ASSESSMENT OF DURABILITY MODELS

Seth Kessler  Jeremy Gregory, Dennis A. Burianek and Mark Spearing

Technology Laboratory for Advanced Composites
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology

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BACKGROUND

• Definition: Prediction of the time it takes for flaws/damage/degradation to begin to initiate in nominal structure
  – In practice must also account for defects present, but undetected - “initiation” implies a scale or severity

• Durability is primarily an economic issue affecting the inspection intervals, repair costs, and service life of a structure

• Multiple mechanisms affect durability - particularly in composite structures

• State of art primarily consists of applying experience to identify likely durability concerns and performing testing accordingly - key aim is to avoid surprises

**Testing is long duration and expensive, must be initiated early in program before design is complete - iteration is difficult**
THE TESTING EXPERIENCE

- A large volume of durability related testing has been conducted on many programs
- Testing is often ad hoc and application specific
- Little or no success in transferring data to other projects
- Experience and best practice is often transferred although underlying rationale is often missing
- Relatively little use is made of test data - loads, environments, time to failure are typical data with little information on failure modes or mechanisms
- Composite primary structures have generally proven to be quite durable, secondary structures less so
THE MODELING EXPERIENCE

• A wide range of models available from previous programs over past 30+ years

• Reasonable success with individual damage/degradation modes, durability related phenomena
  
  – Physical aging, creep, thermal and moisture diffusion, off-axis ply cracking, stiffness reduction due to damage, fatigue delamination growth and others (list not complete)

• Less success with modeling coupled damage or damage/degradation modes and hence overall life prediction
  
  – Moisture/temperature-accelerated crack growth, delamination and off-axis ply cracking
  
  – Some success with ad hoc models for specific situations

• Gap in connecting phenomena at constituent to lamina/laminate scale
EXAMPLE: MODELING TiGr FATIGUE

Burianek and Spearing, Engineering Fracture Mechanics, 2003

- Metal/PMC hybrid laminates exhibit fatigue cracking in face-sheet accompanied by core/facesheet delamination
- Use 2-D quasi-3D model or full 3-D model
- Calculate global G for delamination
- Calculate crack tip G for facesheet - bridging model
- Incrementally grow delamination and facesheet crack according to separate Paris type power laws - update delamination shape
- Fatigue growth laws for facesheet and delamination are independently calibrated
FATIGUE LIFE DATA

![Graph showing fatigue life data with markers for fracture, delamination failure, runout, and 50% stiffness drop. The x-axis represents log(N) cycles, and the y-axis represents maximum cyclic stress (ksi).]
STIFFNESS REDUCTION

Relative Stiffness ($K/K_0$) vs. log(N) cycles for various OHT conditions:
- 10% OHT
- 15% OHT
- 30% OHT
- 38% OHT
- 45% OHT
- 53% OHT
- 60% OHT
EFFECT OF TEMPERATURE ON DAMAGE GROWTH (OH SPECIMENS)

Consistent with delamination growth observed from seams
Temperature is an important environmental stress factor.
FACESHEET CRACK MODEL IN TiGr

No calibration required
Works out of the box!

Applied SIF in titanium facesheet

\((\Delta K_{\text{appl}})_{\text{Ti}}\) (MPa-m^{0.5})

- \(\sigma_{\text{max}} = 314\) MPa
- 3D model (\(\sigma_{\text{max}} = 314\) MPa)
- \(\sigma_{\text{max}} = 419\) MPa
- 3D model (\(\sigma_{\text{max}} = 419\) MPa)
- \(\sigma_{\text{max}} = 524\) MPa
- 3D model (\(\sigma_{\text{max}} = 524\) MPa)

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Monolithic Ti 15-3
TEMPERATURE EFFECTS

- Projected operating temperature for HSCT is 177°C, therefore elevated temperature behavior is a key factor for TiGr.
- Previous experiments indicated significant increase in delamination growth rate for elevated temperatures.

Temperature does not change facesheet crack growth rate significantly, weak effect due to R-Ratio - predicted by model - potential for significant saving in testing.
DATA COMPARED TO MODEL FOR STIFFNESS REDUCTION
MODEL-BASED S-N CURVE FOR TiGr

\[ \sigma_{\text{max}} \] vs. Cycles

- Experiment
- Tuned model
AIM-C PHILOSOPHY

• Provide designer with access to relevant data/models with indication of applicability/limitations

• Guide designer/durability engineer in making best use of testing and modeling

• Interface with structures methodology: stress and fracture-based methods running within FE framework

• Be realistic in making claims for predictive capability
  – Likely to evolve from current testing-based approach to durability
  – Metrics for success are acceleration of test programs, reduction in testing cost - not total elimination of testing
  – Must allow for possibility of breakthroughs in predictive modeling capability, improvement of models - open architecture
A PROPOSED METHODOLOGY

1. A checklist of potential durability issues to prompt designer/durability expert
   - list of questions/decision tree/links to similar designs
   - Includes potential for interactions between factors

2. A library of available models and data
   - supports item 1 and 3, allows for quantitative assessment of threats - comparisons of relative severity rather than high fidelity predictions

3. Guidelines for specifying a test matrix
   - acceleration factors, interactions, identification of worst loading/environment/geometry combinations, measurements/observations

4. Interpretation of test data and application to structural design
   - (re)-calibration of models from 2), construction of ad hoc models, life prediction of structure, update library in 2
Empirical models exist for all phases of life

- \( N_I \) – matrix cracking initiation from transverse tensile data
- \( N_O \) – delamination onset from onset fatigue data
- \( N_G \) – crack growth from delamination growth data
ENVIRONMENTAL EFFECTS

\[
\frac{G_{c,\text{onset}}(T)}{G_c(T_0)} = 1 + a_s + a_\phi(T) \cdot b \cdot \log N
\]

\[
\frac{da}{dn}(T) = a_{TH} \cdot B \cdot (\Delta G)^{a_\phi(T) \cdot n}
\]

• Determine delamination onset and crack growth shift factors as a function of temperature and moisture

• Combine with models for other failure modes (cracking, sublamineate buckling)
MOISTURE DIFFUSION/ABSORPTION

• Predictive codes
  – Flaggs “Elastic Stability of Laminated Composite Plates Including Hygrothermal Effects”
    – Fickian diffusion model coded (Matlab & CO)
  – Chamis “Simplified Composite Micromechanics Equations for Hygral, Thermal and Mechanical Properties” – Hygrothermal property formulas for layered composites coded (Matlab)
  – Springer “Moisture Absorption and Desorption of Composite Materials” – Estimations for time to maximum % (Matlab)

• Experimental results
  – Kaelble (HTS/907, HTS/3002)
  – Springer (T300/1034)
  – Tenney (T300/5208)
MOISTURE ABSORPTION IN COMPOSITES

Moisture Models, User Interface

**MOISTURE ABSORPTION IN COMPOSITES**

**Key Property**
(Other laminate properties currently embedded in Matlab code - could link to lamina/laminate)

**Plotting Parameters**

**BC’s**

### Last Updated: January 27, 2003

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<th>Units</th>
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<td>T^0.5 days^0.5</td>
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</table>
Linked Models Encoded

**Moisture Profile Across Laminate**

- Top 50%, Bottom @ 5%, 3 days

**Moisture Absorption Over Time**

- Top & bottom @ 50%
- Middle ply 50/100
- 40/100
- ¼ ply 25/100
- 10/100
- Bottom ply 1/100

Initial @ 5% 

Allows designer to obtain time to saturate, can also cope with moisture/temperature cycling, feeds into other models
CRACK DENSITY

- Predictive codes
  - Nairn “The Formation and Propagation of Matrix microcracks in Cross-ply Laminates during Static Loading” – Crack Density from static loading (still working on coding this in Matlab)
  - McManus “On Microcracking in Composite Laminates under Thermal and Mechanical Loading” – Microcracks from cyclic thermo-mechanical loading (FORTRAN, needs user interface)

- Experimental results
  - Hashin (T300/934)
  - Sandeckji (T300/934)
  - Kobayashi (AS4/PEEK)
  - McManus (AS4/3501-6)
MECHANICAL PROPERTY DEGRADATION

• Predictive codes
  – Hashin “Micromechanics Aspects of Damage in Composite Materials” – Reduced $E$, $G$, $\alpha$ based on crack density (Matlab & CO)
  – McManus “Mechanism-Based Modeling of Long-Term Degradation” – Reduced strength and toughness based on crack density (FORTRAN, needs user interface)

• Experimental results
  – Kaelble (HTS/907, HTS/3002)
  – Hashin (Glass/Epoxy)
  – McManus (AS4/3501-6)
OTHER DURABILITY MODELS

• Moisture Absorption
  – Roy “Modeling of Moisture Diffusion in the Presence of Bi-Axial Damage in Polymer Matrix Composite Laminates” – Non-Fickian moisture absorption model, experimentally fit 7 constants

• Crack Density
  – Nairn “Hygrothermal Aging of Polyimide Matrix Composite Laminates” – Microcrack toughness over time in hygrothermal environment, master curve requires experimentally fit constant

• Reduced Properties
  – Kaelble “Hydrothermal Aging of Composite Materials” – Reduced shear strength with load and hygrothermal exposure, experimentally fit 3 constants
CRACK DENSITY PREDICTIONS

![Graph showing crack density predictions for different Gic values against number of cycles and temperature.]

- **Gic = 250**: Crack density increases with increasing number of cycles and decreases with increasing temperature.
- **Gic = 200**: Similar trend but with different values for crack density.

Number of Cycles: 1 to 1000
Temperature (K): 0 to 70
Crack Density in Center Ply Group (1/cm): 0 to 6
CRACK DENSITIES FEED INTO REDUCED PROPERTY MODEL

<table>
<thead>
<tr>
<th>Reduction Properties Model, User Interface</th>
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<tbody>
<tr>
<td>Gergana Bounova, Last Updated: January 29, 2003</td>
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</table>

### Hashin Model

- Exo - Young’s modulus of uncracked laminate: 21 Msi
- EA - Axial Young’s modulus of ply: 29 Msi
- ET = Transverse Young’s modulus of ply: 10 Msi
- GT = Transverse shear modulus of ply: 6 Msi
- GA = Axial shear modulus of ply: 6 Msi
- sigma_o = Applied stress: 50 Ksi
- sigma_1 = Stress in 90 degrees ply of uncracked laminate: 10 Ksi
- t1 - thicknesses of 90 degrees ply: 0.005 in
- t2 - thicknesses of 0 degrees ply: 0.005 in
- 2a - intercrack distance: 0.01 in
- υA - Axial Poisson Ratio: 0.34
- υT - Transverse Poisson Ratio: 0.22

*The cracked laminate Youngs modulus is:* 19.925 Msi
SUMMARY

- Key aim is to guide designer/durability engineer in making best use of testing and modeling

- Advocate a model-augmented approach to durability assessment/assurance

- Models exist that are ready and useful to contribute to this.

- Need to be realistic in making claims for predictive capability
  - Likely to evolve from current testing-based approach to durability
  - Metrics for success are acceleration of test programs, reduction in testing cost - not total elimination of testing
  - Must allow for possibility of breakthroughs in predictive modeling capability, improvement of models - open architecture