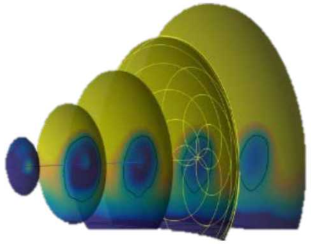
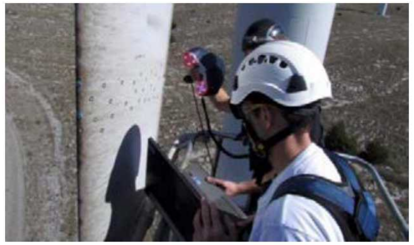
Sandia National Laboratories

SAND2019-13720C

Blade Design: Understanding the relationship between design, certification testing of details and the occurrence of detail weaknesses





PRESENTED BY

Josh Paquette, Principal Member of the Technical Staff

U.S. DEPARTMENT OF ENERGY   NNSA

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Life of a Blade

Standards

Design

Manufacturing

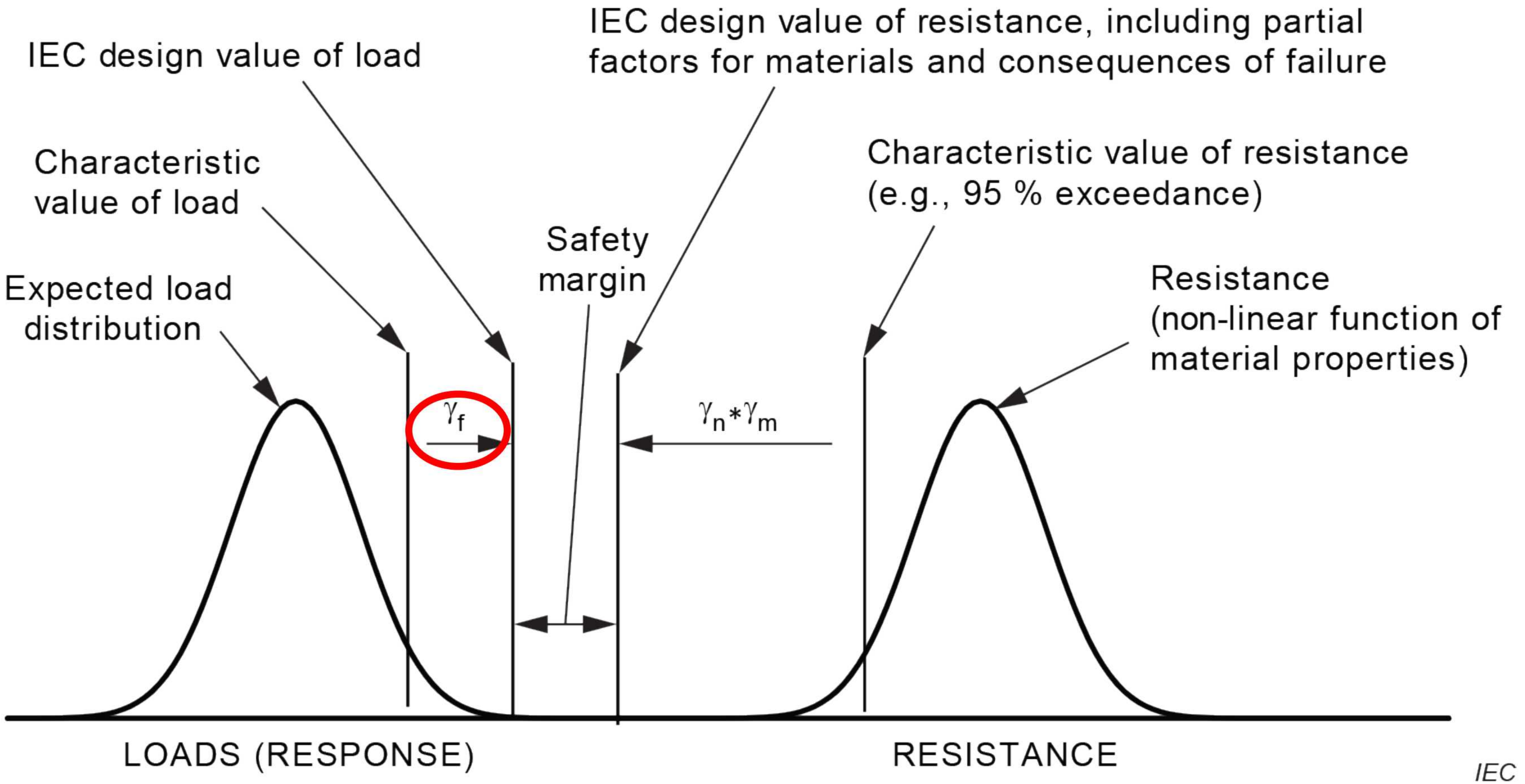
Transportation/
Assembly

Operation

Life Extension

De-Commissioning

Standards



$$P_F^t = 5 \times 10^{-4}$$

Source: IEC 61400-5 Blade Design Standard

Loads

Uncertainties from complex wind plant flows → Power Production

Uncertainties from higher number of faults → Power Production with faults

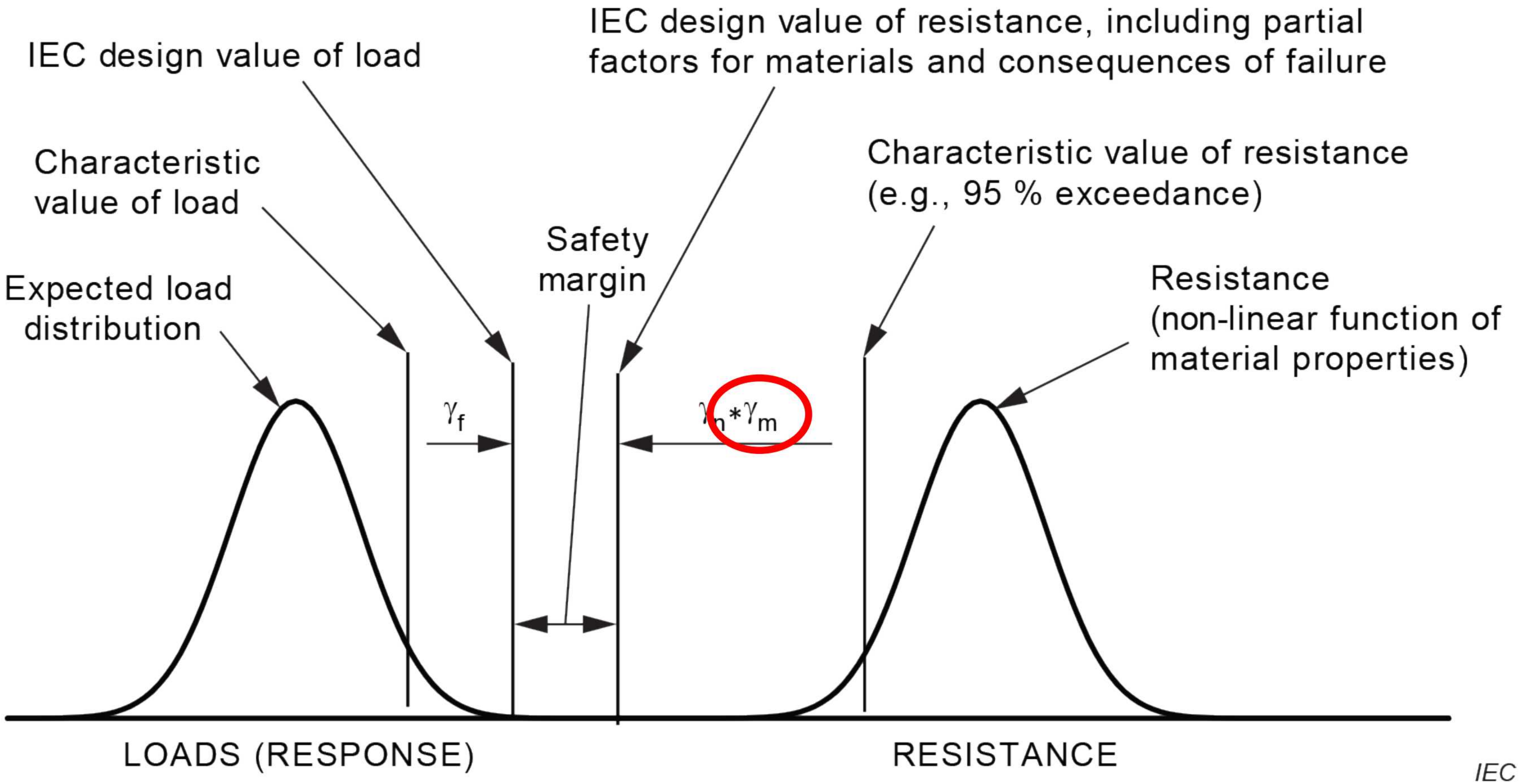
Uncertainty from excessive e-stops → Emergency Stop

Uncertainty from transport/assembly → Transport, Assembly, Maintenance, and Repair

Design Situation	Wind Conditions	Analysis Type
Power Production	Normal Turbulence Extreme Turbulence Directional Gust Extreme Wind Shear	Ultimate, Fatigue
Power Production with faults	Normal Turbulence Extreme Gust	Ultimate, Fatigue
Start-up	Extreme Gust Directional Gust	Ultimate, Fatigue
Normal Shutdown	Extreme Gust	Ultimate, Fatigue
Emergency Stop	Normal Turbulence	Ultimate
Parked	Extreme Winds Normal Turbulence	Ultimate, Fatigue
Parked with Fault	Extreme Winds	Ultimate
Transport, Assembly, Maintenance, and Repair	Normal Turbulence Extreme Turbulence	Ultimate

Source: IEC 61400-1 Blade Design Standard

Standards



$$P_F^t = 5 \times 10^{-4}$$

Source: IEC 61400-5 Blade Design Standard

Resistance Levels

Types of analyses

- Ultimate
- Fatigue
- Stability (Buckling)
- Deflection

Partial Safety Factors

- γ_{m0} = Base
- γ_{m1} = Environmental Degradation
- γ_{m2} = Temperature
- γ_{m3} = Manufacturing Effects
- γ_{m4} = Calculation Accuracy
- γ_{m5} = Load Characterization

$$\gamma_m = \gamma_{m0}\ \gamma_{m1}\ \gamma_{m2}\ \gamma_{m3}\ \gamma_{m4}\ \gamma_{m5}$$

Source: IEC 61400-5 Blade Design Standard

Combined Safety Factor γ_m

Analysis	Min SF	Max SF
Laminate Ultimate	1.2	3.0
Laminate Fatigue	1.2	2.5
Inter Fiber Failure	1.5	1.9
Sandwich Panel Ultimate	1.2	3.9
Blade Buckling	1.2	2.2
Faceplate Buckling	1.2	2.1
Bond Ultimate	1.2	4.1
Bond Fatigue	1.2	3.6

Source: IEC 61400-5 Blade Design Standard

γ_{m3} = Manufacturing Effects

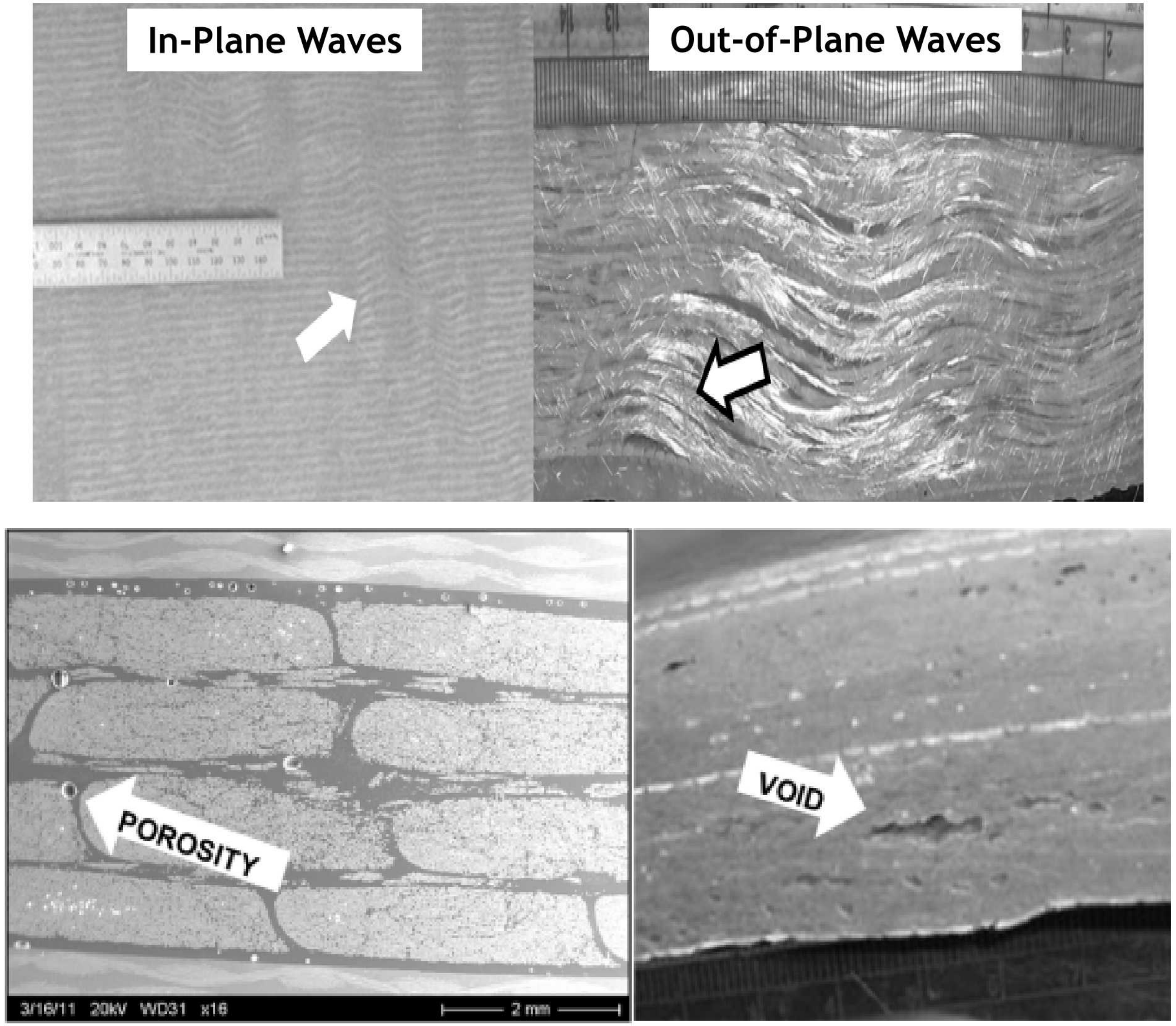
1.30 – The blade analysis is performed using nominal design properties.

1.10 – The blade analysis is performed using design properties that include the quantified effect of the dominant manufacturing tolerances.

1.00 – The blade analysis is performed using design properties that include the verified effect of the dominant manufacturing tolerances based on process validation and measurements.

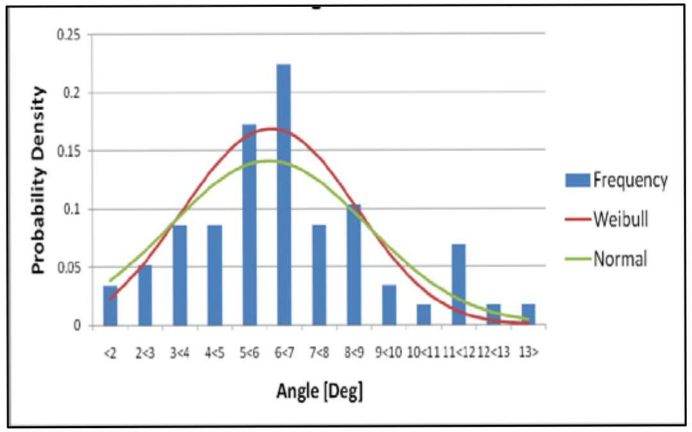
Source: IEC 61400-5 Blade Design Standard

Effect of Defects

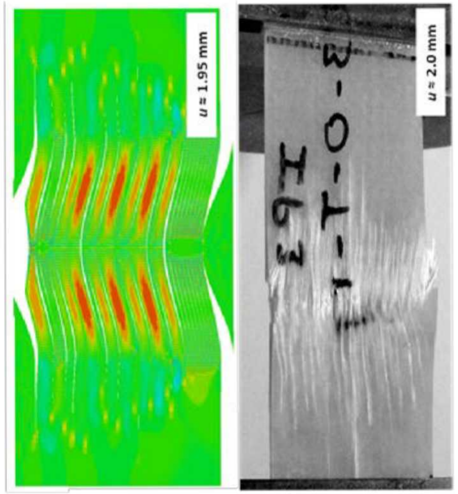


Source: Sandia/Montana State

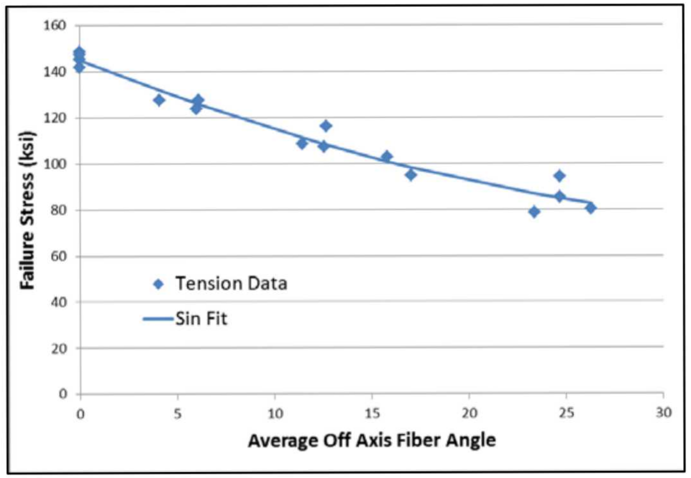
Effects of Defects



Flaw Distribution



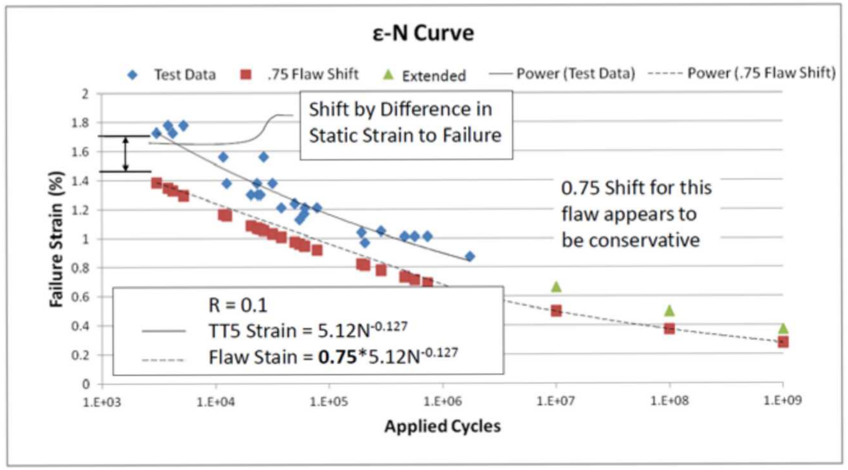
Coupon Test



Ultimate Strength

Specimen Production

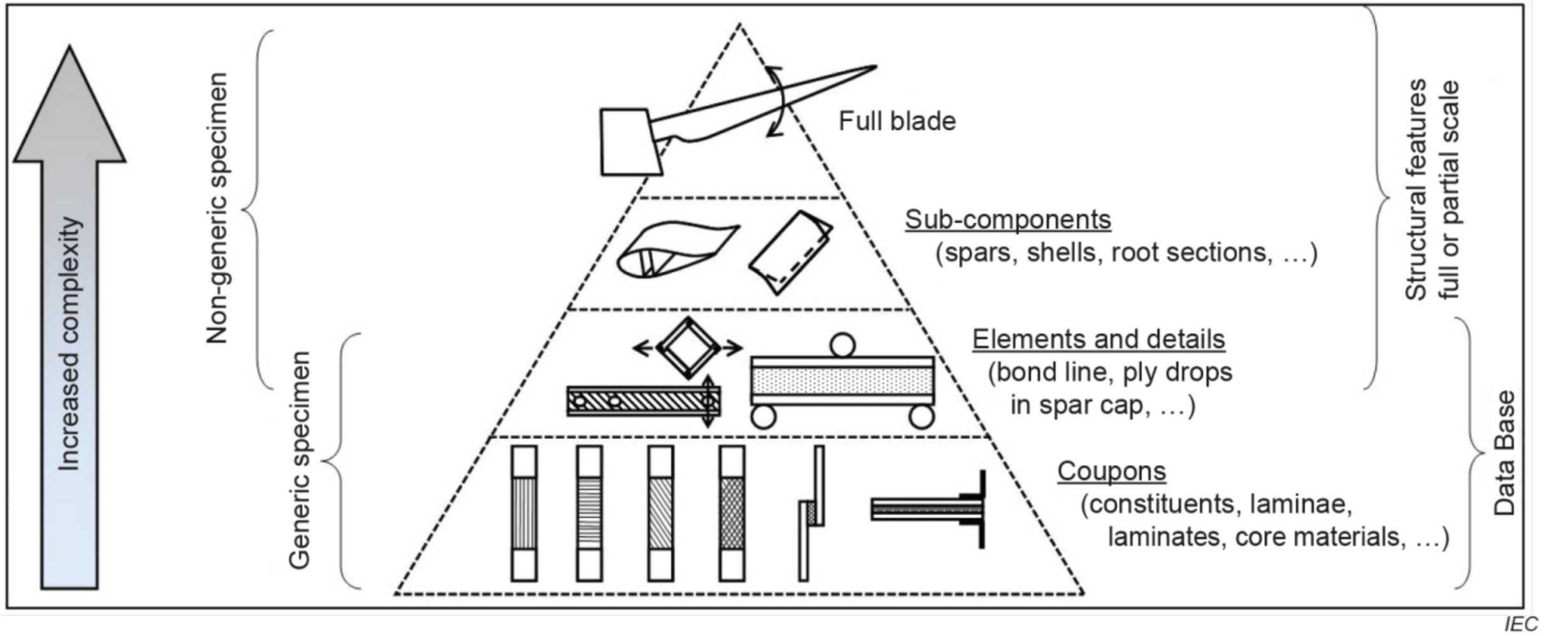
Detail/Substructure Test



Fatigue

Source: Sandia/Montana State

Certification Testing

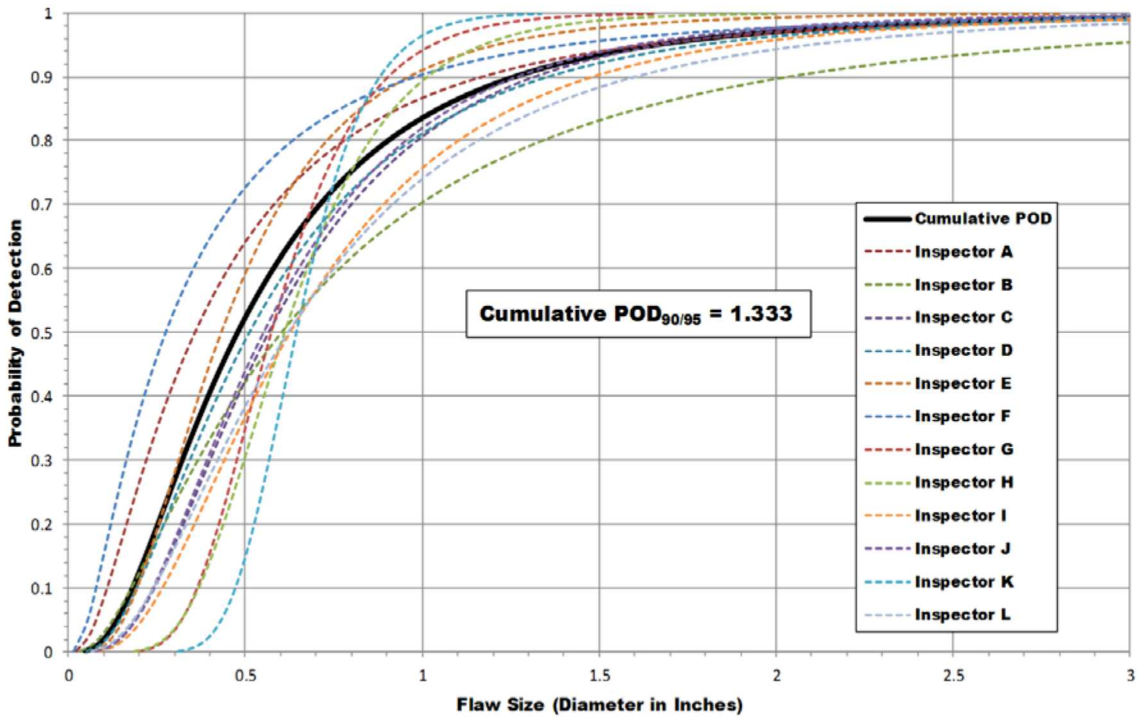


Sub-structures

Full Blade

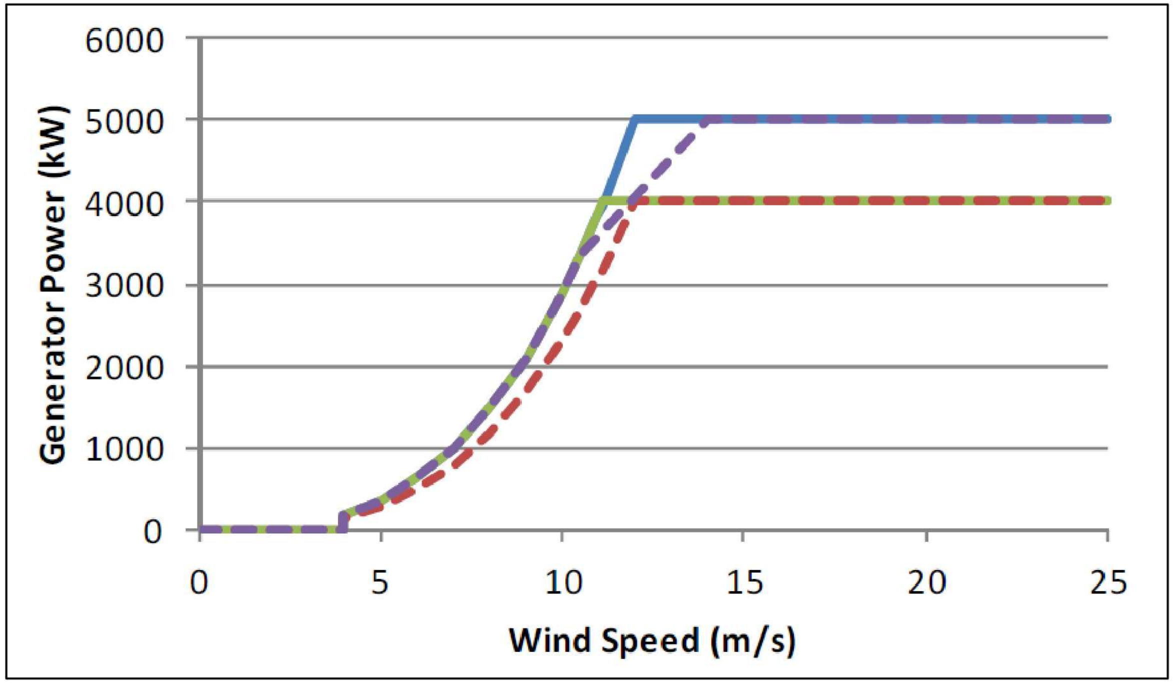
Sources: IEC 61400-5 Blade Design Standard, Fraunhofer IWES

Inspection

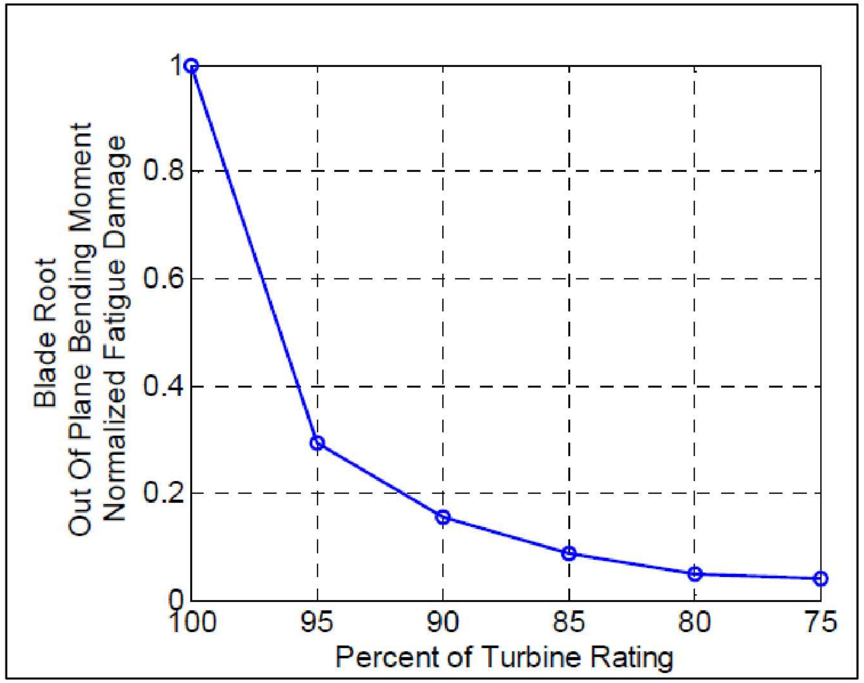


Sources: Sandia, SkySpecs, ICM

Prognostics



Operational Strategies



Fatigue Accumulation (Damage Growth)

Damage Disposition

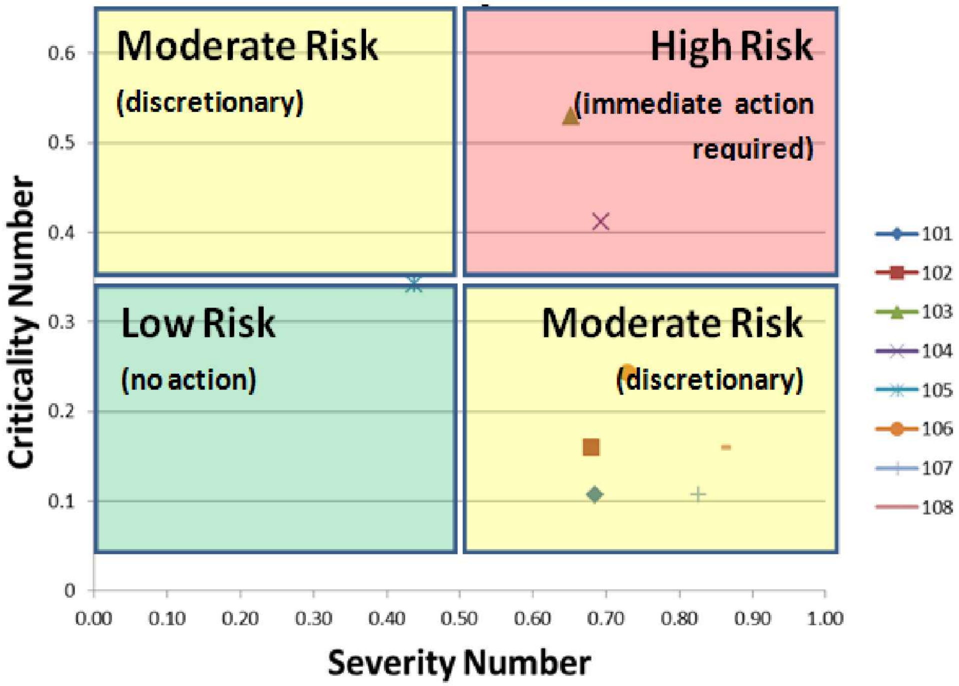
Modeled after NASA/DOD Failure Mode and Effects Analysis (FMEA)

Risk of operating flawed structure; scrap, repair, operate as-is

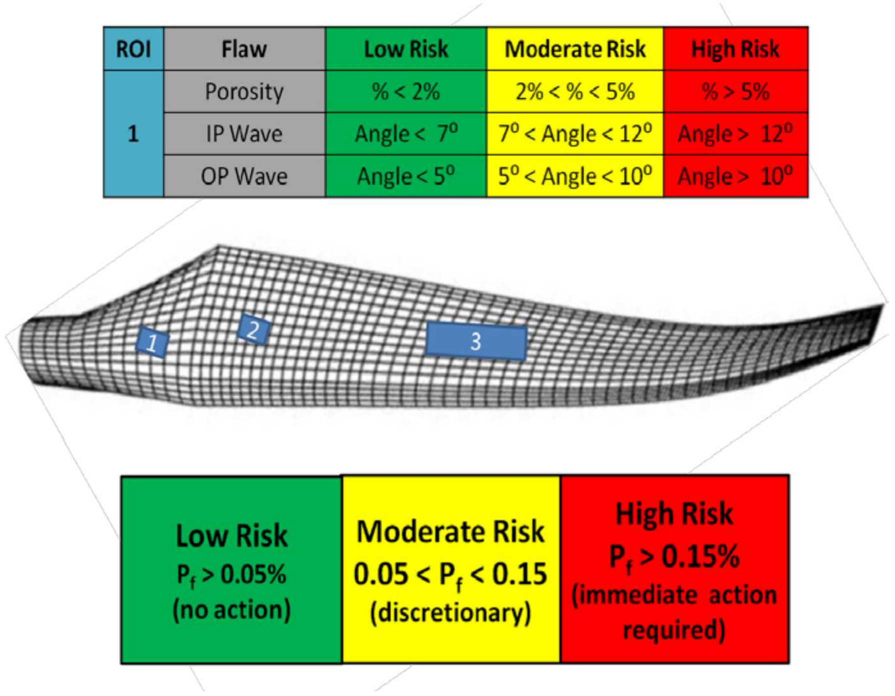
Criticality = Normalized Strain by Location

Severity = Complement of Flaw Knockdown

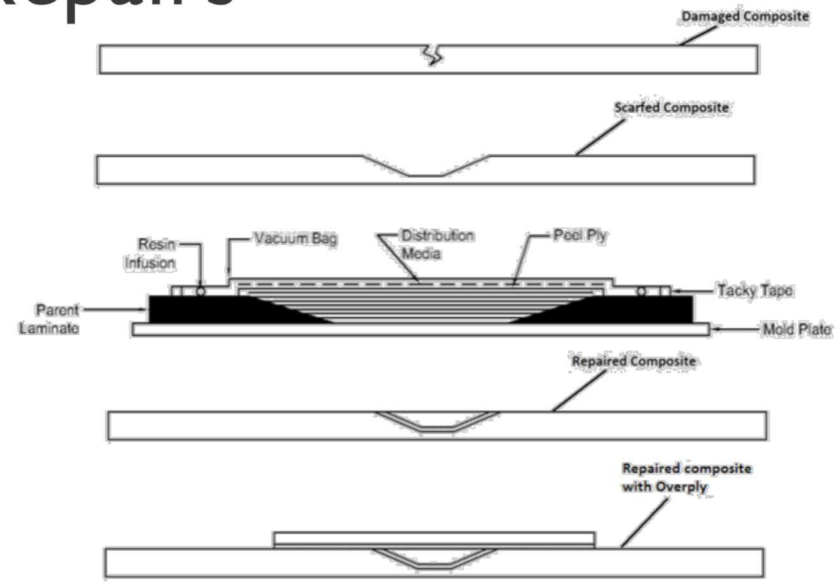
Criticality Matrix

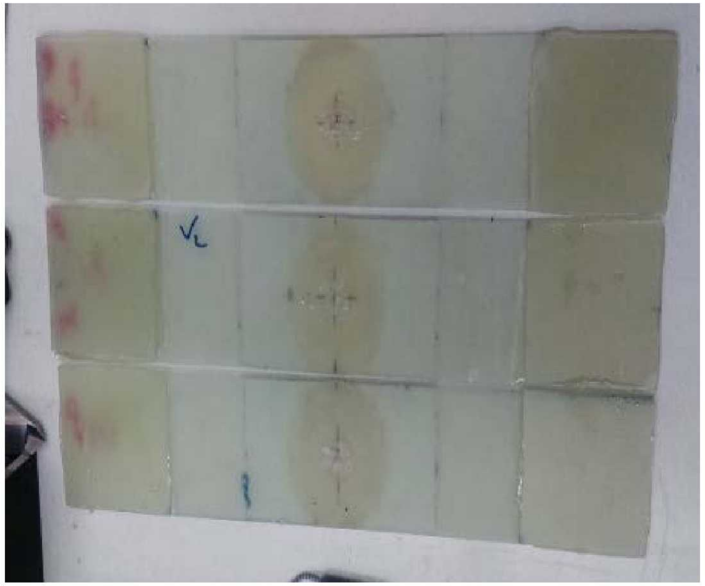


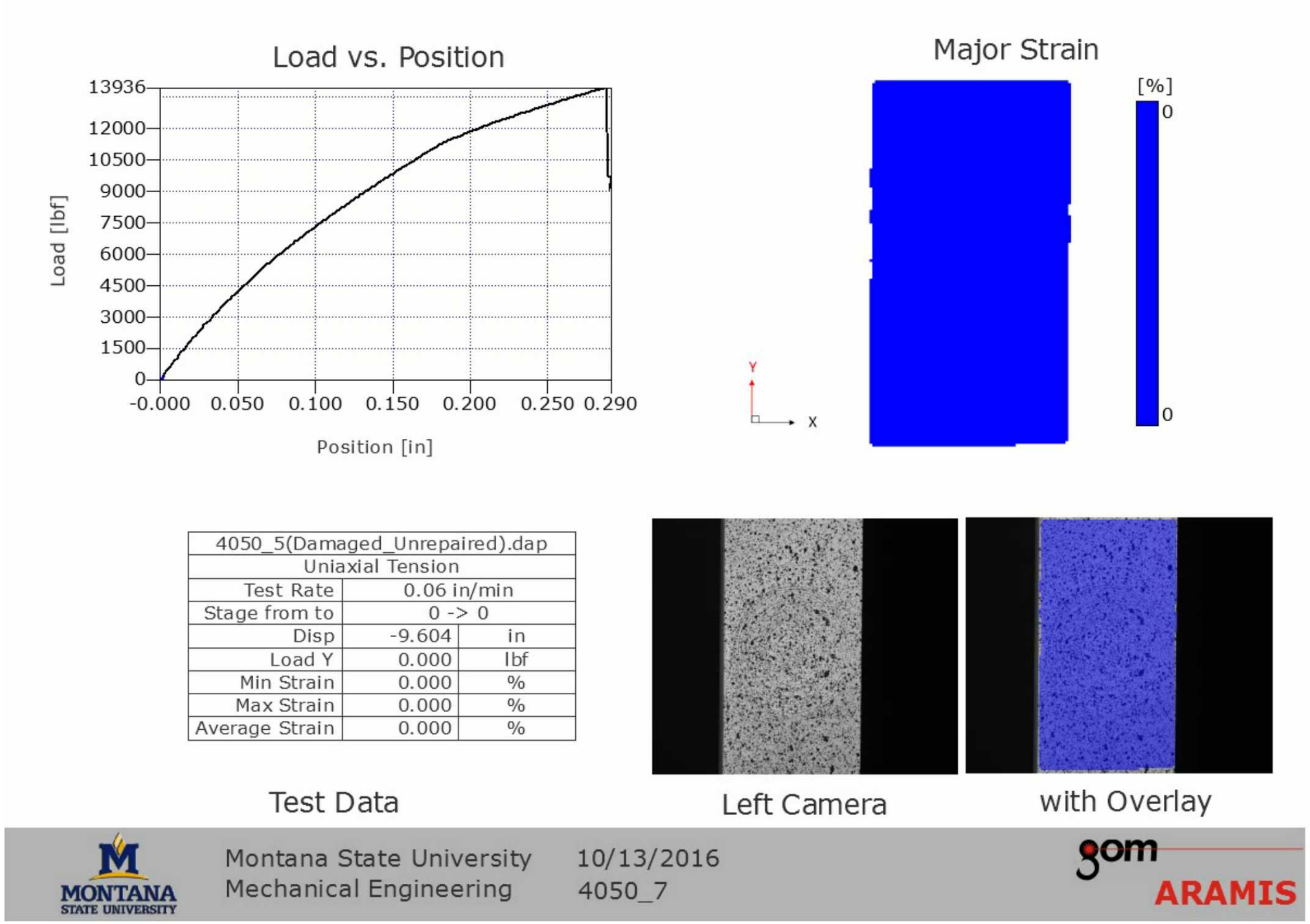
Criticality Map



Repairs


Damaged Composite
Scarfed Composite
Resin Infusion
Vacuum Bag
Distribution Media
Peel Ply
Tacky Tape
Parent Laminate
Mold Plate
Repaired Composite
Repaired composite with Overply




Load vs. Position
Load [lbf]
Position [in]
Major Strain
[%]
4050_5(Damaged_Unrepaired).dap
Uniaxial Tension
Test Rate 0.06 in/min
Stage from to 0 -> 0
Disp -9.604 in
Load Y 0.000 lbf
Min Strain 0.000 %
Max Strain 0.000 %
Average Strain 0.000 %
Test Data
Left Camera
with Overlay
MONTANA STATE UNIVERSITY
Montana State University
Mechanical Engineering
10/13/2016
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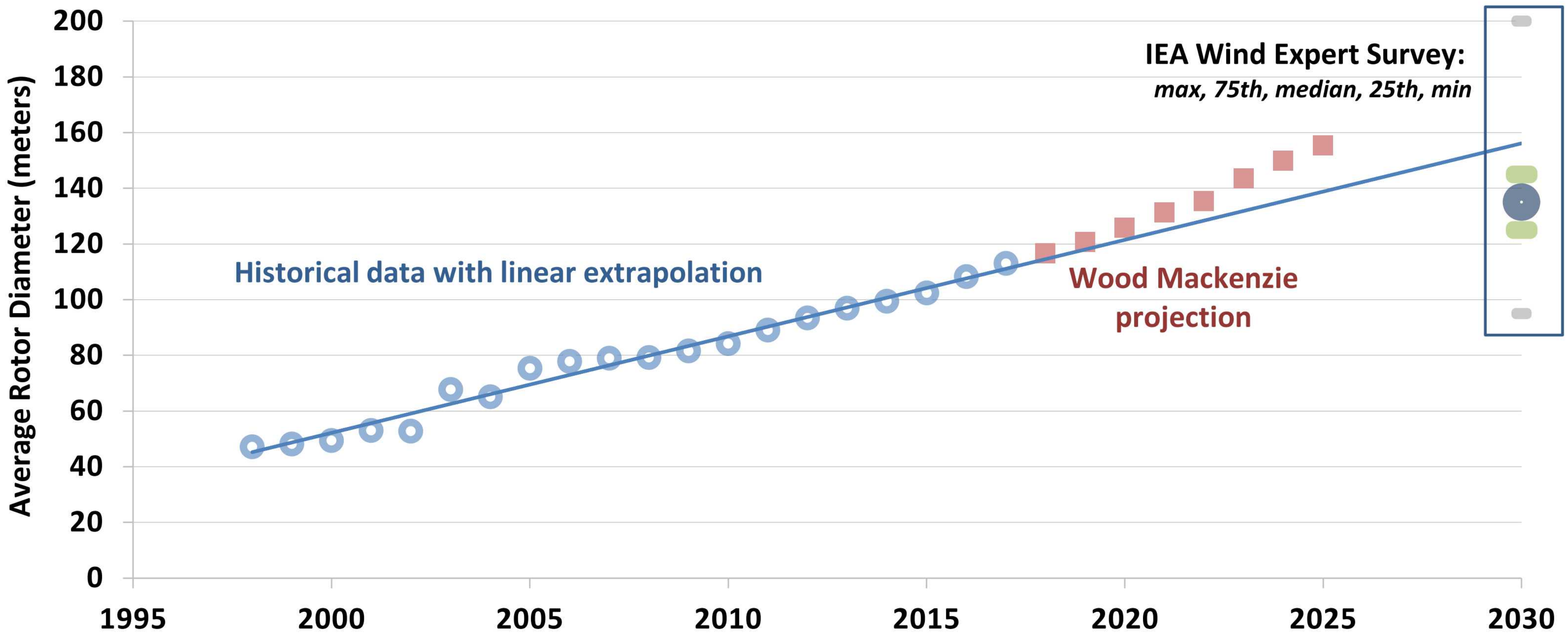
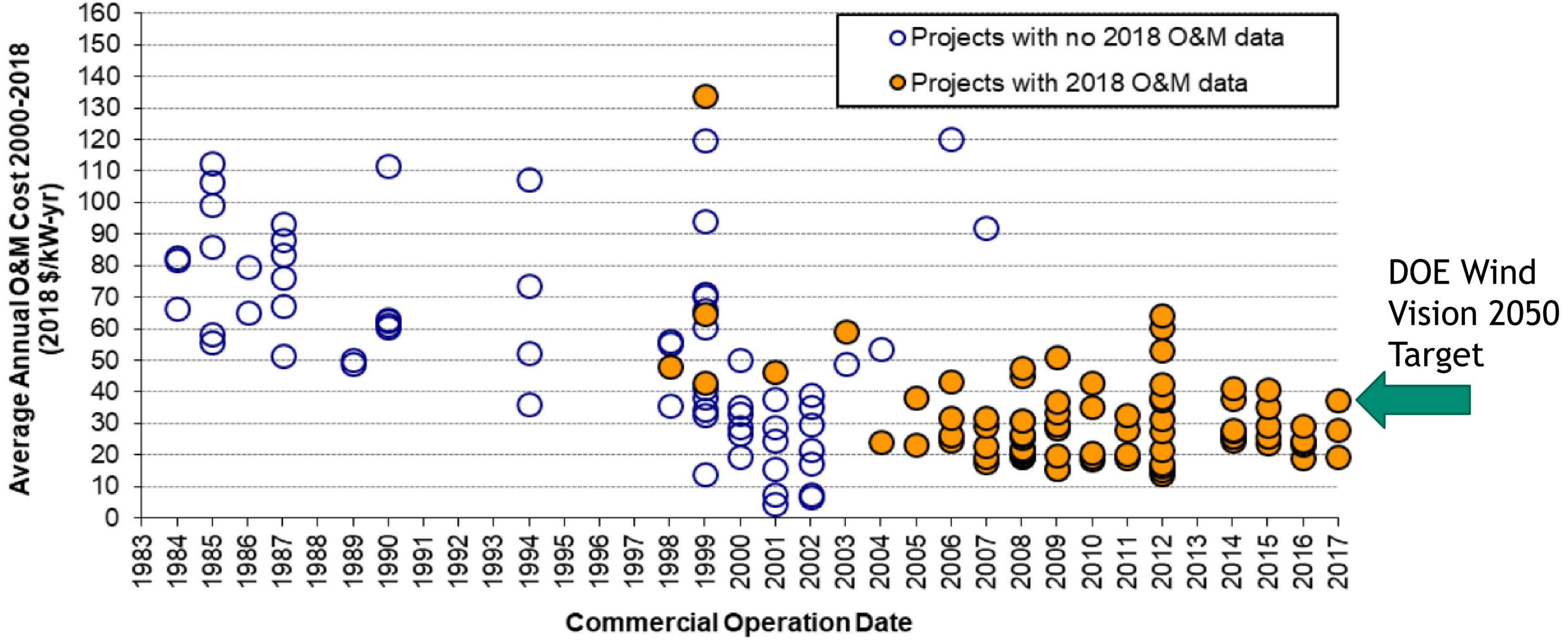
ARAMIS

Land-Based Turbine Trends: Rotor Size



Source: Lawrence Berkeley National Laboratory

O&M Cost Trends



Source: Lawrence Berkeley National Laboratory

Summary

Have blades become too fragile in order to be cheaper and lighter? What is the cost of more efficient blades to the operations and maintenance budget?

- Maybe/maybe not.
- Standards are likely conservative in some ways and non-conservative in others -- right for the wrong reason.
- Predicting the lifetime value of a blade (energy-produced/cost-incurred) remains difficult.

How can you assess blade defects before fitting? Will there ever be certification testing of design details?

- Request the history of manufacturing non-conformance and repairs.
- Yes, there has to be to take advantage of lower safety factors. OEM's are already doing some of this and new/better methods are being developed.

Summary

Why is there a lack of quality assurance testing throughout the manufacturing process of the blade? What can owner-operators do to ensure quality assurance of the blade?

- It's variable from one manufacturer to another, but the industry has made enormous progress in inspections.
- Variance in inspectability of certain areas/flaws.
- At the same time, blades have grown much larger.

What are the latest innovations in blade design that are going to change operations and maintenance in the future?

- Blades will continue to get lighter and more flexible.
- Design margins will get tighter, but with less uncertainty.
- Autonomous inspection will get more sophisticated.
- Repairs will be better engineered and quantified for quality.