NASA Langley Damage Tolerance Experiences

by

Ivatury S. Raju
NASA Engineering and Safety Center
NASA Langley Research Center
Hampton, Virginia

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Outline

- NASA Langley’s Composites Programs
- SOA Analysis
- Emerging Continuum Methods
- Future Directions
Durability and Damage Tolerance Requirements

Structural durability affects the frequency and cost of inspection, replacement, repair, or other maintenance.

Structural damage tolerance ensures damage will be found by maintenance practices before becoming a safety threat.

Discrete source events (e.g., engine burst, birdstrike) can cause severe damage but it is known to pilot.

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

(FAR 25.571 & Mil-17)
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

- Stitching
- Spaced At 3.2mm
- Load Direction

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

Compression After Impact Strength

- Stitched AS4/3501-6
- Toughened Matrix Composites
- Unstitched AS4/3501-6

Impact Energy, J vs. Comp. Stress, MPa
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-)

- **Dislocations**, **Twinning**, **Stacking Fault**
  - \([1 \ 1 \ 0]\)
  - \([0 \ 0 \ 1]\)
  - \([1 \ 1 \ 0]\)
- **Void Coalescence**
- **Damage Science**
  - 10 nm
- **Emerging Continuum Methods**
- **Complexity, Computational Expense**
  - Time
  - \(\frac{1}{4}, \frac{1}{2}, \frac{3}{4}, 0, 1\)
  - \(\frac{G T}{G + G_I}, \frac{G_I c}{G + G_I - G_I c}\)
- **LaRC Decohesion Element** (Technology adopted by ABAQUS)
  - Mixed-Mode Fracture
  - Bilinear Traction-Displacement Law
  - Perfectly plastic (pp)
  - Linear softening (lin)
  - Progressive softening (pro)
  - Regressive softening (reg)
- **G**
- **σ**
- **σ**
- **Needleman (Ne)**
- **F** = \(\int \sigma \delta \delta_0\)
- **Wide range of element sizes**
- **Narrow range**
- **Classical**
- **Enhanced**
- **Enhanced formulation** allows the use of elements up to three times larger than with the classical damage model.
- **MMB Specimen**
  - Delamination growth
  - FY05 Advances
  - Current State--ofof--the--Art--Art
  - Pressure, \(P\) (psi)
  - \(b = 0.750\) in.
  - \(b = 0.625\) in.
  - \(b = 0.500\) in.
- **Evolution of Damage Tolerance at NASA Langley (1999-)**
Hypersonic Experimental Vehicle (X-33 Program)

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

Local FE Model

Global FE Model

Lug and Pin
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

- Peak Fres
- Peak Mx
- Onset of Damage

Graph showing the relationship between Load Factor and Fres (MN) and Mx (kN-m).
Comparison of Predicted and Test Results

Test Failure Load 907 kN
Predicted Failure Load 896 kN

Failed Test Lug

Elements with predicted damage
Unsymmetric damage due to loading

Predicted Failures
W375 Accident Conditions – Damage

Elements with Predicted Damage

Unsymmetric Damage Due to Configuration and Applied Moments

Load

FWD

Abstract

Unsymmetric Damage Due to Configuration and Applied Moments
Normalized Failure Load for 1985-Certification Test, 2003-Subcomponent Test and W375 Accident Condition

- PFA Analysis Failure Load
- PFA Analysis Load at Maximum Moment $M_X$
- Test Failure Load

Normalized Failure Load, kN

- 1985 Test
- SC Test
- W375 Accident Case
Evolution of Damage Tolerance at NASA Langley (1999-)

Current State-of-the-Art

Emerging Continuum Methods

Damage Science

Spin-Offs

Complexity, Computational Expense

Time

Natalie B. (NASA Langley)
Building Block Integration.

Certification Methodology (Mil-Hbk.-17)

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Chronological Sequence
Specimen Complexity

Number of Specimens

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

Graph showing the relationship between Design Knowledge, Design Freedom, and Knowledge about Design over the Time into Design Process, divided into Conceptual, Preliminary, and Detailed phases.
Building Block Approach

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

Structural Levels of Testing & Analysis

- High-Fidelity Progressive Failure Analysis
- Reduced reliance on testing
- Faster design process
- More accurate design tools

Reduced non-recurring costs

Reduced recurring costs

NASA
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
- $\sigma_{22}$, $\tau_{12}$

Fiber Compression
- $\sigma_{11}$, $\sigma_{22}$

Matrix Compression and Shear
- $\tau_{12}$, $\sigma_{22}$

LaRC04 Criteria
- In-situ matrix strength prediction.
- Advanced fiber kinking criterion.
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- Criteria used as activation functions within framework of damage mechanics.
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: \[ \varepsilon = \frac{\partial G}{\partial \sigma} = H : \sigma + \alpha \Delta T \]

Lamina Secant Relation

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

Rate of Damage Growth

\[ d_i = 1 - \frac{1}{f_i (r_i)} \exp (A_i (1 - f_i (r_i))) \]

\[ f_i: \text{LaRC04 failure criteria as activation functions} \]

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

*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

\[
\frac{G_T}{G_k + (G_{IIc} - G_k)\left(\frac{G_{II}}{G_T}\right)^\eta} \geq 1
\]

3D Problems Contain Mode III

circular delamination

contours show out-of-plane displacement

sublamineate buckling problem

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

edge crack torsion test
Proposed 3D Mixed-Mode Criterion

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

- 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-)

Dislocations
Twinning
Stacking Fault

*1 1 0*
*0 0 1*

Void Coalescence

10 nm

Damage Science

Emerging Continuum Methods

Time

Complexity, Computational Expense

LaRC Decohesion Element

Mixed-Mode Fracture

Bilinear Traction-Displacement Law

Perfectly plastic (pp)
Linear softening (lin)
Progressive softening (pro)
Regressive softening (reg)

Needleman (Ne)

σ
0

CGd

F

δ

σ

δ

0

G

σ

pro lin reg

GII

GIII

GT

(η + GIIIc − GIIc)(GIII + GII)

≥ 1

t ≈ 0

FY05 Advances

Enhanced formulation allows the use of elements up to three times larger than with the classical damage model.

MMB Specimen

Delamination growth

Current State-of-the-Art

Evolution of Damage Tolerance at NASA Langley (1999-)

Pressure, P (psi)

b=0.750 in.
b=0.625 in.
b=0.500 in.

QuickTime™ and a decompressor are needed to see this picture.
Damage Science

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

**Experimental Damage Science**

- 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

**Computational Damage Science**

- Mechanisms of Nano-crack Propagation
- Calculation of Normal Stress and Crack Opening
- Continuum Representation of Atomistic Behavior

**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.

**Materials characterization and in-situ mechanical testing with environmental capabilities**

**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
Test Article failed at 83% of DUL under combined bending & torsion

- Unanticipated shear failure mode at out-of-tolerance gap

NASA ACT Program – Center Wing Box Test (1991)
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

FY04
- LaRC04 Failure Criteria
- Enhanced Decohesion Element & High-Cycle Fatigue Model

FY05-06
- In-Situ Strengths
- Continuum Damage Model

LaRC04 Decohesion Elements

Enhanced Decohesion Element & High-Cycle Fatigue Model