A SELECTION OF COMPOSITES SIMULATION PRACTICES AT NASA Langley Research Center

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MSC Software
Composites Consortium Meeting

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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
NASA LANGLEY RESEARCH CENTER

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
- Hypersonics 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

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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

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

Bench Top Test System

- 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)
- decohesision elements

Slide provided by C. Davila
PROGRESSIVE FAILURE MATERIAL MODEL

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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**

  \[
  \frac{\sigma_{11}}{X_T} \leq 1 \text{ for } \sigma_{11} \geq 0; \quad \frac{|\sigma_{11}|}{X_C} \leq 1 \text{ for } \sigma_{11} \leq 0
  \]

  \[
  \frac{\sigma_{22}}{Y_T} \leq 1 \text{ for } \sigma_{22} \geq 0; \quad \frac{|\sigma_{22}|}{Y_C} \leq 1 \text{ for } \sigma_{22} \leq 0
  \]

  \[
  \frac{\sigma_{33}}{Z_T} \leq 1 \text{ for } \sigma_{33} \geq 0; \quad \frac{|\sigma_{33}|}{Z_C} \leq 1 \text{ for } \sigma_{33} \leq 0
  \]

  \[
  \frac{\tau_{12}}{S_{XY}} \leq 1; \quad \frac{\tau_{23}}{S_{YZ}} \leq 1; \quad \frac{\tau_{13}}{S_{XZ}} \leq 1
  \]

- **Tsai-Wu polynomial failure criterion**

  \[
  \phi = F_1\sigma_{11} + F_2\sigma_{22} + F_3\sigma_{33} + F_{11}(\sigma_{11})^2 + F_{22}(\sigma_{22})^2 + F_{33}(\sigma_{33})^2
  \]

  \[
  + 2F_{12}\sigma_{11}\sigma_{22} + 2F_{23}\sigma_{22}\sigma_{33} + 2F_{13}\sigma_{11}\sigma_{33}
  \]

  \[
  + F_{44}(\sigma_{13})^2 + F_{55}(\sigma_{23})^2 + F_{66}(\sigma_{12})^2 \geq 1
  \]
### 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 \(b_i\)

\[
C_{ij}^{\text{degraded}} = C_{ji}^{\text{degraded}} = 0 \text{ for } i \neq j \\
C_{ii}^{\text{degraded}} = \beta_i C_{ii}
\]
MATERIAL MODELING OPTIONS

Orthotropic layers

Smeared laminate (uniform through-thickness properties)

Laminate Modeling

Outer layers

Inner layers

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

\[
G_I = \frac{1}{2\Delta ab} \cdot Z'_L \cdot \left( w'_L - w'_{L^*} \right)
\]

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

\[
G_{III} = \frac{1}{2\Delta ab} \cdot Y'_L \cdot \left( v'_L - v'_{L^*} \right)
\]
STRINGER STIFFENED PANEL SUBJECTED TO SHEAR LOADING

- Testing of Stiffened Shear Panel
  Boeing, Philadelphia*

- Original Boeing ABAQUS Shell Model*

*Pierre Minguet, Boeing
SHELL FE-MODEL WITH LOCAL 3D MODEL

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

Shell region replaced by local 3D model

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COMPUTED ENERGY RELEASE RATES

- Increment 5, \( u = v = 0.2 \text{ mm}, 3.3\% \)
- Increment 41, \( u = v = 6.35 \text{ mm}, 100\% \)

\[ a = 82 \text{ mm} \]

\[ G, \quad \text{J/m}^2 \]

location along delamination front, \( s \)
DECOHESION ELEMENTS FOR SIMULATING DELAMINATION

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Mixed-Mode Fracture

\[ G_{IC} + (G_{IIc} - G_{IC}) \left( \frac{G_{II}}{G_I + G_{II}} \right)^n = 0 \]

Bilinear Traction-Displacement Law

\[ \int_0^{\delta_F} \sigma(\delta) d\delta = G_C \]

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Decohesion elements used to predict delamination in skin / stringer specimen
SKIN / STRINGER SEPERATION SPECIMEN
NTSB Board Meeting
AA Flight 587

Structures Investigation

Brian K. Murphy - NTSB

Detailed Lug Analysis Team - NASA LaRC
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

Extensive Damage
FINITE ELEMENT MODEL OF DELAMINATION IN A ROTORHUB FLEXBEAM

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FINITE ELEMENT MODEL OF DELAMINATION IN A ROTORHUB FLEXBEAM

Finite element model of flexbeam with internal ply-drops

Delaminations initiate at ply endings

intact flexbeam
delaminated flexbeam

Helicopter Rotorhub

transverse load
axial load
Fatigue toughness data for modeled material

Calculated fatigue life curve

N, cycles to delamination onset

G_{max} = cN^b

G_c

N, cycles to delamination onset

Flexbeam test data

Flexbeam strain

VCCT used to calculate G as delamination grows

Peak G_{FE}

Delamination length

G

FLEXBEAM FATIGUE LIFE METHODOLOGY
MIXED-MODE FAILURE CRITERIA FOR DELAMINATION IN COMPOSITE LAMINATES

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2D MIXED MODE FRACTURE CRITERION

- Experimental data

![Graph](image)

- Curve fit equation by Benzeggagh and Kenane, 1996

\[ G_c = \left( G_{Ic} + (G_{IIc} - G_{Ic}) \cdot \left( \frac{G_{II}}{G_T} \right)^\eta \right) \]
**PROPOSED 3D MIXED MODE FRACTURE CRITERION**

- Mode III - ECT Specimen
- Proposed 3D failure criterion**

\[
G_T \geq 1
\]

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

- 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™, Formula 1 auto racing

Z-Pin preform: Insertion side*

Z-pin bridging mode I delamination

Z-Pins protruding from laminate

Fiber misalignment from z-pins**

*Pierre Minguet, Boeing  **Jeffery Schaff, Sikorsky Aircraft.
1. Discrete spring used to represent individual z-pins
   (Traction law assigned for representing z-pin failure)

\[ k_i = \begin{cases} 
  k_0 & \text{if } z_i \leq z_0 \\
  (1 - d)k_0 & \text{if } z_0 < z_i \leq z_f \\
  0 & \text{if } z_i > z_f 
\end{cases} \]

2. Springs inserted into finite element model

3. Delamination growth tracked using contact pressure

Contact surfaces
Springs

Nodes at which contact pressure is monitored
Dark blue = no contact pressure

Estimated delamination front

Finite Element Analysis
**BEAM THEORY ANALYSIS**

- 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

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