NASA Perspectives on Airframe Structural Substantiation: Past Support and Future Developments

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Outline of Briefing

- History of NASA Composite Structures Programs
  - Applications in Commercial Aircraft
    - NASA Aircraft Energy Efficiency Program (1972-1986)
    - NASA Advanced Composites Program (1989-2000)
  - Applications in Space Transportation Vehicles
    - NASA Space Shuttle (1974 – present)
    - New space launch vehicles (1996 – present)
- Progress in Composites Damage Mechanics Research….
  Past, present, and future

Aircraft Energy Efficiency (ACEE) Program
(1972-1986)

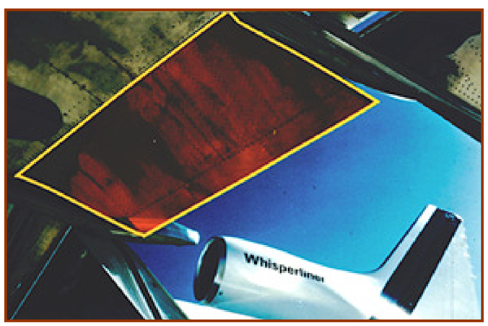
Program Goals:

- Obtain actual flight experience
- Obtain environmental exposure data

Boeing 727 composite elevator

Boeing 737 composite horizontal stabilizer

Lockheed L-1011 composite aileron



Douglas DC-10 composite Rudder and vertical stabilizer

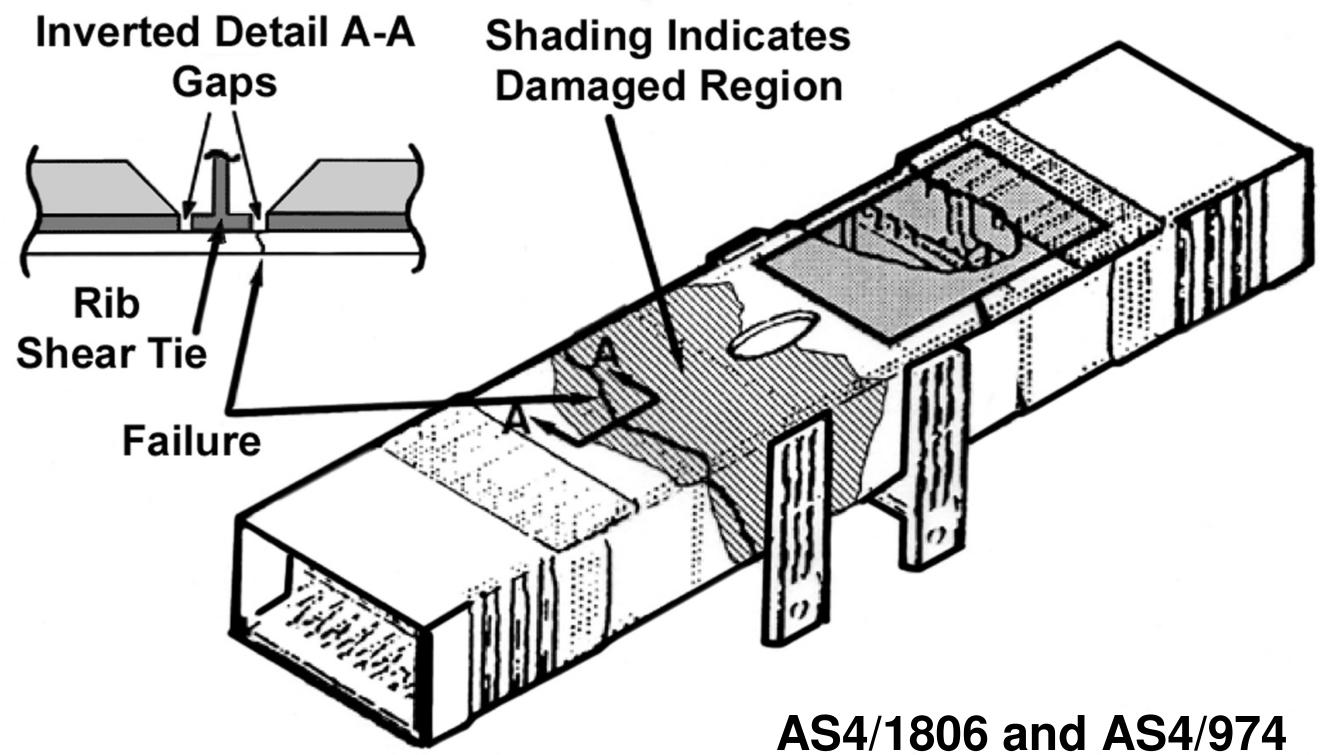
350 Composite components accumulated over 3.5 million flight hours by 1993!

Advanced Composites Technology (ACT) Program (1989-2000)

Program Goals:

- 25% structural weight reduction
- 20% structural fabrication cost reduction

Center Wing Box Test (1991)



AS4/1806 and AS4/974

- **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**

NASA ACT Program -- Full Scale Wing Box Test (2000)

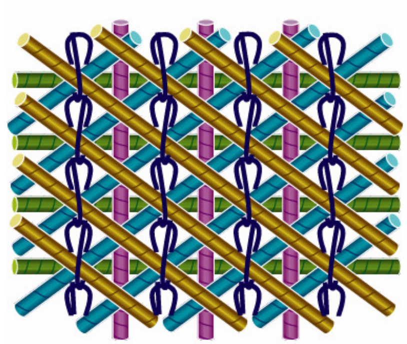
AS4/3501-6 and IM7/3501-6 in textile preform

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

Improving Damage Tolerance (1990's)

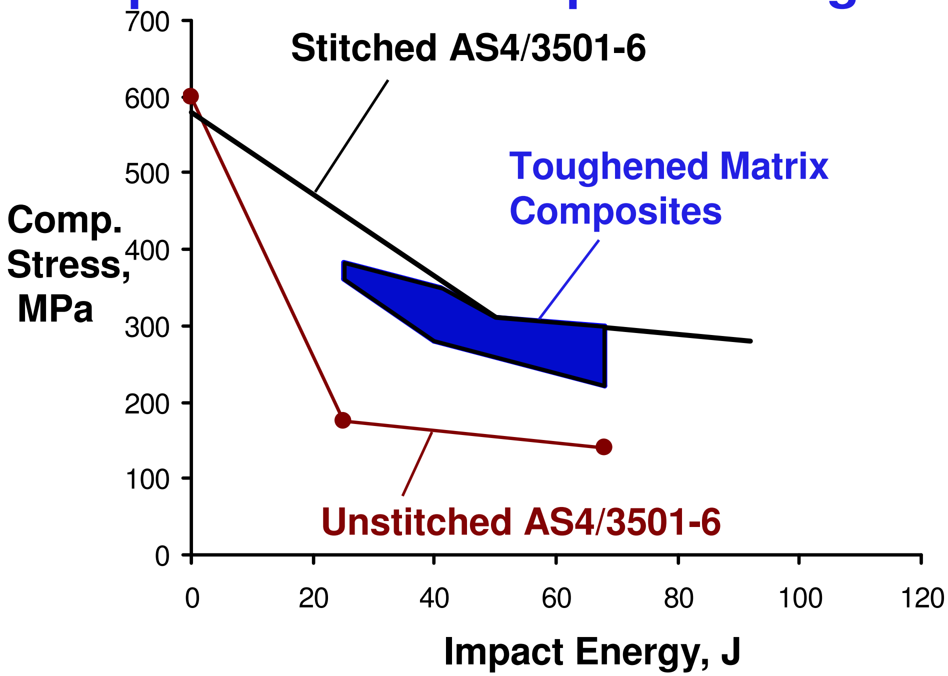
Stitched Textile Composites

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

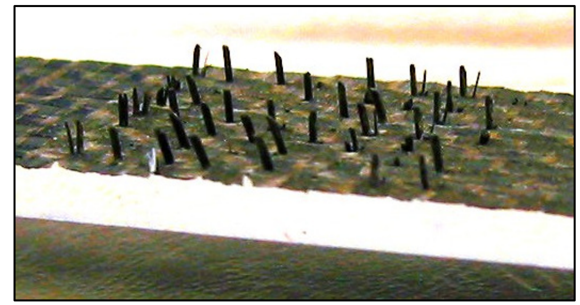


Multiaxial warp knit (stitched & unstitched)

Compression After Impact Strength

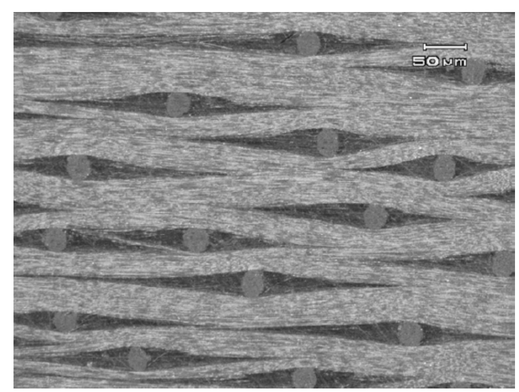


Z-pin Technology



Pultruded graphite rods stuck through the laminate

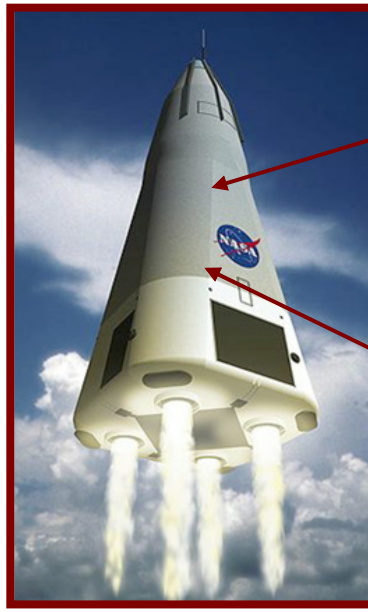
- Improve transverse strength
- Prohibit delamination
- Degrade laminate properties

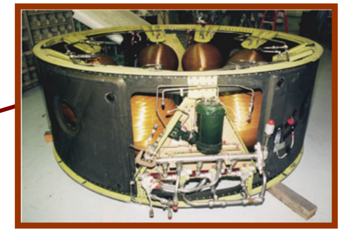


Fiber misalignment from z-pins

Applications in Space Transportation Vehicles

Shuttle Orbiter
1974 – present
Carbon/carbon: Nose Cone and Wing Leading Edge Panels
Graphite Epoxy: Cargo Bay Doors, Robotic Arm, OMS pods

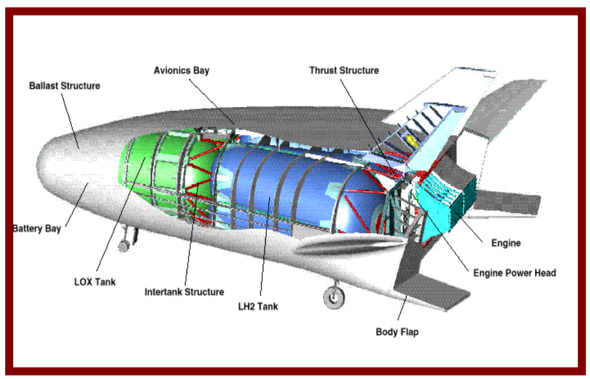




Composite Intertank

Composite LH_2 Tank

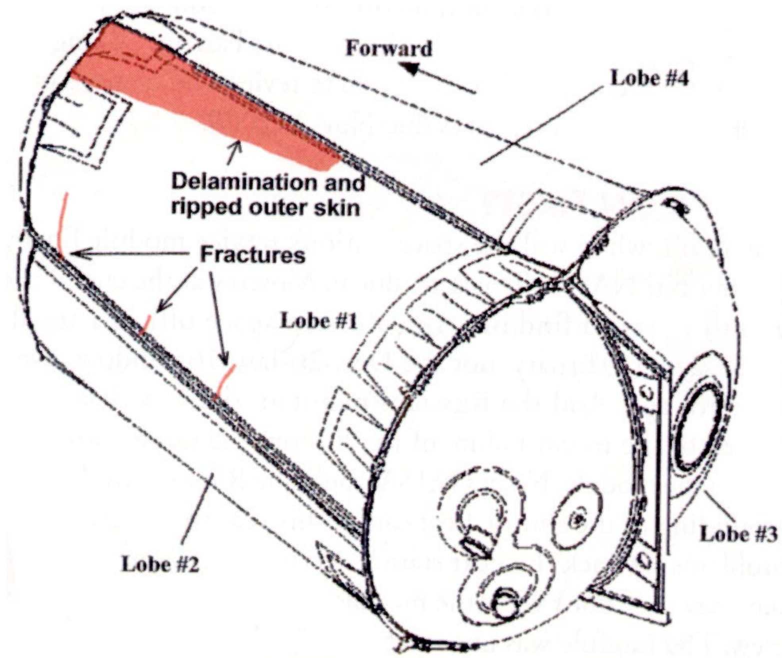
DC-XA Flight Test Vehicle, 3 flights (1992-1996)



Program cancelled after composite LH2 tank failure during prototype proof test

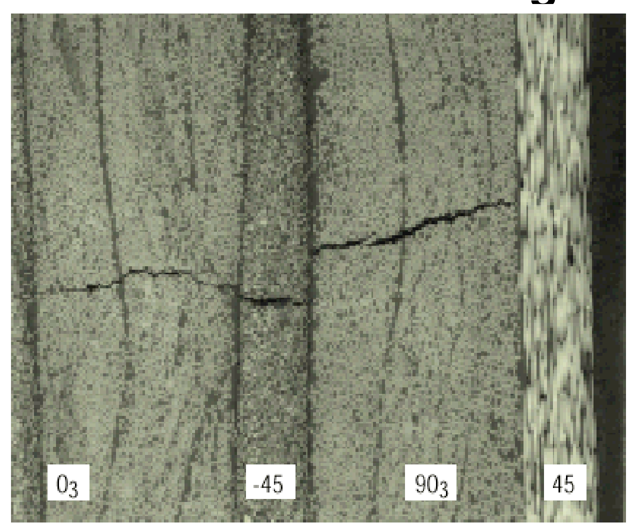
X-33 SSTO Flight Test Vehicle (1996-2000)

Causes of the X-33 Composite Tank Failure



Teflon Tape in Core

Inner Skin Microcracking

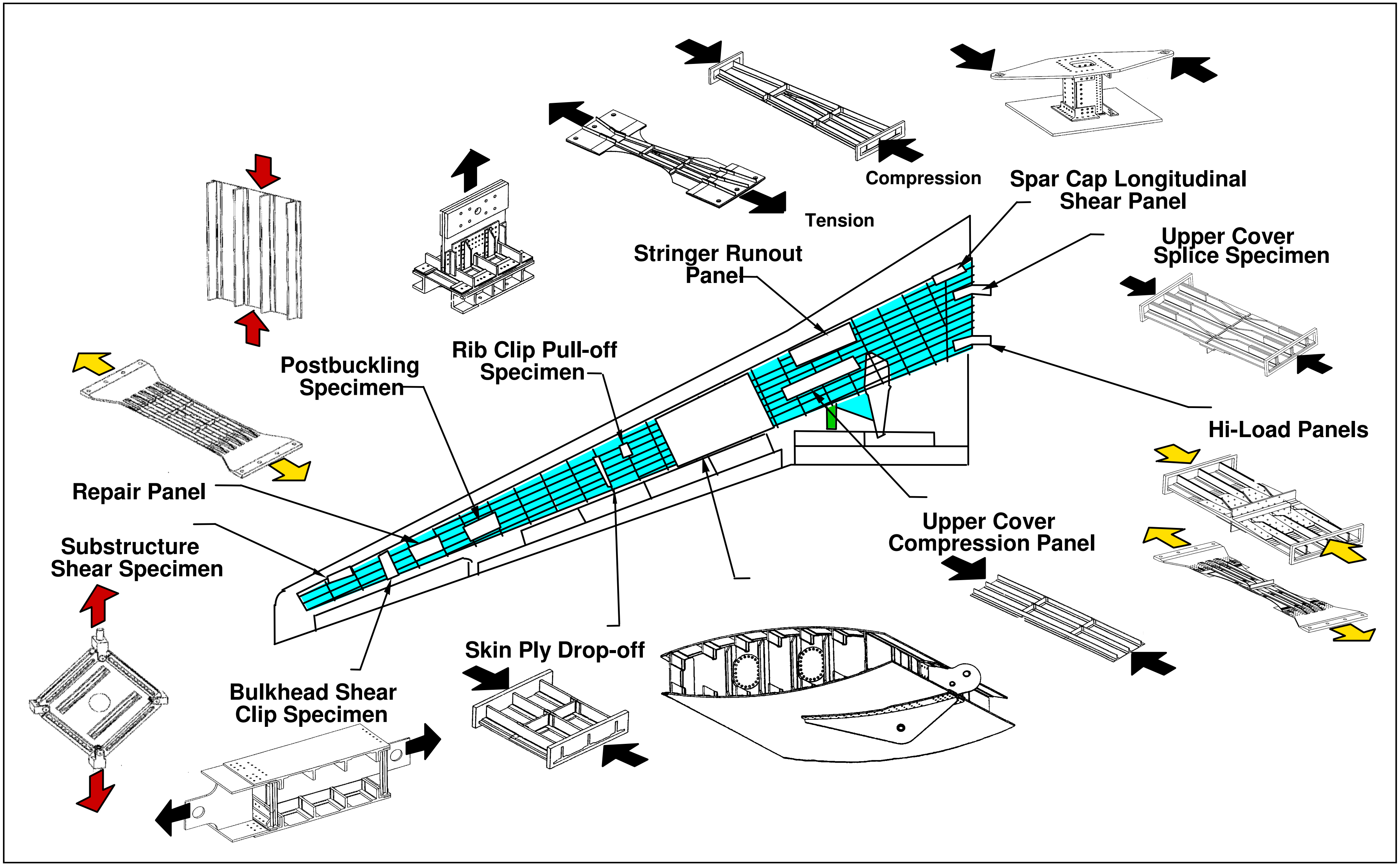


Weak Core to Face Sheet Bond Strength/Toughness

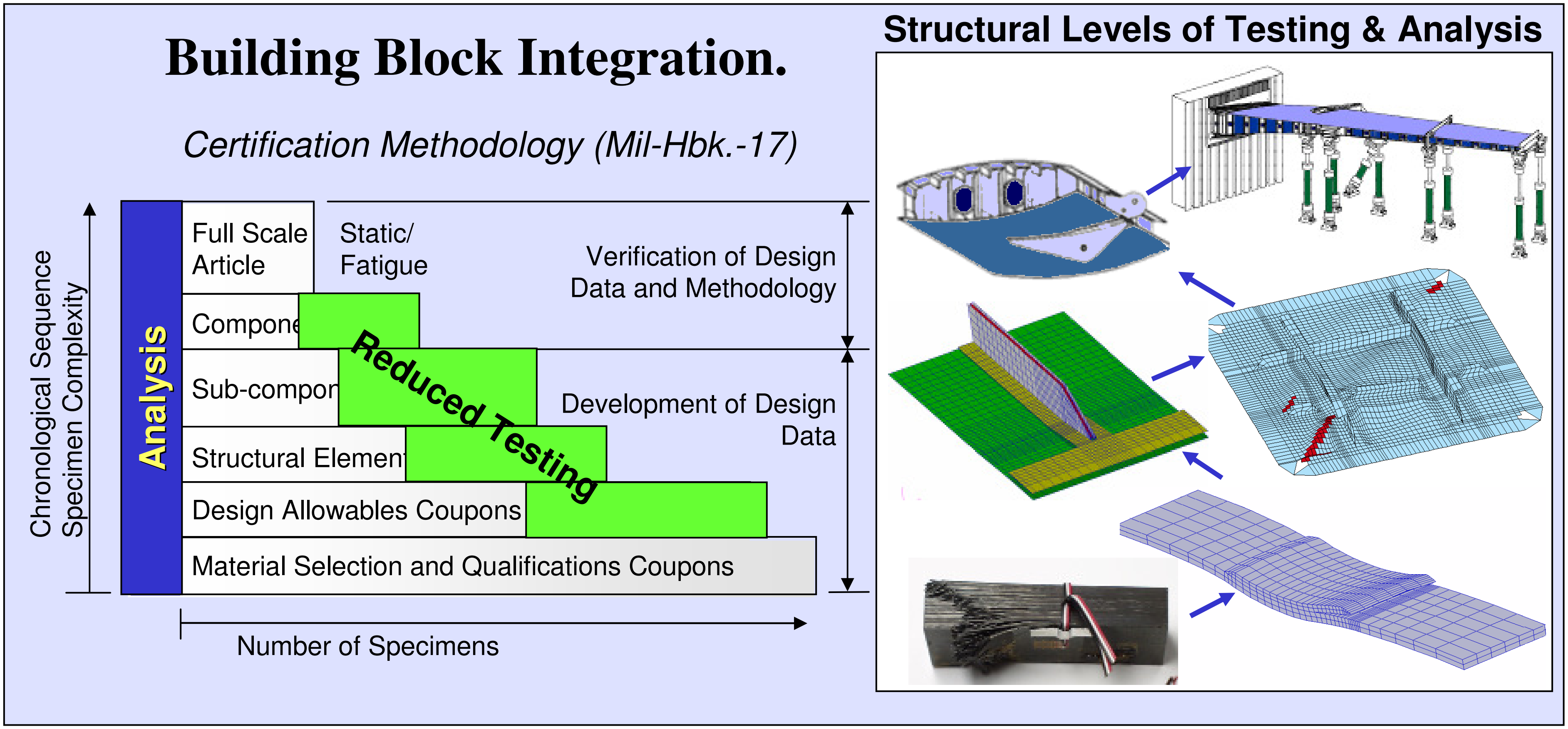
Progress in Composite Damage Mechanics

- Building Block Approach
- Progressive damage analysis for through-thickness notches
- Delamination growth
- Sandwich Structure
- Textiles
- Damage Tolerant Concepts
- Composites Damage Science

Conventional Building Block Approach - Reliance on Extensive Testing



Building Block Approach Augmented by Analysis

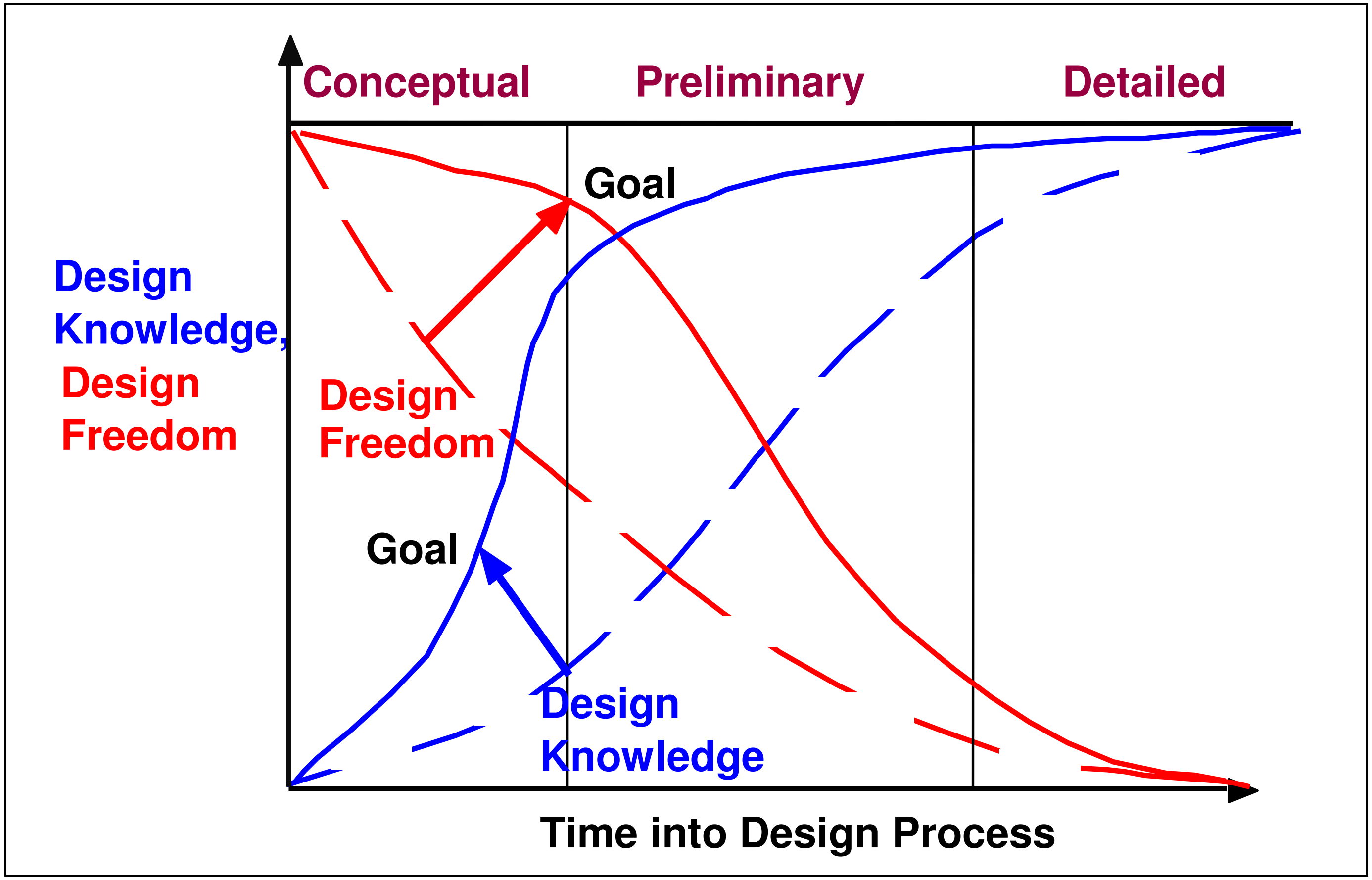


- High-fidelity Progressive Damage Analysis
  - reduced reliance on testing
  - faster design process

  } ➡ reduced non-recurring costs

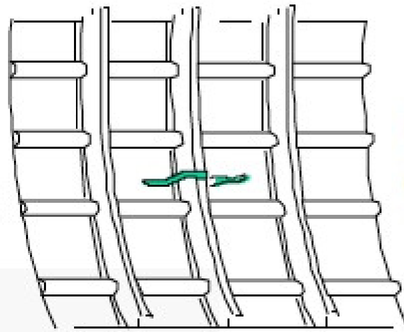
  - more accurate design tools ➡ reduced recurring costs

Knowledge versus Design Freedom

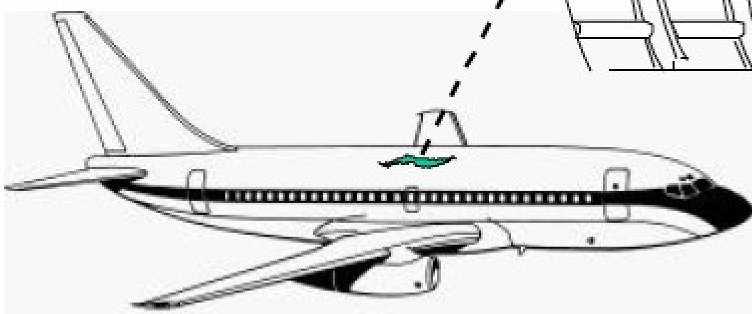


Analysis for Through-Thickness Notches

Fuselage Panel With Discrete Source Damage was analyzed and tested during the AST ACT Program



Damage tolerance test panel was designed and fabricated by Boeing

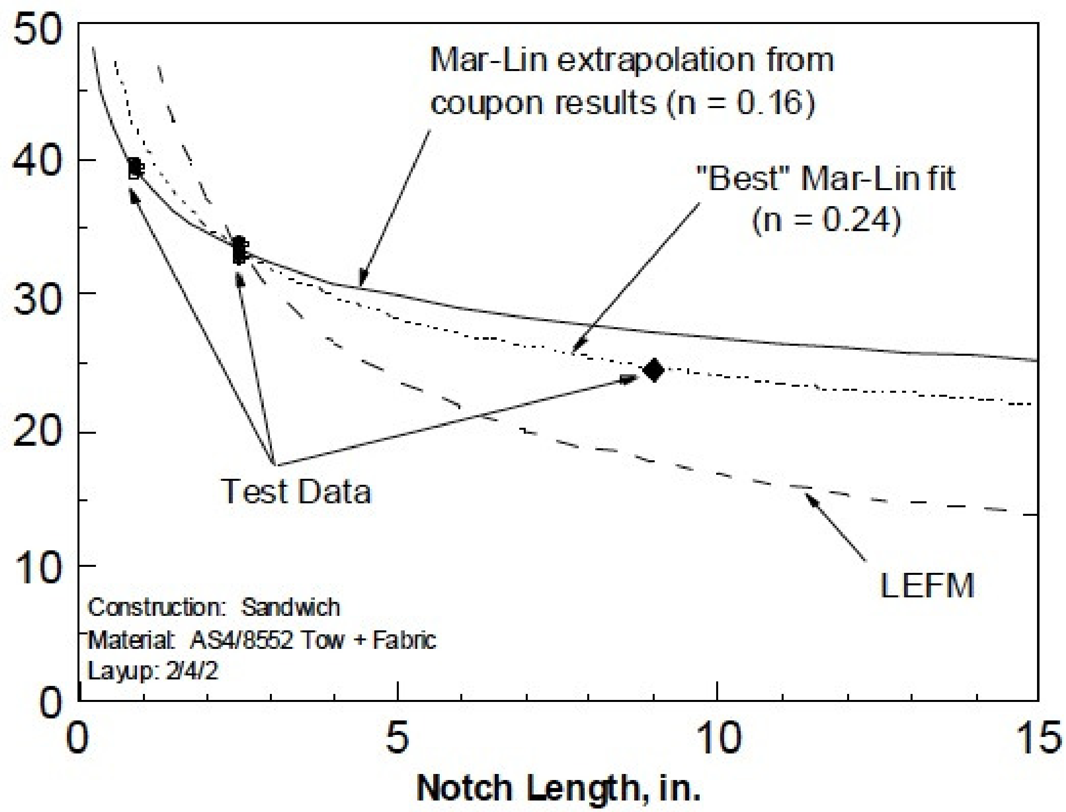


Crown region of the fuselage is designed by damage tolerance requirements.

Panels tested in LaRC pressure box

1996

In the absence of progressive damage analysis methods, an empirical approach must be used.

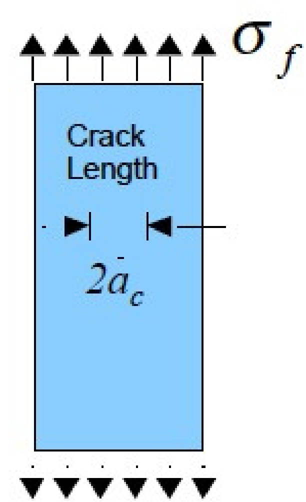


LEFM

$$\sigma_f = K_{IC}(\pi a_c)^{-1/2}$$

Mar-Lin

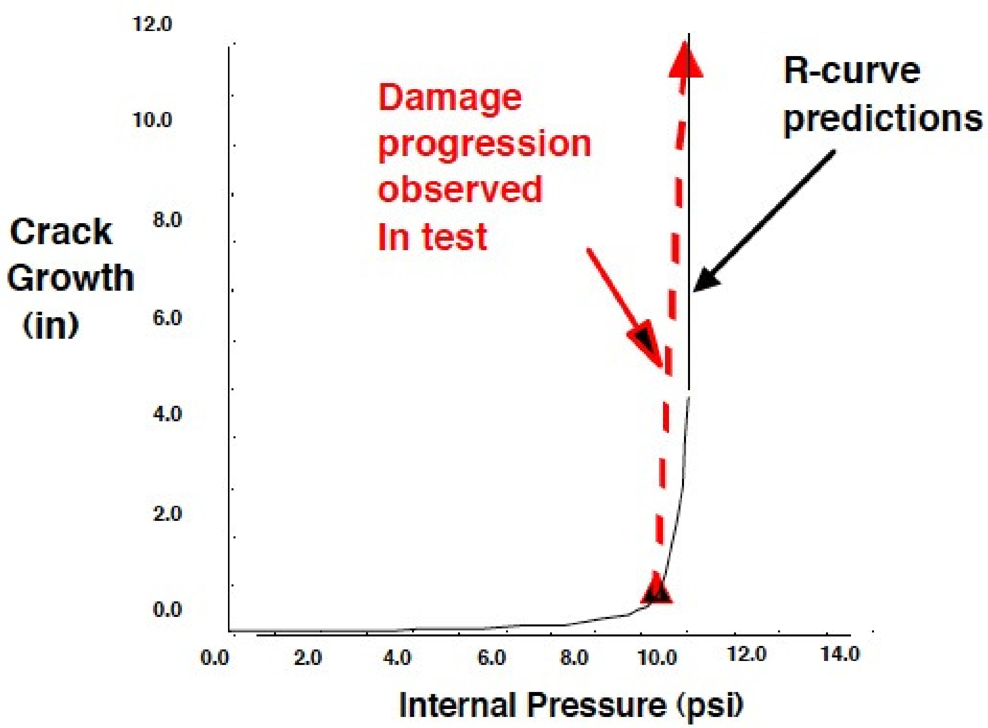
$$\sigma_f = H_C(2a_c)^{-m}$$



Fracture parameters must be empirically determined from wide panel test data.

Analysis of Laminates with Through-Thickness Notches

1996



R-curve Predictions and Test Results

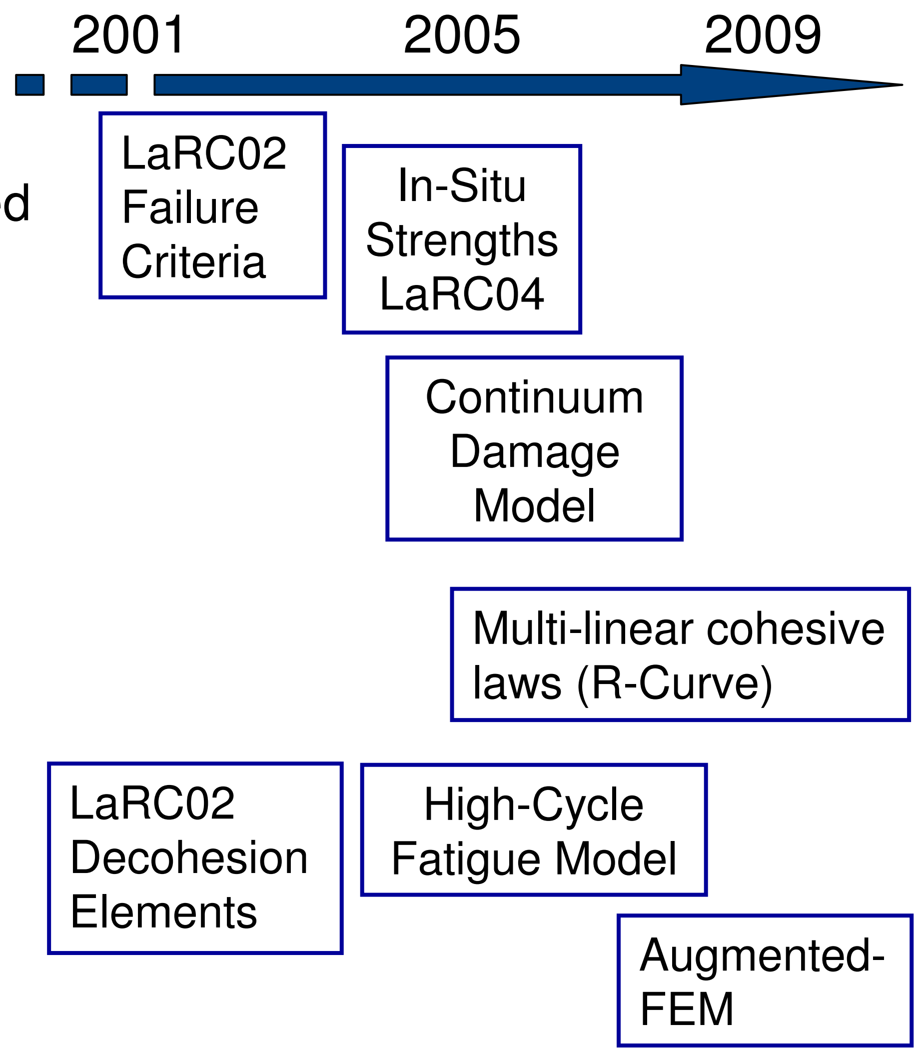
1998

- Progressive Damage Analysis of Laminated Composite (PDCALC), in NASA Comet FE Code
- PDCALC accurately predicts empirical R-curve
- Primitive tool
    - Strength criteria
    - Damage evolution laws

Progressive Damage Analysis Roadmap

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

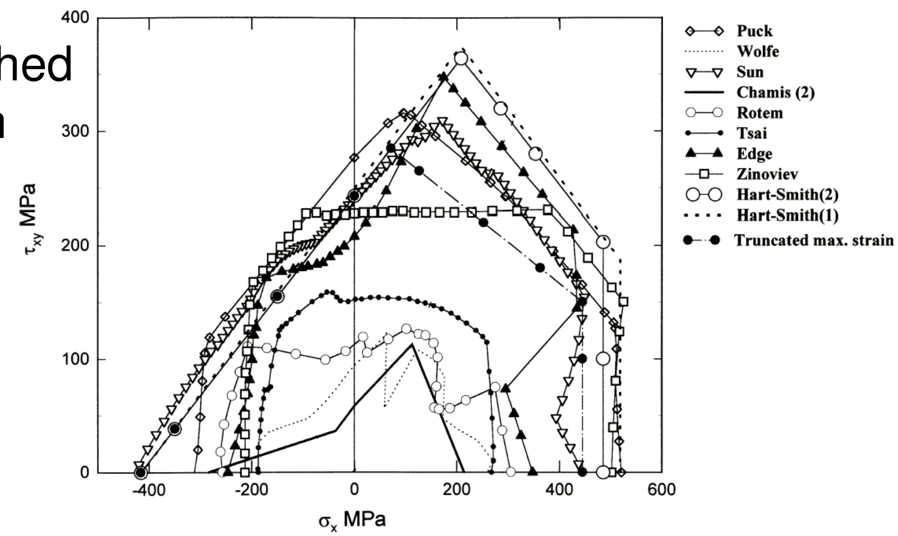


Failure Criteria for Laminated Composites

1998: World-wide failure exercise (during ACT program)

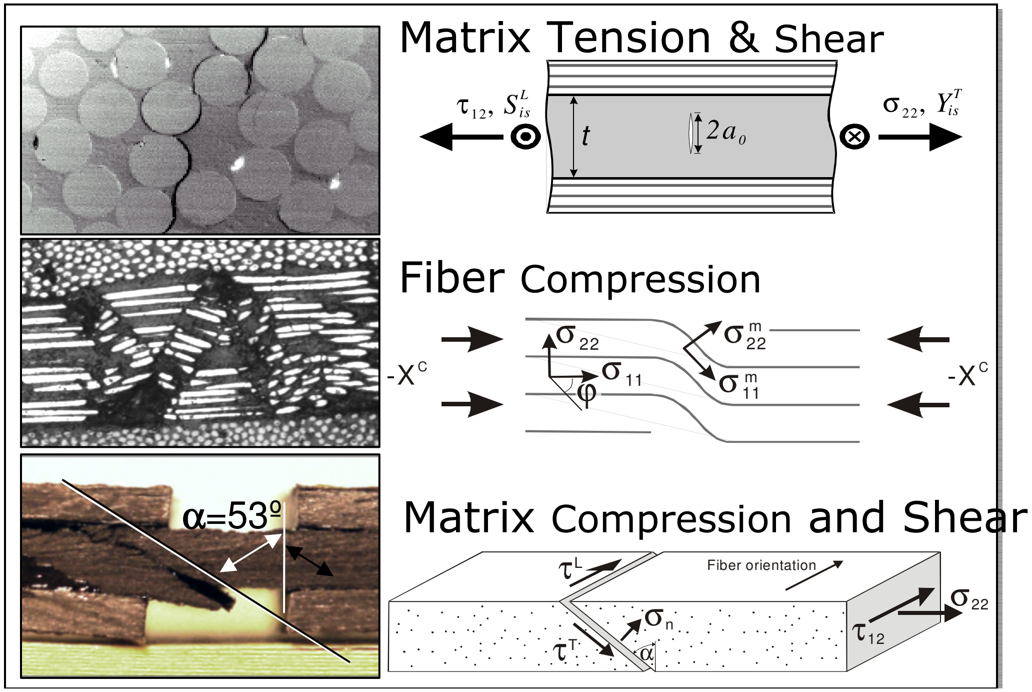
- There was no consensus among leading researchers regarding valid methods and failure criteria

Un-notched Strength Criteria



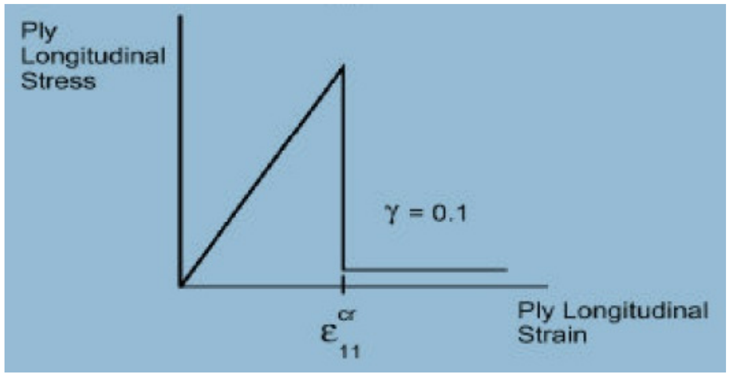
2004: LaRC04 Criteria

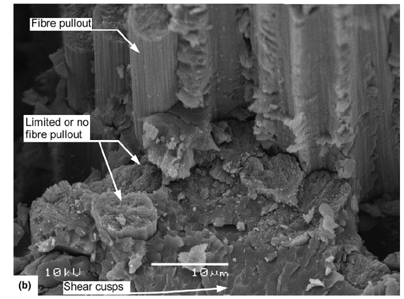
- In-situ matrix strength prediction
- Advanced fiber kinking criterion
- Prediction of angle of fracture (mat. Compression)

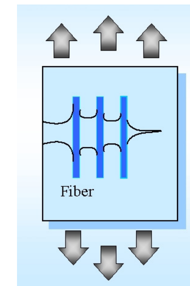


Damage Evolution Laws in Continuum Damage Model (CDM)

1998





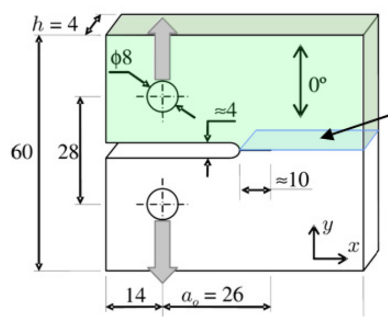


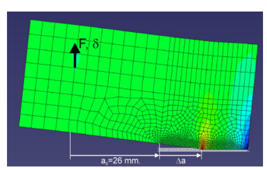
Micrographs reveal brittle fracture and pullout, fibers bridging the fracture zone.

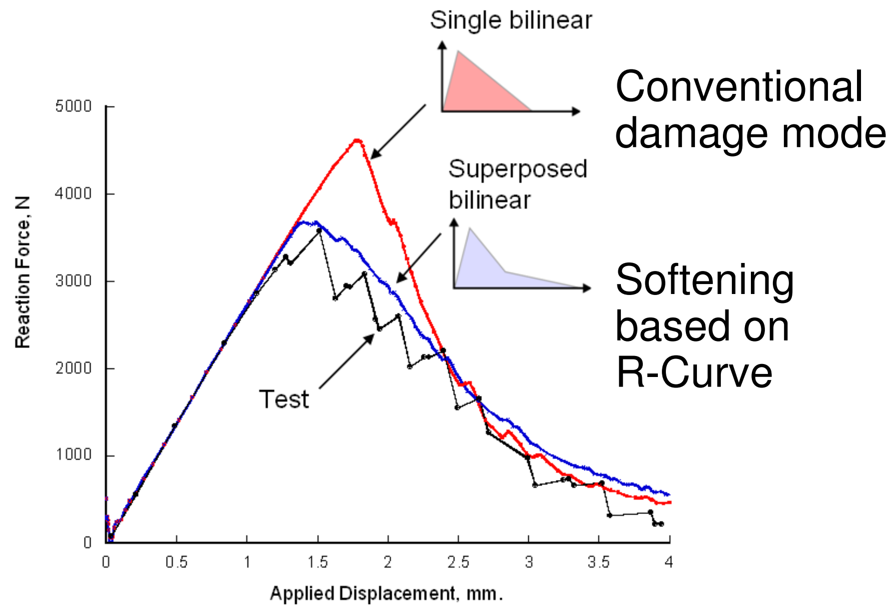
2008

- Softening Laws Based on Measured R-Curves
- Defines process to determine softening law from material characterization experiments

Compact Tension Specimen



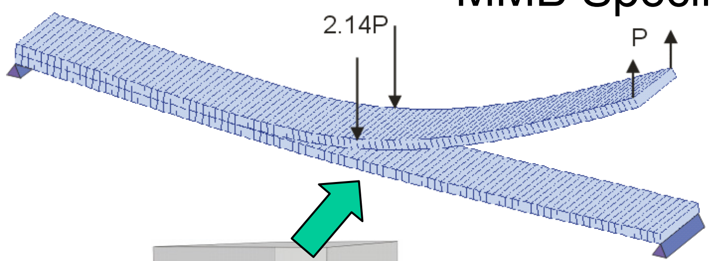


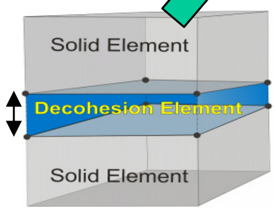


- Thermodynamically-consistent softening : mesh insensitivity in FEM

Delamination Growth

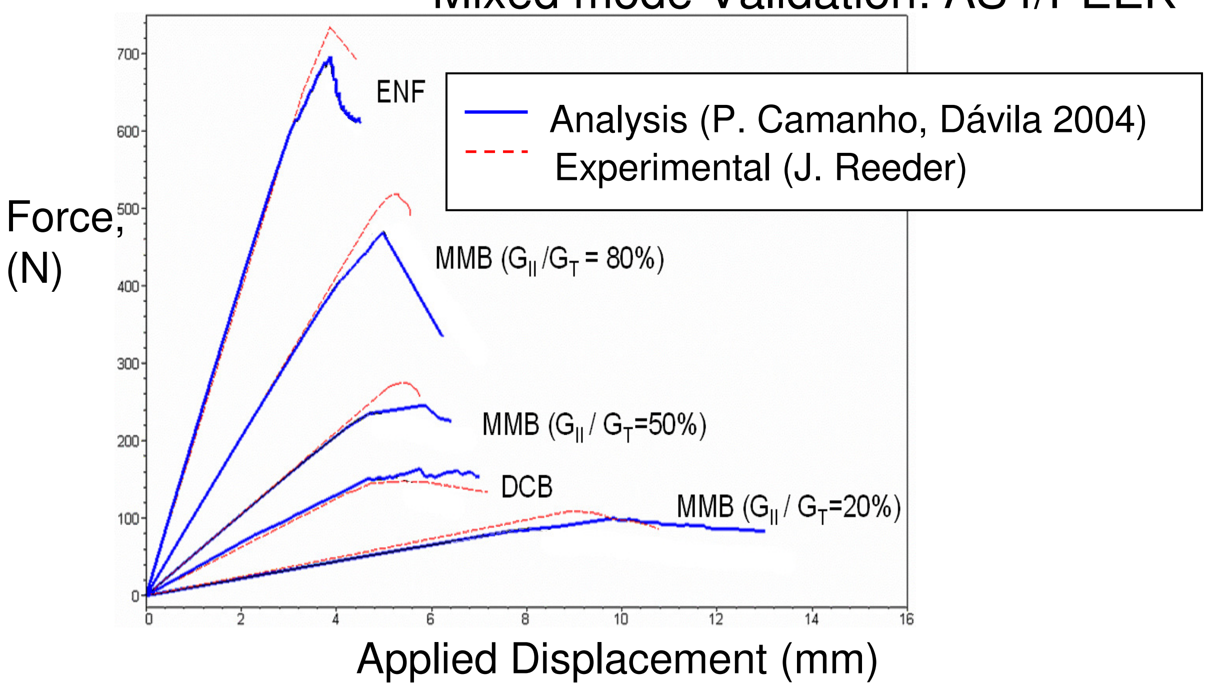
MMB Specimen





Cohesive Elements

Mixed mode Validation: AS4/PEEK



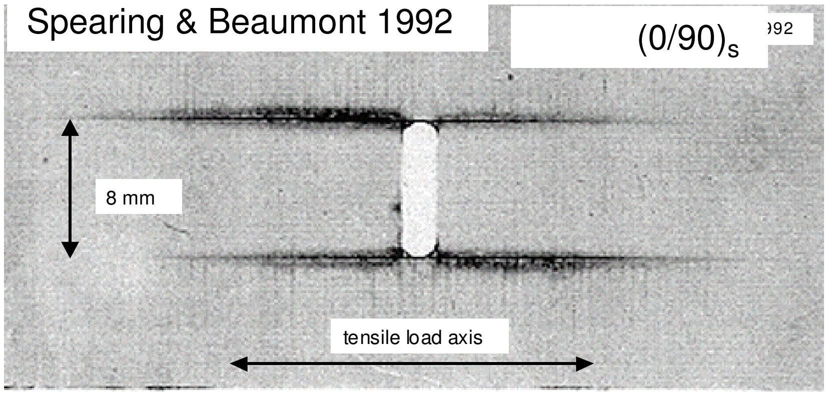
VCCT: ABAQUS, NASTRAN

- Composite Materials Handbook 17 (CMH-17)
  - Delamination fatigue onset document to be incorporated in Rev.G
  - Proposed delamination fatigue methodology for composite structures to be submitted in 2012

- New cohesive law uses Paris Law for fatigue damage growth (Turon-Camanho, 2007).

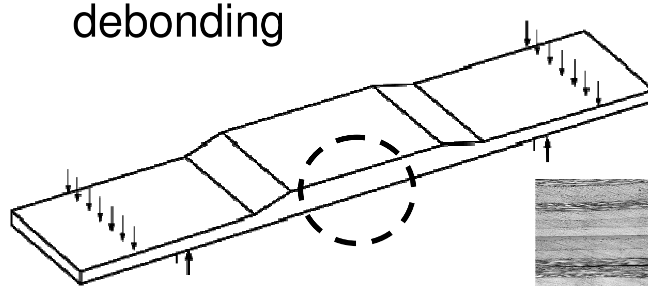
Challenges in Progressive Damage Analysis

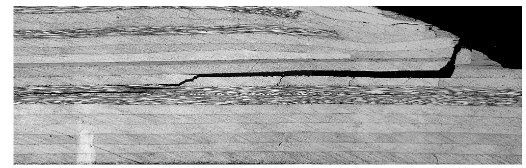
Splitting



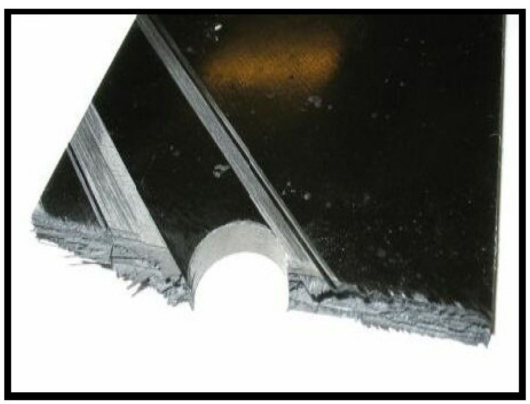
Delamination Branching

skin/stringer
debonding

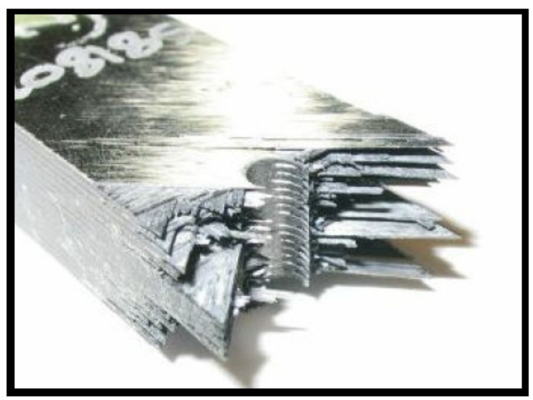




Effects of Ply Thickness and Delamination (Hallet, 2007)



Brittle

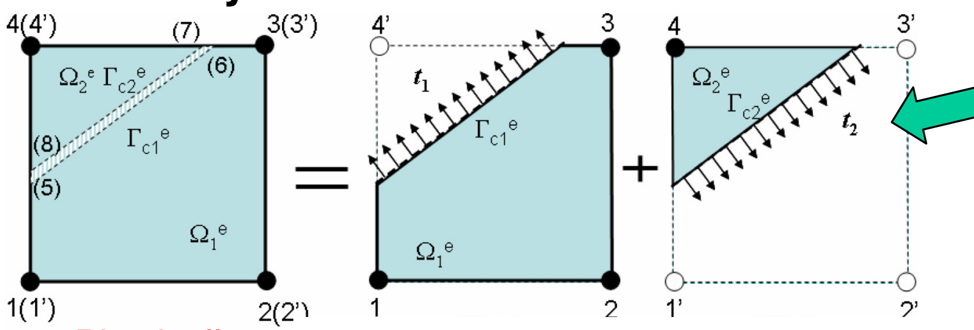


Pull-out

Delamination

Augmented Finite Elements (A-FEM) Coupled with Cohesive Elements

Discontinuity across a continuum element



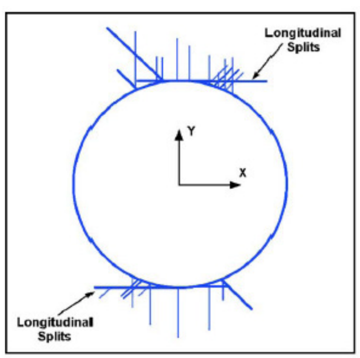
Physically discontinuous element (PDE)

Mathematical element 1 (ME1)

Mathematical element 2 (ME2)

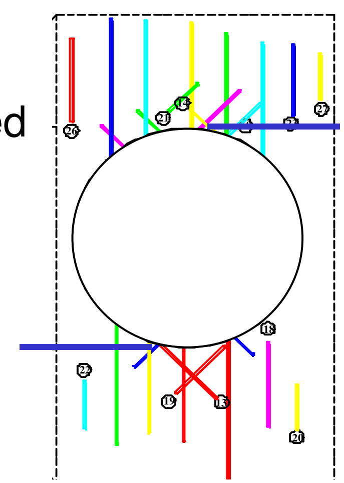
- Cohesive law for crack initiation and propagation
- Cohesive elements for delamination initiation and propagation
- Implemented as user-element in ABAQUS

Simulation of Open-Hole Tension Specimen-$[0/90/+45/-45]_s$ Laminate



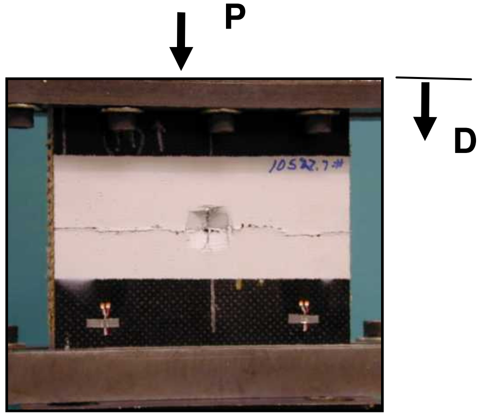
X-Ray damage pattern (Iarve et al, 2005)

Predicted damage pattern

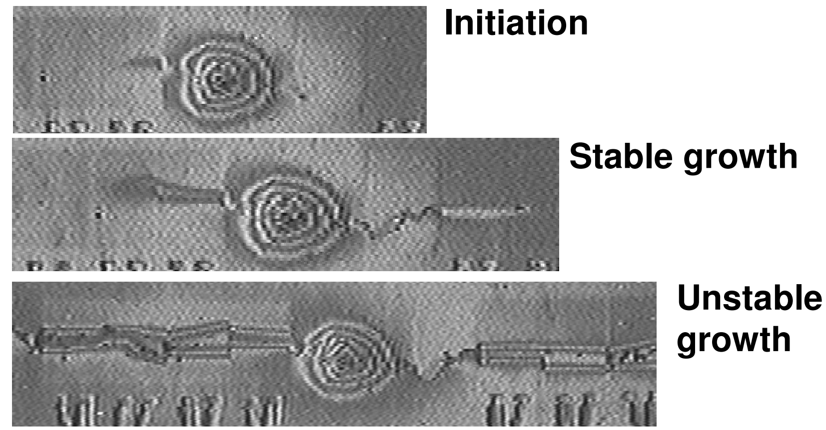


Rapid, Design-Oriented Compression-After-Impact Strength Analysis for Sandwich Panels

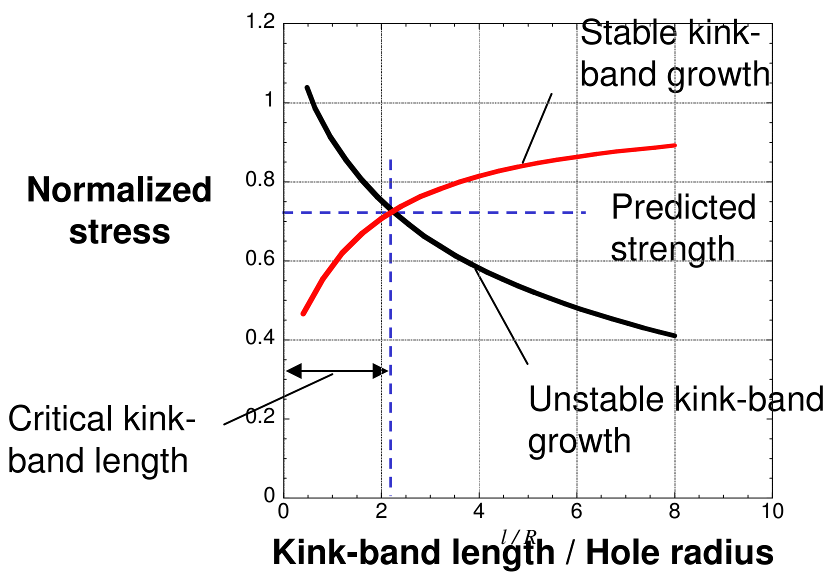
Impact damaged specimen subjected to compression load



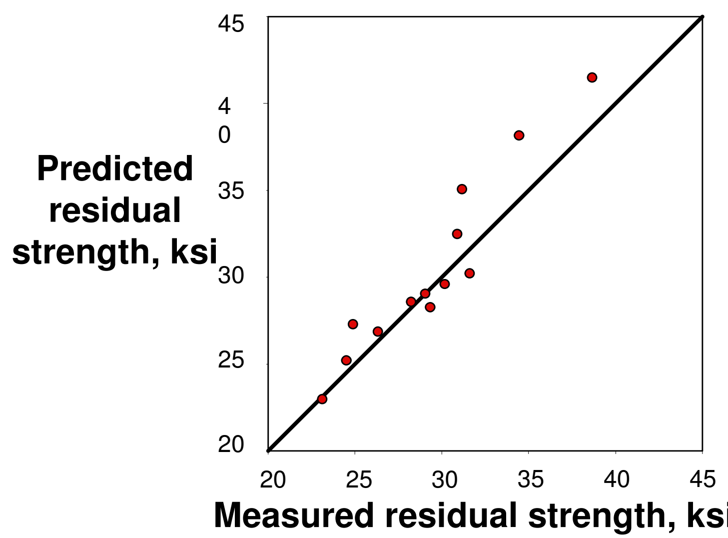
Kink-Band Propagation



Residual Strength Analysis

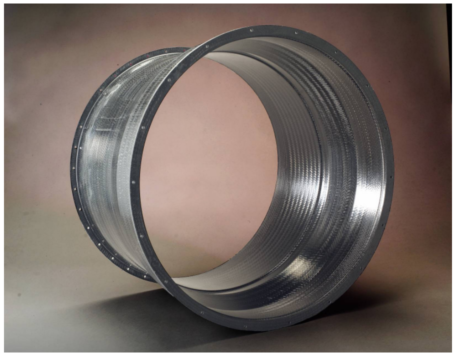


Comparisons with tests (< 7% difference)



Textiles

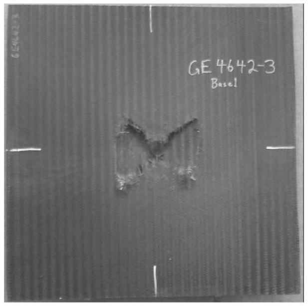
Composite engine fan case



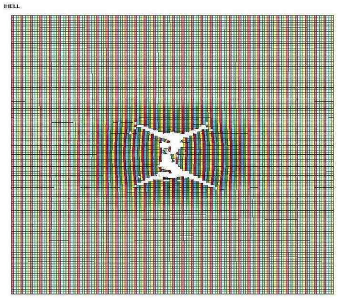
Engine Blade-off Test

Modeling Impact

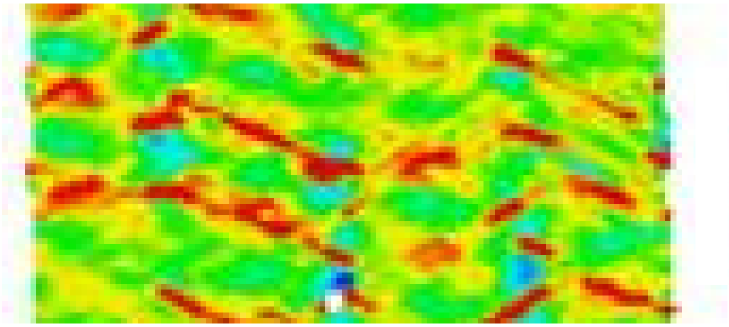
Test



LS-DYNA

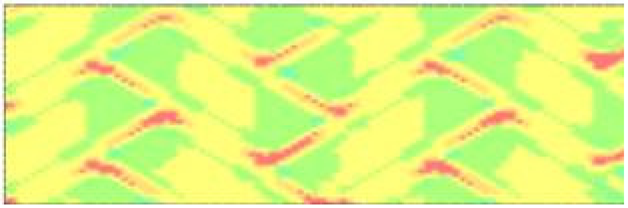


Local strain on top surface



Test: ARAMIS

Modeling textile substructure

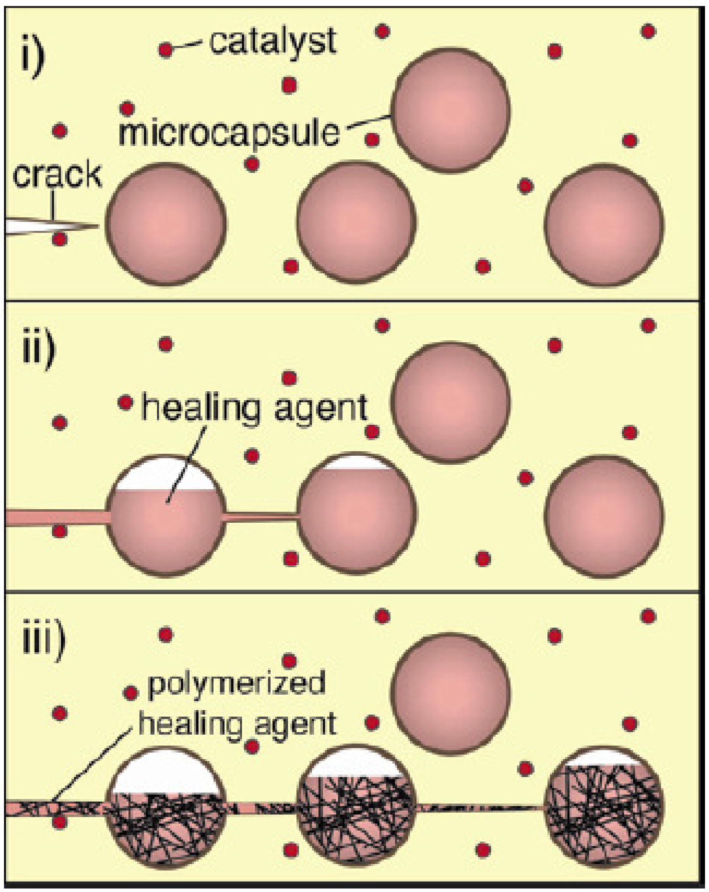


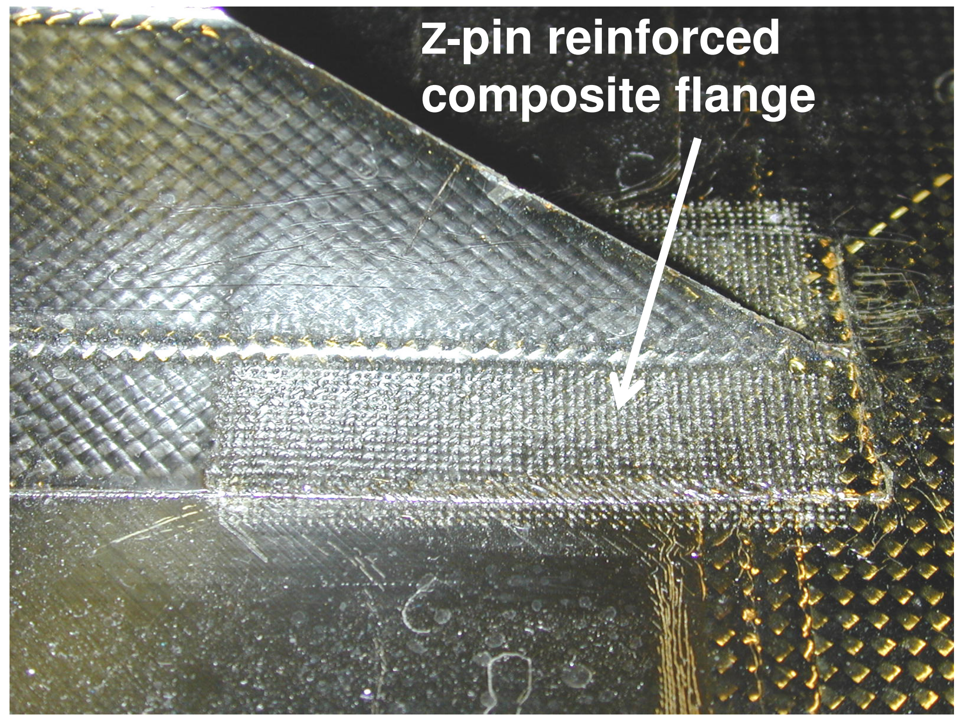
LS-DYNA

Advanced Composite Concepts

Durable and Damage Tolerant Self Healing Composites

Matrix with catalyst and healing agent microcapsules

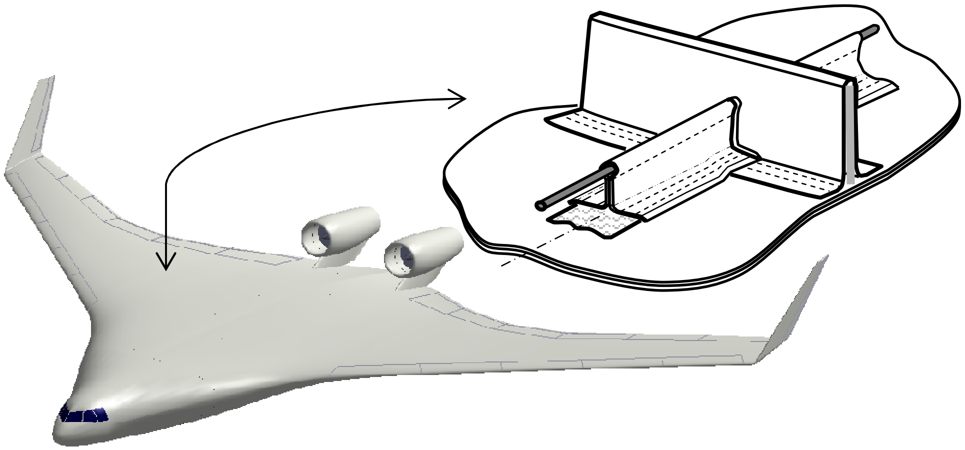


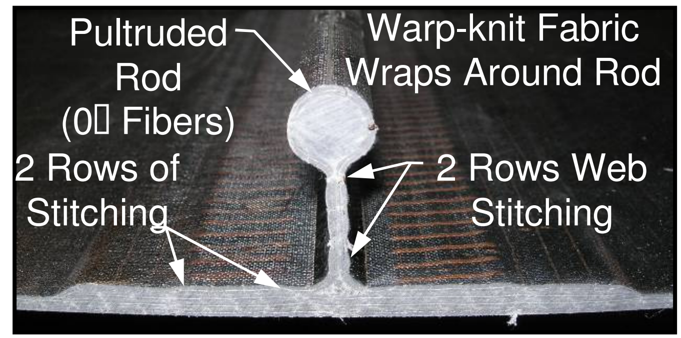


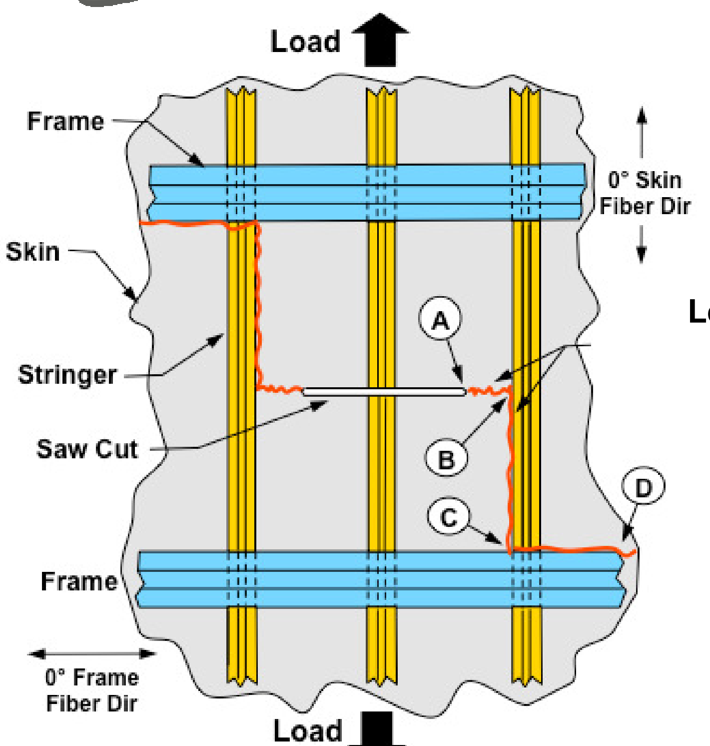
- **Z-pin reinforcement provides time for healing under load**

Advanced Composite Concepts (cont.)

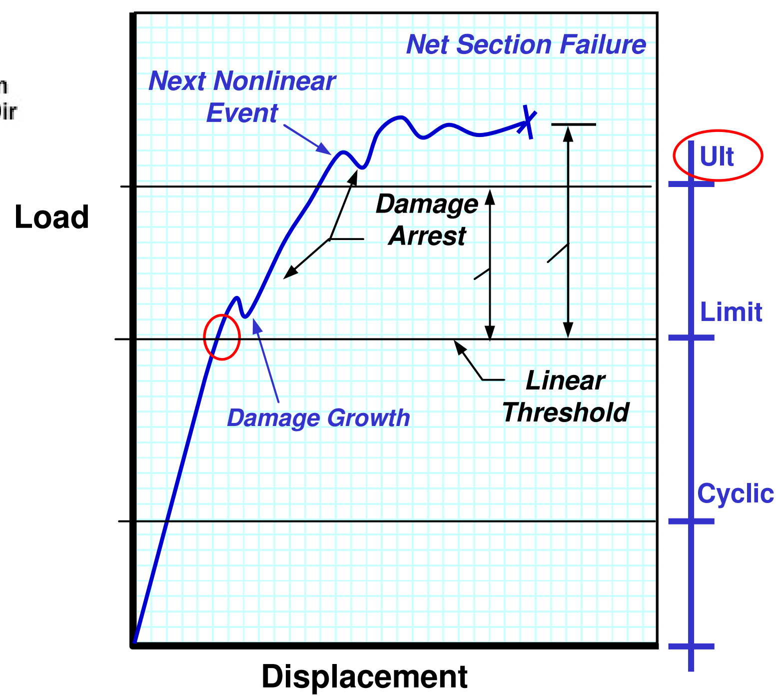
PRSEUS (Pultruded Rod Stitched Efficient Unitized Structure)





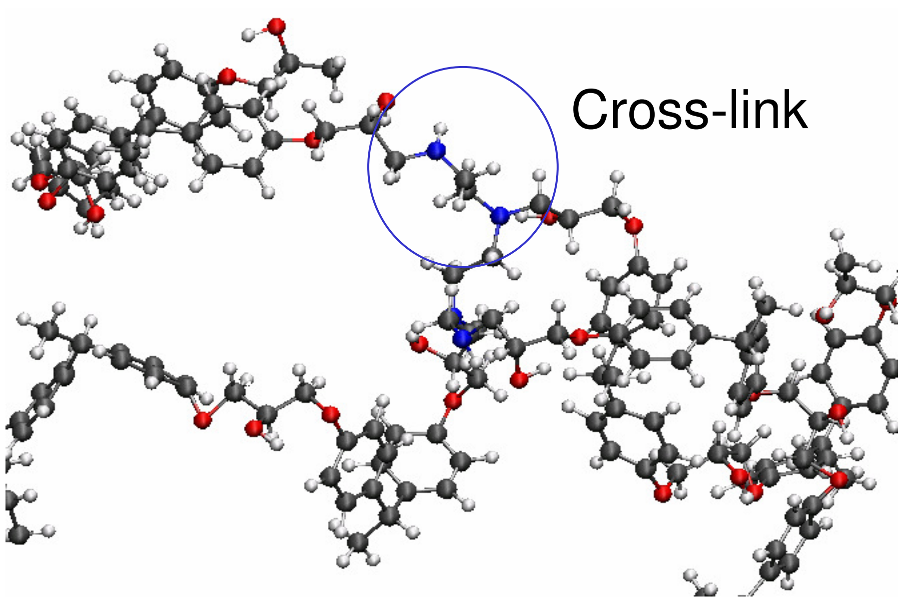


Stiffened Panel Geometry

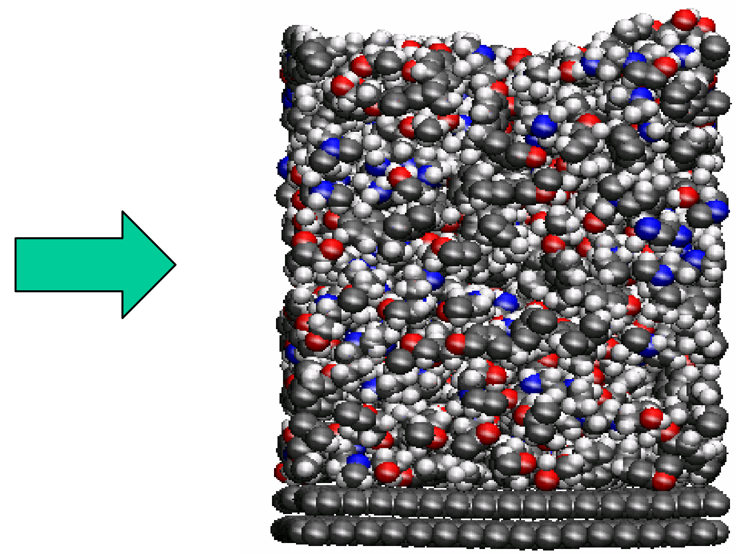


- Arrested damage enables fail-safe design philosophy

Composites Damage Science: Physics-Based Computational Molecular Modeling



Atomistic Modeling of Epoxy Network



Molecular Dynamics Simulation of Epoxy on Surface

- Structure-property relationships: composition, degree of cure, absorption/diffusion of water, fluids
- Interface strength: bonded joints, fiber-matrix interface

Summary

- Technology development programs 1980's and 1990's
  - Manufacturing, proof of damage tolerance, repair substantiation
  - Successes … but several premature failures attributed to details
- Composites have complex failure modes, unique challenges
- Building-block design approach, enhanced by analysis
- Early Damage Tolerance methods emperically-based
- Progressive Failure Analysis methods are maturing
- Damage tolerant concepts are being studied
- Long term composites damage science research initiated