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)

• Test Article failed at 83% of DUL under combined bending & torsion
• Unanticipated shear failure mode at out-of-tolerance gap
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
\([+45/0/-45/90]_6s\)

Z-pin Technology
Pultruded graphite rods stuck through the laminate

Compression After Impact Strength

-  Improve transverse strength
-  Prohibit delamination
-  Degrade laminate properties

Toughened Matrix Composites

-  Pultruded graphite rods stuck through the laminate

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


Program cancelled after composite LH2 tank failure during prototype proof test

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

**Building Block Integration.**

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

- Full Scale Article
- Component
- Sub-component
- Structural Element
- Design Allowables Coupons
- Material Selection and Qualifications Coupons

**Analysis**

- Static/Fatigue
- Verification of Design Data and Methodology
- Development of Design Data

- Number of Specimens

**Structural Levels of Testing & 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

Conceptual | Preliminary | Detailed
---|---|---

Design Knowledge, Design Freedom

Goal

Design Knowledge

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

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

LEFM

\[ \sigma_f = K_{IC} \left( \pi a_c \right)^{1/2} \]

Mar-Lin

\[ \sigma_f = H_C \left( 2a_c \right)^{-m} \]
Analysis of Laminates with Through-Thickness Notches

1996

- 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

1998

- R-curve Predictions and Test Results

Crack Growth (in)

R-curve predictions

Damage progression observed in test

Internal Pressure (psi)

0.0  2.0  4.0  6.0  8.0  10.0  12.0  14.0

0.0  2.0  4.0  6.0  8.0  10.0  12.0  14.0  16.0
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

2001

LaRC02 Failure Criteria

In-Situ Strengths
LaRC04

Continuum Damage Model

Multi-linear cohesive laws (R-Curve)

2005

LaRC02 Decohesion Elements

High-Cycle Fatigue Model

2009

Augmented-FEM
1998: World-wide failure exercise (during ACT program)
- There was no consensus among leading researchers regarding valid methods and failure 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
- Softening Laws Based on Measured R-Curves
- Defines process to determine softening law from material characterization experiments

2008
- Thermodynamically-consistent softening: mesh insensitivity in FEM

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

• Softening Laws Based on Measured R-Curves
• Defines process to determine softening law from material characterization experiments
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**
Spearing & Beaumont 1992

(0/90)$_s$ $^{192}$

**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 (larve 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
- Initiation
- Stable growth
- Unstable growth

Residual Strength Analysis
- Predicted residual strength, ksi
- Measured residual strength, ksi

Comparisons with tests (< 7% difference)

Normalized stress
Critical kink-band length
Stable kink-band growth
Unstable kink-band growth

Stable growth
Unstable growth

Kink-band length / Hole radius

Predicted residual strength, ksi
Measured residual strength, ksi
Textiles

Composite engine fan case

Engine Blade-off Test

Modeling Impact

Test: ARAMIS

Local strain on top surface

Modeling textile substructure

Test: ARAMIS

LS-DYNA

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

[Diagram: Illustration of matrix with catalyst and healing agent microcapsules]

[Image: Z-pin reinforced composite flange with arrows indicating reinforcement and healing process]

- Z-pin reinforced composite flange
Advanced Composite Concepts (cont.)

PRSEUS (Pultruded Rod Stitched Efficient Unitized Structure)

- 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 empirically-based
  • Progressive Failure Analysis methods are maturing
  • Damage tolerant concepts are being studied
  • Long term composites damage science research initiated