Addressing Safety Margins in Reliability-Based Design of Wind Turbines

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Outline

- Notion of a "Limit State"
- Safety Margins and Partial Safety Factors
- Two Examples
  - Wind Turbine Partial Safety Factors
- Code Calibration; Other Industries
- Load Extrapolation, LRFD, and the Role of Testing and Simulation
- Other Issues & Concluding Thoughts …

Notion of a "Limit State"

Failure

Intact state → damaged/deteriorated/failed state

Limit State

Boundary between a safe and a failed state

Limit State Function, $g(\boldsymbol{X})$

$\boldsymbol{X}$ = stochastic variables describing strength, stiffness, geometry, loading, etc.

$g(\boldsymbol{X}) < 0$ ➔ failed state; $g(\boldsymbol{X}) > 0$ ➔ safe state

$P[g(\boldsymbol{X}) > 0]$ = Reliability; $P[g(\mathbf{X}) > 0]$ = Probability of failure

Notion of a "Limit State"

Probability of failure = $P_f = P[g(\boldsymbol{X}) < 0]$
Reliability = $1 - P_f$
Reliability Index, $\beta = -\Phi^{-1}(P_f)$

In terms of a "load" (L) and resistance" (R),

$g(\boldsymbol{X}) = R - L$

$$P_f = P[R - L < 0] = \int_{R-L<0} f_R(r) f_L(l) dr dl$$

It is possible to solve for the "reliability" or "probability of failure" using numerical integration, simulation, first- and second-order reliability methods, etc.

Can even identify the "design point" ($\boldsymbol{X}^*$).

P_f	β
0.01	2.32
0.001	3.09
0.0001	3.71
0.00001	4.26

Notion of a "Limit State"

Different types of limit states

Ultimate Limit State (ULS)

associated with limit on load-carrying capacity of a structural component (e.g., buckling, plastic yield, etc.)

Serviceability Limit State (SLS)

associated with excessive deformation

Fatigue Limit State (FLS)

associated with damage accumulation (cyclic loading)

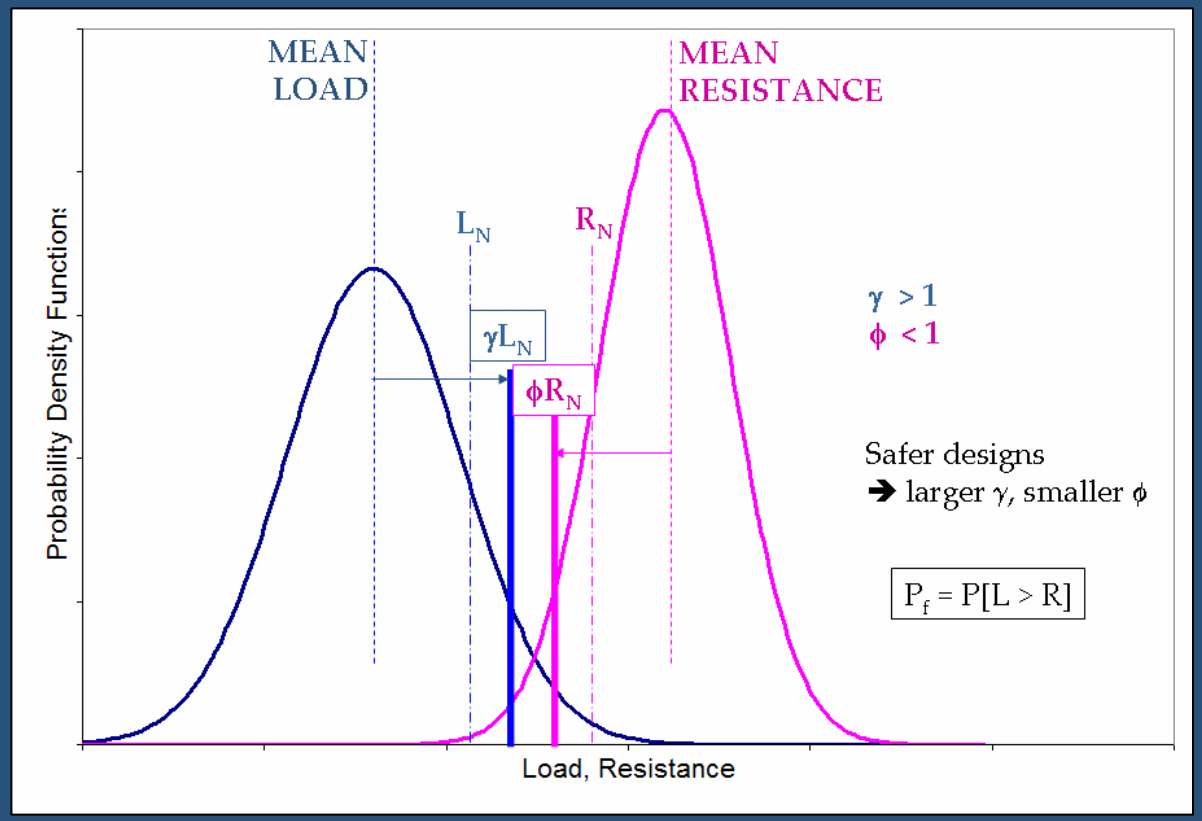
Safety Margins and Partial Safety Factors

Code format for design of wind turbines (as in many industries) is
LOAD AND RESISTANCE FACTOR DESIGN (LRFD)
format:

$$\phi R_N > \gamma L_N$$

or, for wind turbines,

$$\frac{1}{\gamma_m} R_N > \gamma_f L_N$$



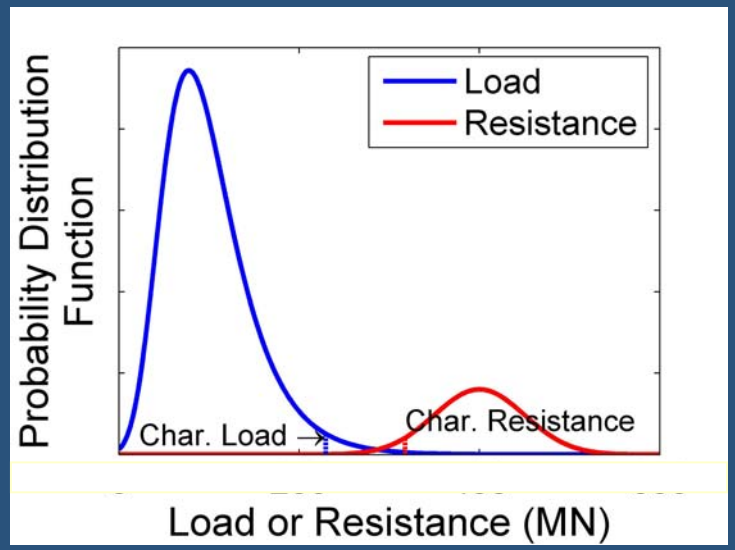
Example: Axial Loaded Steel Tower (Ultimate Limit State)

Limit State Equation: $g = \sigma A - Q$ $\sigma \sim$ Normal $Q \sim$ Gumbel

Q = (annual) maximum axial force; σ = yield strength of steel

E[Q] = 50 MN, COV of Q = 6%; E[σ]= 400 MPa, COV of σ = 6%

For a target failure probability = 1×10^{-5}, *design* A = 0.20 m^2.



Design point from reliability analysis:

$$q^* = 70.89 \text{ MN}; \sigma^* = 353.2 \text{ MPa}$$

Factored Limit State Equation:

$$g = \frac{1}{\gamma_m}\sigma_c A - \gamma_f q_c = 0$$

Characteristic values: Resistance at 5 percentile; load at 98 percentile (50-year)

Compare characteristic values to design values (through g) to obtain safety factors.

$$\gamma_f = \frac{q^*}{q_c} = 1.23; \quad \frac{1}{\gamma_m} = \frac{\sigma^*}{\sigma_c} = \frac{1}{1.02}$$

Example: Fatigue of WT blade in bending (Fatigue Limit State)

$g = 1 - D$ $\quad$ $D = \text{Cumulative Damage}$

$$D = \sum_i \frac{\Delta n(s_i)}{N(s_i)}$$

$n(s_i)$ = Number of stress cycles at stress range, s_i.
$N(s_i)$ = Number of stress cycles at stress range, s_i required for failure.

$S \sim \text{Exponential}$ Use S-N curve with variability.

For a target reliability index, β, of 3.29 or P_f of 0.0005 over the design life, *Design* section modulus $W = 0.0021$ m^3, from reliability analysis.

Use a characteristic load distribution (the long-term stress range distribution).
Use a characteristic S-N curve two standard deviations below the mean curve.
Load factor, $\gamma_f = 1.0$; Material factor, $\gamma_m = 1.15$ in LRFD equation.

Guidelines for Target Failure Probabilities

Table 2-3. Target annual failure probabilities P_{FT} and corresponding reliability indices β_T.

	Failure consequence		
Failure type	**Less serious** LOW SAFETY CLASS (small possibility for personal injuries and pollution, small economic consequences, negligible risk to life)	**Serious** NORMAL SAFETY CLASS (possibilities for personal injuries, fatalities, pollution, and significant economic consequences)	**Very serious** HIGH SAFETY CLASS (large possibilities for personal injuries, fatalities, significant pollution, and very large economic consequences)
Ductile failure with reserve capacity (redundant structure)	$P_F = 10^{-3}$ $\beta_T = 3.09$	$P_F = 10^{-4}$ $\beta_T = 3.72$	$P_F = 10^{-5}$ $\beta_T = 4.26$
Ductile failure with no reserve capacity (significant warning before occurrence of failure in non-redundant structure)	$P_F = 10^{-4}$ $\beta_T = 3.72$	$P_F = 10^{-5}$ $\beta_T = 4.26$	$P_F = 10^{-6}$ $\beta_T = 4.75$
Brittle failure (no warning before occurrence of failure in non-redundant structure)	$P_F = 10^{-5}$ $\beta_T = 4.26$	$P_F = 10^{-6}$ $\beta_T = 4.75$	$P_F = 10^{-7}$ $\beta_T = 5.20$

DNV/Risø Guidelines

ULS Partial Safety Factors for Wind Turbine Components

Limit State Equation: $g = \frac{1}{\gamma_m}\text{Resistance} - \gamma_f \text{Load}$ used for blades, tower

Physical Random Variables

Structural strength, Σ ~ Lognormal

- Structural Steel: COV ~ 5%
- FRP: COV ~ 10%
- Concrete: COV ~ 15%

Model Uncertainties

Strength, X_R ~ Lognormal, COV ~ 5%

Gravity vs. aerodynamic load effects accounted for.

Risø-R-1319(EN), 2002 study

Physical Random Variables

Extrapolated response, T ~ Gumbel
Turbulence intensity, I ~ Lognormal
Mean wind pressure, P ~ Gumbel
Self weight, G ~ Normal

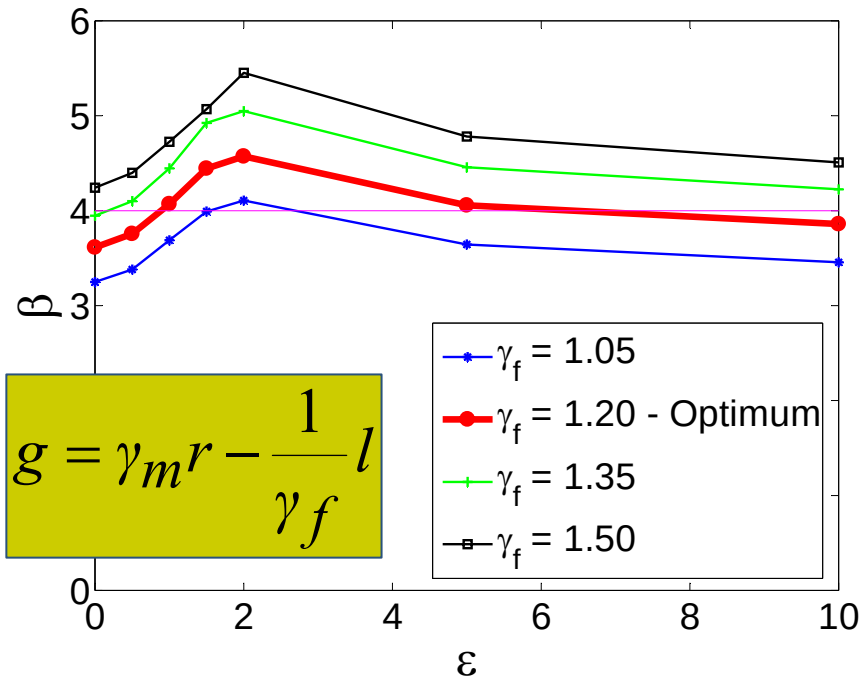
Model Uncertainties

Exposure, X_{exp} ~ Lognormal, COV ~ 20%
Climate, X_{st} ~ Lognormal, COV ~10%
Model scale, X_{aero} ~ Gumbel, COV ~ 20%
Dynamics, X_{dyn} ~ Lognormal, COV ~ 20%
Simulation, X_{sim} ~ Normal, COV ~ 5%
Extrapolation, X_{ext} ~ Lognormal, COV ~ 5%

Code Calibration

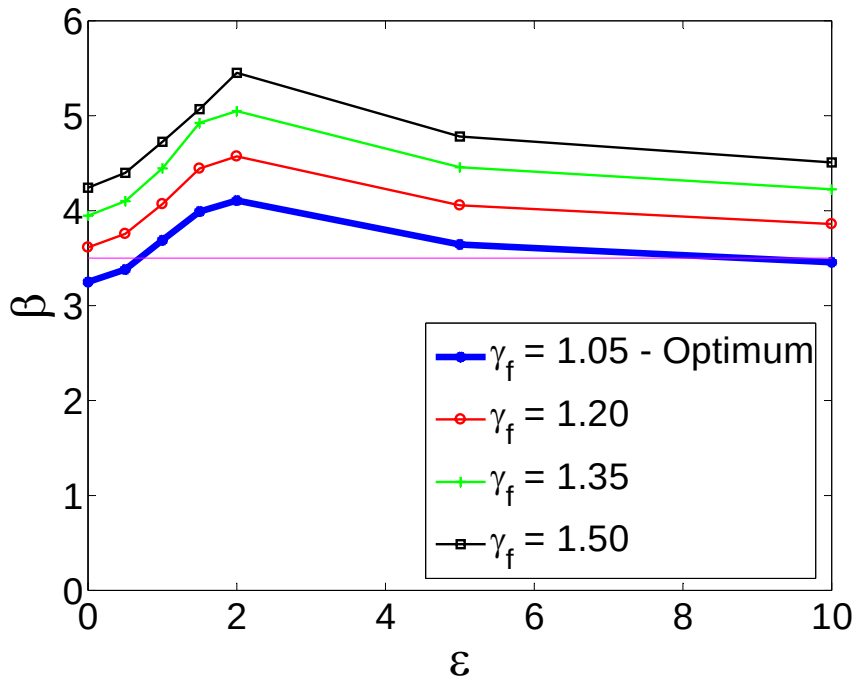
- Design codes give partial safety factors that are obtained by calibration
- Calibration is essentially an optimization exercise
  - For a range of different structures (sometimes represented with the help of one or more parameters in the limit state equation), the aim is to obtain small dispersion in the reliability (index) about a target or acceptable level of reliability; the corresponding values of the partial safety factors are thus "calibrated."

Code Calibration: Offshore Wind Turbine Example



$$g = \gamma_m r - \frac{1}{\gamma_f} l$$

Target $\beta = 4.0$; Optimum $\gamma_f = 1.20$



Target $\beta = 3.5$; Optimum $\gamma_f = 1.05$

Optimum load factor γ_f:
The γ_f that gives least mean square error between target and computed β, over all ε.
The parameter, ε represents relative influence of aerodynamic to hydrodynamic loads.

Model: Combined wind and wave, with both the wind and wave at 100-year level.

Other Industries using LRFD

- Most structural design codes "evolved" from Working Stress Design (WSD) or Ultimate Strength Design (USD) approaches

  WSD: $L_N < R_N/\gamma_R = R_{allowable}$

  USD: $R_N > \gamma_L L_N = L_{ultimate}$

- LRFD was <u>calibrated</u> against WSD and USD-based designs that were thought to be acceptable from experience

Other Industries using LRFD

- API (American Petroleum Institute)
- ACE (American Concrete Institute)
- AISC (American Institute of Steel Construction, Inc.)
- AASHTO (American Association of State Highway and Transportation Officials)

- API RP2A-LRFD, for example, requires 100-year oceanographic criteria. Considers type of platform (whether major, manned/unmanned), current, wave, wind conditions and joint distributions, etc.

Load Extrapolation and LRFD

Table 2 – Design load cases

Design situation	DLC	Wind condition		Other conditions	Type of analysis	Partial safety factor
1) Power production	1.1	NTM	$V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N
	1.2	NTM	$V_{in} < V_{hub} < V_{out}$		F	*
	1.3	ETM	$V_{in} < V_{hub} < V_{out}$		U	N

7.6.2 Ultimate strength analysis

The limit state function can be separated into load and resistance functions S and R so that the condition becomes

$$\gamma_n \cdot S(F_d) \leq R(f_d) \tag{30}$$

The resistance R generally corresponds with the maximum allowable design values of material resistance, hence $R(f_d) = f_d$, whilst the function S for ultimate strength analysis is usually defined as the highest value of the structural response, hence $S(F_d)=F_d$. The equation then becomes

$$\gamma_f F_k \leq \frac{1}{\gamma_m \gamma_n} f_k \tag{31}$$

Load Extrapolation and LRFD

For DLC 1.1 the characteristic value of load shall be determined by a statistical load extrapolation and correspond to an exceedance probability, for the largest value in any 10-min period, of less than or equal to $3{,}8 \times 10^{-7}$, (i.e. a 50-year recurrence period) for normal design situations. For guidance see Annex F.

50 yrs = (50 × 365.25 × 24 × 6) 10-min periods = 2,629,800 10-min periods

Return Period of 50 yrs = P[No exceedance in 10 min] = 1/2629800 = 3.8×10^{-7}

Need to **extrapolate** to these rare load fractiles from limited simulation

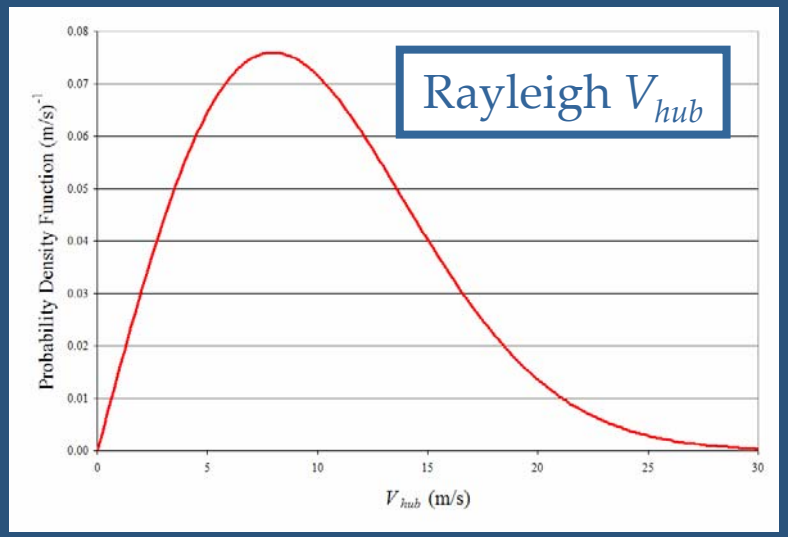
Table 3 – Partial safety factors for loads γ_f

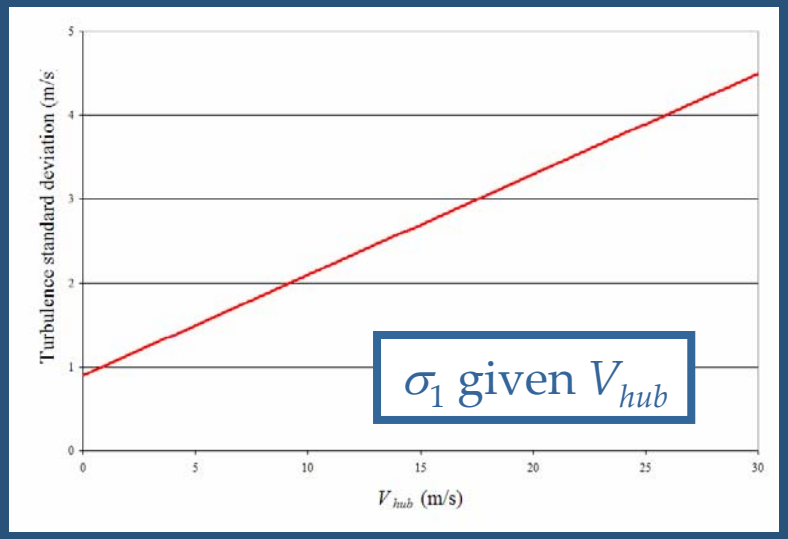
Unfavourable loads			Favourable[10] loads
Type of design situation (see Table 2)			All design situations
Normal (N)	Abnormal (A)	Transport and erection (T)	
1,35*	1,1	1,5	0,9

* For design load case DLC 1.1, given that loads are determined using statistical load extrapolation at prescribed wind speeds between V_{in} and V_{out}, the partial load factor for normal design situations shall be γ_f =1,25.

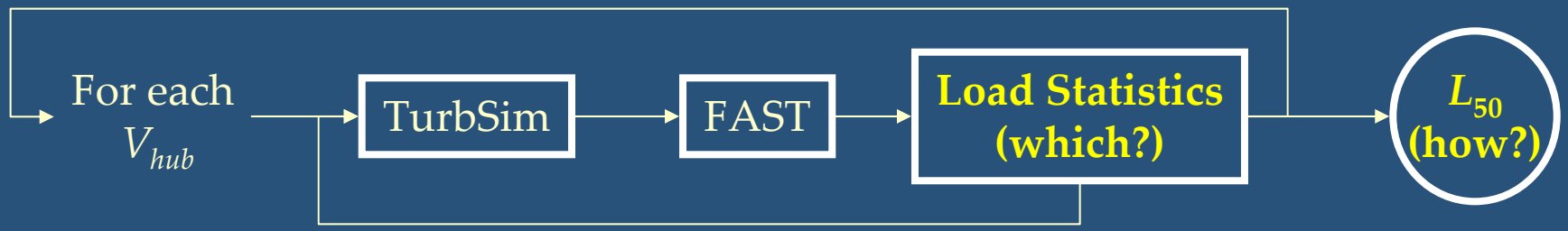
Load Extrapolation using Simulations

Example: Class I-A Site





Simulate V_{hub}: V_{ref} = 50 m/s, V_{ave} = 10 m/s
I_{ref} = 16% and σ_1 (given V_{hub}) is as shown above.



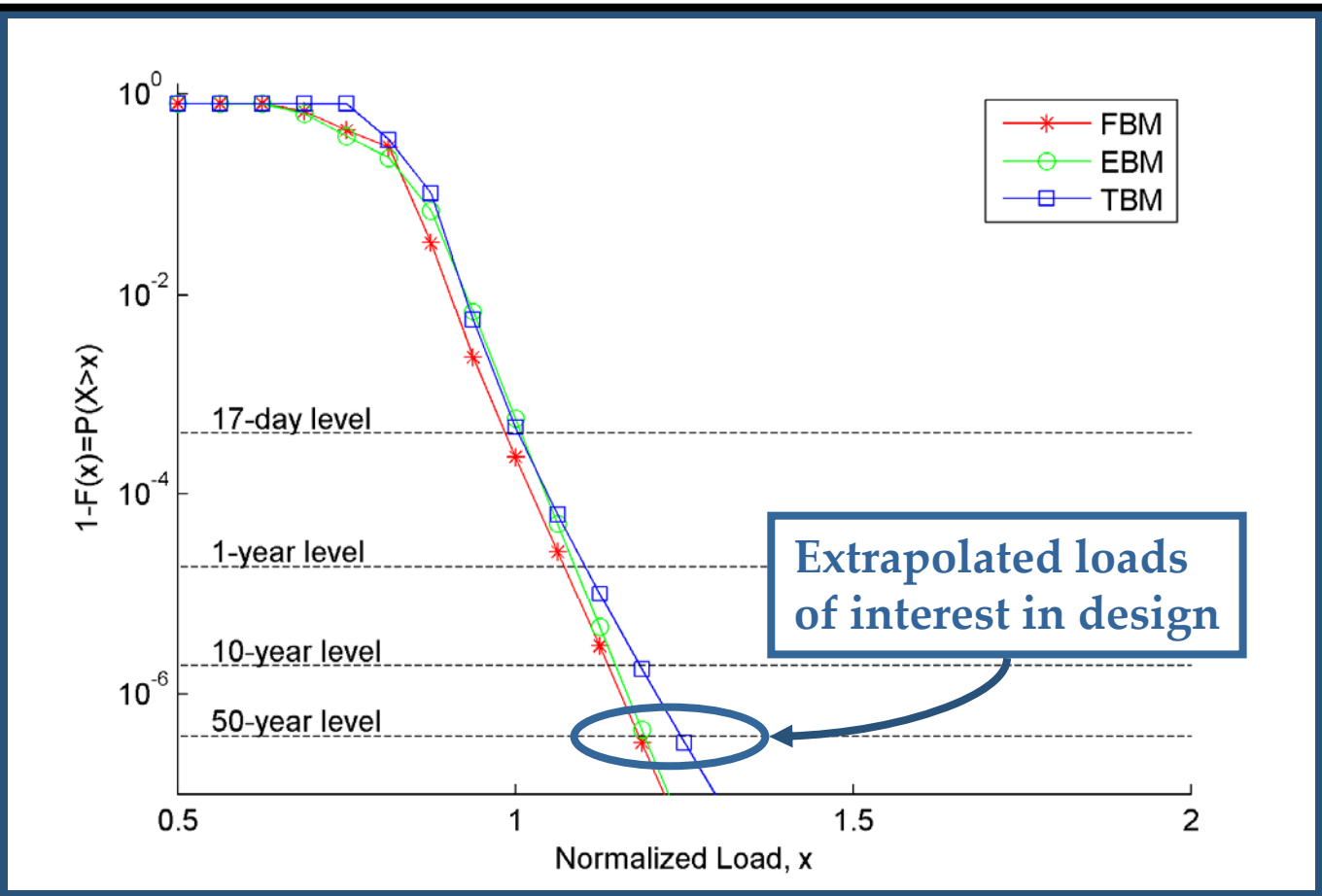
Extreme Load Extrapolation and Fatigue Load Spectra using Field Data

1.5MW Wind Turbine, Lamar Site

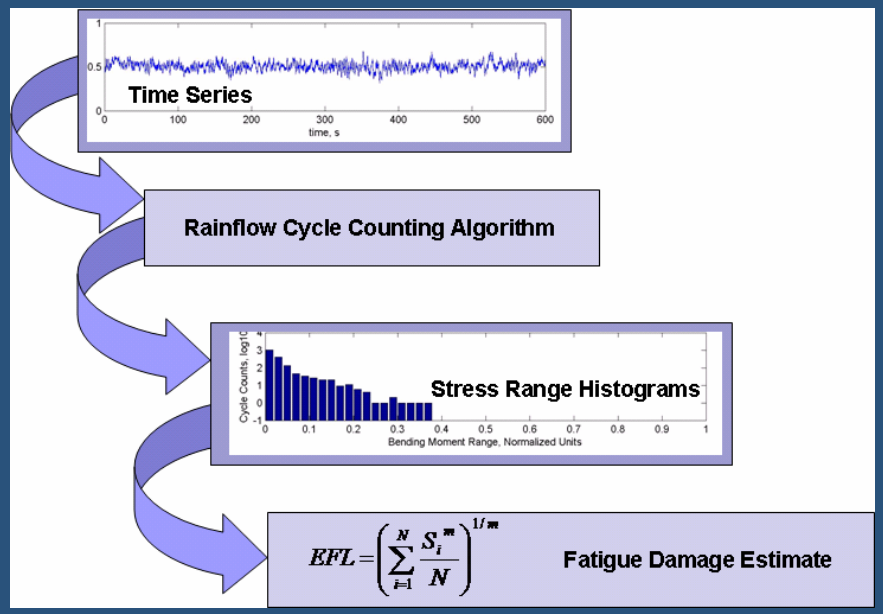
- Three load extrapolation approaches
  - Global Maxima
  - Peak-Over-Threshold (POT)
  - Moment-Based Process Model
- Two long-term fatigue load spectra approaches
  - Time-domain (with rainflow cycle counting)
  - Frequency-domain (Dirlik's method)

Load Extrapolation: Long-Term Load Distributions

$$P(M_t > x) = \int_V P(M_t > x \mid V) f(V) = \sum_V (1 - (F_V(x - u_V))^{\lambda_v t}) p(V)$$

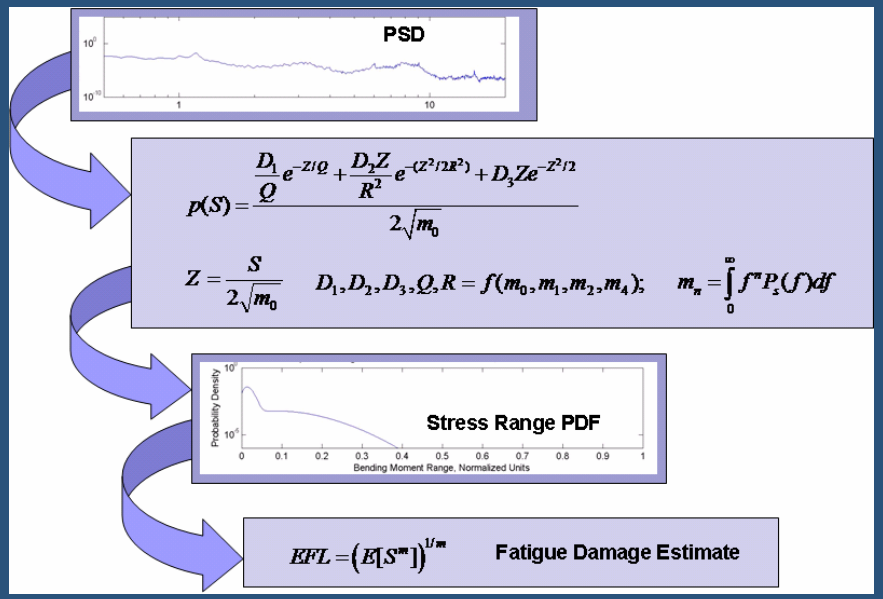


Long-term fatigue load analysis (from field data)

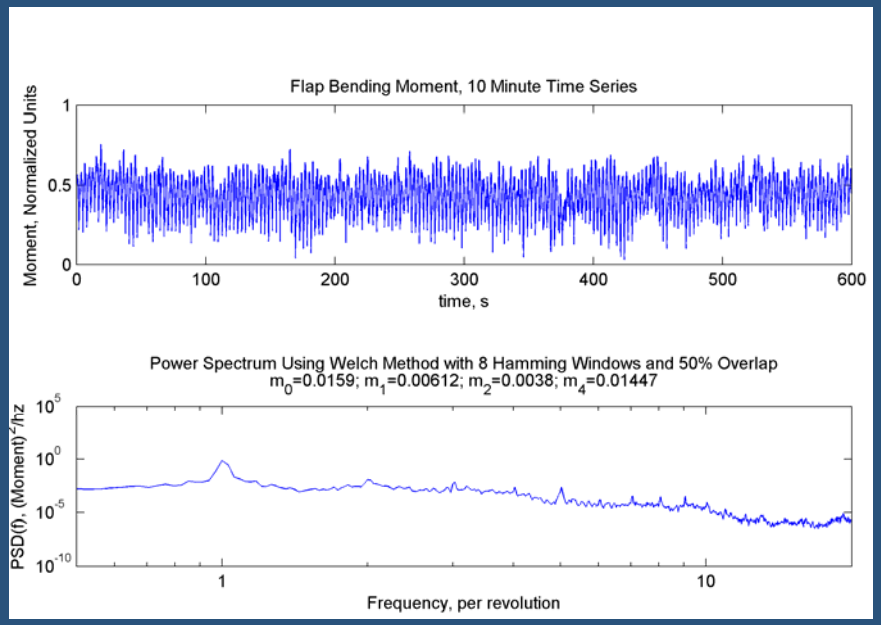


Time-domain method
Rainflow Cycle Counting

Frequency-domain method
Dirlik's method

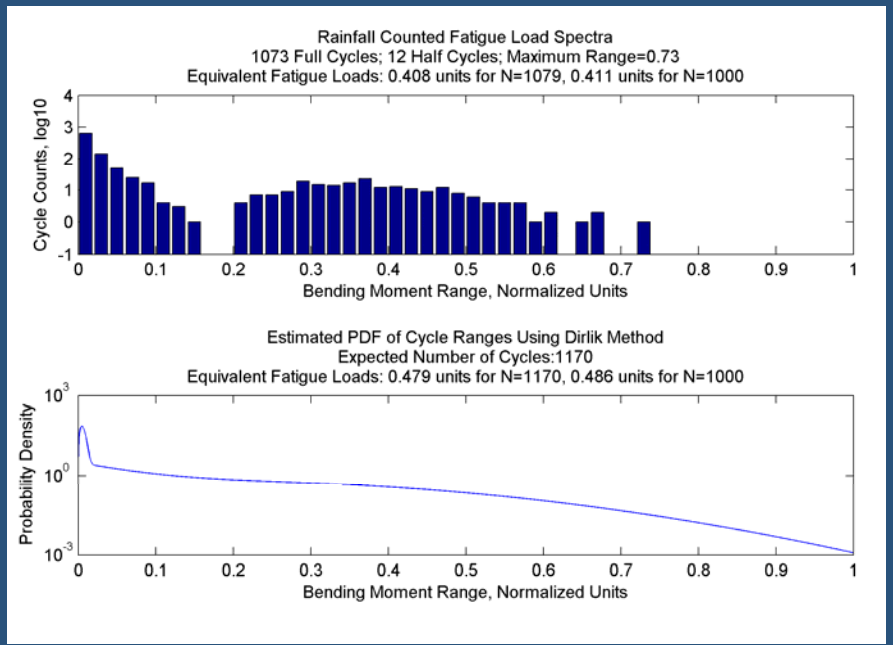


Long-term fatigue load spectra (from field data)



Flap Bending Moment
Time Series and Power Spectrum

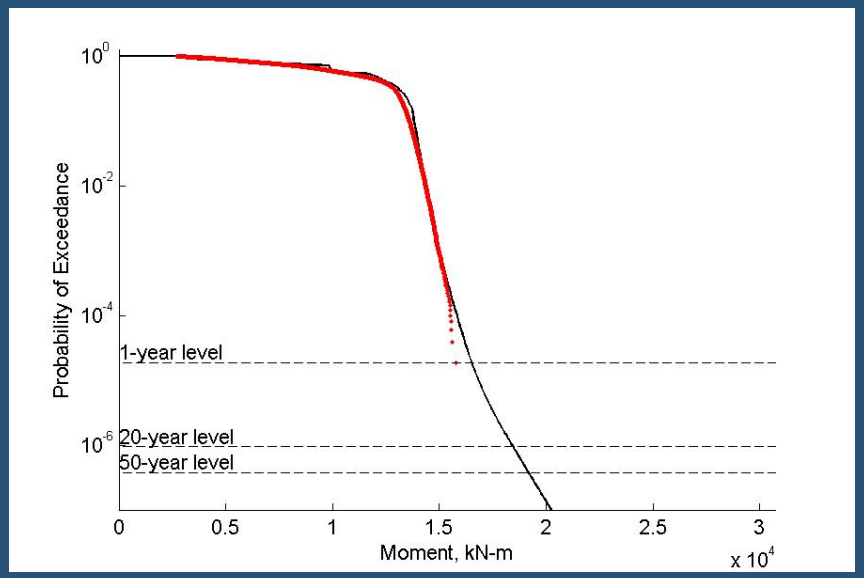
Long-term fatigue load histograms using both approaches

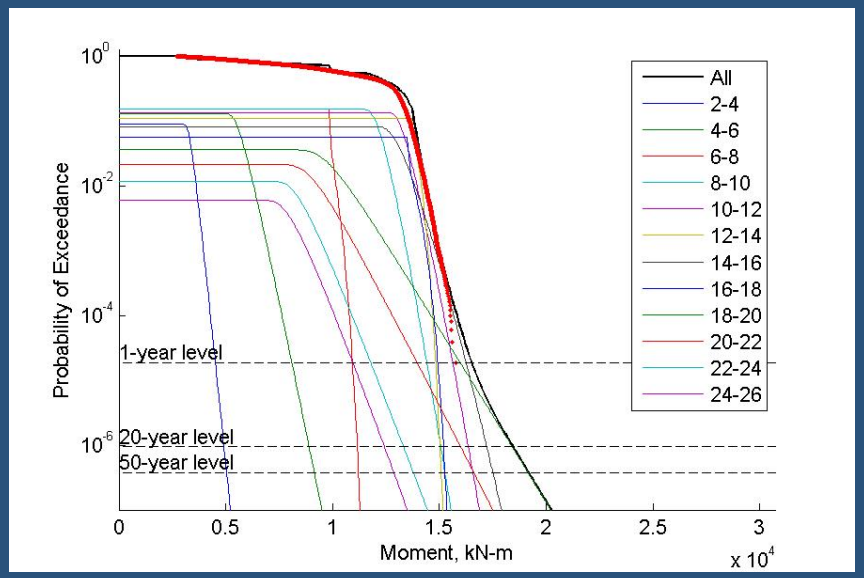


LE^3
Load Extrapolation Evaluation Exercise

- 5MW Baseline Wind Turbine Model (NREL)
- Effort undertaken by 8-10 active participants
- Critically examine Annex F of IEC 61400-1
- Use simulation data of two types
- Simulation Set 1
  - 200 simulations in 14 wind speed bins
  - NTM model (Rayleigh V; $\sigma(V) = \sigma_{90}|V$ as in IEC)
- Simulation Set 2
  - Roughly 5 × 50,000 ten-minute simulations representing five full years
- Study several alternatives for extrapolation

LE³ – Long-term extreme loads





Flap bending moment

Data shown are from one year's simulation
These data were not used in establishing the long-term distribution

Extrapolation for offshore wind turbine loads (simulated)

NREL 5 MW Baseline Model

Hub-height:	90 m
Rotor diameter:	126 m
Water depth:	20 m
Monopile dia.:	6 m

On Turbine Rotor

IEC Class I-B wind regime for turbulence

On Support Structure

Linear irregular waves

Environmental Random Variables

Mean wind speed (V); $V \sim$ Rayleigh

Significant wave height (H_s); $H_s | V \sim$ Weibull

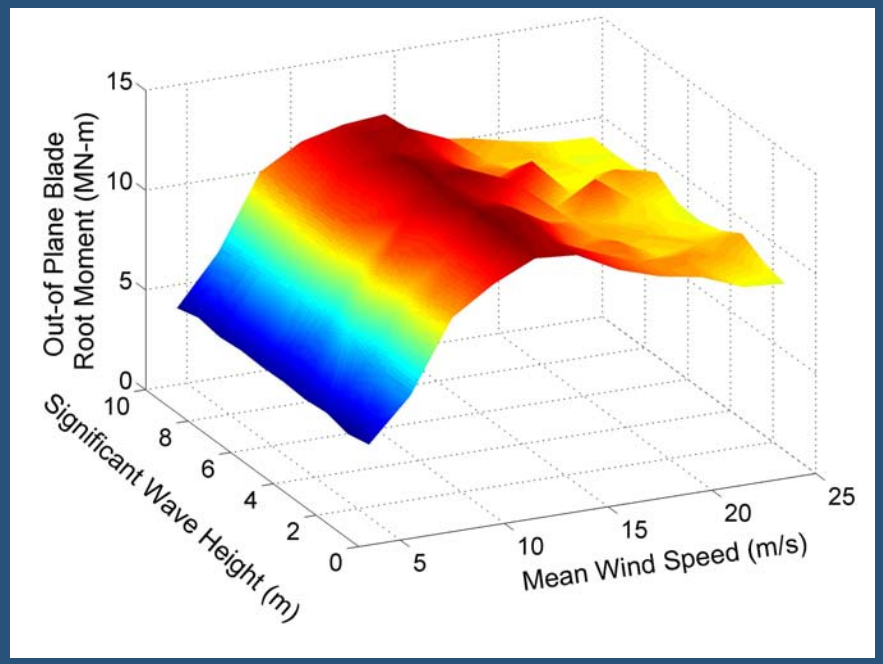
Simulation Grid

$3 < V < 25$, $\Delta V = 2$ m/s; $0 < H_s < 10$, $\Delta H_s = 1$ m.

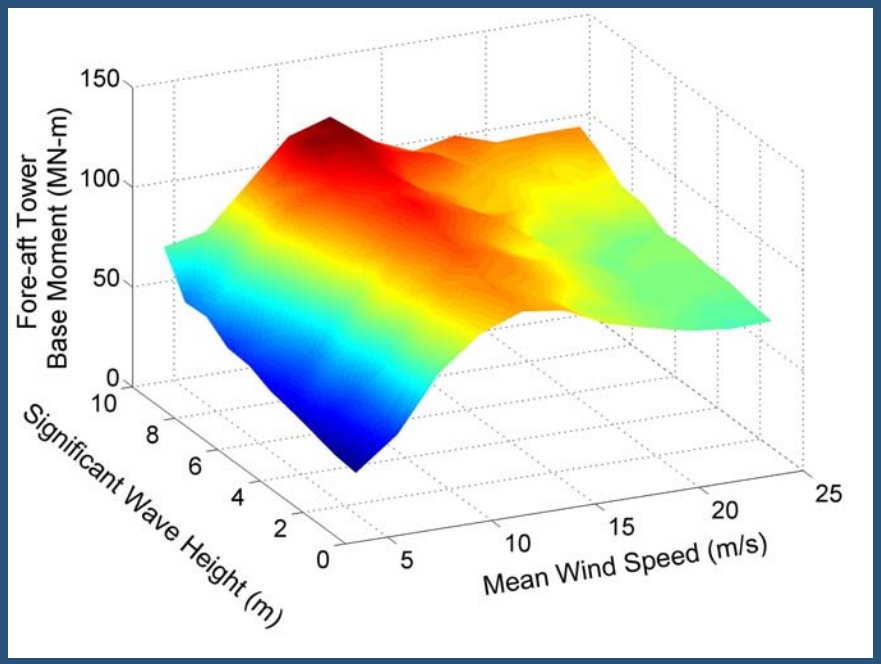
6 simulations per (V, H_s)

Offshore Short-Term Load Extremes

Out-of-plane blade root moment (OoPBM)



Fore-aft tower base moment (TBM)



Offshore 20-year loads

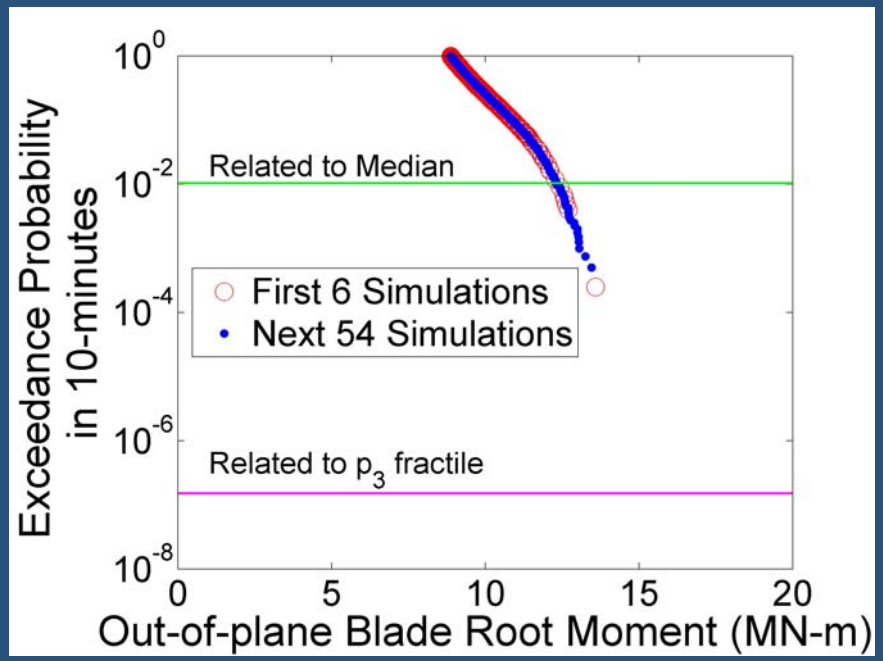
Method	OoPBM (MN-m)			TBM (MN-m)		
	V	H_s	OoPBM	V	H_s	TBM
	m/s	m	MN-m	m/s	m	MN-m
2-D Inverse FORM	12.0	6.2	12.8	12.0	6.2	105.2
3-D Inverse FORM	14.0	5.5	13.6	16.0	5.5	119.9
Direct Integration (3-D)	-	-	13.6	-	-	119.9

Inverse FORM (First-Order) Reliability Method Used

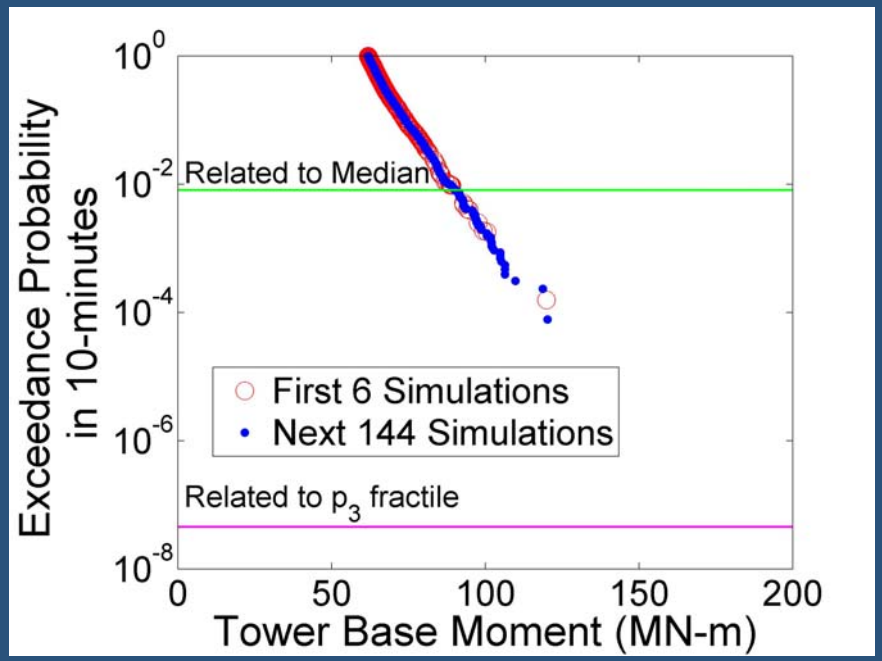
With either POT or Global Maxima models for short-term loads, very rare fractiles are needed for load conditional on V and H_s ➔ large no. of simulations are required

Offshore 20-year loads

Short-term load distributions for important wind speeds and wave heights



V = 14.0 m/s; H_s = 5.5 m



V = 16.0 m/s; H_s = 5.5 m

As many as 150 ten-min simulations are needed for desired Inverse-FORM load fractile (stable tails)

Other issues and concluding thoughts…

- A rational design procedure is possible that accounts for load and resistance variability, target safety levels, adequate margins, etc.
- Parts reliability (and measures such as MTBF, etc.) cannot be used for wind turbine structural components such as the tower
- Some considerations in reliability-based design are similar to other industries; others are not
- Data needs cannot be overemphasized
- Especially load extrapolation is a challenge and can involve extensive simulations
- Calibration of codes (e.g., for offshore wind turbines) can follow conventional practice.

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