MOMENT-BASED FATIGUE LOAD MODELS FOR WIND ENERGY SYSTEMS

LeRoy M. Fitzwater, Steven R. Winterstein
Civil & Envir. Eng. Dept., Stanford University

Lance Manuel
Civil Eng. Dept., University of Texas at Austin

Paul S. Veers
Wind Energy Tech. Dept., Sandia National Laboratories

To be presented at ICOSSAR 2001, Newport Beach, June 2001.

Stochastic Fatigue Analysis

Fatigue: What We Care About:

- R = stress ranges from random time history (e.g., rainflow-counted from measured or simulated history)

- Mean Fatigue Damage:

$$E[D] \propto E[R^b] \quad \text{where}$$

$$\begin{aligned} E[\cdot] &= \text{average ("expected' value)} \\ b &= \text{material parameter from } S\text{–}N \text{ curve; e.g.,} \end{aligned}$$

Welded steels: $b \approx 3$
Fiberglass composites: $b \approx 9$

Resulting Complications:

- Choice of material affects how "tail-sensitive" to rare loads; hence optimal modelling given limited data

- Complicated dynamics of wind turbines: rotational sampling of wind field, gravity plus turbulence effects, bimodal probability densities of R

Moment-Based Fatigue Load Models

- **Standard Weibull model** of R (two moments)
  - *Definition:* $P[R > r] = \exp[-(\frac{r}{\alpha_R})^{\beta_R}]$
  - *Parameters:* α_R, β_R
  - *Preserves:* $E[R]$ and $E[R^2]$ (or σ_R^2)

- **Quadratic Weibull model** of R (three moments)
  - *Starts with:* W=standard Weibull model of R
  - *Definition:* $R = R_0 + \kappa[W + \epsilon W^2]$
  - *Parameters:* R_0, κ, ϵ
  - *Preserves:* $E[R]$, $E[R^2]$, and $E[R^3]$

- **Damage-based Weibull model** of R
  - *Definition:* Apply Weibull model to $W = R^{b_{min}}$ *where* b_{min} = minimum value of b to be expected (e.g., b_{min}=3–5).
  - *Preserves:* $E[R^{b_{min}}]$ and $E[R^{2b_{min}}]$

TRADEOFFS: Moment-Based Models

- **Standard Weibull model** of R (two moments)
  - Standard relations to fit parameters to moments
  - Preserves $E[R]$ and $E[R^2]$ $\rightarrow$ requires least data
  - May not represent upper tail accurately
- **Quadratic Weibull model** of R (three moments)
  - Preserves $E[R]$, $E[R^2]$, and $E[R^3]$ $\rightarrow$ can capture non-Weibull trends in upper tail
  - Requires more data than ordinary Weibull
  - Needs numerical algorithm to estimate parameters from moments. *Algorithms:* `FITS`, `MAXFITS`
- **Damage-based Weibull model** of R
  - Preserves $E[R^{b_{min}}]$, $E[R^{2b_{min}}]$ (e.g., b_{min}=3–5)
  - Weibull fit to $R^{b_{min}}$; standard relations between parameters and moments
  - Preserves damage exactly if b=b_{min} or $b = 2b_{min}$ (presumably good accuracy for intermediate b values)
  - Most tail sensitive; e.g., matches moments 3 and 6, or 4 and 8, ... $\rightarrow$ requires most data

Description of Field Data

Data from Instrumented Wind Turbine:

- 110kW Horizontal Axis Wind Turbine (WINCON 110XT) in Lavrio, Greece

- Wind characterized by
  - $\overline{V}$=mean wind speed
  - $I=\sigma_V/\overline{V}$=turbulence intensity

- 101 10-minute samples ($15 \leq \overline{V} \leq 19$ m/s)

- In-plane (edge) and Out-of-plane (flap) bending measured

- Histograms of R=rainflow-counted bending moment ranges provided

Long-Term Analysis

- Characterize each necessary range moment μ_i by power-law regression:

$$\mu_i = a_i(\frac{V}{V_{ref}})^{b_i}(\frac{I}{I_{ref}})^{c_i}$$

(e.g., i=1,2,3 for quadratic Weibull)

- Estimate uncertainty in regression parameters θ given limited data:

$$\theta = [a_1, b_1, c_1, a_2, b_2, c_2, a_3, b_3, c_3]$$

- Resulting long-term distribution of fatigue ranges R:

$$F(r|\theta) = \int_{all\ \overline{V}} \int_{all\ I} F(r|\overline{V}, I|\theta)\ d\overline{V}\ dI$$

- Simulation of many $\theta \rightarrow$ range of possible $F(r|\theta)$; rank to provide confidence intervals of F for fixed r.

Summary and Conclusions

- **Set of Models** (increasingly tail-sensitive):

Model	**Quantities Preserved:**
Standard Weibull	$E[R]$, $E[R^2]$
Quad Weibull	$E[R]$, $E[R^2]$, $E[R^3]$
Damage-based Weibull	$E[R^{b_{min}}]$, $E[R^{2b_{min}}]$
Quad Damage-based Weib	$E[R^{b_{min}}]$, $E[R^{2b_{min}}]$, $E[R^{3b_{min}}]$

- **Most Efficient:** Quadratic Weibull
  - Least tail-sensitive generalization of Weibull
  - Parameters found numerically; often need data threshold

- **Simplest to Automate:** Damage-based Weibull
  - No subjective choice of threshold, etc.; ensured to give consistent damage ($b_{min} \leq b \leq 2b_{min}$)
  - Simple parameter estimation (Weibull)
  - Can be quite tail-sensitive