Damage Tolerance Testing and Analysis Protocols for Full-Scale Composite Airframe Structures under Repeated Loading - Fluid Ingression & Ground-Air-Ground Effects

2011 Technical Review

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Wichita State University/NIAR
Fluid Ingression & Ground-Air-Ground Effects

• Motivation and Key Issues
  – Fluid ingression phenomenon and the progressive damage growth due to entrapped fluids in sandwich structures
  – Thermo-mechanical loads during ground-air-ground (GAG) cycling result in localized mode I stresses that cause further delamination/disbond/core fracture growth creating more passageways for fluid migration.

• Objective
  – The influence of sandwich parameters such as core size, density, and facesheet/core stiffness ratio on the onset and damage growth rate of sandwich composite
  – Understand the Ground-air-ground effect on onset and damage growth

• Approach
  – Damage growth in sandwich structures
    ▪ Core types, core densities (24, 32 and 48kg/m³) & F/C thicknesses
  – Mechanics of different damage sources
    ▪ Fluid ingression (GAG effects)
    ▪ Impact damages
    ▪ Repairs (improper repairs and process deviations)
Fluid Ingression & Ground-Air-Ground Effects

• Principal Investigators & Researchers
  – John Tomblin, PhD, and Waruna Seneviratne, PhD
  – Shawn Denning

• FAA Technical Monitor
  – Curtis Davies

• Other FAA Personnel Involved
  – Larry Ilcewicz, PhD

• Industry Participation
  – Cessna, Bombardier, Hawker Beechcraft, and Spirit Aerosystems
Challenges

• Standardized test methods
  – Test procedures
  – Data reduction techniques

• Complex damage mechanics
  – Onset
  – Propagation
  – Multiple constituents

• Tools for stress analysis
  – Crack-tip mode mixity

• Publically available data
  – Service findings
  – Component-level test data
Approach

Stress Analysis

Failure Analysis

Experimental Data

Analytical Tools

Service Findings

Validation

Guidelines
Overview Coupon Tests

- **Double Cantilever Beam (DCB) [Modified ASTM D5528]**
  - Laminate/adhesive Mode I fracture toughness
  - Test method and data reduction
    - Static
    - Fatigue
  - Static test summary
  - R-curves
  - Fatigue curves

- **Single Cantilever Beam (SCB) [Standards under development]**
  - Sandwich Mode I fracture toughness (DOE)
  - Test method and data reduction
    - Static
    - Fatigue
  - Static test summary
  - R-curves
  - Fatigue curves

- **Flatwise Tension (FWT) [ASTM C297]**
  - Static test summary

- **SKYDROL**
  - Conditioning parameters
  - Procedures
Materials

• Core
  – Hexel HexWeb HRH -10 Aramid Fiber/Phenolic Honeycomb
    ▪ Hexagonal
    ▪ Over-expanded

• Facesheet material
  – Cytec AS4/E7K8 PW
  – Facesheet layups
    ▪ 4 ply: [0°/45°]_s
    ▪ 16 ply: [0°/45°]_{4S}

• Adhesive
  – Cytec FM 300 epoxy film adhesive
### DCB Test Matrix

<table>
<thead>
<tr>
<th>Material</th>
<th>Description</th>
<th>Layup Sequence</th>
<th>Test Cond.</th>
<th>Static</th>
<th>Fatigue</th>
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<td>Baseline</td>
<td>Fluid Ingressed</td>
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<td>Laminate</td>
<td>AS4/E7K8 PW</td>
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<td>Total Specimens</td>
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</table>

- ASTM D5528 Mode I – double cantilever bending (DCB)
  - Modified for fabric
  - Modified for adhesive

Test in progress
DCB Experimental Procedure - Static

- Static Testing follows modified ASTM D 5528-01
  - Visual Inspection (Microscope) for RTD testing
  - Crack propagation gages (CPG) and crack detection gages (CDG) for ETD testing
DCB Experimental Procedure - Fatigue

- Fatigue Testing follows a NIAR procedure developed for ASTM round robin testing
  - Delimitation growth rate

\[
\frac{\delta^2_{max}}{[\delta_{cr}]_{av}} = \frac{G_{I_{max}}}{G_{fc}} = 0.9
\]

\[
\delta^2_{max} = \frac{2b_{av}[C^2]_{av} \cdot 0.9[G_{fc}]_{av}}{\delta[C]_{av}}
\]

\[
da = \frac{a_{i+1} - a_i}{N_{i+1} - N_i}
\]

\[
G_{I_{max}} = \frac{3P_{max} \delta_{max}}{2b(\bar{a} + |\Delta|_{av})}
\]

\[
\bar{a} = \frac{1}{2}(a_{i+1} + a_i)
\]
## DCB Static Baseline Test Summary

<table>
<thead>
<tr>
<th>Material</th>
<th>Test Environment</th>
<th>Mode I</th>
<th>Average $G_{IC}$ [kJ/m²]</th>
<th>Standard Deviation [kJ/m²]</th>
<th>Coefficient of Variation [%]</th>
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<tbody>
<tr>
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<td>GIC (NL)</td>
<td>0.339</td>
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<td>1.093</td>
<td>0.156</td>
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Test Data: Laminate - Static

GIC [kJ/m²]

Crack Length a [mm]

NIS11 - SDT - 31 - LM - BL - MODE1 - SL1 - 1
NIS11 - SDT - 31 - LM - BL - MODE1 - SL1 - 2
NIS11 - SDT - 31 - LM - BL - MODE1 - SL1 - 3
NIS11 - SDT - 31 - LM - BL - MODE1 - SL1 - 4
NIS11 - SDT - 31 - LM - BL - MODE1 - SL1 - 5
NIS11 - SDT - 31 - LM - BL - MODE1 - SL1 - 6
NIS11 - SDT - 31 - LM - BL - MODE1 - SL1 - 7

CECAM

JAMS

AMTAS
Test Data: Adhesive - Static
Test Data: Fatigue - RTD

Laminate

Adhesive
<table>
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<tr>
<th>Material</th>
<th>Core Type</th>
<th>Core Thickness (in)</th>
<th>Facesheet</th>
<th>Cell Size (in)</th>
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Test in progress
### FWT Baseline Test Summary

| Core - Hex 1/8 - 3 | 0.379 | 0.012 | 3.252 |
| Core - Hex 3/16 - 2 | 0.229 | 0.009 | 3.934 |
| Core - Hex 3/16 - 3 | 0.355 | 0.004 | 0.985 |
| Core - Hex 3/16 - 6 | 0.727 | 0.02 | 2.819 |
| Core - Hex 3/8 - 3 | 0.301 | 0.01 | 3.408 |
| Core - OX 3/16 - 3 | 0.295 | 0.028 | 9.479 |

**Reasonable data scatter!**

![Graph showing FWT Strength vs Cell Size and Core Density](image)

**Graph 1:** FWT Strength (ksi) vs 3/16 Cell Size - Core Density (psf)

**Graph 2:** FWT Strength (ksi) vs 3 psf Core - Cell Size

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**CECAM**

**JAMS**

**AMTAS**
<table>
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<tr>
<th>Material</th>
<th>Core Type</th>
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<th>Facesheet (per F/C)</th>
<th>Cell Size (in)</th>
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Sub Totals 144 144

Total Specimens 288

Test in progress
SCB Method

- Static testing follows Modified ASTM D 5528-01
  - 2 X 10-inch specimen
  - Initial disbond length = 2.5-inch
  - Use SCB fixture instead of DCB fixture
    - Prevents asymmetric loading
    - Prevents mixed-mode mechanics
    - Prevents kinking
**SCB Method - MBT**

- **Modified Beam Theory (MBT)**

\[
\delta_1 = \frac{Pa}{bh_c G_{xz}} + \frac{Pa^3}{3b \left( D - \frac{B^2}{A} \right)}
\]

\[
\delta_2 = \frac{Pa^3}{3E_{f2}I_{f2}}
\]

\[
C = \frac{1}{b} \left[ \frac{a^3 b}{3E_{f2}I_{f2}} + \frac{a^3}{3 \left( D - \frac{B^2}{A} \right)} + \frac{a}{h_c G_{xz}} \right]
\]

\[
G = \frac{P^2 a^2}{2b^3} \left[ \frac{b}{E_{f2}I_{f2}} + \frac{1}{D - \frac{B^2}{A}} + \frac{1}{a^2 h_c G_{xz}} \right]
\]

\[
G_1 = \frac{3Pb}{2b(a + |\Delta|)}
\]
SCB Method - EF

- Elastic Foundation (EF)

\[ G = \frac{P^2}{2b} \frac{dC}{da} \]

\[ = \frac{P^2}{2b^2} \left\{ \frac{1}{h_c G_{xx}} + \frac{a^2}{(D - B^2)} + \frac{12a^2}{E_{12} h_{f2}^3} \left[ 1 + 1.28 \left( \frac{h_{f2}}{a} \right) \left( \frac{E_{12}}{E_c} \right)^{1/4} \left( \frac{h_c}{h_{f2}} \right)^{1/4} + 0.41 \left( \frac{h_{f2}}{a} \right)^2 \left( \frac{E_{12}}{E_c} \right)^{1/2} \left( \frac{h_c}{h_{f2}} \right)^{1/2} \right] \right\} \]
**SCB Methods**

- Fatigue Testing follows a NIAR procedure developed from round robin testing

\[
\frac{\delta_{cr}^2}{\delta_{cr}^2} = \frac{G_{I, \text{max}}}{G_{Ic}} = 0.9
\]

\[
\delta_{\text{max}}^2 = \frac{2b \left[ C^2 \right]_{\text{av}} \cdot 0.9 \left[ G_{Ic} \right]_{\text{av}}}{\partial \left[ C \right]_{\text{av}}} \frac{\partial a}{\partial a}
\]

\[
da = a_{i+1} - a_i
\]

\[
dN = N_{i+1} - N_i
\]

\[
G_{I, \text{max}} = \frac{3 P_{\text{max}} \delta_{\text{max}}}{2b(a + \Delta)_{\text{av}}}
\]

\[
\bar{a} = \frac{1}{2}(a_{i+1} + a_i)
\]
### SCB Static Baseline Test Summary

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<thead>
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<th>Mode I</th>
<th>AVERAGE G\textsubscript{IC} [kJ/m\textsuperscript{2}]</th>
<th>STANDARD DEVIATION [kJ/m\textsuperscript{2}]</th>
<th>COEFFICIENT OF VARIATION [%]</th>
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<td>GIC (VIS)</td>
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<td>HEX-3/8 - 3</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>GIC (NL)</td>
<td>0.282</td>
<td>0.057</td>
<td>20.197</td>
</tr>
<tr>
<td>GIC (VIS)</td>
<td>0.513</td>
<td>0.047</td>
<td>9.099</td>
</tr>
<tr>
<td>GIC (5%/max)</td>
<td>0.526</td>
<td>0.121</td>
<td>22.954</td>
</tr>
</tbody>
</table>

![Graph showing Mode I Fracture Toughness (kJ/m\textsuperscript{2})](image)
SCB Static Test Data - RTD

HEX 3/16 - 2
SCB Static Test Data - RTD

![Graph showing SCB Static Test Data with Crack Length a [mm] on the x-axis and G_c [kJ/m²] on the y-axis. The graph includes data points for different conditions labeled as HEX 3/16 - 3.]
SCB Static Test Data - RTD

Hex 3/8 - 3

$G_{IC}$ [kJ/m$^2$] vs. Crack Length $a$ [mm]
Data Scatter!!!

- Test method
- Initial flaw
- Failure mechanism
**DCB vs. SCB**

- Failure mechanism is drastically different for DCB and SCB
  - Onset
  - Propagation

What is realistic?
Skydrol Conditioning

- Conditioning guidelines
  - Mix ratio
  - Temperature
  - Time

- Damage mechanism

<table>
<thead>
<tr>
<th>Mix Ratio</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skydrol</td>
<td>Water</td>
</tr>
<tr>
<td>25%</td>
<td>75%</td>
</tr>
<tr>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>75%</td>
<td>25%</td>
</tr>
</tbody>
</table>

Test in progress
Further Studies

- Large damage scenarios (flexure, CAI)
  - 1D
  - 2D

- Other damage scenarios
Finite Element Analysis

- Analysis address complete damage growth mechanism
- Evaluate predictive capabilities
  - Onset & propagation
- Element selection
  - Evaluation of stress/strain
- Crack propagation
  - Virtual Crack Closure Technique (VCCT) element
  - Cohesive element
  - Applicability since the crack is not in plane ➔ Alternatives
- Use of experimental data
Looking Forward

• Benefit to Aviation
  – Guidelines for substantiating sandwich structures
    ▪ Fluid ingression phenomenon
    ▪ GAG effects on damage growth
    ▪ Effects of geometry and sandwich parameters on fracture toughness and damage growth rates

• Future needs
  – Field history data related to sandwich data growth phenomenon
  – Analytical methods
  – Standardized test procedures
End of Presentation.

Thank you.