Designing blades as they are really manufactured

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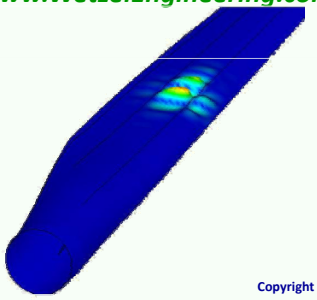

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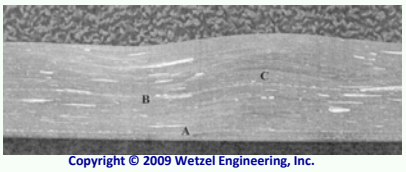
Albuquerque, New Mexico

Reliability: Engineering –vs– Manufacturing

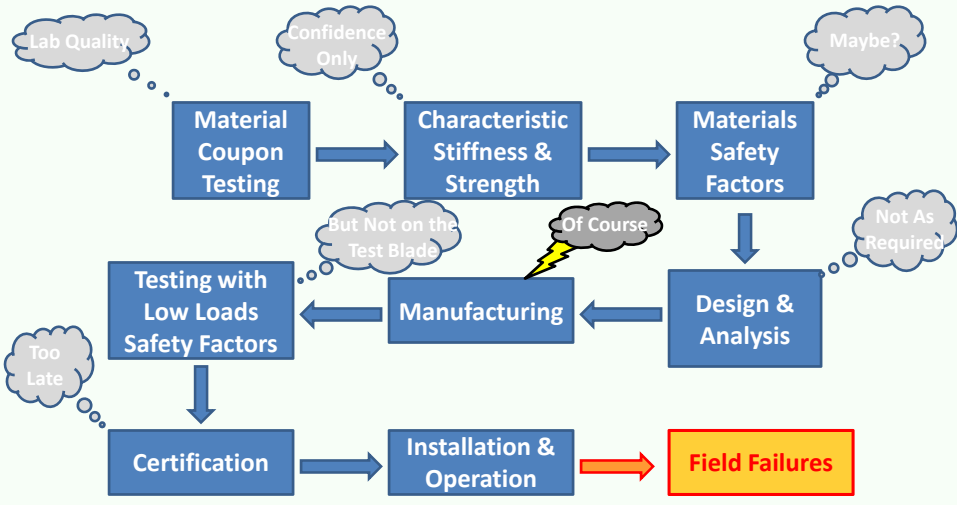
- Field failures of blades are almost always blamed on manufacturing failures
- But do blade design and engineering fail to reflect the realities of blade manufacturing?
- Improving blade reliability requires that the engineering and manufacturing reflect common specifications.

Common Blade Manufacturing Issues

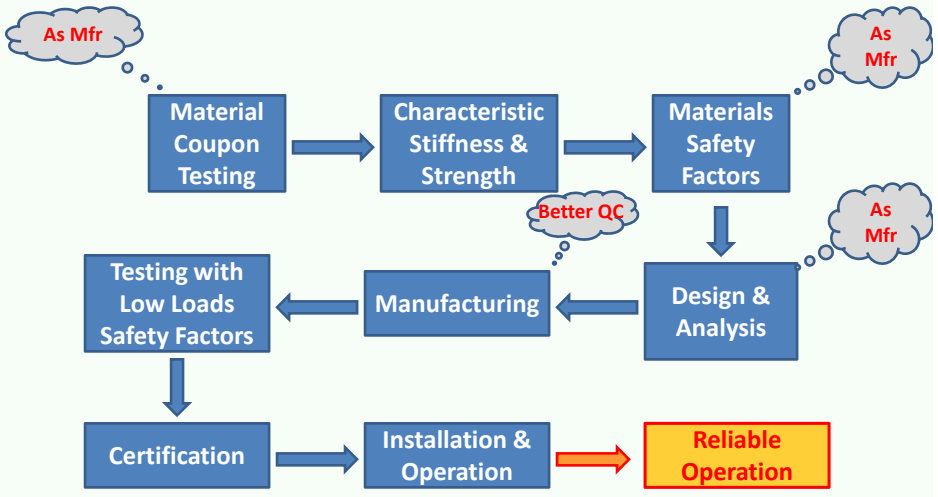
- Adhesive Bond Defects
  - Thickness out of Tolerance
  - Voids (to the point of missing adhesive
- Laminate Defects
  - Ply Wrinkling & Waviness
  - Misplaced Laminates
  - Fiber Orientation Issues
- Fiber Fraction Problems
  - Resin-Rich Regions
  - Dry Spots
- Etc.



Where are Defects in Current Practice?



How Should Defects be Accounted?



Safety Factors Per GL

Partial Safety Factor		x=a Lam Strength	x=b Lam Fatigue	x=c Static Stability	x=d Bond Strength	x=e Bond Fatigue
γ_{m0}	Base	1.35	1.35	1.35	1.35	1.35
C_{1x}		1.35 Aging	n/a	1.0-1.3 Type of Structure	1.5 Aging	n/a
C_{2x}	Temperature	1.1	1.1	1.1	1.0	1.1
C_{3x}		1.1-1.2 Process	1.0-1.2 Fabric		1.1 Surface Reproducibility	
C_{4x}	Post-Cure	1.0-1.1	1.0-1.1		1.0-1.1	1.0-1.1

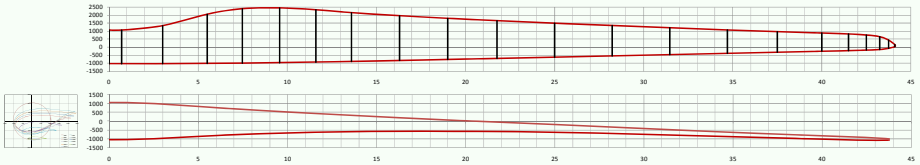
- γ_{m0} & C_3 may be intended to include discrepancies between coupon data and parts as fabricated
- This is dangerous to assume
- These factors account for many influences, not just defects

Analysis with Defects

- Only Analysis including realistic defects and appropriate SFs can help ensure structural integrity and sufficient life
- This should be applied to all typical defects
- GL only addresses defects in bonds
  - Guidelines §5.5.6 specifies
    "Stress concentrations within the bonding surfaces and flaws shall be taken into account"
  - This is widely ignored or addressed unrealistically

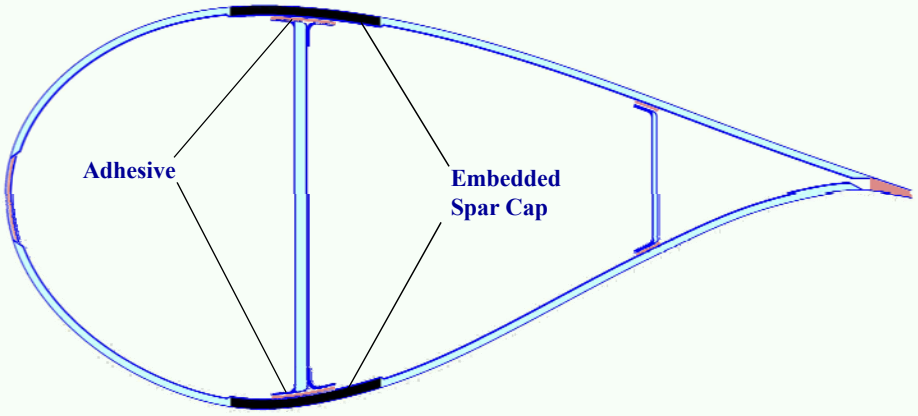
Present Study – Bond Defects

- Analyzed 2 44m Blades for a 2.0MW Turbine
  - Both blades use the same aerodynamic contour
  - DU25 to DU40 airfoils through the mid-span
  - NACA636XX in the tip



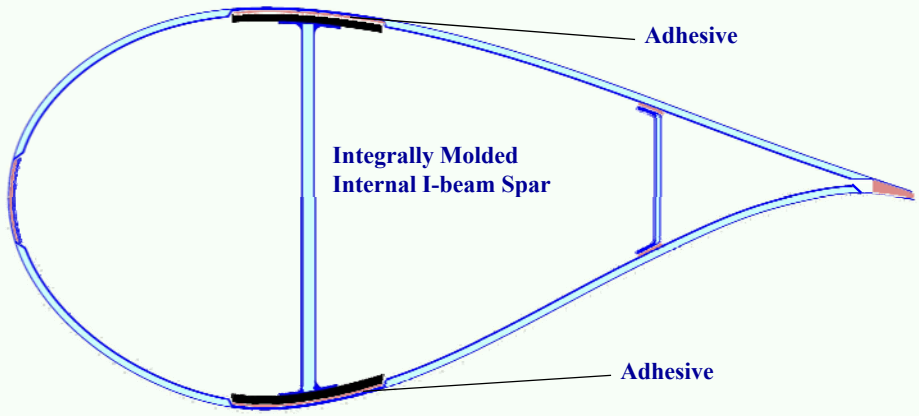
Present Study – Bond Defects

- Analyzed 2 44m Blades for a 2.0MW Turbine
  - Blade A: Spar Caps embedded in outer shells bonded to internal shear webs

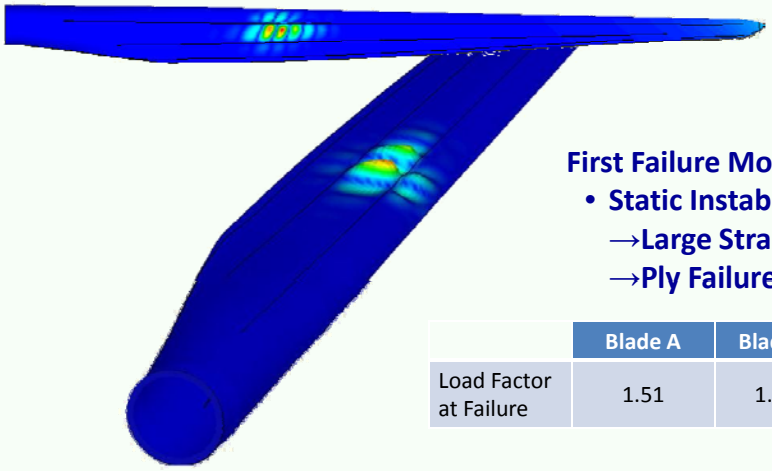


Present Study – Bond Defects

- Analyzed 2 44m Blades for a 2.0MW Turbine
  - Blade B: Internal spar is bonded to cosmetic shells



Base Buckling Mode



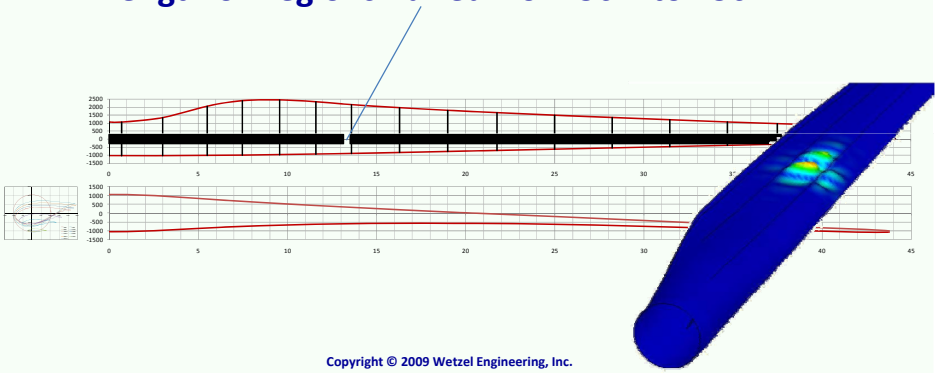
First Failure Mode:
- **Static Instability**
  - **→Large Strain**
  - **→Ply Failure**

	Blade A	Blade B
Load Factor at Failure	1.51	1.56

Note: Missing GL-required SF=1.35x1.1=1.49 for buckling

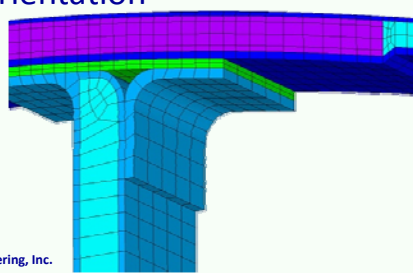
Present Study – Bond Defects

- **Analyzed 2 44m Blades for a 2.0MW Turbine**
  - **Examined Regions of Adhesive Missing in the Critical Buckling Zone**
  - **Length of Regions Varied from 5cm to 25cm**

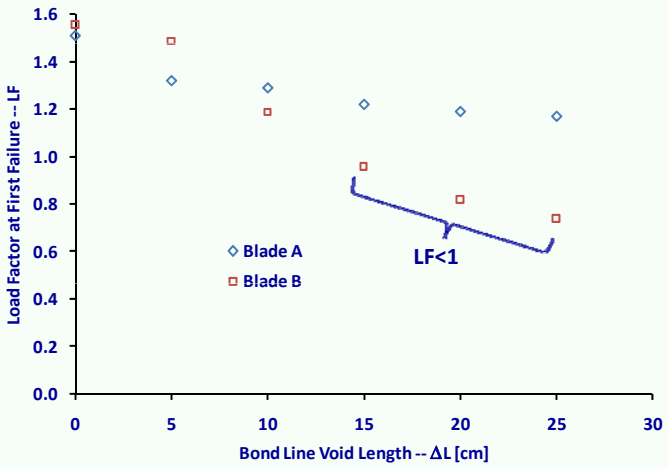


Finite Element Modeling

- Shell elements cannot adequately capture lap shear stresses in adhesive bonds
- 20-node Layered bricks
- Laminate modeled as separate layers
  - Ply material, thickness, & orientation
- 1.16million elements, 17 million DOFs



Influence of Defects



Conclusions

- Blades with embedded spar caps might be more tolerant of voids in adhesive bonds
- The bond gap thickness does not appear to be a strong influence of structural integrity
- Standard SFs may be inadequate to accurately reflect the influence of some bond line defects

Recommendations

- Reassess standard practice for analysis of blade structures
  - Include realistic defects in the FEM
  - Adjust the SFs down to account for the fact that defects are included in the analysis

To Better Blades

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