Analytical Fatigue Life Determination based on Residual Strength Degradation of Composites

Damage Tolerance Testing and Analysis Protocols for Full-Scale Composite Airframe Structures under Repeated Loading

2018 Technical Review

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Research Team

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AFRL

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Tara Storage
Variable Amplitude Fatigue Damage Growth (Background)

• Due to the anisotropy and heterogeneous nature of composites, fatigue damage growth characteristics of composites are complex and predictive methodologies are at their infant stages.

• Therefore, overly conservative assumptions are made for fatigue life assessment without taking full advantage of fatigue capabilities of composites.

• In order to design efficient composite structures, a greater understanding of fundamentals of fatigue damage initiation and growth characteristics of composite is needed.

• Need to understand the interaction of high-cycle (low stress) and low-cycle (high stress) fatigue on the life assessment of composite.

The primary goal of this research is to investigate the fatigue damage growth of composites under variable amplitude fatigue loading. The secondary goal of the program is to develop tools for determining the residual strength degradation or wearout.
The primary goal of this research is to develop techniques to enhance advanced material characterization and structural certification aided by high-fidelity damage modeling and efficient protocol for structural substantiation.
Overview of the Presentation

• Development of Strength Tracking (ST) Methodology
  • Variable Amplitude Fatigue Analysis
  • Validation

• High-Fidelity Inspections for Damage Characterization
  • X-Ray Computed Tomography (XCT)
  • High-fidelity inspection database

• High-Fidelity Finite Element Analysis
  • Regularized Extended Finite Element Analysis (Rx-FEM)
  • Validation with XCT and test results
Development of Strength Tracking (ST) Methodology
Variable Amplitude Fatigue Testing & Analysis
Constant Amplitude vs. Variable Amplitude (Spectrum)

**Constant amplitude:**

\[ A = \frac{\sigma_{\text{max}} + \sigma_{\text{min}}}{2} \]

**Random Spectrum:**


**Block Spectrum:**

Stress Ratio ($R$)

$R = \frac{\text{min}}{\text{max} \text{ stress}}$

- $R > 1$: C-C
- $1 > R > 0$: T-T
- $R < 0$: C-T

Ref: DOT/FAA/AR-10/6
Fatigue Scatter Analysis Techniques

- Individual Weibull
- Joint Weibull

\[
\sum_{i=1}^{n} \left[ \frac{\sum x_i^2 \cdot \ln(x_i)}{n} - \frac{1}{\alpha} \cdot \sum \ln(x_i) \right] = 0
\]

- Sendeckyj Equivalent Strength Model

\[
\sigma_v = \sigma_s \left( \frac{\sigma_v}{\sigma_s} \right)^{Y_0} + (N_f - 1) \cdot C
\]

Data Pooling Techniques
Wearout under Constant Amplitude Fatigue

\[ \sigma_r = \sigma_e + \left( \frac{\sigma_u - \sigma_e}{N_f(\sigma_u)} \right) \cdot n_f \]

\[ \sigma_r = \sigma_u \left( \frac{\sigma_e}{\sigma_u} \right)^{\frac{1}{s}} - C(n_f - 1) \]

- S-N data (fitted using Sendeckyj)
- Linear loss of residual strength
- Sendeckyj residual strength
- Stress level 1
- Stress level 3
- Number of Cycles
- Stress (psi)
Residual Strength Degradation - Variable Amplitude Fatigue

Fatigue Profile 5

<table>
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<tr>
<th>Stress Level</th>
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Fatigue Profile 6

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### Strength Tracking (ST) Method

**Fatigue Model Based on Residual Strength Degradation (Wearout)**

<table>
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<th>Block No.</th>
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<th>Stress Level</th>
<th>Number of Cycles in Block</th>
<th>Cumulative Cycles</th>
<th>Residual Strength</th>
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<td>$n_1$</td>
<td>$RS_1$</td>
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<td>$n_3$</td>
<td>$n_1 + n_2 + n_3$</td>
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</table>
1. Fatigue testing and generate SN data
2. Fatigue data scatter analysis of SN data
   • Generate fitting parameters for Sendeckyj analysis
   • Fatigue data scatter is considered (reliability!)
3. Generate residual strength degradation models
4. Use the residual strength degradation for each block
   • Sequencing effects are considered
5. Predict residual strength degradation or fatigue life
   • Applied stress $\geq$ Residual strength $\Rightarrow$ Fatigue failure
ST Method - Spectra with Multiple Stress Ratios

ST Method for Structural Applications

Critical Design Details
- CDD₁, CDD₂, ..., CDDₙ

Failure Modes
- FM₁, FM₂, ..., FMₙ

Design Spectrum

Usage Spectrum

Stress Ratios
- R₁, R₂, ..., Rₙ

SN Curves
- SN₁, SN₂, ..., SNₙ
  (Material, R, failure mode, etc.)

Residual Strength Degradation Models

Normalized Residual Strength

Strength Tracking Technique
- Applied stress → Residual strength → Fatigue failure

Fatigue Life Assessment

Service Life Assessment & Service Life Extension
<table>
<thead>
<tr>
<th>SPECIMEN #</th>
<th>R-Ratio</th>
<th>Max Stress [ksi]</th>
<th>Min Stress [ksi]</th>
<th>Cycles Survived</th>
<th>Load Block 1</th>
<th>Load Block 2</th>
<th>Load Block 3</th>
<th>Load Block 4</th>
<th>Load Block 5</th>
<th>Total # of Cycles Survived</th>
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**Validation of ST Method – 25/50/25 PW Preliminary Results**

### Fatigue Analysis

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<th>S</th>
<th>C</th>
<th>R</th>
<th>σₑ</th>
<th>σₑmax</th>
<th>σₑmin</th>
<th>n₁</th>
<th>nₑqv</th>
<th>nₑtot</th>
<th>σₑ(R,σₑ)</th>
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### Fatigue Test Results

**R = 5**

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**R = -1**

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**R = 5 & -1**

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| 202518 | 415445 |     |     |     |     |     |     |     |     |     |     |        |

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**Fatigue Analysis**

**Fatigue Test Results**
Validation of ST Method – 25/50/25 PW Load Sequencing

<table>
<thead>
<tr>
<th>NAME</th>
<th>n=0 Reference</th>
<th>70% - n=1,040 Load Block 1</th>
<th>40% - n=401,050 Load Block 2</th>
<th>55% - n=415,610 Load Block 3</th>
<th>40% - n=815,620 Load Block 4</th>
<th>55% - n=830,180 Load Block 5</th>
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<td>PW-OH-1</td>
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Fatigue Profile 5

Failed at 823,523 cycles

Failed at 827,830 cycles

Failed at 815,550 cycles

Failed at 822,849 cycles

Failed at 816,002 cycles

ST Predictions
n = 830,180

T650/5320 PW
25/50/25
R = -1
F = 5 Hz
## Validation of ST Method – 40/20/40 PW Preliminary Results

### Fatigue Analysis

<table>
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<tr>
<th>Block</th>
<th>$\Sigma n$</th>
<th>$\sigma_{\text{ax}}$</th>
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<th>$R$</th>
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<th>$n_i$</th>
<th>$n_{eqv}$</th>
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### Fatigue Test Results

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<th>$\sigma_{\text{ax}}$</th>
<th>$S$</th>
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<th>$R$</th>
<th>$\sigma_{\text{ax}}$</th>
<th>$\sigma_{\text{max}}$</th>
<th>$\sigma_{\text{min}}$</th>
<th>$n_i$</th>
<th>$n_{eqv}$</th>
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<th>$\sigma_i(n,R_s)$</th>
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3 Specimens of $R = 5$ survived 1,103,000 cycles

### Gallery

**R = -1**
- 550,165
- 539,141
- 523,164
- 521,419
- 533,781
- 522,465

**R = 5 & -1**
- 1,015,810
- 1,046,541
- 1,037,451

**R = -1 & 5**
- 1,000,190
- 1,006,941
- 1,035,966
- 1,037,451
- 1,014,366
High-Fidelity Inspections for Damage Characterization

X-Ray Computed Tomography (XCT)
High-Fidelity Inspections: NSI X7000 X-Ray CT System

• **Dual X-ray Tubes**
  - 225kV Micro-focus (6 μm) for low attenuating/low density materials, e.g. Carbon Fiber Composites.
  - 450 kV Mini-focus for high attenuating/high density materials, e.g. Metals

• **Dual Detectors**
  - Perking Elmer flat panel detector 16”×16”
  - Linear Diode Array (LDA) allows high precision data acquisition

• **Software**
  - NSI proprietary software for reconstruction of 3D volume
  - Materialise Mimics and 3Matic is used for data segmentation and data export into formats conducive for analysis

• **Portable Load Fixture**
X-Ray CT: Damage Monitoring

- High-fidelity ply-by-ply damage information
- Initiation site(s) detection and propagation details
- Interaction of different failure modes
- Multi-site damage interactions

Fatigue damaged open-hole test specimen
Feature Segmentation – Effects of Defects

- Segment and isolate the features of interest in Mimics
- These features can be meshed and exported as STL files for further analysis
- This information can be used as input parameters for damage modeling

Voxel Size
- Pre-Test: 98.2 micron
- Post-Test: 64.2 micron

Spatial distribution of defects
Technique Development

• Partial Rotation vs Full Rotation
  • Usually CT captures images from 360° around the object.
  • Using partial rotation scans it is possible to obtain higher resolution images of a smaller area.
  • This is a useful option to have when the object dimensions are larger than the area of interest.
  • Number of projections can be increased.

Area of interest can be moved closer to the source improving resolution.
High-Fidelity NDI for Damage Characterization (Database)

4D ply-by-ply NDI comparison of XCT and DR

Fatigue Life
DR vs. CT for Characterizing Fatigue Damage
4D XCT - Fatigue Damage Progression (Ply-by-Ply)

- OH-UNI-10 [45/0/-45/90]_3s
  - Stress level – 55% (27.3 ksi)
  - R = -1

Ply #5/24 [45°]  N = 25,000

Ply #6/24 [0°]  N = 25,000
3D XCT - Open-Hole (Plain Weave fabric)

T650/5320-1 PW
PW-OHC-8 (40/20/40)
Quasi-Isotropic
Constant Amplitude (R = -1)
Stress Level = 35 ksi
n = 22,250
• OH-PW-8 \([0/90/0/90/45/-45/90/0/90/0]\)\(_s\)
  • Stress = 35 ksi
  • R = -1
  • n = 25630
High-Fidelity Finite Element Analysis
Regularized Extended Finite Element Analysis (Rx-FEM)
High-Fidelity Analysis

Delamination and open matrix cracks
@ predicted failure strength of 375MPa

Mesh-independent regularized extended finite element modeling (Rx-FEM)

[45/90/-45/0/45/90/-45/0/0/-45/90/45/0/-45/90/45]

Potential “crack path” if crack continued
Rx-FEM - Matrix and Fiber Cracks in UNI OHC

0° ply

-45° ply

90° ply

Fiber break near hole on 0°

[45/90/-45/0/45/90/-45/0/-45/90/45/0/-45/90/45]
Rx-FEM - Delamination Propagation in UNI OHT

Delamination in 0/-45 interface

Delamination in -45/90 interface

Delamination in 90/45 interface

[45/90/-45/0/45/90/-45/0/0/-45/90/45/0/-45/90/45]
Rx-FEM - Matrix Crack Growth in UNI OHT

[45/90/-45/0]₂S
Summary - Strength Tracking (ST) Method

- Fatigue damage growth of composites under constant or variable amplitude (block/random) fatigue loading can be assessed
  - Can handle multiple R ratios
  - Sequencing effects will be incorporated
- Any validated residual strength degradation (wearout) model can be used
  - Sendeckyj wearout model is used for examples due to its robustness (ex., fitting curve for SN data provides an assessment of fitting parameters)
    - Incorporate reliability (analysis of fatigue data scatter)
    - Residual strength degradation for arbitrary stress levels
    - Simple Excel worksheet can be setup for life assessment
- Provide opportunity to improve the technique for future developments of wearout models, both semi-empirical and analytical models
Summary – Damage Characterization (XCT)

- XCT system has significantly enhanced the research quality
  - Provided insight to interrogate internal defects/features of various material systems
  - Damage growth mechanics of advanced material systems under cyclic loading
  - Post-failure and accident investigation without sectioning
- Technique development is underway to enhance the quality of inspections
- Mimics software is used successfully for segmentation of various features from XCT reconstructions for analyses
Looking Forward

• Benefit to Aviation
  • High-fidelity database of fatigue damage growth characteristics of composites under variable amplitude fatigue loading
  • Development of engineering tools for determining the residual strength degradation and fatigue life under variable amplitude fatigue cycling

• Future needs
  • Variable amplitude fatigue data for fatigue analysis and validation of wearout models for analytical life predictions
  • Analytical models for predicting residual strength degradation (wearout)