Statistical Post-Processing of General Time Series Data - With Wind Turbine Applications

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Implementation/Interpretation of Standards: IEC & IS0

- Issues:
  - How to “Fill In”/Extrapolate Load Spectra for Ultimate & Fatigue Loads:
    - US wind consultants (e.g. Kamzin)
    - National Labs (e.g. RISO-Denmark, ECN-Netherlands, NREL/Sandia-United States)
    - Academic Research (e.g. RMS)
  - Design Bases for Ultimate Loads:
    - Series of Design Gust Scenarios
    - Full Turbulence Simulation

Implementation/Interpretation of Standards: IEC & IS0

- Issues: (cont'd)
  - How Much Data?
    - How Uncertain Given the Imperfect Information
      - Limited Data from Prototype Machines
      - Imperfect Analysis Models (e.g. C_d Uncertainty)
    - Cover with Appropriate "Safety" Factor

Loads: A Bottom-Up Approach

- Short-term Problem (Given a Stationary Wind/Sea State)
  - Have loads data $\{L_1, \ldots, L_n\}$, (e.g., rainflow ranges) for a given wind condition $\rightarrow$ model statisitical moments μ_i:
    - μ_1 = Average (Mean) Load

$$m_1 = \frac{1}{n}\sum_{i=1}^{n} L_i$$

    - μ_2 = Normalized second-moment (Coefficient of Variation):

$$m_2 = \frac{s}{m_1}; \quad s^2 = \overline{(L - \overline{L})^2}$$

    - μ_3 =Normalized third-moment (Coefficient of Skewness):

$$m_3 = \frac{\overline{\left(L - \overline{L}\right)^3}}{s^3}$$

    - μ_1 =Normalized fourth-moment(Coefficient of Kurtosis):

$$m_4 = \frac{\overline{\left(L - \overline{L}\right)^4}}{s^4}$$

  - Algorithm: `FITS` estimates load distribution from μ_i

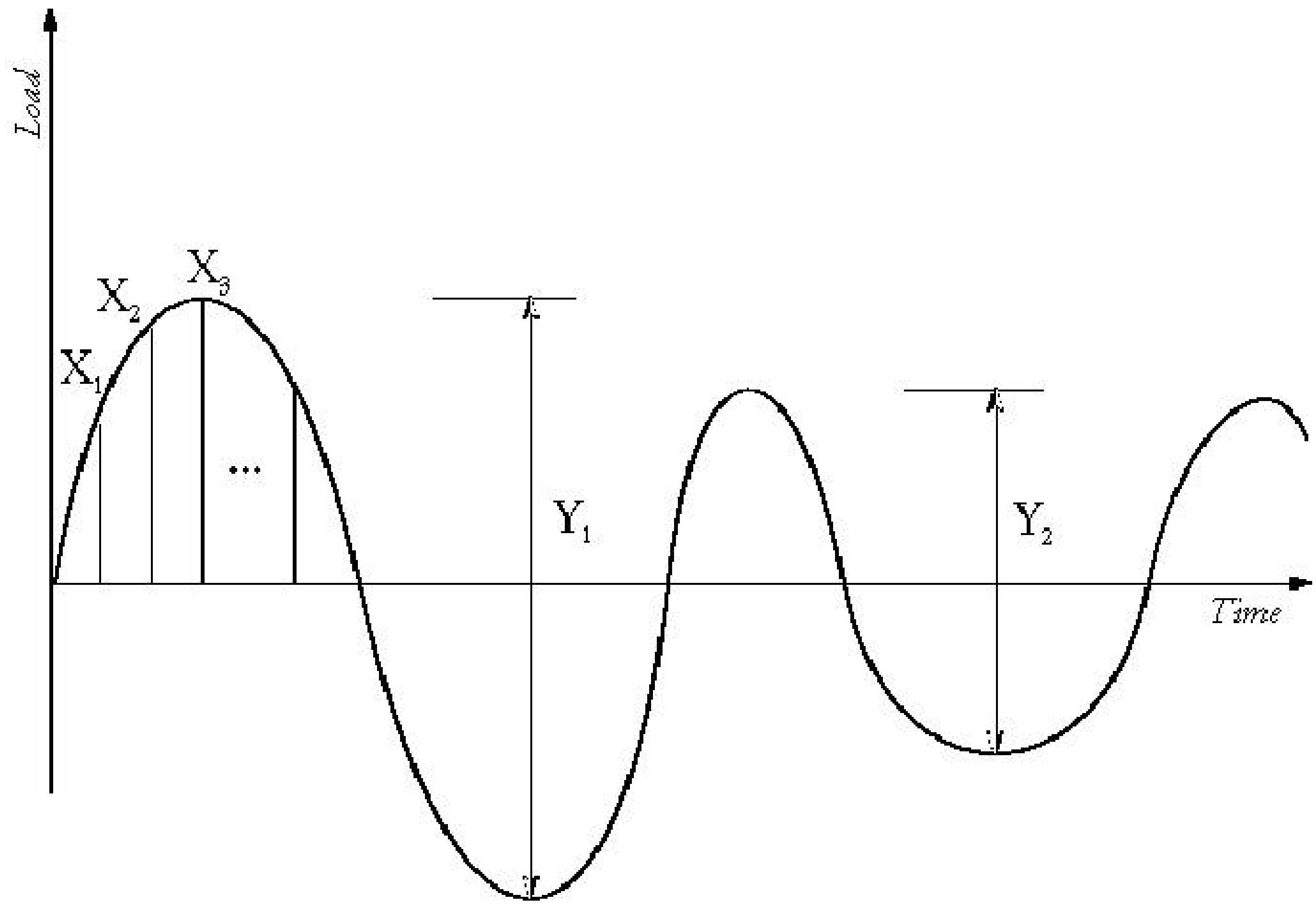
Loads: A Bottom-Up Approach

- Long-term Problem
  - Across multiple wind conditions: Model load moments mi vs. wind parameters V and I:

$$m_i = a \cdot \left(\frac{V}{V_{ref}} \right)^b \cdot \left(\frac{I}{I_{ref}} \right)^c$$

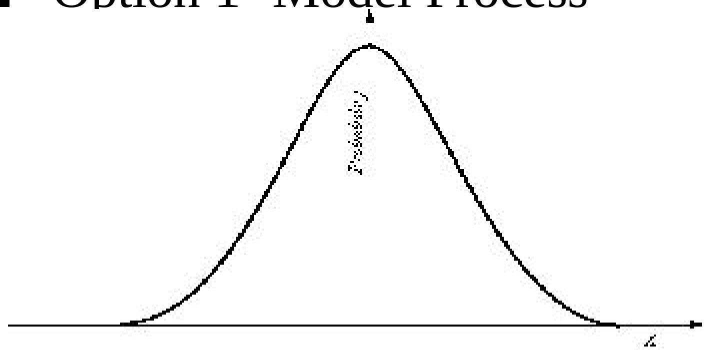
  - Where
    - Power -law flexible form; permits:
      - Linear dependence (b,c = 1)
      - Superlinear Dependence (b,c > 1)
      - Sublinear Dependence (b,c < 1)
      - No dependence (b,c = 0)
    - a,b,c estimated by linear regression (and their uncertainties)
    - V_{ref}, I_{ref} = central V, I values (geometric means)
  - Algorithm: `PRECYCLES` estimates a, b, c, and their uncertanties; provides input to reliability analysis routine `CYCLES` (`FAROW`)

Moment-Based Models of Dynamic Loads & Response



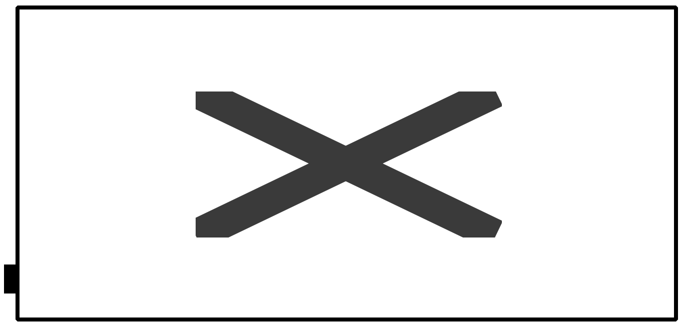
Moment-Based Models of Dynamic Loads & Response - Two Options

- Option 1- Model Process



- Two-Sided Distribution
- $X=C_0+C_1N+C_2N^2+C_3N^3$
  - N=Normal
  - C_i's depend on the 4 Statistical Moments of X
    - α_3= skewness (right vs. left tail)
    - α_4=Kurtosis ("heaviness" of both tails)

- Option 2- Model Ranges/Peaks



- $Y=C_0+C_1W+C_2W^2$
  - W=Weibull
  - C_i's depend on the 3 Statistical Moments of Y

Moment-Based Models of Dynamic Loads & Response - Critical Issues & Tradeoffs

- Option 1- Model Process
  - Only Need Original History
    - No Peak Counting
  - Must Approximate Peaks
    - Narrow Band Approximation
  - Can Model Fatigue and Extremes
- Option 2 - Model Ranges/Peaks
  - Can use Stats of Rainflow Ranges Directly (often stored)
  - Fewer Moments Needed; Simpler Fitting
  - May Need to Filter Small/Uninteresting Ranges
  - Can Model Fatigue and Extremes

Data Analysis Algorithm: FITS
(Stanford University/Sandia National Laboratory)

Data Sets

Raw Data → **FITS** → Probabilistic Distribution Function fits to data

Histograms

Moments

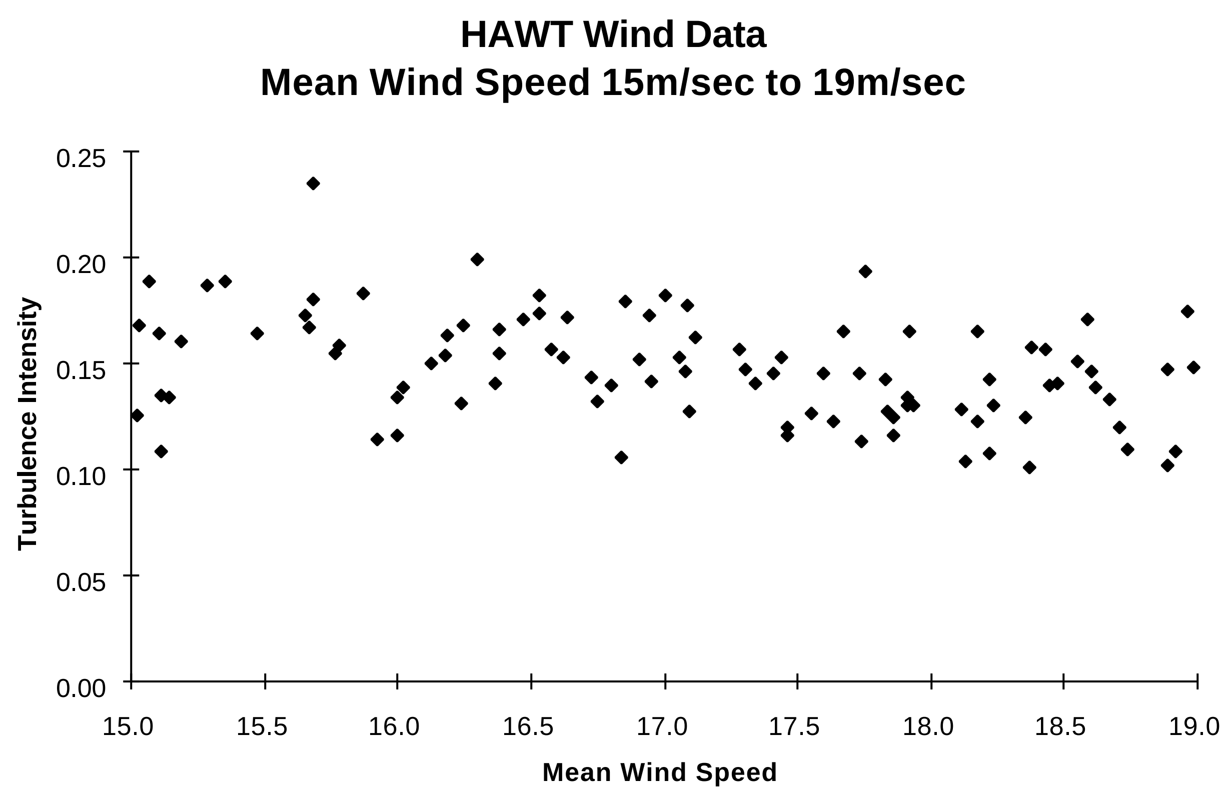
Select from among:
- Normal
- Lognormal
- Exponential
- Weibull
- Gumbel
- Shifted Exponential
- Shifted Weibull
- Quadratic Weibull
- Shifted Quadratic Weibull

- Other Routines
  - `FITTING`: 4-Moment Distortions of Normal and Gumbel Distributions
  - `FAROW/CYCLES`: Fatigue Reliability Analysis (Given Moment Based Loads)
  - `PRECYCLES`: Fits Moments vs. V, I → Input to `FAROW/CYCLES`

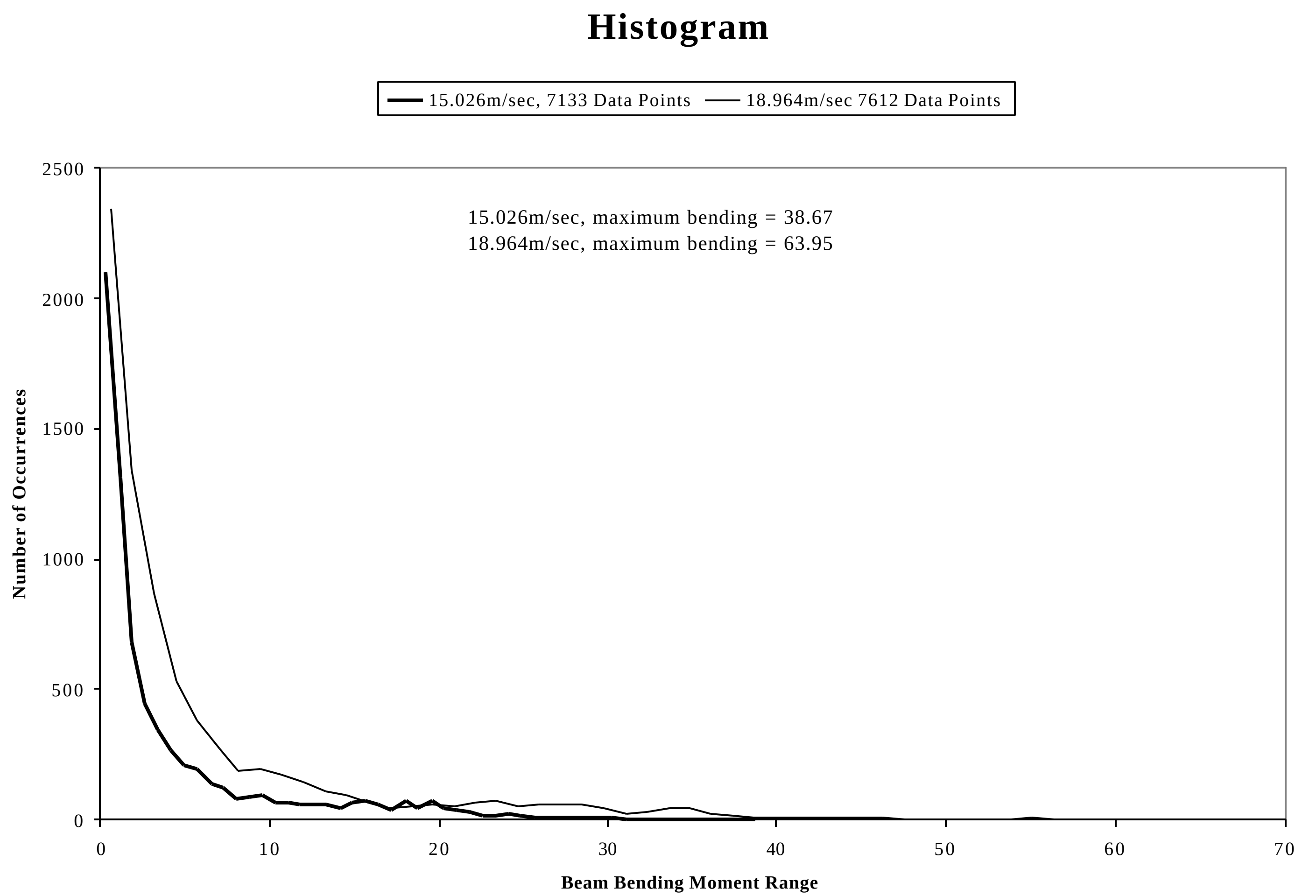
HAWT Data Set

- Description:
  - Horizontal Axis Wind Turbine (HAWT)
  - 101 Data Sets; each of Ten-Minute Duration
  - Wind Speed: 15 to 19m/sec
    - Subset of Collected Data
  - Turbulence Intensity: 10 to 23 percent
  - Rainflow-counted cycles or ranges available
  - Flap(Beam) and Edge(Chord) Bending Moment ranges available
  - Data were gathered as counts of ranges exceeding specific levels of a bending moment range.
- Goal:
  - Long Data Sets - "True" Long Run Statistics
  - Fit to Subsets - Assess:
    - Accuracy (Bias)
    - Uncertainty

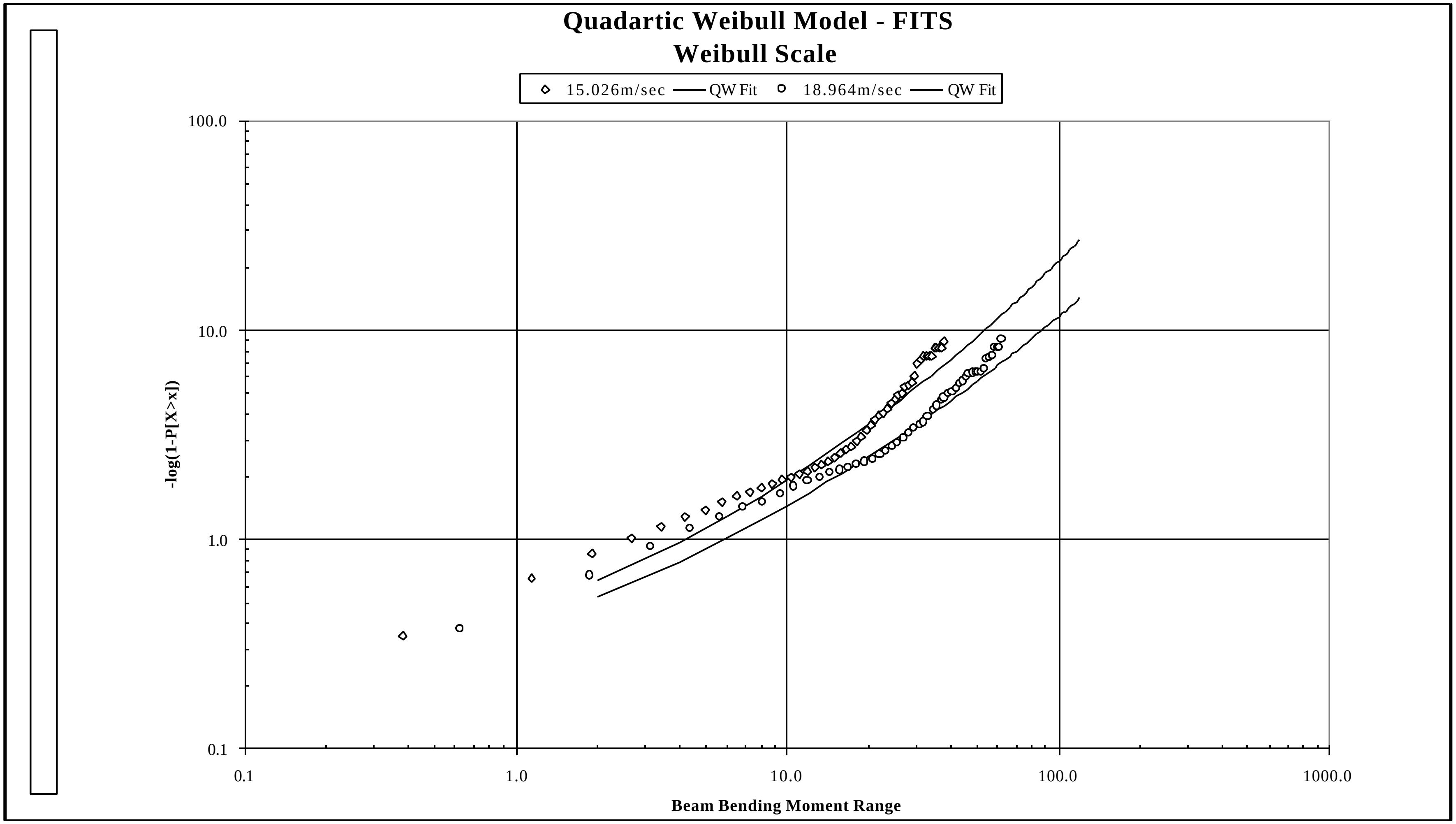
HAWT - Turbulence vs. Wind Speed



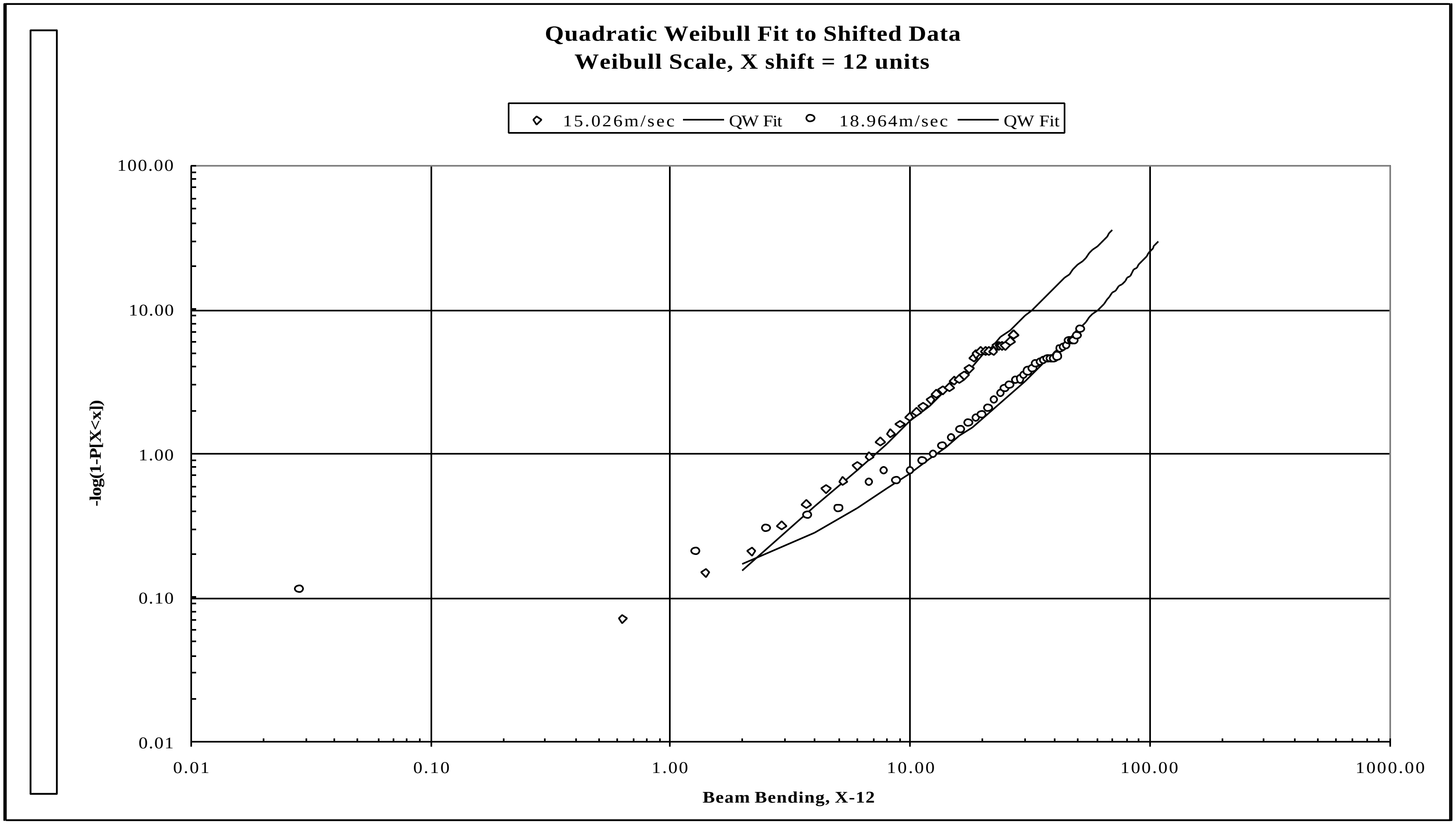
HAWT - Typical Histograms



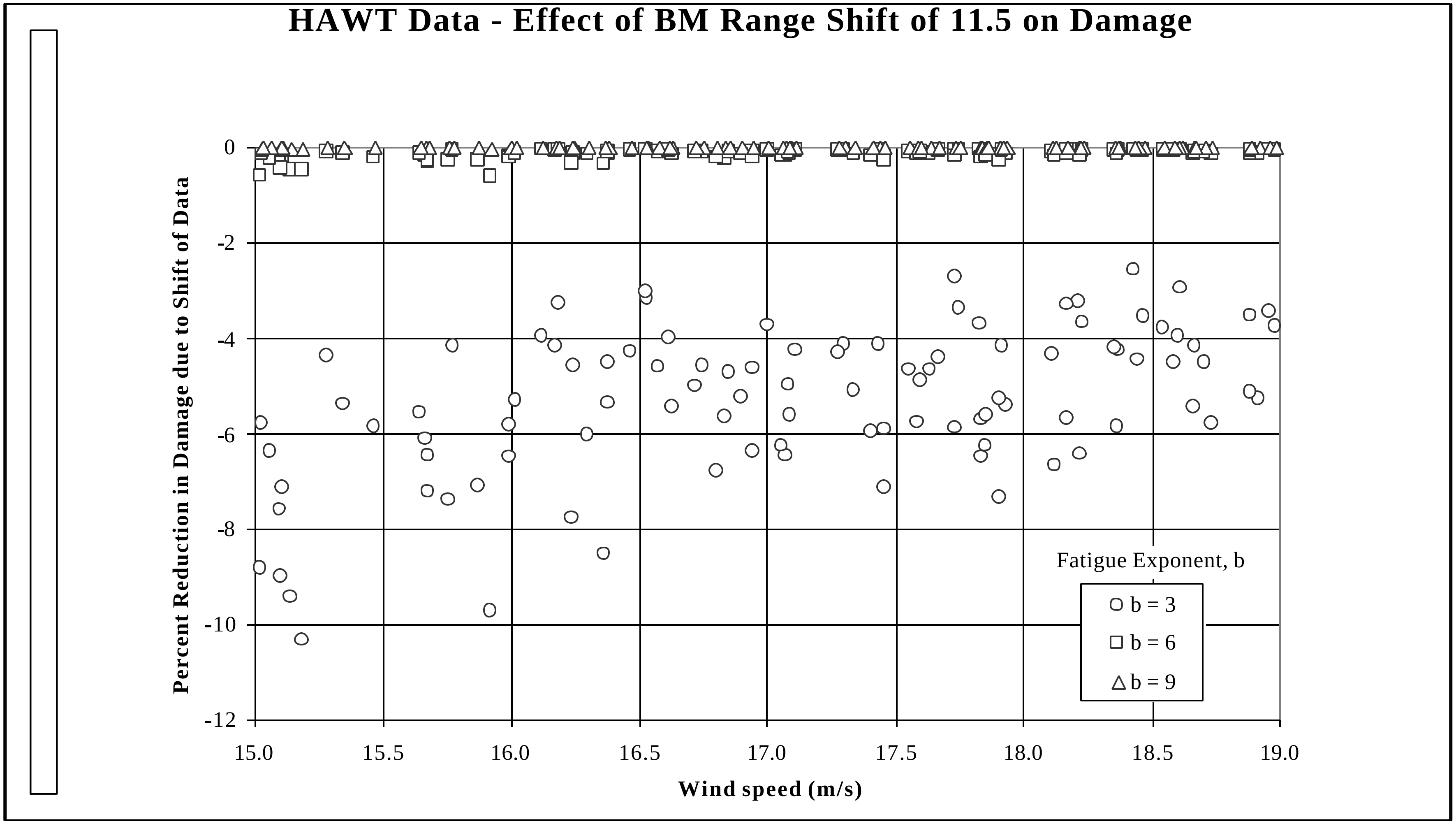
HAWT - Fitted Distribution



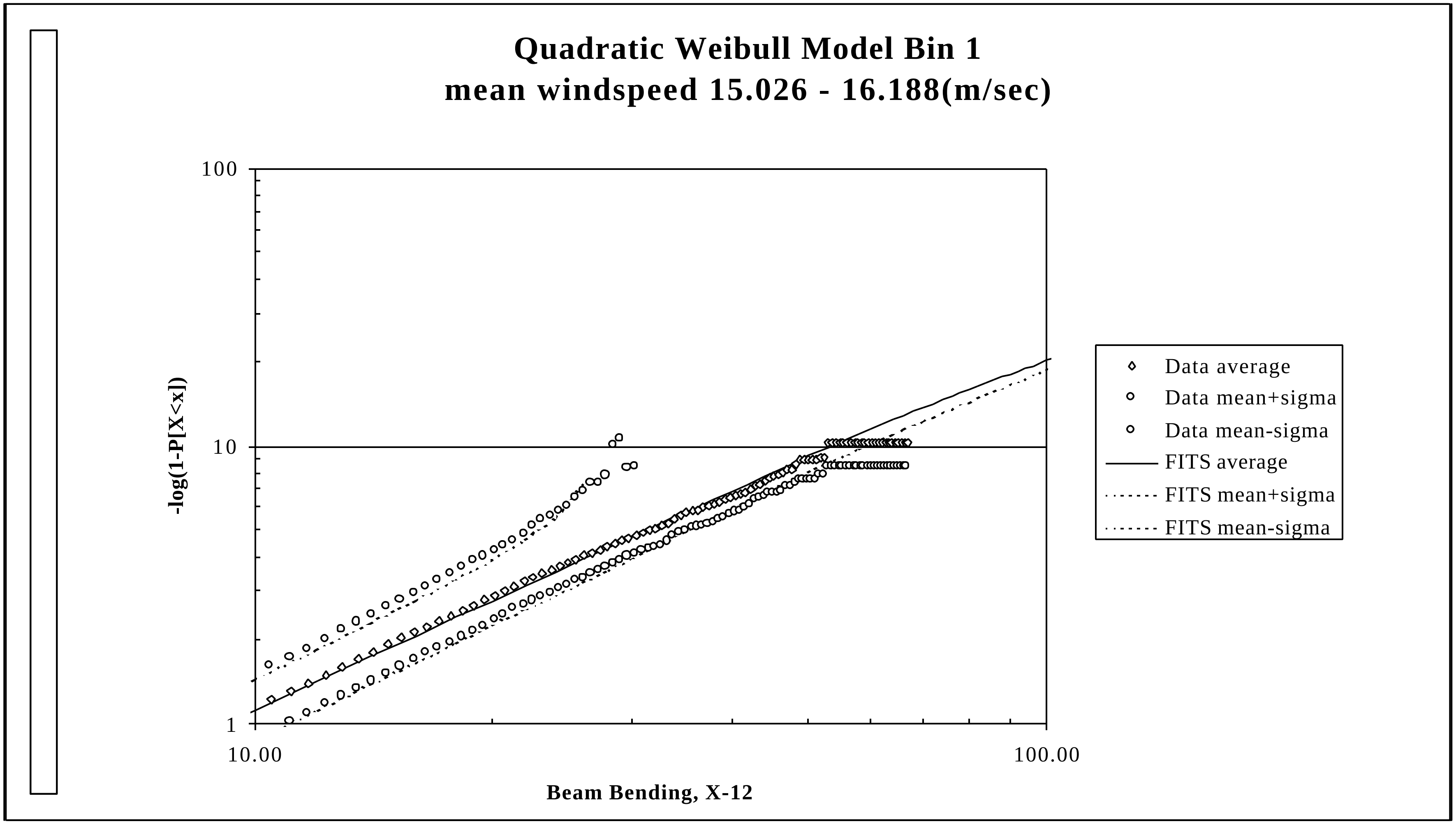
HAWT - Shifted Data



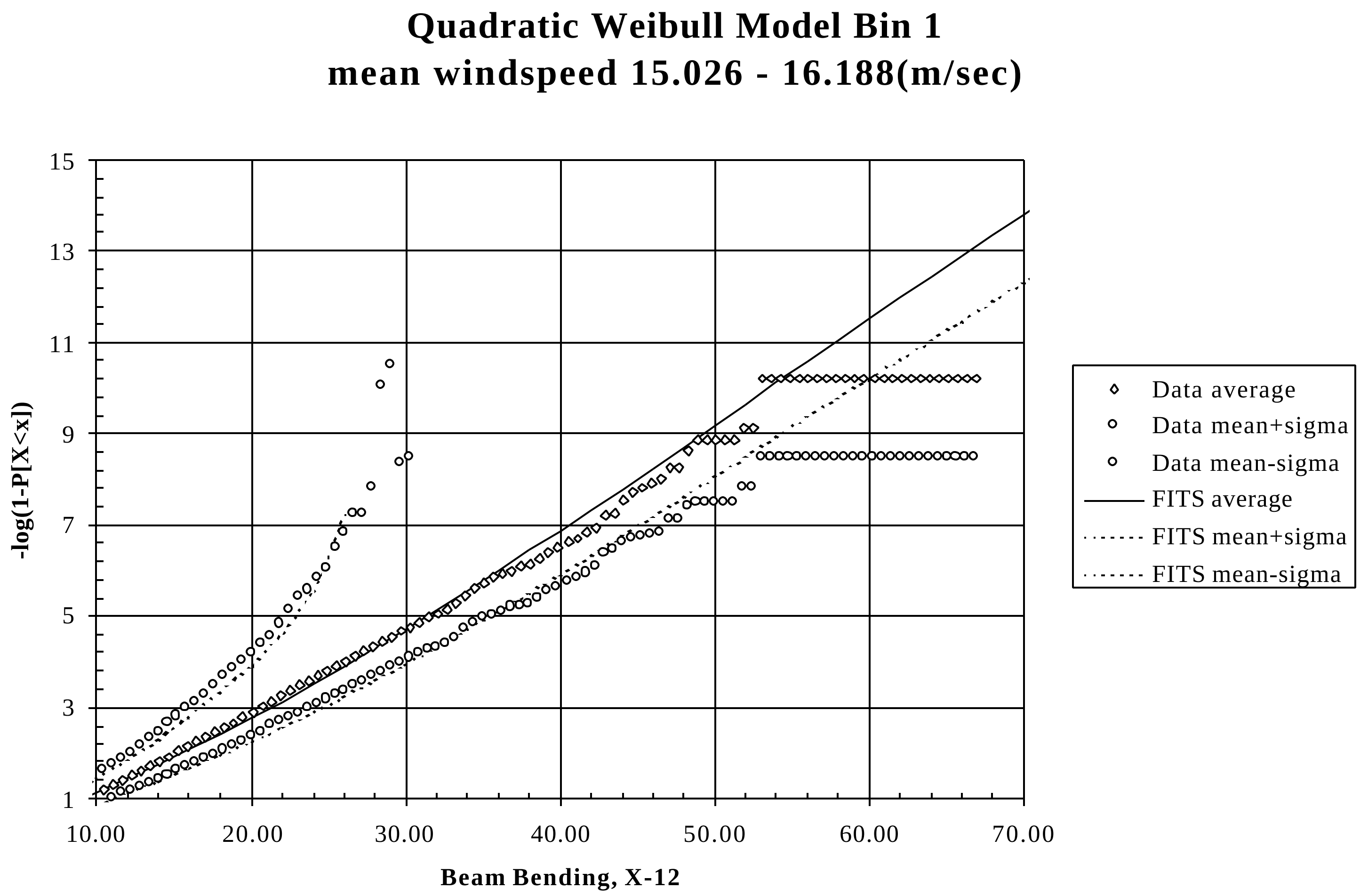
HAWT - Damage Reduction



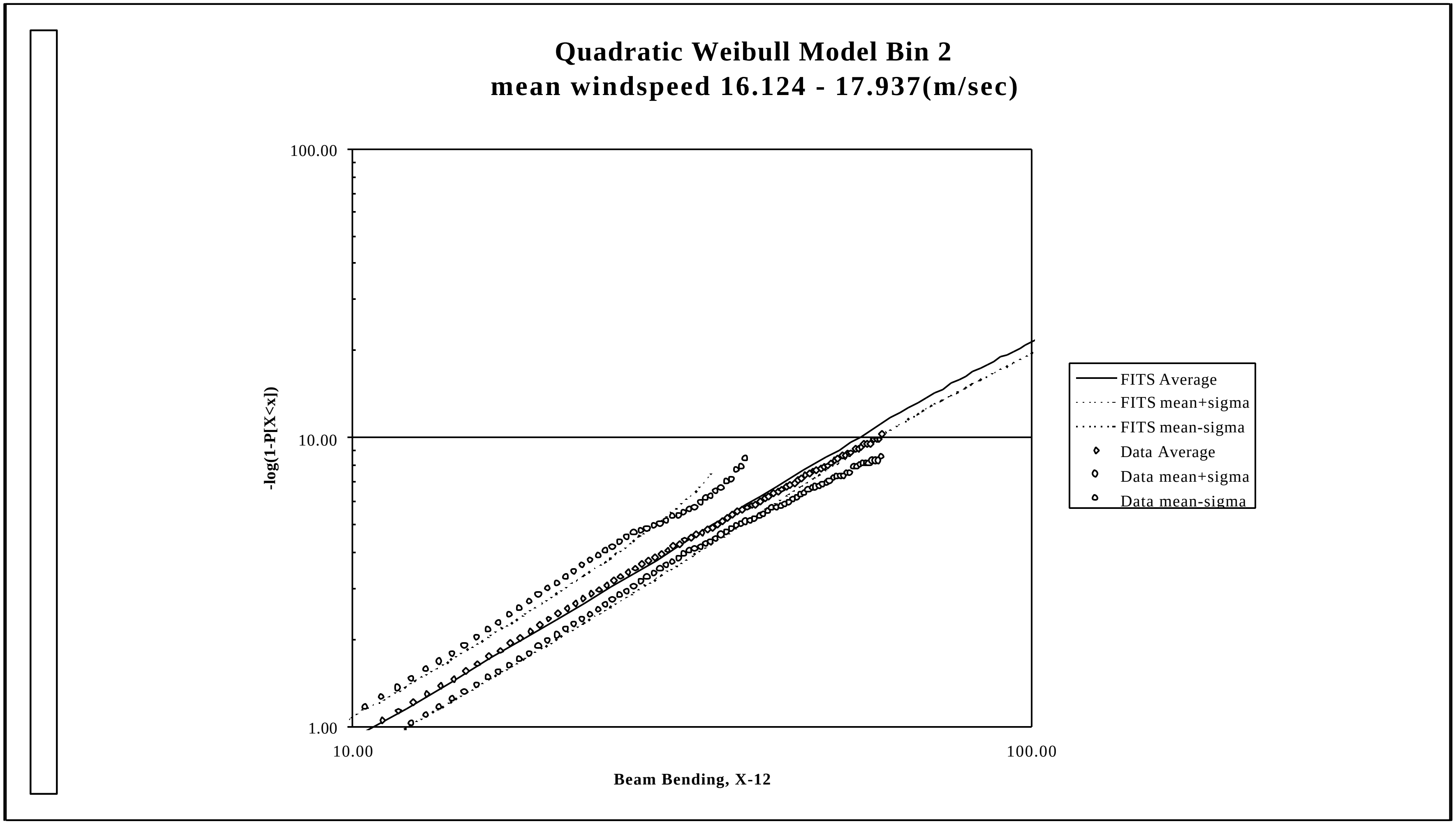
HAWT - Data vs. Fit, Range 1



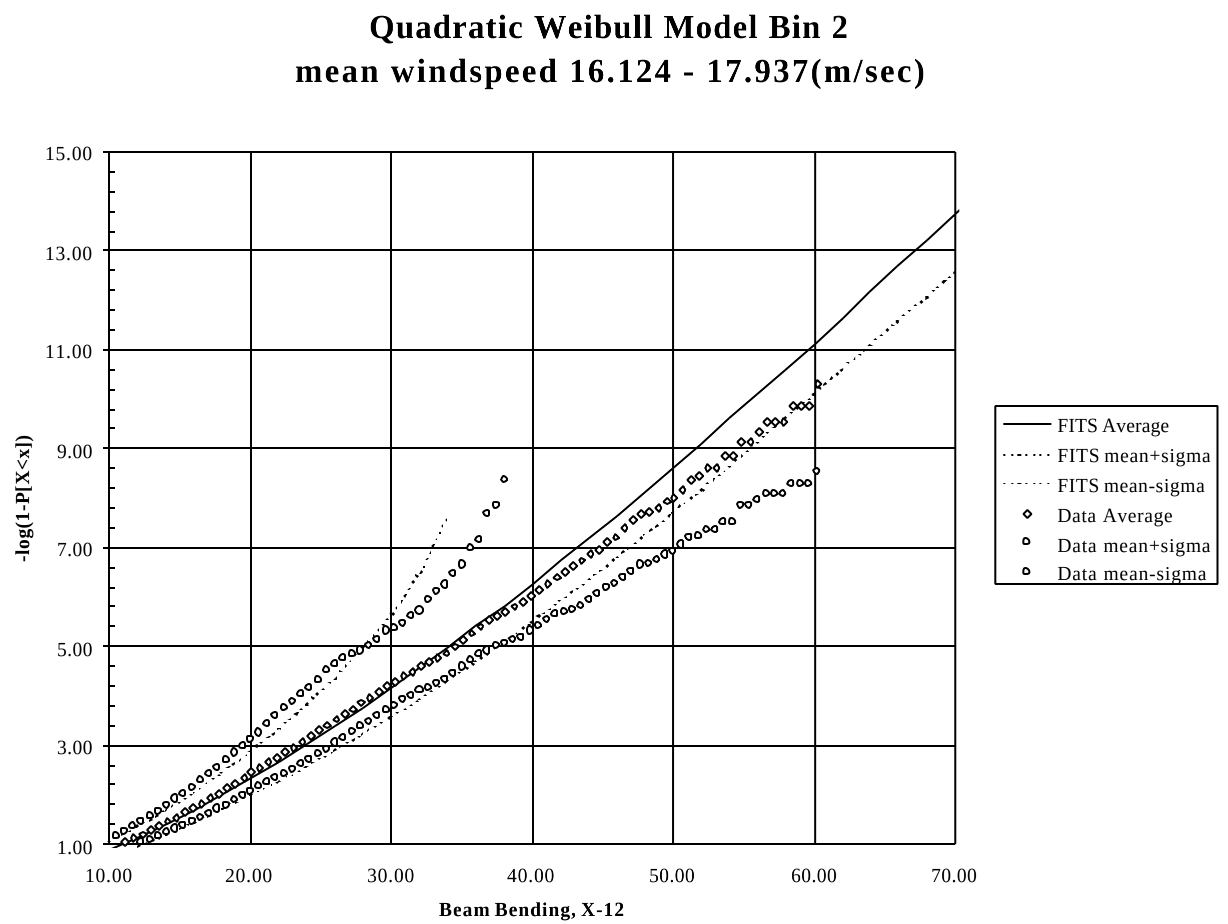
HAWT - Data vs. Fit, Range 1



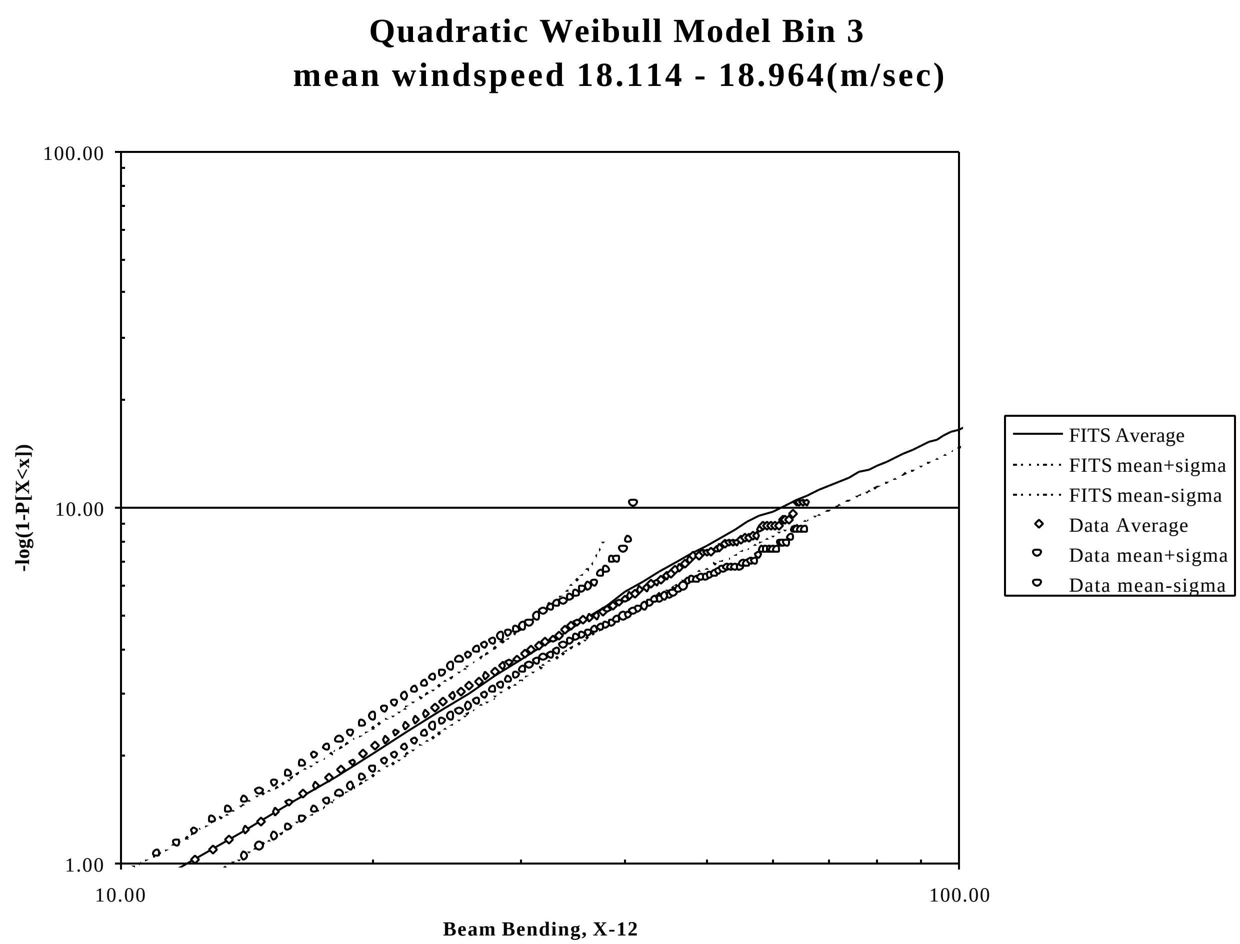
HAWT - Data vs. Fit, Range 2



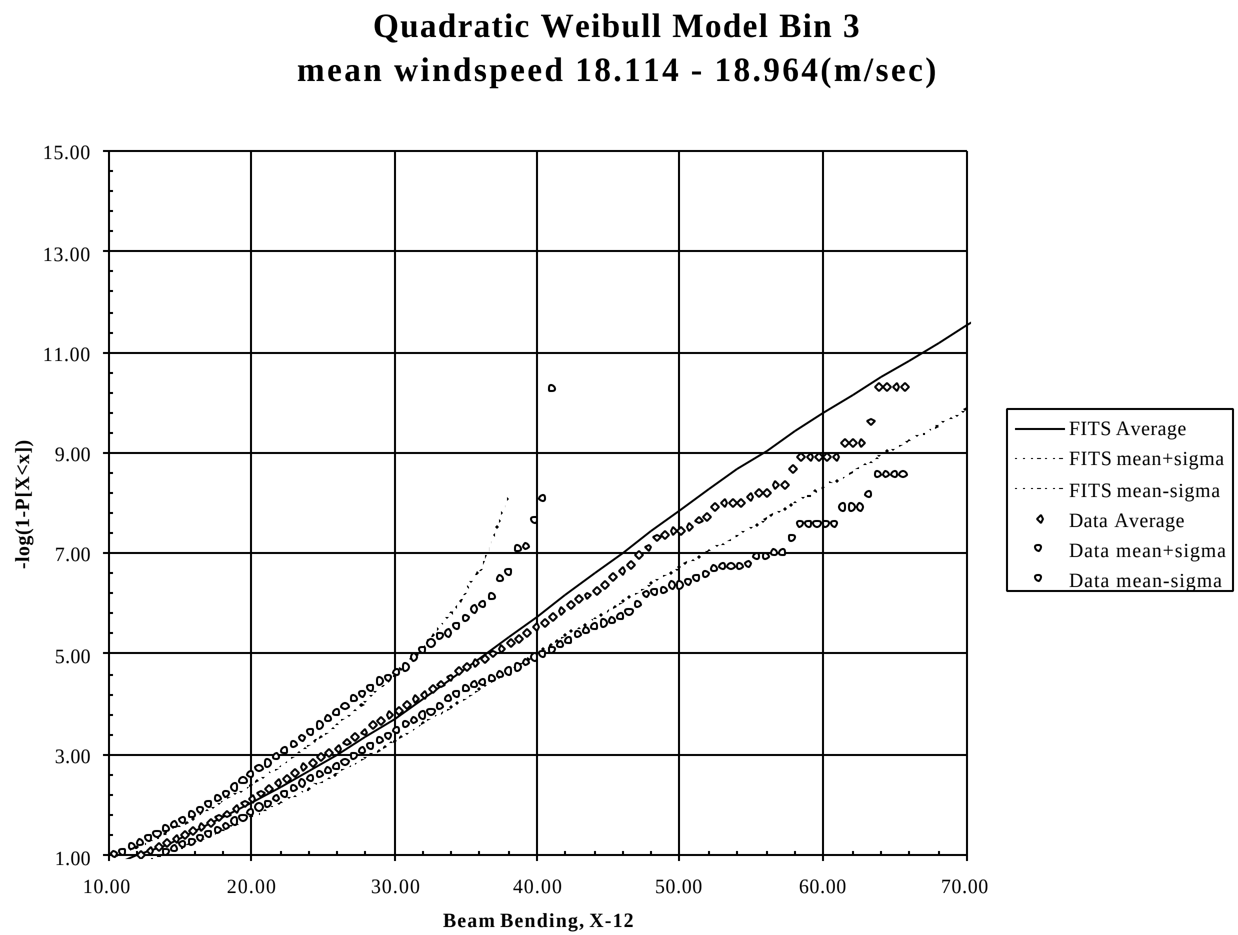
HAWT - Data vs. Fit, Range 2



HAWT - Data vs. Fit, Range 3



HAWT - Data vs. Fit, Range 3



Summary

- I. Estimating Load Distributions (Spectra) From Statistical Moments
  - Fairly Mature (2nd Generation)
  - Special Issues:
    - Fit Process or Ranges/Peaks
    - Periodicity
    - Response Events
- II. Uncertainty/Confidence Bands From Limited Data
  - Methods Available - Simulation vs. Bootstrap (e.g. `MAXFITS`)
  - Tests Needed to Validate (via Long Data Sets)

Summary (cont'd)

- I + II $\rightarrow$ Statistical Load Characterization
  - Combine with Reliability Analysis
    - P_f (case specific)
  - Proposed Guidelines/Standards
    - Implied P_f Across Cases
  - Target P_f
    - Consistent Safety Factors (information sensitive)