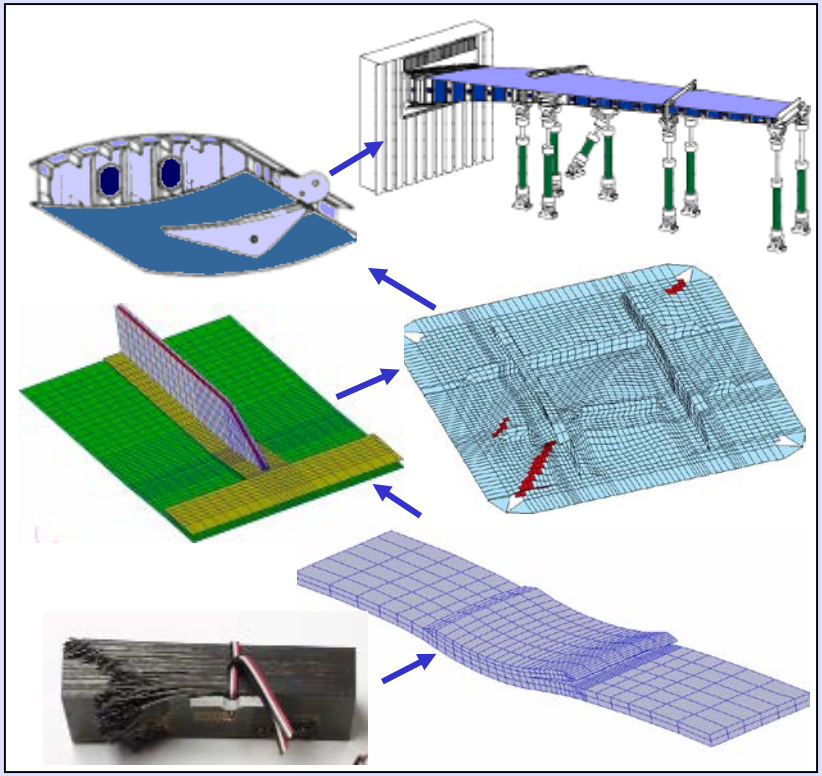



## Structural Levels of Testing & Analysis



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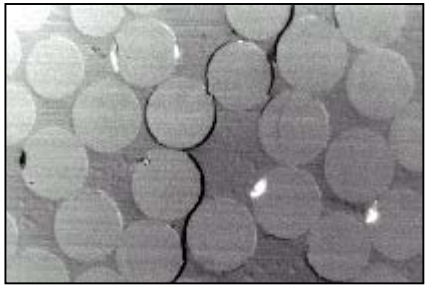
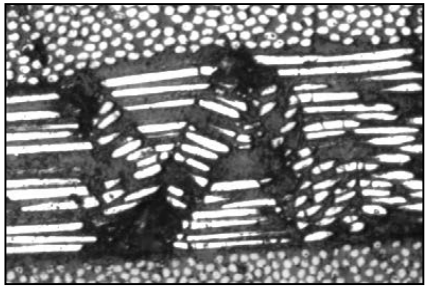
# Failure Criteria for Laminated Composites

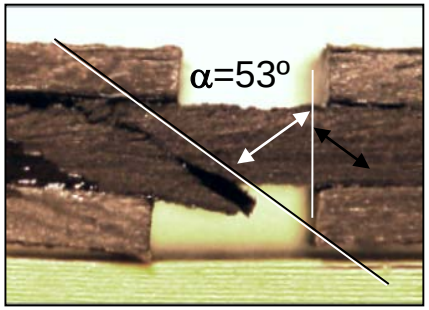
- Failure Criteria are used for predicting damage initiation and final failure
- Composites have multiple damage modes; each requires a different criterion

## LaRC04 Criteria

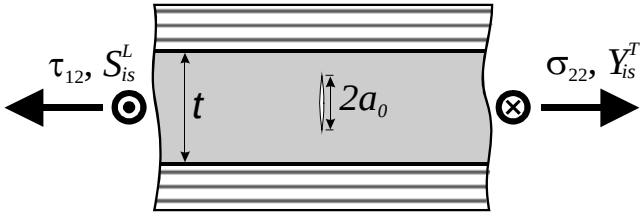
- In-situ matrix strength prediction
- Advanced fiber kinking criterion
- Prediction of angle of fracture (mat. compression)
- Criteria used as activation functions within framework of damage mechanics



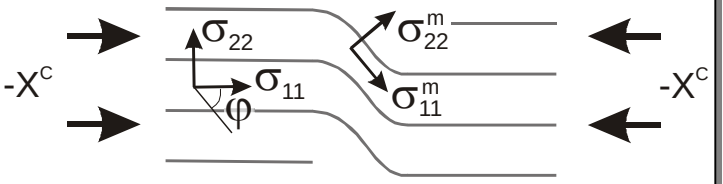




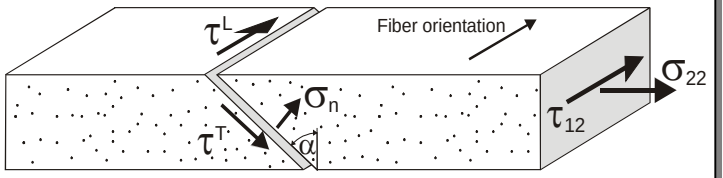

Matrix Tension & Shear




Fiber Compression




Matrix Compression and Shear



# LaRC04 in Continuum Damage Model

**Gibbs Free Energy**

$$G = \frac{1}{2}\sigma : H : \sigma + \sigma : \alpha\Delta T =$$

$$= \frac{\sigma_{11}^2}{2(1-d_1)E_1} + \frac{\sigma_{22}^2}{2(1-d_2)E_2} + \frac{\nu_{12}}{E_1}\sigma_{11}\sigma_{22} + \frac{\sigma_{12}^2}{2(1-d_6)G_{12}} + (\alpha_{11}\sigma_{11} + \alpha_{22}\sigma_{22})\Delta T$$

**Strains:** $\varepsilon = \dfrac{\partial G}{\partial \sigma} = H : \sigma + \alpha\Delta T$

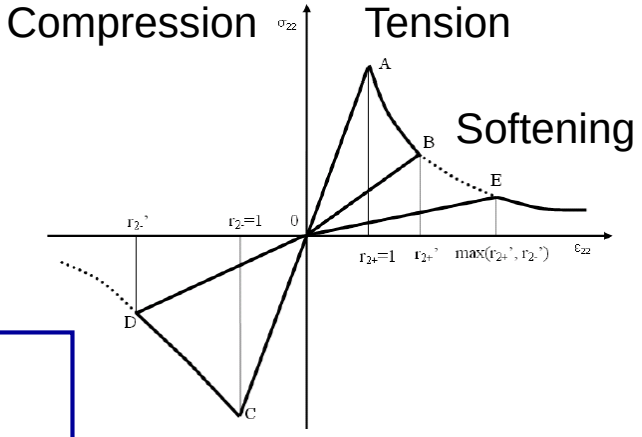
**Lamina Secant Relation**

$$H = \frac{\partial^2 G}{\partial^2 \sigma} = \begin{bmatrix} \frac{1}{(1-d_1)E_1} & -\frac{\nu_{21}}{E_2} & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{(1-d_2)E_2} & 0 \\ 0 & 0 & \frac{1}{(1-d_6)G_{12}} \end{bmatrix}$$

**Rate of Damage Growth**

$$d_i = 1 - \frac{1}{f_i(r_i)} \exp\left(A_i\left(1 - f_i(r_i)\right)\right)$$

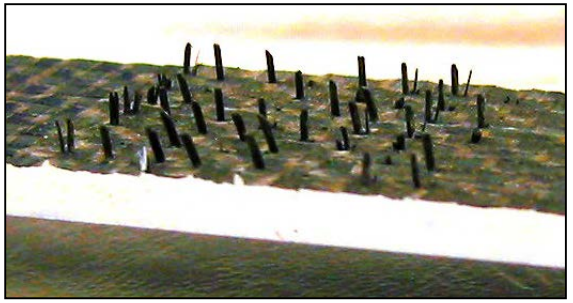
$f_i$: LaRC04 failure criteria as activation functions




**CDM ensures consistent material degradation and mesh-independent solution**

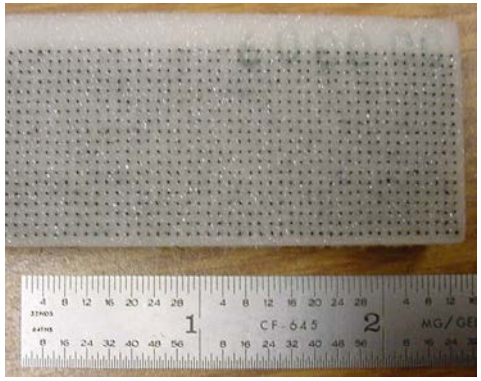
# Z-Pin Technology

- **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 / Drawbacks**
  - Improve composite laminate transverse strength
  - Prohibit delamination
  - Degrade laminate (in-plane) properties, see micrograph
- **Applications**
  - Areas with significant out-of-plane loads such as bonded stiffener termination
  - Areas exposed to impact damage threat

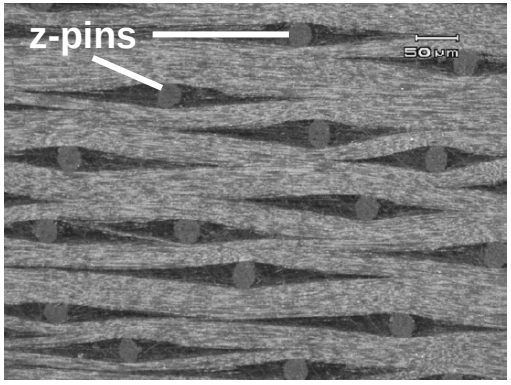


Z-Pins protruding from laminate*

Z-Pin preform: Upper side**



Z-Pin preform: Insertion side**



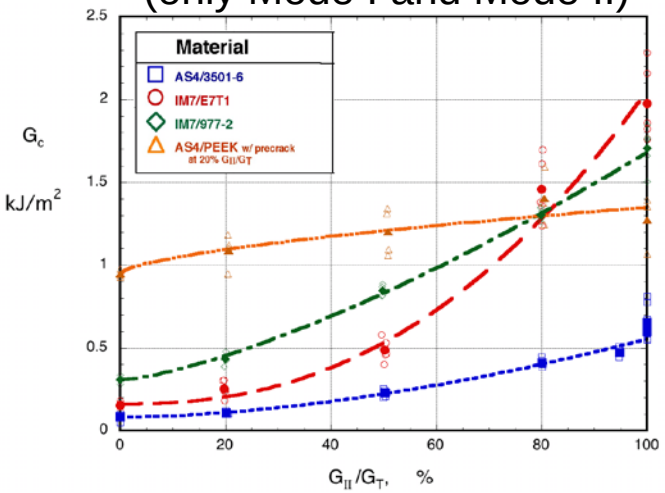

Fiber misalignment from z-pins***

*James Ratcliffe, NIA. **Pierre Minguet, Boeing. ***Jeffery Schaff, Sikorsky Aircraft.

# New Delamination Criterion Needed

## 2D Fracture Criterion

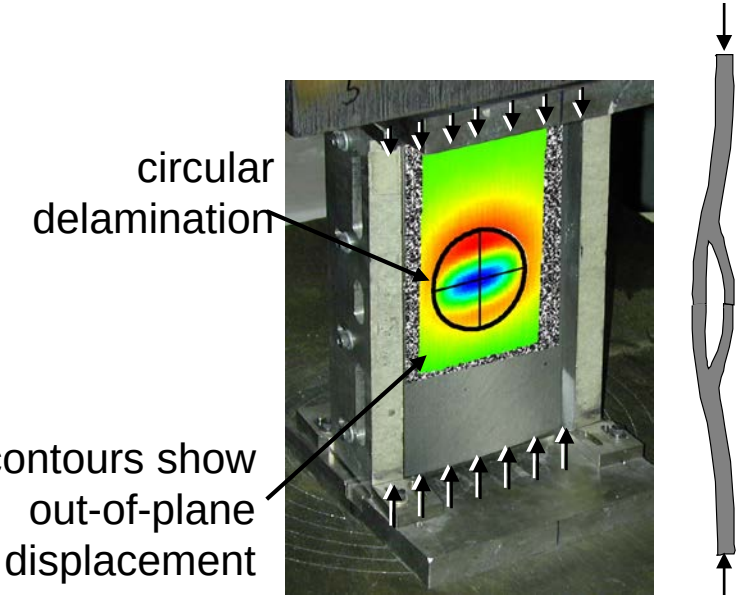
(only Mode I and Mode II)



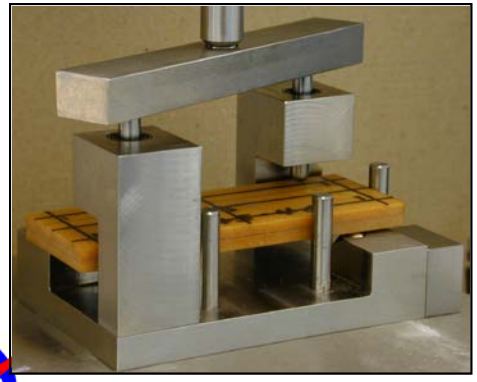

## B-K Criterion

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

## 3D Problems Contain Mode III




sublaminate buckling problem



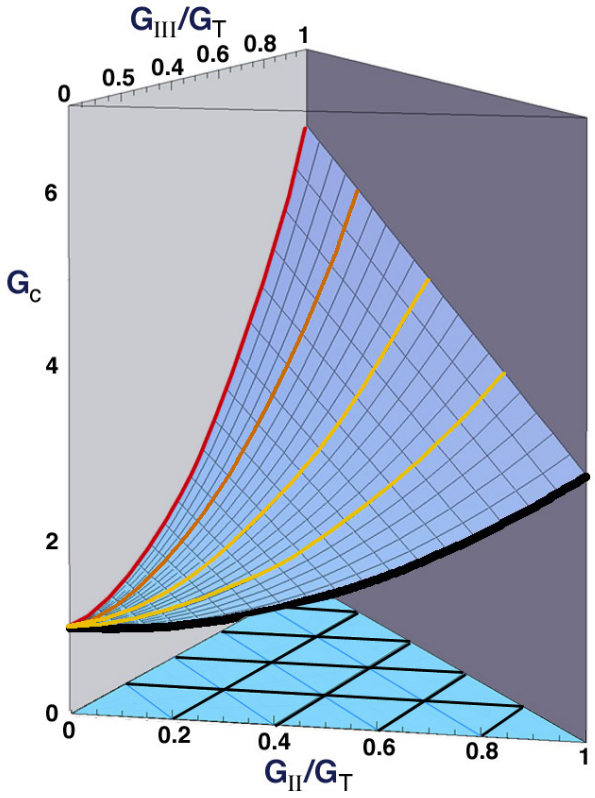
edge crack torsion test

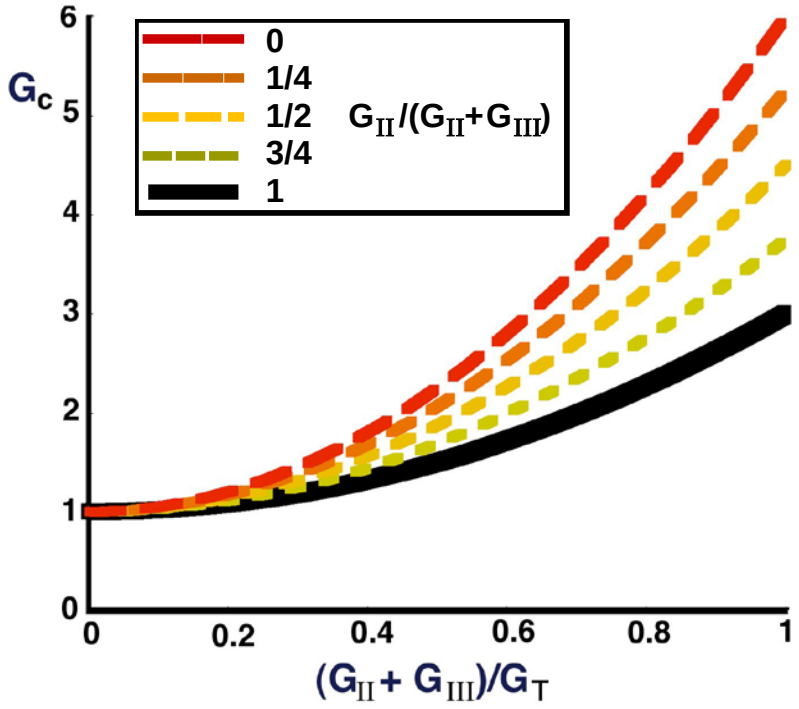
## Pure Mode III Testing

- ECT produces pure mode III data
- $G_{IIIc}$ normally higher than $G_{IIc}$
- No mixed-mode test with mode III component

# Proposed 3D Mixed-Mode Criterion

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



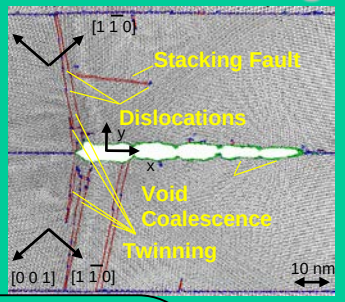

- Mode I-III interaction similar to the measured mode I-II interaction
- Linear interpolation between mode III and mode II

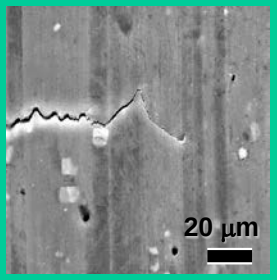
# Evolution of Damage Tolerance at NASA Langley (1999-)

Complexity, Computational Expense

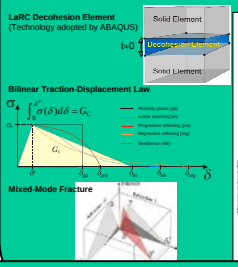
Time

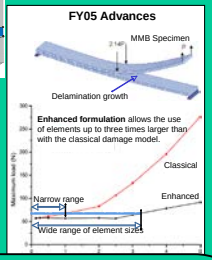
## Damage Science

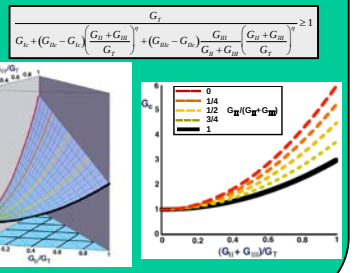



## Emerging Continuum Methods

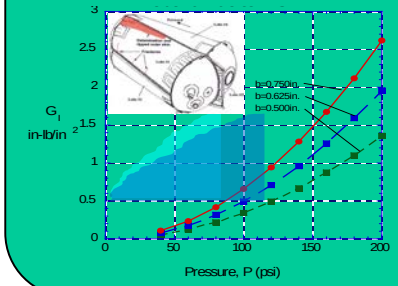


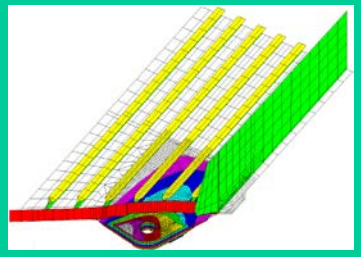



Spin-Offs

## Current State-of-the-Art



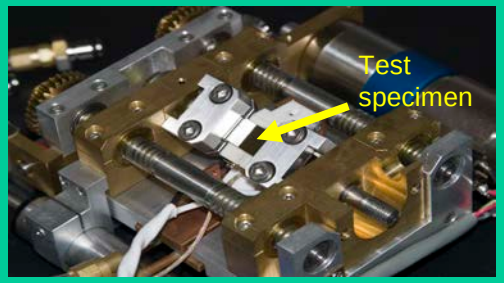
Spin-Offs

# Damage Science

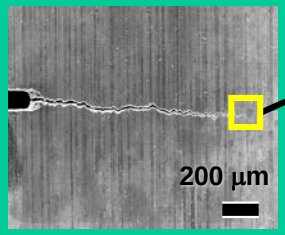
## Develop a fundamental understanding of the underlying damage processes that contribute to fracture initiation and propagation

### Experimental Damage Science

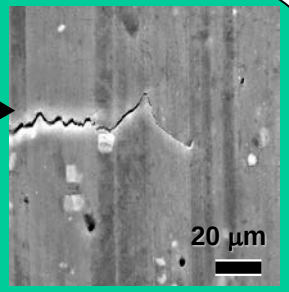
Materials characterization and in-situ mechanical testing with environmental capabilities




In-situ loading frame with heater/cooler and specimen tilt for EBSD analysis



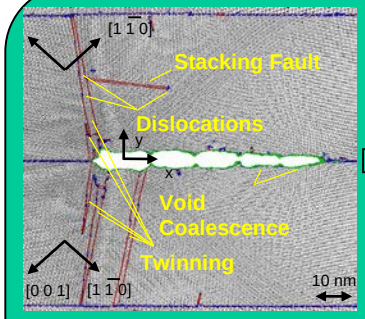

SEM micrograph of fatigue crack emanating from EDM notch



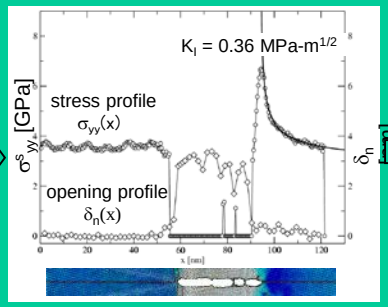

SEM micrograph of fatigue crack tip

**Develop multi-disciplinary Damage Science approach to:**
1) Characterize material structure and characteristic damage processes,
2) Develop multi-scale models to predict damage, and
3) Validate models through examination of near-tip damage processes.

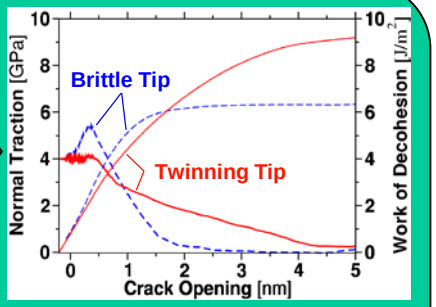
### Computational Damage Science



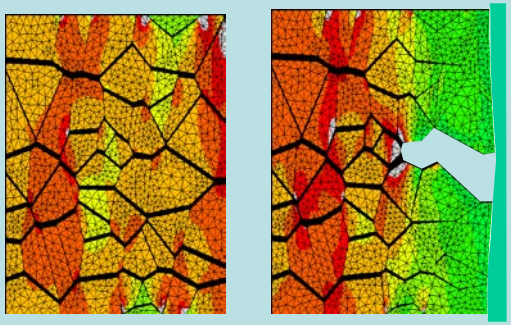

Mechanisms of Nano-crack Propagation




Calculation of Normal Stress and Crack Opening




Continuum Representation of Atomistic Behavior

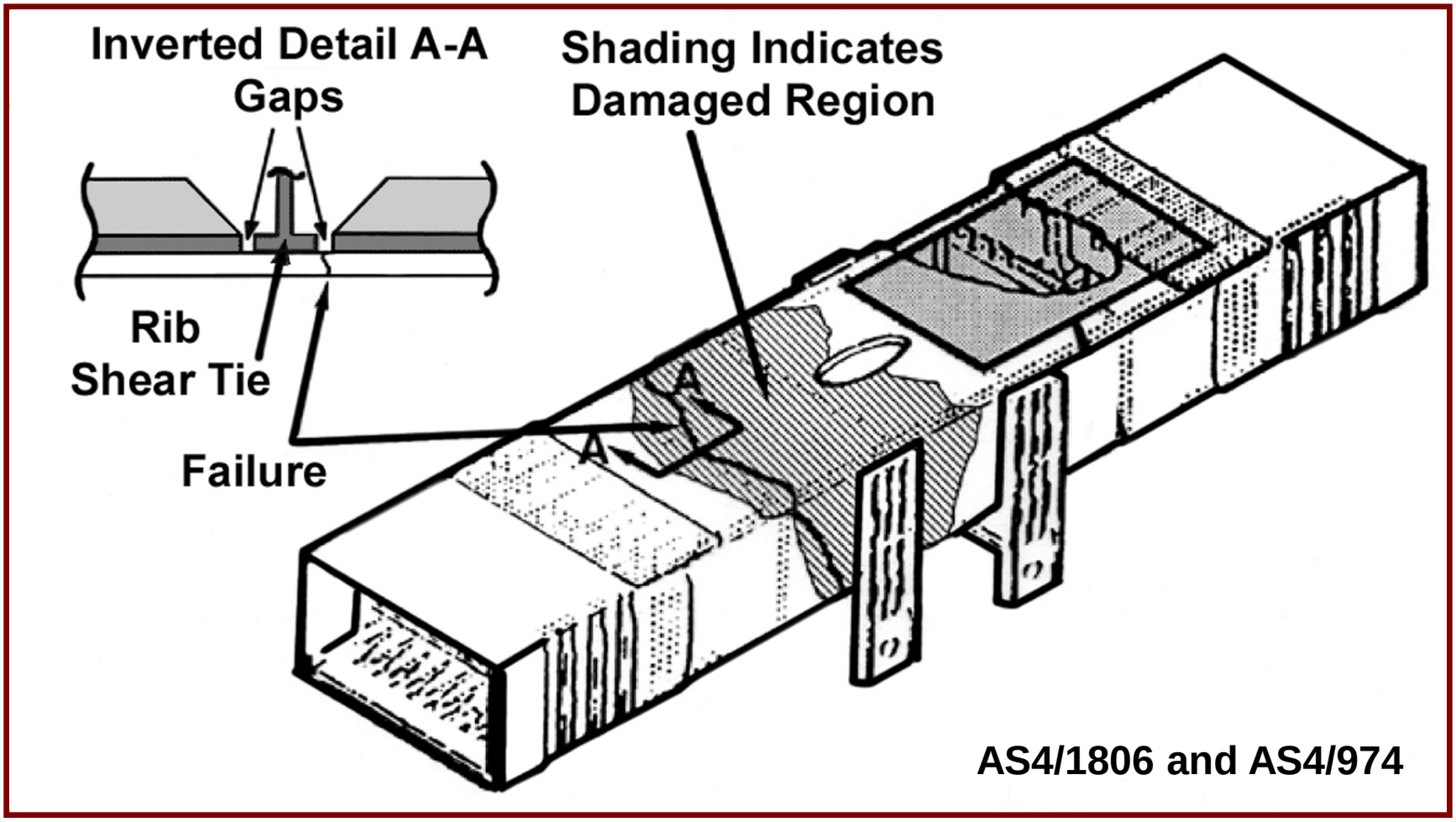


Micro-Scale Crack Growth

# Summary

- Damage tolerance of composite wing boxes and full scale wing structures
  - Textile composites
  - Stitching
  - Efficient analysis methods
- SOA analysis demonstrated on
  - X-33 LH2 tank failure
  - AA587 composite lug analysis
- Emerging continuum methods
  - New criteria for interlaminar and intralaminar failure
  - Continuum damage models - Mesh independence
  - Z-pinning
- Damage science to understand failure initiation and growth - Damage Tolerance

# NASA ACT Program – Center Wing Box Test (1991)



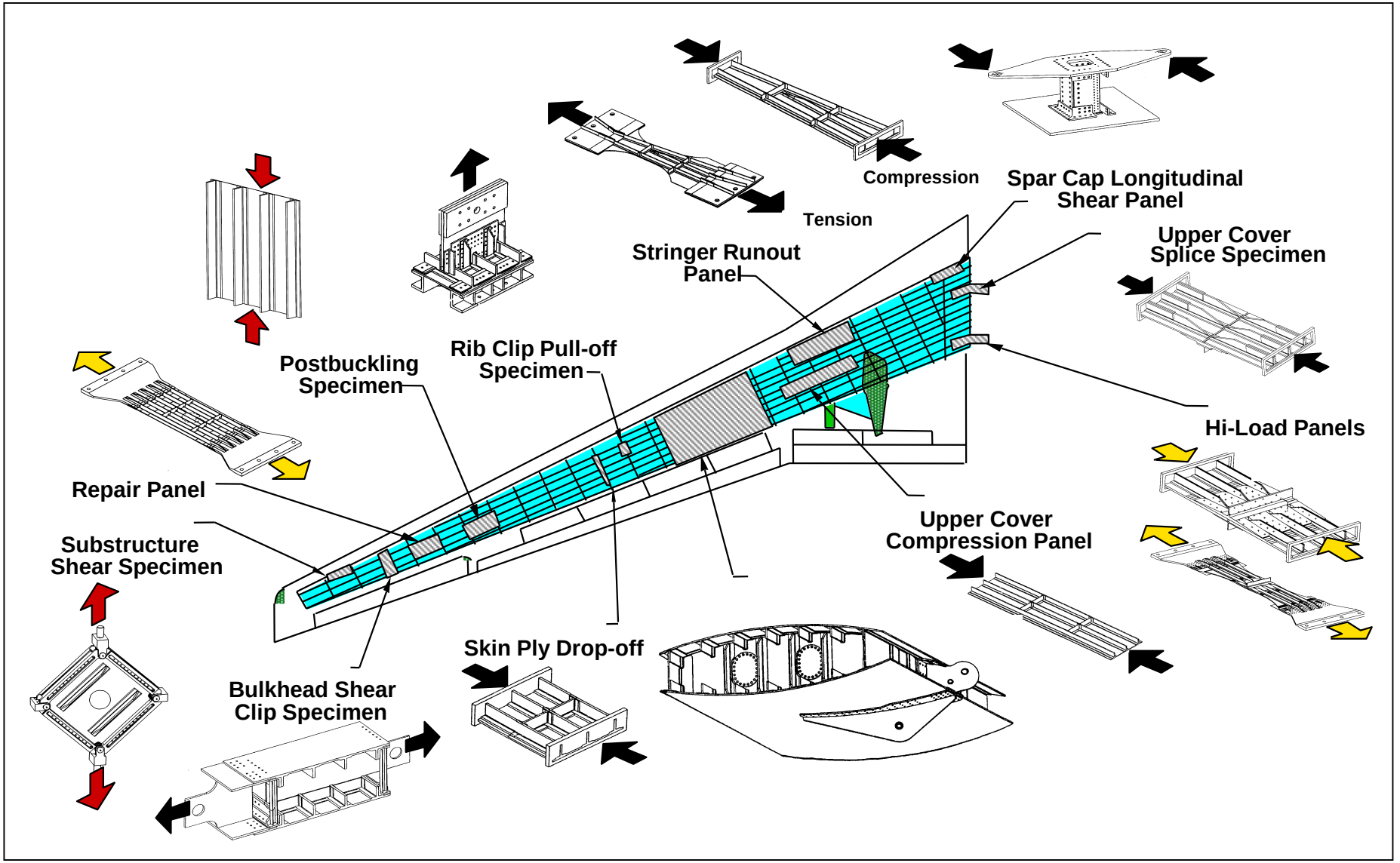

- Test Article failed at 83% of DUL under combined bending & torsion
- Unanticipated shear failure mode at out-of-tolerance gap

# NASA ACT Program – Wing Stub Box Test (1996)


**AS4/3501-6 and IM7/3501-6 in textile preform**

- **Test article failed at 94% of DUL due to nonvisible impact damage**
- **Compression after impact (CAI) strength allowable did not account for damaged elements (skin/stiffener) interaction**

# Building Block Approach – Reliance on Extensive Testing



# Progressive Damage Analysis

## Modeling Complexities

- Failure of unidirectional and laminated composites (in-situ)
- Material nonlinearity & material degradation laws
- Thermal residual stresses
- Effects of stress gradients & notches
- Size Effects
- Finite Element implementation
- Delamination growth: static & fatigue
- Damage mode interaction
- Stitched composites and textiles