Methods for probabilistic design of wind turbines

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Methods for Probabilistic Design of Wind Turbines

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December 1998

Abstract

This report gives a brief introduction to the project “Probabilistic Design Tool for Wind Turbines” – PRODETO – which was carried out during the years 1996-98 with partial funding from the European Commission under the Non-Nuclear Energy Programme JOULE III. The report gives an overview of the objectives and motivation for the project, and the methodology used. In this context, an example of reliability-based wind turbine design against fatigue failure is outlined with emphasis on the various important steps herein, which include probabilistic load and resistance modelling, calculation of failure probability, and calibration of partial safety factors for use with a deterministic design code format. The results of the project are presented with emphasis on a developed computer program and its capabilities, and the various elements of an executed case study are outlined. A list of project reports concludes the report.

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Contents

1 INTRODUCTION

During the period January 1996 through November 1998, the project "Probabilistic Design Tool for Wind Turbines" (PRODETO) has been carried out by a consortium, consisting of the following parties:

- two research institutes (ECN, The Netherlands (Coordinator), and Forskningscenter Risø, Denmark)
- a wind turbine manufacturer (NEG-Micon A/S, Denmark)
- a blade manufacturer (Aerpac, The Netherlands)
- two certifying bodies (Germanischer Lloyd, Germany, and Det Norske Veritas, Denmark)

This report gives an overview of the objectives of the project, and an introduction to the motivation for development of a probabilistic design tool for wind turbines. The methodology used is presented briefly, and the application of the methodology is illustrated by an example for design against fatigue failure. Further, a presentation of the results from the project is given with focus on the developed computer program and the case study that has been carried out. A list of project reports concludes the presentation.

2 OBJECTIVES

The main objectives of the PRODETO project are:

- Development of a computer code for wind turbine manufacturers and certifying bodies to be used partly as a tool for structural reliability analyses of wind turbine components and partly as a tool for calibration of partial safety factors. The prime focus of the computer code is on design of rotor blades against fatigue failure, and the code is able to handle measured as well as theoretically predicted 10-minute load series.
- Transfer of know-how regarding structural reliability analyses and partial safety factor calibration to manufacturers and certifying bodies.
- Extension of the focus of probabilistic analysis of wind turbines to include design against failure in ultimate loading in addition to design against fatigue failure, which has been dominating in studies hitherto.

The project is to a large extent based on procedures developed or described in previous research projects, including European Wind Turbine Standards I, Subproject 2, "Calibration of Safety Factors" [1, 2]. The project is thus mainly an

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[1] C. J. Christensen, E. Jørgensen, K. O. Ronold, J. Wedel-Heinen, B. van der Horn, L. Rademakers: *Calibration of Safety factors*, Part 2, European wind turbine standards, Project Results, EUR 16898 EN, Luxembourg, 1996.

implementation project. One of its prime purposes, in the context of wind turbine design, is to provide a better understanding of what partial safety factors represent and how they are derived and calibrated.

3 MOTIVATION

Safety against failure is the dominating objective in structural design calculations. Safety is a probabilistic concept and can be studied by usual probabilistic theory of structural reliability. This theory concerns the strength of structures that are correctly planned and built. Wind turbines that are correctly planned and built are considered here, and the probabilistic theory of structural reliability is therefore the fundamental basis for the present project.

Structural reliability methods are a family of analysis methods, which can be used to assess structural safety within a probabilistic framework. The structural safety is then expressed in terms of the probability of survival or, alternatively, in terms of its complement, the probability of failure. A traditional design calculation, by a safety check according to a structural design code, is a simplified way of making sure that the probability of failure is acceptably small. The characteristic values of load and resistance, specified by such codes and used for this purpose, are usually specified as certain quantiles in the probability distributions of load and resistance. Structural reliability methods carry this one step further by utilizing more of the information, which is embedded in these probability distributions, to actually calculate probabilities of failure.

Structural reliability methods form the formal and rational basis for calibration of structural design codes. In practice, this means that structural reliability methods can be used as a basis for calibration of the partial safety factors, which are used in traditional deterministic design. A calibration of partial safety factors implies calculation of the values that the partial safety factors need to have such that they, when used in conventional design, ensure that a required low probability of failure is achieved.

Such a calibration is by no means a trivial task. It requires probabilistic models for representation of load and resistance to be established and combined for use in structural reliability analyses. The results of such reliability analyses come out in terms of estimates of failure probabilities. In a probabilistic design, the reliability analyses are tuned by adjusting the structural design appropriately until a required safety level in terms of a particular prescribed failure probability is met. When the particular structural design that exactly meets the prescribed safety thus is established, the corresponding requirement to the partial safety factors in a deterministic code format can be determined.

The application of probabilistic methods to partial safety factor calibration within the wind turbine community is fairly new. During the work on development of design codes for wind turbines in recent years, the need for probabilistic models of load and resistance has become still more evident. In the past few years, work has therefore been undertaken to develop such probabilistic models

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[2] K. O. Ronold, J. Wedel-Heinen, C. J. Christensen, and E. Jørgensen, *Reliability-based Calibration of Partial Safety Factors for Design of Wind Turbine Rotor Blades against Fatique*, EWEC’94, 10-14 Oct. 1994, Thessaloniki, Greece.

for load and resistance. Part of the present project uses the results of some of this work by implementing them within a framework of reliability analyses. This first of all refers to models required for fatigue analyses.

Probabilistic load models necessary for analysis of failure in ultimate loading have been established within the present project. The implementation is made partly in terms of development of a computer code for structural reliability analysis of wind-turbine rotor blades, and partly in terms of demonstration of examples of applications.

4 METHODOLOGY

Structural malperformance is classified into modes of failure, each of which is usually associated with a limit state. Examples are fatigue failure and failure in ultimate loading. Structural reliability methods are used to evaluate the structural safety with respect to one or more failure modes.

As stated above, structural reliability methods form the formal and rational basis for calibration of structural design codes. Structural reliability methods require a mathematical engineering model for the structural problem, which is being considered. The mathematical engineering model is usually based on suitable models for load and for resistance, and it is expressed in terms of the governing load and resistance variables. Further, the structural reliability methods require a probabilistic representation of these governing variables, because they are characterized by randomness and may be encumbered with uncertainties. Such randomness and uncertainty can be categorized into

- natural variability (inherent variability, such as the variability or gustiness of the wind speed, at a given location, over time)
- limited data (statistical uncertainty, such as the uncertainty in a parameter estimate owing to a limited amount of data for the estimation)
- measurement uncertainty (uncertainty due to imperfection of an instrument used to register a quantity)
- model uncertainty (uncertainty due to idealizations and simplifications in engineering models used to represent reality)

and the governing variables are accordingly represented by their probability distributions.

Structural reliability methods give estimates of the probability of failure, P_F.

The application of the methodology to wind turbines is illustrated by an example for fatigue in the following section.

5 EXAMPLE OF RELIABILITY-BASED WIND TURBINE DESIGN: FATIGUE

For fatigue assessment, a model for cumulative damage is used

$$D = \sum_{i=1}^{k} \frac{\Delta n(S_i)}{N(S_i)}$$

in which $\Delta n(S_\mathrm{i})$ is the number of load cycles at stress range S_i, extracted from the stress range distribution over the design life, $N(S_\mathrm{i})$ is the number of cycles to failure at stress range S_i, and the sum is over an appropriate discretisation of the stress range axis. The cumulative damage model used here is the simplest possible Miner-sum model; i.e. it does not take into account in which order the different stress ranges appear. Neither is the mean value of the stress taken into account. Such effects could have been accounted for through application of appropriately chosen correction factors.

Fatigue failure is defined to occur when

$$D \geq 1.0$$

The failure probability is

$$P_\mathrm{F} = P[D \geq 1.0]$$

The capacity or resistance is given by the so-called S–N curve, shown in Fig. 1.

The S–N curve gives on log-log scale the number of cycles N to failure at stress range S. Actually, the curve gives the expected value of log$N$, given log$S$, and there is a natural variability about the expected value of log$N$. The natural variability is illustrated in the diagram, for a particular stress range level, by the associated probability distribution.

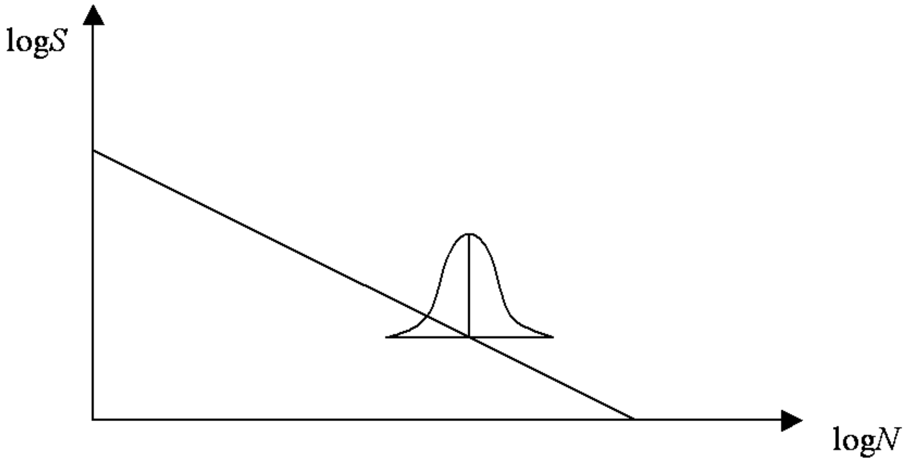

Figure 1: S–N curve.

When n pairs (S_i,N_i) of coherent values of stress range S and number of cycles to failure N are available from measurements on n coupon tests, the S–N curve can be expressed by

$$\log_{10} N_i = \log_{10} K - m \log_{10} S_i + e_i \ , i=1,...n$$

The coefficients ($\log_{10}K$, m) describe the expected behaviour of the S–N curve and can be estimated by a linear regression analysis based on the data. The zero-mean terms e_i denote residuals that represent local variations from test specimen to test specimen, or from one point of the rotor blade to another. $\log_{10}K$, m and e are used as basic stochastic variables, their mean values and standard deviations containing the required information about uncertainties associated with the S–N curve.

The loading is represented by the distribution of the load ranges over the design life of the structure. There are two possible sources for obtaining this distribution. One is an aeroelastic model, which will allow for theoretical predictions of the load range distribution by a simulation technique. The other is a distribution based on full-scale measurements on a specific turbine. Regardless of which approach is chosen, a number of 10-minute time-series are collected, and based on these load series rain-flow counted load range distributions are calculated. Only limited data are available, and the load distributions are sorted by

- 10-minute mean wind speed U_{10}
- 10-minute mean turbulence intensity I_T

and interpreted with respect to load range distributions conditioned on the wind climate (U_{10},I_T). The conditional load range distributions are fitted to some suitable generic distribution, e.g. a three-parameter Weibull distribution. Uncertainty in this distribution owing to the limited amount of data can now be represented as statistical uncertainty in the three Weibull-parameters. In practice, these three parameters are therefore represented by probability distributions. The variation of the distribution parameters and their uncertainties over the mean wind speed U_{10} and the turbulence intensity I_T is described in a suitable mathematical form, e.g. a polynomial of order 2 in U_{10} and I_T. The polynomial coefficients are then determined by estimation from the available measured or simulated load range distributions.

Integration of the conditional load range distributions with respect to the site-specific distribution of the wind climate (U_{10},I_T) leads to the unconditional long-term distribution of load ranges over a specified design life. For fatigue of the rotor blade at the blade root, the load range will typically be the bending moment range M. The corresponding stress range S is then obtained by dividing by the section modulus W, $S=M/W$. Reference is made to Figure 2, in which n denotes the number of bending moment ranges exceeded at level M.

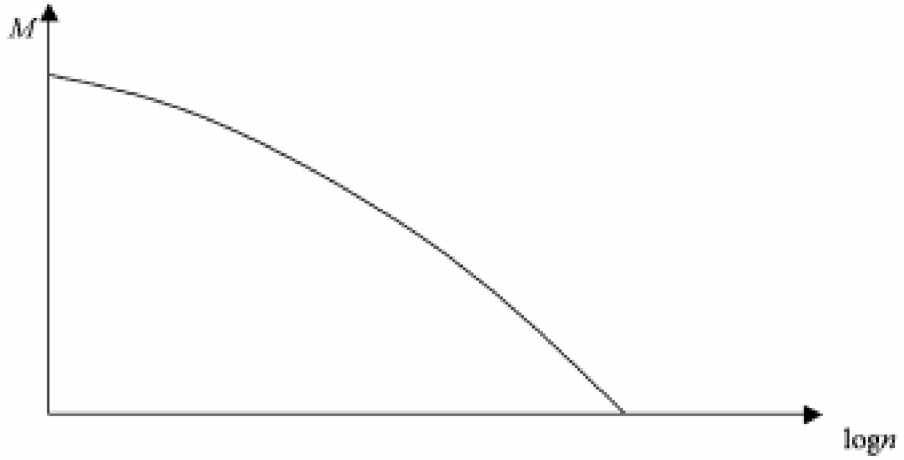

Figure 2: Long-term distribution of bending moment range over design life.

The load distribution is now represented with the following uncertainties included

- statistical uncertainty owing to limited data, included as uncertainty in the three Weibull distribution parameters
- model uncertainty owing to use of idealized (generic) distribution model, included as a random factor on the damage predicted by the Miner's sum

Likewise, the resistance model (S–N curve) is represented with the following uncertainties included

- statistical uncertainty owing to limited data, included as uncertainty in the estimates of the coefficients ($\log_{10}K$, m)
- natural variability in number of cycles to failure, represented by the distribution of the residual e

Note that there may be other uncertainties present, such as model uncertainties associated with the S–N curve formulation and the use of Miner's sum for damage prediction, but they have not been considered here.

The probability of failure

$$P_F = P[D \geq 1.0]$$

can be calculated in a selected critical point, for example at the blade root, and a structural reliability method is used for this purpose. P_F will change when the section modulus W is changed. W is used as design parameter and is adjusted until a satisfactory P_F is achieved from the reliability analysis. Typically, a target value of P_F shall be in the range 10^{-4}-10^{-5} per year.

The above forms the probabilistic basis for the calibration of partial safety factors. In conventional deterministic design one will need to define characteristic loads and characteristic resistance and then by means of partial safety factors establish design loads and design resistance and carry out the design.

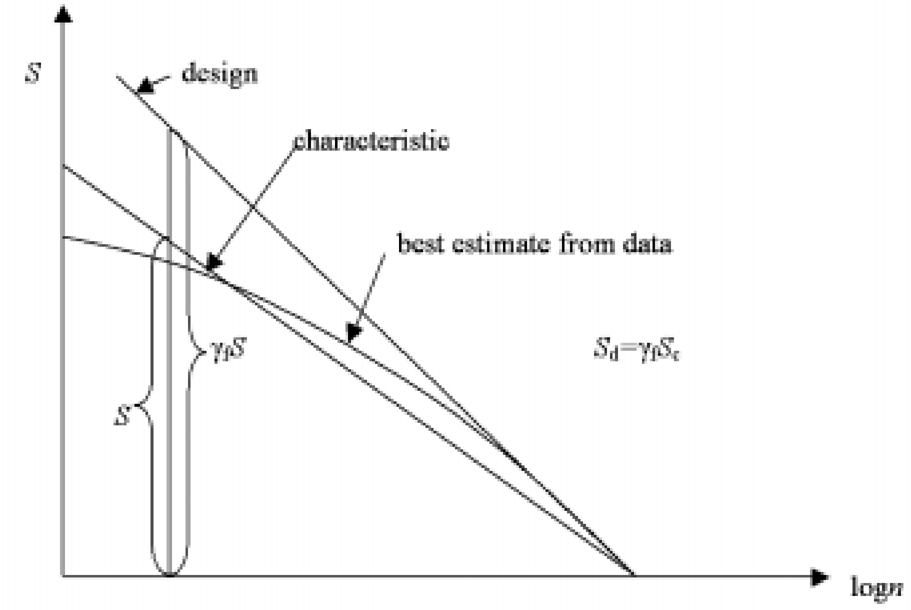

Figure 3: Expected load distribution based on data, characteristic load distribution, and design load distribution.

Consider first the load distribution. The characteristic load distribution is taken as some idealized load distribution, usually close to the expected distribution as based on data. The idealization may for example consist of using a straight line as shown in the diagram. The design distribution is obtained by multiplying all characteristic stress range values by a partial safety factor γ_f. This factor is usually referred to as a load factor. Reference is made to Figure 3.

Consider next the resistance. Reference is made to the *S*–*N* curve representation in a log*S*-log*N* plot. The characteristic *S*–*N* curve is taken as the curve that results when the mean curve estimated from data is shifted to the left by two standard deviations of the variability in log*N* about the mean curve. The design *S*–*N* curve is obtained by dividing all characteristic stress range values by a partial safety factor γ_m. This factor is usually referred to as a materials factor. Reference is made to Figure 4.

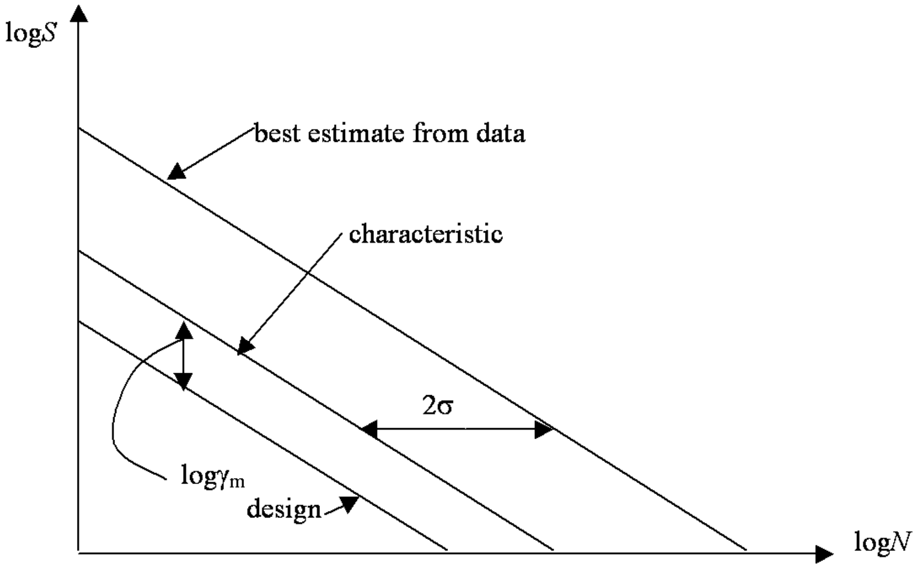

Figure 4: Mean S–N curve, characteristic S–N curve, and design S–N curve

The design criterion is a criterion on the design damage

$$D_d = \sum_{i=1}^{k} \frac{\Delta n_d(S_i)}{N_d(S_i)} = 1.0$$

i.e. in deterministic design one will for

- given characteristic load distribution
- given characteristic *S*–*N* curve
- given set of partial safety factors (γ_f,γ_m)

determine the particular section modulus *W* that yields D_d=1.0.

The calibration of partial safety factors for a specific design case of one wind turbine and one specific location can now be carried out in the following two steps:

- By structural reliability analysis, determine the value of *W* that leads to the desired (target) failure probability $P_{F,T}$.
- For this particular value of *W* and the specified characteristic load and resistance, find the set (γ_f,γ_m) which leads to D_d=1.0. This particular set (γ_f,γ_m) is the requirement to the partial safety factors that will lead to a design, which meets the target failure probability $P_{F,T}$.

Note that different sets (γ_f, γ_m) will result for different wind turbines and for different locations. The ultimate goal in a calibration of a design code would be to find a common set of partial safety factors that can be used for a family of design cases (combinations of wind turbines and locations) such that the resulting safety levels would get minimum deviation from the target. This ultimate step has not been dealt with in the PRODETO project, and results are limited to calibration of site- and turbine-specific sets of partial safety factors for a limited number of failure modes.

Note also that the chosen characteristic curves for load and resistance may not necessarily reflect the true measured or physical curves particularly well. However, they are part of a chosen code format and represent practical choices that are easy to operate on. The partial safety factors are defined with reference to this choice, and the subsequent calibration of the partial safety factors ensures that a requirement to the safety factors comes out that will lead to designs with the prescribed safety level.

6 COMPUTER PROGRAM

A computer program for structural reliability analysis of wind-turbine rotor blades subjected to fatigue loading has been developed. The program is based on the general-purpose structural reliability program RELIAB1, which is commercially available, and which has been tailor fitted with the necessary subroutines for carrying through probabilistic fatigue analyses of rotor blades. RELIAB1 is marketed by CSR Consult.

With pre-processors that can transform measured or theoretically predicted loads to distributions of load range by rain-flow counting, and with a family of generic distribution models for parametric representation of these distributions available, this computer program allows for reliability analysis of rotor blade roots against fatigue failure. The available distribution models are general enough that flapwise as well as edgewise loading can be treated.

The program has been subject to extensive verification including comparisons with results obtained by similar computer programs with comparable capabilities.

The program comprises the following main features

- representation of wind climate in terms of generic long term distributions of 10-minute mean wind speed and turbulence intensity
- parameterization of short-term distribution of bending moment range distributions in the rotor blades, conditional on the wind climate, in terms of the three first statistical moments, which can be estimated from measurements or from simulated distributions, and which may be encumbered with statistical uncertainty owing to limited data
- characterization of the statistical moments of the bending moment range distributions in the rotor blades, and of the standard deviations in their statistical estimates, as functions of the 10-minute mean wind speed and the turbulence intensity
- representation of short-term distribution of bending moment ranges in the rotor blades, conditional on the wind climate, by a generic distribution such as the three-parameter Weibull distribution, and representation of the statistical uncertainty in the distribution parameters by modelling these with a random variation
- representation of the long-term distribution of bending moment ranges in the rotor blades, i.e. the so-called lifetime load spectrum, by integration of the short-term distributions over all wind climates during the design life according to their distribution
- representation of the fatigue properties of the rotor blade material in terms of an ε–N curve that gives the number of cycles to failure N for given values of the strain amplitude ε. A linear relationship leads from strain ε to bending stress ranges S.
- representation of the inherent uncertainty in the fatigue strength by a random variation of N about the mean ε–N curve, and representation of statistical uncertainty in the mean ε–N curve by a random variation of the coefficients that describe this mean curve
- characterization of cumulative fatigue damage by a Miner’s sum approach
- representation of model uncertainties associated with various idealizations and simplifications made, e.g. in the load characterization by generic distributions and in the use of the Miner’s sum approach, by a random model uncertainty factor on the fatigue damage predicted by Miner’s sum
- estimation of the probability of fatigue failure in the design lifetime of a rotor blade by a first-order reliability method

7 CASE STUDY

7.1 Fatigue failure in flapwise bending

A case study has been performed, covering analyses of the rotor blades of a prototype wind turbine. The prime focus of the analyses has been on design against fatigue failure in flapwise bending, with application of the procedures outlined above. One set of analyses has been carried out based on load measurements obtained at two different locations, one in Denmark and one in the Netherlands. Another set of analyses has been based on predicted load distributions, simulated according to state-of-the-art theory of aeroelasticity.

The results of the analyses have been interpreted with respect to estimation of the probability of fatigue failure in the design lifetime of the rotor blades, and with respect to identification of the most important uncertainty sources. It is a general finding from all analyses performed that the single most important uncertainty source is the inherent variability in the number of cycles to failure as represented by the ε–N curve. The analyses have all been carried one step further in the sense that they have been used as a basis for calibration of a site- and turbine-specific set of two partial safety factors, one on load and one on resistance, for use in conventional deterministic fatigue design. The analysis outlined above only yields a requirement on the product of the two safety factors. A procedure is given for how to transform this requirement to separate requirements on the two safety factors based on detailed results from the underlying reliability analysis.

7.2 Fatigue failure in edgewise bending

Some thoughts regarding fatigue failure in edgewise bending have been given, although no detailed fatigue analysis has been carried through. The major difference between flapwise and edgewise bending is that the loading in edgewise bending is dominated by a gravity term. Whereas a three-parameter Weibull distribution is an adequate short-term distribution for the flapwise bending moment, a bimodal distribution, whose domineering upper part is well represented by a two-parameter Weibull distribution, is a suitable model for the short-term distribution of the edgewise bending moment.

7.3 Failure in ultimate loading

A study of the reliability against failure in ultimate loading has also been carried out. However, this study has been limited to failure in flapwise bending in the normal operating condition at one location only. The marginal distribution of local maxima of the flapwise bending moment response at the blade root has been calibrated from measurements of the flapwise bending moment response process. The governing strength has been taken as the tensile strength in the direction of the fibers in the laminated rotor blade. The probability of failure in ultimate loading has been calculated by integration of probability contributions from all local maxima of the bending moment in the normal operating condition over the design life of the wind turbine. This has been accomplished through the execution of a so-called nested reliability analysis. It has been demonstrated that it would have been insufficient to consider only the failure probability for the largest bending moment in the normal operating condition over the design life, as other bending moments than the largest contribute significantly to the total failure probability. The analysis results were found to be very sensitive to the choice of the cutout wind speed that separates the normal operating condition from standstill in the high wind speed region. As the deterministic cutout wind speed thus to a large extent governs the loading, it was not unexpected to find from the analysis that the uncertainty in the tensile strength of the rotor blades is the single most important uncertainty source. Also the analysis of failure in ultimate loading has been carried one step further by calibration of a site- and turbine-specific set of two partial safety factors, one for load and one for resistance, for use in conventional deterministic design.

7.4 Variability of wind speed

The relation between the longitudinal wind speed standard deviation and the mean wind speed has also been studied as part of this project. This is essential for the present project for two reasons. First, the wind speed standard deviation is the crucial climate parameter that governs the various extreme wind situations required in the wind turbine code, IEC 61400-1. Second, the distribution of standard deviations plays an important role in the climate description used for the probabilistic fatigue analysis model presented above. Essential results from this study include: A proposal for a new and milder design turbulence intensity prescription for offshore applications, which are currently becoming of great interest. An investigation of the relation between the mean wind speed and the 80% quantile of the distribution of the wind speed standard deviation, given in IEC 61400-1, ed. 2, revealed a certain degree of conservatism in this code with respect to the Danish climate data used. It was found that the distribution of the turbulence intensity might be described by some Weibull type distribution for this purpose. Further studies of the tails of the distribution seem warranted, as a lognormal distribution appears to be advantageous for other purposes.

8 SUMMARY

A brief introduction to the project “Probabilistic Design Tool for Wind Turbines” – PRODETO – has been given. This project was carried out during the years 1996-98 with partial funding from the European Commission under the Non-Nuclear Energy Programme JOULE III. An overview of the objectives and motivation for the project has been given, and the applied methodology has been outlined. In this context, an example of reliability-based wind turbine design against fatigue failure has been presented. This has been done with emphasis on the various important steps during such a design, including the probabilistic load and resistance modelling, the calculation of the failure probability, and the calibration of partial safety factors for use with a deterministic design code format. The results of the project have been presented with emphasis on the developed computer program and its capabilities, and on the executed case study. The focus in the case study has been on the design of a rather specific detail of a rotor blade, namely the blade root, which has been selected as a hot spot, and which has been considered with respect to a couple of different failure modes. Nevertheless, it is important to acknowledge that the methods are generally applicable and can be applied to design at any point along the rotor blade. The methods are also applicable to design against other failure modes than those considered, e.g., buckling. A list of project reports has been given.

9 LIST OF PROJECT REPORTS

L.W.M.M. Rademakers, P. Vink, P.A. van der Werff, *Mechanical Measurements at the Micon M1500 - 600/150kW with Aerpac APX40-T Blades*, ECN Report No. ECN-CX--96-123, Petten, The Netherlands, May 1997. (Confidential.)

Ronold, K.O., *Calibration of Partial Safety Factors for Design of Wind-Turbine Rotor Blades against Fatigue Failure in Flapwise Bending – Micon M1500*, DNV Report No. 97-2049, Høvik, Norway, September 1997. (Confidential.) This is an early interim report. An updated version of this report is included as a separate chapter in the case study report.

Braam, H., *Results of Probabilistic Fatigue Analyses for the Micon M1500 Wind Turbine in Lutjewinkel*, ECN Memo, Petten, The Netherlands, 1998.

Braam, H., C.J. Christensen, J.J.D. van Dam, G.C. Larsen, K.O. Ronold, and M.L. Thøgersen, *Probabilistic Design Tool (PRODETO). Final Report*, ECN, Petten, The Netherlands, October 1998. (Confidential.)

Braam, H., K.O. Ronold, C.J. Christensen, *PRODETO – Computer Program. Theory and program structure*, ECN Report No. ECN-C--97-093, Petten, The Netherlands, May 1998.

van Dam, J.J.D., and P.A. van der Werff, *Load Calculations for the Micon M1500-600/150 kW with Aerpac APX40-T Blades*, ECN Report No. ECN-C--98-062, Petten, The Netherlands, June 1998. (Confidential.)

Ronold, K.O., *Reliability Analysis of Wind-Turbine Rotor Blades against Failure in Ultimate Loading in the Normal Operating Condition – Micon M1500*, DNV Report No. 98-2043, Høvik, Norway, August 1998. (Confidential)

Christensen, C.J., J.T. Petersen, K.O. Ronold, G.C. Larsen, and M. Thøgersen, *PRODETO. Case Study of a Micon M1500/600 Wind Turbine with Aerpac APX40 Blades*, Risø Report No. Risø-I-1306(EN), Risø, Denmark, October 1998. (Confidential.)

Larsen, G.C., and H.E. Jørgensen, *Variability of Wind Speeds*, Risø, Denmark, 1998.

H. Braam, C.J. Christensen, J.J.D. van Dam, G. Larsen, K.O. Ronold, M.L. Thøgersen, K. Argyriadis. J. de Boer, *Probabilistic Design Tool (PRODETO). Publishable Final Report*, ECN, Petten, The Netherlands, November 1998.

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18	0	5	2

Abstract (max. 2000 characters)

This report gives a brief introduction to the project “Probabilistic Design Tool for Wind Turbines” – PRODETO – which was carried out during the years 1996-98 with partial funding from the European Commission under the Non-Nuclear Energy Programme JOULE III. The report gives an overview of the objectives and motivation for the project, and the methodology used. In this context, an example of reliability-based wind turbine design against fatigue failure is outlined with emphasis on the various important steps herein, which include probabilistic load and resistance modelling, calculation of failure probability, and calibration of partial safety factors for use with a deterministic design code format. The results of the project are presented with emphasis on a developed computer program and its capabilities, and the various elements of an executed case study are outlined. A list of project reports concludes the report.

Descriptors INIS/EDB
Structural reliability, wind turbines, partial safety factors, fatigue failure, probabilistic design, rotor blades, GRP, turbulence, ultimate loading

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