Application of Aerospace Durability and Damage Tolerance Approaches to Wind Blade Design
Outline

Introduction

Aerospace Industry - Durability and Damage Tolerance

Durability and Damage Tolerance Analysis & Test

Wind Blade Analysis Examples

Summary and Discussion
Company Background

NSE Composites

- Engineering company specializing in the field of advanced composite structures
- Three principal engineers, three structural analysts, plus consultants
- Founded in 1996, located in Seattle, WA

Engineering Services

- Structural Design & Analysis
- Certification of Aerospace Structures
- Structural Optimization
- Finite Element Analysis
- Structural Testing
- Research & Development
- Analysis Software Development

View of Lake Union from NSE offices in Seattle
Example Customers

AEROSPACE

- Boeing
- Bombardier
- Spirit AeroSystems
- Fokker Aerostructures
- General Electric Global R&D
- Federal Aviation Administration (FAA)
- Hexcel Composites
- Bell Helicopter

WIND ENERGY

- GE Renewable Energy
- General Electric Global R&D
- General Electric Wind
- Frontier Wind (Energy Unlimited)
- Knight & Carver Wind Blade Division
- Global Energy Concepts (now DNV-GL)
- Dynamic Design
- Kenetech Windpower, Inc.
Typical Analysis Projects

**Finite Element Analysis (FEA)**

- Wing, fuselage, engine/rotor/wind turbine blades
- Nonlinear geometry and material modeling
  - In-plane progressive damage analysis
  - Delamination and disbond analysis under static and fatigue loading
- Buckling stability analysis
  - Eigenvalue buckling
  - Nonlinear post-buckling response

**Damage Tolerance Analysis Methods**

- Skin-stringer applications with large notches/damage
- Impacted sandwich structure
- Nonlinear FEA and semi-empirical methods
Bonded Joints & Fracture Mechanics

VCCT Finite Element Development

- Developed and validated Boeing’s VCCT user element (in collaboration with Boeing).
  - *Eventually implemented in ABAQUS.*

- Developed an approach for automated progressive damage under fatigue loading.
  - *Documented in ASTM Fracture Workshop presentation (2004).*


- Ongoing involvement with ABAQUS developers to support enhancements for static and fatigue VCCT analysis.
FAA Guidance Material & Safety Initiatives

**CMH-17 Composite Material Handbook – 17**

- NSE active in CMH-17 since 1996.
- Co-Chairs of Damage Tolerance Working Group
- Primary authors of many sections in Volume 3, Chapter 12: “Damage Resistance, Durability, and Damage Tolerance”.

**CSET – Composite Structural Engineering Technology Course**

- Contracted by the FAA to author sections of an FAA-developed course covering structural substantiation, damage tolerance, and certification.
- Course content expands on certification guidance in AC 20-107B: “Composite Aircraft Structure” is the primary source of advisory information for composite aircraft structure (released in 2009).
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Summary and Discussion
Safe Life vs. Durability & Damage Tolerance

- **Safe Life** - Adequate fatigue life of a structural member is ensured by limiting its allowed operational life.

- **Durability** - The structure retains adequate properties throughout its life, such that any deterioration can be found and repaired.

- **Damage Tolerance** - The structure retains the required strength for a period of time after sustaining damage.
Durability & Aging Considerations

Service Life Limits

- The service life limits of composite aircraft components are *not* generally driven by fatigue and aging (i.e., durability).
- Material property degradation due to fatigue loading and environmental exposure is avoided through design and material screening based on testing and service history.

Aerospace Industry Best Practices

- Use **traditional designs and materials** (with service history).
- Perform **material screening** (test at expected temperature/moistures/fluid exposure).
- Keep design **strains below fatigue thresholds** (no damage growth allowed).
- Take caution with fatigue susceptible designs (see next slide).
- Pay **special attention to bonded joints and sandwich structure** (limit use of bonded joints in primary load paths, use arrestment features to stop disbonds).
- Use robust finishes to protect from moisture and UV (inspect and repair in-service).
Sensitive details typically evaluated by test and analysis at mid-level of building block.

[1] Figure courtesy of Christos Kassapoglou
Design Criteria for Damage and Defects

Damage Threat Assessment

- Define damage/defect types, locations, and severity levels that may occur in the structure during manufacturing and service.
- Consider allowable manufacturing defects as well as possible “escapements” (process failures missed by QC during manufacturing).

Damage-Related Criteria

- Define a set of criteria that are representative and conservative for the full list of expected damage/defect types and locations, that can be substantiated with analysis and test.
  - Use simplified damage states.
- Criteria are grouped into Categories of Damage and Defects [1].
  - Defined load levels.
  - Probability of detection is associated with production and in-service inspection methods.

Load Levels for Categories of Damage \[1\]

Match design load levels with visibility and likelihood of detection.

- **Ultimate**
  - 1.5 Factor of Safety
  - For non-detectable and acceptable damage

- **Limit**
  - ~ Maximum load per lifetime
  - For detectable damage to be found and repaired through maintenance
  - Continued safe flight

- **Allowable Damage Limit (ADL)**
  - For damage occurring with flight crew’s knowledge

- **Critical Damage Threshold (CDT)**

**Increasing Damage Severity**

Is there an equivalent to Ultimate and Limit load levels in the wind industry?

[1] Figures from CSET – Composite Structural Engineering Technology Course
Damage & Defects - Category 1 [1]

Definition

- Likely damage or defects that are either not detectable or are deemed acceptable during manufacturing inspections and service inspections.

Load Requirements

- Must withstand **Ultimate Load** and not impair safe operation of the aircraft for its lifetime.

[1] Figures from CSET – Composite Structural Engineering Technology Course
Category 1 damages and defects

- Barely visible impact damage (BVID)
- Small holes, scratches, cracks, gouges
- Minor environmental damage including erosion
- Allowable manufacturing defects
  - Bondline flaws and voids
  - Porosity
  - Waviness

[1] Figures from CSET – Composite Structural Engineering Technology Course
Strength Allowables

- Strength allowables take into account possible damages and defects.
  - Simplified damage states used to cover for impact damage variability.
  - Analysis is calibrated/validated with testing with the same damage and defects.

- ½” by ½” delamination assumed for analysis at critical location in radius or stiffener terminations.

- ¼” by infinite disbond assumed along stiffener flange-to-skin bondline.
Damage & Defects - Category 2 [1]

Definition

- Damage that is detectable during maintenance inspections at specified intervals and is deemed unacceptable (repair scenario).

Load & Life Requirements

- Must withstand a once per lifetime load (i.e., Limit load), which is applied following repeated service loads occurring during the applicable inspection interval.

Category 2 damages and defects

- Visible impact damage (VID)
- Deep gouges, larger holes, dents
- Manufacturing defects/escapements
- Major local heat or environmental degradation

[1] Figures from CSET – Composite Structural Engineering Technology Course
**Definition**

- Obvious damage that will be reliably detected within a few flights of occurrence by operations or ramp maintenance personnel during routine activities (repair scenario).

**Load Requirements**

- Must withstand **Limit or near-Limit Load**.
- Required load levels generally decrease with increasing damage severity (and increasing detectability).
- Must maintain load capability **for a “few” flights** (damage is readily detectible during pre-flight walk around).

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[1] Figures from CSET – Composite Structural Engineering Technology Course
Category 3 Damages & Defects – Examples [1]

**Category 3 damages include:**

- Holes punched by unknown objects
- Large gouges, dents
- Multiple dents or holes
- Areas of heat scorching
- Lost repair patch

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[1] Figures from CSET – Composite Structural Engineering Technology Course
Category 2 & 3 Damage & Defects – Analysis Examples

**Large Notch Damage Tolerance**

- Skin crack with a severed stringer simulates in-service damage.
  - *Simplified damage state covers for a wide range of possible in-service damage scenarios.*

- Analysis predicts through-thickness skin crack growth and skin/stringer delamination.
  - *Ranges from closed-form methods to progressive damage FEA.*
  - *Validation is done with large-scale tests of multi-stringer panels.*

**Fuselage Skin-Stringer Panel with Notch**

[Diagram of fuselage skin-stringer panel with notch]
Skin Buckling with Defects

- Disbonded stringer simulates in-service damage or a manufacturing escapement.
- Disbond length is typically set at arrestment features (frames).
- Limit Load level used for margin of safety calculations.
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Summary and Discussion
Building Block Approach \[1\]

Testing for Damage Tolerance

- The **mid-level building block tests** (elements and subcomponents) are used to evaluate damage and defects (static and “no growth” fatigue testing).

- Testing must include realistic boundary conditions and allow for load redistribution (not possible at coupon level). Test articles must be representative of production structure.

Delamination & Disbond Analysis

Fracture Mechanics Approach

- Use of fracture mechanics has become common practice in the aerospace industry to characterize the onset and growth of delaminations and disbonds.
- The virtual crack closure technique (VCCT) is widely used for computing energy release rates based on results from finite element (FE) analyses.
- Closed-form methods exist for some configurations, where the near crack tip loading is well-understood.

Crack Path Discretized with Interface Elements
Fracture Failure Predictions

Modes of Fracture

- Mode I (opening)
- Mode II (sliding)
- Mode III (tearing)

Example Mixed-Mode Failure Criterion \[ f = \frac{G_T}{G_{Ic} + \left( \left( G_{IIc} - G_{Ic} \right) \frac{G_{II}}{G_T} + \left( G_{IIIc} - G_{Ic} \right) \frac{G_{III}}{G_T} \right) \left( \frac{G_{II} + G_{III}}{G_T} \right)^{\eta^{-1}}} \]

failure is predicted when \( f > 1.0 \).

Fracture Toughness Testing (Mode I)

ASTM D5528-13 – Double Cantilever Beam (DCB) Test

- The ASTM standard is for static testing.
- Includes options for toughness values.

Crack Growth Data (Fatigue)

- Modified DCB test standard used for fatigue.
- Crack growth rate data (da/dN vs. G) is determined from a single test in which G decreases as the crack length increases
  - Provides a range of growth rates as the crack grows.
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Wind Blade Design - Partial Safety Factors

Material Partial Safety Factors (MPSFs)

- MPSFs are utilized in wind blade designs to take into account the following:
  - Material properties variation between as-built blades and test coupons
  - Manufacturing tolerance and defects within drawing limit
  - Environmental effect and degradation
  - Other uncertainties of blade structural margin not captured by blade analysis and testing

Certification Guidelines

- MPSFs defined in commonly used certification guidelines were mostly established based on empirical experience.
  - e.g., GL2010, DNV-DS-J102, DNVGL-ST-0376

<table>
<thead>
<tr>
<th>MPSFs for BONDLINES per GL2010</th>
<th>VALUE</th>
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</thead>
<tbody>
<tr>
<td>General material partial factor</td>
<td>1.35</td>
</tr>
<tr>
<td>Influence of aging</td>
<td>1.50</td>
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<tr>
<td>Temperature effect</td>
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<tr>
<td>Bonding surface reproducibility</td>
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</tr>
<tr>
<td>Post-cured/Non-post-cured bond</td>
<td>1.00/1.10</td>
</tr>
</tbody>
</table>
Evolving Wind Blade Certification Guidelines

- More recent certification guidelines such as DNVGL-ST-0376, IEC61400-5 (not released yet) encourage building-block approach
  - Sub-component/sub-scale/full-scale testing, and advanced analysis methods by allowing lower MPSFs.

Possible Approach Similar to Aerospace?

- Is “Ultimate” vs. “Limit” load equivalent to “all” vs. “some” of the partial safety factors?
- Would evaluation of structure with defined damage result in a more robust design than the full partial safety factor approach?
Analysis Example – Buckling

**Buckling Stability Analysis** [1]

- Sensitivity to facesheet disbond (due to manufacturing defect or in service damage) can be evaluated using an FE model with an assumed flaw.
- Facesheet buckling and delamination growth is investigated with FE-based stability analysis and fracture mechanics.

Disbond can be simulated in critical region with a flaw assumed between facesheet and core.

Adhesive Bondline Strength & Fatigue Life

Sensitivity to disbonds (static and fatigue) can be evaluated with assumed flaws and FE-based fracture mechanics.

Overall Reliability Considerations

Structural Reliability is Affected by Combination of:

- **Design criteria** including assumed damage and defect sizes.
- **Material strength and fatigue properties** including statistical and environmental knockdowns.

Damage Tolerance Considerations

- The combination of assumed damage and defects may be **overly conservative** if used in combination with existing design approaches and safety factors.
- **For example**, if a worst-case flaw in a bondline is assumed at the critical location, the use of a statistical knockdown on material properties may not be needed to achieve a reliable design.
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Summary and Discussion
Summary

The aerospace industry typically uses a **damage tolerance approach** for composite structures to achieve reliable designs.

- The damage and defect sizes are categorized and are associated with varying load requirements (larger damage = lower loads).
- Damage states are often simplified to cover for a range of scenarios.

**Durability and aging issues** are addressed by design and material screening.
- Careful attention paid to bonded joints and fatigue sensitive details.

Analysis is performed with **assumed damage and defects**.
- Fracture mechanics analysis is commonly used to evaluate interlaminar and adhesive bondline failures starting with an assumed damage or defect.

**Building block testing** is used to evaluate sensitive design details and validate analysis.
Conclusions

- Wind blade design may benefit from using a damage tolerance approach.
  - Evaluation of discrete damage and defect scenarios may lead to an improved understanding of blade reliability.

- Overall reliability should be considered when developing damage and defect criteria.
  - Using a damage tolerance approach with the existing design knockdowns (e.g., partial safety factors) may be overly conservative.

- Evolving certification guidelines for wind blades may provide the flexibility needed to use a similar approach as used for aerospace composites.