

# An Overview: Challenges in Wind Technology Development

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# AN OVERVIEW: CHALLENGES IN WIND TECHNOLOGY DEVELOPMENT

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## Abstract

Developing innovative wind turbine components and advanced turbine configurations is a primary focus for wind technology researchers. In their rush to bring these new components and systems to the marketplace, designers and developers should consider the lessons learned in the wind farms over the past 10 years. Experience has shown that a disciplined design approach is required that realistically accounts for the turbulence-induced loads, unsteady stall loading, and fatigue effects. This paper reviews past experiences and compares current modelling capabilities with experimental measurements in order to identify some of the knowledge gaps that challenge designers of advanced components and systems.

## Background

The recent operating performance of the wind farms in California has been good. Well-run wind farms are able to achieve availabilities above 95%. In the past, however, a number of technical and operational problems impeded improved performance. Figure 1 shows the annual impact of these operating problems on revenue for 1986, as compiled by Lynette (1). The figure breaks out the problems according to root cause, and clearly shows that about 75% of the problems are associated with fundamental atmospheric, aerodynamic, structural dynamic, electrical, and controls causes. Ongoing research is addressing and correcting these problems, improving the annual energy generated, and reducing maintenance costs. Increased emphasis on redesign and retrofit activities is occurring today in anticipation of the transition from the very favorable power purchase agreements under which the wind farms sell electricity to a lower rate over the next few years. For this reason, wind farm owners and operators would like to upgrade in order to maintain profitability.

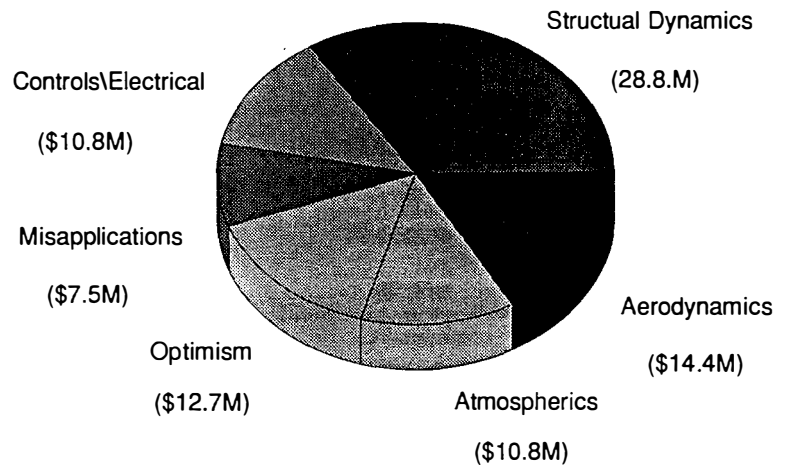
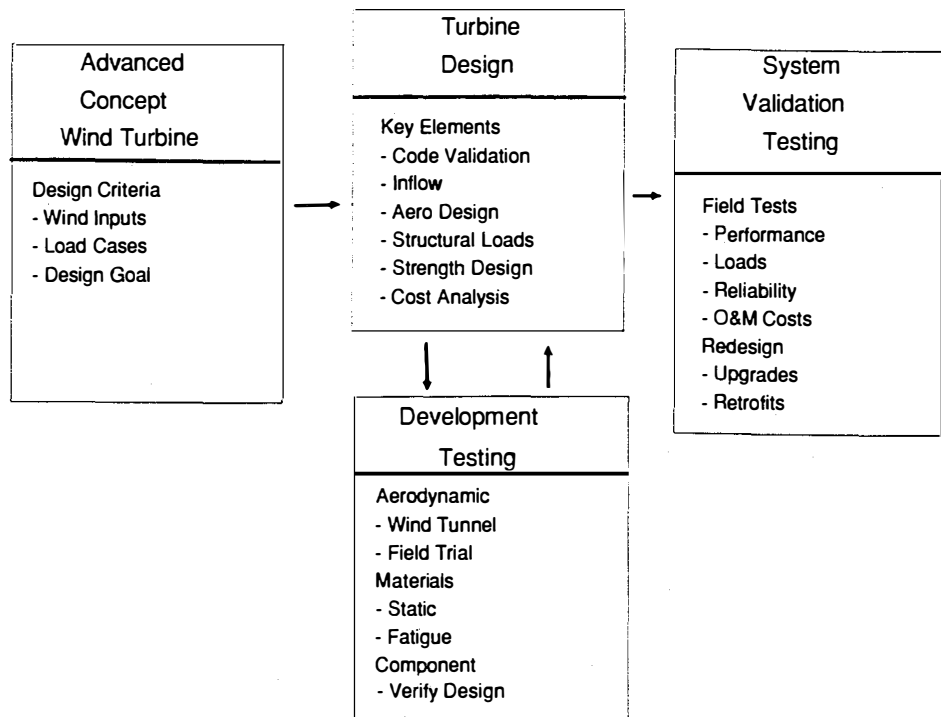


Figure 1. Annual Impact of Problems on Revenue for Wind Power Stations, 1986 (Reference 1)

Interest in new advanced wind turbine systems has also been growing. Utilities are beginning to acknowledge that wind energy is a relatively inexpensive, nonpolluting renewable energy that can be easily added to the generation mix in small modules. The recent, favorable operating experience in the California wind farms has demonstrated

that wind energy can be integrated with other generation systems with few problems and minimal cost. In addition, wind resources are relatively widespread and abundant. An advanced wind turbine that could generate electricity for 5 cents/kWh at 13 mph wind sites would be competitive in the electricity market and could displace more expensive petroleum-fueled generation.

Many technical lessons have been learned during the turbine development programs of the late 1970s and early 1980s. In addition, the operating problems documented in Figure 1 should serve as a reminder to designers that the development of new wind turbines is both technically challenging and often humbling. We believe that the development of new hardware must be based on a disciplined approach employing careful analysis, development testing, and full-scale verification field testing. Figure 2 outlines such an approach for new hardware development. The approach requires an accurate definition of the design criteria, validated design codes and tools, associated development testing to guide the design process, and full-scale field testing to validate the final design.



**Figure 2. An Approach to Wind Turbine Design and Development**

### Technical Challenges

Past experience and recent research indicate that four difficult technical challenges must be overcome in order to develop reliable advanced wind turbines. These four challenges are:

- 1) Definition of the turbine inflow environment in wind farm arrays
- 2) Development of reliable predictive design methods in the unsteady stalled flow regime of wind turbine operation
- 3) Development of improved systems dynamics models that account for three-dimensional stochastic wind inputs and unsteady stall, and include the important structural motions.
- 4) Implementation by turbine designers of comprehensive stress and fatigue analysis tools and techniques.

Each of these challenges will be considered and discussed in the following sections of this paper.

## Design Inflow Environment

Field experience has demonstrated that turbines located on high-turbulence sites are less reliable and require more maintenance. In addition, from a turbine design prospective, the inflow environment is critical because the aerodynamic and structural responses depend directly on the inflow. The higher the inflow turbulence level, the higher the dynamic and fatigue loads.

Figure 3 shows comparisons between the measured turbulence intensity at a San Gorgonio wind farm and the specified turbulence intensity for the Advanced Wind Turbine Conceptual Design Studies for both free-stream and mid-park locations. The array spacing for the measured data is 1.5D x 7D.

The Conceptual Design Studies specified the turbulence intensity using the equation:

$$\text{Turbulence intensity} = \frac{\sigma}{V_w} = \frac{K}{\ln(z/z_0)} \quad (1)$$

where  $V_w$  is the wind speed,  $S$  is the standard deviation of the wind speed,  $z$  is the height above ground,  $z_0$  is the roughness height, and  $K$  is an empirical constant equal to unity for natural flow conditions, or 1.3 for a wind farm array. Although there is a large body of data that correlates reasonably well with Equation (1), the San Gorgonio measurements taken by Kelley (2) clearly show a decreasing turbulence intensity with increasing wind speed, which Equation (1) does not model. Figure 4 illustrates a comparison between the distribution of turbulence levels (standard deviation) at Row 1 (Natural Flow) and Row 41 (Internal Park Flow) for an average 10 m/s wind speed. The standard deviation within the wind farm is about 50% higher than in the natural flow, and the distributions are quite different. Structural dynamics analysis codes use a spectral representation of the turbulence, and Figure 5 compares the streamwise wind turbulence spectra at Row 1 and Row 41 for this same case. Figures 4 and 5 clearly illustrate the difference in the turbulence inflow environment for a natural flow environment and in a wind farm array.

These turbulence plots were taken from measurements and analysis developed by Kelley (3). Reference (3) contains additional results and comparisons and clearly shows that the turbulence is more severe inside the wind farm. However, this wind farm has rows spaced at about seven turbine diameters, which is considered quite close. Furthermore, these data may or may not be representative of other wind farm environments. Developing design criteria based on a single data set may be risky, but it is the only comprehensive set available for a large, closely spaced wind farm. If the design turbulence levels are set too low, then turbines will fail or wear out prematurely. Conversely, if the design turbulence levels are unrealistically high, then the turbines will be overdesigned, expensive, and economically uncompetitive.

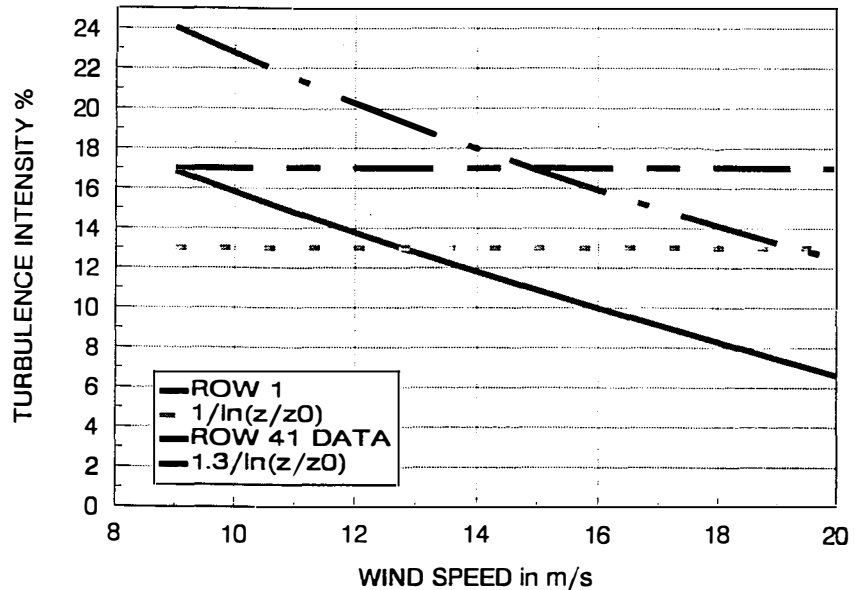


Figure 3. Measured Turbulence Intensity at a San Gorgonio Wind Farm Compared with NREL Design Specifications

## Stall Behavior

The majority of wind turbines operating today make use of stall to regulate power output in high winds. Figure 6 is a power versus wind speed curve taken from testing by Tangler, et al. (4). The figure shows the mean power curve with two typical instantaneous data sets superimposed to form a scatter plot illustrating the range of values that comprise the mean power curve. Both the high-wind-speed data set and the low-wind-speed data set cover 20 minutes of operation.

The large scatter observed is characteristic of wind turbine power output. In the lower wind speed region below 15 m/s, this scatter is easily explained by the lack of correlation between the wind speed measured some distance away from the turbine and the disk-averaged wind speed at the turbine. However, in the region where the rotor is well into stall, above 15 m/s, the large amount of scatter is unexpected. Once the rotor is in deep stall, the power output should become quite insensitive to wind speed, and so a lack of correlation would not matter. Figure 6, however, shows large power excursions in the stall region, demonstrating that there is an unsteady process at work.

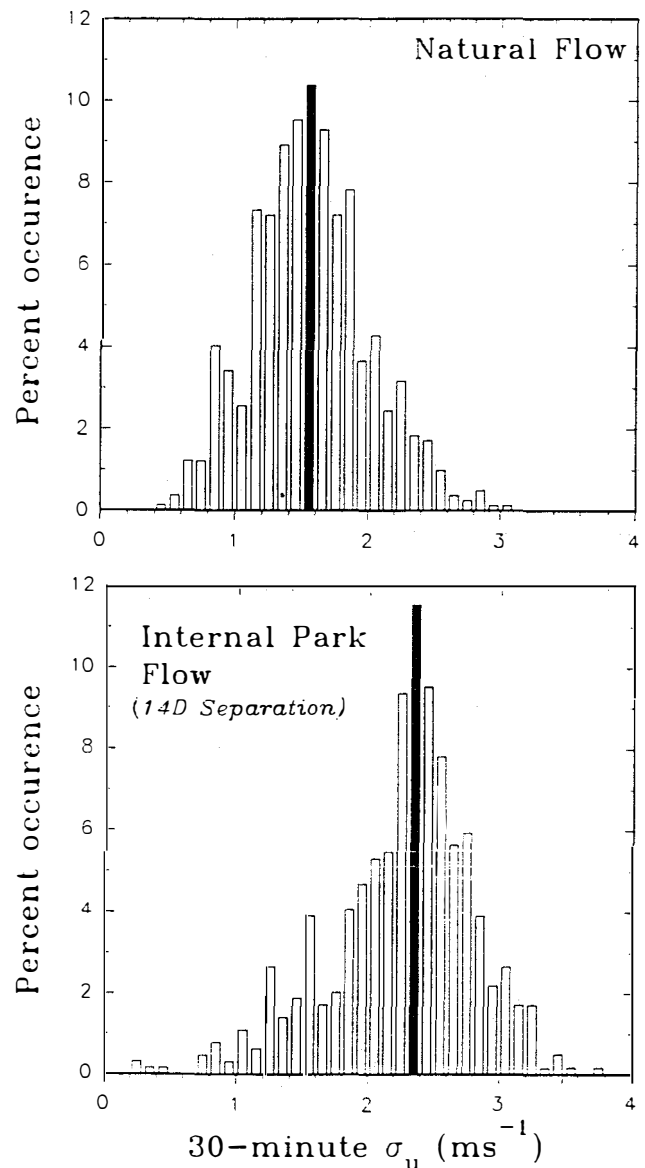


Figure 4. Comparison of the Distribution of Turbulence Levels for Natural and Internal Wind Farm Inflow

Figure 7 confirms the unsteady nature of stalled flow on rotating wind turbine blades in a turbulent inflow environment. The figure illustrates a lift coefficient versus angle-of-attack curve taken from the experimental measurements of Butterfield, et al. (5). As the angle-of-attack reaches 8 degrees and the airfoil begins to stall, the data scatter increases significantly. The plot shows that the lift coefficient varies by over a factor of two in the stall region and deviates significantly from the Colorado State University(CSU) wind tunnel results.

Unless these unsteady stall effects are modelled in dynamics codes, the load predictions may be subject to large errors. This is indicated in Figure 8 where comparisons are made between root bending moment power spectral densities for experimental measurements and predictions using the dynamics code FLAP developed at NREL. The comparison is shown for an 80-ft-diameter teetered rotor operating in a 36-mph wind where the rotor is in stall. The FLAP dynamics code, which assumes that the lift coefficient is constant in the stall region, is inadequate.

Not all of the discrepancies can be attributed to the deficient stall model. The FLAP code models only the rotor blade flap dynamics, and the turbulent inflow for the Figure 8 comparison was generated using a one-dimensional

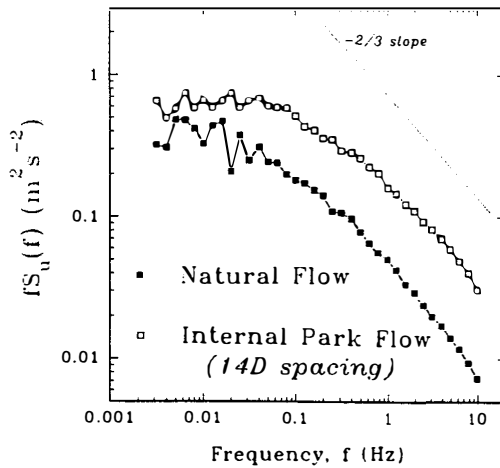


Figure 5. Stream Wise Wind Spectra for Natural and Internal Wind Farm Inflow at Near-Neutral Stability and 10 M/S Wind Speed

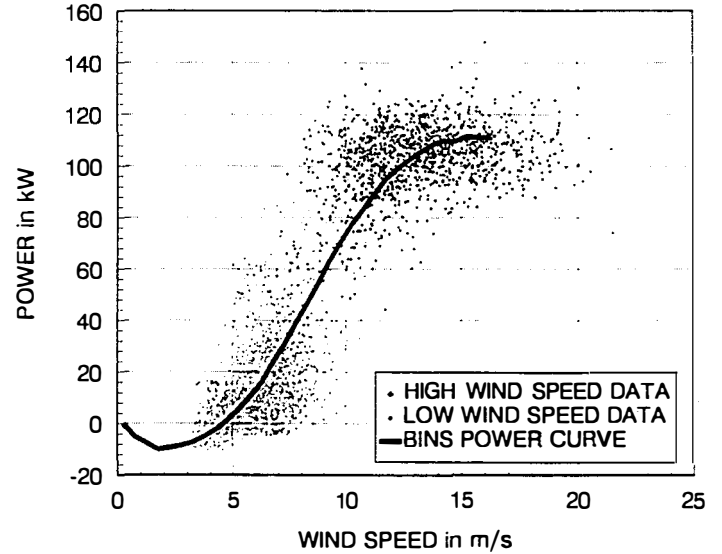


Figure 6. Typical Power Versus Wind Speed Curve Showing Data Scatter

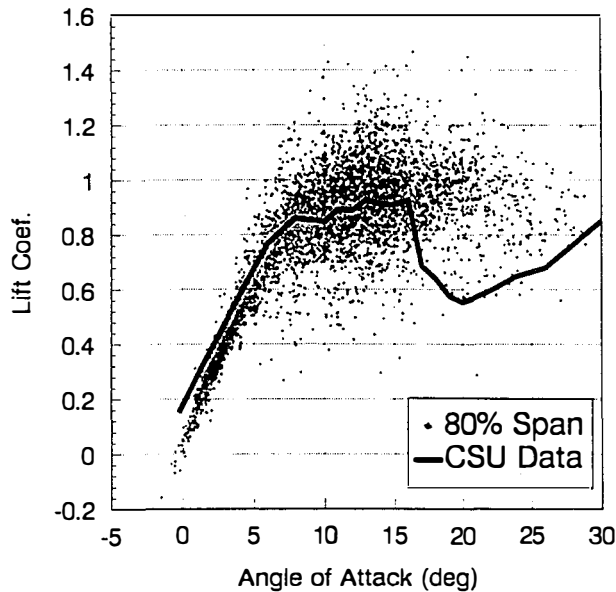


Figure 7. Lift Coefficient Versus Angle-of-Attack from Atmospheric Test Data

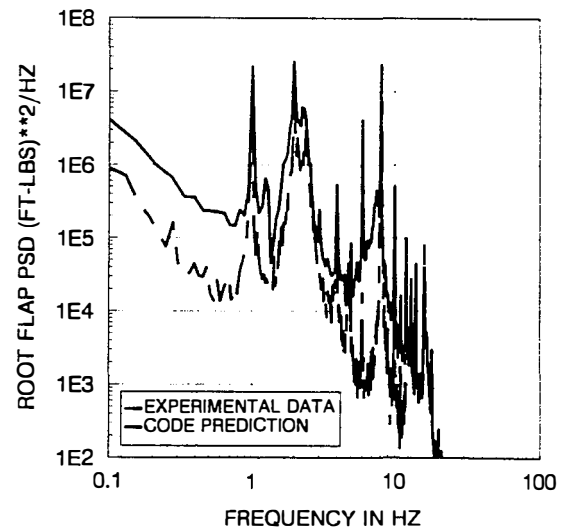


Figure 8. Comparison of Predicted and Measured Root Flap Moment Spectral Densities for Stalled Flow

simulated turbulent wind field, which may contribute to the lack of agreement. However, similar comparisons at lower wind speeds show much better agreement. For this reason, we feel that better models are needed for the stall regime in order to develop acceptable performance and load analyses for advanced rotor systems.

### Fatigue Analysis

Component fatigue failures appear first in complex transition regions where the local stresses are highest. Figure 9 shows the results of a finite element analysis, performed by R. Lynette & Associates, of a wind turbine mainframe and gearbox structural case. The shading indicates the stress distribution throughout these components. The dark regions are the most highly stressed areas where fatigue cracks would first be expected to appear. This finite

element analysis clearly shows the regions of highest stress and gives the designer the opportunity to change the design if the stresses are excessively high. In addition, the high stress regions can be instrumented for laboratory or field testing to validate the final design. The finite-element analysis provides an accurate and practical means to go from applied loads to internal stresses. It is much more accurate than a strength-of-materials analysis for complex components, and it is a critical step in fatigue analysis.

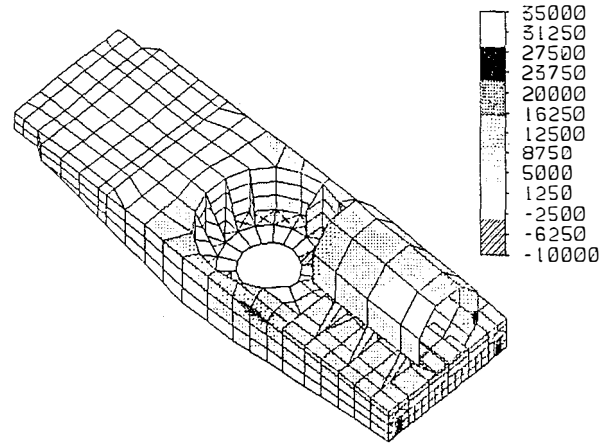


Figure 9. Mainframe Finite Element Model with Gearbox Structure

Sutherland (6) has developed a fatigue analysis code, called the LIFE2 code, for wind turbine design. The methodology of the code requires a stress (strain) time history record as input, uses the Rainflow cycle counting method, and employs either a Fracture Mechanics or Miners Rule approach to accumulate fatigue damage. Figure 10 illustrates the process in general terms. Reference 6 contains additional details on the code. For fiberglass composite rotor blades, a Miners Rule approach to fatigue damage accumulation is generally used. Figure 11 is a strain-versus number-of-cycles-to-failure curve taken from Bach (7) that provides the essential materials damage data for the application of the Miners Rule. The upper curve in Figure 11 is for a stress ratio,  $R = .1$ , where  $R$  is the minimum strain divided by the maximum strain. For  $R = .1$ , the material experiences a cyclic tension loading. For the lower curve, where  $R = -1.0$ , the material experiences cyclic loading that varies from tension to compression. Note the slope of the two curves is much different, as is the allowable strain amplitude at  $10^8$  cycles. This illustrates that the failure mode and damage accumulation rate is different for the two  $R$  ratios.

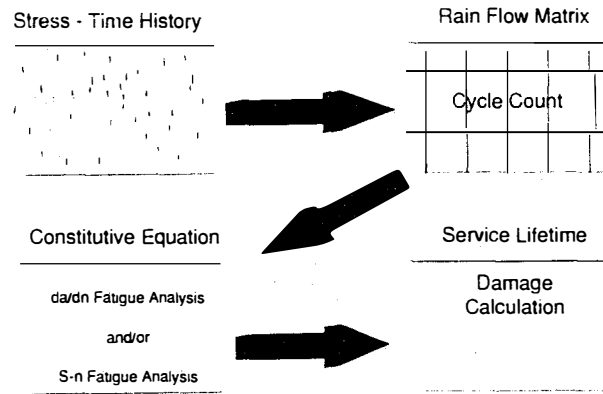


Figure 10. General Analysis Framework for the LIFE2 Code

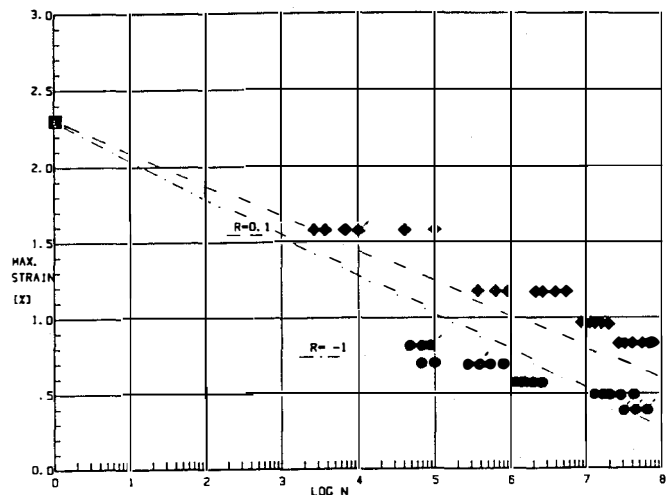


Figure 11. Cyclic Strain Amplitude Versus Cycles to Failure for E-Glass Polyester, 35% Fiber Volume



There are several important fatigue design lessons that can be drawn from this discussion. The fatigue damage rate depends almost entirely on local stresses (strains), and the damage rate is a function of the cyclic amplitudes applied as accumulated using the Rainflow cycle counting scheme. The fatigue failure mode is also important and, for the composite material of Figure 7, is controlled by the cyclic stress state (R value). All of the steps in the fatigue analysis must be accomplished with great care, but perhaps the most difficult task is to experimentally establish the fatigue behavior past  $10^8$  cycles. This is a time-consuming task, and the inherent data scatter often requires a number of replicas be tested to obtain a good statistical basis for the characterization. Furthermore, most fatigue testing is accomplished on small samples of the basic material, which does not represent actual "as-built" structural components very well. For complex shapes the stress state and failure mode may be quite different from a simple flat coupon of the basic material. All of these factors indicate the need to test full-scale substructures, at least to verify the failure modes and design models at higher-than-expected stress levels.

## Conclusions

Based upon the discussions presented in this paper, the authors conclude the following:

1. More information is needed on the turbulence characteristics at potential wind farm locations, both under natural flow conditions and inside of a wind farm where wake effects are important.
2. Unsteady stall affects both performance and loads, and must be accounted for during the design of new components and systems.
3. The structural design and fatigue life analyses must accurately account for:
  - Realistic inflow conditions
  - Unsteady stall
  - Both deterministic and stochastic loads
  - Stress concentrations
  - Rainflow accumulation of cycles
  - Material fatigue past  $10^8$  cycles in the appropriate failure mode
4. A disciplined design process based on careful analysis, development testing, and full-scale verification field testing is essential for the design of reliable new components and systems.

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