Research on Structural Test & Analysis Protocol: Progress and Plans

John S. Tomblin
Waruna Seneviratne

National Institute for Aviation Research
Wichita State University
Wichita, KS

Commercial Aircraft Composite Repair Committee (CACRC)
Meeting & Workshop for Composite Damage Tolerance & Maintenance
Amsterdam, Netherlands
May 9-11, 2007
Research Program Objectives

**Primary Objective**

_Demonstrate acceptable means of compliance for fatigue, damage tolerance and static strength substantiation of composite airframe structures_

**Secondary Objectives**

- Evaluate existing analysis methods and building block database needs as applied to practical problems crucial to composite airframe structural substantiation
- Investigate realistic service damage scenarios and the inspection & repair procedures suitable for field practice
Goals of the Program

- Produce a guideline FAA document which demonstrates a “best practice” procedure for full-scale testing protocols for composite airframe structures with examples.
Candidate Research Tasks

1. Load Enhancement Factor Approach and Fatigue Life Assessment
   • Various approaches which have been or are currently being used
   • Guidance on Cycle Truncation
   • Address Environmental Factors used during testing
   • Full-Scale Validation and Examples

2. Damage Tolerance and Repair Substantiation
   • Categories of damage

3. Analysis Methods
   • Define procedures necessary to support testing and building block approaches
Transport Aircraft Applications

We all think about these applications … but …
Other Applications of Advanced Materials

Cirrus

Lancair

Horizon

Adam Aircraft

Spectrum

Predator

Lancair

Javelin

Premier I

Epic

Honda

Global Hawk

SpaceshipOne

Liberty

Toyota Aircraft
Main Working Group

- Federal Aviation Administration
  - Curtis Davies
    • FAA William J. Hughes Technical Center, NJ
  - Larry Ilcewicz
    • FAA/Seattle Aircraft Cert. Office
  - Lester Cheng
    • FAA-Small Airplane Directorate
  - Evangelina Kostopoulous
    • FAA ACO - Chicago
  - David Ostrodka
    • FAA ACO - Wichita
  - Peter Shyprykevich
    • Consultant

PLUS OTHER INDUSTRY PARTNERS
Load Enhancement Factor Approach and Fatigue Life Assessment

- Background – most test programs reference the Navy/FAA reports by Whitehead, Kan, et. al. (1986) and follow that approach
- Most test programs have used the conclusions developed in this report regardless of design features, failure modes and/or materials
- EADS-CASA study used the same approach (2001) but redefined the shape factors
LEF - Overview of Methodology

Comparison of graphite-epoxy and aluminum fatigue life scatter distributions

Data was pooled on the basis that the life scatter is not significantly influenced by load level, loading mode, laminated layup, fatigue life and failure mode.
Life Factor Approach

- Structure is tested for additional fatigue life to achieve the **desired level of reliability**

![Graph showing Wiebull Shape Parameter (a) with curves for different n values (n=1, n=5, n=15) and Comparison Graph showing Composite life exceeds significantly that of Metal.](image)

### Mean Value/B-Basis

<table>
<thead>
<tr>
<th></th>
<th>n=1</th>
<th>n=5</th>
<th>n=15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composites Alpha = 1.25</td>
<td>13.558</td>
<td>9.143</td>
<td>7.625</td>
</tr>
<tr>
<td>Metals Alpha = 4.0</td>
<td>2.093</td>
<td>1.851</td>
<td>1.749</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
N_F &= \frac{\Gamma\left(\frac{\alpha L + 1}{\alpha L}\right)}{\left[\frac{-\ln(p)}{\chi^2(2n)}\right]^\frac{1}{\alpha L}} \\
\end{align*}
\]
Load Enhancement

- Increase the applied loads in the fatigue tests so that the same level of reliability can be achieved with a shorter test duration.
Load Enhancement Factor Approach

\[ \text{LEF} = \left[ p \left( \frac{\alpha_L + 1}{\alpha_R} \right) \right]^{1/\alpha_R} \left[ \frac{-\ln(p)^n}{\chi^2(2n)/2n} \right]^{1/\alpha_R} \]

<table>
<thead>
<tr>
<th>test duration</th>
<th>load enhancement factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>1.177</td>
</tr>
<tr>
<td>1.5</td>
<td>1.148</td>
</tr>
<tr>
<td>2.0</td>
<td>1.127</td>
</tr>
<tr>
<td>3.0</td>
<td>1.099</td>
</tr>
<tr>
<td>13.3</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Fatigue Data Fitting Models

Equivalent static strength values for fatigue data
Load Enhancement Factor Approach

Comparisons of NAVY/FAA data and EADS CASA data

1986 study conservatively estimated static shape parameter at 20

EADS CASA Static Strength tests

1986 study conservatively estimated fatigue shape parameter at 1.25

EADS CASA Fatigue Strength Tests

Leads to conservative LEF
Load Enhancement Factor

Comparisons of NAVY/FAA data and EADS CASA data

Load Enhancement Factors

Confidence limits set based on fatigue strength only since the mean and mode static strength values seem stable
Load-Life Combined Approach

\[
\text{LEF} = \left[ f \left( \frac{\alpha_L + 1}{\alpha_R} \right) \frac{\alpha_L}{\alpha_R} \right] \frac{\alpha_L^{1/3}}{\left( \frac{1}{2} \ln(p) \cdot N \right)^{(2/3)}}
\]
Task Research Objectives

• Generate data and guidelines for the generation of Weibull shape parameters for
  - Different material systems
  - Loading modes and geometries
  - Environments
  - Bonded joints (2 thicknesses)
  - Sandwich construction
  - Multiple R-ratios

Develop shape parameters for different geometries, environments, layups, and loading modes
Data Development

- Use existing lamina and laminate data for static strength

- Static / Fatigue Loading
  - Notched Tension
  - Notched Compression
  - Bonded joints
  - Interlaminar shear
  - Sandwich construction
  - RTD and ETW

- Fatigue
  - Const. amplitude (5 Hz)
  - R-ratios
    - 0 (Fuselage)
    - -0.2, 5 (Wing)
    - -1 (Control Surface)
<table>
<thead>
<tr>
<th>Laminate</th>
<th>Test Method</th>
<th>Loading Condition</th>
<th>Standard</th>
<th>Specimen Dimension (wxL)</th>
<th>Static Test Environment</th>
<th>RTD - Cyclic Test R ratio (3 Stress Levels)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RTD</td>
<td>ETW</td>
</tr>
<tr>
<td>10/80/10 Laminate</td>
<td>Open-Hole</td>
<td>Tension</td>
<td>ASTM D5766</td>
<td>1.5x12&quot;</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Comp.</td>
<td>ASTM D6484</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bonded Joint</td>
<td>Tension</td>
<td>Modified ASTM</td>
<td></td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>(t=0.01-inch)</td>
<td></td>
<td>D3165</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bonded Joint</td>
<td>Shear</td>
<td>Interlaminar</td>
<td></td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>(t=0.06-inch)</td>
<td></td>
<td>Shear</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Double</td>
<td>Comp. - BVID</td>
<td>ASTM D7137</td>
<td>4x6&quot;</td>
<td>5</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Notch Compression</td>
<td>Comp. - VID</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CAI [20 plies]</td>
<td>Comp. - BVID</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Comp. - VID</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CAI [40 plies]</td>
<td>Comp. - BVID</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Comp. - VID</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25/50/25 Laminate</td>
<td>Open-Hole</td>
<td>Comp. - RTD</td>
<td>ASTM D6484</td>
<td>1.5x12&quot;</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Comp. - ETW</td>
<td></td>
<td></td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>CAI</td>
<td>Comp. - BVID/RTD</td>
<td>ASTM D7137</td>
<td>4x6&quot;</td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Comp. - VID/RTD</td>
<td></td>
<td></td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Comp. - BVID/ETW</td>
<td></td>
<td></td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Comp. - VID/ETW</td>
<td></td>
<td></td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td>40/20/40 Laminate</td>
<td>CAI</td>
<td>Comp. - BVID</td>
<td>ASTM D7137</td>
<td>4x6&quot;</td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Comp. - VID</td>
<td></td>
<td></td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td>All 45's</td>
<td>Open-Hole</td>
<td>Comp. - RTD</td>
<td>ASTM D6484</td>
<td>1.5x12&quot;</td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Comp. - ETW</td>
<td></td>
<td></td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>TAI</td>
<td>Shear - BVID/RTD</td>
<td>Modified ASTM</td>
<td>4x10&quot;</td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shear - VID/RTD</td>
<td>D6148</td>
<td></td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shear - BVID/ETW</td>
<td></td>
<td></td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td>Sandwich 3-Ply</td>
<td>3-Ply Face sheet</td>
<td>4-Point Bend</td>
<td>ASTM C393</td>
<td>3x8&quot;</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Facesheet w/ 0.25-inch Core</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
T700SC-12K-50C/#2510 - Plain Weave Fabric

Lamina Statistical Allowable Generation for Fiber-Reinforced Composite Materials:

Lamina Variability Method

\[ \beta = 2.9412, \eta = 39.8364, \rho = 0.9955 \]

\[ \alpha = 2.941 \]

\[ \beta = 39.836 \]

\[ \alpha_R = 34.587 \]

MODAL (EXTREME)

Total of 873 specimens

\[ T \]

\[ \beta = 2.9412, \eta = 39.8364, \rho = 0.9955 \]

\[ \alpha = 2.941 \]

\[ \beta = 39.836 \]

\[ \alpha_R = 34.587 \]
LEF - AS4/ E7K8 & T700/ #2510

\[ \alpha = 1.6647, \quad \beta = 42.0614 \]

**MODAL (EXTREME) V**

\[ \alpha_R = 24.231 \]

**Preliminary LEF calculations**
(testing is in progress)

\[ \beta = 1.5915, \quad \eta = 1.5485 \]

\[ N \text{ (test duration)} = 1 \]

\[ N \text{ (# of test articles)} = 1 \]

<table>
<thead>
<tr>
<th>( \alpha_R )</th>
<th>( \alpha_L )</th>
<th>( N_F )</th>
<th>LEF</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19.63</td>
<td>2.74</td>
<td>3.019</td>
<td>1.167</td>
</tr>
<tr>
<td>20</td>
<td>1.25</td>
<td>13.558</td>
<td>1.177</td>
</tr>
<tr>
<td>NAVY</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24.231</td>
<td>1.741</td>
<td>6.094</td>
<td>1.139</td>
</tr>
<tr>
<td>0.831</td>
<td>62.000</td>
<td></td>
<td>1.152</td>
</tr>
<tr>
<td>AS4/E7K8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>34.587</td>
<td>1.872</td>
<td>5.308</td>
<td>1.095</td>
</tr>
<tr>
<td>1.496</td>
<td>8.463</td>
<td></td>
<td>1.097</td>
</tr>
</tbody>
</table>

\[ \beta = 1.5915, \quad \eta = 1.5485 \]

Without DOT/FAA/AR-03/56 adhesive fatigue data

With DOT/FAA/AR-03/56 adhesive fatigue data
Fatigue Life Shape Parameter

**CASA Study**
- [302 static; 48 fatigue specimens]
- Interlaminar shear test that exhibited low fatigue life
- Relatively less scatter
- Steep LEF curve & Low \( N_F \)
- High \( \alpha_L \)
- Combined Approach

<table>
<thead>
<tr>
<th></th>
<th>( \alpha_R )</th>
<th>( \alpha_L )</th>
<th>( N_F )</th>
<th>( N=1.00 )</th>
<th>( N=1.25 )</th>
<th>( N=1.50 )</th>
<th>( N=1.75 )</th>
<th>( N=2.00 )</th>
<th>( N=2.25 )</th>
<th>( N=2.50 )</th>
<th>( N=2.75 )</th>
<th>( N=3.00 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASA</td>
<td>19.63</td>
<td>2.74</td>
<td>3.019</td>
<td>1.167</td>
<td>1.131</td>
<td>1.103</td>
<td>1.079</td>
<td>1.059</td>
<td>1.042</td>
<td>1.027</td>
<td>1.013</td>
<td>1.001</td>
</tr>
<tr>
<td>NAVY</td>
<td>20</td>
<td>1.25</td>
<td>13.558</td>
<td>1.177</td>
<td>1.161</td>
<td>1.148</td>
<td>1.137</td>
<td>1.127</td>
<td>1.119</td>
<td>1.111</td>
<td>1.105</td>
<td>1.099</td>
</tr>
<tr>
<td>AS4/E7K8</td>
<td>24.231</td>
<td>1.741</td>
<td>6.094</td>
<td>1.139</td>
<td>1.121</td>
<td>1.106</td>
<td>1.094</td>
<td>1.083</td>
<td>1.074</td>
<td>1.066</td>
<td>1.059</td>
<td>1.052</td>
</tr>
<tr>
<td>T700/#2510</td>
<td>34.587</td>
<td>1.872</td>
<td>5.308</td>
<td>1.095</td>
<td>1.081</td>
<td>1.071</td>
<td>1.062</td>
<td>1.054</td>
<td>1.048</td>
<td>1.042</td>
<td>1.036</td>
<td>1.031</td>
</tr>
</tbody>
</table>

- **Reliability (p)**: 0.9
- **Confidence Level (\( \gamma \))**: 0.95
- **# of Test Articles (n)**: 1
**LEF - Automation**

![Image of FAA-LEF Calculations interface]

### Equivalent Static Strength Data

**Graph:**

- X-axis: Cycles, N
- Y-axis: Stress (ksi)

- Data points showing cyclic fatigue behavior

**Equation:**

\[
\text{LEF} = \frac{\left[ \Gamma \left( \frac{\alpha_L + 1}{\alpha_L} \right) \frac{\alpha_L}{\alpha_R} \right]}{\left[ -\ln(p) \cdot \frac{\alpha_L^{1/\alpha_L}}{\chi^2(2n)/2n} \right]}
\]
Environmental Enhancement Factor

- Develop guidelines for the development of environmental enhancement factors for static strength loading
- Use data developed at lamina, laminate, element and subcomponent to demonstrate application
Damage Tolerance Substantiation

PROGRAM OBJECTIVES

• Provide guidance documentation as to industry “best practices” to damage tolerance substantiation in full-scale test protocols
  - Address different damage categories
  - Address Allowable Damage Limit (ADL)
  - Address damage growth threshold and definition of Critical Damage Threshold (CDT)
  - Assess repairs and repair’s repeated load capability and address Repairable Damage Limit (RDL)
# Categories of Damage & Defect Considerations for Primary Composite Aircraft Structures

<table>
<thead>
<tr>
<th>Category</th>
<th>Examples</th>
<th>Safety Considerations (Substantiation, Management)</th>
</tr>
</thead>
</table>
| Category 1: Damage that may go undetected by field inspection methods (or allowable defects) | BVID, minor environmental degradation, scratches, gouges, allowable mfg. defects | Demonstrate reliable service life  
Retain Ultimate Load capability  
Design-driven safety |
| Category 2: Damage detected by field inspection methods @ specified intervals | VID (ranging small to large), mfg. defects/mistakes, major environmental degradation | Demonstrate reliable inspection  
Retain Limit Load capability  
Design, maintenance, mfg. |
| Category 3: Obvious damage detected within a few flights by operations focal | Damage obvious to operations in a “walk-around” inspection or due to loss of form/fit/function | Demonstrate quick detection  
Retain Limit Load capability  
Design, maintenance, operations |
| Category 4: Discrete source damage known by pilot to limit flight maneuvers | Damage in flight from events that are obvious to pilot (rotor burst, bird-strike, lightning) | Defined discrete-source events  
Retain “Get Home” capability  
Design, operations, maintenance |
| Category 5: Severe damage created by anomalous ground or flight events | Damage occurring due to rare service events or to an extent beyond that considered in design | Requires new substantiation  
Requires operations awareness for safety (immediate reporting) |
Work Tasks

- Fatigue & damage tolerance substantiation after static strength substantiation on a separate test article
- Fatigue, static strength and damage tolerance substantiation using the same test article
- One of the above but with variations in the loading, and/or severity of damage to demonstrate an ability to measure early warnings of failure in the test (and predict a failure)
- Supporting data needs
  - Static load cases and repeated loading envelopes
  - Test fixture design, fabrication & setup and test article instrumentation
  - Building block testing to support analysis groups
  - LEF & truncation limits for repeated load testing (shared databases)
  - Environmental factors for residual strength testing

Note: Test plans consider damages ranging from allowable damage limit (ADL) to critical damage threshold (CDT) and repairs up to the repairable damage limit (RDL)
Validation and Test Examples on Full-Scale Structures

• Need multiple, representative full-scale structures for testing
  – Demonstrate effects in multiple full-scale tests
  – Characterize load versus life effect on multiple full-scale articles
  – Damage Tolerance substantiation articles for various categories of damage
  – Multiple repair substantiation articles

• Problem ??? - cost of multiple structures for tests
Full-Scale Specimens

14 articles

Approx. average of 1000 flight hours (assume minimal aging effect), NDE examination
Full-Scale Specimens

FAA programs (assessing any age effects as well as DT), NDE examination

Currently 1 article is planned (documentation example)
Full-Scale Specimens

Liberty XL2

- Two fuselage tests are planned
- Structure is sandwich construction / minimum gage
Additional Full-Scale Tests

- Using the FASTER facility at the FAA Technical Center (Atlantic City, NJ)
- Fuselage loading – tension loading including pressure
- Test articles are representative of general aviation fuselage (sandwich construction)
Characterize LEF Baseline Structural State

- **Category 1 damage state** – BVID, minor environmental degradation, manufacturing defects, minor service damage
- *Retain ultimate load and reliable service life*
- *Constant amplitude* repeated loading \((N)\)
- \(N\) and load levels selected to produce fatigue failures
- Compression dominant
- NDI & Compliance check

![Scaling of LEF](image)
Damage Tolerance Testing

• Category 2 Damage – VID, major environmental degradation
• Demonstrate reliable inspection and define intervals
• Compression
• Impact Damage
• Spectrum Loading
• Retain Limit Load capability
• Demonstrate no or minor growth under repeated loading (inspection interval)
Damage Tolerance Testing

- Category 3 Damage – damage obvious to operator – should be detected within a few flights
- Demonstrate quick detection
- Define damage threshold
- Compression Loading / Impact Damage
- Spectrum Loading (LIMITED CYCLES)
- Retain Limit Load capability
Example of Test Results

Static Strength  Canard #2 - Failure Analysis
Repair Substantiation

- Demonstrate repair for category 2 and 3 damage states
- Work with OEM to develop guidelines for Repairable Damage Limit (RDL)
- Demonstrate restoration of full service life under spectrum loading
- Demonstrate restoration of ultimate load
Enhanced Combined Approach
[Life-Load-Damage]

Not to scale!!!

TEST DURATION (N)

MAXIMUM APPLIED STRESS

CAT-1
CAT-2
CAT-3

DEFINE DAMAGE TOLERANCE THRESHOLDS
Help define ADL
Help define CDT
Help define inspection intervals
Enhanced Combined Approach
[Life-Load-Damage]

LOAD FACTOR

LIFE FACTOR

INTEGRATES WELL INTO THE BUILDING BLOCK APPROACH BASED UPON DESIGN SPECIFIC INFORMATION GAINED FROM VARIOUS COUPON AND SUBELEMENT TESTS

PROVIDES OPPORTUNITY TO FURTHER INTEGRATE THE CERTIFICATION APPROACH
Contact Information

John Tomblin
National Institute for Aviation Research
1845 Fairmount
Wichita, KS  67260-0093
ph : (316) 978-5234
fx : (316) 978-3175
john.tomblin@wichita.edu