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FATIGUE CASE STUDY AND RELIABILITY ANALYSES FOR WIND TURBINES*

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ABSTRACT

Modern wind turbines are fatigue critical machines used to produce electrical power. To insure long term, reliable operation, their structure must be optimized if they are to be economically viable. The fatigue and reliability projects in Sandia's Wind Energy Program are developing the analysis tools required to accomplish these design requirements. The first section of the paper formulates the fatigue analysis of a wind turbine using a cumulative damage technique. The second section uses reliability analysis for quantifying the uncertainties and the inherent randomness associated with turbine performance and the prediction of service lifetimes. Both research areas are highlighted with typical results.

INTRODUCTION

Most large, modern wind turbines are used to produce electrical power for utility applications. The largest concentration of this class of turbines in the world (about half of the world's capacity) is in three California sites. California has over 16,000 turbines with a total rated capacity of between 1500 and 1600 MW, generating approximately 1% of California's total electrical usage. In 1992, they generated 2.8 billion kWH of electricity, which is sufficient to supply the residential electricity needs of a city the size of San Francisco or Washington DC for one year. In that year alone, they averted emissions of more than 2.8 billion pounds of carbon dioxide, a major greenhouse gas, and 17 million pounds of other pollutants that would otherwise be produced by fossil-fuels [Phillips, 1992, and Energy Outlook, 1993]. While additional developments are continuing throughout the U.S., additions to European wind installations are projected to surpass U.S. capacity before the turn of the century, when Europe will have two-thirds of the world's wind power.

From their inception in the early 80's, wind turbines have experienced fatigue problems. Virtually all the turbines built then in California have experienced fatigue problems in "energetic" sites (sites with an average wind speed of 7 m/s or more). Blades have been repaired or replaced on most of the turbines. Inspection and maintenance programs have progressed tremendously as the operators gain the wisdom of thousands of hours of operating experience on thousands of turbines. Turbines installed more recently have demonstrated tremendous improvements in availability. In addition, research programs at the national laboratories are measuring material fatigue properties, defining turbine loadings, and creating fatigue lifetime estimation tools for use in the design of the new generation of machines currently on the drawing board at a handful of U.S. companies.

This paper discusses two aspects of Sandia's Wind Energy Program that address the design of a long-lived, reliable structure for wind turbines. The first section of the paper presents a case study of fatigue in wind turbines. The second section concerns the use of reliability analysis for quantifying the uncertainties and the inherent randomness associated with turbine performance and the prediction of service lifetimes. Both research areas are highlighted with typical results.

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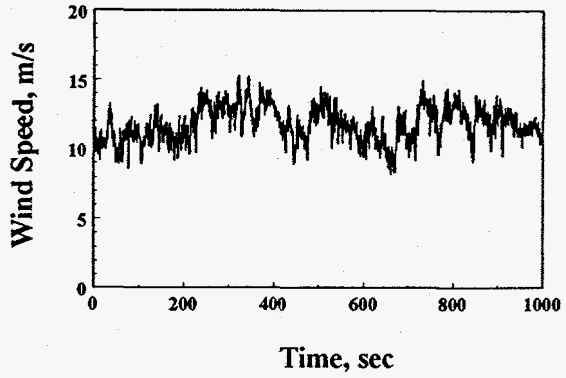


Figure 1. Typical Wind Speed Time Series Data.

CASE STUDY: FATIGUE OF WIND TURBINES

A wind turbine residing in a farmer's pasture on a midwestern plain or in a mountain pass near a hot California desert is subject to the whims of Mother Nature. It must rotate when the wind is blowing anywhere from 5 to 25 m/s (12 to 60 mph), enduring many cycles of vibration. The machine must also be able to stop in any wind condition and survive (in a parked condition) bone-rattling gusts greater than 55 m/s (120 mph).

At rotation rates of from 30 to 60 rpm, it does not take long to accumulate large numbers of oscillations. The blades of a 30-year life turbine typically must withstand at least 10^9 cycles, quite large for any rotating piece of equipment. The stress concentrations at "hot spots" are often not known, and the fatigue properties of typical turbine materials are not well characterized.

Summarized here is an article the authors wrote with T. D. Ashwill entitled "Fatigue Life Prediction for Wind Turbines: A Case Study on Loading Spectra and Parameter Sensitivity" [Sutherland, Veers, and Ashwill 1995] for the American Society of Testing Materials (ASTM) *Symposium on Case Studies for Fatigue Education*. This case study presents the problems encountered in analyzing the very complex mechanical system of a wind turbine, which is subjected to random loadings. The article demonstrates the sensitivity of fatigue calculations to the variability of the loading spectra and to operational and environmental parameters, and indicates many of challenges encountered when designing to this severe loading environment.

The case study was written as a special technical publication (STP) of the Society, primarily for student use. Thus, its structure is not that of a typical technical article, because its purpose is to describe a series of events reflecting the engineering activity *as it actually happened*. Writers for this series are asked to suppress their own opinions and conclusions, allowing the reader to deal with the information and learn from the experience of drawing independent conclusions. Thus, this article is summarized here to provide the reader with an overview of the data and techniques required to design this complex system for long-lived, reliable operation.

The article begins with a general description of wind turbines and their importance to the generation of electricity. Using turbines in wind farms in California as an example, wind turbines are presented as fatigue-critical machines, giving past examples of fatigue problems in both research and commercial wind turbine development. Those wishing more detail about the summary presented below should consult the full article.

The Problem of Predicting Fatigue Life

To analyze the fatigue life of a wind turbine, the designer must bring together large data sets that typically come from many sources. Typical raw data from operating wind turbines are presented first to illustrate typical environments, loadings, and material properties for wind turbines. For example, Figure 1 illustrates the inflow wind characteristics via a wind time series from the Texas Panhandle, and Figures 2 and 3 show typical turbine loads for the Sandia/DOE 34-m Test Bed turbine. The latter two figures illustrate the strong dependence of the stresses on inflow conditions.

Fatigue properties of typical blade materials are difficult to find because turbine materials are rarely used in aerospace or ground vehicle applications. As a result, specialized fatigue data have been obtained for typical turbine blade materials under the auspices of the US wind program. Figure 4 illustrates this specialized fatigue data base with characterizations of extruded aluminum and unidirectional fiberglass composite.

The case study presents the authors' approach to the problem as one alternative for the analysis of service lifetimes. In this approach, 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.

Using work by Ashwill, Sutherland and Veers [1990], the above approach can be applied to an actual wind turbine blade joint for the analysis of fatigue lifetimes. Using realistic parameter sensitivities for the inputs that define the turbine environment, stress response, and material properties, fatigue lifetimes can be calculated using the LIFE2 fatigue analysis program, developed at Sandia by Sutherland and Schluter [1989]. The LIFE2 code is a PC-based, menu-driven package that leads a 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 used.

LIFE2 Analysis of Service Lifetimes

The LIFE2 code requires four sets of input variables: 1) the wind speed distribution for the turbine site as an average annual distribution, 2) the material fatigue properties required by the damage rule being used to predict the service lifetime of the component, 3) a joint distribution of mean stress and stress

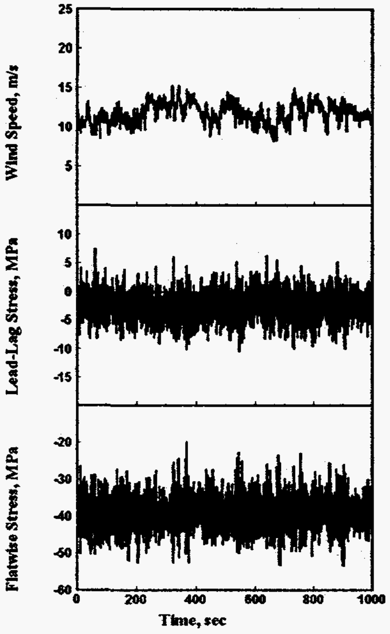


Figure 2. Test Bed Blade Stresses, Flatwise and Lead-Lag in 11 m/s Winds.

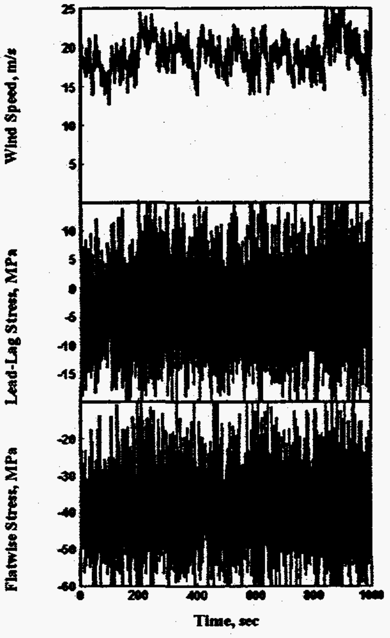
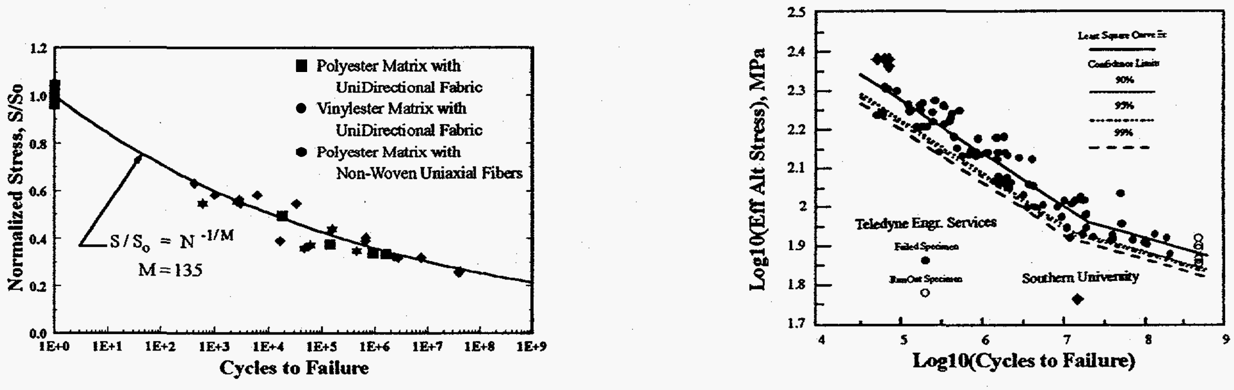


Figure 3. Test Bed Blade Stresses, Flatwise and Lead-Lag in 19 m/s Winds.

amplitude (stress states) for the various operational states of the turbine, and 4) the operational parameters for the turbine and the stress concentration factor(s) for the turbine component. The third set of input variables are "cycle count matrices" that define the operational states of the turbine. Each one of these matrices can be obtained from simulated or measured time series data (using rainflow counting techniques) or from analytical/numerical models.

Figures 4, 5, 6 and 7 present the input data used in the example case study cited. These data were obtained from the 34-m Test Bed Vertical Axis Wind Turbine (VAWT). This research turbine was erected by Sandia near Bushland, Texas. 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.

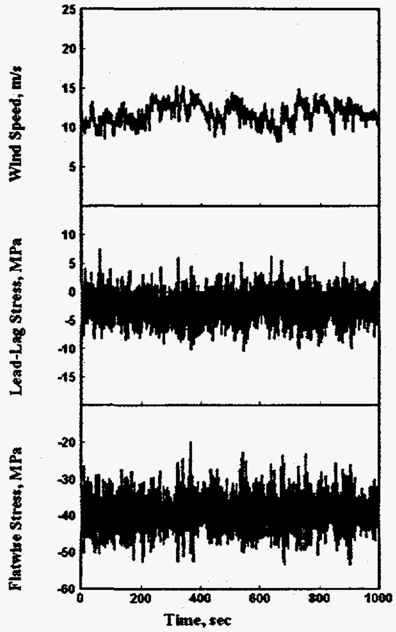
The predicted service lifetime for the turbine is obtained by summing the damage caused by the stress cycles at each operational state over the distribution wind speed. The results are presented in the article. The sensitivity of the fatigue calculations to the variations in the input parameters is emphasized by presenting the results in tabular form.



a. 6063 Aluminum.

b. Unidirectional Fiberglass Composite.

Figure 4. Fatigue Test Results.



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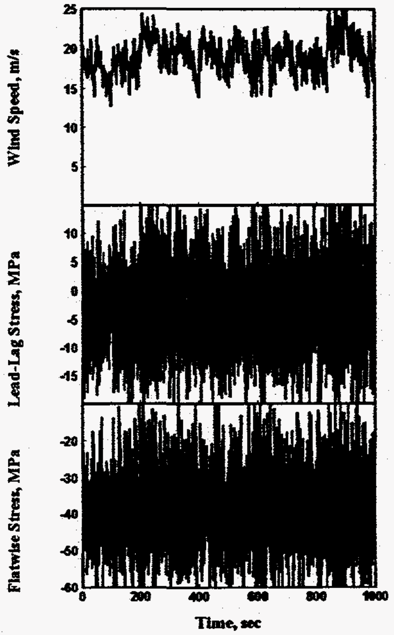

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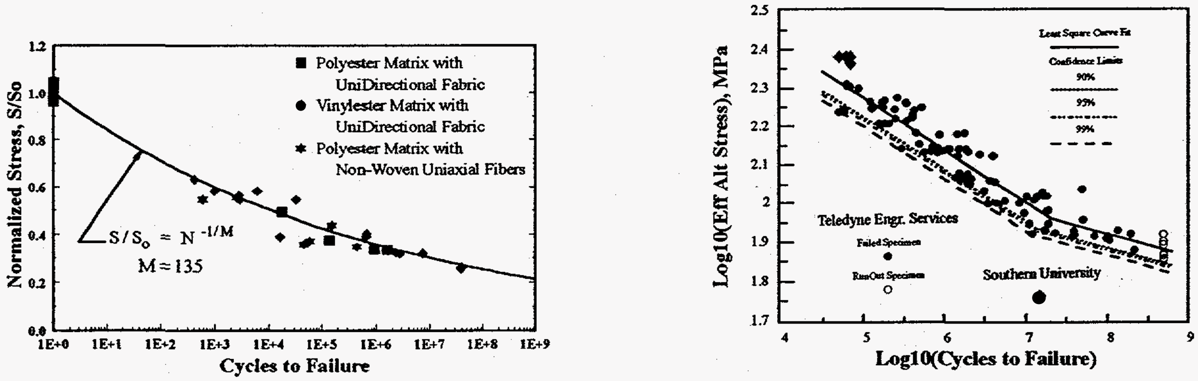

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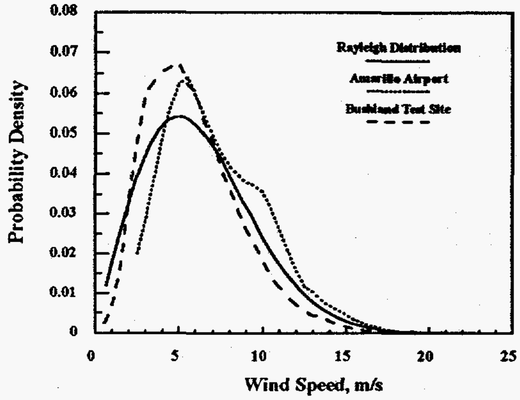

Figure 5. Typical Wind Speed Distributions.

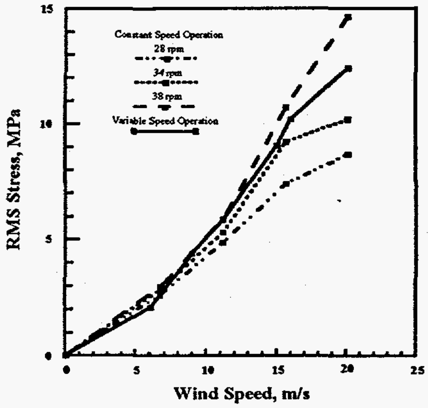

Figure 6. Predicted Flatwise RMS Stresses at the Upper Root.

Typical Results

The sensitivity of the predicted service lifetime to the input parameters is examined here by varying the site's wind regime over the three wind speed distributions, shown in Figure 5. Each of these distributions represent wind speed distributions for a "typical" North Texas site. The three distribution are a Rayleigh distribution with a 6.3 m/s (14 mph) average (R); the Amarillo Airport (located 20 miles across flat terrain from Bushland) distribution with a 6.6 m/s (15 mph) average (A); and the Bushland site distribution with a 5.8 m/s (13 mph) average (B). For these estimated service lifetimes, see Table I, both the analytically predicted (Ana), see Figure 6, and measured (Mea) operating stresses, see Figure 7 are used to describe the stress state of the joint. For the analytical case, a published "reference" S-n curve (Ref) is used. For the measured case, a least squares curve fit (LSC) to S-n data for 6063 aluminum is used, see Fig. 5a. As shown in Table I, the predicted lifetimes vary by a factor of 50, depending on the input parameters.

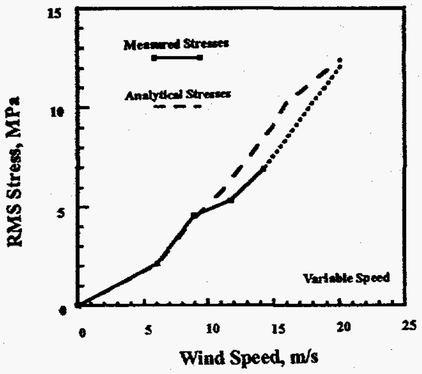

Figure 7. Predicted and Measured Flatwise RMS Stresses at the Upper Root.

Case Study Conclusions

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 neither perfect nor exhaustive, but serves to illustrate how sense can be made out of complete randomness. This 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.

Table I. Effect of the Wind Regime on Lifetime (in years)

Wind	S-n Curve	Operating Stresses	Fatigue Life
R	Ref	Ana	11.9
A	Ref	Ana	7.86
B	Ref	Ana	29.4
R	LSC	Mea	150.
A	LSC	Mea	100.
B	LSC	Mea	391.

RELIABILITY ANALYSIS

Every designer of fatigue-sensitive structures would like to know the lifetime of the design with perfect accuracy. The design could then be fine tuned to eliminate needless costs while maintaining acceptable durability. Unfortunately, designers are often disappointed with fatigue life computation results. Not only are the techniques difficult to apply, requiring a daunting level of detail of the machine and its environment, but the results are highly sensitive to changes in the inputs, as shown by the previous example. Ranges of plausible answers from a few years to centuries erode the value of the results and make the process frustrating. The knowledge that this sensitivity is inherent to the fatigue problem is of little comfort.

A good designer will therefore put appropriate safety factors on all the uncertain quantities that affect fatigue life. It would be beneficial, however, to provide a more quantitative measure of the design conservatism. The proper question may not be "what is the actual fatigue life of this component?" but rather "with what confidence will the component meet its target design life?" Such questions are naturally addressed by the theory of structural reliability.

The main result of a reliability analysis is the probability of failing to meet a specified target lifetime. This result alone provides a more accurate sense of the quality of a component design than a deterministic time to failure based on qualitative safety factors. But structural reliability methods provide much more information than just probability of failure. *Importance factors*, which indicate how much each random variable contributes to the total probability of failure, are also calculated. By focusing on the most *important* of the random variables in prototype testing and design refinement, the developers can efficiently work toward a more reliable design. Structural reliability methods also estimate the *sensitivity* of the reliability to each of the controlling parameters, both random and deterministic. Again, the wind turbine developer is provided direction as to which of the parameters have the greatest overall impact on fatigue durability. This kind of information is a natural byproduct of using structural reliability methods in the fatigue analysis of wind turbine components.

FAROW Overview

The FAROW code was named to describe its function, calculating the Fatigue And Reliability Of Wind Turbines. It is based on a deterministic fatigue life formulation for the specific case of wind turbine components loaded by continuous operation in a typical (user-specified) wind environment. This formulation is used by a reliability analysis engine to produce the desired probabilistic results.

The fatigue formulation is intended to capture uncertainty in environmental loading, gross structural response and local fatigue properties. Fatigue damage is modeled probabilistically using Miner's Rule and the effects of variable loads, mean stress, and stress concentration factors. Uncertainty in the fatigue properties themselves is included. A critical distinction here is between continuously varying quantities such as an environmental parameter (e.g., instantaneous wind speed V, applied stress amplitude S versus time, etc.) and fixed parameters which may be uncertain (e.g., fatigue law coefficients, distribution parameters of V, S given V, etc.). Continuously varying quantities are reflected here implicitly, through their average effect on fatigue damage, just as in the LIFE2 code. In contrast, parameter uncertainty doesn't average out over fatigue life, and is modeled here explicitly.

FAROW uses assumed functional forms for the controlling quantities of fatigue life. The functions are defined by parameters such as S-N coefficient and exponent, RMS stress level at a characteristic wind speed, average wind speed, etc. There is a trade-off between the level of generality and the ease of use; the restrictive assumptions catalogued in the user's manual [Veers et al., 1994] permit definition of the entire problem with a condensed data set. The emphasis has been on keeping the input simple and easy to use.

The probability of failure is calculated using the general purpose FORM/SORM (first- and second-order reliability methods) package developed by Rackwitz [1985]. Importance factors and sensitivities are calculated as well. The analysis is made specific to the wind turbine problem with an appropriate failure state function and by adding the necessary input and output coding.

FAROW Capabilities

As previously stated, calculating probabilities of failure is only one of the many results provided by FAROW that aid in understanding the fatigue reliability of a component and indicate how to improve it. The many capabilities alluded to above are:

- Mean time to failure is estimated using median parameter values.
- The probability of failing to meet a lifetime target is determined.
- The evolution of the probability of failure is determined as a function of time.
- The relative importance of each source of uncertainty is calculated.
- The sensitivity of the reliability to each of the input quantities, both constant inputs and the parameters of the distributions of random variables, is estimated.
- Monte Carlo simulation for brute force estimates of the probability of premature failure is included as an option.
- The inputs are taken from a set of descriptive parameters in a user edited file.
- Random variables are selected from a library of distribution functions.

Reliability Estimate

Using the FAROW code, a reliability analysis was performed on the Sandia 34-m turbine case study laid out in the first part of this paper. The inputs to LIFE2 were replaced by parameters describing the important quantities. Rather than using deterministic parameters, several were defined as random variables to model the uncertainty in the inputs. Relatively low levels of uncertainty were assumed to fit the situation in which substantial test data have already been obtained. The distributions for the random variables are shown in Table II.

The resulting median lifetime is 370 years; however, the estimated probability of less than a 20-year target lifetime is about 2% (1.8% with FORM and 2.2% using SORM with reliability indices of 2.1 and 2.0, respectively). Importance factors are also calculated, see Figure 8. The high variability of the S-n data dominates the uncertainty, while the stress concentration factor and wind speed distribution shape make up the bulk of the remainder.

TABLE II.
DEFINITION OF VARIABLES IN THE CLOSED FORM SOLUTION.

Definition	Mean	COV	Distribution
S-n Coefficient	5×10^{21}	0.613	Weibull
Avg. Frequency	2.0 Hz	0.2	Normal
RMS Slope	0.45 MPa/(m/s)	0.05	Normal
Stress Con. Factor	3.5	0.10	Normal
Mean Stress	25 MPa	0.20	Normal
Mean Wind Speed	6.3 m/s	0.05	Normal
Dist. Shape	2.0	0.10	Normal
S-n Exponent	7.3	-	Constant
Ultimate Strength	285 MPa	-	Constant

Remarks

The calculation of fatigue lifetimes indicates the sobering variability in predictions with relatively small changes in inputs. A fatigue reliability calculation shows that even with a median lifetime of hundreds of years, the probability of premature failure is still over 2% at 20 years. The greatest sources of this variability in fatigue lifetimes, identified by the importance factors, are the material properties.

Sensitivity estimates were also conducted and tend to follow the importance factors. However, sensitivities are not only calculated with respect to each random variable, but to each of the coefficients describing the random variables and to the input constants as well. The most sensitive input is the fatigue exponent (slope of the S-n curve), which is usually considered a constant while all the uncertainty in the material fatigue properties is modeled in the variability of the S-n coefficient.

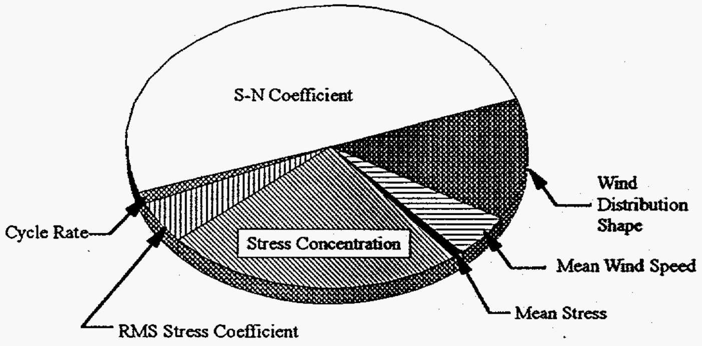

Figure 8. Importance Factors .

Material properties are therefore both the most sensitive and most important in this example. Sensitivities to the mean values tended to be about an order of magnitude greater than sensitivities to the variation about the mean. Therefore, when little is known about the range of possible values for an uncertain parameter, one can still obtain reasonable reliability estimates with a good estimate of the mean and a rough estimate of the variance.

Many factors that are commonly thought to be controlling parameters in the fatigue lifetime are relatively uninvolved in the total variation in fatigue lifetime estimates when all sources of variation are considered. Even in this example, where only seven random variables were used, the mean stress and average cycle frequency hardly participated in the variation in predicted life, even though each was given a relatively large coefficient of variation. (COV = 0.2).

The results indicate there is room for improvement by reducing uncertainty in those parameters that are random because of incomplete knowledge. The material properties are intrinsically random, as shown in Figure 4. Their uncertainty cannot be reduced, and hence reliability cannot be increased by adjusting them. But the other parameters are uncertain mostly because of incomplete knowledge. The greatest increase in reliability may be obtained by getting a better handle on the stress concentration factor, keeping in mind that a better estimate may indicate that it is worse than the assumed mean. If it is in fact worse, then action can be taken to adjust the design and reduce the stress concentration.

CONCLUDING REMARKS

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. The first section of the paper uses a case study approach to describe how an analysis procedure for the prediction of service lifetimes for turbine components might be developed. The procedure developed at Sandia National Laboratories, the LIFE2 code, is used to illustrate how the analysis can be implemented.

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. In the second section of this paper, the uncertainties and the inherent randomness associated with turbine performance and the predicted service lifetimes are used to quantify the probability of failure. The results illustrate that even for a comparatively well understood and tested turbine with a long median lifetime, the probability of failure is relatively high, even for less than 10 percent of its median life.

In the final analysis, wind turbines today are significantly more reliable than their predecessors. Current turbines designs have demonstrated tremendous improvements in availability. However, for wind turbines to be economically viable, designs must "push the envelope" to improve the efficiency of the design and to reduce costs. The size and cost of many turbine components is constrained by fatigue durability. Fatigue and reliability tools like LIFE2 and FAROW enable turbine designers to fine tune their designs, minimizing costs while maintaining machine reliability, availability and performance.

ACKNOWLEDGMENTS

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