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

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Prepared by

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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

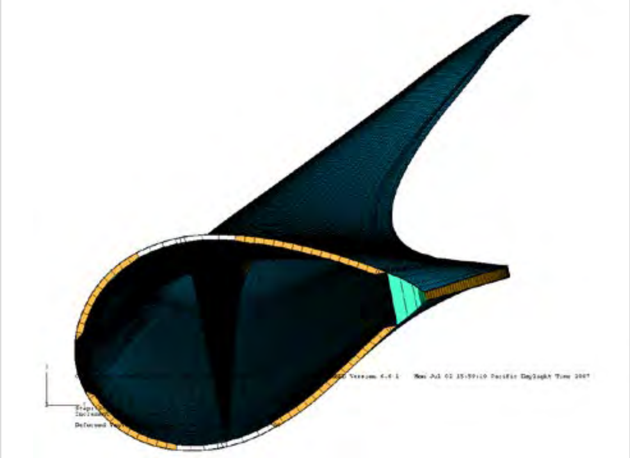
Finite Element Analysis (FEA)

- 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*

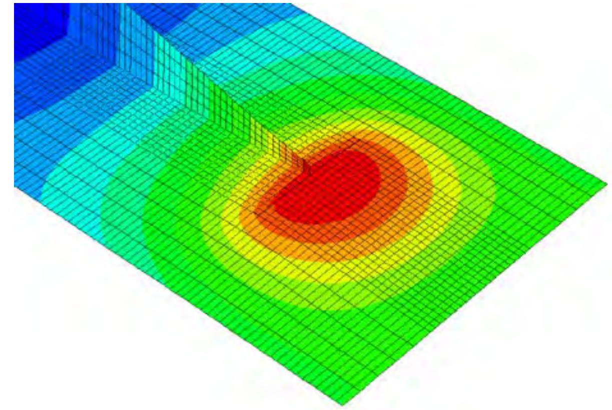
Damage Tolerance Analysis Methods

- Skin-stringer applications with large notches/damage
- Impacted sandwich structure
- Nonlinear FEA and semi-empirical methods

Sweep-Twist Wind Blade FEM



Stiffener Delamination FEM



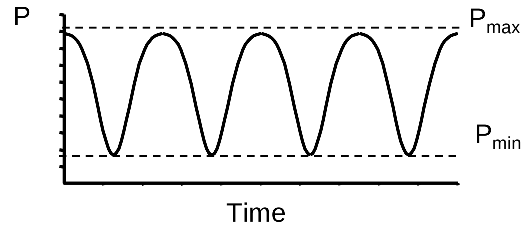
VCCT Finite Element Development

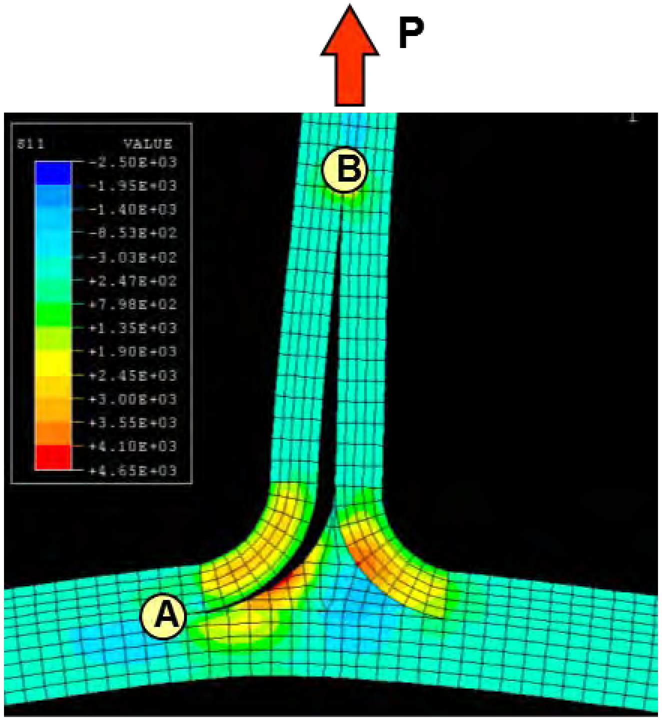
- Developed and validated Boeing's VCCT user element (in collaboration with Boeing).
  - *Eventually implemented in ABAQUS.*

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

ABAQUS Fracture Customer Review Team (2007 – 2017)

- 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”.

CMH-17
COMPOSITE MATERIALS HANDBOOK

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).

Federal Aviation Administration

Outline

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Summary and Discussion

Durability & Damage Tolerance Approaches

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

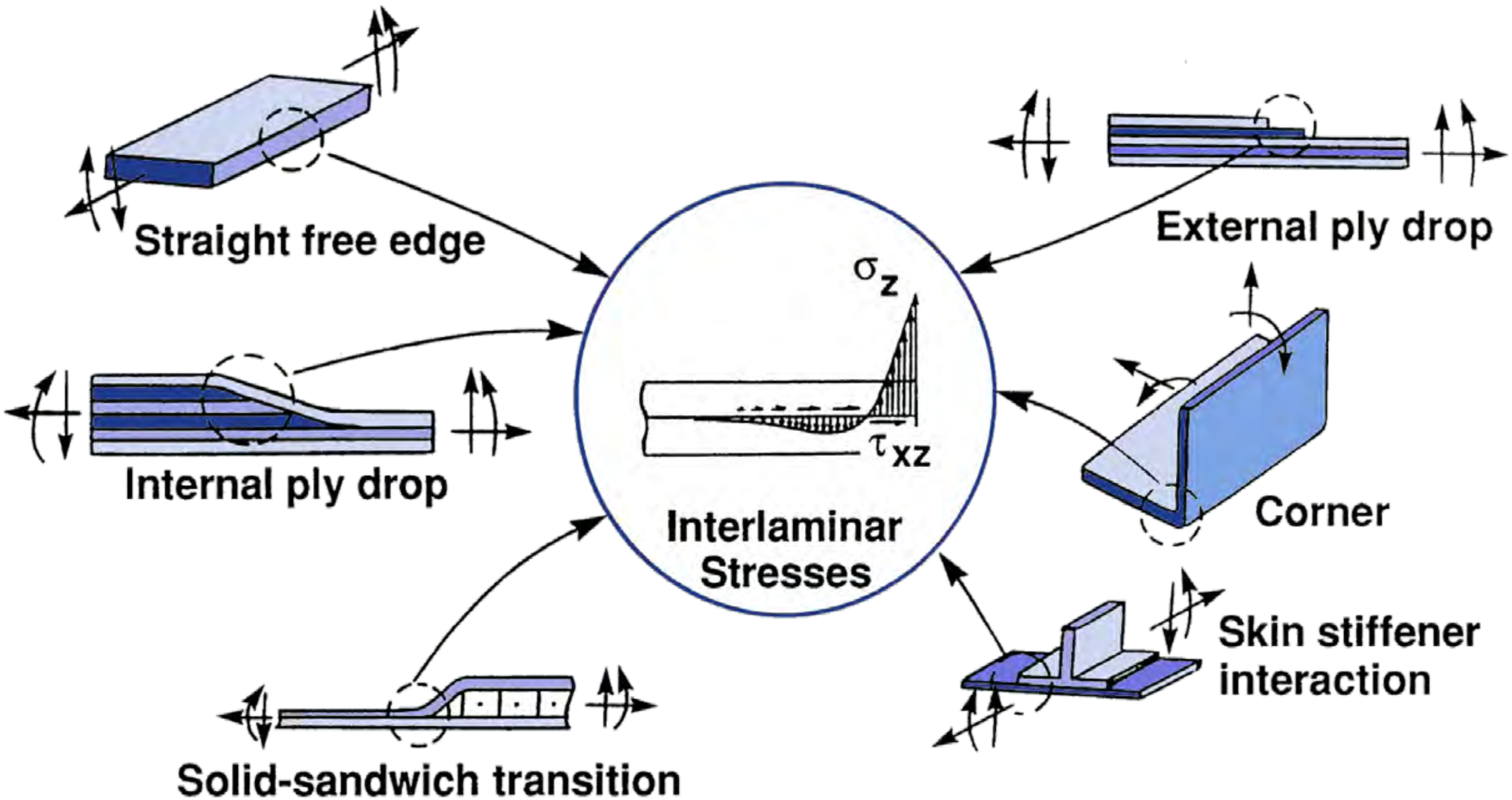
- The service life limits of composite aircraft components are *not* generally driven by fatigue and aging (i.e., durability).
- Material property degradation due to fatigue loading and environmental exposure is avoided through design and material screening based on testing and service history.

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).

Fatigue & Damage Sensitive Design Details [1]

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).

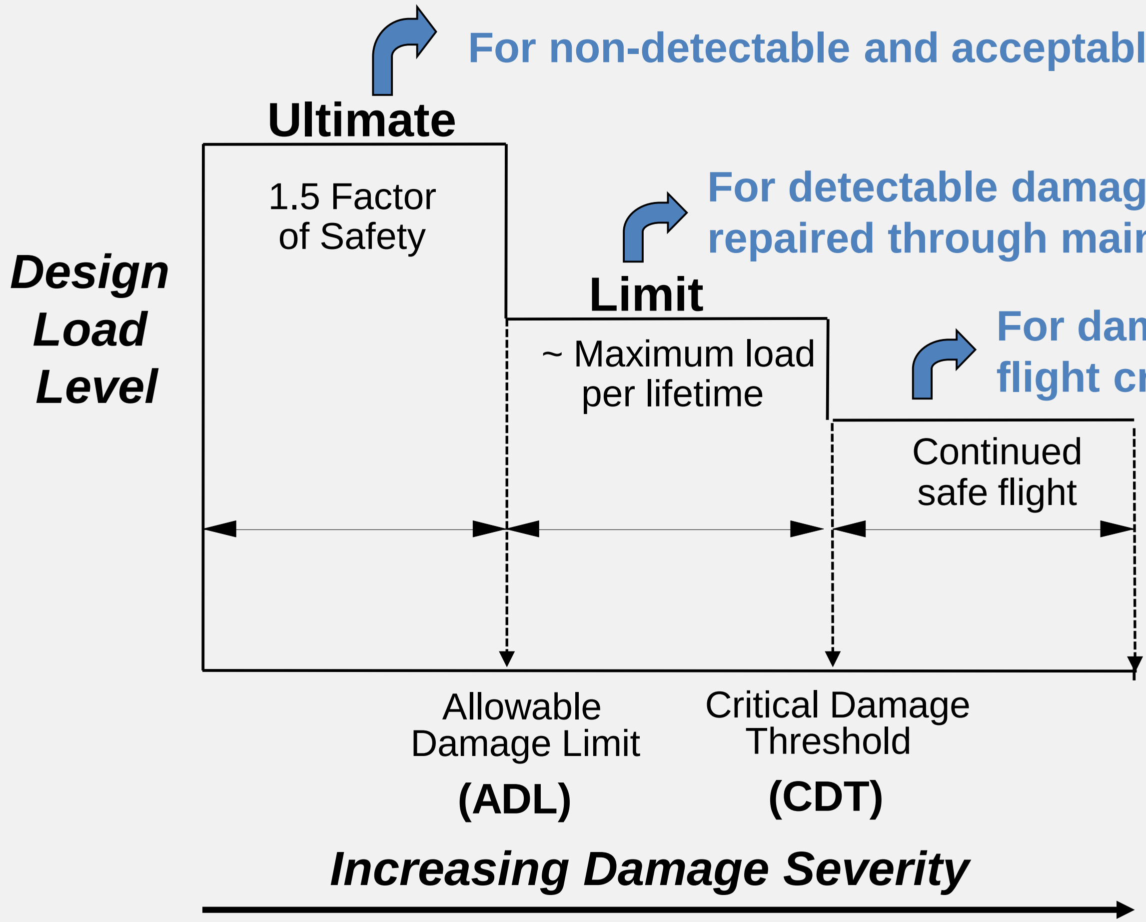
Damage-Related Criteria

- 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.*

[1] Federal Aviation Administration. Advisory Circular No:20-107B, 2009.

Load Levels for Categories of Damage [1]

Match design load levels with visibility and likelihood of detection.



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

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

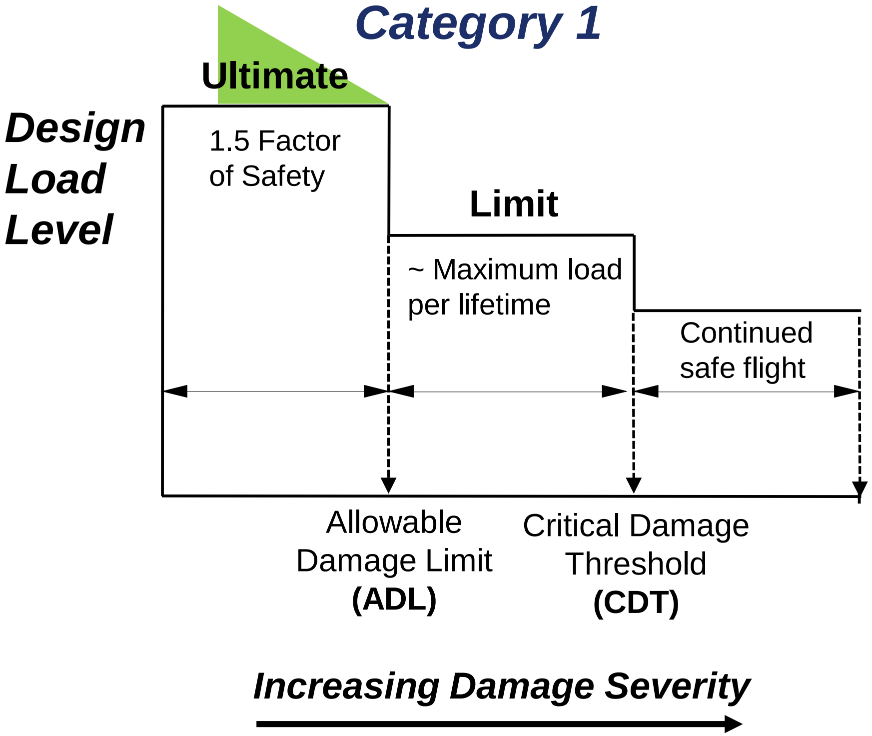
Damage & Defects - Category 1 [1]

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**.



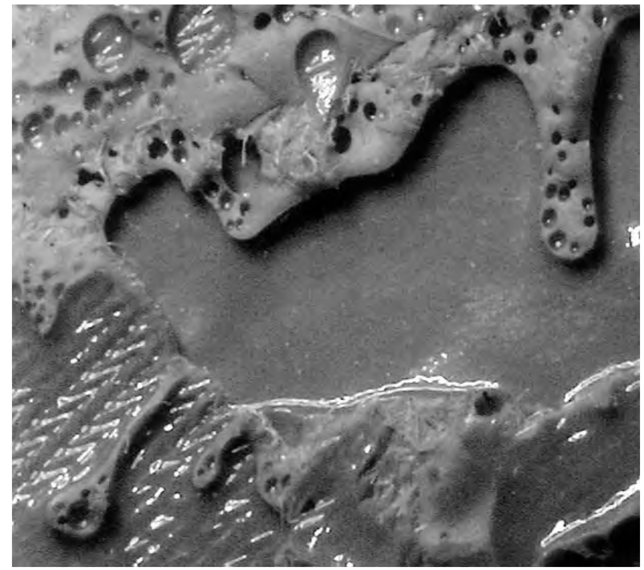
[1] Figures from CSET – Composite Structural Engineering Technology Course

Category 1 Damage & Defects – Examples [1]

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*

Bondline Void



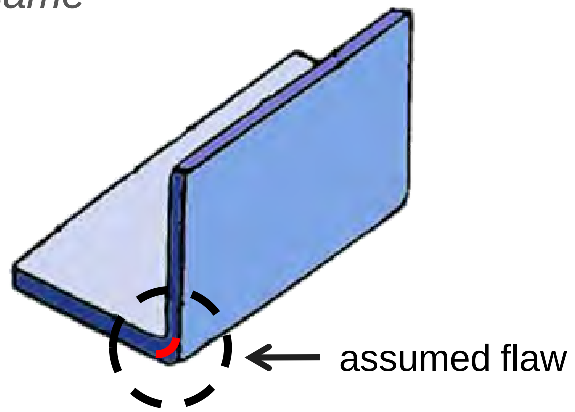
Cross-Section of BVID at a Skin-to-Flange

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

Category 1 Damage & Defects – Analysis Examples

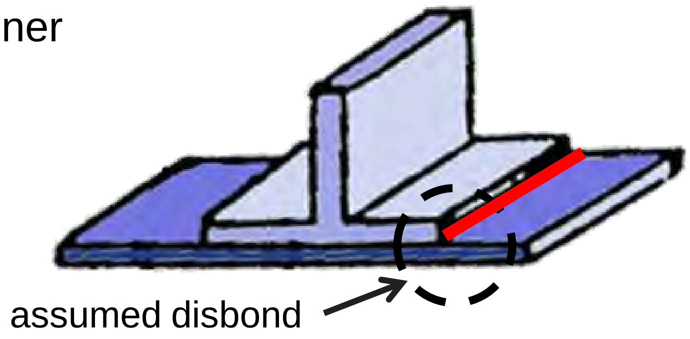
Strength Allowables

- 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.

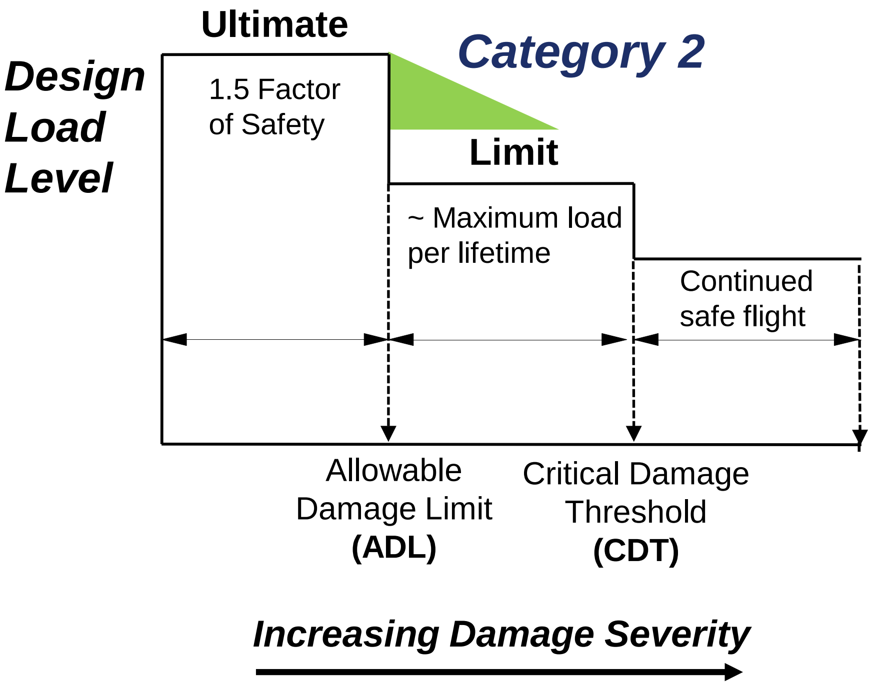
- **¼" by infinite disbond assumed** along stiffener flange-to-skin bondline.



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**.

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

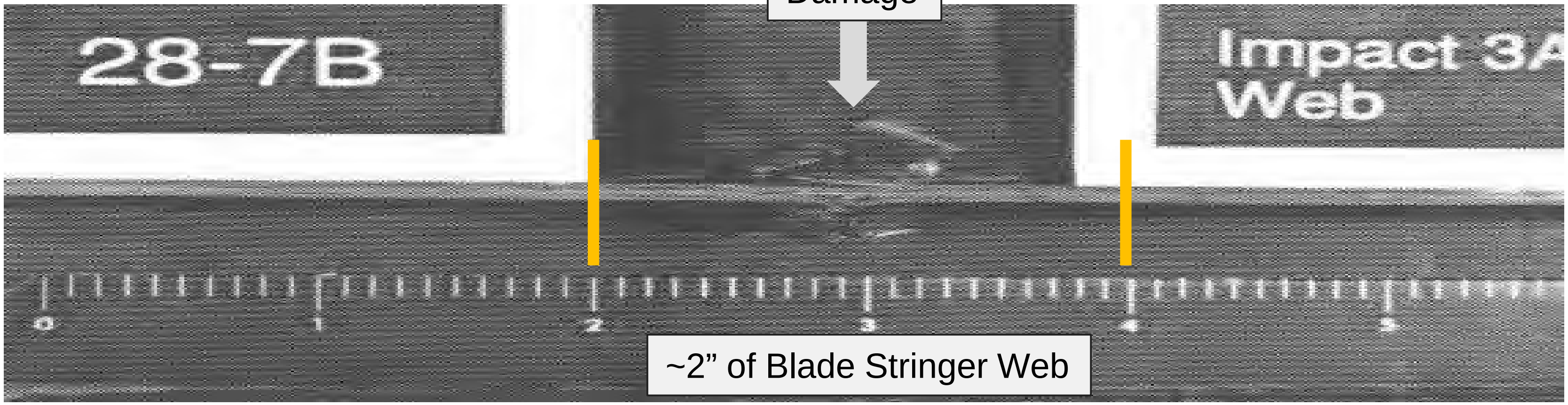
Category 2 Damage & Defects – Examples [1]

Category 2 damages and defects

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

Exterior Skin Damage

Interior Blade Stringer Damage



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

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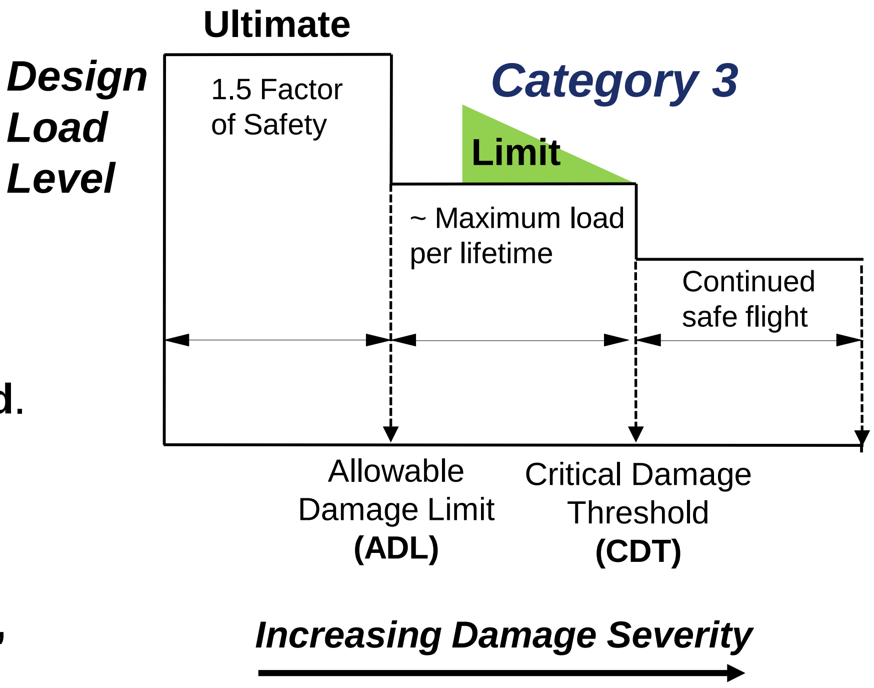
Damage & Defects - Category 3 [1]

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).

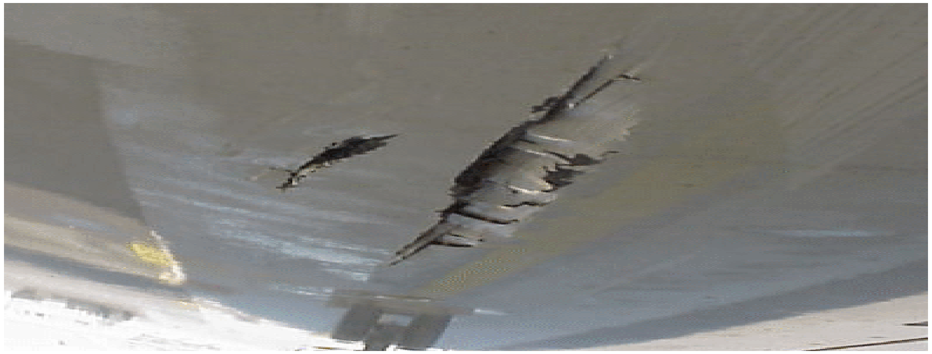
[1] Figures from CSET – Composite Structural Engineering Technology Course

Category 3 Damage & 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

Accidental Damage to Lower Fuselage



Lost Bonded Repair Patch

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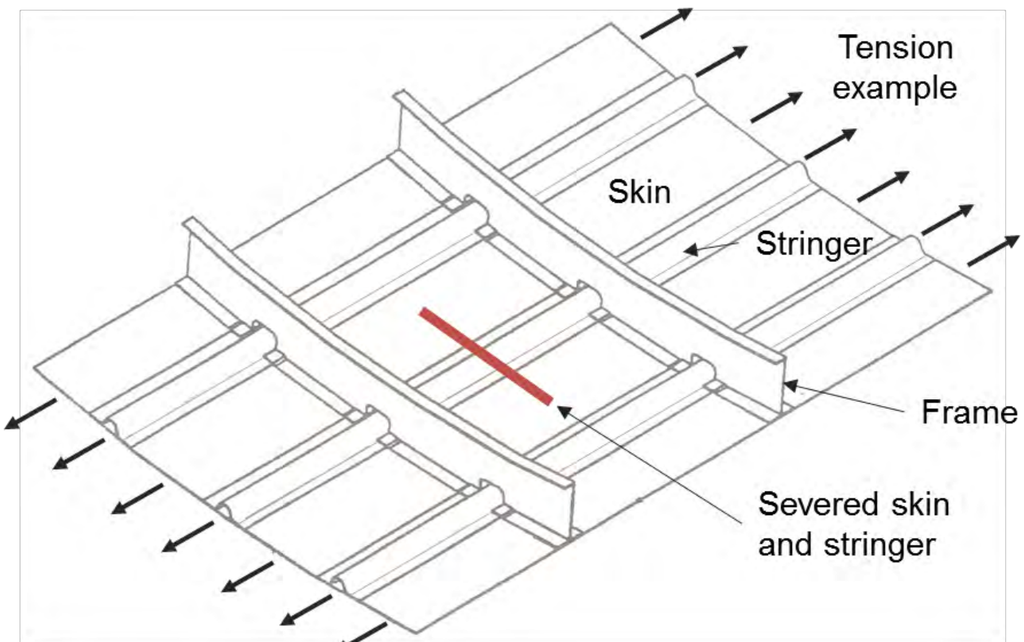
Category 2 & 3 Damage & Defects – Analysis Examples

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

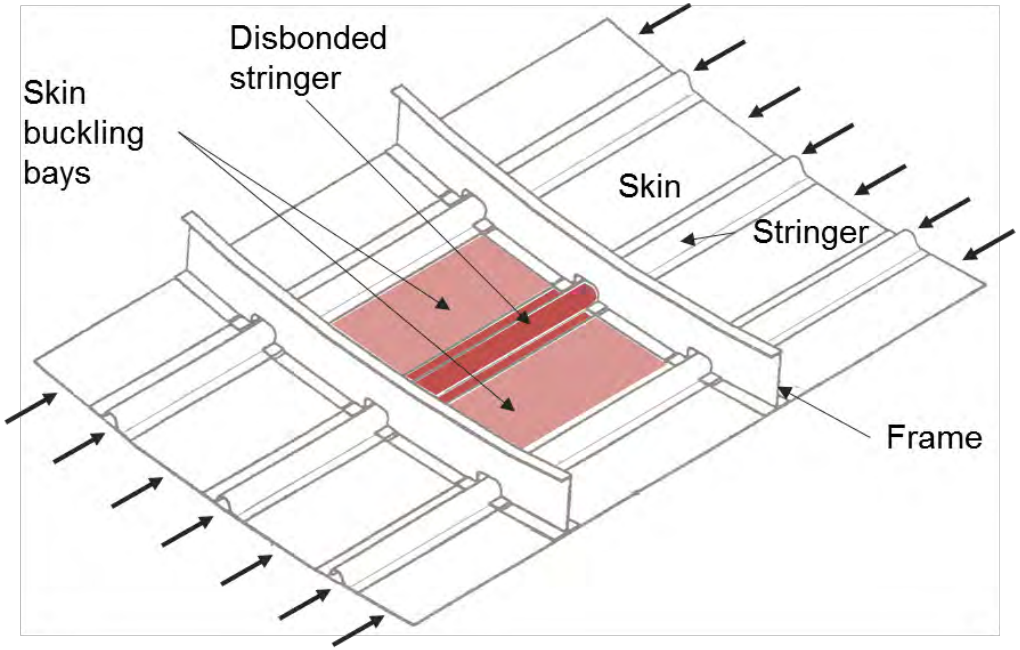


Category 2 & 3 Damage & Defects – Analysis Examples

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.

Skin-Stringer Panel with Disbonded Stringer



Outline

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Aerospace Industry - Durability and Damage Tolerance

Durability and Damage Tolerance Analysis & Test

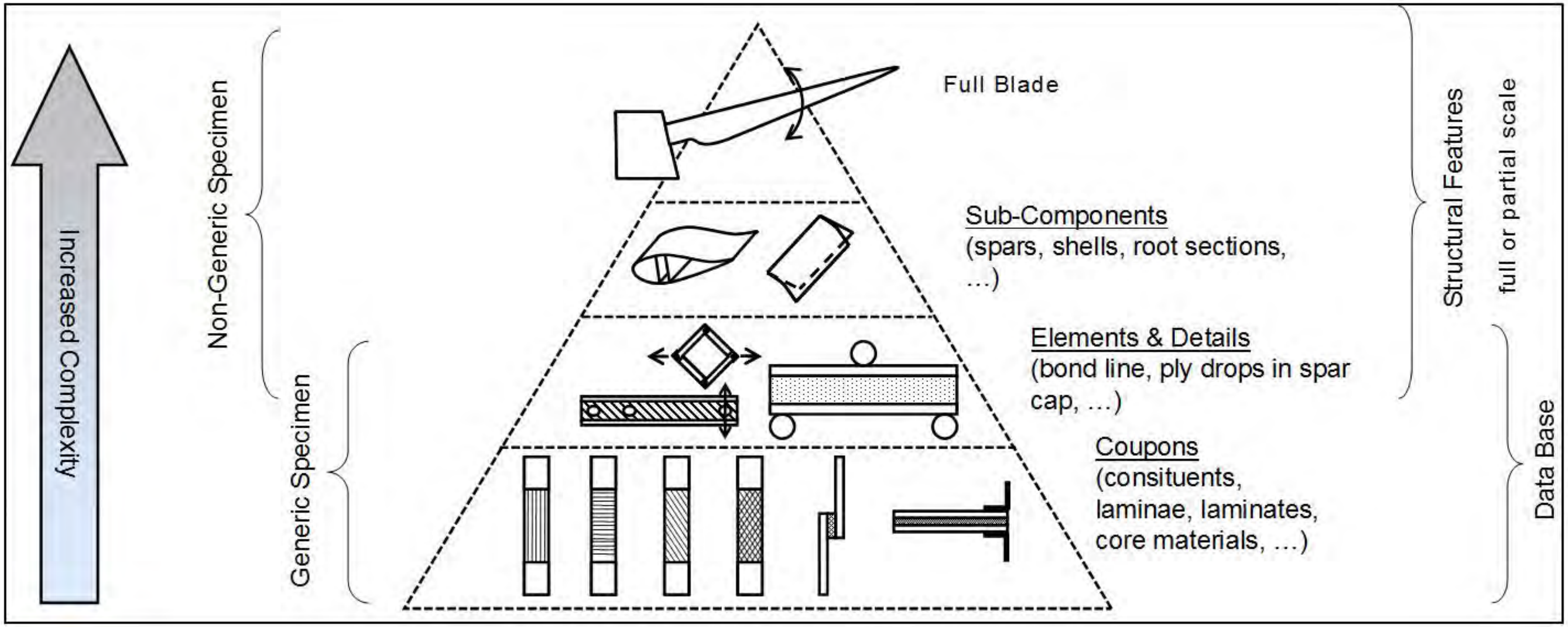
Wind Blade Analysis Examples

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.

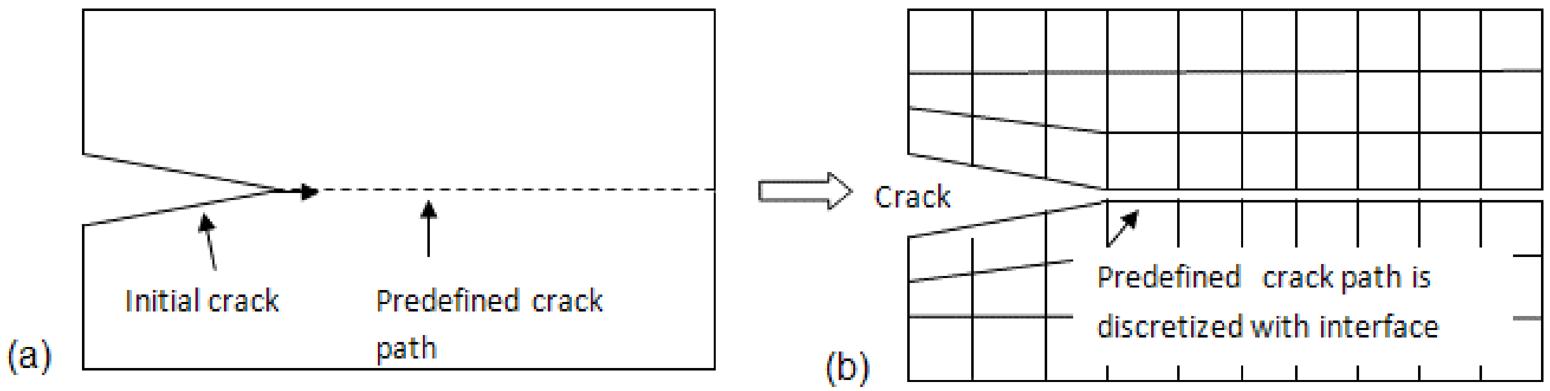


[1] IEC 61400-5 Ed.1: Wind energy generation systems - Part 5: Wind Turbine Rotor Blades (DRAFT).

Fracture Mechanics Approach

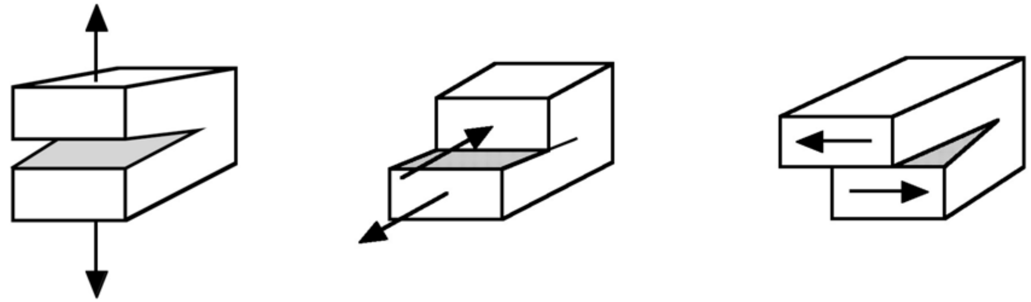
- Use of fracture mechanics has become common practice in the aerospace industry to characterize the onset and growth of delaminations and disbonds.
- The virtual crack closure technique (VCCT) is widely used for computing energy release rates based on results from finite element (FE) analyses.
- Closed-form 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 [1]

$$f = \frac{G_T}{G_{Ic} + \left((G_{IIc} - G_{Ic})\frac{G_{II}}{G_T} + (G_{IIIc} - G_{Ic})\frac{G_{III}}{G_T} \right)\left(\frac{G_{II} + G_{III}}{G_T} \right)^{\eta - 1}}$$

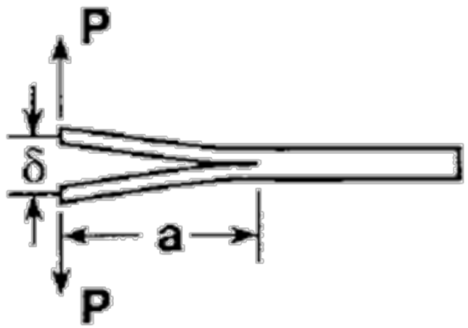
failure is predicted when f > 1.0.

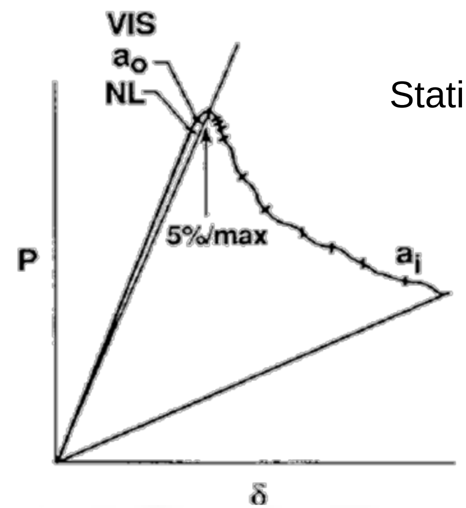
[1] Reeder, James R. 3-D "Mixed Mode Delamination Fracture Criteria - An Experimentalist's Perspective", American Society for Composites 21st Annual Technical Conference; 17-20 Sep. 2006; Dearborn, MI; United States.

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.

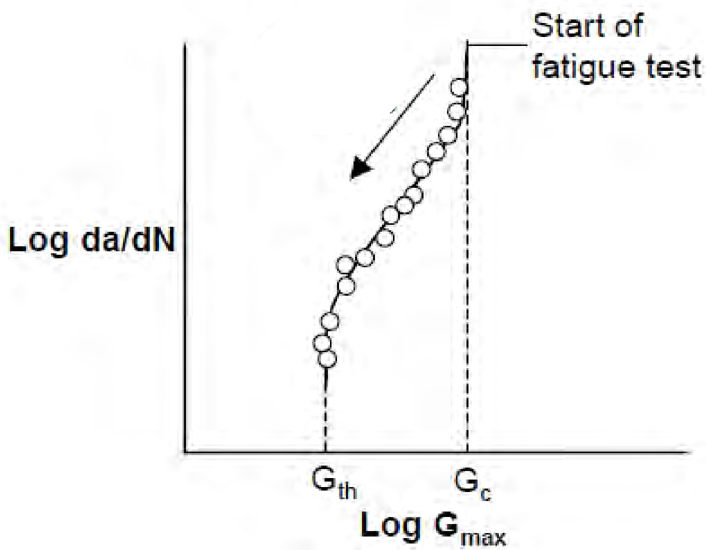




Static Test

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*

MPSFs for BONDLINES per GL2010	VALUE
General material partial factor	1.35
Influence of aging	1.50
Temperature effect	1.00
Bonding surface reproducibility	1.10
Post-cured/Non-post-cured bond	1.00/1.10

Wind Blade Design – Evolving Certification Guidelines

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.*

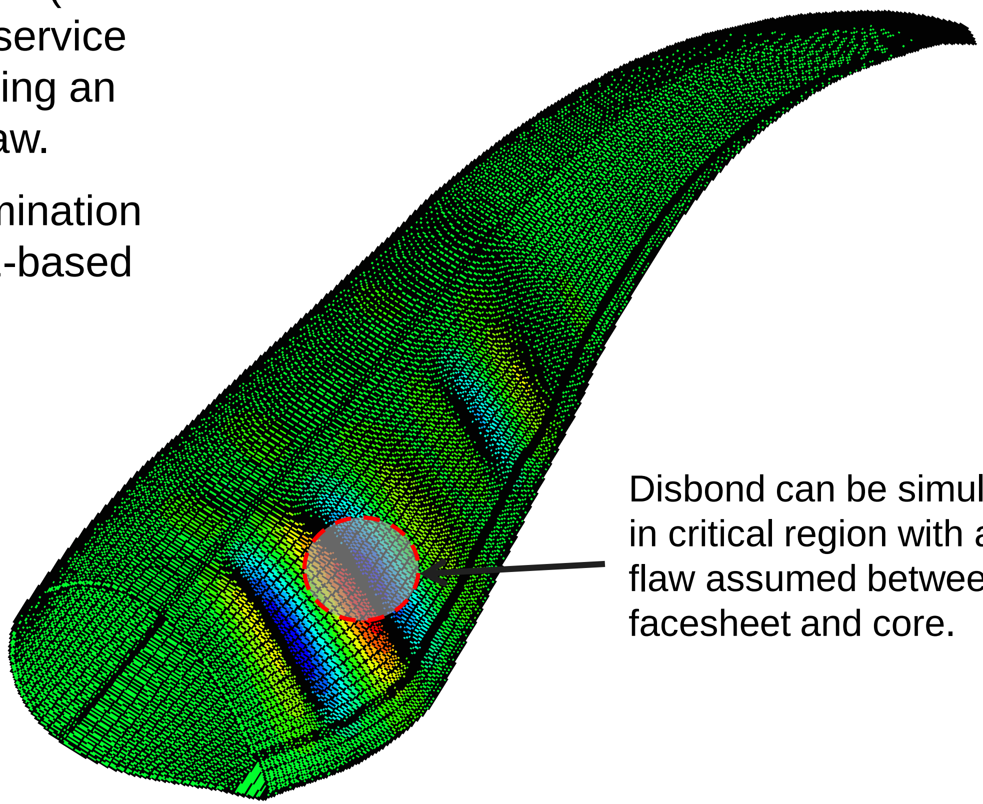
Possible Approach Similar to Aerospace?

- 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.

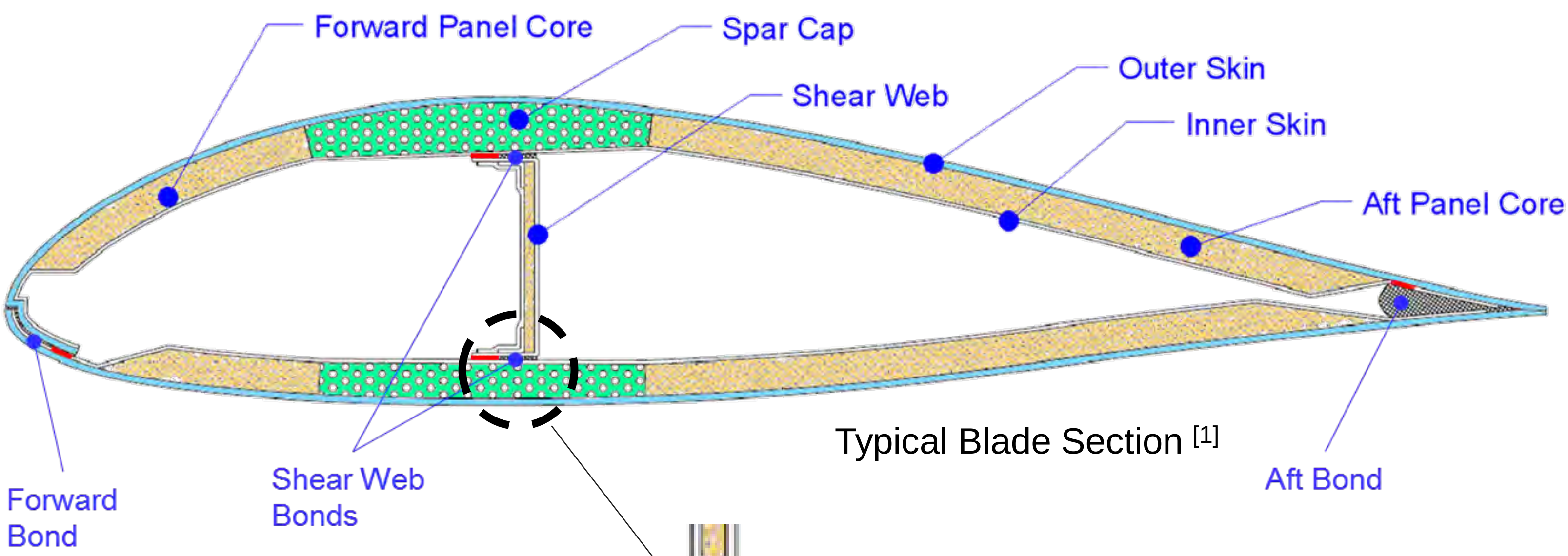


Disbond can be simulated in critical region with a flaw assumed between facesheet and core.

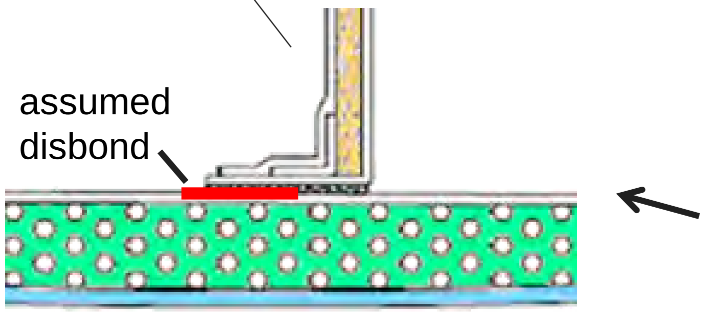
[1] Sweep-Twist Adaptive Rotor Blade: Final Project Report, Knight & Carver Wind Group, Sandia Report SAND2009-8037.

Analysis Example – Adhesive Bondlines

Adhesive Bondline Strength & Fatigue Life



Typical Blade Section [1]



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

[1] Sweep-Twist Adaptive Rotor Blade: Final Project Report, Knight & Carver Wind Group, Sandia Report SAND2009-8037.

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 & Conclusions

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.

Summary & Conclusions

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 reliably 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.**