IEA Fatigue Experts Meeting, April 1994, pp. 77-87.
SAND2011-8337C

FATIGUE CASE STUDY AND LOADING SPECTRA FOR WIND TURBINES*

Herbert J. Sutherland
Wind Energy Technology
Sandia National Laboratories
Albuquerque, NM 87185-0708

ABSTRACT *

The paper discusses two aspects of Sandia's Wind Energy Program. The first section of the paper presents a case study of fatigue in wind turbines. This case study was prepared for the American Society of Testing Material's (ASTM) Standard Technical Publication (STP) on fatigue education. Using the LIFE2 code, the student is lead through the process of cumulative damage summation for wind turbines and typical data are used to demonstrate the range of life estimates that will result from typical parameter variations. The second section summarizes the results from a workshop held by Sandia and the National Renewable Energy Laboratory (NREL) to discuss fatigue life prediction methodologies. This section summarizes the workshop discussions on the use of statistical modeling to deduce the shape and magnitude of the low-probability-of-occurrence, high-stress tail of the load distribution on a wind turbine during normal operation.

CASE STUDY: FATIGUE OF WIND TURBINES

The first section of this paper presents a case study of fatigue in wind turbines. The article was developed by Sutherland, Veers and Ashwill [1] for inclusion in the ASTM STP on case studies in fatigue education. As discussed in the "Call for Papers" and introductory materials [2] for the *ASTM Symposium on Case Studies for Fatigue Education*, the purpose of the STP is to provide educators with engineering case studies that involve real-world fatigue problems and situations. Thus, its structure was not that of a typical technical article; that is to say, its purpose is "... not to make his [the author's] point as simply and directly as possible using a logical sequence for presenting findings, conclusions, and opinions." Rather, engineering case studies describe "a series of events which reflects the engineering activity as it actually happened, warts and all. The case writer suppresses his own opinions and conclusions so the reader can deal with the information and learn from the experience of drawing his own conclusions."

For the wind turbine case study, the article started with a general description of wind turbines, and their importance to the generation of electricity. The California experience is used to introduce the student to wind turbines as fatigue-critical machines and on the difficulties and constraints of the wind business. Historical examples of fatigue problems in both research and commercial wind turbine development are presented.

Introduction of the Problem

After the brief perspective of the wind business, the article turns to the problem of predicting fatigue lives for wind turbine components. First, raw data from operating wind turbines are presented to illustrate typical environments, loadings, and material properties for wind turbines.

The inflow wind characteristics are introduced to the student via a wind time series from the Texas Panhandle, Figure 1. Typical turbine loads are then introduced using experimental data from the Sandia/DOE 34-m Test Bed turbine, see Figures 2 and 3. These two figures are used to illustrate the dependence

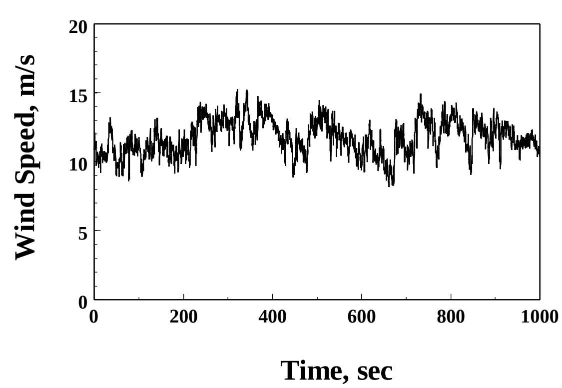


Figure 1. Typical Wind Speed Time Series Data.

*This work is supported by the U.S. Department of Energy under contract DE-AC04-76DP00789.

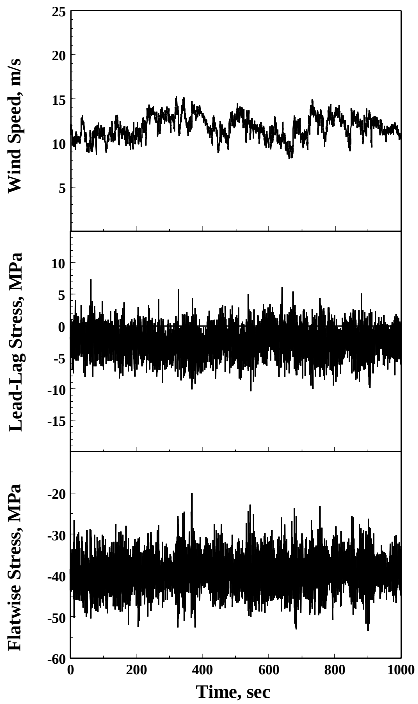


Figure 2. Test Bed Blades Stresses, Flatwise and Lead-Lag in 11 m/s Winds.

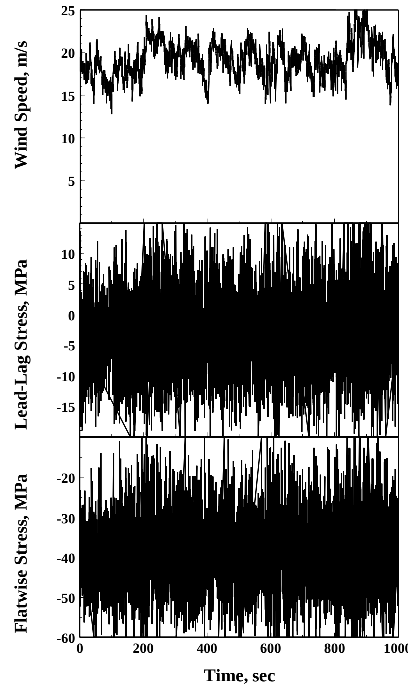


Figure 3. Test Bed Blades Stresses, Flatwise and Lead-Lag in 19 m/s Winds.

of the stresses on inflow conditions.

Fatigue properties of typical blade materials are then discussed. The article notes that it can be difficult to find fatigue characterizations for typical turbine materials because they are rarely used in aerospace or ground vehicle applications. Fatigue data obtained through the auspices of the US wind program on extruded aluminum and unidirectional fiberglass composite are cited in the article to acquaint the student with data from wind turbine materials.

Before a description of how the authors have chosen to attack the cumulative damage assessment, the reader is asked to stop and reflect on questions about how to approach the cumulative damage assessment under such circumstances.

The article then presents the authors approach to the problem. Special emphasis is placed on the development of a loading spectrum for use in the fatigue analysis. Less attention is paid to methods of cumulative damage assessment; Miner's rule and constant amplitude S-n data are used.

A case study then applies the solution technique to an actual wind turbine blade joint. The wind turbine is the 34-meter diameter vertical axis wind turbine (VAWT) erected by Sandia National Laboratories near Bushland, Texas. The case study examines parameter sensitivities for realistic uncertainties in inputs defining the turbine environment, stress response and material properties. This case study is based on the previous work of Ashwill, Sutherland and Veers [3].

The fatigue lifetimes are calculated using a fatigue analysis program, called LIFE2, which was developed at Sandia [4]. The LIFE2 code, described in an appendix to the case study, is a PC-based, menu-driven package that leads the user through the steps required to characterize the loading and material properties, then uses Miner's rule or a linear crack propagation rule to numerically calculate the time to failure. Only S-n based cumulative damage applications are illustrated in the case study.

Example Problem for the Case Study

Using the data from the 34-m analysis, the student is lead through the analysis using the LIFE2 code. Four sets of input variables are required by the code. Each of these inputs is described for the student. First, the wind speed distribution for the turbine site is described by an average annual distribution. The second input describes the material fatigue properties required by the damage rule being used to predict the service lifetime of the component. The third input is a joint distribution of mean stress and stress amplitude (stress states) for all of the various operational states of the turbine. These "cycle count matrices" can be defined for each operational state using time series data. They may be obtained from simulated or measured time series, using a rainflow counting algorithm, or from analytical/ numerical models. The fourth input describes the operational parameters for the turbine and the stress concentrations factor(s) for the turbine component. Graphical representations of the inputs used in the article are given in

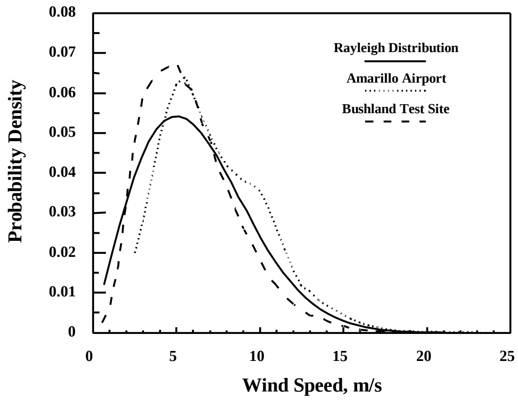
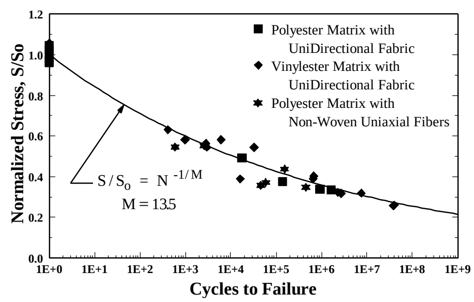
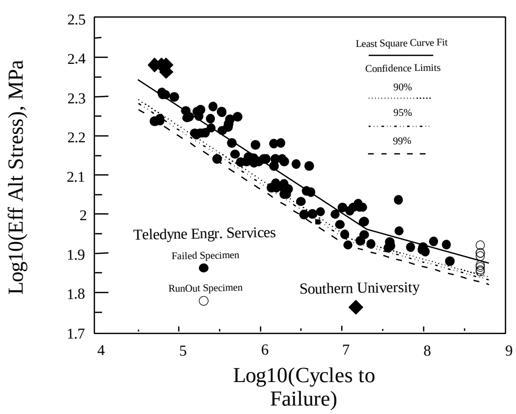


Figure 4. Typical Wind Speed Distributions.



a. 6063 Aluminum.



b. Unidirectional Fiberglass Composite.

Figure 5. Fatigue Test Results.

Figures 4, 5 and 6. As illustrated in these figures, the inputs to real-world problems are not defined by a single curve or parameter, rather each is subject to inherent randomness and to the variability of nature.

Finally, the damage caused by cycles at each "stress state" can be summed, first over the distribution of operational stress states at each wind speed, and then over all wind speeds and

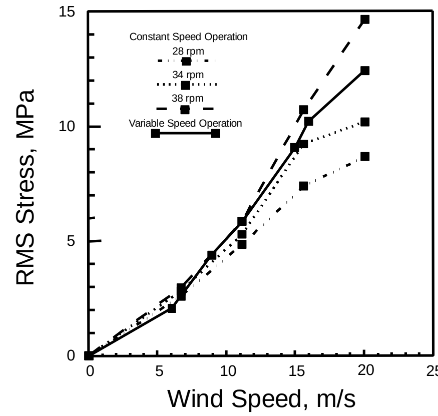


Figure 6. Predicted Flatwise RMS Stresses at the Upper Root.

other turbine states. The results are presented in tabular form in the article. The sensitivity of the fatigue calculations to the variations that one observes in the input parameters is emphasized in the article.

Case Study Conclusions

The conclusions drawn in this article summarize the fatigue analysis case study. Wind turbines are subjected to a severe and unrelenting environment driving the materials to their limits of fatigue endurance. The loadings are random in nature and continuously fluctuating in both cyclic amplitude and global intensity. Formulating the problem requires breaking it down into manageable pieces while making simplifying assumptions to permit tractable solutions. The procedure developed at Sandia National Laboratories is presented here as a case study. It is neither perfect nor exhaustive, but serves to illustrate how sense can be made out of complete randomness. The LIFE2 fatigue and fracture analysis code used for the calculations in the case study is explained in an appendix. The case study illustrates the tremendous variability in life predictions that can occur with relatively modest changes in turbine placement, stress analysis results, or assumptions on uncertain inputs. With the LIFE2 code, additional studies or specific problem assignments can be formulated to lead students through the process of cumulative damage summation and to demonstrate the range of life estimates that will result from parameter variations.

Fatigue Life Methodologies Workshop

The second section of this paper reports on a workshop entitled “Fatigue Life Methodologies”. The workshop was hosted by Sandia National Laboratories (SNL) and the National Renewable Energy Laboratory (NREL) from March 31 - April 1, 1993. The purpose of this workshop was to bring together a representative panel of experts to discuss the prediction and measurement of infrequent events that contribute significantly to the damage of wind turbine components. The diverse backgrounds of the participants yielded discussions that covered a wide range of research and design activities from many varying viewpoints. The workshop discussions have been summarized by Sutherland and Butterfield [5].

This section of the paper summarizes the workshop discussions on the use of statistical modeling to deduce the shape and magnitude of the low-probability-of-occurrence, high-stress tail of the load distribution on a wind turbine during normal operation.

Figure 7 illustrates a "representative sample" of the load distribution on a typical wind turbine blade obtained by cycle counting time series data. To predict the lifetime cycle loads from this and other, similar samples, many designers simply scale the loads with time. They note that these simulations define the main body of the distribution of cyclic loads on the turbine, and that the simulations capture all of the necessary loads on the turbine to define its service lifetime. Other designers note that the tail of the distribution contained in the cycle count matrices alter, and distribution tails fill in, as more and more data are added to the record [6]. They note that the existence of a "high stress tail" on the distribution has significant influence on the predicted service lifetime of the turbine, and they believe that it must be contained in the analysis. The latter group of designers typically extrapolate from the body of the cycle count distribution to this tail. Some truncate the distribution because they question the magnitude of the loads predicted by the extrapolations. Others use the entire extrapolated distribution.

The importance of this procedure to the prediction of service lifetimes was illustrated by Veers in the workshop [7]. In this presentation, Veers presented an analytical solution for predicting the service lifetime for a wind turbine. In his analyses, the importance of correctly predicting the functional form for the distribution of load cycles was addressed. He conducting a comparison of fatigue life estimates based on the shape of the tail of the distribution. Using a Miner's Rule analysis of a typical uniaxial fiberglass material, Veers assumed that the distribution of load cycles for normal operation of the turbine was described by either a Rayleigh or an exponential distribution (two of the most popular distributions currently in use). The mean and standard deviation (RMS) of the two distributions were held equal to one another. The predicted service lifetime for the exponential distribution was a factor of 1000 lower than the prediction for the Rayleigh distribution. This analysis illustrates that the prediction of the fatigue life for a wind turbine component that is based on the curve fitting techniques is extremely sensitive to the mathematical form chosen for distribution.

The critical issue in this discussion centers on the use of statistical modeling to deduce the shape and magnitude of the low-probability-of-occurrence, high-stress tail of the load distribution. In a probabilistic framework, large loads are possible, but they are associated with a decreasing rate-of-occurrence (large return period, decreasing exceedence probability). Hence they may quickly become irrelevant in practical applications, such as wind turbines with a finite service lifetime. While there may truly be a finite "possible" (credible) load level in reality, this level is controversial and typically difficult to estimate from data. Thus, the level for credible loads on the wind turbine during its finite lifetime is the area of disagreement between the two groups.

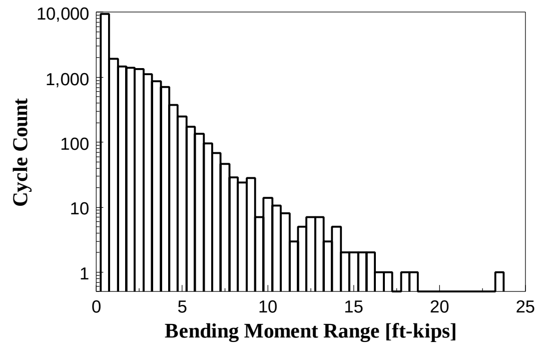


Figure 7. Typical HAWT Flatwise Cycle Count.

Extraordinary Events

One important question raised in the workshop was: do the extrapolation techniques predict load states that do not exist in nature?

Several researchers have examined extensive data sets from operating wind turbines to determine if these extraordinary load events exist and to define their cause (in this case, extraordinary events refer to those load events that occur in the low-probability-of-occurrence, high-stress tail of the load distribution).

Of note are the studies presented by Kelly [8] and Hansen [9] at the workshop. Kelly took a rather unique approach to his analysis of an extensive data set from two Micon 65 turbines. The turbines were mounted side-by-side in San Gorgonio Pass in California. The first turbine had NREL 7.9-m blades, and the second had Aerostar 7.5-m blades. To locate extraordinary load states, Kelly used stress histograms of the root flapwise bending moment to identify excursions from the nominal spectrum of load states. Then, he examined the inflow to find their cause.

Kelley's analysis of the detailed inflow gradient and vorticity characteristics revealed there is significant evidence of a large, coherent turbulent structure that produced extraordinary loads on the turbines. One of these events is shown in Figure 8. As shown in this figure, the period of the excursions was generally much less than one rotor revolution. These loads are repeated comparatively infrequently and only during certain atmospheric conditions. Thus, Kelly was able to find and describe at least one physical phenomenon that produces extraordinary loads on wind turbines during "normal" operating conditions.

In the workshop, turbulence was the primary mechanism cited as the producer of extraordinary loads on a wind turbine. However, Hansen's presentation brought this rather simplistic view back to reality. His studies illustrate that the interaction of the turbine and its control system with changing environmental

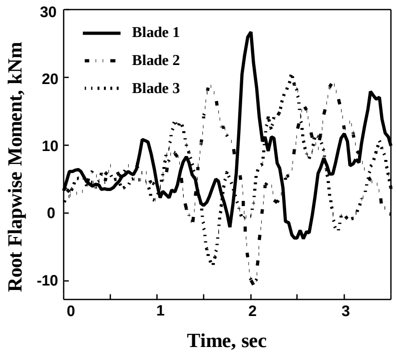


Figure 8. Typical Extraordinary Peak Stress Cycle Observed for the NREL Rotor.

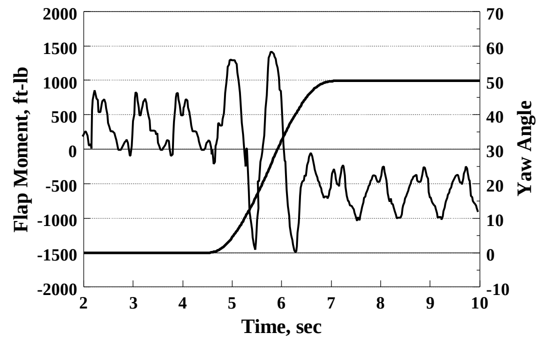


Figure 9. Simulation of a High Yaw Rate Event for the Combined Experiment Rotor.

conditions can produce extraordinary loads on the turbine as well. Hansen presented an analysis of the "Combined Experiment" turbine subjected to a large, fast change in wind direction. In this case, the nominal blade flap moments were increased by more than a factor of 3, see Figure 9. Hansen also identified many other causes of extreme loads. His list includes, but is not limited to, mass imbalance, shut-down with a drive-train brake, changes in wind direction, changes in wind speed, wind shear, and array effects. Thus, Hansen has demonstrated that the analysis framework for wind turbines must include turbine controls if the full load spectrum is to be predicted.

Statistical Distributions

As discussed by Winterstein [10] and Peterka [11] in their keynote workshop presentations, the wind turbine industry is not alone in its desire to predict extraordinary events from limited data. Winterstein's presentation centered on the use of curve fitting techniques to define entire distributions. His discussion provided a review of his research into processes where the tail of the distribution may not be mathematically consistent with its main body. His presentation was illustrated with examples from the off-shore oil and gas industry. Winterstein also offered insights from his current research regarding the use of these techniques for wind turbine specific problems.

While it is not the purpose of this paper to summarize the entire presentation, Winterstein did provide a very useful formulation that warrants discussion here. In particular, he illustrated a graphical technique to define and evaluate the "goodness of fit" of a distribution to a given data set. In a typical evaluation, the distribution is plotted as an x-y plot of the independent variable vs. the probability of occurrence. To illustrate, consider the HAWT cycle count data shown in Figure 7. An assumed mathematical description may be plotted on top of this distribution to permit comparison. This comparison may be complicated, however, by the curvature the data displays on the semi-log scale, as well as the relatively low resolution in the tail of the distribution. Winterstein notes that by plotting the cumulative distribution of the data on a "Weibull scale," any Weibull distribution plots as a straight line that is independent of bin size, see Figure 10 (here, the exceedence function F(x) is the fraction of data not exceeding level x.). In this form, it is easy to pick up deviations of the data from the assumed distribution. And, the tail of the distribution is not lost due to a resolution problem. Moreover, the generalized Weibull scale offers a wide range of mathematical descriptions that encompass the two most popular distributions currently in use, namely the exponential (Weibull slope of 1) and the Rayleigh distributions (slope of 2).

The importance of defining the correct distributions of cycle counts in a fatigue analysis of wind turbine was discussed by Veers at the workshop. His dramatic results, discussed above, illustrate that the fit to the distribution of stress cycles significantly affects the predicted fatigue life and should be chosen with the greatest care.

Winterstein used damage density functions to illustrate the importance placing the "best-fit" distribution in context; namely finding the average damage rate for the turbine blades. Using the distribution of stress cycles shown Figure 7, Winterstein examined the damage density functions for two different classes of materials. As illustrated in Figure 11, the damage accumulated in a typical metal (fatigue exponent of 2) is primarily derived from the body of the distribution (the fatigue exponent is the slope of the S-n curve: typical values for steel and aluminum are 2 and 7, respectively). For typical fiberglass

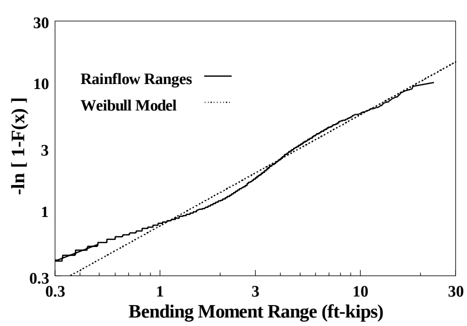


Figure 10. Cumulative Distribution Plot, Weibull-Scale.

blade materials, the exponent is larger than 10. The damage associated with the tail of the distribution is relatively small for small exponents. However, for relatively large fatigue exponents (composite blades), most of the damage is associated with the tail of the distribution, see Figure 12. Thus, the blade material directs the curve fitting procedure: for small exponents (metals), it is more important to fit the body of the distribution, and for large exponents (composites), it is more important to fit the tail of the distribution.

Workshop Conclusions

The workshop was originally intended for a discussion of "Fatigue Life Methodologies" for wind turbines. As one may observe from the complete discussion of the proceeding [5], the workshop covered a wide range of research and design activities that are currently in use. The workshop brought forth a reasonably complete spectrum of the many areas that govern the prediction of service lifetimes. The opinions expressed in the workshop came from a variety of participants who represented vastly different viewpoints and interests. Consensus was not reached on most of the questions raised at the workshop. However the workshop concluded that several areas need further investigation to determine and/or validate current understanding and analysis methodologies for the fatigue analysis of wind turbines. Thus, the workshop laid the foundation for a program that will address these questions so that reliable fatigue life prediction methodologies can be formulated and validated.

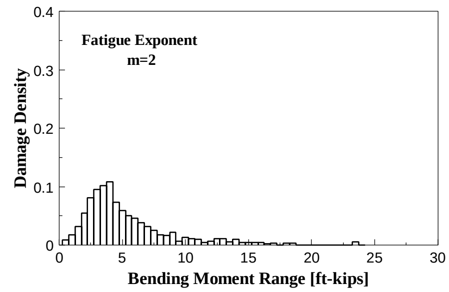


Figure 11. Damage Density, Fatigue Exponent of 2.

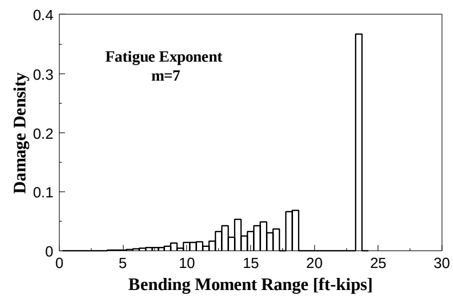


Figure 12. Damage Density, Fatigue Exponent of 7.

BIBLIOGRAPHY

1. H. J. Sutherland, P. S. Veers and T. D. Aswill, "Fatigue Life Prediction for Wind Turbines: A Case Study on Loading Spectra and Parameter Sensitivity," *Case Studies for Fatigue Education*, ASTM STP, in publication.

2. G. Kardos, and C. O. Smith, "On Writing Engineering Cases," *Engineering Case Studies Conference Proceedings*, ASEE, reprint, Symposium communication, Carleton University, Ottawa, Ontario.

3. T. D. Ashwill, H. J. Sutherland and P. S. Veers, "Fatigue Analysis of the Sandia 34-Meter Vertical Axis Wind Turbine," *Ninth ASME Wind Energy Symposium*, SED-Vol. 9, ASME, 1990.

4. H. J. Sutherland and L. L. Schluter, "The LIFE2 Computer Code, Numerical Formulation and Input Parameters," *Proc. of WindPower '89*, SERI/TP-257-3628, 1989.

5. H. J. Sutherland and C. P. Butterfield, "A Summary of the Workshop on Fatigue Life Methodologies for Wind Turbines," *Wind Power '94*, in publication.

6. R. W. Thresher, S. M. Hock and R. M. Osgood, "Data Record Length Effects on Rainflow Analysis," *Proceedings of the Eleventh ASME Wind Energy Symposium*, ASME, 1992.

7. P. S. Veers, *Life Prediction Based on Only Structural Analysis Results*, presentation at the Fatigue Life Methodologies Workshop, Golden, 1993.

8. J. Tangler, N. Kelly, D. Jager, and B. Smith, "Measured Structural Loads for the Micon 65/13," *Proceedings on the Thirteenth ASME Wind Energy Symposium,*" ASME, 1994.

9. A. C. Hansen, *Predicting Time-Series of Extreme Load Events Using ADAMS*, presentation at the Fatigue Life Methodologies Workshop, Golden, 1993.

10. S. R. Winterstein, *Statistical Uncertainty for Limited Data: Methods and Experiences*, Keynote Presentation at the Fatigue Life Methodologies Workshop, Golden, 1993.

11. J. A. Peterka, *Extreme Wind Loads for Buildings*, Keynote Presentation at the Fatigue Life Methodologies Workshop, Golden, 1993.